The LHC and Beyond - Past, Present and Future

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This paper presents CERN's scientific plans for the LHC 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 nominal 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 paper 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.

1 Introduction - The Physics

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

By colliding unparalleled high-energy and high-intensity beams, the LHC will open 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 fb^{-1} are needed. However, even with 1 fb^{-1} per experiment, discovery of the Standard Model Higgs Boson is still possible in certain mass regions beyond the lower limit of 114.4 GeV from direct searches at LEP2. At a centre-of-mass energy of 7 TeV and for 300 pb^{-1} per experiment, combining the results from ATLAS and CMS would provide a 3 σ sensitivity for a Standard Model Higgs Boson mass of 160 GeV, and will exclude the Standard Model Higgs Boson between 145 GeV and 180 GeV for 1 fb^{-1} per experiment. Exclusion of the full mass range down to the LEP2 lower limit requires 1.5 fb^{-1} per experiment at 14 TeV centre-of mass-energy, while the discovery of a Standard Model Higgs Boson at the LEP2 lower limit requires 10 fb^{-1} per experiment at 14 TeV centre-of-mass energy.

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

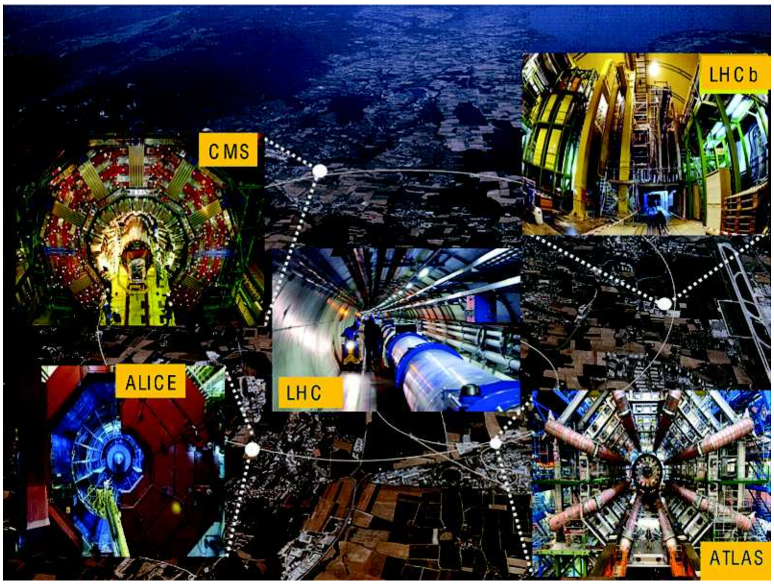

Figure 1: The LHC accelerator and the ALICE, ATLAS, CMS and LHCb experiments. There are also three smaller experiments - LHCf, MoEDAL and TOTEM.

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 400 GeV for 100 pb^{-1} and up to 800 GeV for 1 fb^{-1} per experiment at 7 TeV centre-of-mass energy. The discovery reach for the new heavy bosons Z' and W' is 1.5 TeV and 1.9 TeV, respectively, for 1 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 and the properties of the quark-gluon plasma at the origin of the Universe.

2 The LHC Programme

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 an enhanced quench protection system was implemented. This has resulted in a significant amount of work and any remaining risks

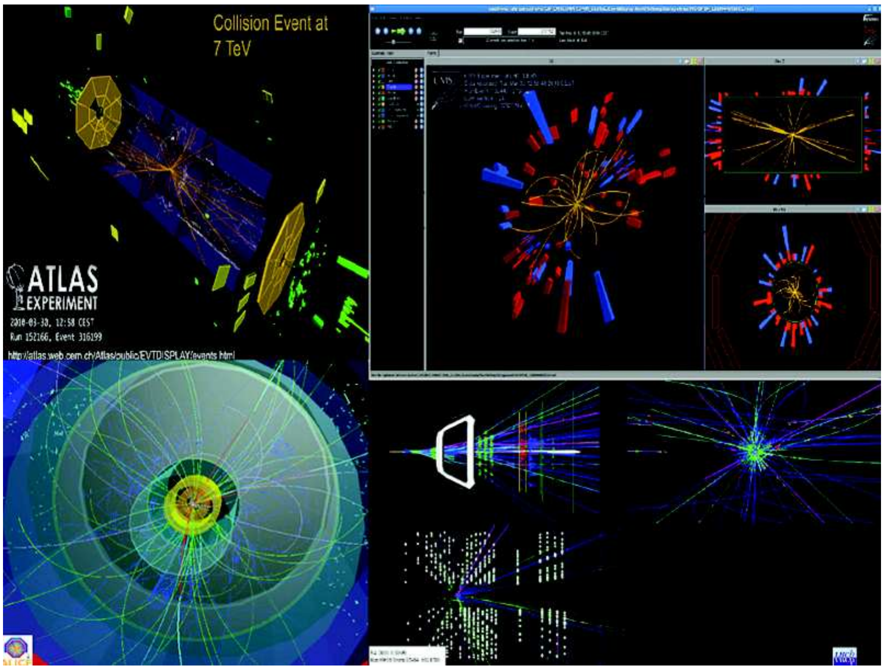

Figure 2: First collisions at 7 TeV centre-of-mass energy.

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 the end of 2009, the LHC accelerator performed exceptionally and the readiness of the experiments and the computing 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.

2.2 The Present

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 Figure 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.

CERN has taken the following decisions that will allow the LHC to provide substantial physics in 2010-2011 and be technically capable of operating at the design energy and high intensities as of 2013:

- The LHC will be operated at 3.5 TeV/beam during 2010 and 2011, with a target integrated luminosity of 1 fb^{-1} and with a heavy-ion run at the end of both years.

- This extended operations period will be followed by a long shutdown (of the order of at least 12 months) in 2012 to repair and consolidate the inter-magnet copper-stabilizers to allow for safe operation at 7 TeV/beam for the lifetime of the LHC.
- In the shadow of the inter-magnet copper stabilizer work, the installation of the fast pressure release valves will be completed and between two and five magnets which are known to have problems for high energy will be repaired or replaced. In addition, SPS upgrade work will be carried out.

2.3 The Future

The coming years will lay the foundation for the next decades of high-energy physics at CERN. The research programme until around 2030 is determined by the full exploitation of the LHC physics potential, consisting of the design luminosity and the high-luminosity upgrade (HL-LHC), together with focused R&D for a Linear Collider (machine and detectors) and for 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;
- improvement to the reliability of the LHC through the construction of LINAC4 [2], which will reduce the risk to LHC operation by replacing the ageing LINAC2, which first came into operation in 1978;
- the R&D and subsequent implementation necessary for a significant luminosity increase of the LHC beyond the design luminosity, i.e. HL-LHC, if necessitated by the physics and/or running experience; in particular it includes the focusing elements in the interaction regions and the upgrades of the injector chain;
- LHC detector modifications to make optimal use of the design LHC luminosity;
- the detector R&D necessary for the luminosity upgrade HL-LHC and the corresponding modifications of the existing LHC experiments.

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.

The ambitious longer-term plans aim at a total integrated luminosity of the order of 3000 fb^{-1} (on tape) by the end of the life of the LHC around 2030. This implies an annual luminosity of about 250-300 fb^{-1} in the second decade of running the LHC. It also calls for a new strategy to optimize the integrated luminosity useful for physics. Therefore, the LHC operation schedule will henceforth be over a two-year cycle, with a short technical stop around Christmas at the end of the first year and a longer shutdown following the end of the second year. Such a schedule is more efficient for the operation of a superconducting accelerator.

In light of the above developments, the following strategy has been introduced:

- The Chamonix LHC Performance Workshop in January 2010 identified the need for a complete refurbishment of all copper-stabilizer joints of the main LHC magnets for safe running at 7 TeV/beam. The copper-stabilizer repair is scheduled throughout 2012 (long shutdown).

- To ensure reliable operation of the LHC in the coming years, there is a need to consolidate intensively the existing LHC injector chain. This is due to the fact that even if approved soon, the low-power superconducting proton linac LP-SPL and PS2 would realistically be available in 2020 at the earliest.

- In order to optimize the strategy towards the HL-LHC, with the goal of maximizing the integrated luminosity useful for physics, CERN has set up a task force. A preliminary recommendation from this task force is to delay the inner triplet replacement to a single HL-LHC upgrade around 2020. The complete HL-LHC upgrade needs a much clearer definition of implementation objectives based on the requirements of the experiments, such as the use of crab cavities, in order for the LHC to operate reliably at luminosities of about $5 \times 10^{34}\ cm^{-2}s^{-1}$. This may include the option of luminosity leveling to ensure a high luminosity lifetime.

- Furthermore, the bottlenecks of the injector chain need to be tackled and hence upgrades are being studied with a view to increasing the extraction energy of the PS Booster as well as upgrades to the SPS, the latter currently being a significant bottleneck for increasing the LHC intensity beyond design.

3 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 open questions left 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) [3] and International Linear Collider (ILC) [4] collaborations. Moreover, the option of a high-energy electron-proton collider (LHeC) [5] 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. As in the past, there is a synergy between collider types proton-proton, electron-positron and electron-proton. 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 [6]. CERN considers that 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 2006 by the CERN Council Strategy Group. The European Strategy for Particle Physics includes several key areas of research, all in line with CERNs plans for the future directions. The years 2010 and 2011 are seeing the start of the LHC physics exploitation leading to important input for the update of the European strategy for particle physics planned for 2012.

4 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 for the field 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 would 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 encouraged.

Particle physics is now entering a new and exciting 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 and global collaboration coupled with stability of support over long time scales.

The particle physics community needs to define now the most appropriate organizational form and needs to be open and inventive in doing so, and it should be a dialogue between the scientists, funding agencies and politicians. 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, namely for the whole particle physics programme. The exciting times ahead should be used to establish such partnerships.

5 Fascinating Science

With the largest and most complex scientific equipment, the LHC accelerator and experiments are today attracting immense attention and the LHC is possibly the most-watched scientific endeavour. The LHC is in the spotlight of not only the scientific community but also of the general public and the international media. It has become so due to its fascinating and forefront science, which addresses long-standing questions of human-kind with vanguard technologies. Moreover, the LHC stimulates general interest, increases knowledge, educates and trains the scientists and engineers of tomorrow and drives innovation and technology. This current interest should be used to promote the field of particle physics.

6 Conclusions

In this paper we have provided a description of the driving factors for the LHC physics programme and for future proton and lepton colliders. In the coming years, the ordered 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 should continue in parallel.

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