Probing the Effects of Dimension-eight Operators Describing Anomalous Neutral Triple Gauge Boson Interactions at FCC-hh

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Abstract

The effects of dimension-eight operators giving rise to anomalous neutral triple gauge boson interactions of $Z\gamma\gamma$ and $Z\gamma Z$ vertices in $l^{-}l^{+}\gamma$ production ($pp \rightarrow l^{-}l^{+}\gamma$) are investigated at 100 TeV centre of mass energy of future circular hadron collider (FCC-hh). The transverse momentum of photon, invariant mass of $l^{-}l^{+}\gamma$ and angular distribution of charged lepton in the rest frame of $l^{-}l^{+}$ are considered in the analysis. The realistic detector effects are also included with Delphes simulation. Sensitivity limits obtained at 95% C.L. for $C_{BW}/\Lambda^{4}$ and $C_{BB}/\Lambda^{4}$ couplings are $[-0.52; 0.52]([-0.40; 0.40])$ TeV$^{-4}$, $[-0.43; 0.43]([-0.33; 0.33])$ TeV$^{-4}$ with $L_{\text{int}}=1$ (3) ab$^{-1}$, respectively. Our results are one order of magnitude better than current LHC results.

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I. INTRODUCTION

The gauge boson self-interactions represented by the non-Abelian $SU(2)_L \times U(1)_Y$ gauge group of the electroweak sector in the Standard Model (SM) are of great interest since it provides valuable information to test the predictions at the TeV energy scale. The triple couplings between the photon and Z boson ($Z\gamma\gamma$ and $Z\gamma Z$) vanish at tree level in the SM. Any deviations of these couplings from SM predictions within the experimental precision can give crucial clues about new physics beyond the SM. A method to parameterize these new physics effects at higher energies is Effective Field Theory (EFT) approach which reduces to the SM at low energies.

The Lagrangian in the framework of an effective field theory for neutral Triple Gauge Couplings (nTGC) imposing local $U(1)$EM and Lorentz symmetry can be written as

$$L^{nTGC} = L^{SM} + \sum_i \frac{C_i}{\Lambda^4} (O_i + O_i^\dagger)$$

where $i$ runs over the label of the four operators expressed as

$$O_{BW} = i H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D_\nu\}$$
$$O_{WW} = i H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D_\nu\}$$
$$O_{BB} = i H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D_\nu\}$$
$$O_{\bar{B}W} = i H^\dagger \bar{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D_\nu\}$$

where $\bar{B}_{\mu\nu}$ is a dual $B$ strength tensor. The following convention in the definitions of the operators are used:

$$W_{\mu\nu} = \sigma^I (\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g_\epsilon_{IJK} W^J_\mu W^K_\nu)$$
$$B_{\mu\nu} = (\partial_\mu B_\nu - \partial_\nu B_\mu)$$

with $\langle \sigma^I \sigma^J \rangle = \delta^{IJ}/2$ and

$$D_\mu \equiv \partial_\mu - igw W^i_\mu \sigma^i - ig' B_\mu Y$$

The coefficients of these four dimension-eight operators describing anomalous Neutral Triple Gauge Couplings (aNTGC) are CP-conserving $C_{\bar{B}W}$ and CP-violating $C_{BB}, C_{BW}, C_{WW}$. They are related to dimension-six operators aNTGC as described in Ref. [1]. The 95%
C.L. current limits on dimension-eight operators converted from coefficients of dimension-six operators for the process $pp \rightarrow ZZ \rightarrow l^+l^-\gamma$ at $\sqrt{s}=13$ TeV and $L_{int}=36.1$ fb$^{-1}$ from ATLAS collaboration are reported as \cite{2}

$$-5.9 \text{ TeV}^{-4} < \frac{C_{BW}}{\Lambda^4} < 5.9 \text{ TeV}^{-4}$$

$$-3.0 \text{ TeV}^{-4} < \frac{C_{WW}}{\Lambda^4} < 3.0 \text{ TeV}^{-4}$$

$$-3.3 \text{ TeV}^{-4} < \frac{C_{BW}}{\Lambda^4} < 3.3 \text{ TeV}^{-4}$$

$$-2.7 \text{ TeV}^{-4} < \frac{C_{BB}}{\Lambda^4} < 2.8 \text{ TeV}^{-4}$$

In this study, we investigate the constrains on dimension eight operators in the $pp \rightarrow l^+l^-\gamma$ process since photon with high transverse momentum enhance the existence of aNTGCs \cite{3-5}. One can expect even further improvements on these bounds with a 100 TeV center of mass energy collider. The Future Circular Collider (FCC) which has the potential to search for a wide parameter range of new physics is the energy frontier collider project currently under consideration \cite{6}. The FCC-hh collider is the design providing proton-proton collisions at the proposed centre-of-mass energy of 100 TeV and its design peak luminosity is $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ \cite{7}.

The tree level Feynman diagrams of the $pp \rightarrow l^+l^-\gamma$ process are shown in Fig. 1. The first two diagrams account for the anomalous $Z\gamma\gamma$ and $ZZ\gamma$ couplings, while the others for SM contributions. In order to calculate the effects of dimension-eight operators on $pp \rightarrow l^+l^-\gamma$ process we use MadGraph5 aMC@NLO \cite{8} after implementation of the operators Eqs. (2)-(5) through Feynrules package \cite{9} as a Universal FeynRules Output (UFO) module \cite{10}. In the next section we give details of the simulation and discuss for the determination of the limits on the dimension-eight $Z\gamma\gamma$ and $ZZ\gamma$ couplings at 95% C.L.

II. ANALYSIS AND SIMULATION DETAILS

The cross sections of the $pp \rightarrow l^+l^-\gamma$ process as a function of mentioned four dimension-eight couplings are shown in Fig. 2. In this figure, only one coupling at a time is varied from its SM value. The cross section is calculated with a set of generator level cuts; photon transverse momentum $p_T^\gamma>100$ GeV and pseudorapidity $|\eta|^<2.5$, charged lepton transverse
momentum $p_T^\gamma > 20$ GeV and pseudorapidity $|\eta^\gamma| < 2.5$. A charged lepton-photon separation in the pseudorapidity-azimuthal angle plane is defined as follows

$$\Delta R(l, \gamma) = \left[ (\Delta \phi_{l,\gamma})^2 + (\Delta \eta_{l,\gamma})^2 \right]^{1/2}$$

We also imposed the cuts on $\Delta R(l, \gamma) > 0.7$. A large separation cut not only suppress photon radiation from the final state lepton but also impose the lepton-photon separation sharply peaks at small value in radiative Z decays due to the collinear singularity associated with diagrams. The invariant mass of final state charged leptons $m_{ll}$ cut is $m_{ll} > 50$ GeV. As it can be seen from Fig. 2, deviation from SM value of the anomalous cross section including $C_{\bar{B}W}$ and $C_{BB}$ couplings is larger than that for $C_{BW}$, $C_{WW}$. Therefore, in our analysis we focus on CP-even $C_{\bar{B}W}$ coupling and CP-odd $C_{BB}$ coupling.

In the analysis, we include effective dimension-eight aNTG couplings and SM contribution as well as interference between effective couplings and SM contributions that lead to $pp \rightarrow l^+ l^- \gamma$ process where $l^\pm = e^\pm, \mu^\pm$. The generated signal (for $C_{\bar{B}W}/\Lambda^4=2.0, 4.0, 6.0$ TeV$^{-4}$; $C_{BB}/\Lambda^4=1.0, 2.0, 3.0$ TeV$^{-4}$) and background events at parton level in MadGraph5_aMC@NLO applying pseudo-rapidity $|\eta_{l,\gamma}| < 2.5$, and transverse momentum $p_T^{l,\gamma} > 20$ GeV cuts are passed through the Pythia 6 [11] for parton shower and hadronization. The detector responses are taken into account with FCC detector card [12] in Delphes 3.3.3 [13] package. Then, all events are analysed by using the ExRootAnalysis utility [14] with ROOT [15]. The kinematical distributions are normalized to the number of expected events which is defined to be the cross section of each processes times integrated luminosity of $L_{int}=1$ ab$^{-1}$. We require one photon and at least two charged leptons ($l^\pm = e^\pm, \mu^\pm$); same flavor but opposite sign. We also require the angular separation $\Delta R(l, \gamma) > 0.7$. In order to define the region for a distinctive signature of the signal, we plot transverse momentum distribution of photon in the final state for $pp \rightarrow l^+ l^- \gamma$ in Fig. 3. It is clearly seen from Fig. 3 that the deviation of the signal from SM background for all couplings starts at about $p_T^\gamma = 200$ GeV. We plot the invariant mass distributions of the $l^+ l^- \gamma$ system for signals and SM background in Fig. 4. It shows the deviations from SM background for signal $C_{\bar{B}W}/\Lambda^4$ and $C_{BB}/\Lambda^4$ couplings, which appears broader especially at large values of $m_{ll\gamma}>500$ GeV. Therefore, to separate signal efficiently from the SM background, we impose the following cuts; $p_T^\gamma > 400$ (300) GeV, $m_{ll\gamma}>500$ GeV and $m_{ll} > 50$ GeV in addition to above mentioned cuts.
Table I: The obtained number of signal events and $\chi^2$ results for various coupling value of $C_{BW}/\Lambda^4$ after applied kinematic cuts using $\cos \Theta^*_i$ distributions with $L_{int} = 1 \text{ ab}^{-1}$

| $C_{BW}/\Lambda^4$ (TeV$^{-4}$) | Number of events | $\chi^2(\delta_{sys} = 0)$ | $\chi^2(\delta_{sys} = 5\%)$ | $\chi^2(\delta_{sys} = 10\%)$ |
|---------------------------------|------------------|---------------------------|-------------------------------|-------------------------------|
| 2.0                            | 3716.56 (7776.9) | 1295.55 (759.12)          | 209.26(49.80)               | 59.53 (13.09)               |
| 4.0                            | 8770.83 (14078.8)| 21583.05 (12330.53)      | 3486.18(808.92)             | 991.68 (212.70)             |
| 6.0                            | 17090.2 (24396.2)| 108559.43 (61371.67)     | 17534.97(4026.18)           | 4988.00 (1058.63)           |

The angular distribution of final state particles of signal and background processes are used effectively to find attainable limits on effective dimension-eight aNTG couplings since the shape of signal is different from the background. Fig. 5 shows $\cos \Theta^*_i$ distributions of signal for $C_{BW}/\Lambda^4$ (left panel), $C_{BB}/\Lambda^4$ (right panel) couplings and SM background. Here, $\cos \Theta^*_i$ is the polar angle in the $l^+l^-$ rest frame with respect to the $l^+l^-$ direction in the $l^+l^-\gamma$ rest frame.

III. RESULTS OF THE ANALYSIS

To obtain 95% C.L. limits on the couplings we use the $\cos \Theta^*_i$ distribution applying $\chi^2$ criterion with and without a systematic error. The $\chi^2$ function is defined as follows

$$\chi^2 = \sum_{i}^{n_{bins}} \left( \frac{N_i^{NP} - N_i^{B}}{N_i^{B} \Delta_i} \right)^2$$  \hspace{1cm} (9)

where $N_i^{NP}$ is the total number of events in the existence of effective couplings, $N_i^{B}$ is total number of events of the corresponding SM backgrounds in $i$th bin of the $\cos \Theta^*_i$ distributions, $\Delta_i = \sqrt{\delta_{sys}^2 + \frac{1}{N_i^{B}}}$ is the combined systematic (\delta_{sys}) and statistical errors in each bin. The number of signal events and one-parameter $\chi^2$ results for $C_{BW}/\Lambda^4$=2.0, 4.0, 6.0 TeV$^{-4}$ and $C_{BB}/\Lambda^4$=1.0, 2.0, 3.0 TeV$^{-4}$ are given in Table II and Table III respectively. In these tables, only one coupling at a time is varied from its SM value. We present numerical results taking into account systematic errors, $\delta_{sys} = 5\%$ and $\delta_{sys} = 10\%$ for $p_T^\gamma > 400$ GeV ( $p_T > 300$ GeV in the parenthesis) at an integrated luminosity of 1 ab$^{-1}$. Here, the number of SM background events is 1098.57. The 95% C.L. intervals are obtained by allowing pairs of $C_{BW}/\Lambda^4$ and $C_{BB}/\Lambda^4$ couplings to vary, while setting the others to zero. The results from two-parameter $\chi^2$ analysis of the $C_{BW}/\Lambda^4$ and $C_{BB}/\Lambda^4$ couplings at $L_{int}$=1 and 3 ab$^{-1}$
Table II: The obtained number of signal events and $\chi^2$ results for various coupling value of $C_{BB}/\Lambda^4$ after applied kinematic cuts using $\cos \Theta^*_l$ distributions with $L_{int} = 1$ ab$^{-1}$

| $C_{BB}/\Lambda^4$ (TeV$^{-4}$) | Number of events | $\chi^2(\delta_{sys} = 0)$ | $\chi^2(\delta_{sys} = 5\%)$ | $\chi^2(\delta_{sys} = 10\%)$ |
|-------------------------------|-----------------|--------------------------|--------------------------|--------------------------|
| 1.0                           | 2686.51 (6469.10) | 179.26 (104.57)          | 28.96 (6.86)            | 8.24 (1.80)             |
| 2.0                           | 4448.03 (8648.37) | 2708.80 (1528.64)        | 437.54 (100.28)         | 124.46 (26.37)          |
| 3.0                           | 7376.82 (12276.60)| 13530.25 (7597.99)       | 2185.46 (498.45)        | 621.68 (131.06)         |

without and with systematic errors (5% and 10%) are shown in Fig. 6. The results on the bounds of dimension-eight aNTG couplings at 95% C.L. for $L_{int} = 1$ and 3 ab$^{-1}$ from Fig. 6 are given in Table III and IV. Our limits without systematic error are one order of magnitude better than recent ATLAS bounds on $C_{\tilde{B}W}/\Lambda^4$ and $C_{BB}/\Lambda^4$ couplings 2. Even including 10% systematic error, we obtain limits for $L_{int} = 1$ ab$^{-1}$, five times better than current experimental limits. Without systematic errors, the integrated luminosity has the effect on the bounds of couplings, however the injection of a systematic error $\delta_{sys} = 5\%$ prevent sensible changes of the coupling bounds when the luminosity increase. As a result, we find that our bounds on the couplings are systematically limited.

IV. CONCLUSIONS

We investigated the effects of dimension-eight operators giving rise to anomalous neutral triple gauge boson interactions of $Z\gamma\gamma$ and $Z\gamma Z$ vertices in $l^{-}l^{+}\gamma$ production ($pp \to l^{-}l^{+}\gamma$) at FCC-hh. Since $pp \to l^{-}l^{+}\gamma$ process is sensitive to transverse momentum of the final state photon, we use this as a tool to probe the sensitivity of $C_{\tilde{B}W}/\Lambda^4$ and $C_{BB}/\Lambda^4$ couplings. Invariant mass of $l^{-}l^{+}\gamma$ and angular distribution of charged lepton in the rest frame of $l^{-}l^{+}$ with realistic detector effects are also considered in the analysis. Assuming that only one dimension-eight operator is non-zero at a time we obtained sensitivity limits at 95% C.L. for $C_{\tilde{B}W}/\Lambda^4$ and $C_{BB}/\Lambda^4$ couplings without systematic errors are $[-0.52; 0.52][-0.40; 0.40]$ TeV$^{-4}$, $[-0.43; 0.43][-0.33; 0.33]$ TeV$^{-4}$ for $L_{int} = 1$ (3) ab$^{-1}$, respectively. We conclude that the future 100 TeV circular hadron collider will be able to provide limits on the $Z\gamma\gamma$ and $Z\gamma Z$ dimension-eight couplings which are one order of magnitude better than those expected from ATLAS collaboration for the process $pp \to ZZ \to l^{+}l^{-}l^{'+}l'^{-}$ at $\sqrt{s} = 13$ TeV.
Table III: Obtained limits on $C_{BW}/\Lambda^4$ and $C_{BB}/\Lambda^4$ at 95% C.L. with $L_{int} = 1$ ab$^{-1}$ by assuming a non-zero dimension-eight operator at a time.

| Couplings (TeV$^{-4}$) | $\delta_{sys} = 0$ | $\delta_{sys} = 5\%$ | $\delta_{sys} = 10\%$ |
|------------------------|-------------------|---------------------|---------------------|
| $C_{BW}/\Lambda^4$     | [-0.52;0.52]      | [-0.83;0.83]        | [-1.13;1.13]        |
| $C_{BB}/\Lambda^4$     | [-0.43;0.43]      | [-0.68;0.68]        | [-0.94;0.94]        |

Table IV: Obtained limits on $C_{BW}/\Lambda^4$ and $C_{BB}/\Lambda^4$ at 95% C.L. with $L_{int} = 3$ ab$^{-1}$ by assuming a non-zero dimension-eight operator at a time.

| Couplings (TeV$^{-4}$) | $\delta_{sys} = 0$ | $\delta_{sys} = 5\%$ | $\delta_{sys} = 10\%$ |
|------------------------|-------------------|---------------------|---------------------|
| $C_{BW}/\Lambda^4$     | [-0.40;0.40]      | [-0.80;0.80]        | [-1.12;1.12]        |
| $C_{BB}/\Lambda^4$     | [-0.33;0.33]      | [-0.67;0.67]        | [-0.93;0.93]        |

and $L_{int} =36.1$ fb$^{-1}$. Even with 10% systematic errors, the obtained bounds for FCC-hh are five times better than current LHC results.

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Figure 1: Feynman diagrams for $pp \to l^- l^+ \gamma$ process contributing in the SM and anomalous $ZZ\gamma$, $Z\gamma\gamma$ vertices (first two).

Figure 2: The signal cross sections of $pp \to l^- l^+ \gamma$ depending on dimension-eight couplings at FCC-hh.
Figure 3: The $p_T^\gamma$ distribution for signal for $C_{BW}/\Lambda^4$ (left panel) and $C_{BB}/\Lambda^4$ (right panel) couplings and corresponding SM background of $pp \rightarrow l^- l^+ \gamma$ process.

Figure 4: The invariant mass distribution of $l^+ l^- \gamma$ system in $pp \rightarrow l^- l^+ \gamma$ process for $C_{BW}/\Lambda^4$ (left panel) and $C_{BB}/\Lambda^4$ (right panel) couplings and corresponding SM background.
Figure 5: $\cos \Theta^*_l$ distributions for $C_{BW}/\Lambda^4$ (left panel) and $C_{BB}/\Lambda^4$ (right panel) and SM background.

Figure 6: Two-dimensional 95% C.L. intervals in plane for $C_{BW}/\Lambda^4$ and $C_{BB}/\Lambda^4$ with taking $\delta_{sys}=0$, $\delta_{sys}=5\%$ and $\delta_{sys}=10\%$ of systematic errors at $L_{int}=1$ and $3 \text{ ab}^{-1}$. 