# A selection of benchmark studies at FCC-ee

*Contribution to Snowmass 2021*

**Abstract**

The FCC-ee is a frontier Higgs, Electroweak, and Flavour factory, to be operated in a 100 km circular tunnel built in the CERN area. In addition to offering an outstanding and largely unique physics program, it serves as the first step of the FCC integrated programme towards 100 TeV proton-proton collisions in the same infrastructure. A selection of significant benchmark studies is proposed. The focus is on measurements that are either unique, or for which the high statistics of FCC-ee lead to the most demanding requirements on detector design or on theoretical calculations. The ultimate goal is that experimental or theory systematic errors match the statistical limit. The list presented in this document is not exhaustive, and will evolve in time.

## Introduction

A brief presentation of the FCC project with a set of references and Snowmass contacts can be found here: https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF-RF-TF-IF-CompF-TOPIC0-003.pdf. To keep informed on FCC-ee and have access to meetings, you can register to the design study by filling this form. Needless to say, the registration to the FCC-ee design study will not lead to signing anything that has not been agreed to, and commitment is limited to participation to the particular work.

The present document lists a non-exhaustive series of abstracts and will evolve with time. Most abstracts address essential FCC-ee physics benchmark measurements, giving rise to requirements on detector performance or design, or on the precision of theoretical calculations and tools. These benchmark measurements are part of a largely unique scientific program [1, 2], made possible by the high luminosity, by the 1-10 ppm beam energy calibration at the Z, WW, ZH, and $t\bar{t}$ energies, and, if possible, by monochromatisation at $\sqrt{s} = m_{\mathrm{H}}$.

- The Tera-Z factory with several trillions of Z produced, offers unique opportunities for a multitude of electroweak measurements, flavour (b, c, $\tau$) physics, and searches for SM symmetry violations and feebly coupled particles.
- The $\mathrm{W}^+\mathrm{W}^-$ phase, with $3 \times 10^8$ W pairs, will allow a relative precision on the W mass of 7 ppm or better, while the $t\bar{t}$ phase, with over a million top pairs, will push the precision on the top quark mass to a few tens of MeV, along with the per-cent level determination of its electroweak couplings.
- The Higgs factory, with over one million Higgs bosons produced at $\sqrt{s} \sim 240$ and 365 GeV, will allow many of the Higgs couplings (with a precision down to the per mil for the HZZ coupling) and the total Higgs boson width (with a precision around the per cent) to be extracted for the first time in a model-independent and absolute way. In particular, the first model-independent demonstration of the existence of the trilinear Higgs self-coupling can be achieved with a combination of the total cross-section measurements at these two energies and, in combination with HL-LHC, a first absolute determination of the top Yukawa coupling can be obtained with a precision better than 3%.
- The possibility to observe the $s$-channel Higgs production, $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}$, leads to a unique chance of measuring the Yukawa coupling of the electron.

With this large leap in precision on all electroweak observables, flavour physics, and Higgs and top properties, the discovery of tiny deviations with respect to the standard model predictions will be sensitive to new physics up to scales from 10 to 100 TeV. Moreover, these essential inputs used as “fixed candles” will enhance and maximise the physics reach of FCC-hh at the precision and the energy frontiers, taking advantage of the multiple complementarities and synergies of FCC-ee and FCC-hh [3]. The high luminosity expected at all centre-of-mass energies also opens the possibility of direct discoveries, either with the observation of new phenomena (typically SM symmetry violation similar to, e.g., neutral currents, neutrino oscillations or CP violation past discoveries);

or with the direct search and the observation of feebly interacting new particles (such as sterile neutrinos, axion-like particles, dark photons, ...) to cover many order of magnitudes of coupling strengths down to $10^{-11}$ of the weak coupling.

**A first list of benchmark studies**

1. Towards an ultimate measurement of $R_\ell = \frac{\sigma(\mathrm{Z}\to\mathrm{hadrons})}{\sigma(\mathrm{Z}\to\mathrm{leptons})}$
2. Towards an ultimate measurement of the Z total width $\Gamma_\mathrm{Z}$
3. Towards an ultimate measurement of the Z peak cross section
4. Direct determination of $\sin^2\theta^\ell_\mathrm{eff}$ and of $\alpha_\mathrm{QED}(m^2_\mathrm{Z})$ from muon pair asymmetries
5. Determination of the QCD coupling constant $\alpha_\mathrm{S}(m^2_\mathrm{Z})$
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23. Construction of CP-odd observables to probe CP-violating Higgs couplings
24. Combined fit of Higgs and top data

More detailed letters of interest and contacts specific to each case study (if not already indicated below) will be available shortly. Meanwhile, Alain Blondel, Patrick Janot, and Markus Klute are the main entry points to these case studies. The complete document is available at https://www.overleaf.com/read/dyjpdszrqxhz and will be regularly updated with more case studies and contacts.

## Contents

# 1 Towards an ultimate measurement of $R_\ell = \frac{\sigma(\mathrm{Z}\to\mathrm{hadrons})}{\sigma(\mathrm{Z}\to\mathrm{leptons})}$

*Alain*

The ratio $R_\ell$ can be measured at FCC-ee with an event sample of $5 \times 10^{12}$ Z produced at $\sqrt{s} = 91.2\,\mathrm{GeV}$, and therefore benefits from a potential relative statistical precision of $\mathcal{O}(3 \times 10^{-6})$ for each lepton type. It is a key quantity [4] that serves – in conjunction with the total Z decay width and the peak hadronic cross section – as input to several fundamental quantities:

i) the measurement of the leptonic Z partial width $\Gamma_{\ell\ell}$, a very clean electroweak observable whose relation to the Z mass is the $\rho$ (or T) parameter, and unaffected by $\alpha_{\mathrm{QED}}(m_{\mathrm{Z}}^2)$, with a $10^{-5}$ relative precision;

ii) the measurement of the strong coupling constant $\alpha_{\mathrm{S}}(m_{\mathrm{Z}}^2)$ with an absolute experimental uncertainty below 0.0001 (Section 5);

iii) the measurement of the number of light neutrinos with a precision of 0.0004.

Experience from LEP showed that a limiting systematic uncertainty comes from the knowledge of the geometrical acceptance for lepton pairs. The requirements on the detector design to match the statistical precision will be studied in the full context of the constraints from the interaction region layout. As a by-product, the determination of the geometrical acceptance for the $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$ process (which may be used for the measurement of the absolute luminosity, potentially with a statistical precision of a few $10^{-5}$) will be investigated – see also Section 3. The knowledge of the acceptance for the more abundant hadronic Z decays, a much easier problem at LEP, will need to be verified at the same level of precision.

# 2 Towards an ultimate measurement of the Z total width $\Gamma_{\mathrm{Z}}$

*Patrick*

The Z total decay width $\Gamma_{\mathrm{Z}}$ can be measured at FCC-ee with sample of $3.5 \times 10^{12}$ $\mathrm{Z} \to$ hadrons events produced around the Z pole at $\sqrt{s} \approx 87.8$, 91.2, and 93.9 GeV, with a statistical precision of 4 keV [5].

Experience from LEP showed that a limiting systematic uncertainty comes from the uncorrelated point-to-point error on the centre-of-mass energies of the three resonance scan points. At FCC-ee, this error can possibly be controlled in situ with the invariant mass distributions obtained from large dimuon event samples [5]. The requirements of the detector design (muon momentum and angular resolution and scale stability) to match the statistical precision will be studied in the context of the constraints from the full interaction region layout (beam crossing angle, beam energy spread, magnetic field). As a by-product, the possible improvements brought about by a five-point scan of the Z resonance will be investigated.

# 3 Towards an ultimate measurement of the Z peak cross section

*Patrick*

The Z peak cross section can be measured at FCC-ee with hadronic and dimuon events produced at $\sqrt{s} = 91.2\,\mathrm{GeV}$, with a potential relative statistical precision of $\mathcal{O}(10^{-6})$. Together with the ratio $R_\ell$ (Section 1), this quantity allows the determination of the number of light neutrino types.

A limiting systematic uncertainty comes from the absolute determination of the integrated luminosity. A determination with low-angle Bhabha scattering is likely to be limited by a relative theoretical precision of $\mathcal{O}(10^{-4})$ [6], but that might not be the case for large angle diphoton production, $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$ (to be checked with actual full two-loop calculations [7]). The requirements on the detector design to measure the absolute luminosity with diphoton events, and in particular to separate these events from the large angle Bhabha background, will be studied.

## 4 Direct determination of $\sin^2\theta_{\rm eff}^{\ell}$ and of $\alpha_{\rm QED}(m_{\rm Z}^2)$ from muon pair asymmetries

*Patrick*

With $1.5\times10^{11}$ dimuon events, the measurement of the muon-pair forward-backward asymmetry $A_{\rm FB}^{\mu\mu}$ at the Z pole ($\sqrt{s} = 91.2\,{\rm GeV}$) will allow the determination of the effective weak mixing angle $\sin^2\theta_{\rm W}^{\ell}$ with an absolute statistical precision of $3\times10^{-6}$ [5]. A $3\times10^{-5}$ relative statistical precision on $A_{\rm FB}^{\mu\mu}$ just below ($\sqrt{s}\sim 88\,{\rm GeV}$) and just above ($\sqrt{s}\sim 94\,{\rm GeV}$) the Z pole also gives access to a direct determination of the QED coupling constant $\alpha_{\rm QED}(m_{\rm Z}^2)$ with a similar statistical accuracy, and with experimental uncertainties that can be kept well below this value [8]. Such an accuracy is an essential input to the new physics interpretation of precision electroweak data.

A limiting systematic uncertainty comes from QED corrections to the $e^+e^-\to\mu^+\mu^-$ process, and in particular from the interference between initial- and final-state radiation (IFI) [9], which modifies very substantially (by a few %) the value of $A_{\rm FB}^{\mu\mu}$. Experimental and phenomenological ways to minimize the effect of IFI on $\alpha_{\rm QED}(m_{\rm Z}^2)$ and $\sin^2\theta_{\rm W}^{\ell}$ will be developed and studied, and control of IFI with independent data will be investigated, in order to estimate the requirements on the theoretical precision with which QED corrections need to be computed.

## 5 Determination of the QCD coupling constant $\alpha_{\rm S}(m_{\rm Z}^2)$

*David*

The FCC-ee will provide an unprecedented sample of $5\cdot10^8$ W bosons and $3\cdot10^{12}$ Z bosons (decaying hadronically), in $e^+e^-$ collisions at the Z pole and WW threshold, respectively. The corresponding high-precision measurements of hadronic W and Z pseudo-observables (total widths $\Gamma_{\rm W,Z}$, ratio of hadronic-to-leptonic widths $R_\ell$, peak hadronic cross section at the Z pole $\sigma_{\rm Z}^{\rm had}$) will allow the extraction of the QCD coupling constant $\alpha_{\rm S}(m_{\rm Z}^2)$ with uncertainties below the 0.2% level [10, 11] in a few different ways. With challengingly small statistical uncertainties, and accounting for the expected progress in the computation of theoretical higher-order N$^4$LO $\mathcal{O}(\alpha_{\rm S}^5)$ QCD, $\mathcal{O}(\alpha^2,\alpha^3)$ electroweak, and mixed QCD$\oplus$EW $\mathcal{O}(\alpha\alpha_{\rm S}^2,\, \alpha\alpha_{\rm S}^3,\, \alpha^2\alpha_{\rm S})$ corrections missing today, the leading propagated uncertainties on $\alpha_{\rm S}(m_{\rm Z}^2)$ will be of experimental systematic nature. The improvements on the detector design expected in order to match the systematic and statistical precision on $\Gamma_{\rm Z}$ (Section 2), $R_\ell$ (Section 1), and $\sigma_{\rm Z}^{\rm had}$ (Section 3) will be studied to determine the ultimate uncertainty eventually reachable in $\alpha_{\rm S}(m_{\rm Z}^2)$ extractions at the FCC-ee.

## 6 Tau Physics, Lepton Universality, and Lepton Flavour Violation

*Alain, Mogens*

The $10^{11}$ $\tau$ pairs produced at FCC-ee offer a number of measurements that are sensitive to the existence of heavy physics and should be included in global fits, such as those involving right-handed neutrinos. The statistical uncertainties will be more than two orders of magnitude smaller than present values. The studies will aim at matching the detector systematics with the statistics available and derive the key detector requirements, which are expected to be some of the most demanding ones. The measurements involved (and corresponding assumed leading detector requirements) are, in particular, as follows:

i) the tau lepton lifetime (and the vertex detector radial alignment);

ii) the tau lepton mass (and the tracker momentum scale);

iii) the tau leptonic branching ratios (and lepton efficiency and identification);

iv) the tau flavour violating decays $\tau\to\mu/e\,\gamma$, etc. (and the lepton momentum resolution).

A first review with many references was made by M. Dam [12].

# 7 Tau exclusive branching ratios and polarization observables

*Alain, Mogens*

The tau polarization in Z decay is one of the most sensitive electroweak observables [4]. It is measured from the charged particle momentum distribution in the semi-leptonic decays $\tau \to \mathrm{e}\nu_{\mathrm{e}}\nu_\tau$, $\mu\nu_\mu\nu_\tau$ or in hadronic decays $\tau \to h\nu_\tau$ where $h$ can be $\pi$, K, $\rho$, K$^*$, $\mathrm{a}_1$ etc. Each channel having its own analysis power, a clean separation is essential. The analysis of the $\tau$ polarization dependence on the scattering angle $\theta$ gives access to both the tau and electron chiral coupling asymmetries $\mathcal{A}_\tau$ and $\mathcal{A}_\mathrm{e}$ independently

$$P(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_\mathrm{e}\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_\mathrm{e}\mathcal{A}_\tau\cos\theta}, \quad (1)$$

and serves as a crucial ingredient of a full lepton-by-lepton extraction of the Neutral Current chiral (or vector and axial-vector) couplings. A closely related outcome is a precise determination of the vector and axial vector spectral functions [13], which provide important information for the extraction of $\alpha_s(m_\tau^2)$ and $\alpha_{\mathrm{QED}}(q^2)$.

A limiting systematic error is associated with cross-channel contamination, implying tight detector requirements on reconstruction of photons, $\pi^0$s and other neutral particles, as well as K/$\pi$ separation.

# 8 Z-pole Electroweak observables with heavy quarks

*Alain, Juan*

Almost a trillion ($10^{12}$) each of Z decays in b and c quark pairs will be the opportunity of measurements of their electroweak properties with a relative statistical precision of $\mathcal{O}$(a few $10^{-6}$), allowing unique tests of quark-lepton universality. The situation at FCC-ee will be further improved w.r.t. LEP or SLD, with the clean experimental conditions and the possibility of a small beam pipe of 10 mm radius. The study of how to perform these measurements, with a systematic precision matching, as much as possible, the available statistics, will be an irreplaceable stepping stone and calibration process towards the precise measurements of similar quantities in W, H and top decays. The topic combines algorithmic methods, with a great variety of lepton, secondary vertex or exclusive decay tagging, detector effects and requirements, and more phenomenological QCD effects. It is expected that the huge statistics will allow a great amount of internal calibration.

The b and c partial widths are sensitive to tagging efficiencies and hemisphere correlations, stemming both from detector effects and from QCD. The QCD part involves gluon emission and gluon splitting into additional heavy quarks.

The measurement of forward-backward asymmetries requires in addition hemisphere charge tagging. Furthermore it is affected by QCD radiation, which affects the measurement of the scattering angle. A detailed study of how to constrain experimentally the (theoretical) QCD corrections from their observation in the data will be of great value [14]. More documentation and references can be found in Ref. [4].

# 9 Long lived particle searches

*Patrizia*

The Tera-Z run will allow for the direct search of new feebly interacting particles that could be good Dark Matter candidates (ALPS, Dark Photon, HNL Sterile Neutrinos). In some cases, the relationship in the model parameters is such that the final state would include a particle with a very long lifetime and detached vertex, for instance as in the case of a heavy sterile neutrino. A sensitivity down to a heavy-light mixing of $10^{-12}$ was obtained, covering a large phase-space for heavy neutrino masses between 5 and 80 GeV [15]. The signal events would be characterised by the Z decaying $Z \to \nu N$ followed by $N \to W^*\ell$ or $Z\nu$. For low values of the mixing angle the decay length of the HNL can be significant, and correspond to a decay vertex at the edge of the tracking volume or beyond. In order to achieve the ultimate sensitivity for these type of events it is necessary to develop, among other things, new tracking and vertex reconstruction algorithms. These algorithms would have to be re-optimised for the different detector concepts (silicon tracker, drift chamber, etc). In turn, these studies could bring in ideas for innovative solutions for new, possibly very large (the caverns being designed already for the FCC-hh detectors), tracking detectors or co-processors that would be optimal for these type of searches in unusual final states

## 10 Measurement of the W mass

*Alain*

The W mass is one of the most sensitive electroweak precision observables. At FCC-ee it will benefit of the availability of accurate beam energy calibration by resonant depolarization at the W threshold energy [5]; it is estimated [1] that a statistical precision of 600 keV can be achieved from a measurement of the cross-section at threshold with beam energy calibration uncertainty of 300 keV. A recent study [16] observed that final state reconstruction and kinematical fit can lead to competitive results, both at threshold and at higher energies. An understanding of the correlation of the two methods and of the subsequent detector requirements, in particular on the lepton momentum scale error and resolution, might lead to a significant improvement of the precision.

## 11 Measurement of the Higgs boson coupling to the c quark

*Patrick*

The SM Higgs boson is expected to decay to $c\bar{c}$ with a branching ratio of about 3%. This decay will be extremely difficult to isolate and measure at LHC, but is directly accessible at FCC-ee if an efficient c-tagging algorithm, able to disentangle $c\bar{c}$ decays from other copious hadronic Higgs boson decays ($b\bar{b}$ and gg, and to a lesser extent, ZZ* and WW*) with high purity, can be designed. An ideal (100% efficient and 100% pure) tagging algorithm would yield a measurement of $\sigma_{ZH} \times BR(H \to c\bar{c})$ with a precision better than 1%.

Starting from the related experience developed at LHC and other $e^+e^-$ collider projects, and with the help of the latest machine-learning technologies, such an algorithm will be developed, first with fast simulation, and then in the full context of the constraints from the interaction region and detector layout. The impact of the interaction-region and detector design (beam pipe radius, vertexing, vertex mass determination, tracker material, ...) on the precision $\sigma_{ZH} \times BR(H \to c\bar{c})$ measurement will be studied. As a by-product, similar studies for the $H \to b\bar{b}$ and $H \to gg$ decays will be conducted as well. The need for calibration data at the Z pole will be estimated (frequency, number of events).

## 12 Measurement of the ZH production cross section

*Patrick*

At FCC-ee, the measurement of the total $e^+e^- \to ZH$ cross section is an essential input to the absolute determination of the HZZ coupling and of the trilinear Higss self-coupling [17]. With one million ZH events expected in three years at $\sqrt{s} = 240\,\text{GeV}$, and 200,000 Higgs events expected at and above the $t\bar{t}$ threshold in five years, the ultimate statistical precision on the production cross section is 0.1% and 0.2%, respectively. If achievable, such a performance would lead to a determination of the Higgs self-coupling $\kappa_\lambda$ with a precision better than 10% in a full EFT fit.

Traditionally, only the leptonic decays of the Z boson ($e^+e^-$ and $\mu^+\mu^-$) are used for the cross-section measurement, as they allow the Higgs boson to be tagged with an efficiency independent of the Higgs decay mode. The small Z leptonic branching ratio is expensive in terms of cross-section precision, which become 0.5% and 1% at 240 GeV and 365 GeV, respectively. Such a decay-mode independent tag is more challenging with hadronic Z decays, and needs to be quantified.

The requirements on the detector design (hadronic mass and hadronic recoil-mass resolutions) to approach the ultimate statistical precision on the Higgs self-coupling will be studied. As a by-product, this precision will be optimized as a function of the centre-of-mass energy (around 240 GeV), to fully benefit from the increase of the ZH cross-section sensitivity to $\kappa_\lambda$ (and of the FCC-ee luminosity) at smaller $\sqrt{s}$ values.

## 13 Measurement of the Higgs boson mass - Part I

*Patrick*

A measurement of the Higgs boson mass with a precision of $\mathcal{O}(10\,\mathrm{MeV})$ is in general sufficient to predict Higgs production cross sections and decay branching fractions with an accuracy sufficiently smaller than the statistical precision expected at FCC-ee. One notable exception is the electron Yukawa coupling determination from the $\mathrm{e^+e^-} \to \mathrm{H}$ resonant production at $\sqrt{s} = 125\,\mathrm{GeV}$, for which a precision significantly smaller than the Higgs total width ($\sim 4\,\mathrm{MeV}$) is needed.

Traditionally, the Higgs boson mass is obtained from a fit to the distribution of the mass recoiling to a leptonically-decaying Z boson ($\mathrm{Z} \to \ell^+\ell^-$) in the $\mathrm{e^+e^-} \to \mathrm{ZH}$ process at $\sqrt{s} = 240\,\mathrm{GeV}$:

$$m^2_{\mathrm{recoil}} = s + m^2_{\ell\ell} - 2\sqrt{s}\,(E_{\ell^+} + E_{\ell^-})\,. \tag{2}$$

The first step in this quest is therefore the determination of the centre-of-mass energy $\sqrt{s}$ with a precision of $\mathcal{O}(1\,\mathrm{MeV})$. The requirements on the detector design to achieve such a precision on $\sqrt{s}$, regarding in particular the lepton and jet angular resolution, as well as the detector acceptance, will be studied with a consolidated analysis of the $\mathrm{e^+e^-} \to \mathrm{Z}(\gamma)$ process at $\sqrt{s} = 240\,\mathrm{GeV}$ – as proposed in Ref. [5] – with $Z \to \ell^+\ell^-$ and $\mathrm{q\bar{q}}$, and with realistic FCC-ee collision parameters (beam energy spread, beam crossing angle). The feasibility of a calibration of the method, to reduce systematic uncertainties of various origins, with $\mathrm{e^+e^-} \to \mathrm{Z}(\gamma)$ events recorded at the WW threshold – where the centre-of-mass energy can be determined with resonant depolarization with a few 100 keV accuracy as well – will be ascertained.

## 14 Measurement of the Higgs boson mass - Part II

*Patrick*

With the ILD detector layout and CEPC machine parameters, a precision on $m_\mathrm{H}$ as small as 5 MeV can be achieved [18] from a fit to the distribution of the mass recoiling to a leptonically-decaying Z boson ($\mathrm{Z} \to \mathrm{e^+e^-}$ or $\mu^+\mu^-$) in the $\mathrm{e^+e^-} \to \mathrm{ZH}$ process at $\sqrt{s} = 240\,\mathrm{GeV}$. The requirements on the detector design (electron energy and muon momentum resolution, in particular) to achieve this statistical precision will be checked with this channel in the FCC-ee context. The feasibility of a calibration of the method – to reduce systematic effects due to, e.g., momentum scale determination and stability – will be ascertained with the $\mathrm{e^+e^-} \to \mathrm{ZZ} \to \ell^+\ell^-\mathrm{X}$ process.

The Higgs boson mass can also be determined with the fully hadronic final state [19]:

$$\mathrm{e^+e^-} \to \mathrm{ZH} \to \mathrm{q\bar{q}b\bar{b}}. \tag{3}$$

The requirements on the detector design (b-tagging efficiency and purity, jet angular resolution), to achieve a precision on the Higgs boson mass of the same order as that obtained in the leptonic final state, will be studied in the context of a full 5C kinematic fit, as described for example in Ref. [16] for the W mass determination at FCC-ee. The feasibility of a calibration of the method – to reduce systematic effects due to, e.g., final-state jet-jet interaction – will be ascertained with the $\mathrm{e^+e^-} \to \mathrm{ZZ} \to \mathrm{q\bar{q}b\bar{b}}$ process.

For both leptonic and hadronic final states, the need for calibration data at the Z pole will be estimated (frequency, number of events).

## 15 Inferring the total Higgs boson decay width - Part I

*Patrick*

Once the Higgs boson coupling to the Z, $g_{\rm HZZ}$, has been determined (Section 12), the measurement of the cross sections for each exclusive Higgs boson decay, $\rm H \to X\overline{X}$,

$$\sigma_{\rm ZH} \times \mathcal{B}(\rm H \to X\overline{X}) \propto \frac{g^2_{\rm HZZ} \times g^2_{\rm HXX}}{\Gamma_{\rm H}} \quad \text{and} \quad \sigma_{\rm H\nu_e\bar{\nu}_e} \times \mathcal{B}(\rm H \to X\overline{X}) \propto \frac{g^2_{\rm HWW} \times g^2_{\rm HXX}}{\Gamma_{\rm H}}, \tag{4}$$

gives access to all other copious decays (down to a branching ratio of a few $10^{-4}$), and to the corresponding couplings in a model-independent, absolute, way. For example, the ratio of the WW-fusion-to-Higgsstrahlung cross sections for the same Higgs boson decay, proportional to $g^2_{\rm HWW}/g^2_{\rm HZZ}$, yields $g_{\rm HWW}$, and the Higgsstrahlung rate with the $\rm H \to ZZ^*$ decay, proportional to $g^4_{\rm HZZ}/\Gamma_{\rm H}$, provides a first determination of the Higgs boson total decay width.

The $\rm H \to ZZ^*$ decay gives rise to a $\rm ZZZ^*$ final state, either fully leptonic (six charged leptons), two-third leptonic (four leptons), one-third leptonic (two leptons), or fully hadronic (no leptons). The first two configurations should be essentially background free, and lead to a "straightforward", albeit statistically limited, determination of the Higgs boson width. The requirements on the detector design to achieve a background-free and highly efficient analysis for final states with at least four leptons will be studied. The other two configurations are potentially more abundant, but are also contaminated by a much larger background, in particular from the ten times more copious $\rm H \to WW^*$ decay, yielding a $\rm ZWW^*$ final state. These final states, however, are kinematically over-constrained, with the knowledge of the Higgs boson mass (one constraint), of the Z and W masses (two constraints), and four total energy-momentum conservation equations (four constraints), allowing the determination of the jet energies to rely on jet directions rather than on direct energy measurements. The requirements on the detector design and on jet clustering algorithms for jet directions, and the development of 7C kinematic fits, to achieve an effective separation between the $\rm H \to ZZ^*$ and $\rm H \to WW^*$ decays, will be among the important outcomes of this study.

# 16 Inferring the total Higgs boson decay width - Part II

*Patrick*

The Higgs decay width can also be obtained from the ratio of rate products, $\sigma_{\rm H\nu_e\bar{\nu}_e}\,\mathcal{B}(\rm H \to b\bar{b}) \times \sigma^2_{\rm HZ}$ to $\sigma_{\rm ZH}\,\mathcal{B}(\rm H \to b\bar{b}) \times \sigma_{\rm ZH}\,\mathcal{B}(\rm H \to WW^*)$, as can be inferred from Eq. 4. The first of these four rates is determined from counting WW-fusion-to-Higgs events in the $\rm b\bar{b}\nu_e\bar{\nu}_e$ final state. This final state is contaminated by several background processes, of which $\rm e^+e^- \to \gamma^*Z$, $\rm e^+e^- \to ZZ$, and $\rm e^+e^- \to HZ$, with $\rm Z \to \nu\bar{\nu}$. The discrimination between these backgrounds and the signal mostly stems the visible invariant mass (which equals the Higgs boson mass for the signal, but also for the $\rm e^+e^- \to HZ$ background), and the missing mass (which equals the Z mass for the $\rm e^+e^- \to HZ$ background, but not for the signal).

The requirements on the detector design to achieve the visible and missing mass resolutions in a hadronic final state (taking into account the total energy and momentum conservation, as well as the mass constraints) necessary for a maximal separation between the signal and the backgrounds, and therefore an optimal determination of the Higgs boson width, will be studied at $\sqrt{s} \sim 365\,\rm GeV$. The exercise will be repeated at $\sim 240\,\rm GeV$, where the separation is less pronounced, and an optimization with respect to the centre-of-mass energy (towards smaller values) will be attempted.

# 17 Determination of the HZ$\gamma$ effective coupling

*Patrick*

The HZ$\gamma$ coupling can be obtained from the measurement of the $\rm H \to Z\gamma$ branching fraction in the ZZ$\gamma$ final state, on the one hand; and from the combined measurement of the $\rm H \to \gamma\gamma$ branching fraction and the $\rm e^+e^- \to H\gamma$ cross section, on the other. The requirements on the detector design (photon identification, photon energy/angular resolutions, in particular) to achieve a meaningful measurement of the HZ$\gamma$ coupling (e.g., with a precision significantly better than HL-LHC projections) will be studied.

## 18 Electron Yukawa via $s$-channel $\mathrm{e^+e^-} \to$ H production at the Higgs pole

*David*

Measuring the electron Yukawa is impossible in Higgs boson decays, $H \to \mathrm{e^+e^-}$, given the smallness of the electron mass that leads to a negligible decay branching ratio. The only direct method to extract it is through resonant $s$-channel production in $\mathrm{e^+e^-}$ collisions running at (exactly) the Higgs pole mass. Such a measurement requires monochromatization of the beams leading to a centre-of-mass energy spread not much larger than the Higgs boson width $\delta\sqrt{s} \approx \Gamma_\mathrm{H} = 4.2$ MeV, as well as an accurate and precise knowledge of the Higgs boson mass, within MeV uncertainties (Sections 13 and 14). A preliminary study, combining 10 different Higgs decay modes, indicates that a $0.7\sigma$ significance above the (much larger) backgrounds can be reached for every 10 $\mathrm{ab}^{-1}$ integrated at the FCC-ee [20]. An update of the analysis, using the latest developments in machine-learning tools, will be carried out in order to further suppress backgrounds, and determine the precision on the electron Yukawa coupling ultimately reachable.

## 19 Measurement of top properties at threshold and above

*Patrizia*

Measuring the properties of the top quark with high precision is a fundamental ingredient to improve the knowledge of the Standard Model and to put strong constraint on BSM contributions. With a threshold scan FCC-ee can measure with high precision the top mass, the top width and possibly extract an estimate for the Yukawa coupling [21]. Above threshold it is possible to measure with high precision the top electroweak couplings [22]. This diverse set of measurements and their precision stands on an optimized selection of the top quark events. Events containing a pair of top quarks have a large number of different final state objects. The top is always an excellent terrain to investigate the performance of any algorithm developed for less dense environments. The optimization of the top selection in terms of S/B will be obtained with:

- a study of the b-tagging algorithms available, and possibly charm as well (to improve the case of hadronic final states).
- a study of jet algorithms
- a reoptimization/development of fitting procedures for the top definition

The uncertainties from the experimental reconstruction on the differential distributions of various top event variables at threshold can be also used to evaluate the performances. Along with the SM process, a study of tt production in few concrete BSM models is relevant to evaluate the sensitivity reach of the measurements precision [23].

## 20 Search for FCNC in the top sector

*Patrizia*

FCNC transitions of the top quark are forbidden at tree level and highly suppressed in the Standard Model, with BR at the level of $10^{-12} - 10^{-15}$. These transitions could be strongly enhanced in BSM models, increasing BR to $10^{-6} - 10^{-8}$. These processes can be studied at the FCC-ee both in the top decay ($t \to q\gamma/Z$) in top pair production at $\sqrt{s} = 365$ GeV or in the anomalous production of $e^+e^- \to tq$ (q=u,c) at $\sqrt{s} = 240$ GeV. Preliminary analysis [24] have shown a sensitivity that could reach $10^{-5} - 10^{-6}$. These analysis are extremely dependent on the performance of b- and c-tagging, both in terms of signal efficiency and background rejection. The plan would be to study the optimization of the flavor tagging algorithms to reach the ultimate sensitivity.

## 21 Theory Needs for FCC-ee

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The FCC-ee is at the High Energy and Precision Frontier and will provide a set of ground-breaking measurements of a large number of new-physics sensitive observables, with improvement by one to two orders of magnitude in experimental precision. The full exploitation of the significantly increased experimental precision in Z-pole observables, W boson and top quark masses, and a broad array of Higgs observables, necessitates SM predictions accurate at a level commensurate with this precision. In this submission we outline the numerous opportunities for significant theoretical and experimental impact through the furtherance of EWPO calculations in the SM, both for electroweak and QCD sectors, and highlight the need for the development of new methods and tools for higher order perturbative calculations. The FCC-ee is a multi-decade project offering theoretical challenges on a comparable timescale.

## 22 Beyond MFV: constraints on RH charged currents and on dipole operators

*Christophe*

If there exists new physics below 100 TeV, it must have a particular flavour structure to accommodate stringent constraints resulting in the SM from the absence of tree-level flavour changing neutral currents and often also from an effective GIM suppression. These constraints can be relaxed if the SM Yukawa interactions are the only sources of flavour violation. On immediate consequence of this structure is the prediction of tiny right handed charge currents as well as suppressed (electric and magnetic) dipole moments for all the SM fermions, except maybe the top quark. The refined measurements performed at FCC-ee will offer to probe this structure and to offer a hint to the origin of flavour.

The direct experimental constraints on these theoretically suppressed interactions will be instrumental to perform a truly global and agnostic EFT fit considering the related operators often set to zero [25, 26].

## 23 Construction of CP-odd observables to probe CP-violating Higgs couplings

*Christophe*

As a result of the non-interference with the SM contributions, inclusive Higgs measurements have a quadratic dependence of the CP-violating Higgs couplings. Interpreted in an EFT framework, this quadratic dependence gives the derived bounds on the related dimension-6 operators a certain model-dependence as it will be formally of the same order as the contribution from CP-conserving dimension-8 operators. To obtain more robust and model-independent bounds, one needs to rely on differential measurements that pick up a linear dependence. Suitable angular distributions of the Higgs decay products easily reconstructible in the clear FCC-ee detector environment will be exploited to this end.

## 24 Combined fit of Higgs and top data

*Christophe*

The combination of the FCC-ee(240) data with the HL-LHC data will provide an absolute measurement of the ttH coupling already with a 3% precision [17]. As mentioned in Section 19, a threshold scan of top pair production offers an alternative way to access this important coupling. At next-to-leading order, the top Yukawa coupling could also leave an imprint in observables at lower energy but measured with greater accuracy. In an EFT analysis, the SMEFT loops involving the top quark will be considered in Higgs rates and a global fit will be performed along the line of what was proposed in Ref.[27]. Low systematic uncertainties as expected at FCC-ee will be needed to mitigate the one-loop suppression factor of the effects considered.

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