

# Top quark flavor changing neutral currents at Future Linear Colliders

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**Abstract.** We discuss the production and the decay of top quark through flavor-changing neutral current (FCNC) interaction at future linear colliders. We first discuss the theoretical predictions of top quark FCNC decays into  $qH$  and  $qZ$  within a class of  $t$ -channel simplified dark matter models. For the existing bounds on the top quark FCNC interactions at the Large Hadron Collider, we estimate the production rates of top quark through FCNC interactions at future linear colliders for energies from 250 GeV to 3 TeV.

## 1 Introduction

In the Standard Model (SM) of particle physics, the flavor changing neutral current (FCNC) interactions are suppressed as a consequence of the Glashow-Iliopoulos-Maiani (GIM) mechanism [1]. Hence, the rates of *e.g.* top quark FCNC decays are extremely small in the SM [2]. It is found that the branching ratios of top quark FCNC decays into  $qX$  ( $X = \gamma, Z, g, H$ ) range from about  $10^{-17}$  to  $10^{-12}$  making the discovery of this phenomena at the LHC impossible if one assumes the SM. Several extensions of the SM predict quite sizeable rates of top quark FCNC decays [3–34]. The relatively large top quark FCNC rates compared to the SM predictions have motivated the ATLAS and CMS collaborations to carry several searches targeting FCNC phenomena in both the production ( $pp \rightarrow tX$ ) and the decay ( $pp \rightarrow t\bar{t} \rightarrow qX + bW$ ) stages – see for example Refs. [35–38] for the most recent results –. Unfortunately, no signal beyond the SM backgrounds was observed and relatively strong bounds on the different top quark FCNC branching ratios were imposed<sup>1</sup>.

Top quark FCNC phenomena may be connected to the nature of neutrino mass, the mechanism of electroweak symmetry breaking or the dark matter (DM) in the universe. We first consider the possibility that DM generates sizable rates for top quark FCNC decays at the one-loop order. As a benchmark model, we study the case of  $t$ -channel simplified DM model that extends the SM with two  $Z_2$  odd particles: a scalar mediator ( $S$ ) carrying the same quantum numbers as of a right-handed up-type quark and a right-handed fermion ( $\chi$ ). In this setup, the mediator  $S$  is a colored scalar and couples to all the quark generations which therefore implies nonzero contributions to top quark FCNC decays at the one-loop order (see section

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<sup>1</sup>We also note that top quark FCNC phenomena has motivated various theoretical studies for future hadron and lepton colliders (see *e.g.* Refs. [39–45]).

2)<sup>2</sup>. We study in particular the decays  $t \rightarrow qZ$  and  $t \rightarrow qH$  – where  $q = u, c$  – in detail and we found that the corresponding branching ratios are related to each other and independent of the light quark mass.

We also discuss the production cross sections for top quark FCNC phenomena at future linear colliders for center-of-mass energies from 250 GeV to 3 TeV. The analysis is done in a model-independent way and using values of the couplings that are allowed by the current bounds. We study processes where top quark FCNC phenomena is involved in the production stage ( $e^+e^- \rightarrow q\bar{t} + \text{h.c.}$ ) and in the decay stage ( $e^+e^- \rightarrow t\bar{t} \rightarrow qXbW$  where  $X = \gamma, Z, g, H$ ).

The remainder of this article is as follows. In section 2 we analyse the top quark FCNC decays generated by the loops of DM sector particles. We discuss the production rates for processes involving top quark FCNC interactions at future linear colliders in section 3. We draw our conclusions in section 4.

## 2 Top quark FCNC decays triggered by dark matter

We consider a  $t$ -channel simplified model which extends the SM with a colored scalar mediator ( $S$ ) and a right-handed fermion ( $\chi$ ) both are odd under an ad-hoc  $Z_2$  symmetry [34]. Under  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ , the new particles transform as

$$S : (\mathbf{3}, \mathbf{1})_{+2/3}, \quad \chi : (\mathbf{1}, \mathbf{1})_0. \quad (1)$$

In this framework, the DM particle interacts primarily with right-handed up-type quarks through a Yukawa-type interaction. Under these symmetry requirements, the most general Lagrangian is given by

$$\mathcal{L} \supset \mathcal{L}_S + \mathcal{L}_\chi - V(S, \Phi), \quad (2)$$

with  $\mathcal{L}_S$ ,  $\mathcal{L}_\chi$  and  $V(S, \Phi)$  being the kinetic Lagrangian of the mediator, the Yukawa-type Lagrangian of the DM particle and the scalar potential respectively. They are given by

$$\mathcal{L}_S + \mathcal{L}_\chi \equiv i\bar{\chi}\not{\partial}\chi^c + \frac{1}{2}M_\chi\bar{\chi}\chi^c + \sum_{q=u,c,t} \left( Y_q\bar{q}_R^c\chi S + \text{h.c.} \right) + (\mathcal{D}_\mu S)^\dagger (\mathcal{D}^\mu S). \quad (3)$$

Here, the first and the second terms refer to the kinetic and mass terms of the right-handed fermion, the third term to the Yukawa-type interaction of the dark-sector particles to the right-handed up-type quarks and the fourth term to the kinetic term of  $S$  where  $\mathcal{D}_\mu$  being the covariant derivative defined as:

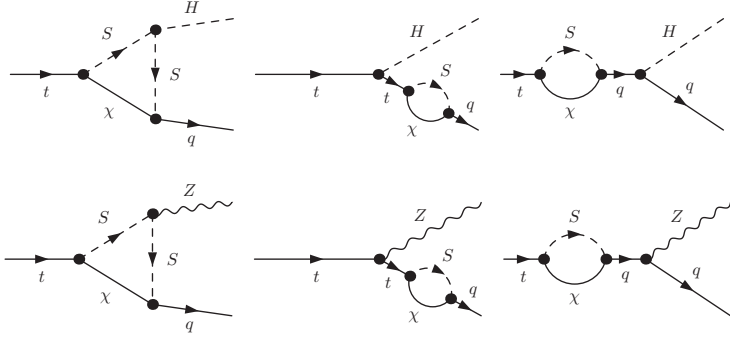
$$\mathcal{D}_\mu = \partial_\mu - ig_s T^a G_\mu^a - \frac{g_1}{2} Y_S B_\mu, \quad (4)$$

where  $Y_S$  being the hypercharge of  $S$  and  $g_1$ ,  $g_s$  are the coupling constants of  $U(1)_Y$  and  $SU(3)_c$  gauge groups respectively. The most general,  $CP$  conserving, renormalizable and gauge-invariant scalar potential is given by

$$V(S, \Phi) = -m_{11}^2 |\Phi|^2 + m_{22}^2 |S|^2 + \lambda_1 |\Phi|^4 + \lambda_2 |S|^4 + \lambda_3 |S|^2 |\Phi|^2, \quad (5)$$

with  $\Phi$  being the SM Higgs doublet. Note that  $\lambda_2$  does not affect the phenomenology of the model and therefore will be set to one without loss of generality.

<sup>2</sup>The phenomenology of this class of models has been extensively studied in the literature (see e.g. Refs. [46–50]). In these studies, it was assumed that each generation of quarks couple to one mediator only in order to avoid the flavor constraints.



**Figure 1.** Examples of Feynman diagrams for the  $t \rightarrow qH$  and  $t \rightarrow qZ$  decays at the one-loop order.

We consider the two-body decays of the top quark into  $qZ$  and  $qH$  ( $q = u, c$ ). Examples of Feynman diagrams at the one-loop order are shown in Fig. 1. The effective operator for these top quark FCNC decays can be generically parameterised as

$$\begin{aligned}
 -\mathcal{L}_{\text{eff}} &= \bar{t}\gamma^\mu(f_{iqZ}^L P_L + f_{iqZ}^R P_R)qZ_\mu + \bar{t}p^\mu(g_{iqZ}^L P_L + g_{iqZ}^R P_R)qZ_\mu \\
 &+ \bar{t}(f_{iqH}^L P_L + f_{iqH}^R P_R)qH + \text{h.c.},
 \end{aligned} \tag{6}$$

with  $f_{iqX}^{L,R}$  ( $X = Z, H$ ) and  $g_{iqZ}^{L,R}$  being the form factors,  $P_{L,R} = (1 \mp \gamma_5)/2$  are the projection operators and  $p^\mu$  is the 4-momentum of the top quark. In the limit of vanishing light quark masses, we have

$$\begin{aligned}
 f_{iqH}^L &\approx \frac{3Y_q Y_t m_t}{16\pi^2} \lambda_3 v C_1, & f_{iqH}^R &\approx 0, \\
 f_{iqZ}^L &\approx 0, & f_{iqZ}^R &\approx -\frac{g_1 s_W Y_q Y_t}{24\pi^2} (2C_{00} + B_{1,t}), \\
 g_{iqZ}^L &\approx \frac{g_1 s_W Y_q Y_t m_t}{12\pi^2} (C_1 + C_{11} + C_{12}), & g_{iqZ}^R &\approx 0,
 \end{aligned} \tag{7}$$

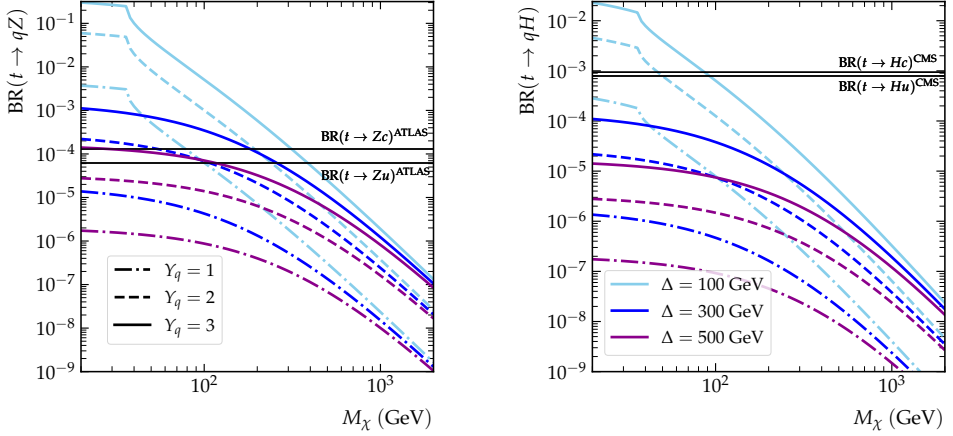
where  $B_{1,t} \equiv B_1(m_t^2, M_\chi^2, M_S^2)$  and  $C_{i,j} \equiv C_{i,j}(m_t^2, M_\chi^2, m_q^2, M_\chi^2, M_S^2, M_S^2)$  refer to the 2- and 3-point scalar Passarino-Veltman functions. The expressions of the form factor have been obtained using FEYNARTS version 3.11 [51] and FORMCALC version 9.9 [52]. We furthermore use LOOPTOOLS version 2.16 for their numerical evaluation [53]. The resulting branching ratios are given by

$$\text{BR}(t \rightarrow qX) = \frac{\Gamma(t \rightarrow qX)}{\Gamma_t}, \tag{8}$$

with  $\Gamma_t \equiv \Gamma(t \rightarrow bW) = 1.32 \text{ GeV}$  being the total width calculated at Next-to-next-to-LO in QCD [54] and  $\Gamma(t \rightarrow qX)$  is the corresponding top FCNC partial width [34]. Note that our model predicts the following relations

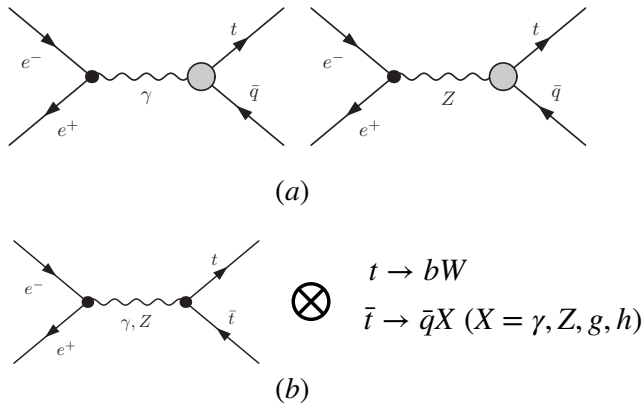
$$\frac{\Gamma(t \rightarrow cX)}{\Gamma(t \rightarrow uX)} \approx \left(\frac{Y_c}{Y_u}\right)^2, \quad \frac{\Gamma(t \rightarrow qZ)}{\Gamma(t \rightarrow qH)} \approx \frac{O(10)}{\lambda_3^2}. \tag{9}$$

In Fig. 2, we show the branching ratios of  $t \rightarrow qZ$  (left) and of  $t \rightarrow qH$  (right) as a function of  $M_\chi$  for different values of the mass splitting  $\Delta$  and of the Yukawa-type coupling



**Figure 2.** The FCNC decay branching ratios as function of  $M_\chi$  for  $t \rightarrow qZ$  (left) and  $t \rightarrow qH$  (right). The results are shown for  $Y_q = 1, 2$  and  $3$  and  $\Delta \equiv M_S - M_\chi = 100, 300$  and  $500$  GeV. Here, we assume that  $Y_q \equiv Y_u = Y_c = Y_t$  and  $\lambda_3 = 1$ . We also show in the same panels the latest exclusion bounds from the searches of FCNC phenomena reported on by the ATLAS [37] and the CMS [35] collaborations.

$Y_u = Y_c = Y_t$ . We can see that, since these two branching ratios scale as  $|Y_q Y_t|^2$ , higher values of  $Y_q = Y_t$  will lead to extremely large branching ratios especially for small  $M_\chi$  and small  $\Delta$  (giving the  $1/M^3$  dependence). Light DM masses of order  $\approx 100$  GeV are still allowed if one considers  $Y_q \approx 1$  and relatively large  $\Delta$ . Finally, the branching ratios do not depend on  $\Delta$  for heavy DM ( $> 1000$  GeV or so). Note that for phenomenologically viable benchmark scenarios (see Ref. [34]) the maximum allowed values of the top FCNC branching ratios are of order  $10^{-6}$ – $10^{-9}$ .



**Figure 3.** Examples of Feynman diagrams for the top quark FCNC phenomena in  $e^+e^-$  collisions. Here we show the FCNC processes at the production stage (upper panels) and at the decay state (lower panels).

### 3 Top quark FCNC at future linear colliders

We now turn into a brief discussion of the top quark FCNC rates at future linear colliders. The model described in section 2 can be probed at lepton colliders in two ways. First, the presence of the new particles lead to sizable top FCNC rates which can be probed in both single and pair production of top quarks. Second, both the DM particle and the scalar mediator can be pair produced through  $SSZ, SS\gamma$  or  $SS\gamma\gamma, SSZ\gamma, SSZZ$  vertices – which can be obtained from the covariant derivative defined in equation 4 –. The  $S$  particle being produced may decay into  $t\chi, u\chi$  and  $c\chi$  leading to unique FCNC plus MET signatures. However, we do not expect that these particles to be tested at center-of-mass energies smaller than 1 TeV or so. A detailed analysis of these channels can be done in a future work. For the production of top quarks through FCNC phenomena, we categorise the relevant processes into

- FCNC phenomena in the production stage in which case the top FCNC interaction vertices are involved at the production level.
- FCNC phenomena in the decay stage in which case top quark pairs are produced through electroweak interactions and then one (anti)top decays into  $bW$  and the other (anti)top decays into  $qX$  ( $X = \gamma, Z, H, g$ ).

Examples of Feynman diagrams are shown in Fig. 3. To estimate the production rates, we consider the most generic dimension five Lagrangian which is based on slightly modified implementation of Refs. [55, 56]<sup>3</sup>

$$\begin{aligned}
 \mathcal{L} = & \frac{g_s}{\Lambda} \bar{q} \lambda^a \sigma^{\mu\nu} \left( \zeta_{qt}^L P_L + \zeta_{qt}^R P_R \right) t G_{\mu\nu}^a - \frac{1}{\sqrt{2}} \bar{q} \left( \eta_{qt}^L P_L + \eta_{qt}^R P_R \right) \\
 & - \frac{g_W}{2c_W} \bar{q} \gamma^\mu \left( X_{qt}^L P_L + X_{qt}^R P_R \right) t Z_\mu + \frac{g_W}{2c_W \Lambda} \bar{q} \sigma^{\mu\nu} \left( K_{qt}^L P_L + K_{qt}^R P_R \right) t Z_{\mu\nu} \\
 & + \frac{e}{\Lambda} \bar{q} \sigma^{\mu\nu} \left( \lambda_{qt}^L P_L + \lambda_{qt}^R P_R \right) t A_{\mu\nu},
 \end{aligned} \tag{10}$$

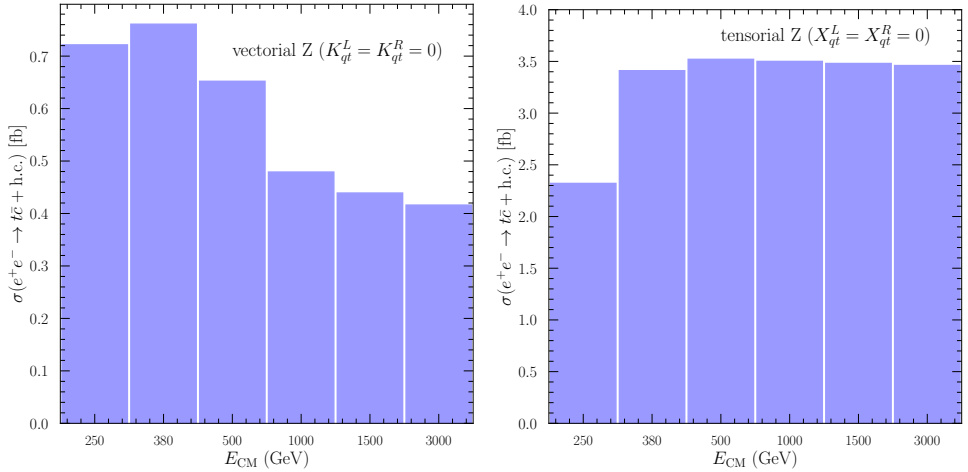
where  $\Lambda$  is a new physics scale which we will set equal to 1 TeV. The current bounds on the top quark FCNC branching ratios from LHC searches can be translated into bounds on the effective couplings that appear in eq. 11. For the  $tqZ$  coupling, the situation is a bit tricky as there are four independent form factors. In what follows we consider two scenarios: (i) the  $tqZ$  vertex is purely vectorial ( $K_{qt}^L = K_{qt}^R = 0$ ) and (ii) the  $tqZ$  vertex is purely tensorial ( $X_{qt}^L = X_{qt}^R = 0$ ). For the case of top quark FCNC phenomena that occur in the decay stage, the total rate can be generically defined as

$$\begin{aligned}
 \sigma & \equiv 2 \times \sigma(e^+ e^- \rightarrow t\bar{t}) \times \text{BR}(t \rightarrow bW) \times \text{BR}(t \rightarrow qX), \\
 & \approx 2 \times \sigma(e^+ e^- \rightarrow t\bar{t}) \times \text{BR}(t \rightarrow qX),
 \end{aligned} \tag{11}$$

since  $\text{BR}(t \rightarrow bW) \approx 100\%$ .

In Fig. 4, we show the cross section for the production of a top (anti)quark in association with a charm (anti)quark for six center-of-mass energies  $E_{\text{CM}} = 250, 380, 500, 1000, 1500, 3000$  GeV which correspond to the expected runs for the International Linear Collider (ILC) and the Compact Linear Collider (CLIC). The production cross sections are estimated for the maximum allowed values of the effective couplings from the LHC searches and assuming a pure vectorial ( $K_{qt}^L = K_{qt}^R = 0$ ) and tensorial ( $X_{qt}^L = X_{qt}^R$ ) couplings. We can see that for the case of a pure vectorial  $tqZ$  vertex, the cross section reaches a maximum of 0.76 fb for  $E_{\text{CM}} = 380$  GeV. The  $1/s$  behavior of the  $tqZ$  contribution is not

<sup>3</sup>Other possible parameterisation can be found in Ref. [58].



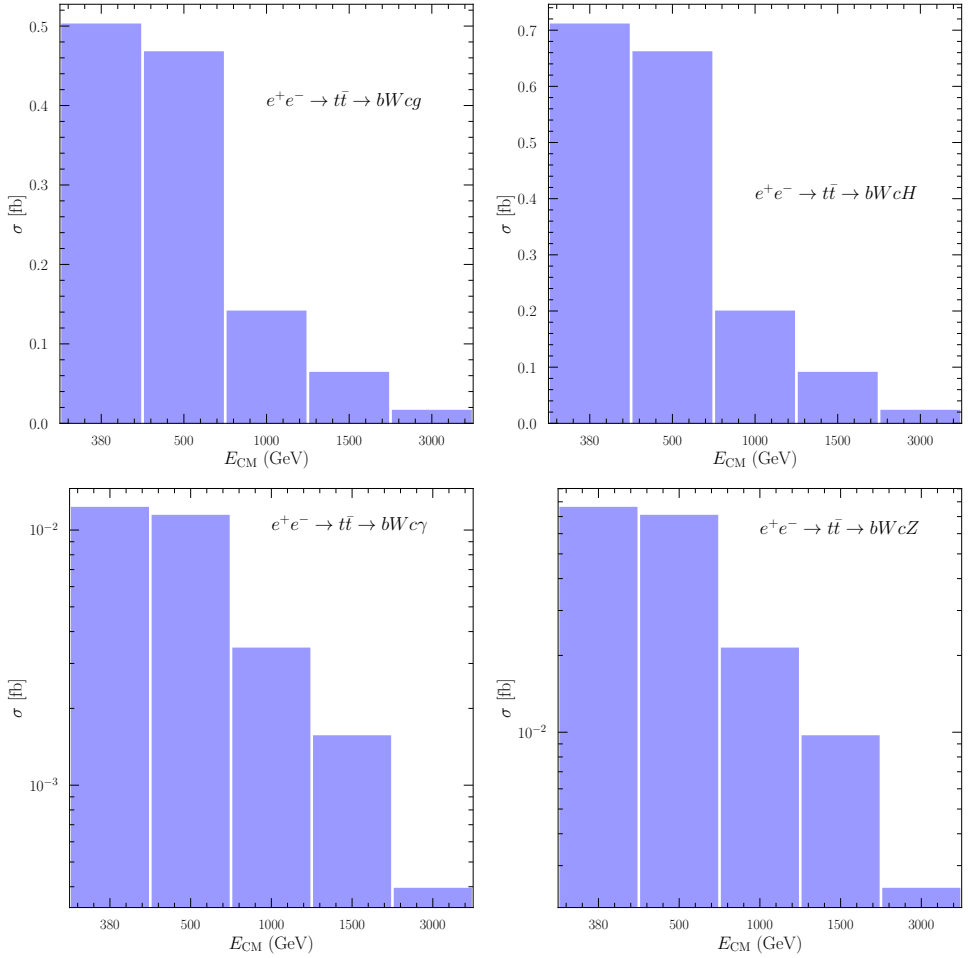
**Figure 4.** The total cross section for the production of a top (anti)quark in association with a charm quark in  $e^+e^-$  as a function of the center-of-mass energy. Here we show the results in the case where the  $tqZ$  coupling is purely vectorial (left) and is purely tensorial (right). All the calculations have been done at the lowest order in perturbation theory.

really dominant as the  $tq\gamma$  contribution scales as  $s$  due to the fact that the corresponding interaction is of a derivative nature. The case of a pure tensorial  $tqZ$  vertex is more interesting as it leads to a cross section of order 3.5 fb for  $E_{CM} = 500$  GeV and it slowly decreases with the center-of-mass energy. Note that with these numbers, we expect about 1400-7000 FCNC events at Linear Colliders. With a small expected backgrounds and a clean environment, analyses of these phenomena at Linear Colliders can lead to impressive bounds. Note shown here, the cross section for the production of a top (anti)quark in association with an up (anti)quark is about a factor of two smaller since the LHC bounds on the corresponding  $tqZ/tq\gamma$  are more stringent.

The total rates for the production of  $t\bar{t}$  where one top quark decays into  $bW$  and the other one decays into  $cX$  are shown in Fig. 5 for five representative center-of-mass energies starting from the  $t\bar{t}$  threshold. Note that for this case, the production cross sections reach the maximum near the  $t\bar{t}$  threshold with values of 0.5 fb and 0.7 fb for the  $cg$  and  $cH$  channels respectively. The cross sections for the  $c\gamma$  and  $cZ$  channels are about one order of magnitude smaller. With these numbers, we can get about  $O(1000)$  events at  $E_{CM} = 380$  GeV. The cross sections for the  $uX$  channels are about a factor of two smaller.

## 4 Conclusions

In this work, we have discussed the top quark FCNC phenomena at future linear colliders. We first discussed a *novel* mechanism where the top quark FCNC decays are generated by the loops of dark sector particles. Within a simplified DM model which consists of two extra dark particles that are odd under an ad-hoc  $Z_2$  symmetry: a colored scalar mediator carrying the same quantum numbers as a right-handed up-type quark and a right-handed fermion. The latter plays the role of the DM candidate. We have found that for phenomenologically viable scenarios, the model leads to sizeable rates for top quark FCNC decays into  $qZ$  and  $qH$ . We then discussed the top quark FCNC phenomena in both the production ( $t\bar{q} + \text{h.c.}$ )



**Figure 5.** The total cross section for the production of  $t\bar{t}$  followed by the decay into  $bWcX$  as a function of the center-of-mass energy. We show the results for  $cg$  (top left),  $cH$  (top right),  $c\gamma$  (bottom left) and  $cZ$  (bottom right). All the calculations have been done at the lowest order in perturbation theory.

and in the decay ( $t\bar{t} \rightarrow qXbW$ ) stages for the most generic dimension five FCNC interaction Lagrangian at future linear colliders. We found that for some processes, the production rates can be important which are about  $O(1)$  fb. Combining the relatively large production cross sections with the clean environment, the discovery prospects of top quark FCNC phenomena are promising but require more work in the future.

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## References

- [1] S. L. Glashow, J. Iliopoulos and L. Maiani, “Weak Interactions with Lepton-Hadron Symmetry,” *Phys. Rev. D* **2** (1970), 1285-1292 doi:10.1103/PhysRevD.2.1285
- [2] G. Eilam, J. L. Hewett and A. Soni, “Rare decays of the top quark in the standard and two Higgs doublet models,” *Phys. Rev. D* **44** (1991), 1473-1484 [erratum: *Phys. Rev. D* **59** (1999), 039901] doi:10.1103/PhysRevD.44.1473
- [3] W. S. Hou, “Tree level  $t \rightarrow c h$  or  $h \rightarrow t$  anti- $c$  decays,” *Phys. Lett. B* **296** (1992), 179-184 doi:10.1016/0370-2693(92)90823-M
- [4] D. Atwood, L. Reina and A. Soni, “Phenomenology of two Higgs doublet models with flavor changing neutral currents,” *Phys. Rev. D* **55** (1997), 3156-3176 doi:10.1103/PhysRevD.55.3156 [arXiv:hep-ph/9609279 [hep-ph]].
- [5] J. L. Lopez, D. V. Nanopoulos and R. Rangarajan, “New supersymmetric contributions to  $t \rightarrow c V$ ,” *Phys. Rev. D* **56** (1997), 3100-3106 doi:10.1103/PhysRevD.56.3100 [arXiv:hep-ph/9702350 [hep-ph]].
- [6] J. M. Yang, B. L. Young and X. Zhang, “Flavor changing top quark decays in r parity violating SUSY,” *Phys. Rev. D* **58** (1998), 055001 doi:10.1103/PhysRevD.58.055001 [arXiv:hep-ph/9705341 [hep-ph]].
- [7] G. Eilam, A. Gemintern, T. Han, J. M. Yang and X. Zhang, “Top quark rare decay  $t \rightarrow ch$  in R-parity violating SUSY,” *Phys. Lett. B* **510** (2001), 227-235 doi:10.1016/S0370-2693(01)00598-6 [arXiv:hep-ph/0102037 [hep-ph]].
- [8] J. A. Aguilar-Saavedra, “Top flavor-changing neutral interactions: Theoretical expectations and experimental detection,” *Acta Phys. Polon. B* **35** (2004), 2695-2710 [arXiv:hep-ph/0409342 [hep-ph]].
- [9] R. Gaitan, O. G. Miranda and L. G. Cabral-Rosetti, “Rare top and Higgs decays in alternative left-right symmetric models,” *Phys. Rev. D* **72** (2005), 034018 doi:10.1103/PhysRevD.72.034018 [arXiv:hep-ph/0410268 [hep-ph]].
- [10] M. Frank and I. Turan, “ $t \rightarrow cg, cy, cZ$  in the left-right supersymmetric model,” *Phys. Rev. D* **72** (2005), 035008 doi:10.1103/PhysRevD.72.035008 [arXiv:hep-ph/0506197 [hep-ph]].
- [11] A. Arhrib, *Phys. Rev. D* **72** (2005), 075016 doi:10.1103/PhysRevD.72.075016 [arXiv:hep-ph/0510107 [hep-ph]].
- [12] S. Bejar, “Flavor changing neutral decay effects in models with two Higgs boson doublets: Applications to LHC Physics,” [arXiv:hep-ph/0606138 [hep-ph]].
- [13] K. Agashe, G. Perez and A. Soni, “Collider Signals of Top Quark Flavor Violation from a Warped Extra Dimension,” *Phys. Rev. D* **75** (2007), 015002 doi:10.1103/PhysRevD.75.015002 [arXiv:hep-ph/0606293 [hep-ph]].
- [14] J. J. Cao, G. Eilam, M. Frank, K. Hikasa, G. L. Liu, I. Turan and J. M. Yang, “SUSY-induced FCNC top-quark processes at the large hadron collider,” *Phys. Rev. D* **75** (2007), 075021 doi:10.1103/PhysRevD.75.075021 [arXiv:hep-ph/0702264 [hep-ph]].
- [15] I. Baum, G. Eilam and S. Bar-Shalom, “Scalar flavor changing neutral currents and rare top quark decays in a two Higgs doublet model for the top quark,” *Phys. Rev. D* **77** (2008), 113008 doi:10.1103/PhysRevD.77.113008 [arXiv:0802.2622 [hep-ph]].
- [16] X. F. Han, L. Wang and J. M. Yang, “Top quark FCNC decays and productions at LHC in littlest Higgs model with T-parity,” *Phys. Rev. D* **80** (2009), 015018 doi:10.1103/PhysRevD.80.015018 [arXiv:0903.5491 [hep-ph]].
- [17] K. Agashe and R. Contino, “Composite Higgs-Mediated FCNC,” *Phys. Rev. D* **80** (2009), 075016 doi:10.1103/PhysRevD.80.075016 [arXiv:0906.1542 [hep-ph]].



- [18] T. J. Gao, T. F. Feng and J. B. Chen, “ $t \rightarrow c\gamma$  and  $t \rightarrow cg$  in warped extra dimensions,” JHEP **02** (2013), 029 doi:10.1007/JHEP02(2013)029 [arXiv:1303.0082 [hep-ph]].
- [19] J. Cao, C. Han, L. Wu, J. M. Yang and M. Zhang, Eur. Phys. J. C **74** (2014) no.9, 3058 doi:10.1140/epjc/s10052-014-3058-1 [arXiv:1404.1241 [hep-ph]].
- [20] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho and K. Tamvakis, “Rare Top-quark Decays to Higgs boson in MSSM,” JHEP **11** (2014), 137 doi:10.1007/JHEP11(2014)137 [arXiv:1409.6546 [hep-ph]].
- [21] G. Abbas, A. Celis, X. Q. Li, J. Lu and A. Pich, “Flavour-changing top decays in the aligned two-Higgs-doublet model,” JHEP **06** (2015), 005 doi:10.1007/JHEP06(2015)005 [arXiv:1503.06423 [hep-ph]].
- [22] F. J. Botella, G. C. Branco, M. Nebot and M. N. Rebelo, “Flavour Changing Higgs Couplings in a Class of Two Higgs Doublet Models,” Eur. Phys. J. C **76** (2016) no.3, 161 doi:10.1140/epjc/s10052-016-3993-0 [arXiv:1508.05101 [hep-ph]].
- [23] U. K. Dey and T. Jha, “Rare top decays in minimal and nonminimal universal extra dimension models,” Phys. Rev. D **94** (2016) no.5, 056011 doi:10.1103/PhysRevD.94.056011 [arXiv:1602.03286 [hep-ph]].
- [24] A. Diaz-Furlong, M. Frank, N. Pourtolami, M. Toharia and R. Xoxocotzi, “Flavor-changing decays of the top quark in 5D warped models,” Phys. Rev. D **94** (2016) no.3, 036001 doi:10.1103/PhysRevD.94.036001 [arXiv:1603.08929 [hep-ph]].
- [25] P. Q. Hung, Y. X. Lin, C. S. Nugroho and T. C. Yuan, “Top Quark Rare Decays via Loop-Induced FCNC Interactions in Extended Mirror Fermion Model,” Nucl. Phys. B **927** (2018), 166-183 doi:10.1016/j.nuclphysb.2017.12.014 [arXiv:1709.01690 [hep-ph]].
- [26] S. Banerjee, M. Chala and M. Spannowsky, “Top quark FCNCs in extended Higgs sectors,” Eur. Phys. J. C **78** (2018) no.8, 683 doi:10.1140/epjc/s10052-018-6150-0 [arXiv:1806.02836 [hep-ph]].
- [27] T. J. Kim, P. Ko, J. Li, J. Park and P. Wu, “Correlation between  $R_{D^{(*)}}$  and top quark FCNC decays in leptoquark models,” JHEP **07** (2019), 025 doi:10.1007/JHEP07(2019)025 [arXiv:1812.08484 [hep-ph]].
- [28] A. Bolaños, R. Sánchez-Vélez and G. Tavares-Velasco, “Flavor changing neutral current decays  $t \rightarrow cX$  ( $X = \gamma, g, Z, H$ ) and  $t \rightarrow c\bar{\ell}\ell$  ( $\ell = \mu, \tau$ ) via scalar leptoquarks,” Eur. Phys. J. C **79** (2019) no.8, 700 doi:10.1140/epjc/s10052-019-7211-8 [arXiv:1907.05877 [hep-ph]].
- [29] Y. Liu, B. Yan and R. Zhang, “Loop induced top quark FCNC through top quark and dark matter interactions,” Phys. Lett. B **827** (2022), 136964 doi:10.1016/j.physletb.2022.136964 [arXiv:2103.07859 [hep-ph]].
- [30] C. H. Chen and T. Nomura, “Scotogenic top-quark FCNC decays,” Phys. Rev. D **106** (2022) no.9, 095005 doi:10.1103/PhysRevD.106.095005 [arXiv:2204.01214 [hep-ph]].
- [31] A. Crivellin, M. Kirk, T. Kitahara and F. Mescia, “Large  $t \rightarrow cZ$  as a sign of vectorlike quarks in light of the W mass,” Phys. Rev. D **106** (2022) no.3, L031704 doi:10.1103/PhysRevD.106.L031704 [arXiv:2204.05962 [hep-ph]].
- [32] C. H. Chen, C. W. Chiang and C. W. Su, “Top-quark FCNC decays, LFVs, lepton  $g - 2$ , and W mass anomaly with inert charged Higgses,” J. Phys. G **51** (2024) no.8, 085001 doi:10.1088/1361-6471/ad560e [arXiv:2301.07070 [hep-ph]].
- [33] M. Frank, B. Fuks, S. K. Garg and P. Poulou, “Flavour-changing top quark decays in the alternative left-right model,” Phys. Lett. B **850** (2024), 138548 doi:10.1016/j.physletb.2024.138548 [arXiv:2312.12523 [hep-ph]].
- [34] A. Jueid and S. Kanemura, “Dark matter as the trigger of flavor changing neutral current decays of the top quark,” [arXiv:2402.08652 [hep-ph]].

- [35] A. Tumasyan *et al.* [CMS], “Search for flavor-changing neutral current interactions of the top quark and the Higgs boson decaying to a bottom quark-antiquark pair at  $\sqrt{s} = 13$  TeV,” JHEP **02** (2022), 169 doi:10.1007/JHEP02(2022)169 [arXiv:2112.09734 [hep-ex]].
- [36] G. Aad *et al.* [ATLAS], “Search for flavour-changing neutral-current couplings between the top quark and the photon with the ATLAS detector at  $s=13$  TeV,” Phys. Lett. B **842** (2023), 137379 [erratum: Phys. Lett. B **847** (2024), 138286] doi:10.1016/j.physletb.2022.137379 [arXiv:2205.02537 [hep-ex]].
- [37] G. Aad *et al.* [ATLAS], “Search for flavor-changing neutral-current couplings between the top quark and the Z boson with proton-proton collisions at  $s=13$  TeV with the ATLAS detector,” Phys. Rev. D **108** (2023) no.3, 032019 doi:10.1103/PhysRevD.108.032019 [arXiv:2301.11605 [hep-ex]].
- [38] G. Aad *et al.* [ATLAS], “Search for flavour-changing neutral tqH interactions with  $H \rightarrow \gamma\gamma$  in pp collisions at  $\sqrt{s} = 13$  TeV using the ATLAS detector,” JHEP **12** (2023), 195 doi:10.1007/JHEP12(2023)195 [arXiv:2309.12817 [hep-ex]].
- [39] J. j. Cao, G. l. Liu and J. M. Yang, Eur. Phys. J. C **41** (2005), 381-391 doi:10.1140/epjc/s2005-02222-1 [arXiv:hep-ph/0311166 [hep-ph]].
- [40] J. j. Cao, G. l. Liu, J. M. Yang and H. j. Zhang, Phys. Rev. D **76** (2007), 014004 doi:10.1103/PhysRevD.76.014004 [arXiv:hep-ph/0703308 [hep-ph]].
- [41] S. Khatibi and M. Moallemi, “Probing FCNC couplings in single top-quark production associated with a neutral gauge boson in future lepton colliders,” J. Phys. G **48** (2021) no.12, 125004 doi:10.1088/1361-6471/ac09dd [arXiv:2106.08231 [hep-ph]].
- [42] W. Liu and H. Sun, “Top FCNC interactions through dimension six four-fermion operators at the electron proton collider,” Phys. Rev. D **100** (2019) no.1, 015011 doi:10.1103/PhysRevD.100.015011 [arXiv:1906.04884 [hep-ph]].
- [43] S. Bhattacharya, S. Jahedi, S. Nandi and A. Sarkar, “Probing flavor constrained SMEFT operators through  $tc$  production at the muon collider,” JHEP **07** (2024), 061 doi:10.1007/JHEP07(2024)061 [arXiv:2312.14872 [hep-ph]].
- [44] Y. B. Liu and S. Moretti, “Probing the top-Higgs boson FCNC couplings via the  $h \rightarrow \gamma\gamma$  channel at the HE-LHC and FCC-hh,” Phys. Rev. D **101** (2020) no.7, 075029 doi:10.1103/PhysRevD.101.075029 [arXiv:2002.05311 [hep-ph]].
- [45] K. Y. Oyulmaz, A. Senol, H. Denizli and O. Cakir, “Top quark anomalous FCNC production via  $tqg$  couplings at FCC-hh,” Phys. Rev. D **99** (2019) no.11, 115023 doi:10.1103/PhysRevD.99.115023 [arXiv:1902.03037 [hep-ph]].
- [46] C. Arina, B. Fuks, J. Heisig, M. Krämer, L. Mantani and L. Panizzi, “Comprehensive exploration of  $t$ -channel simplified models of dark matter,” Phys. Rev. D **108** (2023) no.11, 115007 doi:10.1103/PhysRevD.108.115007 [arXiv:2307.10367 [hep-ph]].
- [47] M. Becker, E. Copello, J. Harz, K. A. Mohan and D. Sengupta, “Impact of Sommerfeld effect and bound state formation in simplified  $t$ -channel dark matter models,” JHEP **08** (2022), 145 doi:10.1007/JHEP08(2022)145 [arXiv:2203.04326 [hep-ph]].
- [48] C. Arina, B. Fuks, L. Mantani, H. Mies, L. Panizzi and J. Salko, “Closing in on  $t$ -channel simplified dark matter models,” Phys. Lett. B **813** (2021), 136038 doi:10.1016/j.physletb.2020.136038 [arXiv:2010.07559 [hep-ph]].
- [49] C. Arina, B. Fuks and L. Mantani, “A universal framework for  $t$ -channel dark matter models,” Eur. Phys. J. C **80** (2020) no.5, 409 doi:10.1140/epjc/s10052-020-7933-7 [arXiv:2001.05024 [hep-ph]].
- [50] K. A. Mohan, D. Sengupta, T. M. P. Tait, B. Yan and C. P. Yuan, “Direct detection and LHC constraints on a  $t$ -channel simplified model of Majorana dark matter at one loop,” JHEP **05** (2019), 115 [erratum: JHEP **05** (2023), 232] doi:10.1007/JHEP05(2019)115

- [arXiv:1903.05650 [hep-ph]].
- [51] T. Hahn, “Generating Feynman diagrams and amplitudes with FeynArts 3,” *Comput. Phys. Commun.* **140** (2001), 418-431 doi:10.1016/S0010-4655(01)00290-9 [arXiv:hep-ph/0012260 [hep-ph]].
- [52] T. Hahn, “A Mathematica interface for FormCalc-generated code,” *Comput. Phys. Commun.* **178** (2008), 217-221 doi:10.1016/j.cpc.2007.09.004 [arXiv:hep-ph/0611273 [hep-ph]].
- [53] T. Hahn, “Loop calculations with FeynArts, FormCalc, and LoopTools,” *Acta Phys. Polon. B* **30** (1999), 3469-3475 [arXiv:hep-ph/9910227 [hep-ph]].
- [54] J. Gao, C. S. Li and H. X. Zhu, “Top Quark Decay at Next-to-Next-to Leading Order in QCD,” *Phys. Rev. Lett.* **110** (2013) no.4, 042001 doi:10.1103/PhysRevLett.110.042001 [arXiv:1210.2808 [hep-ph]].
- [55] J. A. Aguilar-Saavedra, “A Minimal set of top anomalous couplings,” *Nucl. Phys. B* **812** (2009), 181-204 doi:10.1016/j.nuclphysb.2008.12.012 [arXiv:0811.3842 [hep-ph]].
- [56] J. A. Aguilar-Saavedra, “A Minimal set of top-Higgs anomalous couplings,” *Nucl. Phys. B* **821** (2009), 215-227 doi:10.1016/j.nuclphysb.2009.06.022 [arXiv:0904.2387 [hep-ph]].
- [57] T. Han, M. Hosch, K. Whisnant, B. L. Young and X. Zhang, “Single top quark production via FCNC couplings at hadron colliders,” *Phys. Rev. D* **58** (1998), 073008 doi:10.1103/PhysRevD.58.073008 [arXiv:hep-ph/9806486 [hep-ph]].
- [58] G. Durieux, F. Maltoni and C. Zhang, “Global approach to top-quark flavor-changing interactions,” *Phys. Rev. D* **91** (2015) no.7, 074017 doi:10.1103/PhysRevD.91.074017 [arXiv:1412.7166 [hep-ph]].