Photo-production of Higgs Boson at the LHeC

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Abstract

In this paper, we study the photo-production of Higgs boson at the LHeC. The process can be used as a complementary precision measurement for Higgs to di-photon partial decay width $\Gamma(h \to \gamma\gamma)$, and it has a clean final state without additional colored particles in the central rapidity region other than the decay products of the Higgs. However, there are some non-photon-fusion processes with final states of this feature, for example, Higgs gluon fusion production from $\gamma g$ scattering. These processes may be indistinguishable from and thus contaminate the photo-production in the detector. We compute the scattering amplitudes for all these processes and estimate their cross sections through Monte Carlo phase space integration. Different photon-PDF sets lead to rather different photo-production cross sections, while give very close results for contaminating processes. We also study the phenomenology of the photo-production at the LHeC via various Higgs decay channels. The signal significance in the standard model can be close to or over $2\sigma$ for $E_e = 60$ GeV or $E_e = 120$ GeV respectively. However, the photo-production and other contaminating processes are hard to distinguish at the detector level, and are hence combined into one signal, to which the photo-production only contributes less than 10%. Therefore, even though the significance of this signal reaches an observable level, it does not imply that the Higgs photo-production can be observed with the assumed experimental conditions in our analysis.
I. INTRODUCTION

Discovery of a 125 GeV standard model (SM) like Higgs Boson by the ATLAS/CMS collaborations at the CERN Large Hadron Collider (LHC) [1, 2] has significantly improved our knowledge over mechanism behind spontaneously electroweak gauge symmetry breaking. On the other hand, neither the mass of the Higgs boson nor the driving force of electroweak symmetry breaking is explained within the SM and these questions have motivated many attempts in extending SM. Besides the direct search of such models of physics beyond SM (BSM), precision measurement of Higgs boson couplings and properties at the same time plays an important role in testing various BSM physics models. For this purpose, proposals of future electron-positron colliders such as, FCC-ee, ILC and CEPC, have been widely discussed in the community. Besides them, there also exists a proposal for an $e^-p$ collider known as LHeC, planned to be constructed by adding one electron beam of 60-140 GeV to the current LHC [3]. LHeC was initially proposed as a TeV deep-inelastic scattering (DIS) facility with 60 GeV electron beam and 2 ab$^{-1}$ designed integrated luminosity to improve the measurement of parton distribution function at large $x$. By upgrading the electron beam energy and designed luminosity, it can potentially be converted into a “Higgs factory”. The leading production mode of Higgs boson at the LHeC is via charged-current weak boson fusion (WBF) : $e + p \rightarrow \nu_e + h + J$. The tagged forward jet is crucial for suppressing the background in a study on $h \rightarrow b\bar{b}$ at the LHeC [4]. Analogous to the use of jet angular correlation in measuring the anomalous coupling in WBF at the LHC [5], the azimuthal angle between the neutrino and forward jet $\Delta \phi_{\nu, J}$ provides a sensitive probe of the anomalous $hWW$ coupling at the LHeC [6].

Diphoton decay of Higgs boson played an important role in discovering Higgs at the LHC. At leading order, SM Higgs decaying into diphoton ($h \rightarrow \gamma\gamma$) arises from the $W$-loop and heavy quark loop processes, where the $W$-loop dominates the decay width. Exotic particles from BSM models such as sfermions in supersymmetric models or charged Higgs models may also contribute to the diphoton decay at one-loop level. Therefore, the loop-induced diphoton decay also provides a sensitive probe to physics at TeV scale. On the other hand, the photon-fusion production rate of Higgs boson is proportional to Higgs diphoton decay width and hence, precision measurement of photon-fusion may be complementary to the diphoton decay measurement.

Recent developments of photon PDF from CT14qed/LUXqed/NNPDF23qed [7,10] have improved our framework for computing photon contribution. While the photon radiation off a point-
like particle like electron can be calculated explicitly or sometimes with Weizsäcker-Williams approximation, photon from proton can arise from both elastic and inelastic processes, where the elastic channel is from the photon radiation off a proton directly, and the inelastic channel is from that off a quark parton. To verify the photon PDF, exclusive muon pair production via $\gamma\gamma \rightarrow \mu^+\mu^-$ has been measured for the first time by CMS [11]. One complication in measuring Higgs photoproduction at $e^-p$ colliders is that the gluon fusion production of Higgs boson contributes in $e^-p$ collisions through $\gamma g$ scattering. In addition, contribution from weak boson PDF may not be neglected either. The calculation of all above related contributions is important for the estimation of the Higgs photo-production, and will be included in the following section. It is followed by a discussion of collider phenomenology on how well one can measure the signal final states. We then conclude in the final section.

II. HIGGS PHOTO-PRODUCTION PROCESS AT THE LHEC

The Higgs photo-production through $W$ or charged fermion loops is shown in Fig 1. The photons are radiated from the proton and electron beams. As the proton remnant has little recoil in the effective photon approximation [12], it moves in the very forward direction and cannot be detected. The process is thus featured with its clean final states without additional colored particles. It is noteworthy that there may be some non-photon-fusion processes whose final state partons (other than those from the Higgs decay) are too soft or collinear to the beams to be tagged. Such processes, as shown in Fig 2, can potentially contaminate the photo-production. In particular, there are gluon initiated processes with more radiations. However, at large center-of-mass energies, the rapid increase of the gluon PDF may result in sizable cross sections; hence, the estimation of their contribution is important.

![Diagram](image)

FIG. 1: Representative diagrams of the Higgs photo-production. $q$ denotes any charged fermions. Top and bottom quark are dominant in the fermion loop.
A. $\gamma\gamma$

An example diagram for Higgs photo-production is shown in Fig. 2 (a). To test the precision of the effective photon approximation, we compute the photo-production cross section in two methods. In the first method, Weizsäcker-Williams approximation is used for the photon splitting process, giving a cross section of 0.476 fb for the incoming electron energy at 60 GeV, computed with the PDF set NNPDF23_nlo_as_0119_qed [7] from the LHAPDF [13]. The calculation is also done with the exact electron-photon vertex, which gives a cross section of 0.518 fb. The accuracy of the approximation is satisfactory.

B. $\gamma g$ and $\gamma q$

The process represented by Fig. 2 (a) also has a clean final state of colored particles in the central rapidity region, despite the additional radiation of the quark pair. In fact, when the electron and quark masses $m_e$ and $m_q$ are much smaller than the center-of-mass energy $\sqrt{s}$, the strongly ordered multiple splittings from Fig. 2 (a) give terms proportional to

$$\alpha_{EM}^2 \alpha_S \ln^3 \left( \frac{s}{m_e^2} \right) - \ln^3 \left( \frac{m_q^2}{m_e^2} \right).$$
These triple logarithms could substantially enhance the cross section in the region where the quark pair is collinear to the electron. Because of this enhancement, the cross section from this channel receives large contribution from the outgoing electron in the very forward region. In principal, one could represent the structure of the electron by parton distribution functions that evolve to account for the effects of the large logarithms to all orders. Since the contribution of this channel is quite small, we perform an order-of-magnitude estimation and include only the contribution from the fixed order diagrams in e.g. Fig. 2 (a), whose collinear singularities are cut off by the electron mass. Also note that due to the multi-logarithmic structure of radiations, Weizsäcker-Williams approximation cannot be used in this case, since additional collinear singularities exist in the hard scattering process even after the electron splitting vertex is factorized. We therefore include the electron line in Fig. 2 (a) to indicate that the exact electron-photon vertex is included in the calculation. The phase space integration of this channel is subject to large numerical uncertainty due to the rapid increase of the scattering amplitude in the collinear region. The cross section for this channel is $\sim 0.0168 \text{ fb}$, where the “$\sim$” indicates the number is presented with large uncertainty and serves only as an order-of-magnitude estimate.

Similar to the case in Fig. 2 (a), the quark radiation in Figs. 2 (b) is also enhanced, but with more mild double logarithms of the form

$$\alpha_{EM}^2 \left[ \ln^2 \left( \frac{s}{m_e^2} \right) - \ln^2 \left( \frac{m_q^2}{m_e^2} \right) \right].$$

In contrast, the gluon radiations from Fig. 2 (c) are not enhanced at large rapidities of the final gluons, in which case single logarithms $\alpha_{EM} \ln(s/m_e^2)$ appear as is prescribed by Weizsäcker-Williams approximation. Note that one cannot invoke Furry’s theorem to discard the pentagon graphs for two obvious reasons: the number of $\gamma$ matrices from the vertices in the loop is even; and there is a mixing of QED and QCD vertices. We obtain 0.000753 fb and 0.000189 fb for the above $\gamma q$ and $\gamma g$ processes, respectively.

C. WBF

WBF processes as in Fig. 2 (d) and (e) are the dominant for Higgs production at the LHeC with a large cross section of $O(10^2)$ fb. Therefore we expect some rate from the WBF processes without spectator partons (those not from Higgs decay) in the central rapidity region. To calculate
the cross section we exclude the region $|\eta^q| \leq 5$, where $q$ denotes the final state quark (not from Higgs decay). The resulting $Z$ exchange cross section is 0.681 fb, comparable to that of the photo-production. The $W$ exchange cross section is 4.82 fb, about an order of magnitude larger.

The cross sections for the processes discussed above are summarised in Table I for two electron beam energies. For comparison we also list the result computed with more recent PDF sets CT14qed_inc proton [8] and LUXqed17_plus_PDF4LHC15_nnlo_100 [9, 10].

| $E_e$ (GeV) | Fig 1 | Figs 2(a) | 2(b) | 2(c) | 2(d), $|\eta^q| \geq 5$ | 2(e), $|\eta^q| \geq 5$
|-----------|------|----------|-----|-----|----------------|----------------|
| 60        | NNPDF23qed | 0.518 | ~0.0168 | $\sim 7.53 \times 10^{-4}$ | $1.89 \times 10^{-4}$ | 0.681 | 4.82 |
|           | CT14qed_inc | 0.391 | ~0.0163 | $\sim 7.64 \times 10^{-4}$ | $1.98 \times 10^{-4}$ | 0.692 | 4.98 |
|           | LUXqed17 | 0.456 | ~0.0173 | $\sim 8.15 \times 10^{-4}$ | $1.99 \times 10^{-4}$ | 0.695 | 4.90 |
| 120       | NNPDF23qed | 0.741 | ~0.0376 | ~0.00162 | $7.79 \times 10^{-4}$ | 1.08 | 7.45 |
|           | CT14qed_inc | 0.641 | ~0.0346 | ~0.00163 | $8.1 \times 10^{-4}$ | 1.09 | 7.62 |
|           | LUXqed17 | 0.743 | ~0.034 | ~0.00175 | $8.14 \times 10^{-4}$ | 1.10 | 7.55 |

TABLE I: Cross sections in fb for processes represented by the diagrams in Figs 2, computed with three different PDF sets. The electron beam energy is 60/120 GeV.

The three PDF sets give very close results for gluon and quark initiated processes. For photo-production, the cross sections differ by a sizable amount because the methods in determining these photon PDFs are quite different. The LUXqed17 result is smaller than NNPDF23qed at large momentum fraction $x$, while gets close when $x$ becomes smaller ($\sim \mathcal{O}(10^{-2})$). The CT14qed_inc cross section is smaller than LUXqed17 in a more broad $x$ region. These observations are in qualitative agreement with the behaviors of the photon PDFs shown in Fig. 4 of the Ref. [9]. The cross sections for $\gamma g$ and $\gamma q$ processes are at most $\sim 5\%$ of that of the photo-production at the energies we are considering.

In the calculation we choose the renormalization and factorization scales to be the center-of-mass energy for the hard scattering processes. The reduction of the pentagon loop integral in Fig. 2

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1 We do not do this for $\gamma q$ and $\gamma g$ processes because their cross sections are negligible already.
(c) requires extra numerical accuracy and is done with the help of Madloop program [14] in MadGraph5_aMC@NLO [15]. Other loop diagrams are calculated with FormCalc and LoopTools [16]. The Monte Carlo phase space integration is performed using VEGAS algorithm implemented in CUBA library [17].

III. PHENOMENOLOGICAL ANALYSIS

We have seen that processes in Fig.2 (a), (b), and WBF processes with the central rapidity cut are difficult to distinguish from the photo-production in Fig.1 kinematically due to lack of spectator partons in the central rapidity region. So we shall just combine them into a single signal in our analysis. It is noteworthy that even if this combined signal can be well separated from the background processes, we cannot conclude that the Higgs photo-production can be observed because the photo-production only contributes less than 10% and is difficult to separate from other signal processes. In the following, we shall only aim to separate the combined signal from potentially important backgrounds, while leave the distinction between photo-production and other signal processes for future studies.

The requirement that no spectator partons appear in the central region separates the signal from traditional Higgs production modes, and also leads to the smaller production rate at the LHeC. In order to explore this process precisely, we will next rely on the kinematic features of three main decay channels ($h \rightarrow b\bar{b}$, $W^+W^-$ and $ZZ$) to distinguish the signal and backgrounds. The backgrounds are predominantly from $\gamma g \rightarrow b\bar{b}$ and $\gamma\gamma \rightarrow W^+W^-$ scattering, as well as fusion production of $Z$ and $W$ bosons. The background simulation is performed with MadGraph5_aMC@NLO [15] at the parton level. The PDF set NNPDF23_nlo_as_0119_qed is used in simulations of both the signal and backgrounds, which includes both elastic and inelastic photon information [7]. As is done in Sec.II we choose two benchmark points with 7 TeV proton beam energy and 60/120 GeV electron beam energy to see whether increasing the electron beam energy helps to improve the Higgs production measurement. The basic cuts on final states $p_T$, $\eta$ and $\Delta R$ are applied as

\[
p_T^\ell \geq 5 \text{ GeV} \quad , \quad p_T^{j} \geq 20 \text{ GeV},
\]
\[
|\eta^\ell| \leq 5 \quad , \quad |\eta^{j}| \leq 5,
\]
\[
\Delta R_{\ell\ell} \geq 0.4 \quad , \quad \Delta R_{jj} \geq 0.4.
\]
A. $b\bar{b}$

The standard $h \to b\bar{b}$ search at the LHeC uses forward jet tagging to improve the signal-to-background rate, which makes possible the bottom Yukawa measurement [4]. In our search the main background process is $\gamma g \to b\bar{b}$. The large difference between gluon and photon PDFs in the proton makes the background cross-section orders larger than that of the signal. In order to pick out the signal events, the $b$-jet transverse momentum could be used because the $b$ quarks from Higgs decay are more boosted. The $b\bar{b}$ invariant mass is another discriminative kinematic variable and only events with $m_{b\bar{b}}$ around $m_h$ should be kept. The $b\bar{b}$ search efficiency also depends heavily on the $b$-tagging efficiency of the LHeC detectors. The signal production cross section is about $0.31 + 0.39 + 2.80$ fb for $E_e = 60$ GeV and $0.45 + 0.62 + 4.38$ fb for $E_e = 120$ GeV with $Br(h \to b\bar{b}) \approx 58\%$. However, the $b\bar{b}$ background cross sections for the two energies are 187.5 pb and 308.6 pb. Even if we apply some strict kinematic cuts, for example $p_T^b \geq 30$ GeV and $|m_{b\bar{b}} - m_h| \leq 15$ GeV, about 3% of the background events could survive. This is still several orders larger than the raw signal events. For this reason, it’s extremely challenging to use $b\bar{b}$ channel for this measurement.

B. $W^+W^-$

The $W^+W^-$ channel is the secondary Higgs decay channel with $Br(h \to W^+W^-) \approx 21.5\%$. In this study, we only consider the pure leptonic sub-channel because when including hadronic final states, the large background from $\gamma g$ scattering are inevitable. The main background is then $\gamma\gamma \to W^+W^-$ with leptonic $W$ decay. In this case, there are two invisible neutrinos contributing to the $E_T$. Though it’s very difficult to reconstruct invariant masses involving neutrinos, kinematic methods for the intermediate-mass Higgs boson search could be applied in this case [18]. The $\ell\bar{\ell}\nu\bar{\nu}$ system transverse mass could be reconstructed with the transverse momenta of the leptons and the missing objects as

$$m_T^2 \equiv (E_{T\ell} + E_T)^2 - |p_T^{\ell\ell} + p_T|^2$$

$$= (\sqrt{|p_T^{\ell} + p_T|^2 + m_{\ell\ell}^2} + |p_T|)^2 - |p_T^{\ell\ell} + p_T + p_T|^2$$

The signal transverse mass distribution has an upper bound at $m_h$, while the background distribution is rather flat and much larger. Other than that, there’s also a difference between the di-lepton
invariant mass distributions. The signal distribution is restricted by the Higgs mass and peaks at small values, while the background has a rather broad distribution. Fig. 3 (a) and (b) show the distributions of the di-lepton invariant mass and the $\ell\ell\nu\bar{\nu}$ system transverse mass. It’s reasonable to set upper bounds for the two reconstructed observables to cut the background. As the two signal leptons are from the Higgs cascade decay, the pseudo-rapidity difference between them should be smaller than backgrounds. One can see in Fig. 3 (c) and (d) that the distributions of the pseudo-rapidity difference and the missing transverse momentum could be effectively used to distinguish the signal and background. The kinematic distributions are not significantly dependent on the electron beam energy, so we only plot the $E_e = 60$ GeV case.

![Graphs showing distributions](attachment:image.png)

**FIG. 3:** (a) and (b) are distributions of $m_{\ell\ell}$ and $m_T$ for the signal (green) and background (blue), reconstructed from events after basic cuts. Distributions of $E_T$ and $\Delta\eta$ are shown in (c) and (d). The electron beam energy is $E_e = 60$ GeV.
According to the discussion, we require $E_T \leq 55$ GeV, $p_T \leq 60$ GeV, $\Delta\eta \leq 3$, $m_{\ell\bar{\ell}} \leq 60$ GeV and $m_T \leq 125$ GeV. The efficiencies of signal and background events after all these cuts are listed in Table II. The efficiency in each column is computed after the corresponding cut is applied in addition to all the cuts from the columns to its left. Although the kinematic cuts can reduce the background by an order, the signal events are still overwhelmed by it. If we apply very strict cuts, the leptonic subchannel cross section is too small for a measurement even with $\mathcal{O}(1)$ ab$^{-1}$ integrated luminosity.

| $E_e = 60$ GeV | Cross Section (fb) | $E_T \leq 55$ GeV | $p_T \leq 60$ GeV | $\Delta\eta \leq 3$ | $m_{\ell\bar{\ell}} \leq 60$ GeV | $m_T \leq 125$ GeV |
|---------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Signal        | $(4.84 + 6.17 + 43.7) \times 10^{-3}$ | 0.762             | 0.623             | 0.615             | 0.568             | 0.565             |
| Background    | 9.08              | 0.543             | 0.134             | 0.114             | 0.053             | 0.051             |

| $E_e = 120$ GeV | Cross Section (fb) | $E_T \leq 55$ GeV | $p_T \leq 60$ GeV | $\Delta\eta \leq 3$ | $m_{\ell\bar{\ell}} \leq 60$ GeV | $m_T \leq 125$ GeV |
|---------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Signal        | $(7.06 + 9.79 + 68.45) \times 10^{-3}$ | 0.760             | 0.621             | 0.615             | 0.563             | 0.560             |
| Background    | 16.02             | 0.535             | 0.129             | 0.105             | 0.047             | 0.045             |

**TABLE II**: The second column gives the cross sections of the signal and background after basic cuts. Other columns are cut efficiencies after corresponding kinematic cuts. The electron beam energy is 60/120 GeV.

**C. ZZ**

The $ZZ$-to-four-lepton channel plays an important role in the discovery of Higgs boson and the measurement of its properties. Here we also choose this sub-channel to extract the Higgs production process. This helps to exclude huge QCD backgrounds because of the pure leptonic final states. There are two same-flavor and opposite-sign(SFOS) lepton pairs from $ZZ$ decay, which leads to the invariant mass of one SOFS pair $m_{\ell\bar{\ell}}$ around $m_Z$, and the total invariant mass $m_4\ell$ close to $m_h$. At the meantime, the rapidity difference between the paired leptons should be small. After the lepton basic cut, the two SFOS leptons with invariant mass $^1m_{\ell\bar{\ell}}$ closest to the $Z$-boson mass are chosen as the first lepton pair. The requirement on $^1m_{\ell\bar{\ell}}$ is $40 \leq ^1m_{\ell\bar{\ell}} \leq 95$ GeV. The two remaining leptons form the second lepton pair, whose invariant mass should satisfy $^2m_{\ell\bar{\ell}} \leq 60$ GeV. Since this process starts with an ergodic pairing, the background lepton-pair mass could possibly mimic the signal with a slightly broader distribution around $m_Z$. Even so, the $m_{4\ell}$ cut could
still eliminate most of the background events because the background distribution is extremely flat, as shown in Fig. 4. Further kinematic requirements on lepton transverse momenta $p_\ell^T$ and pseudorapidity difference $\Delta \eta$ in the first and second lepton pairs are listed in Table III.

The four-lepton channel production cross sections and cut efficiencies are also shown in the Table III. Although we could reduce the background to nearly 1% while keeping almost 70% of the signal events, the huge difference between the cross sections makes it impossible to perform the measurement in this channel.

![Graph](image)

FIG. 4: $m_{4\ell}$ distributions of the signal (green) and twentyfold scaled background (blue).

| $E_e$ (GeV) | Cross Section (fb) | $20 \leq p_\ell^T \leq 55$ GeV | $1 \Delta \eta \leq 3$ | $2 \Delta \eta \leq 2$ | $115 \leq m_{4\ell} \leq 125$ GeV |
|------------|--------------------|-------------------------------|----------------------|----------------------|---------------------------------|
| Signal     | $(5.60 + 7.15 + 50.58) \times 10^{-5}$ | 0.761                         | 0.746                | 0.741                | 0.692                           |
| Background | 0.44               | 0.209                         | 0.154                | 0.121                | 0.011                           |
| $E_e = 120$ GeV | Cross Section (fb) | $20 \leq p_\ell^T \leq 55$ GeV | $1 \Delta \eta \leq 3$ | $2 \Delta \eta \leq 2$ | $115 \leq m_{4\ell} \leq 125$ GeV |
| Signal     | $(8.17 + 13.33 + 93.21) \times 10^{-5}$ | 0.764                         | 0.750                | 0.744                | 0.699                           |
| Background | 0.71               | 0.206                         | 0.144                | 0.112                | 0.008                           |

TABLE III: The second column gives the cross sections of the signal and background after basic cuts. Other columns are cut efficiencies after corresponding kinematic cuts. The electron beam energy is 60/120 GeV.
IV. RESULTS

We calculate the signal significance \( Z \) after partonic simulation through the formula:

\[
Z = \frac{S}{\sqrt{S + B}}
\]

where \( S \) represents the number of signal events. The overall background \( B \) including the 1% systematic error is computed as \( B = \Sigma_i B_i + \Sigma_i (0.01 B_i)^2 \). The significance (\( Z \)) and signal-to-background (\( S/B \)) are quite different in the three decay channels we chose. In \( h \to b\bar{b} \) decay channel, the background is several times larger than the signal after kinematic cuts, the signal-to-background cannot reach up to percent level. In \( h \to ZZ \) leptonic decay channel, the cross section is limited by the small branch ratio, which leads to the low significance even though it has an acceptable signal-to-background. The significance does not improve when we set \( E_e = 120 \) GeV, and we expect further studies on this channel. The most promising channel is the \( h \to WW \) leptonic decay due to the comparatively large branch ratio and distinguishable backgrounds. When the effective coupling of \( h\gamma\gamma \) equals to its SM value, the significance can be close to or over 2\( \sigma \) for \( E_e = 60 \) GeV or \( E_e = 120 \) GeV respectively, with a 6.6% signal-to-background in both cases, as shown in Fig. 5.

![Graphs showing the dependence of significance \( Z \) on the ratio \( \kappa_{h\gamma\gamma} \) between the effective coupling of \( h\gamma\gamma \) and its SM value for two electron beam energies.](a) \( E_e = 60 \) GeV  
(b) \( E_e = 120 \) GeV

FIG. 5: The dependence of significance \( Z \) on the ratio \( \kappa_{h\gamma\gamma} \) between the effective coupling of \( h\gamma\gamma \) and its SM value. The plots are shown for two electron beam energies.
V. CONCLUSION

In this paper, we study the photo-production of the Higgs boson and related contaminating processes at the LHeC. The cross sections are computed for all relevant processes. We find that the photo-production is severely overshadowed by other processes whose spectator partons are collinear to the proton beam and cannot be tagged. This leads to a signal of mixed processes. Nonetheless, we still explore the phenomenology of these processes and calculate the significance and signal-to-background. When the $h \gamma \gamma$ effective coupling equals to its SM value, the significance is close to $2\sigma$ for $E_e = 60$ GeV, with a 6.6% signal-to-background. However, with the photo-production process contributing less than 10% to the signal cross section, it is still difficult to observe photo-production by itself at the LHeC.

To conclude, it is difficult to make this complementary precision measurement for $\Gamma(h \rightarrow \gamma\gamma)$ at the LHeC using the method presented in this paper, and we hope that more discriminative methods can be developed to efficiently separate Higgs photo-production from other signal processes as well as from the background processes.

VI. ACKNOWLEDGEMENT

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[1] ATLAS, 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. B716 (2012) 1–29, arXiv:1207.7214 [hep-ex].

[2] CMS, S. Chatrchyan et al., “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” Phys. Lett. B716 (2012) 30–61, arXiv:1207.7235 [hep-ex].

[3] LHeC Study Group, J. L. Abelleira Fernandez et al., “A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector,” J. Phys. G39 (2012) 075001, arXiv:1206.2913 [physics.acc-ph].

[4] T. Han and B. Mellado, “Higgs Boson Searches and the H b anti-b Coupling at the LHeC,” Phys. Rev. D82 (2010) 016009, arXiv:0909.2460 [hep-ph].

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[5] V. Hankele, G. Klamke, D. Zeppenfeld, and T. Figy, “Anomalous Higgs boson couplings in vector boson fusion at the CERN LHC,” *Phys. Rev.* **D74** (2006) 095001, arXiv:hep-ph/0609075 [hep-ph].

[6] S. S. Biswal, R. M. Godbole, B. Mellado, and S. Raychaudhuri, “Azimuthal Angle Probe of Anomalous $HWW$ Couplings at a High Energy $ep$ Collider,” *Phys. Rev. Lett.* **109** (2012) 261801, arXiv:1203.6285 [hep-ph].

[7] NNPDF, R. D. Ball, V. Bertone, S. Carrazza, L. Del Debbio, S. Forte, A. Guffanti, N. P. Hartland, and J. Rojo, “Parton distributions with QED corrections,” *Nucl. Phys.* **B877** (2013) 290–320, arXiv:1308.0598 [hep-ph].

[8] C. Schmidt, J. Pumplin, D. Stump, and C. P. Yuan, “CT14QED parton distribution functions from isolated photon production in deep inelastic scattering,” *Phys. Rev. D93* 11, (2016) 114015, arXiv:1509.02905 [hep-ph].

[9] A. Manohar, P. Nason, G. P. Salam, and G. Zanderighi, “How bright is the proton? A precise determination of the photon parton distribution function,” *Phys. Rev. Lett.* **117** 24, (2016) 242002, arXiv:1607.04266 [hep-ph].

[10] A. V. Manohar, P. Nason, G. P. Salam, and G. Zanderighi, “The Photon Content of the Proton,” *JHEP* **12** (2017) 046 arXiv:1708.01256 [hep-ph].

[11] CMS, S. Chatrchyan *et al.*, “Exclusive photon-photon production of muon pairs in proton-proton collisions at $\sqrt{s} = 7$ TeV,” *JHEP* **01** (2012) 052 arXiv:1111.5536 [hep-ex].

[12] V. M. Budnev, I. F. Ginzburg, G. V. Meledin, and V. G. Serbo, “The Two photon particle production mechanism. Physical problems. Applications. Equivalent photon approximation,” *Phys. Rept.* **15** (1975) 181–281.

[13] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, “LHAPDF6: parton density access in the LHC precision era,” *Eur. Phys. J.* **C75** (2015) arXiv:1412.7420 [hep-ph].

[14] V. Hirschi, R. Frederix, S. Frixione, M. V. Garzelli, F. Maltoni, and R. Pittau, “Automation of one-loop QCD corrections,” *JHEP* **05** (2011) 044 arXiv:1103.0621 [hep-ph].

[15] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations,” *JHEP* **07** (2014) 079 arXiv:1405.0301 [hep-ph].
[16] T. Hahn and M. Perez-Victoria, “Automatized one loop calculations in four-dimensions and D-dimensions,” *Comput. Phys. Commun.* **118** (1999) 153–165, arXiv:hep-ph/9807565 [hep-ph].

[17] T. Hahn, “CUBA: A Library for multidimensional numerical integration,” *Comput. Phys. Commun.* **168** (2005) 78–95, arXiv:hep-ph/0404043 [hep-ph].

[18] V. D. Barger, G. Bhattacharya, T. Han, and B. A. Kniehl, “Intermediate mass Higgs boson at hadron supercolliders,” *Phys. Rev.* **D43** (1991) 779–788.