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Perspective

Crucial Years for the Next Generation of High Energy Accelerators

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Abstract: The paper presents the most recent updates toward the definition of the strategy for the future high energy accelerators, with a particular emphasis on FCC-ee. After a brief description of the various proposals, the preliminary conclusions recently reached on the high priority choices for the next generation of colliders will be discussed.

Keywords: FCC-ee; FCC-hh; International Linear Collider; Compact Linear Collider; Muon Collider; Large Hadron electron Collider; LEP3

1. Introduction

The discussion on the future facilities for High-Energy physics was boosted by the discovery of the Higgs boson in 2012. In fact, it began even earlier, just after the special seminar held at CERN on 13 December 2011. As soon as myself and Fabiola Gianotti, at the time spokespersons of the CMS and ATLAS experiments respectively, presented the first hints of the presence of a Higgs boson in LHC data at a mass around 125 GeV/c^2 [1], the entire high energy-physics community used this first evidence as a guideline for planning future machines.

It was not by chance that just two days later Yoshihiko Noda**,** Prime Minister of Japan, gave a speech at the International Linear Collider symposium held in Tokyo [2]. Discussions on a future e^+e^- linear collider were ongoing since 2010 and an informal international collaboration, led by Barry Barish, had been set-up to study possible sites for the new machine. On 15 December 2011, the 150+ members of the ILC collaboration heard directly from Prime Minister Noda and other representatives of the Japanese government that “the ILC is the project that Japan should promote as a national commitment.” Unfortunately, this early enthusiasm did not materialize in a real commitment to build ILC in Japan.

Soon afterwords a group of visionary CERN physicists, led by Alain Blondel and Patrick Janot, started discussing a new project, called TLEP, acronym for TeraLEP or TetraLEP [3], a high luminosity circular e^+e^- collider to be housed in a gigantic tunnel, 80–100 km in length, to be excavated at CERN.

With the announcement of the discovery of the Higgs boson on 4 July 2012 [4,5], the discussions on the future projects for the high-energy community took off. Different variants of Higgs factories were soon proposed, together with ambitious plans to build new proton-proton colliders yielding up to 100 TeV center-of-mass collisions. It took more than 13 years to define a clear strategy for future accelerators and now we are there. In the following we describe the major steps that led to this fundamental milestone.

2. Why New Particle Accelerators

It is well known that the Higgs discovery has completed the particle spectrum predicted by the Standard Model (SM). First time ever, we have a consistent, relativistic, quantum mechanical theory that is weakly coupled, unitary, renormalizable and vacuum-quasi-stable. It appears to be valid up to an exponentially high scale, perhaps even to the Planck mass.

Nowadays the beautiful conjecture developed in the mid '60 s looks like a complete and consistent theory. It does explain an impressive number of experimental results and is capable to predict a huge number of observables with extremely high precision. However, the list of unsolved questions is still too long and frankly embarrassing: neutrino masses, dark matter and dark energy, the dynamics of inflation, the matter-antimatter asymmetry, the hierarchy problem et al., not to mention the role of gravity. In other words, we know for sure that new physics exists, but there is no clue on the energy scale at which it will manifest.

After the discovery of the Higgs, the ATLAS and CMS Collaborations studied extensively its properties, including its couplings to other SM particles and continued their searches for physics beyond the standard model (BSM). Since 2012 a large set of collisions data, as of today roughly 500 fb-1, was collected at different center-of-mass energies, $\sqrt{s}$ = 7, 8, 13 and 13.6 TeV, but no sign of new physics appeared in data.

The fact that the impressive amount of data collected by LHC experiments did not show any evidence of physics beyond the Standard Model means that we cannot count neither on well-established experimental hints, nor on precise theoretical constrains that could suggest the best direction to go. We have no clear indication of the energy scale at which new physics will appear. We don't even know the coupling strengths of these new particles to the SM particles. We are moving in the most complete darkness, this is why the new facilities must be versatile and capable to explore a wide range of options.

First, the Higgs itself could be a fundamental tool for new discoveries. It could decay into invisible particles that might be potential dark matter candidates. It could show anomalies in its properties or in some of its rare decays. By producing huge amounts of Higgs bosons in clean experimental conditions it would be possible to test these hypotheses. In addition, thanks to the large statistics, the coupling constants of the new fundamental scalar could be measured with high precision. Many models of new physics imply tiny deviations with respect to the expected SM couplings. Firmly established deviations from these values would be indirect evidence of BSM physics and would indicate the energy scale where new particles or new interactions could appear.

An electron-positron high luminosity collider would be a perfect machine to address these issues. For instance, the measurement at percent level of the couplings of the Higgs to the up and down quarks will also shed light on the fine tuning required to achieve stability of the nuclei. By measuring, with unprecedented precision, the couplings of the Higgs to the W and Z gauge bosons we could check the presence of very tiny anomalies in a parameter that ultimately controls the lifetime of the Sun and all the other stars.

This set of studies should be complemented by precision studies of the most sensitive electroweak parameters. By measuring, with ultimate precision, mass and properties of Z, W and top quarks we will have another fundamental tool to identify unambiguous signatures of BSM. This would be possible only in new accelerators optimized for the mass production of unprecedented quantities of the heaviest particles of the SM.

The experimental program could be completed by building a new proton-proton high-energy collider yielding huge statistics on some of the rarest Higgs decays. A high-energy, high-luminosity hadron collider would be the perfect machine to access some decay modes of the Higgs boson barely accessible to electron-positron colliders. It would allow to study in detail some of the most intriguing questions, still open even after the completion of the high-luminosity phase of LHC (HL-LHC). The exact mechanism of electroweak symmetry breaking could be investigated studying the behavior of the Higgs potential away from its usual equilibrium conditions. The precise measurement of the top quark Yukawa coupling and a good measurement of the Higgs self-coupling will allow to understand better the dynamics of the electroweak phase transition and might have an impact in understanding the present, huge unbalance between matter and antimatter in the universe.

Lastly a 100 TeV hadron collider will allow to probe directly new physics by producing and studying any sort of new particle in a mass range as high as several tens of TeV.

3. The Role of the Update of the European Strategy for Particle Physics

In 2013 the CERN Council decided to insert the various activities studying future colliders within Europe in the general framework of the Update of the European Strategy for Particle Physics (ESPPU) [6]. As described in its official web page "The European Strategy for Particle Physics is the cornerstone of Europe's decision-making process for the long-term future of the field. Mandated by the CERN Council, it is formed through a broad consultation of the grass-roots particle physics community, it actively solicits the opinions of physicists from around the world, and it is developed in close coordination with similar processes in the US and Japan to ensure coordination between regions and optimal use of resources globally."

The Update of the European Strategy for Particle Physics (ESPPU) stated, among other, that…"Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update" and that "CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."

In response to this recommendation, the Future Circular Collider (FCC) study was launched as a world-wide international collaboration under the auspices of the European Committee for Future Accelerators (ECFA). The FCC study was mandated to deliver a Conceptual Design Report (CDR) in time for the following update of the European Strategy for Particle Physics.

In addition to FCC, additional study groups proposing various solutions were involved in the evaluation. Among them the most relevant ones are the Linear Collider Facility (LCF), the Compact Linear Collider (CLIC), the Muon Collider (MC), the LEP3 and the Large Hadron electron Collider (LHeC). In the following the main features of the proposed solutions will be quickly described.

4. The Linear Collider Option

The proposal to build a linear collider, as next generation machine after LHC, dates back at the beginning of the years 2000, but, as already discussed, the pace of the activities increased substantially after the discovery of the Higgs boson. Knowing the mass of the new particle allowed projects to focus on the main physics goals and to optimize the machine parameters in order to obtain the best performance.

The Linear Collider Facility collaboration [7] proposed to build at CERN a 33.5 km long linear accelerator, equipped with general-purpose detectors housed in two interaction regions. The machine would produce polarized electron-positron collisions at an initial center-of-mass energy of 250 GeV and a luminosity of 2.7×10^{34} $cm^{-2}s^{-1}$ for an estimated initial cost of 8.3 BCHF. The Linear Collider Facility would use superconducting RF cavities as accelerating elements and could be put in operation around 2045. Successive upgrades of the machine could double the initial luminosity and increase the collision energy at around 550 GeV. The costs for these upgrades were estimated around 6.3 BCHF. Additional upgrades in energy up to 1 TeV could be made possible depending upon the progress in accelerating techniques. The physics program of the machine would include measurements of the Higgs boson properties using two major production mechanisms, namely Higgs-strahlung, $e^+e^- \rightarrow ZH$ and WW fusion, $e^+e^- \rightarrow \nu\nu H$. The machine would make possible precision measurements of gauge boson interactions as well as of the W, H and top-quark masses. Longer term physics plans include measurement of the top-quark Yukawa coupling through $e^+e^- \rightarrow ttH$, measurement of the Higgs boson self-coupling through HH production, and precision measurements of the electroweak couplings of the top quark.

A variant of the linear collider option is the CLIC accelerator [8], an ambitious machine aiming at colliding electrons and positrons at energies up to several TeV. The plan is to build the accelerator in three stages, corresponding to collision energies of 380 GeV, 1.5 TeV and 3 TeV respectively, for a site length extending from 11 to 50 km. CLIC's design incorporates radiofrequency (RF) cavities and a very challenging two-beam acceleration concept to produce accelerating fields as high as 100 MV per meter. The RF power needed to accelerate the main beam is generated locally by decelerating a second high-intensity electron beam—the "drive beam"—in special power-extraction structures. The estimated cost of the first two stages is 14.3 BCHF, similar to the first two stages of the Linear Collider Facility. A realistic date for the initial operations at 380 GeV would be 2045.

5. The Circular Collider option

The FCC study explores the feasibility and scientific potential of a very complex collider program based on a new, circular tunnel of 90.7 km circumference to be excavated at CERN. In the first phase the huge infrastructure will house a high-luminosity electron–positron collider, FCC-ee [9]. After about 20 years of operation FCC-ee will be dismantled and a high-energy proton–proton collider, FCC-hh [10], will be installed within the same infrastructure.

The FCC-ee design is based on well-established technologies and a significant fraction of its infrastructure will be reused later for the hadron collider. The physics program of the electron-positron machine foresees four different running periods, characterized by diverse luminosities and center-of-mass collision energies. A few years of running at the Z pole, $\sqrt{s} = 91.2$ GeV, with instantaneous luminosity exceeding 1.4×10^{36} $cm^{-2}s^{-1}$, will allow the production of 6×10^{12} Z. More than 10^8 W pair could be produced with the machine running at $\sqrt{s} = 160$ GeV, and $L = 2 \times 10^{35}$ $cm^{-2}s^{-1}$. With collision energy raised to 240 GeV the most important production mode will become the associated production of a Higgs together with a Z boson. With $L = 7.5 \times 10^{34}$ $cm^{-2}s^{-1}$, FCC-ee will be able to produce, in a few years, more than 2×10^6 H. Lastly, running some years at $\sqrt{s} = 365$ GeV and $L = 1.4 \times 10^{34}$ $cm^{-2}s^{-1}$ the machine would yield about 2×10^6 t-tbar pairs.

The unprecedented luminosities achievable by FCC-ee would make it an extremely powerful precision instrument for the study of the heaviest elementary particles. The real challenge at the new machine will be the control of the systematic errors at a level that will allow to cope with the huge statistics of Z, W, H and top quarks that could be collected. If this would be achievable FCC-ee would offer outstanding sensitivity to physics beyond the Standard Model.

The total cost of FCC-ee is estimated at 15.3 BCHF, dominated by about 9 BCHF for the tunnel and basic infrastructure. The initial date for the operation is expected to be 2046.

FCC-hh will be a hadron collider installed in the same tunnel after the end of the operation of FCC-ee. Initial date for the operation of this new collider will be 2074–2079 for a total additional cost of 19.7 BCHF, dominated by the production of the thousands of new superconducting bending magnets necessary for the machine. Various scenarios are under study for what concerns the technology to be used for these magnets. As usual, the dipole field will decide the maximum attainable energy. If we consider today's technology, based on Nb_3Sn filaments as semiconductors, we could reach a field of ~14 T at 1.9 K operating temperature. This would correspond to a center-of-mass energy of 84 TeV for realistic filling factors in a 90.7 km accelerator. Since a very promising R&D activity is ongoing on High Temperature Semiconductors (HTS), there are plans to use this new technology for the FCC-hh magnets. In principle HTS magnets could reach higher fields with respect to more conventional Nb_3Sn magnets. By equipping FCC-hh with 16 T HTS dipoles will bring the collision energy to 100 TeV. Further extrapolation to a very aggressive 20 T field, in principle achievable with HTS dipoles, would push the center-of-mass energy of the new machine up to 120 TeV.

The extremely high collision energy of the new hadron collider coupled to instantaneous luminosity estimated around 3×10^{35} $cm^{-2}s^{-1}$ would make FCC-hh an ideal machine in terms of direct discovery potential for new physics phenomena.

6. Other Options

Together with the traditional linear and circular options a few other collider layouts were studied. LEP3 [11] is the proposal of installing an electron-positron machine in the LHC tunnel at the end of the HL-LHC data taking. The basic idea is to use superconducting, modern RF cavities and a two-ring concept: one to handle the acceleration and a collision ring. Under these assumptions it seems to be possible to realize an electron-positron collider that can reach center-of-mass energy of 240 GeV, with instantaneous luminosity of 10^{34} $cm^{-2}s^{-1}$. The new collider could be considered a low-cost Higgs factory, since the total investment necessary to dismount LHC and equip the new machine will be about 4.1 BCHF. The machine could run also at 160 GeV to collect large statistics of W boson pair, however, although interesting, its physics potential cannot be compared with the circular collider option.

Another idea was developed around the concept of producing electron-proton collisions in LHC. The Large Hadron electron Collider, LHeC [12] proposal considers building an Energy Recovery Linac (ERL) based accelerator to deliver 50 GeV high-intensity electron beams brought to collision with the HL-LHC protons. According to the study centre-of-mass energies around 1 TeV per nucleon could be achieved with luminosities around 10^{34} $cm^{-2}s^{-1}$. The project would fit in the years between the end of the regular HL-LHC program (around 2041) and the start of a new major hadron collider at CERN.

The total cost of LHeC is estimated around 2.1 BCHF, but the physics potential of the new machine is considered marginal.

Lastly, one of the most innovative proposals came from the Internation Muon Collider, IMC, collaboration [13]. They propose to build a new accelerator based on high energy collisions of muons. The idea of a Muon Collider was first introduced around 50 years ago. Muons are point-like particles that can be accelerated at very high energies without losing too much energy in the bremsstrahlung processes typical of the circular accelerators. Being 200 times heavier than electrons, muons emit about two billion times less synchrotron radiation.

The major technical challenges come from the short muon lifetime of 2.2 μs and from the difficulty to produce high density, low emittance bunches of muons to achieve high luminosity. The IMC proposes a substantial R&D program aiming at developing first a proton driver, to produce high intensity beams of protons impinging on special targets to produce high quantities of muons. A second stage, based on powerful solenoidal magnets, will be used to cool them down and to increase the density and the quality of the muon bunches that will be later pre-accelerated to be lastly injected in a collider ring. Ideally, a Muon Collider in the multi-TeV energy range, namely $\sqrt{s} = 3$–7 TeV, would be a fantastic accelerator, extremely promising both as a precision and as a discovery machine. Considering the many uncertainties of the proposed technology it would be impossible, so far, to evaluate the total investment cost, as well as envisaging a realistic time-scale.

7. The New Proposed Strategy

The mechanism to define the process leading to the choice among the various options was set-up by the CERN Council in 2024. A European Strategy Group, ESG, was formed, led by Karl Jacobs, and the major steps of the decision process were defined:

- 31 March 2025 Deadline for the submission of the main inputs of the community.
- 23–27 June 2025 Collective discussions at the Open Symposium in Venice (Italy).
- 14 November 2025 Deadline for the submission of the national inputs to the ESG.
- 1–5 December 2025 ESG drafting session.
- 12 December 2025 Preliminary conclusion of the ESG presented to the CERN Council.
- 31 January 2026 Submission of the draft document to the Council.
- March/June 26 Discussion within the Council and update of the strategy.
- 2027/2028 Final deliberation of the Council and formal project approval.

It is worth to notice that both in the Venice Symposium and within formal documents or informal discussions at the Council, an overwhelming majority of scientists and countries express support in favour of the integrated FCC-ee-FCC-hh programme as next flagship project for high-energy physics in Europe. It must be highlighted that of the 24 CERN member states, 21 support the new large accelerator.

After the last CERN Council meeting, on 12 December 2025, a press release was issued stating explicitly [14,15]. The electron–positron Future Circular Collider (FCC-ee) is recommended as the preferred option for the next flagship collider at CERN. It would provide a platform for a visionary physics programme addressing many of the open questions in particle physics, notably about the Higgs boson, that are critical to understanding the foundations of the Standard Model and to opening up opportunities for discovering new physics beyond the Standard Model, while at the same time driving the development of new technologies that will have a significant positive impact on society."

8. Conclusions

Although we are still in the middle of the process of formally approving the new accelerator complex, I consider this result a major milestone for the high-energy physics community. These will be crucial years for our field at large. If the FCC-ee/FCC-hh project will be formally approved in the next few years this will shape the future of physics for the whole century and will allow new generations of scientists to take the challenge of chasing physics beyond the Standard Model with some of the most sophisticated tools ever conceived.

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Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

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