Top quark flavor changing neutral currents and dipole moments through three and four top-quark productions at the LHC

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Abstract.
In this paper, the top quark flavor changing neutral current (FCNC) interaction is studied through the process of the three-top quark production at the LHC for center-of-mass energy of 14 TeV. We also investigate the anomalous top quark chromoelectric and chromomagnetic dipole moments through the four top-quarks production signal at the center-of-mass energy of 13 TeV. We demonstrate that these processes are powerful tools to constrain the top quark FCNC couplings as well as the top dipole moments.

1. Introduction
The top quark with its unique features like large mass and extremely short lifetime, provides a great opportunity to test the standard model (SM) of particle physics as well as probing new physics (NP) beyond the SM (BSM) [1, 2]. Besides the dominant production of top quark pairs with a small contribution of single top quark production, it is also possible to have three or four top-quark production at the large center-of-mass energy in proton-proton (pp) collisions at the LHC [3, 4]. The top quark is expected to decay to a W boson and a b-quark in the SM [5]. In flavour changing neutral current (FCNC) interactions, the top quark decays to a neutral boson and an up or charm quark. In the SM, FCNC transitions are not only forbidden at tree level but also suppressed at higher orders due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [6]. In some NP models, a significant enhancement of top quark FCNC couplings are predicted [7, 8].

We explore the top quark FCNC interactions through processes with only three top-quark in the final state. In the second part of this analysis, the strong and electroweak dipole moments of the top quark are studied. Even though dipole interactions do not exist at the leading order in the SM, we explore the sensitivity of the four top-quark production at the leading order (LO) to the strong and weak top quark dipole moments.

2. Theoretical framework and assumptions
The new physics effects may be described in a model-independent way using an effective Lagrangian with the following form [9, 10, 11, 12],

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}^{d=6}_i + \text{h.c.},$$

(1)
where $c_i$ are a set of dimensionless coefficients and the NP effects are parameterized with dimension-six operators $O_i$ which satisfy the SM symmetries and $\Lambda$ in Eq. 1 is the scale of NP. In this analysis, our aim is to probe the sensitivity of dimension-six operators which contain FCNC ($tqg$, $tqZ$, $tq\gamma$, $tqH$) vertices as well as those which contribute to $gt\bar{t}$ and $Zt\bar{t}$ vertices in the four top-quark production at the LHC. The most general effective Lagrangian describing the FCNC interactions, has the following form [6, 7]:

$$
L_{\text{FCNC}} = \sum_{q=u,c} \left[ \frac{g_s}{2m_t} \bar{q}_a \gamma^\mu q_b \left( \zeta_{qt}^L P_L + \zeta_{qt}^R P_R \right) t G^{a\mu}_{\nu} - \frac{1}{\sqrt{2}} \eta_{qt}^L P_L + \eta_{qt}^R P_R \right] t H
- \frac{g_W}{2c_W} \bar{q} \sigma^{\mu\nu} (X_{qt}^L P_L + X_{qt}^R P_R) t Z_{\mu\nu}
+ \frac{g_W}{4c_W m_Z} \bar{q} \sigma^{\mu\nu} (\kappa_{qt}^L P_L + \kappa_{qt}^R P_R) t Z_{\mu\nu}
+ \frac{\kappa}{2m_t} \bar{q}_a \gamma^{\mu} (\lambda_{qt}^L P_L + \lambda_{qt}^R P_R) t A_{\mu\nu} \right] + \text{h.c.},
$$

(2)

where $\zeta_{qt}$, $\eta_{qt}$, $X_{qt}$, $\kappa_{qt}$, and $\lambda_{qt}$ are the real parameters indicating the strength of FCNC interactions with the gluon, Higgs, $Z$ and photon, respectively.

In the SM, all the above coefficients vanish at tree-level. The effective Lagrangian considering dimension-six operators for $gt\bar{t}$ and $Zt\bar{t}$ can be parameterized as [9, 13]:

$$
L_{gt\bar{t}} = -g_s \frac{\lambda}{2} \gamma^\mu t G^{a}_{\mu} - g_s \frac{\lambda}{2} \gamma^\mu t G^{a}_{\mu} \left( d_V^Q + i d_A^Q \gamma_5 \right) t G^{a}_{\mu},
$$

(3)

and

$$
L_{Zt\bar{t}} = -\frac{g_W}{2c_W} \bar{t} \gamma^\mu \left( X_{tt}^L P_L + X_{tt}^R P_R - 2 s_W^2 Q_t \right) Z_{\mu} - \frac{g_W}{2c_W} \bar{t} \gamma^\mu \left( d_V^Q + i d_A^Q \gamma_5 \right) t Z_{\mu}.
$$

(4)

The couplings $d_V^{(Z)}$ and $d_A^{(Z)}$ are real parameters indicating the strong (weak) magnetic and strong (weak) electric dipole moments of the top quark, respectively. In the SM, at tree-level, $d_V^{(Z)} = 0.0$ and $d_A^{(Z)} = 0.0$. The values of $X_{tt}^L$ and $X_{tt}^R$ parameters are equal to one and zero in the SM, respectively.

3. Sensitivity of three-top quark production to FCNC couplings

In this section, we examine the sensitivity of the three top-quark production cross section to the FCNC couplings of $tqg$, $tq\gamma$, $tqZ$, and $tqH$. All FCNC couplings of $tqg$, $tq\gamma$, $tqZ$, and $tqH$ ($q = u, c$) are studied independently. We mainly focus on a clean signature with two same-sign leptons, where the lepton could be an electron or a muon. So, the signal events are specified by the presence of two isolated same-sign charged leptons, large missing transverse energy, and several jets from which three come from $b$-quarks. Furthermore, we consider $ttW$, $ttZ$, SM four top, $ttWW$, $ttZZ$ and $WWZ$ as the background processes. The analysis is performed for 300 and 3000 fb$^{-1}$ at the LHC at the center-of-mass energy of 14 TeV. For generation of both the signal and the background processes, the MadGraph5 aMC@NLO package [14] is used. Figure 1 illustrates the lowest-order Feynman diagram for the three top-quark production from $tqg$ FCNC coupling with the leptonic decay of the $W$ boson from top quark and hadronic decay of the $W$ boson from anti-top quark. For separating signal from background events, the following simple criteria are applied, (I) Two same-sign charged lepton with $p_T > 10$ GeV, $|\eta| < 2.5$, (II) Missing Transverse Energy (MET) > 30 GeV (III) At least five-jets with $p_T > 20$ GeV, $|\eta| < 2.5$, $\Delta R(\ell, j) > 0.4$, $\Delta R(j_1, j_2) > 0.4$ (IV) At least three $b$-jets. The $b$-jet multiplicity for the FCNC couplings of $tqg$ and $tqH$ are shown in the left panel of Figure 2.
**Figure 1.** A leading order Feynman diagram of the $tqg$ FCNC contributions to the three top-quark production considering the lepton decay of the $W$ boson from the top quark decay and hadronic decays of the $W$ boson from the anti-top quark.

**Figure 2.** The $b$-jet multiplicity (left) and invariant mass of dilepton (right) for $tqg$ and $tqH$ signal scenarios at leading-order at $\sqrt{s} = 14$ TeV. The sum of all backgrounds is presented as well.

As can be seen, the FCNC signals peak is at three while the backgrounds peak is at two. The invariant mass distribution of dilepton is illustrated on the right side of Figure 2. Since the $tqg$ FCNC interactions are momentum dependent, there is a shift in the $tqg$ signal with respect to the background and the $tqH$ signals. The upper limits on signal rates calculated in terms of the upper bounds on the FCNC branching fractions $B(t \to qX)$ are summarized in Table 1 for two scenarios of integrated luminosities 300 and 3000 fb$^{-1}$ of data. The results from a recent ATLAS experiment analysis based on the $\bar{t}\bar{t}$ process in which one of the top quark decays via FCNC and another one decays in the normal way are also presented for comparison.

As the comparison with the ATLAS limits shows, the three top-quark signal can reach similar sensitivity to ATLAS in the $tqH$ FCNC coupling.
Table 1. The upper limits on the tqX FCNC at 95% confidence level (CL) obtained at the $\sqrt{s} = 14$ TeV based on the integrated luminosities of 300 and 3000 fb$^{-1}$. The HL-LHC results from a recent ATLAS experiment study which uses $t\bar{t}$ process are presented for comparison [15].

| Branching fraction | three-top, 300 fb$^{-1}$ | three-top, 3 ab$^{-1}$ | other-channels, HL-LHC, 3 ab$^{-1}$ |
|--------------------|--------------------------|-----------------------|------------------------------------|
| $B(t \rightarrow uH)$ | $1.03 \times 10^{-3}$   | $3.09 \times 10^{-4}$ | $2.4 \times 10^{-4}$ [15]          |
| $B(t \rightarrow cH)$ | $8.52 \times 10^{-3}$   | $2.54 \times 10^{-3}$ | $2.0 \times 10^{-4}$ [15]          |
| $B(t \rightarrow ug)$ | $4.00 \times 10^{-4}$   | $1.19 \times 10^{-3}$ | -                                  |
| $B(t \rightarrow cg)$ | $4.51 \times 10^{-3}$   | $1.35 \times 10^{-3}$ | -                                  |
| $B(t \rightarrow uZ) - \sigma_{\mu\nu}$ | $2.73 \times 10^{-3}$   | $8.18 \times 10^{-4}$ | $4.3 \times 10^{-5}$ [15]          |
| $B(t \rightarrow cZ) - \sigma_{\mu\nu}$ | $2.67 \times 10^{-2}$   | $7.98 \times 10^{-3}$ | $5.8 \times 10^{-5} [15]$          |
| $B(t \rightarrow uZ) - \gamma_{\mu}$ | $5.73 \times 10^{-3}$   | $1.71 \times 10^{-3}$ | $4.3 \times 10^{-5} [15]$          |
| $B(t \rightarrow cZ) - \gamma_{\mu}$ | $4.52 \times 10^{-2}$   | $1.35 \times 10^{-2}$ | $5.6 \times 10^{-5} [15]$          |
| $B(t \rightarrow u\gamma)$ | $2.18 \times 10^{-2}$   | $6.53 \times 10^{-3}$ | $2.7 \times 10^{-5} [16]$          |
| $B(t \rightarrow c\gamma)$ | $2.14 \times 10^{-1}$   | $6.40 \times 10^{-2}$ | $2.0 \times 10^{-4} [16]$          |

4. Sensitivity of four-top quark production to the top quark weak and strong dipole moments

In the following section, we investigate the sensitivity of four top-quark production in proton-proton collisions at the center-of-mass energy of 13 TeV to the strong ($d^A_{\mu\nu}$) and weak ($d^Z_{\mu\nu}$) top quark electric and magnetic dipole moments. Figure 3 presents leading order Feynman diagrams including the contributions of strong dipole moments. By assuming at most one effective vertex in each diagram, the total four top cross section becomes at most a quadratic function of dipole moments,

$$
\begin{align*}
\sigma(pp \rightarrow t\bar{t}t\bar{t}) \ (fb) &= \sigma_{SM} + 154.82 \times d^0_{\mu\nu} + 3404.44 \times (d^0_{\mu\nu})^2, \\
\sigma(pp \rightarrow t\bar{t}t\bar{t}) \ (fb) &= \sigma_{SM} + 2731.27 \times (d^A_{\mu\nu})^2, \\
\sigma(pp \rightarrow t\bar{t}t\bar{t}) \ (fb) &= \sigma_{SM} - 0.689 \times d^Z_{\mu\nu} + 37.05 \times (d^Z_{\mu\nu})^2, \\
\sigma(pp \rightarrow t\bar{t}t\bar{t}) \ (fb) &= \sigma_{SM} + 27.96 \times (d^Z_{\mu\nu})^2, \\
\end{align*}
$$

where $\sigma_{SM}$ is the SM four top cross section and the linear terms present the interference between the SM and NP and its contribution is at $\Lambda^{-2}$ order. The quadratic terms in the

![Figure 3](image-url)
Table 2. Limits on $d_{g,Z}^A$ and $d_{g,Z}^V$ at 95% CL corresponding to current and future four-top cross section measurements.

| Coupling | Current four-top with 35.6 fb$^{-1}$ | Future four-top-quark with 300 fb$^{-1}$ |
|----------|-----------------------------------|------------------------------------------|
| $d_{g}^V$ | [-0.20, 0.11]                      | [-0.07, 0.03]                             |
| $d_{g}^A$ | [-0.16, 0.16]                      | [-0.05, 0.05]                             |
| $d_{v}^V$ | [-1.42, 1.45]                      | [-0.45, 0.47]                             |
| $d_{v}^A$ | [-1.65, 1.65]                      | [-0.53, 0.53]                             |

cross section correspond to the power of $\Lambda^{-4}$ which are the first contributing terms of the strong and weak dipole moments. To determine the coefficients of cross sections in Eq. 5, the calculations with different values of $d_{A}^{g,Z}$ and $d_{V}^{g,Z}$ are done and fit the obtained cross sections to quadratic polynomials. The upper limits at 95% CL on the strong ($d_{A,V}^{g}$) and weak ($d_{A,V}^{Z}$) dipole moments using the recent CMS experiment measurement [4] are presented in Table 2. The resulting bounds are compatible with the ones obtained from top quark pair cross sections at the Tevatron as well as the LHC.

5. Summary and conclusions
In this paper, we have explored the FCNC couplings via a model-independent way in three-top quark production. Upper limits on the FCNC branching fractions are calculated. We demonstrate that the three-top quark production is more sensitive to the FCNC couplings of $tqH$. Moreover, we investigate the sensitivity of the four-top cross section to the strong and weak top quark dipole moments. Upper limits are set on the top quark dipole moments which are compatible with other bounds extracted from different processes at the LHC.

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