

$ZH \rightarrow 6$ leptons analysis at FCC-ee

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Abstract

One of the main physics goals at FCC-ee is the Higgs precision program. Here, we analyze the 6 lepton ($\ell = e, \mu$) final state of $\sigma(ZH) \cdot BR(H \rightarrow ZZ)$ at $\sqrt{s} = 240$ GeV that contributes to the total measurement of $\sigma(ZH) \cdot BR(H \rightarrow ZZ)$ with 29.7 % precision.

1 Introduction

Since the discovery of the Higgs boson at the LHC at CERN in 2012, the particle has stood in the current research spotlight. It gives all other particles in the Standard Model of particle physics their masses while the Higgs potential determines the stability of our universe. Therefore, we want to study the Higgs boson's properties thoroughly. The Future Circular Collider (FCC) is a proposed machine to study the Higgs boson with electron-positron collisions (FCC-ee) and later on with proton-proton collisions (FCC-hh). Colliding elementary particles as electrons and positrons represents a unique opportunity to study the Higgs boson as, compared to hadron machines, the initial four-momentum of the collision is known. For example, we can measure the total width of the Higgs boson Γ_H at such machine.

2 Motivation of the measurement

2.1 Determination of the Higgs width

To measure the total width of the Higgs boson at FCC-ee, we need two measurements [1].

1. **Recoil mass method to determine $\sigma(ZH)$** [2, 3]: The cross-section σ of the Higgsstrahlung process $e^+e^- \rightarrow ZH$ is proportional to the square of the coupling of the Higgs boson to the Z boson $\sigma(ZH) \propto g_Z^2$. This measurement is only accessible at electron-positron collisions because the initial four-momentum of the collision must be known to use the recoil mass method. Due to more than 2 million Higgsstrahlung events at FCC-ee at 240 GeV, $\sigma(ZH)$ can be determined with high precision.
2. **Measurement of $H \rightarrow ZZ^*$ decay:** The cross-section times the branching ratio of the Higgs to Z decay $\sigma(ZH) \cdot BR(H \rightarrow ZZ^*)$ is proportional to $\propto \frac{g_Z^4}{\Gamma_H}$. As the branching ratio of $H \rightarrow ZZ^*$ is $\approx 2\%$, we only expect 50 k events of which we might capture 10 k events. This gives a relative error of $\frac{\sqrt{N_S+N_B}}{N_S} \approx \frac{1}{\sqrt{N_S}} = 1\%$ on this measurement. The precision of this measurement will, therefore, dominate the precision of the total Higgs width.

By combining these two measurements, we can determine Γ_H . For high precision, we need to optimize the precision on $\sigma(ZH) \cdot BR(H \rightarrow ZZ^*)$ and therefore need to study all possible final states of this process.

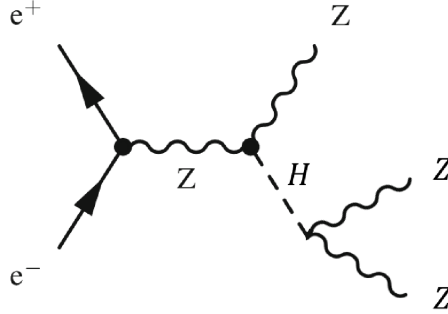


Fig. 1: Feynman diagram of $HZ; H \rightarrow ZZ$

Figure 1 shows the Feynman diagram of the Higgsstrahlung process and the Higgs decay to two Z bosons. The Z boson can decay hadronically and leptonically. Here, we discuss the fully leptonic final state where the Z bosons decay into leptons, so the final event signature has six leptons. We restrict the analysis to electrons and muons ($\ell = e, \mu$).

2.2 Expected sensitivity of the 6ℓ channel

This analysis is statistically limited by the amount of signal data. Considering the branching ratio of Higgs to four leptons $BR(H \rightarrow 4\ell) = 1.251 \cdot 10^{-4}$ for $\ell = e, \mu$ [4] and the branching ratio of the Z to leptons $BR(Z \rightarrow \ell\bar{\ell}) = N_\ell \cdot 0.036$ with $N_\ell = 2$, the more than 2 million Higgsstrahlungs events reduce to $N(6\ell) = 2.16\text{mio} \cdot BR(H \rightarrow 4\ell) \cdot BR(Z \rightarrow \ell\bar{\ell}) \approx 19$ events. Even without any background, the highest precision achievable in this channel is $\frac{1}{\sqrt{N_S}} = 23\%$.

3 Simulated data generation

To simulate data at FCC-ee, we use the IDEA detector [5] and the fast simulation framework DELPHES [6–8]. The reconstruction algorithm is based on a particle-flow algorithm. The generated data is part of the winter 2023 production campaign [9].

3.1 Signal generation

The signal events are generated with WHIZARD [10] and available on the central production [9]. We generate 100 k events with $\ell = e, \mu, \tau$ named `wzp6_ee_1lH_HZZ_1l1l1_ecm240` with following cuts [11]:

1. the invariant mass of the lepton pairs must be greater than 5 GeV
2. the polar angle of the produced leptons must be greater than 50 mrad

3.2 Background generation

Background events are either events with a 6 lepton final state (6ℓ) that do not involve the Higgs boson or events with high energetic jets where a lepton in a jet is wrongly identified to be isolated ($4\ell 2j$). We apply the same cuts as on the signal events.

3.2.1 Generation with whizard

There is already some background data available in the central production, namely `wzp6_ee_1lH_HZZ_qql1_ecm240` and `wzp6_ee_qqH_HZZ_1l1l1_ecm240` that is generated using WHIZARD [10]. We still need to produce a four lepton and two jets final state without using the Higgs and the six lepton final state without using the Higgs. Generating process `proc = e1, E1 => 1 L 1 L 1 L` (with $l = e^-, \mu^-$ and $L = e^+, \mu^+$) directly is not possible as the estimated time to generate 10 k events is prohibitively large (more than 100 days) due to the six particle final state. Therefore, we try process `proc = e1, E1 => 1, L, Z, Z { $restrictions = "!H" }` and decay the Z bosons with PYTHIA6 [12]. With this set-up, the natural width of the Z boson is not simulated and the data does not represent physics events. Hence, we use MADGRAPH [13, 14] for the background data generation.

3.2.2 Generation with MadGraph

We use MadGraph5_aMC v3.5.7 [13, 14] for the event generation of the missing background processes. Madgraph can directly decay the Z boson into leptons without PYTHIA and therefore accounts for the natural width of the Z boson. In order to reduce simulation time, we choose to explicitly generate one or two on-shell Z bosons in the process. The MADGRAPH configurations are shown in the Appendix 1, 2, 3. We generate a 6 lepton final state via one or two on-shell Z bosons and a two quarks (u, d, s, c, b , their anti-particles or g) four leptons final state. These Les-Houches-Event (LHE) files are then processed with PYTHIA8 [15] and propagated with DELPHES through the IDEA detector. To reproduce these steps, see Appendix 4, 5.

Via this solution we neglect the six lepton (and two quark, four leptons) final states that are produced without any on-shell Z bosons and Higgs bosons. We estimate this background to be very small and negligible.

4 Analysis of the 6-lepton final state

The analysis strategy follows a "cut-and-count" approach. We find six isolated lepton pairs by selecting events with

1. Six or more electrons or muons,
2. Exactly six isolated leptons (electrons or muons),
3. Lepton pairs by requiring opposite charge and same flavor.

The four possible combinations after this selection are: $3e^+e^-$, $3\mu^+\mu^-$, $1e^+e^-2\mu^+\mu^-$, $2e^+e^-1\mu^+\mu^-$. The signal also has other unique signatures. Two lepton pairs must have an invariant mass compatible with the Higgs boson and the other lepton pair must have a recoil mass compatible with the Higgs boson. As we have six leptons in total and need to consider charge and flavor, we have two (in the case of two same flavor pairs) possible combinations e.g. for $4e, 2\mu$ they are $(e_1^-e_1^+)(e_2^-e_2^+)(\mu^-\mu^+)$, $(e_1^-e_2^+)(e_2^-e_1^+)(\mu^-\mu^+)$ or six (in the case of three same flavor pairs) possible combinations e.g. for $6e$ they are $(e_1^-e_1^+)(e_2^-e_2^+)(e_3^-e_3^+)$, $(e_1^-e_3^+)(e_2^-e_1^+)(e_3^-e_2^+)$, $(e_1^-e_2^+)(e_2^-e_3^+)(e_3^-e_1^+)$, $(e_1^-e_2^+)(e_2^-e_1^+)(e_3^-e_3^+)$, $(e_1^-e_1^+)(e_2^-e_3^+)(e_3^-e_2^+)$, $(e_1^-e_3^+)(e_2^-e_2^+)(e_3^-e_1^+)$ to form Z boson candidates. To find the best combination we apply a χ^2 minimization as

$$\chi^2 = \left(\frac{m_{\ell\ell,1} - m_Z}{\sigma_Z}\right)^2 + \left(\frac{m_{\ell\ell,2} - m_Z}{\sigma_Z}\right)^2 + \left(\frac{m_{\ell\ell,3} - m_{Z,\text{offshell}}}{\sigma_{Z,\text{offshell}}}\right)^2 \quad (1)$$

with $\sigma_Z = 2$ GeV as the natural resolution of the Z and $\sigma_{Z,\text{offshell}} = 10$ GeV. We calculate χ^2 of the three permutations for one six lepton combination and select the smallest. Then, we select the pairing with the smallest χ^2 which identifies two on-shell Z bosons candidates and one off-shell Z boson candidate. We do not use the Higgs mass constraint in this first step to avoid background sculpting. Next, we select the best on-shell off-shell Z boson pair combination to reconstruct the Higgs boson and are left with one on-shell Z boson that comes from production.

We can then apply further selections on:

1. the Higgs mass via the invariant mass of the four selected leptons m_H
2. the recoil mass of the Z boson from production m_{recoil}

Selection Cut	ZH-6l	llH-qql	qqH-4l	llZ(Z)-4l	qqZ(Z)-4l	prec (%)
All events	55 (100.0)%	412 (100.0)%	407 (100.0)%	9 (100.0)%	2 (100.0)%	53.4%
$N(e) + N(\mu) \geq 6$	16 (30.2)%	4 (1.1)%	6 (1.6)%	3 (34.3)%	0 (1.0)%	33.0%
$N(e_{\text{iso}}) + N(\mu_{\text{iso}}) = 6$	15 (27.6)%	2 (0.5)%	2 (0.7)%	2 (32.2)%	0 (0.4)%	31.3%
l pairs	14 (25.7)%	0 (0.2)%	1 (0.2)%	2 (29.9)%	0 (0.2)%	30.4%
$115 < m_H < 127$	12 (22.1)%	0 (0.0)%	0 (0.0)%	0 (9.6)%	0 (0.0)%	29.7%
$122 < m_{\text{recoil}} < 160$	11 (21.2)%	0 (0.0)%	0 (0.0)%	0 (7.1)%	0 (0.0)%	29.9%

Fig. 2: Cut-flow table of $ZH \rightarrow 6$ lepton analysis at $\sqrt{s} = 240$ GeV with $\ell = e, \mu$. The highest precision is 29.7 %.

The cut-flow table of the analysis is shown in Figure 2. The signal is labeled as **ZH-6l** and counts 55 initial events. The number of signal events comes from the WHIZARD cross-section calculation $\sigma = 5.17$ ab with the selected cuts and $\ell = e, \mu, \tau$. When applying the first selection criteria of at least six electrons or muons, the τ events get rejected, and the number of signal events reduces to 16 events. Also, all backgrounds are greatly reduced. The next cut requires six isolated leptons. We lose one signal event (which indicates that the isolation criteria could be optimized) but are also left with no more than two events for every background. After requiring lepton pairs considering charge and flavor, only three background events are left. The next selection, a loose cut on the invariant mass of the Higgs formed by four leptons, reduces the background to zero. This is the optimal step to stop as the following selection, which considers the recoil mass of the other two leptons, reduces the precision. The recoil mass of the selected lepton pair m_{recoil} is shown in Figure 3.

We identify that finding three isolated lepton pairs and a loose cut on the Higgs mass gives the highest precision in this analysis, which is 29.7 %.

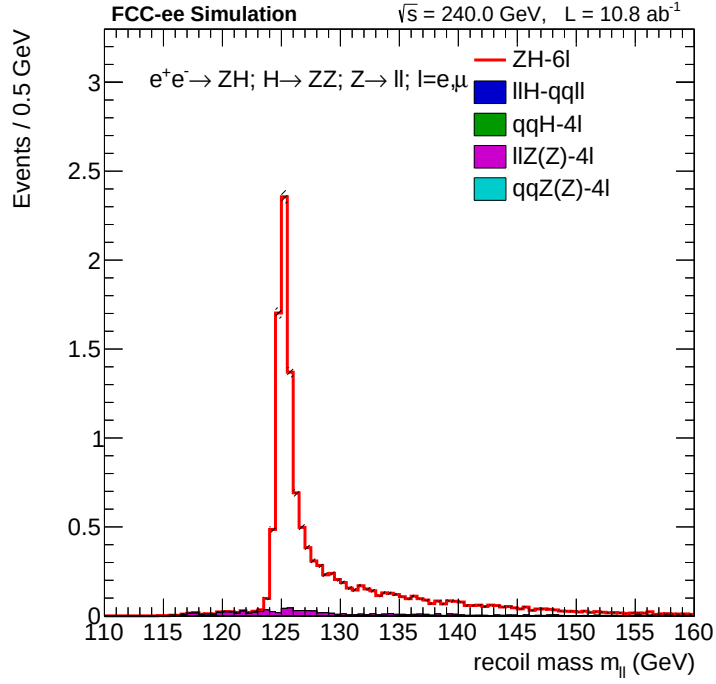


Fig. 3: Histogram of the recoil mass m_{ll} for the signal (red line) and backgrounds after optimal selections

5 Conclusion and Outlook

The 6 lepton final state of the $ZH; H \rightarrow ZZ$ process has only few signal events, in the case of $l = e, \mu$ the predicted number of events at $\sqrt{s} = 240$ GeV is only 19. Hence, the theoretical highest precision of this channel is 23 %. Still, it contributes to the overall precision of the cross section. In this analysis, we determine a precision of 29.7 %.

The analysis can be easily extended to $\sqrt{s} = 365$ GeV. If the $Z \rightarrow \tau^+\tau^-$ channel was included in the analysis, we would expect 64 signal events. An other analysis could explore the precision achievable in this channel.

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Appendix

Listing 1: MADGRAPH [13, 14] configuration to generate a six lepton final state via one or two on-shell Z bosons. The generation accounts for symmetries to obtain a correct cross section calculation.

```
import model sm-lepton-masses

define l = e+ e- mu+ mu- ta- ta+

generate e+ e- > l l z z $z /h, z > l l
add process e+ e- > z l l z $z /h, z > l l @1
add process e+ e- > z z l l $z /h, z > l l @2

add process e+ e- > z l l l l $z /h, z > l l @3
add process e+ e- > l l z l l $z /h, z > l l @4
add process e+ e- > l l l l z $z /h, z > l l @5

output /path/to/output/

launch /path/to/output/ -n run_name

set pdlabel fcce2401l
set lpp1 -3
set lpp2 +3
set ebeam1 120
set ebeam2 120

set nevents 10000
set mml 5
```

```

set maxjetflavor 5
set etal 3.68867

set cut_decays True

done

```

Listing 2: MADGRAPH [13, 14] configuration to generate a two jets, four lepton final state via one Z boson. The final cross section must be multiplied by two to account for symmetries.

```

import model sm-lepton_masses

define l = e+ e- mu+ mu- ta- ta+
define j = g u c d s b u~ c~ d~ s~ b~

generate e+ e- > j j l l z $z /h, z > l l

output /path/to/output/

launch /path/to/output/ -n run_name
set pdlabel fcce24011
set lpp1 -3
set lpp2 +3
set ebeam1 120
set ebeam2 120

set nevents 1000000
set mml 5
set maxjetflavor 5
set etal 3.68867

set cut_decays True

done

```

Listing 3: MADGRAPH [13, 14] configuration to generate a two jets, four lepton final state via two Z bosons. The final cross section must be multiplied by two to account for symmetries.

```

import model sm-lepton_masses

define l = e+ e- mu+ mu- ta- ta+
define j = g u c d s b u~ c~ d~ s~ b~

generate e+ e- > j j z z $z /h, z > l l

```

```

output /path/to/output/

launch /path/to/output/ -n run_name
set pdlabel fcce24011
set lpp1 -3
set lpp2 +3
set ebeam1 120
set ebeam2 120

set nevents 1000000
set mml 5
set maxjetflavor 5
set etal 3.68867

set cut_decays True

done

```

Listing 4: PYTHIA8 [15] configuration to process LHE files generated by MADGRAPH. Official values for vertex smearing can be found [here](#).

```

! 1) Settings used in the main program.

Main:numberOfEvents = 100000          ! number of events to generate
Main:timesAllowErrors = 150          ! how many aborts before run stops

! 2) Settings related to output in init(), next() and stat().

Init:showChangedSettings = on        ! list changed settings
Init:showChangedParticleData = off   ! list changed particle data
Next:numberCount = 100               ! print message every n events
Next:numberShowInfo = 1              ! print event information n times
Next:numberShowProcess = 1           ! print process record n times
Next:numberShowEvent = 1             ! print event record n times

! Vertex smearing
Beams:allowVertexSpread = on
Beams:sigmaVertexX = 9.80e-3         ! 9.80 mm
Beams:sigmaVertexY = 25.4E-6         ! 25.4 nm
Beams:sigmaVertexZ = 0.64            ! 0.64 mm

! 3) Set the input LHE file

Beams:frameType = 4 ! Reads info of beam parameters from LHE file
Beams:LHEF = /path/to/run_name/unweighted_events.lhe

```

Listing 5: Command to process LHE files from MADGRAPH via PYTHIA8 and DELPHES [6–8]

```
source /cvmfs/sw.hsf.org/spackages6/key4hep-stack/2022-12-23/  
x86_64-centos7-gcc11.2.0-opt/ll3gi/setup.sh
```

```
DelphesPythia8_EDM4HEP \  
  card_IDEA.tcl \  
  edm4hep_IDEA.tcl \  
  p8_config_card.cmd \  
  /path/to/output/p8_ee_llZZ_Zll_ecm240.root
```