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 \(3\sigma\) 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) \(tcZ/tc\gamma\) 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 \(k_{tqg}/\Lambda < 6.9 \times 10^{-3}\) TeV\(^{-1}\) and \(k_{cqt}/\Lambda < 1.6 \times 10^{-2}\) TeV\(^{-1}\) assuming only one coupling is kept nonzero [22], while D0 set limits are \(k_{tqg}/\Lambda < 0.013\) TeV\(^{-1}\), \(k_{tcg}/\Lambda < 0.057\) TeV\(^{-1}\) [23] and CDF set limits are \(k_{tqg}/\Lambda < 0.018\) TeV\(^{-1}\), \(k_{tcg}/\Lambda < 0.069\) TeV\(^{-1}\) [24]. Recent observed upper limits on the coupling strengths from CMS collaboration, which analyzed both \(gqt\) and \(Zqt\) vertices probed simultaneously, are \(k_{gqt}/\Lambda < 0.10\) TeV\(^{-1}\), \(k_{gct}/\Lambda < 0.35\) TeV\(^{-1}\), \(k_{Zct}/\Lambda < 0.45\) TeV\(^{-1}\), and \(k_{Zct}/\Lambda < 2.27\) 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
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

$$L_s = -g_\epsilon Q_t \gamma^\mu t' A_\mu$$

$$- g_\epsilon t'^a \gamma^\mu t' G^a_\mu$$

$$- \frac{g_\epsilon}{2 s_W c_W} \gamma^\mu \left( g_{W^0} - g_A \gamma^5 \right) t' Z^0_\mu$$

$$- \frac{g_\epsilon}{2 \sqrt{2} s_W} V_{\ell \ell} t'^a \gamma^\mu \left( 1 - \gamma^5 \right) q_\ell W^\pm_\mu + \text{h.c.,}$$

where $A_\mu$, $G^a_\mu$, $Z^0_\mu$, and $W^\pm_\mu$ are the vector fields for photon, gluon, $Z$ boson, and $W$ boson, respectively. $g_\epsilon$ is the electroweak coupling constant and $g_\epsilon$ is the strong coupling constant. $T^a$ are the Gell-Mann matrices; $Q_t$ is the electric charge of heavy quark $t'$. $g_W$ 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 $e^-e^+ \rightarrow W^*b\bar{q}$ ($q = \bar{u}, \bar{c}$).

Figure 7: The invariant mass distribution of the final state $Wb$ 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.

$\sqrt{s}=3$ TeV

\[ \frac{d\sigma}{dM_{Wb}} \text{ (pb/GeV)} \]

- SM Bg
- $m_{t'} = 600$ GeV
- $m_{t'} = 700$ GeV

$\sqrt{s}=3$ TeV

\[ \frac{d\sigma}{d\eta_b} \text{ (pb/GeV)} \]

- SM Bg
- $m_{t'} = 600$ GeV
- $m_{t'} = 700$ GeV

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

Table 1: Main parameters of the CLIC.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{cm}(\sqrt{s})$</td>
<td>TeV</td>
</tr>
<tr>
<td>$L$ (10$^{24}$ cm$^{-2}$ s$^{-1}$)</td>
<td>5.9</td>
</tr>
<tr>
<td>$N$ (10$^{10}$)</td>
<td></td>
</tr>
<tr>
<td>$\sigma_x$ (nm)</td>
<td>44</td>
</tr>
<tr>
<td>$\sigma_y$ (nm)</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_z$ (µm)</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{f}$ (nm)</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{g}$ (nm)</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{h}$ (nm)</td>
<td></td>
</tr>
</tbody>
</table>

Here, $N$ is the number of particles in bunch; $\sigma_x$ and $\sigma_y$ are beam sizes; and $\sigma_z$ is the bunch length.

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

\[ L_a = \sum_{q_i = u, c, t} Q_{q_i} \frac{g_e}{\Lambda} \sigma_{\mu\nu} \left( k^{q_i}_{\gamma} - i\tilde{k}^{q_i}_{\gamma} \right) q_i F^{\mu\nu} \]

\[ + \sum_{q_i = u, c, t} \frac{g_e}{2\Lambda s_W c_W} \sigma_{\mu\nu} \left( k^{q_i}_Z - i\tilde{k}^{q_i}_Z \right) q_i Z^{\mu\nu} \]

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

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 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

\[ L_a = \sum_{q_i = u, c, t} Q_{q_i} \frac{g_e}{\Lambda} \sigma_{\mu\nu} \left( k^{q_i}_{\gamma} - i\tilde{k}^{q_i}_{\gamma} \right) q_i F^{\mu\nu} \]

\[ + \sum_{q_i = u, c, t} \frac{g_e}{2\Lambda s_W c_W} \sigma_{\mu\nu} \left( k^{q_i}_Z - i\tilde{k}^{q_i}_Z \right) q_i Z^{\mu\nu} \]
changing around 27%–63% BR. Total decay widths of $t'$ quark 
dependence on $\tilde{\kappa}/\Lambda$ are given in Figure 2 for $m_{t'} = 600 \text{ and } 700 \text{ GeV with } \kappa/\Lambda = 0 \text{ and } 0.1 \text{ TeV}^{-1}$.

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 $m_{t'} = 600 \text{ and } 700 \text{ GeV with } \kappa/\Lambda = 0 \text{ and } 0.1 \text{ TeV}^{-1}$. 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 $p_T > 50 \text{ GeV}$ 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 $\kappa/\Lambda = 0$ TeV$^{-1}$ for the CLIC at $\sqrt{s} = 3$ TeV with integrated luminosity of $5.9 \times 10^4$ pb$^{-1}$.

<table>
<thead>
<tr>
<th>$m_t$ (GeV)</th>
<th>$\sigma_S$ (fb)</th>
<th>$\sigma_B$ (fb)</th>
<th>SS</th>
<th>$\sigma_S$ (fb)</th>
<th>$\sigma_B$ (fb)</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>3.01</td>
<td>$8.92 \times 10^{-2}$</td>
<td>19.72</td>
<td>$1.50 \times 10^{-2}$</td>
<td>$8.92 \times 10^{-3}$</td>
<td>1.10</td>
</tr>
<tr>
<td>700</td>
<td>2.63</td>
<td>$1.14 \times 10^{-2}$</td>
<td>18.43</td>
<td>$1.31 \times 10^{-2}$</td>
<td>$1.14 \times 10^{-2}$</td>
<td>0.95</td>
</tr>
</tbody>
</table>

In Figure 6, we plot the rapidity distributions of final state $b$ quark in signal and background processes. According to these figures, the cut $|\eta|^2 < 2.5$ 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 $t'\bar{q}$ quark over the background.

In Table 2, we calculate cross sections of the signal and background and the statistical significance (SS) by taking $\nu$ for the anomalous couplings in the $t'\bar{q}$ plane. The lower limits of $\kappa/\Lambda$ and $\bar{\kappa}/\Lambda$ are about 0.033 TeV$^{-1}$ at the CLIC energy.

To analyze the case of $\bar{\kappa}_Z/\Lambda \neq \bar{\kappa}_Z/\Lambda$, the $3\sigma$ contour plots for the anomalous couplings in the $\bar{\kappa}_Z/\Lambda - \bar{\kappa}_Z/\Lambda$ plane are presented in Figure 9 at $\sqrt{s} = 3$ TeV with (a) $m_t = 600$ GeV and (b) $m_t = 700$ GeV by taking into account different values of $\kappa/\Lambda$. According to these figures, the lower limits of $\bar{\kappa}_Z/\Lambda$ and $\bar{\kappa}/\Lambda$ are about 0.038 TeV$^{-1}$ for $m_t = 600$ GeV and 0.019 TeV$^{-1}$ for $m_t = 700$ GeV with $\kappa/\Lambda = 0.01$ 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 $3\sigma$ observation limits for (a) $m_t = 600$ GeV and (b) $m_t = 700$ GeV at $\sqrt{s} = 3$ TeV depending on anomalous couplings in Figure 10. In the case of $\kappa/\Lambda = \bar{\kappa}/\Lambda = 0.1$ TeV$^{-1}$, it is seen that from these figures, $t'$ quarks with masses 600 and 700 GeV can be observed at $3\sigma$ 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 ($\kappa$, $\bar{\kappa}$) can be obtained for $m_t = 600$ GeV about (0.033, 0.033) and (0.035, 0.038) for $\kappa = 0.01$, and for $m_t = 700$ GeV ($\bar{\kappa}$, $\bar{\kappa}_Z$) values can be obtained about (0.019, 0.0195) for $\kappa = 0.01$ with $\Lambda = 1$ TeV. We also find the lowest necessary luminosity limit values at the order of $10^5$ pb$^{-1}$ for CLIC.

Conflict of Interests

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

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References


