Precision measurement of Higgs production cross section in the four-lepton final state at the FCC-ee

Yehia Mahmoud[1,2*], Nicola De Filippis[3,4*], Michele Selvaggi[5*] and Jan Eysermans[6*]

[1]Centre of Theoretical Physics, British University in Egypt, Cairo, Egypt.
[2]Department of Physics, Cairo University, Cairo, Egypt.
[3]INFN Sezione di Bari, Bari, Italy.
[4]Politecnico di Bari, Bari, Italy.
[5]CERN, Geneva, Switzerland.
[6] Particle Physics Collaboration, Massachusetts Institute of Technology, 77 Massachusetts Ave, Boston, Cambridge, 02139, MA, USA .

*Corresponding author(s). E-mail(s): yehia.mahmoud@cern.ch; nicola.de.filippis@cern.ch; michele.selvaggi@cern.ch; jan.eysermans@cern.ch;

1 Introduction

The standard model (SM) of particle physics is one of the most successful theories in particle physics. It describes the most basic fundamental particles in the universe and their interactions. The standard model explains the origin of the masses of the fundamental particles through their interaction with a scalar field called the Higgs field and its excitation gives rise to a particle called the Higgs boson. The Higgs boson was discovered in 2012 by the CMS and ATLAS experiments [1–3]. Measurement of the properties of the Higgs boson has been going on since then at the LHC. Measuring the Higgs boson properties with high precision provides a tool to constrain contributions from beyond standard model (BSM) or anomalous Higgs interactions to Higgs couplings. The precision of the LHC is not enough to make these measurements due to its large QCD background which limits its energy resolution. However, future lepton colliders like the Future Circular Collider (FCC-ee) [4] can improve these kind of measurements over the its LHC counterpart.

The Higgs boson production at the FCC-ee can be in two mechanisms, the Higgstrahlung $e^+e^- \rightarrow ZH$ and the Vector Boson Fusion production ($e^+e^- \rightarrow W^+W^-H$). It is expected for the FCC-ee to have around 2×10^6 ZH events at $\sqrt{s} = 240$ GeV and 2×10^6 WWH events at $\sqrt{s} = 365$ GeV for a total integrated luminosity of 10.8 ab^{-1}. The FCC-ee as a lepton collider provides a way to measure the inclusive ZH cross-section σ_{ZH} in a model independent way without knowledge of any specific decay of the Higgs which is not possible at the LHC. Knowledge of σ_{ZH} can be used in calculating the Higgs width and couplings to SM particles. This article is focused on analysis of ZH events at $\sqrt{s}$=240 GeV at the FCC-ee for the $H \rightarrow ZZ* \rightarrow 4l$ and $Z \rightarrow jj/\nu\nu$ to measure the total decay width of the Higgs boson. The next section in this article will discuss the mechanism of extracting the knowledge of the Higgs width and couplings from lepton colliders. The third section will discuss the data sets, the fourth section will discuss the analysis strategy and the last section will discuss the results.

2 Higgs cross section measurement at the FCC

Measurement of the Higgs boson width at the LHC was performed by the CMS and ATLAS experiments [5, 6] in the $H \rightarrow ZZ \rightarrow 4l$ channel reporting an uncertainty of 50% on the Higgs total decay width. The method used the LHC is to calculate the Higgs width is to measure its off-shell production cross-section and relating it to its on-shell production.
However at a e^-e^- collision environment, it is possible to measure the inclusive ZH cross-section in a model independent way without looking at Higgs decays. This method is unique to lepton colliders and exploits our knowledge of the initial state of the collision since electrons are elementary particles and don't have any internal structure. Only the decay products of the Z boson and the center of mass energy is needed and the Higgs is reconstructed as a recoil particle against the Z with mass of Higgs calculated from:

$$m_H^2 = m_{ll}^2 + s - 2\sqrt{s}E_{ll} \tag{1}$$

Measurement of σ_{ZH} directly gives us information on the coupling of Higgs to ZZ $\sigma_{ZH} \propto g_{HZZ}^2$. By measuring the exclusive cross section of the ZH production and the decay of Higgs to ZZ*, it is possibe to obtain information on the total decay width of the Higgs

$$\sigma_{ZH,HZZ^*} \propto \frac{g_{HZZ}^2 \times g_{HZZ}^2}{\Gamma_H} \tag{2}$$

Figure 1 shows the feynman diagram of the ZH(HZZ) process. Other Higgs couplings can also be calculated from measurement of Higgs decays to other states

$$\sigma_{ZH,HXX} \propto \frac{g_{HZZ}^2 \times g_{HXX}^2}{\Gamma_H} \tag{3}$$

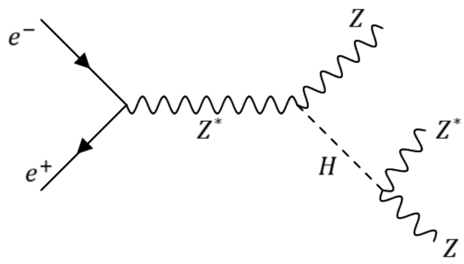


Fig. 1: Feynman diagram of ZH production and Higgs to ZZ decay

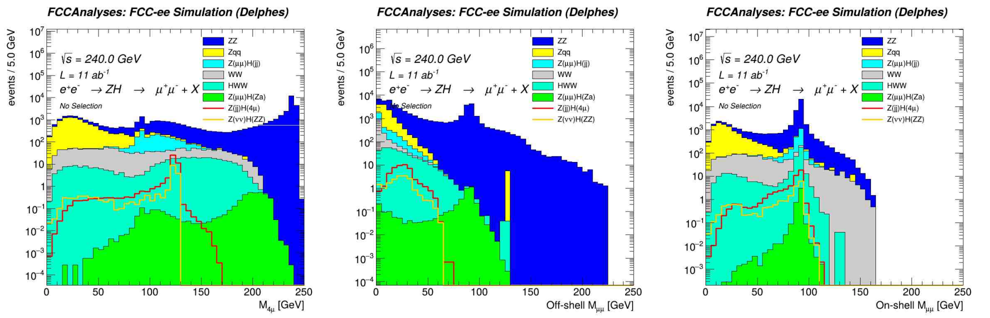
3 Data samples

The data sets used in this study are obtained from centrally produced MC generated electron-positron collisions at FCC-ee (Winter 2023 samples). The generators used are Pythia8 [7] and WHIZARD [8]. Fast simulation of the IDEA detector concept [9] at FCC is done with DELPHES [10]. Information on the data sets, the generators used and their cross-section can be found here. The expected background processes that include similar final state to that of the signal are: Diboson pair production ZZ/WW with ZZ being the main irreducible background, Higgs to WW (HWW), Higgs to jets (Hjj), Higgs to charged leptons (Hll), Higgs to Za (HZa).

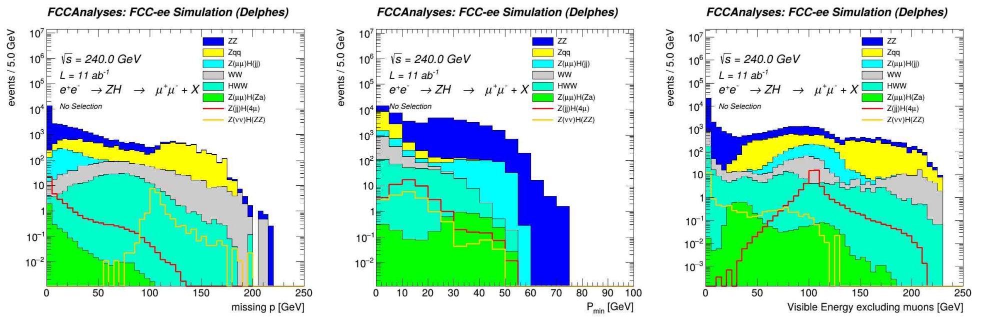
4 Analysis strategy

We studied the case of ZH production at $\sqrt{s} = 240$ GeV with the hadronic/invisible decay of Z and the decay of Higgs into 4 four leptons from ZZ* pairs with one the Z bosons being Off-shell due to the kinematical constraints of the Higgs mass. This is because the Higgs mass is smaller than twice the Z boson mass so it can't decay to two on-shell Z bosons. First the On-Shell Z is reconstructed by forming all the possible oppositely charged lepton pairs and choosing the pair whose invariant mass is closest to the nomional Z mass. The Off-shell Z is reconstructed by choosing the two highest momentum oppositely charged lepton pair from the remaining pairs. The Higgs mass is then obtained from the invariant mass of the four leptons. Figures 2,3,4 shows the distribution of the invariant mass of the Four lepton, on-Shell dilepton and off-Shell dilepton for the signal and background events normalized to their cross-sections and luminosity of 10.8 ab^{-1} for the case of a four muon, four electron and mixed final states respectively.

A set of selection cuts where applied to reject SM background events and discriminate the signal from the background. The first is a cut on the momentum of the minimum momentum lepton to remove soft leptons from hadronic background which was taken to be larger than 5 GeV. Then we have a cut on the missing momentum to eliminate processes with invisible final states WW/HWW. It was taken to be less than 40 GeV for the Z(jj)H(4l) signal and more than 100 GeV for the Z(vv)H(4l) signal. We also applied a cut on the visible energy $E_{visible}$ of all the remaining reconstructed particles after removing the chosen four leptons . The signal events of Z(jj)H(4l) contain hadronic jets from the decay of the Z boson besides the four leptons, while the ZZ background only contains the four leptons, which makes it a good discriminator of the Z(jj)H(4l) signal against the ZZ background. It was taken to be larger than 30 GeV. We also selected events whose off-shell dilepton invariant mass lies between 10 GeV < $M_{\mu\mu}$ <65 GeV. This cut is also efficient in eliminating the ZZ background which doesn't have an off-shell Z. Lastly, we apply a mass window on the four lepton invariant mass around the Higgs mass 124 GeV< M_{4l} < 125.5 GeV.This is the most powerful cut and it rejects all the remaining SM background. The number of events remaining after each cut for the hadronic and invisible channels are given in table 1 and table 2 respectively.

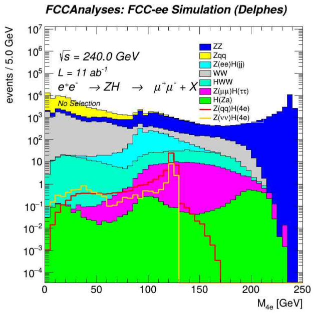


(a) Four muon invariant mass (b) Off-Shell dimuon invariant mass (c) On-Shell dimuon invariant mass

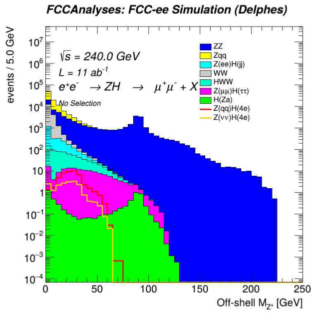


(d) Missing momentum (e) Momentum of lowest momentum muon (f) Visible energy excluding 4 muons

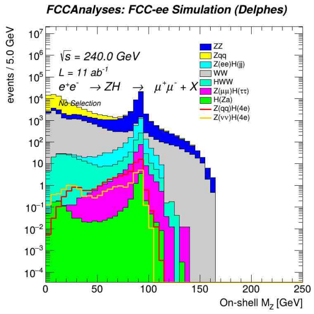
Fig. 2: Distributions of the signal and background events for the 4μ final state. The background processes are stacked while the signal processes are overlayed.



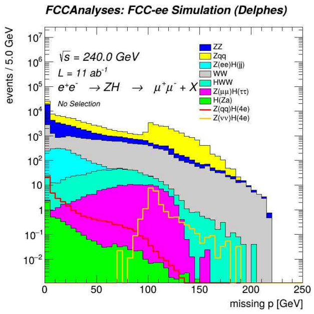
(a) Four electron invariant mass



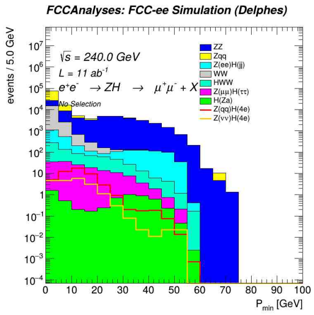
(b) Off-Shell dielectron invariant mass



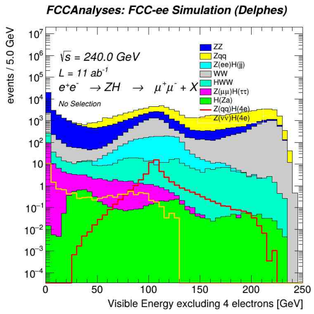
(c) On-Shell dielectron invariant mass



(d) Missing momentum

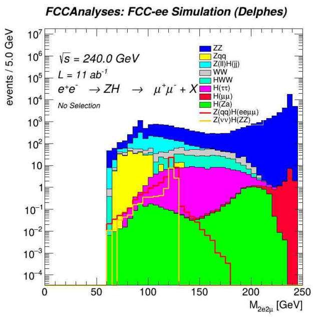


(e) Momentum of lowest momentum electron

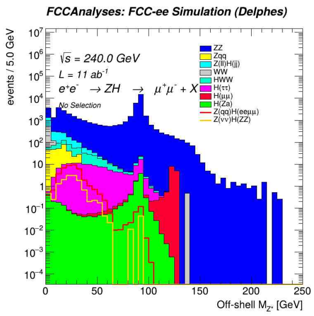


(f) Visible energy excluding 4 electron

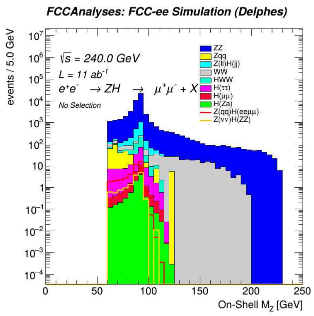
Fig. 3: Distributions of the signal and background events for the 4e final state. The background processes are stacked while the signal processes are overlayed.



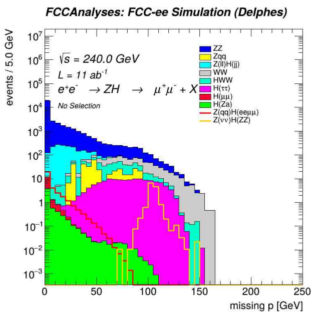
(a) Four lepton invariant mass



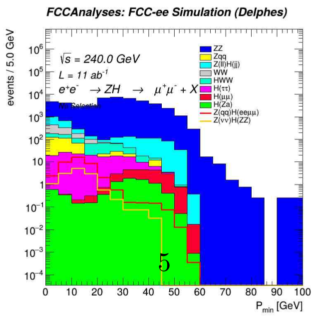
(b) Off-Shell dilepton invariant mass



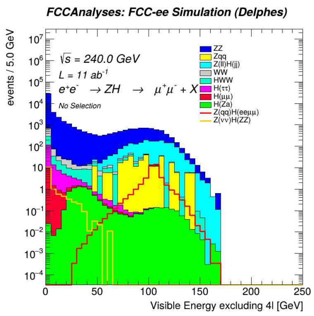
(c) On-Shell dilepton invariant mass



(d) Missing momentum



(e) Momentum of lowest momentum lepton



(f) Visible energy excluding 4 leptons

Fig. 4: Distributions of the signal and background events for the 2e2μ final state. The background processes are stacked while the signal processes are overlayed.

5 Results

As shown in tables 1, 2 the cuts were successful in rejecting the background while keeping a considerable number of signal events. Table 3 shows the value of $s/\sqrt{s+b}$ reached for each channel.

To obtain a statistical interpretation of the result, a statistical test is performed with the parameter of interest being the signal strength μ. The best-fit value of the signal strength $\hat{\mu}$ is obtained with the uncertainty on its value at 68% Confidence Level. Also, systematic uncertainties on the ZZ and Hjj processes were taken into account with 10% uncertainty on each. An uncertainty of 12% was reached for the Z(jj)H(4l) channel, while for the Z(vv)H(4l), an uncertainty of 22% was reached. Combining both channels, a precision of 10% is reached.

cut	Bckg (4μ)	Z(jj)H(4μ)	Bckg (4e)	Z(jj)H(4e)	Bckg ($2e2\mu$)	Z(jj)H($2e2\mu$)
No selection	50514	47	121755	49	48513	80
$p_{min} > 5GeV$	36048	44	46564	44	43851	74
$p_{miss} < 20GeV$	26890	39	30891	39	37651	70
$E_{vis} > 95GeV$	2327	37	6353	37	1470	66
$10 < M_{Z*} < 65$	1184	37	2742	37	537	66
$124 < M_{4l} < 125.5$	3	26	8	19	5	40

Table 1: Event yield of the signal and background for the hadronic channel normalized to their cross section at a total integrated luminosity of 10.8 ab^{-1}

cut	Bckg (4μ)	Z(vv)H(4μ)	Bckg (4e)	Z(vv)H(4e)	Bckg ($2e2\mu$)	Z(vv)H($2e2\mu$)
No selection	50514	18	121755	19	48513	26
$p_{min} > 5GeV$	36048	15	46564	15	43851	24
$p_{miss} > 100GeV$	1146	14	2944	13	175	22
$10 < M_{Z*} < 65$	683	13	969	13	97	22
$124 < M_{4l} < 125.5$	4	9	2	6	3	14

Table 2: Event yield of the signal and background for the invisible channel normalized to their cross section at a total integrated luminosity of 10.8 ab^{-1}

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signal	s/$\sqrt{s+b}$	precision on μ at 68%
Z(jj)H(4μ)	4.828	1$\pm$ 0.2075
Z(jj)H(4e)	3.656	1$\pm$0.2755
Z(jj)H(2e2μ)	5.9628	1$\pm$0.2505
Z(jj) combined	8.45	1$\pm$0.122
Z(vv)H(4μ)	2.49	1$\pm$0.403
Z(vv)H(4e)	2.12	1$\pm$0.4735
Z(vv)H(2e2μ)	3.39	1$\pm$0.4535
Z(vv) combined	4.71	1$\pm$0.222
Total	9.674	1$\pm$0.107

Table 3: Significance and uncertainty on Higgs measurement in the Higgs to 4 lepton decay channel at FCCee $\sqrt{s} = 240$ GeV and 10.8 ab^{-1} total integrated luminosity.

References

[1] G. Aad, et al., Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. Phys. Lett. B **716**, 1–29 (2012). https://doi.org/10.1016/j.physletb.2012.08.020. arXiv:1207.7214 [hep-ex]

[2] S. Chatrchyan, et al., Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC. Phys. Lett. B **716**, 30–61 (2012). https://doi.org/10.1016/j.physletb.2012.08.021. arXiv:1207.7235 [hep-ex]

[3] S. Chatrchyan, et al., Observation of a New Boson with Mass Near 125 GeV in *pp* Collisions at $\sqrt{s} = 7$ and 8 TeV. JHEP **06**, 081 (2013). https://doi.org/10.1007/JHEP06(2013)081. arXiv:1303.4571 [hep-ex]

[4] A. Abada, et al., FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2. Eur. Phys. J. ST **228**(2), 261–623 (2019). https://doi.org/10.1140/epjst/e2019-900045-4

[5] G. Aad, et al., Evidence of off-shell higgs boson production from zz leptonic decay channels and constraints on its total width with the atlas detector. Physics Letters B **846**, 138223 (2023). https://doi.org/10.1016/j.physletb.2023.138223. URL http://dx.doi.org/10.1016/j.physletb.2023.138223

[6] C. Collaboration. Measurement of the higgs boson mass and width using the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ tev (2024). URL https://arxiv.org/abs/2409.13663

[7] C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, P. Ilten, L. Lönnblad, S. Mrenna, S. Prestel, C.T. Preuss, T. Sjöstrand, P. Skands, M. Utheim, R. Verheyen. A comprehensive guide to the physics and usage of pythia 8.3 (2022). URL https://arxiv.org/abs/2203.11601

[8] W. Kilian, T. Ohl, J. Reuter, Whizard—simulating multi-particle processes at lhc and ilc. The European Physical Journal C **71**(9) (2011). https://doi.org/10.1140/epjc/s10052-011-1742-y. URL http://dx.doi.org/10.1140/epjc/s10052-011-1742-y

[9] T.I.S. Group. The idea detector concept for fcc-ee (2025). URL https://arxiv.org/abs/2502.21223

[10] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, M. Selvaggi, Delphes 3: a modular framework for fast simulation of a generic collider experiment. Journal of High Energy Physics **2014**(2) (2014). https://doi.org/10.1007/jhep02(2014)057. URL http://dx.doi.org/10.1007/JHEP02(2014)057