Double Higgs production at FCC-he and prospects for measurements of self-coupling

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Abstract. The measurement of the triple Higgs boson coupling is one of the most important goals of the Higgs physics program in present and future collider experiments. This would provide the first direct information on the Higgs potential, which is responsible for electroweak symmetry breaking mechanism. We present a double Higgs production scenario at the Large Hadron-Electron Collider (LHeC) and Future Circular Hadron-Electron Collider (FCC-he) through $e^-p$ collisions, which will provide information about trilinear coupling and the possibility of probing new physics, if there is any. The LHeC will provide $e^-$ beams to collide head-on with proton beams of 7 TeV from the Large Hadron Collider (LHC). The prospect of replacing the LHC with the high energy FCC, with proton beams of 50 TeV, is used for FCC-he studies. Energy of the $e^-$ is taken to be 60 GeV for both LHeC and FCC-he. Effects of non-standard CP-even and CP-odd couplings for $hhh$, $hWW$ and $hhWW$ have been studied and constrained at a 95% C.L.

1. Introduction

The long awaited scalar particle in the Standard Model (SM) of particle physics, known as the Higgs boson, is here to stay as is evident from the results of Run I of the ATLAS and CMS collaborations of the Large Hadron Collider (LHC). It is certain that the new particle is a Higgs boson. But still there are some doubts whether it is the Higgs boson of the SM. To confirm, that one needs to understand and probe its properties and interactions with other existing fermions and bosons. Especially for the Higgs self coupling ($\lambda$), which rests on a very high pedestal as far as its importance in understanding the scalar sector goes. It will help us understand the electroweak symmetry breaking (EWSB) mechanism. And if we consider it as the SM Higgs boson then one could only see this interaction through multi-Higgs productions. A major constraint in the extraction of such signals with respect to the backgrounds is that it is highly dependent on the type of collider. Each collider, be it the FCC-hh (Future Circular Hadron-Hadron Collider), LHC, ILC (International Linear Collider) or something else, has its own challenges in detection of double Higgs signals. Therefore, one should look for all the possibilities, even those beyond these colliders. Here we consider double Higgs production in...
high energy $e^-p$ collisions for the first time. Numerous studies show that, at hadron colliders like the LHC, it would be a very difficult task to extract the precise information about $\lambda$. And we hope that the high energy $e^-p$ collider, on top of the LHC, will be used to probe these properties, including others like the CP behaviour of effective $hWW$ and $hhWW$ couplings.

2. LHeC and FCC-he

One of the proposed colliders, in the new energy frontier at the LHC, is to inject an electron beam which will collide head-on with the available proton beam. This $e^-p$ collision option with center of mass energy $\sqrt{s} \approx 1.3$ TeV (where $e^-$ energy $E_e = 60$ GeV, and the proton beam energy $E_p = 7$ TeV) is known as the **Large Hadron Electron Collider** (LHeC). Its many physics goals, like QCD precision, electroweak physics, probing high parton densities and physics beyond the SM (BSM), can be found in Ref. [1], along with the technical details of collider configuration. The Ring-Ring (RR) option assumes $E_e = 50 - 100$ GeV, whereas the Linac-Ring (LR) option can be realised with $E_e = 60 - 140$ GeV for the LHeC. The design for the new collider is still going through intense scrutinization, the details of which can be found in Ref. [2].

However, further upgrades to the high-energy LHC (HE-LHC) would provide proton beam energies up to 50 TeV. This is another available option, popularly known as the **Future Circular Hadron-Electron Collider** (FCC-he). This upgrade, with $E_p = 50$ TeV, assumes a maximum of $E_e = 250$ GeV in the RR option and the working energy in the LR option for electrons assumes potential reuse of the LHeC with $E_e = 60$ GeV. In this proceeding we present the double Higgs production at the FCC-he with $\sqrt{s} \approx 3.5$ TeV and the prospects of measurements of the involved couplings with preferred LR configuration.

3. The Higgs boson at the LHeC

As is evident from the introduction, the Higgs boson searches are of utmost importance for quite a few past and present colliders, and its properties are needed to be measured accurately to get more precisely insight into the laws of nature. In this respect the future colliders will play a very important role in sectors where the LHC would have limited access even after its upgrades. In one such study, the authors of Ref. [3] investigated the bottom Yukawa coupling at the LHeC. They used the forward jet tagging to improve the Higgs boson signal significantly in the $h \rightarrow b \bar{b}$ decay mode from deep inelastic electron-proton scattering at the LHC. In the process we see that the requirement of forward jet tagging in the charged current events strongly enhances the signal-to-background ratio in their study. It is also to be noted that the charged current process at the LHeC proceeds through $W$-vector boson fusion. Here, in the absence of the contamination from the $hZZ$ coupling, one could directly measure $hWW$ coupling strength as well. CP properties of the Higgs boson can be determined considering an effective five-dimensional vertex given by [4]

\[
\Gamma_{\mu\nu}(p,q) = \frac{g}{m_W} \left[ \lambda_C(p \cdot q g_{\mu\nu} - p_\mu q_\nu) + i\lambda'_V \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma \right], \tag{1}
\]

where $\lambda_C$ and $\lambda'_V$ are the effective coupling strengths for the anomalous CP-conserving and the CP-violating operators respectively. They have shown that the azimuthal angle between missing energy and non-$b$ jet, $\Delta\phi_{MET-J}$, is a powerful and unambiguous probe of the anomalous $hWW$ couplings, both for CP-conserving and violating type.

4. Double Higgs boson production at the FCC-he

In our present work [5], we would like to see the double Higgs production through charged currents in $e^-p$ collisions and the representative leading order (LO) Feynman diagrams are shown in Fig. 1. At the LHeC, the center of mass energy is such that the double Higgs production is suppressed by phase space. As a result, the signal efficiency would be too low to detect the
events. But there is a further plan for the HE-LHC that would provide 50 TeV protons. This would increase the LHeC center of mass energy up to \( \sim 3.5 \) TeV with 60 GeV electrons. This energy would present an opportunity to probe Higgs self coupling strength (\( \lambda \) of the introduction) through double Higgs boson production.

4.1. Theoretical Framework

For our study we have parametrized all the bosonic couplings (since the possible fermionic couplings involved are highly constrained) that appear in the processes of Fig. 1 by the following effective Lagrangians:

\[
L_{hhh}^{(3)} = \frac{m_h^2}{2v} (1 - g_{hhh}^{(1)}) h^3 + \frac{1}{2} g_{hhh}^{(2)} h \partial_\mu h \partial^\mu h, \\
L_{hWW}^{(3)} = - \frac{g}{2m_W} g_{hWW}^{(1)} W^\mu W^\nu W_\mu^\nu W_\nu^\nu h - \frac{g}{m_W} \left[ g_{hWW}^{(2)} W^\nu \partial_\mu W_\mu^\nu h + \text{h.c.} \right] \\
- \frac{g}{2m_W} \bar{g}_{hWW} W^\mu W^\nu W_\mu^\nu h, \\
L_{hhWW}^{(4)} = - \frac{g^2}{4m_W^2} g_{hhWW}^{(1)} W^\mu W^\nu W_\mu^\nu W_\nu^\nu h^2 - \frac{g^2}{2m_W^2} \left[ g_{hhWW}^{(2)} W^\nu \partial_\mu W_\mu^\nu h^2 + \text{h.c.} \right] \\
- \frac{g^2}{4m_W^2} \bar{g}_{hhWW} W^\mu W^\nu W_\mu^\nu h^2.
\]

Here \( g_{hhh}^{(1)} \) is defined such that it appears as a multiplicative constant to \( \lambda_{SM} \), i.e., \( \lambda \to g_{hhh}^{(1)} \lambda_{SM} \) in the expression of EWSB potential in the SM:

\[
V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \to \frac{1}{2} m_h^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4,
\]

with \( \lambda = \lambda_{SM} = m_h^2/(2v^2) \approx 0.13. \) The effective couplings appearing in the above mentioned Lagrangian \( g_{hhh}^{(1)} \), \( g_{hhh}^{(2)} \), \( g_{hWW}^{(1)} \), \( g_{hWW}^{(2)} \), \( g_{hhWW}^{(1)} \), and \( g_{hhWW}^{(2)} \) are CP-conserving, whereas \( \bar{g}_{hWW} \) and \( \bar{g}_{hhWW} \) are CP-violating couplings. \( m_h \) and \( m_W \) are respectively masses of the Higgs and W-bosons, \( W^{\mu \nu} = \partial^\mu W^\nu - \partial^\nu W^\mu \). The vacuum expectation value (vev) for the SM Higgs-doublet is \( v \approx 246 \) GeV and \( g \) is the electroweak coupling in the SM.

Here we consider the speculated detector parameters, and cut-based analysis, to get charged current signals with respect to all possible charged/neutral current and photo-production backgrounds. A statistical analysis is also performed to find the sensitivity of \( g_{hhh}^{(1)} \) with other effective couplings.
The ∆ cut based analysis the signal events are expected signal (structure functions); which is calculated with the “Improved Weizsaecker-Williams formula” [6]. Backgrounds, and those backgrounds are estimated through “Equivalent photon approximation b Cross sections (in fb): Table 1: 4.2. Cross section, Detector setup and cut-based analysis We present the fiducial cross sections for the signal as well as the backgrounds, before cut-based analysis, in Table 1. For the signal we consider the charged current process \( e^- \rightarrow e^- h h j, h \rightarrow b b \). Photo-production backgrounds are very important, with other charged/neutral-current backgrounds, and those backgrounds are estimated through “Equivalent photon approximation structure functions”; which is calculated with the “Improved Weizsaecker-Williams formula” [6].

In the detector setup the maximum rapidity |\( \eta \)| range is up to 7. For the b-tagging, the jets with |\( \eta \)| < 5 and transverse momentum \( p_T > 15 \) GeV is taken. The fake rate for a c-initiated jet and a light jet to the b-jet is 10% and 1% respectively. The weight corresponding to the b-tagging efficiency, or fake rate, is assigned to each event. Furthermore the following cut flows are taken for analysis:

- Select 4 \( b + 1 \)-jet: \( p_T^{jet} > 20 \) GeV, |\( \eta \)| < 7 for non-\( b \)-jets, |\( \eta \)| < 5 for \( b \)-jets. The four \( b \) jets must be well separated within \( \Delta R > 0.7 \) in case of overlapped truth matching in the b-tagging.
- Rejecting leptons with \( p_T^\ell > 10 \) GeV (to suppress the neutral-current process).
- Rapidity of the forward jet \( \eta_{\text{forward-jet}} > 4.0 \), the forward jet as defined as the non-\( b \)-jet which has the largest \( p_T \) after selecting at least 4 \( b \)-jets.
- The missing transverse energy \( E_T^{miss} > 40 \) GeV and \( \Delta \Phi_{E_T^{miss},leadingjet} > 0.4 \), \( \Delta \Phi_{E_T^{miss,subleadingjet}} > 0.4 \).
- Pair the four \( b \)-jets into two pairs and calculate the invariant masses of each pair. The composition of the pair which has the smallest variance of mass to \( (m_H - 40) \) GeV is chosen. The first pair is defined as 90 < \( M_1 < 125 \) GeV, which must have the leading \( b \)-jet. The other pair is defined as 75 < \( M_2 < 125 \) GeV.
- Choosing the invariant mass of all four \( b \)-jets greater than 280 GeV.

And the signal significance is calculated with a Poisson distribution considering the expected signal \( (S) \) and background \( (B) \) yields at 10 ab\(^{-1}\) luminosity. After performing these cut based analysis the signal events are \( \sim 63 \) with respect to total background events \( \sim 35 \) and \( s = 8.7 \). A 5% systematic error is introduced into signal and backgrounds.

\[ \begin{array}{|c|c|c|c|}
\hline
\text{Process} & \text{CC (fb)} & \text{NC (fb)} & \text{PHOTO (fb)} \\
\hline
\text{Signal:} & 2.40 \times 10^{-4} \\
\text{\( b b b b \):} & 8.20 \times 10^{-4} & 3.60 \times 10^{-4} & 2.85 \times 10^{-4} \\
\text{\( b b j j \):} & 6.50 \times 10^{-4} & 2.50 \times 10^{-4} & 1.94 \times 10^{-4} \\
\text{\( z z j (z \rightarrow b b) \):} & 7.40 \times 10^{-4} & 1.65 \times 10^{-4} & 1.73 \times 10^{-4} \\
\text{\( t t j \) (hadronic):} & 3.30 \times 10^{-4} & 1.40 \times 10^{-4} & 3.27 \times 10^{-4} \\
\text{\( t t j \) (semi-leptonic):} & 1.22 \times 10^{-4} & 4.90 \times 10^{-4} & 1.05 \times 10^{-4} \\
\hline
\end{array} \]

Table 1: Cross sections (in fb): \( E_e = 60 \) GeV, \( E_p = 50 \) TeV, \( j = qudds \). Initial cuts: |\( \eta \)| ≤ 10 for jets, leptons and \( b \), \( p_T \geq 10 \) GeV, \( \Delta R_{\text{min}} = 0.4 \) for all particles.
4.3. Statistical analysis

Following the method given in Ref. [7], exclusion limits for $g_{h_{hh}}^{(1)}$ are calculated. Fig. 2 shows significant behaviour of cross section variation with respect to $g_{h_{hh}}^{(1)}$ which is expected due to interference between resonant and non-resonant Higgs mediation in the charge-current signal process. The 95% upper limits of all effective couplings appear in the Lagrangian Eqs. (2), (3) and (4), due to cross section influence are also calculated and shown in Fig. 3. The sensitivity of CP-even and odd $h_{WW}$ effective couplings, $g_{h_{WW}}^{(1)}$ and $\tilde{g}_{h_{WW}}$, are of the same order as $g_{h_{hh}}^{(1)} \sim 10^0$. However for $g_{h_{hh}}^{(2)} \sim 10^{-3} - 10^{-4}$ and $g_{h_{WW}}^{(1,2)}$, $\tilde{g}_{h_{WW}}$, these are of the order $\sim 10^{-2}$.

5. Conclusion

We performed a detailed analysis of the double-Higgs production at the FCC-he, an $e^- p$ machine with $\sqrt{s} \approx 3.5$ TeV. Considering the speculated detector parameters, we found the feasibility of such machine for Higgs physics scenarios. It is shown that this machine will provide high precision for the measurement of not only Higgs-self-coupling strengths, but also other effective couplings, which appear in the production mechanism of double-Higgs through $e^- p$ collisions. Furthermore, we approached two aspects of this project:

- Taking different channels of Higgs decays $h \rightarrow c\bar{c}, \mu^+\mu^-$, $\tau^+\tau^-$ and
- Performing a global fit-analysis with the involved Wilson coefficients of the effective six dimension operators appearing in combinations with the effective couplings in this study.

As such, we hope all the above works not only provide the physics potential of $e^- p$ machine to study the Higgs-physics, but also provide information on the quantitative value of the parameters needed to build detectors at this facility.

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Figure 3: The limits on the coupling strength, derived at 0.4 ab$^{-1}$. The $g^{(2)}_{hhh}$ has only the upper limit because the cross section dependence is monotonic in this region.

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