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OPTIONS AND PROSPECTS FOR THE FUTURE OF ACCELERATOR-BASED HIGH-ENERGY PHYSICS

F. Gianotti, CERN, Geneva, Switzerland

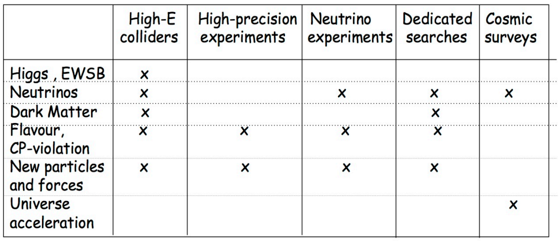
Abstract

Recent results from the LHC and other facilities have had significant impact on the landscape of particle physics. This paper summarises the main outstanding questions in high-energy physics and the strategy to address them. Options for future accelerator facilities and their motivations are discussed.

INTRODUCTION

With the discovery of a Higgs boson [1], the Standard Model (SM), the theory that describes the elementary particles and their interactions, is now complete, after decades of superb theoretical and experimental efforts. However, the SM is not the ultimate theory of particle physics, as many crucial questions, raised also by numerous experimental observations, remain unanswered. These questions, which include the motivation for the small Higgs boson mass, the composition of dark matter, the source of the universe matter-antimatter asymmetry and the origin of neutrino masses, call for physics beyond the SM. The energy scale(s) at which the new physics lies is not known, although there are reasons to believe that at least part of it should be at approximately the TeV scale. It is therefore very puzzling that no new particles have been observed as yet, and that no significant deviations from the SM expectation have been measured at accelerators and other facilities (although the non-vanishing neutrino masses are difficult to accommodate in the Standard Model).

The outstanding questions are compelling, difficult and intertwined; therefore they can only be successfully addressed by the variety of approaches that the particle physics community has conceived and developed, thanks also to strong technological advances in the field. A simplified summary of the main questions and approaches is presented in Fig. 1.



	High-E colliders	High-precision experiments	Neutrino experiments	Dedicated searches	Cosmic surveys
Higgs , EWSB	x				
Neutrinos	x		x	x	x
Dark Matter	x			x	
Flavour, CP-violation	x	x	x	x	
New particles and forces	x	x	x	x	
Universe acceleration					x

Figure 1: The main questions in particle physics today (first column) and the main experimental approaches (top row). The crosses indicate the questions that each approach can address.

The combination of all available approaches is crucial to explore the largest range of energy scales (directly or indirectly) and, if new physics is observed, build a coherent picture of the underlying theory.

Historically, accelerators have been the most powerful tools for exploration through all methods and techniques shown in Fig. 1, except cosmic surveys.

There are two main ways to search for, and study, new physics at accelerators:

- Direct production of a new or known particle. For example, a future electron-positron (e^+e^-) collider running at a centre-of-mass energy of at least $\sqrt{s}\sim240$ GeV would produce the Higgs boson through the $e^+e^- \rightarrow HZ$ process, and allow detailed measurements of its properties. These studies require both energy and luminosity.
- Precise measurements of known processes. Here the goal is to look for possible, tiny deviations from the SM expectations that could be produced, through quantum effects (loops, virtual particles), by new physics sitting at a high-energy scale (Λ). These measurements provide sensitivities to Λ values much larger than the kinematic reach of the accelerator, though only indirectly (i.e. without observation of new particles). They require both energy and luminosity. Similarly, rare decays that are suppressed in the SM (e.g. $\mu \rightarrow e\gamma$) could be enhanced in the presence of new physics. Their search and measurement can therefore provide evidence for the new physics. High-intensity beams are the primary requirement in this case.

This paper summarises the main options for future accelerators, as well as their ability to address the outstanding questions in particle physics.

MAIN OPTIONS FOR FUTURE ACCELERATORS

Three facilities have been strongly supported by the strategic plans developed in Europe, the US, and Asia: high-energy proton-proton (pp) colliders, linear and circular e^+e^- colliders, and high-intensity accelerators for neutrino experiments. Other interesting options (e.g. muon, electron-proton and photon-photon colliders, B-factories, high-intensity beams for kaon and muon experiments) are not covered here.

High-energy Proton-proton Colliders

There is international consensus that the priority for the short- and medium-term future is the full exploitation of the LHC, including its luminosity upgrade (the so-called HL-LHC). The LHC is the highest-energy accelerator in

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the world, able to explore the TeV energy scale in detail, with a direct discovery potential, in the HL-LHC phase, up to m~10 TeV in terms of masses of new particles. It will also allow measurements of the Higgs boson couplings to the few percent level, and inform the future of the discipline. It is expected to operate until ~2035.

Two projects [2] are currently being considered for higher-energy pp colliders: the Super proton proton Collider (SppC) in China and the Future Circular Collider (FCC-hh) at CERN. The Chinese project envisages either a 50 km accelerator ring equipped with 12 T magnets, achieving a pp centre-of-mass energy of 50 TeV, or a more ambitious 70 km ring with 19 T magnets, providing pp collisions at $\sqrt{s}$= 90 TeV. Instantaneous luminosities in the range $2\text{-}3\times10^{34}$ cm^{-2} s^{-1} are anticipated. The conceptual design for the FCC-hh project foresees a 80-100 km ring equipped with 15-16 T magnets, to reach a pp centre-of-mass energy around 100 TeV, and luminosities of at least 5×10^{34} cm^{-2} s^{-1}. The earliest timeframe for the beginning of operation is ~2040 for both projects. The main technological challenge is the development of high-field superconducting magnets and their industrialization at an affordable cost. While Nb_3Sn allows fields of 15-16 T to be achieved, high-temperature superconducting materials, which are at a much earlier stage of development, are needed for higher fields [3].

Electron-positron Colliders

The projects being considered are: the International Linear Collider (ILC) [4], for which Japan has expressed interest as host country; the Compact Linear Collider (CLIC) [5], being developed at CERN; the Circular electron positron Collider (CepC) in China [2]; and a possible e^+e^- intermediate option of the FCC project (FCC-ee) at CERN [2]. The expected energy and luminosity ranges of these machines are shown in Fig. 2.

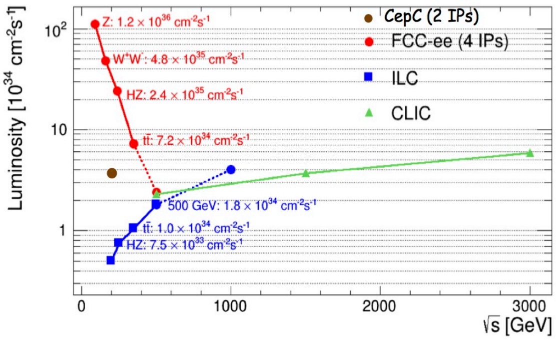

Figure 2: Instantaneous luminosity, multiplied by the number of interactions points (IP), as a function of centre-of-mass energy, for future e^+e^- colliders (modified version from [6]).

Due to limitations from synchrotron radiation, circular colliders cannot reach energies much larger than about 350 GeV. The luminosity increases with decreasing energy because synchrotron radiation decreases, and the saved RF power (typically 50 MW per beam) can be used to accelerate more bunches (up to 16700 for FCC-ee at $\sqrt{s}$ ~90 GeV). A large number of bunches requires a two-ring machine, as envisaged for FCC-ee, whereas the baseline option for CepC is one ring, explaining the difference in luminosity between the two colliders shown in Fig. 2. Due to rapid luminosity burn-off (the lifetime is about 20' at $\sqrt{s}$ ~240 GeV for FCC-ee), both facilities will need an additional booster ring for continuous top-up injection.

Only linear colliders can potentially reach energies of up to several TeV. They have, however, a low repetition rate (5-50 Hz) and their luminosity, which increases with energy due to decreasing beam size, is lower than that achievable at circular colliders, where many bunches can be injected in the ring and several interaction points are available. Nanometer-size beams are therefore needed to reach instantaneous luminosities of a few 10^{34} cm^{-2} s^{-1}, with big challenges in terms of machine alignment, final beam focus, and beamsstrahlung backgrounds in the detectors.

The needed RF gradients range from 20 MV/m for circular colliders to 31 MV/m for a $\sqrt{s}$ ~500 GeV ILC and 100 MV/m for CLIC at $\sqrt{s}$ ~3 TeV. Whereas the technology for the ILC, CepC and FCC-ee is mature, so that construction could technically start before the end of the decade, a few issues (e.g. power optimisation, efficient RF power transfer from the drive beam to the main beam) remain to be solved in the case of CLIC, demanding a few more years of development.

In terms of physics opportunities, the full energy range from $\sqrt{s}$ ~90 GeV to several TeV is of great interest. Operation at the Z-boson mass with the high luminosities envisaged at the FCC-ee would allow electroweak measurements to be made with much higher precision than at LEP and SLC, thereby providing indirect sensitivities to energy scales as large as Λ ~100 TeV. Precise measurements of WW and tt cross sections at threshold, through energy scans around $\sqrt{s}$ ~180 GeV and $\sqrt{s}$ ~350 GeV, should enable measurements of the W-boson and top-quark masses with unprecedented precisions of ~1 MeV and a few 10's MeV, respectively. Higgs boson studies requires a centre-of-mass energy $\sqrt{s}$ ~240 GeV to produce the HZ process, whereas the $H\nu\nu$ process is detectable for $\sqrt{s} \geq 350$ GeV. Higher energies are necessary to study heavy final states, like ttH and HH production, and for direct searches for new particles.

Facilities currently under construction will provide very useful technological demonstrations for future e^+e^- colliders. The European XFEL [7] represents a 5% size "prototype" of the ILC, and SuperKEKB [8] will address many of the challenges for future circular colliders (momentum acceptance, lifetime, etc.).

Physics Opportunities at High-energy Colliders

Two relevant examples are discussed here, followed by some concluding remarks.

Detailed measurements of the Higgs boson, a very special particle because it is the only elementary scalar observed so far, are a top priority of present and future colliders. These measurements are interesting on their own and as a doorway to new physics. Physics beyond the SM is expected to alter the interaction strengths (the so-called couplings) of the Higgs boson with fermions and bosons according to the following approximate law:

$$\frac{\Delta k}{k} \approx \frac{5\%}{\Lambda^2}$$

where Δk is the deviation of a given coupling k from the SM expectation, and Λ (in TeV) is the scale of new physics. New physics sitting at the TeV scale may therefore affect the interactions of the Higgs boson at the few percent level. The interest of these measurements resides in the fact that, although in most scenarios of physics beyond the SM new particles are expected to be observed at the LHC, in some cases [9] the new particles are too heavy to be produced at $\sqrt{s}$ ~14 TeV, and the only manifestation of the new physics may be through anomalies in the interactions of the Higgs boson. Experimental precisions from a few permil to few percent are required in order to observe these effects with a significance of ≥ 3σ for several couplings, and therefore obtain convincing evidence of the existence of new physics.

Higgs-boson couplings to fermions and bosons are experimentally accessible from the measurements of production and decay modes. For instance, H→ ZZ decays give access to the couplings to the Z boson, whereas ttH associated production (Fig. 3, top row) enable extraction of the coupling to the top quark.

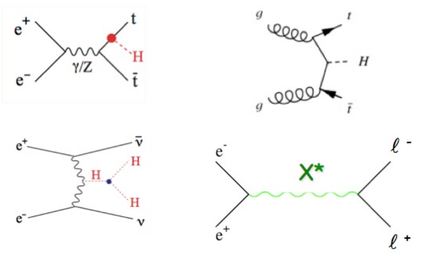

Figure 3: Feynman diagrams for several processes: ttH production at e^+e^- (top left) and hadron (top right) colliders; HH production at e^+e^- colliders (bottom left); example of a virtual (heavy) particle contributing to lepton-pair production at e^+e^- colliders.

Using the full dataset recorded during the first LHC run (about 25 fb^{-1}), ATLAS [10] and CMS [11] have measured the couplings of the Higgs boson to W, Z, gluon, γ, and to fermions of the first generation (τ-lepton and b-quark) with typical precisions of 20%. By ~2020, with 300 fb^{-1} per experiment at $\sqrt{s}$ ~14 TeV, the uncertainties should decrease to 5-10%. The HL-LHC, with a factor of ten more integrated luminosity, should allow precisions of 2-5% to be achieved for most k's, and enable observation, for the first time, of the coupling to second-generation fermions through the rare H→ μμ decay.

Future accelerators can improve significantly on these results. The highest precision (few permil) can be achieved at the FCC-ee, because of the clean environment of an e^+e^- collider and the huge integrated luminosity of this machine (large number of bunches, several interaction points). Figure 4 shows that about 2 million Higgs boson events can be produced at the FCC-ee in ten years of operation. However, two important processes are not accessible at circular e^+e^- colliders: ttH production, which requires $\sqrt{s} \geq 350$ GeV, and HH production (bottom left process in Fig.3), which requires $\sqrt{s} \geq 1$ TeV. The former allows the measurement of the Higgs-top coupling, especially important because of the strangely heavy mass of the top quark; the latter allows the measurement of the Higgs boson self-coupling, thereby providing access to the scalar potential in the Standard Model Lagrangian. These two heavy final states can be measured with precision of a few percent at linear e^+e^- colliders and/or future pp colliders (ttH can already be constrained to ~5% at the HL-LHC). As shown in Fig. 4, the number of Higgs boson events produced at pp colliders exceeds by orders of magnitude the samples available at e^+e^- colliders, thanks to the much larger cross-sections (about 60 pb at $\sqrt{s}$ = 14 TeV and 900 pb at $\sqrt{s}$ = 100 TeV, to be compared to 200-500 fb at e^+e^- machines). However, in contrast to the clean e^+e^- environment, only a small fraction of these events (less than 10%) can be extracted from the huge backgrounds and used for precise measurements. Furthermore, only ratios of Higgs boson couplings can be measured in a model-independent way at hadron colliders, i.e. without assumptions about the Higgs production cross-section and intrinsic width.

	$\sqrt{s}$ (TeV)	L (ab^{-1})	N_H (10^6)	N_{ttH}	N_{HH}
FCC-ee (4 IP)	0.24+0.35	10	2	--	--
ILC	0.25+0.5	0.75	0.2	1000	100
ILC-1TeV	0.25+0.5+1	1.75	0.5	3000	400
CLIC	0.35+1.4+3	3.5	1.5	3000	3000
HL-LHC (2 IP)	14	3	180	3600 ttγγ	250 bbγγ
FCC-hh (2 IP)	100	6	5400	12000 tt4l	20000 bbγγ

Figure 4: Numbers of Higgs boson events expected to be produced at future colliders: total (3rd column), ttH final states (4th column), and HH final states (5th column). The integrated luminosities (2nd column) correspond approximately to a total of ten years of operation at e^+e^- colliders (at various energy points, as given in the 1st column), and five years at pp colliders. The number of assumed interaction points (IP) is also indicated. For the ttH and HH processes, the numbers of events expected at pp colliders are given for illustrative detectable final states.

Searches for new particles at e^+e^- colliders allow direct discovery up to the kinematic limit, i.e. m~$\sqrt{s}$/2, for any state coupling to the Z boson and/or virtual photons γ*. Electron-positron machines provide much greater indirect sensitivity, up to energy scales Λ~100-300 TeV, through precise measurements of known processes (see for instance the bottom right process in Fig. 3).

While the HL-LHC can discover new particles up to masses close to ~10 TeV, 100 TeV hadron colliders are the instruments to explore the 10-50 TeV energy scale directly. For instance, the discovery potential for excited quarks (which are expected if quarks are composite particles) and Z' bosons (which are expected if additional forces exist) extends up to masses of ~50 TeV and ~30 TeV, respectively. The lightest neutralino predicted by Supersymmetric theories, which is currently one of the best candidates for the universe dark matter, can be discovered up to masses of about 4 TeV, thereby covering the entire region allowed by cosmology.

The roadmap for future collider(s) will be based on several considerations, the physics landscape emerging from future LHC runs being perhaps the most important one. A few preliminary remarks about the physics case can nonetheless be made already at this stage. The first LHC run has established the Higgs boson and the Brout-Englert-Higgs mechanism [12, 13] as the origin of electroweak symmetry breaking (EWSB) and particle masses. The newly discovered scalar boson needs to be studied with the highest precision, as it may also provide clues about physics beyond the SM. In general, electron-positron colliders allow the most precise and model-independent measurements; the low mass of the Higgs boson makes it accessible to both circular and linear colliders, with different advantages and disadvantages. A definitive exploration of EWSB, including unravelling any new dynamics contributing to it, requires studies of WW, ZZ and HH production at high masses of the boson pairs, which calls for multi-TeV machines (CLIC, SppC, FCC-hh). If new physics is discovered at the LHC or HL-LHC, completion of the particle spectrum and detailed understanding of the underlying theory will likely necessitate a future high-energy pp collider. Such a machine would also be strongly motivated if the HL-LHC and/or an e^+e^- collider find indirect evidence for new physics in the 10-50 TeV energy range.

Regardless of the detailed scenario, and even in the absence of theoretical or experimental preference for a specific energy scale, the requirements for future colliders are clear: the largest energies and luminosities are needed, to explore directly energy scales in the range 10-50 TeV and to probe higher energy scales indirectly through precise measurements. As a result also of strong technological advances in our field, many exciting opportunities are available today; none of them is inexpensive, none is easy. The decision on how to proceed, and the time sequence of the various projects, will be based on science (e.g. future LHC results), maturity of the technology, cost and availability of funding, as well as on the global (worldwide) perspective of the discipline.

Neutrino Physics at High-intensity Accelerators

Over the past ten years, neutrino oscillations between different species, e.g. $\nu_\mu \rightarrow \nu_e$, have been firmly established also at accelerators, after initial discoveries with solar [14, 15] and atmospheric [16] neutrinos. Oscillations imply that neutrinos have masses and that they mix, i.e. the observed physical states (ν_e, ν_μ, ν_τ) are mixtures of mass eigenstates (ν_1, ν_2, ν_3) through some mixing angles ϑ_{ij} (with $i\neq j$=1,2,3). The probability P for e.g. $\nu_\mu \rightarrow \nu_e$ oscillation is given, in the simplified case of only two neutrino families, by the following equation:

$$P(\nu_\mu \rightarrow \nu_e) = sin^2\, 2\vartheta_{12}\, sin^2\,(1.267\, \Delta m_{12}^2\, \frac{L}{E})$$

where $\Delta m_{12}^2 = m_2^2 - m_1^2$ is measured in eV^2, L is the distance travelled by the neutrinos in km and E the neutrino energy in GeV. Hence, if a pure ν_μ beam is produced at the source, by the time it reaches the detector sitting at a distance L some of the ν_μ's have transformed into ν_e's. Mixing angles and mass differences have been measured over the past 15 years with typical precisions between a few percent and 20%. In spite of these significant accomplishments, several open questions remain: What is the origin of the neutrino masses and why are neutrinos so much lighter than the other fermions? What is the mass hierarchy between eigenstates, i.e. is ν_3 the heaviest or the lightest of the three states? Do neutrinos and antineutrinos behave in a different way, thereby violating charge-parity (CP) symmetry, as quarks and antiquarks do? Why is the mixing in the neutrino sector so much larger than in the quark sector? Are there additional neutrino species, beyond the three we know, as some anomalies in the data seem to indicate?

The primary task of future accelerator-based neutrino physics is to address some of the above questions. The most convenient process is $\nu_\mu \rightarrow \nu_e$, because very intense and pure ν_μ beams can be produced by protons on target, followed by pion production and decay. Because neutrinos are very elusive particles (they interact only through the weak force) and the effects being searched for are tiny, the crucial experimental issues in this case are the availability of high-intensity proton sources (about 0.5 MW has been achieved so far, more than 1 MW is desired in the future), high-power targets, and very massive detectors.

Two accelerator-based facilities are currently considered in the world. The US project, LBNE (Long Baseline Neutrino Experiment) [17], is based on a ν_μ beam produced at Fermilab, directed to a liquid-argon detector located 1300 km away in the Sanford Underground Research Facility (SURF) in South Dakota. The Fermilab accelerator complex is being upgraded from the current power of 350 kW to reach more than 1 MW in ~2030, when data-taking is expected to start. Muon-neutrino interactions in the detector produce muons, from which the spectrum of the incident neutrinos can be reconstructed. Because neutrinos oscillate during their flight from Illinois to South Dakota, the measured number of ν_μ in the detector will be smaller than expected without oscillations, and the shape of the spectrum will be distorted. The disappearance of muon neutrinos from the beam is compensated by the appearance of electron neutrinos from $\nu_\mu \rightarrow \nu_e$ oscillations. The detection and measurement of an electron "signal" in the detector will provide information about the rate and energy of the ν_e's appearing in the beam (Fig. 5). The shape of the reconstructed ν_μ and ν_e spectra will also enable precise measurements of the oscillation parameters, allowing some of the above questions (e.g. CP-violation) to be addressed. To accomplish this physics programme, an exposure of at least 600 MW×kton×years is targeted, which can be achieved in 15 years of data-taking with a 34 kton liquid-argon detector and a 1.2 MW proton source.

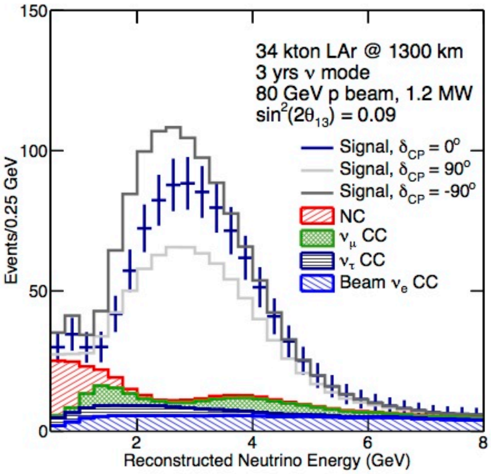

Figure 5: Expected "appearance signal in the LBNE detector", i.e. ν_e energy distribution, after three years of data-taking with a 34 kton liquid-argon detector and a 80 GeV, 1.2 MW proton beam. The three open histograms are obtained for three different values of the CP-violation parameter δ, while the shaded histograms show the background contributions [17].

Japan is considering sending a high-intensity ν_μ beam from J-PARC to a mine in the Kamioka region, 300 km away, where a new, very massive device, Hyper-Kamiokande [18], would be installed. Hyper-Kamiokande is a water Čerenkov detector as its predecessors (Kamiokande and Super-Kamiokande), but with a mass of 1 Mton (560 kton fiducial volume), i.e. 25 times larger than the current Super-Kamiokande detector. It would be located 2.5^0 off-axis, thereby receiving a narrow-band neutrino beam peaking at ~600 MeV. The plan is to upgrade the J-PARC proton source to reach 750 kW by the end of the decade, and ultimately more than 1 MW. Construction of Hyper-Kamiokande could start, if approved, in 2018.

The two projects, LBNE and Hyper-Kamiokande, are complementary. They feature not only different detector technologies, but also different baselines and beam properties, thereby providing different sensitivities to the various oscillation parameters. The Hyper-Kamiokande narrow-band E_ν~600 MeV beam should yield a high-statistics data sample at the first oscillation maximum, whereas the LBNE wide-band E_ν~3 GeV beam should enable shape measurements of the oscillation spectrum.

CONCLUSIONS

The extraordinary success of accelerator-based particle physics is the result of the ingenuity, vision and perseverance of the worldwide high-energy physics community, and of decades of talented, dedicated work. The demonstrated strength of the field is an asset for future, more ambitious projects.

With the discovery of the Higgs boson by the ATLAS and CMS experiments at the CERN Large Hadron Collider, the Standard Model is now complete. However, major, exciting questions remain unanswered. The full exploitation of present accelerators, as well as the construction of future, more powerful machines, is needed to address the outstanding questions and thus advance our knowledge of fundamental physics.

Without a doubt, future high-energy and/or high-intensity accelerators will be extremely challenging. However, the correct approach is not to abandon the exploratory spirit of our discipline because of technical and financial challenges. The correct approach is to use our creativity to develop the transformational technologies needed to make future projects technically feasible and financially affordable.

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