Abstract
The physics case for electron-positron beams at the Future Circular Collider (FCC-ee) is succinctly summarized. The FCC-ee core program involves $e^+e^-$ collisions at $\sqrt{s} = 90, 160, 240,$ and $350$ GeV with multi-ab$^{-1}$ integrated luminosities, yielding about $10^{12}$ $Z$ bosons, $10^8$ $W^+W^-$ pairs, $10^6$ Higgs bosons and $4 \cdot 10^5 \bar{t}t$ pairs per year. The huge luminosities combined with $\mathcal{O}(100$ keV$)$ knowledge of the c.m. energy will allow for Standard Model studies at unrivaled precision. Indirect constraints on new physics can thereby be placed up to scales $\Lambda_{\text{NP}} \approx 7$ and $100$ TeV for particles coupling respectively to the Higgs and electroweak bosons.

1 Introduction
The Standard Model (SM) of particle physics is a renormalizable quantum field theory encoding our knowledge of the fundamental particles and their (electroweak and strong) interactions. Despite its tremendous success to describe many phenomena with high accuracy
for over 40 years—including the recent experimental confirmation of the existence of its last missing piece, the Higgs boson—fundamental questions remain open (such as the small Higgs boson mass compared to the Planck scale, dark matter, matter-antimatter asymmetry, neutrino masses,...) which may likely not be fully answered through the study of proton-proton collisions at the Large Hadron Collider (LHC). Notwithstanding their lower center-of-mass energies, high-energy $e^+e^-$ colliders feature several advantages in new physics studies compared to hadronic machines, such as direct model-independent searches of new particles coupling to $Z^*/\gamma^*$ with masses up to $m \approx \sqrt{s}/2$, and clean experimental environment with initial and final states very precisely known theoretically, (i.e. well understood backgrounds without “blind spots” of p-p searches). Combined with high-luminosities, an $e^+e^-$ collider can thus provide access to studies with $\delta X$ precision at the permille level, allowing indirect constraints to be set on new physics up to very-high energy scales $\Lambda_{\text{NP}} \propto (1 \text{ TeV})/\sqrt{\delta X}$. Plans exist to build future circular (FCC-ee) and/or linear (ILC, CLIC) $e^+e^-$ colliders (Fig. 1). The advantages of circular machines are (i) their much higher luminosity below $\sqrt{s} \approx 400$ GeV (thanks to much larger collision rates, adding continuous top-up injection to compensate for luminosity burnoff), (ii) the possibility to have several interaction points (IPs), and (iii) a precise measurement of the beam energy $E_{\text{beam}}$ through resonant transverse depolarization. Linear colliders, on the other hand, feature (i) much

![Figure 1: Target luminosities as a function of center-of-mass energy for future circular (FCC-ee, CEPC) and linear (ILC, CLIC) $e^+e^-$ colliders under consideration.](image-url)
larger $\sqrt{s}$ reach (circular colliders are not competitive above $\sqrt{s} \approx 400$ GeV due to synchrotron radiation scaling as $E_{\text{beam}}^4/R$), and (ii) easier longitudinal beam polarization. At the FCC (with a radius $R = 80–100$ km), $e^+e^-$ collisions present clear advantages with respect to LEP (e.g. $\times 10^4$ more bunches, and $\delta E_{\text{beam}} \approx \pm 0.1$ MeV compared to $\pm 2$ MeV) and to ILC (crab-waist optics scheme, up to 4 IPs) yielding luminosities $\times (10^4–10)$ larger in the $\sqrt{s} = 90–350$ GeV range. Table 1 lists the target FCC-ee luminosities, and the total number of events collected at each $\sqrt{s}$ obtained for the following cross sections (including initial state radiation, and smearings due to beam-energy spreads): $\sigma_{e^+e^-\rightarrow Z} = 43$ nb, $\sigma_{e^+e^-\rightarrow W^+W^-} = 4$ pb, $\sigma_{e^+e^-\rightarrow HZ} = 200$ fb, $\sigma_{e^+e^-\rightarrow t\bar{t}} = 0.5$ pb, and $\sigma_{e^+e^-\rightarrow VV\rightarrow H} = 30$ fb. With these target luminosities, the completion of the FCC-ee core physics program (described in the next sections) requires 10 years of running.

Table 1: Target luminosities, events/year, and years needed to complete the W, Z, H and top programs at FCC-ee. [$\mathcal{L} = 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ corresponds to $\mathcal{L}_{\text{int}} = 1 \text{ ab}^{-1}/\text{yr}$ for $1 \text{ yr} = 10^7 \text{ s}$].

| $\sqrt{s}$ (GeV): | 90 (Z) | 125 (eeH) | 160 (WW) | 240 (HZ) | 350 ($t\bar{t}$) | 350 (VV $\rightarrow H$) |
|-------------------|---------|------------|----------|----------|------------------|----------------------|
| $\mathcal{L}$/IP (cm$^{-2}$s$^{-1}$) | 2.2·10$^{36}$ | 1.1·10$^{36}$ | 3.8·10$^{35}$ | 8.7·10$^{34}$ | 2.1·10$^{34}$ | 2.1·10$^{34}$ |
| $\mathcal{L}_{\text{int}}$ (ab$^{-1}$/yr/IP) | 22 | 11 | 3.8 | 0.87 | 0.21 | 0.21 |
| Events/year (4 IPs) | 3.7·10$^{12}$ | 1.3·10$^4$ | 6.1·10$^7$ | 7.0·10$^5$ | 4.2·10$^5$ | 2.5·10$^4$ |
| Years needed (4 IPs) | 2.5 | 1.5 | 1 | 3 | 0.5 | 3 |

2 Indirect constraints on BSM via high-precision Z, W, top physics

Among the main goals of the FCC-ee is to collect multi-ab$^{-1}$ at $\sqrt{s} \approx 91$ GeV (Z pole), 160 GeV (WW threshold), and 350 GeV ($t\bar{t}$ threshold) in order to measure with unprecedented precision key properties of the W and Z bosons and top-quark, as well as other fundamental parameters of the SM. The combination of huge data samples available at each $\sqrt{s}$, and the precise knowledge of the c.m. energy leading to very accurate threshold scans, allows for improvements in their experimental precision by factors around $\times 25$ (dominated by systematics uncertainties) compared to the current state-of-the-art (Table 2). In many cases, the dominant uncertainty will be of theoretical origin, and developments in the calculations are needed in order to match the expected experimental uncertainty. The FCC-ee experimental precision targets are e.g. $\pm 100$ keV for $m_Z$, $\pm 500$ keV for $m_W$, $\pm 10$ MeV for $m_t$, a relative statistical uncertainty of the order of $3\cdot 10^{-5}$ for the QED $\alpha$ coupling (through muon forward-backward asymmetries above and below the Z peak), 1-permille for the QCD coupling $\alpha_s$ (through hadronic Z and W decays), and $10^{-3}$ on the electroweak top
Table 2: Examples of achievable precisions in representative Z, W and top measurements.

![Figure 2: Left: 68% C.L. limits in the $m_t$–$m_W$ plane at FCC-ee and other colliders. Right: Energy reaches for dim-6 operators sensitive to EWPT, obtained from precision measurements at FCC-ee and ILC.](image)
3 Indirect constraints on BSM via high-precision Higgs physics

In the range of c.m. energies covered by the FCC-ee, Higgs production peaks at $\sqrt{s} \approx 240$ GeV dominated by Higgsstrahlung ($e^+e^- \rightarrow HZ$), with some sensitivity also to vector-boson-fusion ($VV \rightarrow H e^+e^-, \nu\nu$) and the top Yukawa coupling ($e^+e^- \rightarrow t\bar{t}$ with a virtual Higgs exchanged among the top quarks) at $\sqrt{s} = 350$ GeV. The target total number of Higgs produced at the FCC-ee (4 IPs combined, all years) amounts to 2.1 million at 240 GeV, 75 000 in $VV \rightarrow H$ at 350 GeV, and 19 000 in s-channel $e^+e^- \rightarrow H$ at $\sqrt{s} = 125$ GeV (Table 1).

With such large data samples, unique Higgs physics topics are accessible to study:

- High-precision model-independent determination of the Higgs couplings, total width, and exotic and invisible decays (Table 3).
- Higgs self-coupling through loop corrections in HZ production.
- First-generation fermion couplings: ($u,d,s$) through exclusive decays $H \rightarrow V\gamma$ ($V = \rho, \omega, \phi$), and electron Yukawa through resonant $e^+e^- \rightarrow H$ at $\sqrt{s} = m_H$.

Figure 3: Distribution of recoil mass against $Z \rightarrow \ell\ell$ (top) and $Z \rightarrow q\bar{q}$ (bottom) in the $e^+e^- \rightarrow HZ$ process with $H \rightarrow b\bar{b}$ (top) and $H \rightarrow \tau\tau$ (bottom).

| Observable | 240 GeV | 240+350 GeV |
|------------|---------|-------------|
| $g_{HZZ}$  | 0.16%   | 0.15%       |
| $g_{HWW}$  | 0.85%   | 0.19%       |
| $g_{Hbb}$  | 0.88%   | 0.42%       |
| $g_{Hcc}$  | 1.0%    | 0.71%       |
| $g_{Hgg}$  | 1.1%    | 0.80%       |
| $g_{H\tau\tau}$ | 0.94% | 0.54% |
| $g_{H\mu\mu}$ | 6.4% | 6.2% |
| $g_{H\gamma\gamma}$ | 1.7% | 1.5% |
| $\Gamma_{tot}$ | 2.4% | 1.2% |
| BR$_{inv}$ | 0.25%   | 0.2%        |
| BR$_{exo}$ | 0.48%   | 0.45%       |

Table 3: Expected model-independent uncertainties on Higgs couplings, total width, and branching ratios into invisible and exotic particles (invisible or not).
The recoil mass method in $e^+e^- \rightarrow HZ$ is unique to lepton colliders and allows for a high-precision tagging of Higgs events irrespective of their decay mode (Fig. 3). It provides, in particular, a high-precision ($\pm 0.05\%$) measurement of $\sigma_{e^+e^-\rightarrow HZ}$ and, therefore, of $g_{HZ}^2$. From the measured value of $\sigma_{e^+e^-\rightarrow H(XX)Z} \propto \Gamma_{H\rightarrow XX}$ and different known decay fractions $\Gamma_{H\rightarrow XX}$, one can then obtain the total Higgs boson width with $\mathcal{O}(1\%)$ uncertainty combining different final states. The $\ell^+\ell^-H$ final state and the distribution of the mass recoiling against the lepton pair can also be used to directly measure the invisible decay width of the Higgs boson in events where its decay products escape undetected. The Higgs boson invisible branching fraction can be measured with an absolute precision of 0.2%. If not observed, a 95% C.L. upper limit of 0.5% can be set on this branching ratio \cite{1}. In addition, loop corrections to the Higgsstrahlung cross sections at different center-of-mass energies are sensitive to the Higgs self-coupling \cite{12}. The effect is tiny but visible at FCC-ee thanks to the extreme precision achievable on the $g_{HZ}$ coupling. Indirect and model-dependent limits on the trilinear $g_{HHH}$ can be set with an absolute precision of 70%. The expected 0.15% precision for the most precise coupling, $g_{HZZ}$, would thus set competitive bounds, $\Lambda_{NP} > 7 \text{ TeV}$, on any new physics coupled to the scalar sector of the SM.

The large Higgs data samples available also open up to study exotic (e.g. flavour-violating Higgs) and very rare SM decays. First- and second-generation couplings to fermions are accessible via exclusive decays $H \rightarrow V\gamma$, for $V = \rho, \omega, \phi$, with sensitivity to the $u,d,s$ quark Yukawas \cite{13}. The $H \rightarrow \rho\gamma$ channel appears the most promising with $\mathcal{O}(50)$ events expected. The low mass of the electron translates into a tiny $H \rightarrow e^+e^-$ branching ratio $\text{BR}_{e^+e^-} = 5 \cdot 10^{-9}$ which precludes any experimental observation of this decay mode and, thereby a determination of the electron Yukawa coupling. The resonant s-channel production, despite its small cross section \cite{15}, is not completely hopeless and preliminary studies indicate that one could observe it at the 5$\sigma$-level accumulating 75 ab$^{-1}$ at FCC-ee running at $\sqrt{s} = 125$ GeV with a c.m. energy spread commensurate with the Higgs boson width itself ($\approx 4$ MeV) which requires beam monochromatization \cite{14}.

Summarizing in terms of new physics constraints, deviations $\delta g_{HXX}$ of the Higgs boson couplings to gauge bosons and fermions with respect to the SM predictions can be translated into BSM scale limits through: $\Lambda_{NP} > (1 \text{ TeV})/\sqrt{(\delta g_{HXX}/g_{HXX}^{\text{SM}})/5\%}$. The expected 0.15% precision for the most precise coupling, $g_{HZZ}$, would thus set competitive bounds, $\Lambda_{NP} > 7$ TeV, on any new physics coupled to the scalar sector of the SM.
4 Direct constraints on BSM physics: dark matter and right-handed neutrinos

The precision electroweak and Higgs boson studies, summarized previously, not only impose competitive constraints on new physics at multi-TeV scales but can also be interpreted in terms of limits in benchmark SUSY models (CMSSM and NUHM1)\(^1\). Other studies exist that have analyzed the impact of FCC-ee on other key BSM extensions such as e.g. direct searches of dark matter (DM)\(^{16}\) and right-handed neutrinos\(^{17}\) through Z and H bosons rare decays. Figure 4 (left) shows the limits in the plane (branching ratio, DM mass) for the decays \(Z, H \to DM\). Measurements of the invisible Z and H widths are the best collider options to test DM lighter than \(m_{Z,H}/2\) that couples via SM mediators. Figure 4 (right) shows the unrivaled limits that can be set in sterile neutrinos searches via decays \(Z \to N\nu_i\) with \(N \to W^\pm \ell, Z^\pm \nu_j\) as a function of their mass and mixing to light neutrinos\(^{17}\).

![Figure 4: Regions of sensitivity of FCC-ee for: (i) Z and H decays into DM in the \(BR_{Z,H \to DM} vs. m_{DM}\) plane (left)\(^{16}\), and (ii) sterile neutrinos as a function of their mass and mixing to light neutrinos (inverted hierarchy) for \(10^{12}\) Z decays (right)\(^{17}\).](image)

5 Summary

Electron-positron collisions at \(\sqrt{s} \approx 90–350\) GeV at the FCC-ee provide unique means to address many of the fundamental open problems in particle physics via high-precision studies of the W, Z, Higgs, and top-quark with permil-level uncertainties, thanks to the huge luminosities \(\mathcal{L} (1–100)\) ab\(^{-1}\) and the exquisite beam energy calibration. Such measurements set indirect constraints on BSM physics up to scales \(\Lambda_{NP} \approx 7, 100\) TeV for new particles coupling to the scalar and electroweak SM sectors, respectively. Rare Higgs and Z bosons decays are sensitive to dark matter and sterile neutrinos with masses up to \(m_{DM,HNL} \approx 60\) GeV.
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