Measurement of Higgs parameters at FCC-ee

Letter of Interest submitted to Snowmass 2021

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Abstract

The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100 km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards 100 TeV proton-proton collisions in the same infrastructure [1]. With its large luminosity at the HZ cross section maximum ($\sqrt{s} \simeq 240\,\mathrm{GeV}$) and at and above the top-pair threshold ($\sqrt{s}$ from 340 to 365 GeV), and its several interaction points, the FCC-ee physics programme includes the measurement of the Higgs parameters with unrivalled accuracy. The high statistics of FCC-ee lead to demanding requirements on detector design or on theoretical calculations, the ultimate goal is that experimental or theory systematic errors match the statistical limit.

Thematic Areas:

■ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
☐ (EF03) EW Physics: Heavy flavor and top quark physics
☐ (EF04) EW Physics: EW Precision Physics and constraining new physics
☐ (EF05) QCD and strong interactions: Precision QCD
☐ (EF06) QCD and strong interactions:Hadronic structure and forward QCD
☐ (EF07) QCD and strong interactions: Heavy Ions
☐ (EF08) BSM: Model specific explorations
☐ (EF09) BSM: More general explorations
☐ (EF10) BSM: Dark Matter at colliders

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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 measurement of **the total $\mathrm{e^+e^-} \to \mathrm{ZH}$ cross section σ_{HZ}** is an essential input to the absolute determination of the HZZ coupling and of the trilinear Higss self-coupling [2]. With one million ZH events expected in three years at $\sqrt{s} = 240$ GeV, and 200,000 Higgs events expected at and above the $\mathrm{t\bar{t}}$ 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 κ_λ with a precision better than 10% in a full EFT fit. Traditionally, only the leptonic decays of the Z boson ($\mathrm{e^+e^-}$ 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 κ_λ (and of the FCC-ee luminosity) at smaller $\sqrt{s}$ values.

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

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}} \quad \text{and} \quad \sigma_{\mathrm{H}\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HWW}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}, \tag{1}$$

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

The $\mathrm{H} \to \mathrm{ZZ}^*$ decay gives rise to a 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 $\mathrm{H} \to \mathrm{WW}^*$ decay, yielding a 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 $\mathrm{H} \to \mathrm{ZZ}^*$ and $\mathrm{H} \to \mathrm{WW}^*$ decays, will be among the important outcomes of this study.

The Higgs decay width can also be obtained from the ratio of rate products, $\sigma_{\mathrm{H}\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}}\,\mathcal{B}(\mathrm{H} \to \mathrm{b\bar{b}}) \times \sigma^2_{\mathrm{HZ}}$ to $\sigma_{\mathrm{ZH}}\,\mathcal{B}(\mathrm{H} \to \mathrm{b\bar{b}}) \times \sigma_{\mathrm{ZH}}\,\mathcal{B}(\mathrm{H} \to \mathrm{WW}^*)$, as can be inferred from Eq. 1. The first of these four rates is determined from counting WW-fusion-to-Higgs events in the $\mathrm{b\bar{b}}\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}$ final state. This final state is contaminated by several background processes, of which $\mathrm{e^+e^-} \to \gamma^*\mathrm{Z}$, $\mathrm{e^+e^-} \to \mathrm{ZZ}$, and $\mathrm{e^+e^-} \to \mathrm{HZ}$, with $\mathrm{Z} \to \nu\bar{\nu}$. 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 $\mathrm{e^+e^-} \to \mathrm{HZ}$ background), and the missing mass (which equals the Z mass for the $\mathrm{e^+e^-} \to \mathrm{HZ}$ 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 $\sqrt{s} \sim 365\,\text{GeV}$. The exercise will be repeated at $\sim 240\,\text{GeV}$, where the separation is less pronounced, and an optimization with respect to the centre-of-mass energy (towards smaller values) will be attempted.

A measurement of **the Higgs boson mass $\boldsymbol{m_{\mathrm{H}}}$** with a precision of $\mathcal{O}(10\,\text{MeV})$ 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 $\sqrt{s} = 125\,\text{GeV}$, for which a precision significantly smaller than the Higgs total width ($\sim 4\,\text{MeV}$) 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 $\sqrt{s} = 240\,\text{GeV}$: $m^2_{\text{recoil}} = s + m^2_{\ell\ell} - 2\sqrt{s}\,(E_{\ell^+} + E_{\ell^-})$. The first step in this quest is therefore the determination of **the centre-of-mass energy $\boldsymbol{\sqrt{s}}$** with a precision of $\mathcal{O}(1\,\text{MeV})$. 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 $\sqrt{s} = 240\,\text{GeV}$ – as proposed in Ref. [3] – 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.

A precision on m_{H} as small as 5 MeV can be achieved [4] 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 $\sqrt{s} = 240\,\text{GeV}$. 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 [5]: $\boldsymbol{\mathrm{e^+e^-} \to \mathrm{ZH} \to \mathrm{q\bar{q}b\bar{b}}}$. 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. [6] 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 all final states, the need for calibration data at the Z pole will be estimated (frequency, number of events).

References

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