Research Article

Analyzing the Anomalous Dipole Moment Type Couplings of Heavy Quarks with FCNC Interactions at the CLIC

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We examine both anomalous magnetic and dipole moment type couplings of a heavy quark via its single production with subsequent dominant standard model decay modes at the compact linear collider (CLIC). The signal and background cross sections are analyzed for heavy quark masses 600 and 700 GeV. We make the analysis to delimitate these couplings as well as to find the attainable integrated luminosities for 3σ observation limit.

1. Introduction

Discovery of new particles performs a crucial role for physics beyond the standard model (SM) and may play a milestone role in the discovery of some open questions like the electroweak symmetry breaking [1–5], fermion mass spectrum hierarchies and mixing angle in quark/lepton sectors [6–10], CP violation, and flavor structure of standard theory [11–17]. The precise determination of heavy quark properties may present the existence of new physics. A heavy down-type quark (b') with mass less than 645 GeV and an up-type quark (t') with mass less than 585 GeV [18] are excluded at 95% confidence level from proton-proton collisions at $\sqrt{s} = 8$ TeV ATLAS detector at the CERN large hadron collider.

Searching for new sources of CP violation beyond the SM is an attractive subject in particle physics, since it explains the asymmetry between matter and antimatter. CP violating anomalous flavor changing neutral current (FCNC) tcZ/tcy couplings have been considered in the literature before at hadron [19] and e^-e^+ [20, 21] colliders. This type of FCNC interactions offer an ideal place to search for new physics. Due to the large mass values, heavy quarks have crucial advantage to new interactions originating at a higher scale as in top quark physics. Recently, anomalous FCNC t quark couplings, such as tqV ($q = uc$, $V = \gamma, Z, g$), were experimentally restricted by some collaborations. For instance,

the upper limits observed from tqg vertices by ATLAS collaboration are $\kappa_{ugt}/\Lambda < 6.9 \times 10^{-3} \text{ TeV}^{-1}$ and $\kappa_{cgt}/\Lambda < 1.6 \times 10^{-2} \text{ TeV}^{-1}$ assuming only one coupling is kept nonzero [22], while D0 set limits are $\kappa_{tgu}/\Lambda < 0.013 \text{ TeV}^{-1}$, $\kappa_{tgc}/\Lambda < 0.057 \text{ TeV}^{-1}$ [23] and CDF set limits are $\kappa_{tug}/\Lambda < 0.018 \text{ TeV}^{-1}$, $\kappa_{tcg}/\Lambda < 0.069 \text{ TeV}^{-1}$ [24]. Recent observed upper limits on the coupling strengths from CMS collaboration, which analyzed both gqt and Zqt vertices probed simultaneously, are $\kappa_{gut}/\Lambda < 0.10 \text{ TeV}^{-1}$, $\kappa_{gct}/\Lambda < 0.35 \text{ TeV}^{-1}$, $\kappa_{Zut}/\Lambda < 0.45 \text{ TeV}^{-1}$, and $\kappa_{Zct}/\Lambda < 2.27 \text{ TeV}^{-1}$ [25].

Serious contributions can be expected for the production of the heavy fermions, due to the anomalous magnetic moment type interactions. Phenomenological studies with these anomalous effects of these quarks have been performed on hadron colliders [26–31], on electron proton colliders [32, 33], and on linear colliders [34]. In this work, we study the production of single heavy t' quark at compact linear collider (CLIC) [35] via both anomalous magnetic and dipole moment type interactions. CLIC, a most popular proposed linear collider on TeV scale, would complete the LHC results by performing precision measurements to provide necessary information about some parameters of heavy quarks. The aim of this study is to delimitate the anomalous magnetic

FIGURE 1: Branching ratios (%) of all t' decay channels depending on $\tilde{\kappa}/\Lambda$ for $m_{t'} = 700$ GeV.

FIGURE 2: The total decay width of the t' quark as function of $\tilde{\kappa}/\Lambda$.

FIGURE 3: Feynman diagram for anomalous single production of t' quark in e^+e^- collision.

and dipole moment type couplings of t' quark from a detailed signal and background analysis including Monte Carlo simulation with the effects of initial state radiation (ISR) and beamstrahlung (BS) in the e^+e^- collisions.

2. Single Production and Decay of t' Quark

The interaction Lagrangian for t' quark within the SM is given by

$$L_s = -g_e Q_{t'} \bar{t}' \gamma^\mu t' A_\mu - g_s \bar{t}' T^a \gamma^\mu t' G_\mu^a$$

FIGURE 4: The total cross sections at $\sqrt{s} = 3$ TeV for the process $e^+e^- \rightarrow t' \bar{q}$ ($\bar{q} = \bar{u}, \bar{c}$) as function of $\tilde{\kappa}/\Lambda$.

FIGURE 5: The differential cross section depending on the transverse momentum of the final state b quark of process $e^+e^- \rightarrow W^+ b \bar{q}$ ($\bar{q} = \bar{u}, \bar{c}$) for SM background (solid line) and signal with different mass values of t' quarks at $\sqrt{s} = 3$ TeV.

$$- \frac{g_e}{2s_W c_W} \bar{t}' \gamma^\mu (g_V - g_A \gamma^5) t' Z_\mu^0 - \frac{g_e}{2\sqrt{2}s_W} V_{t'q_i} \bar{t}' \gamma^\mu (1 - \gamma^5) q_i W_\mu^+ + \text{h.c.}, \quad (1)$$

where A_μ , G_μ , Z_μ^0 , and W_μ^+ are the vector fields for photon, gluon, Z boson, and W boson, respectively. g_e is the electroweak coupling constant and g_s is the strong coupling constant. T^a are the Gell-Mann matrices; $Q_{t'}$ is the electric charge of heavy quark t' . g_V and g_A are the vector and axial-vector type couplings of the neutral weak current with

FIGURE 6: The rapidity distribution of the final state b quark at $\sqrt{s} = 3$ TeV for the process $e^+e^- \rightarrow W^+b\bar{q}$ ($\bar{q} = \bar{u}, \bar{c}$).

FIGURE 7: The invariant mass distribution of the final state Wb system for SM background (solid line) and signal from t' decay for $m_{t'} = 600$ GeV (dashed line) and $m_{t'} = 700$ GeV (dot-dashed line) at $\sqrt{s} = 3$ TeV.

t' quark; θ_W is the weak mixing angle, $s_W = \sin \theta_W$ and $c_W = \cos \theta_W$. $V_{t'q}$ denotes the elements of extended 4×4 CKM mixing matrix which are constrained by flavor physics.

The anomalous magnetic and dipole moment type interactions among heavy quark t' , ordinary quarks q , and the neutral gauge bosons $V = \gamma, Z, g$ can be described by an effective Lagrangian which contains the anomalous magnetic and dipole moment type couplings given by

$$L'_a = \sum_{q_i=u,c,t} Q_{q_i} \frac{g_e}{\Lambda} \bar{t}' \sigma_{\mu\nu} (\kappa_\gamma^{q_i} - i\tilde{\kappa}_\gamma^{q_i} \gamma_5) q_i F^{\mu\nu} + \sum_{q_i=u,c,t} \frac{g_e}{2\Lambda s_W c_W} \bar{t}' \sigma_{\mu\nu} (\kappa_Z^{q_i} - i\tilde{\kappa}_Z^{q_i} \gamma_5) q_i Z^{\mu\nu}$$

FIGURE 8: The 3σ contour plot for the anomalous couplings reachable at $\sqrt{s} = 3$ TeV with $L_{\text{int}} = 5.9 \times 10^5 \text{ pb}^{-1}$ for $m_{t'} = 600$ GeV.

TABLE 1: Main parameters of the CLIC.

Parameters	CLIC
$E_{\text{cm}} (\sqrt{s})$ TeV	3
$L (10^{34} \text{ cm}^{-2} \text{ s}^{-1})$	5.9
$N (10^{10})$	0.372
σ_x (nm)	45
σ_y (nm)	1
σ_z (μm)	44

Here, N is the number of particles in bunch; σ_x and σ_y are beam sizes; and σ_z is the bunch length.

$$+ \sum_{q_i=u,c,t} \frac{g_s}{2\Lambda} \bar{t}' \sigma_{\mu\nu} (\kappa_g^{q_i} - i\tilde{\kappa}_g^{q_i} \gamma_5) T^a q_i G_a^{\mu\nu} + \text{h.c.}, \quad (2)$$

where $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G^{\mu\nu}$ are the field strength tensors of the gauge bosons; $\sigma_{\mu\nu} = i(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)/2$; Q_{q_i} is the electric charge of the quark (q). $\kappa_\gamma(\tilde{\kappa}_\gamma)$, $\kappa_Z(\tilde{\kappa}_Z)$ and $\kappa_g(\tilde{\kappa}_g)$ are the anomalous magnetic (dipole) moment type couplings with photon, Z boson, and gluon, respectively. Note that $\tilde{\kappa}$'s are CP violating and Λ is the cutoff scale of new interactions and we assume $\kappa_\gamma = \kappa_Z = \kappa_g = \kappa$ and $\tilde{\kappa}_\gamma = \tilde{\kappa}_Z = \tilde{\kappa}_g = \tilde{\kappa}$.

CP violating flavor changing neutral current processes within the SM with the b' and t' quarks are analyzed by constructing and employing global unique fit of the unitary 4×4 CKM mass mixing matrix at $m_{t'} = 600$ and 700 GeV separately, in [36]. In our calculations we use this parameterization for values of the 4×4 CKM matrix elements and we assume $m_{t'} > m_{b'}$ with a mass splitting of $m_{t'} - m_{b'} \approx 50$ GeV. We implement the related interaction vertices, given in the effective Lagrangian, into the tree level event generator CompHEP package [37] for numerical calculations. In Figure 1, branching ratios (BR) dependence on $\tilde{\kappa}/\Lambda$ for SM decay channels ($Wd(s, b)$) and anomalous decay channels ($Vu(c, t)$) of t' quark which are calculated by using Lagrangians (1) and (2) are given for $m_{t'} = 700$ GeV and $\kappa/\Lambda = 0.1 \text{ TeV}^{-1}$. As seen from this figure, SM t' decay channel, $t' \rightarrow Wb$, is dominant for $\tilde{\kappa}/\Lambda$ less than 0.2

FIGURE 9: The 3σ contour plot for the anomalous dipole moment type couplings reachable at (a) $m_{t'} = 600$ GeV and (b) $m_{t'} = 700$ GeV.

FIGURE 10: The attainable integrated luminosity for 3σ observation limit for (a) $m_{t'} = 600$ GeV and (b) $m_{t'} = 700$ GeV for $\sqrt{s} = 3$ TeV depending on anomalous dipole moment type couplings.

changing around 27%–63% BR. Total decay widths of t' quark dependence on $\tilde{\kappa}/\Lambda$ are given in Figure 2 for $m_{t'} = 600$ and 700 GeV with $\kappa/\Lambda = 0$ and 0.1 TeV^{-1} .

The contributing tree level Feynman Diagram for the anomalous single production of t' quark in e^+e^- collision is shown in Figure 3. In Figure 4, the total cross sections for single production of t' quark are plotted at collision center of mass energy of 3 TeV with respect to $\tilde{\kappa}/\Lambda$ for $m_{t'} = 600$ and 700 GeV with $\kappa/\Lambda = 0$ and 0.1 TeV^{-1} . Initial state radiation (ISR) and beamstrahlung (BS) are specific features of the linear colliders. We take the beam parameters for the CLIC given in Table 1, when calculating the ISR and BS effects. Hereafter, in all our numerical calculations we take into account ISR + BS effects.

3. Signal and Background Analysis

The signal process of single production of t' quark including the dominant SM decay mode over anomalous decay is $e^+e^- \rightarrow t'\bar{q}_i \rightarrow W^+b\bar{q}_i$, where $\bar{q}_i = \bar{u}, \bar{c}$. The dominant source of SM background process is $e^+e^- W^+b\bar{q}_i$ for the corresponding signal processes.

In the transverse momentum, rapidity, and invariant mass distributions analysis, we assume $\tilde{\kappa}/\Lambda = \kappa/\Lambda = 0.1 \text{ TeV}^{-1}$. In Figure 5, the transverse momentum (p_T) distributions of the final state b quark for signal and background are shown for CLIC energy. We applied a p_T cut of $p_T > 50$ GeV to reduce the background, comparing the signal p_T distribution of b quark with that of the corresponding background.

TABLE 2: The signal and background cross sections and signal statistical significance (SS) by taking $\kappa/\Lambda = 0 \text{ TeV}^{-1}$ for the CLIC at $\sqrt{s} = 3 \text{ TeV}$ with integrated luminosity of $5.9 \times 10^5 \text{ pb}^{-1}$.

$m_{t'}$ (GeV)	$\tilde{\kappa}/\Lambda = 0.1 \text{ TeV}^{-1}$			$\tilde{\kappa}/\Lambda = 0.01 \text{ TeV}^{-1}$		
	σ_S (fb)	σ_B (fb)	SS	σ_S (fb)	σ_B (fb)	SS
600	3.01	8.92×10^{-3}	19.72	1.50×10^{-2}	8.92×10^{-3}	1.10
700	2.63	1.14×10^{-2}	18.43	1.31×10^{-2}	1.14×10^{-2}	0.95

In Figure 6, we plot the rapidity distributions of final state b quark in signal and background processes. According to these figures, the cut $|\eta^b| < 2.5$ can be applied to suppress the background while the signal remains almost unchanged.

In Figure 7, the invariant mass distributions for the W^+b system in the final state are plotted. From these figures, we can see that the signal has a peak around mass of t' quark over the background.

In Table 2, we calculate cross sections of the signal and background and the statistical significance (SS) to discuss the observability of 600 and 700 GeV t' quark for $\tilde{\kappa}/\Lambda = 0.1$ and 0.01 TeV^{-1} by taking $\kappa/\Lambda = 0 \text{ TeV}^{-1}$ at CLIC. The SS of the signal is obtained by using the following formula:

$$SS = \left(\frac{\sigma_S}{\sqrt{\sigma_S + \sigma_B}} \right) \sqrt{\text{BR}(W \rightarrow l\nu_l) \cdot L_{\text{int}}}, \quad (3)$$

where σ_S is the signal and σ_B is the background cross sections for the $e^+e^- \rightarrow t'\bar{q}_i \rightarrow W^+b\bar{q}_i$ process, respectively, and $l = e, \mu$. We take into account finite energy resolution of the detectors for realistic analysis. In our numerical calculations we use the mass bin width $\Delta m = \max(2\Gamma, \delta m)$ to count signal and background events with the mass resolution δm . The mentioned p_T and η cuts are applied assuming the integrated luminosity given in Table 1.

After this point, we will focus on limiting the anomalous magnetic and dipole moment type couplings. Firstly, in Figure 8, we present the 3σ contour plot for $\tilde{\kappa}/\Lambda$ - κ/Λ plane at $\sqrt{s} = 3 \text{ TeV}$ with $m_{t'} = 600 \text{ GeV}$. According to these figures, the lower limits of κ/Λ and $\tilde{\kappa}/\Lambda$ are about 0.033 TeV^{-1} at the CLIC energy.

To analyze the case of $\tilde{\kappa}_Y/\Lambda \neq \tilde{\kappa}_Z/\Lambda$, the 3σ contour plots for the anomalous couplings in the $\tilde{\kappa}_Z/\Lambda$ - $\tilde{\kappa}_Y/\Lambda$ plane are presented in Figure 9 at $\sqrt{s} = 3 \text{ TeV}$ with (a) $m_{t'} = 600 \text{ GeV}$ and (b) $m_{t'} = 700 \text{ GeV}$ by taking into account different values of κ/Λ . According to these figures the lower limits of $\tilde{\kappa}_Y/\Lambda$ and $\tilde{\kappa}_Z/\Lambda$ are about 0.038 TeV^{-1} for $m_{t'} = 600 \text{ GeV}$ and 0.019 TeV^{-1} for $m_{t'} = 700 \text{ GeV}$ with $\kappa/\Lambda = 0.01 \text{ TeV}^{-1}$. In Figures 8 and 9, allowed parameter space area of t' quark is above the lines.

We plot the lowest necessary luminosities with 3σ observation limits for (a) $m_{t'} = 600 \text{ GeV}$ and (b) $m_{t'} = 700 \text{ GeV}$ at $\sqrt{s} = 3 \text{ TeV}$ depending on anomalous couplings in Figure 10. In the case of $\kappa/\Lambda = \tilde{\kappa}/\Lambda = 0.1 \text{ TeV}^{-1}$, it is seen that from these figures, t' quarks with masses 600 and 700 GeV can be observed at 3σ observation limit with lowest integrated luminosity at the order of 10^4 pb^{-1} at CLIC.

4. Conclusion

The anomalous FCNC interactions of heavy quarks could be important for some parameter regions due to the expected large masses. The sensitivity to the anomalous couplings (κ , $\tilde{\kappa}$) and ($\tilde{\kappa}_Y$, $\tilde{\kappa}_Z$) can be obtained for $m_{t'} = 600 \text{ GeV}$ about (0.033, 0.033) and (0.035, 0.038) for $\kappa = 0.01$, and for $m_{t'} = 700 \text{ GeV}$ ($\tilde{\kappa}_Y$, $\tilde{\kappa}_Z$) values can be obtained about (0.019, 0.0195) for $\kappa = 0.01$ with $\Lambda = 1 \text{ TeV}$. We also find the lowest necessary luminosity limit values at the order of 10^4 pb^{-1} for CLIC.

Conflict of Interests

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

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