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Probing Anomalous *WWγ* and *WWZ* Couplings with Polarized Electron Beam at the LHeC and FCC-Ep Collider

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***Abstract*—**We study the anomalous *WWγ* and *WWZ* couplings by calculating total cross sections of two processes at the LHeC with electron beam energy Ee=140 GeV and the proton beam energy Ep=7 TeV, and at the FCC-ep collider with the polarized electron beam energy Ee=80 GeV and the proton beam energy Ep=50 TeV. At the LHeC with electron beam polarization, we obtain the results for the difference of upper and lower bounds as (0.975, 0.118) and (0.285, 0.009) for the anomalous (Δκγ, λγ) and (Δκz, λz) couplings, respectively. As for FCC-ep collider, these bounds are obtained as (1.101, 0.065) and (0.320, 0.002) at an integrated luminosity of L_{int}=100 fb^{-1}.

***Keywords*—**Anomalous Couplings, Future Circular Collider, Large Hadron electron Collider, *W*-boson and *Z*-boson.

I. Introduction

THE *SU*(2)×*U*(1) gauge symmetry of the Standard Model (SM) results in the triple gauge boson interactions. 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*γ 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]-[3] and [4], respectively. An investigation of the potential of the LHeC to probe anomalous *WW*γ coupling has been presented in [5], [6].

The present bounds on the anomalous *WWγ* and *WWZ* couplings are provided by the LEP [7], Tevatron [8], [9] and LHC [10], [11] experiments.

Recently, the ATLAS [10], [11] and CMS [12], [13] Collaborations have established updated constraints on the anomalous WWγ and *WWZ* couplings from the *γW(Z)* and W^+W^- production processes. The results from ATLAS and CMS experiments based on two-parameter analysis of the anomalous couplings are given in Table I.

In this work, we investigate the $ep\rightarrow\nu_e q\gamma X$ and $ep\rightarrow\nu_e qZX$ processes with anomalous *WW*γ and *WWZ* couplings at the high energy electron-proton collider LHeC and FCC-ep (Future Circular Collider-electron proton) collider [14]. LHeC is considered to be realised by accelerating electrons 140 GeV and colliding them with the 7 TeV protons. We take into account the energies of the FCC-ep as 80 GeV for electron beam and 50 TeV for proton beam. We also consider the possibility of the electron beam polarization at LHeC [15] and FCC-ep which extends the sensitivity to anomalous triple gauge boson couplings.

TABLE I
THE AVAILABLE 95% C.L. TWO-PARAMETER BOUNDS ON ANOMALOUS COUPLINGS (Δκγ, λγ) AND (ΔΚZ, λZ) FROM THE ATLAS AND CMS EXPERIMENTS

	ATLAS	CMS	ATLAS (upper-lower)	CMS (upper-lower)
Δκγ	-0.420,0.480	-0.250, 0.250	0.900	0.500
λγ	-0.068,0.062	-0.050, 0.042	0.130	0.092
Δκz	-0.045,0.045	-0.160, 0.180	0.090	0.340
λz	-0.063,0.063	-0.055, 0.055	0.126	0.110

II. Anomalous Couplings

The *WW*γ and *WWZ* interaction vertices are described by an effective Lagrangian with the coupling constants $g_{WW\gamma}$ and g_{WWZ} and dimensionless parameter pairs (Δκγ,λγ) and (Δκz, λz)

$$L = igww_\gamma[g_1^\gamma(W_{\mu\nu}^\dagger W^\mu A^\nu - W^{\mu\nu}W_\mu^\dagger A_\nu) + \kappa_\gamma W_\mu^\dagger W_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu A^{\nu\rho}] + igww_Z[g_1^Z(W_{\mu\nu}^\dagger W^\mu Z^\nu - W^{\mu\nu}W_\mu^\dagger Z_\nu) + \kappa_Z W_\mu^\dagger W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu Z^{\nu\rho}] \quad (1)$$

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 [16]. 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=γ,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 *WWγ* and *WWZ* vertices within the framework of the SM have been studied in [17]-[19]. These corrections to the $\Delta\kappa_V$ and λ_V have been found to be of the order of 10^{-2} and 10^{-3}, respectively. The values of the

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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 $\Delta\kappa_V(q^2)=\Delta\kappa_V(0)/(1+q^2/\Lambda^2)^2$ and $\lambda_V(q^2)=\lambda_V(0)/(1+q^2/\Lambda^2)^2$ where $V=\gamma,Z$. The q^2 is the square of momentum transfer into the process and Λ 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 ($\Lambda^2>q^2$). We take $\Delta\kappa_V$ and λ_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 [20].

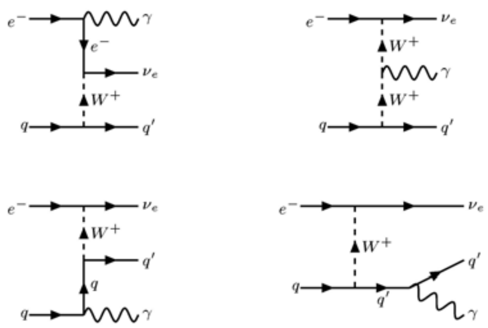

Fig. 1 Representative Feynman diagrams for subprocess $eq\to\nu_e\gamma q'$

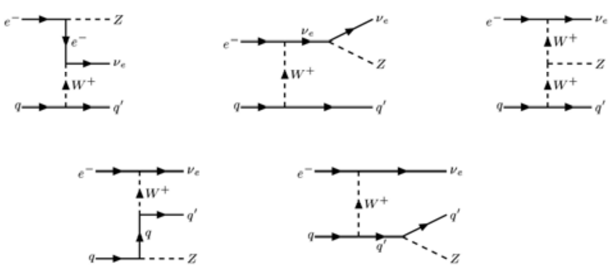

Fig. 2 Representative Feynman diagrams for subprocess $eq\to\nu_e Zq'$

III. PRODUCTION CROSS SECTIONS FOR LHEC

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 $ep\to\nu_e q\gamma X$ and $ep\to\nu_e qZX$, 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 $p_T^\nu > 20$ 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 [21], the total cross sections of the process $ep\to\nu_e q\gamma X$ as a function of anomalous couplings $\Delta\kappa_\gamma$ and λ_γ for E_e=140 GeV with electron beam polarizations $P_e=\pm0.8$ and $P_e=0$ are presented in Figs. 3 and 4. In Figs. 5 and 6, the total cross sections of the $ep\to\nu_e qZX$ process are given for the same energy. It is clear from these figures that the polarization ($P_e=-0.8$) enhances the cross sections according to the unpolarized case.

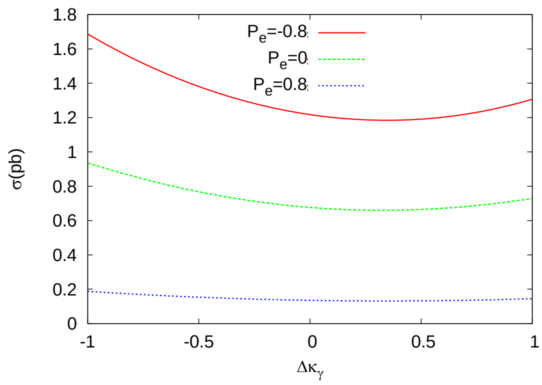

Fig. 3 The cross section depending on anomalous coupling Δκγ of the process $ep\to\nu_e q\gamma X$ at Ee=140 GeV for different electron beam b polarizations

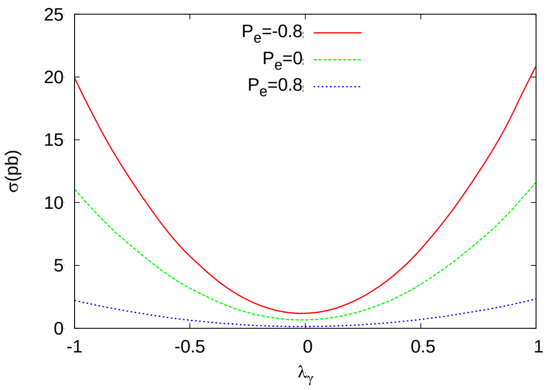

Fig. 4 The cross section depending on anomalous coupling λγ of the process $ep\to\nu_e q\gamma X$ at Ee=140 GeV for different electron beam polarizations

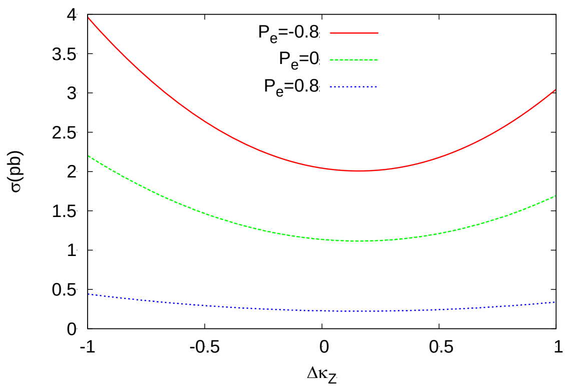

Fig. 5 The cross section depending on anomalous $\Delta\kappa_Z$ coupling of the process $ep\to\nu_e qZX$ for E_e=140 GeV

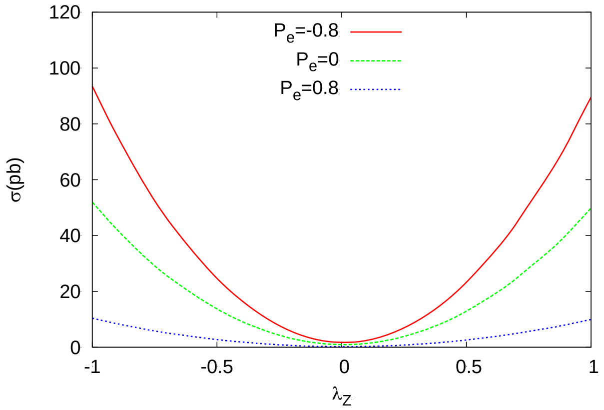

Fig. 6 The cross section depending on anomalous λ_Z coupling of the process $ep\rightarrow\nu_e qZX$ for E_e=140 GeV

IV. Analysis for LHEC

In order to estimate the sensitivity to the anomalous $WW\gamma$ and WWZ couplings, we use the χ^2 function:

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

where $\Delta\sigma_{SM} = \sigma_{SM}\sqrt{\delta^2_{stat.}}$ with $\delta_{stat.} = 1/\sqrt{N_{SM}}$ and $N_{SM}=\sigma_{SM}.L$. In our calculations, we consider that two of the couplings ($\Delta\kappa$,λ) 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 $\Delta\kappa_\gamma$- λ_γ plane for the integrated luminosities of 10 fb^{-1} and 100 fb^{-1} at electron beam energies E_e=140 GeV are given in Fig. 7. The contour plots of anomalous couplings in $\Delta\kappa_Z$-λ_Z plane for the integrated luminosities of 10 fb^{-1} and 100 fb^{-1} at electron beam energies of E_e=140 GeV are shown in Fig. 8.

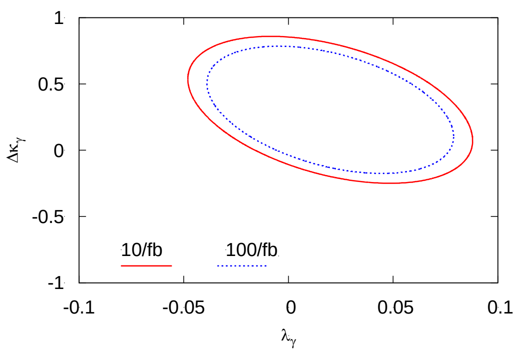

Fig. 7 Two dimensional 95% C.L contour plot anomalous couplings in the $\lambda_\gamma-\Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy E_e=140 GeV with polarization P_e=−0.8

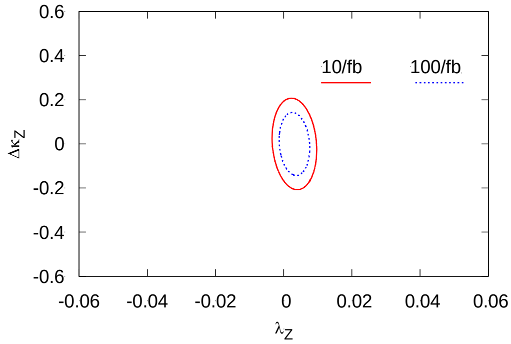

Fig. 8 Two-dimensional 95% C.L contour plot of anomalous couplings in the λ_Z -$\Delta\kappa_Z$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy E_e=140 GeV with polarization *Pe=-0.8*

The difference of the upper and lower bounds on the anomalous couplings $\Delta\kappa_V$ and λ_V (where V=γ, Z) can be written as

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

The current limits on anomalous couplings and the difference of the upper and lower bounds for electron beam energies of 140 GeV with integrated luminosities L_{int}=10 fb^{-1} and 100 fb^{-1} at LHeC with the unpolarized (polarized) electron beam are given in Table II. 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 limits on $\delta\lambda_Z$ is found to be much more sensitive than the current limits.

TABLE II
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 GeV with L_{INT}=100 fb^{-1} for Polarized and Unpolarized Electron Beam

Pe	**Δκγ**	**δΔκγ**	**λγ**	**δλγ**
-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
Pe	**Δκz**	**δΔκz**	**λz**	**δλz**
-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

V. Production Cross Sections for FCC-EP

For calculate the cross sections for the process $ep\rightarrow\nu_e q\gamma X$ and $ep\rightarrow\nu_e qZX$, we apply the transverse momentum cut on photon and jet as $p_T^\gamma > 20$ GeV, $p_T^j >$ 20 GeV; missing transverse momentum cut $p_T^\nu > 20$ GeV, pseudorapidity cuts $\eta_{\gamma,j}$ the range of between -5 and 0; Using these cuts and the parton distribution functions of CTEQ6M [14], the total cross sections of the process $ep\rightarrow\nu\gamma qX$ as a function of anomalous couplings $\Delta\kappa_\gamma$ and λ_γ for E_e=80 GeV with (P_e=±0.8) and without (P_e=0) electron beam polarization are presented in Figs. 9 and 10. It is clear from these figures that the polarization (P_e=−0.8) enhances the cross sections according to the unpolarized case.

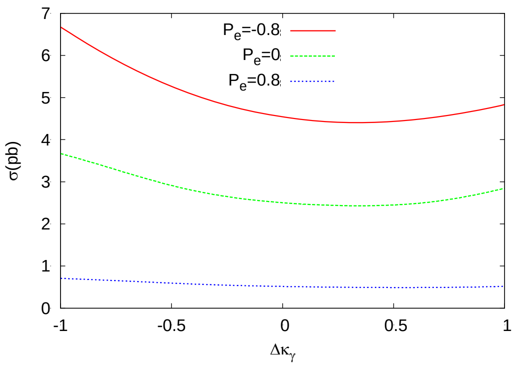

Fig. 9 The cross section depending on anomalous coupling $\Delta\kappa_\gamma$ of the process $ep\to\nu_e q\gamma X$ at E_e=80 GeV for different electron beam polarizations

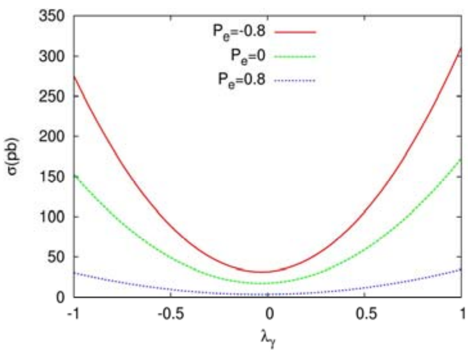

Fig. 10 The cross section depending on anomalous λ_γ coupling of the process $ep\to\nu_e q\gamma X$ for E_e=80 GeV

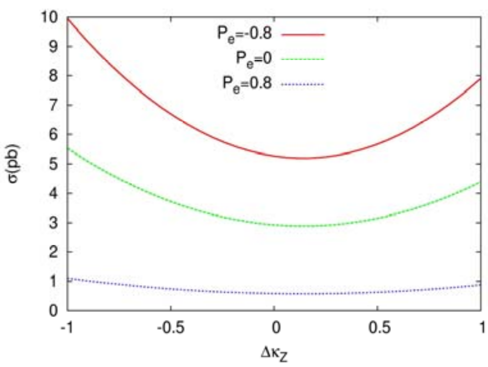

Fig. 11 The cross section depending on anomalous $\Delta\kappa_Z$ coupling of the process $ep\to\nu_e qZX$ for E_e=80 GeV

The cross sections depending on anomalous couplings $\Delta\kappa_Z$ and λ_Z of the process $ep\to\nu_e qZX$ for E_e=80 GeV with P_e=±0.8 and without (P_e=0) electron beam polarization are presented in Figs. 11 and 12.

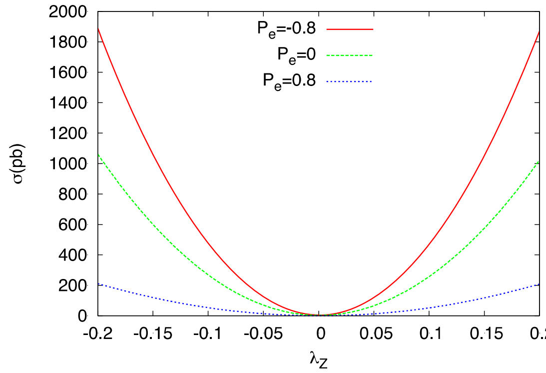

Fig. 12 The cross section depending on anomalous λ_Z coupling of the process $ep\to\nu_e qZX$ for E_e=80 GeV

VI. Analysis for FCC-ep

The contour plots of anomalous couplings in $\Delta\kappa_\gamma$- λ_γ plane for the integrated luminosities of 10 fb^{-1} and 100 fb^{-1} at electron beam energies E_e=80 GeV are given in Fig. 13. For the process $ep\to\nu_e qZX$, we make analysis of the signal and backgrounds when Z decays leptonically, $Z\to l^+l^-$ where l=e, μ. The contour plots of anomalous couplings in $\Delta\kappa_Z$-λ_Z plane for the integrated luminosities of 10 fb^{-1} and 100 fb^{-1} at electron beam energies of E_e=80 GeV are presented in Fig. 14.

The difference of the upper and lower bounds on the anomalous couplings $\Delta\kappa_V$ and λ_V (where V=γ, Z) can be written as

$$\delta\Delta\kappa_V = \Delta\kappa_V^{upper} - \Delta\kappa_V^{lower}, \delta\lambda_V = \lambda_V^{upper} - \lambda_V^{lower} \qquad (4)$$

The current limits on anomalous couplings and the difference of the upper and lower bounds for electron beam energies of E_e=80 GeV with integrated luminosities 100 fb^{-1} at FCC-ep with the unpolarized (polarized) electron beam are given in Table III. 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 FCC-ep.

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=80 GeV with L_{INT}=100 fb^{-1} for Polarized Electron Beam

Pe	Δκγ	δΔκγ	λγ	δλγ
-0.8	-0.100:1.001	1.101	-0.026:0.039	0.0650
Pe	Δκz	δΔκz	λz	δλz
-0.8	-0.019:0.301	0.320	-0.0011:0.0012	0.0023

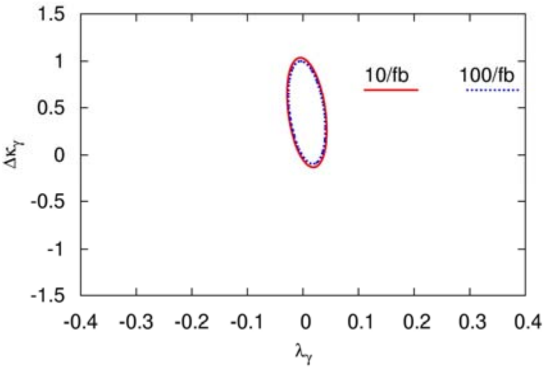

Fig. 13 Two dimensional 95% C.L contour plot anomalous couplings in the $\lambda_\gamma-\Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy E_e=80 GeV with polarization P_e=−0.8

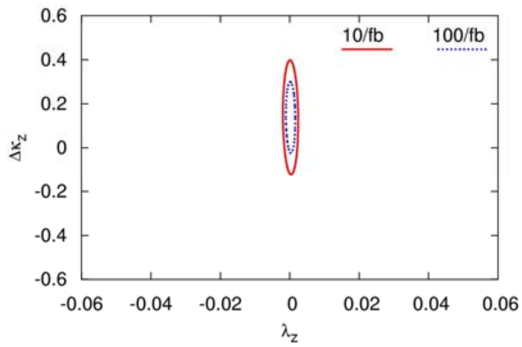

Fig. 14 Two-dimensional 95% C.L contour plot of anomalous couplings in the $\lambda_Z-\Delta\kappa_Z$ plane for the integrated luminosity of 10fb^{-1} and 100 fb^{-1} at electron beam energy E_e=80 GeV with polarization

VII. Conclusion

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 and FCC-ep. We obtain two-parameter accessible ranges of triple gauge boson anomalous couplings at LHeC and FCC-ep with the polarized electron beam at the energies E_e=140 GeV and E_p=7 TeV, and E_e=80 GeV and E_p=50 TeV, respectively. Our limits compare with the results from two-parameter analysis given by ATLAS and CMS Collaborations [10]-[13]. We find that the sensitivities to anomalous couplings $\Delta\kappa_V$ (V=γ, 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 couplings λ_γ and λ_Z can be well constrained with the sensitivity of the order of 10^{-2} and 10^{-3} at the FCC-ep with polarized electron beam. The LHeC and FCC-ep could give complementary information about anomalous couplings compared to Tevatron and LHC.

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