Prospects in Electroweak, Higgs and Top physics at FCC

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Abstract

The FCC integrated programme offers a unique opportunity to comprehensively explore the Higgs, electroweak and top sectors. The FCC-ee clean experimental conditions and well-defined initial state enable the exploitation of all produced Higgs, W, Z bosons and top quarks and allow, in a record time, for a precise characterisation of the Standard Model properties with unrivalled precision. The model-independent determination of Higgs and Top couplings at FCC-ee provides an absolute normalisation for FCC-hh measurements. With the large production rates at FCC-hh, complementary precision measurements of rare Higgs decay modes and an unparalleled characterisation of the Higgs self-interaction become possible. The extended kinematic range provides indirect probes of new physics via precision measurements in the multi-TeV regime. Together, the FCC-ee and the FCC-hh comprehensively explore potential new physics through precision measurements in complementary energy regimes.

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The FCC integrated programme consists of an intensity-frontier electron-positron (e^+e^-) collider (FCC-ee) spanning centre-of-mass energies from below the Z pole to beyond the top-pair production threshold, followed by an energy-frontier hadron collider (FCC-hh) designed to collide protons at a centre-of-mass energy of 84 TeV. This short document compiles the expected precision of a variety of measurements in the Higgs, electroweak and top sectors, after 15 (25) years of operation at FCC-ee (FCC-hh). The detailed run plans (and possible variations) of the two facilities are discussed in separate documents [1–3] and in the FCC feasibility study report [4]. The baseline integrated luminosities (and run durations) at all centre-of-mass energies are displayed in Table 1, summed over the four (two) interaction points equipped with general-purpose detectors at FCC-ee (FCC-hh).

Table 1: Run durations (in years) and integrated luminosities (in ab^{-1}) at various centre-of-mass energies ($\sqrt{s}$) for the baseline physics programme at FCC-ee and FCC-hh.

	FCC-ee				FCC-hh
$\sqrt{s}$	88-94 GeV	157-163 GeV	240 GeV	340-365 GeV	84 TeV
Run duration (years)	4	2	3	5	25
Integrated luminosity (ab^{-1})	205	19.2	10.8	3.12	30

Unless stated otherwise, the studies reported here rely on simulated event samples generated by the MADGRAPH_AMCATNLO [5, 6], POWHEG [7], WHIZARD [8] and PYTHIA [9, 10] Monte Carlo (MC) programs, and processed through the fast detector simulation package DELPHES [11]. The IDEA detector model [12] was chosen for the FCC-ee physics studies. Details of the DELPHES simulations used for the studies reported here can be found in Refs. [4, 13]. The baseline detector concept used for the FCC-hh physics studies is described in Ref. [14, 15] and its parameterisation DELPHES in Ref. [16]. The projections discussed in the following account for statistical and experimental systematic uncertainties. A clear roadmap has been defined during the FCC Feasibility Study to bring the theoretical uncertainties to a level as close as possible to the expected statistical precision.

1 Higgs measurements at FCC

The FCC integrated programme offers a unique opportunity to comprehensively explore the Higgs sector. The FCC-ee clean experimental conditions and well-defined initial state enable the exploitation of all produced Higgs bosons and allow, in a record time, for a model-independent characterisation of the Higgs properties with unrivalled precision. With the large production rates at FCC-hh, complementary precision measurements of rare Higgs decay modes and an unparalleled characterisation of the Higgs self-interaction become possible. The model-independent determination of Higgs and top couplings at FCC-ee also provides an absolute normalisation for FCC-hh measurements. These complementarities and synergies between FCC-ee and FCC-hh make the integrated Higgs physics programme unique in the long list of proposed future collider facilities.

1.1 Higgs measurements at FCC-ee

With almost three million Higgs bosons produced, FCC-ee can achieve a model-independent determination of many Higgs couplings with precisions down to a per mil, the Higgs boson width to better than a per cent and the Higgs boson mass to a few MeV. At FCC-ee, Higgs boson production proceeds mainly via the Higgs-strahlung process $e^+e^- \to ZH$ and the WW fusion process $e^+e^- \to H\nu_e\bar{\nu}_e$.[1]. At $\sqrt{s} = 240\,\mathrm{GeV}$, FCC-ee is expected to deliver approximately 2.2×10^6 Higgs bosons produced in the ZH mode, plus 6.5×10^4 events from WW fusion. At the top-pair threshold and beyond, the integrated luminosity of $3.12\,\mathrm{ab}^{-1}$ yields 3.7×10^5 ZH events and 9.2×10^4 WW-fusion events. The high luminosity delivered at FCC-ee also opens possibilities for dedicated Higgs studies at lower energies. For example, a direct measurement of the electron Yukawa coupling at $\sqrt{s} = m_H$ would be possible with appropriate centre-of-mass energy monochromatisation.

The cornerstone of the FCC-ee Higgs physics programme is the determination of the total ZH cross section σ_{ZH}. This measurement provides an absolute measurement of the g_{HZZ} coupling with a per-mil precision in three years. This same process allows for an accurate determination of the Higgs boson mass via the recoil-mass technique. Once the total ZH cross section is measured, the measurements of cross section times exclusive branching fractions, $\sigma_{ZH} \times \mathcal{B}$, enable the determination of the other Higgs boson couplings and of its total decay width.

[1] The WW-fusion cross section is defined as the difference of the cross sections of the processes $e^+e^- \to H\nu_e\bar{\nu}_e$ and $e^+e^- \to H\nu_\mu\bar{\nu}_\mu$

In the following studies, background distributions are directly fit from the data, and uncertainties on their normalisations are taken into account. Systematic uncertainties related to object identification are negligible (hence neglected) in all channels. Indeed, regular short runs at the Z pole and the large samples of $\mathrm{f\bar{f}}\gamma(\mathrm{g})$ available at 240 and 365 GeV allow for continuous calibration of electrons, photons, muons, τ, and heavy-quark and gluon jets at the level of 10^{-4} or less, which exceeds the precision required for Higgs precision measurements. The absolute luminosity will be determined with low-angle Bhabha scattering and wide-angle $\mathrm{e^+e^-} \to \gamma\gamma$ events, well within the required precision.

The results presented in the following give a snapshot of the analysis performance at this point in time. A number of studies can still benefit from substantial optimisation, and a few final states could not be addressed yet (in which case the projections used for the FCC CDR are used). With these caveats in mind, the current (conservative) prospects for Higgs precision measurements at FCC-ee are summarised in Table 2.

Table 2: Projected precision on Higgs measurements as obtained from FCC-ee simulations at $\sqrt{s} = 240$ and 365 GeV. Experimental systematics include background normalisation uncertainties. Efficiencies and luminosity systematics are expected to be negligible. The entries preceded by a ± sign are relative uncertainties (in %) on $\sigma_{\mathrm{ZH}} \times \mathcal{B}$ and $\sigma_{\mathrm{WW}\to\mathrm{H}} \times \mathcal{B}$ (where $\mathrm{WW} \to \mathrm{H}$ includes the interference with $\mathrm{Z}(\nu_e\bar{\nu}_e)\mathrm{H}$), while the entries preceded by "<" sign represent 95% CL upper limit on $\mathcal{B}$. The projected precision on $\sigma_{\mathrm{ZH/WW}\to\mathrm{H}} \times \mathcal{B}(\mathrm{H} \to \mathrm{jj})$ for the hadronic Higgs decay modes ($\mathrm{jj} = \mathrm{b\bar{b}}$, $\mathrm{c\bar{c}}$, gg, and $\mathrm{s\bar{s}}$) is obtained from a fit where the signal strengths of these processes extracted simultaneously. The corresponding correlation matrix can be found in Ref. [17]). A $^{(*)}$ indicates that the values are rescaled from the FCC CDR [18, 19] to the baseline integrated luminosity.

$\sqrt{s}$	240 **GeV**		365 **GeV**	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
$\mathrm{H} \to \tau\tau$	±0.58		±1.2	$\pm 5.6^{(*)}$
$\mathrm{H} \to \mu\mu$	±11		±25	
$\mathrm{H} \to \mathrm{WW}^*$	±0.80		$\pm 1.8^{(*)}$	$\pm 2.1^{(*)}$
$\mathrm{H} \to \mathrm{ZZ}^*$	±2.5		$\pm 8.3^{(*)}$	$\pm 4.6^{(*)}$
$\mathrm{H} \to \gamma\gamma$	±3.6		±13	±15
$\mathrm{H} \to \mathrm{Z}\gamma$	±11.8		±22	±23
$\mathrm{H} \to \nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

The ZH production cross section and the Higgs boson mass

In $\mathrm{e^+e^-}$ collisions, the total energy and momentum of the final states are well-known, only smeared by effects such as initial state radiation (ISR) and beam-energy spread (BES) caused by synchrotron radiation and beamstrahlung effects. Provided that the Z boson decay products can be unambiguously identified, the energy and momentum of the Higgs particle, and therefore its mass, can be entirely determined with excellent precision from the Z boson kinematics, independently of the Higgs boson decay mode. This calculated mass, dubbed *recoil mass* m_{rec}, is obtained from energy-momentum conservation as $m^2_{\mathrm{rec}} = s + m^2_{\mathrm{Z}} - 2\sqrt{s}\,E_{\mathrm{Z}}$, where m_{Z} and E_{Z} are the measured invariant mass and energy sum of the identified Z decay products.

The analysis of the leptonic final state, with $\mathrm{Z} \to \ell\ell$ ($\ell = \mathrm{e}, \mu$ in this document), targets the total cross section and the Higgs boson mass (m_{H}) measurements [20]. Events with two opposite-charge leptons (e or μ), among which one must be isolated, are preselected. For the Higgs boson mass determination, events are categorized based on whether the leptons are in the central or forward regions, resulting in three event categories. A simultaneous fit of the m_{rec} distribution in both the di-electron and di-muon channels and at $\sqrt{s} = 240$ and 365 GeV provides a combined expected precision of $\delta(\mathrm{m_H}) = 3.97$ MeV. The sensitivity is dominated by the $\sqrt{s} = 240$ GeV energy point due to the larger statistics and smaller BES. The measurement is statistics dominated ($\delta_{\rm stat}(\rm m_H) = 3.05\,\rm MeV$). The dominant systematic error, itself statistics limited, originates from the absolute beam energy calibration, conservatively[2] taken to be $\delta_{\sqrt{\rm s}}(\rm m_H) = 2\,\rm MeV$.

The event selection for the leptonic cross-section extraction follows the mass analysis selection, with the additional exclusion of lepton pairs compatible with the Higgs boson mass. The event selection efficiency is independent of the Higgs decay (within 0.2%). A multivariate (MVA) discriminant is trained to further separate signal from background, using only lepton kinematics and angular observables in order to retain model independence. It is used to categorise events into a signal and a control region, where a simultaneous fit of $\rm m_{rec}$ is used to extract $\sigma_{\rm Z(\ell\ell)H}$. The SM background normalisation is allowed to float within 1% of its SM value. The muon and electron channels yield 0.68% and 0.81% precision, respectively, and a combined precision of 0.52% at $\sqrt{s} = 240\,\rm GeV$ is obtained. A similar analysis is performed at $\sqrt{s} = 365\,\rm GeV$, yielding a total uncertainty of 1.35%.

The $\rm Z \to jj$ mode is selected by identifying the two jets that minimise $\chi^2 = (\rm m_{jj} - m_Z)^2 + (m_{rec} - m_H)^2$, where $\rm m_{jj}$ is the two-jet invariant mass. Several jet clusterings (inclusive or exclusive with 2/4/6 jets with the Durham $\rm k_T$ algorithm) are tried. The jet pair that yields the lowest χ^2 over all possible pairings and clusterings is selected. A loose selection, orthogonal to the leptonic channel, is applied. Events compatible with the WW background are rejected using a dedicated selection. A boosted decision tree (BDT) further discriminates against the WW and $\rm Z\gamma$ backgrounds. Finally, a two-dimensional fit of $\rm m_{rec}$ vs. $\rm m_{jj}$ mass is performed in two regions of the MVA discriminant, which leads to an expected precision of 0.38% on $\sigma_{\rm Z(jj)H}$ at $\sqrt{s} = 240\,\rm GeV$ and 0.57% at $\sqrt{s} = 365\,\rm GeV$ [22]. Bias tests are performed by perturbing any given $\sigma_{\rm ZH} \times \mathcal{B}$ by 1% of the total $\sigma_{\rm Z(jj)H}$ one at a time and down-scaling the sum of the others by an equal amount. The fit to the resulting pseudo-data results in biases on the measured $\sigma_{\rm Z(jj)H}$ that are smaller than 1%, thus ensuring that the extraction of the hadronic cross-section is model-independent, according to the procedure defined in Ref. [23]. Combining the leptonic and hadronic cross-section measurements yields a relative precision on $\sigma_{\rm ZH}$ of 0.31(0.52)% at $\sqrt{s} = 240(365)\,\rm GeV$ respectively.

Hadronic Higgs decays

Fully hadronic final states are produced in most Higgs boson decays in the SM. The large and clean sample of Higgs bosons produced at FCC-ee, coupled with detectors with unprecedented performance for jet flavour identification and energy resolution, provide an ideal environment for measuring Higgs hadronic decays. Jets are reconstructed using the Durham algorithm [24] in exclusive mode, i.e., by clustering all the particles in the events into the required number of jets. A Graph Neural Network (GNN) jet flavour tagger [25, 26] is then used to assign each jet a probability of originating from one of seven species: gluon (g), up (u), down (d), strange (s), charm (c), bottom (b), or tau (τ). The tagger uses the information of all particle-flow candidates within a jet, including kinematic, impact parameters, and particle identification (cluster-counting and time-of-flight).

The hadronic Higgs final states are studied in 3 orthogonal samples defined by the Z decay mode $\rm Z \to jj, \nu\nu, \ell\ell$. After the event selection, events are classified into independent categories of hadronic Higgs decay modes (bb, cc, ss, gg, WW, and ZZ). A separate analysis, only performed in the Z($\nu\nu$) category, is also designed to maximise the sensitivity to light quark flavours (uu, dd) and flavour-violating decays (bs, bd, sd, and cu). The results for each analysis are determined by a binned, maximum-likelihood fit to the distribution of one or two quantities that discriminate between the signals and the background. These are the recoil mass in the $\rm Z \to \ell\ell$ analysis, the visible mass and the recoil mass in the $\rm Z \to \nu\nu$ analysis, and the dijet invariant mass of the Higgs boson candidate together with the invariant mass of the system recoiling against it in the $\rm Z \to jj$ analysis. In the $\nu\nu$ final state, the ZH and the WW→H (plus interference) contributions are extracted simultaneously from a 2D fit on the missing and visible mass. Templates for the various signal and background processes are determined from the simulation. The normalisation of the signal processes is floating, expressed as the product of a signal strength μ_i (i=bb, cc, etc.) times the SM expected yield for the corresponding Higgs boson decay in the targeted Z boson decay channel. The background normalisations are constrained to the SM expectations within a 5% uncertainty. Further details on the analysis can be found in Ref. [17], and the results are summarised in Table 2. A similar analysis exploits the powerful jet flavor tagger to constrain light quark yukawas (up and down), as well as flavor changing neutral currents (FCNCs) in Higgs decays ($\rm H \to bs, bd, sd, cu$). FCC-ee is able to constrain these extremely rare decays to the $10^{-3} - 10^{-4}$ level as documented in Ref. [27] and shown in Table 2.

[2] At $\sqrt{s} = 240\,\rm GeV$ the centre-of-mass energy can be determined in-situ with radiative Z(γ) events with 1 MeV precision [21].

$H \to \tau\tau$

The $\mathrm{H} \to \tau\tau$ analysis [28] at $\sqrt{s} = 240\,\mathrm{GeV}$ exploits categories of events defined by the possible combinations of the Z(jj, $\nu\nu$, $\ell\ell$) and $\tau\tau$ ($\tau_\ell\tau_\ell, \tau_\ell\tau_\mathrm{h}, \tau_\mathrm{h}\tau_\mathrm{h}$) decay modes, where τ_ℓ and τ_h denote the leptonic and hadronic τ decays. For each category, events must contain the exact number of reconstructed objects (electrons or muons, taus, and jets) expected from the target decay mode. Tau leptons are identified from jets with the jet flavour tagger [25, 26]. The signal-to-background discrimination is optimised with a BDT classifier trained with missing momentum, the opening angle between the reconstructed taus, and reconstructed Z and H kinematics. Systematic uncertainties for this analysis include a 1% normalisation uncertainty on background processes including WW, ZZ, ZH (other than the signal), DY, and photon-induced processes. The relative uncertainty on $\sigma(ZH) \times \mathcal{B}(H \to \tau\tau)$, is found to be 0.58%. The analysis at $\sqrt{s} = 365\,\mathrm{GeV}$ follows the same strategy, the only difference being the additional $\mathrm{WW} \to \mathrm{H}$ signal in the $\nu\nu$ categories, which is separated from the ZH signal with BDT multi-classifiers. Fits are performed with the same systematic uncertainty assumptions, leading to a relative uncertainty of 1.2% on ZH and 25% on $\mathrm{WW} \to \mathrm{H}$.

$H \to ZZ^*$

Measuring the $\mathrm{H} \to \mathrm{ZZ}^*$ decay mode is crucial for determining the Higgs total width. This decay mode was studied only in the ZH production mode at $\sqrt{\mathrm{s}} = 240\,\mathrm{GeV}$ so far. Since all the analyses at $\sqrt{s} = 365$ GeV, have yet to be performed, in Table 2 we quote the results from the FCC-ee CDR [18]. The numerous possible final states are defined by the decay modes of the three Z's. To simplify notation, we write the final state compactly as $\ell\ell\nu\nu\mathrm{jj}$, which refers, for example, to $\mathrm{Z}(\ell\ell)\mathrm{Z}(\nu\nu)\mathrm{Z}^*(\mathrm{jj})$. In the $(\nu\nu/\ell\ell)$jjjj final states, the obtained precision is 11%, 7.6% respectively [17]. An analysis [29] on the fully hadronic mode (6 jets) makes use of exclusive N=6 jet clustering and a $\chi^2 = (\mathrm{m_{ij}} - \mathrm{m_Z})^2 + (\mathrm{m_{kl}} - \mathrm{m_Z})^2 + (\mathrm{m_{klmn}} - \mathrm{m_H})^2$ minimisation over all possible six jet permutations to reconstruct the on-shell production Z, and both on and off-shell boson candidates originating from the Higgs decay. A first BDT is constructed to maximise the $\mathrm{H} \to \mathrm{ZZ}^*$ vs $\mathrm{H} \to \mathrm{WW}^*$ separation, based on all the available kinematic information and flavour properties of the jets, followed by a second BDT in each of these categories to reject diboson backgrounds. A simultaneous fit for $\mathrm{H} \to \mathrm{ZZ}^*$ and $\mathrm{H} \to \mathrm{WW}^*$ on the resulting BDT discriminants results in a precision of 8.20% on $\mathrm{H} \to \mathrm{ZZ}^*$. The largest sensitivity is obtained in the two leptons, two neutrinos, and two jets final states. A BDT is trained using lepton and jet kinematics to suppress the large backgrounds from di-boson and $\mathrm{H} \to \mathrm{WW}^*$ for three of the six possible sub-channels separately [30]. Orthogonality between channels is implemented with simple analysis cuts, and the obtained sensitivity is 4.7%, 5.0%, and 7.3% for the $\nu\nu\ell\ell$jj, $\ell\ell\nu\nu jj$, and $\ell\ell jj\nu\nu$ channels, respectively. Two separate and orthogonal analyses [31] of the jj$\ell\ell\nu\nu$ and jj$\nu\nu\ell\ell$ final states obtain a respective precision of 13% and 19%. Higgs production into four leptons with $\mathrm{Z} \to \mathrm{jj}/\nu\nu$ was studied in 6 possible final states ($\mathrm{H} \to 4\mu$, $4e$, $2e2\mu$) [32]. On-shell and off-shell Z bosons are reconstructed from opposite-sign lepton pairs with a missing momentum (invisible) or visible energy (hadronic) selection. A final selection based on the four lepton invariant masses in each 4ℓ lepton final state for the hadronic (invisible) channels, respectively. A combined fit of the 4ℓ channels leads to a precision of 10%. The 6ℓ final state was also analysed and gives a precision of 30% [33]. The overall combined precision on $\sigma(\mathrm{ZH}) \times \mathcal{B}(\mathrm{H} \to \mathrm{ZZ}^*)$, using only the above subset of possible final states, is 2.5%. We note that several final states (the $\nu\nu$jjjj and $\nu\nu$jj$\ell\ell$, and final states including taus) have not yet been analyzed and are expected to lead to further substantial improvements.

$H \to WW^*$

Measuring the $\mathrm{H} \to \mathrm{WW}^*$ decay mode is crucial for determining the Higgs coupling to W bosons and provides a complementary and powerful constraint to the total Higgs width when combined with the total cross section and the $\sigma \times \mathcal{B}(\mathrm{H} \to \mathrm{bb})$ measurements. Only the fully hadronic WW decays have been studied so far. The $\mathrm{Z}(\nu\nu)\mathrm{H}[\mathrm{W(jj)W(jj)}]$ sensitivity is derived from the Higgs hadronic analysis described above and in Ref. [17], and yields 1.3% at $\sqrt{s} = 240\,\mathrm{GeV}$. A dedicated analysis [34] targeting the $\mathrm{Z}(\ell\ell)\mathrm{H}[\mathrm{W(jj)W(jj)}]$ and extracting the signal contribution from a likelihood fit of the recoil mass distribution yields 1.6% precision. Finally, the simultaneous extraction of $\mathrm{H} \to \mathrm{WW}^*$ and $\mathrm{H} \to \mathrm{ZZ}^*$ in the fully hadronic hadronic final state described earlier leads to an expected precision of 1.48% on $\mathrm{H} \to \mathrm{WW}^*$ [29]. The combined relative precision of the $\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{WW}^*)$ is 0.8% at $\sqrt{\mathrm{s}} = 240\,\mathrm{GeV}$. As for the $\mathrm{H} \to \mathrm{ZZ}^*$ case, several final states (the 3ℓ and 4ℓ channels, the $\mathrm{Z}(\nu\nu,\mathrm{jj})\mathrm{H}[\mathrm{W}(\ell\nu)\mathrm{W}(\ell\nu)]$, and final states including taus) have not yet been analyzed and will lead to substantial improvement in the expected precision. Also, in this case, all the analyses at $\sqrt{s} = 365$ GeV, have yet to be performed and therefore in Table 2 we quote the results from the FCC-ee CDR [18].

$H \to \gamma\gamma$, $Z\gamma$, $\mu\mu$

The extraction of $\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \gamma\gamma)$ relies on the identification of two isolated high-momentum photons and a selection on the acolinearity and acoplanarity of the event to reject the Z + photons background. Events are then categorised according to the decay of the Z, based on the presence of two leptons, two jets, or missing momentum, and the signal is extracted from a simultaneous fit on the $m_{\gamma\gamma}$ distributions. The combined sensitivity at $\sqrt{\mathrm{s}} = 240\,\mathrm{GeV}$ is 3.6%, dominated by the $\mathrm{Z}(\nu\nu)$ and Z(jj) channels. At $\sqrt{\mathrm{s}} = 365\,\mathrm{GeV}$, the signal is also split by production mode in the $\nu\nu$ channel, yielding combined precisions of 13% and 15% for ZH and WW→H, respectively [35].

For the $\mathrm{Z}\gamma$ decay mode, the targeted final states are $\mathrm{Z}(\nu\nu)\mathrm{H}[\mathrm{Z}(\mathrm{jj})\gamma]$ and $\mathrm{Z}(\mathrm{jj})\mathrm{H}[\mathrm{Z}(\nu\nu)\gamma]$. The signal is extracted using a fit to a BDT discriminant built from the invariant masses and angular variables of the reconstructed visible objects. The combined precision for $\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma)$ is 11.8% at $\sqrt{\mathrm{s}} = 240\,\mathrm{GeV}$, whereas at $\sqrt{\mathrm{s}} = 365\,\mathrm{GeV}$ combined precisions of 22% and 23% are achieved for for ZH and WW→H production modes, respectively [35].

The expected sensitivity to $\mathrm{H} \to \mu\mu$ is documented in Ref. [36]. The ZH production mode is used with Z boson decaying to electrons, muons, neutrinos, and hadrons. All channels have a requirement on the reconstructed Z boson mass to reduce backgrounds, predominantly from WW production. After this selection, the ZZ background dominates in all channels apart from the $\mathrm{Z} \to \nu\nu$ one, where WW is very large. No additional requirements are imposed in the electron and muon channels. The background in the $Z \to \nu\nu$ channel is reduced by the missing transverse momentum requirements and the opening angle between the two muons. In the $\mathrm{Z} \to$ hadrons channel, a veto on events with photons reduces the $\mathrm{Z}\gamma$ background. Fitting the di-muon invariant mass then leads to precisions of 11% and 26% at $\sqrt{\mathrm{s}} = 240$ and $365\,\mathrm{GeV}$, respectively, with the hadronic channel being by far the dominant one.

$H \to$ invisible

The FCC-ee has considerable advantages over hadron machines in the search for the decay of H to invisible particles: the Higgs boson mass can be fully reconstructed in the ZH production mode thanks to the known beam energies, and the Z boson can be fully reconstructed in many of its decay channels. In the SM, the Higgs boson can decay to invisible particles via $\mathrm{H} \to \mathrm{ZZ}^* \to \nu\nu\nu\nu$ with a branching ratio 0.106%, but there is a possibility that it could also decay to new particles, e.g., dark matter. The analysis [37] covers decays of the Z boson to electrons, muons, light quarks, c quarks, and b quarks. The different quark flavours are distinguished given their different WW backgrounds. The other main backgrounds are ZZ, $\mathrm{Z}\gamma^*$, $\nu\nu\mathrm{Z}$, and H decays to other final states. The main selection consists in requirements on the missing transverse momentum to reduce the Z/γ^* background and on the visible mass to reduce the WW background. A likelihood fit of the missing mass distribution is used to extract the expected precision on the SM measurement and a 95% C.L. upper limit on non-SM invisible H decays. It is found that SM measurements of 25% and 77% precisions are possible at $\sqrt{\mathrm{s}} = 240$ and $365\,\mathrm{GeV}$, respectively. The $\mathrm{Z} \to$ light hadrons is the most sensitive channel. If the SM contribution to $\mathrm{H} \to \mathrm{inv.}$ is treated as a background, upper limits of 0.055% and 0.16% can be obtained on $\mathcal{B}(\mathrm{H} \to \mathrm{inv.})$ at $\sqrt{\mathrm{s}} = 240$ and $365\,\mathrm{GeV}$, respectively.

CP violation in ZH production

The ZH production mode allows to test the CP properties of the $\mathrm{g}_{\mathrm{HZZ}}$ coupling. The parameter of interest $f_{\mathrm{CP}}^{\mathrm{HZZ}}$, defined in Ref. [38], quantifies the degree of CP-oddness in the HZZ interaction. It is extracted from a 3-dimensional fit of the complete set of angular distributions that characterise ZH production. As documented in Ref [39], this parameter can be constrained at FCC-ee to $f_{\mathrm{CP}}^{\mathrm{HZZ}} < 1.2 \times 10^{-5}$.

Electron Yukawa

The measurement of the electron Yukawa coupling is expected to be possible at FCC-ee through s-channel $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}$ production at $\sqrt{s} = m_{\mathrm{H}}$ [40]. However, several challenges need to be addressed to perform this measurement: the Higgs boson mass uncertainty and BES should be reduced at the level of the Higgs width, and, to exploit the most significant $\mathrm{H} \to \mathrm{gg}$ channel, a powerful gluon jet tagging algorithm is required to reduce large $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q\bar{q}}$ background. As shown in Ref. [20], the Higgs boson mass can be measured to the required accuracy at FCC-ee. The BES can be reduced to match the Higgs width with monochromatisation [41] at the expense of luminosity. Reference [40] demonstrates that if such conditions are fulfilled, a significance of 2.6σ per year can be reached, assuming a BES of 4.1 MeV and an integrated luminosity of 40 ab^{-1}. In 4 years this would translate in a discovery and, equivalently, in a 20% precision measurement of the electron Yukawa coupling.

γH production

The $\mathrm{e^+e^-} \rightarrow \gamma\mathrm{H}$ process provides an alternative way to probe the effective HZγ vertex [42]. The cross-section is maximal at $\sqrt{\mathrm{s}} = 240\,\mathrm{GeV}$. As for the ZH production process, the Higgs kinematics can be fully reconstructed using the recoil technique, solely from the reconstructed final-state monochromatic photon kinematics. The main background is $\mathrm{f\bar{f}} + \gamma$ production. The signal is extracted from fitting the $\mathrm{m_{rec}}$ distribution. The relative expected precision on $\sigma_{\gamma\mathrm{H}}$ is 230%. An exclusive selection requesting in addition the presence of two b-jets using the jet flavour tagger from Ref. [25, 26] improves the expected precision to 150%.

1.2 Higgs measurements at FCC-hh

Ultimately, the FCC-hh will produce 20 billion Higgs bosons and 30 million Higgs pairs, providing incomparable measurements of the Higgs self-coupling, top-quark Yukawa coupling, and rare or invisible modes. A full investigation of the potential of FCC-hh Higgs physics is out of scope here and was presented in Ref. [14]. The current document focuses on new Higgs measurements studies where FCC-hh can provide complementary information to the FCC-ee. The flagship measurement of FCC-hh is the Higgs self-coupling through HH production. A new analysis describing the reach of FCC-hh using the $\mathrm{HH} \rightarrow \mathrm{bb}\gamma\gamma$ final state is described. Rare Higgs production decays can be accessed with exquisite precision at FCC-hh by capitalising on the copious single H production rates at large $\mathrm{p_T}$ and by making use of ratios of observables that allow for the cancellation of correlated (theoretical and experimental) uncertainties. For example, the ratio of ttH/ttZ studied in Ref. [14] in the $\mathrm{H(Z)} \rightarrow \mathrm{b\bar{b}}$ final states, in conjunction with the absolute ttZ coupling measurement at FCC-ee, can provide an absolute top Yukawa measurement with percent-level precision at FCC-hh. Additional measurements of ratios of rare Higgs boson decays rates, are described below. The current results for the baseline scenario at $\sqrt{s} = 84\,\mathrm{TeV}$ are described in Table 3.

Table 3: Projected precision on Higgs measurements as obtained from FCC-hh simulations. Experimental systematics include background normalisation uncertainties. Efficiencies and luminosity systematics are included, while theoretical systematics are not included. An $^{(*)}$ indicates that the values are rescaled from the FCC-hh CDR [14, 19] from 100 TeV to 84 TeV assuming the same integrated luminosity.

observable	**param**	**stat.**	**stat. + syst.**	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)$	$\delta\mu$	0.1%	1.4%	(*)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \mu\mu)$	$\delta\mu$	0.4%	1.2%	
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \ell\ell\ell\ell)$	$\delta\mu$	0.2%	1.8%	(*)
$\mu = \sigma(\mathrm{H}) \times \mathcal{B}(\mathrm{H} \rightarrow \gamma\ell\ell)$	$\delta\mu$	1.1%	1.7%	(*)
$\mu = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)$	$\delta\mu$	0.4%	2.2%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \mu\mu)/\mathcal{B}(\mathrm{H} \rightarrow \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)/\mathcal{B}(\mathrm{H} \rightarrow \mathrm{ee}\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	0.8%	(*)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \gamma\gamma)/\mathcal{B}(\mathrm{H} \rightarrow \mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	0.5%	1.3%	(*)
$\mathrm{R} = \mathcal{B}(\mathrm{H} \rightarrow \mu\mu\gamma)/\mathcal{B}(\mathrm{H} \rightarrow \mu\mu\mu\mu)$	$\delta\mathrm{R}/\mathrm{R}$	1.6%	2.0%	(*)
$\mathrm{R} = \sigma(\mathrm{ttH})\, \mathcal{B}(\mathrm{H} \rightarrow \mathrm{b\bar{b}})/\sigma(\mathrm{ttZ})\, \mathcal{B}(\mathrm{Z} \rightarrow \mathrm{b\bar{b}})$	$\delta\mathrm{R}/\mathrm{R}$	1.2%	2.0%	(*)
$\mathrm{R} = \sigma(\mathrm{VBF-H}))\, \mathcal{B}(\mathrm{H} \rightarrow \mathrm{e}\mu\nu\nu)/\sigma(\mathrm{VBS-WW}))\, \mathcal{B}(\mathrm{WW} \rightarrow \mathrm{e}\mu\nu\nu)$	$\delta\mathrm{R}/\mathrm{R}$	1.9%	2.0%	
$\mathcal{B}(\mathrm{H} \rightarrow \mathrm{invisible})$	$\mathcal{B}$@95%CL	1.2×10^{-4}	2.6×10^{-4}	(*)
$\sigma(\mathrm{HH})$	$\delta\kappa_\lambda$	3.5%	5.2%	

Single Higgs production

The Higgs rare decays into $\gamma\gamma$, $\mathrm{Z}\gamma$, $\mu\mu$, 4ℓ have been re-analysed. The approach relies on measuring ratios of branching fractions to $\mathcal{B}(\mathrm{H} \rightarrow \mathrm{ZZ})$, with final states featuring correlated systematic uncertainties between the numerator and the denominator, e.g., $\mathcal{B}(\mathrm{H} \rightarrow \mu\mu)/\mathcal{B}(\mathrm{H} \rightarrow \mu\mu\mu\mu)$. This new analysis improves upon the previous one [14] by extracting the precision of the ratio of signal strengths in a likelihood fit over the reconstructed 2-dimensional distribution of $(p_\mathrm{T}(\mathrm{H}), m_\mathrm{H})$. A differential measurement of $\mathrm{d}\sigma(\mathrm{H})/\mathrm{d}p_\mathrm{T}$ is also provided. Details can be found in Ref. [43].

A novel approach to measure the HWW coupling by measuring the ratio of Vector Boson Fusion Higgs and WW production (or Vector Boson Scattering) $R = \mathrm{VBF(H \rightarrow WW)/VBS(WW)}$ has been proposed and documented in Ref. [44]. The ratio is extracted from a template fit on the Higgs transverse mass, and yields a relative statistical precision of 1.9%. A list of proposed measurements and first projections for measuring the HWW, Hbb and H$\tau\tau$ coupling in Higgs associated production is documented in Ref. [45].

A novel analysis addressing the $\mathrm{ttH}(\gamma\gamma)$ channel has been performed and documented in Ref [46]. The strategy involves selecting semi-leptonic top decays (hence one isolated lepton, two b-jets, and missing transverse energy) and extracting the signal contribution via a fit over the $m_{\gamma\gamma}$ in several $p_{\mathrm{T}}^{\gamma\gamma}$ regions, by exploiting the superior mass resolution and better S/B in the large $\mathrm{p}_{\mathrm{T}}^{\gamma\gamma}$ bins. A precision of $0.4(\mathrm{stat.}) + 2.1(\mathrm{syst.})\%$ is obtained on the signal strength. Assuming a similar precision can be obtained on the ratio $R = \mathrm{ttH}(\gamma\gamma))/\mathrm{ttZ}(\mathrm{ee})$, this measurement could provide a sub-per-cent level accuracy to the top Yukawa coupling.

Double Higgs production

The expected precision on the Higgs boson self-coupling at FCC-hh, combining the sensitivity in the $\mathrm{bb}\gamma\gamma$, $\mathrm{bb}\tau\tau$, bbbb and bbZZ final states, was reported to be 3-7% at 100 TeV in Ref [47]. A new analysis, fully re-optimised on $\mathrm{bb}\gamma\gamma$ final-state at 84 TeV, has been performed [48]. The signal-to-background strategy discrimination is based on a Deep Neural Network (DNN) trained on the event kinematic information. The events are divided in three categories of increasing significance according to the DNN discriminant, and the signal is then extracted using a profiled likelihood fit on the 2D ($m_{\gamma\gamma}$, m_{bb}) distribution, which provides a robust data-driven estimate of the background contributions. The projected precision on the self-coupling is $\delta\kappa_{\lambda} = 3.5(\mathrm{stat.}) + 3.8(\mathrm{syst.})$ using the $\mathrm{bb}\gamma\gamma$ channel alone. At 84 TeV, preliminary results [49] show that the HH cross-section could be measured with a precision at the 3% level using the $\mathrm{bb}\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel alone, which promises to further improve the self-coupling coupling precision when combining with the $\mathrm{bb}\gamma\gamma$ analysis. A new analysis of the bbWW final state [50] obtains 30% precision on the self-coupling. Ultimately, combining all HH channels, including $\mathrm{bb}\tau\tau$, and using state-of-the-art object identification and analysis techniques used in current HL-LHC projections [51] will allow the self-coupling precision to be reduced to 2-3% precision.

2 Electroweak and top

The top-quark and electroweak sectors of the SM will be probed to an unprecedented level of precision at FCC. The exceptional luminosity at FCC-ee enables measurements of exquisite precision, orders of magnitude beyond LEP, near production thresholds. Conversely, FCC-hh accesses unprecedented high-energy regimes (multi-tens of TeV), providing unique sensitivity to physics at very high momentum transfer. Together, the two stages comprehensively explore potential new physics through precision measurements in complementary energy regimes.

Table 4: Present and projected uncertainties on Z-pole line shape measurements. The projected statistical and experimental systematic error is given.

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_{Z} (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration [52]
Γ_{Z} (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_{\mathrm{Z}}^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small small (tbc)	From A_{FB}^{μ} off peak [53] From $\mathcal{R}_{\mathrm{e}^-/\ell^\pm}(\theta)$ on peak [54] QED&EW uncert. dominate
σ_{had}^0 (pb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section luminosity measurement

2.1 Electroweak and top measurements at FCC-ee

Precision measurements at FCC-ee critically rely on the accurate knowledge of beam parameters, such as the centre-of-mass energy, energy spread, and luminosity, and on a detailed understanding of detector acceptance [57] and reconstruction efficiencies. Matching the statistical precision of the Tera Z programme with comparable systematic accuracy is an active area of study that requires detectors and machine optics and operations to be designed and optimised accordingly.

Measurements at the Z pole

The line-shape Z pole scan has been a cornerstone of the Electroweak precision programme at LEP [58]. The FCC-ee will run off and on-peak at $\sqrt{s} = 87.9, 91.2, 94.3\,\mathrm{GeV}$ (or at suitable energies for calibration) and will collect

Table 5: Projected uncertainties on and partial-width ratios, forward-backward and polarisation asymmetries obtained on peak at the Z-pole at the FCC-ee assuming no lepton universality [55]. When two numbers are given (separated by a $\pm$ sign), the first and second correspond to the projected statistical and experimental systematic uncertainties, respectively. Experimental uncertainties only have been included, as they set the target requirements for the accuracy with which the theoretical calculations must be performed and the detector and accelerator built. For reference, we also provide in () the earlier projections on the partial width ratios and asymmetries given in Ref. [56] that assumed less informed and more conservative assumptions on the experimental systematic uncertainties.

fermion (f)	$R_f \equiv \Gamma_{had}/\Gamma_f$ relative (10^{-6})	$\mathcal{A}_f$ (10^{-6})	$A_{FB}^{0,f}$ (10^{-6})	comment
e	$\pm 3.4 \pm 2.3 (300)$	$\pm 14 \pm 11$	$\pm 3.3 \pm 2.4$	from $e^+e^- \to e^+e^-$
e	-	$\pm 7 \pm 20$	-	from $A_{FB}^{pol(\tau)}$
e	-	± 13.5 (20)	-	combined
μ	$\pm 2.4 \pm 2.3$ (50)	± 32 (32)	$\pm 2.3 \pm 2.4$	from $e^+e^- \to \mu^+\mu^-$
τ	$\pm 2.7 \pm 2.3$ (100)	± 34	$\pm 2.8 \pm 2.4$	from $e^+e^- \to \tau^+\tau^-$
τ	-	$\pm 5 \pm 200$	-	from τ polarisation
τ	-	± 34 (200)	-	combined
b	$\pm 1.2 \pm 1.6$ (300)	± 98 (210)	$\pm 4 \pm 4$	
c	$\pm 1.4 \pm 2.2$ (150)	± 60 (150)	$\pm 5 \pm 5$	
s	$\pm 2.5 \pm 11$	± 124	$\pm 7.4 \pm 7.4$	

40, 125 and 40 ab^{-1} of collisions data respectively. The absolute beam energy will be measured with a precision of 100 keV with the resonant depolarisation technique and will result in a similar uncertainty on the Z mass m_Z determination. The expected precision on the Z width [59], $\delta\Gamma_Z = 4\,(\text{stat.}) + 12\,(\text{syst.})\,\text{keV}$, is dominated by the relative (point-to-point) uncertainties in the collision energy $\delta(\sqrt{s})_{p.t.p}$ and the luminosity $\delta(\mathcal{L})_{p.t.p}$. The absolute luminosity measurement, determined using $e^+e^- \to \gamma\gamma$ events [60, 61] with a relative precision of 2×10^{-5} at the Z pole, dominates the precision of the peak hadronic cross-section σ^0_{had}. The electromagnetic coupling constant $\alpha_{QED}(m_Z^2)$ can be measured via the muon forward-backward (FB) asymmetry $A_{FB}^{\mu\mu}$ below and above the Z pole [53] with a relative statistical precision of 3×10^{-5}. An alternative, potentially even more precise method [54], proposes to measure it with 6×10^{-6} statistical accuracy via differential ratios of electrons to muons and positrons in the forward region on the peak. The expected precision on the Z lineshape measurements are summarised in Table 4.

Despite the absence of longitudinal beam polarisation, the chiral coupling asymmetries, $\mathcal{A}_e$, in particular, are accessible at FCC-ee via the τ polarisation measurement. The dominant systematic uncertainty originates from the knowledge of the non-τ related backgrounds, which should be obtained with an order of magnitude or more improvement than LEP due to the large control data samples available at FCC-ee. An orthogonal estimate of $\mathcal{A}_e$ is obtained from the FB asymmetry $A_{FB}^{0,e}$ in the lineshape scan and is limited by the point-to-point uncertainty $\delta(\sqrt{s})_{p.t.p}$. An expected uncertainty of $\mathcal{O}(10^{-5})$ on $\mathcal{A}_e$ is obtained by combining these two measurements. Likewise $A_{FB}^{0,\mu}$ is used to determine $\mathcal{A}_\mu$, together with knowledge of $\mathcal{A}_e$. The statistical uncertainty $A_{FB}^{0,\mu}$ is smaller than $A_{FB}^{0,e}$ due to the absence of the t-channel Bhabha contribution (and the interference with s-channel) that needs to be subtracted. The R_ℓ observables, defined as $R_\ell = \Gamma^0_{had}/\Gamma^0_\ell$, will be statistically limited by the size of the dilepton samples, provided that the acceptance uncertainty is minimised with a comparable precision [2, 57, 62]. To do so, the positioning of the low angle acceptance cut should be known with a precision of 10-20 μm (at about 2.5 m from the IP), depending on the angular selection.

The projection of precision for quark electroweak quantities has been considerably improved compared to previous estimates when results of jet tagging algorithms for FCC-ee became available. Compared to LEP, smaller beam size and vacuum pipe radius, along with great progress in vertex detector impact parameter accuracy and modern Machine Learning (ML) techniques, promise huge improvements in flavour tagging efficiencies and purities. The hemisphere tagging efficiencies can be estimated in situ with the multi-tag method [58, 63] with comparable statistical precision to the R_q. Other experimental errors are driven by mis-tagging efficiencies (which will be controlled, e.g., by using different taggers for different hemispheres in individual events) and hemisphere correlations. Most can be directly extracted or controlled from the data guided by the identification, in the Monte Carlo, of effects which modify the tagging efficiency in a correlated way for the two hemispheres, and can be measured in the data. Such are the polar angle, hard gluon emission, and main vertex reconstruction. Many ancillary quantities (such as gluon splitting) can be extracted from dedicated analysis in the data. The required precision should be comparatively less demanding than at LEP because of the higher efficiency (factor 5) and much reduced contamination (by factors going from 50 for s-quarks to 1000 for b quarks).

To determine the quark asymmetries, the jet-charge method is also self-calibrating, and uncertainties are dominated by quantities measurable in the data. Finally, we note that the Tera Z will produce large datasets of clean exclusive heavy-flavor decay modes, which also allow for measurements of efficiency, contamination and jet charge with high signal purities and very small and reliable systematic uncertainties [64, 65].

Assuming that this programme will be successful, the corresponding systematics can be reduced to the target statistical accuracy [55], we obtain the projected statistical and experimental uncertainties on the partial-width ratios, forward-backward, and polarisation asymmetries at the Z-pole for all fermions species without assuming lepton universality in Table 5. For reference and comparison, we also provide the earlier projections given in Ref. [56] that assumed less informed and more conservative assumptions on the experimental systematic uncertainties.

Measurements at the WW threshold

The W mass can be precisely determined by measuring the W-pair production cross section near its kinematic threshold. Rescaling to account for the difference in integrated luminosity the projected statistical uncertainty on the mass m_W and the width Γ_W obtained in Ref. [66] one obtains 0.43 and 1.03 MeV. The W mass and width can also be determined from the kinematic reconstruction of the W-pair decay products at all energies above the WW threshold. This approach was applied in semi-leptonic ($\ell\ell j\nu$) events [67] at the WW threshold. The kinematic fit exploits the constraints from total momentum conservation to improve the jet energy resolution. From a maximum likelihood template fit of the reconstructed W mass distributions, the value of m_W and Γ_W can be extracted with a respective precision of 0.21 and 0.28 MeV. The combined expected uncertainty is given in Table 6. Beam energy calibration through resonant depolarisation will ensure the uncertainty on the absolute collision energy will not be a limiting factor for the W mass reconstruction with the data taken at 162.6 GeV.

With almost 5×10^8 W bosons produced at the WW, ZH, and $t\bar{t}$ thresholds, FCC-ee will be able to probe the leptonic branching fractions $\mathcal{B}(W \to e\nu, \mu\nu, \tau\nu)$ of the W with a precision of 1.3×10^{-4}. The luminosity will be the dominant systematics of these measurements.

Measurements of the $e^+e^- \to W^+W^-$ process at the WW threshold and, in particular, at higher energies also bring the possibility of testing the presence of anomalous triple gauge couplings (aTGC). Studies of the FCC-ee sensitivity to such interactions have been performed in the context of the SMEFT, using the formalism of statistical optimal observables and following the details that can be found in [68, 69]. A global study found that FCC-ee could probe the aTGC with an absolute precision better than 10^{-3}.

At the WW threshold and above, it is possible to measure the Z coupling to electron neutrino $g_Z^{\nu_e}$ by exploiting the interference between s-channel Z exchange and t-channel W exchange in the $e^+e^- \to \nu\nu\gamma$, with a statistical uncertainty of 0.7% [70].

The projected uncertainties for precision measurements at the WW threshold and above are summarised in Table 6. We finally note that all the asymmetries, ratios, and forward-backward asymmetries discussed above can also be measured, with almost purely statistical uncertainty at the WW threshold and above. The corresponding projections are summarised in [55].

Table 6: Present and projected uncertainties on WW threshold (and above) measurements. The projected statistical and experimental systematic error and source is given.

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee syst.	Comment and leading uncertainty
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	WW threshold scan Beam energy calibration
$\mathcal{B}(W \to e\nu_e) \times 10^4$	1071	±	16	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \mu\nu_\mu) \times 10^4$	1063	±	15	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \tau\nu_\tau) \times 10^4$	1138	±	21	**0.13**	0.15	From WW scan ZH threshold luminosity
$g_Z^{\nu_e}$	1.06	±	0.18	**0.007**	small	From WW threshold

Measurements at the top threshold

The top quark mass ($\mathrm{m_{top}}$) and the width (Γ_{top}) are crucial inputs to the electroweak precision fit. A novel study of the $\mathrm{t\bar{t}}$ threshold scan at FCC-ee, including estimates of experimental, machine-related, and theoretical uncertainties, can be found in Ref. [71]. The study demonstrates that the WbWb production rate can be determined with negligible impact from systematic uncertainties at centre-of-mass energies ranging from 340 to 365 GeV. The signal is extracted from a simultaneous fit to the fully and semi-leptonic final states. The values of $\mathrm{m_{top}}$ and Γ_{top} are then extracted via a fit to the $\mathrm{N^3LO}$ theoretical prediction [72] of the $\mathrm{t\bar{t}}$ threshold scan. The impact of parametric uncertainties, such as the strong coupling constant and the top-quark Yukawa coupling, and the effect of machine-related uncertainties, such as luminosity and beam energy calibrations, are incorporated in the fit. When considering a 10-point scan between 340 and 345 GeV, the value of m_{top} can be measured with a total (statistical and experimental systematic) uncertainty of 6.5 MeV. The top-quark width can be determined with a total uncertainty of 11.5 MeV. The leading systematic uncertainty for both quantities is the parametric uncertainty in the top-quark Yukawa coupling, which is assumed to be known at the 3% level from HL-LHC. The fit is also extended to include the 365 GeV run, which makes it possible to constrain the top-quark Yukawa coupling to 2.1%, assuming a ttZ coupling compatible with the SM. The impact of theoretical uncertainties is also investigated by varying the renormalisation scale in the $\mathrm{N^3LO}$ calculation and is found to be the limiting factor. In particular, the theoretical uncertainty is about 35 and 25 MeV for m_{top} and Γ_{t}, respectively.

The FCC-ee can also measure the electro-weak couplings to the top quark [73–75], particularly ttZ. The CP odd BSM modifications of the ttZ couplings (Vector and Axial) can be constrained to 10^{-3} or below. In addition, the top left and right-handed SM couplings can be measured with a precision of 0.5% and 1.5%. A forthcoming study will provide a combined determination of the top Yukawa and ttZ couplings at $\sqrt{s} = 365$ GeV. The projections for top precision measurements at FCC-ee are summarised in Table 7. Additional FCC-ee studies of non-standard top-quark interactions in the EFT formalism can be found in [76]. These use the same statistical optimal observable method used in [73–75] but extend the analysis to a more general set of top-quark interactions. This includes, in particular, four-fermion $e^+e^-t\bar{t}$ operators, where FCC-ee can largely improve the HL-LHC reach.

Table 7: Present and projected uncertainties on top threshold measurements. The projections include statistical and experimental systematic error only, theoretical uncertaintes are not included. The leading experimental systematic error is given. $^{(*)}$ We note that the leading systematic error in the $\mathrm{m_{top}}$, Γ_{top} and y_{top} determination is parametric, and de facto of statistical nature.

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_{top} (MeV)	172 570	±	290	**4.2**	4.9*	From $\mathrm{t\bar{t}}$ threshold scan parametric, beam calibration
Γ_{top} (MeV)	1 420	±	190	**10.0**	6.0*	From $\mathrm{t\bar{t}}$ threshold scan parametric, beam calibration
y_{top}		±	10%	**1.5%**	1.5%*	From $\sqrt{s} = 365$ GeV run paramteric, beam calibration
$\mathrm{g_{ttZ}}$ (L-R)		±	10-30%	**0.5–1.5** %	small	From $\sqrt{s} = 365$ GeV run

2.2 Electroweak and top measurements at FCC-hh

Differential measurements at large $\mathrm{Q^2}$

Precision in SM differential measurements, particularly in the high $\mathrm{Q^2}$ regime, can offer a complementary view of the FCC-hh physics reach of FCC-hh compared to the searches. Studies of top production and properties using the 10^{12} top-pairs produced at FCC-hh are documented in [77]. A new study on the expected precision in differential $\mathrm{t\bar{t}}$ production in the fully hadronic final state, WW production in the $e\mu$ final state, and $\mathrm{t\bar{t}t\bar{t}}$ production in the fully leptonic final state has been documented in Ref. [78]. The differential yields and corresponding statistical and systematic uncertainties are also provided for a possible re-interpretation of the pseudo-data. The key conclusions of this study indicate that an overall uncertainty below 10% can be achieved for the measurement of the $\mathrm{t\bar{t}}$ invariant mass up to 30 TeV, of the eμ invariant mass from WW decays up to 8.5 TeV, and an overall uncertainty of 4% in the production of four-top final states, with the prospect for a further reduction to the per-cent level from a more refined analysis.

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