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Probing Anomalous $WW\gamma$ and WWZ Couplings with Polarized Electron Beam at the LHeC and FCC-Ep Collider

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***Abstract*—**We study the anomalous $WW\gamma$ 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 ($\Delta\kappa\gamma$, $\lambda\gamma$) and ($\Delta\kappa z$, 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 $SU(2)\times U(1)$ 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 $WW\gamma$ 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]-[3] and [4], respectively. An investigation of the potential of the LHeC to probe anomalous $WW\gamma$ coupling has been presented in [5], [6].

The present bounds on the anomalous $WW\gamma$ 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 $\gamma W(Z)$ 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 $WW\gamma$ 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 ($\Delta\kappa\gamma$, $\lambda\gamma$) AND (ΔKz, λZ) FROM THE ATLAS AND CMS EXPERIMENTS

	ATLAS	CMS	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
λz	-0.063,0.063	-0.055, 0.055	0.126	0.110

II. 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 ($\Delta\kappa\gamma$,$\lambda\gamma$) and ($\Delta\kappa z$, 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 $WW\gamma$ 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*γ 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].

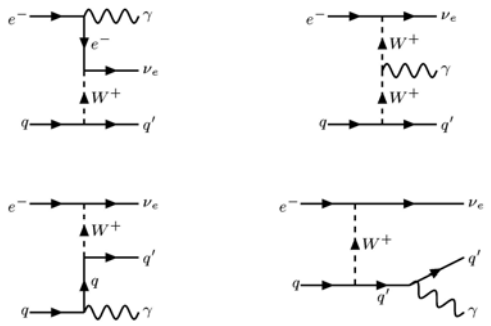

Fig. 1 Representative Feynman diagrams for subprocess $eq\rightarrow\nu_e\gamma q'$

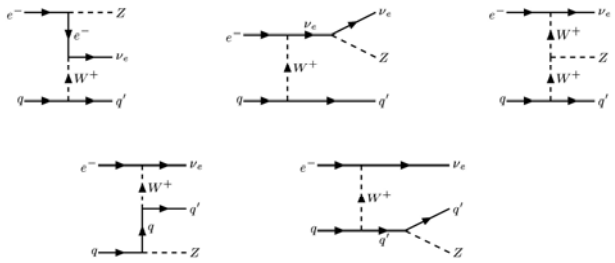

Fig. 2 Representative Feynman diagrams for subprocess $eq\rightarrow\nu_e Zq'$

III. Production Cross Sections for LHEC

According to the effective Lagrangian, the anomalous vertices for triple gauge interactions *WW*γ 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 $ep\rightarrow\nu_e qZX$, 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 $ep\rightarrow\nu_e q\gamma X$ 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 $ep\rightarrow\nu_e qZX$ 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.

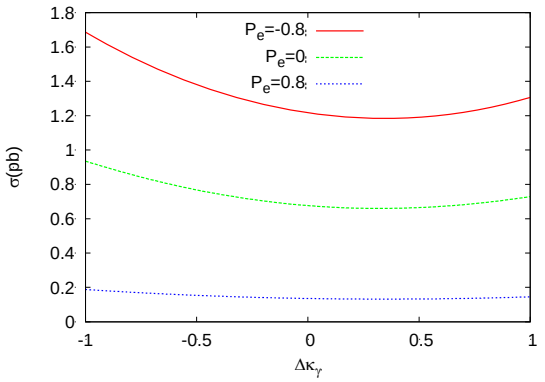

Fig. 3 The cross section depending on anomalous coupling Δκγ of the process $ep\rightarrow\nu_e q\gamma X$ at Ee=140 GeV for different electron beam b polarizations

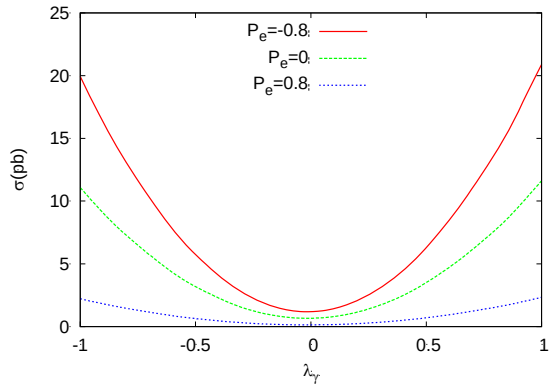

Fig. 4 The cross section depending on anomalous coupling λγ of the process $ep\rightarrow\nu_e q\gamma X$ at Ee=140 GeV for different electron beam polarizations

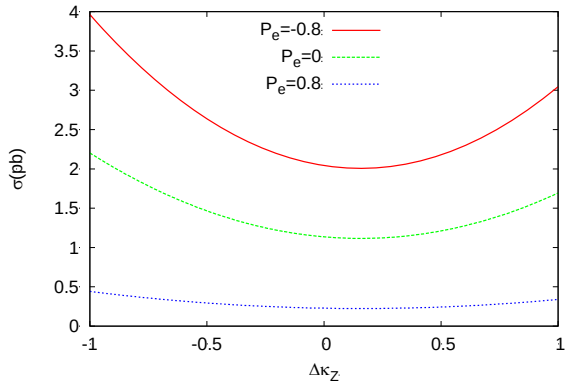

Fig. 5 The cross section depending on anomalous $\Delta\kappa_Z$ coupling of the process $ep\rightarrow\nu_e qZX$ for E_e=140 GeV

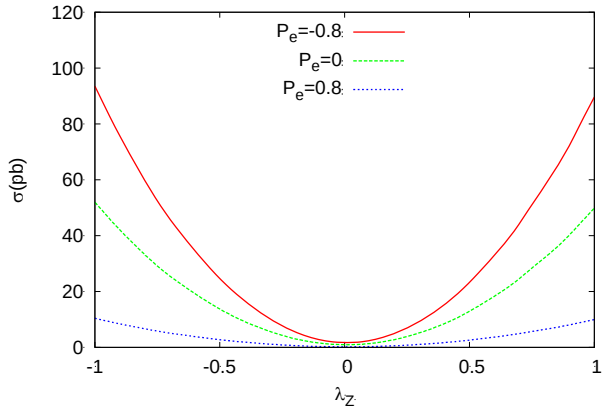

Fig. 6 The cross section depending on anomalous λ_Z coupling of the process $ep \to \nu_e qZX$ for E_e=140 GeV

IV. Analysis for LHEC

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

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

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 ($\Delta\kappa,\lambda$) 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 $\Delta\kappa_\gamma$ - 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.

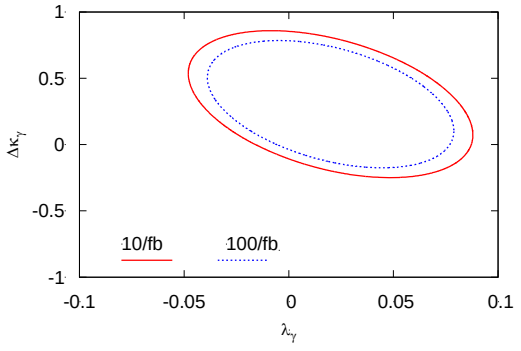

Fig. 7 Two dimensional 95% C.L contour plot anomalous couplings in the λ_γ–$\Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy E_e=140 GeV with polarization P_e=–0.8

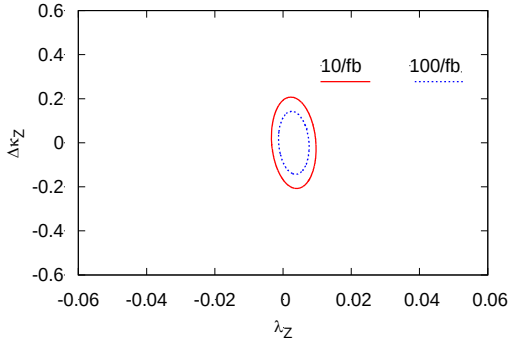

Fig. 8 Two-dimensional 95% C.L contour plot of anomalous couplings in the λ_Z -$\Delta\kappa_Z$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy E_e=140 GeV with polarization *Pe=-0.8*

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

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

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 $ep \to \nu_e q\gamma X$ and $ep \to \nu_e qZX$, we apply the transverse momentum cut on photon and jet as $p_T^\gamma > 20$ 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 $ep \to \nu\gamma qX$ 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.

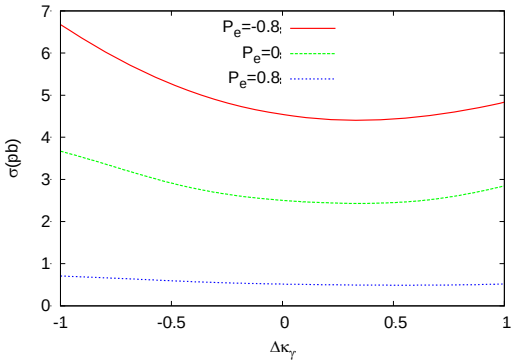

Fig. 9 The cross section depending on anomalous coupling $\Delta\kappa_\gamma$ of the process $ep\to\nu_e q\gamma X$ at E_e=80 GeV for different electron beam polarizations

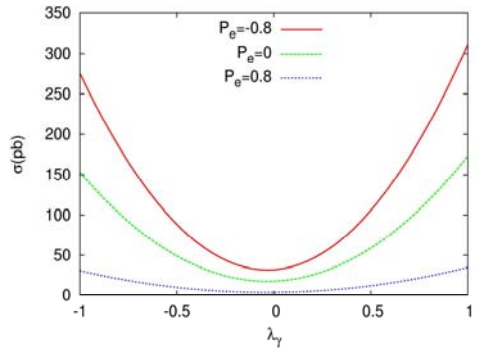

Fig. 10 The cross section depending on anomalous λ_γ coupling of the process $ep\to\nu_e q\gamma X$ for E_e=80 GeV

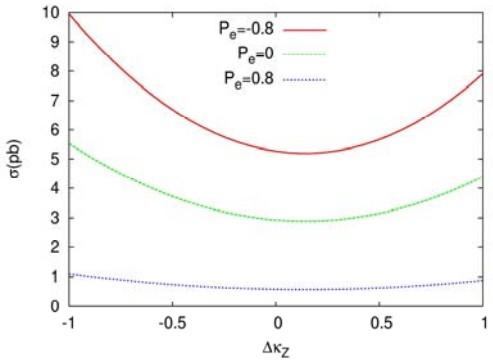

Fig. 11 The cross section depending on anomalous $\Delta\kappa_Z$ coupling of the process $ep\to\nu_e qZX$ for E_e=80 GeV

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.

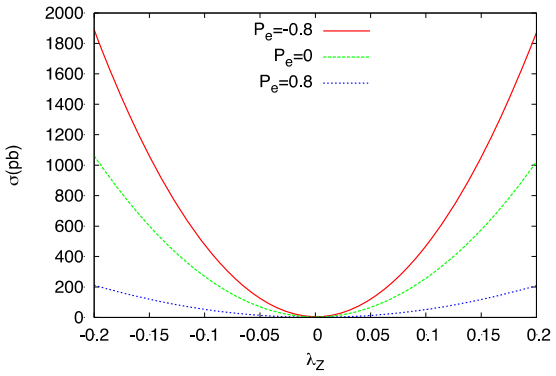

Fig. 12 The cross section depending on anomalous λ_Z coupling of the process $ep\to\nu_e qZX$ for E_e=80 GeV

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

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

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

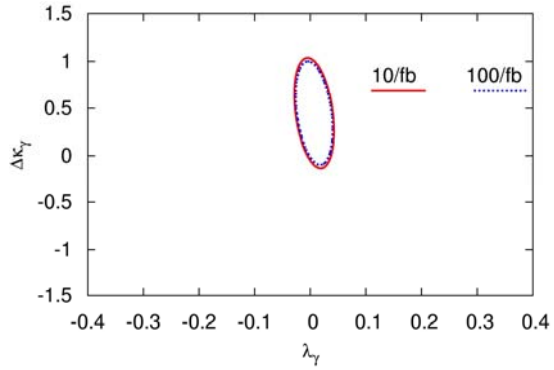

Fig. 13 Two dimensional 95% C.L contour plot anomalous couplings in the $\lambda_\gamma - \Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at electron beam energy E_e=80 GeV with polarization P_e=−0.8

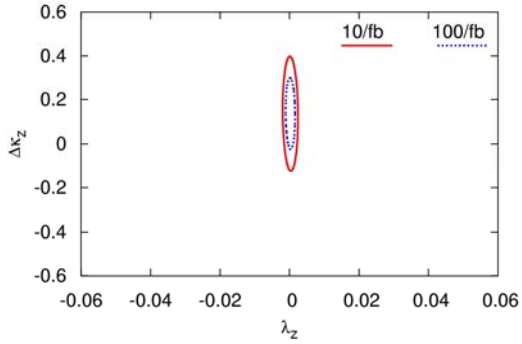

Fig. 14 Two-dimensional 95% C.L contour plot of anomalous couplings in the $\lambda_Z - \Delta\kappa_Z$ plane for the integrated luminosity of 10fb^{-1} and 100 fb^{-1} at electron beam energy E_e=80 GeV with polarization

VII. Conclusion

The *WWγ* and *WWZ* anomalous interactions through the processes $ep \to \nu_e q\gamma X$ and $ep \to \nu_e qZX$ 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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