

## CERN and the future of particle physics

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**Summary.** — This paper presents CERN and its current scientific programme and outlines options for high-energy colliders at the energy frontier for the years to come. The immediate plans include the exploitation of the LHC at its design luminosity and energy as well as upgrades to the LHC and its injectors. This may be followed by a linear electron-positron collider, based on the technology being developed by the Compact Linear Collider and by the International Linear Collider, or by a high-energy electron-proton machine, the LHeC. This contribution describes the past, present and future directions, all of which have a unique value to add to experimental particle physics, and concludes by outlining key messages for the way forward.

PACS 14.80.Da – Supersymmetric Higgs bosons.

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PACS 12.38.Mh – Quark-gluon plasma.

PACS 12.15.Ff – Quark and lepton masses and mixing.

### 1. – CERN - A global laboratory for particle physics

The mission of CERN is fourfold:

- Push back the frontiers of knowledge. This includes gaining further understanding of the secrets of the early Universe shortly after the Big Bang and the nature of matter within the first moments of the Universe's existence.
- Develop new technologies for accelerators, detectors and computing. These technologies can subsequently be transferred to other applications, something which has happened with the World Wide Web and the Grid in information technology and with diagnosis and therapy techniques in medicine.
- Train the scientists and engineers of tomorrow.
- Unite people from different countries and cultures.

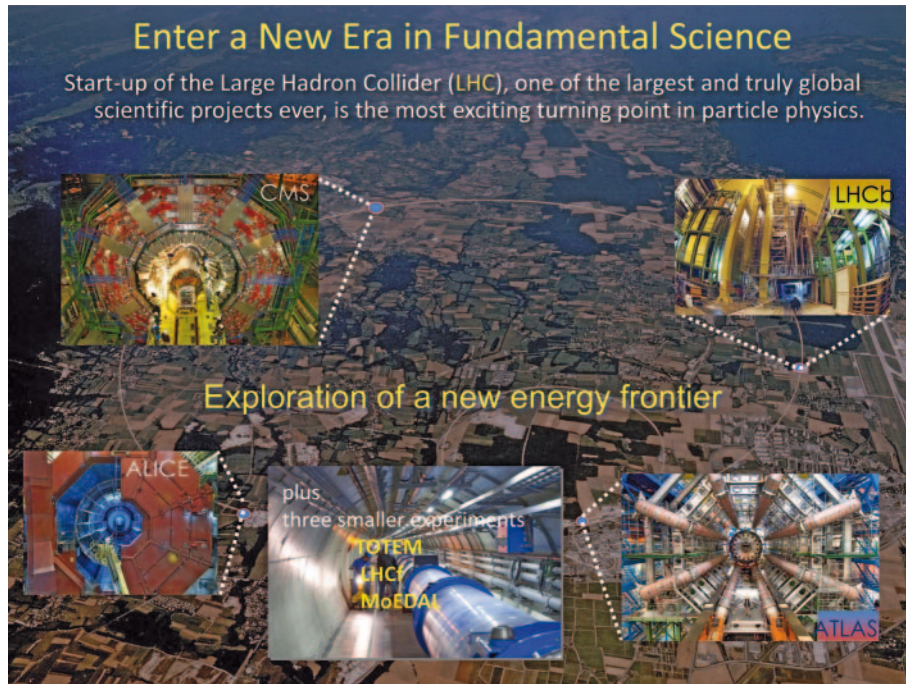


Fig. 1. – The LHC accelerator and the ALICE, ATLAS, CMS and LHCb experiments. There are also three smaller experiments - LHCf, MoEDAL and TOTEM.

The above mission is supported by the more than 10 000 scientific users from the Member States, Observer States and states with which CERN has concluded co-operation agreements. A survey conducted in March 2009 shows that the age of scientists at CERN peaks in the 20s and that there are more than 2 500 PhD students in the LHC experiments alone. Earlier surveys of the destination of students during the LEP period showed that after completing their PhDs most students went on to careers in the private sector.

Amongst the numerous education and training programmes, the CERN Summer Student Programme is of particular note. About 250 advanced undergraduate students joined the programme in 2010, originating from both Member States and non-Member States. Moreover, the High School Teacher Programme has been highly successful in bringing to CERN about 3 000 teachers during the period 1998-2010, with close to 1 000 teachers in 2010 alone. The knowledge and skills they obtain during their stays at CERN is then transferred to the classroom, with highly visible effects in capturing the interest and imagination of the next generation of would-be scientists.

## 2. – The Large Hadron Collider

**2.1. The Physics.** – The Large Hadron Collider (LHC) [1] is primarily a proton-proton collider (see fig. 1) with a design centre-of-mass energy of 14 TeV and nominal luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , and will also be operated in heavy-ion mode. The high 40 MHz proton-proton collision rate and the tens of interactions per crossing result in an enormous challenge for the experiments and for the collection, storage and analysis of the data.

By colliding unparalleled high-energy and high-intensity beams, the LHC is opening up previously unexplored territory at the TeV scale in great detail, allowing the experiments to probe deeper inside matter and providing further understanding of processes that occurred very early in the history of the Universe.

Of central importance to the LHC is the elucidation of the nature of electroweak symmetry breaking, for which the Higgs mechanism and the accompanying Higgs boson(s) are presumed to be responsible. In order to make significant inroads into the Standard Model Higgs Boson search, sizeable integrated luminosities of several  $\text{fb}^{-1}$  are needed. However, even with  $1 \text{fb}^{-1}$  per experiment, discovery of the Standard Model Higgs Boson is still possible in mass regions beyond the lower limit of 114.4 GeV from direct searches at LEP2. At the initial LHC centre-of-mass energy of 7 TeV and with  $1 \text{fb}^{-1}$  per experiment, combining the results from ATLAS and CMS would provide a  $3 \sigma$  sensitivity to a Standard Model Higgs Boson mass in the range 135 GeV to 475 GeV, and will exclude the Standard Model Higgs Boson between 120 GeV and 530 GeV at 95% CL. Combining the results from ATLAS and CMS at 7 TeV centre-of-mass energy and assuming about  $10 \text{fb}^{-1}$  per experiment would exclude at 95% CL the mass range from 600 GeV down to the LEP2 lower limit and would also provide a  $3 \sigma$  sensitivity to a Standard Model Higgs Boson in the same mass range.

The reach for new physics at the LHC is considerable already at LHC start-up. In Supersymmetry (SUSY) theory, due to their high production cross-sections, squarks and gluinos can be produced in significant numbers even at modest luminosities. This would enable the LHC to start probing the nature of dark matter. The LHC discovery reach for SUSY particles is up to a mass of about 700 GeV for  $1 \text{fb}^{-1}$  per experiment at 7 TeV centre-of-mass energy.

The discovery reach for new heavy bosons  $Z'$  and  $W'$  is about 1.6 TeV and 2.1 TeV, respectively, for  $1 \text{fb}^{-1}$  per experiment at 7 TeV centre-of-mass energy.

The LHC will also provide information on the unification of forces, the number of space-time dimensions and on matter-antimatter asymmetry. With the heavy-ion collision mode, the LHC will probe the formation of the quark-gluon plasma at the origin of the Universe.

## 2.2. LHC Operations

**2.2.1. The Past.** The start-up of the LHC on 10 September 2008 was a great success for both the accelerator and the experiments. Circulating beams were established rapidly and the beams were captured by the radiofrequency system with optimum injection phasing and with the correct reference. The incident of 19 September 2008, caused by a faulty inter-magnet bus-bar splice, resulted in significant damage in Sector 3-4 of the accelerator. Actions were taken immediately to repair the damage and to introduce measures to avoid any re-occurrence. The damaged thirty-nine main dipole magnets and fourteen quadrupole magnets were removed and replaced. Fast pressure release valves (DN200) were added on the main magnets, an improved anchoring on the vacuum barriers was introduced around the ring, and most importantly an enhanced quench protection system was implemented. Any remaining risks to the LHC, due to the shortcomings of copper-stabilizer joints of the main LHC magnets, are minimized by limiting the top beam energy in the first years of LHC operation.

Excellent progress was made in the above-mentioned repair, consolidation and improvement work, and first collisions at the LHC were recorded by the experiments on 23 November 2009 at a centre-of-mass energy of 900 GeV. During this first physics run at

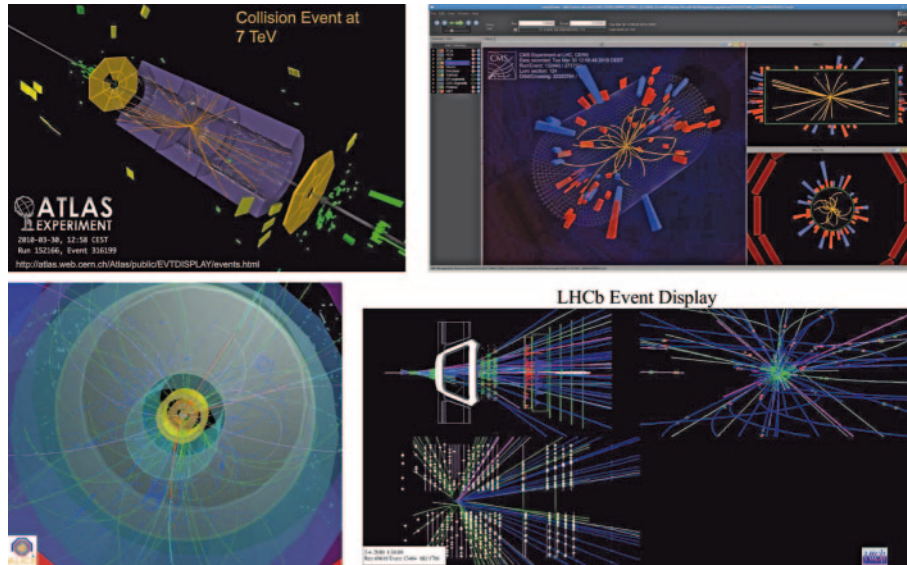


Fig. 2. – First collisions at 7 TeV centre-of-mass energy.

the end of 2009, the LHC accelerator performed exceptionally and the readiness of the experiments and the computing Grid was excellent, resulting in impressive preliminary results provided already at an open seminar held at CERN on 18 December 2009 and the prompt publication of the first physics results by year's end.

First LHC beams for 2010 were available on 27 February for commissioning the accelerator with beam. This was followed by first physics collisions at 7 TeV centre-of-mass energy on 30 March (see fig. 2) and by the first physics runs with a stronger focusing at the interaction points. During the 2009 and 2010 LHC physics runs, data has been collected at 900 GeV, 2.36 TeV and 7 TeV centre-of-mass energies with increasing instantaneous luminosities.

The main LHC achievements for 2010 can be summarized as follows:

- Excellent performance of the LHC machine for both proton and Pb-ion beams. Beam operation availability was 65% on average. Peak instantaneous luminosities of  $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  were attained for proton-proton collisions, which were a factor of two above the 2010 goal and which resulted in almost  $50 \text{ pb}^{-1}$  of integrated luminosity delivered to the experiments. Following a short 4-day switch-over to Pb-ion beams, peak luminosities of  $3 \times 10^{25} \text{ cm}^{-2} \text{ s}^{-1}$  were attained for Pb-Pb collisions with almost  $10 \mu\text{b}^{-1}$  of integrated luminosity delivered to the experiments.
- The experiments took data of excellent quality and with high efficiency. The physics analyses re-measured the science of the Standard Model of Particle Physics, in many instances superseding limits set at the Tevatron while taking the LHCs first steps into new territory. As a result, 54 physics papers based on the 2010 data were published and more than 1140 conference presentations were made by the LHC experiments.
- The performance of the LHC Computing Grid was also outstanding, exceeding the design bandwidth and allowing a very fast reconstruction and analysis of the data.

**2.2.2. The Present.** At the LHC Performance Workshop in Chamonix, held at the end of January 2011, the current state of the LHC was evaluated and presented, leading subsequently to the following decisions:

- The LHC will be operated during 2011 and 2012 with target integrated luminosities of  $1 \text{ fb}^{-1}$  by the end of 2011 at 3.5 TeV/beam and of several  $\text{fb}^{-1}$  by the end of 2012. Heavy-ion runs are scheduled at the end of both years, each of about 4 weeks duration. A technical stop of about 3 months around Christmas 2011 is needed.
- This extended operations period will be followed by a long shutdown (of about 20 months beam-to-beam) starting at the end of 2012 to repair and consolidate the inter-magnet copper-stabilizers (splices) to allow for safe operation up to 7 TeV/beam for the lifetime of the LHC.
- In the shadow of the inter-magnet copper-stabilizer work, the installation of the pressure rupture disks (DN200) will be completed and around 20 magnets which are known to have problems for high energy will be repaired or replaced. In addition, PS and SPS consolidation and upgrade work will be carried out.
- During this shutdown, the collimation system will also be upgraded at region Point 3 of the LHC.
- The experiments will use the shutdown to implement a programme of consolidation, improvements and upgrades.

**2.2.3. The Future.** The coming years will lay the foundation for the next decades of high-energy physics at the LHC. The LHC research programme until around 2030 is determined by the full exploitation of its physics potential, consisting of the design luminosity and the high-luminosity upgrade (HL-LHC), together with superconducting higher-field magnets for a higher-energy proton collider (HE-LHC), if necessitated by the physics. These initiatives will position CERN as the laboratory at the energy frontier.

The strategy for the LHC for the coming years is the following:

- Exploitation of the physics potential of the LHC up to design conditions in the light of running experience and by optimizing the schedule for physics.
- Preparation of the LHC for a long operational lifetime through appropriate modifications and consolidation to the machine and detectors and through the build-up of an adequate spares inventory.
- In the years 2015, 2016 and 2017, the LHC will be operated towards 7 TeV/beam with increased intensities and luminosities.
- In 2017/2018, a long shutdown is scheduled to connect LINAC4 [2], to complete the PS Booster energy upgrade, to finalize the collimation system enhancement and to install LHC detector improvements. After this shutdown, a further period of three years of LHC operation at 7 TeV/beam and at least the design luminosity is planned (with short technical stops around the end of each year).
- The ambitious longer-term plans include a total integrated luminosity of the order of  $3000 \text{ fb}^{-1}$  (on tape) by the end of the life of the LHC. This High-Luminosity LHC (HL-LHC) implies an annual luminosity of about  $250\text{-}300 \text{ fb}^{-1}$  in the second decade



of running the LHC. The HL-LHC upgrade is also required to implement modifications to elements in the insertion regions of the machine whose performance has deteriorated due to radiation effects, such as the inner triplet quadrupole magnets. The HL-LHC upgrade is scheduled for the 2021/2022 long shutdown.

- LHC detector R&D and upgrades to make optimal use of the LHC luminosity.

This strategy is also driven by the necessity to bring the LHC injector chain and the technical and general infrastructure up to the high standards required for a world laboratory in order to ensure reliable operation of the CERN complex.

### 3. – Fixed-target physics

CERN has a rich fixed-target physics programme, consisting of experiments at the facilities of the Antiproton Decelerator (AD) [3], the neutron Time-of-Flight (nTOF) [4], the On-Line Isotope Mass Separator (ISOLDE) [5], the axion search experiments [6] and at the external lines of the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS). Information on all fixed-target experiments can be found in the CERN Database of Experiments [7] and only a few examples are given here.

The Antiproton Decelerator is a unique machine providing low-energy antiprotons for studies of antimatter and in particular for creating anti-atoms. In 2002 the ATHENA and ATRAP experiments at the AD successfully made large numbers of anti-atoms for the first time. Currently, the AD serves three experiments that are studying antimatter: ALPHA, ASACUSA and ATRAP. A fourth experiment, ACE, also uses antiprotons, in this case to assess the suitability of antiprotons for cancer therapy. The highlight for 2010 was the first trapping of anti-hydrogen atoms by the ALPHA and ASACUSA experiments, which attracted much interest in the international media and which was cited as Breakthrough of the Year by the Physics World Magazine.

The CERN Neutrinos to Gran Sasso (CNGS) [8] programme has the aim of studying neutrino oscillations. The CNGS beam consists primarily of muon neutrinos sent from CERN to the Gran Sasso National Laboratory (LNGS), 732 km away in Italy. There, two experiments, OPERA [9] and ICARUS [10], measure the oscillation of muon neutrinos to tau neutrinos in the intervening long baseline. Recently, OPERA has observed the first tau neutrino candidate event in their detector and ICARUS has detected the first neutrino interaction in their T600 module.

The CLOUD experiment [11] is using a cloud chamber to study the possible link between cosmic-rays and cloud formation. The CLOUD experiment recorded very clean data in 2010, which allowed the first measurement of the critical cluster at the molecular level for various temperatures.

### 4. – The way forward and the European strategy for particle physics

The LHC will provide a first indication of any new physics at energies of the TeV scale. Many of the questions left open by the LHC and its upgrades may be addressed best by an electron-positron collider, based on technology developed by the Compact Linear Collider (CLIC) [12] and International Linear Collider (ILC) [13] Collaborations. Moreover, the option of a high-energy electron-proton collider (LHeC) [14] is being considered for the high-precision study of QCD and of high-density matter.

Great opportunities are in store at the TeV scale and a fuller understanding of Nature will come about through a clearer insight at this energy level. The discovery of the

Standard Model over the past few decades has advanced through the synergy of hadron-hadron (*e.g.*, SPS and the Tevatron), lepton-hadron (HERA) and lepton-lepton colliders (*e.g.*, LEP and SLC). Such synergies should be continued in the future and thus a strategy has been developed along these lines. An upgrade to the LHC will not only provide an increase in luminosity delivered to the experiments, but will also provide the occasion to renew the CERN accelerator complex. The ILC could be constructed now whereas further R&D is needed for CLIC. There is a drive to converge towards a single electron-positron linear collider project. The above effort on accelerators should advance in parallel with the necessary detector R&D. First results from the LHC will be decisive in indicating the direction that particle physics will take in the future.

European particle physics is founded on strong national institutes, universities and laboratories, working in conjunction with CERN. The increased globalization, concentration and scale of particle physics require a well-coordinated European strategy. This process started with the establishment of the CERN Council Strategy Group, which organized an open symposium in Orsay in 2006, a final workshop in Zeuthen in May 2006 and with the strategy document being signed unanimously by Council in July 2006 in Lisbon [15]. CERN considers experiments at the high-energy frontier to be the premier physics priority for the coming years. This direction for future colliders at CERN follows the priorities set in the strategy document. The European Strategy for Particle Physics includes several other key areas of research, all in line with the plans of CERN for the future directions. The start of the LHC physics exploitation is leading to important input for the update of the European strategy for particle physics planned for 2012.

CERN Council opened the door to greater integration in particle physics when it recently unanimously adopted the recommendations to examine the role of CERN in the light of increasing globalization in particle physics. The key points agreed by Council include a) all states shall be eligible for CERN Membership, irrespective of their geographical location; b) a new Associate Membership status is to be introduced to allow non-Member States to establish or intensify their institutional links with CERN; and c) the participation of CERN in global projects is to be enabled wherever they are sited.

## 5. – Future high-energy linear colliders

**5.1. *The Compact Linear Collider (CLIC)*.** – The conceptual lay-out of CLIC is based on using lower-energy electron beams to drive high-energy beams. The fundamental principle is that of a conventional AC transformer. The lower-energy drive beam serves as an RF source that accelerates the high-energy main beam with a high-accelerating gradient. The nominal centre-of-mass energy is up to 3 TeV, the luminosity exceeds  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , the main linear accelerator frequency is 12 GHz, the accelerating gradient is 100 MeV/m and the total length of the main linear accelerators is 48.3 km.

CLIC requires more R&D. In particular, the target accelerating gradient is considerably high and requires very aggressive performance from the accelerating structures. The nominal CLIC accelerating gradient has been exceeded in an unloaded structure with a very low breakdown probability of less than  $3 \times 10^{-7}$  per metre after RF conditioning for 1200 hours.

The mandate of the CLIC team is to demonstrate the feasibility of the CLIC concept by the year 2012 in a Conceptual Design Report. If this effort is successful, and if the new physics revealed by the LHC warrants, the next phase of R&D on engineering and cost issues will be launched. This would serve as the basis for a Technical Design Report and a request for project approval.

**5.2. *The International Linear Collider (ILC).*** – The ILC, which is an option for a linear electron-positron collider at lower energies than CLIC, is based on a more conventional design for acceleration using superconducting standing wave cavities with a nominal accelerating field of 31.5 MeV/m and a total length of 31 km at 500 GeV centre-of-mass energy and upgradable to around 1 TeV. A two-stage technical design phase during 2010-2012 is presently underway. A major contribution from Europe and from DESY to the ILC Global Design Effort is the European X-ray Laser Project XFEL at DESY. The purpose of the facility is to generate extremely brilliant and ultra-short pulses of spatially-coherent X-rays. The electron energy is brought up to 20 GeV through a superconducting linear accelerator, of length one-tenth that of the ILC superconducting linear accelerator, and conveyed to long undulators where the X-rays are generated and delivered to the experimental stations. The XFEL technical design is ready and the aim is to start operation of the XFEL in 2015.

The strategy to address key issues common to both linear colliders involves close collaboration between ILC and CLIC. Recent progress has been encouraging in this respect and common meetings between ILC and CLIC are being held regularly.

**5.3. *Detector challenges.*** – R&D on key components of the detector for a linear collider is mandatory and also well underway. High-precision measurements demand a new approach to the reconstruction. Particle flow, namely reconstruction of all particles, is thus proposed requiring unprecedented granularity in three dimensions of the detection channels.

## 6. – Key messages

Particle physics will need to adapt to the evolving situation. Facilities for high-energy physics (as for other branches of science) are becoming larger and more expensive. Funding is not increasing and the timescale for projects is becoming longer, both factors resulting in fewer facilities being realized. Moreover, many laboratories are changing their missions. All this leads to the need for more co-ordination and more collaboration on a global scale. Expertise in particle physics needs to be maintained in all regions, ensuring the long-term stability and support through-out. It will be necessary to engage all countries with particle physics communities and to integrate the communities in the developing countries. The funding agencies should in their turn provide a global view and synergies between various domains of research, such as particle physics and astroparticle physics should be exploited.

Particle physics is now entering a new era. The start-up of the LHC allows particle physics experiments at the highest collision energies. The expectations from the LHC are great, as it could provide revolutionary advances in the understanding in particle physics and a fundamental change to our view of the early Universe. Due to the location of the LHC, CERN is in a unique position to contribute to further understanding in particle physics in the long term.

Results from the LHC will guide the way in particle physics for many years. It is expected that the period of decision-making concerning the energy frontier will be in the next few years. Particle physics is now in an exciting period of accelerator planning, design, construction and running and will need intensified efforts in R&D and technical design work to enable the decisions for the future course. Global collaboration coupled with stability of support over long time scales is mandatory.



The particle physics community needs to define now the most appropriate organizational form and needs to be open and inventive in doing so, and there should be a dialogue between scientists, funding agencies and governments. It is mandatory to have accelerator laboratories in all regions as partners in accelerator development, construction, commissioning and exploitation. Furthermore, planning and execution of high-energy physics projects today require world-wide partnerships for global, regional and national projects, *i.e.* for the whole particle physics programme. The exciting times ahead should be used to establish such partnerships.

## 7. – Conclusions

In this paper we have provided an overview of CERN, focusing on the LHC and some aspects of the fixed-target physics programme as well as on future projects in particle physics at the energy frontier, such as high-energy linear electron-positron colliders and an electron-positron collider. In the coming years, the priorities are the full exploitation of the LHC, together with preparation for a possible luminosity upgrade and the consolidation and optimization of the CERN infrastructure and the LHC injectors. It will be necessary to keep under review the physics drivers for future proton accelerator options and it will be necessary to compare the physics opportunities offered by proton colliders with those available at a linear electron-positron collider and an electron-proton collider. The R&D associated with future colliders needs to continue in parallel.

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