Studies on anomalous triple gauge boson couplings (aTGC) at FCC-he and LHeC

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Previous works of the study group:

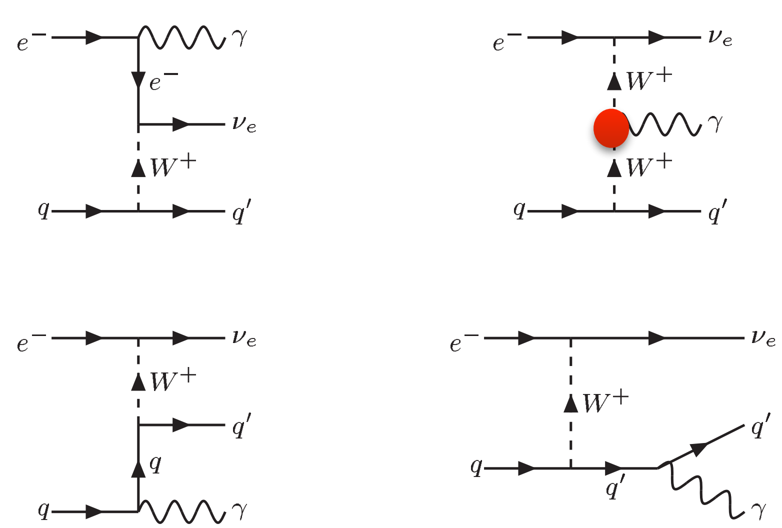
1. Search for anomalous WWγ and WWZ couplings with polarised e-beam at the LHeC *

Lagrangian:

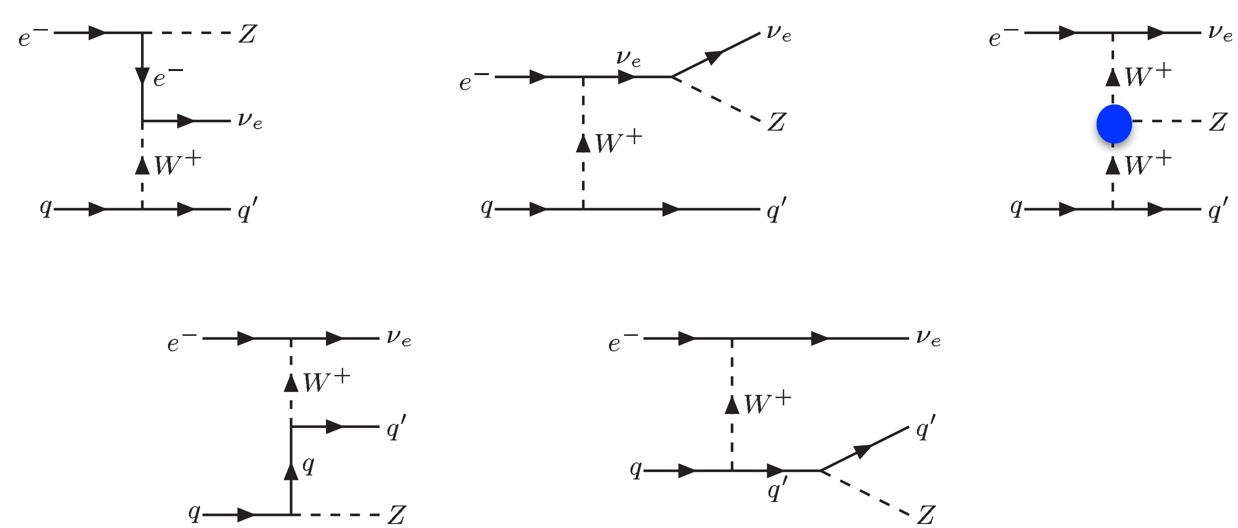
$$\mathcal{L} = ig_{WW\gamma}\left[g_1^\gamma\left(W^\dagger_{\mu\nu}W^\mu A^\nu - W^{\mu\nu}W^\dagger_\mu A_\nu\right) + \kappa_\gamma W^\dagger_\mu W_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu A^{\nu\rho}\right] + ig_{WWZ}\left[g_1^Z\left(W^\dagger_{\mu\nu}W^\mu Z^\nu - W^{\mu\nu}W^\dagger_\mu Z_\nu\right) + \kappa_Z W^\dagger_\mu W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu Z^{\nu\rho}\right],$$

Processes:

$$eq \to \nu_e \gamma q'.$$



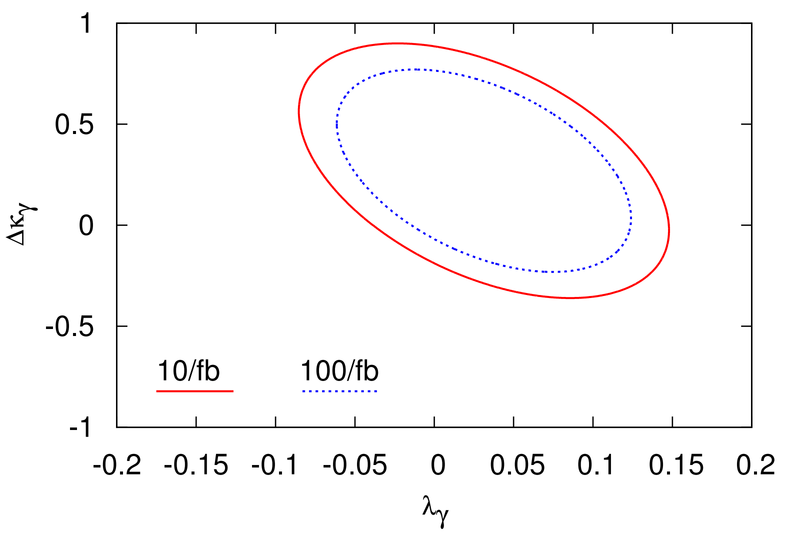
$$eq \to \nu_e Z q'.$$

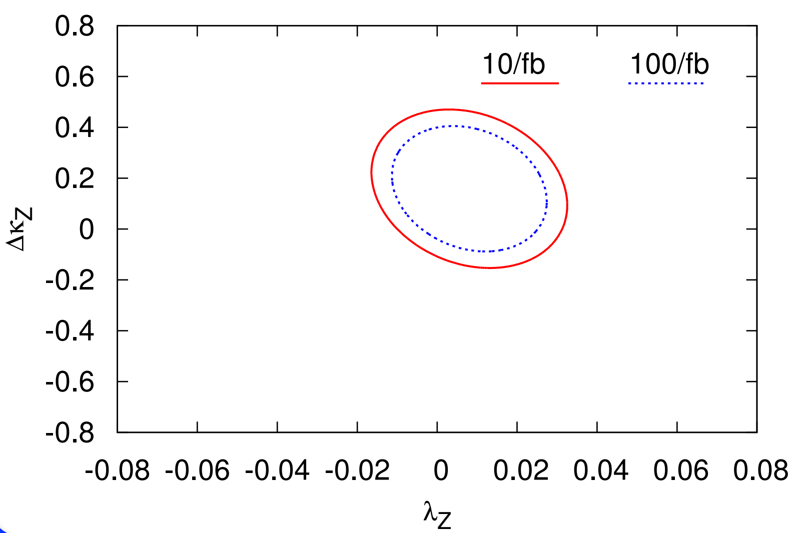


[*] I.T.~Cakir, O.Cakir, A.Senol and A.T.Tasci, Acta Phys.Polon. B45 (2014) no.10, 1947

Results for LHeC (E_e=60 GeV):

Two dimensional 95% C.L. contour plot of anomalous couplings for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} with polarization P_e = -0.8.





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

P_e	$\Delta\kappa_\gamma$	$\delta\Delta\kappa_\gamma$	λ_γ	$\delta\lambda_\gamma$
-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	$\Delta\kappa_Z$	$\delta\Delta\kappa_Z$	λ_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 available 95% C.L. two-parameter bounds on anomalous couplings ($\Delta\kappa_\gamma$, λ_γ) and ($\Delta\kappa_Z$,λ_Z) from the ATLAS and CMS experiments. The difference of the upper and lower bounds are shown in the last two columns.

	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
λ_γ	$[-0.068, 0.062]$	$[-0.050, 0.042]$	0.130	0.092
$\Delta\kappa_Z$	$[-0.045, 0.045]$	$[-0.160, 0.180]$	0.090	0.340
λ_Z	$[-0.063, 0.063]$	$[-0.055, 0.055]$	0.126	0.110

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

$$\delta\Delta\kappa_V = \Delta\kappa_V^{\mathrm{upper}} - \Delta\kappa_V^{\mathrm{lower}}, \qquad \delta\lambda_V = \lambda_V^{\mathrm{upper}} - \lambda_V^{\mathrm{lower}}.$$

[7] ATLAS Collaboration, Phys. Rev. D87, 112001 (2013); D87, 112003 (2013).

[8] CMS Collaboration, Eur. Phys. J. C73, 2610 (2013); Phys. Rev. D89, 092005 (2014).

The recent results from ATLAS*

Dataset	Coupling	Expected	Observed
13 TeV	Δg_1^Z	[-0.017; 0.032]	[-0.016; 0.036]
	$\Delta\kappa_1^Z$	[-0.18; 0.24]	[-0.15; 0.26]
	λ^Z	[-0.015; 0.014]	[-0.016; 0.015]
8 and 13 TeV	Δg_1^Z	[-0.014; 0.029]	[-0.015; 0.030]
	$\Delta\kappa_1^Z$	[-0.15; 0.21]	[-0.13; 0.24]
	λ^Z	[-0.013; 0.012]	[-0.014; 0.013]

Table 3: Expected and observed one-dimensional 95% CL intervals for the anomalous coupling parameters using $\Lambda_{co} = \infty$.

The recent results from CMS**

Table 4: Expected and observed limits at 95% C.L. on single anomalous couplings (other couplings set to zero).

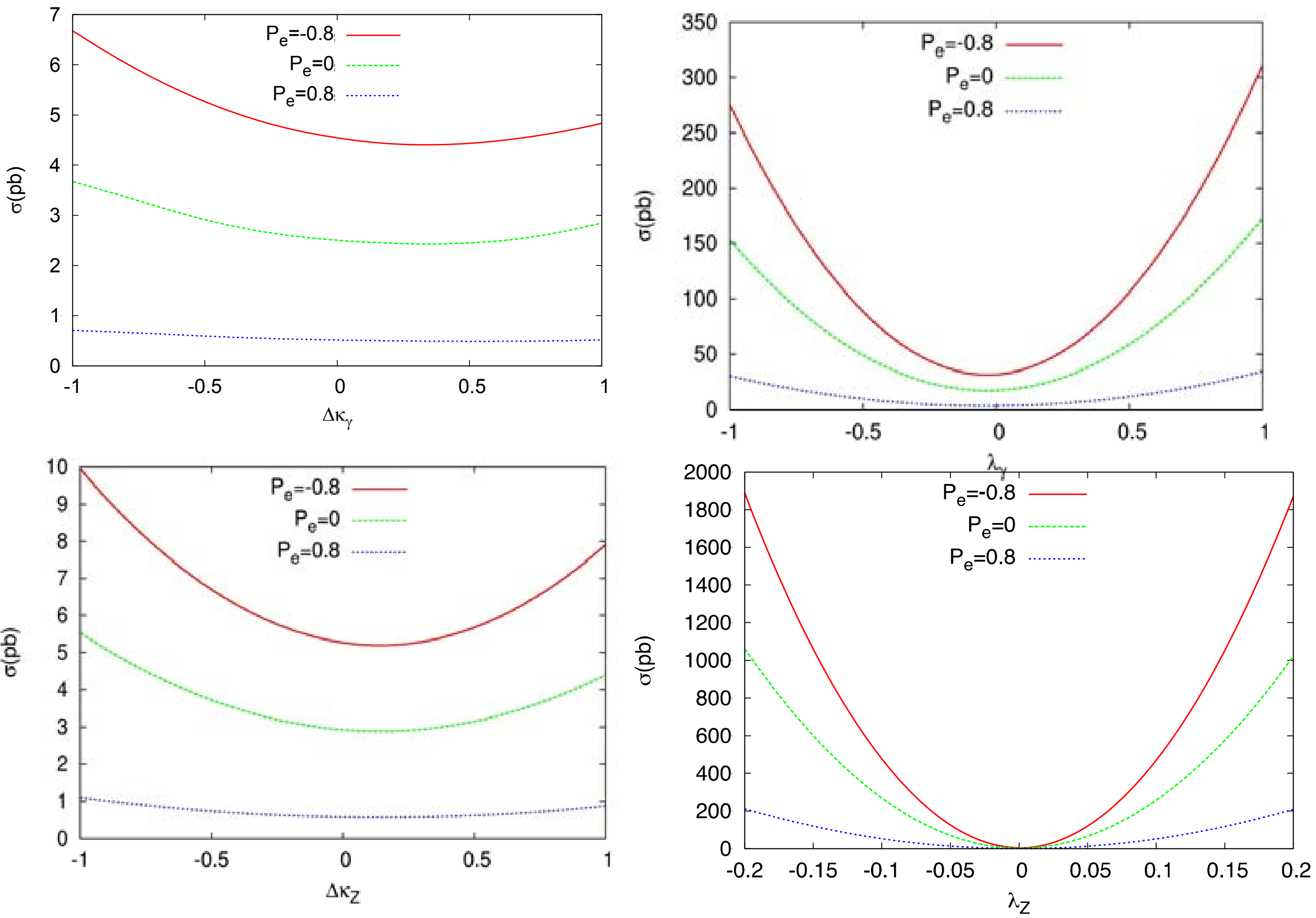
	aTGC	expected limit	observed limit
EFT param.	$\frac{c_{WWW}}{\Lambda^2}$ (TeV^{-2})	[-8.73 , 8.70]	[-9.46 , 9.42]
	$\frac{c_W}{\Lambda^2}$ (TeV^{-2})	[-11.7 , 11.1]	[-12.6 , 12.0]
	$\frac{c_B}{\Lambda^2}$ (TeV^{-2})	[-54.9 , 53.3]	[-56.1 , 55.4]
Vertex param.	λ	[-0.036 , 0.036]	[-0.039 , 0.039]
	Δg_1^Z	[-0.066 , 0.064]	[-0.067 , 0.066]
	$\Delta\kappa_Z$	[-0.038 , 0.040]	[-0.040 , 0.041]

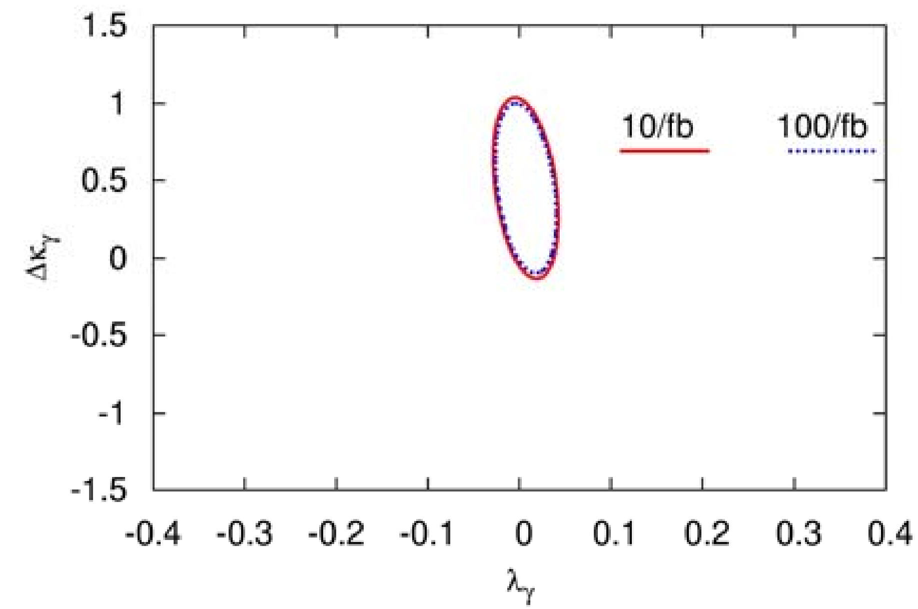
[*] S. Hassani [ATLAS Collaboration], ”Measurement of the W^+W^- -> ell nu ell nu production cross section at sqrt(s) = 8 TeV and 13 TeV and limits on anomalous triple gauge couplings with the ATLAS detector,'' PoS ICHEP 2016, 670 (2016).

[**] CMS Collaboration, “Search for anomalous couplings in semileptonic WW and WZ decays at sqrt(s) = 13 TeV,” CMS-PAS-SMP-16-012.

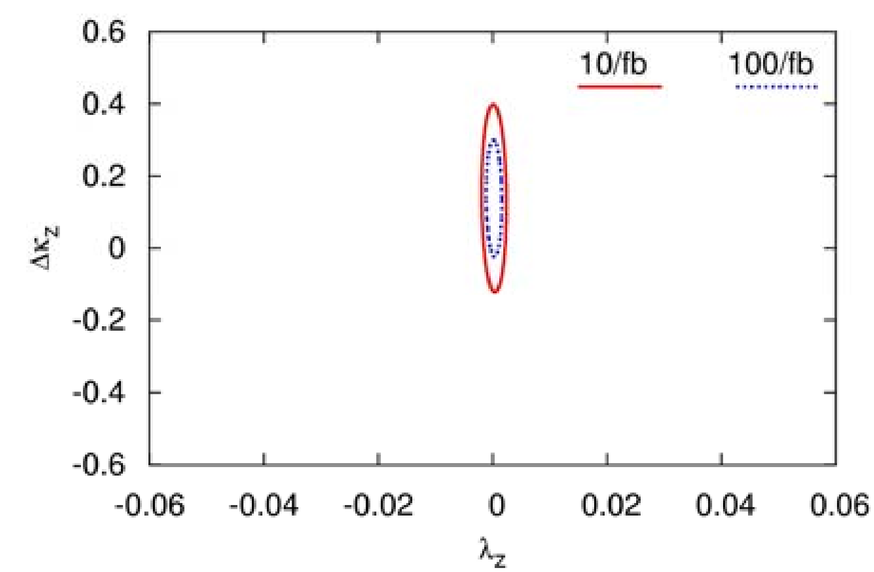
2. Probing Anomalous WW γ and WWZ Couplings with Polarized Electron Beam at the LHeC and FCC-ep Collider**

Results for FCC-ep (E_e=80 GeV):





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 FCC-ep with electron beam energy E_e =80 GeV with polarization P =−0.8 .

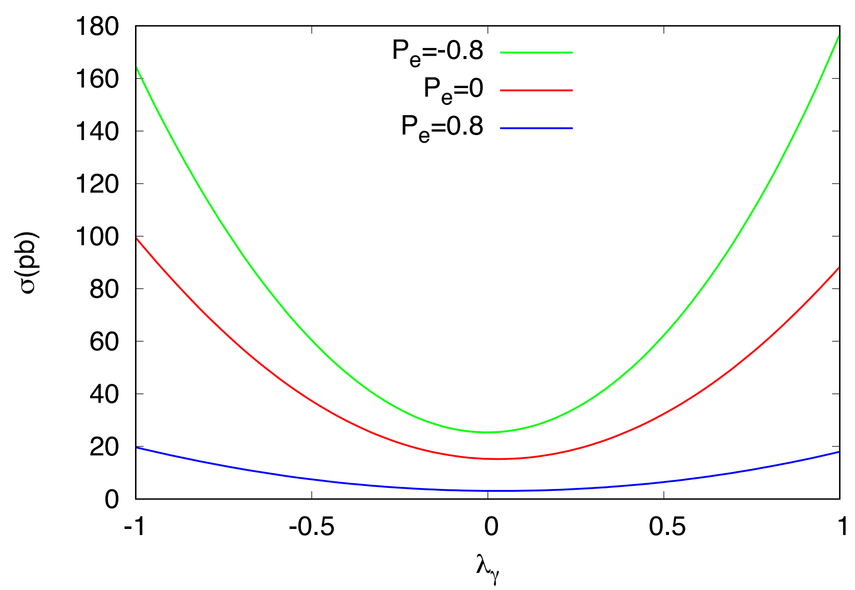


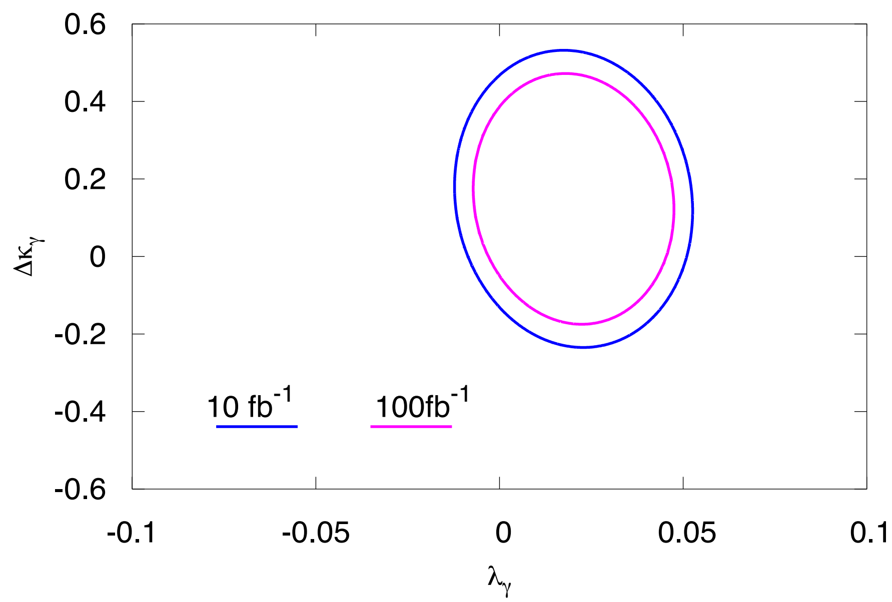
Two-dimensional 95% C.L contour plot of anomalous couplings in the λ_Z $-\Delta\kappa_Z$ plane for the integrated luminosity of 10 fb^{-1} and 100 fb^{-1} at FCC-ep with electron beam energy Ee=80 GeV with polarization P=-0.8.

At the FCC-ep with electron beam polarization, we obtain the results for the difference of upper and lower bounds as (1.101, 0.065) and (0.320, 0.002) for the anomalous ($\Delta\kappa_\gamma,\lambda_\gamma$) and ($\Delta\kappa_Z,\lambda_Z$) couplings, respectively at an integrated luminosity of L_{int}=100 fb^{-1}.

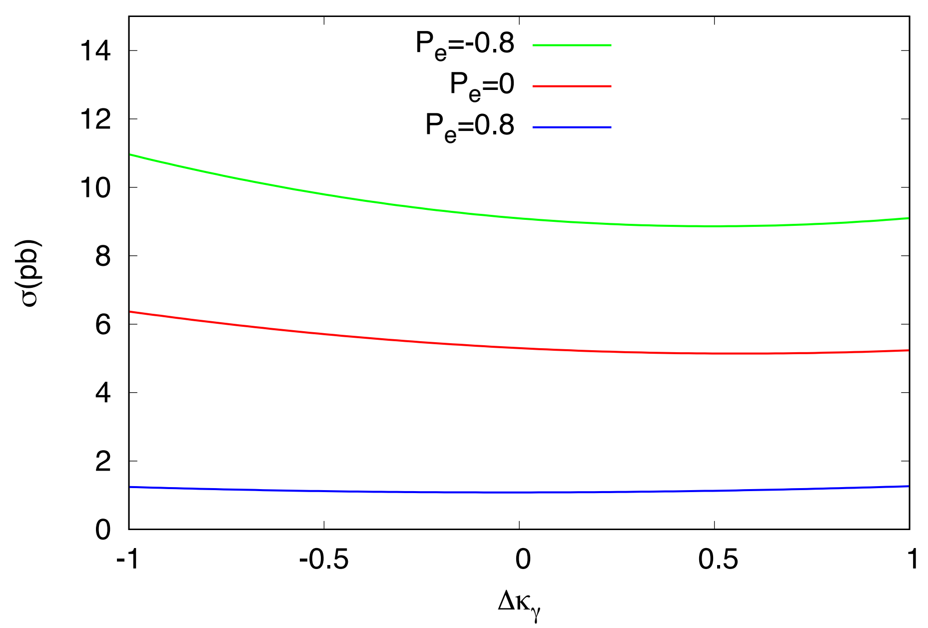
[**] I. Turk Cakir, A. Senol, A. T. Tasci, O. Cakir
***Int. J. Chem. Mol. Nucl. Mater. Metal. Eng.* 9, 1 (2015) pp.34-38**

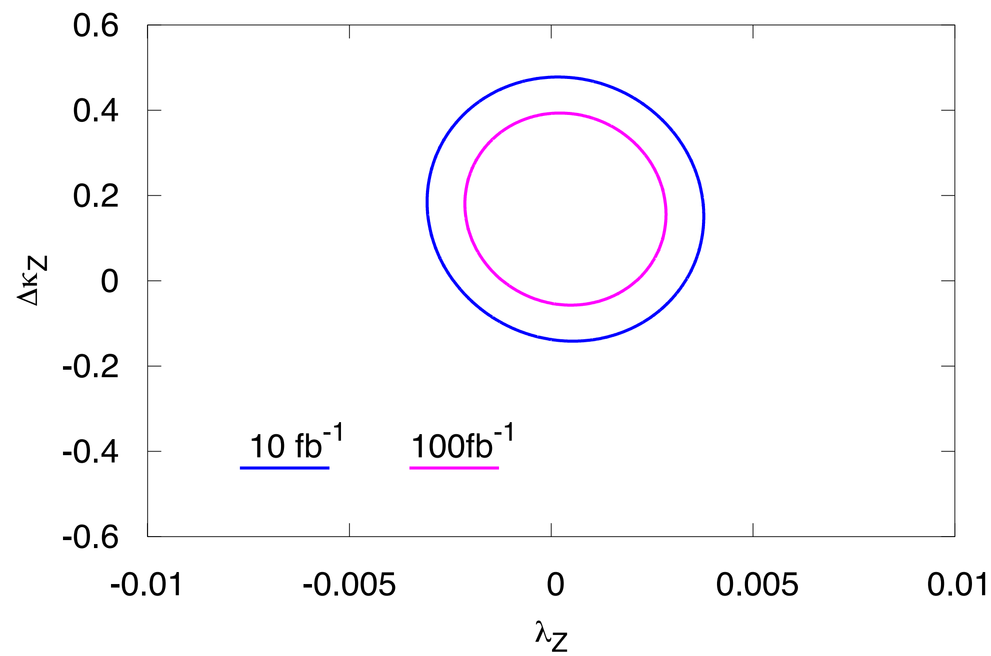
The Results updated for FCC-ep (E_e=60 GeV)**:





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 FCC-ep with electron beam energy E_e =60 GeV with polarization P =−0.8 .





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 FCC-ep with electron beam energy Ee=60 GeV with polarization P=-0.8.

Sensitivities to anomalous couplings $\lambda_Z \sim 10^{-3}$

[**] BSM searches at FCC-eh, 1st FCC Physics Week January 19th 2017

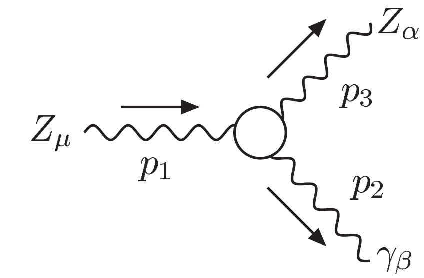
New Study:

Probing dimension-8 operators for anomalous neutral triple gauge boson interactions at FCC-he and LHeC

Dimension-6 vertices was studied at ep-collider[1,2]:

$$ie\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,q_3) = \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left[f_4^V(q_3^\alpha g^{\mu\beta}+q_3^\beta g^{\mu\alpha}) - f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right], \quad (1.1)$$

$$ie\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,q_3) = \frac{-e(q_3^2-m_V^2)}{M_Z^2}\left\{h_1^V(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{M_Z^2}q_3^\alpha[(q_3q_2)g^{\mu\beta}-q_2^\mu q_3^\beta] - h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{M_Z^2}q_3^\alpha\epsilon^{\mu\beta\rho\sigma}q_{3\rho}q_{2\sigma}\right\} \quad (1.2)$$



$$= ie\Gamma^{\alpha\beta\mu}_{Z\gamma Z}(p_1,p_2,p_3)$$

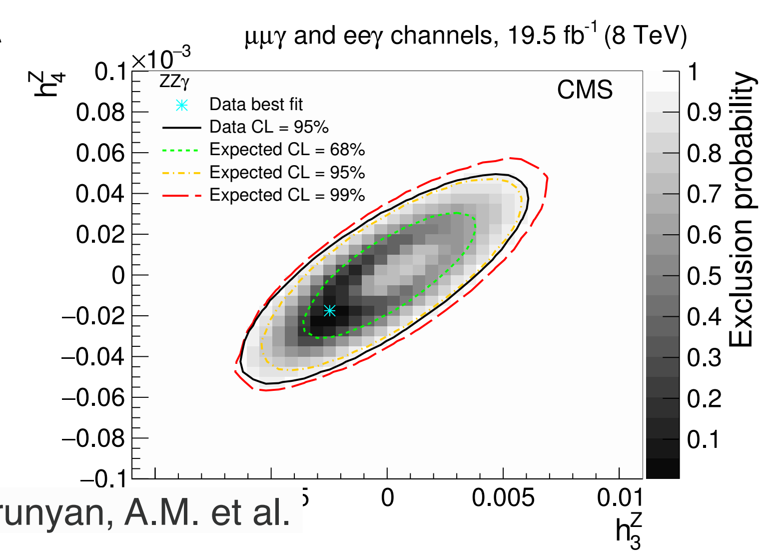
[1] Y.A. Coutinho, A.J. Ramalho, R. Walsh, S. Wulck, Bounds on the ZγZ anomalous couplings from radiative ep scattering at the Very Large Hadron Collider, Phys.Rev. D64 (2001) 115008

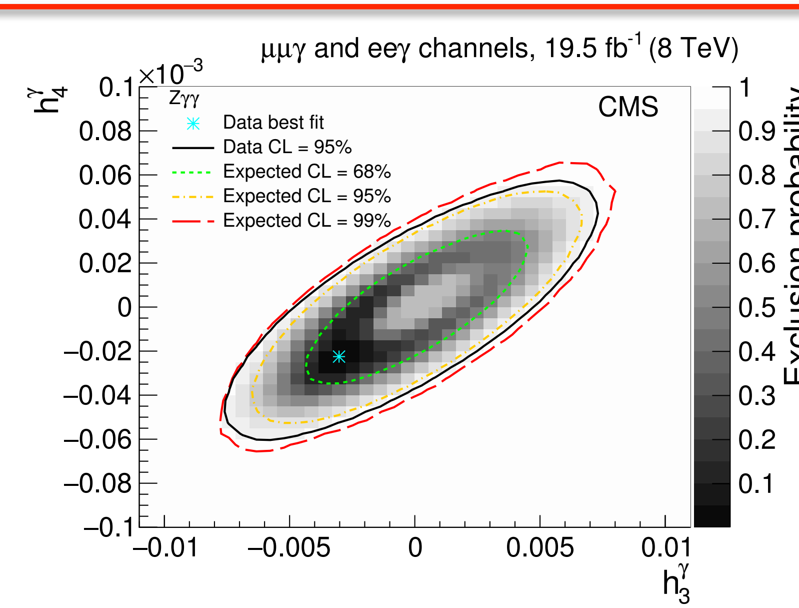
[2] I.Turk Çakır, Probing anomalous triple gauge boson couplings in gamma p ---> Z b X process, Acta Phys.Polon. B40 (2009) 309-318,

the sensitivity can be reached O(10^{-4})

The recent LHC results*

$$-3.8\times10^{-3} < h_3^Z < 3.7\times10^{-3}$$
$$-3.1\times10^{-5} < h_4^Z < 3.0\times10^{-5}$$
$$-4.6\times10^{-3} < h_3^\gamma < 4.6\times10^{-3}$$
$$-3.6\times10^{-5} < h_4^\gamma < 3.5\times10^{-5}.$$





[*] The CMS collaboration, Khachatryan, V., Sirunyan, A.M. et al. J. High Energ. Phys. (2015) 2015: 164.

Dimension-8 operators for anomalous neutral triple gauge boson interactions*

CP-conserving couplings

$$f_5^Z = 0$$

$$f_5^\gamma = \frac{v^2 M_Z^2}{4c_w s_w}\frac{C_{\widetilde{B}W}}{\Lambda^4}$$

$$h_3^Z = \frac{v^2 M_Z^2}{4c_w s_w}\frac{C_{\widetilde{B}W}}{\Lambda^4}$$

$$h_4^Z = 0$$

$$h_3^\gamma = 0$$

$$h_4^\gamma = 0$$

CP-violating couplings

$$f_4^Z = \frac{M_Z^2 v^2\left({c_w}^2\frac{C_{BB}}{\Lambda^4} + 2c_w s_w\frac{C_{BW}}{\Lambda^4} + 4{s_w}^2\frac{C_{WW}}{\Lambda^4}\right)}{2c_w s_w}$$

$$f_4^\gamma = -\frac{M_Z^2 v^2\left(-c_w s_w\frac{C_{BB}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4}\left({c_w}^2 - {s_w}^2\right) + 4c_w s_w\frac{C_{WW}}{\Lambda^4}\right)}{4c_w s_w}$$

$$h_1^Z = \frac{M_Z^2 v^2\left(-c_w s_w\frac{C_{BB}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4}\left({c_w}^2 - {s_w}^2\right) + 4c_w s_w\frac{C_{WW}}{\Lambda^4}\right)}{4c_w s_w}$$

$$h_2^Z = 0$$

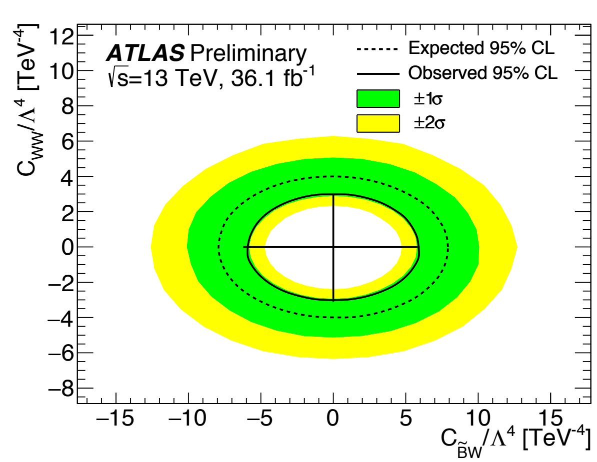
$$h_1^Z = -\frac{M_Z^2 v^2\left({s_w}^2\frac{C_{BB}}{\Lambda^4} - 2c_w s_w\frac{C_{BW}}{\Lambda^4} + 4{c_w}^2\frac{C_{WW}}{\Lambda^4}\right)}{4c_w s_w}$$

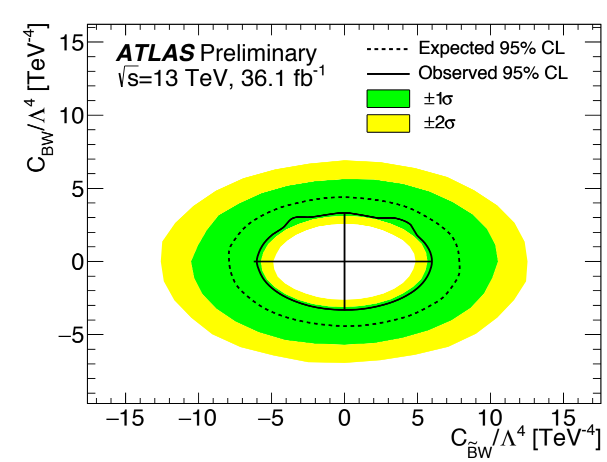
$$h_2^\gamma = 0.$$

[*] A basis of dimension-eight operators for anomalous neutral triple gauge boson interactions
Celine Degrande (Illinois U., Urbana). Aug 28, 2013. 17 pp.

95% CL intervals on EFT parameters at LHC**:

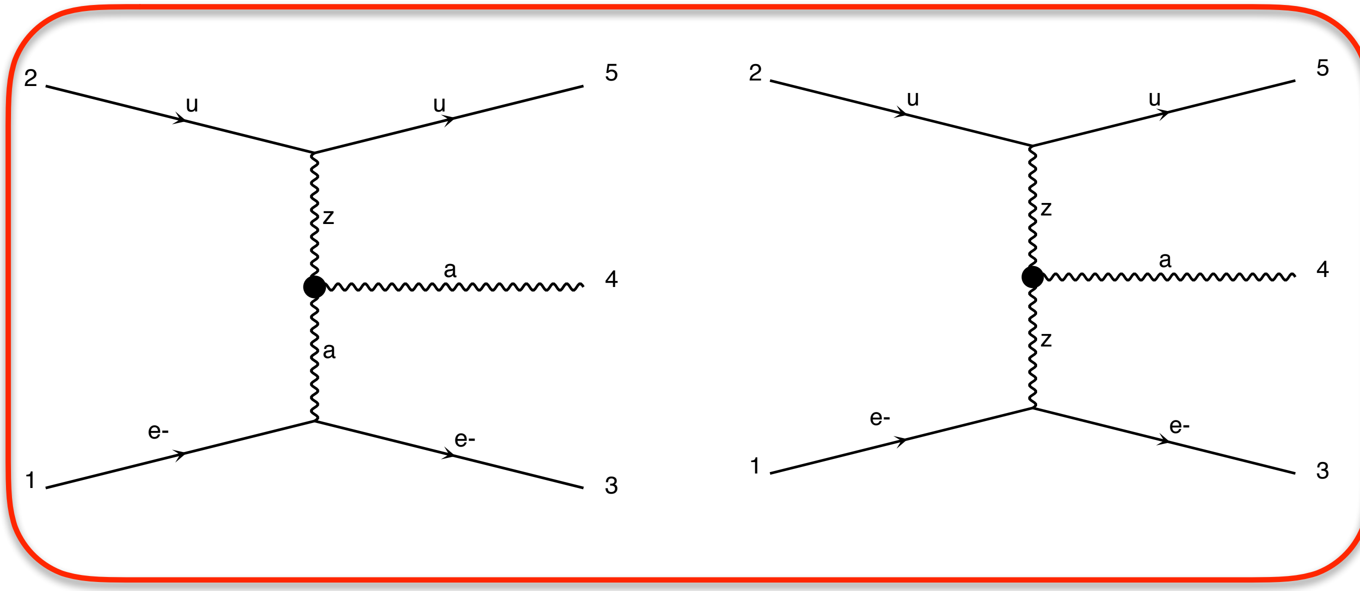
EFT parameter	Expected 95% CL [TeV^{-4}]	Observed 95% CL [TeV^{-4}]
$C_{\tilde{B}W}/\Lambda^4$	−8.1, 8.1	−5.9 , 5.9
C_{WW}/Λ^4	−4.0, 4.0	−3.0 , 3.0
C_{BW}/Λ^4	−4.4, 4.4	−3.3 , 3.3
C_{BB}/Λ^4	−3.7, 3.7	−2.7 , 2.8





[**] ATLAS-CONF-2017-031

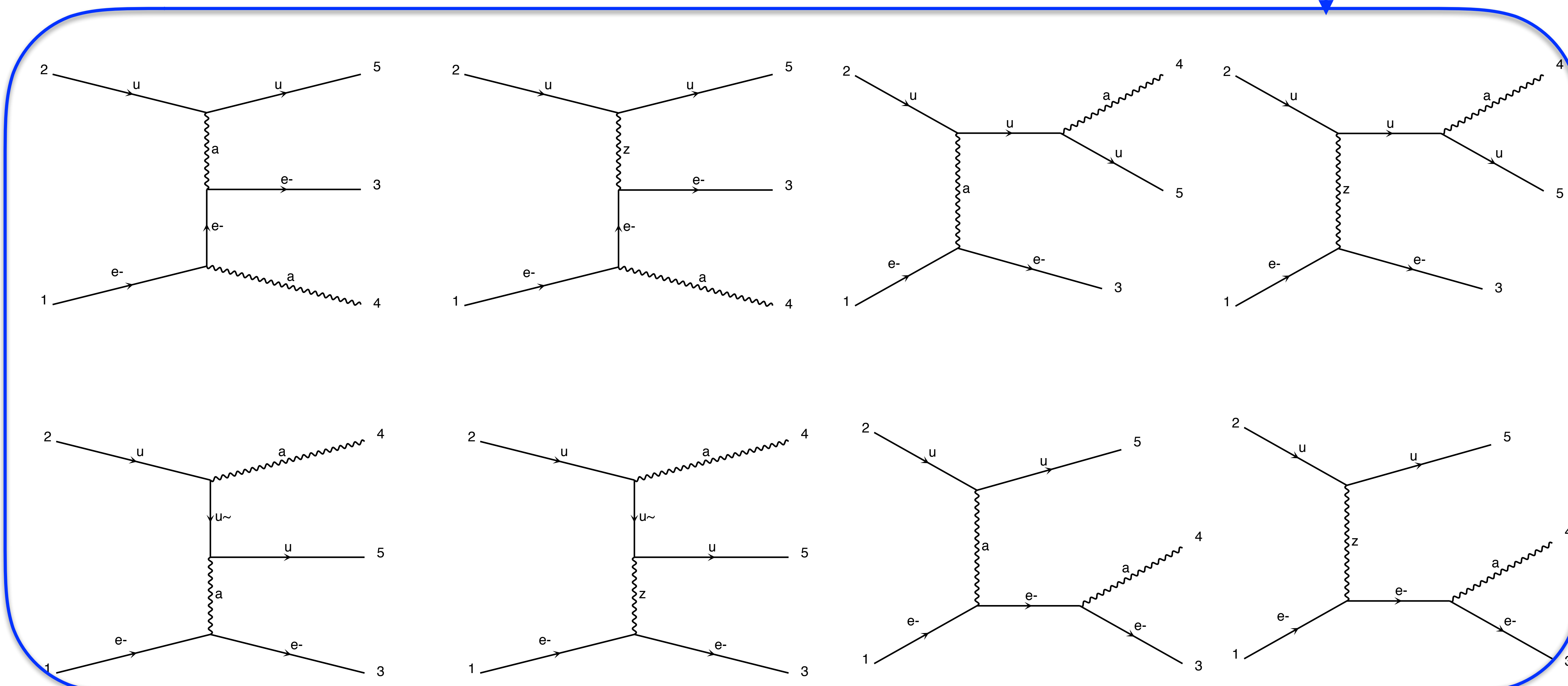
Our interested Process: $e^{-}q \to e^{-}\gamma q$



account for the anomalous Zγγ and ZZγ couplings,

+

the others depict the SM contributions.



Total cross sections for $e^- q \to e^- \gamma q$ process at FCC-he (E_e=60 Gev)

$C_{\tilde{B}W}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
4.0	34.73
6.0	34.74
8.0	34.75

$C_{BW}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
2.0	34.73
4.0	34.74
6.0	34.75

$C_{WW}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
2.0	34.74
4.0	34.77
6.0	34.75

$C_{BB}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
2.0	34.70
4.0	34.73
6.0	34.71

The cross sections of SM part is 34.60 pb

MadGraph 2.4.2 version

with nTGC effective theory model

Total cross sections for $e^- q \to e^- \gamma q$ process at LHeC (E_e=60 Gev)

$C_{\tilde{B}W}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
4.0	15.55
6.0	15.55
8.0	15.56

$C_{BW}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
2.0	15.53
4.0	15.54
6.0	15.56

$C_{WW}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
2.0	15.55
4.0	15.54
6.0	15.54

$C_{BB}/\Lambda^4 (TeV^{-4})$	$\sigma(pb)$
2.0	15.54
4.0	15.54
6.0	15.55

The cross sections of SM part is 15.52 pb

MadGraph 2.4.2 version

with nTGC effective theory model

Next Steps:

1. Kinematic distributions of electron, photon and jet

2. Signal and background cross section dependence on electron energy.

3. Study for polarisation effect.

4. Signal and background simulation.

5. Comparison the result with current limits