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Araştırma Makalesi / Research Article

Prediction for the Anomalous ZZZ and $ZZ\gamma$ Couplings via two Z-boson Production at the CLIC

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Abstract

The non-Abelian nature of the Standard Model (SM) entails the existence of the gauge bosons' self-interactions. The gauge bosons' self-interactions are important to test the SM and see the new physics effects. These effects can be analyzed in the effective theory approach which is the main aim of this study. We examine the ZZZ and $ZZ\gamma$ anomalous neutral triple gauge couplings (aNTGC) via the process $e^{-}e^{+} \to ZZ$ with both unpolarized and polarized electron beam with the $\sqrt{s} = 3$ TeV at CLIC. In the final state, semi-leptonic decay of Z-bosons ($Z \to jj$, $Z \to \nu_l\bar{\nu}_l$) are considered. We focused on CP-violating $\frac{C_{BB}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$ and CP-conserving $\frac{C_{\widetilde{B}W}}{\Lambda^4}$ couplings. The sensitivities are obtained at 95% Confidence Level with luminosities of $\mathcal{L}_{int} = 5$ ab^{-1}, $\mathcal{L}_{int} = 1$ ab^{-1} and $\mathcal{L}_{int} = 4$ ab^{-1} for unpolarized, 80% and -80% polarized electron beams, respectively. Obtained sensitivities on anomalous couplings are 3-20 times stringent than the current experimental limits and comparable with the related phenomenological studies in the literature.

Keywords: Electroweak Interaction, Anomalous Triple Gauge Boson Couplings, Beyond Standard Model.

CLICte iki Z-Bozonu Üretimi Aracılığıyla Anormal ZZZ ve $ZZ\gamma$ Bağlaşımlarının Tahmini

Öz

Standart Modelin abelyen olmayan doğası ayar bozonlarının kendileriyle öz etkileşmelerinin varlığını gerektirir. Bu etkileşmeler Standart Modeli test etmek ve yeni fizik etkilerini görmek için önemlidir. Bu etkileri efektif teori kapsamında analiz etmek bu çalışmanın ana motivasyon kaynağını oluşturmaktadır. Bu çalışmada CLIC çarpıştırıcısında $\sqrt{s} = 3$ TeV de polarize ve polarize olmayan elektron için $e^{-}e^{+} \to ZZ$ süreci aracılığıyla ZZZ ve $ZZ\gamma$ anormal yüksüz üçlü ayar bozonu bağlaşımları incelenmiştir. Son durumda Z-bosonunun yarı-leptonik bozunumu ($Z \to jj$, $Z \to \nu_l\bar{\nu}_l$) dikkate alınmıştır. Burada CP ihlal eden $\frac{C_{BB}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$ ve CP koruyan $\frac{C_{\widetilde{B}W}}{\Lambda^4}$ bağlaşımlarına odaklanılmıştır. Duyarlılıklar 95% güvenilirlik seviyesinde, sırasıyla polarize olmayan, 80% ve -80% polarize elektron için $\mathcal{L}_{int} = 5$ ab^{-1}, $\mathcal{L}_{int} = 1$ ab^{-1} ve $\mathcal{L}_{int} = 4$ ab^{-1} ışınlılık değerleri kullanılarak hesaplanmıştır. Anormal bağlaşımlar için elde edilen duyarlılıklar deneysel limitlerden 3-20 kat daha sınırlayıcı iken literatürdeki ilgili fenomenolojik çalışmalarla karşılaştırılabilir seviyededir.

Anahtar Kelimeler: Elektrozayıf Etkileşmeler, Anormal Üçlü ayar bozonu bağlaşımları, Standart Model Ötesi.

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1. Introduction

The non-Abelian character of the Standard Model indicates the gauge bosons' self-interactions like triple and quartic gauge boson couplings. These interactions are important to test the validity of the Standard Model. In the Standard Model; ZZV, $ZV\gamma$ and WWV ($V = \gamma, Z$) are defined (Baur et al., 2000). Z-boson has no electrical charge and does not interact with photon. Because of that SM does not include $Z\gamma\gamma$, $ZZ\gamma$ and ZZZ vertices at the tree-level. Therefore, an Effective Field Theory (EFT) is useful to investigate the contributions of new physics effects. In this work, we focus on the dim-8 operators defining the aNTGC. For doing this, we used the effective Lagrangian of the NTGC that includes SM interactions and new physics effects coming from dim-8 operators that are running by dim-8 anomalous couplings can be given as (Degrande, 2014). On the other hand, there are several phenomenological studies in the literature on e^-e^+ and pp colliders to examine the aNTGCs (Choudhury et al., 2000, Atağ et al., 2004, Ots et al., 2004, Ots et al., 2006, Gutierrez-Rodriguez et al., 2009, Ananthanarayan et al., 2012, Ananthanarayan et al., 2014, Rahaman et al., 2016, Rahaman et al., 2017, Ellis et al., 2020, Fu et al., 2021, Ellis et al., 2021, Yang et al., 2022, Baur et al., 1993, Senol et al., 2018, Rahaman et al., 2019, Senol et al., 2019, Senol et al., 2020, Yilmaz et al., 2020, Yilmaz, 2021, Hernandez-Juarez et al., 2021, Biekötter et al., 2021).

$$\mathcal{L}^{NTGC} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^4}\left(\mathcal{O}_i + \mathcal{O}_i^{\dagger}\right) \tag{1}$$

Here, the dim-8 couplings are normalized to dim-4 by Λ new physics scale. On the other hand, $\mathcal{O}_i$ describes the operators given below.

$$\mathcal{O}_{\tilde{B}W} = iH^{\dagger}\tilde{B}_{\sigma\rho}W^{\sigma\mu}\{D_\mu D^\rho\}H, \tag{2}$$

$$\mathcal{O}_{BW} = iH^{\dagger}B_{\sigma\rho}W^{\sigma\mu}\{D_\mu D^\rho\}H, \tag{3}$$

$$\mathcal{O}_{WW} = iH^{\dagger}W_{\sigma\rho}W^{\sigma\mu}\{D_\mu D^\rho\}H, \tag{4}$$

$$\mathcal{O}_{BB} = iH^{\dagger}B_{\sigma\rho}B^{\sigma\mu}\{D_\mu D^\rho\}H, \tag{5}$$

where

$$B_{\sigma\nu} = (\partial_\sigma B_\nu - \partial_\nu B_\sigma) \tag{6}$$

$$W_{\mu\nu} = \sigma^i\left(\partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon_{ijk}W_\mu^j W_\nu^k\right) \tag{7}$$

With $\langle\sigma^i\sigma^j\rangle = \frac{\delta^{ij}}{2}$ and

$$D_\mu = \partial_\mu - \frac{ig'}{2}B_\mu Y - ig_w W_\mu^i\sigma^i) \tag{8}$$

In the above equations, $B_{\mu\nu}$, $W_{\mu\nu}$ and D_μ are the field strength tensor and the covariant derivative, respectively.

At the lowest order, dim-8 operators have the effect of $\frac{\upsilon^2\hat{s}}{\Lambda^4}$ while the dim-6 operators have zero. On the other hand, dim-6 operators have induced an effect of $\frac{\alpha\hat{s}}{4\pi\Lambda^2}$ at the one-loop which is negligible compared with the effects coming from dim-8 operators that are $\Lambda \leq \sqrt{\frac{4\pi\hat{s}}{\alpha}}$ (Degrande, 2014). Here, υ is the expectation value in the vacuum. The effective Lagrangian for the aNTGC including the both dim-6 and dim-8 operators studied in the literature is given in the following equation (Gounaris et al., 2000).

$$\mathcal{L}_{aNTGC}^{dim-6,8} = \frac{e}{m_Z^2} - \left[f_4^\gamma\left(\partial_\mu F^{\mu\beta}\right) + f_4^Z\left(\partial_\mu Z^{\mu\beta}\right)\right]Z_\alpha\left(\partial^\alpha Z_\beta\right) + \left[f_5^\gamma\left(\partial^\sigma F_{\sigma\mu}\right) + f_5^Z\left(\partial^\sigma Z_{\sigma\mu}\right)\right]\tilde{Z}^{\mu\beta}Z_\beta - \left[h_1^\gamma\left(\partial^\sigma F_{\sigma\mu}\right) + h_1^Z\left(\partial^\sigma Z_{\sigma\mu}\right)\right]Z_\beta F^{\mu\beta} - \left[h_3^\gamma(\partial_\sigma F^{\sigma\rho}) + h_3^Z(\partial_\sigma F^{\sigma\rho})\right]Z^\alpha\tilde{F}_{\rho\alpha} - \left\{\frac{h_2^\gamma}{m_Z^2}\left[\partial_\alpha\partial_\beta\partial^\rho F_{\rho\mu}\right] + \frac{h_2^Z}{m_Z^2}\left[\partial_\alpha\partial_\beta(\square + m_Z^2)Z_\mu\right]\right\}Z^\alpha F^{\mu\beta} + \left\{\frac{h_4^\gamma}{2m_Z^2}\left[\square\partial^\sigma F^{\rho\alpha}\right] + \frac{h_4^Z}{2m_Z^2}\left[(\square + m_Z^2)\partial^\sigma Z^{\rho\alpha}\right]\right\}Z_\sigma\tilde{F}_{\rho\alpha}] \tag{9}$$

Here, f_4^V, h_1^V, h_2^V are the CP-violating and f_5^V, h_3^V, h_4^V are the CP-conserving couplings ($V = \gamma, Z$) that all are zero at the lowest order. In above Lagrangian only h_2^V and h_4^V couplings are related to dim-8. On the other hand, the couplings given in Eqs. (2-5) are related with the couplings in Eq.(9) when considering the $SU(2)_L \times U(1)_Y$ gauge invariance (Rahaman, 2020). The CP-conserving couplings with the two on-shell Z-bosons and an off-shell γ or Z-boson are given by (Degrande, 2014).

$$f_5^Z = 0, \tag{10}$$

$$f_5^\gamma = \frac{\upsilon^2 m_Z^2}{4c_\omega s_W}\frac{C_{\tilde{B}W}}{\Lambda^4} \tag{11}$$

Besides, the CP-violating anomalous couplings are given as follows.

$$f_4^Z = \frac{\upsilon^2 m_Z^2\left(c_\omega^2\frac{C_{WW}}{\Lambda^4}+2c_\omega s_W\frac{C_{BW}}{\Lambda^4}+4s_\omega^2\frac{C_{BB}}{\Lambda^4}\right)}{2c_\omega s_W} \tag{12}$$

$$f_4^\gamma = -\frac{\upsilon^2 m_Z^2\left(-c_\omega s_W\frac{C_{WW}}{\Lambda^4}+\frac{C_{BW}}{\Lambda^4}(c_\omega^2-s_\omega^2)+2c_\omega s_W\frac{C_{BW}}{\Lambda^4}+4s_\omega^2\frac{C_{BB}}{\Lambda^4}\right)}{2c_\omega s_W} \tag{13}$$

The CP-conserving couplings with an on-shell Z-boson and γ in addition to an off-shell γ or Z-boson are given in the following equations (Degrande, 2014).

$$h_3^Z = \frac{\upsilon^2 m_Z^2}{4c_\omega s_W}\frac{C_{\tilde{B}W}}{\Lambda^4} \tag{14}$$

$$h_3^\gamma = h_4^\gamma = h_4^Z = 0, \tag{15}$$

Finally, the CP-violating couplings are given as follows.

$$h_1^Z = -\frac{\upsilon^2 m_Z^2\left(-c_\omega s_W\frac{C_{WW}}{\Lambda^4}+\frac{C_{BW}}{\Lambda^4}(c_\omega^2-s_\omega^2)+4c_\omega s_W\frac{C_{BB}}{\Lambda^4}\right)}{4c_\omega s_W} \tag{16}$$

$$h_2^Z = h_2^\gamma = 0 \tag{17}$$

$$h_1^\gamma = -\frac{\upsilon^2 m_Z^2\left(s_\omega^2\frac{C_{WW}}{\Lambda^4}-2c_\omega s_W\frac{C_{BW}}{\Lambda^4}+4c_\omega^2\frac{C_{BB}}{\Lambda^4}\right)}{4c_\omega s_W} \tag{18}$$

The best limits on dim-8 $\frac{C_{\tilde{B}W}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$ and $\frac{C_{BB}}{\Lambda^4}$ anomalous couplings are determined for the process $pp \to Z\gamma \to \nu\nu\gamma$ at $\sqrt{s} = 13$ TeV at the LHC with 95% Confidence Level (C.L.) which are given in Eqs. (19-22) (Aaboud et al., 2018).

$$-1.1\ TeV^{-4} < \frac{C_{\tilde{B}W}}{\Lambda^4} < 1.1\ TeV^{-4} \tag{19}$$

$$-2.3\ TeV^{-4} < \frac{c_{WW}}{\Lambda^4} < 2.3\ TeV^{-4} \quad (20)$$

$$-0.65\ TeV^{-4} < \frac{c_{BW}}{\Lambda^4} < 0.64\ TeV^{-4} \quad (21)$$

$$-0.24\ TeV^{-4} < \frac{c_{BB}}{\Lambda^4} < 0.24\ TeV^{-4} \quad (22)$$

Apart from this, many phenomenological studies have been performed to obtain the CP-violating $\frac{c_{WW}}{\Lambda^4}$, $\frac{c_{BW}}{\Lambda^4}$, $\frac{c_{BB}}{\Lambda^4}$ and CP-conserving $\frac{c_{\widetilde{B}W}}{\Lambda^4}$ couplings (Choudhury et al., 2000, Atağ et al., 2004, Ots et al., 2004, Ots et al., 2006, Gutierrez-Rodriguez et al., 2009, Ananthanarayan et al., 2012, Ananthanarayan et al., 2014, Rahaman et al., 2016, Rahaman et al., 2017, Ellis et al., 2020, Fu et al., 2021, Ellis et al., 2021, Yang et al., 2022, Baur et al., 1993, Senol et al., 2018, Rahaman et al., 2019, Senol et al., 2019, Senol et al., 2020, Yilmaz et al., 2020, Yilmaz, 2021, Hernandez-Juarez et al., 2021, Biekötter et al., 2021).

2. Materials and Methods

2.1 Cross-sections and Events

A cut base analysis is handled in this study. We examined the process $e^-e^+ \rightarrow ZZ \rightarrow jj\nu_l\overline{\nu_l}$ in the stage-3 scenerio of the CLIC. Using FeynRules (Alloul et al., 2014) package with dim-8 effective Lagrangians, the ZZZ and $ZZ\gamma$ aNTGC are imported to the MadGraph5_aMC@NLO (Alwall et al., 2011, Alwall et al., 2014). We give the related Feynman diagrams in Fig.1.

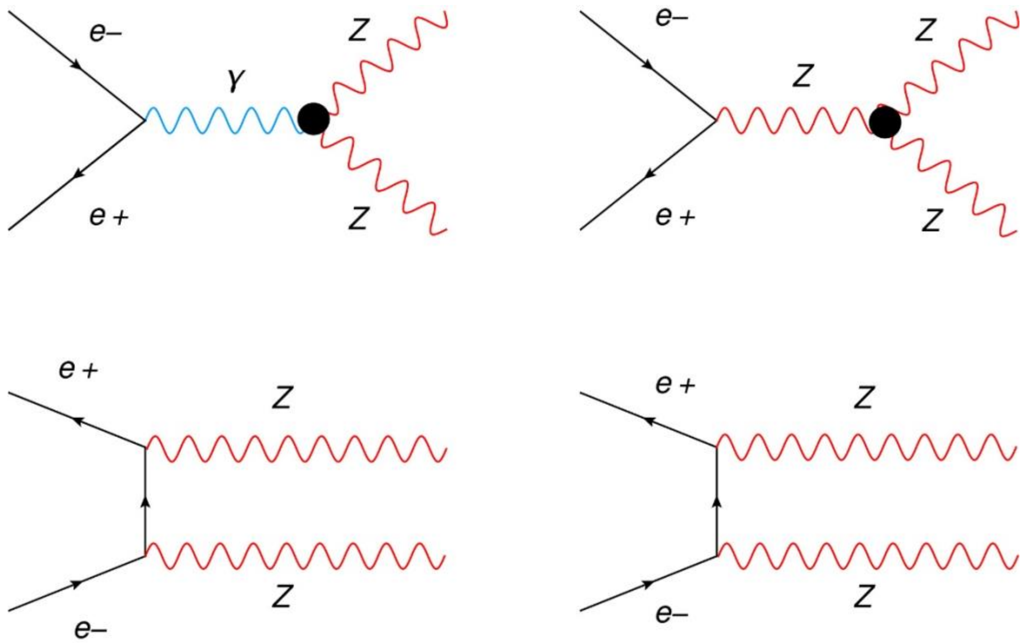

Figure 1. Schematic diagrams for the process $e^-e^+ \rightarrow ZZ$ including the anomalous contribution of ZZZ and $ZZ\gamma$ vertices and the SM.

As the first step we produced the signals and relevant SM background events at tree-level by importing dim-8 anomalous $\frac{C_{\tilde{B}W}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$ and $\frac{C_{BB}}{\Lambda^4}$ couplings implemented UFO model file into MadGraph5_aMC@NLO with cut-0 case to determine the optimal cuts. The analysis is presented at parton-level without taking into account any detector response. Here, Cut-0 refers to the default cut set of the MadGraph5_aMC@NLO to keep down the infrared divergence and singularities. In Figs. 2-4, we have given the missing energy transverse, p_T^j and η^j plots of the signals and related SM background for the Cut-0 case.

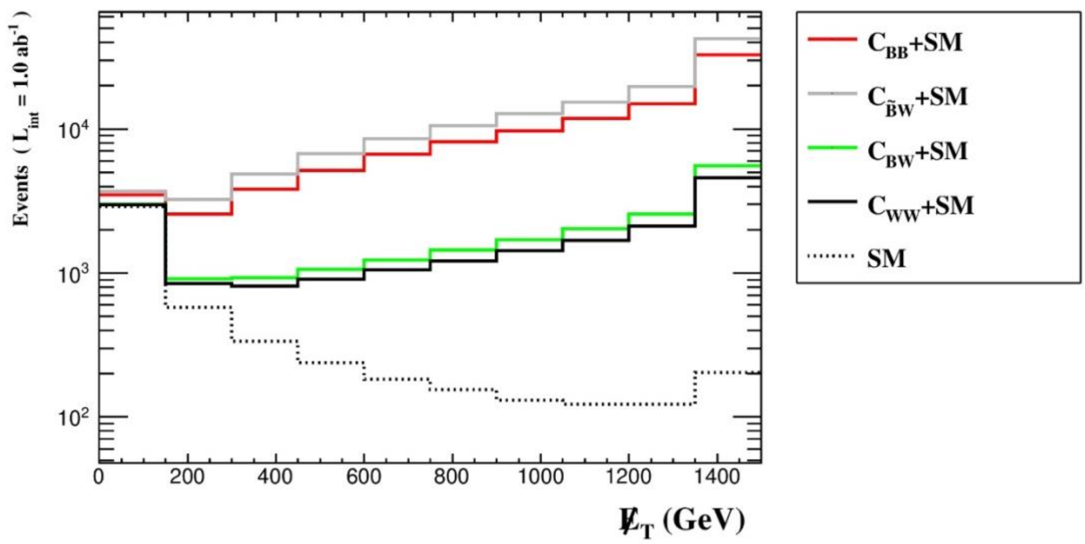

Figure 2. The number of events as a function of MET for the $e^-e^+ \rightarrow ZZ \rightarrow jj\nu_l\overline{\nu_l}$ signal and relevant SM background with $P_e = 0\%$. Each coupling has been taken the value of 1 TeV^{-4}.

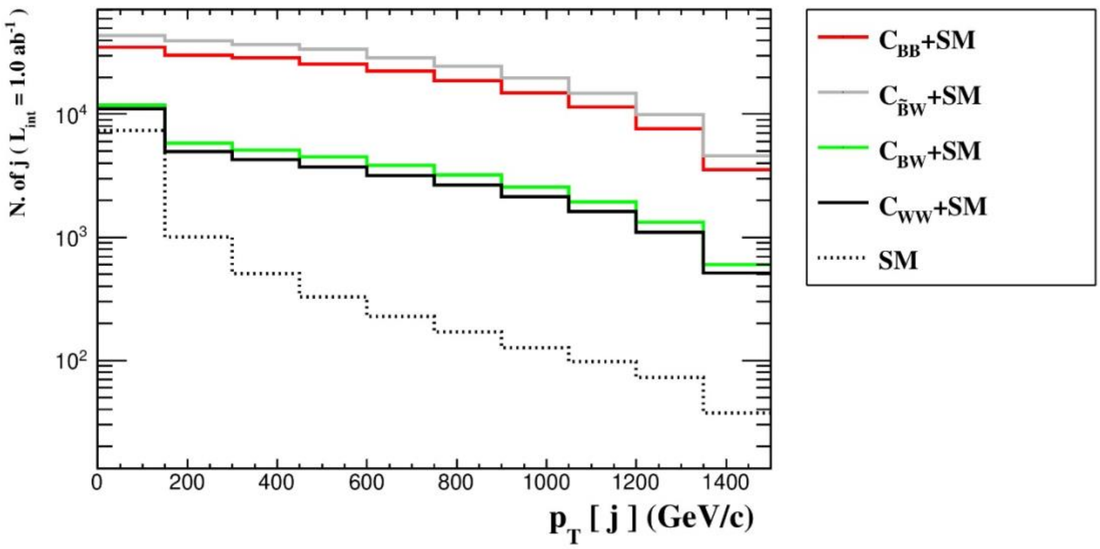

Figure 3. The number of events as a function of p_T^j for the $e^-e^+ \rightarrow ZZ \rightarrow jj\nu_l\overline{\nu_l}$ signal and relevant SM background with $P_e = 0\%$. Each coupling has been taken the value of 1 TeV^{-4}.

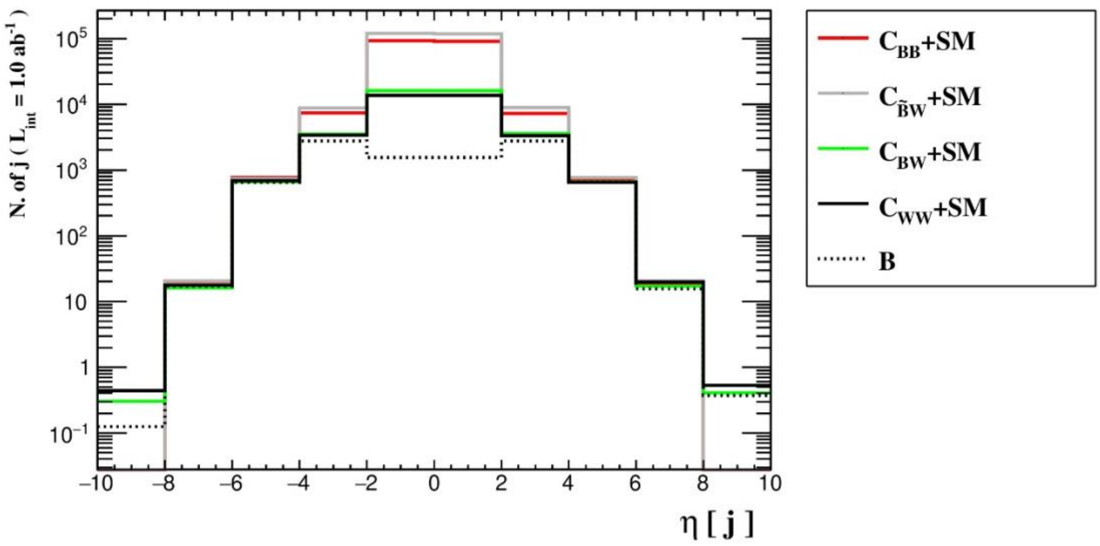

Figure 4. The number of events as a function of η^j for the $e^-e^+ \rightarrow ZZ \rightarrow jj\nu_l\overline{\nu_l}$ signal and relevant SM background with $P_e = 0\%$. Each coupling has been taken the value of 1 TeV^{-4}.

In the second step we determined the optimal kinematic cuts using those figures. Doing this, we have taken the separating value of the signals and background for every objects and composed the optimized cuts given in Table I.

Table 1. Selected cuts for the $e^{-}e^{+} \rightarrow ZZ \rightarrow jj\nu_l\overline{\nu_l}$ signal.

	$\frac{C_{\bar{B}W}}{\Lambda^4}, \frac{C_{WW}}{\Lambda^4}, \frac{C_{BW}}{\Lambda^4}, \frac{C_{BB}}{\Lambda^4}$
Cut-1	$\lvert\eta^j\rvert < 2.5$, $p_T^j > 100$ GeV
Cut-2	$MET > 200$ GeV
Cut-3	$\Delta\mathrm{R(j,j)} > 0.4$
Cut-4	$80 < M_{jj} < 100$ GeV

For Cut-I, we applied $\lvert\eta^j\rvert < 2.5$ and $p_T^j > 100$ GeV as seen in Figs. 3-4. In the second base MET > 200 GeV is applied to separate signals and background more clearly which is easy to see in Fig.2. For Cut-3, we applied the angular separations $\Delta\mathrm{R} = ((\Delta\phi)^2 + (\Delta\eta)^2)^{\frac{1}{2}})$ for final state jets as $\Delta\mathrm{R(j,j)} > 0.4$. We also applied invariant-mass cut to final state jets $80 < M_{jj} < 100$ GeV closest to the mass of Z which is tagged Cut-4. In Table-II we have given the events for signals and SM background after applying selected cuts step-by-step. On the other hand we used polarized beam options for electron due to the CLIC experiment program in our calculations to increase the signals and reduce the unwanted background effects (Gurkanli et al., 2021, Franceschini, 2020, Roloff et al., 2018, Weber, 2020, Spor et al., 2021).

Table 2. Events for the process $e^{-}e^{+} \rightarrow ZZ \rightarrow jj\nu_l\overline{\nu_l}$, the SM and relevant backgrounds with applied cuts. All couplings are taken 1 TeV^{-4}.

	$\frac{C_{BB}}{\Lambda^4}$	$\frac{C_{\bar{B}W}}{\Lambda^4}$	$\frac{C_{BW}}{\Lambda^4}$	$\frac{C_{WW}}{\Lambda^4}$	SM
Cut-0	99250	128100	20420	17650	4976
Cut-1	95482	124089	17333	14592	2035
Cut-2	94946	123435	17056	14326	1817
Cut-3	14580	18735	3224	2802	975
Cut-4	13539	17425	2995	2605	905

3. Findings and Discussion

3.1 Sensitivities on ANTGC

The sensitivities on aNTGCs $\frac{C_{\bar{B}W}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$ and $\frac{C_{BB}}{\Lambda^4}$ are obtained with χ^2 method at the 95% Confidence Level. It is defined with the following equation.

$$\chi^2 = \left(\frac{\sigma_{Tot}\left(\frac{C}{\Lambda^4}\right) - \sigma_{SM}}{\sigma_{SM}\sqrt{(\delta_{st})^2 + (\delta_{sys})^2}}\right)^2 \qquad (23)$$

Here, δ_{st} is the statistical error which is defined by $\delta_{st} = \frac{1}{\sqrt{N_{SM}}}$. On the other hand, N_{SM} is the number of events related to the SM which is given by the following equation.

$$N_{SM} = \mathcal{L} \times \sigma_{SM}. \quad (24)$$

In Eq. 23 $\sigma_{Tot}\left(\frac{C}{\Lambda^4}\right)$ refer to the cross-section of the signal $e^-e^+ \to ZZ \to jj\nu_l\bar{\nu_l}$ with the contribution of ZZZ and $ZZ\gamma$ aNTGC while the σ_{SM} is the SM cross-section of the related process. While obtaining the sensitivities, we also take into account the systematic uncertainties δ_{sys} which may arise from related backgrounds, lepton identification and jet-photon misidentification (Khoriauli, 2009, Senol et al., 2022). In this context, we have given the sensitivities under the systematic uncertainty values of $\delta_{sys} = 0\%$, 3% and 5%. The sensitivities on aNTGCs $\frac{C_{\bar{B}W}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$ and $\frac{C_{BB}}{\Lambda^4}$ for the process $e^-e^+ \to ZZ \to jj\nu_l\bar{\nu_l}$ at $\sqrt{s} = 3$ TeV with unpolarized and polarized electron beams and under various systematic uncertainties are given in Table III.

Table 3. Bounds on $\frac{C_{\bar{B}W}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$ and $\frac{C_{BB}}{\Lambda^4}$ via $e^-e^+ \to ZZ \to jj\nu_l\bar{\nu_l}$ process.

P_e		0%	-80%	80%
		$\mathcal{L}_{int} = 5$ ab^{-1}	$\mathcal{L}_{int} = 4$ ab^{-1}	$\mathcal{L}_{int} = 1$ ab^{-1}
$\frac{C_{BB}}{\Lambda^4}$	$\delta_{sys} = 0\%$	$[-6.71; 6.74] \times 10^{-2}$	$[-1.02; 1.04] \times 10^{-1}$	$[-7.66; 7.95] \times 10^{-2}$
	$\delta_{sys} = 3\%$	$[-7.72; 7.75] \times 10^{-2}$	$[-1.17; 1.19] \times 10^{-1}$	$[-7.88; 8.17] \times 10^{-2}$
	$\delta_{sys} = 5\%$	$[-8.89; 8.93] \times 10^{-2}$	$[-1.35; 1.37] \times 10^{-2}$	$[-8.23; 8.52] \times 10^{-2}$
$\frac{C_{\bar{B}W}}{\Lambda^4}$	$\delta_{sys} = 0\%$	$[-5.77; 6.03] \times 10^{-2}$	$[-0.53; 0.80] \times 10^{-1}$	$[-0.79; 0.88] \times 10^{-1}$
	$\delta_{sys} = 3\%$	$[-6.65; 6.91] \times 10^{-2}$	$[-0.62; 0.89] \times 10^{-1}$	$[-0.81; 0.91] \times 10^{-1}$
	$\delta_{sys} = 5\%$	$[-7.68; 7.95] \times 10^{-2}$	$[-0.73; 0.99] \times 10^{-1}$	$[-0.85; 0.94] \times 10^{-1}$
$\frac{C_{BW}}{\Lambda^4}$	$\delta_{sys} = 0\%$	$[-1.66; 1.66] \times 10^{-1}$	$[-4.11; 4.10] \times 10^{-1}$	$[-1.75; 1.74] \times 10^{-1}$
	$\delta_{sys} = 3\%$	$[-1.91; 1.91] \times 10^{-1}$	$[-4.70; 4.69] \times 10^{-1}$	$[-1.80; 1.80] \times 10^{-1}$
	$\delta_{sys} = 5\%$	$[-2.20; 2.20] \times 10^{-1}$	$[-5.40; 5.39] \times 10^{-1}$	$[-1.87; 1.87] \times 10^{-1}$
$\frac{C_{WW}}{\Lambda^4}$	$\delta_{sys} = 0\%$	$[-1.83; 1.84] \times 10^{-1}$	$[-1.49; 1.53] \times 10^{-1}$	$[-5.77; 5.78] \times 10^{-1}$
	$\delta_{sys} = 3\%$	$[-2.10; 2.11] \times 10^{-1}$	$[-1.71; 1.75] \times 10^{-1}$	$[-5.93; 5.94] \times 10^{-1}$
	$\delta_{sys} = 5\%$	$[-2.42; 2.43] \times 10^{-1}$	$[-1.97; 2.00] \times 10^{-1}$	$[-6.19; 6.20] \times 10^{-1}$

The best sensitivities on aNTGCs are obtained as expected under $\delta_{sys} = 0\%$ systematic uncertainties which are given in Eqs. 25-28.

$$\frac{C_{BB}}{\Lambda^4} = [-6.71; 6.74] \times 10^{-2} \text{ TeV}^{-4} \quad (25)$$

$$\frac{C_{\bar{B}W}}{\Lambda^4} = [-5.77; 6.03] \times 10^{-2} \text{ TeV}^{-4} \quad (26)$$

$$\frac{C_{BW}}{\Lambda^4} = [-1.66; 1.66] \times 10^{-1} \text{ TeV}^{-4} \quad (27)$$

$$\frac{C_{WW}}{\Lambda^4} = [-1.49; 1.53] \times 10^{-1} \text{ TeV}^{-4} \quad (28)$$

We have given the figures of production cross-section in terms of $\frac{C_{\tilde{B}W}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$ and $\frac{C_{BB}}{\Lambda^4}$ couplings for different electron polarizations in Figs. 5-7.

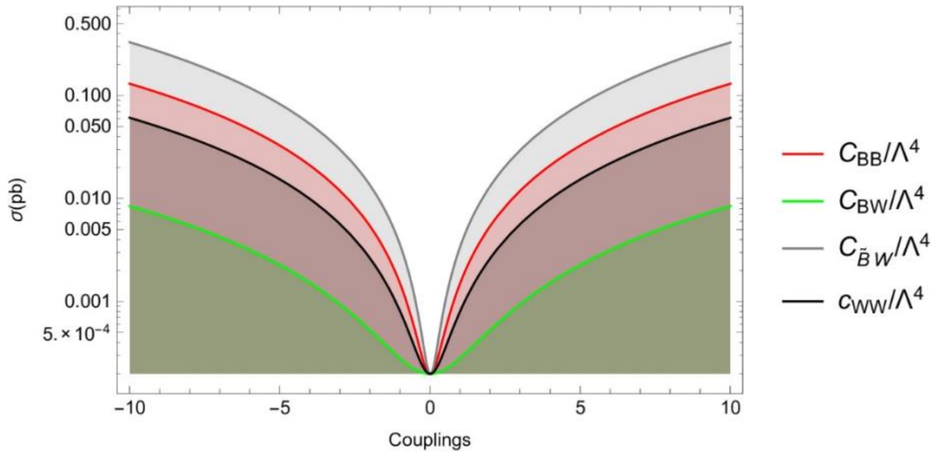

Figure 5. Cross-section of $e^-e^+ \to ZZ \to jj\nu_l\bar{\nu}_l$ process in terms of the anomalous $\frac{C_{\tilde{B}W}}{\Lambda^4}$, $\frac{C_{WW}}{\Lambda^4}$, $\frac{C_{BW}}{\Lambda^4}$, $\frac{C_{BB}}{\Lambda^4}$ couplings at the $\sqrt{s} = 3$ TeV and $P_{e^-} = -80\%$.

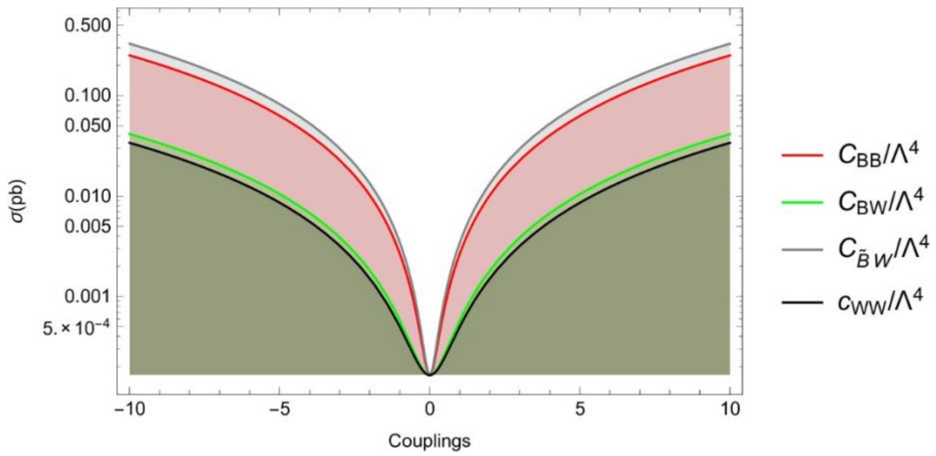

Figure 6. Same as Fig.5 but for unpolarized beams $P_{e^-} = 0\%$.

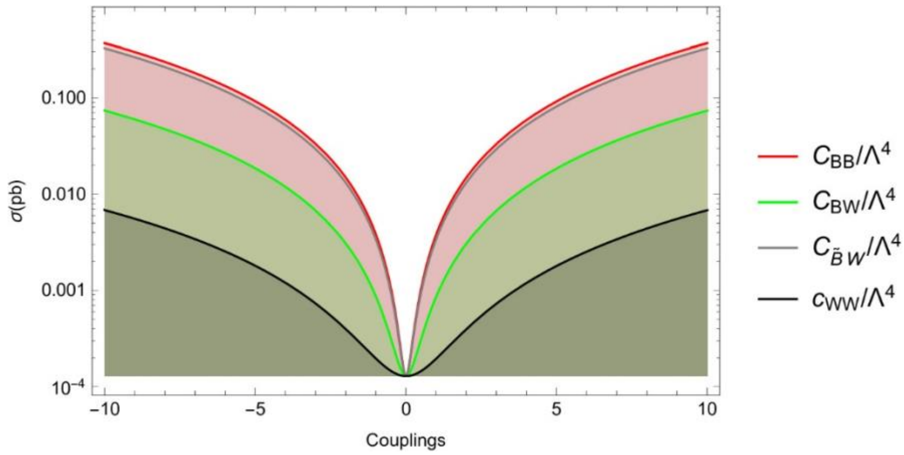

Figure 7. Same as Fig.5 but for unpolarized beams $P_{e^-} = 80\%$.

We also have given barcharts in the Figs. 8-11 to compare our results with latest experimental limits given in the Eqs. 19-22. As seen in those figures, our result improved the boundries by a factor of 3-20 times. Also, the sensitivities they are comparable with the related phenomenological results in the literature.

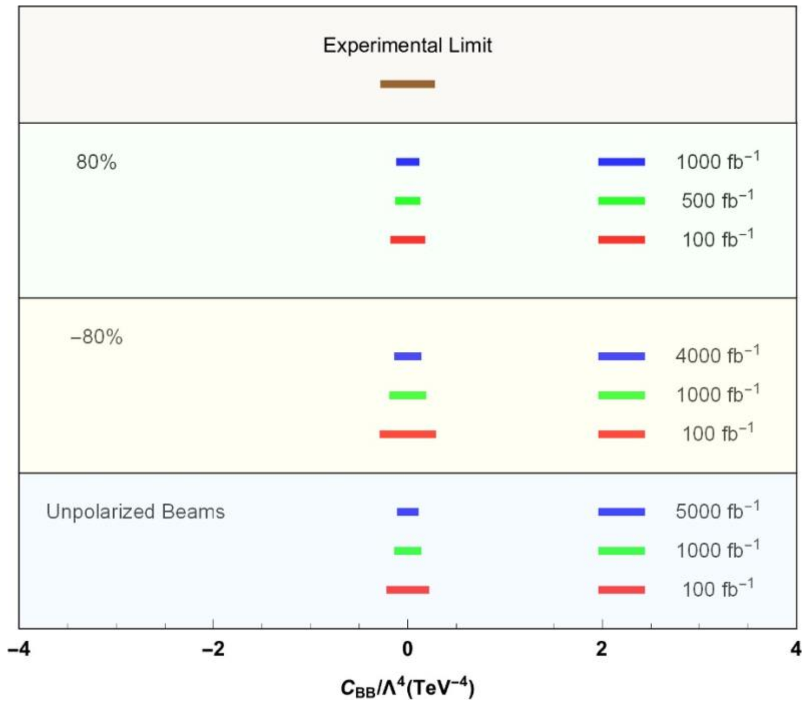

Figure 8. Comparison of the current experimental limits and sensitivities on the anomalous $\frac{C_{BB}}{\Lambda^4}$ coupling for the luminosities of $\mathcal{L}_{int} = 5000, 4000, 1000, 500\ 100$ fb^{-1} and $\sqrt{s} = 3$ TeV.

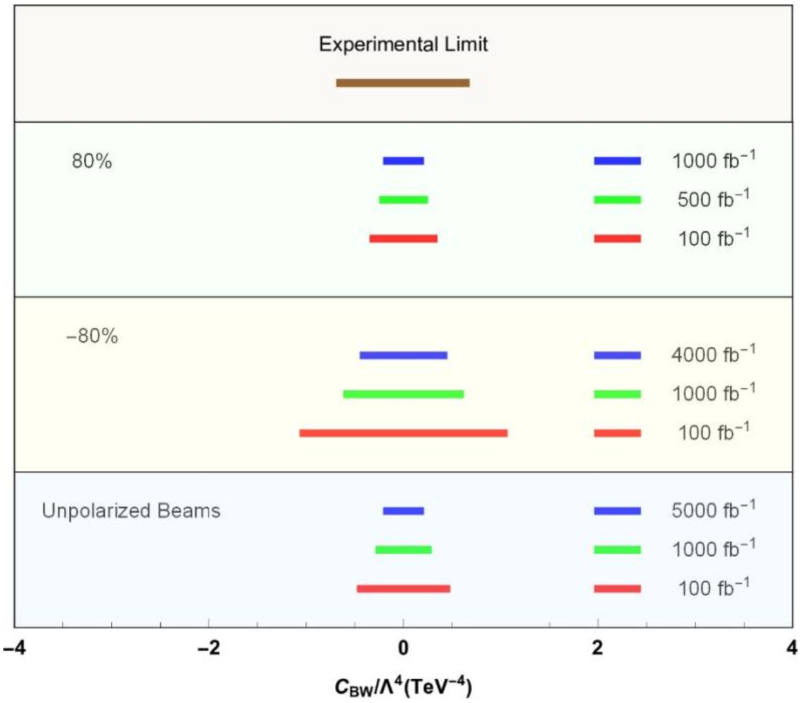

Figure 9. Same as Fig.8 but for the anomalous $\frac{C_{BW}}{\Lambda^4}$ coupling.

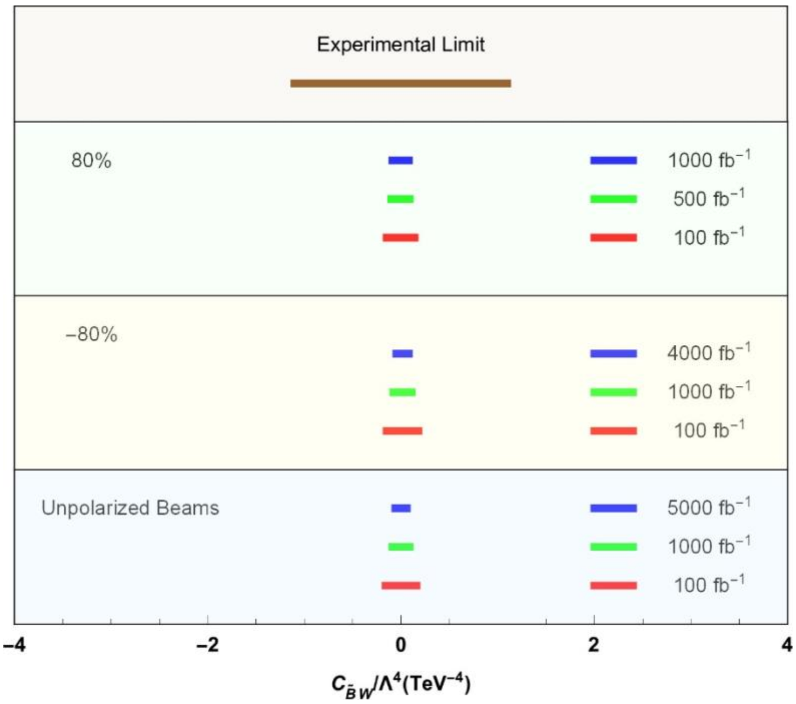

Figure 10. Same as Fig.8 but for the anomalous $\frac{C_{\tilde{B}W}}{\Lambda^4}$ coupling.

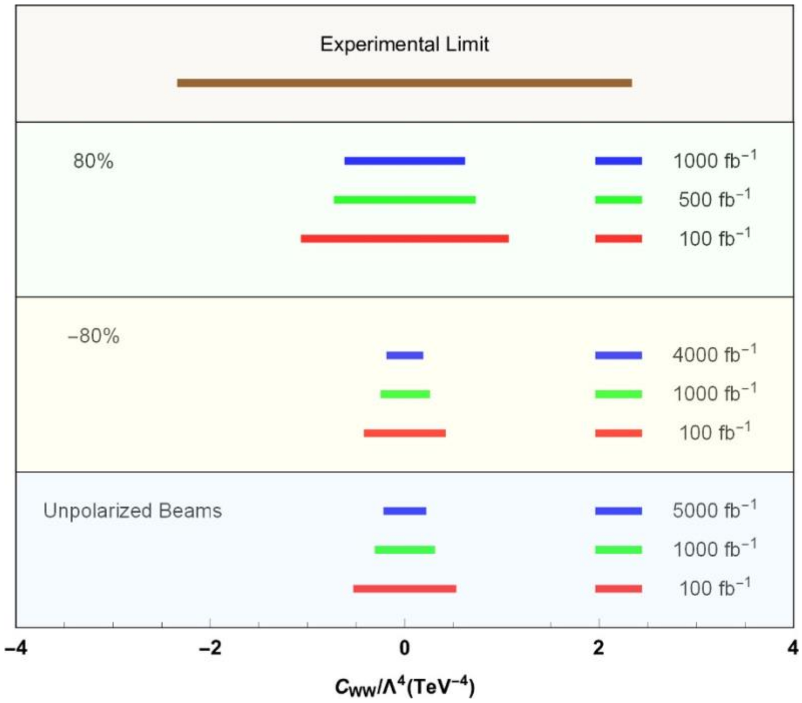

Figure 11. Same as Fig.8 but for the anomalous $\frac{c_{WW}}{\Lambda^4}$ coupling.

4. Conclusions and Recommendations

In the study, we perform the $e^-e^+ \to ZZ$ process for the decay of $Z \to jj$, $Z \to \nu_l\bar{\nu}_l$ to probe the ZZZ and $ZZ\gamma$ aNTGC. We performed the calculations for both unpolarized and polarized electron beams at CLIC with a CoM energy of $\sqrt{s} = 3$ TeV. A cut-based analysis is carried out to separate the signals and related SM background. While doing this, we composed a cut-flow chart to show the effects of selected cuts on the generated events step-by-step. Finally, we obtained the sensitivities of $\frac{c_{\widetilde{B}W}}{\Lambda^4}$, $\frac{c_{WW}}{\Lambda^4}$, $\frac{c_{BW}}{\Lambda^4}$ and $\frac{c_{BB}}{\Lambda^4}$ couplings at 95% Confidence Level for unpolarized, 80% and -80% polarized electron beams with the luminosities of $\mathcal{L}_{int} = 5$ ab^{-1}, $\mathcal{L}_{int} = 1$ ab^{-1} and $\mathcal{L}_{int} = 4$ ab^{-1}, respectively. Also, we give our results under systematic uncertainties of 0%, 3% and 5% .Our sensitivities improve the latest experimental results by a factor of 3-20 times and are comparable with the related phenomenological studies in the literature.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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