Probing Anomalous $HZZ$ Couplings at the LHeC

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Abstract

We examine the sensitivity to the couplings of the Higgs boson to neutral gauge bosons in a model independent way at the Large Hadron electron Collider (LHeC). We have obtained the constraints on anomalous couplings for $HZZ$ vertex via the process $e^-p \rightarrow e^-HqX$. We find the accessible limits of the anomalous coupling $b_Z$ as $(-0.12, 0.43)$ and $(-0.10, 0.33)$, while the limits on coupling $\beta_Z$ as $(-0.32, 0.32)$ and $(-0.24, 0.24)$ at the electron beam energy $E_e = 60$ GeV and $E_e = 140$ GeV, respectively.

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I. INTRODUCTION

The recent discovery of a new boson with a mass of 125 GeV at the CERN LHC \cite{1, 2} matches many of the properties of the Higgs boson from the Higgs mechanism within the standard model (SM). With more data analyzed, the LHC is expected to be able to probe the detailed properties of this new scalar particle, and verify its nature.

A first determination of the couplings, spin and parity properties can be performed with the current results. The ATLAS \cite{3} and CMS \cite{4} Collaborations have presented that the observed state resembles very closely to the Higgs boson. Searching for the properties of this new boson can extend our knowledge of the electroweak symmetry breaking (EWSB) sector. This search has also very important consequences on theories beyond the SM.

From the theoretical side, there could be different EWSB scenarios in which the Higgs boson can be elementary and weakly interacting \cite{5} or composite and related to a new strongly interacting sector \cite{6}. Under the assumption there is new physics associated with the EWSB sector, its effects on the phenomenology of the Higgs boson can be parametrized in terms of an effective Lagrangian at the electroweak scale. In this framework, the corrections from higher dimensional operators to the Higgs boson ($H$) couplings to the gauge bosons ($V$) can be expressed through an effective Lagrangian. The effective operators give rise to anomalous $HVV$ couplings, and these operators can modify both the Higgs boson production and its decay rates \cite{7}.

Extensive studies about the anomalous $HZZ$ couplings described by a model independent effective Lagrangian approach have been performed in the literature at hadron colliders \cite{7–14} and lepton colliders \cite{15–25}.

The predictions on the measurement of ratios of the Higgs couplings with an accuracy at the level of a few percent have been given in \cite{26} for the LHC at $\sqrt{s} = 14$ TeV with a high luminosity of 300 fb$^{-1}$. Furthermore, the precision measurement of the self-couplings of this new boson is very important for the future experiments since it could well point the new physics beyond the SM.

The LHeC could probe the $HZZ$ couplings without any assumption on the $HWW$ couplings. It has the unique opportunity to probe $HZZ$ couplings in Higgs production via weak vector boson fusion, in contrast to the production at the LHC where the contributions come from the $HWW$ and $HZZ$ couplings. Therefore, it is a particular interest since these
couplings could receive sizeable anomalous contributions from physics beyond the SM.

A high energy electron-proton collider can be realised by accelerating electrons in a linear accelerator (linac) to 60-140 GeV and colliding them with the 7 TeV protons incoming from the LHC. The anticipated integrated luminosity is about in order of 10 and 100 fb$^{-1}$ \cite{27}.

In this work, we study the sensitivity to the anomalous $HZZ$ couplings in a model independent way at the Large Hadron electron Collider (LHeC) via the production process $e^{-}p \rightarrow e^{-}HqX$. We calculate the production cross sections depending on the anomalous couplings. The results of our analyses are given through the 95% C.L. contour plots.

II. THE $HZZ$ COUPLINGS

Providing the Lorentz and gauge invariance, a general $HZZ$ couplings structure may be expressed \cite{17, 28} as

$$
\Gamma_{\mu\nu} = g_Z \left[ a_Z g_{\mu\nu} + \frac{b_Z}{m_Z^2} (k_2 \mu k_1 \nu - g_{\mu\nu} k_1 \cdot k_2) + \frac{\beta_Z}{m_Z^2} \epsilon_{\alpha\beta\mu\nu} k_1^\alpha k_2^\beta \right] \tag{1}
$$

where $k_1$ and $k_2$ are the momenta of two $Z$ bosons with $g_Z = 2g_e m_Z / \sin 2\theta_W$. In the context of the SM, at the tree level, $a_Z = 1$, while the other couplings $b_Z$ and $\beta_Z$ vanish identically. We define $\Delta a_Z = a_Z - 1$ in order to deal with a SM like Higgs boson, and hence we set $\Delta a_Z = 0$ in the SM case. The couplings $b_Z$ and $\beta_Z$ can arise from higher order terms in an effective theory, where $b_Z$ and $\beta_Z$ are the CP conserving and CP violating couplings, respectively.
III. THE CROSS SECTION

The calculation of the cross sections for signal and background is performed usingCalcHEP [29] with parton distribution function CTEQ6L [30]. For the background process $e^- p \rightarrow e^- HqX$, we calculate the cross section values as 15.68 fb and 39.75 fb for the center of mass energies $\sqrt{s} = 1.29$ TeV and $\sqrt{s} = 1.98$ TeV, respectively. Here the anomalous couplings $\Delta a_Z$, $\beta_Z$, and $b_Z$ are taken to be zero for calculation of the cross sections corresponding to the SM case. Although hadronic jets from $b$ quarks would tag with high efficiency, lighter quarks tagging displays strong rejections. We assume $b$ jet tagging efficiency of $\epsilon_b = 60\%$ in the range $|\eta| < 2.5$, apply the cuts on transverse momentum of all final state particles of $p_T^{e,j} > 30$ GeV and pseudorapidity cut of $|\eta| < 5$ on electron and jets.

Total cross section for $ep \rightarrow eHqX$ process as a function of anomalous couplings $\Delta a_Z$, $\beta_Z$ and $b_Z$ are given in Fig. 2 and Fig. 3 for 60 and 140 GeV energies of incoming electron, respectively. From these figures, we can see a symmetric behavior around zero point for $\beta_Z$ and increasing behaviour for $\Delta a_Z$, while the minimum of cross section behaves shifted to about 0.2 for $b_Z$. 

Figure 2: For the process $e^- p \rightarrow e^- HqX$, the dependence of the cross section on anomalous couplings $\Delta a_Z$, $b_Z$ and $\beta_Z$ for electron beam energy of 60 GeV.
Figure 3: The same as [2] but for the electron beam energy of 140 GeV.

IV. CONSTRAINTS ON ANOMALOUS COUPLINGS

In this section, the sensitivity of the anomalous $HZZ$ couplings is discussed. We estimate the sensitivity to these couplings at LHeC for the integrated luminosities of 10 and 100 fb$^{-1}$. We use $\chi^2$ function to obtain sensitivity:

$$\chi^2 = \left( \frac{\sigma_{SM} - \sigma_A}{\Delta \sigma_{SM}} \right)^2$$  \hspace{1cm} (2)

where $\sigma_A$ is the cross section including the anomalous couplings $\Delta a_Z, b_Z$ and $\beta_Z$. The error on the SM cross section is defined as $\Delta \sigma_{SM} = \sigma_{SM} \delta_{\text{stat.}}$, with $\delta_{\text{stat.}} = 1/\sqrt{N_{SM}}$; $N_{SM}$ is the number of events within the SM calculated as $N_{SM} = \sigma_{SM} \times BR(H \rightarrow b\bar{b}) \times (\epsilon_{b-\text{tag}})^2 \times L_{\text{int}}$. The SM cross section ($\sigma_{SM}$) corresponds to process $ep \rightarrow eHjX$ with vanishing anomalous couplings, where $j$ denotes light quarks.

For an electron beam energy of $E_e = 60$ GeV, the 95% C.L. accessible region in the plane $b_Z - \beta_Z$ is presented in Fig. 4 for the integrated luminosities 10 fb$^{-1}$ and 100 fb$^{-1}$. As one can see, higher luminosity provides better limits on the anomalous couplings. One can benefit from the higher center of mass energy corresponding to $E_e = 140$ GeV in order to obtain more sensitivity on the anomalous couplings as shown in Fig. 5. The contours has
an origin at (0.15, 0.0) for $(b_Z, \beta_Z)$, which is due to the cross section behaviour as a function of the parameter $b_Z$ as shown in Fig. 2. Assuming the SM value for \( \Delta a_Z = 0 \) and \( L_{\text{int}} = 10 \) fb\(^{-1} \), the accessible limits for the anomalous couplings are obtained as $-0.29 < b_Z < 0.61$ ($-0.51 < \beta_Z < 0.51$) and $-0.21 < b_Z < 0.45$ ($-0.37 < \beta_Z < 0.37$) at $E_e = 60$ GeV and $E_e = 140$ GeV, respectively. For an integrated luminosity of \( L_{\text{int}} = 100 \) fb\(^{-1} \), we find the limits on the couplings $-0.12 < b_Z < 0.43$ ($-0.32 < \beta_Z < 0.32$) and $-0.10 < b_Z < 0.33$ ($-0.24 < \beta_Z < 0.24$) at $E_e = 60$ GeV and $E_e = 140$ GeV, respectively.

V. CONCLUSIONS

The $e^- p \rightarrow e^- HqX$ process has smaller cross section when compared to $e^- p \rightarrow \nu_e HqX$ process [31–33], but it has the advantage of electron identification according to the missing neutrino in the latter case. We benefit from the kinematical cuts explained in the previous section to reduce leading background arising from the reactions including two $b$-jets in the
Figure 5: Accessible region (with 95% C.L.) of anomalous couplings at $E_\text{e} = 140$ GeV.

final state. We show that the LHeC at $\sqrt{s} = 1.9$ TeV with luminosity of $100 \ fb^{-1}$ could allow the measurement of $HZZ$ anomalous couplings $b_Z$ in the interval $(-0.10, 0.33)$ and $\beta_Z$ in $(-0.24, 0.24)$. This result can be compared with the result from [34] which establishes a limit on anomalous coupling $\beta_Z = 0.25$ at the LHC with $14$ TeV and $L = 30 \ fb^{-1}$. Using the feasibility of measurement of the bottom Yukawa coupling at the LHeC, it has the potential to enhance the efficiency of the overall Higgs boson signal.

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