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Future Circular Colliders succeeding the LHC

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Particle physics has arrived at an important moment of its history. The discovery of the Higgs boson has completed the Standard Model, the core theory behind the known set of elementary particles and fundamental interactions. However, the Standard Model leaves important questions unanswered, such as the nature of dark matter, the origin of the matter–antimatter asymmetry in the Universe, and the existence and hierarchy of neutrino masses. To address these questions and the origin of the newly discovered Higgs boson, high-energy colliders are required. Future generations of such machines must be versatile, as broad and powerful as possible with a capacity of unprecedented precision, sensitivity and energy reach. Here, we argue that the Future Circular Colliders offer unique opportunities, and discuss their physics motivation, key measurements, accelerator strategy, research and development status, and technical challenges. The Future Circular Collider integrated programme foresees operation in two stages: initially an electron–positron collider serving as a Higgs and electroweak factory running at different centre-of-mass energies, followed by a proton–proton collider at a collision energy of 100 TeV. The interplay between measurements at the two collider stages underscores the synergy of their physics potentials.

The Standard Model (SM) was first spelled out in the 1960s, theoretically consolidated in the early 1970s, and confirmed through a series of discoveries over decades of experimentation. The SM describes with great precision innumerable physical phenomena observed in the laboratory and in the cosmos, linking present day experiments with the first 10^{-11} seconds of the Universe. This achievement does not stop the need for further exploration: there remain many unanswered questions, with the origin of the Higgs boson on top of the list, which can only be answered by more powerful lepton and hadron colliders.

Is the Higgs boson an elementary particle, or a composite state of confined particles? What mechanism generates its mass and self-interaction, leading to electroweak (EW) symmetry breaking and to the generation of particle masses? Is the Higgs mass calculable, or is it an arbitrary parameter fixed by hand? What was the nature of the phase transition that led, in the early Universe, to EW symmetry breaking? Addressing these questions requires precision measurements of the Higgs boson properties and of EW interactions above the weak scale. High-energy colliders are the exclusive tool to study the Higgs boson in a controlled environment.

In parallel, future experiments should extend the search for new phenomena possibly related to the open questions that the SM presently does not explain. There are no experimental hints pointing clearly to the origin of these phenomena, and, for the first time since the Fermi theory of weak interactions, there is no clear energy scale or coupling strength for new physics. Past experience has shown that measurements at the limit of precision and sensitivity often provide clues of new physics before the latter can be revealed directly by high-energy collisions.

The Future Circular Collider (FCC) builds on the success and experience of the Large Electron–Positron (LEP) and Large Hadron Collider (LHC), integrating the complementary qualities of circular electron–positron and proton–proton colliders within a largely common, and partly existing, infrastructure.

The FCC is currently foreseen to operate in two stages[1]. First, the FCC-ee[2] will collide e^+e^- pairs at several centre-of-mass energies, $\sqrt{s}$, producing large numbers of Z^0 bosons, $W^\pm$ pairs and top quarks (t) in a clean environment (see Table 1) enabling their high-precision measurement. The FCC-ee also foresees the production of Higgs bosons (H) via Higgsstrahlung, $e^+e^-\to Z^0H$, at $\sqrt{s}$ = 240 GeV, and through W-boson fusion, $e^+e^-\to H\nu\bar{\nu}$, at 365 GeV. In addition, the challenging direct Higgs production, $e^+e^-\to H$, at the Higgs mass of 125 GeV, is being investigated with the help of a 'monochromatization' scheme[3]. Subsequently, the FCC-hh[4] will collide protons at $\sqrt{s} = 100$ TeV, accumulating a dataset corresponding to a total luminosity of $L_{\rm int} = 20$ ab^{-1} per experiment, producing 5×10^{10} Higgs bosons, 10^{13} $W^\pm$ bosons and 10^{12} top quarks. For studies of the quark–gluon plasma and of strong interactions at high density and temperature, the FCC-hh could support heavy ion collisions, for example, lead–lead collisions at $\sqrt{s} = 39.4$ TeV per nucleon. For complementary studies of Higgs, top and EW interactions, further searches of new physics, and to refine the knowledge of the proton structure, the FCC could allow electron–proton collisions at $\sqrt{s}$ = 3.5 TeV, collecting $L_{\rm int}$ = 2 ab^{-1} concurrently with proton–proton operations (FCC-eh).

Long-term strategy and readiness

The construction of any future collider will require a substantial investment. It should be an integral part of a long-term vision of high-energy physics, maximising the total physics output, while minimising overall cost and providing a diverse physics programme. This can be achieved by sharing or reusing most of the new infrastructure and profiting from already existing facilities, including their technical and administrative know-how. The FCC[1,2,4] and its integrated plan[5,6], extending over 70 years in time as illustrated in Fig. 1, was developed to fulfil all the aforementioned goals. The European Strategy process in 2019 has revealed "a clear support … for an e^+e^- Higgs factory as the next large-scale facility after the LHC"[7], a role well-suited to the FCC-ee. The schedule for the FCC foresees the start of the electron–positron collider operation at the end of the LHC, with immediate discovery potential already at the Z^0 pole, and it also provides a reasonable spending profile as well as an adequate time window for the development of affordable high-field magnets required for the FCC-hh.

Circular colliders are intrinsically energy efficient because they collide the same particle bunches over many turns. The beam energy lost by synchrotron radiation increases with the fourth power of the beam energy. Yet, in the energy range up to the top quark, the FCC-ee will operate efficiently in terms of total luminosity per electrical power, as illustrated in Fig. 2. The expected AC site power

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Table 1 | Run plan for the FCC-ee

FCC-ee phase	Run duration (yr)	$\sqrt{s}$ (GeV)	L_{int} (ab^{-1})	Event statistics
Z^0	4	88–95	150	3×10^{12} hadronic Z^0 decays
W^+W^-	2	158–192	12	3×10^8 W^+W^- pairs
Z^0H	3	240	5	10^6 Z^0H events
$t\bar{t}$	5	345–365	1.5	10^6 $t\bar{t}$ and 6×10^4 $H\nu\bar{\nu}$ events
H (optional)	3	125	21	Optional run on H resonance

The different data-taking periods, so-called runs, of the FCC-ee in its baseline configuration with two experiments, and an optional run on the Higgs resonance are listed with the respective run duration, centre-of-mass energy and integrated luminosity as well as event statistics.

consumption for Higgs production, calibrated to performance (in ab^{-1} TWh^{-1}), is probably the lowest for the FCC-ee, compared with other proposed future projects. Assuming an electricity price of €50 MWh^{-1}, the FCC-ee electricity cost amounts to about €200 per Higgs boson[2,8].

The FCC-ee construction cost, calibrated to performance (in billion CHF per ab^{-1}), is also among the lowest. Taking the Z^0H operation at a centre-of-mass energy of 240 GeV with 5 ab^{-1} accumulated over 3 years as an example, the total investment cost for the FCC-ee corresponds to CHF10,000 per produced Higgs boson and for the four-year operation at the Z^0 pole with 150 ab^{-1} recorded, this amounts to CHF10,000 per 5×10^6 Z^0 bosons, which equals the number of Z^0 bosons collected by each experiment during the entire LEP programme[2].

Each key 'ingredient' of the FCC-ee has already been demonstrated at one or several previous colliders or test facilities. Such proven ingredients include, for example, the vertical spot size and the transverse emittances of the beams, the synchrotron-radiation photon energies, and synchrotron-radiation power per unit length, the bunch charge, the 'crab-waist' collision scheme, the radiofrequency system and the positron production rate. For example, the FCC-ee poses rather relaxed demands on positron production. The world record for positron production rates is still held by the positron source at the SLAC Linear Collider (SLC). Figure 3 compares the demonstrated positron production at SLC in the US, the Japanese facilities KEKB and SuperKEKB with the needs for future electron–positron colliders. The SLC and SuperKEKB sources would already meet the FCC-ee requirements. Therefore, the FCC-ee research and development is focused on cost-effective and energy-efficient technologies, which includes high-performance robust superconducting radio-frequency (RF) cavities, high-power RF couplers and efficient RF power sources on the one hand, and novel low-power inexpensive two-in-one arc magnets on the other.

For the 100 TeV hadron collider, the key technology is high-field magnets, and the underlying superconductor. The ongoing high-luminosity upgrade of the LHC represents an important milestone, including a few tens of dipole or quadrupole magnets with a peak field of 11–12 T, based on state-of-the-art Nb_3Sn conductor. For the FCC-hh, various configurations of 16 T Nb_3Sn magnets are under development. In spring 2019, an accelerator dipole demonstrator at FNAL in the US has reached 14 T both at 1.9 K and at 4.5 K (ref. [9]). A second test with additional pre-stress will aim at exceeding the design field of 15 T, just below the FCC-hh target. A higher-quality conductor is important to achieve a higher field and to lower the cost, reducing the amount of superconductor needed. Over the past year, advanced wires containing artificial pinning centres, produced by two US teams, have reached the target critical current density of 1500 A mm^{-2} at 16 T (refs. [10,11]). The artificial pinning centres also decrease magnetization heat during field ramps, improve the magnet field quality, and reduce the probability of flux jumps[12]. It is expected that the 16 T high-field magnets will be ready for a ten-year serial production from about 2045 onwards[13], matching the FCC integrated plan (Fig. 1).

Synergies and complementarity

As discussed, the pillars of the FCC physics programme are the precision, the sensitivity and the ultimate energy reach. Both FCC-ee and FCC-hh stages offer a coherent and unique landscape of discovery opportunities, and their integration greatly enhances the potential to discover new physics.

Many manifestations of new physics do not leave clear imprints detectable through indirect precision measurements. If new physics generates effective operators through loop effects, precision EW or Higgs data might only be sensitive to mass scales Λ below the TeV scale. For example, the best LEP limits on supersymmetry came from direct searches, because supersymmetric particles heavier than the production threshold could have left marginal signatures in the LEP precision data. The exploration in the multi-TeV domain, for scenarios beyond the SM of this type, requires the highest energies, highlighting the complementarity between electron and proton colliders, and the necessity to plan for both.

While the FCC-hh will be the ultimate discovery machine at the high-energy frontier, any discovery will be only the first step towards a complete exploration and understanding of the new phenomena, for example, to identify the correct underlying model will require extensive inputs. It took many years and many experiments, addressing the EW, quantum chromodynamics (QCD) and flavour sectors, to firmly establish the SM as 'the' reference theory. It will likewise take multiple inputs to identify the new theory underlying a new signal observed at the FCC-hh. While any signal or deviation seen at the FCC-ee could directly guide studies at the FCC-hh, the FCC-ee precision will be critical in selecting viable models, even if its findings were fully consistent with the SM. The SM consistency measured at LEP remains, today, one of the strongest constraint on our interpretation of the anomalies emerging occasionally from experimental data. The interplay between measurements at electron and proton colliders underscores the synergy of their physics potentials.

Heavy-ion collisions and electron–proton scattering, unattainable at linear-collider facilities, further enhance the diversity and completeness of the FCC programme.

Higgs properties

The cornerstone of the Higgs measurement programme is the direct and model-independent determination of its coupling to the Z^0 boson, g_{HZZ}, through the study of the Z^0 recoil mass spectrum M_X in $e^+e^- \rightarrow Z^0+X$ events at $\sqrt{s} = 240$ GeV. By identifying the Z^0 as recoiling against a Higgs boson mass, the total Higgs production rate is determined independently of the Higgs decay mode. This measurement can only be performed at lepton colliders. The measurement of the $H \rightarrow Z^0Z^0$ decay rate provides then the total Higgs width. Absolute values of the other Higgs couplings follow from the relative rates of different production and decay channels, directly enhancing the robustness of the LHC and FCC-hh Higgs measurements. The FCC potential to promote Higgs physics to a precision science is summarized in Fig. 4. The improvement over the projected LHC results approaches one order of magnitude, reaching a parts-per-thousand precision on g_{HZZ} and remaining well below the percent level for couplings to gauge bosons, the muon, and to the fermions heavier than a GeV. The knowledge of the Higgs mass, m_H, to within a few MeV allows the FCC-ee to run at $\sqrt{s} = m_H$ to probe the otherwise inaccessible Higgs coupling to the electron in the s-channel mode $e^+e^- \rightarrow H$ (ref. [14]), which requires the statistics of

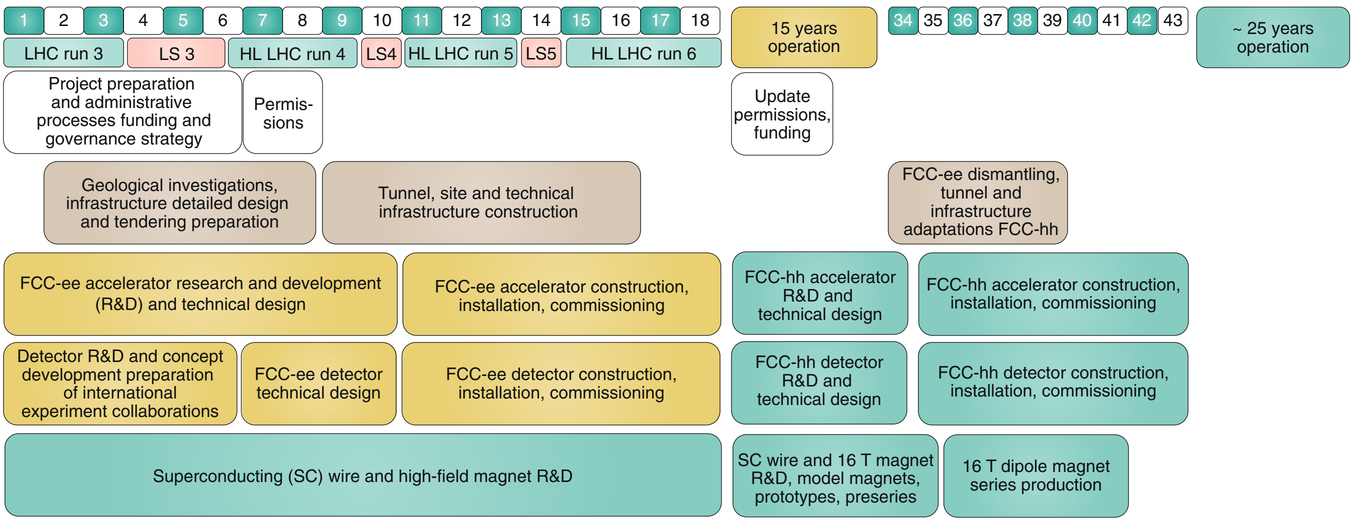

Fig. 1 | Technical schedule of the FCC integrated project. The FCC project extends over 70 years with a starting date (year 1), for example, in year 2021 (ref. [18]). The top two rows show the LHC and high-luminosity LHC schedule, including years of operation (numbered along the top), four data-taking periods (runs), and intermittent maintenance periods, so-called long-shutdowns (LS). In the rows below, the FCC administrative processes (in white), infrastructure activities (in grey), the FCC-ee schedule (in yellow), and the FCC-hh schedule (in green) are depicted.

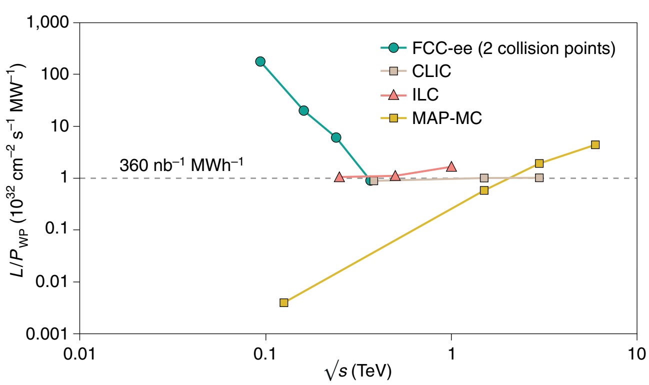

Fig. 2 | Total luminosity per electrical power. The total luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders: the FCC-ee with experiments at two collision points, the International Linear Collider (ILC), the Compact Linear Collider (CLIC) and the Muon Collider designed by the US Muon Accelerator Program (MAP-MC)[7]. A value of 1 in the vertical units corresponds to 360 nb^{-1} MWh^{-1} as indicated by the dashed line. We caution that the design of the Muon Collider may be less mature than the other three colliders presented. Figure adapted with permission from ref. [7], CERN under CC BY 4.0.

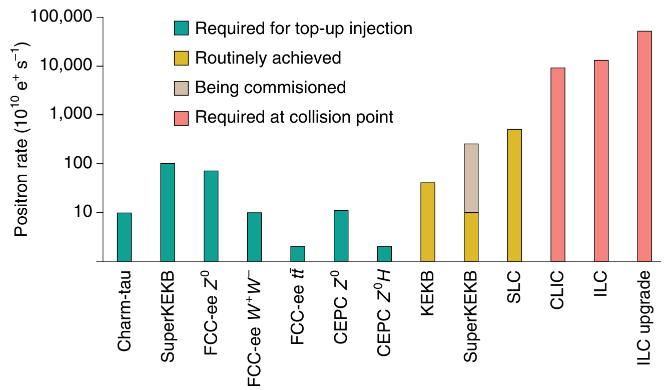

Fig. 3 | Positron production rates. The positron production rates achieved at SLC, KEKB and SuperKEKB (in blue) are compared with those required for 'top-up injection' (that is, a frequent, quasi-continuous injection to maintain nearly constant beam currents and luminosity in the collider) at future circular electron–positron colliders such as the different phases of the FCC-ee or of the Circular Electron Positron Collider (CEPC) in China (green), the proposed charm-tau factories in Russia and China[19,20], and at the collision point of future linear electron–positron colliders (red). Figure adapted with permission from ref. [21], APS.

several ab^{-1} of integrated luminosity, with monochromatic beams, and continuous parts-per-million control of the centre-of-mass energy (enabled by resonant depolarisation).

The interplay between the FCC-ee and FCC-hh stages is essential for a broad spectrum of unique Higgs measurements. The hadron collider alone has the statistics required to probe, at the parts-per-thousand level, the Higgs couplings to the muon, to the photon, and to the $Z\gamma$ pair. The measurement of g_{HZZ} at the FCC-ee then allows extraction of the absolute values of these Higgs couplings via ratios of decay branching fractions. The clean FCC-ee final states enable the reconstruction of Higgs decays to charm quarks or gluons, and probe beyond-the-SM decays — otherwise elusive to the FCC-hh — with a branching fraction sensitivity of 10^{-4}. The fifty billion Higgs bosons collected at the FCC-hh, on the other hand, allow detailed studies of the associated production of a Higgs boson with top quarks and of Higgs pairs. The decay of a Higgs boson into an invisible final state, possibly exposing dark matter (DM) particles, can be explored down to a branching fraction level of 2.5×10^{-4}, below the 2×10^{-3} SM rate for the decay $H\rightarrow Z^0Z^0\rightarrow4\nu$. The short-distance structure of the Higgs is probed by producing it far off-shell or at large transverse momentum. The sensitivity to exotic decays, such as the lepton-flavour-violating decay $H\rightarrow\mu\tau$, which is forbidden in the SM, extends below 10^{-4}. The FCC-ee and FCC-hh combined sensitivity to deviations in the SM Higgs couplings and self-coupling, and to the direct production of new particles coupled to the Higgs boson, can furthermore elucidate the nature of the cosmological EW phase transition, conclusively testing beyond-SM models that would cause it to be of strong first order.

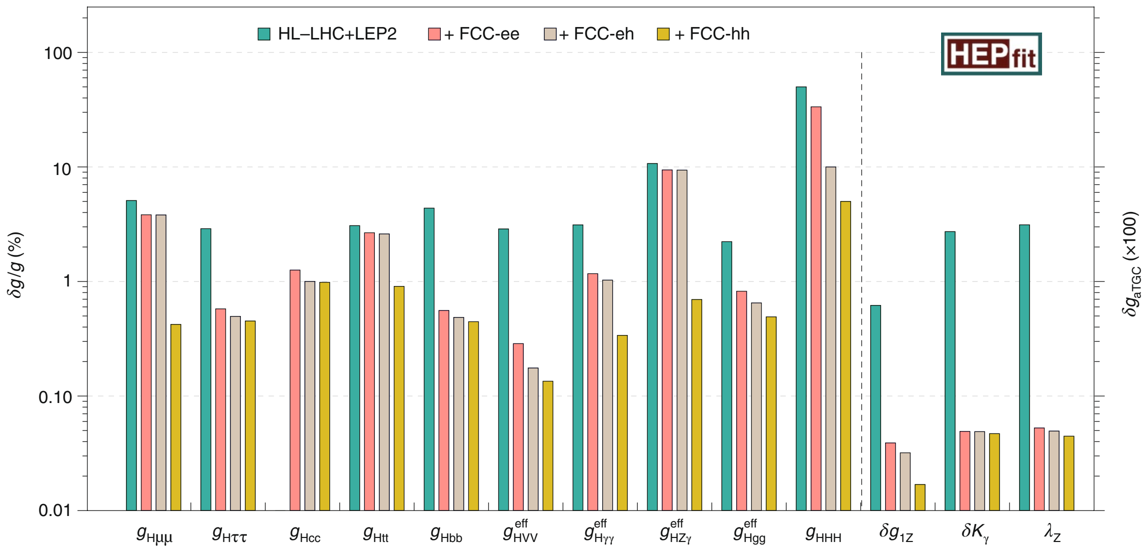

Fig. 4 | Reach on the Higgs and anomalous gauge couplings. One standard deviation precision expected for various Higgs and EW couplings, displayed on a semi-log scale. The g_{HXX} labels refer to the coupling with particle *X*. The $g^{\rm eff}_{HXY}$ labels characterize the effective Higgs coupling to a pair of bosons *X* and *Y*. The last three couplings to the right of the dashed line correspond to anomalous triple-gauge-boson couplings (aTGC). Absolute precision in the EW parameters is assumed. The bars illustrate the improvements in precision that could be reached by combining each FCC stage with the knowledge available at that time, starting from the expected results at the high-luminosity LHC (HL-LHC) combined with the high-energy runs of LEP (LEP2). Figure reproduced with permission from ref. [1], Springer Nature Ltd under CC BY 4.0.

Electroweak interactions

The EW precision measurements enabled by the FCC-ee phases will be an indispensable counterpoint to the Higgs studies and an opportunity to reveal possible tenuous effects of new physics. The circular electron–positron collider offers several advantages over other facilities such as large achievable luminosities, precise determination of the centre-of-mass energies at the ppm level using resonant beam depolarisation[15] and clean experimental conditions required to precisely determine the luminosity.

The Tera-Z phase (the four years of Z^0 operation in Table 1), producing 5×10^{12} Z^0 bosons, will improve the LEP precision of EW and QCD parameters and observables by up to two orders of magnitude, for example, measurement of the Z^0 decay width at a precision down to 10 ppm. The effective weak mixing angle $\sin^2\theta_W$ will be measured at 5 ppm accuracy, and the electromagnetic coupling constant at the Z^0 scale, $\alpha(m_Z)$, will reach the precision of 30 ppm (ref. [16]). The W^+W^- phase will allow a relative precision on the $W^\pm$ mass of 7 ppm, while the $t\bar{t}$ phase will push the precision on the top quark mass m_t to a few tens of MeV, along with the determination of its EW couplings. New physics could impact the precision observables in various ways: through direct mixing with heavier particles, or via quantum effects involving new phenomena affecting the interaction vertex or the propagators. These precision tests will be extremely sensitive probes of effects of physics beyond the SM, provided the heavier phenomena have sufficiently strong coupling.

The impact of these results on various effective operators O parameterizing new physics[2] is shown in Fig. 5, illustrating the complementarity between EW and Higgs measurements. The results are expressed as the ratio $\Lambda/\sqrt{|c|}$ between the actual mass scale of new physics, Λ, and the strength $\sqrt{|c|}$ of its coupling to the SM particles. For strongly coupled objects, $\sqrt{|c|}\approx 1$, the sensitivity extends up to several tens of TeV, calling on a 100-TeV-scale collider for their direct detection. But even for weakly coupled objects with $\sqrt{|c|}\approx\sqrt{4\pi\alpha}\approx 0.3$, the sensitivity extends beyond the mass scales reachable by the LHC.

Figure 5 also shows the significant impact of theoretical uncertainties, and the considerable gains that will result from a world-wide targeted programme of precision theoretical calculations[17]. The precision presented in the FCC-ee Conceptual Design Report for many EW precision measurements is provisional, and much work is awaiting researchers to reduce systematic uncertainties to the level of the statistical precision.

Further inputs will come from the FCC-eh and FCC-hh. The former can measure the neutral couplings of up and down quarks individually — better than is possible with Z^0 decays — where up and down quark final states are indistinguishable. The latter can probe EW interactions at the highest energies by measuring Drell–Yan production and vector boson scattering in the multi-TeV region.

The Tera-Z will also allow precision measurements in the flavour sector of the charm and bottom quark and the tau lepton in the post-LHCb and Belle II era. A considerable discovery potential exists, through precision measurements and searches for rare or forbidden processes[1]. For example, 200,000 reconstructed rare $B^0\to K^{0*}e^+e^-$ decays are expected, 100 and 10 times more than at Belle II and at the upgraded LHCb detector, respectively.

Direct searches for new physics

The direct search for new physics at the FCC has several goals, from extending the reach for generic beyond the SM scenarios to higher masses, to tackling specific targets, like weakly interacting massive particles (WIMPs) as DM candidates. The FCC-hh will extend the LHC mass reach for most searches by a factor of 5–7. For example, s-channel resonances will be probed up to ~40 TeV, at the limit of the regime of indirect sensitivity explored by the precise EW and Higgs studies discussed earlier. Supersymmetric partners of SM quarks, squarks, and the SM gluon, gluinos, can be discovered up to masses of 15–20 TeV, and the partner of the SM top quark, stop, up to ~10 TeV, accessing parameter regions where a large fraction of the most common realizations of supersymmetry models could be conclusively found or ruled out. Most importantly, the energy and luminosity will allow probing of the WIMP spectrum over the full range of masses allowed by cosmology for this type of DM candidates, promising a confirmation or rejection of the WIMP DM hypothesis. The sensitivity of the FCC-ee and FCC-hh to invisible

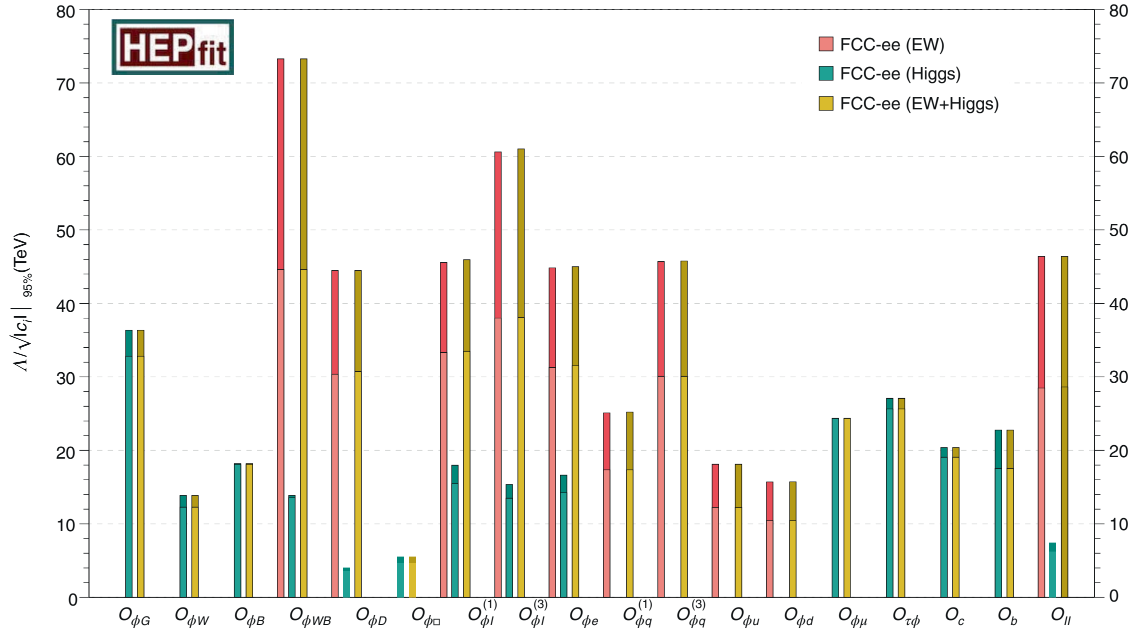

Fig. 5 | Constraints on the energy scale of effective field theory operators. Comparison of the separate and combined EW and Higgs constraints on the energy scale of possible new physics interactions, parameterized by the different effective field theory operators O_{xy} shown on the horizontal axis, and described in detail in ref. [2]. The vertical axis shows the energy scale Λ that can be probed at the 95% of confidence level, divided by the effective couplings $\sqrt{|c_i|}$ specific to each operator O. Darker shades of each colour indicate the results, where the SM theory uncertainties were neglected. Figure reproduced with permission from ref. [2], Springer Nature Ltd under CC BY 4.0.

decays of the Z^0 and H bosons adds a further dimension to the FCC programme of searches for dark sectors, probing regions of parameter space otherwise inaccessible[1].

The FCC will also explore unchartered domains in the search for the origin of neutrino masses[1]: $Z{\rightarrow}\nu N$ decays at the FCC-ee, with $N{\rightarrow}\nu\ell_i\ell_j$ ($\ell_{i,j} = e,\mu,\tau$), can reveal heavy sterile neutrinos N with masses from 20 up to ~90 GeV if the νN mixing angle $|\Theta_{\nu N}|^2 \approx m_\nu/m_N$ is as small as 10^{-11}. This is five orders of magnitude better than the present best limit from LEP, and close to the 'see-saw limit', where leptogenesis could explain the baryon asymmetry in the Universe. A similar parameter space can be covered later by the FCC-hh with $W{\rightarrow}\ell_i N(N{\rightarrow}\ell_j W^*)$ decays, where the relation between the flavour and charge of the charged leptons from the W and N decays might reveal lepton-flavour or even fermion to anti-fermion transition in the process. Charged-current processes at the FCC-eh can extend the mass reach up to 1 TeV, if $|\Theta_{\nu_e N}|^2 \gtrsim 10^{-5}$.

Experimental challenges and detector requirements

In order to exploit the physics opportunities of the FCC, various experimental challenges must be overcome. For the FCC-ee, synchrotron radiation from the last arc bending magnets and the final focusing quadrupoles is a source of background, mitigated through an asymmetric interaction region layout with minimum bending over the last 450 m before the collision point, and masks situated upstream of the detector beam chamber. Another background is caused by beamstrahlung, photons emitted during the collision, in the field of the opposite bunch. Full simulations of these backgrounds have been performed, concluding that experimental conditions will be similar to those of LEP, and easier to deal with than at linear colliders.

Obtaining a detector acceptance starting at 100 mrad from the beams, as requested by precision measurements, requires special design of the interaction region superconducting magnets. For the Z^0 and W^+W^- phases, resonant depolarisation of pilot bunches will provide frequent absolute beam energy calibration at the 10^{-6} level, which is the cornerstone of the FCC-ee EW physics programme. The feasibility of detectors for the FCC-ee, despite the high event rate at the Tera-Z run and the high frequency bunch crossing, was motivated in ref. [2]. The detectors designed for the Compact Linear Collider could be suitably modified. Matching the statistical precision of the Tera-Z exposure will require further detector accuracy, and unprecedented hermeticity, high mechanical precision and time stability. The flavour physics programme requires particle identification performance well beyond that of most detectors designed for the LHC or future linear colliders.

For the 100 TeV collider, the experimental challenges are far more daunting. The energies of the produced particles will be higher than at the LHC, requiring a larger detector and further improvements in detector technology to keep the individual particle measurement precision adequate. Innovative yoke-free superconducting magnets are envisaged to reduce the weight, size and cost of the FCC-hh experiments. Moreover, the pile-up of up to 1,000 events per bunch crossing at the FCC-hh is a major challenge. Experience from the LHC has shown that, as energy increases, the relative importance of the low transverse momentum backgrounds decreases compared to the increasing transverse momentum of the interesting physics. Physics channels that are difficult to study at the LHC will be much easier to investigate at the FCC-hh. Nevertheless, considerable improvements in triggers, data acquisition and computing methods will be necessary. The community appears ready to address these technological challenges, starting with the developments performed for the upgrades of the LHC detectors. Given the time available, a deep investigation of new concepts for the FCC-hh detection and analysis methods will be undertaken.

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Competing interests

The authors declare no competing interests.

Additional information

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