Research Article

Probe of the Anomalous Quartic Couplings with Beam Polarization at the CLIC

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We have investigated the anomalous quartic couplings defined by the dimension-8 operators in semileptonic decay channel of the $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ process for unpolarized and polarized electron (positron) beam at the Compact Linear Collider. We give the 95% confidence level bounds on the anomalous f_{S0}/Λ^4 , f_{S1}/Λ^4 , and f_{T0}/Λ^4 couplings for various values of the integrated luminosities and center-of-mass energies. The best sensitivities obtained on anomalous f_{S0}/Λ^4 , f_{S1}/Λ^4 , and f_{T0}/Λ^4 couplings through the process $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ with beam polarization at $\sqrt{s} = 3$ TeV and an integrated luminosity of $L_{\text{int}} = 2000 \text{ fb}^{-1}$ are $[-4.05; 3.67] \times 10^{-12} \text{ GeV}^{-4}$, $[-3.08; 2.12] \times 10^{-12} \text{ GeV}^{-4}$, and $[-1.98; 0.64] \times 10^{-13} \text{ GeV}^{-4}$, which show improvement over the current bounds.

1. Introduction

The Standard Model (SM) has been proven to be highly successful through many significant experimental tests, in particular the discovery of a new particle consistent with the SM Higgs boson with a mass between 125-126 GeV detected by the ATLAS and the CMS experiments at the LHC [1, 2]. On the other hand, since many important questions such as the origin of mass, the large hierarchy between electroweak and the Planck scale, the strong CP problem, and the matter/antimatter asymmetry remain unanswered in the SM, we need to study physics beyond the SM. One of the ways of probing new physics beyond the SM is to investigate the anomalous gauge boson interactions. Gauge boson self-interactions in the SM are exactly described by the $SU_L(2) \times U_Y(1)$ gauge symmetry. The precision measurements of gauge boson self-interactions can further verify the SM. Furthermore, the existence of anomalous gauge boson couplings may be a sign of new physics beyond the SM. The effective Lagrangian approach is one of the common ways for searching new physics beyond the SM in a model independent way. In particular, the anomalous quartic gauge

boson couplings can be examined with the aid of the effective Lagrangian approach. Such an approach is parameterized by high-dimensional operators which induce anomalous quartic gauge couplings that modify the interactions between the electroweak gauge bosons.

The LHC is expected to reply some of the fundamental open questions in particle physics. Nevertheless, the analysis of the LHC data is quite difficult due to remnants of the usual proton-proton deep inelastic processes, whereas collisions between electrons and positrons are much simpler to investigate than proton-proton collisions. A linear electron-positron collider with high luminosity and energy is the best option to complement and to expand the LHC physics program. The CLIC is one of the most popular linear colliders, purposed to follow out electron-positron collisions at energies from 0.35 TeV to 3 TeV [3]. To have its high luminosity and energy is quite important with regard to new physics research beyond the SM. Since the anomalous quartic couplings defined through effective Lagrangians have dimension-8, they have very strong energy dependence. Therefore, the anomalous cross section including these vertices has higher energy dependence than the SM cross section. Hence, CLIC will have

a great potential to examine the anomalous quartic gauge boson couplings.

High-dimensional effective operators describing the anomalous quartic gauge boson couplings are expressed by either linear or nonlinear effective Lagrangians. Nonlinear effective Lagrangians are considered if there is no Higgs boson in the low energy spectrum. However, linear effective Lagrangians are obtained by using a linear representation of gauge symmetry that is broken by the conventional SM Higgs mechanism. It becomes important to study the anomalous quartic gauge boson couplings based on linear effective Lagrangians due to the discovery of a Higgs boson in the LHC. For these reasons, we only deal with dimension-8 operators in our work.

In this paper, we will analyze the anomalous quartic couplings via $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ process with semileptonic decay including polarized electron (positron) beam effects at the CLIC for the center-of-mass energies of 1.4 and 3 TeV.

2. Dimension-Eight Operators for Quartic Gauge Couplings

There are three classes of operators that describe the anomalous quartic couplings. The first class of operators can be parameterized in terms of only the covariant derivative of the field $D_\mu \Phi$. This class includes two independent operators [4]:

$$\begin{aligned} L_{S0} &= \frac{f_{S0}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right], \\ L_{S1} &= \frac{f_{S1}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger D_\mu \Phi \right] \left[(D^\nu \Phi)^\dagger D^\nu \Phi \right]. \end{aligned} \quad (1)$$

The second class of operators are related to $D_\mu \Phi$ and the field strength. These seven operators are given as follows [4]:

$$\begin{aligned} L_{M0} &= \frac{f_{M0}}{\Lambda^4} \text{tr} [W_{\mu\nu} W^{\mu\nu}] \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right], \\ L_{M1} &= \frac{f_{M1}}{\Lambda^4} \text{tr} [W_{\mu\nu} W^{\nu\beta}] \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right], \\ L_{M2} &= \frac{f_{M2}}{\Lambda^4} [B_{\mu\nu} B^{\mu\nu}] \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right], \\ L_{M3} &= \frac{f_{M3}}{\Lambda^4} [B_{\mu\nu} B^{\nu\beta}] \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right], \\ L_{M4} &= \frac{f_{M4}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\mu \Phi \right] B^{\beta\nu}, \\ L_{M5} &= \frac{f_{M5}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger W_{\beta\nu} D^\nu \Phi \right] B^{\beta\mu}, \\ L_{M6} &= \frac{f_{M6}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi \right], \\ L_{M7} &= \frac{f_{M7}}{\Lambda^4} \left[(D_\mu \Phi)^\dagger W_{\beta\nu} W^{\beta\mu} D^\nu \Phi \right]. \end{aligned} \quad (2)$$

The remaining operators contain, solely, the field strength tensors. These operators can be expressed as [4]

$$L_{T0} = \frac{f_{T0}}{\Lambda^4} \text{tr} [W_{\mu\nu} W^{\mu\nu}] \text{tr} [W_{\alpha\beta} W^{\alpha\beta}],$$

$$L_{T1} = \frac{f_{T1}}{\Lambda^4} \text{tr} [W_{\alpha\nu} W^{\mu\beta}] \text{tr} [W_{\mu\beta} W^{\alpha\nu}],$$

$$L_{T2} = \frac{f_{T2}}{\Lambda^4} \text{tr} [W_{\alpha\mu} W^{\mu\beta}] \text{tr} [W_{\beta\nu} W^{\nu\alpha}],$$

$$L_{T5} = \frac{f_{T5}}{\Lambda^4} \text{tr} [W_{\mu\nu} W^{\mu\nu}] B_{\alpha\beta} B^{\alpha\beta},$$

$$L_{T6} = \frac{f_{T6}}{\Lambda^4} \text{tr} [W_{\alpha\nu} W^{\mu\beta}] B_{\mu\beta} B^{\alpha\nu},$$

$$L_{T7} = \frac{f_{T7}}{\Lambda^4} \text{tr} [W_{\alpha\mu} W^{\mu\beta}] [B_{\beta\nu} B^{\nu\alpha}],$$

$$L_{T8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta},$$

$$L_{T9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}.$$

(3)

The complete list of quartic vertices modified by these operators is given in Table 1.

There are total 59 Feynman diagrams for process $e^+e^- \rightarrow \nu_e W^+ W^- \bar{\nu}_e$ including anomalous quartic $WWWW$, $WWZ\gamma$, and $WWZZ$ couplings. The three diagrams in presence of anomalous quartic $WWWW$, $WWZ\gamma$, and $WWZZ$ couplings are shown in Figure 1. We can see from Table 1 that while L_{S0} and L_{S1} operators modify the anomalous $WWWW$ and $WWZZ$ couplings, dimension-8 effective L_{T0} operator causes the anomalous $WWWW$, $WWZ\gamma$, and $WWZZ$ vertices.

There have been many studies for the anomalous gauge self-interactions at linear and hadron colliders. On the other hand, the anomalous quartic couplings arising from dimension-8 operators at the LHC and the future hadron colliders have been investigated in [5–39]. In our paper, we choose L_{S0} , L_{S1} , and L_{T0} operators to investigate anomalous quartic couplings. In the literature, these couplings have been examined three different f_{S0}/Λ^4 , f_{S1}/Λ^4 , and f_{T0}/Λ^4 couplings. Reference [5] has been experimentally obtained the bounds on the f_{S0}/Λ^4 and f_{S1}/Λ^4 using proton-proton collision data corresponding to an integrated luminosity of 20.3 fb^{-1} at a center-of-mass energy of 8 TeV collected by the ATLAS detector at the LHC. In [6], the sensitivity bounds are obtained only on f_{S0}/Λ^4 and f_{S1}/Λ^4 at 99% confidence level (CL) for $\sqrt{s} = 14 \text{ TeV}$ via $pp \rightarrow jj e^\pm \mu^\pm \nu \nu$ process. Similarly the sensitivity bounds on f_{T0}/Λ^4 with 95% CL via triboson production at the proton-proton colliders for $\sqrt{s} = 14 \text{ TeV}$ are obtained in [8]. In [7], the f_{S0}/Λ^4 , f_{S1}/Λ^4 , and f_{T0}/Λ^4 couplings have been studied via WWW final state with full leptonic decay and semileptonic decay for $\sqrt{s} = 14 \text{ TeV}$ at the LHC and $\sqrt{s} = 100 \text{ TeV}$ for future hadron collider. The best available constraints on f_{S0}/Λ^4 , f_{S1}/Λ^4 , and f_{T0}/Λ^4 parameters defining these anomalous quartic couplings obtained from one parameter analysis in [5–8] are summarized in Table 2. In [39] the authors examine the nonlinear parametrization through the processes $pp \rightarrow l^\pm \nu_l l^\mp \nu_l jj$ and $pp \rightarrow l^\pm \nu_l l^\mp \nu_l jj$ at the LHC.

FIGURE 1: The Feynman diagrams for the $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ process in the presence of anomalous quartic $WWWW$, $WWZ\gamma$, and $WWZZ$ couplings.

TABLE 1: Quartic vertices modified by each dimension-8 operator are marked with X [4].

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
L_{S0}, L_{S1}	X	X	X						
$L_{M0}, L_{M1}, L_{M6}, L_{M7}$	X	X	X	X	X	X	X		
$L_{M2}, L_{M3}, L_{M4}, L_{M5}$		X	X	X	X	X	X		
L_{T0}, L_{T1}, L_{T2}	X	X	X	X	X	X	X	X	X
L_{T5}, L_{T6}, L_{T7}		X	X	X	X	X	X	X	X
L_{T8}, L_{T9}			X			X	X	X	X

3. Numerical Analysis

The important features of a linear collider are its clean experimental environment, high energy, and polarized beams. A polarized electron beam would provide suitable platform searching of the SM and for diagnosing new physics. Observation of even the tiniest signal which conflicts with the SM expectations would be a convincing evidence for physics beyond the SM. Proper selections of the electron and positron beam polarization may therefore be used to enhance the new physics signal and also to considerably suppress backgrounds.

We use MadGraph5 [40] to generate the signal and background events with the effective Lagrangian implemented through FEYNRULES [41]. In order to probe the sensitivity of anomalous quartic couplings (L_{S0} , L_{S1} , and L_{T0}), we analyzed the process $e^+e^- \rightarrow W^+(\rightarrow l^+\nu)W^-(\rightarrow \text{jets})\nu_e\bar{\nu}_e$. In our analysis the main background processes yield identical final states to the signal process. Here we assume that one of the W 's in the final state decays into leptonic channel and the other one decays into hadronic channel. Therefore, the final state signal and background topology of the process consists of an energetic lepton (l), neutrinos (missing E_T), and two hadronic jets ($2j$). We apply following set of cuts in order to suppress the backgrounds and enhance the signal for the anomalous quartic interactions in $e^+e^- \rightarrow W^+W\bar{\nu}_e\nu_e$ process:

- (1) $P_{Tj} > 10 \text{ GeV}$, $|\eta_j| < 5$,
- (2) $E_{\text{miss}} > 10 \text{ GeV}$ (missing E_T (sum of neutrino's momenta)),
- (3) $|M_{jj} - M_W| < 15 \text{ GeV}$,
- (4) $\Delta R > 0.4$,

where $j = u, d, s, c$ and ΔR is the angular separation between any two objects. $\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$ with φ representing the azimuthal angle with respect to the beam directions.

If the electroweak nature of the interactions of the processes is taken into account, for a process with electron

and positron beam polarization, the cross section can be expressed as [42]

$$\sigma = \frac{1}{4} (1 - P_{e^+}) (1 + P_{e^-}) \sigma_{-1+1} + \frac{1}{4} (1 + P_{e^+}) (1 - P_{e^-}) \sigma_{+1-1}. \quad (4)$$

Here σ_{ab} represents the calculated cross section with fixed helicities a for positron and b for the electron. P_{e^-} is the electron beam and P_{e^+} is the positron relative polarization. It may be noted that the considered process includes only a weak interaction. Therefore, only left-handed electrons (right-handed positrons) should be taken into account because of the structure of the $W e^- \nu_e$ ($W e^+ \bar{\nu}_e$) vertex. Hence, the left-polarized electron (right-polarized positron) beam would enhance the cross section. This effect can be seen in Figures 2–7 for various polarization schemes. The total cross section of the $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ process as a function of f_{S0}/Λ^4 coupling for 1.4 and 3 TeV center-of-mass energies is shown in Figures 2 and 3, respectively. Figures 4 and 5 depict the total cross section depending on the anomalous f_{S1}/Λ^4 coupling at $\sqrt{s} = 1.4 \text{ TeV}$ and $\sqrt{s} = 3 \text{ TeV}$ energies, respectively. The total cross sections are plotted in Figures 6 and 7 with respect to f_{T0}/Λ^4 coupling for the center-of-mass energies of 1.4 TeV and 3 TeV, respectively. As can be seen from Figures 2 and 7, the polarization ($P_{e^-} = -80\%$; $P_{e^+} = +60\%$) enhances the cross sections the most compared to the other considered to polarization schemes. The lowest points of the curves in Figures 2 and 7 correspond the value of the SM cross section. As seen from the figures, the increase of the center-of-mass energy leads to remarkable enhancement of the deviations from the SM. For instance, in Figure 2 cross section increases nearly by a factor of 10 from the SM for $f_{S0}/\Lambda^4 = 1 \times 10^{-9} \text{ GeV}^{-4}$ at 1.4 TeV. However, cross section increases nearly by a factor of 100 at 3 TeV for the same value for f_{S0}/Λ^4 . On the other hand, the obtained cross sections are very sensitive to the anomalous parameters. For instance, in Figure 3 cross section increases two orders of magnitude as f_{S1}/Λ^4 increases

TABLE 2: Current sensitivity bounds on anomalous parameters for 95% CL with 20.3 fb^{-1} for $\sqrt{s} = 8 \text{ TeV}$ [5], 99% CL with 100 fb^{-1} for $\sqrt{s} = 14 \text{ TeV}$ [6], 95% CL with 100 fb^{-1} for $\sqrt{s} = 14 \text{ TeV}$ [7], 5σ with 300 fb^{-1} for $\sqrt{s} = 14 \text{ TeV}$ [8], and 95% CL with 3000 fb^{-1} for $\sqrt{s} = 100 \text{ TeV}$ [7].

$L \text{ (fb}^{-1}\text{)}$	$\sqrt{s} \text{ (TeV)}$	$f_{S0}/\Lambda^4 \text{ (GeV}^{-4}\text{)}$	$f_{S1}/\Lambda^4 \text{ (GeV}^{-4}\text{)}$	$f_{T0}/\Lambda^4 \text{ (GeV}^{-4}\text{)}$
20.3 [5]	8	$[-0.13; 0.18] \times 10^{-8}$	$[-0.25; 0.31] \times 10^{-8}$	—
100 [6]	14	$[-2.2; 2.4] \times 10^{-11}$	$[-2.5; 2.5] \times 10^{-11}$	—
100 [7]	14	$[-1.8; 1.8] \times 10^{-10}$	$[-2.7; 2.8] \times 10^{-10}$	$[-5.8; 5.9] \times 10^{-13}$
300 [8]	14	—	—	$[-1.2; 1.2] \times 10^{-12}$
3000 [7]	100	$[-2.9; 3.0] \times 10^{-12}$	$[-1.3; 1.1] \times 10^{-12}$	$[-3.7; 3.0] \times 10^{-15}$

FIGURE 2: The total cross section for $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ processes as a function of f_{S0}/Λ^4 at the $\sqrt{s} = 1.4 \text{ TeV}$ for different polarization of the positron and electron beams.

FIGURE 3: The total cross section for $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ processes as a function of f_{S0}/Λ^4 at the $\sqrt{s} = 3 \text{ TeV}$ for different polarization of the positron and electron beams.

from 0 to $1 \times 10^{-9} \text{ GeV}^{-4}$. As seen from these figures, the total cross sections depend on the center-of-mass energy. When the center-of-mass energies are changed from 1.4 TeV to 3 TeV, the cross sections nearly increase by a factor of 100. The cross sections are almost symmetric with respect to change in the sign of anomalous couplings. Therefore, main contribution comes from the quadrupole anomalous couplings terms.

In order to examine the sensitivity to the anomalous couplings, we use one parameter χ^2 criterion without systematic error. The χ^2 function is defined as follows:

$$\chi^2 = \left(\frac{\sigma_{\text{SM}} - \sigma_{\text{NP}}}{\sigma_{\text{SM}} \delta_{\text{stat}}} \right)^2, \quad (5)$$

where σ_{NP} is the total cross section including SM and new physics, $\delta_{\text{stat}} = 1/\sqrt{N}$ is the statistical error, and N is the number of background events $N = L_{\text{int}} \sigma_{\text{SM}}$, where L_{int} is the integrated CLIC luminosity. We have obtained 95% CL limits on the anomalous coupling parameters using this analyze method at $\sqrt{s} = 1.4 \text{ TeV}$ and 3 TeV for different integrated luminosity values and final polarization configurations. Polarization improves the sensitivity bound of anomalous parameters as seen from Tables 3–8. As we expected,

FIGURE 4: The total cross section for $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ processes as a function of f_{S1}/Λ^4 at the $\sqrt{s} = 1.4 \text{ TeV}$ for different polarization of the positron and electron beams.

FIGURE 5: The total cross section for $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ processes as a function of f_{S1}/Λ^4 at the $\sqrt{s} = 3$ TeV for different polarization of the positron and electron beams.

FIGURE 7: The total cross section for $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ processes as a function of f_{T0}/Λ^4 at the $\sqrt{s} = 3$ TeV for different polarization of the positron and electron beams.

FIGURE 6: The total cross section for $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$ processes as a function of f_{T0}/Λ^4 at the $\sqrt{s} = 1.4$ TeV for different polarization of the positron and electron beams.

the best limits are obtained for the $P_{e^-} = -80\%$; $P_{e^+} = 60\%$ polarization state.

The expected best sensitivities on f_{S0}/Λ^4 and f_{S1}/Λ^4 couplings in Tables 3–6 are far beyond the sensitivities of the LHC. Also, we observe that our limits for f_{S0}/Λ^4 in Table 3 at $\sqrt{s} = 1.4$ TeV are competitive with the results in [6] and one order of magnitude better than the ones reported for the LHC with $L = 100 \text{ fb}^{-1}$ by [7]. Additionally, our limits for $\sqrt{s} = 3$ TeV are at the same order of magnitude with the LHC results for the $L = 3000 \text{ fb}^{-1}$ and $\sqrt{s} = 100$ TeV. These results can be seen if Table 2 is compared to Table 4. Similar interpretations can be made for our bounds on f_{S1}/Λ^4 from Tables 5 and 6.

In addition, we can see from Table 7 that the limits on f_{T0}/Λ^4 for $\sqrt{s} = 1.4$ TeV are very close to the LHC bounds for 5σ with 300 fb^{-1} for $\sqrt{s} = 14$ TeV. However, the bounds for $\sqrt{s} = 100$ TeV future hadron collider with $L = 3000 \text{ fb}^{-1}$ are better than our limits on f_{T0}/Λ^4 as stated from Table 8. In the meantime, the relation between linear and nonlinear parametrization is shown in [4] as the following formations:

$$\alpha_4 = \frac{f_{S0}}{\Lambda^4} \frac{v^4}{8}, \quad (6)$$

$$\alpha_4 + 2\alpha_5 = \frac{f_{S1}}{\Lambda^4} \frac{v^4}{8}.$$

In [39] the authors study the nonlinear parametrization through the processes $pp \rightarrow l^\pm \nu_l l^\pm \nu_l jj$ and $pp \rightarrow l^\pm \nu_l l^\mp \nu_l jj$ at the LHC as mentioned above. This process can isolate the $WWWW$ vertex. The best 95% CL bounds they have found are $\alpha_4 = [-0.0011; 0.0016]$ and $\alpha_5 = [-0.0022; 0.0016]$ for the $\sqrt{s} = 14$ TeV and $L = 3 \text{ ab}^{-1}$. By using (6), these limits can be converted to linear parametrization. The results obtained in this case are $f_{S0}/\Lambda^4 = [-2.40 \times 10^{-12}; 3.50 \times 10^{-12}] \text{ GeV}^{-4}$ and $f_{S1}/\Lambda^4 = [-1.20 \times 10^{-11}; 1.75 \times 10^{-11}] \text{ GeV}^{-4}$. As seen from the Tables 4 and 6, these limits are of the same order as our best limits for the f_{S0}/Λ^4 , but the best limits we obtain for f_{S1}/Λ^4 are one order of magnitude better. Additionally, when the 10% systematic uncertainty factor is taken into account, the sensitivity of our best obtained bounds decreases by about one order magnitude for f_{S0}/Λ^4 and f_{S1}/Λ^4 and 3-time decrease for f_{T0}/Λ^4 coupling.

4. Conclusions

The CLIC is a high energy collider which has TeV scale energy and very high luminosity. Particularly, operating with its high energy and luminosity is extremely important in order

TABLE 3: Sensitivity of f_{S0}/Λ^4 at 95% CL for $\sqrt{s} = 1.4$ TeV in units of GeV^{-4} .

L (fb^{-1})	Unpolarized	$P_{e^-} = -80\%; P_{e^+} = 0$	$P_{e^-} = -80\%; P_{e^+} = 60$
50	$[-10.02; 9.67] \times 10^{-11}$	$[-8.63; 8.39] \times 10^{-11}$	$[-7.72; 7.70] \times 10^{-11}$
250	$[-6.76; 6.41] \times 10^{-11}$	$[-5.81; 5.57] \times 10^{-11}$	$[-5.22; 4.90] \times 10^{-11}$
500	$[-5.71; 5.36] \times 10^{-11}$	$[-4.91; 4.67] \times 10^{-11}$	$[-4.41; 4.09] \times 10^{-11}$
750	$[-5.18; 4.83] \times 10^{-11}$	$[-4.44; 4.21] \times 10^{-11}$	$[-4.00; 3.69] \times 10^{-11}$
1000	$[-4.83; 4.48] \times 10^{-11}$	$[-4.14; 3.90] \times 10^{-11}$	$[-3.74; 3.42] \times 10^{-11}$
1250	$[-4.58; 4.23] \times 10^{-11}$	$[-3.93; 3.69] \times 10^{-11}$	$[-3.54; 3.23] \times 10^{-11}$
1500	$[-4.38; 4.04] \times 10^{-11}$	$[-3.76; 3.52] \times 10^{-11}$	$[-3.39; 3.08] \times 10^{-11}$

TABLE 4: Sensitivity of f_{S0}/Λ^4 at 95% CL for $\sqrt{s} = 3$ TeV in units of GeV^{-4} .

L (fb^{-1})	Unpolarized	$P_{e^-} = -0.80\%; P_{e^+} = 0$	$P_{e^-} = -0.80\%; P_{e^+} = 0.60$
50	$[-12.99; 12.27] \times 10^{-12}$	$[-11.26; 10.56] \times 10^{-12}$	$[-9.89; 9.51] \times 10^{-12}$
250	$[-8.81; 8.09] \times 10^{-12}$	$[-7.65; 6.95] \times 10^{-12}$	$[-6.68; 6.29] \times 10^{-12}$
400	$[-7.88; 7.16] \times 10^{-12}$	$[-6.84; 6.14] \times 10^{-12}$	$[-5.96; 5.58] \times 10^{-12}$
800	$[-6.69; 5.96] \times 10^{-12}$	$[-5.81; 5.11] \times 10^{-12}$	$[-5.04; 4.66] \times 10^{-12}$
1200	$[-6.08; 5.36] \times 10^{-12}$	$[-5.29; 4.59] \times 10^{-12}$	$[-4.56; 4.19] \times 10^{-12}$
1600	$[-5.69; 4.96] \times 10^{-12}$	$[-4.95; 4.25] \times 10^{-12}$	$[-4.27; 3.89] \times 10^{-12}$
2000	$[-5.40; 4.67] \times 10^{-12}$	$[-4.70; 4.00] \times 10^{-12}$	$[-4.05; 3.67] \times 10^{-12}$

TABLE 5: Sensitivity of f_{S1}/Λ^4 at 95% CL for $\sqrt{s} = 1.4$ TeV in units of GeV^{-4} .

L (fb^{-1})	Unpolarized	$P_{e^-} = -0.80\%; P_{e^+} = 0$	$P_{e^-} = -0.80\%; P_{e^+} = 0.60$
50	$[-6.82; 6.62] \times 10^{-11}$	$[-5.92; 5.69] \times 10^{-11}$	$[-5.26; 5.07] \times 10^{-11}$
250	$[-4.60; 4.39] \times 10^{-11}$	$[-3.99; 3.77] \times 10^{-11}$	$[-3.55; 3.36] \times 10^{-11}$
500	$[-3.88; 3.68] \times 10^{-11}$	$[-3.38; 3.15] \times 10^{-11}$	$[-2.99; 2.81] \times 10^{-11}$
750	$[-3.52; 3.31] \times 10^{-11}$	$[-3.06; 2.84] \times 10^{-11}$	$[-2.72; 2.53] \times 10^{-11}$
1000	$[-3.28; 3.08] \times 10^{-11}$	$[-2.86; 2.64] \times 10^{-11}$	$[-2.54; 2.35] \times 10^{-11}$
1250	$[-3.11; 2.90] \times 10^{-11}$	$[-2.71; 2.49] \times 10^{-11}$	$[-2.40; 2.22] \times 10^{-11}$
1500	$[-2.98; 2.77] \times 10^{-11}$	$[-2.59; 2.37] \times 10^{-11}$	$[-2.30; 2.11] \times 10^{-11}$

TABLE 6: Sensitivity of f_{S1}/Λ^4 at 95% CL for $\sqrt{s} = 3$ TeV in units of GeV^{-4} .

L (fb^{-1})	Unpolarized	$P_{e^-} = -0.80\%; P_{e^+} = 0$	$P_{e^-} = -0.80\%; P_{e^+} = 0.60$
50	$[-8.85; 7.99] \times 10^{-12}$	$[-7.62; 6.87] \times 10^{-12}$	$[-6.92; 5.97] \times 10^{-12}$
250	$[-5.72; 5.16] \times 10^{-12}$	$[-5.23; 4.47] \times 10^{-12}$	$[-4.80; 3.85] \times 10^{-12}$
400	$[-5.08; 4.52] \times 10^{-12}$	$[-4.70; 3.94] \times 10^{-12}$	$[-4.33; 3.38] \times 10^{-12}$
800	$[-4.25; 3.69] \times 10^{-12}$	$[-4.02; 3.26] \times 10^{-12}$	$[-3.73; 2.77] \times 10^{-12}$
1200	$[-3.82; 3.26] \times 10^{-12}$	$[-3.67; 2.91] \times 10^{-12}$	$[-3.42; 2.47] \times 10^{-12}$
1600	$[-3.54; 2.98] \times 10^{-12}$	$[-3.44; 2.69] \times 10^{-12}$	$[-3.22; 2.27] \times 10^{-12}$
2000	$[-3.33; 2.77] \times 10^{-12}$	$[-3.28; 2.52] \times 10^{-12}$	$[-3.08; 2.12] \times 10^{-12}$

TABLE 7: Sensitivity of f_{T0}/Λ^4 at 95% CL for $\sqrt{s} = 1.4$ TeV in units of GeV^{-4} .

L (fb^{-1})	Unpolarized	$P_{e^-} = -0.80\%; P_{e^+} = 0$	$P_{e^-} = -0.80\%; P_{e^+} = 0.60$
50	$[-4.86; 3.25] \times 10^{-12}$	$[-4.30; 2.75] \times 10^{-12}$	$[-4.04; 2.38] \times 10^{-12}$
250	$[-3.58; 1.97] \times 10^{-12}$	$[-3.20; 1.65] \times 10^{-12}$	$[-3.07; 1.40] \times 10^{-12}$
500	$[-3.18; 1.57] \times 10^{-12}$	$[-2.86; 1.31] \times 10^{-12}$	$[-2.77; 1.10] \times 10^{-12}$
750	$[-2.98; 1.37] \times 10^{-12}$	$[-2.69; 1.14] \times 10^{-12}$	$[-2.61; 0.95] \times 10^{-12}$
1000	$[-2.85; 1.24] \times 10^{-12}$	$[-2.58; 1.03] \times 10^{-12}$	$[-2.52; 0.85] \times 10^{-12}$
1250	$[-2.76; 1.15] \times 10^{-12}$	$[-2.50; 0.95] \times 10^{-12}$	$[-2.45; 0.78] \times 10^{-12}$
1500	$[-2.68; 1.08] \times 10^{-12}$	$[-2.44; 0.89] \times 10^{-12}$	$[-2.40; 0.73] \times 10^{-12}$

TABLE 8: Sensitivity of f_{T0}/Λ^4 at 95% CL for $\sqrt{s} = 3$ TeV in units of GeV^{-4} .

L (fb^{-1})	Unpolarized	$P_{e^-} = -0.80\%; P_{e^+} = 0$	$P_{e^-} = -0.80\%; P_{e^+} = 0.60$
50	$[-4.44; 3.09] \times 10^{-13}$	$[-3.91; 2.59] \times 10^{-13}$	$[-3.58; 2.24] \times 10^{-13}$
250	$[-3.24; 1.90] \times 10^{-13}$	$[-2.89; 1.57] \times 10^{-13}$	$[-2.68; 1.34] \times 10^{-13}$
400	$[-2.97; 1.63] \times 10^{-13}$	$[-6.84; 6.14] \times 10^{-13}$	$[-2.48; 1.14] \times 10^{-13}$
800	$[-2.64; 1.30] \times 10^{-13}$	$[-2.38; 1.07] \times 10^{-13}$	$[-2.24; 0.90] \times 10^{-13}$
1200	$[-2.47; 1.13] \times 10^{-13}$	$[-2.24; 0.92] \times 10^{-13}$	$[-2.11; 0.78] \times 10^{-13}$
1600	$[-2.37; 1.03] \times 10^{-13}$	$[-2.15; 0.83] \times 10^{-13}$	$[-2.04; 0.70] \times 10^{-13}$
2000	$[-2.29; 0.95] \times 10^{-13}$	$[-2.09; 0.77] \times 10^{-13}$	$[-1.98; 0.64] \times 10^{-13}$

to investigate the anomalous f_{S0}/Λ^4 , f_{S1}/Λ^4 , and f_{T0}/Λ^4 couplings through the process $e^+e^- \rightarrow \nu_e W^- W^+ \bar{\nu}_e$. Since the anomalous couplings depend on energy strongly, the cross sections that contain these couplings would have momentum dependence compared to those of the SM. We have found that the contribution of the anomalous quartic couplings to the total cross section increases with increasing center-of-mass energy. Because of the structure of $We^- \nu_e$ ($We^+ \bar{\nu}_e$) vertex, it is found that certain polarization of the beam increases the cross sections. In this respect, we find the better sensitivity for the $P_{e^-} = -80\%$; $P_{e^+} = 60\%$ polarization state.

As a result, the CLIC with very clean experimental conditions and being free from strong interactions with respect to LHC, high colliding energy, and very high luminosity has a potential advantage over the LHC in studying the anomalous f_{S0}/Λ^4 , f_{S1}/Λ^4 , and f_{T0}/Λ^4 couplings.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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