Neutrino physics: Switzerland in the Global context

Executive summary

Version 5.0, 28 October 2014

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1 Neutrino physics as first hint of BSM physics

Following the Higgs boson discovery, massive neutrinos are firmly set at the frontier of knowledge in particle physics. The nature of the neutrino mass generation; the pattern of mixing angles and masses with the possibility of CP violation; the absolute neutrino mass scale; the search for the elusive right-handed neutrinos, will constitute conceptual and experimental problems for decades to come. The reward is potentially very high, as massive right-handed neutrinos could well hold the solution of two other outstanding questions in particle physics: the nature of Dark Matter and the origin of the dominance of matter over anti-matter in the Universe. The priority in the Swiss Particle Physics activities should grow correspondingly, in agreement with the role they have in the Swiss Particle Physics Road Map.

2 Neutrino Oscillations : the long baseline program

Neutrino oscillations are the only phenomenon in which neutrino masses have so far manifested themselves. Many aspects of this phenomenon remain uncharted: the mass hierarchy among neutrino flavors, the possibility of CP symmetry violation in neutrino oscillations, and more generally a detailed study of the phenomenon, justify an important experimental program. The European Strategy for Particle Physics (ESPP) of 2013 has classified the long baseline neutrino program as one of the four scientific objectives with required international infrastructure:

CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

2.1 The Japanese program

2.1.1 The T2K experiment

The Swiss groups of Bern, Geneva and ETHZ have been involved in the Japanese accelerator-based neutrino oscillation program, using water-Cherenkov as far detector technology, since its inception in 2001 with the K2K experiment. An important contribution is given by the ancillary hadro-production measurements at CERN (HARP and now NA61/SHINE experiment) in which the Swiss groups are playing a leading role.

The T2K experiment has first demonstrated the existence of the $\nu_\mu \rightarrow \nu_e$ transition and contributed to the measurement of various parameters of the PMNS matrix, notably the

θ_{13} and θ_{23} angles. The experiment is looking towards a 10-fold increase in statistics by 2020, in which sensitivity to a first evidence (3σ) of CP violation could be obtained. After significant hardware contributions from Swiss groups to the near ND280 detector during the construction period 2006-2010, an important activity of upgrades is now ongoing, both on the beam and on near detector to improve the systematic errors, paving the way to future precision measurements.

2.1.2 The HYPERK project

HyperK is a new, megaton scale water Cherenkov detector project offering a 25-fold increase of fiducial volume over the existing 50 kton (22.5 fiducial) SuperK detector. This will provide decisive improvements in the non-accelerator experiments such as proton decay, detection of solar and atmospheric neutrinos and the detection of supernovae neutrinos. Exposed to the anticipated upgraded beam of T2K reaching a power 750kW, the T2HK project will allow decisive discovery of CP violation (5σ) over more than 75% of the parameter space in 6 years of running. The international collaboration proposal has been classified at government level within the high priority science projects in Japan, and is proceeding to prepare a full-fledge technical project with well-defined international contributions, led by an International Board (of which A. Blondel is the Swiss representative) within the next three years. The aim is to start data taking in the mid-2020's. The development of a visible, leading, contribution to HyperK electronics, data acquisition and near detector is under discussion within the Swiss groups in partnership with other European partners, with prototyping planned to take place in the CERN neutrino platform (see below).

2.2 Liquid Argon based long baseline experiments

The liquid Argon TPC technology has been initially developed in Europe and Switzerland hosts some of the most advanced technological knowledge in this domain, at the University of Bern and ETHZ. The liquid argon detectors feature outstanding pattern recognition and background rejection, and, importantly for long baseline experiments seeking CP-violation and mass hierarchy determination via the spectral (L/E) information, an excellent total energy reconstruction over a wide range of energies; thus they constitute a powerful exploration tool for neutrino oscillations, complementary to the more massive but less detailed water Cherenkov approach. Technological developments are still necessary towards the affordable realization of a deep-underground detector of the large mass (≥ 30kton) needed for a competitive long baseline experiment. Short baseline experiments and focused R&D in charged particle beams using smaller detectors constitute an important means to develop usage of the technology (see below).

2.2.1 LAGUNA-LBNO

The Swiss groups of Bern, Geneva and ETHZ have participated in the EU-funded, and CERN and APPEC supported, design studies LAGUNA and LAGUNA-LBNO. These efforts, led by ETHZ, successfully led to the feasibility studies of a pan-European infrastructure for Large Apparatus for Grand Unification, Neutrino Astrophysics and Long Baseline Neutrino Oscillations. CERN has developed a conceptual design for the CN2PY beam based on the upgraded SPS and HPPS accelerators. The conclusions of the design studies have been delivered in August 2014. Three detector options were developed with great engineering detail thanks to the support of industrial partners, and detailed designs, construction plans and cost estimates were made for a 20 kton and 50 kton fiducial double-phase liquid argon TPC, a 50 kton liquid scintillator and 500 kton Water Cerenkov detector. A comprehensive site search in Europe identified the Pyhäsalmi mine in Finland as the most optimal far detector site, offering a comprehensive physics programme at Long Baseline and unique accessibility advantages. The distance (2300km) from the proposed CN2PY beam from CERN allows a thorough study of a full oscillation (including first and second maximum), including a solid determination of the matter effects and mass hierarchy; the energy of the first oscillation maximum being situated above the tau production threshold provides an extended test of the three family paradigm. The LBNO EOI was submitted to CERN in June 2012, foreseeing an incremental approach, with an initial 20 kton liquid argon TPC complemented by a magnetized iron neutrino and muon detector. A near detector concept based on a high-pressure argon TPC was developed as well. The full development of the concept to a 70kton detector and a 2MW beam would allow CP violation detection fully complementary to HyperK. The non-accelerator physics capabilities comprise detection of proton decay in channels difficult to address with the Water Cherenkov, a complementary sensitivity to supernovae neutrinos, as well as detection of atmospheric neutrinos with a better angular resolution. For the initial phase of development at the Pyhäsalmi mine, the concept of a “pilot” project has been developed by the LAGUNA-LBNO consortium.

2.2.2 The LBNF initiative

In line with the recommendations of the ESPP quoted above, the Swiss groups are actively investigating the prospects offered in the USA for a liquid Argon long baseline program and in the definition of it. The recent strategic USA “P5” report has emphasized the high priority given to the future research on neutrino oscillation physics. This recommendation has been widely endorsed by the international community and, notably, by the CERN Council.

Recommendation 12: *In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.*

The international LBNF project is based on the earlier LBNE layout and discusses a 40 kton liquid argon TPC detector situated in the Sanford Underground Research Facility (SURF) at a distance of 1300 km from FNAL, where a new neutrino beam line and near detector facilities would be constructed. Physics goals include both the mass hierarchy and the CP violation. The original LBNE was considered to lie above the funding level that could be supported by the US funding agencies. Starting from the foundations laid by LBNE and LBNO, a new process towards the international LBNF was initiated by the Fermilab management, giving an International Interim Executive Committee (IIEB), of which both A. Ereditato and A. Rubbia are members, the mission to develop and submit a Letter of Intent to the FNAL Physics Advisory Committee (PAC) in 2015 and foster the participation of international partners and agencies. The LOI will be followed by a full TDR soon after, with the goal to reach DOE CD-2 in FY 2018. Full data taking is planned to start around 2025 and last more than a decade.

2.2.3 MicroBoone, LAr1ND and the Fermilab Short Baseline Neutrino program

Various neutrino experiments have reported evidence for a anomalies, following the original LSND experiment, that do not fit the present understanding of neutrino production, neutrino interactions and the standard 3x3 neutrino oscillation paradigm. The origin of these phenomena is unclear at this moment, although a plausible explanation in terms of oscillations could be the coupling of the known neutrinos with 'sterile neutrinos' (i.e. new neutrinos which do not couple to the other fermions, except for the oscillation mechanism). This calls for a definitive oscillation experiment at short baseline using two or more fine-grained detectors such as liquid Argon TPCs.

Also in this case, the P5 recommendations states:

Recommendation 15: *Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.*

The Fermilab plans in this respect are first based on the Microboone experiment, a 150 ton liquid argon TPC with cold electronics, which is in commissioning phase on the Booster Neutrino Beam. MicroBooNE, situated at 470 m from the BNB target, aims at the observation and first detailed analysis of neutrino interactions in liquid argon to understand if they could be a source of some of the anomalies observed in previous experiments. In order to establish or rule out the oscillation hypothesis, explicit appearance, as well as CC and NC disappearance signals are essential by comparing detectors situated at different distances.

Several proposals have been put forward to complement MicroBooNE, namely the LAr1-ND at 100 m built on a similar technology as MicroBooNE, and the ICARUS T600 module at 600 m, according to a comprehensive program under scrutiny at Fermilab, the SBN. At its last meeting in June 2014, the FNAL PAC recommended "...*Fermilab provide resources for LAr1-ND detector R&D (which has now received NSF funding) to move ahead (perhaps by designating it a Test experiment) in preparation for the submission of a proposal."* After that, LAr1-ND has got the approval status (T1053) and also local funding through Fermilab R&D money and from NSF. A full proposal for the whole SBN program is expected by the beginning of 2015.

The Bern group is playing a leading role in both MicroBooNE and in the LAr1-ND project (M. Weber is MicroBooNE physics coordinator and A. Ereditato is LAr1-ND Board Chair), with important contributions in the hardware, analysis and management. In addition to hopefully bringing to a definitive conclusion the 20-years LSND/MiniBooNE anomaly, this effort provides important experience and measurements in view of the long baseline experiments.

2.2.4 The CERN neutrino platform

Following the recommendations of the ESPP, CERN has engaged in the design of a facility to assist the European neutrino physicists for detector R&D and for their participation in long term common plans. In June 2014, CERN Council has approved the Neutrino platform and its provisional funds in the Medium Term Plan. The consideration of the R&D projects WA104, WA105 has already been approved by the CERN Research Board following the positive recommendation of the WA105 Technical Proposal by the SPSC, and others expressions of interest are encouraged. CERN has begun the construction of the large neutrino test area (EHN1 extension) with capability of charged beams in the range 0.5-20 GeV relevant for neutrino experiments. The following projects involving Swiss groups are in the process of formal agreement.

WA105 (LBNO-DEMO): led by ETHZ, it consists of R&D on 2 phases large 1x1x3 m^3 and 6x6x6 m^3 double phase LAr TPC prototypes, as development of the critical technology for large and affordable liquid argon detectors for the long baseline. An international WA105 Collaboration was formed in October 2014. A Rubbia has been elected Spokesperson and A. Blondel is a member of the executive committee. The 1x1x3m^3 already in construction and will take data in 2015. The construction of the 6x6x6m^3 could start when the ENH1-X hall is commissioned (presently scheduled for fall 2016).

MIND: R&D on magnetized iron detectors muon tracking detectors as designed for LAGUNA-LBNO. The use of the MIND prototype for the T2K upgrade is under discussion. The MIND project is led by University of Geneva.

LBNF: Test of a LBNE single-phase module inside a cryostat inspired by that designed for WA105.

Also being prepared for the CERN neutrino platform are a proposal for liquid Argon single phase modular structures (ARGONCUBE), a project led by the University of Bern, and test beam studies of a large water Cherenkov prototype led by the HyperK-EU collaboration involving Geneva in particular.

2.3 A coherent Swiss plan for long baseline neutrino experiments

The Japanese program with T2K, its supporting hadro-production measurements in NA61, and its upgrades, as well as the preparation for the HyperK experiment towards a definitive discovery of neutrino CP violation, will continue to constitute the backbone of the involvement of the Swiss neutrino groups in long baseline neutrino experiments.

There is a physics case for a complementary experiment using a smaller but finer grain far detector. Swiss neutrino groups are actively engaged in studies towards liquid Argon based long baseline experiments, and in discussion with the high priority US program LBNF. The critical WA105 R&D at CERN towards affordable large liquid Argon detector volumes, as well as the execution and analysis of short baseline experiments with liquid argon detectors at Fermilab (SBN), provide a complementary and coherent approach by the Swiss groups.

The involvement of Swiss groups on neutrino detector R&D towards long baseline experiments using the CERN neutrino platform should be strongly supported.

3 Non accelerator neutrino oscillation experiments

The discovery of CP violation in neutrino oscillation requires appearance experiments, specific of accelerator-based experimentation. The question of the mass hierarchy can be addressed also by non-accelerator experiments, either by a fine analysis of the solar-atmospheric interference in a long baseline reactor experiment (JUNO in China), or using atmospheric neutrinos as in the case of the PINGU experiment.

The Precision IceCube Next Generation Upgrade (PINGU) is a proposed low-energy infill extension to the IceCube Observatory. With detection technology modeled closely on the successful IceCube example, PINGU will feature the world's largest effective volume for neutrinos at an energy threshold of a few GeV, allowing it to reach sensitivity to the neutrino mass hierarchy (Normal or Inverted MH) on short time schedule and at modest cost. Although PINGU cannot distinguish between ν and anti-ν events, the different cross-sections, kinematics and different ν, anti-ν contributions to the atmospheric flux make it possible thanks to high statistics, to distinguish an oscillation pattern generated by the Normal MH from the Inverted one. The ability to perform successfully this measurement in a definite fashion will depend on mastering of a number of systematic uncertainties in the energy reconstruction and in the ice properties which are still under development. Besides a rich program on neutrino oscillations, PINGU will increase IceCube sensitivity for dark matter, supernova neutrinos and neutrino earth tomography. The group of T. Montaruli at University of Geneva is member of the PINGU project through its participation in IceCube. Recently, the IceCube Gen 2 Collaboration was formed incorporating new institutions for the program on low and high energy extensions of IceCube. Although no construction funds will be requested on the short term to the FLARE program for PINGU, the group will continue making substantial contributions to IceCube Gen 2.

4 Neutrinoless double beta decay

Double beta decay searches provide a fundamental probe of the nature of neutrinos and of lepton number violation. The observation of the neutrinoless double beta (0νββ) decay would prove that the neutrino is a Majorana fermion (thus has a Majorana mass term) and that fermion number is violated in Nature. The measurement of its rate is also expressed in terms of the so-called effective "Majorana electron-neutrino mass", m_{eff}. While many isotopes are available to search for this rare decay, currently the best limits on its half-life come from experiments using 76Ge, 130Te and 136Xe. Two world-leading experiments, GERDA (76Ge) and EXO (136Xe), have significant Swiss contributions and the capability to probe the inverted mass hierarchy scenario in their next phase.

GERDA searches for the 0νββ-decay in enriched 76Ge detectors at the Gran Sasso Laboratory (LNGS). It uses a novel shielding concept, with Ge crystals being operated directly in a 65 m3 volume of liquid argon, surrounded by a large water Cherenkov shield. The experiment proceeds in several phases. Phase I used an array of 16 enriched, HPGe detectors, and achieved a result excluding the existing hint of a signal from the Heidelberg-Moscow experiment. GERDA phase II will start in late 2014; it will use 30 additional enriched broad-energy germanium (BEGe) detectors, aiming for a total exposure of 100 kg yr. The half-life sensitivity will be $T_{1/2} > 2x10^{26}$ y, corresponding to a range of effective neutrino masses of 0.09- 0.15 eV. After phase II, GERDA will proceed to a ton-scale Ge experiment, within an international collaboration; an MoU with the Majorana experiment in the US is in place. The UZH group has been involved in the GERDA project since 2007, it has crucial responsibilities (the calibration system, tests of enriched BEGe detectors, contribution to the liquid argon veto instrumentation, analysis of weekly calibration runs, physics runs analysis) and plans to maintain its leading contribution in the future as well.

EXO searches for 0νββ-decay in enriched 136Xe using liquid xenon TPCs. EXO-200, an intermediate size prototype of 200 kg with 80% enriched xenon has already made the first-time observation of the two-neutrino double beta decay in Xe-136. Also, very stringent limits were obtained for the neutrino-less double beta decay. This first phase of the experiment has paved the way for a 5-tonnes detector, nEXO, able to sample the most interesting theoretical parameter space. The next generation neutrino-less double beta decay experiments, with a very large active mass and ultra low background, like the proposed nEXO, will have sensitivity to the half-life of the order of 10^{28} years. To this effect, parallel to increasing the detector mass, new techniques for large background reduction is mandatory. The EXO collaboration proposes to use the 136Ba ion from the double beta decay of 136Xe as an additional handle, which allows to completely reject the residual radioactive background. Single ion detection and identification (aka tagging) capability has been demonstrated only for baryum ions, applying Ba ion tagging to a massive LXe detector is a novel challenge. The R&D program conducted at the Bern University, in coordination with the EXO collaboration, will provide a definitive answer about the feasibility of Ba ion tagging for nEXO. It is planned to take data with nEXO by the end of the decade and nEXO is designed for an ultimate sensitivity to the effective neutrino mass in the range 4 - 6 meV, which fully covers the inverted hierarchy mass scenario.

5 The search for right-handed neutrinos

The existence of neutrino oscillations implies that neutrinos have mass. There is no unique way to upgrade the Standard model to provide neutrinos a mass. There are two possible mass terms for a neutral particle: 1) the 'Dirac' mass term similar to those of the other charged fermions, and represented in the Standard Model by their Yukawa couplings to the Higgs boson; 2) the 'Majorana' mass term, in which a neutrino is transformed into its (opposite helicity) anti-particle. The situation in which both terms are present generates the well-known 'see-saw' mechanism in which appear (mostly) right-handed, sterile, neutrinos of different masses than their left-handed partners – designated as Heavy Neutral Leptons HNL. Traditionally the HNLs have been considered to be very heavy (10^{10} GeV), but it has been pointed out that masses in the range of a few keV to the Z mass are perfectly plausible; the resulting states can still play a role of dark matter and generator of the Baryon asymmetry of the Universe, while their minute coupling compared to neutrinos ($|U|^2 \sim m_\nu/m_{HNL}$) has so far prevented their observation.

Two developments have recently taken place in the search for right-handed neutrinos, in which Swiss physicists have played a seminal role, showing that neutrino physics is likely to expand well beyond its traditional experimental techniques in the not so far future.

The SHIP experiment proposal, following an observation by M. Shaposhnikov, is based on the possibility to search for the decays in flight of long-lived HNL produced in a beam dump experiment in a long instrumented decay channel. The experiment is sensitive to masses for masses comprised between the pion mass and the charmed meson mass. The experiment is sensitive to many other 'dark sector phenomena', and is able to perform a rich program of tau neutrino interactions. The SHiP proto-collaboration LOI has received encouragement from CERN to prepare a technical proposal by a strengthened collaboration. The SHiP proto-collaboration now consists of 41 institutes from 14 countries. The Swiss institutes involved in this project are EPFL and the universities of Geneva and Zürich. Mikhail Shaposhnikov from EPFL is responsible for the theory support to the experiment, while Nicola Serra from the university of Zürich is convener of physics performances and background studies.

Finally, it was recently noted that FCC-ee (a.k.a. TLEP), the high luminosity e^+e^- machine of the Future Circular Collider study undertaken by CERN and an international collaboration, is able to perform direct observation of the decays of right-handed neutrinos HNLs. The FCC-ee is completely unique in that luminosity at the Z peak is over $2x10^{36}$ /cm^2/s in each of up to four collision point and might allow collection of 10^{13} Z decays in a few years. In this exposure, the decay in flight of several long lived right handed neutrinos would be observed if their mass is situated between 20 and 80 GeV. (Blondel, Graverini, Serra, Shaposhnikov).