SWISS NATIONAL SCIENCE FOUNDATION

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Wildhainweg 3, Postfach 8232, CH-3001 E

Formulaire de requête mySNF

Instrument **PRN - esquisse**

1ère partie: indications générales

Aperçu général

Titre du projet	The Universe: Constituents, Forces, Space-Time
Titre en anglais	The Universe: Constituents, Forces, Space-Time

Domaine de recherche	Mathématiques et sciences naturelles
Discipline principale	20403 Physique des particules élémentaires
Institution hôte	Université de Genève - GE

Requérant-e-s

Requérant-e responsable	**Martin Pohl**

Requête

Montant sollicité (CHF)	Total	**19'380'000**
Début sollicité	**01.01.2014**	
Durée sollicitée (mois)	**48**	

Annexes

Description du projet	SciencePart_NCCR-Universe.pdf
CV et liste de publications	CV_Publist_Pohl.pdf
	CV_Publist_Kirch.pdf
	CV_Publist_Iacobucci.pdf
	CV_Publist_Spira.pdf
	CV_Publist_Durrer.pdf
	CV_Publist_Rivkin.pdf
	CV_Publist_Blondel.pdf
	CV_Publist_Neronov.pdf
	CV_Publist_Refregier.pdf
Lettre d'accompagnement	NCCR_Universe_coverletter.pdf
Autres annexes	brochure_final_prelim_version_20120115.pdf
Lettre de soutien de l'institution hôte	Eigenleistungen_Letter_Mesot_Kirch_Universe_PSI.pdf
	Eigenleistungen_Heiminstitution_NCCR_Universe_PSI.pdf
	Pohl_Commitment_HomeInstitution.pdf
	Pohl_Selffunding_Homeinstitution.pdf
Budget	Budget_NCCR_Universe.pdf

Documents envoyés par courrier

1. Requérant-e responsable (directeur /trice du PRN)

Nom	**Pohl**
Prénom	**Martin**
Fonction (titre)	Professeur
Grade universitaire	Prof.
Date de naissance	18.09.1951
Sexe	masculin
Etat civil	Marié-e
Langue	Français
Nationalité	Suisse
Adresse de correspondance pour la requête	Adresse prof.

Adresse privée

Complément à l'adresse	
Rue, no	Avenue de Champel 4
Case postale	
NPA	1206
Lieu	Genève
Pays	Suisse

Adresse de l'institut

Nom de l'institution I (par ex. laboratoire)	
Suite 2 (par ex. Inst/dép)	DPNC
Suite 3 (par ex. Université)	Université de Genève
Rue, no	24, quai Ernest-Ansermet
Complément à l'adresse 1 (par ex. bâtiment)	
Complément à l'adresse 2 (par ex. bureau)	
Case postale	
NPA	1211
Lieu	Genève 4
Pays	Suisse

Communication

Tél. secrétariat (p.ex. +41 31 643 44 55)	+41 22 379 62 73
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Tél. direct	+41 22 379 68 23
Téléfax (prof.)	+41 22 379 69 92
Tél. privé	+33 450 40 40 75
Tél. mobile	+41 76 487 04 05
Site Web	http://dpnc.unige.ch
Adresse courriel	martin.pohl@unige.ch

2. Données de base I

Titre original	The Universe: Constituents, Forces, Space-Time
Titre en anglais	The Universe: Constituents, Forces, Space-Time
Début sollicité	01.01.2014
Durée sollicitée (mois)	48
Domaine de recherche	Mathématiques et sciences naturelles
Discipline principale	20403 Physique des particules élémentaires
Autre-s discipline-s	20200 Astronomie, astrophysique et recherche spatiale
	20401 Physique théorique

3. Données de base II

Résumé

The NCCR Universe proposes to federate Swiss research in the fields of particle physics, cosmology and astrophysics to advance the extraordinary capability and visibility of our country by allowing science to develop in new directions and inspire new generations of visionaries. The creation of NCCR Universe will allow Switzerland to not only strengthen its activities in fundamental physics, but also implement transversal structures between the main directions of existing and future efforts. It will provide a "home" for the large pool of national and international scientists who have established their research in proximity of Geneva in the past decades. It will also refocus on activities at our national laboratory PSI. Organizing and managing the national network of academic and applied research will optimize efficiency and resources as well as help modernize teaching.

NCCR Universe proposes an innovative approach by organizing the research by themes and thus crossing traditional boundaries. Using the existing "resources" (neutrino, high energy and astroparticle physics), three scientific topics have been identified as the major Challenges of our times: elementary constituents and forces, dark matter and dark energy, sources and acceleration of particles. Never yet addressed as such in Switzerland, these research themes seek answers to issues on the basic laws of Nature, the role of gravity, and inconsistencies of the Standard Model with our current understanding of particle physics.

Studied by physicists from different disciplines - experimental particle physics, astrophysics, observational cosmology and theoretical physics - these Challenges allow us to combine insights from controlled accelerator experiments as well as make use of data from astrophysical and cosmological observations. The approach also allows us to exploit the phenomenal synergies between the traditional research directions in terms of experimental techniques, analysis methodology and cross-fertilization between theory and experiment.

Switzerland's large public investment in CERN's infrastructure has led to attract and form leaders in the field of experimental physics in our region. Yet, the return in terms of developments in fundamental research done in Swiss institutions and the resonance of our country abroad has not been able to match this effort due to a lack of a global centralizing body and a long term investment in manpower. The opportunity to create an NCCR providing a unique academic and research infrastructure in particle physics would streamline and solidify our field within Switzerland and position it worldwide.

Mots clés	Particle physics
	Cosmology
	Astrophysics
Langue de correspondance	Français
Service de gestion des subsides	Université de Genève Comptabilité centrale

4. Institution hôte

Institution hôte	Université de Genève - GE
Remarques	Co-leading house: Paul Scherrer Institut - PSI

5. Besoin financier

Budget par an (aperçu)

Subside

Rubrique	Total FNS (CHF)	Année 1	Année 2	Année 3	Année 4
Octroi global	19'380'000	4'720'000	4'820'000	4'870'000	4'970'000
Total FNS (CHF)	**19'380'000**	**4'720'000**	**4'820'000**	**4'870'000**	**4'970'000**
Total FNS (CHF)	**19'380'000**	**4'720'000**	**4'820'000**	**4'870'000**	**4'970'000**

Budget par an (détail)

Values in brackets represent items requested from other sources than SNF

Pas de sous-projet

	Total FNS (CHF)	Année 1	Année 2	Année 3	Année 4
Subside					
Octroi global					
Personnel and operational cost estimate	19'380'000	4'720'000	4'820'000	4'870'000	4'970'000
Self-funding, sum of cash and in-kind contributions by UniGe and PSI	*(7'400'000)*	*(1'450'000)*	*(1'650'000)*	*(1'950'000)*	*(2'350'000)*
Total FNS (CHF)	**19'380'000**	**4'720'000**	**4'820'000**	**4'870'000**	**4'970'000**

6. Remarques générales relative à la requête

Désignation abrégée	
Communication	
Confidentiel	Non

UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES

SECTION DE PHYSIQUE
DÉPARTEMENT DE PHYSIQUE NUCLÉAIRE ET CORPUSCULAIRE
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Tél. +41 22 379 68 23 | Fax +41 22 379 69 92
http://dpnc.unige.ch

Martin Pohl
Directeur du DPNC

Swiss National Science Foundation SNSF
NCCR Programme Office
P.O. Box
3001 Bern

Subj: Proposal Sketch for the NCCR "The Universe: Constituents, Forces, Space-Time"

Genève, 16 janvier 2012

Dear Colleagues,

Please find enclosed our pre-proposal for an NCCR entitled: "The Universe: Constituents, Forces, Space-Time". This sketch represents an innovative approach to fundamental questions in the fields of particle physics, cosmology and high-energy astrophysics. Traditional research lines are seen as resources, dedicated to answer concise questions about ordinary matter, dark matter and dark energy as well as particle sources and acceleration, both man-made and of cosmic origin. The federation of resources and researchers in these disciplines will liberate an enormous synergy and ensure our efficient and sustainable utilization of existing and future infrastructure.

Making researchers in particle physics, cosmology and astrophysics work together is not a trivial matter, since these fields involve different methodology, nomenclature and scientific culture. Making theoretically and experimentally oriented physicists work together more closely is an equally challenging project. The proponents, almost 50 Swiss researchers active in the field, firmly believe that an NCCR is the right approach to confront these challenges. As the LHC starts to provide answers to fundamental questions like the existence of the Higgs particle, as first class astrophysical instruments deliver statistically significant and systematically reliable data on dark matter and dark energy, as new ideas are required to respond to old questions, it is the right time to attribute the human resources required to ensure an important Swiss footprint in this multidisciplinary field.

We gratefully acknowledge the strong support and encouragement by the prospective home institutions, as expressed in the commitments both University of Geneva and the Paul Scherrer Institut are prepared to make. Together with the partner institutions from across Switzerland, this will ensure the success of this NCCR once approved.

We are at your entire disposal for any further information you may wish to have in the context of this proposal sketch.

Best regards

Martin Pohl

Martin Pohl

UNIVERSITÉ DE GENÈVE
RECTORAT

Le Recteur
Professeur Jean-Dominique Vassalli
Ligne directe: 022 379 75 13
Jean-Dominique.Vassalli@unige.ch

Fonds national suisse
Division IV
Pôles de recherche nationaux
Case postale 8232
Wildhainweg 3
3001 Berne

Genève, le 16 janvier 2012

Concerne : 4ème mise au concours des Pôles de Recherche Nationaux (PRN)
Projet ***Universe*** - Soutien de l'institution-hôte

Monsieur le Président, Madame, Monsieur,

Le projet *UNIVERSE* se propose d'établir, à l'Université de Genève, la *leading house* d'un Pôle de recherche national (PRN) dans le domaine de la physique des particules, de la cosmologie et de l'astrophysique. L'institut Paul Scherrer est fortement impliqué dans ce projet et sera *co-leading house*.

Avec l'établissement du CERN sur son territoire, Genève est devenu le principal lieu de recherche au monde dans le domaine de la physique des particules. Ce domaine s'est rapproché dans les dernières années de la cosmologie et de l'astrophysique par une fertilisation croisée. D'un côté, l'univers recèle des particules atteignant des énergies impossibles à reproduire sur terre. De l'autre, la physique des particules est, aujourd'hui, un outil indispensable à la compréhension de la formation et du développement de l'univers.

Au lieu de s'organiser autour des champs traditionnels de recherche ou des techniques d'investigation disponibles, ce projet innovant s'articule autour de trois sujets qui représentent des défis majeurs à la compréhension de notre univers : 1) les forces et constituants élémentaires, 2) la matière noire et l'énergie noire, 3) les sources et l'accélération des particules.

Si la qualité scientifique et l'intérêt global de ce projet nous semblent ne pas pouvoir soulever de doute et suscitent notre enthousiasme, d'autres dimensions de ce projet interpellent également très fortement l'institution d'accueil choisie par les auteurs du projet. Nous relevons plus particulièrement les aspects suivants:

- Le caractère très fédérateur de ce projet qui rassemblera toute la communauté scientifique dans le domaine de la physique des particules en Suisse.

- Le fort ancrage de ce projet sur le plan international, de par ses relations avec les organisations internationales, et grâce à la forte implication des *Project leaders* dans des projets internationaux, dont des projets de l'Union européenne (chapitre 5 de la requête au sujet du *International networking),* constitue également un soutien à la politique de développement de l'Université de Genève dont une des priorités est de renforcer la dimension internationale de l'institution.

- Le fait que les *Project leaders* impliqués dans ce projet jouissent d'une excellente réputation nationale et internationale, confirmée par la reconnaissance de leurs pairs. Cette excellence se reflète également dans leur capacité d'acquisition de fonds de recherche.

1) Adéquation du projet avec la politique institutionnelle

Le Rectorat de l'Université de Genève peut confirmer que le projet *UNIVERSE* se trouve en pleine conformité avec sa politique de développement, ce qui constitue un gage pour la mise à disposition de ce PRN des conditions cadres favorables. Le projet répond très clairement à plusieurs objectifs stratégiques institutionnels. Nous mentionnerons plus particulièrement les objectifs stratégiques suivants de notre institution:

Le projet *UNIVERSE* s'inscrit pleinement dans la stratégie de l'Université de Genève puisque le renforcement d'un pôle d'excellence en sciences physiques, incluant l'astrophysique, fait partie des priorités de son plan stratégique à long terme « Vision pour 2020 ». L'Université a aussi comme objectifs « l'intensification de la présence de l'institution dans la cité », avec en particulier le développement des liens avec la Genève internationale, et « le renforcement de la dimension internationale de l'institution ». Ce projet contribuera fortement à la réalisation des ces objectifs.

Le développement de notre Université est étroitement lié au renforcement de l'ensemble du système universitaire suisse et de son niveau d'excellence. Les PRN sont un instrument privilégié d'une telle vision pour l'avenir de la science sur le plan national. Notre Rectorat s'engage à soutenir cet effort commun. Nous relevons que le projet *UNIVERSE* associera des groupes de recherche d'autres universités suisses: Les Universités de Bâle, de Berne et de Zurich, les écoles polytechniques fédérales de Lausanne et de Zurich, et l'institut Paul Scherrer sont invités à la direction de projets individuels. Cette circonstance est de nature à conférer à ce pôle une véritable dimension nationale et à renforcer les liens de notre Université avec ses partenaires suisses, ce qui correspond à nos objectifs institutionnels.

Ce projet constitue de ce fait non seulement un facteur déterminant pour le développement scientifique en général, mais il contribuera aussi au développement de son institution d'accueil dans son ensemble comme à celui de ses institutions partenaires.

Pour ces raisons, le Rectorat de l'Université de Genève s'engage à soutenir ce PRN sur les plans financiers et organisationnels. Il mettra tout en œuvre pour se porter garant auprès du Fonds national de la recherche scientifique d'un développement de ce pôle dans la durée.

2) Mesures structurelles prévues

Notre université a une expérience confirmée d'accueil de Pôles de Recherche Nationaux et l'attribution par le FNS de plusieurs PRN à l'Université de Genève a profondément remodelé la structure de cette dernière.

Le Rectorat de l'Université mettra un accent particulier sur le renforcement de la recherche scientifique et la formation de la relève dans le domaine du PRN.

D'ores et déjà en 2011 la conversion d'un poste de MER en Professeur ordinaire au Département de physique nucléaire et corpusculaire vers le domaine « astroparticules expérimentales » et la création d'un poste de professeur ordinaire au département de physique théorique dans le domaine « astroparticules théoriques et cosmologie » en 2011 attestent du renforcement de la thématique au sein de la Faculté des sciences.

L'Université veillera également à tenir compte des besoins du PRN lors des successions professorales futures. Il est déjà prévu la nomination d'un Maître d'Enseignement et de Recherche en astroparticules au Département de physique nucléaire et corpusculaire, la nomination d'un professeur assistant ou associé dans le domaine « physique des particules aux collisionneurs » et la conversion d'un poste de MER en professeur associé dans le domaine « astroparticules expérimentales ».

De plus, en cas d'acceptation du projet par le FNS, l'Université de Genève assurera le financement de postes structurels supplémentaires, notamment la création d'un nouveau poste de professeur assistant *tenure track* dans le domaine du PRN.

L'Université de Genève a récemment renforcé la visibilité de la physique des particules en regroupant la section de physique et le département d'astrophysique au sein du Centre pour la physique des Astroparticules (CAP) créé en 2011. Si ce projet de PRN est retenu, il pourra être intégré dans le nouveau « Centre des sciences astronomiques, physiques et mathématiques » de l'Université de Genève, actuellement en phase de planification, et qui inclut un nouveau bâtiment et de nouvelles structures. Cela permettra de promouvoir des projets interdisciplinaires, d'encourager des recherches dans ces domaines, de garantir la visibilité de cet axe prioritaire et de lui donner une ouverture vers la cité.

3) Dimensions financières

En cas d'acceptation du PRN *UNIVERSE* l'Université de Genève s'engage à contribuer aux prestations indiquées dans le formulaire « Prestations propres de l'institution hôte » et en particulier :

- une décharge d'enseignement au professeur Martin Pohl afin qu'il puisse assumer les tâches liées à sa fonction au sein de ce PRN. La contribution de notre institution est évaluée à cet égard à CHF 280'000 pour la première phase quadriennale du projet.
- une contribution directe *(cash money)* apportée par le Rectorat au nom de l'institution d'accueil, de CHF 1'600'000 pour la première phase quadriennale.
- des prestations in kind apportées par le Rectorat et les facultés (total CHF 1'800'000).

Comme mentionné ci-dessus, en cas d'acceptation du projet par le FNS, l'Université de Genève assurera le financement de postes structurels supplémentaires, notamment la création d'un nouveau poste de professeurs assistants à partir de 2015. Une enveloppe de CHF 600'000 est comprise à cet effet dans le tableau « in kind contribution ».

Les autres postes dans le budget in kind comprennent notamment l'augmentation des forfaits FNS pour les doctorant(e)s à hauteur de CHF 800'000.

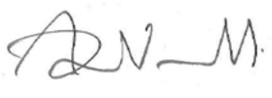
Nous tenons pour finir à rappeler que les engagements pris par l'Université de Genève pour les PRN qu'elle héberge ont, par le passé, non seulement été tenus mais systématiquement dépassés, démontrant ainsi que notre institution soutient avec le plus grand sérieux ces instruments de développement mis en place par le Fonds National.

Dans ce sens, les chiffres indiqués ci-dessus doivent être compris comme un engagement assuré de l'Université de Genève auquel s'ajouteront certainement des moyens supplémentaires en soutien au développement d'un PRN qui est parmi nos priorités majeures.

Il va de soi que l'Université assurera la mise à disposition des infrastructures existantes et de l'équipement de base du pôle selon les normes en vigueur pour les PRN existants.

Nous voudrions conclure en réaffirmant qu'à nos yeux, le pôle de recherche national *UNIVERSE* est un projet de grande envergure et d'intérêt majeur pour la science et l'avenir de notre pays. Nous sommes confiants que ce pôle va produire des résultats scientifiques de premier ordre.

En restant à votre disposition pour tout complément d'information, je vous prie de recevoir, Monsieur le Président, Madame, Monsieur, l'expression de nos sentiments dévoués.



Prof. Jean-Dominique Vassalli
Recteur

Prof. Guillemette Bolens
Vice-rectrice

Copie : Prof. Martin Pohl – Université de Genève

PAUL SCHERRER INSTITUT

Prof. Dr. Joël Mesot
Director PSI
Prof. Phys. ETH Zurich & EPF Lausanne
5232 Villigen PSI
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Swiss National Science Foundation SNSF
Waldhainweg 3
P.O. Box 8232
3001 Bern

13 January 2012

NCCR: The Universe – Constituents, Forces, Space-Time

Letter of Support of the Home Institution

Ladies and Gentlemen,

It is my pleasure to give the fullest support of the Paul Scherrer Institut as the co-leading house of the proposed National Competence Center for Research: The Universe – Constituents, Forces, Space-Time.

This initiative aims at innovatively combining efforts of Particle Physics, Astroparticle Physics and Cosmology throughout Switzerland and thereby creating a real lighthouse in an internationally very competitive environment. Particularly crucial in my view is the combination of emphasizing world class accelerator physics, large facilities at PSI, synergies with CERN and new ideas to investigate thrilling questions to nature. The track record of these fields, especially also at PSI, shows that the endeavour for insight into the most fundamental aspects of nature often comes along with considerable benefits and spin-offs for society.

The work outlined in this NCCR proposal belongs to the key components of PSI's research portfolio and strategic planning. PSI fully supports this activity as outlined under point 7 in the proposal. The co-leadership of University of Geneva and the Paul Scherrer Institut in this NCCR emphasizes the strategic collaboration between universities and PSI, as the national laboratory for particle physics, and the ETH domain in general. Together with internationally renowned groups from all institutes in Switzerland active in the field, the co-leading houses will provide an operational and cultural balance, guaranteeing the success of the proposed research.

The Department for Research with Neutrons and Muons (NUM) and the Laboratory for Particle Physics (LTP) as well as the Department for Large Research Facilities (GFA) strongly support this NCCR proposal contributing infrastructure, manpower and supporting funds.

To further substantiate our support of this excellent initiative, PSI will centrally provide additional funds of 2 Mio Swiss francs for the NCCR Universe for the first 4 year period. We would like to emphasize again the vital importance of accelerator research and particle detection technology which are at the heart of this fundamental science and a unique knowledge base at our institute. In close collaboration with all other Swiss partners, and the University of Geneva in particular, the Paul Scherrer Institut would be honored to fulfill the role as a co-leading house of this national competence center of research.

With kind regards,

PAUL SCHERRER INSTITUT

Joël Mesot

SWISS NATIONAL SCIENCE FOUNDATION

www.snf.ch
Wildhainweg 3, P.O. Box 8232, CH-3001 Berne

Programmes Division
National Centres of Competence in Research

NCCR Pre-proposal – Cover sheet

Title of the NCCR	**The Universe: Constituents, Forces, Space-Time**
NCCR Director	**Martin Pohl**
Home Institution(s)	**Université de Genève, Paul Scherrer Institute**

Content

1. Summary
2. Scientific question and its reference to society
3. Research programme for the first four years
4. Research plans of the individual projects
5. International networking
6. Goals and action plans for:
    a. Knowledge and technology transfer
    b. Advancement of young researchers and of women
    c. Communication
7. Structural goals of the Home Institution
8. Organisation of the NCCR
9. Annexes (to be uploaded as separate documents):
    a. List of the individual projects (project titles, project leaders)
    b. CV and list of the publications over the past 5 years of the NCCR Director, the Deputy Director and the project leaders
    c. Budget for the first phase
    d. Letter of support from the Home Institution

15/07/2011

M. Pohl, R. Durrer, K. Kirch[1] **Draft 4.1, 16.1.2012**

The Universe
Constituents, Forces, Space-Time

Making Particle Physics, Cosmology and Astrophysics Work Together

Contents

[1]Coordinating authors, with contributions from all project coordinators

1 Summary

Particle physics, cosmology and astrophysics have long been a topic of focus in Geneva. With the establishment of CERN at the end of the Second World War a handful of visionary scientists created a European particle physics laboratory, instituting the first steps towards thriving research in the field of what matter and energy are made of. A complementary corner stone of particle physics is strong national research laboratories, in Switzerland since 1974 represented by SIN, today PSI Villigen, and its unique proton accelerator and meson factory. These developments have led scientists throughout Switzerland to have an important impact in these fields and gain the respect of their peers worldwide.

Today, we propose to federate Swiss research in the fields of particle physics, cosmology and astrophysics to advance the extraordinary capability and visibility of our country by allowing science to develop in new directions and inspire new generations of visionaries. The creation of NCCR Universe will allow Switzerland to not only strengthen its activities in fundamental physics, but also implement transversal structures between the main directions of existing and future efforts. It will provide a "home" for the large pool of national and international scientists who have established their research in proximity of Geneva in the past decades. It will refocus on activities at our national laboratory. Organizing and managing the national network of academic and applied research will optimize efficiency and resources as well as help modernize teaching.

NCCR Universe proposes an innovative approach by organizing the research by themes and thus crossing traditional boundaries. Using the existing "resources" (neutrino, high energy and astroparticle physics), three scientific topics have been identified as the major Challenges of our times: elementary constituents and forces, dark matter and dark energy, sources and acceleration of particles. Never yet addressed as such in Switzerland, these research themes seek answers to issues on the basic laws of Nature, the role of gravity, and inconsistencies of the Standard Model with our current understanding of particle physics.

Studied by physicists from different disciplines – experimental particle physics, astrophysics, observational cosmology and theoretical physics – these Challenges allow us to combine insights from controlled accelerator experiments as well as make use of data from astrophysical and cosmological observations. The approach also allows us to exploit the phenomenal synergies between the traditional research directions in terms of experimental techniques, analysis methodology and cross-fertilization between theory and experiment. Switzerland's large public investment in CERN's infrastructure has led to attract and form leaders in the field of experimental physics in our region. Yet, the return in terms of developments in fundamental research done in Swiss institutions and the resonance of our country abroad has not been able to match this effort due to a lack of a global centralizing body and a long term investment in manpower. The opportunity to create an NCCR providing a unique academic and research infrastructure in particle physics would streamline and solidify our field within Switzerland and position it worldwide.

The Swiss Institute of Particle Physics, CHIPP, created in 2003 and gathering the most prominent research groups in Switzerland, embraces this initiative. It is committed to support the development of the NCCR Universe as well as perpetuate its work after its completion.

As highlighted in its long-term strategic plan, the University of Geneva has decided to put the future of research in Physics at the highest priority level. In particular, it is putting considerable resources into the development on a new facility focused on fundamental research in its various fields of expertise (physics, mathematics and astrophysics). Since the inception of CERN, the University of Geneva has been able to offer leading scientists an academic environment to conduct fundamental research in this field. A first step towards a higher degree of integration between the disciplines concerning this NCCR has already been made in Geneva with the foundation of the Center for Astroparticle Physics, CAP Geneve.

For PSI, particle physics and accelerators are key components of its strategic planning. PSI is at the forefront of accelerator development with its new SwissFEL project, with the SLS, with the medical cyclotron and with the world's most powerful proton accelerator, the PSI ring cyclotron. PSI is providing such large research infrastructure to national and international users and is at the same time developing this important technology further. The Development Plan for 2012-2016 has "Particle Physics and the Structure of Matter" as one of its five thematic areas of legal PSI responsibilities and places a strong emphasis on its user laboratory function.

The co-leadership of University of Geneva and PSI in this NCCR emphasizes the strategic collaboration between the universities and the ETH system as well as the operational and cultural balance throughout the country. With its proven record as leading house for other NCCRs, the University of Geneva and its Faculty of Sciences are committed to financially and organizationally support the establishment of a new NCCR. PSI is the world leading federal institution in accelerator development and high intensity beams. It is the home of unique precision particle physics experiments with highest international visibility. The co-leading institutes find themselves today in a natural position to host and manage this project of national interest with international outreach.

2 Scientific Question and its Reference to Society

Physics provides the building blocks for all sciences. Fundamental research seeks to identify and understand the unknown, to push the boundaries of knowledge, fueling innovation and leading society into the future.

Particle Physics, cosmology and astrophysics are with no doubt the fields of physics that address the most questions of society's concerns since the beginning of times: What is the origin of matter, of energy? What is the origin of the Universe, of our planet? What are we made of? How are particles created at first? What are the dimensions of space-time and what is the role of gravity?

Although research in these fields has been active and productive for decades, the physics community still faces today fundamental challenging questions. There seems to be a huge discrepancy between what is seen and what is expected. Theories are developed and experiments validate, hopefully, over time. One stubborn candidate though is the Standard Model. This theory of particle physics explains a large variety of phenomena down to the smallest distances accessible to present day particle physics experiments. It has been a solid basis for almost everything, describing the particle-forces interactions that constitute matter. The Standard Model is able to explain all experimental data produced to date from man-made accelerators. Yet this model bases itself on many unexplained parameters, making it theoretically unsatisfactory. One of the key ingredients of the theory, the generation of mass through the Higgs mechanism, is on the verge of being proven or disproven. With today's extremely sophisticated experimental tools, we are able to push research further than ever before.

Despite the impressive agreement between theory and numerous precision experiments, it has become clear over the last decades that there remains a number of observed phenomena that the Standard Model in its original form cannot explain. Observations and analysis reveal that only 4% of the energy density of the Universe is ordinary matter, the matter we know how to describe with quarks and leptons, the rest consisting of 70% "dark energy" and 26% "dark matter". Dark energy is, however, only a word that describes the cause of the observed apparent acceleration of cosmic expansion, while dark matter describes massive particles that are, to date, observed only through their gravitational pull. We also know that the complex structures observed in the present Universe, galaxies, clusters of galaxies and voids, emerged from an almost uniform early Universe. They grew from small initial fluctuations that are also imprinted on the cosmic microwave background. We assume that an inflationary phase of very rapid expansion has generated these initial fluctuations out of the vacuum.

Providing a unified view of the Universe requires a deeper understanding or a new vision. Cosmological observations combined with the application of the laws of particle physics to the expanding Universe lead to a number of observations that point beyond the present Standard Model. These investigations are central to this NCCR, seeking to answer the following:

- Baryon asymmetry of the Universe: What ensures that there is much less anti-matter than matter in the Universe today?
- Dark Matter: What accounts for some 26% of the total matter density in the present Universe?
- Inflation: If the homogeneity and flatness of the Universe is explained by a period of the rapid accelerated expansion, what is the mechanism that drives it?
- Dark Energy: Is the accelerated expansion of the Universe caused by a small cosmological constant or by some other, yet to be discovered substance or mechanism?

The work undertaken within this NCCR will point the way towards future progress in answering some of these most fundamental questions that can be asked about Nature, formulated in the Swiss Road Map [1, 2]. However, these questions can be investigated only by a combination of precise, controlled experiments like those now in operation at CERN at the LHC – the Large Hadron Collider – on one hand, and cosmological and astrophysical observations on the other. Among the most strikingly successful examples of such combination is the recent progress in neutrino physics coming from the combination of solar neutrinos, atmospheric neutrinos and neutrinos from accelerators and reactors. Moreover, the analysis of the observed large-scale structure of the Universe as well as the properties of individual galaxies and galaxy clusters allows to robustly excluding the possibility that dark matter is made of the (massive) neutrinos of the Standard Model. This makes dark matter one of the major "beyond the Standard Model" problems.

Particle, astroparticle physics and cosmology are of strategic importance for Swiss research. As one of the CERN host states, Switzerland has traditionally well supported basic research in particle physics and the efforts of federal and cantonal authorities have been widely acknowledged. Basic research is recognized as one of the major drivers for innovation beyond the gradual improvement of existing technologies. A competitive edge for Swiss researchers in particle physics can be derived from their privileged geographical position close to CERN, the major center of competence in this field worldwide. Independently, cosmology research as a novel approach to questions from particle physics and fundamental interactions has developed in different places in Switzerland – in Geneva, at EPFL and ETHZ, at University of Zürich. However, exploiting this edge requires an optimization of Swiss research structures aiming at an intelligent combination of these competences and also a sustainable coverage of the very long life cycle of particle and astroparticle physics experiments. Fostering this process is the role of the Swiss Institute of Particle Physics CHIPP, a bottom-up association with an outstanding track record covering all particle, astroparticle and nuclear physics in Switzerland.

NCCR Universe takes the scope of CHIPP a step further and broader. It focuses on the tremendous synergies between traditional particle physics, astrophysics and cosmology. These synergies concern the research questions but also the experimental techniques used in these fields. Here, especially astrophysical observations profit already from techniques developed for particle physics experiments. By intensifying the collaboration between particle physics, astrophysics and cosmology, educating graduate and undergraduate students in these increasingly intertwining fields, and developing infrastructure (especially in computing but also in detector development for future experiments), this NCCR will help us address the problems mentioned above and seek answers to the major challenges of our understanding of Nature.

With the worldwide political and public debates about the dangers of nuclear energy, the risks of nanoscience, or more generally on the value of spending on scientific research as society faces difficult times, there is an increasing need for physicists to open up and share the value of their work. Bridging the gap with society by providing a relevant dialogue permits an increased level of awareness and more educated decisions. Sharing the passion and discoveries of research awakens new vocations and promotes the freedom of the mind necessary to imagine what has not yet been formulated.

CERN offers a rare example of outreach, where scientists share between themselves their challenges and discoveries at the same time as they explain it to the rest of the world. The open-door concept of exposing science to outside communities, even possibly amateurs, proves its usefulness by providing additional brainpower to the issue, or simply by the benefit of having had to formulate it differently. NCCR Universe will not only naturally contribute to these efforts, it will enhance them by providing an academic perspective on the matter. With its other national partners and the co-leading house PSI, it can focus on the more fundamental questions and show how scientific thinking can enable new perspectives. The NCCR's extended network will also permit to reach out more precisely to the Swiss community, throughout its linguistic and cultural differences.

Through an innovative approach of interactive communications using virtual platforms, a well-coordinated program will target all actors of society, whether the scientific community, the industry or youth. Adapting our outreach with new tools will greatly increase the dialogue, stimulate technology transfer and revitalize scientific education.

At a time when one speaks of A Knowledge-Based Society, NCCR Universe aims at creating knowledge and pushing its limits beyond today's comfort, all while making research available and sharing science with the stakeholders capable of leveraging on those efforts and produce collateral benefits.

3 Research Program 2014-2017

A schematic representation of projects for NCCR Universe is shown in Figure 1, exhibiting the three scientific themes mentioned in Section 1. While the projects of this proposal have been assigned to one of these themes, the scientific topics in fact largely overlap; a Venn diagram is thus the appropriate way to present them. In choosing the three themes, the NCCR contributors make a strategic choice following the recommendations of the CHIPP Road Map [1, 2]. At the same time, the themes cover some of the main directions followed worldwide in search for the ingredients of the successor to today's Standard Model. Such a New Standard Model ought to repair the known shortcomings of the existing one, integrate important missing pieces such as dark matter, neutrino masses, matter-antimatter asymmetry, Dark Energy, and point the way toward future research.

It is obvious that experimental and theoretical subjects of this fundamental nature require a sustainable long duration support. The LHC project and its experiments, to name a prominent example, started with first conceptual studies in the early 1990's, leading to the project approval by the CERN Council in 1994. Excavation started in 1998 and civil engineering took until 2003 to complete. The experiments published a series of technical design reports from 1999 to 2005. Finally, in 2009, first beams were produced and in 2010 routine operation was achieved at half the design energy and with luminosities exceeding all expectations. Full energy will be reached in 2014 and the current experimental program is expected to continue until at least

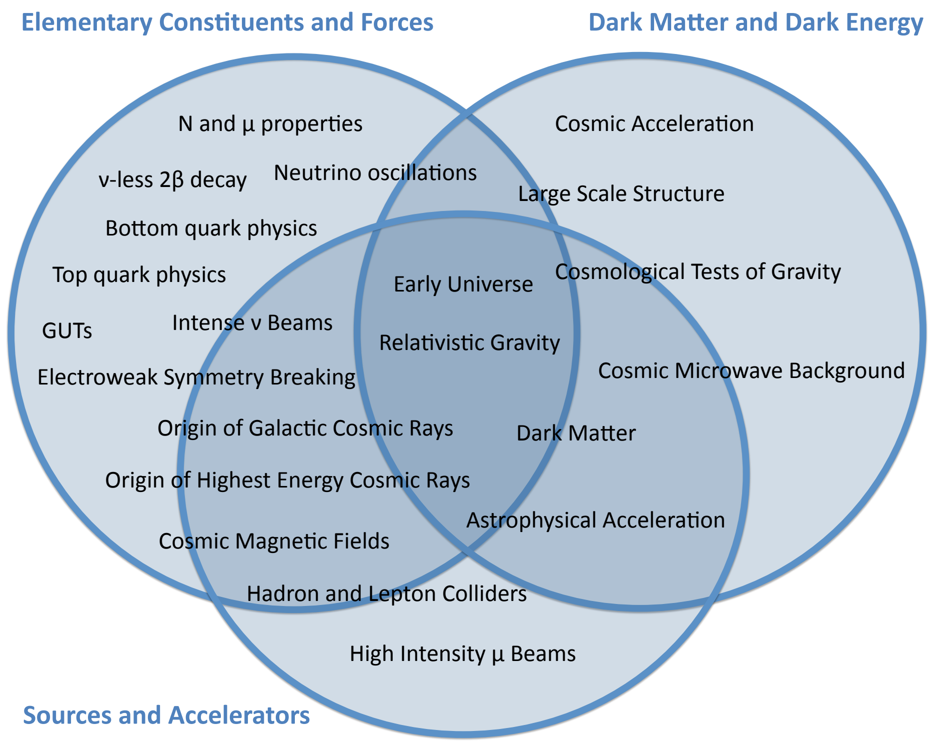

Figure 1: Conceptual chart of the NCCR Universe showing its main research themes and projects.

2020. After reaching full energy and luminosity of the LHC, CERN currently intends to extend the machine luminosity around 2020 by an additional factor. This will require a thorough update of the LHC detectors. The construction and operation life cycle of the LHC and its experiments thus spans over more than three decades. Similarly, data analysis and interpretation will dominate particle physics in a period of several decades.

Comparable life cycles have been observed for non-accelerator experiments, such as particle detectors in space and large underground facilities. The INTEGRAL satellite project, which started in 1999, will likely extend beyond 2017. The AMS cosmic ray observatory, bringing modern particle detection technology to space, took two decades from concept to deployment and will take data over the remaining lifetime of the International Space Station. The IceCube project, with its predecessor Amanda, or the presently running Planck satellite took similar time spans to complete. Future large-scale underground facilities and the recently approved ESA satellite Euclid will no doubt take a similar time to plan, complete and operate. With their long duration, NCCR are an appropriate instrument to cover the typical life cycles of experimental and theoretical programs.

It must be emphasized that the NCCR is not proposed to fund investment into experimental infrastructure, detector construction or upgrade. Existing funding lines like SNF grants, FORCE, FINES and their successor FLARE, EU Framework Programs like AIDA, ESA's PRODEX program and others are better suited for this purpose. Instead, the NCCR Universe will install structures that coordinate and support cooperation between different theoretical and experimental approaches to confront these challenges. In particular it will:

- Lead a joint program addressing the most fundamental challenges of the present day physical picture of the Universe by combining and coordinating the efforts of Swiss theoretical and experimental groups working in cosmology, particle physics and astrophysics.

- Coordinate and support the Swiss scientific return of investment from LHC experiments, neutrino and astroparticle physics experiments by creating PhD student and post-doctoral fellowships, closely networked and embedded in a Swiss-wide doctoral and post-doctoral research and education program.

- Intensify the contribution of Swiss research groups to particle physics experiments at PSI, enabling new experiments that require more intense beams and novel detection techniques.

- Increase the Swiss impact in the planning process for future accelerator facilities, focusing on CERN projects for and beyond the present LHC. In this context, the visible Swiss contribution to the European Strategy Session of the CERN Council is especially important. In 2006, the European Strategy Session of the CERN Council has adopted 17 Strategy Statements concerning the scientific, organizational and social relevance issues for elementary particle physics in Europe. They are periodically updated reflecting the progress in the field.
- Implement a cooperative multi-messenger approach to high-energy astrophysics between Swiss groups to identify the nature of astrophysical particle sources and accelerators. One of the important steps in this direction will be the establishment of a multi-messenger data repository for astroparticle physics, the Swiss Data Center for Astroparticle Physics, which will provide access to data and support users from inside and outside of Switzerland.

The goals of the NCCR require an ever-increasing exchange of ideas and cooperation between Swiss groups and their international partners. The NCCR will help this evolution by implementing platforms for theoretical and experimental work, as well as joint research and development on experimental techniques and data analysis related to all aspects of the physics of the Universe.

The activities of the NCCR in the context of the three themes are detailed in Section 4. They are briefly summarized in the following.

3.1 The Challenge of Elementary Constituents and Forces

Ordinary matter, composed of the known fermions – quarks and leptons – as well as gauge bosons, represents less than 5% of the energy density in the Universe, yet it forms all known objects. A lot is known about its detailed properties, while important challenges remain. Fermionic matter comes in three generations comprising each four particles: up- and down-type quarks, charged leptons and neutrinos. There is no known compelling reason why there should be three and only three "light" fermion generations. Each charged particle has its antiparticle – neutrinos being neutral may or may not be their own antiparticles. The three generations are classified by the increasing mass of the charged particles; we do not know if neutrinos follow the same hierarchy or not. Each particle carries a quantum number called flavor, which is conserved in strong and electromagnetic interactions, and presumably gravity. Electroweak interactions induce quark flavor transitions, mostly within each generation, but also to a lesser extent across generations, by what is called mixing, described in the current Standard Model by a mixing matrix. This matrix can also accommodate a breaking of the symmetry between the properties of particles and their antiparticles – called CP violation– by including a complex phase. A CP asymmetry is indeed observed in the quark sector and at the actual level of precision well described by such a phase. Whether a corresponding mixing can also occur for the charged leptons is an important open issue in flavor physics and most sensitively studied in rare muon decay searches.

CP violation is a crucial ingredient for the explanation of the observed asymmetry between matter and antimatter in the Universe. The amount of the CP violation within the Standard Model seems to be not enough to account for the asymmetry observed in the cosmos; the baryon asymmetry calls for physics beyond the Standard Model. The asymmetry might be due to new elementary constituents appearing around the electroweak energy scale. This scenario is dubbed electroweak baryogenesis. It is testable through the observation of new states at the LHC or via observation of non-standard CP violation in the B meson systems. New CP violation at the electroweak scale usually also leads to sizeable permanent electric dipole moments (EDM) of particles, e.g., of the neutron. Remarkably, a null result in future high sensitivity EDM searches may exclude electroweak baryogenesis as a viable option in many attractive theoretical models. If, however, CP violation is introduced at a higher energy scale, the generation of the baryon asymmetry may be directly related to the fact that neutrinos are massive. Indeed, if the neutrinos are Majorana particles (i.e. their own antiparticles), their mass may be due to the presence of very heavy (right-handed) neutrinos through the so-called see-saw mechanism. The decay of these heavy states in the early universe could give rise to a lepton/baryon asymmetry. This scenario is dubbed leptogenesis. CP violation in the neutrino sector can be measured via suitable neutrino oscillation experiments and Majorana mass terms in neutrino-less double beta decay.

The interpretation of the indirect tests of the Standard-Model-particle properties requires a direct search for the new particles involved in any extension of the Standard Model. This can only be performed at the high-energy frontier, i.e. the LHC and a potential future linear e^+e^- collider. One of the primary challenges at the LHC is the search for the Higgs boson in order to establish (or exclude) the perturbative Higgs mechanism for electroweak symmetry breaking which gives rise to the mass and mixing matrices of the Standard Model. Present observations are compatible with the existence of the Standard Model Higgs particle and its non-existence as well. Further data collection will lead to a decisive picture. If no Higgs will be found at the LHC, searches for strong WW scattering have to be pursued in order to clarify the origin of electroweak symmetry breaking. The LHC running at 14 TeV center-of-mass energy will give the first hints towards the physics behind this option.

Deviations of the neutron EDM and the lepton-flavour violating $\mu \to e\gamma$ decay from the Standard Model prediction require new physics at a high-energy scale. One of the top candidates for new physics is a supersymmetric extension of the Standard Model. The direct search for the supersymmetric partners of each Standard Model particle ranges among the top priorities at the LHC. If these particles will be found a detailed investigation of their properties is mandatory in order to test their consistency with the low-energy constraints coming from the neutron EDM, $\mu \to \mathrm{e}\gamma$ and cosmological data.

The challenge represented by the incomplete understanding of ordinary matter and forces is taken up by the first scientific theme of the NCCR, with the following main projects:

- An **electric dipole moment (EDM) of the neutron** violates time-reversal invariance (as well as matter-antimatter symmetry) and is expected to be very small in the Standard Model ($< 10^{-31}\,e$cm). Explanations of the apparent matter-antimatter asymmetry observed in the Universe require extra sources of a "large" CP violation. These extra sources may also lead to a large neutron EDM. The best present experimental upper bound is $3 \times 10^{-26}\,e$cm. A new experiment striving to observe such an EDM is in preparation at PSI and would shed new light on the origin of the matter-antimatter asymmetry of the Universe and the properties of light quarks and hadrons.

- **Bottom hadron physics** aims at understanding the detailed properties of b quarks and hadrons containing them. A major objective is to completely measure the elements of the quark mixing-matrix and test its unitarity. CP violation in heavy quarks ought to be observed and its description by a complex phase in the matrix tested. Establishing the exact size of the matter-antimatter asymmetry in this sector is important for the understanding of the corresponding asymmetry in the Universe. The current LHCb experiment is conceived to make an important contribution to these questions. Future experiments at the next generation of b-factories may add precision to the answers obtained.

- **Top quark physics** is both a laboratory for "bare" quark properties and a means to find signs of heavy new states of matter. Since top quarks decay before forming hadrons, their production and decay properties uniquely reflect the properties of the quarks themselves. Many potential new states of matter decay into top quarks. It is therefore important to be able to unambiguously and efficiently identify top quark jets, both near and far above threshold. The LHC detectors ATLAS and CMS are well equipped to observe these signals. Corresponding analysis methods, especially to identify boosted top systems, are under development.

- **Exotic hadrons** may form under extreme conditions in a composition other than the known three-quark baryons and quark-antiquark mesons. These conditions can be found in very hot or very dense environments like for example in the early universe or in neutron stars. A detailed study of exotic forms of colorless, strongly interacting matter can both be performed at accelerators like FAIR in Darmstadt, and with high sensitivity relic searches using space-bound detectors like AMS-02.

- **Electroweak symmetry breaking:** One of the major challenges of LHC experiments is to discover the mechanism that reconciles gauge symmetry, massive force carriers and massive matter particles. In fact we should be able to explain the very different patterns of mass hierarchy observed among leptons and quarks. If the symmetry breaking mechanism is indeed spontaneous, as postulated in the Standard Model, one or several Higgs particles ought to be observed even before the start date of this NCCR. In this case, collaboration between theory and experiment is required to establish that the observed particle indeed serves the postulated purpose. Should a Higgs particle not exist, alternative mechanisms and their experimental signatures must be explored.

- **Neutrino Oscillations** have demonstrated that neutrinos have mass, in contradiction to Standard Model assumptions. Experiments have measured quadratic mass differences and elements of the mixing matrix. As a complement, the analysis of large-scale structure formation and cosmic microwave background will help to fix the overall scale of neutrino masses. A supernova collapse in the mid term future is highly probable, and may distinguish between normal and inverse neutrino mass hierarchies. It will be observed by IceCube with unprecedented statistics. Precise measurements at accelerators are necessary for the observation of a CP asymmetry, as well as to study the neutrino mixing with a precision similar to that of quarks. They require substantial increases in the neutrino beam intensities and in the mass and quality of detectors. Experimental hints may also come from observation of new particles involved in neutrino mass generation at the LHC or beam dump experiments at CERN, from indirect tests of neutrino mass mechanisms, e.g. via a non-unitarity of the leptonic mixing matrix, or from the observation of neutrinoless double beta decay. Theoretical issues regarding extensions of the Standard Model with massive neutrinos, their influence on the early Universe and their tests with accelerator based, cosmological and astrophysical observations, will be the subject of theoretical activities in this project.

- Observation of **neutrino-less double beta decay** is the most promising way to establish fermion number violation by neutrinos and their Majorana nature. If it exists at all, this is an extremely rare process with a lifetime exceeding many times the age of the universe. These experiments require detectors made of large masses of special isotopes and extreme energy resolution. There is a clear but challenging path from the current state-of-the-art experiments to the ultimate answers for this question.

- In **Grand Unified Theories** (GUTs), the forces of the Standard Model are described by a unified force at high energies. This typically leads to predicted relations between the properties of the elementary particles (e.g. between their masses) at high energies. To compare such GUT predictions with the experimental data, a careful model analysis has to be performed. In addition to predictions for the properties of the charged particles, GUTs also provide mechanisms for giving small masses to the neutrinos. Due to these attractive properties, GUTs provide a promising approach towards a more fundamental theory of the elementary constituents and their interactions.

- If **flavor violation** exists also for the neutral weak interaction of leptons, it can be observed in muon decays. Signals would e.g. be the decays $\mu \to e\gamma$ and $\mu \to 3e$. Tiny decay modes of this kind are ideally searched for using the high intensity muon beams at the PSI laboratory. To digest these high rates, and to distinguish the signal from concurrent background requires novel approaches to low energy particle detection and high rate data acquisition and analysis.

- **Cosmic magnetic fields** are observed in galaxy clusters and probably even in voids. Their generation is an open challenge: Can ordinary astrophysical processes in the late universe produce them? Are they generated during phase transitions in the early Universe? Or do they come from inflation? How do they evolve once generated? Clearly this question will need an effort coming from all directions: particle physics beyond the Standard Model (which might make the electroweak phase transition first order), ideas about non-standard couplings of the electromagnetic field to gravity, to the inflaton or to quintessence (dark energy) and numerical simulations which include not only dark matter, but also ordinary matter and magnetic fields. All this expertise is present in Switzerland and will be concerted in this effort.

3.2 The Challenge of Dark Matter and Dark Energy

Most of our understanding of ordinary matter and its interactions comes from accelerator and cosmic ray experiments. Dark matter is being investigated through cosmological and astrophysical observations and its nature is being explored with colliders and non-accelerator experiments. Dark energy until now is being explored through cosmological observations only.

Dark matter has been first postulated by the Swiss astrophysicist Fritz Zwicky, who realized that the luminous mass in galaxy clusters is not sufficient to gravitationally bind the objects and explain the velocities of their components. Later, it has been realized that dark matter must be non-baryonic in order not to spoil the success of Big Bang Nucleosynthesis (BBN), which successfully explains the abundance of Helium and Deuterium in the Universe. The Standard Model neutrinos (the only stable neutral massive particles known) are too light to explain observed large scale structure of the Universe as well as the dynamics of individual galaxies and clusters. Therefore, the dark matter particle hypothesis necessarily implies an extension of the Standard Model.

Dark energy has been proposed by several cosmologists in the 90ies. In 1998, observations on Type-1a supernovae (SN1a) have yielded a distance-redshift relation, which is not compatible with a decelerating universe. The 2011 Nobel Prize in physics has been awarded to these observations. Gravity of ordinary matter is attractive and therefore leads to a decelerated expansion of the Universe. To obtain accelerated expansion, a strong negative pressure is needed, so that gravity becomes repulsive. The simplest proposal for dark energy is vacuum energy or, equivalently, a cosmological constant. Other possibilities are a dynamical scalar field (quintessence) or an infrared modification of General Relativity. Another idea is that back-reaction from cosmic structure may spoil the distance redshift relation of a homogeneous and isotropic Universe in such a way as to mimic Dark Energy.

The second theme is broken down into the following projects, which are however not all independent and will profit from exchanges among themselves and with projects of the first and third challenge:

- **Cosmic Large Scale Structure** (LSS) has formed by gravitational instability from primordial fluctuations. Observations of LSS and comparison with theoretical predictions and cosmological simulations therefore provide a wealth of information how gravity has acted in the Universe and allow to check our understanding of the evolution of the Universe, including its early stage, when unknown physics was important. We can compare observations of the galaxy distribution with cosmological N-body simulations. Here, not only the power spectrum, which is related to the two-point correlation function, but also higher order correlations, non-Gaussianity, are investigated. Though in principle superb, this tool is hampered by the fact that we only observe galaxies directly and most of their matter is actually dark matter. The question of biasing, i.e. the relation between the galaxy distribution and the underlying dark matter distribution, has to be included in such studies: under which conditions does a gravitational potential well, generated mainly by dark matter, lead to the formation of one or several luminous galaxies?

- **Cosmological tests of gravity:** We can use cosmological observations to test the properties of dark energy or modifications of gravity via measurements of weak gravitational lensing, by observations of the cosmic matter distribution, and by measuring velocity flows generated by gravity. The advantage of these probes is that lensing and velocities respond to the total gravitational mass and not only to the visible mass. There are several interesting experiments currently taking data or under planning. The most challenging one is Euclid, an ESA satellite project (recently approved M3 mission) currently under planning with strong involvement from Geneva (DPT, Department of Astronomy, ISDC) and EPFL (astrophysics). At this stage, we can still influence the experimental strategy to optimize the information about dark energy and dark matter properties as well as modified gravity.

- **Dark Matter:** Cosmological data rule out the possibility that significant fraction of dark matter particles remained relativistic up until the matter-dominated epoch (which is the case for neutrinos). dark matter is therefore formed by heavy particles and can be detected as follows:

  - *Direct detection:* Maybe the most popular dark matter candidates are weakly interacting massive particles (WIMPs) – stable non-relativistic particles with the mass in the GeV to TeV range. The interest for these candidates is due to their potential relation to the electroweak symmetry breaking, which is being tested at the LHC, as well as physics beyond the standard model. WIMPs can be detected through their interaction with ordinary matter. Several such direct detection experiments are underway in Switzerland and in other countries with important Swiss contributions.
  - *Indirect detection:* WIMPs can be detected indirectly through their annihilation when trapped in celestial bodies. Ordinary particles are then produced such as neutrinos, photons and electrons/positrons. Indirect detection is complementary to direct detection and to searches at colliders. But WIMPs by no means exhaust the list of possible dark matter candidates. The dark matter particles can be lighter, need not be stable, can be relativistic in the early Universe, modify formation of structures at galactic scales, etc. A significant combined effort from astrophysics, cosmology and particle physics is required to determine the properties of dark matter and distinguish among various particle physics candidates. Such an effort is a central theme of the NCCR project on dark matter.

- **Cosmic acceleration:** So far, we simply know that the explanation of the observed relation between distance and redshift within a Friedman-Lemaître universe requires cosmic acceleration, and this can be achieved with a form of energy, Dark Energy, that exerts a very negative pressure. In the future we want to investigate Dark Energy from all is facets: Can Dark Energy be simple vacuum energy? Why is the vacuum energy so small? What about quintessence? How can we best distinguish it from a cosmological constant? Does it leave traces in LSS? How can we discover them? What about gravity? Might General Relativity be violated at very large scales, in the infrared? How can we test massive gravity and other models of de-gravitation with observations/experiments?

- **Cosmic Microwave Background (CMB):** The anisotropies and the polarization of the CMB are a superb cosmological tool. On the one hand, they can be calculated with high accuracy nearly fully within cosmological perturbation theory. On the other hand, high precision data is available and much more is coming, especially from the Planck satellite currently in orbit. Several of the NCCR participants are members of the Planck team and have access to this data. Its analysis and interpretation will be a major tool to learn more not only about cosmological parameters, but also about the initial perturbations coming from inflation: Is there a gravitational wave components? Can non-Gaussianities be detected? First results from the Planck satellite will be published in 2013, but the project, especially the analysis in which we are involved, will continue largely into the funding period, even beyond the first four-year period. Follow-up experiments, especially to measure B-polarisation of the CMB, are under construction or being planned.

- The **early universe** was a unique laboratory for particles and fields at high temperatures. The models of baryogenesis, inflation, tests of theoretical ideas (such as e.g. Grand Unified theories) will be the subject of the theoretical investigations in this project, using the input from particle physics experiments and observational cosmology, especially the cosmic microwave background and cosmic large scale structure and providing, in return, predictions of possible properties of new particles to be searched.

3.3 The Challenge of Particle Sources and Acceleration

The future of precision particle physics hinges critically on progress in accelerator technology; major developments in particle physics since the 1950s have resulted almost entirely from the parallel development of powerful and increasingly sophisticated accelerator facilities. Since the 1990's, the exploitation periods of collider and accelerator complexes at CERN and elsewhere indeed define eras, such as the past LEP era and the current LHC era, producing a coherent chain of results dominating particle physics over many years. It is thus primordial that progress in particle accelerator and collider technology be supported by investing into accelerator research and development and by encouraging new ideas. This concerns on one hand the high-energy frontier, with the immediate necessity to support LHC machine upgrades towards higher luminosities and the long-term goal of defining the next lepton collider. It also concerns the intensity frontier, where more intense proton beams serve the purpose of supplying neutrino and muon beams of unprecedented intensity and quality. The time scale for accelerator development is long. As a result, on-going accelerator R&D is impossible to disentangle from the perspective of physics requirements for the future.

It is remarkable that, although Switzerland hosts CERN and the world class facility for low energy beams PSI, accelerator research and development has so far not received the support it deserves. The NCCR Universe proposes to change this by incorporating important R&D projects in this area.

Despite all foreseeable progress in the field of man-made accelerators, they will never be able to rival cosmic accelerators as far as the attainable energies are concerned. In fact, ultra-high energy cosmic rays reach macroscopic energies. This is due to the extreme sizes and fields that cosmic accelerators can have, which are unique environments to study the behavior of matter under extreme conditions. Just 100 years after the discovery of cosmic rays, their sources, acceleration and transport mechanisms are still unclear. In particular, powerful accelerators must exist inside our galaxy but have so far remained unidentified. The origin of ultra-high energy cosmic rays is completely unknown, but must also be sought at relatively modest distances.

There is little – if any – technological synergy between man-made accelerators and the observational and theoretical techniques for studying cosmic ones. However, the intellectual challenge to reach energies and intensities as close as possible to conditions in the early universe provides a strong link. Consequently, the third challenge addressed by the NCCR will comprise important research projects in both fields:

- **Hadron and lepton colliders:** The Large Hadron Collider (LHC) has been exploring the new energy frontier since 2009, gathering a global user community of 7,000 scientists. It will define the high-energy frontier exploration for at least two decades, and its full exploitation is the highest priority in the European Strategy for Particle Physics, adopted by the CERN Council and integrated into the ESFRI Roadmap. To extend its discovery potential, two major upgrades are under study today. The High Luminosity LHC (HL-LHC) upgrade, to be implemented around 2020, is to increase its luminosity (i.e. the rate of collisions) by a factor of 10 beyond the design value. The High Energy LHC (HE-LHC) upgrade aims at doubling the energy of the LHC collider by developing 20 Tesla dipole magnets to replace the present 8.33 Tesla nominal LHC magnets. At the same time Linear Collider study groups are pursuing R&D on possible high-energy lepton collider options. Superconducting RF technology of the International Linear Collider (ILC) and the two-beam scheme of the Compact LInear Collider (CLIC) are under investigation at the accelerator laboratories around the world. The final choice will depend on the physics results coming out of LHC in the near future.

- **High intensity muon beams at PSI:** With the unique power of the 590 MeV proton beam, PSI generates the world's highest intensity and brightness continuous beams of low momentum pions, muons and ultra-cold neutrons. Most experiments at the high precision and intensity frontier performed today at PSI, can only be performed here. To build upon this and further strengthen precision muon physics, R&D on transport of higher muon intensities from production targets and on cooling of a high intensity secondary beam to form a very bright slow muon beam will be pursued at PSI. At 1.4 MW beam power, delivered in continuous wave mode (CW), the PSI proton accelerator holds the world record. To make this high power operation possible, the relative beam losses in the accelerator chain have to be kept in the lower 10^{-4} range. PSI has developed unique expertise in several areas, such as the design and operation of high-power targets, RF-resonators for cyclotrons, or the technical interlock systems that ensure the safe operation of the high intensity beam.

- **Intense neutrino beams:** The next generation of neutrino beams, which experiments require, constitute a considerable challenge, both to achieve a high intensity and to control the beam parameters well enough to reach the desired systematic precision. The LAGUNA-LBNO program foresees the study of neutrino beams from CERN in collaboration with CERN AB department. The Swiss institutes are involved in measurements of the pion and kaon production in neutrino targets, as well as in the design of the best focusing and instrumentation of the beam (near detectors). On a longer time scale a neutrino factory where muons produced from pion decay are stored in a storage ring with long straight sections directed towards far detectors have been shown to provide the intense and well defined beams ideal for precise measurements of neutrino oscillations. This may be the first step towards muon colliders, which offer an alternative type of high-energy lepton collider with distinct specificity. Ionization cooling is an essential technique to master for these machines. Swiss scientists (in Geneva with help from PSI) are leading the experiment aimed at making the first demonstration and study of this pioneering technique, the Muon Ionization Cooling Experiment (MICE). The first four years of the proposed NCCR will see the completion of the first phase of MICE with demonstration of ionization cooling, and the generation of a new project such as a small muon storage ring (mini-neutrino factory) for precision measurements of the neutrino cross-sections required for the neutrino CP violation program.

- **Origin of Galactic cosmic rays:** Nature-made particle accelerators much more powerful than existing and future man-made accelerator machines are operating in our Galaxy. These nature made particle accelerators produce cosmic rays, which are high-energy particles penetrating into the Solar System and hitting the Earth atmosphere. The power of particle accelerators operating in the Galaxy, $\sim 10^{28}$ MW, is so high that cosmic rays significantly affect the structure of the interstellar medium and magnetic fields. 100 years after the discovery of cosmic rays, the nature of particle accelerators producing them is unknown. Energetic considerations and chemical composition suggest that cosmic ray acceleration accompanies phenomena related to supernova explosions. Remnants of supernovae might be the main cosmic ray sources in the energy range up to the "knee", a spectral feature in the cosmic ray spectrum at $\simeq 10^{15}$ eV. Two fundamental questions addressed by this project are: What is the origin of the bulk of Galactic cosmic rays? What are the maximal energies to which cosmic rays are accelerated by sources in the Milky Way? A number of puzzling features of the observed cosmic ray flux, like the difference of spectral slopes of hydrogen and helium species, spectral breaks in the nuclear and electron/positron components and an anisotropy of the cosmic ray flux in the TeV band, possibly provide clues on the nature and location of the nearest galactic cosmic ray source(s). Detailed high-statistics measurements of the chemical and isotopic content of cosmic ray flux up to the multi-TeV energies with the AMS-02 detector on board of International Space Station and at still higher energies with CTA and the IceCube-IceTop ground-based detectors will be used to clarify the nature of these features and possibly lead towards the resolution of the long standing problem of the origin of Galactic cosmic rays.

- **Origin of the Highest Energy Cosmic Rays:** Nature made accelerator machines outperform the man-made ones not only in power, but also in the attainable energy scales. The observed cosmic ray spectrum extends at least to 10^{20} eV, i.e. to the energies seven orders of magnitude higher than the energy scale reached by LHC. Our current knowledge of particle acceleration mechanisms in astrophysical environments indicates that none of the known types of particle accelerators in our Galaxy is capable to produce cosmic rays with energies much above the "knee" at 10^{15} eV. Ultra-High-Energy Cosmic Rays (UHECR) with energies up to 10^{20} eV are thus most probably produced by accelerators outside the Milky Way. Gamma-ray data suggest that such particle accelerators might be powered e.g. by the activity of supermassive black holes in active galactic nuclei. Extragalactic particle accelerators responsible for the observed UHECR flux are situated in our cosmological "backyard" at distances not larger than $\simeq 50$ Mpc. Inevitable energy losses on the way from the sources to Earth suppress the UHECR flux from sources at larger distances. The main goals of this project are: identification of the nearby UHECR sources;

clarification of the mechanism of their operation; and exploration of the limiting high-energy scales in Nature. A unique property of UHECR is that their energy is so high that they cross cosmic magnetic fields without being significantly deflected. UHECR sources could, therefore, be found by tracing back the UHECR arrival directions. The next generation UHECR detector JEM-EUSO will have a sufficiently large collection area and exposure to find UHECR sources in this way. Suppression of the cosmic ray flux at energies above 10^{20} eV is now firmly established. However, the nature of this suppression is not clear. It could be produced by effects related to the propagation of UHECR through the intergalactic medium or it might be an intrinsic feature of UHECR sources. Studies of neutrino (IceCube) and gamma ray (CTA) emission from UHECR interactions will be used to clarify this suppression. The center-of-mass energy of collisions of UHECR at these limiting energies in the atmosphere reaches some $\simeq$ 100 TeV, which is an order-of-magnitude higher than the energies attained at LHC. UHECR data will therefore provide information on the behavior of hadronic interaction cross-sections at these highest energies thus complementing the information obtained from the man-made particle accelerators.

- **Cosmic Sources in a Multi-Messenger Strategy:** Understanding of the mechanisms of operation of the nature-made cosmic particle accelerators requires a combination of information from cosmic ray particle detectors with that obtained using "cosmic messengers": photons and neutrinos. Contrary to charged particles, gamma-rays and neutrinos are neutral and travel along straight lines, pointing back to their production sites. Sources of cosmic rays operate not only as particle accelerators, but also as particle colliders, dumping beams of accelerated charged particles in matter or ambient photons in the source. In some source classes, like gamma-ray bursts or active galactic nuclei, the acceleration – beam dump events happen in short activity periods (from seconds to months). The only possibility to study these transient acceleration episodes is using a system which includes monitoring of a large number of objects on the sky and distribution of alerts about activity episodes of particular sources. These alerts generate "target-of-opportunity" programs for different observation facilities with the goal to get as complete picture of the physical processes in the source as possible. Such system already operates successfully in the "multiwavelength" astronomy, combining observations of transient astronomical phenomena in different bands, from radio through infrared, visible, UV, X-ray to gamma-ray bands. An immediate goal is to generalize this approach to include neutrino messengers, to increase the discovery potential of new high-energy neutrino astronomy, with larger observational power, but of difficult detection. Numerous sources of gamma-rays with energies above 100 GeV have been discovered recently in our Galaxy (supernova remnants, pulsars and their winds in nebulae, binary systems with black holes or neutron stars) and outside it (super-massive black holes in galactic nuclei, starburst galaxies, gamma-ray bursts). In some of those sources, gamma-rays measured by HESS, MAGIC, VERITAS telescopes and in the future by CTA are produced in interactions of cosmic rays which also produce neutrinos detectable by IceCube neutrino telescope. Estimates of expected neutrino fluxes based on the gamma-ray data show that discovery of first astronomical sources of high-energy neutrinos is within the reach of IceCube. This will be extremely important because it will clarify which types of the newly discovered gamma-ray sources are responsible for production of cosmic ray protons and nuclei.

- **Nature of Relativistic Gravity:** Gravitational interactions between high-energy particles are extremely weak. Because of this, gravity is the only fundamental interaction which is not accessible for particle colliders. The only possibility to understand the nature of relativistic gravity is to use natural cosmic-scale laboratories in which gravitational interactions play important role. Relativistic gravity shapes the space-time around supermassive black holes in the nuclei of galaxies, stellar mass black holes X-ray binary systems and around neutron stars. It also governs the dynamics of the Universe. Our understanding of the nature of relativistic gravity, in particular in the strong-field regime is not complete. The best illustration for this is the fact that possible solutions of the dark matter – dark energy problems include modifications of General Relativity, which is considered as the best candidate for the consistent relativistic gravity theory. The goal of this project is to study the nature of relativistic gravity using astronomical observations. This includes the work on preparation of a space-based gravitational wave detector LISA, which is expected to directly detect signals from a variety of astronomical soruces, from merging stellar binary systems to the Early Universe. A complementary study will concentrate on X-ray and gamma-ray spectral and timing observations of astrophysical processes in vicinity of stellar mass black holes and neutron stars in binary systems and in supermasive black holes in active galactic nuclei.

- **Neutrinos from Supernovae:** Massive stars undergo core-collapse at the end of their evolution and are observed as supernovae, optically and in neutrino emission, if occurring close enough. Neutrino physics has a large impact on the dynamics and the cause of the explosion and the composition of the ejecta. A high level of resolution permits detailed three-dimensional models, similar to cosmology and large scale structure simulations, but with a more complex set of input physics and the coupling of hydrodynamics to radiative neutrino transfer. The mass hierarchy of neutrinos can be determined from the observation of the neutrino signal of a future galactic supernova because of resonant matter-oscillation effects in the supernova mantle and envelope [3]. One requirement to observe any oscillation effects in neutrinos from supernovae is that the fluxes and/or spectra are different for different flavors, which needs to be determined from collapse simulations with neutrino transport. A further effect which can only occur in a high density "neutrino plasma", as experienced in supernova cores, is related to neutrino flavor transformations in the presence of neutrino self-coupling, also termed collective neutrino oscillations.

In order to advance the idea of multi-messenger approaches to astroparticle physics it is mandatory to establish a common data repository for experiments sensitive to photons, cosmic rays, neutrinos and gravitational waves. In order to be useful, interfaces to these data should be provided, which allow a coherent analysis approach and take care of experimental systematics. In this way, the current ansatz towards multi-wavelength analysis of photon data can be extended and enhanced to a cover the full spectrum of information about astrophysical objects. The tool to achieve this goal will be the Swiss Data Center for Astroparticle Physics.

3.4 Draft Perspective for the Second Four Year Period

The second four-year period of the NCCR Universe from 2018 to 2021 will be characterized by the simultaneous exploitation of major facilities in particle and astroparticle physics, as well as progress in the definition of future directions.

The LHC upgrade, towards higher luminosities or higher energies, will have been defined and its implementation will have started. In parallel, the corresponding upgrades of LHC detectors will be constructed. In this important preparatory period for the "second life" of the LHC, Swiss groups from NCCR Universe will have an important role in providing the ground for consolidating new phenomena and study their properties. Both upgrade options also allow to extend the discovery reach of the LHC to still higher mass scales. There also, the optimization of the LHC experiments to cope with the ultimate high rates and high energies, will be a central subject of the NCCR projects concerned. It is conceivable, that the new physics uncovered at the LHC, in precision experiments at PSI or elsewhere will require the construction of specialized experiments at a smaller scale than the multi-purpose experiments ATLAS and CMS. These might, e.g., be experiments at highest energies at CERN or at highest intensities at PSI. In either case, NCCR participants will no doubt be involved in their design and construction.

In parallel to the implementation of the next phase of LHC and its detectors, the plans for large future facilities will be concretized. This concerns linear electron-positron colliders, next generation b-factories as well as first generation neutrino factories. In all of these activities, the projects of the first four-year NCCR period provide crucial input; it is thus logical that the projects in the second phase of the NCCR will shape these future facilities.

Within the next four year period, the design study of a new facility at CERN (LAGUNA-LBNO) will have been concluded, as well as the MICE experiment, the Neutrino Factory design report and more complete studies of the ways to tackle systematic uncertainties in the search for neutrino CP violation. A choice of the next facility to be realized at the time scale of 2020 will have occurred at the international level with considerable participation and leadership of the Swiss groups. The implementation and participation in this program will constitute the priority of the activity in the accelerator-based study of neutrino oscillations, with the aim of reaching, first, approval and then substantial progress in the construction of the facility and ancillary experiments. The neutrino-less double beta decay experiments will have reached a first level of precision in the next four years; given this experience and depending on this first set of results, the community will be in position to propose a more ambitious next step with ten-fold increased sensitivity. With increased focus, the Swiss groups will be in a position to take a leading role in the proposals and execution of this future program.

The second period of the NCCR Universe will also see the simultaneous exploitation of next generation instruments for the X-ray, gamma-ray and cosmic ray observations.

Astro-H X-ray telescope will open new era for the study of black hole and neutron star powered astronomical sources. It will provide, for the first time, high spectral resolution camera (developed with Swiss participation), reaching the resolution equivalent to that of the optical spectrometers and sufficient to measure relativistic gravity effects on the atomic line emission in the direct vicinity of horizons of black holes in X-ray binaries. It will also extend the energy range available for focusing imaging techniques toward the hard X-ray band 10-100 keV, thus providing a huge improvement compared to existing instruments like INTEGRAL, which use non-focusing optics. A dedicated ESA X-ray timing mission LOFT, with leading Swiss involvement, will start to provide data on the variability of X-ray emission from accreting stellar mass black holes, with signal statistics sufficient to resolve time scale shorter than the periods of rotation around orbits near the black hole horizon. POLAR detector of gamma-ray bursts, in which Switzerland also takes the leading role, will provide the data on the polarization properties of gamma-rays, thus giving strong constraints on the (yet uncertain) physical mechanism of generation of extremely powerful burst events accompanying formation of black holes in core collapses of massive stars. Main focus of research will be on collection, analysis and interpretation of the new X-ray data, with the goal to understand the mechanisms of activity of astrophysical black holes and neutron stars and the role of relativistic gravity effects in this activity.

In the gamma-ray domain, the next-generation CTA array will start operation in the second phase of NCCR. It will provide order-of-magnitude improvement in sensitivity, compared to existing ground-based gamma-ray telescopes, thus enabling detailed studies of newly discovered sources of very-high-energy gamma-rays. Improvement of signal statistics will also allow better localization of the sources, enabling identification of the lower energy counterparts of numerous "unidentified" sources revealed by the current generation telescopes. These unidentified sources give significant contribution to the very-high-energy power output of our Galaxy and, most probably, host cosmic ray accelerators. We plan to concentrate our efforts on the collection of the CTA data on these sources and detailed study of physics guiding the source activity. Improvement of the signal statistics achieved by CTA will also allow high timing resolution study of activity of supermassive black holes in galactic nuclei, with the quality of the data equivalent to the quality of LOFT data in the case of stellar mass black holes. This should allow the study of physical processes responsible for the high-energy emission from supermassive black holes and clarification of the origin of spectacular phenomena of ejection of large scale jets.

In the final phase of exploitation of the International Space Station, AMS-02 and JEM-EUSO cosmic ray detectors will simultaneously take data, covering an unprecedented range of energies for cosmic ray studies. Large exposure of accumulated by AMS-2 will allow to extend the direct measurements of composition and anisotropy properties of the cosmic ray flux to the energies which which up to now are reachable only for the ground-based detectors of cosmic ray induced extensive air showers. Such measurements suffer from large uncertainties related to the uncertainties of the physics of hadronic interactions in the showers. Multi-year exposure of AMS-2 will lift this uncertainty and open a precision era in the study of Galactic cosmic rays far beyond TeV energies. In the second phase of NCCR we plan to concentrate on the analysis of large AMS-2 data sets and on the interpretation of the data. In a similar way, JEM-EUSO will open a new high-statistics era of UHECR studies. Main efforts of JEM-EUSO related research during the second phase of NCCR will be on the analysis of the cosmic ray data and on the calibration of the instrument and of the atmosphere below the telescope which serves as the cosmic ray detector. Study of implications of JEM-EUSO data for the problem of the origin of UHECR and for cosmic magnetic fields will become possible toward the end of NCCR.

Similarly to AMS-2, the neutrino telescope IceCube and its surface array IceTop will collect large multi-year data sets during the second stage of NCCR. Taking into account the extremely low signal statistics, such multi-year exposure is essential for detection of the first astronomical high-energy neutrino sources. Several developments of IceCube telescope, aimed at improvement of its sensitivity in different energy ranges are foreseen. Of particular importance is the Deep Core compact sub-array which will improve the sensitivity at low energies (100 GeV-TeV), which will provide a significant overlap with the gamma-ray data, thus allowing a sensible study of cosmic ray interactions in Galactic sources. Swiss groups will contribute to the upgrades of the IceCube telescope and to the development of data analysis techniques with the goal to exploit the full discovery potential of the large multi-year neutrino data sets of IceCube in combination with the gamma-ray and cosmic ray data.

Large amount of data produced by the currently operating and next generation cosmic ray, gamma-ray and neutrino detectors will require a new approach to the data management, which will allow quick and efficient data sharing between cosmic ray, neutrino and multiwavelength astronomy communities. We foresee a set up of a dedicated Swiss Data Center for Astroparticle Physics which will have a central role in providing access to all relevant data for different research groups in Switzerland and worldwide. This should allow a full-scale implementation of the multi-messenger approach in high-energy astroparticle physics.

In principle, the ESA satellite Euclid is going to be launched in 2018. Even though we may realistically expect this launch to be somewhat delayed, clearly the period 2018-2022 will be very exciting and crucial for the problem area of dark matter and especially dark energy. We will already be in posession of the data from the Planck satellite and from smaller large scale probes like DES and BOSS. Even though we shall certainly still continue to exploit these data during that period, the theoretical directions we shall pursue will depend on what we have learned. Furthermore, this first round of large scale structure data will be very useful to optimize the observational strategy for Euclid.

We also might already have some indication on the nature of dark matter, especially if it is a WIMP, from LHC or from other dark matter experiments. Our experimental and especially theoretical efforts in this second period will strongly depend on the findings of the first period. For example, if no deviation in the equation of state from $w = -1$, i.e. from a cosmological constant have been found, we will have to maximize our efforts in understanding how clustering properties of large scale structure might show deviation from a cosmological constant and what is the best observational strategy of revealing them. Theoretically, we shall want to make progress in understanding and resolving the cosmological fine tuning problems: why does the cosmological constant have the observed value? Why does it come to dominate just now? Could we be "fooled" by backreaction? If not, how can we exclude this?

In what concerns the early Universe, we might have measured primordial gravitational waves from inflation by CMB polarization experiments like QUIET-II or POLARBEAR. This will be very important to constrain inflationary models. Even a null result until 2018 will be very relevant as it will exclude the simplest single field models of inflation. Furthermore, if Planck has measured non-Gaussianities, the era of exploration very high energy (the scale of inflation may be as high at 10^{16}GeV) physics interactions will start. On the other hand, simple single field slow roll models of inflation predict primordial non-Gaussianities which are much too small to be measurable with Planck or any of the planned experiments.

4 Research Plans of Individual Projects

4.1 The Challenge of Elementary Constituents and Forces

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Research question and state of the art:

Properties of light quarks and muons are studied using the unique opportunities of the **Swiss national laboratory PSI**, with an excellent international reputation. In addition to its involvement in LHC experimentation and theory, PSI supports an active program of precision physics using the 1.4 MW proton cyclotron delivering a beam of 590 MeV. This figurehead facility delivers the world's most intense beams of low-energy pions, muons and ultra-cold neutrons. Projects are ongoing or planned for further intensity upgrades in view of a next generation of experiments. The flagship particle physics experiments taking place at PSI are searches for the lepton flavor violating decay $\mu \to e\gamma$ (MEG) and for the CP-violating electric dipole moment of the neutron (nEDM), with important Swiss contributions. Both are unique opportunities to discover physics beyond the Standard Model and complementary to collider experiments. Extensions of these searches are being planned, investigating options for an improved search for the decay $\mu \to eee$. Other experiments that have received considerable attention are: the measurement of the Lambshift in muonic hydrogen, of the positive muon lifetime (FAST and MuLAN), of the negative muon capture on protons (MuCAP) and of the pion branching ratio to electrons versus muons (PEN). Further development of ultracold neutron sources as well as muon beams is foreseen, both for improving intensity and beam quality for precision experiments.

Heavy quarks and leptons – b and t quarks and tau leptons – play an important role in the study of ordinary matter. The properties of b and t quarks are studied at **LHC**, where they are abundantly produced. At LHC, proton-proton collisions – today at 7 TeV center-of-mass energy, at twice that energy in the future – are used to produce known and unknown particles and states of matter. The LHC went into operation in 2009 with its four large detectors ALICE, ATLAS, CMS and LHCb. Swiss groups are active since many years in ATLAS (Universities of Bern, Geneva), CMS (ETHZ, PSI, University of Zürich) and LHCb (EPFL, University of Zürich), with important contributions to the design, construction, commissioning and exploitation of the experiments, and with important management and coordination responsibilities. ATLAS and CMS are general-purpose detectors, designed to exploit the full potential of the LHC, while LHCb will take advantage of the high statistics available at the LHC to investigate the subtle differences between hadronic matter and antimatter, using particles composed of b quarks. Top quarks, as studied with ATLAS and CMS, constitute a laboratory in themselves, in that they decay before having a chance to form hadrons, as all other quarks do. Their interaction and decay products thus directly reflect properties of bare quarks. At the same time, this property makes their study especially challenging. As the heaviest known elementary particles, they show up in the decay chains of many postulated extensions to the Standard Model. Swiss groups are contributing in an important way to the research of top quark properties with ATLAS and CMS, as well as b quark properties with LHCb.

The incompatibility between gauge symmetry and massive particles is still one of the mysteries behind the apparent success of the Standard Model. Various viable alternatives for generating masses without violating gauge symmetry are vigorously pursued using LHC data. The possibility of the Standard Model Higgs mechanism should have been eliminated or confirmed before the start of the NCCR. Depending on the outcome, either detailed properties of the Higgs boson(s), or alternative symmetry breaking mechanisms must be determined.

To increase the impact of Swiss groups on the analysis of LHC data, the Swiss University Conference (SUK) approved the formation of the "Swiss Center of Advanced Studies in Particle Physics in the LHC Era" (Innovation and Cooperation Project C-15). The program supports a total of nine additional post-doctoral fellows from 2008 to 2012 and is very successful indeed[2]. In parallel, a ProDoc entitled "Particle Physics in the LHC Era" supports a comparable number of additional graduate students and a doctoral program in particle physics. Despite this effort, there is room for improvement as far as the usage of LHC by Swiss researchers is concerned. As a numerical example, the total Swiss contribution to the construction of the LHC experiments covered about 9% of their total cost, while less than 2% of the authors of current LHC publications work for a Swiss institution. Even though these numbers only poorly represent the importance of Swiss contributions, it is clear that the utilization of infrastructure by Swiss institutions is severely hampered by the lack of funds for scientific personnel.

Research on **neutrinos** and their properties focuses on four main scientific questions: What is the mass of neutrinos? What are the precise values of the leptonic mixing matrix elements? Is there a measurable amount of matter-antimatter symmetry violation in the leptonic sector and can its action be described by a phase in the mixing matrix, as seems to be the case in the quark sector? Is the neutrino its own antiparticle (Majorana type particle) or not (Dirac type particle)?

Swiss researchers participate in the international long baseline neutrino oscillation program in a coordinated fashion. Initially the Bern group was member of OPERA and the ETHZ group of ICARUS, both experiments located at the underground Laboratori Nazionali del Gran Sasso (LNGS) on the CNGS beam from CERN. Meanwhile, the University of Geneva group spearheaded studies of future neutrino facilities, including the HARP experiment at CERN, which led to participation in the K2K and T2K experiments in Japan. The K2K experiment observed first the disappearance of a man-made muon neutrino beam. The Swiss groups have now achieved convergence into two main streams with OPERA and T2K. This focus of Swiss neutrino resources has made most efficient use of investments, and increased the impact and visibility of Switzerland in those experiments.

The OPERA experiment has successfully run from 2008 to 2010 collecting several thousand neutrino interactions. The experiment sees a strong Swiss participation with a leading scientific and management role of researchers from Bern and ETHZ. In 2010 the collaboration published the observation of a first tau-neutrino candidate event. With the final statistics collected until 2012 the experiment will reach a sensitivity adequate to establish the discovery of the $\nu_\mu \rightarrow \nu_\tau$ transition.

The T2K experiment, using the newly built very high intensity proton accelerator J-PARC complex in Japan, is the logical continuation of the line of research in neutrino oscillation physics beyond K2K and OPERA. A very visible Swiss participation with a leading scientific and management role of researchers from Bern, ETHZ and Geneva was established since 2006. A most important contribution by the Swiss groups is the measurement of particle production in the T2K target by the NA61/SHINE experiment at CERN allowing neutrino flux predictions with unprecedented accuracy. The experiment started collecting data in 2010 and will continue for five years. The experiment proceeds with a high-sensitivity measurement of ν_μ disappearance and will be the world most sensitive search for the heretofore unobserved $\nu_\mu \rightarrow \nu_e$ appearance. First indications of the latter have recently been observed. This reaction is precisely the one in which CP violation can be observed and is of paramount importance for the future program.

The GERDA and EXO experiments aim at the detection of the neutrino-less double beta decay in ^{76}Ge and ^{136}Xe, respectively, and hence probe the nature of massive neutrinos (Majorana versus Dirac particle), as well as possible lepton number violation. Both experiments feature a visible participation of the Swiss groups of Zürich and Bern (former Neuchatel group). GERDA at LNGS makes use of bare, high-purity germanium (HPGe) crystals enriched in 76-Ge, operated in a cryostat with 100 tons of ultra-pure liquid argon surrounded by a large water Cerenkov shield. The commissioning phase has started in summer 2010. The first science run, using 20 kg of enriched HPGe detectors commenced early 2011. In parallel, the production and testing of an additional 20 kg of HPGe will be pursued. EXO will operate a liquid xenon time projection chamber in a low-background shield at the WIPP underground site in Carlsbad, USA. The commissioning with 200 kg of natural xenon has started, while a science run using 200 kg of enriched 136-Xe started during 2011. Several

[2]See Midterm Report on the SUK C-15 Project: "Center for Advanced Studies in Particle Physics", attached to this NCCR Sketch

methods to tag the resulting 136-Ba^{++} ions are being investigated for a larger scale experiment.

Intended contribution to the NCCR:

The NCCR Universe will contribute in a major way to the LHC program in Switzerland. It will increase the return on investment for Swiss groups having contributed to the LHC detectors ATLAS, CMS and LHCb by increasing data analysis personnel in Swiss groups and coordinate their effort better. It will increase the visibility of Swiss groups inside and beyond their respective collaborations by helping them to reach critical mass, by means of cooperation with other experimental groups and with theorists in Switzerland. It will coordinate the upgrade contributions of Swiss groups to the LHC detectors. And it will enhance the educational program and public awareness of high-energy particle physics by organizing schools, workshops and public events on the subject.

Cooperation between theory and experiment is not sufficiently developed in Switzerland. The NCCR Universe will act to improve the situation by forming small joint research teams, regrouping theorists and experimentalists, experienced researchers and PhD students. This will also help smaller research groups in individual universities to reach the necessary critical mass and increase their visibility and competitive edge.

The NCCR Universe will take over and enhance the C-15 and ProDoc programs running out in 2012. Postdoctoral fellowships will be attributed to the experimental and theoretical physicists working on LHC physics on the basis of their record of scientific excellence and future promise. With similar criteria PhD fellowships will be made available for first class doctoral students. A selection committee will be set-up to attract the best young scientists worldwide to study and work in Switzerland. This will increase the scientific impact in the physics exploitation and will add visibility and prestige to the existing world-class scientific research and education in Switzerland. It represents a reinforcement of excellence through international competition. The graduate and postgraduate education of these students will be the common responsibility of the participating universities. It will be structured into a doctoral program integrating existing resources as outlined below.

The high-energy frontier is complementarily pushed with high precision experiments at low energies. In certain scenarios, energy scales and masses of hypothetical particles are being tested even beyond the reach of direct searches at available or future high-energy accelerators. One of the forefront facilities for this kind of research is centered on the high intensity proton accelerator at PSI. The NCCR will enable a new generation of experiments on flavor changing neutral current decays of the muon by coordinating development of even more intense beam lines and detector development to cope with the high data rates and supreme experimental resolutions required by these experiments.

As far as neutrino properties are concerned, the Swiss groups will continue the participation in the OPERA and T2K experiments and actively prepare the next steps. The results of T2K on ν_e appearance will contribute in guiding the next steps worldwide. The NCCR will enhance the already important Swiss contributions to OPERA and T2K, including the NA61/SHINE experiment at CERN, by making additional analysis personnel available and coordinating experimental efforts.

The logical next aim will be the search for CP violation in neutrino oscillations and the measurement of the δ_{CP} phase. This can be achievable by comparing the transitions $\nu_\mu \rightarrow \nu_e$ with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ or by precision study of the energy dependence of the $\nu_\mu \rightarrow \nu_e$ or $\nu_e \rightarrow \nu_\mu$ appearance probability. The measurement method varies with the magnitude of the transition which depends on the last unmeasured angle of the neutrino mixing matrix, called θ_{13}; high statistics is always required, implying high intensity beams and very large detectors.

This challenging measurement requires a next-generation giant neutrino detector at the 100 to 1000 kton scale, located at the proper distance of a MW-class conventional neutrino beam source, or of a more powerful neutrino facility of a new type. By locating the detector underground, a rich particle and astro-particle physics program can also be covered, e.g. proton decay searches, the study of neutrinos of astrophysical origin, etc. A second phase FP7 design study has been approved (LAGUNA-LBNO), involving Bern, ETHZ, and Geneva, where by 2014 long baseline neutrino beams from CERN will be studied and detector designs developed with the aim of designing a future long baseline neutrino oscillation experiment. By then, results by T2K on θ_{13} will be available to optimize the experimental design. The NCCR Universe will help Swiss scientists develop a program with a broad international participation towards the realization of the next generation neutrino experiment, including the large underground observatory, a suitable high intensity beam and the necessary instrumentation and near detectors.

GERDA and EXO will eventually reach a sensitivity of 130 meV for the effective Majorana neutrino mass. They will explore the nearly degenerate mass pattern of neutrinos within the next years using different isotopes and technologies. The two projects will probe the mass range predicted by neutrino oscillation experiments for the case of an inverted neutrino mass hierarchy. The NCCR will enhance Swiss participation in these projects by making additional manpower available. Options to address the next level of sensitivity, requiring one ton of a double-beta emitter and a background level below one count per year and ton, will be studied with a visible contribution from the NCCR. Given the increased complexity of such projects, these will likely be realized in the framework of larger interregional collaboration.

Following the successful example of the C-15 and ProDoc programs for LHC physics, the NCCR Universe will thus implement a PhD student and post-doc program for neutrino physics, attributed on a merit basis in international competition. The organization of this fellowship program will be analogous to the one for LHC physics (see above).

4.1.1 Project: Electric Dipole Moment of the Neutron

Coordinators: K. Kirch (PSI and ETHZ), A. Weis (Fribourg)

Research question and state of the art

Some of the most stringent constraints on models of CP violation (CPV) today come from the non-observation of electric dipole moments (EDM) of fundamental systems like the neutron, atoms and molecules [4, 5]. An electric dipole moment of a spin 1/2 particle like the neutron would violate both parity and time reversal symmetry and by the CPT theorem also CP. The electric dipole moment of the neutron has been searched for since the 1950s with ever improving precision and results still consistent with zero. Already the present upper limit of $2.9 \times 10^{-26}\, e$cm at 90% C.L. [6] poses severe theoretical problems: (i) The so-called 'strong CP-problem' is the fact that no QCD-induced CPV has been found so far, limiting by experiment the so-called Θ_s parameter (naturally of order 1) to be smaller than about 10^{-10}. (ii) The so-called 'SUSY CP-problem' describes the fact that simple supersymmetric models with particle masses in the TeV range also already now require a small CPV phase or cancelations between various contributions. More generically, in new physics models the EDM of the neutron can be related to a CPV phase and the typical mass scale of particles involved. With a phase of order 1 the present EDM limit is already sensitive to order 10 TeV masses and future improvements will push this to 100 TeV and beyond.

Searches for CPV are of special importance because a yet unknown source of CPV is thought to be required in order to explain the observed baryon asymmetry of the universe. Extensions to the Standard Model of particle physics often lead to observable particle EDM. Clearly, the observation of a finite neutron EDM would be a sensation. But highly interesting is also the fact that its non-observation together with an improvement of the upper limit by two orders of magnitude can rule out electro-weak baryogenesis in connection with many models, e.g. with the so called Minimal Supersymmetric Standard Model [7].

Improvements in experimental sensitivity for neutron EDM experiments are thus considered to be of high priority and are pursued by several experimental collaborations worldwide. One international collaboration resides at PSI aiming at an improvement of almost two orders of magnitude [8, 9]. It is presently working on a factor 5 improvement and planning for a major next step thereafter in the years 2014-2017. PSI has over the past years constructed a new world class facility to produce the highest intensity of ultracold neutrons needed for the EDM experiment [10]. This source has been commissioned in 2010/11 and delivered the first UCN to the present neutron EDM effort. The UCN source at PSI constitutes a user facility with two experimental areas and beam time assigned after review by an international physics advisory committee (PAC). The neutron EDM experiment is approved at PSI and continuously monitored by a special PAC subcommittee.

With an experimental apparatus on the floor and the PSI UCN source running, the international neutron EDM collaboration at PSI has an excellent chance to push the precision frontier. The Swiss groups from PSI, University of Fribourg and the ETH Zürich involved in the neutron EDM effort play a crucial role within the international consortium, they have contributed and prepare major contributions for the next analysis and upgrade steps.

Intended contribution of the project

The project here concerns the next phase of the search for the neutron electric dipole moment starting 2014. A new 'n2EDM' experimental apparatus will be used to improve the sensitivity by another order of magnitude into the region of several $10^{-28}\, e$cm. Specific contributions from the Swiss partners to n2EDM are the UCN guiding system, the active surrounding field compensation system, the passive multi-layer mu-metal magnetic shield, mercury co-magnetometry [11] and multi-sensor optical Cs magnetometry [12]. Especially the issues of providing a magnetically suitable environment by means of active and passive shielding and of precisely measuring the magnetic field and actively feed-back stabilizing it are of utmost importance and of greatest interest. The Swiss partners in n2EDM have already secured a considerable amount of funding for investments into the experimental hardware like the passive multi-layer shield. The project here is about the implementation of a magnetometry and shielding knowledge center by collecting all relevant know-how and assemble a group of sensor and analysis experts with critical mass to guide the technical design effort and to fully exploit the physics data. In particular, the following activities will be pursued within the project:

- Complete characterization and optimization of a multi-sensor active feed-back stabilization system for the magnetic field surrounding the passive mu-metal shield.
- Optimization of the passive multi-layer shield with emphasis on the innermost shielding layer, which is most crucial for the low noise performance of all subsystems inside the shield and for the homogeneity of the magnetic field over the relevant measurement volume.
- Implementation and full exploitation of a laser system in n2EDM for pumping and probing of ^{199}Hg used as co-magnetometer. Specific studies on related false effects due to light shift effects, gravitational offsets and geometric phase effects.
- Optimization for highest sensitivity and full exploitation of arrays of laser optically pumped Cs magnetometers. Implementation of high precision, absolute magnetic field measurements. Development and characterization of vector magnetometry and studies of fully optical operation of the sensors.
- Full system analysis of magnetic shielding and magnetic field measurements. Correlation studies of all subsystems and development of counter measures to systematic false effects for the neutron electric dipole moment experiment.
- Independent physics analysis group to contribute at all levels to the n2EDM analysis. This affects service work like the preparation of raw magnetometry data for the collaboration to a stand-alone blind neutron analysis.
- A systematic theoretical analysis of the reach of the neutron EDM experiment with respect to physics beyond the Standard Model will be aimed at. Cooperation of experimental and theoretical physicists will allow to investigate possible side-tracks and spin-offs in the physics analysis. The collaboration has already in the past performed first measurements limiting neutron – mirror-neutron oscillations [13, 14], limiting Lorentz violation effects [15, 16] and searching for anomalous spin gravity couplings [15]. The experiment will also be sensitive to new short range interactions and check on models of extra-dimensions [17]. With improved precision, these and potentially other well motivated exotic physics searches can be pursued, complementary to other efforts at low and high energies.

Links to other projects of this NCCR

The collaboration to search for the EDM of the neutron will contribute in many ways to the NCCR. The participating Swiss partners of the neutron EDM collaboration will integrate their other project-oriented manpower into the NCCR. The involved senior scientists (2 from Fribourg, 5 from PSI, 1 from ETHZ) will be associate members of the NCCR. Besides the manpower coming from the NCCR, about 3 Postdocs and 3 PhD students will be contributing. Progress and results of the EDM project will regularly be reported in NCCR meetings, at the annual Swiss Physical Society meeting, and obviously at international conferences. In cooperation with other high precision and intensity oriented projects of the NCCR, the EDM project will organize workshops on precision physics and work on establishing various aspects of complementarity between high energy and precision also in the particle physics outreach and education. The project will establish cross links within the NCCR and connections to the outside, especially trying to set up a dialogue with particle theory to map the reach of the neutron EDM experiment in particular and low energy precision experiments in general. With the example of the neutron EDM we will investigate options for other high precision experiments with UCN making use of the unique Swiss UCN facility at PSI. As another contribution to the NCCR and beyond, the project will work on increasing the awareness concerning novel, strictly non-magnetic materials and their machining (workshop know-how), magnetic field measurement capabilities and magnetic shielding. We will analyze the potential to transfer aspects of the related know-how to other partners in the NCCR and to industry.

4.1.2 Project: Searches for New Physics using Bottom Hadrons

Coordinators: O. Schneider (EPFL), U. Straumann (UniZH)

Research question and state of the art

This project is motivated by one of the outstanding scientific challenges of particle physics, namely the understanding of the origin of the observed matter-antimatter asymmetry in the Universe. So far, all measurements of

CP violation in the quark sector are compatible with a single source of asymmetry arising from the irreducible complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix between the three known generations of quarks. However, this Standard Model explanation is quantitatively insufficient, by far, to account for the baryonic asymmetry of the Universe. Therefore other sources of CP violation must exist. New sources may well exist in the lepton sector or an extended gauge sector. However, with the copious production of charm and beauty hadrons available at the LHC or planned at super-flavour factories, the quark sector will remain, for at least the next decade, the best place to look for non-standard CP violation effects.

More generally, flavour observables are sensitive to physics beyond the Standard Model, both in models with or without new sources of CP violation. Indeed yet unknown particles may affect the decay properties of charm and bottom hadrons through quantum corrections. This is expected to be more easily visible in flavour-changing neutral current (FCNC) transitions, which are suppressed in the Standard Model. Measuring such transitions and comparing them with the Standard Model predictions is viewed as indirect searches for new physics, in contrast to the direct searches aiming at the observation of new particles produced at the high-energy frontier colliders. Both approaches are complementary: while the indirect approach is sensitive to higher energy scales and may therefore sense a new effect earlier, the direct observation of any new particle is necessary to establish its unambiguous discovery as well as to measure its main properties. A tantalizing possibility would be the discovery of new particles constituting the dark matter of the Universe. New Physics at the TeV scale would need to have a non-trivial flavour structure in order to provide the suppression mechanism for the already observed FCNC processes. Only indirect measurements can access the phases of the new couplings and therefore shed light on the new physics flavour structure.

During the last decade, heavy flavour physics has been dominated by the experiments running at the B factories, i.e. e^+e^- colliders operating just above the open beauty threshold. Together, the BaBar experiment at PEP-II (SLAC, USA) and the Belle experiment at KEKB (KEK, Japan) recorded more than 1.24 billion $\Upsilon(4S) \to B\bar{B}$ events in the period 2000–2008. While the final data analysis is still ongoing, important break-throughs are no longer expected. All B-factory measurements appear to be consistent with the Standard Model: some interesting (but not very significant) hints for New Physics have appeared along the road, but in many cases their significances diminished with time. Global fits [18] of flavour measurements and CP-violation results show a reasonable overall consistency within the Standard Model, although some tension exists (at the level of 2.6σ) between the measurements of the $B^+ \to \tau^+\nu_\tau$ branching fraction and those of mixing-induced CP-violation in B^0 decays governed by $b \to c\bar{c}s$ transitions [19]. Some B-factory measurements still have large statistical errors. The most striking example is perhaps that of the angle γ, the least well measured angle of the Cabibbo-Kobayashi-Maskawa unitarity triangle. The current uncertainty obtained from the combination of all direct γ measurements is approximately 14 degrees [19]. A substantial reduction is very desirable as it would allow to test more deeply the consistency of the Kobayashi-Maskawa picture of CP violation.

While a number of B_s^0 physics results have been obtained by Belle using a data sample collected at the $\Upsilon(5S)$ resonance, the most interesting B_s^0 measurements were pioneered by high-energy hadron collider experiments, where larger statistics and better decay time resolution are available. The operation of the Tevatron (USA), a $p\bar{p}$ collider at a centre-of-mass energy of 2 TeV, came to an end in September 2011, with the two experiments CDF and DØ having each collected a data sample of approximately 10 fb^{-1}; some B physics analyses still use only half of this data sample, so improved results are still expected in the next year or two. On the other hand, the LHC experiments, in particular LHCb which has collected 1.2 fb^{-1} of data at $\sqrt{s} = 7$ TeV in 2011, are now overtaking the Tevatron experiments. The most important B_s^0 physics results have been obtained in the following indirect searches for New Physics:

- The $B_s^0 \to \mu^+\mu^-$ decay is very suppressed in the Standard Model, with an expected branching fraction of $(3.2 \pm 0.2) \times 10^{-9}$ [20], but many New Physics models predict a significant enhancement. The LHCb and CMS experiments have now shown 95% upper limits on the $B_s^0 \to \mu^+\mu^-$ branching fraction of 14×10^{-9} [21] and 19×10^{-9} [22], respectively, with a combined limit of 11×10^{-9} [23], much more stringent than previous upper limits [24, 25], below the central value obtained by CDF [25], but still a factor 3.4 away from the Standard Model value.

- Similarly, the weak phase $\phi_s^{J/\psi\phi}$ governing mixing-induced CP violation in the $B_s^0 \to J/\psi\phi$ decay is expected to be very small in the Standard Model, $(\phi_s^{J/\psi\phi})_{\rm SM} = -2\beta_s = -0.0363 \pm 0.0017$ [18], but could be significantly enhanced in various New Physics models. While previous Tevatron results generated a lot of excitement with a deviation from the Standard Model prediction in excess of 2σ, recent updates [26, 27] are now in fair agreement with the prediction. Also compatible with the Standard Model, but with much smaller uncertainties, is the recent LHCb measurement $\phi_s = +0.07 \pm 0.17 \pm 0.06$ [28] combining $B_s^0 \to J/\psi\phi$ [29] and $B_s^0 \to J/\psi f_0(980)$ [28] results.

- In 2010, the DØ collaboration obtained an evidence for an anomalous charge asymmetry for dimuon pairs from semi-leptonic b-hadron decays [30], indicative of CP violation in $B^0 - \bar{B}^0$ and/or $B_s^0 - \bar{B}_s^0$ mixing. A recent update of this analysis with more statistics now yields $A_{\rm sl}^b = (-0.787 \pm 0.172 \pm 0.093)\%$ [31], which represents a 3.9σ deviation from the Standard Model prediction of $(-0.023^{+0.005}_{-0.006})\%$.

More generally the full heavy flavour physics programme at LHC is now being deployed, with LHCb taking the lead for the next several years. This includes not only indirect New Physics searches in B decays, but also in charm decays where CP violation, predicted to be very small in the Standard Model, has been evidenced for the first time by LHCb [32].

The next-generation collider experiments dedicated to flavour physics are being planned at two new B factories with design luminosities in the range $(0.8-1) \times 10^{36}$ cm^{-2} s^{-1} [33]. The Belle II detector will operate at the SuperKEKB collider [34], an upgraded version of KEKB scheduled to be commissioned starting in 2015, and is expected to collect an integrated luminosity of 50 ab^{-1} by $\sim$ 2021. A similar project in Europe is called SuperB [35], to be built from scratch in Italy; the proposed schedule is very aggressive, with the aim of being ready just one year after SuperKEKB and collecting up to 75 ab^{-1} by the year 2022.

Intended contribution of the project

We propose contributions, through new and high-statistics measurements of b-hadron decays, to searches for effects of processes beyond the Standard Model and to characterize the nature of the underlying physics. This will be done by analyzing the data collected by the LHC experiments. The most significant contributions are expected from LHCb, and will be obtained under the responsibility of the Swiss research groups involved in LHCb, at the University of Zurich and at the Swiss Institute of Technology of Lausanne (EPFL). The ATLAS and CMS experiments can contribute to a restricted number of topics, as shown by the PSI group in CMS. All Swiss groups interested in B physics are heavily involved in their experiments since many years and have acquired significant experience in data analysis, having contributed for example to the first physics results with $B^0_{(s)} \to \mu^+\mu^-$ and $B_s^0 \to J/\psi\phi$ decays.

The LHCb experiment recently placed itself at the forefront of beauty physics, where virgin territory can be explored for many years with a large number of decay channels. During the first phase of LHCb, defined as the data-taking period with the current detector configuration until the start of the upgrade shutdown currently foreseen in 2018, an expected total integrated luminosity in the range $6-10$ fb^{-1} will be collected. This unprecedented statistics will be sufficient to either find or exclude large deviations from the Standard Model predictions. As part of this NCCR we plan to continue or launch efforts on a number of fronts which may include

- the search for the rare decays $B_s^0 \to \mu^+\mu^-$, where the sensitivity should be enough to observe any signal larger than the Standard Model prediction,
- the measurement of mixing-induced CP violation in B_s^0 decays involving a $b \to c\bar{c}s$, where a determination of ϕ_s with a statistical precision comparable to the central value of the Standard Model can be achieved,
- the measurements of branching fractions and CP observables in not well known or yet unobserved charmless b-hadron decays involving FCNC transitions,
- a measurement of the angle γ, e.g. with $B_s^0 \to D_s^{\mp} K^{\pm}$, where a combined precision of a few degrees can be expected.

In parallel, the LHCb experiment will be upgraded [36] such as to be able to collect, starting in 2019, an integrated luminosity of $\sim$ 5 fb^{-1}/year with a more flexible and efficient software-based trigger. The upgrade involves a full detector readout at 40 MHz, new front-end electronics, as well as the replacement of some subdetectors needed to cope with the increased occupancy. The Swiss groups will design and build new tracking stations. The upgraded detector will bring the experiment to the next level of precision, uniquely equipped to fully exploit the flavour physics potential ofthe LHC. In case of direct discoveries by ATLAS and CMS of new signals beyond the Standard Model, the role of the upgrade LHCb experiment will be understand which is the correct theoretical model describing the new phenomena and measure its parameters. In the opposite scenario, LHCb may still be able to provide evidence for New Physics beyond the limit for direct production.

Links to other projects of this NCCR

The ideal contribution of this project to the NCCR would be the indirect discovery of new phenomena contributing to the mixing or decay of b-hadrons, correlated with a direct observation of new particles observed at the LHC, and explained by a theoretical extension of the Standard Model incorporating dark matter candidates.

In a less exciting but nonetheless interesting scenario where no new effects are seen in b-hadron decays, this project will provide severe constraints on new models, including those with cosmological consequences. In order to obtain these results, to reach any firm scientific conclusion from them, and finally to communicate them to the public, significant efforts will be needed from both the experimental and theoretical sides.

This NCCR should provide, within Switzerland, an appropriate framework for such efforts to be developed and coordinated at three different levels: between the experimental groups at LHC working on B physics, between these groups and the theorists using the B physics results as contraints in the models, and finally more widely together with cosmologists. For the first two levels, this will be achieved, as explained in Section 4.1, by developing the cooperation between the research groups, forming new joint research teams, and/or allocating a number of post-doctoral and PhD fellowships. This will increase both the impact and visibility of the project.

4.1.3 Project: Searches for New Physics using the Top Quark

Coordinators: G. Iacobucci (UniGe), R. Wallny (ETHZ), M. Weber (UniBe).

Research question and state of the art

One of the expected signatures of new physics at the LHC is the abundant presence of heavy Standard Model (SM) particles in the final state. The top quark, in particular, is very often part of the decay chain of such new particles in numerous extensions of the SM and therefore its accurate reconstruction is an essential tool in searches for new physics.

The top quark was discovered in 1995 at the Tevatron [37, 38], after many years of searching. At the LHC, SM $t\bar{t}$ pairs are produced through the strong interaction with about 85% of events coming from the fusion of two gluons from the colliding protons. Due to its high mass of 173.2 $\pm$ 0.9 GeV/c^2 [39], it has an extremely short life-time. Therefore its electroweak decay occurs on timescales shorter than that of the strong interaction, with the consequence that the top quark decays before it hadronizes. The only observed decay of the top quark is the weak decay to a b-quark and a W-boson. The identification of the two b-quarks in the final state plays a vital role in top physics since much of the other SM backgrounds do not contain heavy-flavour particles. In addition, the two W-bosons decays, either leptonic or hadronic, characterize $t\bar{t}$ event topologies further. Searches for new physics using top quarks have been performed at the Tevatron and the first LHC results are being published.

Most of the current BSM theories predict new particles just above the electroweak scale, of the order of one to a few TeV, and thus within the reach of the LHC. Due to its anomalously high mass, the top quark plays a special role in searching for new physics in a number of BSM models [40], in particular those with alternative methods of electroweak symmetry breaking (EWSB). Examples of such models include dynamical EWSB that could be caused by a new strongly interacting sector [41, 42, 43], and seesaw mechanisms of quark condensation [44]. Some flavours of technicolor [45, 46, 47] predict a special role for the top quark. Models that incorporate gravity will generally produce enhanced couplings of the mediators of gravity to top quarks, in particular extra dimension models where the gravitons can propagate through to the extra dimensions [48, 49, 50, 51]; if the extra dimensions are small, this could explain the mystery of the large mass hierarchy observed between particles.

Many of these models predict new resonances or gauge bosons that are strongly coupled to the top quark or produce particles with signatures very similar to those of top quarks or that decay to top quarks. Examples of the first category are Z' bosons [52, 53] as well as the previously mentioned gravitons in extra dimension models. The second category includes the supersymmetric (SUSY) partner of the top quark ($\tilde{t}$ or stop) [54, 55], a vector-like T, sometimes referred to as $\tilde{t}'$, predicted in a number of Little Higgs theories [56, 57], top partners $T_{5/3}$ with electric charge 5/3 predicted in models where the Higgs is a pseudo-Goldstone boson [58], or fourth generation t' quarks [59, 60].

Intended contribution of the project

SUSY and the 3^{rd} generation: Searches for SUSY are presently being vigorously pursued at the current LHC run at 7 TeV. In the simplest SUSY scenario, low mass squarks and gluinos are pair-produced and decay in spectactular cascade decay chains including the production of several jets, leptons and missing transverse energy from the lightest supersymmetric particle (LSP). It is however conceivable that SUSY manifests itself at a higher energy scale than targeted with these “early” LHC SUSY searches. The third generation would be especially important for such a scenario as the lightest squark initiating such a decay chain is expected to be one mass eigenstate of the left and right handed stop quarks. This is due to the large SM top quark mass and the resulting large mass splitting in the stop quark sector, particularly in high $\tan\beta$ scenarios of the Minimal Supersymmetric Standard Model (MSSM). In the main part of the mass range allowed for stop quarks, stop quarks would decay primarily to a top quark and a neutralino, $\tilde{t} \rightarrow t\tilde{\chi}_2^0$, giving rise to a top quark and large missing transverse energy and possibly further leptons from the $\tilde{\chi}_2^0$-decay to the lightest supersymmetric particle. In the direct production process stop quarks will look very much like top quarks in terms of the final state but have different kinematics due to e.g. their different spins.

These 3^{rd} generation SUSY searches will therefore be important for the 14 TeV run of the LHC, which will take place during the timescale of this NCCR. Due to the similarity of the signal and the background, these searches will have to employ sophisticated multivariate analysis techniques, such as boosted decision trees, neural nets and matrix element methods. Establishing such analyses techniques and commissioning them on data is therefore a major contribution to this NCCR project. Pinning down the SM background, in particular $t\bar{t}+X$ production where X could produce significant missing transverse energy (such as $Z \to \nu\nu$) will be particularly important for these searches as well. Another milestone for this NCCR project would therefore be the measurement of SM $t\bar{t}+Z$ production. The $t\bar{t}+X$ topology is furthermore important for establishing the existence of the SM Higgs boson in the top quark associated production mode, $t\bar{t}H$ (see section 4.1.5). This SM Higgs boson search is strongly dependent on the accuracy of the determination of the irreducible backgrounds with top quarks, such as $t\bar{t}b\bar{b}$ and $t\bar{t}jj$. A generic program of studying the $t\bar{t}+X$ topology is therefore of broad interest. Researchers participating in this NCCR are already deeply involved in current inclusive SUSY searches and are well poised to tackle the search for SUSY at higher mass scales using top quarks in the final state.

Boosted top quarks: One research topic, which is considered to be among the most powerful probes for discovery of new physics at the LHC and therefore has rapidly gained interest in spite of the several experimental challenges, is that of boosted-top production[3]. Numerous extensions to the Standard Model predict massive particles whose couplings to top quarks are enhanced, which implies that decays to top-quark pairs are favored [48, 49, 50, 51, 61, 62, 63, 64, 65, 66]. One example is the production of Z' bosons. Due to constraints from experiments at the LHC and at earlier colliders, the postulated BSM particles must be considerably more massive than top quarks. Therefore, top quarks produced in the decay of such resonances would be emitted with very high momenta, i.e. the top quarks will be highly boosted. The researchers of this NCCR plan to be involved in searching for resonant production of top quark pairs from a new particle and for heavy new particles that have signatures similar to $t\bar{t}$ or that decay to top quarks and other particles. Research activity is already going on in Switzerland in this framework.

Boosted-top identification constitute a challenge with respect to the reconstruction of the events. Currently, most of the effort in top physics has been focused on the individual reconstruction of the decay particles of the top quark. For boosted systems it might not be possible to resolve all of the particles, since they would appear in the detectors as a collimated jet-like structure (*"fat jets"*). In order to not lose acceptance, in particular for searches in the tails of transverse momentum distribution, or in measurements accessing the forward rapidity regions, algorithms are being developed to enable the reconstruction of the decay products of the top quark into a single large radius jet. Although the limits obtained so far using boosted systems [67, 68] are slightly lower than for the traditional $t\bar{t}$ resonance search, the gain will become very significant at higher invariant masses. The researchers of this NCCR are deeply involved in this program, in both the ATLAS and CMS collaborations. The NCCR will allow acquisition of a leading role in this field within the international community.

Links to other projects in this NCCR

The search for new particles and physics phenomena is a motivation to other projects in the challenge of constituents and forces of this NCCR. By combining the information from different projects we can gain a more complete picture of possibly discovered new physics. As an example, an indirect signal of new physics from a non-vanishing neutron EDM would have to be confirmed by the direct search from this project. The relation to the EWSB and Higgs project is very close, as has been pointed out above, due to the massive coupling of the top quark to the Higgs and also for the exploration of EWSB theories proposing new particles as searched for in this project. The discovery of SUSY would be an important step also towards GUT models.

This project also links to the Dark Energy and Dark Matter challenge of this NCCR. Indeed, a lightest supersymmetric particle in R-parity conserving SUSY, which is being searched for at the LHC, is a candidate for dark matter in the universe.

4.1.4 Project: Exotic hadrons, hadron-in-medium properties, and (exotic) hadronic matter

Coordinators: B. Krusche (UniBs)

Research question and state of the art

Although according to present knowledge our universe is composed of $\approx 4\%$ baryonic matter, $\approx 26\%$ Dark

[3]Boost here refers to the Lorentz boost due to the top quark being produced not at rest in the lab frame.

Matter and $\approx$ 70% Dark Energy, so far only baryonic matter has been directly observed and forms all visible structures like stars, planets, and galaxies. An understanding of the development and structure of the Universe is impossible without a detailed knowledge of the properties of hadrons – strongly interacting particles – also under extreme conditions as they can be found in very hot or very dense environments like for example in the early universe or in neutron stars.

The project concentrates on the search for "exotic" types of hadrons, i.e. strongly interacting particles that are not made of quark-antiquark pairs (mesons) or three quarks (baryons), on the modification of hadron properties in nuclear matter, and on the properties of exotic types of matter such as mesic nuclei. It is currently based on medium-energy electron accelerators (MAMI in Mainz, 1.5 GeV and ELSA in Bonn, 3.5 GeV) with state-of-the-art detector systems. Together with Jlab in the United states these are the world-wide leading facilities in this field. In the near future, the upcoming PANDA detector at the HESR antiproton-ring of the new FAIR facility in Darmstadt, Germany, will open exciting new opportunities for this project.

Quantum Chromodynamics (QCD), the theory of strong interactions, allows in principle the existence of many different types of hadrons, which must only fulfill the condition of being colorless objects. However, so far only mesons and baryons have been observed in experiments. Other types of hadrons like di-baryons (six-quark systems), penta-quarks ($qqqq\bar{q}$), glueballs, hybrids of mesons and glueballs, and objects called 'strangelets', which involve a similar numbers of up, down, and strange quarks [69], have been much discussed, but for none of them conclusive experimental evidence has yet been reported. However, there are experimentally observed structures, which are so far not understood.

A few years ago, several experiments (see e.g. [70, 71, 72, 73, 74]), claimed the observation of a very narrow state assigned to a manifestly exotic ($uudd\bar{s}$) member of the predicted anti-decuplet of pentaquark states [75] termed Θ^+. However, follow-up experiments, partly done by the same groups (see e.g. results from the CLAS collaboration [76]) could not confirm this finding. A very recent somewhat different analysis [77] of the same CLAS data (although not supported by the CLAS collaboration) again claims a signal. Therefore, the situation is still not completely settled, although there is certainly no generally accepted evidence for the Θ^+.

During the excitation created by the early pentaquark-search results, also predictions for the properties of other members of the anti-decuplet, in particular the non-strange P_{11}-like state were made (see e.g. [78, 79]). This state was expected at $\approx$1.7 GeV mass with a width Γ <30 MeV, a comparably large decay branching ratio to $N\eta$ and a much stronger electromagnetic coupling to the neutron than to the proton. Therefore, such a state should be observable in photoproduction of η-mesons off the neutron, $\gamma n \rightarrow n\eta$. Surprisingly, all experiments that looked at η-photoproduction off the neutron in the relevant energy range (GRAAL/Grenoble [80], CBESLA/Bonn [81, 82], LNS/Sendai [83], Crystal Ball@MAMI [84]) immediately observed a prominent, unusually narrow structure (Γ <50 MeV) around $\sqrt{s}$ $\approx$1.68 GeV, which is not observed for the proton. Due to the lack of photoproduction data off the neutron, it had been previously overlooked. The statistical significance of this structure cannot be disputed; however, its nature is not yet revealed. Apart from a relation to exotic hadrons, other explanations like intricate interference and/or cusp effects are under discussion. One should, however, note that for photoproduction reactions in this energy range the structure is quite a unique feature. Currently, programs are active at the MAMI and ELSA accelerators to investigate it with polarized photon beams and polarized targets in order to collect information about the relevant partial waves.

Intended contribution of the project

The further investigation of the hadron spectrum, in particular the $c\bar{c}$ system, glueballs and hybrids will largely profit from the upcoming Proton-Antiproton facility with the PANDA detector at FAIR in Darmstadt, which is the leading international project in this field. Construction of the detector is under way and recently also civil engineering has started at the accelerator construction side.

The generation of the mass of hadrons is a central problem in the theory of strong interactions. Most of the mass of hadrons from light quarks is generated by dynamical effects and a central role is played by the spontaneous breaking of chiral symmetry. However, those properties might significantly change when hadrons are embedded in nuclear matter in particular at high temperature and/or high density, where theory predicts at least a partial restoration of chiral symmetry. Such questions are partly investigated with ultra-relativistic heavy ion beams, but also in the range of normal nuclear matter densities signatures should show up and are then more easily interpreted than in the complicated environments of heavy ion reactions. Actually, interaction of hadrons with nuclear matter and the in-medium properties of hadrons form a significant part of the photon-induced research program at ELSA and MAMI and in future also for the antiproton induced reactions at PANDA.

Here we mention few examples which are under way at the photon beams. There is a long, controversial discussion in the literature, whether it is possible to form (quasi)bound states of mesons and nuclei via the strong interaction. So far, all known meson-nucleus bound states involve at least partly the electromagnetic interaction (pionic atoms: purely electromagnetic, deeply bound pionic states: superposition of repulsive s-wave π^--nucleus interaction with attractive Coulomb force). Neutral mesons could form quasi-bound states only via the strong interaction. This would constitute a new type of hadronic matter and could serve for detailed studies of the meson-nucleus interactions. The meson-nucleus interaction for slow pions is much too weak to produce such states, but the situation may be different for η, η', and ω-mesons. In fact, for the η-meson, experiments at the MAMI accelerator have shown an extremely strong enhancement of the cross section at the (coherent) η-production threshold from ^{3}He nuclei [85, 86] that seems to indicate a resonant-like behavior. These results are corroborated by the investigation of hadron induced reactions, which have also observed very strong threshold effects [87, 88]. Further experiments are planned for the ^{4}He nucleus, using coherent photoproduction of $\pi^0\eta$ pairs (because coherent production of single η mesons is forbidden on spin- and isospin-zero nuclei).

Another example is the in-medium behavior of the σ-meson. This particle is the chiral partner of the pion and if chiral symmetry were respected, should be degenerate in mass with it. In vacuum the symmetry is strongly broken, and the σ is much heavier, but already for normal nuclear matter models predict a significant reduction of its mass [89]. Since the main decay channel of the σ-meson is to pion pairs, such a signal can be searched for in the invariant mass spectra of pion pairs produced in nuclei [90, 91]. The interpretation of the results requires of course a careful investigation of final state interaction effects of the pions [92].

Links to other projects of this NCCR

The properties of nuclear matter and its equation of state (EoS), also under extreme conditions, are important for many astrophysical phenomena. Also here we like to shortly discuss two examples, the proton fraction in supernovae formation and neutron stars and the strangeness contribution to the EoS, which are relevant for the supernova evolutions studied by the Basel theory group [93].

Neutron stars are created with high temperatures in supernovae explosions and then cool by neutrino emission, mainly by the modified URCA reaction $n + n \to n + p + e^- + \bar{\nu}_e$. However, recent x-ray observations of neutron stars with low surface temperatures have raised the question of faster, more efficient cooling mechanisms. The most conservative mechanism that has been discussed in this context is the direct URCA mechanism $n \to p + e^- + \bar{\nu}_e$ followed by electron capture $e^- + p \to n + \nu_e$. The probability of this reaction chain is very sensitive to the proton fraction present in the neutron star, which in turn depends sensitively on the symmetry energy of nuclear matter under extreme conditions. Model calculations [94] have shown that the relevant properties of the nuclear force can be constrained by the measurement of the 'neutron skin' of heavy nuclei such as ^{208}Pb, which is also very sensitive to the symmetry energy. A large experimental program to measure the neutron distribution of nuclei is under way at Jlab, using parity violating electron scattering. An alternative approach to study nuclear mass distributions via the coherent photoproduction of π^0-mesons has been developed by our group at the MAMI accelerator [95] and will be further explored in collaboration with the group from the University of Edinburgh. First attempts have also been made to use coherent production of $\pi^0\eta$-pairs to get better estimates on systematic effects from final state interaction processes.

The upcoming PANDA experiment at FAIR will significantly contribute to the investigation of baryons with strange quarks – hyperons – in nuclei. The physics program of the collaboration includes detailed investigations of strange hypernuclei and in particular also of strange-double hypernuclei. The strangeness degree of freedom is expected to soften the EoS with respect to a purely nucleonic EoS and thus would limit the maximum mass/radius of neutron stars. The recent observation of a neutron star with two times the solar mass [96] therefore puts limits on the behavior of the EoS and seems to disfavor scenarios with hyperon contributions unless effects like the three-body repulsion known for conventional nuclear systems or effects from the strong interaction coupling constant and/or color superconductivity provide an additional stiffening.

The concept of stable strange matter ('strangelets') has been much discussed in the literature and would have significant impact on astrophysical questions. The recently launched Alpha Magnetic Spectrometer (AMS) has the capability of direct searches for such particles. However, so far not much is known for the elementary interaction of particles with strangeness, which is at the root of this concept. Here, the investigation of double-strange hypernuclei with PANDA will for the first time allow to study directly the $\Lambda\Lambda$-interaction in nuclear matter.

4.1.5 Project: Electroweak Symmetry Breaking

Coordinators: G. Dissertori (ETHZ), M. Grazzini (UZH)

Research question and state of the art

The Standard Model (SM) of particle physics is a $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory that describes the strong and electroweak interactions of the known subatomic particles at an impressive level of accuracy. The validity of the SM has been established during the last 30 years. The experimental facilities that played a major role in validating the model are SPS at CERN, where the W and Z bosons were first observed, HERA at DESY, where the proton structure was studied in detail, LEP and SLC, where accurate tests of the SM where performed, the Fermilab Tevatron, where the top quark was discovered, and finally the LHC, where the SM is tested at unprecedented energy scales.

Despite its success, the SM has some well known problems. In particular the mechanism that gives masses to the particles remains to be understood. Gauge boson mass terms are forbidden because they violate gauge invariance. Moreover, contrary to what happens in vector theories like QED and QCD, also fermion mass terms are not allowed: the $SU(2) \times U(1)$ electroweak sector is in fact a *chiral* theory: left and right handed fermions couple differently to the gauge group. The solution to this problem is provided by the concept of Spontaneous Symmetry Breaking (SSB). Through SSB the Lagrangian remains gauge invariant, but the gauge symmetry is not respected in the spectrum of the physical states.

There are several possibilities to realize SSB: the standard one, which is implemented in the minimal version of the SM is to introduce a complex scalar $SU(2)$ doublet endowed with a symmetry breaking potential. Three out of the four degrees of freedom go to give mass to the W and Z bosons, leaving the photon massless, and the fourth remains present in the spectrum, the so-called Higgs boson [97, 98, 99]. More involved models imply the existence of more than one Higgs doublet, such that more than one Higgs boson exists in the spectrum. It is clear that, since such Higgs boson(s) play a central role in giving masses to the elementary particles, their experimental search is one of the most important tasks of modern high energy particle physics.

It is important to note that SSB does not necessary imply the existence of Higgs boson(s). Besides direct tests of the SSB sector through Higgs searches, there are other processes that are directly sensitive to the breaking of the electroweak symmetry. If the Higgs boson does not exist, vector boson pair production violates the unitarity constraint at high energies, and thus some new physics effect must play a role to restore unitarity of the corresponding high energy scattering amplitudes.

Even if the Higgs boson is not observed, if it exists it must manifest itself in loop corrections. In particular, it will affect the self energies of the W and Z bosons, and thus precision electroweak data provide indirect information on the Higgs mass, as has happened in the past for the top quark. As a consequence, a precise knowledge of the electroweak parameters (such as gauge boson masses M_W, M_Z, top-quark mass M_t, Weinberg angle θ_w) can be used to constrain the Higgs mass. The top mass appears quadratically in the one-loop radiative contributions. For this reason the top mass was predicted with good precision before its discovery. Unfortunately the Higgs mass enters only logarithmically at one-loop order, and it is difficult to obtain stringent constraints. The present electroweak data suggest that the Higgs boson should be light ($M_H \lesssim 200$ GeV).

Up to now the Higgs boson has not yet been observed. LEP experiments have put a lower limit to the Higgs mass at $M_H > 114.4$ GeV [100]. Tevatron experiments recently excluded the SM Higgs in the mass region $156 < M_H < 177$ GeV and $M_H < 108$ GeV [101]. Higgs searches are now being carried out by the ATLAS and CMS experiments at the LHC. Very recently, these efforts have entered a crucial phase and reached first important milestones. Thanks to the high-luminosity LHC running in 2011, the ATLAS and CMS collaborations were able to present important progress from their analyses of many Higgs production and decay channels [102, 103]. Currently, the main conclusion is that the SM Higgs boson, if it exists, is most likely to have a mass constrained to the range 116 to 130 GeV by the ATLAS experiment, and 115 to 127 GeV by CMS. An intriguing excess of events in this mass region has been found by both experiments. However, with the available statistics this excess is compatible with both hypotheses, namely the existence as well as non-existence of a SM Higgs boson. Additional data, to be collected in 2012 before the long LHC shutdown in 2013 and 2014, should allow to obtain firm conclusions on this all-important question.

Intended contribution of the project

Under the assumption that there is indeed (at least one) Higgs boson with mass in the 115 to 130 GeV region, a central focus point of the future LHC activities, in particular during the high-energy (13 to 14 TeV) and high-luminosity running after the long shutdown in 2013/2014, will be the in-depth study of the properties of this boson. These studies will comprise observations and cross section measurements in as many channels as possible, in an attempt to obtain first determinations of Higgs coupling constants to fermions and vector bosons (or at least ratios of a set of branching ratios). The cross section and branching ratio measurements are important steps towards establishing if the observed new state corresponds to what is expected for a SM Higgs boson or not. An important element of the efforts will be to observe the Higgs boson also in the $t\bar{t}H$ channel. This is interesting since the top-Higgs Yukawa coupling might play a central role in the understanding of electroweak symmetry breaking. However, it constitutes a real challenge because of the large and complicated backgrounds to be controlled in this channel. It is clear that this activity will considerably profit from the synergy with another project of this NCCR (Top Quark Physics, cf. Sec. 4.1.3).

On the other hand, if it turns out that the LHC completely rules out the mass range still allowed for a SM Higgs boson, the focus will shift to the preparations of the experimentally even more challenging study of vector boson scattering, which requires both highest possible centre-of-mass energy and luminosity (hundreds of inverse femtobarns). Because of the required tagging of forward jets, the very forward regions of the LHC detectors will get more and more attention, and the envisaged upgrade activities, in particular for the Phase 2 upgrades, will change part of their focus to this area.

Links to other projects of this NCCR

Researchers involved in this NCCR are expected to make substantial contributions, both in terms of preparing and executing the data analysis, towards a precise mapping of the properties of an assumed light Higgs boson. Considerable synergy can be exploited with another projects of this NCCR, on Top Quark Physics, as well as in general among the experimental and theoretical particle physics groups in Switzerland. For both areas we are in the fortunate position to have many world-leading experts among us, thus a yet closer collaboration fostered by this NCCR will allow them to have an even stronger impact. Indeed, the theoretical physicists contributing to this NCCR will play a crucial role in providing state-of-the art, high precision predictions of signal and background processes, implemented in modern and efficient computational tools, then used by the experimental groups to optimize their analysis strategies.

In the scenario of an exclusion of a SM Higgs boson by the end of 2012, the researchers of this NCCR are expected to contribute to two research lines: (a) further extensions and improvements of the existing search analyses, towards probing of smaller than expected Higgs production cross sections and/or non-standard decay mechanisms; (b) start a concerted effort towards the preparation and execution of the necessary long-term plans for measuring vector-boson scattering, including the possible upgrades and improvements of the very forwards LHC detector regions.

4.1.6 Project: Neutrino Oscillations

Coordinators: A. Blondel (UniGe), A. Ereditato (UniBe), M. Shaposhnikov (EPFL)

Research question and state of the art

The physics of neutrino oscillations [104][105] can be separated in two classes: i) the study of transitions between the three known active left-handed neutrinos; ii) the search for departure from this minimal scenario that could point to the existence of sterile right-handed neutrinos [106] and to other unexpected phenomena.

The neutrino oscillation between the three known active neutrinos is described as follows. The three flavors of neutrinos ν_e, ν_μ, ν_τ are quantum superpositions of the mass-eigenstate neutrinos labeled ν_1, ν_2, ν_3, with numbers increasing with decreasing electron-neutrino content, and masses m_1, m_2, m_3. The relationship between flavor eigenstates and mass eigenstates is described by the PMNS neutrino mixing matrix which can be seen as a succession of three rotations in the three dimensional Hilbert space, by angles θ_{12}, θ_{13} and θ_{23}; similarly to the quark mixing matrix the unitary neutrino mixing matrix contains a phase δ. The present status of neutrino mixing parameter measurements can be found in [107, 108]. The measurements of solar parameters $\Delta m^2_{21} = m^2_2 - m^2_1$, $\sin^2 2\theta_{12}$ were obtained from very long baseline experiments (oscillation maximum at L/E = 16000km/GeV) using electron neutrinos from the sun or electron anti-neutrinos from nuclear reactors. The measurements of atmospheric parameters $\Delta m^2_{32} = m^2_3 - m^2_2$, $\sin^2 2\theta_{23}$ have been obtained using atmospheric neutrinos or with accelerator-based muon-neutrinos beams from horn focused pion decays, with a shorter baseline (oscillation maximum at L/E = 500km/GeV); at that wavelength it is expected that muon neutrinos turn essentially into tau neutrinos; this has received some confirmation with the observation of a first tau-neutrino event in the OPERA experiment [109]. While the sign of Δm^2_{21} is determined to be positive from matter effects in the sun, the sign of Δm^2_{32} is unknown: it is not clear yet whether 'normal' or 'inverted' hierarchy of neutrino masses is realized in Nature. The phase δ is presently unknown.

The best estimate of the value of the third mixing angle θ_{13} was until recently consistent with zero. In 2011 a substantial step was achieved: T2K [110], first, then MINOS [111], both in the $\nu_\mu \to \nu_e$ appearance channel, and the nuclear reactor Double Chooz experiment [112] reported indications consistent with a large value of $\sin^2(2\theta_{13}) \simeq 0.080 \pm 0.025$. This value is important as it governs the ability to measure the sign of Δm^2_{32} by matter effects of high energy neutrinos, and to observe a difference between the oscillations of neutrinos and those of antineutrinos, a possible signature of CP violation. In the three neutrino mixing picture this originates from the existence of a complex phase δ in the mixing matrix.

Among the unexpected observations, the recent measurement of time-of-flight of neutrinos in the OPERA experiment[113], which seems to be shorter than expected. If this were confirmed, the fact that neutrinos travel faster than the speed of light would be of earth-shattering importance. The measurement will be verified by OPERA itself, but it could also by tested by the MINOS and T2K long baseline experiments. More data will be available in 2012 also from other experiments at the Gran Sasso laboratory.

Intended contribution of the project

The main objectives of the neutrino oscillations program are:

1. To confirm the large value of θ_{13} by acquiring more statistics on T2K. At present an exposure of 150 kW.10^7 seconds has been accumulated and the experimentis restarting with an ultimate aim of 5x 750 kW.10^7 seconds thus a multiplication by a factor 25 of the integrated exposure, and should allow a determination of θ_{13} with a precision of better than ± 0.01.

2. To complete precise measurements of mixing parameters, with a precision similar to those of the quark mixing matrix; a first measurement of the atmospheric neutrino parameters was recently produced by T2K [114] by study of the $\nu_\mu \rightarrow \nu_\mu$ disappearance.

3. The search for sterile neutrinos in the accessible parameter range and for unexpected phenomena will continue. This will require close collaboration between theorists and experimenters and excellent understanding of the systematics on fluxes and cross-sections.

Improvement of the T2K measurements will constitute the core of the common experimental activity of the Swiss groups for the next ~ 5 years. This will involve continuation of ongoing activities:

1. the measurement of particle production in the T2K target is performed at CERN in the NA61/SHINE experiment [115][116][117]. The swiss groups have contributed the time-of-flight and trigger system and performed the largest part of the analysis and publication effort so far, with more precise data and analysis remaining to reach a flux prediction with a few percent accuracy.

2. Studies of cross-sections and systematic errors will be performed in the T2K near detector. The Swiss groups have contributed in a considerable fashion with the T2K ND280 near detector magnet delivery, magnetic measurements and commissioning, and with the TPC module construction and tests, and are presently engaged in the cross-section measurements.

In addition to this already ongoing and approved program, the Swiss researchers will study the possible extension of the program to allow the determination of the neutrino mass hierarchy and search for leptonic CP violation. This has been the object of considerable study [118],[119],[120];[121];[122], and will undoubtedly require new facilities with improved beams and detectors. There are several aspects to this; 1) phenomenological and simulation studies of various scenarios of oscillation facilities, including beams and baselines, near and far detectors and ancillary measurements; 2) studies of new long baseline neutrino beams (this is described in more detail in subsection 4.3.3); 3) a vibrant program of detector R&D to establish the feasibility and performance of the desired detector systems.

All three Swiss experimental groups of Bern, ETHZ and Geneva are involved in the LAGUNA-LBNO FP7 design study started in September 2011 for three years, with the ETHZ group coordinator of the project. The outcome should be the design of a long baseline neutrino experiment including a far detector site, a near detector complex and a neutrino beam design, building on the studies made in EUROnu and for CNGS. CERN is one of the main partners. The present priority of the LAGUNA-LBNO consortium is the design of a beam driven by the CERN SPS, taking stock of possible intensity improvements associated with the LHC injector upgrade, aimed at a far detector site situated at 2300 km in the Pyhasalami mine in Finland. At that distance, and for values of $\sin^2(2\theta_{13}) \geq 0.05$, a determination of the mass hierarchy of neutrinos can be made with a fine grain detector of moderate mass (10 kton) with the available SPS intensities in 5 years [123]. This distance is also consistent with an extension to a more powerful beam from a new high power proton accelerator at CERN, or from a Neutrino Factory based on a muon storage ring. This program is complementary to the Japanese proposal T2HK[124] which is primarily sensitive to the CP violation.

The work program for the next few years will consist of:

- continuing the developments towards very large Liquid Argon detectors, with innovative methods of readout, intermediate steps including a 5m drift prototype, large prototype exposure to test beam for study of e/π^0 separation, and design of multi-kton detectors.

- study of the near detector station and of the solid scintillator detector options, including the large Magnetized Iron Detector (MIND) appropriate as Neutral Current detector or as muon spectrometer for a fine grained detector, and on a longer time scale for a neutrino factory detector.

- study of possibilities to use the same beam for sterile neutrino searches.

The NCCR will strongly support this detector R&D. By the end of the first four years of the NCCR, the neutrino design studies should have led to the a large scale proposal to CERN.

Links to other projects of this NCCR

The discovery that neutrinos have mass is arguably one of the most significant step in particle physics, and the first indication of physics beyond the Standard Model established in the 70s. The scheme for generation of neutrino masses is not unique and could lead to the solution of a number of pending problems in our understanding of the Universe. Sterile neutrinos with masses ranging from hundreds of MeV to the GUT scale could lead to an explanation of the matter-antimatter asymmetry of the universe by leptogenesis for which leptonic CP violation and fermion number violation are essential ingredients. Sterile neutrinos could also constitute a significant or all of the dark matter of the Universe [106], [125]. Neutrino oscillations experiments address directly the issues of the mass spectrum of neutrinos, of the mixing angles, of the Matter-antimatter asymmetry, and via sterile neutrino searches within the accessible range, the question of neutrino mass generation.

The experimental program is challenging, requiring new, large infrastructures and technologies. The Swiss groups have established a remarkable level of international leadership and initiative in this program, in the T2K and NA61 experiments, the OPERA experiment, the MICE and LAGUNA projects. The Swiss groups have achieved a high level of integration and complementariness with each other. The possibility that a new neutrino beam could be built at CERN towards a long baseline location will generate considerable activity and require competence in the physics of the experiment, in beam physics, in the near and far detector technologies and in project management. The acquired competence as well as the continuous interest and expected physics rewards should make neutrino oscillation physics one of the highlights of the scientific life and output of the NCCR.

4.1.7 Project: Neutrino-less Double Beta Decay

Coordinators: L. Baudis (UniZh), R. Gornea (UniBe)

Research question and state of the art

During the last decades, neutrino oscillation experiments using solar, reactor, atmospheric and accelerator neutrinos have established that neutrinos being produced as a certain flavor eigenstate can be detected as a different flavor eigenstate after they propagate over macroscopic distances. The interpretation of these observations is that neutrinos have mass and that, like in the quark sector, the mass eigenstates are different from the weak eigenstates, i.e. neutrinos mix. The aim of ongoing research is to determine the full mixing matrix of neutrinos, including CP violating phases. While neutrino oscillation experiments have provided measurements of the mass-squared differences and mixing angles, some of the goals of current and next-phase neutrino experiments are to measure the value of θ_{13} as precisely as possible, to clarify the Dirac or Majorana nature of neutrinos and to fix their absolute mass scale. The observation of the neutrinoless double beta ($0\nu\beta\beta$) decay would prove that the neutrino is Majorana fermion and that lepton number is violated. The measurement of its rate would provide information on the so-called effective Majorana neutrino mass, $\langle m\rangle_{eff} = |\Sigma_i U_{ei}^2 m_i|$, where the sum is over the mass eigenstates, and U_{ei}, the corresponding entries in the lepton mixing matrix are complex numbers [126]. Current best experimental limits on $\langle m\rangle_{eff}$ are of the order $\langle m\rangle_{eff} \leq 0.2 - 0.9$ eV, with the most stringent upper limits from ^{76}Ge coming from the past Heidelberg-Moscow [127] and IGEX [128] experiments. The best limits for ^{130}Te and ^{100}Mo, of $\langle m\rangle_{eff} \leq 0.3 - 0.7$ eV, and $\langle m\rangle_{eff} \leq 0.45 - 0.9$ eV, respectively, come from the CUORICINO [129] and NEMO-3 experiments [130].

To scan most of the parameter space predicted by theory, multiple detectors with sufficient sensitivity are needed. Two existing experiments, GERDA and EXO, have significant Swiss contributions.

GERDA is an experiment to search for the $0\nu\beta\beta$-decay in enriched ^{76}Ge detectors at the Gran Sasso Laborator. It uses a novel shielding concept, with Ge crystals being operated directly in a 65 m^3 volume of liquid argon (LAr). The argon serves as a passive shield against the external radioactivity and is in addition surrounded by a 3 m thick water buffer instrumented with PMTs to detect the Cerenkov light from muons passing through the water. A clean room for Ge diode handling is installed on top of the tank, with a lock at its center that is used for transferring detectors into the argon atmosphere. The experiment proceeds in two phases: Phase I employs HPGe detectors from the Heidelberg-Moscow and IGEX experiments, with a total mass of 17.7 kg, as well as natural Ge detectors from the Genius Test Facility [131]. The goal is to improve upon current limits and scrutinize the hint of a signal [132] after one year of data taking with an exposure of 15 kg·y and a background of 10^{-2} counts/(keV kg y). In case no events will be observed above background, a half-life limit of $T_{1/2} > 3\times10^{25}$ y can be established, resulting in an upper limit for the effective neutrino mass of $\langle m \rangle_{eff} \leq 0.23 - 0.39\,\mathrm{eV}$. Phase II will use additional enriched broad-energy germanium detectors, aiming for a total exposure of 100 kg·y. With a background goal of 10^{-3} counts/(keV kg y), the half-life sensitivity is $T_{1/2} > 20{\times}10^{25}$ y and the corresponding range of effective neutrino masses is $\langle m \rangle_{eff} \leq 0.09 - 0.15\,\mathrm{eV}$, taking into account the uncertainty in the matrix element and neglecting new lepton number violating interactions.

The construction and commissioning of GERDA were completed in November 2010 and 2011, respectively, the physics run with eight enriched Ge detectors has started.

For GERDA phase II, a higher total mass, and a background lower by another order of magnitude is needed. The lower background can be reached by instrumenting the LAr with PMTs and by an effective pulse shape analysis (PSA) in the Ge diodes, to distinguish among so-called single-site events (SSE), which include the signal events, from multiple scatters, or multiple-site events(MSE), which are background. Given the excellent pulse shape discrimination (PSD) performance of p-type, broad energy Ge detectors (BEGe) [133, 134] and their simple geometry with a single readout (compared to segmented detectors), the collaboration has decided in summer 2010 to adopt this technology for phase II. The entire production chain was validated with depleted Ge, and four detectors were fully characterized regarding their charge collection, spectroscopic and PSD performance, as well as long-term stability [135]. The production of enriched BEGe detectors with existing GeO_2 material has started in 2011. The detectors will be tested during the second half of 2012 and commissioned in early 2013.

The Enriched Xenon Observatory (EXO) proposes to search for the $0\nu\beta\beta$ decay with a ton-scale TPC (Time Projection Chamber) using xenon highly enriched in the isotope Xe-136 which is a favorable source and particle detection medium. Substantial reduction of the cosmic ray flux is needed, making the installation of such a detector deep underground an imperative. Also, the unprecedented reduction of the residual radioactive background is mandatory and imposes the establishment of a severe material screening program and the development of an optimized detector design and ultra-clean construction techniques. EXO proceeds through a multi-phase program which balances between an intense R&D effort in preparation of the EXO-full detector and the prototype EXO-200, employed as an R&D test bench and as a physics detector. Indeed, EXO-200 (a double-barrel TPC with both charge and scintillation light readout, loaded with 200 kg of 80% enriched liquid xenon) has been in operation since fall 2010 and has clearly demonstrated the extremely low radioactive background obtained through the massive material screening effort [136] . EXO-200 is also the first detector which has been able to provide a clear signal for the allowed (two-neutrino) double beta decay [137] as predicted by the standard model and thus giving confidence for the numerical calculations of the nuclear matrix elements for Xe-136. Presently, EXO-200 setup undergoes optimization and final preparation for a two-year run optimized for $0\nu\beta\beta$ decay search. The collaboration predicts an excellent performance even in the case that no $0\nu\beta\beta$ signal is detected. EXO-200 should be able to provide a lower limit on the half-life better than 6.4×10^{25} years or equivalently a higher limit of the effective neutrino mass of 130 meV. For the EXO-full detector the collaboration proposes the use of barium tagging for the complete reduction of the residual radioactive background. This novel technique is based on the extraction and identification of each Ba-136 ion produced by the decay of Xe-136 along with the two electrons which classically provide the signal in the detector.

EXO-200 will run until middle of 2014 and requires monitoring shifts and a continuous effort for data analysis. Depending on the results obtained, EXO-200 operation may be extended past 2014. Meanwhile, the EXO collaboration already looks forward in preparation of EXO-full and has the ambition of finalizing the major R&D elements by 2014 so that EXO-full design and construction can start then. Depending on the development status of the underground facilities, EXO-full location would be decided sometimes until 2014. Presently two locations are investigated: DUSEL and SNOLab. The Swiss contribution to the EXO project has been extremely valuable and the Swiss expertise in frontier neutrino physics should be maintained.

Intended contribution of the project The Zurich groups is responsible for the calibration system of GERDA. For the hardware part, the group has designed, built and installed a fully motorized source insertion system, along with custom made, low-neutron emission sources in collaboration with PSI, which is used for the operation of the three strings of enriched Ge detectors. The group is in charge of analyzing the weekly calibration runs and monitor the stability performance of the Ge diodes, regarding their energy calibration and resolution. For the next phase of GERDA, the Zurich group is involved in the production and testing of enriched BEGe detectors, after the entire diode production chain starting from raw GeO_2 material, had been validated using germanium material depleted in ^{76}Ge. In addition, the group participates in the design and testing of the instrumentation of the liquid argon cryostat with light sensors. The liquid argon veto will be used to further reduce the backgrounds in the second phase of the experiment.

The EXO-200 cryostat has been designed and manufactured by the Swiss group from University of Bern, Laboratory for High Energy Physics (LHEP). in collaboration with the Swiss Welding Institute in Yverdon-les-Bains. The Bern group has been extensively involved with the deployment and commissioning of the EXO-200 detector at WIPP (Waste Isolation Pilot Plant, New Mexico, USA) and still contributes to the shift and data analysis effort. The critical competence of various Swiss members regarding EXO-200 operation has been acknowledged by the collaboration with the installation of the only remote experiment control center in Europe. There are two Swiss contributions to the R&D effort for EXO-full. First, for the gas option, the use of large-gap Micromegas for charge readout in high-pressure xenon mixtures is studied in collaboration with RD51 group at Cern which manufactures the Micromegas planes. Second, for the baseline option of EXO-full (a liquid xenon TPC), the development of an efficient barium ion extraction device has started. Once it is well tested in Bern, it will be merged with the laser-based barium ion tagging apparatus developed by the group at Stanford University.

Links to other projects of this NCCR

The groups involved in the NCCR are expected to significantly contribute to the data analysis effort of these projects. Within the NCCR, the science data of GERDA and EXO will be analyzed coherently in view of the various double beta decay channels: the Standard Model allowed process with emission of two neutrinos, and, most importantly, beyond-SM processes such as the neutrinoless double beta and various other decay modes predicted by Beyond-Standard-Model physics. The goal is to explore the predicted parameter space using these two different experimental techniques, and thus different systematics, as well as two double beta emitters with different uncertainties in the theoretically predicted matrix elements for the various decay channels.

4.1.8 Project: Grand Unification

Coordinators: S. Antusch (UniBs), A. Rubbia (ETHZ)

Research question and state of the art

What is the origin of the three forces between the known elementary particles described by the SM? Are they unified at high energies, i.e. can they be derived from a single "unified force"? These questions are addressed in so-called Grand Unified Theories (GUTs) [138]. Unification is one of the key ideas towards a more fundamental understanding of elementary particles. The idea of GUTs is supported, for instance, by the renormalisation group (RG) running of the gauge couplings in supersymmetric extensions of the SM, which meet at high energy $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, as well as by the automatic cancellation of gauge anomalies, and by the quantized values of the electric charges of the SM particles. GUT models have been constructed based on various symmetry groups G_{GUT}, which contain the symmetries of the SM as subgroups, $\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}} \subset G_{\mathrm{GUT}}$, for example $G_{\mathrm{GUT}} = \mathrm{SU}(5)$ [138] or SO(10) [139]. Many GUTs are formulated in the framework of supersymmetry. In addition to the above-mentioned meeting of the gauge couplings at $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, another argument in favor of supersymmetry is that it provides an attractive solution to the so-called "hierarchy problem", i.e. the quantum instability of the electroweak scale of the SM. The hierarchy problem typically arises whenever new physics is added to the SM at high energies, as this is the case in GUTs.

Beyond explaining the origin of the three forces of the SM, GUTs have other far-reaching consequences. For instance, in GUTs not only the forces are unified, but also the different types of elementary particles of a given family. GUTs are therefore often deeply related to the question of the origin of the observed flavour structure, i.e. of the masses and mixing properties of the elementary matter particles. This question is known as the "flavour puzzle". GUTs may furthermore be connected to the question why neutrino masses are so small compared to the masses of the charged particles of the SM. From the point of view of effective field theory, the scale Λ at which neutrino masses are generated by an extension of the SM is related to the electroweak scale $v_{\mathrm{EW}} \sim 175$ GeV of the SM by the relation $m_\nu \sim (175\,\mathrm{GeV})^2/\Lambda$ [140]. Interestingly, with Λ about 10^{16} GeV, i.e. around the GUT scale M_{GUT}, one would expect neutrino masses of about 10^{-3} to 10^{-2} eV, which is in the range indicated by the smaller of the two observed mass squared differences. Although this is only a very rough estimate, and an explicit model is needed to make precise statements about the scale of mass generation, the argument indicates that the puzzle of small neutrino masses may be related to GUT scale physics. Finally, there are also hints that GUTs are connected to puzzles in very early universe cosmology. In particular, the flatness of the universe and its homogeneity on large scales points to an epoch of cosmic inflation at early times. In inflation, a large vacuum energy is required to drive the accelerated expansion. To be consistent with the amplitude of the small temperature fluctuations in the CMBR, the vacuum energy V_0 during inflation is typically of the size $V_0 \sim (10^{16}\ \mathrm{GeV})^4 \sim (M_{\mathrm{GUT}})^4$.

Although progress has been made towards the construction of realistic GUTs, various aspects still remain challenging. For instance, it turned out to be quite difficult to build GUTs with realistic predictions for the relations between the masses of quarks and charged leptons. Regarding neutrinos, although left-right symmetric

GUTs have successfully predicted that they have small masses, there are currently no indications which of the possible mechanisms to generate the masses (such as seesaw type I [141, 142, 143, 144], type II [145] or type III [146]) is the right one. Another challenge regards the hierarchical pattern of the quark and charged lepton masses. An explanation for the mass hierarchies can be provided by additional family symmetries [147]. In the so-called Froggatt-Nielsen mechanism, the smaller fermion masses are generated by effective operators, which are suppressed by (powers of) the ratios of the vacuum expectation values of the family symmetry breaking "flavour-Higgs" fields, the so-called "flavons", over some scale of new physics. Compared to GUT symmetries, which unify different types of elementary particles on joint representations, family symmetries can unify particles of different generations (or families). Often, GUTs are therefore combined with family symmetries. Further long-standing issues of GUTs concern the so-called "doublet-triplet splitting", or more generally the problem of constructing a viable GUT-Higgs sector. Regarding early universe cosmology, it is currently investigated how to construct supersymmetric GUTs capable of predicting a viable evolution of the universe, including inflation, the generation of the baryon asymmetry and dark matter. The research towards the development of predictive GUT theories which can address the above questions will be subject of the theoretical part of this project.

Another challenge of GUTs consists in the fact that they operate at such high energies that they can only be probed indirectly. The smoking gun signal of Grand Unification is the decay of the proton (or of the bound neutron). In this context, massive underground neutrino detectors can be considered as sort of observatories for rare physics phenomena such as nucleon decays[148]. Nucleon decay signal events are experimentally characterized by (a) their topology (b) their kinematics. By topology, we mean the necessary presence of a lepton (an electron, a muon or a neutrino) in the final state, in general, few particles in the end products (for example, two body decays are believed to be favored), and obviously no other energetic nucleon in the final state. The exact kinematics of the event depends on the type of target. For free protons (target with hydrogen), the total momentum of the event should be compatible with zero, while for nucleon decays occurring in nuclear targets, we expect a smearing from Fermi motion and also other nuclear effects (rescattering, absorption, etc.). The total energy of the event should be equal to the nucleon mass, which means in the GeV range. These kinematical features and their exclusive final state topologies allow, if well reconstructed in the detector, separating nucleon decay signals from the much more abundant and mundane atmospheric neutrino interactions, with a level of suppression that increases with improved spatial granularity and energy resolution. Two complementary technologies are presently discussed for potential future applications: Water Cerenkov ring imaging (WC) and liquid Argon Time Projection Chamber (LAr TPC). The Japanese proposal HyperKamiokande[124] considers a next-generation 540 kton fiducial mass detector, continuing the path defined by the predecessors Kamiokande and SuperKamiokande. Among Swiss groups, the focus has been on the complementary approach provided by a Giant liquid Argon TPC, called GLACIER[149, 150]. A liquid argon detector of 100 kton = 6×10^{34} nucleons yields a sensitivity for protons of $\tau_p/Br > 10^{34}$ years $\times$ T(yr)$\times\ \epsilon$ at the 90% C.L. in the absence of background. This means that lifetimes in the range of 10^{35} years can be reached within 10 years of operation. Channels like $p \to \nu K$ have been shown to be indeed essentially background free, even at shallow depths [151]. We conclude by stressing the complementarity of the two approaches, HyperKamiokande characterized by the huge volume and GLACIER by its smaller mass but finer resolution, noting however that, given the foreseeable timescale for these next generation experiments, the new challenging technique of the LAr TPC might offer more discovery potentials.

Intended contribution of the project

The goal of the project is to contribute to the development of realistic GUTs which can resolve the above mentioned open issues in GUT model building as well as to the development of techniques to experimentally test the predictions of GUTs, in particular proton decay. The topics for research in this project will include:

- **Proton decay experiments**: Massive underground detectors are designed by optimizing their performance for the search of nucleon decays. However, such detectors will have a much larger physics program, for example with the observation and study of astrophysical (solar, atmospheric, and supernova neutrinos) and artificial beam neutrinos. Such a comprehensive physics program, possibly with non-accelerator and accelerator-based components, makes massive underground detectors "general purpose" facilities, sort of observatories for rare physics phenomena. The European **LAGUNA** design study [152], coordinated by ETHZ, is dedicated to the feasibility of such an underground neutrino experiment of next generation. GLACIER will be further developed as one of the detector option considered. A letter of intent will be submitted to CERN.

- **Neutrinos and GUTs**: Left-right symmetric GUTs, based for instance on SO(10), predict the existence of right-chiral neutrinos which generate small neutrino masses by a so-called type I seesaw mechanism

[141, 142, 143, 144]. Variants of this mechanism with different new particles can be found in GUTs as well, and are referred to as type II [145] or type III [146] seesaw mechanisms. One question to be addressed is the interplay between the mechanism for neutrino mass generation and the other aspects of GUT model building such as flavour issues and cosmology. In neutrino model building, one key aspect is provided by the question how the difference between the large mixing in the lepton sector and the small mixing in the quark sector can be explained in GUTs in a predictive way. New ways to predict the quark and lepton flavour structures in the context of GUTs will therefore be investigated as well.

- **Supersymmetric GUTs and the early universe**: As mentioned above, connecting inflation with GUT scale physics is attractive since the required vacuum energy V_0 is typically around the GUT scale M_{GUT}. Recently, new classes of inflation models have been proposed where the inflaton resides in the matter sector of a supersymmetric GUT theory, allowing for particularly close connections between inflation and particle physics [153]. Cosmology in supersymmetric theories faces some challenges, such as the "cosmic moduli problem" [154] or the "gravitino problem" [155], but also some benefits, for example the lightest neutralino or the gravitino as promising candidates for the dark matter particle. One task of this project will be the construction of supersymmetric GUT models of inflation and their phenomenological analysis, including the above mentioned issues.

Links to other projects of this NCCR

Direct evidence for GUT and baryon number violation represents one of the outstanding goals of particle physics.

As has beed described above, GUTs are deeply connected to various of the other projects of the NCCR proposal. One particular contribution of the project *Grand Unification* will be to "unify" the theoretical and experimental progress in the various fields towards a more fundamental theory framework. Since the research within the project is linked to various other projects, it will benefit strongly from the new interactions and collaborations that will be initiated by the NCCR.

4.1.9 Project: Lepton Flavor Violation

Coordinators: S. Ritt (PSI), A. Bravar (UniGe)

Research question and state of the art

It is by now well established that neutrinos have mass and that the three families mix, requiring, therefore, an extension of the Standard Model (SM). The nature of the required new physics, however, remains elusive. There are strong experimental and theoretical efforts to shed light on the correct roadmap.

In the neutrino sector, lepton flavor violation (LFV) has been observed in the form of neutrino mixing. Lepton flavor symmetry therefore is a broken symmetry, and LFV is expected also in the charged lepton sector. Observation of LFV in the charged lepton sector, however, is still lacking: processes like the decay $\mu^{\pm} \to e^{\pm}e^{+}e^{-}$, or $\mu^{+} \to e^{+}\gamma$, or the $\mu^{\pm}A \to e^{\pm}A$ conversions have not been observed yet. The exact mechanism of LFV and the size of this effect are at present unknown. LFV is connected to neutrino mass generation, CP violation, new physics beyond the SM, and addresses the fundamental issue of the role played by leptons in the mechanism generating the Universe's baryon asymmetry (leptogenesis).

In the SM charged LFV processes are forbidden at tree level and can be induced by lepton mixing through higher order loop diagrams. Loop diagrams involving neutrinos are strongly suppressed with branching ratios $B < 10^{-40} - 10^{-50}$ for muon decays. This huge suppression despite the large mixing of neutrinos comes from the fact that neutrinos are much lighter than charged leptons and that the mass differences are very small compared to the W-boson mass. If new particles beyond the SM are introduced the situation, however, changes completely.

Sizable LFV effects are expected in many extensions of the SM such as grand unified models (GUTs), supersymmetric models, compositness, leptoquarks, left-right symmetric models, models with an extended Higgs sector, dynamically broken electroweak symmetry models, extra dimensions, etc. These models predict an experimentally accessible amount of LFV in a large region of the parameters space ([156] [157]). The observation of LFV in one channel would require a systematic study of all possible LFV channels. Depending, however, on the underlying mechanism, LFV effects might not be visible in some channels. The search for the dacays $\mu^{+} \to e^{+}\gamma$ or $\mu^{+} \to e^{+}e^{+}e^{-}$ are sensitive to many such models. The $\mu^{+} \to e^{+}\gamma$ decay, however, is not sensitive e.g. to LFV four-fermion contact interactions.

These LFV experiments are highly complementary to other searches for physics beyond the Standard Model, i.e. direct searches performed at the LHC. The observation of LFV in the charged lepton sector would be a sign for new physics at scales far beyond the reach of direct observation, up to several 1000 TeV.

Several experiments have been performed or are in operation searching for LFV in the decay of muon or tau leptons. The best current limit on the LFV are set by PSI muon experiments. In the 80s the SINDRUM experiment searched for the $\mu^+ \to e^+e^+e^-$ decay. No signal was observed and a limit $B(\mu^+ \to e^+e^+e^-) < 10^{-12}$ was set at a 90% C.L. [158]. Note that the experiment was statistics and not systematics limited. The SINDRUM II experiment searched for the $\mu^- A \to e^- A$ conversion using different targets. The strongest of these limits has been obtained using a gold target with $B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$ compared to capture decay rates [159].

In the 90s, the experiment MEGA at Los Alamos searched for the LFV $\mu^+ \to e^+\gamma$ decay setting a limit on $B(\mu^+ \to e^+\gamma)$ of $1.2 \cdot 10^{-11}$ at a 90% C.L. [160]. The MEG experiment at PSI (see below) is taking physics data since 2008 and is searching for the $\mu^+ \to e^+\gamma$ decay. No LFV decay signal was observed yet, setting a limit on $B(\mu^+ \to e^+\gamma)$ of $2.4 \cdot 10^{-12}$ at a 90% C.L. [161]. The search of $\mu^+ \to e^+\gamma$ decays sets stringent bounds on models predicting new heavy particles mediating LFV dipole couplings. The present MEG limit for $\mu^+ \to e^+\gamma$ of $2.4 \cdot 10^{-12}$ is more incisive (about 10 times) than the SINDRUM II limit of $7 \cdot 10^{-13}$ since in BSM models $B(\mu^+ \to e^+e^+e^-)/B(\mu^+ \to e^+\gamma) \sim O(\alpha_{EM})$ and $B(\mu^+ A \to e^+ A)/B(\mu^+ \to e^+\gamma) \sim O(\alpha_{EM})$.

New very ambitious projects searching for the conversion $\mu A \to eA$ are planned at Fermilab (Mu2e) and J-PARC (COMET and PRISM) for the end of the decade. They aim for branching ratios of 10^{-16} or smaller relative to the captured muon decay.

In the 1990's, the proton beam intensity and therefore the muon intensity available at PSI increased steadily, making it possible to improve existing limits on the $\mu \to e\gamma$ decay. In 2000, a collaboration has been formed with a strong participation of PSI to push for the MEG experiment, a new $\mu \to e\gamma$ search aiming to improve the existing limit by two orders of magnitude. A relatively long R&D phase was necessary to develop the novel liquid xenon calorimeter, which finally improved the resolutions in time, position and energy to new limits unprecedented in this energy range. Another challenge was the drift chamber system needed to detect the positron from the $\mu \to e\gamma$ decay. This ultra-low mass detector was designed and built at the PSI detector group together with the associated readout-electronics. For the readout of all detector signals in the MEG experiment a new ASIC chip named DRS4 has been developed at PSI. The DRS4 is now also used in the MAGIC and FACT gamma-ray Cherenkov Telescopes.

Intended contribution of the project

The MEG experiment started taking data in 2008 and published a first improvement of the BR $\mu \to e\gamma$ of $2.4 \cdot 10^{-12}$ in 2011 [161]. The experiment will continue taking data in the current configuration until the end of 2012, aiming for a limit of a few times 10^{-13}. A possible upgrade of MEG is currently under discussion. Since the experiment runs presently only at 1/3 of the maximum muon rate possible at PSI, higher statistics can be reached by increasing the rate of stopped muons. This requires however better pile-up rejection and higher resolutions in order to suppress the background from accidental overlaps of ordinary muon decays. Possible scenarios require the usage of SiPMs for part of the xenon calorimeter readout with higher granularity or a novel drift chamber with even less mass and improved resolutions utilizing a new cluster counting technology. All upgrades involve significant involments from the PSI detector and electronic groups as well as from the associated PSI scientists.

A new experiment, Mu3e, to search for the LFV decay $\mu^+ \to e^+e^+e^-$ is being proposed at PSI. Mu3e aims at a sensitivity of one in 10^{16} muon decays, i.e. four orders of magnitude better than previous searches. This sensitivity requires a muon stopping rate of $2 \cdot 10^9$ μ^+ muons per second and a high geometrical coverage. A good performance at this high rate is possible thanks to modern tracking detectors based on thin monolithic active silicon pixel sensors with high granularity (high voltage monolithic active pixel sensors - HV-MAPS) providing high spatial resolution. The detector is complemented by scintillating fiber hodoscopes and scintillating tiles coupled to silicon photomultipliers (Si-PMs) providing very precise timing infromation at high particle rates. By combining both detector systems (tracking and timing) the aimed sensitivity corresponding to $B(\mu^+ \to e^+e^+e^-) < 2 \cdot 10^{-16}$ at 90% C.L. in absence of a signal can be reached.

After an initial R&D phase which has already started, the experiment will be performed in two phases. In the first phase (2014 - 2017) an existing muon beamline at PSI will provide a sensitivity of about $B(\mu^+ \to e^+e^+e^-) \sim 10^{-15}$. The construction of a new beamline to increase the beam intensity to $2 \cdot 10^9$ muons per second is currently under investigation (see section 4.3.2). In the second phase (2018 - 2020) the experiment will reach the ultimate sensitivity of $B(\mu^+ \to e^+e^+e^-) \sim 10^{-16}$ with this new beamline. Reaching this sensitivity requires the ability to suppress any possible background to a level below 10^{-16}.

In Mu3e, surface muons of 28 MeV/c produced by the PSI beamline are stopped on a hollow double cone aluminum target. Electrons from muon decays will be detected by two cylindrical double layer silicon pixel detectors (HV-MAPS). The detectors sit in a strong solenoidal magnetic field. Curling tracks will be measured by a second double layer cylindrical silicon pixel detector upstream and downstream of the central detector in order to improve the momentum resolution for a total of 6 measured space points per track. The silicon tracker will be complemented by a cylindrical time of flight (TOF) detector consisting of a scinitillating fiber hodoscope in the central region with a time resolution of few 100 ps. The curling tracks will be measured with scintillating tiles, with a 50 ps time resolution. The granularity of the system (fibers and tiles) will be such to keep the single channel event rate below 1 MHz. The scintillating fibers and tiles will be readout with Si-PMs.

The final sensitivity of the proposed experiment depends on the ability to reduce accidental backgrounds, which scale with the square of the beam intensity, and irreducible backgrounds such as the $\mu^+ \to e^+e^+e^-\nu\nu$ decays. The former source of background can be efficiently suppressed by an excellent timing (~ 100 ps) and vertex resolution, the latter with a high momentum resolution of the detector ($\sigma_E < 1$ MeV).

The Swiss institutions that expressed interest in this experiment (UniGe, ETHZ, UniZ, PSI) are particularly interested in developing the ToF system for the experiment (scintillating fibers hodoscopes and tiles). These groups will also perform detailed simulation of the detector including background studies, and contribute further to the conceptual development of the detector. Later they will participate in the analysis. The data acquisition including the data management and storage, and the slow control will be taken care of by PSI.

A vigorous R&D program is being planned for the next two years to achieve the desired performances of the ToF system. The R&D activity will cover all the aspects of the ToF detector development: scintillators, SiPMs, and front end electronics. It is planned to develop Si-PMs that will match precisely the requirements of the ToF system. For the readout of the fibers and tiles it is planned to use the well-established waveform digitizing technology used already in the MEG experiment. This technology is based on the switched capacitor array chip DRS4 developed at PSI which is capable to sample the SiPM signal with up to 5 giga samples per second and a resolution close to 12 bits. The advantage of this technology compared to traditional constant fraction discriminators and TDCs is that pile-up can be effectively recognized and corrected for. In addition, pulse height information becomes available which can be used to discriminate signals. To cope with the high rates expected during the second phase of the Mu3e experiment a new version of the chip, the DRS5, capable of sustaining continuous rates of 2 MHz will be developed by the same PSI group.

Links to other projects of this NCCR

The activities described in the field of Lepton Flavor Violation in the charged sector offer great opportunities for Swiss contributions to fundamental questions in particle physics at low energy. The NCCR Universe will ensure a coherent operation of these experiments and enhance exchange of information between them. Technical developments in one experiment can often be used in another one. With the help of the NCCR these synergy effects will be fostered to the benefit not only for the experiments in LVF but even beyond. The DRS4 chip is already now also used in gamma-ray Cherenkov Telescopes, and the DRS5 chip will have even more applications. The development of the high intensity muon beamline described in section 4.3.2 is another example for interdisciplinary efforts enabled by the NCCR Universe.

4.1.10 Project: Cosmic Magnetic Fields

Coordinators: A. Boyarski (EPFL), A. R. Durrer (UniGe)

Research question and state of the art

Magnetic fields are ubiquitous in the Universe. Fields of several μGauss are observed in nearby and high redshift galaxies. Also in galaxy clusters μGauss fields are found. Somewhat smaller fields have been observed even in filaments [162, 163, 164]. Recently, it has been argued that the absence of GeV radiation from blazars, which emit TeV gamma rays, requires magnetic fields even in voids with an amplitude of at least 10^{-16}Gauss, if the coherence scale is 1Mpc or larger [165, 166]. Suggestions how the observed large scale coherent magnetic fields in the Universe might have formed range from late formation during structure formation in galaxies [167, 168] over formation during phase transitions in the primordial Universe [169] to inflation [170, 171].

If the fields have been formed during galaxy formation, it is difficult to understand how such fields could have been expelled into intergalactic space to fill out the voids. One may suggest that they have formed before galaxy formation, when fluctuations were still relatively small. However, as long as fluctuations are small, magnetic field generation is suppressed: it is second order in perturbation theory, since vector perturbations are needed. The fields generated are of the order of 10^{-28}Gauss [172, 173]. These very small fields are most probably not sufficient even if galaxy formation leads to a strong amplification of primordial fields by dynamo action. It has been estimated that for dynamo amplification to be successful in generating the observed magnetic fields also in galaxies at redshifts $z = 1$ to 2, one needs seed fields of the order of at least 10^{-22}Gauss [174].

Another suggestion has been that magnetic fields form during the electroweak or the QCD phase transition. The problem with this process is that purely from the fact that magnetic field generation is causal, one can conclude that the magnetic field spectrum after the phase transition is very blue [175, 176]

$$\frac{d\rho_B(k)}{d\log k} = \rho_c\epsilon(k/k_*)^5, \qquad \frac{d\Omega_B}{d\log(k)} = \epsilon\Omega_r\left(\frac{k}{k_*}\right)^5 \tag{1}$$

for all $k < k_*$, where k_* is the (comoving) correlation scale of the magnetic fields and $\epsilon < 1$ in order for the magnetic fields not to overclose the Universe. Certainly, k_* is smaller than the Hubble scale at the transition, but more likely it is of the order of the largest bubbles at the end of the phase transition which gives $k_* \sim 100\mathcal{H}_*$, where $\mathcal{H}$ denotes the comoving Hubble parameter. If no inverse cascade is active and the magnetic fields on large scale evolve passively, this leads to very small fields on large scales. For the electroweak phase transition with $k_* = \mathcal{H}_* \simeq 10^{-4}$Hz, we obtain an upper bound for magnetic fields on large scales, say $k_1 = 10/\text{Mpc}$, of $B(k_1) < 10^{-29}$Gauss. Somewhat more realistic values for k_* give even more stringent bounds. For the QCD phase transition these bounds are relaxed by about 3 orders of magnitude but the resulting fields are still much too small to yield the observed fields in galaxies, even via very optimistic dynamo amplification. If the magnetic fields are helical, an inverse cascade is expected [177, 178]. This can mitigate the limits somewhat, but it will still not be able to generate 10^{-16}Gauss fields on Mpc scales [179].

These results lead us to consider inflation as the most promising mechanism for magnetic field generation. Inflationary magnetic fields can have different spectra. Depending on the coupling strength one can even obtain a scale invariant magnetic field spectrum [170]. The magnetic field is then constrained e.g. by the CMB yielding $d\rho_B(k)/d\log k = k^3P_B/2 \lesssim 10^{-6}\rho_{\rm rad}$. In terms of magnetic field amplitude this requires $\sqrt{k^3B^2} \lesssim 10^{-8}$Gauss. Depending on the measurement considered, this limit can become somewhat more stringent [180, 181]. This limit applies only on very large scales relevant for CMB anisotropies.

Recently, some of us [182] have demonstrated that magnetic fields generated during inflation contribute to the Bardeen potential in such a way that the Universe becomes rapidly strongly inhomogeneous and anisotropic after inflation. This result probably rules out inflationary magnetic field generation altogether. However, it has been proposed, that the chiral anomaly of the standard model might lead to a strong inverse cascade, moving small scale power of magnetic fields to much larger scales [183].

Intended contribution of the project

In a first project we want to study quantitatively whether the mechanism proposed in [183], may help to resurrect magnetic fields generated during phase transitions. Can it move sufficient power to sufficiently large scales so that these fields become viable? What exactly are the equations that govern the evolution of magnetic fields in the highly conducting Universe filled with relativistic particles? We also want to investigate the influence of this evolution on CMB constraints.

A second project is to take into account the effects of magnetic fields on structure formation. This project is already under way, but it is still in its infancy.

Last but not least, we want to make progress on the experimental side: the lower limit on magnetic fields in voids originally comes from a Swiss group [165]. We want to improve this limit from both sides: by simulations which compute the expected cascade radiation with higher accuracy and by observations, best simultaneously in the TeV and GeV range for the same object.

Links to other projects of this NCCR

Our project is obviously related to the numerical simulation of large scale structure, project 4.2.3, and to the CMB project 4.2.6. But also to the high energy gamma-ray observations as the large scale magnetic fields in voids are detected in this way. Magnetic fields can be produced in the early Universe, e.g. during the electroweak phase transition and baryogenesis (see section 4.2.1 on the early Universe). Such primordial magnetic fields, would affect every important process in the early Universe (baryo- and lepto-genesis, DM production (see sections 4.2.1 and 4.2.5), can change the nature of the QCD phase transition (see Ref. [183]). A correct description of a magnetized Early Universe is important to derive reliable conclusions about beyond the Standard Model particle physics from cosmology. If these primordial fields can survive until now and if they can be related to the observed large scale magnetic fields, their theoretical and experimental study might open a new window to the early Universe and provide a new tracer of these fundamental phenomena. This is the core of this NCCR: observing and understanding the Universe, can teach us about fundamental physical interactions, testable with particle physics experiments.

4.2 The Challenge of Dark Energy and Dark Matter

Coordinating authors: Ruth Durrer (UniGe) and Alexandre Refregier (ETHZ)

Research question and state of the art

This theme is concerned with 96% of the content of the Universe: dark energy and dark matter. These two mysterious cosmological components have, so far, only been detected via their gravitational action. Dark matter provides about 23% of the energy density and has been inferred from the rotation curves of dwarf and ordinary galaxies, from the velocity dispersion in cluster, from strong and weak lensing, via structure formation and via the observed anisotropies of the cosmic microwave background. Hence it has been detected on scales ranging from dwarf galaxies to the Hubble scale (i.e. the size of the observable Universe). For dark energy the situation is more mysterious: even though it provides the bulk part (more than 70%) of the energy density of the Universe, it has been inferred so far only via cosmological expansion: the observed relation between the redshift and the distance of far away objects is compatible with a homogeneous and isotropic universe (a Friedmann Universe) only, if it is dominated by a component with a strong negative pressure. Gravity of ordinary matter is attractive and therefore leads to decelerated expansion of the Universe. To obtain the observed accelerated expansion a strong negative pressure is needed so that gravity becomes repulsive. The physics Nobel Prize 2011 has been awarded for the discovery of cosmic acceleration.

If Dark Matter is made of particles (a very plausible and well grounded hypothesis), this particle can not be a Standard Model particle (see section 4.2.5). Contrary to accelerator particle physics, cosmological experiments already demand extensions of the standard model. The Dark Energy puzzle is related to the most fundamental problems of particle physics (the cosmological constant problem) and gravity. Therefore, any improvement of our understanding of possible nature of these phenomena, e.g. constraints on mass and interaction strength of DM particles, on the equation of state for Dark Energy or interaction between them, provides a most valuable input for particle physics

Intended contribution to the NCCR:

The simplest proposal for dark energy is vacuum energy or, equivalently, a cosmological constant. Other possibilities are a dynamical scalar field (quintessence) or an infrared modification of General Relativity. Another idea is that backreaction from cosmic structure may affect the distance-redshift relation of a homogeneous and isotropic Universe in such a way as to mimic Dark Energy. Moreover, only the the total dark energy momentum tensor have been measured so far, which is then conveniently split into a clustering dark matter component and a non-clustering dark energy component. It is not clear, whether this is really correct, or in other words, whether dark energy and dark matter interact with each other. The sub-project Cosmic Acceleration 4.2.2 addresses all aspects of these questions and are connected with the other sub-projects, especially those concerned with the primary cosmological probes, the cosmic Large Scale Structure (LSS) 4.2.3 and the Cosmic Microwave Background (CMB) 4.2.6.

We assume that the observed large-scale structure has grown out of small initial fluctuations from inflation by gravitational clustering. This process is modeled via cosmological perturbation theory and via N-body simulations, see projects LSS: modeling and CMB. To compare calculations with observations (see project LSS: observations) we have to take into account the problem of biasing, and more generically astrophysical systematics (see project LSS: astrophysical systematics): we observe only galaxies while theory predicts only the distribution of dark matter. How are these related? We can address this biasing problem to some extent by including baryonic interaction (hydrodynamics) into the simulations and on the other hand by inferring LSS power spectra from weak lensing, which is sensitive to the total mass, and by comparing them with those from galaxy surveys. We also want to investigate whether relativistic effects play a role in N-body simulations (so far they have mostly been neglected).

Another interesting aspect of both CMB fluctuations and LSS is non-Gaussianity: the simplest models of inflation, where self-interactions of the inflaton or between several possible degrees of freedom are neglected, predict Gaussian initial fluctuations that are fully characterized by their power spectrum. However, on the next level, taking into account interactions, i.e. higher that quadratic terms in the Lagrangian, inflation also predicts some degree of non-Gaussianity, which usually is very characteristic for the model of inflation. In order to detect it, we first have to compute (and subtract) non-Gaussianities due to non-linear clustering. Non-gaussianities are probably also relevant for the biasing problem, especially on large scales, where they mix with possible dark energy clustering. Therefore, to understand dark energy, we also have to study non-Gaussianity which in turn are intimately linked to the physics of inflation, the early Universe, see project Early Universe 4.2.1.

Ultimately, we also want to use cosmological observations to test general relativity, see project Cosmological

Tests of Gravity 4.2.4. One example in this direction are the two Bardeen potentials: if gravity is described by general relativity and dark energy is vacuum energy or a quintessence field, the two scalar gravitational potentials of linearized gravity, the Bardeen potentials, Φ, Ψ , are identical, $\Phi = \Psi$. However, if dark energy comes from a modification of gravity, they are generically different. Such a difference can be measured by combining weak lensing surveys, which respond to the sum $(\Phi + \Psi)$ with dark matter clustering observations, which responds to the 'Newtonian potential', Ψ.

Observing CMB anisotropies and polarization and LSS, we have concluded that the initial fluctuations have been generated during an inflationary phase. However, a satisfactory, generally accepted particle physics theory that identifies the inflaton as a physical degree of freedom is still lacking. To make progress in this direction we want to investigate, e.g., whether initial fluctuations contain a gravitational wave component or cosmic strings. It is fascinating that at present our most promising path to physics of the highest energies, GUT scale or the scale of quantum gravity, actually leads through the largest structures of the Universe, the fluctuations and polarization of the CMB.

We also address the challenge of dark matter 4.2.5: what is dark matter, how does it interact with ordinary matter? For this we want to detect dark matter directly, *i.e.* by other means than through its gravitational interaction. The best strategy for such searches depends on the nature of dark matter. If it is the most popular candidate, a WIMP (weakly interacting massive particle), this can be done best with direct dark matter detection experiments as those which are underway now in Switzerland and at LHC. However, WIMPs by no means exhaust the list of possible dark matter candidates. Although it is usually said that cosmological data favor Cold Dark Matter, this actually just means the hot dark matter (e.g. the standard model neutrinos) are disfavored.

The difference between cold and warm dark matter particles appears at approximately galactic scales and only recently we are able to resolve these low amplitude small scale effects both theoretically, via N-body simulation and experimentally via precise measurements of the galaxy power spectrum on small scales. This small difference (from cosmological point of view) is of crucial importance for particle physics, as it could mean a huge difference in the properties of the corresponding DM particle. Therefore, it is very important to study it. Moreover, already a first analysis shows that, for example, the structure and abundance of dwarf galaxies provide tantalizing evidence that dark matter may be warm, as if it were made up, for example, of sterile neutrinos. Sterile neutrinos are very strongly motivated from the particle physics point of view, they can play an important role in the Early Universe and be related to baryogenesis, see 4.2.1 below. The hypothesis of sterile neutrinos is also bears connections to our other neutrino projects 4.1.7 and 4.3.8.

Finally, dark matter may be annihilating or decaying. The search for decaying dark matter dark matter demands for a very different strategy than searching for its annihilating counterpart. One searches for decaying dark matter by looking for a monochromatic decay line in the spectra of dark matter-dominated objects. This is a very promising, clean signal. An extensive program of search for a decaying dark matter signal has already been realized (led by the EPFL group, M.Shaposhnikov, A.Boyarsky). The XMM-Newton satellite delivers the best searching capabilities for the weak extended signal of decaying dark matter, Chandra, Suzaku and INTEGRAL have also been used.

If dark matter is a gravitino, sterile neutrino or an axion, none of the above mentioned "direct detection experiments" will detect it, but different astrophysical and laboratory methods (discussed in this project) have great potential to uncover nature of dark matter particles.

Below we detail the following sub-projects and their connections

- **Early Universe:** inflation, phase transitions, baryon- and lepton-asymmetry.
- **Cosmic Acceleration:** is it quintessence, modified gravity, back-reaction or simply a cosmological constant?
- **Large Scale Structure:** we split this three separate but linked sub-projects: Modeling, Observations and Astrophysical Systematics.
- **Testing General Relativity on Cosmological Scales:** how can we distinguish between a 'dark energy' component and modified gravity?
- **Dark Matter:** this is a double project, concerning both, direct and indirect searches.
- **Cosmic Microwave Background:** this most pristine cosmological dataset still contains unexplored information.

4.2.1 Project: Particles and Fields in the Early Universe

Coordinators: M. Shaposhnikov (EPFL), A. Riotto (UniGe)

Research question and state of the art

Most properties of the Universe we observe today are believed to be determined at very early times by the laws of fundamental physics, most notably by gravity and high energy physics. The list of questions includes: Why is the Universe isotropic and homogeneous at large scales? How are the primordial density fluctuations which seed the formation of structures in the present Universe generated? Why do the cosmological parameters have the values we observe today? Why does the Universe contain more matter than antimatter? What is the nature of the dark matter, observed at present by gravitational effects only? It is already clear that the Standard Model (SM) of elementary particles cannot provide the answers to these questions, meaning that an extension is required. This leads to a number of particle physics questions, such as: What kind of new physics is necessary for addressing these problems? Which particle physics experiments together with cosmological and astrophysical observations can reveal new physics?

Very active theoretical research in this field has started soon after the discovery of cosmic microwave background (CMB) radiation in 1964, with a huge progress over the last years. The theory of Big Bang Nucleosynthesis, able to predict the light element abundances in the Universe was formulated already in forties and now has entered into precision stage. The conditions for baryogenesis (the creation of the baryon asymmetry) in the early Universe were formulated, and a number of possible mechanisms leading to a baryon asymmetric universe have been suggested [184]. The theory of the inflationary Universe, according to which the Universe suffered a period of violent acceleration just after the Big Bang, has been put forward and it beautifully explains why the Universe appears so homogeneous and isotropic on cosmological large scales. As a by-product, during inflation quantum fluctuations are amplified and stretched to cosmological scales and we are now confident that these inhomogeneities developed through gravitational instability into the observed large scale structure of the Universe [185]. In-spite of this success, a general unified picture, together with many important details, is missing. We still do not know whether one or several new particles or fields are needed for cosmological inflation. We are ignorant about the precise mechanism responsible for the generation of the inflationary quantum fluctuations. It is not clear what is exactly the source of CP-violation and deviations from thermal equilibrium, leading to a baryon asymmetric Universe. We do not know whether the baryon asymmetry was created at an energy scale testable by current experiments. It is not even clear whether the "dark matter" is a new particle. We do not know whether the observed present cosmic acceleration is due to some new light degree of freedom, dubbed "quintessence", or a manifestation of some modification of gravity (general relativity) at large distances.

Though these questions were around already for quite some time, only now the progress in high energy physics experiments (e.g. LHC at CERN) and cosmological observations (the Planck mission measuring the properties of the CMB anisotropies and current and future galaxy surveys, like the recently selected Euclid satellite mission of ESA measuring the properties of large structure of the Universe) will allow to make a considerable progress in the near future.

Intended contribution of the project

Our primary goal is to take advantage of the impressive flow of data that both particle physics and cosmology experiments will provide in the next decade to learn more about the early Universe dynamics. We will contribute to improve our understanding of the inflationary picture from the CMB anisotropy and large scale structure observations. By studying the statistical properties of the cosmological inhomogeneities in the Universe today, we will characterize the dynamics of inflation and understand the process of quantum generation of fluctuations. As the power spectra of initial fluctuations contaim information about the evolution of free fields during inflation, higher order correlations, non-Gaussianity contains information about their interactions. In this sense, observing primordial non-Gaussianities plays the role of the LHC collider of inflationary physics. In the coming decade primordial non-Gaussianity, i.e. the study of primordial non-linear contributions to the correlations of cosmological fluctuations and other cosmological observables, will become a fundamental probe of the physics interactions, which were acting during the inflationary primordial epoch. We have all the expertise to play a leading role in this line of research [186, 187]. The very same set of data will be analyzed to furnish crucial information about the present-day cosmic acceleration, possibly confirming and/or ruling out the revolutionary idea that Newtonian gravity is modified on large scales.

Thanks to high energy physics experiments we will possibly identify and study the true mechanism responsible for baryogenesis as well as the true nature of dark matter, which even might be related. For instance, if the LHC provides evidence of that physics beyond the SM, we will thoroughly investigate its properties to understand if baryogenesis can be ascribed to physics close to the electroweak energy scale. At the same time, we intend to make use of observations of non-accelerator experiments testing the flavour structure of the particle content within the SM (e.g. in the neutrino sector) to scrutinize other scenarios of baryogenesis whose energy scale is not directly accessible to colliders.

Another direction of research is based on the principle of "minimality". We will investigate the possibility that all the observational problems of the SM can be solved without introducing any new energy scale between the Fermi and Planck scales, with a minimal number of new particles and new physics principles introduced [188]. A possible theory of this sort contains, in addition to SM fields, just three extra particles – right-handed neutrinos, completing the fermionic content of SM in left-right symmetric way. Here the Higgs boson of the SM leads to cosmological inflation [189] and generates the masses of elementary particles, whereas the extra fermions are responsible for the baryon asymmetry of the Universe, for dark matter, and for neutrino masses and oscillations. The cosmology and phenomenology of this type of theories will be elucidated, with an outcome for cosmology (properties CMB, of dark energy, and of dark matter) and for particle physics (mass of the Higgs boson and parameters of heavy neutral fermions).

Links to other projects of this NCCR

Reconstructing a fundamental theory of nature from the full body of experimental data is a principal challenge of physics. The investigations of physics of the Early Universe give an indispensable input to particle physics, otherwise hardly achievable. They provide a consistent framework for addressing the problems that cannot be explained by the SM, and will suggest in what ways the new physics can be found through cosmological and astrophysical observations and laboratory experiments. It is at the base of the NCCR Universe that this quest now connects to all the LHC experiments discussed in the first challenge (Constituents and Forces), Section 4.1 and to the LSS and CMB experiments, sections 4.2.3 and 4.2.6 discussed in this challenge (Dark Matter and Dark Energy). Of course also future terrestrial and space accelerators discussed in the third challenge can provide most valuable data to unravel the physics beyond the standard model which is crucial for the early Universe.

Finally, the results of the Dark Matter project 4.2.5 will be most relevant for the construction of the "minimal" extension of the SM with sterile neutrinos. Astrophysical and cosmological studies of super-WIMPs will allow to probe the parameter space of sterile neutrino dark matter. In combination with theoretical investigations that are the objectives of this project, this will allow us to restrict the parameters of heavier sterile neutrinos and make a detailed predictions for the future accelerator (e.g. beam dump) experiments, capable of discovering these new particles.

4.2.2 Project: Cosmic Acceleration

Coordinators: M. Maggiore, M. Kunz (UniGe)

Research question and state of the art

Understanding the origin of dark energy is one of the most important challenges facing cosmology and theoretical physics. Its discovery at the end of the 90's [190, 191, 192] has led to the Nobel Prize in physics of 2011. Even though the experimental situation is at present convincing, a theoretical understanding is still completely lacking. The solution of this problem will require a combined approach by theorists and observers, and will certainly require both a significant observational effort as well as the development of new theoretical ideas. For a review see [193].

On the observational side, it is crucial that as much information is gathered as possible. This requires measurements of cosmic expansion and cosmic growth of structure at percent levels and correspondingly tight control of systematic errors. It also requires a robust understanding and careful modeling of astrophysical and instrumental uncertainties, including the effects of non-linear clustering, as they will render the comparison of observations to theory difficult and may hide elusive observational clues about the nature of the dark energy. Additionally, comparing observations to theoretical predictions requires a meaningful parametrization of the space of testable models.

These issues require close collaboration between theorists, data analysis experts, and observers and instrument builders. This NCCR is uniquely positioned to address these problems in a unified manner, since it will unite experts from all these areas. The interpretation of the future experimental evidence will be intensely discussed between the members.

Intended contribution of the project

In particular, we will focus on the investigations associated with the approaches based on measurements of weak gravitational lensing, galaxy clustering, redshift space distortions, Lyman-alpha and galaxy clusters from a wide range of large scale structure surveys (SDSS, LSST, EUCLID), as well as measurements of cosmic microwave background anisotropies by Planck and WMAP and earth bound CMB experiments. Several participants in this proposal are involved directly in many of these surveys.

This observational effort will probe the nature of the dark energy at different levels. On the one hand the observations will test the homogeneous cosmology predictions of distance redshift relations. These distances will be measured using standard rulers, e.g. baryon acoustic oscillations in the CMB, large galaxy surveys and the Lyman alpha forest, as well as standard candles like type Ia supernovae. On the other hand, they also provide constraints based on the growth of structure in the universe, such as weak lensing, galaxy clustering, redshift-space distortions, galaxy cluster counts and luminosity functions, Lyman-alpha forest and cross-correlations of the large scale structure with the CMB.

We believe that a more coherent approach to the issue of cosmological data analysis and interpretation is needed not only in the context of Dark Energy, but also of other topics discussed in other sections of this proposal. We have to unify the methodology of data analysis and of statistical reporting and interpretation. By bringing together numerous experts in several of these areas, the proposed NCCR will take on this role. Combining the different data sets to obtain stronger cosmological constraints on dark energy has been one of the main research activities by partners of the NCCR (e.g. V. Desjacques, M. Kunz, J. Lesgourgues, U. Seljak [194, 195, 196, 197, 198, 199, 200]) and we will continue activities in this direction by incorporating the latest data sets, many of which will be delivered by members of our center.

On the theoretical side, there are many crucial open questions. First of all, the 'simplest solution', a so called cosmological constant is by no means natural. Experimentally, there is no way to distinguish a cosmological constant from vacuum energy. We therefore think that we should also not distinguish them theoretically. However, the vacuum energy of a quantum theory is not protected from radiative corrections and it scales like the cutoff energy scale to the 4th power. To understand how to 'fine tune' it to the measured small value of

$$\rho_{\rm vac} = \frac{\Lambda}{8\pi G} \simeq (2.3 \times 10^{-3}{\rm eV})^4$$

we probably have to investigate the basis of quantum field theory on a non-perturbative level.

One important aspect of the problem is already to understand what is the effect of vacuum fluctuations of quantum fields on the cosmological expansion. This is a domain where cosmology meets quantum field theory on curved space. At a more phenomenological level, it is important to develop field-theoretical models based on extensions of General Relativity, to compare them with the data and to the "standard" ΛCDM cosmological model that at present is consistent with the observations but, at the conceptual level, gives no convincing explanation for the coincidence problem, namely why the dark energy density becomes relevant just at the present epoch of the universe.

These issues require field-theoretical competences, as well as experience in applying these theoretical ideas to cosmological problems, and fall within the domains of expertise of several members of our center (L. Alvarez-Gaume, G. Giudice, M. Maggiore, R. Rattazzi, A. Riotto M. Shaposhnikov [201, 202, 203, 204]). In this direction also goes the effort of distinguishing 'standard' dark energy components from modifications of gravity.

The last years have also seen a strong effort towards identifying the degrees of freedom that can be probed by cosmological observations, with the goal of providing a unified parametrized framework within which theoretical predictions can be compared to observational results [196, 197, 198, 199, 200], disentangling the signature of dark energy and massive neutrinos on the growth of structure [205] and performing detailed calculations of relativistic effects relevant for future large surveys [206] as well as of the impact of non-linear clustering [207, 208, 209] (M. Maggiore, A. Riotto, U. Seljak, V. Desjacques). In order to successfully shed light on the physical nature of the dark energy, all these different research strands need to be united into a single, coherent effort. To provide an institutional framework for this work is one of the main goals of the NCCR.

Finally, might it be that there is no cosmic acceleration and we are just too naive in applying the distance redshift relation of a homogeneous Friedmann Universe to the real inhomogeneous universe? It has been shown that by modifying somewhat (by about 20%) the distance redshift relation, we can get rid of dark energy and with it cosmic acceleration [210]. But what is the 'real' geometry that induces such a modification? All trials with toy models, which cluster non-linearly only on scales up to about 50–100h^{-1}Mpc, as the observed Universe, lead only to very small changes in the distance redshift relation, maximally a few percent. As an example of such a toy model see [211]. This is expected, as one assumes that on large scales the clustering effects 'average out'. However, since General Relativity is non-linear, this 'averaging process' is not guaranteed to work even on cosmological scales. Hence, despite the negative findings from simple toy models, the problem remains open. Since it is known that Newtonian gravity does not lead to significant back-reaction [212, 213], the problem has to be tackled with non-linear GR simulations which we want to perform in collaboration between UniZh (B. Moore, U. Seljak) and UniGe (M. Kunz, V. Desjacques, R. Durrer).

Links to other projects of this NCCR

This project is the theory counterpart of the three sub-projects on LSS 4.2.5 and the CMB project 4.2.6. It is also intimately related to the sub-project on tests of gravity 4.2.4 as the cosmic acceleration might be due to a modification of GR. Finally, there are links to the early Universe project; first of all, also inflation represents a phase of accelerating expansion and secondly, all our LSS and CMB fluctuations measurements depend on the initial fluctuations generated during inflation. Also, the aim of this effort is the find out whether cosmic acceleration is related to a new 'constituent': dark energy, or to the modification of a well known 'force', gravity. In this sense the project is related also to the first challenge of this NCCR.

4.2.3 Project: LSS as a Probe of Fundamental Physics

Coordinators: See sub-projects below

Research question and state of the art

To address the fundamental questions coming from extragalactic cosmology, we rely on measurements of the large scale properties of the Universe. Four techniques have emerged as standard probes of the low redshift Universe. These are (i) gravitational lensing, (ii) distribution of galaxies, (iii) supernovae and (iv) galaxy clusters. Each one of these measures has its particular statistical power and susceptibility to systematic errors. It is the combination of these probes, with the cross checks that multiple measures allow, that leads to overwhelming evidence that the Universe is currently going through a phase of accelerated expansion. Looking forward to upcoming experiments, weak lensing and the statistics of the spatial distribution of galaxies stand out as the two large-scale structure (LSS) probes with the greatest promise. This is due to both their statistical power and their weak sensitivity to the complicated physical processes that govern galaxy formation.

Gravitational Lensing: The bending of light from distant galaxy, due to intervening mass along the line of sight, leads to a phenomenon known as gravitational lensing. In weak lensing, the lensing effects of large-scale structure leads to a correlated distortion pattern being imprinted onto galaxy images. This effect is subtle and hard to detect due to the weak signal. The difficulty for lensing experiments is further compounded by the fact that the galaxies we wish to measure are small and faint due to their distance from us, and their images are further corrupted by the Earth's atmosphere and the telescope's own instrument effects. Though difficult, these challenges are observational and, thus, can be solved by carefully building high precision experiments.

Distribution of Galaxies: Galaxies are embedded in a cosmic web of dark matter, and their distribution is a biased tracer of the underlying dark matter distribution. There are a number of features of the statistics of a galaxy distribution that can be used to make cosmology measurements. The simplest is to measure the Baryon Acoustic Oscillations (BAO), which are the same acoustic features seen in the Cosmic Microwave Background (CMB). These can be viewed as a standard ruler and used to measure the angular diameter distance as a function of redshift. The observed clustering of galaxies can also be used to study the way structure grows over time, which is seen as an important test of gravitational theories. Another important quantity is the velocity field probed by the galaxies, which induces fluctuations in the measured redshift (the so-called redshift space distortions). The key to such experiments is to determine the redshifts, preferably spectroscopically, of a large number (millions) of galaxies. As we move forward, the difficulty for this technique will be to understand the bias between the galaxies and the underlying dark matter, especially on scales that are becoming non-linear today.

A large number of experiments are being built, with the next round due to come online in the coming years. In the case of weak lensing, the measurements rely on high resolution, multiband imaging over wide area surveys. In the short term (next five years), data is expected from KIDS, PanSTARRS, DES and HyperSuprimeCam. These large dedicated programs are driven by weak lensing and will image several thousand square degrees to sub arc second resolution. This is a substantial increase over current surveys, such as the CHFTLS and COSMOS, which cover 170 and 2 square degrees, respectively. The generation of experiments on time scales of 10 years that will follow these survey are also being planned. These include LSST, Euclid and WFIRST. These ambitious missions will take high quality images over roughly half the night sky. In parallel to this, studies of the statistics of galaxy distributions rely more heavily on wide area spectroscopy survey. In this respect, the Sloan Digital Sky Survey (SDSS) has had enormous success. The SDSS galaxies cover an area of 1700 square degrees out to a redshift of roughly $z = 0.2$. Upcoming surveys, such as BOSS, DESpec and BigBOSS, Euclid and WFIRST, will extend the galaxies being measured out to redshifts of $z=1$ and beyond. This will greatly improve the volume, and hence the statistical power and allow us to measure the evolution of LSS as a function of redshift. This wide array of exciting experiments will lead to an enormous expansion in this field.

These cosmological probes, developed to study the combined Dark Sector of Dark Matter and Dark Energy are based on large scale surveys of the extragalactic Universe extending out to redshifts $z \sim 2$. They provide a measure of the Universe through the extended epoch during which Dark Energy came to dominate the overall expansion of the Universe. The surveys are intended to provide a three-dimensional view of the development of structure in the Universe to complement the essentially 2-dimensional single epoch "snapshot" that is obtained from the cosmic microwave background at $z \sim 1050$.

Because of this, the implementation of these probes will require a sophisticated astrophysical understanding of potential **systematic effects**, both in galaxy *measurement* and in the understanding of baryonic *modifications* to the otherwise simple cosmological signatures of the Dark Matter and Dark Energy which are introduced by the more complex physical processes associated with the baryonic component of the Universe. These astrophysical intrusions into particle cosmology are particularly evident in the exploitation of weak lensing data, but are also applicable to a varying degree to the other cosmological probes.

Previous work by the proposers

The proposing team has extensive and complementary experience in the planning, observations, analysis and interpretation of cosmological surveys as well as in the theoretical and numerical modeling of cosmic structure formation. We have world class leaders in analyzing both spectroscopic and imaging data.

At ETH-Zurich, A. Refregier, S. Lilly and M. Carollo and their groups have played leading roles in the development and analysis of wide field surveys. They have also developed a number of high precision techniques for the analysis of cosmological data and applied these methods to derive statistical properties of cosmic large scale structures and to study the formation and evolution of galaxies. At the University of Zurich, U. Seljak is a leading expert in the field of theoretical cosmology. At the University of Geneva, V. Desjacques, M. Kunz and A. Riotto have strong expertise in numerical simulations of the large scale structure, analytic approaches such as perturbation theory, theoretical and phenomenological modeling of dark energy, as well as the analysis and interpretation of large scale structure data. The ISDC, part of the Observatory of Geneva, is a center of competence for the analysis of space missions and will provide the Swiss Science Data Center for Euclid. S. Paltani is strongly involved in the Euclid mission. G. Meylan and his group at the EPF Lausanne have expertise in strong and weak lensing.

Intended contribution of the project

4.2.3.1 Sub-Project: LSS: Observations

Coordinators: A. Amara (ETHZ), M. Kunz (UniGe)

Development of analysis pipelines: Given the extensive experience that exists in Swiss institutes, we are well placed to develop pioneering analysis pipelines for both imaging and spectroscopic data. These will enable us to perform weak lensing, galaxy clustering (including BAO) and redshift space distortions measurements. The different information that comes from each of these probes is not independent, therefore, it is important to fully understand the cross-correlation to allow for their combination. This is a substantial task that will require interdisciplinary knowledge of each of the probes.

Analysis of current surveys: We will apply our analysis pipelines to existing data that we have access to, these include the SDSS galaxy survey, COSMOS and zCOSMOS. Though these data sets have been extensively analyzed, they still remain excellent repositories that will allow us to develop further our data analysis methods that we plan to deploy on upcoming surveys. The goal here is to provide constraints on cosmological parameters, with special emphasis on dark energy properties (as outlined in the Cosmological Tests of Gravity sub-project, section 4.2.4) with an emphasis on the extra gains from probe combination.

Analysis of upcoming surveys: In the time frame covered by this proposal, we expect to see an explosion of imaging and spectroscopic data. We will directly collaborate on their analysis and provide basic products such as e.g. mass maps and power spectra (density, velocity, lensing potential, etc) for the LSS surveys, both as a function of scale and redshift.

Preparation of future surveys: We are members in a range of future surveys like e.g. Euclid for which the 2014-2017 period will be a crucial development phase. We will provide forecasts for the expected performance of the future surveys, help to optimize their design, and work on the analysis pipeline.

4.2.3.2 Sub-Project: LSS: modelling

Coordinators: V. Desjacques (UniGe), U. Seljak (UniZh)

The combination of numerical simulations and analytic methods will enable the development of accurate models, which can be used to forecast constraints on cosmological parameters.

Numerical simulations of LSS: Numerical simulations bridge the gap that often exist between theoretical models and observational data. They will be used extensively to predict the signal imprinted by viable inflationary models, dark energy or modified gravity, neutrinos and exotic dark matter particles on galaxy clustering and weak lensing data. While pure dark matter simulations combined with models of the Halo Occupation Distribution (HOD) should be enough to accurately predict the signatures in correlation functions of the galaxy distribution, the interpretation of weak lensing measurements, which aim at measuring the matter power spectrum at 1% accuracy on scales $0.1 < k < 10h\mathrm{Mpc}^{1}$, will require hydrodynamical simulations which realistically include the effect of baryons. Series of large-volume simulations will be employed to calibrate the theoretical models, identify parameter degeneracies and estimate covariances in the measurements. Past light-cones will be extracted and "degraded" to account for instrumental noise, photometric errors, flux limits etc., in order to create mock surveys of galaxies. Another important aspect will be the development of numerical codes that can setup and follow the evolution of cosmic structures in non-standard cosmologies, and efficiently compute statistics such as the 3-point correlation functions of galaxies on massively parallel computers.

Analytic models of LSS: On the theoretical side, perturbative expansion approaches and sophisticated extension such as resummed perturbation theory and time-renormalization group methods will be developed to model the nonlinear evolution of the mass density field and the galaxy distribution. These analytic models will provide useful physical insights into nonlinear clustering and help understanding the systematics of the numerical simulations. Their precision and convergence will be tested against the outcome of simulations. Regarding galaxy bias, one of the novel aspects will be to look beyond conventional approaches, in which bias is approximated by a continuous function of spatial location, and consider statistics of point processes. This will help understanding the stochastic nature of galaxy bias and developing optimal methods that can minimize the impact of cosmic variance and shot noise on, e.g., measurements of the growth factor f or the nonlinear parameter f_{NL}. We will also work out all relativistic effects relevant for LSS observations, such as lensing and magnification effects in the galaxy and supernovae surveys. These effects will become measurable with future surveys.

4.2.3.3 Sub-Project: LSS: Astrophysical Systematics

Coordinators: S. Lilly, M. Carollo (ETHZ)

Of central importance for weak lensing is the estimation of redshifts for huge numbers of galaxies ($10^8 - 10^9$), which cannot possibly be observed spectroscopically. This necessitates the use of photometrically-estimated redshifts. While the required random uncertainty, $\sigma_z \sim 0.05(1+z)$ is relatively straightforward to achieve, the required *systematic* uncertainty, of order $0.002(1+z)$ in the mean redshift of a given set of objects, is very much more challenging. Despite recent progress by ourselves and others, much further work needs to be done to develop photo-z techniques to the point where this level of precision is confidently achievable. One focus will be to improve the ways in which other, non-photometric, information is used in photo-z schemes, e.g. information on the structural morphologies of the galaxies, including possible orientation effects. The other will be to explore more generalized approaches using optimized eigen-spectral energy distributions.

One of the most important difficulties is securing spectroscopic redshifts of sufficient quality such that the reliability of photo-z schemes can be accurately characterized. This requires large numbers of highly complete and highly secure spectroscopic redshifts. Spectroscopic redshift surveys, such as zCOSMOS and other similar ones, have been optimized with other considerations and are not sufficient for this task: there are many galaxies where the photo-z and spectro-z are discrepant, some due to photo-z failures and some due to incorrect spectroscopic identifications. It would therefore be very attractive to undertake a dedicated redshift survey optimized for photo-z calibration, e.g. as an ESO Public Spectroscopic Survey using the VIMOS spectrograph, a call for wish is expected in the near future.

In addition to photo-z, there are also formidable challenges to be faced in the measurement of faint galaxy shapes in practical imaging instruments. In addition to the well-known issues surrounding what is effectively a deconvolution of the galaxy image from the instrument point-spread function (PSF), there are a number of more subtle effects to worry about. First, the shapes must be optimally characterized: At first, a simple second moment of the image was taken to yield a "size" and "orientation" [214]. Later, an orthogonal set of "shapelets" was introduced [215], which has the advantage that the effect of a lensing shear distortion can be readily calculated. However, the general shapelet set is non-optimal - in essence too many individual shapelet components are required and they become too noisy to be used [216]. A more optimized basis set, starting around the typical profiles of faint galaxies would be much better - see [217, 218, 219]. There are close analogies here to the "template-fitting" approach to photometric redshifts where one uses similar astrophysical "information" on the spectral energy distributions of galaxies to optimize the information content rather than using a completely general (e.g. Fourier) decomposition.

As a further complication, any practical imaging system will have a PSF that is wavelength dependent. While this could in principle be taken care of by reconstructing the effective PSF for a given galaxy [220], second-order effects will enter if galaxies have internal colour gradients and/or if internal sub-structure has different colours. Both of these are known to be the case. The likely impact of these effects is unknown, nor do we have in place any strategies to recognize and deal with them on a galaxy-by-galaxy basis.

Links to other projects of this NCCR

The LSS project is linked to the Early Universe project 4.2.1 as especially non-Gaussianities will give us information not only on the non-linear evolution of gravitational clustering, but also on primordial non-Gaussianities. While the power spectrum is mainly related to the free inflaton field and its cosmic evolution during inflation, primordial non-Gaussianities are related to interactions. They therefore are our access to physical interactions at very high energies which we cannot probe in terrestrial accelerators.

Furthermore, all the LSS observations will be combined with CMB observations, see project 4.2.6, to best constrain the cosmological parameters which describe the present Universe and the nature of the fluctuations.

The tools to overcome the serious measurement issues for *cosmological* studies using large samples of faint galaxies can fortunately be developed using the astrophysical information on the galaxy population that is coming out of the intensive work to understand galaxy evolution. This is done in our sub-project on astrophysical systematics which is relevant for all observations of LSS.

This same research program is also leading to a more sophisticated understanding of how and where galaxies form, which is associated with the cosmological "bias" between the distribution of dark and luminous matter, and in how heating and cooling of the baryonic component leads to redistribution of the baryonic material that is relevant for any study attempting to relate the distribution of these two components.

The aim of the sub-project on astrophysical systematics is to develop those bits of *astrophysics* that are of most relevance to the measurement and interpretation of the purely *cosmological* signals in very large surveys of galaxies in the late epoch $0 < z < 2$ regime described in the other sub-projects of LSS. It can also be useful for indirect detections of dark matter discussed in section 4.2.5 and for the magnetic field project, section 4.1.10 of this proposal.

Weak lensing and Lyman-α forest data are crucial to distinguish between "cold" or "warm" dark matter with severe impact on theoretical understanding of the nature of dark matter. Therefore the control of astrophysical systematics will play a crucial role for the identification of dark matter, project 4.2.5. In combination with the theoretical computations on the physics of the early Universe, project 4.2.1, these data allow to determine the nature of the dark matter particles (e.g. sterile neutrinos) that can be searched in laboratory experiments. The LSS observations will provide the data (density maps and galaxy counts) necessary for the search for decaying dark matter, project 4.2.5.

4.2.4 Project: Cosmological Tests of Gravity

Coordinators: M. Kunz (UniGe) and A. Refregier (ETHZ)

Research question and state of the art

The presence of the dark energy is very puzzling, and one possible explanation is that General Relativity itself breaks down on large scales. But even beyond this urgent question we may ask how can we use cosmological observations to test General Relativity (GR)? On solar system scales GR is well tested by classical solar system tests, like e.g. lunar laser ranging or light deflection by the sun; but also by using data from binary pulsar systems which provide very accurate clocks. These observations have let to the development of the PPN (Parametrized Post-Newtonian) formalism [221] within which deviations from GR are cast in so called 'post-newtonian parameters'. Since we are now developing similarly accurate cosmological datasets, can we define 'post-friedmannian parameters' which in a similar way are sensitive to modifications of GR?

At a very basic level, we can measure the geometry of the Universe, or in other words the metric by observing the motion of massive and massless freely falling particles (galaxies and photons). From the metric we can compute the Einstein tensor $G_{\mu\nu}$. If GR is correct then we can use the Einstein equations to infer the energy momentum tensor of whatever is accelerating the expansion of the Universe. But we can do the same computation even if GR is not correct, giving us an effective energy momentum tensor, from which we can derive an effective pressure (defined through the background equation of state w and the pressure perturbation δp) and anisotropic stress π of the dark sector [196, 199],

$$G_{\mu\nu}[H, \phi, \psi] = 8\pi G T^{\text{eff}}_{\mu\nu}[\rho, p, \delta\rho, \delta p, V, \pi]. \tag{2}$$

This is the important difference to solar system or binary pulsar constraints: there energy momentum tensor is vanishing in the part of spacetime under consideration. In cosmology, determining the energy momentum tensor is an important part of the problem. Nevertheless, the situation is not completely hopeless.

We explicitly write the dependence on the geometry, given by the background expansion rate $H(t)$, and the gravitational potentials $\phi(x,t)$ and $\psi(x,t)$ that quantify the scalar metric perturbations (for simplicity we assume a spatially flat Universe because of inflation, and only consider the scalar-type perturbations here, in reality these assumptions would be relaxed). The covariant conservation of the effective energy momentum tensor, $\nabla_\mu T_\nu^{\mathrm{eff},\mu} = 0$ allows to eliminate one background and two perturbation quantities, typically ρ, $\delta\rho$ and V. We see that after this elimination, the degrees of freedom of the geometry (one background and two perturbative quantities) match the effective fluid degrees of freedom (also one background variable, the pressure p usually parameterized with the equation of state parameter $w = p/\rho$, and two perturbations). In this formalism both dark energy and possible modifications of gravity are unified, which has the big advantage that we can directly apply it to observations. However, how we can now disentangle the different possibilities? Acceleration today implies $w(t_0) < -1/3$, but to go beyond just the existence of acceleration we have to look at possible models of the dark sector. For example, scalar field dark energy, quintessence or k-essence, generically gives rise to a sound horizon below which the dark energy perturbations are suppressed, which implies a specific functional form of δp. This sound horizon leaves traces in the gravitational potentials, a bit like a finger print of this specific model (see, e.g. [197]). Modifications of General Relativity on the other hand generically produce an effective anisotropic stress [200] ($\pi \neq 0$) that is not present in uncoupled scalar field models.

Intended contribution of the project

In this project we will hunt for the finger prints of gravity and its modifications in the large scale structure data. The only model that leaves no trace at all in the perturbations is a cosmological constant. All other explanations of the accelerated expansion perturb in some specific way the Universe on large scales. For some models these perturbations can, however, be very small, for example the perturbations from scalar field dark energy can only be detected if it is “cold” and has a sufficiently small speed of sound [198]. Deviations from General Relativity, on the other hand, tend to produce much larger signatures.

To identify the physics behind the accelerated expansion and test gravity on large scales, we first have to be able to measure the metric. In practice this means measuring both gravitational potentials, ϕ and ψ. This can done for example by combining weak lensing observations (since light deflection depends on $\phi + \psi$) and the galaxy velocity field (as non-relativistic “test particles” are accelerated by the gradient of the ψ potential alone). Several of the proposers are world experts in these surveys. For example, A. Refregier, S. Lilly and A. Amara of ETHZ have extensive experience in large scale structure surveys, and the Universities of Geneva, Zürich as well as the EPFL are actively involved in the Euclid satellite project.

Based on these measurements we will then derive key variables like the sound speed and the effective anisotropic stress of the dark energy. This in turn places constraints on the space of allowed models. In fundamental physics, the quantity that really describes a physical model is its action, and we will be able to directly measure certain terms in a general action for the dark sector. For example we can start with an Ansatz like

$$S \sim \int d^4x \sqrt{-g} \Big[\frac{1}{2} f(\varphi) R + K(X) - V(\varphi) + \mathcal{L}_m \Big] \tag{3}$$

where $\mathcal{L}_m$ is the matter part of the action, φ is a scalar field with $X \equiv -1/2(\nabla\varphi)^2$ and R the Ricci (curvature) scalar of the action of General Relativity. In this case, the potential $V(\varphi)$ is important for modeling the accelerated expansion of the Universe, while the kinetic function $K(X)$ will determine the sound speed of the dark energy. The effective anisotropic stress on the other hand is directly linked to the modification of the gravity part part of the action, i.e. to the derivative $f'(\varphi)$.

However, there are still many possible dark sector actions to explain the observed effective fluid properties. But, as mentioned above, on “small” scales, e.g. inside the solar system, General Relativity has been extremely well tested. Any viable modification of gravity needs to contain a non-linear mechanism that allows it to revert to GR in high-density regions. Several such mechanisms have been identified e.g. the Vainshtein mechanism of massive gravity or the Chameleon mechanism for scalar fields, see e.g. [222]. If large-scale measurements indicate a likely breakdown of GR, then the precise way in which these deviations are suppressed as a function of scale holds further crucial clues as to the shape of the action that needs to be considered. Based on their experiences, the proposers are well placed to work out this mapping from observations through to the action. M. Kunz (UniGe) has been at the forefront of research in the interpretation of effective dark fluid quantities and is co-coordinator of the Euclid theory group, R. Rattazzi (EPFL) is a world-leading expert in field theory and its cosmological applications, as are M. Maggiore and A. Riotto (UniGe), who in addition have also extensive experience in computing predictions for the non-linear evolution of the Universe.

The goal of this project is go all the way from cosmological observations through an effective fluid description of the dark energy to inferences on the allowed actions to describe the dark sector. In this NCCR we have been able to assemble a team of the foremost experts in the large-scale structure observations necessary to measure the metric quantities needed, experts of the formalism to infer the fluid quantities from the metric, and experts in field theory that links the fundamental description of the dark sector in terms of an effective action to the properties of the dark fluid inferred from observations. In this way we will be able to link cosmological data with the physics of the dark sector and test gravity on large scales that cannot be accessed in any other way.

Links to other projects of this NCCR

This project is of course strongly related to the project of cosmic acceleration, as modification of GR might be at the origin of this observation. Furthermore, most experimental/observational progress is expected via the cosmological probes offered by LSS and CMB observations. Hence there are strong connections to all three LSS projects and to the CMB project. But of course as it is testing one of the fundamental forces of nature, gravity, this project is also related to the challenge 'Forces and Constituents'.

4.2.5 Project: Dark Matter: Direct and indirect detection

Coordinators: L. Baudis (UniZh), A. Boyarsky (EPFL), J. Read (ETHZ)

Research question and state of the art

The nature of Dark Matter (DM) is among the most intriguing questions of modern physics. Its resolution will have a profound impact on the development of particle physics. The Standard Model of elementary particles does not contain a viable DM candidate. Therefore, the DM particle hypothesis necessarily implies an extension of the Standard Model. Candidate DM particles in such hypothetical Standard Model extensions differ drastically in their properties (such as mass, interaction strength, clustering properties) and therefore in their observational signatures. By constraining properties of DM particles one can differentiate among extensions of the Standard Model and learn about the fundamental properties of matter.

Swiss groups are leading many important directions in the direct and indirect searches for Dark Matter and have extensive plans till 2017, implying close collaborations between cosmology, astrophysics, theoretical and experimental particle physics.

At the largest distances, modern cosmological and astronomical observational data are successfully described by the simplest cold DM model that assumes that DM particles decouple from primordial plasma non-relativistically. Maybe the most popular DM candidates of this class are weakly interacting massive particles – WIMPs. These stable particles interact with the Standard Model sector with roughly electroweak strength. The interest for these candidates is due to their potential relation to the electroweak symmetry breaking, which is being tested at the LHC. To give a correct DM abundance, these particles should have a mass of $\sim 10-10^3$ GeV. The WIMP searches are important scientific goals of many experiments. One of the main scientific objectives of the Fermi mission is to search for the gamma-rays from WIMP annihilation. Dozens of laboratory experiments are conducted to detect WIMPs in the Galaxy's DM halo by searching their interaction with nucleons. Direct dark matter detection experiments with leading Swiss participation use the noble liquids argon and xenon as WIMP targets. The ArDM (Argon Dark Matter) experiment [223], using 850 kg of liquid argon (LAr) to search for nuclear recoils induced by WIMP scatters, is lead by ETH Zurich (A. Rubbia, spokesperson). ArDM has been constructed and is in commissioning at CERN; it will be installed at the Canfranc Underground Laboratory (Spain) by the end of 2011. The goal is to test the discrimination capability against beta decays from ^{39}Ar, and to probe WIMP-nucleon cross sections down to $\sim 5\times 10^{-45}$ cm^2.

The XENON100 experiment [224] is taking science data at the Gran Sasso Underground Laboratory (LNGS) since 2009. It uses 62 kg of liquid xenon in a time projection chamber, surrounded by 99 kg of liquid xenon veto, both viewed by arrays of photo-multipliers capable to detect the primary and secondary scintillation signals after a particle interacts in the active xenon volume of the time projection chamber. Data from the first 100 live-days of dark matter search showed that the XENON100 background is two orders of magnitude below the one of any other direct detection experiment [225], provided the world's best limits on the spin independent WIMP-nucleon interaction cross section [226] and excluded inelastic dark matter as an explanation of DAMA [227]. A second science run started in March 2011. Concomitantly, the XENON1T detector, which will feature a total of 2.4 tons of liquid xenon was proposed to be built in a large water Cerenkov shield at LNGS and approved to be installed in Hall B in April 2011. The project, which is led by Columbia (E. Aprile, spokesperson), UZH (L. Baudis, deputy spokesperson) and MPIK Heidelberg (M. Lindner, chair of the collaboration board) is presently in advanced preparation and will start its construction phase in mid 2012, with data science exploration to begin by 2015. XENON100 will probe WIMP-nucleon cross sections down to $2\times10^{-45}\text{cm}^2$, and XENON1T is designed to improve this sensitivity by at least one order of magnitude.

However, WIMPs by no means exhaust the list of possible DM candidates. Cosmological data rule out the possibility that a significant fraction of DM particles remained relativistic up until the matter-dominated epoch (which is the case for the usual neutrinos). Other than that, the mass and interaction strength of DM particles remain largely undefined. We only know (from studies of the phase space density of DM dominated objects) that fermionic DM particles should have a mass above $\sim$ 400 eV [228].

There is a large class of extensions of the Standard Model, which predict super-weakly interacting DM candidates (super-WIMPs) with much more feeble interaction strength than that of WIMPs. This changes their properties in two crucial ways: (i) a correct abundance of DM may be produced with a mass of DM particles as low as few keV; (ii) super-WIMPs can decay (with a lifetime exceeding the age of the Universe). These particles may be produced relativistic and suppress primordial density fluctuations at sub-Mpc scales. Such models (often called warm dark matter) fit the CMB and large scale structure data equally well as the ΛCDM "concordance" model [229].

The super-WIMP candidates are also motivated by particle physics. For example, the minimal extension of the Standard Model by three sterile neutrinos, (the νMSM [230]) provides a viable and unified description of three main observed "beyond the Standard Model" phenomena in particle physics – Dark Matter, neutrino flavor oscillations and baryogenesis (matter-antimatter asymmetry). The DM in the νMSM should be lighter than 50 keV and is produced with a non-thermal velocity spectrum [231, 188]. This theory is among a very few models that provide testable resolution of the "beyond the Standard Model" puzzles in the situation when no new physics is found at the LHC. However, to achieve sufficient predictive power, the νMSM requires significant input from astrophysics and cosmology.

The search for super-WIMP DM demands a very different strategy. These particles posess a 2-body decay channel, producing a monochromatic photon. The search for decaying DM by looking for a line in the spectra of DM-dominated objects is very promising, as the DM origin of any "suspicious" line can be unambiguously checked. Indeed, the decay signal is proportional to the column density $S = \int \rho_{DM}(r)dr$ along the line of sight and not to the $\int \rho^2_{DM}(r)dr$ (as it is the case for annihilating DM). As a result a vast variety of astrophysical objects of different nature would produce a comparable decay signal [232]. Therefore: (i) one has the freedom of choosing the observational targets, avoiding complicated astrophysical backgrounds; (ii) if a candidate line is found, its surface brightness profile can be measured and distinguished from astrophysical lines (which usually decay much faster in outskirts) and compared among objects with the same expected signal. This promotes the search for decaying DM to a direct detection experiment [233, 234]. An extensive program of search for a decaying DM signal has already been realized (led by EPFL group, M.Shaposhnikov, A.Boyarsky). XMM-Newton delivers the best searching capabilities for the weak extended signal of decaying DM [235]; Chandra, Suzaku and Integral have also been used. The best current results on the searches of signatures of warm and cold+warm DM models in cosmological data (including Lyman-α forest [236, 229]) were obtained by Swiss groups (Boyarsky, Lesgourgues, Riotto, Seljak).

Intended contribution of the project

WIMPS: The two ton-scale experiments (ArDM and XENON1T) will be in their commissioning and construction phases, respectively, starting in 2012. XENON1T will start commissioning in mid 2014, when the construction of the underground infrastructure, of the shield and veto, of the detector and cryostat as well as of the cryogenic infrastructure will have ended. The dark matter run is planned for 2015-2016.

To convincingly demonstrate the dark matter nature of a potential signal, and to determine WIMP properties such as its mass and scattering cross section, measurements of the interaction rate with multiple targets and much larger target masses are mandatory [237]. DARWIN [238] is an R&D and design study for a multi-ton scale LAr and LXe dark matter search facility, with the goal of probing the cross section region below 10^{-47}cm^2, and providing a high-statistics measurement of WIMP interactions in case of a positive detection by one of the aforementioned experiments. Approved by ASPERA [239] in late 2009, DARWIN coordinates the European groups active in the noble liquid dark matter search field, and runs under Swiss leadership (L. Baudis, project coordinator, A. Rubbia, WP4 leader). DARWIN thus uses techniques which have already been successfully proven in 10 kg to 100 kg prototypes, and which will be studied in ton-scale detectors in the very near future. In conjunction with other WIMP targets, with indirect searches and with the LHC, DARWIN should allow us to learn not only about the WIMP properties, but also about their density and velocity distribution in our local vicinity in the Milky Way. The DARWIN study has officially started in April 2010, and the Technical Design Study is expected to be delivered in 2013. The letter of intent and the proposal for the construction of the facility would be submitted by mid and late 2014, respectively, with the construction and commission phases scheduled for 2015-2016. The period of operation and physics data taking is foreseen for 2017-2020, i.e. during the second period of the NCCR Universe.

Super-WIMPs in high-energy astronomy: As the intrinsic width of the expected decay line is more narrow than the spectral resolution of XMM-Newton, to improve the bounds and advance into the theoretically interesting regions of particle physics models, one needs (i) to combine a large number of archival observations of objects where the strongest signal is expected and (ii) cross-correlate observations of DM-dominated objects (EPFL group). In particular, this will be done for the zCOSMOS (PI S. Lilly, ETHZ) deep field and X-ray diffuse flux measured by the XMM-COSMOS project. If a candidate line is found, deep ($\sim$1 Msec) observations of the most promising targets will allow to confirm its nature. Finally, at energies above 20 keV the SPI spectrometer of the INTEGRAL satellite delivers the required spectral resolution [240] (ISDC and EPFL groups).

To resolve the DM decay line one needs an instrument with improved spectral resolution. Two such instrument are planned for the nearest future. The first mission using the new technology (X-ray microcalorimeter) is Astro-H, scheduled for 2014 with an important ISDC contribution. Its observations (including galaxy clusters) will be useful for the combined analysis and a new strategy of search of a weak omni-present line should be developed [235] (EPFL group). Another instrument – LOFT, with contributions from ISCD and DPNC – with very good sensitivity for decaying DM due to its large collecting area and field-of-view was recently selected by ESA as one of the 4 space missions concepts of the Cosmic Vision program.

Super-WIMPs in Structure formation: By 2014 about $160,000$ quasar spectra will be provided by the successors of the SDSS survey, drastically improving the sensitivity of the Lyman-α forest method. Weak lensing is another promising tool to probe the imprints of primordial DM properties on structure formation, aiming to measure the matter power spectrum on even smaller scales with a few % precision. The Kilo-Degree Survey (KiDS) (starts 2011, PI: K. Kuijken, Leiden) should be completed by 2014. The Euclid mission will measure matter power spectrum over large range of scales, ultimately resolving the question of primordial velocities of DM particles.

To take advantage of their high precision, both methods require theoretical predictions at about percent accuracy. These predictions and subsequent data analysis of SDSS Ly-α, KiDS (with Leiden observatory) and Euclid data will be performed by the EPFL and UniZh groups.

The combination of astrophysical X-ray observations, cosmological data on structure formation (EPFL/UniZh), theoretical work on the physics of the early Universe (EPFL, UniGe, see sections on the Early Universe, baryogenesis, and cosmic magnetic fields) will give crucial input for the accelerator super-WIMP searches in "intensity frontier" experiments (e.g. predict the parameters of sterile neutrinos and allow to test experimentally neutrino minimal extension of the Standard Model).

Links to other projects of this NCCR

As described above, observations of LSS can contain information on dark matter, especially whether it might be warm or interacting with itself or with dark energy. This effect, however, should be disentangled from astrophysical feedbacks on matter power spectrum. All LSS projects (modeling, observations, uncertainties, see 4.2.3) are therefore related to the DM question.

Furthermore, there are suggestions that dark matter might be observable at LHC especially if it is a WIMP. Hence the SUSY searches at LHC are most relevant to Dark Matter. Finally, dark matter might have been generated with the baryon asymmetry in the early Universe, using the cosmic magnetic fields as messengers. This relates this sub-project to the projects Particles and Fields in the Early Universe 4.2.1 and to the Cosmic Magnetic Fields 4.1.10.

4.2.6 Project: Cosmic Microwave Background

Coordinators: J. Lesgourgues (CERN), A. Rassat (EPFL)

Research question and state of the art

Detailed observations of CMB anisotropies by COBE, WMAP and earth-based experiments provide one of the most robust and accurate ways to test the standard cosmological model, for a summary of present data see Fig. 2. Starting from January 2013, the Planck collaboration will periodically release new data of unprecedented precision, stimulating a feverish activity for extracting all cosmological information from the maps, challenging the ΛCDM paradigm, and testing its alternatives. Planck will represent the ultimate measurement of temperature anisotropies, but the quest for polarisation anisotropies will go on, in order to extract even more information on the early universe. A particularly exciting challenge will consist in finding the B-mode (or in better measuring its shape in case Planck provides a preliminary indication on its amplitude). Detecting B-mode polarisation would offer a unique opportunity to test the inflationary paradigm, to estimate the energy scale at which primordial fluctuations have been generated, and maybe to probe other mechanisms leading to gravitational wave production (reheating, phase transitions, topological defects). Polarisation anisotropies will be observed in patches of the sky by several ground-based experiments after Planck (EBEX, POLARBEAR, etc.) and the community tries to support a new space-based CMB mission.

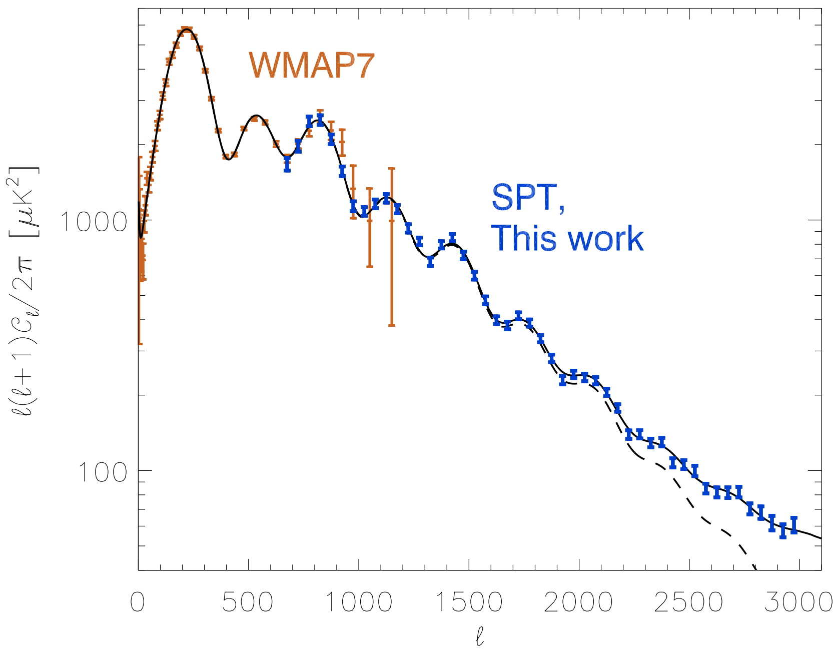

Figure 2: Present CMB anisotropy data from WMAP7 and the South Pole Telescope. Similar precision has been attained with the Atacama Cosmology Telescope. Figure from [241].

Several partners in this NCCR have worked on the foundations of cosmological perturbation theory and on CMB physics for the past twenty years. R. Durrer and U. Seljak have written several pioneering papers in the 1990's. More recently, many of us have used current CMB observations in combination with other datasets to constrain the parameters of the ΛCDM model, and several of its possible extensions. For instance, members of the NCCR have played a world-leading role in particular topics such as studying the impact of magnetic fields, topological defects and modified gravity (R. Durrer, M. Kunz), constraining inflation or primordial isocurvature modes (R. Durrer, A. Riotto, J. Lesgourgues), testing dark matter candidates and neutrino physics (R. Durrer, J. Lesgourgues). They have played a key role in theoretical developments for predicting or for measuring non-Gaussian statistics in CMB maps (A. Riotto, R. Durrer, M. Kunz), for calculating the effect of vector modes (R. Durrer), or for tackling with CMB lensing extraction techniques (U. Seljak, J. Lesgourgues). They have worked on cross-correlation methods of CMB and large-scale structure maps in order to measure the late Integrated Sachs Wolfe (ISW) effect as well as reconstruct ISW maps (A. Rassat, M. Kunz, J. Lesgourgues). They have developed crucial numerical tools for computing CMB anisotropies and derived quantitites, like the famous CMBFAST code (U. Seljak), or more recently the iComso package (A. Refregier, A. Rassat) or the CLASS code (J. Lesgourgues). They are involved in the on-going Planck experiment, and in studying the potential of CMB satellite proposals like CMBpol or CORE (M. Kunz, J. Lesgourgues, U. Seljak).

This shows that the NCCR gathers almost all types of expertise on CMB physics, ranging from data analysis up to the most involved theoretical developments. It puts the group in a very good position for making the best possible use of future CMB data.

Intended contribution of the project

For most topics listed above, rough constraints can be derived from current data, but most of the potential for discovery is contained in future Planck temperature maps, and in post-Planck polarisation maps. Hence, it will be fascinating to apply the methods discussed so far for testing with precision the physics of inflation, or the existence of mechanisms in the early universe generating non-gaussianity, isocurvature modes, vector modes, magnetic fields, topological defects or other CMB-contributing features. Such mechanisms are not necessary to explain current data, but if any of their signatures were observed, a new window would open on particle physics at ultra-high energy and in the far past.

CMB lensing extraction is a technique for probing clustering in the universe up to high redshift ($z = 1$ to 3), in complement to galaxy lensing experiments sensitive to smaller redshifts. This technique just started to be applicable with the South Pole Telescope data. Exciting improvements can be expected with Planck and other future observations, and the team is well positioned for performing such analyses. In order to understand the nature of dark energy (or to probe departures from Einstein gravity), it will be extremely useful in the future to use CMB priors when fitting Large Scale Structure (LSS) data from galaxy weak lensing, galaxy redshift surveys, etc. On top of that, by cross-correlating CMB maps and CMB lensing maps with LSS maps, one can obtain further information and eliminate some systematic uncertainties. The NCCR gathers experts on both the CMB and LSS sides, ready to push these techniques to their limits.

The CMB has little to say about neutrino masses, but encodes lots of information about the amount and the properties of relativistic species in the early universe. Current data show a marginal preference for extra relativistic species. If confirmed, this feature could be connected with particle physics (like recent anomalies in short-baseline neutrino oscillation experiments). The group incorporates experts on this topic, who will explore all indications from the data and possible interpretations.

Finally, CMB observations could provide major surprises like the need to depart from the standard Friedmann model. Current observations provide some (yet inconclusive) hints for large voids, a north-south asymmetry or low-multipole anomalies. By providing better statistics, independent systematic effects and a better understanding of foreground contamination, future data will shed a new light on these issues, and tell us whether they require some fundamental explanation. For a selection of relevant books and papers, see Refs. [242, 243, 244, 245, 246, 247, 248, 205, 249, 250, 251, 252].

Links to other projects of this NCCR

Up to date, the CMB is our most clean and precise dataset from cosmology. This makes it very relevant do all the cosmology related questions of this NCCR: the early Universe, cosmic magnetic fields, cosmic acceleration, tests of gravity, just to name some. To exemplify let us outline the connection to primordial magnetic fields. If magnetic fields are generated before recombination they affect the CMB in several different ways: Alfvén waves and magnetosonic waves modify the CMB anisotropy peak-structure, Faraday rotation induces B-polarization and the non-Gaussianity of the magnetic field energy momentum tensor leads to higher order correlations, e.g. a bi-spectrum. All these effects can be used to place limits on primordial magnetic fields, for a review see [180]. But even if one is not primarily interested in primordial magnetic fields, these effects have to be taken into account as a possible noise source when one is interested in other phenomena, which leave their traces in the CMB.

4.3 The Challenge of Particle Sources and Acceleration

Coordinating authors: Lenny Rivkin, Alain Blondel, Andrii Neronov

Research question and state of the art

Man-made Accelerators: The main accelerator R&D at CERN is directed towards:

- full exploitation of the LHC physics potential by insuring fast ramp up to the design parameters and high-luminosity and high-energy (HE-LHC) upgrades;
- a future multi-TeV e^+e^- Compact LInear Collider (CLIC). CERN intends to produce a Technical Design Report (TDR) and to demonstrate the feasibility of the CLIC technology by 2011 using the CTF3 test facility. The scientific case for CLIC, which can also operate as a sub-TeV machine, is strong and will be influenced by results from the LHC;
- exploratory studies in collaboration with other European labs to achieve higher gradients, involving plasma and laser acceleration;
- studies related to the high intensity frontier with the study of the Superconducting Proton Linac SPL and future neutrino facilities (superbeam, betabeam and neutrino factory in the framework of EUCARD and of the EUROnu and LAGUNA-LBNO design studies).

It is widely recognized that accelerator R&D at CERN is curtailed by the need to maintain and upgrade the running accelerators. A large collaboration with European institutions and universities is seen critical to ensure the future of the field.

Accelerator activities at PSI have extended outside of particle physics to the construction of the Swiss Light Source (SLS), the use of proton beams for the Neutron Spallation Source (SINQ) and the world?s first scanning gantry proton therapy facility. Under construction at PSI is the SwissFEL, a hard X-Ray Free Electron Laser based on a 6 GeV linear electron accelerator. As in the case of CERN, the needs of the new projects at PSI strain the PSI abilities to further develop and maintain the High Intensity Proton Accelerator – the base for the high precision experiments utilizing secondary beams of muons and neutrons. This reservoir of accelerator expertise at PSI is an extremely important resource. Collaboration already exists between the accelerator activities of PSI and CERN but this should be extended and made more visible.

Accelerator physics is a science in its own right and should be promoted in Universities. The decision by EPFL and PSI in 2001 to create a Chair in Accelerator Science was a very positive step, in view of the need to maintain excellence in accelerator design in Switzerland and at CERN. The proposed accelerator R&D will provide excellent additional research opportunities at master, doctoral and post-doctoral level. These in turn require additional supervisory capacity at EPFL.

Among the novel technologies for accelerators, neutrino factories using decays of muons in a storage ring to produce high unique energy electron-neutrino beams have been proposed. On a much longer time scale, mastering this technology would open the way to the realization of muon colliders allowing very high-energy point-like collisions to be achieved. Success of these machines depends on

- the ability to provide multi-MW proton drivers together with the corresponding targets that will have to be developed and optimized to withstand the extreme thermo-mechanical conditions. PSI carries out a research and development program on high power targets to optimize the performance of the muon and neutron sources presently under operation there. The world highest power 1.4 MW proton beam is a unique resource that enables PSI to contribute in this field.
- the ability to operate high gradient RF cavities in solenoidal magnetic fields, in particular for muon cooling. This is the object of the MICE experiment, proposed and led by researchers at University of Geneva and carried out at the Rutherford Appleton Laboratory in UK. This essential accelerator R&D requires high precision particle physics techniques for the measurement of the emittance reduction and could not have been performed without a strong involvement of experimental groups.

Cosmic Accelerators and Sources: Contrary to the man-made accelerators, operation of the cosmic particle accelerators responsible for production of cosmic rays is out of our control. We only have a possibility to obtain data from these accelerators in the form of different cosmic "messengers", high-energy particles which come from space. These messengers include charged cosmic rays with energies from below GeV up to 10^{20} eV, photons with energies from 10^{-6} eV (radio band) to 10 TeV (very-high-energy gamma-rays) and neutrinos with energies from MeV to EeV. These data could be used to understand the physical processes involved in particle acceleration and interactions in the nature-made cosmic accelerators. As a matter of fact, these cosmic accelerators operate in extreme physical environments, which could not be created in laboratory conditions on Earth, such as extremely strong gravitational and magnetic fields or extremely high matter densities. This opens a possibility to use the data provided by the nature-made accelerators to investigate the limits of applicability of the known fundamental physics laws in such unique physical environments. Cosmic scale laboratories are also our unique possibility to study physical phenomena which could not be assessed in the man-made laboratory conditions, like e.g. relativistic gravity effects: gravitational waves and black holes.

Almost 100 years after the discovery of cosmic rays, our understanding of their origin is completely unsatisfactory. We know that the bulk of the cosmic ray flux arriving at the Earth is composed of atomic nuclei with energies close to the mass of the proton and that the spectrum of cosmic rays extends as an almost perfect power law up to energies exceeding 10^{20} eV. However, we do not know what kind of astrophysical sources/phenomena is responsible for the cosmic ray production in any part of the energy spectrum. At low energies, the chemical composition and individual spectra of all the components are measured, including rare electrons, positrons and anti-protons. There are strong hints that the chemical composition changes with energy, but measurements at high energies prove to be extremely difficult and no firm conclusion can yet be driven. We don't have a clear explanation of the observed energy dependence of the composition of the cosmic ray flux. The recently launched AMS detector (with contributions from Geneva and ETHZ) will allow to measure the low energy part of the cosmic ray with unprecedented precision, also being sensitive enough to search for anisotropies and temporal variations in the flux and composition. At the highest energies, a suppression of the cosmic ray flux is observed, which might be due to the effect of pion production by proton cosmic rays with the CMB photons, or due to photo-disintegration of heavier nuclei in interactions with cosmic infrared background. Alternatively, the high-energy suppression might be just the limiting energy scale accessible to the nature-made particle accelerators.

Because the trajectories of charged particles are modified by the omnipresent magnetic fields (except eventually for ultra-high energy particles), locating the cosmic accelerators as origin of the cosmic rays must be done using electrically neutral particles, i.e high-energy gammas-rays or neutrinos. While neutrino-astronomy is still at its infancy, the high-energy gamma-ray astronomy is currently a very active and successful field of research. With ground-based dedicated high-energy telescopes like MAGIC (with important contribution from ETHZ), more than 140 galactic and extragalactic cosmic accelerators have been identified. The amount of sources is much larger than expected ten years ago, and contains several different classes like supernova remnants, pulsars and pulsar wind nebula, binary stellar systems in our Galaxy as well as far away starburst galaxies and active galactic nuclei powered by super-massive black holes. Understanding of physics behind the high-energy activity of these cosmic accelerators starts only now, with extended coordinated multi-wavelength observations including radio, optical, X-ray, gamma-ray and high-energy instruments.

The information on the physics of cosmic particle accelerators transferred by the gamma-ray messengers might be transformed or completely washed out on the way from the source to the telescope on the Earth due to interactions of gamma-rays with low energy photons, including starlight, infrared light and CMB. In this respect, the neutrino messengers provide a cleaner signal. Neutrino signal, if detected, could come from more compact sources and from high-energy sources at larger cosmological distances, enabling the study of cosmological evolution of high-energy activity of sources in the Universe.

On the other hand, the phenomenon of interaction of very-high-energy gamma-rays in the intergalactic space could be used to probe the properties of the intergalactic medium, which are otherwise difficult to assess. The main examples of such probes are the measurements of the total amount of light produced by all galaxies in the course of cosmological evolution and the probes of intergalactic magnetic fields. In this way, high-energy particles produced by nature-made particle accelerators serve as auxiliary tools in the conventional astronomical research.

Intended contribution to the NCCR

Man-made Accelerators: The NCCR Universe will closely collaborate with CERN and PSI in research and development of future accelerators. Depending on the nature and energy scale of new phenomena discovered at LHC, several types and specifications of a future high-energy accelerator project may be envisaged. Superconducting linear colliders or two-beam accelerators of the CLIC type may be appropriate, if an electron-positron collider is the right answer to the physics questions of the next generation. Other options include a possible electron-proton extension of the LHC. More unconventional approaches, such as plasma wake field accelerators or a muon collider, may also qualify as options for the future.

Design and construction of future machines is a decadal program. Therefore, R&D activities cannot wait until LHC results will narrow down the choice. Instead, it is necessary to pursue R&D studies for all viable options, with the aim to have sufficient information available when a decision is called for.

Long-term accelerator R&D is essential to realize neutrino beams of sufficient intensity to access the possible leptonic CP-violation effects, an essential step towards understanding the matter-antimatter asymmetry in the Universe. The R&D necessary for a neutrino factory has started since several years with the MICE experiments. Now, a full design study, EuroNU, is ongoing to study and compare cost and feasibility of super-beam, beta-beam and neutrino factory with support from the European Union. All possible options for high intensity neutrino beams require a very high-intensity proton source. Such a source would also benefit other aspects of CERN activities, from future luminosity upgrades at the LHC to nuclear physics and even material sciences. Subsequent intensity increases would require the development of many other new techniques to prepare, accelerate and store muons that subsequently decay into neutrinos. That work started already ten years ago and is continued with the effective participation of Swiss institutes. An assessment on the technical feasibility and on the costs of such facilities should emerge towards the end of the EuroNU design study around mid-2012

The most sensitive facility, the neutrino factory, depends critically on the feasibility of a novel accelerator technique, studied by the MICE experiment at RAL, in which Geneva plays a leading management role, and is constructing instrumentation. The experiment has already commissioned the beam and much of the infrastructure, and will be carrying out the first measurements of cooling starting in 2012. In 2014-2016 measurements including RF acceleration of muons will be performed thus demonstrating the feasibility of an operational cooling channel.

Cosmic Accelerators and Sources: The problem of the origin of cosmic rays can only be approached via understanding of physical processes in extreme environments, with the help of new tools in gamma-ray and neutrino astronomy, combined with more precise measurements of the cosmic-ray spectra, anisotropy, chemical and isotopic composition at different energies. The proposed NCCR will thus address the challenge of the origin of cosmic rays by creating and exploiting the potential of such a "multi-messenger" approach.

Measurements at rather low energies just have started with AMS, and analyzing these data will result in a wealth of new information about the cosmic rays. For higher energies, because of very low particle flux, satellites cannot be used. Instead one needs to include the earth atmosphere as part of the detector. The Cherenkov Telescope Array (CTA) will use the technique of imaging of the Cherenkov light produced by high-energy particle showers in the atmosphere to detect high-energy cosmic rays and gamma rays. CTA technique will be used to measure the chemical composition of cosmic rays via detection of Cherenkov emission from the primary cosmic ray particles at high altitudes. At still higher energies, JEM-EUSO space-based detector will image fluorescence emission exited along the tracks of the particle showers initiated by 10^{20} eV cosmic rays. These facilities will be used in the course of NCCR to obtain the best possible information on the spectrum, composition and anisotropy properties of the cosmic ray flux across all the energy range from GeV to 10^{20} eV.

The cosmic ray data will be complemented by the multiwavelength photon and neutrino data. With its tenfold higher sensitivity and improved angular resolution compared to current instruments like MAGIC, CTA will for the first time be able to scan the full sky looking for very-high-energy gamma-rays from cosmic accelerators. This will be especially important for the detection of extragalactic objects, since so far only targeted observations of few source classes were feasible. CTA will also be able to explore morphologies of extended Galactic sources, an extremely important contribution for understanding the acceleration and propagation of cosmic rays in the Galaxy. Strong expertise of the Swiss group in the field of high-energy astrophysics will be used to fully exploit the potential of CTA for the solution of the problem of the origin of cosmic rays and for understanding of the mechanisms of operation of cosmic particle accelerators. Swiss experimental astroparticle groups have joined forces to contribute to CTA in a visible way. The main contributions of the groups involved in the NCCR will be the development of a the focal surface instrumentation for the telescopes, based on a novel type of high quantum efficiency photosensors and on the set up of CTA Data Centre.

Construction of the first km^3 scale neutrino telescope IceCube at the South Pole has just been completed in 2011. Operation of IceCube will open, within several years, the new field of very-high-energy neutrino astronomy. In spite of extremely different detection techniques the sensitivity of IceCube for astronomical sources of high-energy neutrinos will match that of the existing space- and ground-based gamma-ray telescopes, although in a somewhat higher energy range. Detection of first astronomical high-energy neutrino sources with IceCube will most probably require information from gamma-ray telescopes which will indicate the locations of the best candidate neutrino sources. Work toward the discovery of first cosmic sources of high-energy neutrinos is foreseen in the framework of NCCR. The discovery of the neutrino emission will unambiguously locate the sources of Galactic and/or extragalactic cosmic rays.

Simultaneous observation of high energy sources with data from cosmic rays, photons and neutrinos in as large an energy range as feasible promises new insights of both astrophysical and particle physics phenomena. The major existing projects with Swiss participation, MAGIC, AMS and IceCube, in addition to scientific goals of their own right, provide a testing ground for the multi-messenger approach. In view of this, it is desirable to establish a multi-messenger data repository in Switzerland. In the mid-term future, major projects such as PEBS, CTA, JEM-EUSO, as well as large underground facilities, will have to include the multi-messenger aspect in their planning and provide wider access to their data.

Cosmic scale laboratories will be also used to explore the nature of relativistic gravity with two complementary probes. Strong, non-perturbative gravity effects will be probed via the study of environments of astrophysical black holes, using the tools of X-ray and gamma-ray astronomy. R&D and construction work for the LISA space-based gravitational wave detector will be aimed at the direct detection of gravitational waves from the merging stellar binary systems and the relic gravitational wave background from the Early Universe.

The research on cosmic accelerators and sources, performed in the course of NCCR, will be a good example of extension of techniques used in the man-made particle accelerators to astronomical and astroparticle research. The AMS-2 cosmic ray detector now installed at the International Space Station is, in fact, a scale-down version of conventional particle detectors used in collider experiments, like LHC. AMS-2 will provide the most precise measurements of the spectra and anisotropy properties of all components of the cosmic ray spectrum, thus constraining the nature of the cosmic particle accelerators. The high timing resolution observations of variable emission from stellar mass black holes in our Galaxy will be done using LOFT X-ray telescope, which will be a large (10 m^2 scale) silicon strip detector of the same type as used in the trackers of LHC experiments. The gamma-ray burst polarimeter POLAR constructed under the lead of Geneva University, will use scintillators+photomultipliers equipped with fast readout electronics similar to those used in most of the particle physics experiments. Measurements by POLAR will clarify the origin of gamma-ray bursts which accompany formation of black holes in the collapse of cores of massive stars at the end of their life. Similar fast nanosecond scale readout electronics typically used in collider experiments, will be used in the cameras of CTA and JEM-EUSO telescopes. Use of extremely fast electronics will allow reduction of the energy threshold of CTA telescopes which will increase the statistics of gamma-ray signal and enable a study of the nature of violent activity of supermassive black holes variable on the time scale of the light crossing time of black hole horizon.

4.3.1 Project: Hadron and Lepton Colliders

Coordinators: L. Rivkin (EPFL, PSI), T. Garvey (PSI)

Research question and state of the art

The European Strategy for Particle Physics, adopted by the CERN Council in 2006 recognized that in order to fully exploit the physics potential of the LHC "a subsequent major luminosity upgrade, motivated by physics results and operation experience, will be enabled by focused R&D". The first year of LHC operation exceeded the integrated luminosity goals of 1 fb^{-1} by a factor of five. It is planned to attain the ultimate luminosity by 2020 and to accumulate a total of 3000 fb^{-1} by 2030, collecting yearly 300 fb^{-1}.

Strong international R&D effort on the high luminosity LHC upgrade with significant contributions from Swiss universities, in particular from EPFL as part of the FP7 High Luminosity Large Hadron Collider Design Study, is on the way. The operational experience with the LHC has pointed out some promising directions towards increasing the integrated luminosity of LHC. These include luminosity leveling, new designs of the interaction region optics, flat beams collisions as well as a "crab-waist" scheme using additional sextupole magnets around the interaction point.

Pushing the energy and luminosity frontier beyond the LHC requires an advanced accelerator R&D for e^+e^- linear colliders. The CLIC two-beam high gradient acceleration scheme has the potential to extend the energy reach of linear colliders towards multi-TeV region. In the framework of the CLIC Collaboration EPFL and PSI are contributing to the development of high gradient X-Band RF accelerating structures. There is substantial interest in such development for the future light source projects and in particular for the SwissFEL project at PSI.

Intended contribution of the project

LHC High Luminosity Upgrade: The integrated luminosity of the LHC can be significantly increased by implementing the so-called luminosity leveling. It consists of maintaining the luminosity in the detector at a constant level by adjusting continuously the beam parameters in order to compensate for the decay of the beam current. One such method, utilizing relative transverse beam displacement, was successfully implemented at the LHCb experiment last year. Detailed analytical and simulation studies, verified by dedicated experiments will be performed as part of the luminosity upgrade to be implemented in all the LHC detectors.

Crab cavities are planned both for compensation of the crossing angle and for luminosity leveling, allowing for optimum integrated luminosity during the collision run without the need of excessive peak intensities.

Several promising ideas and their combination are under consideration for luminosity upgrade. The first is a large "Piwinski angle", $\phi = \theta_c\sigma_z/(2\sigma_x^*) > 1$, where θ_c represents the full crossing angle between the two colliding bunches, σ_z the rms bunch length, and σ_x^* the rms beam size at the collision point in the crossing plane. The second is flat-beam collisions ($\beta_x \neq \beta_y$), and the third a so-called "crab-waist" collision scheme, using suitable sextupole magnets. Such a crab-waist scheme has recently been successfully tested at the DAϕNE e^+e^- collider in Frascati. Flat beams and large Piwinski angle by themselves could boost the luminosity of the existing collider as built, but are also prerequisites for a crab-waist scheme that suppresses the non-linear betatron resonances and increases the beam-beam interaction limit, allowing for additional luminosity increase.

The new interaction region optics could offer a substantial luminosity increase. Among the options a flat-beam optics and flat-beam scenario will be explored, with a much reduced interaction-point ?-function in one plane. That increases subsequently the Piwinski angle, opening the possibility to implement a crab-waist collision scheme. Included will also be a study of options for correcting chromatic aberrations from the optics focal system near the experiments.

High gradient X-Band accelerating structures: The Compact Linear Collider (CLIC) project is an international collaborative effort led by, and centered at, CERN. The study aims at the realization of an e^+e^-

collider of 3 TeV in the c.o.m. The CLIC Test Facility-3 (CTF3) is a prototype accelerator complex which has been built by the collaboration to demonstrate that many of the key accelerator and technology challenges which would be required for CLIC can indeed be met. The EPFL has contributed to CTF3 through the participation of doctoral students in the CTF3 program.

The CLIC concept is based on the use of accelerating structures operating at an unusually high frequency and high accelerating gradient. The only existing "linear" collider to date was the Stanford Linear Collider (SLC). This machine operated with classical "S-band" (3 GHz) accelerating structures running at gradients of the order of 20 MV/m. If one wishes to construct a multi-TeV e^+e^- collider it is imperative to increase the gradient in order to limit the real-estate required for the machine. The achievement of such gradients requires, in turn, the use of higher frequencies with their corresponding increase in the k factor ($k = \omega R'/4Q$), a measure of the achievable accelerating field for a given level of radio-frequency (RF) input power. The use of higher frequencies also favors improved efficiency as the stored energy in the structure which is not extracted by the accelerated beam is dissipated as heat in the structure. Therefore, higher frequency structures, with their inherently reduced volume, are more efficient.

The CLIC project aims to operate with "X-band" (12 GHz) structures at a gradient of 100 MV/m. The development of such structures, appropriate for use in CLIC, is a considerable technical and scientific challenge. PSI and EPFL, supported by FORCE funding, are already contributing to such studies and would increase their participation through their contribution to NCCR Universe.

There are numerous difficulties with the development of an acceptable X-band structure for CLIC. Although the choice of higher frequency increases the k factor of the fundamental (accelerating) mode it also increases the strengths of the so-called "higher-order-modes" (HOMs) of the structure (eigen-modes). This in turn implies that the structure's transverse and longitudinal "wake-fields" will also be increased. These fields are generated by the passage of a bunch of charged particles through the structure and can be of sufficient strength, and persist sufficiently long, so as to have a detrimental effect on subsequent bunches traversing it. The design of the structure must, therefore, include features to reduce the strengths of the wake-fields if the collider is required to accelerate several bunches per RF pulse. This latter condition is necessary to meet the luminosity requirements of the collider.

An additional figure of merit for these structures is their "breakdown" rate. Even at these high frequencies the structures require input power levels of the order of 100 MW per meter of length to establish the high gradients. Consequently, there is a possibility of electrical breakdown during the passage of RF in the structure. Such breakdowns, which essentially occur in a random fashion, have to be monitored and inter-locked to prevent damage to the accelerator. If they were to occur too frequently then they could severely diminish the luminosity of the collider. The reduction in the initial breakdown rate of any RF structure is achieved through a process of "conditioning" in which the RF pulse amplitude and duration is gradually increased in a controlled manner while monitoring vacuum levels and reverse RF power from the structure (this is analogous to the "training" of super-conducting magnets, whereby their field levels are gradually increased to overcome quenches). However, although conditioning may resolve breakdown problems in any given structure, the time to condition may depend on the structure's geometric design and, if too long, could render the choice of geometry unacceptable (recent prototypes have needed several hundreds of hours of conditioning before achieving an acceptable breakdown rate).

Our intended contribution then is to perform studies that would result in a structure that would meet the conflicting requirements of a high accelerating gradient with low levels of wake-fields and low breakdown rates and at an acceptable production cost. The preferred approach to the reduction of wake-fields at present is to reduce their strengths by "damping" them with ohmically lossy ceramic material (such as silicon-carbide) built into the structure. Such material can be built into slots machined into the cell volume perpendicular to the structure's axis. The slot width is chosen to minimize any reduction in the shunt impedance of the accelerating mode while allowing the HOMs to propagate into the slot and to be damped by the ceramic. Wake-field simulations indicate that the quality factor, Q, (the number of oscillations required for one e-folding of the field) of such modes has to be reduced below ten. Care must be taken in the choice of damping material. Candidate materials are available from industry but their RF properties at high frequencies are, in general, not well known. It is important for the design of the structure to have accurate experimental determination of the frequency dependence of the loss tangent and dielectric constant of the materials at high frequencies.

Electromagnetic simulations show that dipole modes at frequencies as high as 40 GHz may be detrimental thus measurements are needed in this region. PSI and EPFL, in collaboration with CERN, are currently performing a survey of possible materials and measuring their properties. With the support of SNF funding PSI is currently working on the design of what would be the "base-line" CLIC accelerating structure. The inclusion of damping slots in the cell geometry breaks the cylindrical symmetry of the cell. Thus the design of a structure is a 3-D problem and complicated electromagnetic simulations are required to yield a structure at the correct frequency and to provide accurate field distributions of the fundamental and higher order modes. The presence of the damping slots inevitably has some effect on the impedance of the fundamental mode and it is important to minimize this.

It is important to experimentally verify the strengths of the wakes by performing tests with beams. As part of our contribution to this project we are working on the design of a “multi-purpose test structure” (MPTS). This structure would correspond to the design of the CLIC base-line but would be machined from aluminium (as opposed to high quality copper for the real structures). We propose to perform experiments in which the wakes are excited in a sequence of (six) structures by a “drive” bunch and the strengths of the wake is indicated by its effect on a trailing “witness” bunch. Such tests are not possible at CTF-3 however they could be performed at the Facility for Advanced Accelerator Experiment Tests (FACET) at SLAC. This facility uses part of the SLAC linac to provide beams for such tests. At the time of writing we have submitted a proposal requesting beam-time on FACET to perform this experiment in 2013. An alternative method of measuring the wake-fields would be to monitor their amplitude directly in “pick-ups” integrated within the damping slots of certain cells. Such wake-field monitors (WFM) could allow one to detect the beam position with respect to the structure axis and thus to center the beam through the structure (the wake-field amplitude for dipole modes is proportional to the transverse offset of the beam when passing through the structure).

An important question is: what is the effect of introducing damping slots on the breakdown rate? Tests of different prototype structures have been performed in recent years in the framework of a CERN/KEK/SLAC collaboration. To date, these tests have been performed on “stand alone” test stands (i.e. without beam) available at KEK and SLAC. They are performed at a frequency of 11.4 GHz due to the availability of the klystron amplifiers at these frequencies. Therefore the structures employed have had to be mechanically ?scaled? to match this frequency. Recently, SLAC have indicated that they will cease this activity and testing at KEK has been greatly reduced following events in Japan in 2011. Thus a new program of structure testing is one of the highest priorities of the CLIC collaboration for the coming years. Recently a consortium of three laboratories, CERN, PSI and Sincrotrone Trieste (ST), has financially supported the development at SLAC of a 50 MW klystron operating at 12 GHz. Four such klystrons have now been built and each laboratory will soon have the potential to test CLIC structures. Free Electron Lasers, such as those under construction at PSI and ST, employ X-band structures to manipulate (linearize) the longitudinal bunch distribution so that the bunches can be longitudinally compressed downstream in magnetic chicanes. This application represents an important synergy between the FELs and CLIC for both X-band structures and high power X-band RF sources.

Links to other projects of this NCCR

Our contributions to the NCCR would thus consist of an optimization of the design of an X-band structure for CLIC. The work would consist of several aspects: experimental determination of the RF properties of possible lossy ceramic materials for the HOM dampers; electromagnetic structure design taking into consideration the properties of the ceramic materials studied; realization of prototype structures for low power RF measurements of the frequencies and Q’s of the HOMs; numerical and experimental tests of the wake-fields generated in prototype structures employing test beams on FACET.

4.3.2 Project: High Intensity Beams at PSI

Coordinators: L. Rivkin (EPFL, PSI), M. Seidel (PSI), P.-R. Kettle (PSI)

Research question, state of the art and intended contribution of the project

Intensity limitations in cyclotrons: Cyclotrons are today the most cost effective and energy effective solution for generation of high intensity beams of protons up to 1 GeV. The 35 year old PSI cyclotron produces the highest intensity proton beam in the world and represents an ideal test bed for studying the fundamental intensity limitations in cyclotrons.

For operational reasons the extraction losses in a high intensity proton accelerator should be kept very low, typically at or below 100 W. High beam power e.g. on the order of 10 MW thus requires achieving 10 ppm relative losses. The present PSI accelerator has so far demonstrated losses below 100 ppm.

The loss is caused by beam tails, generated by beam dynamics effects such as space charge, coupling/beam mismatch and/or by unfavorable initial phase space at the source. Better understanding of tail generation mechanisms is necessary for further improvements of the PSI facility or extrapolation to other cyclotron designs.

The goal of this R&D is to understand the tail production mechanisms at PSI operating conditions via

- analytical studies;

- numerical tracking studies using High Power Computing;
- experimental studies and verification at the operating PSI cyclotron.

The results will be used to propose measures for further improvements (loss reduction) at the PSI High Intensity Proton Accelerator (HIPA). They will also be used to propose key aspects of a next generation very high power cyclotron facility.

High intensity muon beam line: The high-intensity frontier coupled with precision-type experiments is an excellent candidate for enabling the search for new physics beyond the Standard Model (SM). Specifically, the search for "rare" decays, which can manifest themselves in signatures hidden to the complementary direct searches at the energy frontier, are those suitable candidates, providing high enough beam intensities can be achieved.

The muon as a laboratory for this type of search is still the most sensitive tool within the frame-work of lepton decays and the study of flavor physics, see Section 4.1.9. Of the three "golden" lepton-flavour violating (LFV) channels, namely, $\mu \to e\gamma$, $\mu \to 3e$, $\mu N \to eN$, the first two, being coincidence experiments, are particularly suited to a DC machine structure such as that of the PSI ring cyclotron. This is due to the lower instantaneous rate, which reduces the accidental background, one of the main limitations of such experiments. Currently, the most sensitive limit to date on the LFV-decay $\mu \to e\gamma$, has been achieved using the world's most intense source of low-energy muons from the PSI PiE5-channel and associated MEG beam line. However, for the next generation of experiments, such as the planned $\mu \to 3e$ experiment at PSI or the $\mu N \to eN$ conversion experiments Mu2e at Fermilab and COMET and PRISM/PRIME at J-Parc, far more intense muon beams are required to reach sensitivities of 10^{-16} and beyond. This in turn requires the development of new high intensity muon sources and transport systems.

One new, yet simple idea of P.-R. Kettle, that of producing a high-intensity source of surface muons (muons obtained from stopped pion decay at the surface of a target) could be achieved by using a spallation neutron source, such as PSI's SINQ source as a production target. Initial muon flux estimates have been confirmed by use of realistic Monte-Carlo simulations and show that enhancement factors of two-to-three orders of magnitude might be possible compared to the current primary target situation. The enhancement is four-fold: the increased number of primary proton interactions, the increase in the pion production cross-section for backward production angles, the increase in the pion production cross-section due to the higher-Z material of such a spallation target and finally the enhancement due to the increased capture probability for higher-energy pions stopping in the spallation target window.

Furthermore, the utilization of part of the upward, incoming proton beam line, in the reverse direction to allow the extraction of the same charged-sign muons via the final proton beam dipole magnet, into an already present underground bunker, to be used as the front-part of the high-intensity surface muon beam line, would technically simplify such a solution.

The impetus for such a high-intensity source at PSI is also confirmed by the need for a multi-GHz muon beam for a phase II $\mu \to 3e$ experiment with a goal of achieving a sensitivity of 10^{-16}. The collaborative synergy between experimental partners and PSI towards the design and construction of such a muon beam line would help maintain the current world class muon beam facilities at PSI, also in the future, with muon intensities similar to the far more complex facilities at Fermilab and J-Parc.

Links to other projects of this NCCR

Proof of principle demonstration of extremely low losses in a High Intensity Proton Accelerator facility like the PSI cyclotron is an essential step towards the future facilities based on high intensity and brightness muon beams.

4.3.3 Project: Intense Neutrino Beams and Factories

Coordinators: A. Blondel (UniGe), A. Rubbia (ETHZ)

Research question and state of the art

Neutrino beams are essential for the study of neutrino oscillations, in particular for the search and measurement of CP violation and the determination of the neutrino mass hierarchy via matter effects. The observation of CP violation requires an appearance measurement, a disappearance $P(\nu_x \to \nu_x)$ being time reversal symmetric and thus insensitive to CP violation if CPT is conserved. Two types of beams can be considered.

i) the conventional neutrino beam where a high intensity proton beam impinging on a target produces hadrons which are focused and sign selected by means of magnetic horns into a decay tunnel. A muon neutrino beam from $\pi \rightarrow \mu\nu_\mu$ decays is produced with some contamination from other decays.

ii) the storage ring neutrino sources, where a beam of muons (in the case of the Neutrino Factory), or beta-decaying ions (in the case of the beta beam) are stored in a ring with long straight sections, in which the decay of the stored particles produce pure and well understood neutrino beams of well defined flavor content.

Conventional neutrino beams operate presently near maximum capacity, but offer still some possibility of optimization, especially once the neutrino mixing parameters are better known[120]. Feasibility and performance studies exist [118] and design studies are ongoing[121],[122] for the storage ring sources, as well as intensive R&D programs.

The present state-of-the-art conventional neutrino beams [253] are the NUMI beam at Fermilab , the CNGS beam at CERN and the T2K beam at J-PARC. The most relevant parameter for neutrino production is proton beam power on target. The other parameter to be optimized is the neutrino beam energy which must be adapted to the baseline L in such a way that the ratio L/E_ν is near the desired oscillation maximum, folded if necessary by the possible neutrino production thresholds in case of muon and mostly tau neutrinos. Roughly speaking, once the proton beam power is given, the number of events near oscillation maximum, and with it the sensitivity of the experiment, scales like neutrino cross-sections, linearly with neutrino beam energy.

The limitations in the performance of conventional beams are 1) the proton beam power available, 2) the resistance of the target to the beam impact and power 3) radiation issues limiting the primary beam power or the environmental radiation around the neutrino beam target, 4) the possibilities of flux control, which requires the presence of a near detector station.

In Japan [254], the T2K beam operates presently with a power of 150 kW, and will progressively increase to achieve the design value of 750 kW in the next 5 years. With significant improvements to the proton accelerator complex, a full beam power of 1.66 MW is hoped for eventually. The near detector of T2K is the magnetized ND280 detector composed of fine grain scintillator and TPC trackers. For the T2HK upgrade a new near detector station will be required, a Water Cherenkov or Liquid Argon detector situated at 2km from the neutrino target have been discussed.

At Fermilab, [255], the NUMI beam operates presently with a beam power of 320 kW, which will be upgraded to 750 kW for the NOvA experiment in 2014. For the DUSEL project a new beamline will be required, with a beam power initially foreseen of 750 kW, to be upgraded with the realization of the 2MW superconducting proton linac known as 'project X'. The NUMI near detectors are small scale replica of the far detectors, respectively of MINOS (magnetized iron + scintillator) and NOvA (totally active liquid scintillator tubes).

The CNGS beam line operates presently at 350 kW on average [256]. There is no near detector station and the beam is optimized at high energy for tau detection. Improvements in the SPS beam power and in the facility design should allow a beam power of about 750 kW to be sustainable. Within LAGUNA-LBNO, a design study is being carried out by CERN of a neutrino beam in the north area able to sustain up to 2 MW and optimized for a neutrino beam energy of 4.6 GeV, matching the first and second oscillation maxima on the CERN to Pyhasalmi 2300 km baseline. For the level or precision required a near detector station will be mandatory.

The CERN to Pyhasalmi baseline [257] has been considered since a long time a very suitable one for a Neutrino Factory [258], [259], in particular because of the very well known geological situation concerning matter effects [260]. The main advantages of the neutrino factory over conventional beams lies in the exquisite knowledge of the flux from muon decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ and charged conjugate by selecting the other muon charge. Muon decay is very well known and given a measurement of the muon beam intensity, energy and angular divergence, the flux can be predicted with a precision of better than 1%, for all four neutrino flavours of interest for both appearance and disappearance experiments. The detector is a rather conventional magnetized iron detector for the $\nu_e \rightarrow \nu_\mu$ 'wrong sign' muon detection, although there are benefits to use magnetized fine grain (e.g. liquid argon) detector for the other oscillation channels. The Neutrino factory is a challenging accelerator to build and relies of the development of technologies similar to those of muon colliders. A critical R&D experiment is the Muon Ionization Cooling Experiment (MICE) presently in progress at RAL(UK)[261].

Intended contribution of the project

The contributions to the project will be structured as follows:

- ETHZ: global design and optimization of SPS neutrino beam from the CERN North Area to Pyhasalmi (C2PY)

- UniBe, ETHZ, UniGe: physics studies for the far detector: Mass hierarchy, CP violation, sterile neutrino searches and tests of unitarity.

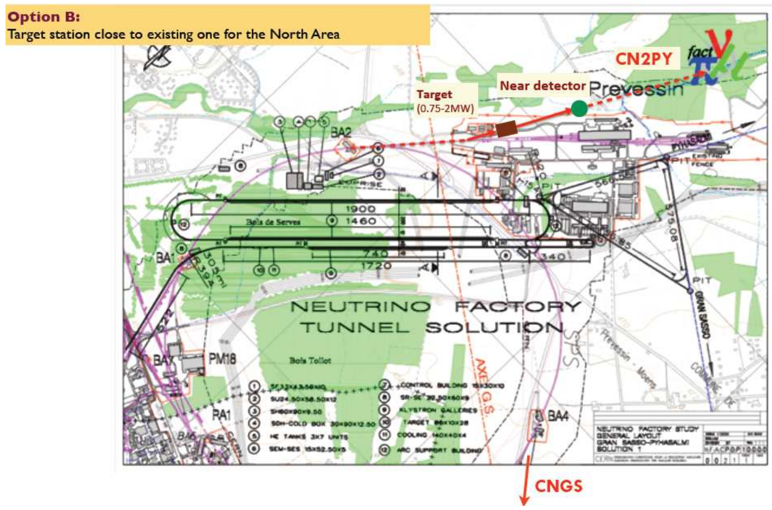

Figure 3: Possible scenario for development of beams at CERN [262][263]

- UniGe: design of near detector for C2PY, and evaluation of small scale muon storage ring for measurements of cross-sections.
- UniBe, ETHZ, UniGe: measurement of particle production off neutrino targets, evaluation of needs and possible improvements for future projects.
- All groups: submission of proposal by the end of LAGUNA LBNO design study in 2014
- UniGe: MICE experiment, completion in 2016; international design study of the neutrino factory (IDS-NF).

These experimental activities will be complemented by associated theoretical and phenomenological work with the theoretical groups at EPFL and UniBs.

Links to other projects of this NCCR

The neutrino beam project is, clearly, of great importance for the neutrino oscillation project. Well designed beams also have an impact on neutrino cross-section measurements and more generally the description of neutrino interactions in a wide range of energies, from the low energy in which the interplay of nuclear effects is not well understood, to high energies where kinematic threshold such as that of charm can be clarified. Hadro-production measurements are important input for the description of cosmic ray air showers. Through the deep underground far detector, the project has considerable synergy with other deep underground physics including proton decay searches, detection of supernovae and detection of atmospheric neutrinos.

The excellence in accelerator technologies related to neutrino beams is synergetic with other aspects of the NCCR: high intensity beam technology for neutrino production is synergetic, especially in the beam handling and high intensity target area, with the development of high intensity muon beams at PSI and uses similar technologies. The development of a new accelerator technique, muon ionization cooling, in the MICE experiment for the neutrino factory is clearly of great interest for a muon collider either aas a Higgs factory or a high energy frontier lepton collider.

The LAGUNA-LBNO and MICE collaborations extend broadly across the boundaries between the communities of accelerator and experimental physics, thus cultivating an essential connection. These projects will greatly benefit from the NCCR environment in which accelerator physics is very present, and, reciprocally, the challenges presented by high intensity neutrino beams will undoubtedly have a beneficial impact on the accelerator community.

These technological requirements place the development of high performance neutrino beams at the center of a network of synergies in particle physics and beyond. Provided these developments are supported at a sufficient level, will be very beneficial to the NCCR and will greatly benefit from it.

4.3.4 Project: Galactic Cosmic Rays

Coordinators: A. Biland (ETHZ), A. Neronov (UniGe)

Research question and state of the art.

Most of the Cosmic Rays (CR) in our galaxy have energies in the 0.1 to 10 GeV range. These CRs are produced by (unknown) cosmic scale particle accelerators in the Milky Way and are playing an important role in the physics and chemistry of the intergalactic medium (ISM). The CR flux in the 0.1 to 10 GeV range is affected by extinction in the Heliosphere, so that the locally measured CR spectrum is not identical to the galactic CR spectrum found in the ISM. Deflections of CRs by galactic magnetic fields preclude the possibility of localization and study of galactic CR particle accelerators. CRs diffuse through the ISM and spread only over distances less than about 1 kpc from their sources during the typical lifetime of 10^7 yr. This implies that the nearest CR accelerators are in our local "galactic backyard". Nearby Supernova Remnants (SNR) and Pulsar Wind Nebulae (PWN) are conjectured to be the main candidate CR acceleration sites. However, a direct proof of this conjecture is missing.

Localization of the CR sources and understanding of the physical phenomena involved in their acceleration becomes possible only now, due to the progress in the domains of γ-ray and neutrino astronomy. Observations by a new generation of space- and ground-based γ-ray telescopes Fermi, AGILE, HESS, MAGIC and VERITAS have revealed numerous sites of particle acceleration in the galaxy. The newly discovered VHE sources include several known astronomical source types, like shell-type SNRs, PWNe and binary systems with black holes or neutron stars. However, the nature of the largest part of galactic VHE sources is uncertain. These unidentified sources are the brightest and hardest spectrum sources in the galaxy. Their energy output is dominated by emission in the γ-ray band, as expected from the "hadronic" sources in which the γ-ray emission is produced by interactions of high-energy protons and nuclei. Clarification of the nature of these sources is key for finding the origin of galactic CRs.

Measurements of the properties of the CR flux at low energies are done with particle detectors mounted on balloons or spacecrafts. ETHZ and UniGE participate in the AMS-02 CR detector which was installed on board of the International Space Station in 2011. AMS-02 will provide precise information on the elemental composition, spectral characteristics and anisotropy of the CR flux penetrating into the Solar system, in the energy range up to 10 to 100 TeV. EPFL and ETHZ are involved in a next-generation balloon based CR detector PEBS optimized for the high-precision measurement of the electron/positron component of the CR flux.

The galactic CR spectrum is believed to extend up to the "knee" energy range at 10^{15} eV. In this energy range the Earth atmosphere is used as particle detector. CRs penetrating the atmosphere initiate Extensive Air Showers (EAS) which can be detected either with particle detectors on the ground of via imaging of Cherenkov light from EAS particles at high altitudes. The best available measurements of the spectrum and composition of the CR spectrum in the knee region are done using surface detectors, like KASKADE-Grande. Higher statistics measurements in the energy range above the knee will be done in the near future with a setup which combines the IceCube neutrino telescope with the IceTop surface array of km^2 collection area. Research groups from EPFL and UniGE participate in IceCube/IceTop experiments.

Measurements done by surface arrays suffer from uncertainties related to the uncertainties of the hadronic interaction models. Complementary measurements can be done via imaging of the Cherenkov light from EAS. This measurement technique will be used by CTA. The Cherenkov light imaging technique is sensitive to the chemical composition of the CR flux because the intensity of Cherenkov emission by the primary CR particle at the top of the atmosphere and the shape of the EAS image depends on the particle charge and mass. Swiss experimental astroparticle groups from EPFL, ETHZ, UniGE and UniZh have joined forces to contribute to CTA in a visible way. The main focus of activity of the Swiss groups is development of the focal surface instrumentation based on the novel type of high photon detection efficiency photosensors and the setup of the CTA Data Centre.

Intended contribution of the project.

Different approaches should be considered to solve the problem of the origin of CRs in different energy bands and for different components of the CR flux. The four projects described below will use different methods to find the origin of the bulk of the CR flux (0.1 GeV to TeV), of the CR electrons/positrons and of the Galactic CRs in the PeV energy band.

Origin of the bulk of Galactic CRs: Only a limited number of astronomical objects in our Galactic backyard could be considered as candidate CR acceleration sites. Discreteness of the CR source distribution should lead to appearance of distinct features in the spectrum and/or angular distribution of CR species. We will look for such features in the spectra and angular distribution of individual components of the CR spectrum (protons, nuclei electrons/positrons) using balloon (PEBS) and spacecrafts (AMS-02) based detectors. The CR spectrum and angular distribution in the 0.1 to 100 GeV range (and possibly up to the TeV band) are modified during CR propagation in the heliosphere. The AMS-02 high-statistics data on the spectra and time variability of the fluxes of different primary and secondary CR species will be used to study the heliospheric distortions of the CR flux. This should allow to deconvolve the spectral and anisotropy features due to the propagation in the heliosphere from the intrinsic features of the galactic CR spectrum. This will also lead to a better understanding of the structure of our Solar System, in particular, of the largely uncertain properties of matter and magnetic fields in the outer part of the heliosphere.

Measurement of CR distribution in the local galaxy: Measurement of the galactic CR spectrum not affected by the effect of Solar modulation can be done in an indirect way via the detection of γ-ray emission from interactions of galactic CRs with large mass concentrations, like Giant Molecular Clouds, or with diffuse local ISM. Such measurements are now possible with space- and ground-based γ-ray telescopes. Detailed study of γ-ray emission signal from the Milky Way and, in particular, from structures within 1kpc from the Solar System will provide information the shape of Galactic CR spectrum and possible variations of the CR density with the distance from the local CR source(s). Such a study can be done with space-based γ-ray detectors, Fermi and AMS-02, below several 100 GeV (probing the distribution of TeV CRs) and at higher energies, up to 100 TeV, with the ground-based γ-ray CTA, which will allow localisation of the local source(s) of PeV CRs.

Origin of CR electrons and positrons: Similarly to the low-energy CR nuclei, CR electrons and positrons cannot travel far away from their sources. Compared to nuclei, electrons and positrons suffer from strong energy losses by inverse Compton and synchrotron emission. These losses prevent electrons positrons with energies above $\sim$TeV from escaping to distances larger than several hundreds of parsecs. Strong energy losses of electrons/positrons are expected to introduce a sharp high-energy cut-off in the CR electron/positron spectrum. Detection of such a cut-off, which will be possible with AMS-02, will provide a measurement of the distance to the nearest cosmic source of high-energy electrons/positrons. A measurement of the anisotropy of the electron/positron flux with AMS-02 will possibly provide a hint on the location of this source on the sky. Recent measurements of the positron spectrum by the PAMELA detector reveal an "anomaly" in the positron flux above $\sim$ 10 GeV. The existence of this anomaly will be clarified with AMS-02, which will provide the measurements of the positron flux to much higher energies and with better precision. If real, the peculiarity of the positron spectrum provides an important clue on the physical processes in the nearby electron/positron cosmic particle accelerator. Complementary information on the local source of electrons/positrons will be obtained with CTA, which will detect γ-ray emission accompanying acceleration/production of electrons in the source and propagation of electrons in the ISM.

Origin of the "knee" of the CR spectrum: It is not clear if our galaxy hosts particle accelerators powerful enough to accelerate protons and heavy nuclei up to the knee energy (10^{15} eV) and beyond. The origin of the knee is equally uncertain. It might be related to a high-energy cut-off in the galactic component of the CR spectrum, or to a change in regime of propagation/escape of CRs through the galaxy. We will use the high-statistics measurement of the CR spectrum, composition and anisotropy at and beyond the knee with IceCube/IceTop and CTA, to clarify the origin of the origin of the knee. This will be done via a measurement of the changes of composition of the CR flux as a function of energy. Complementary measurements will be done in the γ-ray and neutrino channels with the high-energy part of the CTA and IceCube: systematic (non)observation of high-energy cut-offs in the spectra of Galactic γ-ray and neutrino sources in the 100 TeV band will tell if the knee feature corresponds to the limiting energy attainable in particle accelerators in the Milky Way.

Links to other projects of this NCCR

Transversal links are established with numerous projects, most notably with the project 4.3.6, which will adress the problem of the origin of CRs using the methods of γ-ray and neutrino astronomy. Similar nature of the problems of the origin of Galactic and extragalactic CRs implies a tight connection of this project to the project 4.3.5. CR propagation is influenced by cosmic magnetic fields (project 4.1.10). Study of the peculiarities on the spectra and angular distribution of CRs might reveal the products of decay/annihilation of DM (project 4.2.5).

4.3.5 Project: Ultra-High Energy Cosmic Rays

Coordinators: A. Neronov (UniGe)

Research question and state of the art.

Maximal energies of CRs reach $\sim 10^{20}$ eV (seven order of magnitude higher than the particle energies reached at LHC). It is not clear at present what physical processes make acceleration to ultra-high energy (UHE) possible. The sources of ultra-high-energy CRs (UHECR) are not known. Energetic considerations suggest several candidate UHECR source classes: supermassive black holes, jets or radio lobes of radio galaxies (a special type of AGN), γ-ray bursts (GRBs) or galaxy clusters.

Similarly to the lower energy CRs, the main obstacle for identification of the sources of UHECR is the intergalactic (IGMF) and galactic (GMF) magnetic field. The effect of the GMF on the spectrum and anisotropy of UHECRs is reasonably small (100 EeV protons are typically deflected by just 1 to 3 degrees). This opens the possibility to identify UHECR sources via back-tracing of the arrival directions of the individual UHECR events. It is not clear if the UHECR could simply stream freely through the intergalactic space, or they diffuse through the IGMF. If the IGMF strength is close the upper bound (~ 1 nG) known from radio observations, the CR gyroradii reach values comparable to distances of nearest extragalactic CR sources (e.g. the closest radio galaxies) only for energies above 10^{20} eV. Deflections by GMF and IGMF are further increased if UHECR are heavy atomic nuclei, rather than protons. In this case identification of UHECR sources should be possible not via direct back-tracing of UHECR events, but via a study of energy- and charge-dependent deflection patterns of UHECR distribution around individual sources. Such a study requires high statistics of events above 10^{20} eV.

The UHECR flux is suppressed above 10^{20} eV. It is not clear if the suppression is due to the effect of propagation of UHECR through the IGM (interactions with CMB and/or with extragalactic background light) or it is due to a high-energy cut-off in the source spectra, i.e. due to the limitations of the particle accelerators. Higher statistics of UHECR events is needed to distinguish between the two possibilities.

The statistics of UHECR events is limited by the effective area of UHECR detectors (1 UHECR hits an area 100 km^2 every 100 yr). Largest effective areas are reached by the currently operating UHECR detection facilities: Pierre Auger Observatory (PAO) and Telescope Array (TA). Both experiments use a combination of surface particle detectors (water tanks in PAO, scintillators in TA) on the ground with the air fluorescence telescopes detecting UV emission from excited air molecules along the path of UHECR induced extensive air shower (EAS) in the atmosphere. An increase of effective collection area will be achieved with JEM-EUSO, a downward-looking fluorescence telescope which will be installed at the International Space Station (ISS) in 2017. Swiss institutions UniGE and CSEM are involved in JEM-EUSO.

The nature of the high-energy suppression of UHECR spectra could be clarified via the search for UHE neutrinos (UHEν). EPFL and UniGE participate in the IceCube neutrino telescope which has a sufficient sensitivity for the detection of the neutrino signal from UHECR protons interacting with the CMB with a multi-year exposure. Measurement of UHEν flux with IceCube will provide information on the cosmological evolution of UHECR sources. A complementary measurement of the neutrino flux will be done with JEM-EUSO. JEM-EUSO measurements will provide information on the maximal energies to which CRs are accelerated in Nature.

Intended contribution of the project.

The identification of UHECR sources requires a higher UHECR statistics, the understanding of the nature of the high-energy suppression of UHECR flux and the knowledge of the GMF and IGMF. These are the main subjects of research in the sub-projects described below.

High-statistics measurements of UHECR flux: JEM-EUSO will observe UHECR events across a 400 km radius region below the ISS, providing an effective collection area > 100 times larger than that of PAO above 10^{20} eV. An important advantage of JEM-EUSO, compared to the existing experiments, will be the all-sky coverage. This will be important for the analysis of large angular scale patterns of the UHECR distribution, if a significant fraction of UHECR are heavy nuclei or if the IGMF is close to the known upper bounds.

JEM-EUSO will use the Earth's atmosphere as an UHECR detector. Detailed knowledge of this detector is required for the proper interpretation of the fluorescence signal from UHECR induced air showers. We will develop a system of monitoring of the atmosphere below the ISS, which will include the necessary information on the presence and UV transmission and scattering properties of clouds and aerosol layers in the JEM-EUSO field of view. This information will be crucial for the success of the JEM-EUSO mission: some 70% of UHECR events will occur in cloudy sky conditions. We will study the development of UHECR air showers in the cloudy sky with the goal to provide a JEM-EUSO data analysis framework, which will correct the UHECR data for atmospheric effects and allow to retain most of the events taken with cloudy conditions for further analysis. The possibility to retain the events occurring in the cloudy sky arises because JEM-EUSO will observe the UHECR induced air showers from above. A significant part of the fluorescence signal is typically produced above the low-altitude clouds in the troposphere. This signal is obscured by clouds for the ground-based fluorescence telescopes, but will be visible for JEM-EUSO.

After the launch of JEM-EUSO, we will analyze anisotropies of the all-sky UHECR data set to search for the individual sources. If UHECR particles are mostly protons, the sources will appear as excesses on the scale of the angular resolution of JEM-EUSO telescope ($\sim 1^\circ$). If a significant fraction of UHECR is heavy nuclei, more complicated energy-dependent angular patterns of the UHECR distribution around sources are expected, because of the stronger deflections of heavy nuclei by magnetic fields. In this case, sources could be identified via a search of energy-dependent template angular distributions of UHECR around the sources, determined by the structure of the galactic magnetic field and by the IGMF.

Galactic and intergalactic magnetic fields: Precise knowledge of the GMF is necessary for a proper understanding of the angular distribution of UHECR events around their sources. We will use the data of new radio telescope survey facilities, LOFAR and (in the near future) SKA to obtain a precise three-dimensional model of the GMF. This model will be available via measurements of Faraday rotation and dispersion measures of polarized radio emission from a large number of pulsars in the Galaxy. Based on the model(s) of GMF, we will calculate the angular distributions of UHECR events around their sources, as a function of the source position.

Contrary to the GMF, no precise information on IGMF will be available form radio observations. Instead, UHECR data will be used to measure or to impose constraints on the IGMF strength and correlation length. Absence of IGMF induced distortions of the angular distribution of UHECR events around the sources will impose a limit on IGMF strength at the level of $\sim 10^{-11}$ G, two orders of magnitude better than the known limits from radio observations. If the IGMF strength is in the range $10^{-11} - 10^{-9}$ G, deviations of the angular distributions from those produced by the GMF will be found in JEM-EUSO data set. Measurement of the deviations will provide a measurement of IGMF strength. Still weaker IGMF will be probed by observations of UHECR induced cascades in the IGM using γ-ray telescopes, in particular, CTA. UHECR and γ-ray measurements will be used together to constrain the nature of the recently discovered IGMF.

Ultra-high-energy neutrinos are produced by UHECR interactions in the intergalactic medium. Contrary to UHECR themselves and to γ-rays, which are also produced in the same interactions, neutrinos are not absorbed during propagation through the intergalactic medium. Neutrinos produced by UHECR injected by sources at cosmological distances could be detected, thus providing information on the cosmological evolution of UHECR sources and on the maximal energies attainable in particle accelerators in the Universe.

We will search for the UHEν signal from UHECR interactions (both inside UHECR sources and in the IGM) using the IceCube neutrino and JEM-EUSO fluorescence telescope. The two telescopes are sensitive to the neutrino flux in adjacent energy bands, from 10^{17} eV up to 10^{20} eV. Similarly to UHECR, UHEν initiate particle cascades in the atmosphere. UHEν air showers can be readily distinguished from UHECR showers, based on the depth of the first interaction. The first interaction point of UHEν could well be not in the atmosphere, but in the ice layer surrounding the IceCube detector. If the UHEν flux will not be detected by IceCube and JEM-EUSO, this will imply that significant part of the observed UHECR flux consists of heavy nuclei, rather than protons, information important for the search of UHECR sources via backtracking of UHECR events.

Complementary information on the interactions of UHECR in the IGM will be obtained from the γ-ray data, in particular, from the measurement of diffuse extragalactic γ-ray background above 100 GeV by CTA and Fermi. UHECR interactions induce electromagnetic cascades in the IGM with most of the released energy finally emitted in the 100 GeV band. The total flux of the 100 GeV γ-rays from UHECR interactions is comparable to the flux of UHEν, so that constraints on the UHECR cascade contribution to the extragalactic γ-ray background in the 100 GeV range can be used to constrain the expected UHEν flux and vise versa.

Links to other projects of this NCCR

This project is tightly related to the project 4.3.4 which will concentrate on the search for the sources of lower energy CRs. The multi-messenger approach to the source identification (via CR, γ-ray and neutrino channels) will be also in the focus of the project 4.3.6. Nuclei of active galaxies, powered by supermassive black holes are possible sites of UHECR acceleration and will be a subject of study in the project 4.3.7. Proper interpretation of the data of UHECR detectors requires knowledge of and provides constraints on the proton interaction cross-section at the highest energies above 10 TeV, an information which is obtained from particle colliders, in particular LHC, which is in the focus of the first Challenge 4.1.

4.3.6 Project: Cosmic Sources in a Multi-Messenger Strategy

Coordinators: T. Montaruli (UniGe), A.Neronov (UniGe), M. Ribordy (EPFL), A. Biland(ETHZ)

Research question and state of the art.

This project concerns the understanding of the highest energy phenomena in the Universe and of the nature of extragalactic and galactic sources of high energy particles through the combination of information from photon, neutrino and cosmic ray (CR) experiments. Currently, our knowledge of these sources comes from the observation of photons from the optical, radio, X-ray and γ-ray regions. Most of the observed photon signals are compatible with emission from high-energy electrons. Nonetheless, solid evidence exists that a part of the power of these sources goes into proton and nuclei acceleration, since we observe CRs from GeV to extreme energies above 100 EeV. It is not evident at today what are the sites of such acceleration, the mechanisms of conversion of such power into matter acceleration and its efficiency. Understanding of the mechanism of operation of sources of high-energy particles is the main goal of high-energy γ-ray, neutrino and CR facilities.

Switzerland is involved in the main existing facilities: the IceCube neutrino telescope operating above 100 GeV (EPFL and UniGe), the space-based soft γ-ray telescope INTEGRAL in the sub-MeV energy range (UniGe), the ground-based γ-ray telescope MAGIC operating above 50 GeV (ETHZ). The ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) use fast cameras to image the Cherenkov light from air showers and detect γ-rays from cosmic sources. A new generation facility for ground-based γ-ray astronomy, the Cherenkov Telescope Array (CTA), is now in design phase and switching to construction phase. The array, a mixture of small, middle and large-size telescopes, will improve the sensitivity of the current generation of telescopes by about a factor of 15. Moreover, it will extend the energy reach down to about 20 GeV, to overlap with Fermi, and it will cover the still unexplored region of up to 100 TeV where hadronic acceleration may become evident. New technology based on Geiger-mode Avalanche PhotoDiodes (G-APDs) has been successfully employed by the prototype telescope FACT. This is the first working proof of this high photon detection efficiency technique in γ-astronomy. The G-APD camera of FACT was developed by ETHZ with participation of EPFL. EPFL and UniGe are involved in the IceCube neutrino telescope which uses the Antarctic ice to measure the Cherenkov light from muons and showers produced by high-energy neutrinos. It is the first cubic kilometer neutrino telescope with more than 6000 large photocathode area PMTs. It will unequivocally prove hadronic acceleration in sources by observing neutrinos produced by high-energy protons interacting with matter or ambient photons in cosmic sources. A LoI to the US National Science Foundation, to which UniGe and EPFL participate, exists to extend its reach to lower energies with a denser core of PMTs. UniGe is also developing a γ-ray polarimeter POLAR to measure polarization of prompt emission from γ-ray bursts (GRBs). POLAR is scheduled for launch in 2014 on the Chinese Space Station TianGong 2.

Intended contribution of the project.

We define 4 projects dedicated to the search and identification of sources of extragalactic and Galactic CRs among Active Galactic Nuclei (AGNs), GRBs and supernova (SN) related phenomena. These main candidate sources are well defined based on energetic considerations. The observed power in the spectrum of UHECRs is compatible with the energy density of observed populations of GRBs and AGNs. Similarly, below the knee of the CR spectrum at 10^{15} eV, SN related phenomena (supernova remnants and pulsar wind nebulae) are considered as the main galactic CR candidate sources.

Jets and supermassive black holes in AGNs: This project aims to understand particle acceleration during the flaring activity of AGNs on time scales from minutes to days. The goal is to understand what causes such impressive episodes during which observed fluxes may rise by up to a factor of 10 to 100. The leptonic models of the broad band spectrum of radio galaxies and blazars assume that gamma-rays are produced by Inverse Compton scattering by high-energy electrons that also produce the synchrotron emission at lower energies. Hadronic models assume that the highest energy photons are produced by interactions of high-energy protons in the jets. Flares can unravel such hadronic phenomena because the time tag helps rejecting the atmospheric backgrounds. Particularly interesting are orphan flares in the TeV band not accompanied by X-ray flares. Orphan flares are very promising in the hunt for the first extragalactic neutrino source, because they are not naturally explained by leptonic models.

We aim at establishing an online search for AGN flares using IceCube data and light curves from Fermi and other experiments. These can be used to establish the long-term behavior of sources while indicating the relative importance of flaring states. Ground-based γ-ray telescopes provide the high energy picture that better correlates with neutrinos detectable by IceCube. This program will profit of the long-term monitoring with the FACT telescope and later with CTA. CTA will be able to provide a wide energy range measurement and high precision spectra. The highest sensitivity of CTA will also enable to study the origin of the minutescale variable emission from blazars. This is interesting to determine if such emission is produced by a small accelerating region at the base of the jet or by intrinsic small scale instabilities at large distances from the black hole. Since neutrinos are not absorbed during their propagation from and inside sources, their observation will provide information on cosmological evolution of AGNs, on the maximum energy achievable in sources and on the nature of accelerated hadronic components.

Gamma-ray bursts: The duration of GRBs indicates that they are produced by two different populations of sources. It is believed that short bursts ($\leq$ 1s) are produced by binary mergers and long bursts ($\sim$ 1 to 1000 s) by core-collapse of massive stars. These hypotheses are yet not fully verified. Equally uncertain is the mechanism of broad band emission from GRBs. The goal of this task is to clarify the origin of the GRB phenomenon and investigate particle acceleration in GRBs and its possible relevance to the problem of the origin of CRs.

The "prompt" emission component in the MeV range could be synchrotron or inverse Compton emission from non-thermal electrons or could be thermal emission form the GRB "fireball". A strong constraint on the mechanism of production of the MeV prompt emission will be imposed by the polarization measurement of the prompt emission signal by POLAR. Observations by Fermi have revealed the existence of an additional power law component of the prompt GRB emission reaching up to 30 GeV. The origin of this component will be clarified through the measurement of the spectrum at higher energy and with high statistics, which will provide information on the energy distribution of particles responsible for the emission. This could be possible with CTA with faster pointing, lower energy reach and large number of telescopes. Most of the observed electromagnetic emission from GRBs is produced by high-energy electrons. The role of hadrons in GRB phenomena, and hence possible significance of GRBs as CR sources, is assessed via IceCube observations. Its stringent limits exclude the possibility that GRBs are the dominant sources of UHECRs or that hadrons are efficiently accelerated in fireballs. We will conduct a continuos monitoring of neutrino emissions in coincidence with registered bursts by Fermi, SWIFT, INTEGRAL and other GRB detectors.

Galactic cosmic ray sources: CRs with energies above TeV, which were recently (over the last 30 kyr) produced by sources, fill regions of $\sim$ 100 pc around them. Interactions of CRs with the interstellar medium in such extended regions lead to detectable γ-ray and neutrino emission. We will search for degree-scale extended γ-ray and neutrino sources in the Galactic Plane using CTA and IceCube. We will test the hypothesis that the extended CR regions are the bright unidentified Galactic sources revealed by the H.E.S.S. Galactic Plane survey and find the points of recent injections of CRs in the Galaxy. Studies of these extended sources will be done using CTA, up to the γ-ray energies of $\sim$ 100 TeV, which correspond to the CR energies in the PeV range. Having precise information on the source spectra and morphology, we will optimize the IceCube analysis for the search of this potentially extended neutrino signal, to verify the CR interaction origin of emission. IceCube, when using upgoing neutrinos, is exposed to part of the galactic plane containing important regions such as Cygnus where PeVatrons have been observed by gamma extensive air shower array such as Milagro.

Supernovae: The end of a star life is one of the richest physics laboratories, as illustrated by the high redshift type Ia SNe in the context of cosmic acceleration and by neutrinos from the SN1987A. Core collapse SNe emit the gravitational energy of the collapsing star almost entirely in neutrinos. The few neutrino events observed from SN1987A contained information on the mechanism of gravitational collapse, on neutrino mass and unitary matrix and led to strong constraints on some of Nature's fundamental symmetries. IceCube will have unprecedented statistics of inverse beta-decay events induced by supernova electron anti-neutrinos. It will reconstruct the neutrino lightcurve and determine the onset of neutrino emission with time precision of ms. IceCube will produce an alert at the level of 3-10 sigma (pre-trial) for a SN in the Large Magellanic Cloud and at more than 25 sigma for a SN in the Galaxy that would be distributed to an alert network of detectors called SNEWS. The coincident observation between detectors would be unequivocally evidence for SN collapse neutrinos. This alert can then be distributed to other telescopes. UniGe and EPFL will participate to this SN monitoring with IceCube. The detection of coincident hits in phototubes of the existing and proposed IceCube cores, will allow the identification of single neutrino events in a galactic SN burst. The combination of the time and energy measurement will provide precise information on the nature of the collapse phenomenon.

Links to other projects of this NCCR

This project is focused on the search of the soruces and understanding of the mechanisms of acceleration of CRs using methods complementary to those pursued in the projects 4.3.4 and 4.3.5. Neutron stars and black holes, which are powering GRBs and AGN, are objects governed by relativistic gravity studied in the project 4.3.7. Supernova phenomenon is in the focus of the project 4.3.8.

4.3.7 Project: Relativistic Gravity

Coordinators: S. Paltani (UniGe), Ph. Jetzer (UniZh)

Research question and state of the art

Three out of four known fundamental interactions can be studied at particle colliders (electromagnetic, weak and strong). Gravitational interaction is not directly accessible in collider experiments. Instead, the main tool for the study of the nature of relativistic gravity (RG) is astronomical observations. Our knowledge of RG is constrained to the weak field and/or mildly relativistic regime, in which the effects of RG appear as corrections to Newton's theory of gravitation. Existing observational data in this regime are consistent with predictions of General Relativity (GR), which is considered as the main candidate for the correct RG theory. GR has not yet been tested in all situations, in particular at very large, cosmological, scales and in the strong field, non-perturbative, regime. Testing the GR in the strong field regime is of the highest importance, since possible deviations of the true RG theory from GR might be related to the Dark Matter and Dark Energy problems.

GR makes very particular predictions on the structure of space time near strongly gravitating systems, such as black holes (BH) or neutron stars (NS). Tests of GR can potentially be done using observations of astrophysical phenomena related to supermassive BHs in the nuclei of galaxies and smaller mass BHs and NSs in stellar systems. Another clear prediction of GR is on the properties of gravitational waves. Search and detection of gravitational waves expected from various types of astronomical phenomena, from binary stellar systems to the Early Universe, will be a strong test of GR and/or any alternative RG theory.

Switzerland is involved (ETHZ and UniZH) in the construction of the LISA-Pathfinder satellite, scheduled for launch in 2014, with the aim to test the technical feasibility of the LISA mission. LISA will be a space-based gravitational wave detector which will use measurements of gravitational wave induced variations of distance between several satellites to detect low frequency gravitational waves in the frequency range 0.1-100 mHz. At present, LISA is under study as an ESA only mission of the L-class.

The 0.1-100 mHz gravitational waves from massive BHs merging at cosmological distances will produce a very clean gravitational wave signal, measurable with high precision with LISA. Alternative RG theories influence the dynamics of such mergers and hence LISA is expected either to directly see the imprints of certain alternative theories or to put severe constraints on them. Apart from the gravitational waves from the merging systems LISA will be able to detect or put strong constraints on the primordial gravitational radiation, which is, just as the cosmic microwave background, a leftover from the Big Bang.

Switzerland (UniGE) is also involved in research on astrophysical BHs and NSs. Activity of astrophysical BHs and NSs induces a range of thermal and non-thermal phenomena and is accompanied by high-energy particle acceleration followed by electromagnetic emission from radio to γ-ray band. Release of the gravitational energy of matter falling into BHs results in heating of the matter up to the keV energies. Observations in the X-ray band provide diagnostics of phenomena in the strong gravitational field near the BH horizon. The focus of activity at ISDC (UniGE) is observations of BH and NS systems in X-rays and γ-rays with existing telescopes (INTEGRAL, XMM-Newton, Fermi and others) and development of next generation instrumentation for the X-ray and γ-ray astronomy (Astro-H, LOFT, POLAR, CTA).

In the stellar mass BHs and NSs the geometrical time scales (light-crossing time of the BH horizon, period of rotation around the innermost stable circular orbit, ISCO) are shorter than 0.01 s, meaning that the GR effects predominantly appear through flux variations on frequencies $> 100\,\mathrm{Hz}$ in the Fourier space. In this frequency range, high-frequency quasi-periodic oscillations (QPOs), have been discovered by RXTE X-ray timing mission. Physics behind these high-frequency QPOs is governed by the RG effects. Several models have been invoked to explain the QPOs, like epicyclic frequencies with a damping mechanism, relativistic precession or resonance(s). A massive step toward understanding of the nature of the high-frequency QPOs will be done with the LOFT, an ESA Cosmic Vision Medium-class candidate mission. UniGE is co-leading this project currently in Assessment Phase, together with SRON, the Dutch space agency, and is actively contributing to the development of silicon-based X-ray sensors that can be deployed over large areas ($> 10\,\mathrm{m}^2$).

Astrophysical BHs generate relativistic jets spreading high-energy particles over very large (megaparsec-scale) distances. The mechanism of generation of the jets and the origin of high-energy particles are not clear. Problem of the origin of jets and mechanism(s) of particle acceleration will be the central research subject of CTA, the next-generation γ-ray telescope in the 10 GeV – 100 TeV energy band. Switzerland (EPFL, ETHZ, UniGE) is involved in the development of the CTA components, in particular of the cameras based on the high photon detection efficiency photodetectors (GAPDs) and in the set-up to the CTA Data Centre.

Intended contribution of the project

LISA and LOFT missions are planned to be launched after 2020, so that the real data will be available at best toward the end of the NCCR project. Main efforts within NCCR will be devoted to the preparation of the missions and to research on the physics related to LISA and LOFT. CTA will start operation within several years. The CTA-related part of the project will concentrate on the analysis of fast-variable γ-ray emission from AGN and its implications of the mechanism of activity of supermassive BHs and for the problem of the origin of relativistic jets.

Gravitational waves: In the course of preparation of the LISA mission a study of the effect of alternative RG theories on the gravitational wave signal from a range of sources will be done. A proper measurement of the parameters of the merging binary systems (e.g. the masses of the merging components) from the gravitational wave signal in LISA could be done only when a number of the relevant physical processes is taken into account. This includes precession of the orbital angular momentum and of the individual spins of components, the spin-orbit and spin-spin couplings as well as orbit eccentricity. Signatures of alternative RG theories could be revealed only when all these factors are taken into account. These signatures will appear as corrections to the phase and (subdominant terms) amplitude of the gravitational wave signal. The Fisher matrix approach used so far for the calculation of these effects can only be taken as an approximation when the signal-to-noise ratios are high and does not necessarily explore the full parameter space. Development of a new code based on the Markov Chain Monte Carlo simulation, better suited for the lower signal-to-noise ratios, is planned. A range of alternative RG theories predicts extra gravitational wave polarizations (such as longitudinal modes). The existence of such extra polarizations would immediately put GR into question and favor proposed alternatives. LISA is not capable of directly detecting extra polarizations. However, such additional degrees lead to faster energy loss in compact binary inspirals, through gravitational radiation. We plan to build a framework which accounts for such effect in parameter estimation for binary inspirals.

High-frequency quasi-periodic oscillations: Nature of the high-frequency QPOs could be constrained by the measurement of lightcurves of X-ray binaries with ms time resolution. This will be possible with LOFT, which will have large enough collection area to achieve sufficient signal statistics on ms time scales. Before the start of operation of LOFT, constraints on the nature of fast QPOs could be imposed via measurement of coherence time scale of QPOs or, equivalently, of the width of the QPO peaks in the Fourier space. Constraints on the coherence times in the range of 0.1 s challenge currently existing theoretical models in which clumps orbiting the BHs are destroyed on much shorter time scales by the differential rotation. Furthermore, there exists an evidence of a drop in the coherence time at the highest frequencies, possibly corresponding to the ISCO. We plan an in-depth study of coherence time scales of high-frequency QPOs and their relation to the dynamics of matter in the direct vicinity of BH horizon. Such a study will reveal the possibilities of testing the GR using X-ray timing data. In particular, GR makes firm testable predictions on the location of the ISCO and its dependence on the BH spin. Apart from the X-ray timning, the location of the ISCO could also be found from the measurable gravitational redshift of the signal (X-ray line emission). Any deviations from GR would affect the location of the ISCO and hence produce an observable signature in the observations of the time profile and in the broad X-ray lines produced by matter moving at the ISCO. Similarly to the study of the effects of alternative RG theories on the gravitational wave signal, signatures of the alternative theories in the X-ray data could be identified only when the degeneracy with the system parameters (the BH spin and mass, radial density profile of the accreting matter etc) is resolved. This will require extremely accurate continuum shape and line profile and timing measurements, which will be possible with the LOFT mission.

Fast variable γ-ray emission from AGN: Observations of γ-ray emission from AGN reveal fast variability on the time scales comparable or shorter than the period of rotation over the ISCO or the BH light crossing time. The nature of such fast variability will be clarified with the systematic characterization of its properties in a large number of sources. This will be possible with CTA which will have an advantage of lower energy threshold and larger effective area, compared to the existing ground-based γ-ray telescopes. We will perform a systematic monitoring of blazars (special type of γ-ray loud AGN) with Fermi, CTA, FACT and other facilities to collect sufficient information on the flaring activity and on the presence/absence of the fast variability in particular sub-classes of the AGNs. Based on this information, we will determine whether the observed fast variability is produced by the high-energy particles injected at the base of the jets, close to the AGN "central engine", the supermassive BHs. If confirmed, location of the fast variable emission region close to the BH will provide a new source of information on the physical processes in the direct vicinity of the BH horizon. It will provide a clue for the understanding of the mechanism of formation of relativistic jets by the BHs.

4.3.8 Project: Neutrinos from Supernovae

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Research question and state of the art:

All stellar burning stages of massive stars (H-, He-, C-, Ne-, O-, Si-burning) start with an initial central contraction, causing a density increase and a temperature increase due to released gravitational binding energy, until ignition sets in when the kinetic energy of the major reaction partners is sufficient to overcome their Coulomb repulsion. Si-burning results in an Fe-core and as nuclei around Fe possess the highest nuclear binding energy no further energy release or burning stage is possible. Thus, the final evolution of massive stars leads to a core-collapse at the end of their evolution which is not halted until nuclear densities are attained. Then the stiffening equation of state (EoS) causes a halt and bounce. For stars with initial masses between 8 and ≈ 25 $M_\odot$ the subsequent evolution is expected to lead to - besides the dense/compact central object, a proto-neutron star - an explosive ejection of the outer layers, observed as supernova (SN), optically and in neutrino emission, if occurring close enough.

The major part of the released gravitational binding energy from core-collapse is released in neutrinos. Energy transport via photons would only be possible on stellar evolution timescales, neutrinos with their extremely small interaction cross sections can escape within seconds. Therefore, they are direct witnesses of the explosion mechanism, if observable via terrestrial detectors. Neutrino physics has also a large impact on the dynamics and the cause of the explosion and the composition of the ejecta.

The observation of neutrinos from a supernova event can address a number of still open aspects in the explosion mechanism: (1) The nuclear equation of state plays an essential role in the initial bounce and the dynamics thereafter. A transition to strange quark matter at relatively low densities would e.g. lead to a second bounce, causing an explosion and a second neutrino burst [264, 265]; (2) After the initial bounce at nuclear densities, a phase of matter accretion onto the proto-neutron star precedes the final explosion. The duration of this phase is determined by the EoS, hydrodynamic instabilities, and neutrino radiation transport which determines the effectiveness of energy transfer from the hot proto-neutron star to the outer (to be ejected) layers [266, 267]; (3) Core collapse with rotation leads to large rotational energy in the proto-neutron star which causes the build-up of magnetic fields. If these fields are strong enough, they alone can cause an explosion with jet ejection along the polar axis [268] with a still to be determined neutrino signal.

Standard supernova models do not yet include neutrino flavor oscillations, but neutrino flavor oscillations are now clearly established from solar and atmospheric neutrino observations and from terrestrial long-baseline experiments. The mass ordering between the three neutrino mass eigenstates, $m_1 < m_2 < m_3$ (normal hierarchy) or possibly $m_3 < m_1 < m_2$ (inverted hierarchy), depends on matter effects in 13 oscillations. This is addressable directly via terrestrial long baseline experiments. However, the mass ordering can also be determined from the observation of the neutrino signal of a future galactic SN in IceCube or in a future LAGUNA experiment because of resonant matter-oscillation effects in the SN mantle and envelope [269]. A further effect which can only occur in a high density "neutrino plasma", as it is established in SN cores, is related to neutrino flavor transformations in the presence of neutrino self-coupling. The latter effect has also been termed "collective neutrino oscillations" [270].

All of the aspects addressed above will manifest themselves in related patterns of neutrino emission, their flavors, their spectra and their total luminosities (the non-spherical multidimensional dynamics also causes gravitational wave emission). Thus, the observation of neutrinos (and gravitational waves) from SNe can provide a direct link to the explosion mechanism and the conditions deep inside the stellar core as well as leading to new insights into fundamental neutrino particle properties [271, 272, 273].

Intended contribution of the project:

Simulations which are required to predict neutrino (and gravitational wave) signals need to follow the fast (dynamical) contraction of the Fe-core and to consider large sets of weak interactions (especially neutrino production and scattering) and a general relativistic treatment of the dense neutron star at the center of the collapse plus possible transitions to a quark phase. The treatment of rotation and magnetic fields requires to solve the equations of (ideal) magnetohydrodynamics (MHD) in three dimensions.. A high level of spatial resolution permits detailed three-dimensional models, similar to cosmology and large scale structure simulations, but with a more complex set of input physics, coupling the hydrodynamics to radiative neutrino transfer.

The difficulty is to reliably quantify the energy transfer that occurs from the small coupling of the large energy reservoir in the proto-neutron star to its surface layers that have densities of $10^{10} - 10^{8}$ g cm^{-3} with much lower characteristic energies. In the neutrino-driven explosion mechanism the energy is transferred by neutrinos. The energy deposition rate depends on their spectra and the propagation angles in the layers that are close to the energy-dependent neutrino-spheres, located at densities $\approx 10^{11} - 10^{12}$ g cm^{-3}, beyond which they can escape freely. Typical dynamical time scales in this less dense regime outside of the neutrinospheres are of order of several 10 ms. In the case of a successful explosion, after several 100 ms, the density may drop from the compact remnant to densities of 1 g cm^{-3} in the ejecta.

In the past the group in Basel has addressed these questions with computational supernova models in spherical symmetric, including general relativistic Boltzmann neutrino transport and detailed nuclear and weak interaction input physics [274, 275] and three-dimensional approaches, including a consistent evolution of fluid instabilities with magnetic fields and sophisticated spectral neutrino transport approximations [274, 276]. In addition to current supernova models targeting the explosion mechanism, we need to implement a scheme for treating collective neutrino oscillations, which is a major part of this project. Besides leading to a better understanding of neutrino physics, the effect of neutrino flavor oscillations and spectral swapping may feed back on the supernova shock evolution and especially on the nucleosynthesis of ejected matter. Therefore it is of strong importance for the understanding of supernova explosions. This will be accompanied by further code improvements and applications to a large variety of SN progenitor stars.

In the event of a SN core collapse in our galaxy, supposedly occurring at a rate of 2 ± 1 per century, a clear signature mainly from CC $\bar{\nu}_{\mathrm{e}}$ interactions would be recorded by the IceCube neutrino telescope and manifest as a sudden increase of the global "noise" rate in the detector. Provided a sufficiently large $\sin^2\theta_{13}$, matter effects would be displayed in the light curves of the ν_{e} signature during the short neutronization burst and $\bar{\nu}_{\mathrm{e}}$ signature during the subsequent neutrino emission phases. The UniGE IceCube group is interested in developing a Multi-Messenger program also presented in this NCCR and in monitoring SN collapses, sharing information with other detectors. The possibility to determine the t_0 of the explosion with IceCube with precision of few ms allows to combine information from different neutrino detectors including gravitational wave ones [8]. Recently, the EPFL IceCube group has conceived and developed an alternative method for SN detection with IceCube, based instead on the measurement of the rate of coincident detection of photons from single positron interactions. In contrast to the "traditional" method, this method has demonstrated additional potential, enabling the disentanglement of the $\bar{\nu}_{\mathrm{e}}$ flux from its average energy $\langle E_{\bar{\nu}_{\mathrm{e}}}\rangle$. The experimental applicability of the new method involved modifications in the DAQ in order to spool all single detected photons, which were recently implemented.

Our contribution will include: (i) a refinement of the analysis of the IceCube potential, based on this new experimental data stream (for instance the resolution of $\langle E_{\bar{\nu}_{\mathrm{e}}}\rangle(t)$ w.r.t. the galactic SN distance); (ii) a Monte Carlo simulation for various configurations of a future densely instrumented core in the center of IceCube. We will study for a SN neutrino burst event and the atmospheric neutrino beam the mixed effects of earth matter oscillations (and subsequent access to the neutrino hierarchy) and core collapse dynamics. Further we will study the distance reach for extra-galactic SN detection. Should it be in excess of several Mpc, several detections during the detector lifetime would be guaranteed.

Links to other projects of this NCCR

Neutrino observation with high statistics of a future galactic SN would offer a huge scientific harvest regarding our understanding of SN physics. This understanding is improved by connecting neutrino observations to photon and gravitational wave ones, so that this project is connected to the project on Multi-Messenger strategies. The neutrino measurement from a SN collapse could reveal the nature of the neutrino mass hierarchy. One requirement to observe any oscillation effects in SN neutrinos is that the fluxes and/or spectra are different for different flavors, which needs to be determined from our collapse simulations with neutrino transport. Possible Earth effects would manifest themselves in an energy-dependent modulation of the SN neutrino signal or by a difference between the measured signals in a detector that measures the SN signal directly and one that measures it shadowed by the Earth. Collective neutrino oscillations will need to be implemented in core-collapse SN simulations. This leads to implications of collective neutrino flavor oscillations for core-collapse SN physics and provides prospects of obtaining and/or constraining fundamental neutrino properties, such as the neutrino mass hierarchy and Θ_{13} from a future observed SN neutrino signal. The NCCR will allow to fund this program with manpower and facilitate exchanges of researchers and students.

5 International Networking

International networking and cooperation is one of the strongest assets of the proposed NCCR Universe. It is the much-needed catalyst linking together tightly all existing initiatives from international organizations, institutions and associations (such as CERN, PSI and CHIPP), and international projects (such as ATLAS, CMS, LHCb, Euclid, Planck, BOSS, EDISCS and AMS). It is the essential initiative, which will help increase the coherence and outreach of fundamental research in particle physics. Switzerland becomes the common destination for data, analysis and research of all international projects in our field.

Beyond our borders, Swiss particle- and astro-physics collaborates dynamically in various international scientific activities of the Swiss confederation through the Swiss Infrastructure Roadmap, the European Strategy Session of Council, the European Commission FP7 programs (LAGUNA, AIDA, CTA, the ITN "Cosmology with Large Surveys", etc.), and international space agencies as ESA (Europe), NASA (USA), JAXA (Japan), and GESSA (China).

Moreover, the Swiss groups also play a leading role in the international networking for future neutrino facilities. They have been strongly involved in the organization of the yearly international workshops NUFACT, for future neutrino beams, and NNN for large underground detectors for neutrino and nucleon decay; the 2011 events were organized in Geneva (NUFACT11) and Zurich (NNN11). The EPFL astrophysics lead the international effort COSMOGRAL (COSmological MOnitoring of GRavitational Lenses). Swiss particle physicists lead the European networking activities in the framework of the FP7 EUCARD program for future accelerators and are taking an important role in the organization of the contributions for the upcoming European Strategy Process.

Scientists by tradition use an extensive international network to support, enable and critique their work. By bringing complementary disciplines together, the added diversity in the language and the way the problem is presented proposes a new interface, a different way of seeing the issue. It triggers, leverages and breeds new approaches allowing others around the world to benefit of this complementarity. NCCR Universe's challenge to unite scientists in the various disciplines of physics (cosmology, astrophysics, particle physics and theoretical physics) on common research projects, thus not only creates additional links, but offers a new dimension to our international networks as well.

This new approach also allows us to extend our networks from individuals or groups to institutions. It thus establishes stronger and more sustainable forms of international collaborations through, for example, exchange programs for students, hosting of postdocs or invitations to leading and Nobel scientists.

These initiatives find strong encouragement and support in Geneva as its University goes through a reorganization and development of its sections of physics and mathematics and the department of astrophysics. The project includes specific developments towards education and training, international forums and conferences, as well as a multimedia infrastructure permitting remote attendance to international events. To the schools organized by this NCCR, we shall not only invite international lecturers but we shall also open the schools for participation by PhD students from abroad.

Particle Physics and Cosmology being international by nature, Swiss researchers have long collaborated individually or in groups not only with their international research collaborators but also with associations such as ECFA, NUPECC, ApPEC and Aspera. The establishment in 2003 of the national centralizing body CHIPP, supporting the active Swiss community in particle physics, offers the added benefit of gathering individual international networks in a common pool. It also demonstrates the experience and know-how of those scientists in leading national and international programs to outstanding results. With over 500 professors and researchers today, CHIPP's commitment to NCCR Universe strengthens our ability to sustain a rich and productive activity with international recognition and support.

Combining this experience with our vision of developing particle physics through new Challenges, NCCR Universe is ready today to institutionalize a sustainable methodology for managing international research projects linking instrumental, theory and academic units. The NCCR Universe will place Switzerland at the epicenter of particle physics in the world.

6 Knowledge and technology transfer, advancement of young researchers and women, communication

Questions on the fundamental nature of the Universe, its origin and future, are not concerns of scientists only. Whether philosophically, religiously or socially, it is a genuine curiosity of human nature to explore these matters and interpret what they see and hear. As the research fields going deep into these issues, particle physics, cosmology and astrophysics have since always been encouraged to outreach. NCCR Universe thus naturally takes on the responsibility to build bridges with the various actors of society, whether industry, general public, students. The topic of this NCCR is quite interdisciplinary in both, subject (particle physics and cosmology) as also methods (theoretical, numerical and experimental). We believe that this makes it especially attractive for women.

Efficient communication and customized education are the tools allowing us to maintain the bridges in a sustainable fashion. The networking of our activities in these areas by combining outreach programs or developing new initiatives should greatly strengthen the community's understanding of what is done in particle physics, of its role and responsibility to society and its development. As co-leading house of NCCR Universe, the PSI, with its recognized experience in the field, will take on an active role in managing the outreach and developing new programs. Offering a more academic and nationally targeted complement to CERN's efforts, as well as benefiting from CHIPP's framework, will be important assets to take into account.

The astrophysics departments at both UniGe and EPFL have a long and successful tradition in public outreach, e.g. with their "Conférence annuelle UniGE-EPFL d'astronomie" which is directed to the general public. They also maintain bloggs and other grass-roots astrophysics outreach like the "Ask me about the Big Bang" initiative (http://web.me.com/anais.rassat/Anais/Ask_me_about_the_Big_Bang.html by Anaïs Rassat). We believe that particle physicists and theorists will be learning a lot from collaborating with their astrophysics colleagues on the outreach issue.

6.1 Knowledge and technology transfer

Particle physics, accelerator and detector technology have demonstrated over the past decades an enormous potential for technology transfer and spin-off companies to the benefit of the economy and society. Some common examples include the development of medical accelerator technology, gamma, Xray and particle detection systems for imaging techniques, monitoring and medical diagnostics, fast data acquisition and information distribution systems for a variety of applications.

All partners involved in this NCCR proposal have offices for technology transfer from the respective university or institution to industry. In particular, University of Geneva recently established the Geneva Creativity Center, which reinforces the upstream efforts of the existing Unitec support to spin-offs. The PSI technology transfer office is also represented in a CERN based HEPTECH network for technology transfer from high-energy physics.

Within this NCCR we plan to establish a technology transfer (TT) and industry communication (IC) node with the aim to integrate them early in the process, and implement especially IC at an early stage of each experimental project. The goal is to establish contacts between the research institutions and potentially interested companies at an early planning stage of R&D efforts. TT can work in both directions and certainly also the projects will gain from the IC effort. It is very desirable to coordinate this in a node on a Swiss scale in order to combine the considerable effort to maintain industry and research group contacts simultaneously and pooling specific field related knowhow. Conflicts between offices of individual institutions will be prevented by clear agreements in particular on intellectual property rights and their exploitation. While this NCCR is not about financing hardware, it is about science projects with potentially very significant technological developments. We cannot promise explicit spin-offs from this NCCR but we will improve the efficiency of knowledge and technology transfer in a sustained way.

6.2 Educational support

The success of particle physics and cosmology research in Switzerland largely results from the highly qualified and innovative scientific and technical teams within Swiss institutes. With this NCCR we do not only want to maintain that quality, but innovate by educating our students in both particle physics and cosmology, and especially the strong connections between these fields. A solid education in particle physics, astrophysics and cosmology in undergraduate physics curricula is mandatory to prepare the next generation of students for the challenges of tomorrow in our field.

NCCR Universe will work towards ensuring a good standard of undergraduate education in particle physics, astrophysics and cosmology. It will further coordinate and streamline the existing doctoral programs in the interrelated fields.

The graduate physics education program in Switzerland has made progress in the last few years, due to the initiative of the Universities. In western Switzerland, CUSO has transformed the successful program of the Graduate School in Physics in French-speaking Switzerland into a coherent and well-supported doctoral program for all PhD students from their member institutions. As far as specialized education in particle physics is concerned, CHIPP initiated a ProDoc program to improve the offer and access conditions of PhD students all over Switzerland to the local and regional doctoral programs. The CHIPP Winter School, the Zuoz Summer School and the CERN School of Physics play an important role in this program. "Universe Schools" will complement the program to educate the students in the NCCR especially also in cosmology and astroparticle physics. Access to all courses will be granted to all Swiss PhD students free of charge and credits will be granted on an equal footing. In order for our students to be exposed to international collaboration already at an early stage, the schools will also be open to students from abroad.

The present doctoral program in particle and accelerator physics (funded through ProDoc and integrated in the Center for Advanced Studies in Particle Physics C15) will be further developed on the basis of existing resources and at the Swiss level. We shall also give all Universe-PhD students the opportunity to spend a semester or even a year at another Swiss University, which collaborates on the same project.

6.3 Advancement of female researchers

Physics in general, and particle physics and cosmology alike, sees a remarkable asymmetry between male and female researchers. As an example, the CMS experiment at CERN's LHC counts [277] 1740 PhD physicists (1490 men, 250 women), 845 physics doctoral students (685 men, 160 women), 790 engineers (700 men, 90 women) and 690 undergraduates (550 men, 140 women). The source of the problem maybe rooted in University education or even before.

While progress has been made in the last years to attract female students to studies in "hard science", the level of female beginners in physics stagnates at a low level. This asymmetry is then propagated into an unsatisfactory female fraction of physics PhD, post-docs and professors. This indicates that the problem needs to be attacked at an early stage in the career of our female students. Even though our NCCR will not be able to completely change the present academic system, we can and will make specific efforts to facilitate and increase the attractiveness of a scientific career for women.

We shall send some of our female researchers to outreach activities in schools in order to play role models for girls.

NCCR Universe will establish a program of tutorships for beginners especially tailored for bachelor and master level female students. The tutors will be advanced female physics students, post-docs and researchers, recruited at all levels. They will provide their younger colleagues with personalized help with their studies and act as role models for younger students. A system of fellowships will support this action at the levels mentioned.

An additional large drop in the percentage of female researchers happens between the PhD and PostDoc level. The fact that permanent jobs are very rare and are obtained only rather late, often at the age of 40, discourages over-proportionally many women researchers. The travel intense Post-Doc years are in a period of their life where most women are building a family. Capable and competitive female researchers give up after their PhD as they are not willing to give up the prospect of family life for a highly unpredictable future, as well as to face a non-negligible risk to be left without a job when reaching the age of forty. For female professors there are programs to organize jobs for their spouses and care for children, similar efforts must be made much earlier in the career at the post-doc level.

As and example, we shall organize childcare facilities during conferences and schools so that also researchers/students in charge of small children can participate.

6.4 Internal and external communication

NCCR Universe will coordinate a more active information exchange among communicators and work towards a higher level of public awareness in our field. Many Swiss groups at their Universities and at PSI pursue outreach activities. A coordinating effort is already made by the CHIPP Outreach Group, bringing together people from all Swiss research sites involved in particle physics to discuss individual and common activities to exchange ideas and contacts. We shall include astrophysics researchers, some of which have considerable expertise in this field, in this effort. One representative from astroparticle physics (ASPERA) links particle physics outreach activities with the growing community of astroparticle physicists in areas of common interest. In addition, a representative from SER acts as observer and brings in advice from a higher-level research and education perspective.

A number of excellent activities, reports and documentation have been produced by the various members of our NCCR, many of which coordinated by the CHIPP Outreach Group – websites and fact-sheets about the Swiss participation in the LHC experiments by CHIPP; European Physics Master classes in Bern, Geneva and Zurich; master class events, special guided tours at CERN and other Swiss labs, PhysiScope Genève, Kinderuniversität Zürich, PSI Forum and iLab, etc. – all targeted at high-school teachers and students. To ensure further developments and adapt our communication to the evolving needs of society, further efforts of coordination must be made. The NCCR will enable us to establish a global communication strategy on particle physics in and from Switzerland. Through the use of the latest communication technologies and enhanced websites, we can not only provide information but engage with our various stakeholders as well. These new tools will push the boundaries of our science and our country far beyond our actual borders.

7 Structural Goals of the Home Institution

In its long term strategic planning [278], the Rectorat of the University of Geneva identifies the physical sciences, enlarged to astrophysics and mathematics, as one of its priorities during the period 2011 to 2015, in the form of a *pôle d'excellence* in research. This priority confirms the support the physics department of University of Geneva had already received during the previous four-year planning period, due to its excellent performance during this time. This strategic direction of development is also reflected in the *Convention d'objectifs quadriennale 2012-2015*, which the University is in the process of concluding with Geneva cantonal authorities.

In spring 2011, the physics section together with the astrophysics department of Geneva University inaugurated CAP (their Center for Astro-Particle Physics) which aims to strengthen activities at the center of this NCCR, bringing together members of the Department of Theoretical Physics (DPT) the Department of particle physics (DPNC) and the Department of Astrophysics. All members of CAP shall actively work on this proposal. In total there are 12 professors with their research groups involved in topics covered in this NCCR.

University of Geneva in fact has ambitious plans for the mid-term future of its mathematics, astronomy and physics departments. A new project uniting these branches of science in a common effort is in an advanced planning process. Supporting this planning, the scientists concerned have developed an innovative usage concept, aiming at liberating the synergies between these sciences much in the same way as this NCCR proposal. In parallel, the education in basic sciences and its services to all students of the Faculty of Sciences is being rethought. At the undergraduate level, new cross-disciplinary branches like biophysics or climatology are installed or in the planning, setting an example for the educational branch of the NCCR Universe.

For PSI, particle physics and accelerators are key components of its strategic planning. PSI is at the forefront of accelerator development with its new SwissFEL project, with the SLS, with the medical cyclotron and with the world's most powerful proton accelerator, the PSI ring cyclotron. PSI is providing such large research infrastructure to national and international users and is at the same time developing this important technology further. The Development Plan for 2012-2016 has "Particle Physics and the Structure of Matter" as one of its 5 thematic areas of legal PSI responsibilities and places a strong emphasis on its user lab function. The PSI laboratory for particle physics runs a research program "Precision and discovery physics at low and high energy" with a major contribution to LHC activities within the Swiss LHC consortium and with unique precision physics experiments at PSI. PSI has over the past few years built a new facility for ultracold neutrons and continues to run and improve its world highest intensity muon beam lines. High-visibility particle physics experiments are supported on these facilities and will be in the future. PSI particle and accelerator physics activities are responsible for major developments and spin-offs into the whole of PSI and very often had fertilizing influence. PSI expects this to continue and promote both the investigation of the most fundamental questions to nature and its positive coupling to other fields. It is committed to high-level education and has a considerable effort in, both, scientific education mostly on the level of doctoral student education and training of apprentices, which, e.g. for electronics, is located in the laboratory for particle physics.

The long-term commitment of the CHIPP partners to the research themes of this NCCR ensures the sustainability of the planned reinforcement beyond the lifetime of the NCCR itself. The partner institutes regularly replace retiring professors in the field concerned by eminent young researchers. The Universities of Bern and of Geneva have recently created new chairs in astroparticle physics, one of the central themes of this NCCR. The implementation report of the CHIPP road map contains a detailed record of the achievement of its members in recent years. All project and sub-project coordinators regularly obtain important funding from the SNSF, cantonal and federal authorities, as well as the European Commission and other international funding bodies.

The University of Geneva has demonstrated its ability to ensure the proper administration and accounting for several NCCRs in basic sciences. Its *Section de physique* has very successfully run the NCCR MaNEP during the past 12 years.

8 Organization of the NCCR

The NCCR Universe will be organized as shown in Figure 4. The functions of its different organs are detailed in the following.

The governing body of NCCR Universe is the **Governing Board**, which consists of the participating Swiss professors. It defines the scientific policy of the NCCR, approves projects, monitors their progress and the

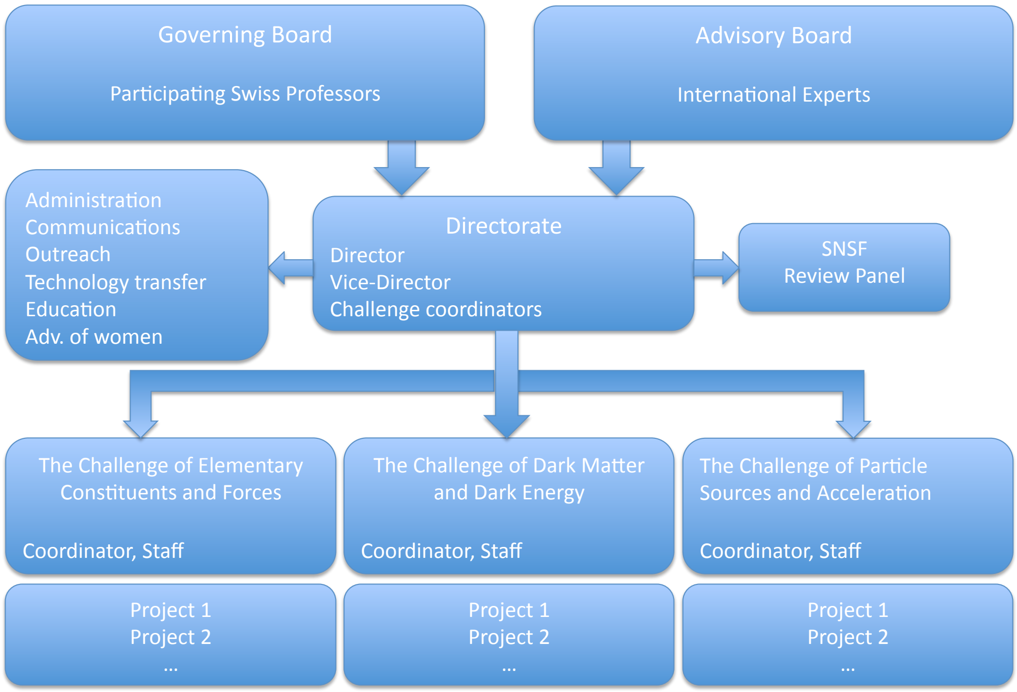

Figure 4: Organizational chart of the NCCR Universe.

conference of the NCCR as a whole. It discusses and approves the yearly report of the Directorate. It takes note of the results of evaluation by the SNF and the Advisory Board and monitors the implementation of their recommendations.

The **Advisory Board** is composed of scientists with an internationally recognized expertise in particle physics, cosmology and astrophysics, and who do not participate in the NCCR. The Board holds a yearly meeting where it hears and discusses reports from the NCCR directorate and the project coordinators. The Advisory Board provides an independent view on the progress of the NCCR as a whole and of its parts. Their written conclusions are transmitted to the Directorate and included in its yearly report.

The **Directorate** of the NCCR consists of the Director, a Deputy Director and the coordinators of the three challenges of the NCCR. The Director heads it. During the first four years period of the NCCR, the Director will be Prof. Martin Pohl of University of Geneva; the Deputy Director will be Prof. Klaus Kirch from PSI and ETHZ. During subsequent periods, it is foreseen that the Director's appointment rotates among the leading houses. The Directorate is responsible for the implementation of the scientific policy of the NCCR. It distributes the budget. It takes on all administrative duties with respect to the leading houses and the SNF and reports to them on a regular basis. In particular, the Directorate prepares and transmits the yearly report on scientific and financial matters. After approval by the Governing Board and the SNF, the yearly report is published.

The Directorate will design and implement through the NCCR an organization methodology fostering the multidisciplinary approach of a sustainable platform aggregating cosmology, astrophysics and particles fundamental research. Part of the implementation will consist of enabling collaboration and transparency, as well as supporting the engagement of the stakeholders. This open approach should and will permit to broaden the commitment of new partners or financial sponsors over time.

The **Staff of the Directorate** comprises the following functions:

- A dedicated **NCCR administrator** supervises all administrative tasks of the NCCR, including in particular contractual, personnel and budgetary issues. The administrator reports to the Directorate. A full time secretary will assist the administrator.

- A part-time **outreach coordinator** takes care of promoting pubic awareness of the NCCR's work, its results and their relevance to society. He/she organizes public events and publications directed towards the general public. He/she collaborates closely with the outreach coordinators of the participating institutions and with those of international partners in the field.

- Communications professionals from the relevant offices of the Leading Houses take care of the external communication of the NCCR progress and results through a coordinated effort. The NCCR finances an additional half-time position of a **communications officer**, dedicated to these tasks. He/she supports the Director with the global external relations strategy including internal communication.

- A coordinator for the **advancement of women** is responsible for gender aspects in the organization and work of the NCCR. Networking among female participants, proposing innovating solutions and coordinate special fellowships are part of his/her responsibilities.

- The relevant offices of the leading houses will coordinate **Technology Transfer**. The general strategy of outreach to industry is coordinated with the Directorate.

- A **coordinator for education** will organize the doctoral program of the NCCR in collaboration with existing organizations like the CRUS and CUSO doctoral program in physics. He/she also makes supporting material available for professors teaching undergraduate courses in the fields covered by the NCCR and will be responsible for publishing a complete catalogue of relevant courses available in the participating institutions. These courses will be open to all students working in the fields covered by the NCCR. The coordinator will also organize the exchange of students among participating institutions.

Appendices

A List of Project Leaders and Titles

The following list is preliminary.

A.1 The challenge of elementary constituents and forces: G. Iacobucci (UniGe), M. Spira (PSI)

- Electric dipole moment of the neutron: K. Kirch (PSI, ETHZ), A. Weiss (UniFr)
- Searches for new physics using bottom hadrons: O. Schneider (EPFL), U. Straumann (UniZh)
- Searches for new physics using the top quark: R. Wallny (ETHZ), G. Iacobucci (UniGe)
- Exotic hadrons: B. Krusche (UniBs)
- Electroweak Symmetry Breaking: G. Dissertori (ETHZ), M. Grazzini (UniZh)
- Neutrino oscillations: A. Blondel (UniGe), A. Ereditato (UniBe), M. Shaposhnikov (EPFL)
- Neutrino-less double beta decay: L. Baudis (UniZh), R. Gornea (UniBe)
- Grand Unification: S. Antusch (UnBs), A. Rubbia (ETHZ)
- Lepton flavor violation: S. Ritt (PSI), A. Bravar (UniGe)
- Cosmic magnetic fields: A. Boyarski (EPFL), R. Durrer (UniGe)

A.2 The challenge of Dark Energy and Dark Matter: R. Durrer (UniGe), A. Refregier (ETHZ)

- Particles and fields in the early universe: M. Shaposhnikov (EPFL), A. Riotto (UniGe)
- Cosmic acceleration: M. Maggiore (UniGe), M. Kunz (UniGe)
- Large scale structures as a probe of fundamental physics:
  - Observations: A. Amara (ETHZ), M. Kunz (UniGe)
  - Modeling: V. Desjaques (UniGe), U. Seljak (UniZh)
  - Astrophysical systematics: S. Lilly (ETHZ), M. Carollo (ETHZ)
- Cosmological tests of gravity: M. Kunz (UniGe), A. Refregier (ETHZ)
- Dark matter, direct and indirect detection: L. Baudis (UniZh), A. Boyarski (EPFL), J. Read (ETHZ)
- Cosmic microwave background: J. Lesgourgues (EPFL), A. Rassat (EPFL)

A.3 The challenge of particle sources and acceleration: L. Rivkin (EPFL, PSI), A. Blondel (UniGe), A. Neronov (UniGe)

- Hadron and lepton colliders: L. Rivkin (EPFL, PSI), T, Garvey (PSI)
- High intensity beams at PSI: L. Rivkin (EPFL, PSI), M. Seidel (PSI), P.-R. Kettle (PSI)
- Intense neutrino beams and factories: A. Blondel (UniGe), A. Rubbia (ETHZ)
- Galactic cosmic rays: A. Biland (ETHZ), A. Neronov (UniGe)
- Ultra-high energy cosmic rays: A. Neronov (UniGe)
- Cosmic sources in a multi-messenger strategy: A. Neronov (UniGe), T. Montaruli (UniGe), M. Ribordy (EPFL), A. Biland (ETHZ)
- Relativistic gravity: S. Paltani (UniGe), Ph. Jetzer (UniZh)
- Neutrinos from Supernovae: F. Thielemann (UniBs), T. Montaruli (UniGe), M. Ribordy (EPFL)

B CV and List of Publications of the NCCR Director, Deputy and Project Leaders

See separate files.

C Budget for the First Phase

Even though the number of partner institutes and participants in this NCCR is large, we estimate that the administrative overhead can be manageable with a single administrator and a secretary, for a personnel cost of about 250 kChf/a. To this must be added the cost of one full time outreach officer and three half-time coordinators for communications, the advancement of women/young researchers and technology transfer (see Section 6 and 8), with a total estimated cost of 230 kChf/a. Consumables and running costs are estimated to another 250 kChf/a. This rather lean administration sums up to a cost of approximately 730 kChf/a, partly covered by cash and in-kind contributions from the leading houses. The estimated cost of freeing the director and his deputy from other administrative and teaching obligations is estimated to 140 kChf/a, again covered by the leading houses.

By construction, this NCCR only finances scientific personnel cost. Other funding mechanisms exist and must be exploited to finance investment and running costs required for experimental and theoretical project activities covered by the goals of this NCCR. The rough financial planning is thus based on salaries averaged between those of a post-doctoral fellow and a PhD student in Swiss institutions, which is about 90 kChf/a. The average reflects the assumption of a roughly equal share of post-doctoral fellows and PhD students to be hired from NCCR funds. The exact repartition is left to the participating institution.

Given the number and importance of the research projects included in this NCCR, we estimate that a personnel increase of the order of 58 positions (as defined above) will be necessary, representing a total personnel cost for research projects of 5'220 kChf/a. This total budget stays within the financial limits of an NCCR when taking into account matching funds pledged by the leading houses. The positions are distributed to the contributing institutions pro rata of the number and size of projects they subscribe to. It is also proposed to respect a certain balance between the three challenges in attributing about equal manpower to all of them.

Considering the size and commitment of participating groups, it is proposed to attribute 1 post to UniFr, 3 posts to UniBs, 4 to UniBe and 8 to 9 scientific posts to the larger participants (UniGe, EPFL, UniZh, ETHZ and PSI). The large commitment of the leading houses by their matching funds is beneficiary for the whole NCCR and reflected only in a slight advantage of 3 additional posts. Although CERN will obviously participate actively, it will not receive NCCR funds.

Within these boundary conditions, the attribution of the posts to projects will be left to the partners. A very rough preliminary idea on the initial distribution of positions to institutes and challenges is shown in Table 1. A more accurate planning will lead to a refined equilibrium during the proposal phase of the NCCR. The final attribution will be made by the NCCR Directorate as explained in Section 8. Not contained in Table 1 are the positions at assistant professor level and of tenure track scientists, contributions of the leading houses which are listed in the separate forms for self-funding contributions.

Partner	Constituents & Forces	Dark Matter & Dark Energy	Sources & Accelerators	Administration
UniGe	3	6	3	2.5
PSI	6	-	6	2
ETHZ	2	5	2	-
EPFL	2	4	3	-
UniZh	3	3	2	-
UniBe	3	-	1	-
UniBs	2	-	1	-
UniFr	1	-	-	-
CERN	-	-	-	-
Total	21	18	19	4.5

Table 1: The rough initial distribution of positions over the three challenges. There are 58 scientific and 4.5 administrative positions. Expected matching funds are taken into account only for the leading houses. We plan to share the scientific positions among post-docs and PhD roughly in a 1:1 ratio.

D Letter of Support from Home Institution

See separate files.

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