THE FUTURE OF HIGH-ENERGY ACCELERATORS

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Abstract

The observation of a Higgs boson by the experiments ATLAS and CMS at the Large Hadron Collider at CERN in 2012 was a centennial discovery and the crowning finale to a hunt that had kept theorists and experimentalists busy for roughly 50 years. However, in a sense the discovery was rather a beginning then an end: the Higgs opens up a completely new window into the unknown world "beyond the standard model" (BSM) of particle physics. But access to this unchartered territory relies on high-energy, high-luminosity colliders. In this contribution, I will outline plans and ideas for future collider facilities, and the strategy processes leading up to them.

INTRODUCTION — THE CASE FOR HIGH-ENERGY ACCELERATORS

Over the past more than 50 years, elementary particle physics has developed the extremely successful framework of the standard model (SM) — a highly predictive theory describing electroweak and strong interactions among all known elementary particles in a way consistent with all measurements performed so far.

But despite its immense success, the standard model fails to provide answers to a number of very fundamental questions. Examples are:

- The SM does not contain a candidate particle for dark matter, which according to observations constitutes about 20% of the universe's energy content;
- the SM does also not explain the asymmetry between matter and antimatter in the universe, which might have its origin in new particles not contained in the SM;
- we are also lacking an understanding of the origin of mass, of electroweak symmetry breaking, and of the structure of the vacuum. Also the mechanism stabilising the huge hierarchy gap between the weak and the Planck scale is a puzzle, as is, e.g., the number of generations (three families of quarks and leptons).

Interestingly, the Higgs boson has turned into an ideal tool to tackle many of the above questions at CERN's Large Hadron Collider (LHC) and other future colliders. For example, precise investigations of the properties of this particle (like its spin, CP eigenvalues, and in particular its couplings to other particles) will allow to address the question if the Higgs is indeed the particle predicted in the SM or an BSM particle, stemming, for instance, from a supersymmetric extention of the SM.

The new physics that is needed to shed light on the points mentioned above may, in general, be discovered in two ways that define the rationale for the directions pursued in accelerator-based particle physics: high energy or high precision. The "high energy" way asssumes that new physics is hidden at high energy and mass scales, i.e. that there are heavy BSM particles that require higher collision energies to be produced and, consequently, ever stronger particle accelerators. The complementary "high precision" approach expects new physics (new particles, new interactions) to show up indirectly, via higher-oder loop effects and potentially tiny deviations from SM expectations. In this case, precision (of measurements and also of predictions) is of utmost importance, and consequently the focus is on statistics and thus on luminosity.

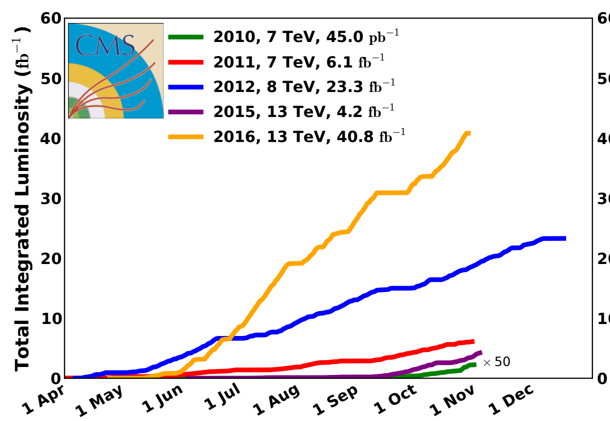

Figure 1: Luminosity production at the LHC (courtesy CERN/CMS).

THE LARGE HADRON COLLIDER

The Large Hadron Collider started routine luminosity production in 2010, first with center-of-mass energies of 7/8 TeV (Run 1), and since 2015 with 13 TeV (Run 2), see Fig 1. All in all, roughly 75 fb^{-1} of integrated proton-proton luminosity have been delivered to the large multi-purpose experiments ATLAS and CMS so far, and more than 1200 publications have sprung from these data, the most prominent ones being those on the Higgs discovery. However, the LHC and its experiments are still only at the beginning of their scientific exploitation. The amount of data recorded so far corresponds to only about 2% of the ultimate goal for the machine, and a physics programme with continuous upgrades has been sketched that last until around 2035 (see Fig. 2):

The current plan for the LHC foresees running until 2023, interrupted by the long shutdown 2 in 2019/20, after which the collision energy will be increased to the design value of 14 TeV. The goal is to collect roughly 300 fb^{-1} per experiment — after which large parts of the detectors will have seen so much radiation that they have to be replaced. There-

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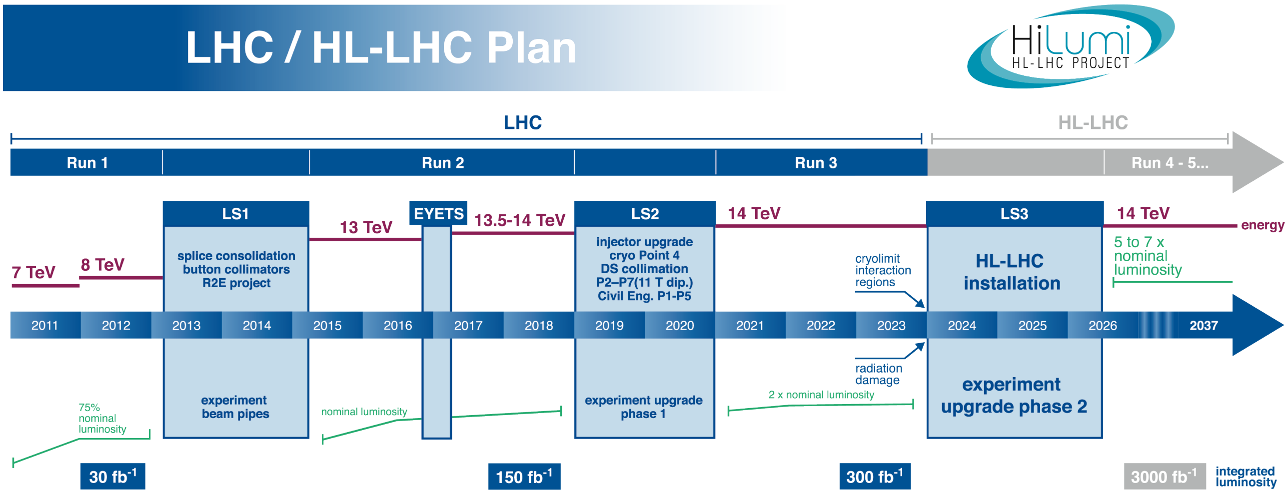

Figure 2: The foreseen schedule of the LHC and the HL-LHC (courtesy CERN).

fore, in 2024 and the following years, the LHC machine will be developed into the "High-luminosity LHC" (HL-LHC), with the goal of accumulating, in the years until about 2035, the total amount of around 3000 fb^{-1}, with instantaneous luminosities five times that of the LHC design, allowing a significant extension of the reach for new particles and phenomena and ultimate statistical precision for LHC measurements. The experiments — ALICE, ATLAS, CMS, LHCb — have to undergo massive upgrade work in order to be able to cope with the data rates and radiation levels provided by the improved HL-LHC machine. These upgrade projects have started and are about to be documented in technical design reports in 2017/18.

Concerning the LHC machine, the NbTi-based superconducting magnet technology is almost exhausted with dipole fields of about 8.3 T necessary for acceleration to 7 TeV beam energy in the LHC. The same magnet technology was already used for the Tevatron and the HERA proton ring, see Fig. 3). Already for the HL-LHC upgrade magnets with fields up to 12 T) are required, and a large magnet R&D programme has been set up with clear synergies to future high enery colliders. Much progress has been made using Nb_3Sn, which promises about twice the maximum field. Also high-temperature superconductors (HTS) are investigated which can reach even higher fields but are not yet as close to applications.

HADRON COLLISIONS BEYOND THE LHC

Because of their energy reach, hadron colliders have always been discovery machine — the bottom and the top quark (Tevatron), the W and Z bosons (SppS), the tau neutrino (Tevatron) and the Higgs boson (LHC) where all first observed at hadron machines, as were a number of other phenomena in particle physics. Bearing the challenges of particle physics discussed above in mind, it is the most natural way forward to study future high-energy hadron colliders.

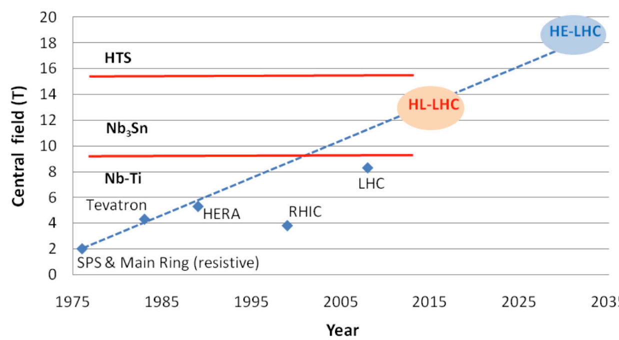

Figure 3: Dipole fields for hadron colliders as function of time (courtesy L. Rossi).

At CERN, the Future Circular Collider (FCC) study has been launched [1]. The study foresees a 100 km tunnel in the Geneva region (see Fig. 4), housing a 100 TeV proton-proton collider (FCC-hh) with an instantaneous luminosity comparable to that of the LHC, tamed by 16 T dipole magnets. The FCC would offer unprecedented center-of-mass energy and a vast expansion of mass reach for BSM particles; however, also the technological, engineering, as well as the political and financial challenges are enormous.

As part of the FCC study the idea of an high-energy LHC (HE-LHC) is investigated. The HE-LHC would be a replacement of the current LHC machine in the existing tunnel by a new, Nb_3Sn-based accelerator that would roughly double the maximum beam energy. FCC-hh with 100 TeV center-of-mass energy would require a new tunnel with about 100 km circumference. Thanks to recent research, carried out in Europe, Japan and the US, these values are quite realistic, with working models of 11 T dipoles and 12 T quadrupoles around, and feasibility tests of 16 T magnets [2]. A conceptual design report for the FCC is expected at the end of 2018, and ideas are around for a start of physics operation after the end of the HL-LHC programme in about 2035 [3].

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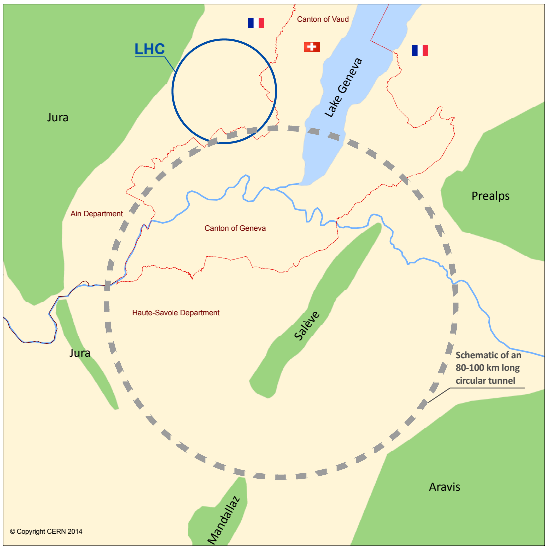

Figure 4: Schematic view of the FCC ring in the Geneva area (copyright CERN 2014).

But plans for ultra-energetic proton-proton collisions are not only pursued at CERN: There are plans for a Chinese project (CEPC, see below), which — in a second phase — could host a proton-proton collider with collision energies between 50 and 90 TeV in a tunnel of 50–70 km circumference. The machine — called SppC [4] — would require 20 T magnets and is currently in the pre-study phase. The R&D phase and the engineering design are foreseen for the years 2020–35, with first data-taking envisaged for the 2040s [5].

PRECISION TOOLS: ELECTRON-POSITRON COLLIDERS

Hadron colliders are discovery machines, offering the highest energy reach available. However, the complex nature of hadrons implies that the initial state of a particle collision cannot precisely be reconstructed and that one has to deal with complex final states. An important example for these limitations is that at hadron machines like the LHC, only ratios of Higgs couplings to other particles can be measured and not the couplings itselves.

In contrast, lepton (and in particular electron-positron) colliders can be regarded as precision tools — leptons being pointlike particles, with fully determined initial-state quantum numbers, simple final states and well-defined missing energy, and the possibility of introducing beam polarisation, which would be particularly relevant for SUSY studies. The drawback of circular electron-positron colliders is, of course, the energy loss by synchrotron radiation, which seems to make such machines unfeasible beyond the top-antitop threshold. The efforts for higher-energy lepton colliders thus focuses on linear machines.

This high achievable precision makes electron-positron colliders the natural choice for detailed investigations of e.g. the Higgs boson and for high-sensitivity indirect searches for new physics in quantum loop corrections. The latter approach is also pursued at the so-called B factories, the Belle II experiment at Japan's KEK laboratory with its SuperKEKB collider being the upcoming flagship in this field of particle physics. Belle II will start physics operation in its design setup in 2018, and the goal is to accumulate a data set of about 50 ab^{-1}, with the hope of pinning down the origin of the matter-antimatter asymmetry and of observing lepton universality violation. In the field of Higgs physics, high-energy lepton colliders promise a significant improvement, e.g. of the coupling measurements by up to a factor 10 (see Fig 5 for a comparison of coupling determinations at the LHC and the ILC) and the potential to perform absolute determinations of these couplings.

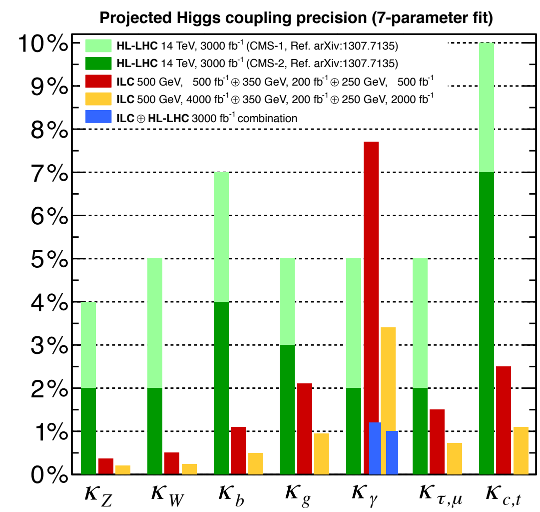

Figure 5: Comparison of Higgs coupling determination precision at the LHC and the ILC [6].

The most advanced of all electron-positron collider studies is that of the International Linear Collider (ILC). A TDR for the project was presented in 2013 [7], and also in 2013 a candidate site in Japan was identified in the northern Kitakami region. The project is currently under political consideration in Japan and receives strong support from the international community: In a 2014 statement [8], ICFA (the International Committee for Future Accelerators [9]) reaffirmed its support of the ILC, stressing the project's mature state of technical development. The ILC also figures prominently in US and European strategy statements, e.g. in the 2013 update of the European strategy, which states that the "initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate" [10].

The ILC baseline design is that of a 500 GeV center-of-mass energy linear electron-positron collider, realised with superconducting niobium RF cavities and a length of 30 km. The machine could be upgraded to 1 TeV. Currently, also staging scenarios are being discussed that, in order to reduce initial investment costs, would start with a 250 GeV "Higgs factory" machine. Two detector concepts — ILD and SiD — have been developed, and a push-pull configuration is foreseen for alternating data-taking with the two experiments.

Site-specific planning work for the ILC has started, and the physics case is robust [6]. The Japanese government is investigating the ILC in Japan, and a statement if Japan is interested to host the ILC is expected in 2018. Construction could in principle start as early as 2023, especially since the technology has been thoroughly tested in a "prototype" machine just going into operation: The European XFEL in Hamburg, Germany — which has just since first laser light — relies on the ILC technology originally developed for the TESLA project at DESY, and it has seen the industrial production of about 800 accelerating cavities, almost satisfying the ILC requirements [12], see Fig. 7.

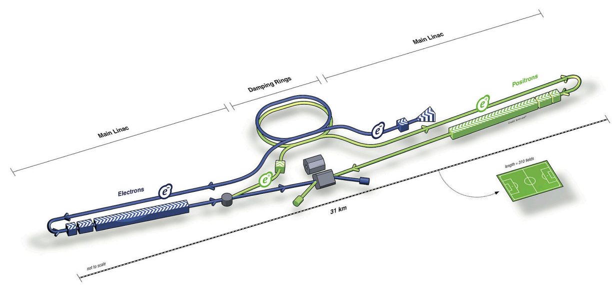

Figure 6: Schematic layout of the international Linear Collider (ILC).

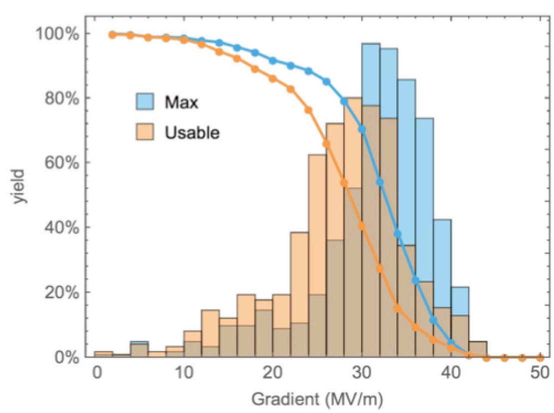

Figure 7: Maximum and usable gradients of superconducting XFEL cavities. Many of the cavities fulfill the ILC requirements (courtesy European XFEL).

An alternative concept for a linear e+e- collider is the Compact Linear Collider (CLIC) study [13] — a concept based on warm accelerating structures and a drive beam (see Fig. 8). CLIC published a conceptual design report in 2012 [14], and currently an in-depth R&D programme is carried out in order to prepare the study for the discussions of the next update of the European strategy in spring 2020. CLIC is superior to the ILC in terms of energy reach, with a design center-of-mass energy of up to 3 TeV. Current ideas comprise initial energy stages of 370 GeV or 500 GeV using conventional klystron-based technology before upgrades in CLIC technology to 1.5 or 3 TeV are undertaken.

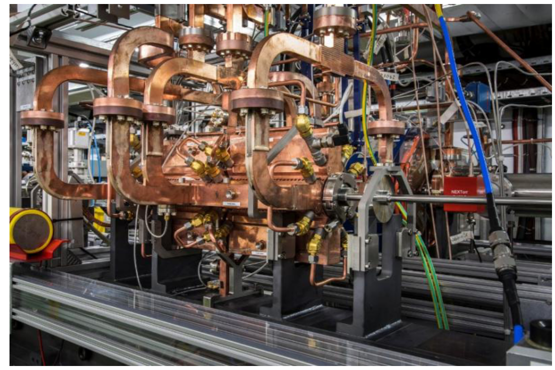

Figure 8: A detail of the CLIC test facility CTF3 (courtesy CERN).

Two more ideas for circular high-energy electron-positron collisions are discussed, both of them connected to projects already discussed above in the hadron-collider section: The FCC study includes an electron-positron machine concept known as FCC-ee. Also an electron-proton, "HERA-like" collider, is being studied. In China, proton collisions in the SppC project are supposed to be preceded in the same tunnel by an electron-positron collider named CEPC [4].

The CEPC study plans for electron and positron beams at around 250 GeV center-of-mass energy, resulting in a "Higgs factory". Two interaction points are foreseen, and at least one of the envisaged detector designs is based on the ideas of the ILD detector. A timeline discussed by the proponents aims for the finalisation of the engineering design around 2020 and start of data-taking in 2028.

FCC-ee assumes electron and positron collisions at center-of-mass energies of up to 350 GeV. The machine would thus allow top-antitop production at threshold, which is important for the precise determination of the top mass. FCC-ee is considered as a potential precursor to FCC-hh, to be realised and operated for a limited time before FCC-hh is installed.

OTHER OPTIONS, NEUTRINO BEAMS, MUON COLLIDERS, AND PLASMA WAKEFIELD ACCELERATION

In accelerator-based neutrino physics, the next generation of experiments is designed to make precision measurements of the neutrino mass hierarchy and to establish CP violation in the lepton sector. Two experiments have been proposed, DUNE in the USA and HyperK in Japan. The neutrino will in both experiments be generated by high-power proton beams. In the DUNE/LBNF case, protons of 60 to 120 GeV extracted from Fermilab's Main Injector will be used, with an initial beam power of 1.2 MW, upgradable to 2.4 MW. HyperK will use protons from JPARC's 50 GeV synchrotron with a beam power of 1.3 MW.

DUNE is already at an very advanced approval stage in the US system. It is based on a liquid-argon TPC for the far

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detector, which is the first application of this technology on such a large scale. HyperK is building on the experience with SuperK and is using a water-Cerenkov-based approach. In the USA, LBNF/DUNE [15] has started with the excavation of the experimental caverns in South Dakota, while HyperK [16] is currently under consideration by the Japanese government. Both experiments target the mid-2020s for the begin of data-taking.

The farther future potentially holds other interesting options, the two maybe most promising ones being a muon collider and a collider based on plasma wakefield acceleration. A muon collider offers the advantages of electron-positron machines with much reduced synchrotron radiation, smaller facility sizes and significantly increased production cross sections for e.g. s-channel Higgs production (factor 40000). However, the technical difficulties — e.g. related to cooling, to radiation, to the small muon lifetime — in realising such a machine are enormous. Plasma wakefield acceleration offers the prospects of achieving much higher field gradients — and thus much smaller and cheaper facilities — than conventional accelerators. Two main directions — laser-driven and beam-driven plasmas — are pursued, and gradients of 10 GV/m have been achieved in table-top experiments. However, also for this technology, there are formidable problems to be dealt with, e.g. the questions of controlling the beam emittance, of staging, etc. At his point no concrete projects are discussed and only the future will show the true potential of these technologies for high energy physics.

CONCLUSIONS

The last round of updates of strategies in the various world regions concluded with the update of the European strategy for particle physics in 2013 [10], the US P5 recommendations (2014, [17]), and a statement by ICFA observing a general global consensus [8]. All of these support post-LHC hadron and electron-positron colliders and emphasise the need of global collaboration. Concerning lepton colliders, the ILC takes a special role because of its technical maturity and the interest in Japan. The coming years will be very important for the future direction of particle physics. Based on the scientific output of the LHC, together with anticipated technological and political progress, the next round of strategy updates in Europe in spring 2020 and the US shortly after will be important for the future development of the field.

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