CERN: the LHC and Switzerland's contributions

1. Introduction

The Large Hadron Collider (LHC), together with its four detectors ALICE, ATLAS, CMS and LHCb, represents the largest and most powerful microscope ever built. Smashing together particles at tera-electronvolt (TeV) energies will make it possible to study the physics of minute distances (about a billionth of the diameter of an atom). The path from electronvolt to tera-electronvolt energy scales leads from chemistry and solid-state electronics (electronvolt, eV) through nuclear reactions (mega-electronvolt, MeV) to the domains investigated by particle physicists over the past 50 years (giga-electronvolt, GeV). In the new tera-electron-volt domain, researchers hope to open up a window for the observation of entirely new physical phenomena. For example, they are searching for the Higgs boson (a particle believed to give other elementary particles their mass), which has not been detectable with the instruments available to date, or the mysterious particles that are thought to constitute dark matter, which in turn makes up the bulk of the matter in the universe.

Over the past 15 years, the LHC has been jointly planned, developed and constructed by physicists and engineers from all over the world. To avoid excessive costs, it was installed in the tunnel that housed CERN's previous accelerator, the Large Electron Positron collider (LEP): this circular tunnel, with a diameter of 8.6 kilometres and a circumference of 27 kilometres, lies at a depth of between 50 and 175 metres in the region between Geneva airport and the Jura Mountains. The new LHC will be commencing operations shortly. The goal of observing proton-proton collisions at 14 TeV should be achieved in 2009.

To identify and study in detail the new elementary particles emerging from these collisions, international consortia (collaborations) of particle physicists have planned, developed, constructed and commissioned four large detectors. These detectors may yield new insights into particle physics, providing a deeper understanding of the structure of matter and the nature of fundamental forces.

Switzerland has made substantial contributions to three of these detectors and, over the next 10 years, will assume responsibility for a correspondingly significant part of their operation and maintenance. Another major challenge will be to analyse the vast quantities of data produced by the detectors, from which the new insights are to be obtained. Switzerland's universities, the Federal Institutes of Technology and the Paul Scherrer Institute PSI are well prepared for this data analysis task.

This fact sheet is designed to provide a brief overview of the LHC and its operations (Sections 2–5), focusing in particular on Switzerland's contributions to the three detectors – or experiments – (Section 6) and to CERN (section 7).

2. The LHC machine

In its basic specifications, the LHC with its colliding particle beams surpasses all previous particle accelerators worldwide. The two proton beams, of the highest energy ever produced in a laboratory, will be kept in their orbits by more than 9000 magnets, most of which are superconducting. To produce these superconducting properties, the magnets have to be cooled by superfluid helium to a temperature of just under 2 K (-271.2°C). They can then conduct the electric current required to create powerful magnetic fields without resistance or loss of energy. The proton beams circulate in opposite directions in two separate tubes combined in a common magnet structure, travelling at 99.9999991% of the speed of light around the 27-kilometre ring. Each proton has a kinetic energy of 7 TeV – i.e. 7000 times greater than its mass at rest (and seven times more than can be achieved in today's highest-energy accelerator, the Tevatron at Fermilab in the US). When the system is running at full capacity, the total energy of the circulating particles will be 362 megajoules (MJ) per beam, which is roughly equivalent to the kinetic energy of a heavily laden freight train travelling at top speed.

The proton beams each consist of 2808 bunches, regularly spaced around the 27-kilometre ring. Each bunch is needle-shaped, a few centimetres long and containing about 100 billion protons. As they approach the four detectors located around the ring, the bunches are squeezed down to 16 microns in diameter (the diameter of a thin human hair). At the centre of the detectors, the bunches cross, producing more than 600 million proton collisions per second. In fact, the collisions involve the building blocks of protons – quarks and gluons. It is these collision events that are now to be studied in detail.

In view of all the engineering challenges, the complexity of the entire system and the large number of suppliers and academic collaborations involved, it is not surprising that the construction process has been delayed by a variety of technical problems. Overall, however, the engineers and scientists are extremely satisfied with the progress of the project. LHC project manager Lyn Evans commented: "For a machine of this complexity, things are going remarkably smoothly."

3. <u>The detectors</u>

Four giant detectors known as ATLAS, CMS, LHCb and ALICE are installed around the collision points; the largest would half-fill Notre-Dame Cathedral in Paris, while the heaviest contains more iron than the Eiffel Tower. These detectors will track and measure the different elementary particles produced in the collisions. To ensure that particle trajectories can be accurately tracked, the detector components have to be positioned with a precision of 50 microns. The 100 million channels of sensor data would fill 100,000 CDs every second. As it is not possible to record all this data, each detector has a multi-level selection (so-called trigger) system, which acts like a large-scale spam filter, sending data from only the few 100 most interesting-looking events per second to the central CERN computer system for storage and distribution to the worldwide computing grid for subsequent analysis. Sophisticated software makes it possible to analyse the particle tracks from these events and hence to calculate the variables of interest for the particles generated (momentum, mass, trajectory, etc.) as well as for their elementary parent particles.

The task to be performed by the detectors and the data processing system is gigantic: at full luminosity, around 20 proton-proton reactions (collisions) are expected to occur with each crossing of the proton bunches, and the next two bunches will cross only 25 nanoseconds later. This means that particles from collisions of the first crossing will still be moving through the outer layers of the detector when the next crossing begins. Accordingly, the detectors are designed on the onion skin principle, with a number of different layers (sub-detectors) devoted to specific particle types or measurement methods.

The detectors were built by international consortia of university departments and research laboratories, known as collaborations. They carried the project through intellectual input and through the development, construction and delivery of detector components. In some cases, hardware was produced at the institutes' own workshops, and in others it was manufactured by industry. While the collaborations for the two large detectors – CMS and ATLAS – comprise around 170 institutions, about 50 are involved in the LHCb and ALICE collaborations. Swiss participants also played key roles in these collaborations; their contributions will be discussed in Section 6.

4. Data processing

In a cluster of a few thousand computers at CERN (Tier 0), the filtered raw data from the detectors is converted into compact datasets, structured so as to allow analysis by physicists. Data analysis is carried out using the Grid, which consists of tens of thousands of computers at institutes around the world (Tier 2), all connected via a dozen nodes (Tier 1 sites) at major research centres on three continents. The nodes are linked with CERN via dedicated fibre-optic cables. To ensure data security, the raw data is archived on magnetic tape both at CERN and at the Tier 1 centres. Today, this is considered to be the safest and most cost-effective method.

The data recording and processing systems were tested before the start-up of the LHC: since cosmic ray particles can also be registered by the detectors, they have been used to test the detectors, the data recording systems and the data analysis software.

5. Scientific goals of the LHC

Exploration of the microworld in the tera-electronvolt domain is expected to yield new insights in the field of particle physics, which will certainly also influence associated areas of science. The physicists expect that this new world will reveal how the fundamental forces of nature – gravitation, the strong nuclear force and the electroweak force – are connected, and how they differ from one another. This should shed new light on fundamental questions, in particular on the question “what causes the fundamental forces and why do they take different forms?”.

In this enterprise, the search for the Higgs boson is merely the first step. In addition, phenomena could be discovered which explain why gravitation is so much weaker than the other fundamental forces and reveal the nature of the dark matter which pervades our universe.

Physicists today work on the basis of the Standard Model, which was developed in the 1970s and 1980s and has been substantially consolidated by experiments over the past 20 years. However, the theoretical picture provided by this model is incomplete, and it fails to explain a number of important observed phenomena. One of the basic principles of the Standard Model is that its equations for matter and antimatter are almost symmetric. However, the world is made up almost exclusively of matter – where does this large asymmetry come from?

Also unclear is the source of particle mass: in recent decades, no other problem has pre-occupied particle physicists more than that of the particle named after the theoretical physicist Peter Higgs, which could provide an answer to the fundamental question of how elementary particles acquire mass. The Higgs boson owes its now almost iconic status to the fact that it is the last building block of the Standard Model of particle physics that has yet to be observed experimentally. For this reason, the detection of the Higgs boson is one of the priority objective of the LHC.

6. Switzerland's contributions to the development of the LHC detectors

Researchers from four universities (Basel, Bern, Geneva, Zurich), the two Federal Institutes of Technology (EPFL and ETHZ) and the Paul Scherrer Institute (PSI) have participated in collaborations (international scientific consortia) and contributed to the development of the LHC detectors. Several of the Swiss researchers concerned have been involved since preparations first began about 15 years ago. Participation in these projects represents an important element in the portfolio of the academic institutions as centres of research and university teaching. Doctoral students who will subsequently assume leading roles in science, industry and government are thus given an opportunity to take part in the construction and operation of a unique research instrument.

Switzerland's scientific contributions to three of the four detectors are summarized in Table 1.[1] These include the intellectual and technical input of the research groups involved, software and hardware developed by the institutes themselves, and components produced by industry. This cooperation gave rise to a creative interchange of knowledge among the project partners and research and educational institutions, which will certainly lead to long-term value creation. Industry and research displayed creativity and ingenuity, especially when innovative technological and engineering solutions were required to achieve a maximum of accuracy and efficiency for detecting the particles. The unique knowledge gained in the process can now also be ploughed back into other projects and products, thereby benefiting the economy as a whole.

Mention should also be made of the active role played by Swiss institutions in the preparations for data analysis, and of the Swiss computing centre (Tier 2) required for evaluation of the results. Jointly initiated by all the participating institutions under the umbrella of the Swiss Institute for Particle Physics (CHIPP, www.chipp.ch), it is located at the Swiss National Supercomputing Centre (CSCS) in Manno (Canton Ticino).

Detector	No. of institutions involved worldwide	Swiss institutions involved	Swiss contributions to development and construction of detectors
ATLAS	169	Bern and University	Silicon strip tracking, calorimeter readout electronics, high-level trigger, data acquisition, event building, data logging, coil-casings, superconducting cable
CMS	183	Basel and Zurich University, ETHZ, PSI	Pixel detector, silicon strip detector, crystals, photo-sensors and readout electronics for electromagnetic calorimeter, superconductor for the 4 Tesla solenoid, magnet procurement
LHCb	51	EPFL, Zurich University	Silicon strip detectors, readout boards for subdetectors, vertex detector readout link, trigger

Table 1: The three LHC detectors with Swiss involvement. Hardware contributions of Swiss research groups are shown in the right-hand column.

Furthermore Swiss Physicists play very active roles in coordinating the projects. They are involved in the management of the collaborations on all levels of the organisation.

[1] No Swiss groups are involved in the fourth experiment (ALICE), which is concerned with heavy ion physics.

On January 1st, 2006, the number of full time equivalent physicists (FTE) from Swiss institutions working for the collaborations amounted to 21 for ATLAS, 38 for CMS and 25 for LHCb. In addition 7 PhD students from Swiss universities were involved in ATLAS, 13 in CMS and 11 in LHCb. From 1996 to 2008 a total of 70 master theses and 55 doctoral thesis were completed in connection with the development and construction of the LHC detectors. In addition, 5 PhD theses were devoted to LHC accelerator physics.

The total amount of investment in the period 1996 to 2008 from Swiss funding sources into the LHC detectors amounts to 130 MCHF, corresponding to about 9% of the total cost of the three detectors.

6.1 Swiss contributions to ATLAS construction

The ATLAS experiment is designed to optimally identify and measure the energy and direction of photons, charged leptons and other charged or neutral particles with high precision and within a dense tracking environment. As a general purpose system it is designed to detect as many physics signatures as possible.

A picture of the detector during the construction phase is shown in Fig. 1. Its size is impressive: it would fill half of Notre-Dame Cathedral in Paris (see size of a human in Fig. 1).

The detector contains a 7 m length inner tracking detector, a combination of discrete semi-conductor pixel and micro-strip elements surrounded by a straw tube tracker with transition radiation capability. The highly granular, very hermetic and radiation tolerant electromagnetic and hadronic calorimeters provide excellent energy measurement performance to within one degree of the beam line. The calorimeters are surrounded by a muon spectrometer, using a large high-field air-core toroid system that defines the overall magnitude of the experiment.

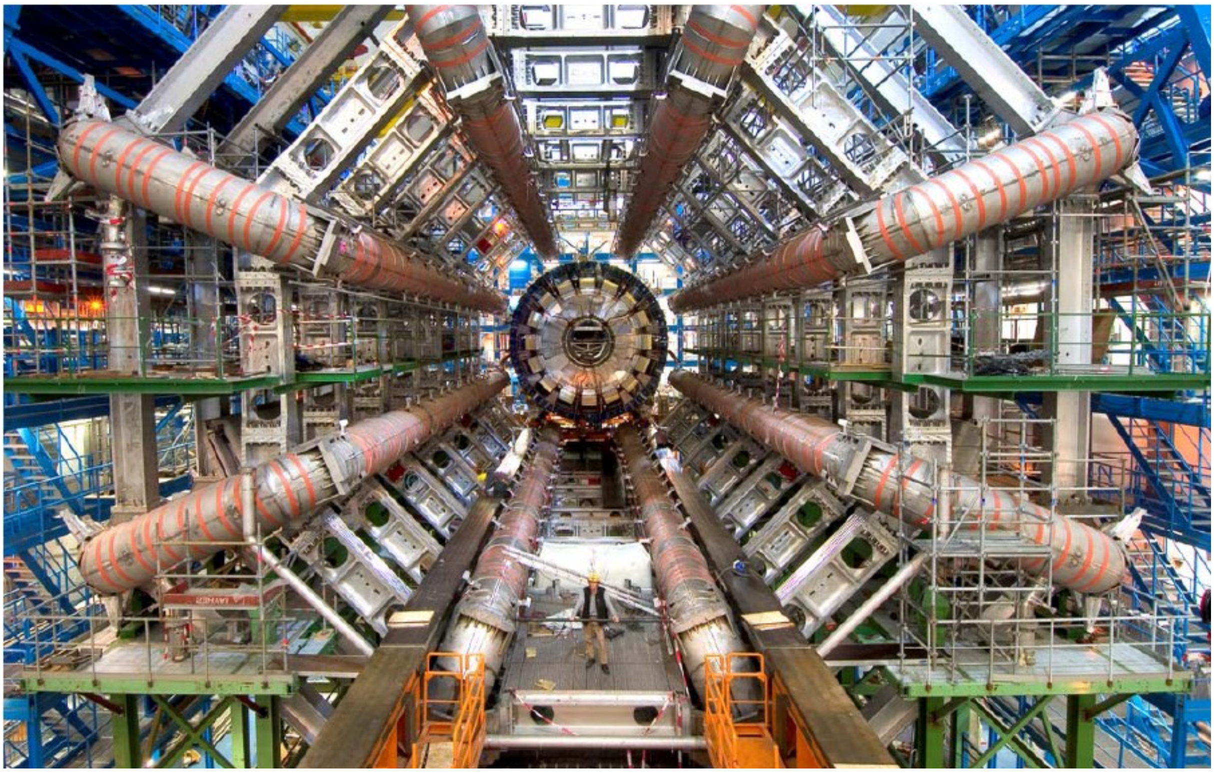

Fig. 1: Photo of the ATLAS detector at the LHC before inserting the detector elements. The eight symmetrically arranged tubes contain the superconducting coils, which generate the large toroidal magnetic field.

The magnet system is based on an inner thin superconducting solenoid surrounding the inner detector cavity and large superconducting barrel toroids consisting of eight independent coils arranged outside the calorimeters.

The following institutes are involved:

University of Bern: Prof. A. Ereditato, Prof. K. Pretzl (till 2006)
University of Geneva: Prof. A. Blondel, Prof. A. Clark, Prof. M. Pohl

Large industrial and service contracts (> 0.2 MCHF) have been placed with the following Swiss companies for a total value of 13.7 MCHF: Alcatel Cables Suisse, Asea Brown Boveri Switzerland, Cicorel SA, Dell Switzerland, EBV Elektronik, Hamamatsu Photonics, SUN Microsystems (in alphabetical order).

They have contributed to ATLAS as follows (see Fig. 2):

- Magnet systems
  U.BE + U.GE: responsibility in the procurements of the superconducting cable and of the aluminium coil casings;
- Silicon tracker:
  U.GE: silicon tracker support structure: design, prototyping, procurement and fitting of four high precision carbon fibre barrel supports, and their delivery for module assembly as well as barrel engineering coordination;
  U.GE: responsibility for the silicon tracker mechanics for the Inner Tracking Detector;
  U.GE: silicon tracker readout: design, prototyping, procurement and testing of the silicon sensors;
  U.GE: participation in the microelectronics design, prototyping, procurement and testing of the front end readout chip;
  U.GE: silicon tracker modules: design and prototyping of modules, assembly and testing of 657 modules (in collaboration with Cracow, Prague and CERN, where component tests and burn-in studies were made)
- Liquid argon calorimeter:
  U.GE: design, construction, testing and integration of a total of 245 readout drivers for the liquid argon calorimeter ROD boards;
- High level trigger and data acquisition system:
  U.BE: design, implementation, integration and commissioning of the event-building, event data routing, data-logging system;
  U.GE: calorimeter trigger and calibration algorithms trigger monitoring, trigger and online integration, commissioning with cosmic rays;
  U.BE + U.GE: design and implementation of the high level trigger steering software, algorithm timing, data preparation.

Overall Swiss spending for ATLAS (R&D and construction) for the period 1996-2008 amounts to 13.6 MCHF[2] with 77% from SNF and 23% from the Cantons (GE, BE)/Universities. During the development of ATLAS 9 master dissertations have been completed as well as 17 doctoral theses. Thanks to the leading-edge technology development, 4 spin-offs have been set up by people working at the two Universities on the ATLAS project.

[2] plus a CERN contribution of 8.8 MCHF following a donation of the Canton of Geneva to CERN (see section 7)

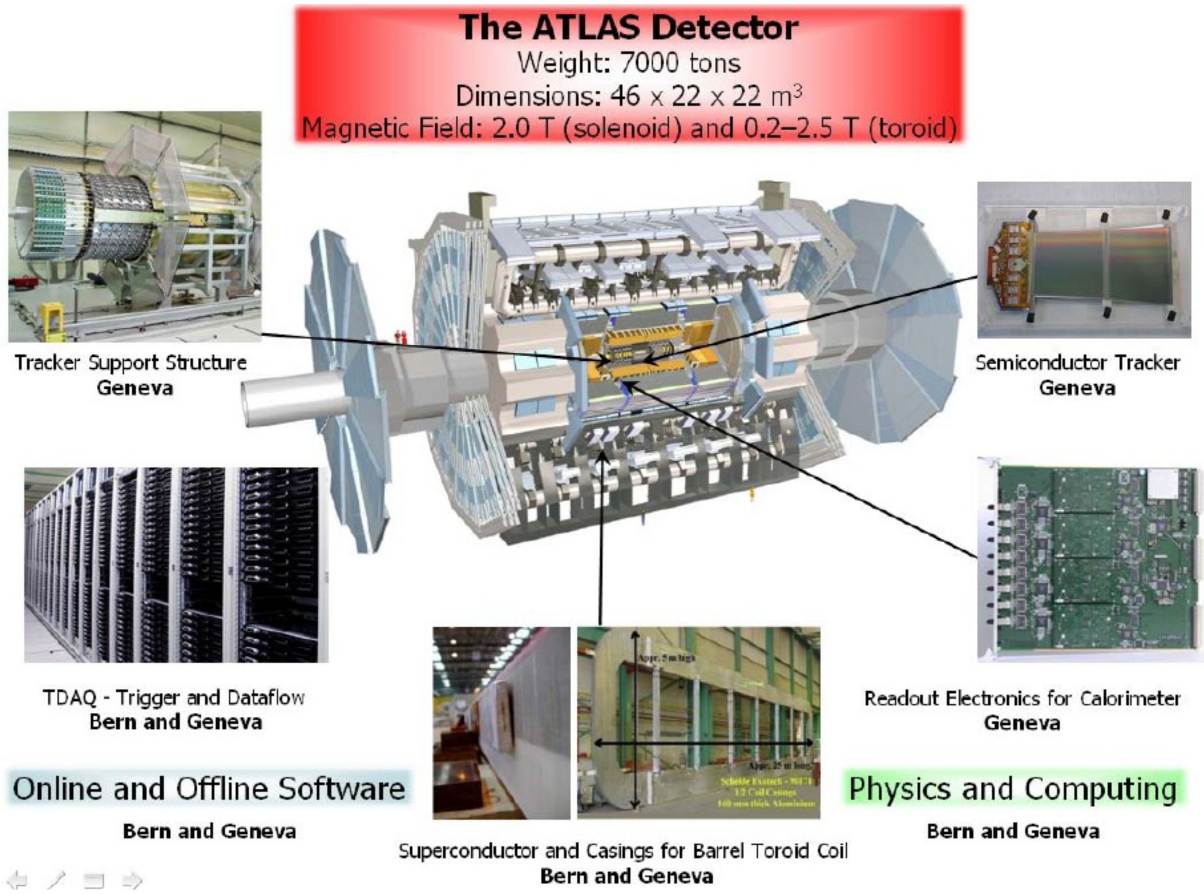

Fig. 2: Schematic view of the ATLAS detector and the various Swiss contributions

6.2 Swiss contributions to CMS construction

CMS is designed to measure the energy and momentum of photons, electrons, muons and other charged particles with high precision, resulting in an excellent mass resolution for particles decaying into these final states. CMS consists of a powerful inner tracking system based on silicon technology (microstrip and pixel), a high precision calorimeter (scintillating lead-tungstate crystals) followed by a sampling hadronic calorimeter made out of plastic scintillator tiles inserted between brass absorber plates, and a high magnetic field (4 Tesla) superconducting solenoid coupled with a multi-layer muon system.

CMS contains more iron than the Eiffel Tower, and the lowering of the detector elements into the underground hall (heavy lifting / lowering operation) constituted one of the most complex crane operations ever undertaken in particle physics. This operation went without problems also for the heaviest element, the 2000 tonne central barrel wheel.

The innermost tracking device of the CMS experiment, the pixel detector is composed of 1440 modules arranged in three barrel layers. The high precision electromagnetic calorimeter contains about 76,000 lead-tungstate crystals (total weight: approx. 80 tonnes) produced in Russia (72'000 crystals) and China (4'000 crystals).

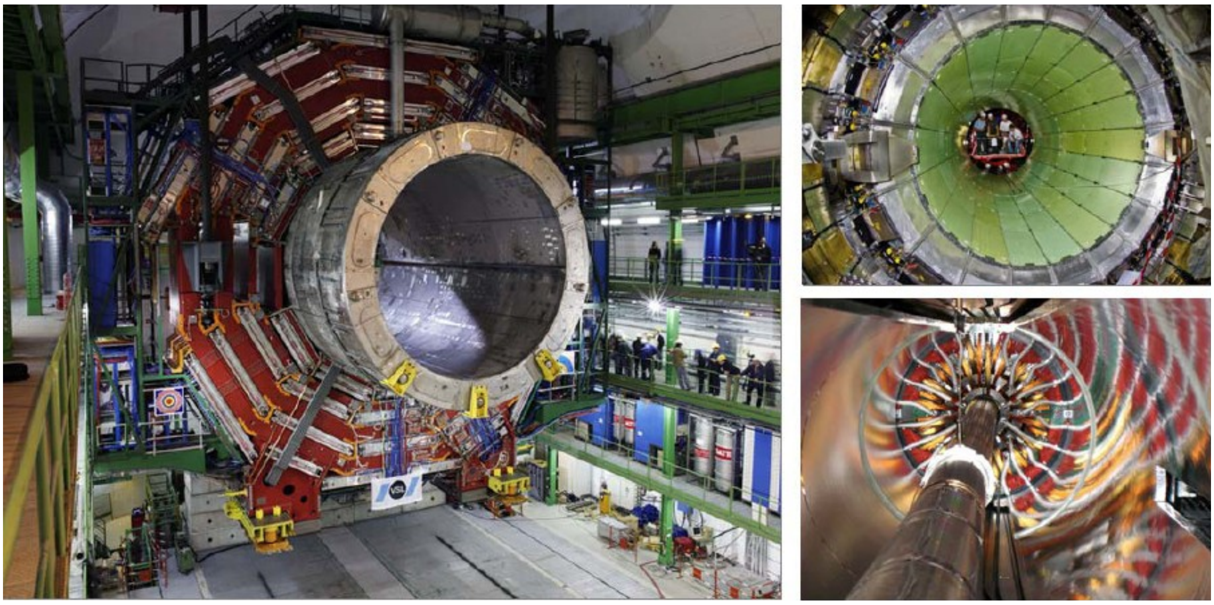

Fig. 3: CMS detector at the LHC:
Left: Lowering of the central and heaviest element in the CMS experimental cavern, 100 meter underground.
Right top: Completion of the barrel crystal calorimeter installation in July 2007.
Right bottom: Completion of the pixel detector installation in July 2008.

The following institutes and industrial companies are involved in CMS:

ETH Zurich: Prof. G. Dissertori, Prof. R. Eichler (till 2007), Prof. C. Grab, Prof. H. Hofer (till 2001), Prof. U. Langenegger, Prof. F. Pauss
Paul Scherrer Institute (PSI): Prof. R. Horisberger, Dr. Q. Ingram, Dr. D. Renker
University of Zurich: Prof. C. Amsler
University of Basel: Prof. L. Tauscher (till 2004)

Large industrial and service contracts (> 0.2 MCHF) have been placed with the following Swiss companies for a total value of 11 MCHF: Alcatel Cables Suisse SA, Ascom Schweiz AG, Brugg Kabel AG, GS Präzisions AG, Hamamatsu Photonics, Hightec Lenzburg, Marti Supratec AG, VSL Schweiz AG (in alphabetical order).

The Swiss groups have been involved in the design and physics evaluation since the early phase of CMS and have contributed as follows (see Fig. 4):

- CMS engineering and integration centre EIC at CERN:
  ETHZ: leader of the CMS EIC at CERN where the production of the various detector components in the different countries is coordinated and controlled;
- Crystal calorimeter:
  ETHZ: procurement and performance evaluation (including irradiation tests) of the 76,000 crystals;
  ETHZ and PSI: design, procurement, testing of electronics components and integration of the readout electronics, including responsibilities for the software.
  PSI: production, delivery and screening of the 140,000 APDs (Avalanche Photo Diodes) for the barrel crystals; a 99.9% reliability for 10 years of operation at LHC is expected;
- Pixel barrel detector:
  PSI and ETHZ: design, construction and commissioning including design and development of the pixel sensor, the detection modules and the readout chip;
  U.ZH: construction of the pixel barrel detector support, its cooling structure and the

supply tube containing the optical links for control and readout; development of critical parts of the software for reconstructing the particle trajectories;

- Superconducting coil of the magnet:
  ETHZ: leading responsibility for the superconducting cable manufacturing processes, and in large part for magnet design and procurement.

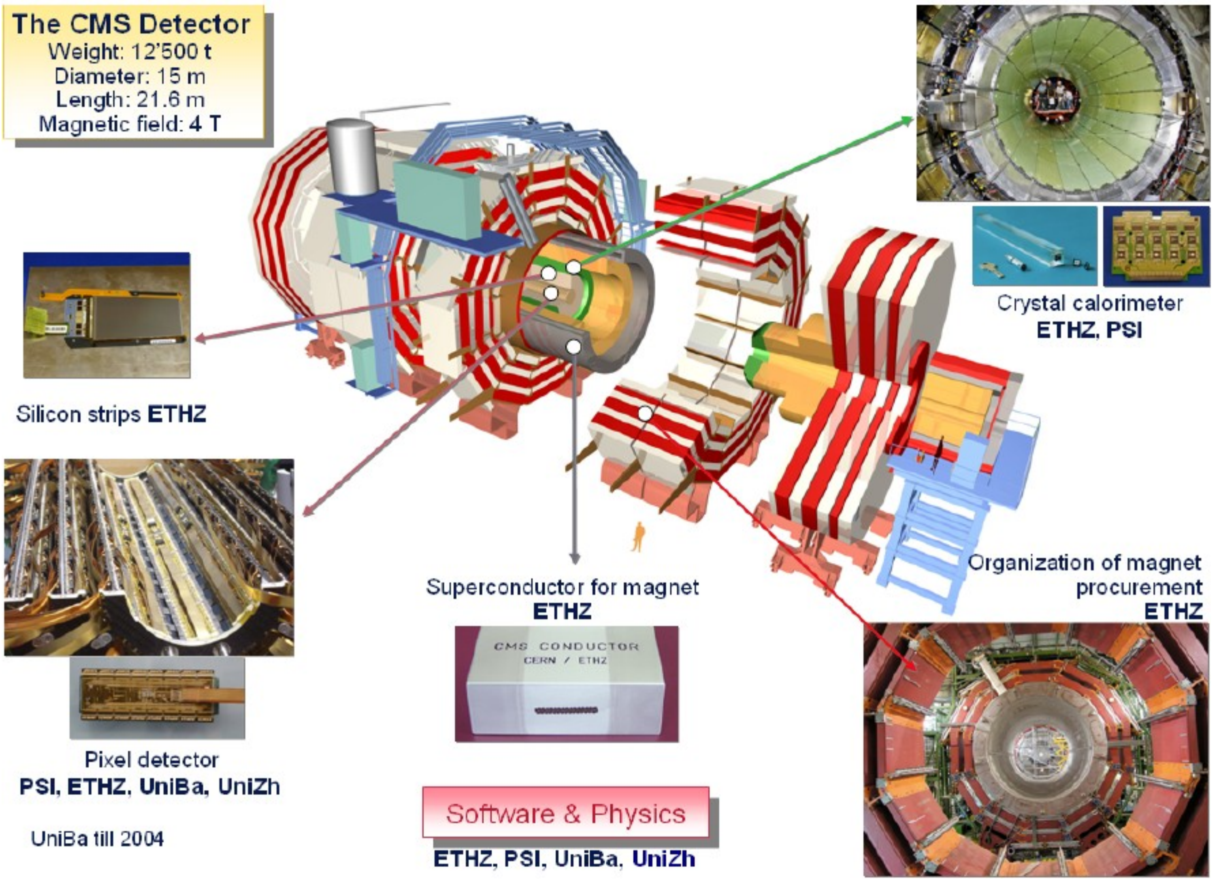

Fig.4: Schematic view of the CMS detector and the various Swiss contributions

Overall Swiss spending for CMS (R&D and construction) for the period 1996-2008 amounts to 107 MCHF with 18% from SNF, less than 1 % from the Cantons (ZH, BS)/Universities, 65% from the ETH; and 16% from the Federal Authorities.[3] During this period 34 master dissertations have been completed as well as 19 doctoral theses. Thanks to the leading-edge technology development, two spin-offs have been set up by people working at the 4 research institutes on the CMS project.

6.3 Swiss contributions to LHCb construction

LHCb is a second generation experiment on b quark physics, which will perform systematic measurements of [4]CP violating processes and rare decays in the B meson systems, with unprecedented precision and in many different decay channels of b quark mesons.

The detector is laid out as a single-arm forward spectrometer, using a large dipole magnet (see photo and side view in Figures 5 and 6 respectively).

[3] no details available from U.BS

[4] Particle and anti-particle symmetry

The following Swiss institutes and industrial companies are involved in LHCb:

EPFL (since 2003; before: University of Lausanne): Prof. A. Bay, Prof. T. Nakada (Spokes-person till 2008; Physics coordinator since 2008), Prof. O. Schneider (Physics coordinator till 2008)
University of Zurich: Prof. U. Straumann

Large industrial and service contracts (> 0.2 MCHF) have been placed with the following Swiss companies for a total value of 2.7 MCHF: EBV Elektronik, Hamamatsu Photonics, Mahr AG Schweiz (in alphabetical order).

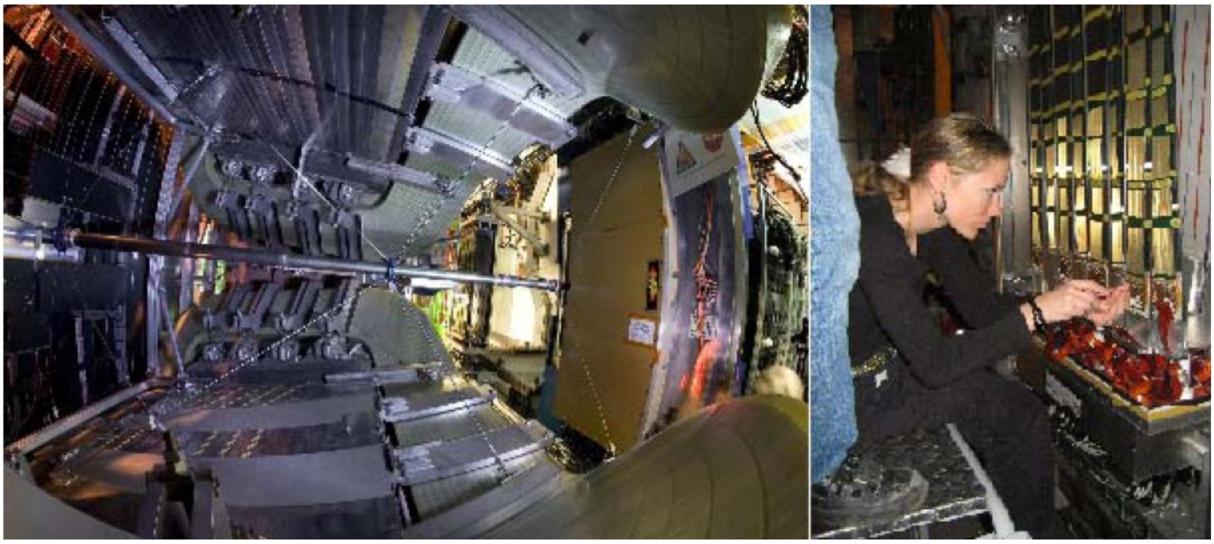

Fig. 5: Photo of the LHCb detector at the LHC.
Left: LHCb Spectrometer Magnet before the installation of the detectors.
Right: Installation of a silicium strip detector “made in Zurich”.

They have concentrated on (see Fig.6):

- development, construction and implementation of the LHCb Silicon Tracker.
  EPFL: Inner Tracker (inner part of T1, T2, T3);
  U.ZH: Trigger Tracker (TT);
- common readout electronics system for Silicon Tracker and the Vertex detector VELO:
  U.ZH: development, construction and commissioning of the on-detector part of the readout electronics of the Silicon Tracker. The digital optical data transfer part of the system is also used by almost all other subdetectors of LHCb;
  EPFL: development of a readout electronic system for VELO and Silicon Tracker (TELL 1). It has been adopted by almost all LHCb sub-detector systems.

Overall Swiss spending for LHCb (R&D and construction) for the period 1996-2008 amounts to 11 MCHF with 56% from SNF, 30% from the Cantons (VD, ZH)/Universities, 14% from the ETH. During this period 27 master dissertations have been completed as well as 19 doctoral theses. No spin-offs have been set up.

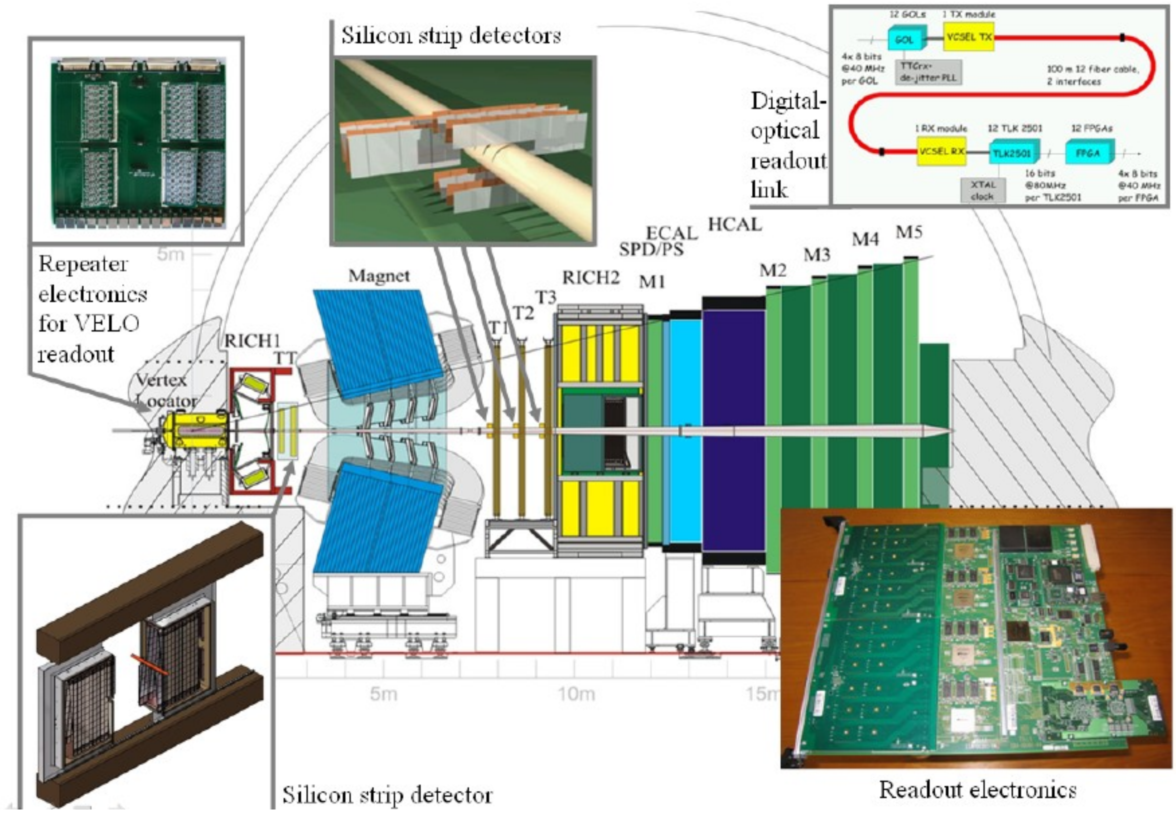

Fig. 6: Schematic side view of LHCb and the Swiss contributions

7. <u>**Contributions of Switzerland as CERN host state and industrial returns**</u>

For many years, in addition to the regular member state contribution of approx. 30 MCHF per year (equivalent to about 3% of the total CERN budget), Switzerland as a host state has provided direct support for CERN through special contributions totalling more than 125 MCHF. These special contributions underline the political will to ensure that CERN as a global particle physics laboratory remains in Switzerland and that its reputation helps to foster a new generation of scientists and technologists in this country.

Special contributions include, for example, advance payment of member state contributions to alleviate cash-flow difficulties, financing of infrastructure (e.g. water pumping stations), granting of an additional adjustment for inflation, contributions to scientific experiments, and a special contribution for implementation of the European Strategy for Particle Physics. In addition, the federal government and Canton Geneva have contributed jointly to infrastructure projects, such as a tunnel connecting the pre-accelerator and the LHC.

Not included in the special contributions are interest-free loans for construction projects (just under 46 MCHF) and the Palais de l'Equilibre from the 2002 Swiss National Exhibition (Expo.02), which Switzerland presented to CERN as a 50th anniversary gift (transported and reassembled by the army). The following list gives an overview of special contributions from the last 20 years.

LEP special contribution	8.1	MCHF
Vengeron pumping station	4.0	MCHF
Interest on advance payments of contributions (1990–1992; 2007–2009)	27.0	MCHF
Additional adjustment for inflation	11.2	MCHF
Neutrino experiment CNGS	1.5	MCHF
LHC test beam at PSI	13.2	MCHF
European Strategy for Particle Physics: special contribution	27.6	MCHF
LHC special contribution (tunnel and ATLAS) *of which Canton Geneva: 16.3 MCHF*	33.8	MCHF
Total value of special contributions	**126.4**	**MCHF**

However, as a host state, Switzerland also benefits from the presence of CERN: compared with its contribution to the budget, Switzerland accounts for a relatively large proportion of CERN staff – 7.4%. Apart from the scientists working at CERN as employees or as visiting researchers, a large number of Swiss nationals have found skilled employment at CERN in administrative or technical positions in particular. In addition, CERN offer more than 20 highly attractive places for apprentices, more than three quarters of which are filled by Swiss candidates.

The people who work at CERN also represent an important economic factor for the region: 2500 staff live here, purchase goods and services and in many cases have bought property. As a result, a large proportion of the salaries paid flows back into Switzerland. The more than 8000 visiting scientists from all over the world who spend a certain amount of time at CERN each year contribute to the local tourism sector.

Even more substantial are the sums returned to Switzerland through industrial supply and service contracts, a relatively high proportion of which are awarded by CERN to Swiss companies – often for location-related reasons. By way of example, the following list shows that, over the past 5 years, net returns amounted to more than 200 MCHF.

	2003	**2004**	**2005**	**2006**	**2007**	**Total**
Returns through supply contracts	35.4	54.1	55.3	49.3	33.5	227.6
Returns through service contracts	28.9	32.2	26.9	29.1	28.7	145.8
Total	**64.3**	**86.3**	**82.2**	**78.4**	**62.2**	**373.4**
Switzerland's annual contribution	35.5	29.5	31.7	32.2	31.5	160.4
Net returns	28.8	56.8	50.5	46.2	30.7	**213.0**