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Original Article

Contribution of Axion-like Particle and Anomalous Couplings to $\gamma e^- e^+$ Final State at Electron – Positron Collider

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Abstract: We investigate the effects of axion-like particle and anomalous triple gauge couplings in γZ production, followed by the leptonic decay of the Z boson with the center – of – mass energy $\sqrt{s} = 500, 1000, 3000$ GeV and the polarized initial beams. We consider the contribution of axion-like particle, photon, and Z boson propagators. We find the mass of axion like particle to enhance the cross-section in case of axion-like particle propagator. The results indicate that with the anomalous coupling $ZZ\gamma$, the cross-section is larger than that with the axion-like particle and photon propagators under the same conditions.

Keywords: axion-like particle, anomalous couplings, γee final state.

1. Introduction

The quest for physics Beyond the Standard Model (BSM) is increasingly centered on the exploration of axion-like particles (ALPs) denoted by a. These light pseudo-scalar bosons emerge as pseudo Nambu-Goldstone bosons (pNGBs) from the spontaneous breaking of global symmetries, representing a theoretical generalization of the QCD axion [1-3]. Unlike the QCD axion, an unfixed relation between mass and couplings allows for a vast range of masses and coupling strengths of ALP. From an Effective Field Theory (EFT) perspective, ALPs are characterized by their model dependent interactions with the SM sector, primarily through couplings to photons, electroweak gauge bosons, and fermions. The phenomenological reach of ALPs spans several orders of magnitude: from ultralight dark matter candidates in the eV to MeV range [1], to heavier MeV–TeV states relevant for collider and flavor

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physics [4-6]. Previous experimental campaigns at SLAC E141 [4], and Belle II [7] have established foundational constraints on the interaction of ALPs with the SM sector. Building upon these results, the next of e^+e^- facilities encompassing both circular designs such as Future Circular Collider (FCC-ee) [8] and the Circular Electron – Positron Collider (CEPC) [9, 10], and linear ones like the International Linear Collider (ILC) and Compact Linear Collider (CLIC) is expected to offer new researches on ALP couplings to SM particles [3]. At high energy colliders, the ALPs can be strategically probed through primary channels: direct production in association with photons, jets, and EW gauge bosons [11-17], as well as via the decay of Z boson [18, 19] and Higgs boson [20-24]. The search for ALPs is also motivated by their dual role as a viable cold dark matter candidate and as a sensitive probe of the ultraviolet completion of the SM.

In the SM, the non-Abelian nature of the $SU(2)_L \times U(1)_Y$ gauge group of the electroweak interactions leads to gauge boson self-interactions through the Triple Gauge Couplings (TGC) and the Quartic Gauge Couplings (QGC) [25]. With the neutral TGC $\gamma ZV\ (V=\gamma, Z)$, the cross-sections for γZ production at e^+e^-, pp colliders are studied, compared their sensitivities in Refs. [26-28]. However, the influence of ALP for cross-section in the γe^+e^- final state, thus far, has been omitted from recent studies, a deficit that the present work aims to address.

Therefore, in this paper, the process $e^+e^- \to \gamma Z \to \gamma e^+e^-$ at ILC and CLIC with polarized electron and positron beams is used to investigate the presence of new physics as ALP, neutral TGC. The work is organized as follows. Section 2 briefly describes the neutral TGC and ALP. Numerical evaluation and discussion are considered in Section 3. Finally, we summarize our conclusions in Section 4.

2. Theoretical Framework

The ALP is a singlet pseudo-scalar of the SM gauge group [3]. The effective Lagrangian describing ALP couplings can be written as [29, 30]:

$$L = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + C_{GG}\frac{\alpha_S}{4\pi f_a}aG_{\mu\nu}^A\bar{G}^{\mu\nu A} + C_{WW}\frac{\alpha_L}{4\pi f_a}aW_{\mu\nu}^I\bar{W}^{\mu\nu I} + C_{BB}\frac{\alpha_Y}{4\pi f_a}aB_{\mu\nu}\bar{B}^{\mu\nu}$$
$$+\frac{\partial^\mu a}{f_a}\sum_F \bar{F}C_F\gamma_\mu F + \frac{C_H}{f_a}\partial^\mu a(H^+ i\overleftrightarrow{D}_\mu H) + \frac{C_{HH}}{f_a^2}(\partial^\mu a)(\partial_\mu a)H^+H. \quad (1)$$

Here f_a is the ALP decay constant. The quantities $C_F\ (F=q,u,d,l,e)$ are 3 x 3 Hermitian matrices in generation space. The coefficients $C_{ii}\ (i=G,W,B,H)$ are real couplings. $\alpha_S, \alpha_L, \alpha_Y$ denote the corresponding coupling parameters. $G_{\mu\nu}^A, W_{\mu\nu}^I, B_{\mu\nu}$ are the field strength tensors of $SU(3)_C$, $SU(2)_L, U(1)_Y$. The Higgs doublet is denoted by H. The sum extends over the chiral fermion multiplets F of the SM. It is worth noting that the couplings of ALP to bosonic fields are loop suppressed, while the fermionic ALP couplings are present at tree level.

After electroweak symmetry breaking, the interaction terms used in this work are expressed as:

$$L_{\text{int}} \supset \frac{a}{f_a}g_{aZ\gamma}F_{\mu\nu}\bar{Z}^{\mu\nu} + \frac{a}{2m_f f_a}g_{aff}\bar{f}\gamma_5\gamma^\mu f. \quad (2)$$

The interaction couplings in the above equation are defined by [31]:

$$g_{aZ\gamma} = \frac{2\alpha}{s_W}\left|\sum_f \frac{\hat{\upsilon}_f}{c_W} N_C Q_f \chi_f \frac{m_f^2}{m_a^2 - m_Z^2}\left(f\left(\frac{m_a^2}{4m_f^2}\right) - f\left(\frac{m_Z^2}{4m_f^2}\right)\right)\right|. \quad (3)$$

$$g_{aff} = \frac{m_f}{f_a} C_{af}. \quad (4)$$

Here $\hat{\upsilon}_f = 2T_f^3 - 4Q_f s_W^2$, with T_f^3 the weak isospin of the fermion considered, s_W, c_W being the sine and cosine of the weak mixing angle, respectively. The functions $f\left(\frac{m_a^2}{4m_f^2}\right)$, $f\left(\frac{m_Z^2}{4m_f^2}\right)$ are given by

$$f(x) = \begin{cases} \text{acrsin}^2\sqrt{x} & x \le 1, \\ -\frac{1}{4}\left(\log\frac{1+\sqrt{1-x^{-1}}}{1-\sqrt{1-x^{-1}}} - i\pi\right)^2 & x > 1, \end{cases} \quad (5)$$

where $x = \frac{m_a^2}{4m_f^2}, \frac{m_Z^2}{4m_f^2}$, respectively. For quarks, $N_C = 3$ and $Q_f = 2/3$ or $-1/3$. For leptons, $N_C = 1$ and $Q_f = 1$. χ_f are the arbitrariness couplings, $\chi_u = \frac{\tan^2\beta}{1+\tan^2\beta}$, $\chi_d = \chi_e = \frac{1}{1+\tan^2\beta}$.

The triple gauge boson couplings $V\gamma Z$ are given by [28]

$$ie\Gamma_{VZ\gamma}^{\alpha\beta\mu}(q_1,q_2,q_3) = \frac{-e\left(q_1^2 - m_V^2\right)}{m_Z^2}\left[h_1^V\left(q_3^\mu g^{\alpha\beta} - q_3^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{m_Z^2} q_1^\alpha\left(q_1 q_3 g^{\mu\beta} - q_3^\mu q_1^\beta\right)\right.$$
$$\left. - h_3^V q_{3\rho}\varepsilon^{\mu\alpha\beta\rho} - \frac{h_4^V}{m_Z^2}\varepsilon^{\mu\beta\rho\sigma} q_1^\alpha q_{1\rho} q_{3\sigma}\right]. \quad (6)$$

While the couplings h_1^V, h_2^V correspond to the CP-odd tensorial structures, h_3^V, h_4^V correspond to the CP-even ones.

3. Numerical Evaluation and Discussion

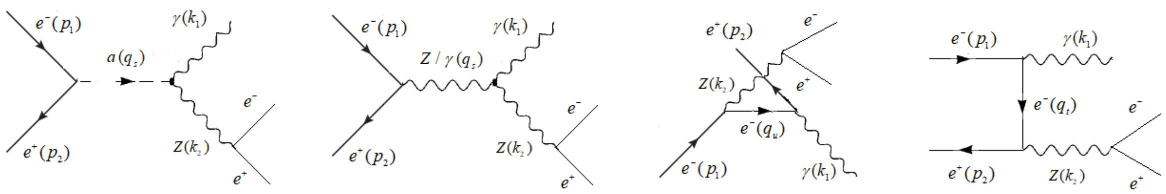

Figure. 1. Feynman diagrams for $e^+e^- \to \gamma Z \to \gamma e^+e^-$ collision, representing the s, u, t-channels, respectively.

We consider the collision process in γZ production, followed by the leptonic decay of the Z boson, at electron-positron collider. In the SM, the process proceeds via the u-, t-channel exchange diagrams at tree level. The presence of new physics signals is via s-channel with the ALP, photon, and Z boson propagators. The Feynman diagrams for $e^+e^- \to \gamma Z \to \gamma e^+e^-$ collision, representing the s, u, t-channels are depicted in Fig. 1.

The transition amplitude representing the s-channel is given by

$$M_s = M_a + M_Z + M_\gamma, \tag{7}$$

here

$$M_a = -\frac{g_{eea} g_{a\gamma Z}}{f_a(q_s^2 - m_a^2)} \varepsilon^{*\mu}(k_1)\varepsilon_{\mu\nu\rho\sigma} k_1^\rho k_2^\sigma \varepsilon^{*\nu}(k_2)\bar{v}(p_2)\gamma^5 u(p_1), \tag{8}$$

$$M_Z = \frac{-\bar{g}_{eeZ}}{q_s^2 - m_Z^2} \varepsilon^{*\mu}(k_1)\Gamma^{Z\gamma Z}_{\sigma\mu\nu}(q_s, k_1, k_2)\varepsilon^{*\nu}(k_2)\left(\eta_{\sigma\beta} - \frac{q_{s\sigma} q_{s\beta}}{m_Z^2}\right)\bar{v}(p_2)\gamma^\beta\left(-1 + 4s_W^2 + \gamma^5\right)u(p_1), \tag{9}$$

$$M_\gamma = \frac{-e}{q_s^2} \varepsilon^{*\mu}(k_1)\Gamma^{\gamma\gamma Z}_{\sigma\mu\nu}(q_s, k_1, k_2)\varepsilon^{*\nu}(k_2)\eta_{\sigma\beta}\bar{v}(p_2)\gamma^\beta u(p_1). \tag{10}$$

The transition amplitude representing the u-channel is given by

$$M_u = \frac{ie\bar{g}_{eeZ}}{q_u^2 - m_e^2} \bar{v}(p_2)\gamma_\mu\left(-1 + 4s_W^2 + \gamma^5\right)\varepsilon^{*\mu}(k_1)\left(\hat{q}_u + m_e\right)u(p_1)\gamma_\nu\varepsilon^{*\nu}(k_2). \tag{11}$$

The transition amplitude representing the t-channel is given by

$$M_t = \frac{ie\bar{g}_{eeZ}}{q_t^2 - m_e^2} \bar{v}(p_2)\gamma_\nu\varepsilon^{*\nu}(k_2)\left(\hat{q}_t + m_e\right)u(p_1)\gamma_\mu\left(-1 + 4s_W^2 + \gamma^5\right)\varepsilon^{*\mu}(k_1). \tag{12}$$

The cross-section for the whole process $e^+e^- \to \gamma Z \to \gamma e^+e^-$ can be calculated as follows

$$\sigma = \sigma(e^+e^- \to \gamma Z) \times Br(Z \to e^+e^-). \tag{13}$$

For numerical evaluation, we choose the maximum value of anomalous couplings in the tightest limits with the corresponding observable set as $h_1^\gamma = 3.6\times10^{-3}$, $h_3^\gamma = 1.3\times10^{-3}$, $h_1^Z = 2.9\times10^{-3}$, $h_3^Z = 2.8\times10^{-3}$, and the parameters h_2^γ, h_4^γ, h_2^Z, h_4^Z are set as zero due to the specific structure and symmetries of the anomalous neutral triple gauge couplings considered in the effective Lagrangian framework [28, 32-36]. $\bar{g}_{eeZ} = 4/c_W$, $\tan\beta = 1$ [31]. The parameters of the future linear colliders such as ILC and CLIC are shown as follows [35]

Table 1. The parameters of the future linear colliders such as ILC and CLIC

Linear colliders	$\sqrt{s}$ (GeV)	L (ab^{-1})	(P_{e^-}, P_{e^+})
ILC	500	2	(0.8, –0.3)
	1000	4	(0.8, –0.3)
CLIC	3000	5	(0.8, 0)

Using the parameters at the ILC and CLIC, we estimate the total cross-section for γe^+e^- production as follows:

Initially, we evaluate the cross-sections with the ALP propagator (σ_a) in case of the different values of energy and polarization in Fig. 2. We choose the range mass of axion like particle

$m_a \sim (10-100)$ GeV on the ALP - electron coupling $g_{eea} = 0.64$ [37] at the ILC and CLIC. The results show that the cross-sections σ_a increase in the range $m_a \sim (10-50)$ GeV, then decrease in the range $m_a \sim (50-100)$ GeV. Therefore, we will use the value $m_a \sim 50$ GeV in the next calculation. The cross-section σ_a can reach at 3.58×10^{-16} fb when $\sqrt{s} = 500$ (GeV), $(P_{e^-}, P_{e^+}) = (0.8, -0.3)$.

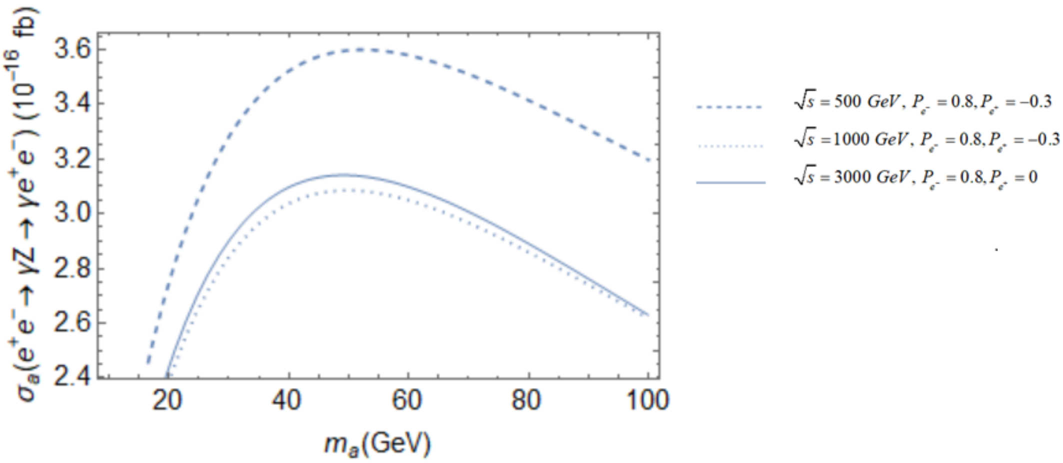

Figure 2. The cross-sections with the ALP propagator (σ_a) at the ILC and CLIC.

Next, we consider the contribution of ALP, photon, and Z boson propagators in case of $(P_{e^-}, P_{e^+}) = (0.8, -0.3)$. The dependence of the cross-sections with ALP (σ_a), photon (σ_γ), Z boson (σ_Z), and SM (σ_{SM}) propagators on the collision energy in Fig.3. While the SM cross-section σ_{SM} decreases, the cross-sections σ_γ, σ_Z increase when the collision energy increase in the range $\sqrt{s} = [500, 1000]$ GeV. Although the ALP cross-section σ_a increases, the effect to SM cross-section is negligible.

We present a Table 2 of the cross-sections for the SM propagator, alongside cases incorporating ALP, photon, and Z boson propagators. The results indicate that at CLIC energy scale (3000 GeV), the cross-sections $\sigma_{\gamma+SM}$ and σ_{Z+SM} are significantly enhanced. Furthermore, the cross-section including the Z boson contribution is larger than those involving ALP and photon propagators.

Table 2. Typical values for the cross-sections in the $e^+e^- \to \gamma Z \to \gamma e^+e^-$ collision at the ILC and CLIC

$\sqrt{s}$ (GeV)	500	1000	3000
(P_{e^-}, P_{e^+})	(0.8, –0.3)	(0.8, –0.3)	(0.8, 0)
σ_{SM} (fb)	399.2121	376.9899	485.6969
σ_{a+SM} (fb)	399.2121	376.9899	485.6969
$\sigma_{\gamma+SM}$ (fb)	402.1998	405.7602	3510.2785
σ_{Z+SM} (fb)	620.2202	3659.7758	342013.4872

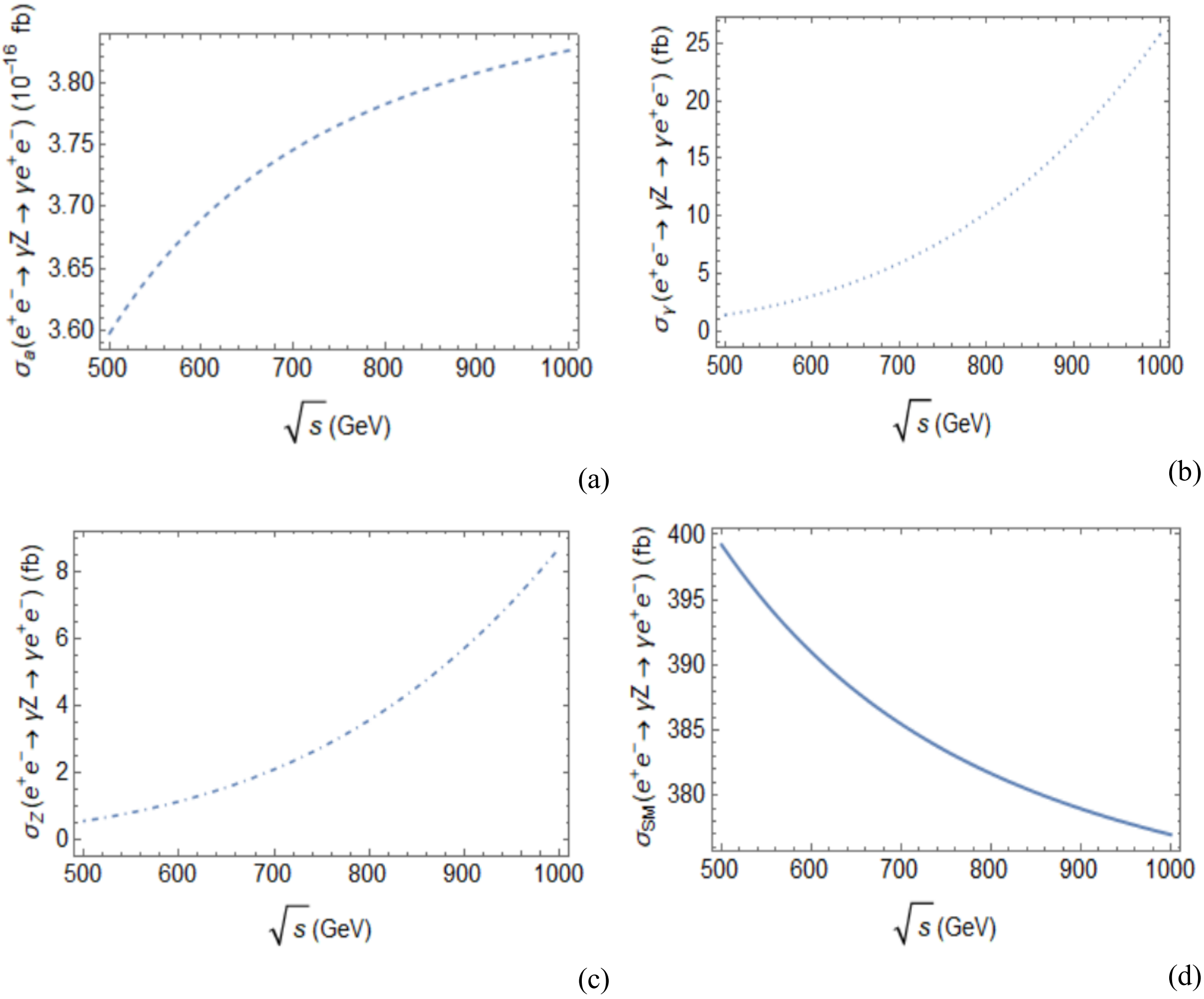

Figure 3. The cross-sections for the whole process $e^+e^- \to \gamma Z \to \gamma e^+e^-$ collision as a function of the collision energy $\sqrt{s}$ in case of (a) ALP propagator, (b) photon propagator, (c) Z boson propagator, and (d) SM propagator, respectively.

The χ^2 function is defined as follows [36, 38]:

$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma_{NP}}{\sigma_{SM}\sqrt{\left(\frac{1}{\sqrt{N_{SM}}}\right)^2 + (\varepsilon_\sigma)^2}} \right)^2 \tag{14}$$

where $\sigma_{NP} = \sigma_{SM} + \sigma_{INT} + \sigma_{BSM}$ is the cross-section containing contributions from presence of both new physics beyond the SM and SM background. The terms for the cross-section of SM background, the interference term between the SM and NP contribution, and the contribution due to BSM physics are denoted by σ_{SM}, σ_{INT}, and σ_{BSM}, respectively. ε_σ is the systematic error. $N_{SM} = \sigma_{SM} \times L$ is the number of events of SM backgrounds, L is the integrated luminosity. The estimated error for cross-section is defined by [28]

$$\delta\sigma = \sqrt{\frac{\sigma_{SM}}{L} + (\varepsilon_\sigma \sigma_{SM})^2}\ . \tag{15}$$

We will evaluate the statistical error $\frac{\delta\sigma}{\sigma_{SM}}$ and the χ^2 function in Table 3 and 4.

Given the SM cross-section σ_{SM} as in Table 2, and luminosity at the ILC, CLIC, we evaluate the relative statistical error for cross-section in Table 3. The systematic error is given as $\varepsilon_\sigma = \{0\%,\ 3\%,\ 5\%\}$ [38]. The results show that the statistical error constitutes the principal component of the total uncertainly. Under the systematic framework provided in Ref. [38], the current results remain statistics dominated, implying that the discovery potential and precision of the analyzed observables will improve with luminosity.

Table 3. The relative statistical error in case of the different values of the systematic error

$\sqrt{s}\ (GeV)$	500	1000	3000
(P_{e^-}, P_{e^+})	$(0.8, -0.3)$	$(0.8, -0.3)$	$(0.8, 0)$
$L\ (ab^{-1})$	2	4	5
$\left.\frac{\delta\sigma}{\sigma_{SM}}\right\vert_{\varepsilon_\sigma = 0\%}$	0.1119%	0.0814%	0.0642%
$\left.\frac{\delta\sigma}{\sigma_{SM}}\right\vert_{\varepsilon_\sigma = 3\%}$	3.0021%	3.0007%	3.0007%
$\left.\frac{\delta\sigma}{\sigma_{SM}}\right\vert_{\varepsilon_\sigma = 5\%}$	5.0013%	5.0006%	5.0004%

Finally, to evaluate the sensitivities of the electron-positron collider to new physics signals at the ILC, we employ a χ^2 statistical analysis, with results summarized in Table 4. The systematic error is chosen as in Table 2. While the sensitivity to ALP propagator is found to be too small, the sensitivities to anomalous triple gauge boson couplings $ZZ\gamma$, $\gamma Z\gamma$ are enhanced at the high energy. We can see that the contribution of the anomalous coupling $ZZ\gamma$ is larger than that of couplings $aZ\gamma$, $\gamma Z\gamma$ under the same conditions.

Table 4. Some typical values of χ^2 statistical analysis for the contribution of ALP, photon, and Z boson propagators at the ILC

$\sqrt{s}$ (GeV)	500	1000
(P_{e^-}, P_{e^+})	$(0.8, -0.3)$	$(0.8, -0.3)$
$L\ (ab^{-1})$	2	4
$\chi_a^2\big\|_{\varepsilon_\sigma=0\%}$	1.9587×10^{-24}	3.4284×10^{-26}
$\chi_a^2\big\|_{\varepsilon_\sigma=3\%}$	2.7220×10^{-27}	2.5243×10^{-29}
$\chi_a^2\big\|_{\varepsilon_\sigma=5\%}$	9.8080×10^{-28}	9.0917×10^{-30}
$\chi_\gamma^2\big\|_{\varepsilon_\sigma=0\%}$	44.719	8.782×10^{3}
$\chi_\gamma^2\big\|_{\varepsilon_\sigma=3\%}$	0.062	6.4665
$\chi_\gamma^2\big\|_{\varepsilon_\sigma=5\%}$	0.022	2.3290
$\chi_Z^2\big\|_{\varepsilon_\sigma=0\%}$	2.447×10^{5}	1.143×10^{8}
$\chi_Z^2\big\|_{\varepsilon_\sigma=3\%}$	340.065	8.419×10^{4}
$\chi_Z^2\big\|_{\varepsilon_\sigma=5\%}$	122.533	3.032×10^{4}

4. Conclusion

In this study, we investigated the impact of anomalous triple gauge boson couplings on γZ production using the parameter of ILC and CLIC. Our results demonstrate that the anomalous coupling $ZZ\gamma$ lead to a significantly more pronounced enhancement compared to the couplings $aZ\gamma$, $\gamma Z\gamma$ under identical parametric conditions. The cross-section in case of ALP propagator is enhanced at $m_a = 50$ GeV. Although the ALP contribution appear relatively modest, they remain an indispensable diagnostic tool for probing BSM physics in high energy. In our future work, we will extend this investigation to pp collisions at the Large Hadron Collider (LHC), focusing on the potential for ALP couplings to reveal the ALP signals.

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