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Probe of the electromagnetic moments of the tau lepton in gamma-gamma collisions at the CLIC

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We have investigated the electromagnetic moments of the tau lepton in $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$ process at the CLIC. We have obtained 95% confidence level bounds on the anomalous magnetic and electric dipole moments for various values of the integrated luminosity and the center of mass energy. We have shown that the $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$ process at the CLIC leads to a remarkable improvement in the existing experimental bounds on the anomalous magnetic and electric dipole moments.

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I. INTRODUCTION

The Landé g factor or gyromagnetic factor g is described by the formula between a particle's magnetic moment $\vec{\mu}$ and its spin $\vec{s}$: $\vec{\mu} = g(\mu_B/\hbar)\vec{s}$, where μ_B is the Bohr magneton. In the Dirac equation, the value of g is 2 for a pointlike particle. Deviation from this value $a = \frac{(g-2)}{2}$ is called the anomalous magnetic moment, and without anomalous and radiative corrections, $a = 0$. However, the anomalous magnetic moment a_e of the electron was first obtained by Schwinger using radiative corrections as $a_e = \frac{\alpha}{2\pi} = 0.001161$ [1]. So far, the accuracy of the a_e has been examined by many theoretical and experimental studies. These studies have provided the most precise determination of fine-structure constant α_{QED}, since a_e is quite senseless to the strong and weak interactions. On the other hand, the anomalous magnetic moment a_μ of the muon enables testing of the Standart Model (SM) and investigating alternative theories to the SM. The a_e and a_μ can be obtained with high sensitivity through a spin precession experiment. Otherwise, the spin precession experiment cannot be used to measure the anomalous magnetic moment a_τ of the tau, because of the relatively short lifetime 2.906×10^{-13} s of tau [2]. So the current bounds of the a_τ are obtained by collision experiments. The theoretical value of the a_τ from QED is given as $a_\tau^{\mathrm{SM}} = 0.001177$ [3,4].

The experimental bounds on the a_τ are provided by the L3: $-0.052 < a_\tau < 0.058$, OPAL: $-0.068 < a_\tau < 0.065$, and DELPHI: $-0.052 < a_\tau < 0.013$ Collaborations at the LEP at 95% C.L. [5–7].

CP violation was first observed in a small fraction of K_L^0 mesons decaying to two pions in the SM [8]. This phenomenology in the SM can be easily introduced by the Cabibbo-Kobayashi-Maskawa mechanism in the quark sector [9]. On the other hand, there is no CP violation in the lepton sector. However, CP violation in the quark sector causes a very small electric dipole moment of the leptons. At least to three loop are required in order to produce a nonzero contributing to the electric dipole moment of the tau in the SM, and its crude estimate is obtained as $|d_\tau| \leq 10^{-34} e$ cm[10].

If at least two of the three neutrinos have different mass values, CP violation in the lepton sector can occur similarly to the CP violation in the quark sector [11]. There are many different models beyond the SM conducive to CP violation in the lepton sector. These models are leptoquark [12,13], SUSY [14], left-right symmetric [15,16], and more Higgs multiplets [17,18].

The bounds at 95% C.L. on the anomalous electric dipole moment of the tau yield by LEP experiments L3: $|d_\tau| < 3.1 \times 10^{-16} e$ cm, OPAL: $|d_\tau| < 3.7 \times 10^{-16} e$ cm, and DELPHI: $|d_\tau| < 3.7 \times 10^{-16} e$ cm. The most restrictive experimental bounds are obtained by BELLE: $-2.2 < \mathrm{Re}(d_\tau) < 4.5 \times (10^{-17} e\ \mathrm{cm})$ and $-2.5 < \mathrm{Im}(d_\tau) < 0.8 \times (10^{-17} e\ \mathrm{cm})$. There are model-dependent and -independent studies on the anomalous dipole moments of the tau lepton in the literature [19–27].

We consider that the difference between a_τ^{SM} (d_τ^{SM}) and a_τ^{exp} (d_τ^{exp}) can be reduced to determine precisely a new term proportional to F_2 (F_3) to the SM $\tau\tau\gamma$ vertex. For this reason, the electromagnetic vertex factor of the tau lepton can be parametrized,

$$\Gamma^\nu = F_1(q^2)\gamma^\nu + \frac{i}{2m_\tau}F_2(q^2)\sigma^{\nu\mu}q_\mu + \frac{1}{2m_\tau}F_3(q^2)\sigma^{\nu\mu}q_\mu\gamma^5, \tag{1}$$

where $\sigma_{\nu\mu} = \frac{i}{2}(\gamma_\nu\gamma_\mu - \gamma_\mu\gamma_\nu)$, q is the momentum transfer to the photon, and $m_\tau = 1.777$ GeV is the mass of tau lepton. In the SM, at tree level, $F_1 = 1$, $F_2 = 0$, and $F_3 = 0$. Besides, in the loop effects arising from the SM and the new physics, F_2 and F_3 may be not equal to zero. For example, the anomalous coupling F_2 is given by

$$F_2(0) = a_\tau^{\mathrm{SM}} + a_\tau^{\mathrm{NP}}, \tag{2}$$

where a_τ^{SM} is the contribution of the SM and a_τ^{NP} is the contribution of the new physics [28–31]. Therefore, the

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q^2-dependent form factors $F_1(q^2)$, $F_2(q^2)$, and $F_3(q^2)$ in limit $q^2 \to 0$ are given by

$$F_1(0) = 1, \qquad F_2(0) = a_\tau, \qquad F_3(0) = \frac{2m_\tau d_\tau}{e}. \tag{3}$$

The Compact Linear Collider (CLIC) is a proposed future e^+e^- collider, designed to fulfill e^+e^- collisions at energies from 0.5 to 3 TeV [32], and it is planned to be constructed with three research regions as given by [33]. The CLIC has been extensively studied for interactions beyond the SM [34–50]. The CLIC enables us to investigate the $\gamma\gamma$ and γe interactions by converting the original e^- or e^+ beam into a photon beam through the laser backscattering procedure [51–53]. One of the other well-known applications of the CLIC is the $\gamma^*\gamma^*$ process, where the emitted quasireal photon γ^* is scattered with small angle from the beam pipe of e^- or e^+ [54–58]. Since these photons have a low virtuality ($Q^2_{\rm max} = 2$ GeV^2), they are almost on mass shell. $\gamma^*\gamma^*$ processes can be described by equivalent photon approximation, i.e., using the Weizsacker-Williams approximation [19,59–70]. Such processes have been experimentally observed at the LEP, Tevatron, and LHC [71–77]. There are two reasons why we have chosen the CLIC in this work: first, the observation of the most stringent experimental bound on the anomalous magnetic dipole moment of the tau lepton by using multiperipheral collision at the LEP through the process $e^+e^- \to e^+\tau\bar{\tau}e^-$ [7], and second, the importance of high center-of-mass energies to examine the electromagnetic properties of the tau lepton since anomalous $\tau\tau\gamma$ couplings depend on more energy than SM $\tau\tau\gamma$ couplings at the tree level. Therefore, we investigate the potential of CLIC via the process $e^+e^- \to e^+\tau\bar{\tau}e^-$ to examine the anomalous magnetic and electric dipole moments of the tau lepton.

II. CROSS SECTIONS AND NUMERICAL ANALYSIS

During calculations, the CompHEP-4.5.1 program was used by including the new interaction vertices [78]. Also, the acceptance cuts were imposed as $|\eta_\tau| < 2.5$ for pseudorapidity, $p_T^\tau > 20$ GeV for transverse momentum cut of the final state particles, $\Delta R_{\tau\bar{\tau}} > 0.5$ the separation of final tau leptons.

We show the integrated total cross section of the process $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$ as a function of the anomalous couplings F_2 and F_3 in Fig. 1 for three different center-of-mass energies. As can be seen in Fig. 1, while the total cross section is symmetric for anomalous coupling F_3, it is nonsymmetric for F_2.

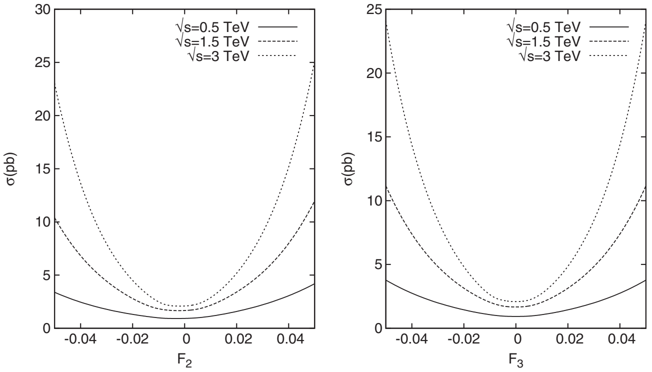

FIG. 1. The integrated total cross section of the process $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$ as a function of anomalous couplings F_2 and F_3 for three different center-of-mass energies.

We estimate 95% C.L. bounds on anomalous coupling parameters F_2 and F_3 using the χ^2 test. The χ^2 function is described by the following formula,

$$\chi^2 = \left(\frac{\sigma_{\rm SM} - \sigma(F_2, F_3)}{\sigma_{\rm SM}\delta}\right)^2, \tag{4}$$

where $\delta = \sqrt{(\delta_{\rm st})^2 + (\delta_{\rm sys})^2}$; $\delta_{\rm st} = \frac{1}{\sqrt{N_{\rm SM}}}$ is the statistical error and $\delta_{\rm sys}$ is the systematic error. The number of expected events is calculated as the signal $N = L_{\rm int} \times {\rm BR} \times \sigma$, where $L_{\rm int}$ is the integrated luminosity. The tau lepton decays roughly 35% of the time leptonically and 65% of the time to one or more hadrons. So we consider one of the tau leptons decays leptonically and the other hadronically for the signal. Thereby, we assume that the branching ratio of the tau pairs in the final state is ${\rm BR} = 0.46$.

There are systematic uncertainties in exclusive production at the lepton and hadron colliders. For the process $e^+e^- \to e^+e^-\tau^+\tau^-$, systematic errors are experimentally studied between 4.3% and 9% at the LEP [7,79]. Recently, exclusive lepton production at the LHC has been examined and its systematic uncertainty is 4.8% [74]. Also, the process $pp \to p\tau^+\tau^-p$ with 2% of the total systematic error at the LHC has been investigated phenomenologically

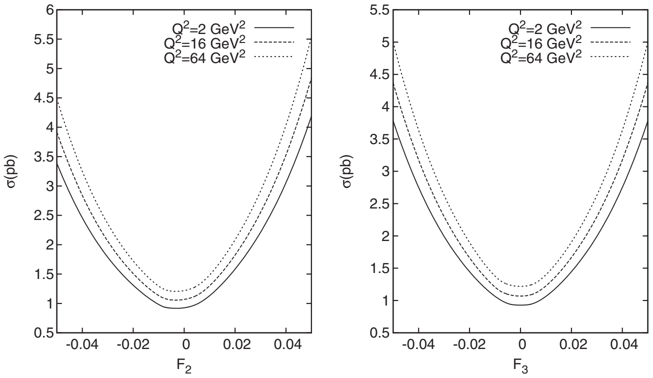

FIG. 2. The total cross section as a function of F_2 and F_3 for different values of Q^2 at the center-of-mass energy $\sqrt{s} = 0.5$ TeV for the process $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$.

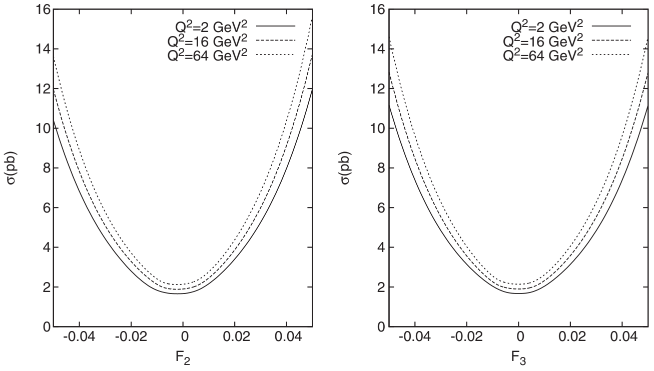

FIG. 3. The same as Fig. 2 but for $\sqrt{s} = 1.5$ TeV.

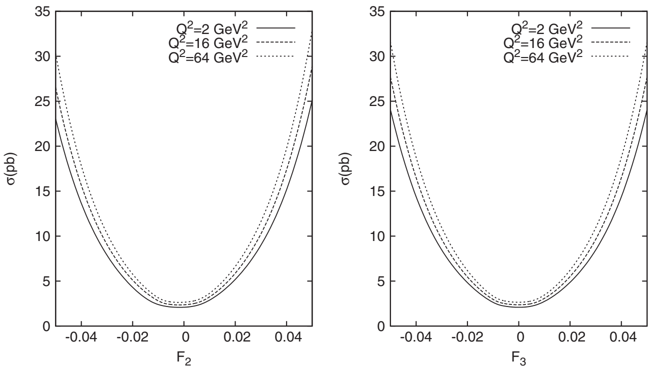

FIG. 4. The same as Fig. 2 but for $\sqrt{s} = 3$ TeV.

in Ref. [19]. Therefore, the sensitivity limits on the anomalous magnetic and electric dipole moments of the tau lepton through the process $e^+e^- \to e^+e^-\tau^+\tau^-$ have been calculated by considering three systematic errors: 2%, 5% and 10%. On the other hand, there may occur an uncertainty arising from the virtuality of γ^* used in the Weizsacker-Williams approximation. In Figs. 2–4, we have calculated the integrated cross sections as a function of F_2 and F_3 for different $Q^2_{\rm max}$ values. We can see from these figures the total cross section changes slightly with the variation of the $Q^2_{\rm max}$ value. The sensitivity limits on the anomalous couplings a_τ and d_τ for different values of photon virtuality, center-of-mass energy, and luminosity have been given in Table I. It has been shown that the bounds on the anomalous couplings do not virtually change

TABLE I. The sensitivity limits on the anomalous couplings a_τ and d_τ for different values of photon virtuality, center-of-mass energy, and luminosity.

$Q^2_{\rm max}$ (GeV^2)	$\sqrt{s}$ (TeV)	Luminosity (fb^{-1})	a_τ	$\lvert d_\tau\rvert(e$ cm)
2	0.5	50	$(-0.0077, 0.0016)$	0.19×10^{-16}
2	0.5	230	$(-0.0068, 0.0007)$	0.13×10^{-16}
2	3	200	$(-0.0043, 0.0005)$	0.08×10^{-16}
2	3	590	$(-0.0036, 0.0003)$	0.06×10^{-16}
16	0.5	50	$(-0.0076, 0.0015)$	0.19×10^{-16}
16	0.5	230	$(-0.0067, 0.0007)$	0.12×10^{-16}
16	3	200	$(-0.0042, 0.0005)$	0.08×10^{-16}
16	3	590	$(-0.0036, 0.0003)$	0.06×10^{-16}
64	0.5	50	$(-0.0076, 0.0015)$	0.18×10^{-16}
64	0.5	230	$(-0.0067, 0.0006)$	0.12×10^{-16}
64	3	200	$(-0.0042, 0.0005)$	0.08×10^{-16}
64	3	590	$(-0.0035, 0.0003)$	0.06×10^{-16}

TABLE II. 95% C.L. sensitivity bounds of the coupling a_τ and d_τ for various integrated CLIC luminosities and systematic uncertainties at the $\sqrt{s} = 0.5$ TeV.

Luminosity (fb^{-1})	$\delta_{\rm sys}$	a_τ	$\lvert d_\tau\rvert(e$ cm)
50	$\delta_{\rm sys} = 0$	$(-0.0077, 0.0016)$	0.19×10^{-16}
50	$\delta_{\rm sys} = 0.02$	$(-0.0098, 0.0037)$	3.44×10^{-16}
50	$\delta_{\rm sys} = 0.05$	$(-0.0130, 0.0065)$	5.27×10^{-16}
50	$\delta_{\rm sys} = 0.10$	$(-0.0153, 0.011)$	7.77×10^{-16}
100	$\delta_{\rm sys} = 0$	$(-0.0073, 0.0013)$	0.16×10^{-16}
100	$\delta_{\rm sys} = 0.02$	$(-0.0097, 0.0036)$	3.33×10^{-16}
100	$\delta_{\rm sys} = 0.05$	$(-0.0128, 0.0064)$	5.21×10^{-16}
100	$\delta_{\rm sys} = 0.10$	$(-0.0152, 0.011)$	7.21×10^{-16}
230	$\delta_{\rm sys} = 0$	$(-0.0068, 0.0007)$	0.13×10^{-16}
230	$\delta_{\rm sys} = 0.02$	$(-0.0096, 0.0036)$	3.22×10^{-16}
230	$\delta_{\rm sys} = 0.05$	$(-0.0126, 0.0062)$	5.10×10^{-16}
230	$\delta_{\rm sys} = 0.10$	$(-0.0151, 0.010)$	6.66×10^{-16}

TABLE III. 95% C.L. sensitivity bounds of the coupling a_τ and d_τ for integrated CLIC luminosities and various systematic uncertainties at the $\sqrt{s} = 1.5$ TeV.

Luminosity (fb^{-1})	$\delta_{\rm sys}$	a_τ	$\lvert d_\tau\rvert(e$ cm)
100	$\delta_{\rm sys} = 0$	$(-0.0051, 0.0008)$	0.11×10^{-16}
100	$\delta_{\rm sys} = 0.02$	$(-0.0076, 0.0032)$	2.78×10^{-16}
100	$\delta_{\rm sys} = 0.05$	$(-0.0102, 0.0060)$	4.33×10^{-16}
100	$\delta_{\rm sys} = 0.10$	$(-0.0132, 0.0092)$	6.66×10^{-16}
200	$\delta_{\rm sys} = 0$	$(-0.0049, 0.0006)$	0.10×10^{-16}
200	$\delta_{\rm sys} = 0.02$	$(-0.0075, 0.0031)$	2.72×10^{-16}
200	$\delta_{\rm sys} = 0.05$	$(-0.0101, 0.0059)$	4.30×10^{-16}
200	$\delta_{\rm sys} = 0.10$	$(-0.0131, 0.0091)$	6.38×10^{-16}
320	$\delta_{\rm sys} = 0$	$(-0.0047, 0.0005)$	0.08×10^{-16}
320	$\delta_{\rm sys} = 0.02$	$(-0.0075, 0.0030)$	2.66×10^{-16}
320	$\delta_{\rm sys} = 0.05$	$(-0.0100, 0.0058)$	4.27×10^{-16}
320	$\delta_{\rm sys} = 0.10$	$(-0.0130, 0.0090)$	6.11×10^{-16}

TABLE IV. 95% C.L. sensitivity bounds of the coupling a_τ and d_τ for integrated CLIC luminosities and various systematic uncertainties at the $\sqrt{s} = 3$ TeV.

Luminosity (fb^{-1})	δ_{sys}	a_τ	$\lvert d_\tau \rvert (e\ \text{cm})$
200	$\delta_{\text{sys}} = 0$	$(-0.0043, 0.0005)$	0.08×10^{-16}
200	$\delta_{\text{sys}} = 0.02$	$(-0.0067, 0.0033)$	2.55×10^{-16}
200	$\delta_{\text{sys}} = 0.05$	$(-0.0090, 0.0055)$	4.10×10^{-16}
200	$\delta_{\text{sys}} = 0.10$	$(-0.0113, 0.0084)$	5.49×10^{-16}
400	$\delta_{\text{sys}} = 0$	$(-0.0039, 0.0004)$	0.07×10^{-16}
400	$\delta_{\text{sys}} = 0.02$	$(-0.0066, 0.0032)$	2.53×10^{-16}
400	$\delta_{\text{sys}} = 0.05$	$(-0.0090, 0.0054)$	4.02×10^{-16}
400	$\delta_{\text{sys}} = 0.10$	$(-0.0112, 0.0083)$	5.46×10^{-16}
590	$\delta_{\text{sys}} = 0$	$(-0.0036, 0.0003)$	0.06×10^{-16}
590	$\delta_{\text{sys}} = 0.02$	$(-0.0066, 0.0032)$	2.50×10^{-16}
590	$\delta_{\text{sys}} = 0.05$	$(-0.0090, 0.0054)$	3.99×10^{-16}
590	$\delta_{\text{sys}} = 0.10$	$(-0.0112, 0.0082)$	5.42×10^{-16}

when Q^2_{max} increases. Therefore, we can understand that the large values of Q^2_{max} do not bring an important contribution to obtain sensitivity limits on the anomalous couplings [5,6,66].

In Tables II–IV, we show 95% C.L. sensitivity bounds of the coupling a_τ and d_τ for various systematic uncertainties, integrated CLIC luminosities, and center-of-mass energies. While calculating the table values, we assumed that at a given time, only one of the anomalous couplings deviated from the SM. In Fig. 5, we demonstrate the sensitivity contour plot at 95% C.L. for the anomalous couplings F_2 and F_3 at the $\sqrt{s} = 0.5$, 1.5, and 3 TeV with corresponding maximum luminosities through process $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$.

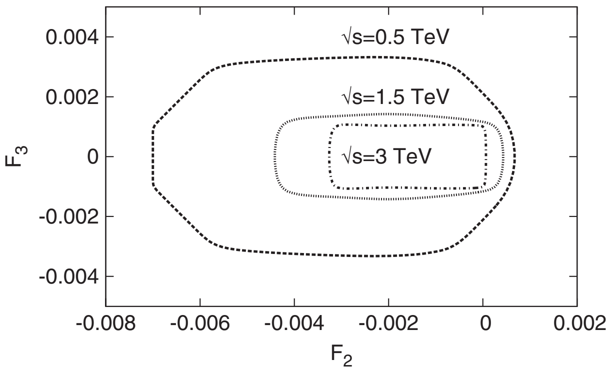

FIG. 5. The contour plot for the upper bounds of the anomalous couplings F_2 and F_3 with 95% C.L. at the $\sqrt{s} = 0.5$, 1.5, and 3 TeV with corresponding maximum luminosities for the process $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$.

III. CONCLUSIONS

The CLIC as a $\gamma^*\gamma^*$ collider using the Weizsacker-Williams virtual photon fields of the e^- and e^+ provides an ideal venue to investigate the electromagnetic moments of the tau lepton. For this reason, we have studied the potential of $e^+e^- \to e^+\gamma^*\gamma^*e^- \to e^+\tau\bar{\tau}e^-$ at the CLIC to examine the anomalous magnetic and electric dipole moments of the tau lepton. The findings of this study show that the CLIC can improve the sensitivity bounds on the anomalous couplings of electromagnetic dipole moments of the tau lepton with respect to the LEP bounds.

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