The Future of High-Energy Collider Physics

John Ellis*
Physics Department, Kings College London, Strand, London WC2R 2LS, UK;
Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland;
National Institute of Chemical Physics & Biophysics, Rävala 10, 10143 Tallinn, Estonia

Abstract

High-energy collider physics in the next decade will be dominated by the LHC, whose high-luminosity incarnation will take Higgs measurements and new particle searches to the next level. Several high-energy $e^+e^-$ colliders are being proposed, including the ILC (the most mature), CLIC (the highest energy) and the large circular colliders FCC-ee and CEPC (the highest luminosities for $ZH$ production, $Z$ pole and $W^+W^-$ threshold studies), and the latter have synergies with the 100-TeV $pp$ collider options for the same tunnels (FCC-hh and SppC). The Higgs, the Standard Model effective field theory, dark matter and supersymmetry will be used to illustrate some of these colliders’ capabilities. Large circular colliders appear the most versatile, able to explore the 10-TeV scale both directly in $pp$ collisions and indirectly via precision measurements in $e^+e^-$ collisions.

1 Introduction

At the time of writing, the Standard Model (SM) still reigns rather supreme. Calculations in its QCD sector are becoming ever more precise, and LHC data are highly compatible with its predictions. Electroweak precision tests are also quite consistent with the SM, modulo longstanding issues such as $Z$ decays to $b$ quarks and the anomalous magnetic moment of the muon. There are some anomalies in $B$ meson decays, but more data are required before any conclusions can be reached. The Higgs boson discovered in 2012 continues obstinately to obey the predictions of the SM.

How will we discover physics beyond the SM? Electroweak, Higgs and flavour data may provide clues or evidence. So might astrophysics and cosmology, e.g., via measurements of cosmic rays or gravitational waves. However, just as previous collider experiments pinned down the SM, future collider experiments with surely be needed to pin down the physics beyond the SM. In this talk I present a personal review of planned and projected future colliders and illustrate how they might take us beyond the SM, using Higgs studies, the Standard Model effective field theory, dark matter and supersymmetry as illustrations.

*e-mail: John.Ellis@cern.ch
2 Possible Future Colliders

2.1 The High-Luminosity LHC

Following Run 2 of the LHC there is a 2-year shutdown for refurbishment and upgrades, following which Run 3 should accumulate about 300/fb of integrated luminosity in each of ATLAS and CMS. After another, longer shutdown for the ultimate upgrades of the accelerator and experiments, the high-luminosity LHC (HL-LHC) will operate for about a decade from 2026 onwards, with an integrated luminosity target of 3000/fb, almost two orders of magnitude more than the luminosities used in most current LHC analyses [1].

The increase in luminosity will make possible much more precise measurements of the properties of the Higgs boson, as illustrated in Fig. 1 [2]. As seen there, for the full benefits of the increased luminosity to be realized, it will be necessary to reduce the systematic uncertainties, hopefully as $1/\sqrt{L}$, and also to halve the theoretical uncertainties, requiring higher-order QCD and electroweak corrections in many cases. HL-LHC will also increase significantly the reach for new massive particles such as those predicted by supersymmetry.

![Figure 1: The prospective accuracies of CMS measurements of $H \rightarrow ZZ^*$ with 300 (3000)/fb of data in the left (right) panel, under less (more) optimistic assumptions about the attainable systematic and theoretical uncertainties in green (red) [2].](image)

The HL-LHC project has been fully approved by the CERN Council and will operate until about 2 decades hence. However, in light of the long lead times for proposing, preparing and constructing new high-energy colliders, there is much ongoing discussion about possible future colliders.

2.2 Possible Future $e^+e^-$ Colliders

In particular, there is much discussion of different possible future high-energy $e^+e^-$ colliders, whose potential energy ranges and luminosities are shown in Fig. 2. The most mature of these projects is the ILC, which is currently proposed to run at 250 GeV in the centre of mass, with possible
upgrades to 500 GeV or 1 TeV. The highest-energy option is CLIC, which aims to reach 3 TeV in the centre of mass. The circular $e^+e^-$ colliders FCC-ee and CEPC are limited to centre-of-mass energies $\lesssim 400$ GeV, but could attain higher luminosities at the $ZH$ and $W^+W^-$ thresholds, as well as at the $Z$ peak.

Figure 2: The prospective centre-of-mass energy reaches and luminosity targets of high-energy $e^+e^-$ collider projects.

The ILC is currently awaiting approval by the Japanese government, and its prospective measurements of Higgs couplings would complement those possible with HL-LHC, as seen in Fig. 3 [3]. On the other hand, the absence of new particles so far at the LHC has diminished the chance that the ILC could discover any, and the higher luminosity of a circular $e^+e^-$ collider would enable it to make more accurate measurements of the Higgs boson, as discussed below.

Figure 3: Complementarities between prospective Higgs coupling measurements at HL-LHC and the ILC [3].
2.3 Possible Circular Colliders

The vision being developed in Europe (FCC) [4, 5] and China (CepC/SppC) [6] is of a ∼ circular tunnel of ∼ 100 km circumference that could house an $e^+e^-$ collider, a $pp$ collider using magnets with fields of 16 to 20 Tesla that would be capable of reaching ∼ 100 TeV in the centre of mass, and an $ep$ collider. Such a complex would be capable of exploring the 10-TeV scale both directly in $pp$ collisions and indirectly in $e^+e^-$ and $ep$ collisions. Another possibility is to replace the present LHC magnets with similar high-field magnets so as to reach ∼ 27 TeV, the HE-LHC [7].

The cross-sections for various Higgs production mechanisms at high-energy $pp$ colliders are shown in Fig. 4. We see that many of the cross-sections increase by almost two orders of magnitude between the LHC and a 100-TeV collider [8]. This is the case, in particular, for double Higgs production. We note also that HE-LHC and FCC-pp have target luminosities up to $3 \times 10^{35}$ cm$^{-2}$s$^{-1}$, a factor ∼ 5 larger than HL-LHC.

![Figure 4: The cross-sections for various Higgs production mechanisms at $pp$ centre-of-mass energies $\lesssim 100$ TeV [8].](image)

These high cross-sections and luminosities will make possible very accurate measurements of Higgs production, of which a couple of examples are shown in Fig. 5. We see in the left panel that a ∼ 1% measurement of the ratio of $H \rightarrow \gamma\gamma$ and $ZZ^*$ branching ratios should be possible at low $p_T$ (with an optimistic estimate of the systematic uncertainties), and even a ∼ 10% measurement at $p_T \sim 1$ TeV [9, 10]. The right panel of Fig. 5 shows that a ∼ 5% measurement of the triple-Higgs coupling should be possible with FCC-hh [11, 10].

The combination of results from $e^+e^-$ and $pp$ collisions (FCC-ee/FCC-pp or CEPC/SppC) would provide important synergies and the greatest precision in measurements of the Higgs couplings. The left panel of Fig. 6 shows the precision in the Higgs coupling modifiers $\kappa_{V,F}$ attainable by combining FCC-ee and FCC-pp measurements, compared with the current accuracies of LHC measurements [12]. Also shown are predictions of two composite Higgs models, MCHM4.5: the present measurements constrain their parameters at the 10 to 20% level, whereas the future measurements could take the accuracy down to a fraction of 1%. The LHC has already measured the Higgs couplings to the third-generation fermions $t, b, \tau$, the coupling to muons is within its reach, and $H \rightarrow c\bar{c}$ could be measured at an $e^+e^-$ collider. However, measuring the Higgs couplings to $u, d, s$ quarks and to electrons remain dreams, though the right panel of Fig. 6 shows that with a suitable running scheme FCC-ee measurements might be able to reach with a factor ∼ 2.2 of the
Figure 5: The potential accuracies of FCC-hh measurements of the ratio of $H \rightarrow \gamma\gamma$ and $ZZ^*$ branching ratios (left panel) [9] and of the triple-Higgs coupling (right panel) [11].

SM value of the $He^+e^-$ coupling at the 95% CL [13].

Figure 6: The potential accuracies of combined FCC-ee and FCC-hh measurements of the Higgs coupling modifiers $\kappa_{V,F}$ (left panel) [12], and FCC-ee could provide interesting constraints on the $H$ coupling to electrons (right panel) [13], under suitable running conditions (red circles).

3 Standard Model Effective Field Theory

In the previous Section various future collider projects were introduced, and their capabilities illustrated via possible Higgs measurements. In this Section I discuss a broader approach to collider physics, based on the Standard Model Effective Field Theory (SMEFT). In this approach one looks systematically for possible new high-mass physics beyond the SM via the higher-dimensional effective interactions that it might induce between SM particles. The most relevant for collider physics are generated by operators of dimension 6 whose coefficients are scaled by $1/\Lambda^2$, where $\Lambda$ is the scale of new physics, so the first step is to classify these operators. Assuming that their coefficients are flavour-independent, just 20 such operators are important for precision electroweak data, diboson and Higgs production. Since their contributions to amplitudes are $\propto 1/\Lambda^2$, their
relative importance increases with the centre-of-mass energy and/or transverse momentum. This gives an advantage to a higher-energy $e^+e^-$ collider such as CLIC, as we see later, and renders kinematic measurements particularly useful.

We recently made a global SMEFT fit to all the available Higgs data from LHC Runs 1 and 2 including a number of kinematic measurements from ATLAS, the most sensitive high-$p_T W^+W^-$ measurement from the LHC, and the precision electroweak and diboson production data from LEP [14]. Constraints on operator coefficients from this fit are shown in Fig. 7. The blue ranges were obtained using only pre-Run-2 data, whereas the orange ranges include all the data. The left panel shows marginalized results when all operators are allowed to contribute, and the right panel shows results when each operator is switched on individually. As could be expected, the fits to individual give, in general, tighter constraints than all operators are included and marginalized. We also see that the fit using Run 2 data gives significantly tighter constraints on many operator coefficients.

![Figure 7: Best-fit values and 95% CL ranges of operator coefficients from global fits (orange) including all operators simultaneously (left panel) and switching each operator on individually (right panel) [14]. Also shown are fits omitting the LHC Run 2 data (blue).](image)

A direct comparison between the 95% CL constraints on operator coefficients in marginalized and individual fits to all the available data is shown in Fig. 8 [14]. As before, we see that the individual fits give significantly tighter constraints on most operator coefficients, extending in many cases to values of $\Lambda$ in the multi-TeV range for coefficients $c = O(1)$. This analysis reveals no hint of physics beyond the SM, since the SMEFT fit has a global $p$-value that is no better than the SM.

As a first attempt to project how these constraints might evolve in the future at the HL- and HE-LHC [15], we have assumed the following simple scaling laws for the experimental, systematic and theoretical uncertainties for each operator coefficient:

$$\frac{\delta O_{\text{HL}}}{\delta O_{\text{today}}} = \sqrt{\frac{L_{\text{today},i}}{L_{\text{HL}}}}, \quad \frac{\delta O_{\text{HE}}}{\delta O_{\text{today}}} = \sqrt{\frac{\sigma_{13} L_{\text{today}}}{\sigma_{27} L_{\text{HE}}}}. \quad (1)$$

On the one hand this is optimistic, since there is no analysis supporting such scaling laws for the systematic and theoretical uncertainties, but on the other hand this is pessimistic, since the higher luminosities and energy will make possible more refined measurements of the kinematic distributions. We assume $L_{\text{today}} \simeq 36 \text{ fb}^{-1}$ for most current LHC measurements, and the benchmark luminosities $L_{\text{HL}} = 3 \text{ ab}^{-1}$ and $L_{\text{HE}} = 15 \text{ ab}^{-1}$ for all the HL- and HE-LHC measurements. The
Figure 8: Comparison of the 95% CL bounds obtained from marginalized (red) and individual (green) fits to the 20 dimension-6 operators contributing to electroweak precision tests, diboson and Higgs measurements [14].

Results for the operator coefficients are shown in Fig. 9, where the current LHC constraints are shown in blue, and the prospective HL- and HE-LHC constraints are in green and purple, respectively.

Results for fits to projected data from the ILC at energies ≤ 250 GeV and from FCC-ee are shown in Fig. 10 [16]. In the left panel we show constraints on the coefficients of operators most strongly constrained by Higgs production and electroweak precision data in individual fits (green) and marginalized fits (red). In each case, the lighter (darker) shadings are for fits with/without theoretical uncertainties in the electroweak measurements. In the right panel we show constraints on operators contributing to Higgs and diboson production, again showing the results of individual fits in green and marginalized fits in red. In this case, we show in different shades the effects of including ILC data on triple-gauge couplings. We see that the FCC-ee constraints are significantly stronger than those from the ILC, in particular because of the greater accuracy in the electroweak precision measurements. We also note the importance of controlling the theoretical uncertainties in the interpretation of the FCC-ee data.

|                  | $\delta\Gamma_Z$ [MeV] | $\delta R_t$ [$10^{-4}$] | $\delta R_b$ [$10^{-5}$] | $\delta\sin^2\theta_{\text{eff}}$ [$10^{-6}$] |
|------------------|------------------------|--------------------------|--------------------------|----------------------------------|
| **Present EWPO errors** |                        |                          |                          |                                  |
| EXP1             | 2.3                    | 250                      | 66                       | 160                              |
| TH1              | 0.4                    | 60                       | 10                       | 45                               |
| **FCC-ee EWPO error estimates** |                      |                          |                          |                                  |
| EXP2             | 0.1                    | 10                       | $2 \div 6$               | 6                                |
| TH2              | 0.15                   | 15                       | 5                        | 15                               |
| TH3              | < 0.07                 | < 7                      | < 3                      | < 7                              |

Table 1: Comparison for selected precision observables of present experimental measurements (EXP1), current theory errors (TH1), FCC-ee precision goals (EXP2), estimates of the theory errors assuming that electroweak 3-loop corrections are known (TH2), and assuming that also the dominant 4-loop corrections are available (TH3). Adapted from [17].

Considerable effort will be needed to reduce the SM theory uncertainties to the level where full
Figure 9: The best-fit values and 95% CL ranges for dimension-6 operator coefficients using current data (blue), and projections with the scaling (1) for HL-LHC (green) and HE-LHC (purple) measurements, including all operators simultaneously (left panel) and switching each operator on individually (right panel) [15].

Figure 10: Summary of the reaches for the dimension-6 operator coefficients when switched on individually (green) and when marginalised (red), from projected precision measurements at the ILC250 (lighter shades) and FCC-ee (darker shades) [16]. The left plot shows constraints from Higgs and electroweak data, with the different shades representing the effects of theoretical uncertainties at FCC-ee. The right panel shows constraints from Higgs physics and triple-gauge couplings, and the different shades of light green show the effect of including the latter in the ILC analysis.

Table 1 lists, for selected electroweak precision observables, the current experimental errors (EXP1), the current theoretical errors (TH1), the prospective measurement errors at FCC-ee [5] (EXP2), the estimated theoretical uncertainties if complete 3-loop calculations are available (TH2), and the estimated theoretical uncertainties if the dominant 4-loop diagrams are also calculated (TH3). Table 2 lists, for $Z \rightarrow b\bar{b}$ decay, the numbers of distinct topologies of diagrams to be calculated, the

benefit can be extracted from the electroweak precision measurements at FCC-ee, in particular. The proceedings of a workshop dedicated to assessing the magnitude of this task are available in [17].
Table 2: Numbers of topologies and diagrams for $Z \rightarrow b\bar{b}$ decays in the Feynman gauge, using topological symmetries of diagrams, and after removing tadpoles and wave-function diagrams. Adapted from [17].

| Number of topologies | 1 loop | 2 loops | 3 loops |
|----------------------|--------|---------|---------|
| 15                   | 1074   | 120472  |
| Fermionic loops      | 0      | 150     | 17580   |
| Bosonic loops        | 15     | 924     | 102892  |
| Planar / Non-planar  | 15 / 0 | 981/133 | 84059/36413 |
| QCD / EW             | 1 / 14 | 98 / 1016 | 10386/110086 |

Fig. 11 shows the prospective sensitivities of CLIC measurements at 350 GeV, 1.4 TeV and 3.0 TeV to the coefficients of various dimension-6 operators [18]. As previously, the green bars are for fits in which each operator is switched on individually, whereas the red bars are for fits including all operators. Also, the lighter (darker) green bars in the left panel include (omit) the prospective HZ Higgsstrahlung constraint. As could be expected, since the effects of higher-dimensional operators increase with energy, the sensitivities are generally enhanced at higher centre-of-mass energies.

Figure 11: The estimated sensitivities of CLIC measurements at 350 GeV, 1.4 TeV and 3.0 TeV to the scales of various dimension-6 operator coefficients, showing individual (marginalised) fit results as green (red) bars [18]. The lighter (darker) green bars in the left panel include (omit) the prospective HZ Higgsstrahlung constraint.
4 Supersymmetry

This (still) my favourite scenario for physics beyond the SM, despite the disappointment that it has not (yet) been discovered at the LHC. Indeed, I would argue that Run 1 of the LHC has, in addition to the traditional motivations of improving the naturalness of the mass hierarchy, its role in string theory and its provision of a dark matter candidate, provided three new reasons for liking supersymmetry. One is that it would stabilize the electroweak vacuum [19], another is that it predicted correctly the mass of the Higgs boson [20], and the third is that predicted correctly that the Higgs couplings should resemble those in the SM [21].

So where is supersymmetry to be found? Fig. 12 shows some results from recent global fits to 11 phenomenological parameters of the minimal supersymmetric extension of the SM (pMSSM11) including the available experimental constraints including those from the first phase of Run 2 of the LHC at 13 TeV [22]. We see that both squarks and gluinos could be as light as \(\sim 1\) TeV if \(g - 2\) is dropped from the fit, whereas somewhat heavier masses are preferred if \(g - 2\) is included in the fit. Either way, strongly-interacting sparticles could well lie within reach of future LHC runs.

A more complete picture of the possible sparticle mass spectrum in the pMSSM11 in the case where \(g - 2\) is dropped from the fit is shown in Fig. 13 [22]. The best-fit mass values are shown as horizontal blue bars, and the vertical orange bands show the 68 and 95% CL ranges for each of the sparticle masses. Also shown as horizontal lines are the kinematic reaches for pair-production of various sparticle species at \(e^+e^-\) colliders with centre-of-mass energies of 500 GeV (green), 1 TeV (red) and 3 TeV (mauve). The two former correspond to possible energy upgrades of the ILC (which is currently proposed to reach 250 GeV), and the third line corresponds to CLIC. We see that a 500-GeV collider would have little chance of producing sparticles in the pMSSM11, whereas a 1-TeV collider would have a better chance, and CLIC could have very interesting prospects for detecting and measuring sparticles - we will know better at the end of LHC Run 2.

The global fits of the pMSSM11 with and without \(g - 2\) and 13-TeV LHC data are all highly compatible with the measured mass of the Higgs boson. Also, as seen in Fig. 14 [22], they prefer values of the branching ratios for \(h \rightarrow \gamma\gamma\) and \(h \rightarrow ZZ^*\) that are similar to those in the SM. However, they also allow for substantial deviations \(\lesssim 20\%\) at the 95% CL. Therefore, low-energy \(e^+e^-\)
Figure 13: Sparticle spectrum for the pMSSM11 with the $g_{\mu} - 2$ constraint applied [22]. The masses at the best-fit points are indicated by horizontal blue lines, and the 68 and 95% CL ranges by vertical orange bands. The kinematic reaches for pair-production of various sparticle species at $e^+e^-$ colliders with centre-of-mass energies of 500 GeV, 1 TeV and 3 TeV are shown as horizontal green, red and mauve lines, respectively.

colliders such as ILC250, FCC-ee or CEPC may still have good prospects for discovering indirect signatures of supersymmetry, even though they may have little chance of producing sparticles directly.

Figure 14: One-dimensional $\chi^2$ functions for the branching ratios for $h \rightarrow \gamma\gamma$ (left panel) and $h \rightarrow ZZ^*$ (right panel) in the pMSSM11 fits with (blue) and without the $g_{\mu} - 2$ constraint (green) and with (solid) and without (dashed) the 13-TeV LHC constraints [22].

What are the prospects for sparticle discovery at a 100-TeV $pp$ collider? The left panel of Fig. 15 shows that the reach for conventional missing-energy searches for squarks and gluinos extends well above 10 TeV [23], as in the vision outlined earlier. Moreover, the reach for various different neutralino candidates extends into the multi-TeV range, as seen in the right panel of Fig. 15.
Figure 15: The reaches at a 100-TeV pp collider for conventional missing-energy searches for squarks and gluinos (left panel) and different neutralino candidates (right panel) [23].

Does this mean that there is a no-lose theorem for discovering supersymmetry at a 100-TeV pp collider? Unfortunately not. Arguments about the possible sparticle mass scale based on the naturalness of the mass hierarchy, grand unification or the stability of the electroweak vacuum do not set very stringent upper limits on the scale of supersymmetry breaking. The tightest constraints known to me come from the density of dark matter, assuming that the lightest sparticle is a stable neutralino. An order-of-magnitude argument suggests that the neutralino should weigh $\mathcal{O}(\text{TeV})$ in order to avoid providing too much dark matter. However, as seen in the right panel of Fig. 15, there are circumstances in which the neutralino could be significantly heavier, specifically when it is almost degenerate with some other sparticle(s), and coannihilations suppress the relic neutralino density. Scenarios that have been studied in some detail include gluino and stop coannihilation and Fig. 16 shows one example of the profile of a stop coannihilation strip in the constrained MSSM [24].

The stop-neutralino mass difference $\delta m$ vanishes when the the supersymmetry-breaking parameter $m_{1/2} \to 16$ TeV, corresponding to neutralino and stop masses $\simeq 8$ TeV. As shown by the red line, the value of $m_h$ calculated using the latest version of the FeynHiggs code is compatible with the experimental value, within the calculational uncertainty represented by the horizontal orange band. This example is certainly quite finely tuned, but it does indicate that new ideas [25] may be needed to be sure of discovering sparticles even at a 100-TeV pp collider.

5 Conclusions

There are many reasons to expect physics beyond the SM, including the apparent instability of the electroweak vacuum calculated within the SM, the nature of dark matter, the origin of matter, the naturalness of the hierarchy of mass scales, neutrino masses and mixing, the mechanism of cosmological inflation, and constructing a quantum theory of gravity. The strongest arguments for new physics at the TeV scale that could be accessible to future high-energy colliders are provided by dark matter and the naturalness problem.

The HL-LHC is on its way, and will take Higgs studies and the search for new particles to the next level, with almost two orders of magnitude more LHC data than have been analyzed so far. There are also many ideas for possible new high-energy accelerators. The ILC may be next, while CLIC is a project for a linear $e^+e^-$ collider at higher energy, which has advantages for both direct and indirect searches for new physics. Future circular $e^+e^-$ colliders, on the other hand, are limited
Figure 16: The profile of the stop coannihilation strip in the constrained MSSM for \( \tan \beta = 5, A_0 = 3m_0 \) and \( \mu > 0 \) \cite{24}. The lower horizontal axis shows \( m_{1/2} \) and the upper horizontal axis shows the corresponding values of the lightest neutralino mass. The blue curve shows the stop-neutralino mass difference, to be read from the left vertical axis. The red line shows the value of \( m_h \) calculated using the latest version 2.14.1 of the FeynHiggs code \cite{26}, to be read from the right vertical axis. Calculations within the orange band may be regarded as acceptable, given the uncertainties in the calculations.

in the centre-of-mass energy they can reach, but offer larger luminosities at low energies end hence a new generation of high-precision electroweak tests. Moreover, a large circular tunnel also offers the prospect of pp collisions at energies as high as 100 TeV, as well as the possibility of ep collisions, representing, in my view, the most versatile way forward.

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