SEARCH FOR ANOMALOUS $WW\gamma$ AND $WWZ$ COUPLINGS WITH POLARIZED $e$-BEAM AT THE LHeC

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We examine the possibility of constraining the anomalous $WW\gamma$ and $WWZ$ couplings by measuring total cross sections of the $ep \rightarrow \nu_e q\gamma X$ and $ep \rightarrow \nu_e qZX$ processes at the LHeC collider with the electron beam energy $E_e = 60$ GeV and $E_e = 140$ GeV. We consider the cases of unpolarized and polarized electron beams. The difference of the upper and lower bounds on the anomalous couplings, $(\delta \Delta \kappa_\gamma, \delta \lambda_\gamma)$ and $(\delta \Delta \kappa_Z, \delta \lambda_Z)$ are obtained as $(0.990, 0.122)$ and $(0.362, 0.012)$ without electron beam polarization at the beam energy of $E_e = 140$ GeV for an integrated luminosity of $L_{\text{int}} = 100$ fb$^{-1}$, respectively. With the possibility of $e$-beam polarization, we obtain more improved results as $(0.975, 0.118)$ and $(0.285, 0.009)$ for $(\delta \Delta \kappa_\gamma, \delta \lambda_\gamma)$ and $(\delta \Delta \kappa_Z, \delta \lambda_Z)$, respectively. The results are found to be comparable with the current experimental limits obtained from two-parameter fits to the data collected in the lepton and hadron colliders. It

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is found that the limits on the anomalous couplings \((\Delta \kappa_Z, \lambda_Z)\) through the process \(ep \rightarrow \nu, qZX\) at the LHeC can further improve the current experimental limits.

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1. Introduction

Triple gauge boson interactions are the consequence of the \(SU(2) \times U(1)\) gauge symmetry of the Standard Model (SM). A precise determination of the trilinear gauge boson couplings is necessary to test the validity of the SM and the presence of new physics up to a high energy scale. Since the tree-level couplings of the \(WW\gamma\) and \(WWZ\) vertices are fixed by the SM, any deviations from their SM values would indicate the new physics beyond the SM. The photoproduction of the \(W\) and \(Z\) bosons through triple gauge boson interactions in the lepton–hadron colliders HERA+LC and in the Large Hadron electron Collider (LHeC) has been studied theoretically in the papers [1] and [2], respectively. An investigation of the potential of the LHeC to probe anomalous \(WW\gamma\) coupling has been presented in Ref. [3].

The present bounds on the anomalous \(WW\gamma\) and \(WWZ\) couplings are provided by the LEP [4], Tevatron [5, 6] and LHC [7, 8] experiments. Recently, the ATLAS [7] and CMS [8] collaborations have established updated constraints on the anomalous \(WW\gamma\) and \(WWZ\) couplings from the \(\gamma W(Z)\) and \(W^+W^-\) production processes. The best available constraints on anomalous couplings \(\Delta \kappa_\gamma, \lambda_\gamma, \Delta \kappa_Z\) and \(\lambda_Z\) obtained from one-parameter analysis at different experiments are summarized in Table I.

| \(\Delta \kappa_\gamma\) | LEP [4] | CDF [5] | D0 [6] | ATLAS [7] | CMS [8] |
|-------------------------|----------|----------|---------|----------|---------|
| \([-0.099, 0.066]\) | \([-0.460, 0.390]\) | \([-0.158, 0.255]\) | \([-0.135, 0.190]\) | \([-0.210, 0.220]\) |
| \(\lambda_\gamma\) | \([-0.059, 0.017]\) | \([-0.180, 0.170]\) | \([-0.036, 0.044]\) | \([-0.065, 0.061]\) | \([-0.048, 0.048]\) |
| \(\Delta \kappa_Z\) | \([-0.073, 0.050]\) | \([-0.414, 0.470]\) | \([-0.110, 0.131]\) | \([-0.061, 0.093]\) | \([-0.160, 0.157]\) |
| \(\lambda_Z\) | \([-0.059, 0.017]\) | \([-0.140, 0.150]\) | \([-0.036, 0.044]\) | \([-0.062, 0.065]\) | \([-0.048, 0.048]\) |

The current limits based on one-parameter analysis at 95% C.L. on the \(\Delta \kappa_\gamma\) and \(\lambda_\gamma\) from the ATLAS Collaboration with \(W\gamma\) production process data at \(\sqrt{s} = 7\) TeV and \(L_{\text{int}} = 4.6\) fb\(^{-1}\) are \((-0.135, 0.190)\) and \((-0.065, 0.061)\) [7]. Similar limits are \((-0.420, 0.480)\) for \(\Delta \kappa_\gamma\) and \((-0.068, 0.062)\) for \(\lambda_\gamma\)
from two-parameter analysis at 95% C.L. Two-parameter 95% C.L. on anomalous couplings $\Delta \kappa_Z$ and $\lambda_Z$ are given as $(-0.045, 0.045)$ and $(-0.063, 0.063)$, respectively.

According to the CMS Collaboration, the current limits for one-parameter 95% C.L. are $(-0.210, 0.220)$ and $(-0.048, 0.048)$ for $\Delta \kappa_\gamma$ and $\lambda_\gamma$ from $W\gamma$ production process at $\sqrt{s} = 7$ TeV and $L_{\text{int}} = 5 \text{ fb}^{-1}$ [8]. From two-parameter contours, the upper and lower limits for $\Delta \kappa_\gamma$ and $\lambda_\gamma$ are $(-0.250, 0.250)$ and $(-0.050, 0.042)$ at the 95% C.L., while one-parameter 95% C.L. on $\Delta \kappa_Z$ and $\lambda_Z$ are $(-0.160, 0.157)$ and $(-0.048, 0.048)$ from $W^+W^- \gamma$ production process at $\sqrt{s} = 7$ TeV. Here, the relation $\Delta \kappa_Z = g_1^Z - \Delta \kappa_\gamma \tan^2 \theta_W$ is used to extract some of the current limits in the LEP scenario. The results from the ATLAS and CMS experiments based on two-parameter analysis of the anomalous couplings are given in Table II.

|                | ATLAS [7]       | CMS [8]        | ATLAS (upper–lower) | CMS (upper–lower) |
|----------------|-----------------|----------------|--------------------|-------------------|
| $\Delta \kappa_\gamma$ | [-0.420, 0.480] | [-0.250, 0.250] | 0.900              | 0.500             |
| $\lambda_\gamma$      | [-0.068, 0.062] | [-0.050, 0.042] | 0.130              | 0.092             |
| $\Delta \kappa_Z$     | [-0.045, 0.045] | [-0.160, 0.180] | 0.090              | 0.340             |
| $\lambda_Z$           | [-0.063, 0.063] | [-0.055, 0.055] | 0.126              | 0.110             |

In this study, we examined the $ep \rightarrow \nu_eq\gamma X$ and $ep \rightarrow \nu_eqZ X$ processes with anomalous $WW\gamma$ and $WWZ$ couplings at the high energy electron–proton collider LHeC. This collider is considered to be realised by accelerating electrons 60–140 GeV and colliding them with the 7 TeV protons incoming from the LHC. We take into account the possibility of the electron beam polarization at the LHeC which extends the sensitivity to anomalous triple gauge boson couplings. The anticipated integrated luminosity is taken at the order of 10 and 100 fb$^{-1}$ [9].

### 2. Anomalous couplings

The $WW\gamma$ and $WWZ$ interaction vertices are described by an effective Lagrangian with the coupling constants $g_{WW\gamma}$ and $g_{WWZ}$, and dimensionless parameter pairs $(\kappa_\gamma, \lambda_\gamma)$ and $(\kappa_Z, \lambda_Z)$,
$$\mathcal{L} = ig_{WW\gamma} \left[ g_1^\gamma \left( W_{\mu\nu}^\dagger A^\mu A^\nu - W^\mu W^\nu W_{\mu\nu} A^\nu \right) + \kappa W_{\mu}^\dagger W_{\nu} A^{\mu\nu} \right] + \frac{\lambda_W}{m_W^2} W_{\rho\mu} W_{\nu}^{\dagger} A^{\mu\nu} + ig_{WWZ} \left[ g_1^Z \left( W_{\mu\nu}^\dagger Z^\nu - W^\mu W_{\mu\nu} Z_{\nu} \right) + \kappa W_{\mu}^\dagger W_{\nu} Z^{\mu\nu} + \frac{\lambda_Z}{m_Z^2} W_{\rho\mu} W_{\nu}^{\dagger} Z^{\mu\nu} \right],$$

(1)

where $g_{WW\gamma} = g_e = g \sin \theta_W$ and $g_{WWZ} = g \cos \theta_W$. In general, these vertices involve six $C$ and $P$ conserving couplings [10]. However, the electromagnetic gauge invariance requires that $g_1^\gamma = 1$. The anomalous couplings are defined as $\kappa_V = 1 + \Delta \kappa_V$ where $V = \gamma, Z$ and $g_1^Z = 1 + \Delta g_1^Z$. The $W_{\mu\nu}, Z_{\mu\nu}$ and $A_{\mu\nu}$ are the field strength tensors for the $W$ boson, $Z$ boson and photon, respectively.

The one-loop corrections to the $WW\gamma$ and $WWZ$ vertices within the framework of the SM have been studied in [11]. These corrections to the $\Delta \kappa_V$ and $\lambda_V$ have been found to be of the order of $10^{-2}$ and $10^{-3}$, respectively. The values of the couplings $\kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$ correspond to the case of the SM. Since unitarity restricts the $WW\gamma$ and $WWZ$ couplings to their SM values at very high energies, the triple gauge couplings are modified as $\Delta \kappa_V(q^2) = \Delta \kappa_V(0)/(1 + q^2/A^2)^2$ and $\lambda_V(q^2) = \lambda_V(0)/(1 + q^2/A^2)^2$, where $V = \gamma, Z$. The $q^2$ is the square of momentum transfer into the process and $A$ is the new physics energy scale. The $\Delta \kappa_V(0)$ and $\lambda_V(0)$ are the values of the anomalous couplings at $q^2 = 0$. We assume the values of the anomalous couplings remain approximate constant in the interested energy scale ($A^2 > q^2$). We take $\Delta \kappa_V$ and $\lambda_V$ as free parameters in the considered range and find the bounds on these couplings effectively. For the numerical calculations, we have implemented interactions terms in the CalcHEP [12].

3. Production cross sections

According to the effective Lagrangian, the anomalous vertices for triple gauge interactions $WW\gamma$ and $WWZ$ are presented in the Feynman graphs as shown in Figs. 1 and 2. In order to calculate the cross sections for the process $ep \rightarrow \nu_e q \gamma X$ and $ep \rightarrow \nu_e q Z X$, we apply the transverse momentum cut on photon and jet as $p_T^\gamma > 50$ GeV, $p_T^j > 20$ GeV; missing transverse momentum cut $p_T^{\nu_e} > 20$ GeV, pseudorapidity cuts $|\eta_{\gamma,j}| < 3.5$; a cone radius cut between photons and jets $\Delta R_{\gamma,j} > 1.5$. Using these cuts and the parton distribution functions of CTEQ6L [13], the total cross sections of the process $ep \rightarrow \gamma q X$ as a function of anomalous couplings $\Delta \kappa_\gamma$ and $\lambda_\gamma$ for $E_e = 60$ GeV (140 GeV) with $(P_e = \pm 0.8)$ and without $(P_e = 0)$ electron beam
polarization are presented in Figs. 3 and 4 (Figs. 5 and 6), respectively. It is clear from these figures that the polarization ($P_e = -0.8$) enhances the cross sections according to the unpolarized case.

The cross sections depending on anomalous couplings $\Delta \kappa_Z$ and $\lambda_Z$ of the process $ep \to \nu Z q X$ for $E_e = 60$ GeV (140 GeV) with ($P_e = \pm 0.8$) and without ($P_e = 0$) electron beam polarization are presented in Figs. 7 and 8 (Figs. 9 and 10), respectively.

Fig. 1. Representative Feynman diagrams for subprocess $e q \to \nu_e \gamma q'$.

Fig. 2. Representative Feynman diagrams for subprocess $e q \to \nu_e Z q'$. 

Fig. 3. The cross section depending on anomalous coupling $\Delta \kappa_{\gamma}$ of the process $e p \rightarrow \nu \gamma qX$ at $E_e = 60$ GeV for different electron beam polarizations.

Fig. 4. The cross section depending on anomalous coupling $\lambda_{\gamma}$ of the process $e p \rightarrow \nu \gamma qX$ at $E_e = 60$ GeV for different electron beam polarizations.

Fig. 5. The same as Fig. 3 but for $E_e = 140$ GeV.
Fig. 6. The same as Fig. 4 but for $E_e = 140$ GeV.

Fig. 7. The cross section depending on anomalous $\Delta \kappa_Z$ coupling of the process $ep \rightarrow \nu ZqX$ for $E_e = 60$ GeV.

Fig. 8. The cross section depending on anomalous $\lambda_Z$ coupling of the process $ep \rightarrow \nu ZqX$ for $E_e = 60$ GeV.
4. Analysis

In order to estimate the sensitivity to the anomalous $WW\gamma$ and $WWZ$ couplings, we use two-parameter $\chi^2$ function

$$
\chi^2(\Delta \kappa_V, \lambda_V) = \left( \frac{\sigma_{SM} - \sigma(\Delta \kappa_V, \lambda_V)}{\Delta \sigma_{SM}} \right)^2,
$$

where $\Delta \sigma_{SM} = \sigma_{SM} \sqrt{\delta_{stat}^2}$ with $\delta_{stat} = 1/\sqrt{N_{SM}}$ and $N_{SM} = \sigma_{SM} L$. In our calculations, we consider that two of the couplings ($\Delta \kappa$, $\lambda$) are assumed to deviate from their SM value. We estimate the sensitivity to the anomalous couplings at 95 C.L. at the LHeC for the integrated luminosities of 10 fb$^{-1}$ and 100 fb$^{-1}$. The contour plots of anomalous couplings in $\Delta \kappa - \lambda$ plane for the integrated luminosities of 10 fb$^{-1}$ and 100 fb$^{-1}$ at electron beam energies $E_e = 60$ (140) GeV with different polarizations are given in Figs. 11–16. For
the process $ep \rightarrow \nu_e qZX$, we make analysis of the signal and backgrounds when $Z$ decays leptonically, $Z \rightarrow l^+ l^-$, where $l = e, \mu$. The contour plots of anomalous couplings in $\Delta \kappa_Z - \lambda_Z$ plane for the integrated luminosities of 10 fb$^{-1}$ and 100 fb$^{-1}$ at electron beam energies of $E_e = 60(140)$ GeV with different polarizations are presented in Figs. 17–22.

Fig. 11. Two dimensional 95% C.L. contour plot of anomalous couplings in the $\lambda_\gamma - \Delta \kappa_\gamma$ plane for the integrated luminosity of 10 fb$^{-1}$ and 100 fb$^{-1}$ at electron beam energy $E_e = 60$ GeV with the beam polarization $P_e = 0.8$.

Fig. 12. The same as Fig. 11 but for $P_e = 0$. 
Fig. 13. The same as Fig. 11 but for $P_e = -0.8$.

Fig. 14. Two dimensional 95% C.L. contour plot anomalous couplings in the $\lambda_\gamma-\Delta\kappa_\gamma$ plane for the integrated luminosity of $10$ fb$^{-1}$ and $100$ fb$^{-1}$ at electron beam energy $E_e = 140$ GeV with polarization $P_e = 0.8$.

Fig. 15. The same as Fig. 14 but for $P_e = 0$. 
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Fig. 16. The same as Fig. 14 but for $P_e = -0.8$ GeV.

Fig. 17. Two dimensional 95% C.L. contour plot of anomalous couplings in the $\lambda_Z-\Delta\kappa_Z$ plane for the integrated luminosity of 10 fb$^{-1}$ and 100 fb$^{-1}$ at electron beam energy $E_e = 60$ GeV with polarization $P_e = 0.8$.

Fig. 18. The same as Fig. 17 but for $P_e = 0$. 
Fig. 19. The same as Fig. 17 but for $P_e = -0.8$.

Fig. 20. Two-dimensional 95% C.L. contour plot of anomalous couplings in the $\lambda_Z - \Delta \kappa_Z$ plane for the integrated luminosity of 10 fb$^{-1}$ and 100 fb$^{-1}$ at electron beam energy $E_e = 140$ GeV with polarization $P_e = 0.8$.

Fig. 21. The same as Fig. 20 but for $P_e = 0$. 
The difference of the upper and lower bounds on the anomalous couplings $\Delta \kappa_V$ and $\lambda_V$ (where $V = \gamma, Z$) can be written as

$$\delta \Delta \kappa_V = \Delta \kappa_V^{\text{upper}} - \Delta \kappa_V^{\text{lower}}, \quad \delta \lambda_V = \lambda_V^{\text{upper}} - \lambda_V^{\text{lower}}. \quad (3)$$

The current limits on anomalous couplings and the difference of the upper and lower bounds for electron beam energies of $E_e = 60$ and $140$ GeV with integrated luminosities $L_{\text{int}} = 10 \text{ fb}^{-1}$ and $100 \text{ fb}^{-1}$ at LHeC with the unpolarized (polarized) electron beam are given in Tables III–VI. We have obtained two-parameter limits on $\delta \Delta \kappa_\gamma$ and $\delta \lambda_\gamma$ which can be compared to the ATLAS and CMS results. However, the current limits on $\delta \lambda_Z$ is found to be much more sensitive at the LHeC.

**TABLE III**

The 95% C.L. current limits on the anomalous couplings and the difference of the upper and lower bounds for electron beam energy of $E_e = 60$ GeV with $L_{\text{int}} = 10 \text{ fb}^{-1}$ for polarized and unpolarized electron beam.

| $P_e$ | $\Delta \kappa_\gamma$ | $\delta \Delta \kappa_\gamma$ | $\lambda_\gamma$ | $\delta \lambda_\gamma$ |
|-------|-------------------------|-------------------------------|------------------|------------------------|
| $-0.8$ | $[-0.366, 0.899]$ | $1.265$ | $[-0.085, 0.148]$ | $0.233$ |
| $0$ | $[-0.421, 0.940]$ | $1.361$ | $[-0.094, 0.159]$ | $0.253$ |
| $0.8$ | $[-0.641, 1.177]$ | $1.818$ | $[-0.141, 0.208]$ | $0.349$ |

| $P_e$ | $\Delta \kappa_Z$ | $\delta \Delta \kappa_Z$ | $\lambda_Z$ | $\delta \lambda_Z$ |
|-------|-------------------|--------------------------|-------------|-------------------|
| $-0.8$ | $[-0.152, 0.471]$ | $0.623$ | $[-0.016, 0.033]$ | $0.049$ |
| $0$ | $[-0.180, 0.498]$ | $0.677$ | $[-0.018, 0.035]$ | $0.053$ |
| $0.8$ | $[-0.293, 0.611]$ | $0.904$ | $[-0.027, 0.044]$ | $0.071$ |
The same as Table III but for $L_{\text{int}} = 100 \text{ fb}^{-1}$.

| $P_e$ | $\Delta \kappa_\gamma$ | $\delta \Delta \kappa_\gamma$ | $\lambda_\gamma$ | $\delta \lambda_\gamma$ |
|-------|-----------------|-----------------|-----------------|-----------------|
| $-0.8$ | $[-0.237, 0.771]$ | $1.008$ | $[-0.061, 0.124]$ | $0.185$ |
| $0$ | $[-0.257, 0.777]$ | $1.034$ | $[-0.064, 0.128]$ | $0.192$ |
| $0.8$ | $[-0.356, 0.893]$ | $1.249$ | $[-0.087, 0.153]$ | $0.240$ |

| $P_e$ | $\Delta \kappa_Z$ | $\delta \Delta \kappa_Z$ | $\lambda_Z$ | $\delta \lambda_Z$ |
|-------|-----------------|-----------------|-----------------|-----------------|
| $-0.8$ | $[-0.088, 0.405]$ | $0.493$ | $[-0.011, 0.027]$ | $0.038$ |
| $0$ | $[-0.104, 0.412]$ | $0.516$ | $[-0.012, 0.028]$ | $0.040$ |
| $0.8$ | $[-0.147, 0.465]$ | $0.612$ | $[-0.016, 0.032]$ | $0.048$ |

The 95% C.L. current limits on the anomalous couplings and the difference of the upper and lower bounds for electron beam energy of $E_e = 140 \text{ GeV}$ with $L_{\text{int}} = 10 \text{ fb}^{-1}$ for polarized and unpolarized electron beam.

| $P_e$ | $\Delta \kappa_\gamma$ | $\delta \Delta \kappa_\gamma$ | $\lambda_\gamma$ | $\delta \lambda_\gamma$ |
|-------|-----------------|-----------------|-----------------|-----------------|
| $-0.8$ | $[-0.255, 0.865]$ | $1.120$ | $[-0.049, 0.088]$ | $0.137$ |
| $0$ | $[-0.288, 0.895]$ | $1.183$ | $[-0.052, 0.092]$ | $0.144$ |
| $0.8$ | $[-0.255, 1.035]$ | $1.120$ | $[-0.070, 0.109]$ | $0.179$ |

| $P_e$ | $\Delta \kappa_Z$ | $\delta \Delta \kappa_Z$ | $\lambda_Z$ | $\delta \lambda_Z$ |
|-------|-----------------|-----------------|-----------------|-----------------|
| $-0.8$ | $[-0.208, 0.207]$ | $0.415$ | $[-0.003, 0.010]$ | $0.013$ |
| $0$ | $[-0.350, 0.170]$ | $0.520$ | $[-0.005, 0.012]$ | $0.017$ |
| $0.8$ | $[-0.407, 0.373]$ | $0.780$ | $[-0.008, 0.014]$ | $0.022$ |

The 95% C.L. current limits on the anomalous couplings and the difference of the upper and lower bounds for electron beam energy of $E_e = 140 \text{ GeV}$ with $L_{\text{int}} = 100 \text{ fb}^{-1}$ for polarized and unpolarized electron beam.

| $P_e$ | $\Delta \kappa_\gamma$ | $\delta \Delta \kappa_\gamma$ | $\lambda_\gamma$ | $\delta \lambda_\gamma$ |
|-------|-----------------|-----------------|-----------------|-----------------|
| $-0.8$ | $[-0.182, 0.793]$ | $0.975$ | $[-0.039, 0.079]$ | $0.118$ |
| $0$ | $[-0.192, 0.798]$ | $0.990$ | $[-0.041, 0.081]$ | $0.122$ |
| $0.8$ | $[-0.251, 0.844]$ | $1.095$ | $[-0.047, 0.086]$ | $0.133$ |

| $P_e$ | $\Delta \kappa_Z$ | $\delta \Delta \kappa_Z$ | $\lambda_Z$ | $\delta \lambda_Z$ |
|-------|-----------------|-----------------|-----------------|-----------------|
| $-0.8$ | $[-0.143, 0.142]$ | $0.285$ | $[-0.001, 0.008]$ | $0.009$ |
| $0$ | $[-0.273, 0.089]$ | $0.362$ | $[-0.003, 0.009]$ | $0.012$ |
| $0.8$ | $[-0.253, 0.215]$ | $0.468$ | $[-0.004, 0.010]$ | $0.014$ |
5. Conclusions

The $WW\gamma$ and $WWZ$ anomalous interactions through the processes $ep \rightarrow \nu_e q\gamma X$ and $ep \rightarrow \nu_e qZX$ can be studied independently at the LHeC. We obtain two-parameter accessible ranges of triple gauge boson anomalous couplings at the LHeC with the polarized and unpolarized beam at the energies of $E_e = 60$ GeV and $E_e = 140$ GeV. Our limits compare with the results from two-parameter analysis given by ATLAS and CMS collaborations [7, 8]. We find that the sensitivities to anomalous couplings $\Delta \kappa_V$ ($V = \gamma, Z$) will be of the order of $10^{-1}$, which is an order of magnitude larger than the SM loop level sensitivity of $10^{-2}$, however a measurement of these couplings above $10^{-2}$ would offer a possible new physics signal. We conclude that the anomalous coupling $\lambda_Z$ can be best constrained with the sensitivity of the order of $10^{-3}$ at the LHeC with polarized electron beam. The LHeC will give complementary information about anomalous couplings compared to Tevatron and the LHC.

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