

Dark matter as the trigger of flavor changing neutral current decays of the top quark

Adil Jueid^a and Shinya Kanemura^b

^a*Particle Theory and Cosmology Group, Center for Theoretical Physics of the Universe,
Institute for Basic Science (IBS),
Daejeon, 34126, Republic of Korea*

^b*Department of Physics, Osaka University,
Toyonaka, Osaka 560-0043, Japan*

E-mail: adiljueid@ibs.re.kr, kanemu@het.phys.sci.osaka-u.ac.jp

ABSTRACT: We suggest a simplified model that simultaneously addresses the dark-matter problem and give rise to top quark flavor changing neutral current (FCNC) interactions at the one-loop order. The model consists of two extra $SU(2)_L$ gauge singlets: a colored mediator of spin zero (S) and a right-handed fermion (χ) both are odd under an ad-hoc Z_2 symmetry. The right-handed fermion plays the role of the dark-matter candidate. In this model, the presence of the two dark sector particles generates one-loop induced FCNC decays of the top quark into light quarks and bosons such as the gluon, the photon, the Z -boson or the Higgs boson. As a case study, we analyze the top quark FCNC decays into light quarks (u or c) and a Z or Higgs bosons. We then study the reliable solutions to the dark-matter problem by estimating the regions in the parameter space that are consistent with the PLANCK measurement of the dark-matter relic density. We also revisit the bounds from the searches of dark matter in events with at least one high- p_T jet and large missing transverse energy at the Large Hadron Collider (LHC). We then define four benchmark points that are consistent with the existing constraints from collider experiments and cosmology. We finally estimate, for these benchmark scenarios, the rates of a broad range of channels that can be used to probe the connection between the top FCNC transitions and dark matter both at the HL-LHC and a future 100 TeV collider.

KEYWORDS: Dark Matter, Top quark FCNC, Large Hadron Collider.

Contents

1	Introduction	1
2	Theoretical framework	3
3	Top quark FCNC decays	5
4	Dark Matter	8
5	Bounds from the LHC searches	9
6	Benchmark scenarios for future collider analyses	12
7	Conclusions	15
A	Impact on Higgs boson couplings	16
B	Contribution to the ρ parameter	18
C	Renormalization group equations and high-energy behavior	19
	C.1 Dark-matter couplings	20
	C.2 Quartic couplings	20

1 Introduction

The Standard Model (SM) of elementary particles predicts that tree-level flavor changing neutral currents (FCNC) transition rates are exactly zero, including those of the top quark. The reason for this is that the biunitary transformations that diagonalize the fermion mass matrices lead to diagonal couplings of the Higgs and the Z bosons to fermions. At the one-loop order, the rates of *e.g.* top quark FCNC decays are very suppressed thanks to the Glashow-Iliopoulos-Maiani (GIM) mechanism [1]. As a consequence of the GIM mechanism, the suppression of the top quark FCNC rates at the one-loop order is due to the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and the smallness of the mass splittings between the different quarks running in the loop. The calculation of the top quark FCNC decay rates in the SM has been done nearly thirty three years ago by the authors of ref. [2]. It is found that the branching ratios of $t \rightarrow cX$ and $t \rightarrow uX$ are generally very small ranging from 10^{-17} to 10^{-12} . Such small rates imply that any observation of the top quark FCNC phenomena at the LHC is a clear sign of new physics beyond the SM (BSM). Several BSM models may give rise to sizeable rates for the top quark FCNC decays [3–24]¹. Searches of top quark FCNC interactions have

¹In Table 1, we give a summary of the branching ratios of the top quark FCNC decays in the SM and some of the well-known BSM extensions.

been carried at the LHC by the ATLAS [25–35] and the CMS collaborations [36–40]. It is found that bounds on the top quark FCNC branching ratios have been improved by about an order of magnitude. This achievement is due to two important factors: (i) the increase on both the center-of-mass energy of the pp collisions at the LHC and on the accumulated luminosity, and (ii) the improvements on the analysis techniques used to perform the signal-to-background optimization, *i.e.* going from simple cut-based methods to novel Machine Learning techniques. It is expected that the HL-LHC with 3000 fb^{-1} of integrated luminosity would enable for more stringent bounds on the top quark FCNC decays which will therefore put stronger constraints on various BSM scenarios.

In this study we consider the possibility that dark matter (DM) and top quark FCNC transitions are connected via new particles that are odd under an ad-hoc Z_2 symmetry. In this category of models, both the production of DM at hadron colliders and its self-annihilation in the universe are mediated by colored mediators in t -channel diagrams. The DM phenomenology at colliders is minimally realized by extending the SM by one mediator (Y) that transforms as a triplet under $SU(3)_c$ and a neutral particle (X) under $U(1)_Y$. The mediators can transform, however, either as singlets or doublets under $SU(2)_L$ while the DM candidate must always transform as a singlet. Assuming that the colored mediator is a singlet under $SU(2)_L$, there are 12 possible categories for these models depending on the underlying assumptions on the spin of the mediators and of the DM candidate. The phenomenology of this class of models have been extensively studied in the literature [41–51]. In the most minimal realizations of these scenarios, the main assumption that has been usually used is that each mediator couples *solely* to one quark generation. This assumption is motivated by the requirement to avoid one-loop induced FCNC transitions. Here, we assume however that the colored mediator(s) can couple simultaneously to all the quark generations with *generally* different coupling parameters. We consider a minimal extension that contains one colored scalar that possesses the same quantum numbers as a right-handed up-type quark and a Majorana fermion both are singlets under $SU(2)_L$. By taking into account this assumption, this model will lead to *non-zero* rates for top quark FCNC transitions at the one-loop order. By analyzing the top quark FCNC decays into qZ and qH within this model and studying the possible constraints from collider experiments and cosmology, we find interesting scenarios that may be amenable to discovery both at the HL-LHC and a future 100 TeV collider.

The rest of this manuscript is organized as follows. In section 2 we present the model and its particle content. We discuss in details the branching ratios for top quark FCNC decays into qZ and qH in section 3. Section 4 is devoted to an analysis of the DM relic density within this model. The impact of LHC constraints from searches of DM in events with multijets plus missing energy on our model is discussed in section 5. We present four benchmark scenarios and discuss their characteristics in section 6. We draw our conclusions in section 7.

Process	SM	2HDM (FC)	2HDM (FV)	MSSM	RPV-MSSM	RS
$\text{BR}(t \rightarrow Zc)$	1×10^{-14}	$< 10^{-10}$	$< 10^{-6}$	$< 10^{-7}$	$< 10^{-6}$	$< 10^{-5}$
$\text{BR}(t \rightarrow Zu)$	7×10^{-17}	–	–	$< 10^{-7}$	$< 10^{-6}$	–
$\text{BR}(t \rightarrow gc)$	5×10^{-12}	$< 10^{-8}$	$< 10^{-4}$	$< 10^{-7}$	$< 10^{-6}$	$< 10^{-10}$
$\text{BR}(t \rightarrow gu)$	4×10^{-14}	–	–	$< 10^{-7}$	$< 10^{-6}$	–
$\text{BR}(t \rightarrow \gamma c)$	5×10^{-14}	$< 10^{-9}$	$< 10^{-7}$	$< 10^{-8}$	$< 10^{-9}$	$< 10^{-9}$
$\text{BR}(t \rightarrow \gamma u)$	4×10^{-16}	–	–	$< 10^{-8}$	$< 10^{-9}$	–
$\text{BR}(t \rightarrow Hc)$	3×10^{-15}	$< 10^{-5}$	$< 2 \times 10^{-3}$	$< 10^{-5}$	$< 10^{-9}$	$< 10^{-4}$
$\text{BR}(t \rightarrow Hu)$	2×10^{-17}	–	$< 6 \times 10^{-6}$	$< 10^{-5}$	$< 10^{-9}$	–

Table 1. Summary of the branching ratios for top quark FCNC decays in the SM along with the highest predicted values in several well-known BSM extensions. The results are taken from the 2013 Top Working Group Report [52].

2 Theoretical framework

In this work, we consider a minimal simplified model with a t -channel scalar mediator (S) that carries a color charge and a right-handed fermion (χ) that plays the role of the DM candidate. In this framework, the DM particle interacts primarily with SM quarks through a Yukawa-type interaction. In this study, we consider one possible scenario where the scalar mediator couples to right-handed up-type quarks². In this framework, the new states transform as

$$S : (\mathbf{3}, \mathbf{1})_{+2/3}, \quad \chi : (\mathbf{1}, \mathbf{1})_0, \quad (2.1)$$

where the numbers refer to their representations under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. On the other hand, both the scalar mediator and the DM candidate are odd under Z_2 symmetry while all the SM particles are even. To ensure that the DM particle is stable we also require that $M_\chi \leq M_S$. The most general Lagrangian is given by

$$\mathcal{L} \supset \mathcal{L}_S + \mathcal{L}_\chi - V(S, \Phi), \quad (2.2)$$

where \mathcal{L}_S , \mathcal{L}_χ and $V(S, \Phi)$ refer to the kinetic Lagrangian of the mediator, the Yukawa-type Lagrangian of the DM particle and the scalar potential respectively. The first two Lagrangian terms are given by

$$\mathcal{L}_S + \mathcal{L}_\chi \equiv i\bar{\chi}\not{\partial}\chi^c + \frac{1}{2}M_\chi\bar{\chi}\chi^c + (\mathcal{D}_\mu S)^\dagger(\mathcal{D}^\mu S) + \left(Y_q\bar{q}_R^c\chi S + \text{h.c.}\right), \quad (2.3)$$

²Besides the minimal model we consider in this study, there are two minimal classes of models depending on how the scalar mediator transforms under $SU(2)_L$ and on the Hypercharge assignments of the scalar mediator. For instance, the scalar mediator may carry the same quantum numbers as a right-handed down-type quark. In this case, there is no influence on the top quark FCNC decays at the one-loop order but only on the rates of the FCNC decays of the SM Higgs boson. In the other scenario, the scalar mediator belongs to a doublet under $SU(2)_L$ which would therefore impact both the top quark FCNC transitions, Higgs boson decays into $b\bar{s}$ and low-energy B -meson FCNC decays.

where the first and second terms refer to the kinetic energy and mass term of the right-hand fermion, the third term refers to the gauge-invariant kinetic term of the scalar mediator and the last term corresponds to the $S\chi q$ interaction (where a sum over the quark generations is implicit). In equation 2.3, $Y_q, q = u, c, t$ are generation-dependent Yukawa-type couplings and \mathcal{D}_μ is the covariant derivative given by:

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

with $T^a = \lambda_1^a/2$ being the generators of $SU(3)_c$, Y_S is the hypercharge of the scalar mediator, g_1 and g_s are the coupling constants of $U(1)_Y$ and $SU(3)_c$ gauge groups respectively. Unless stated explicitly in the text, we assume that the DM Yukawa-type couplings are universal in the sense that $Y_u = Y_c = Y_t$. In the last term of the Lagrangian in equation 2.3 one can see that only one scalar mediator couples to all the SM quark generations. Therefore, one can generate top quark FCNC decays at the one-loop order mediated *solely* by the dark particles of the model. Assuming CP -conservation, the most renormalizable and gauge-invariant scalar potential is given by

$$V(S, \Phi) = -m_{11}^2 |\Phi^\dagger \Phi| + m_{22}^2 |S^\dagger S| + \lambda_1 |\Phi^\dagger \Phi|^2 + \lambda_2 |S^\dagger S|^2 + \lambda_3 |S^\dagger S| |\Phi^\dagger \Phi|, \quad (2.4)$$

here $\Phi = (0, (v + H)/\sqrt{2})^T$ refers the SM Higgs doublet given in the unitary gauge. All the parameters in the scalar potential are assumed to be real-valued parameters. Note that the quartic coupling λ_2 does not influence the phenomenology of the model and henceforth will be set to be equal to 1. On the other hand, λ_3 is subject to constraints from $H \rightarrow gg$ and $H \rightarrow \gamma\gamma$ signal strength measurements. The effects of the model parameters on the Higgs decay observables is shown in Appendix A. Note that in this model, the contribution to the ρ parameter is exactly zero as shown in Appendix B. We close this section by a discussion of the decays of the colored mediator (S) in this model. The partial decay width of S into χq is given by

$$\begin{aligned} \Gamma(S \rightarrow q\chi) &\equiv \frac{Y_q^2 M_S}{16\pi} \left(1 - \frac{M_\chi^2 + m_q^2}{M_S^2}\right) \sqrt{\lambda\left(1, \frac{M_\chi^2}{M_S^2}, \frac{m_q^2}{M_S^2}\right)}, \\ &\approx \frac{Y_q^2 M_S}{16\pi} \left(1 - \frac{M_\chi^2}{M_S^2}\right)^2, \quad m_q \ll M_S. \end{aligned} \quad (2.5)$$

where $\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2(xy + xz + yz)$ is the Källén function. A few comments are in order here. First, for $\Delta \equiv M_S - M_\chi \leq m_t$, the scalar mediator decays *solely* to an up quark or a charm quark plus χ with branching ratios satisfying:

$$\frac{\text{BR}(S \rightarrow u\chi)}{\text{BR}(S \rightarrow c\chi)} \approx \left(\frac{Y_u}{Y_c}\right)^2. \quad (2.6)$$

Once Δ becomes larger than the top quark mass, the decay $S \rightarrow t\chi$ opens up with a branching going from a few percents near the threshold and becomes very significant for $M_S \gg m_t$. Note that these features are very important in connection with DM phenomenology and collider studies as we will see in the next sections.

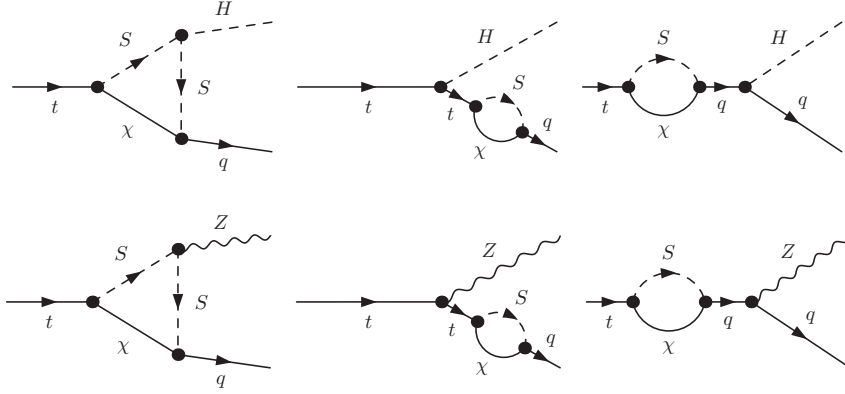


Figure 1. Examples of Feynman diagrams for the $t \rightarrow qH$ (upper panel) and $t \rightarrow qZ$ (lower panel) decays.

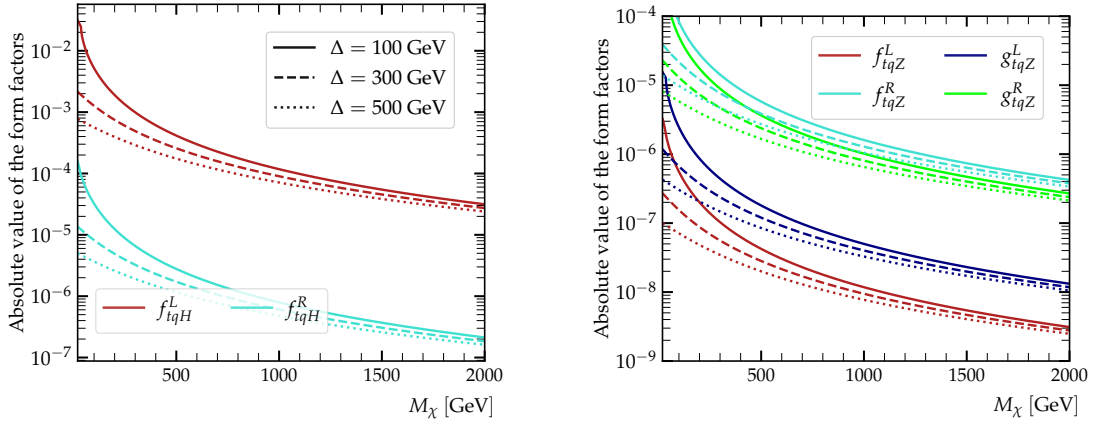


Figure 2. The absolute value of the form factors for $t \rightarrow qH$ (left) and $t \rightarrow qZ$ (right) as a function of M_χ for $\Delta = 100$ GeV (solid), $\Delta = 300$ GeV (dashed) and $\Delta = 500$ GeV (dashdotted). Here we assume that the light quark q is the charm quark and we take $Y_c = Y_t = 1$ and $\lambda_3 = 1$.

3 Top quark FCNC decays

In this work, we consider the FCNC two-body decays of the top quark into qZ and qH where q refers to either an up quark or a charm quark. They are mediated by the loops of the scalar mediator and the DM particle as we can clearly see in fig. 1. The generic expression of the effective operators for the $t \rightarrow qZ$ and $t \rightarrow qH$, $q = u, c$ is given by

$$\begin{aligned}
 -\mathcal{L}_{\text{eff}} = & \bar{t}\gamma^\mu(f_{tqZ}^L P_L + f_{tqZ}^R P_R)qZ_\mu + \bar{t}p^\mu(g_{tqZ}^L P_L + g_{tqZ}^R P_R)qZ_\mu \\
 & + \bar{t}(f_{tqH}^L P_L + f_{tqH}^R P_R)qH + \text{h.c.},
 \end{aligned}
 \tag{3.1}$$

where $f_{tqX}^{L,R}$ ($X = Z, H$) and $g_{tqZ}^{L,R}$ are form factors that are calculable at the one-loop order, $P_{L,R} = (1 \mp \gamma_5)/2$ are the projection operators and p^μ is the four-momentum vector of the

decaying top quark.

The expressions of the one-loop induced form factors are found using FEYNARTS version 3.11 [53] and FORMCALC version 9.9 [54] while their numerical evaluations have been done using LOOPTOOLS version 2.16 [55]. The form factors for $t \rightarrow qH$ are given by

$$\begin{aligned} f_{tqH}^L &= \frac{Y_q Y_t m_t}{16\pi^2} \left(3\lambda_3 v C_1 + \frac{m_q^2}{v(m_t^2 - m_q^2)} (B_{1,t} - B_{1,q}) \right), \\ f_{tqH}^R &= \frac{Y_q Y_t m_q}{16\pi^2} \left(3\lambda_3 v C_2 + \frac{m_t^2}{v(m_t^2 - m_q^2)} (B_{1,t} - B_{1,q}) \right). \end{aligned} \quad (3.2)$$

While for $t \rightarrow qZ$, the form factors are given by

$$\begin{aligned} f_{tqZ}^L &= \frac{g_1 m_q m_t (3c_W^2 - s_W^2)}{96s_W \pi^2} \frac{Y_q Y_t}{(m_t^2 - m_q^2)} (B_{1,t} - B_{1,q}), \\ f_{tqZ}^R &= -\frac{g_1 s_W Y_q Y_t}{24\pi^2} \left(2C_{00} + \frac{1}{m_t^2 - m_q^2} (m_t^2 B_{1,t} - m_q^2 B_{1,q}) \right), \\ g_{tqZ}^L &= \frac{g_1 s_W Y_q Y_t m_t}{12\pi^2} (C_1 + C_{11} + C_{12}), \\ g_{tqZ}^R &= \frac{g_1 s_W Y_q Y_t m_q}{12\pi^2} (C_2 + C_{12} + C_{22}). \end{aligned} \quad (3.3)$$

In eqs. 3.2 and 3.3, $B_{1,Q} \equiv B_1(m_Q^2, M_\chi^2, M_S^2)$ and $C_{i,ij} \equiv C_{i,ij}(m_t^2, M_X^2, m_q^2, M_\chi^2, M_S^2, M_Z^2)$ refer to the two-point and three-point Passarino-Veltman scalar loop functions [56]. Here, $M_X = m_H$ for $t \rightarrow qH$ and $M_X = M_Z$ for $t \rightarrow qZ$. It is clear from eqs. 3.2 and 3.3 that $f_{tqH}^L \gg f_{tqH}^R$ and $f_{tqZ}^R \simeq g_{tqZ}^L \gg g_{tqZ}^R > f_{tqZ}^L$ given the mass dependence of these form factors. This can clearly be seen in fig. 2, where we show the absolute values of the form factors as a function of the DM mass (M_χ) for three different values of the mass splitting $\Delta \equiv M_S - M_\chi$. We have checked that our results are free of UV divergences and independent of the nonphysical renormalization scale.

Neglecting light quark masses, the resulting decay widths for $t \rightarrow qH$ and $t \rightarrow qZ$ are given by

$$\begin{aligned} \Gamma(t \rightarrow qH) &= \frac{m_t}{32\pi} \left(1 - \frac{m_H^2}{m_t^2} \right)^2 |f_{tqH}^L|^2, \\ \Gamma(t \rightarrow qZ) &= \frac{1}{16\pi m_t} \left(1 - \frac{M_Z^2}{m_t^2} \right) \left[\kappa_1 |f_{tcZ}^R|^2 + \kappa_2 |g_{tcZ}^L|^2 - 2 \kappa_3 \text{Re}(g_{tcZ}^L f_{tcZ}^{R,*}) \right], \end{aligned} \quad (3.4)$$

with κ_1, κ_2 and κ_3 being functions of m_t and M_Z :

$$\begin{aligned} \kappa_1 &\equiv \frac{m_t^4}{2M_Z^2} \left(1 + \frac{m_t^2}{M_Z^2} - \frac{2M_Z^4}{m_t^4} \right), \\ \kappa_2 &\equiv \frac{m_t^2}{8M_Z^2} \left(1 - \frac{M_Z^2}{m_t^2} \right) \times (m_t^2 - M_Z^2)^2, \quad \kappa_3 \equiv \frac{m_t}{4M_Z^2} (m_t^2 - M_Z^2)^2. \end{aligned}$$

Note that the inclusion of the light-quark mass effects would induce a correction that is below 0.1% to the partial widths of the top quark. The resulting branching ratios are given

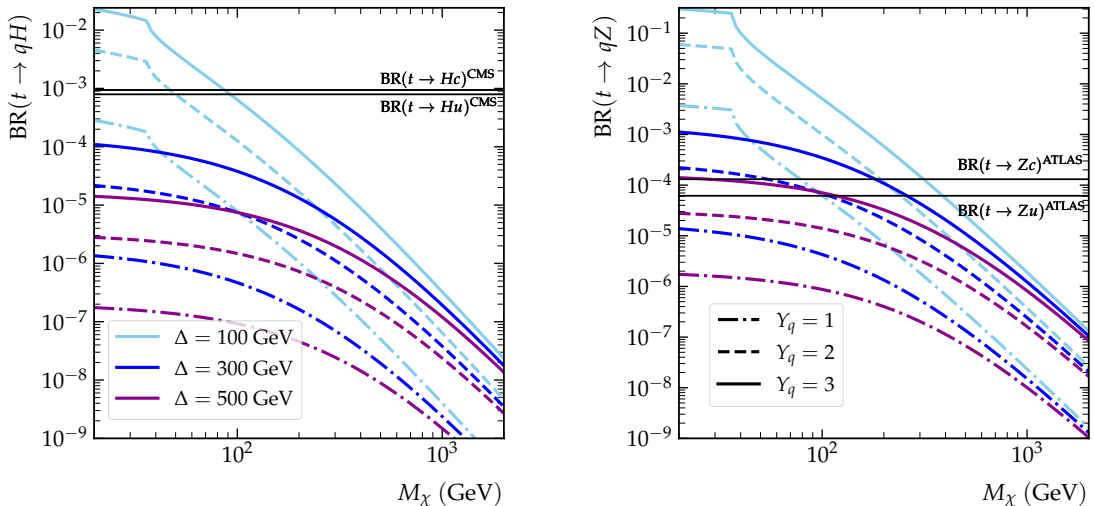


Figure 3. The FCNC decay branching ratios as function of the dark matter mass (M_χ) for $t \rightarrow qH$ (left) and $t \rightarrow qZ$ (right). The results are shown for $Y_q = 1$ (dashdotted), $Y_q = 2$ (dashed) and $Y_q = 3$ (solid). For each case, we calculate the branching ratios for $\Delta = 100$ GeV (turquoise), $\Delta = 300$ GeV (blue) and $\Delta = 500$ GeV (purple). For $t \rightarrow qH$, we choose $\lambda_3 = 1$. We also display the latest exclusion bounds from the searches of FCNC production of top quark reported on by ATLAS [34] and CMS [40] collaboration. More details can be found on the text.

by

$$\text{BR}(t \rightarrow qX) = \frac{\Gamma(t \rightarrow qX)}{\Gamma_t}, \quad (3.5)$$

where $\Gamma_t \equiv \Gamma(t \rightarrow bW) = 1.32$ GeV calculated at Next-to-Next-to-Leading Order in QCD including the finite mass and width effects and Next-to-Leading Order electroweak corrections [57]. We note that our model predicts that

$$\frac{\Gamma(t \rightarrow cX)}{\Gamma(t \rightarrow uX)} \approx \left(\frac{Y_c}{Y_u} \right)^2,$$

since the m_q^2 corrections to the FCNC partial widths are extremely small. This model predicts a ratio

$$\frac{\Gamma(t \rightarrow qZ)}{\Gamma(t \rightarrow qH)} \approx \frac{r}{\lambda_3^2}, \quad (3.6)$$

where r is a factor that depends on the DM mass and the mass splitting (Δ) and varies between 5 and 15. We find that r is smaller for high M_χ and higher for small M_χ .

In fig. 3, we display the branching ratios of $t \rightarrow qH$ (left) and of $t \rightarrow qZ$ (right) as a function of M_χ for different values of the mass splitting Δ and of the Yukawa-type coupling $Y_q = Y_t$. Here, we show the results for $Y_q = 1, 2$ and 3 with the choices of $\Delta = 100$ GeV (turquoise), $\Delta = 300$ GeV (blue) and $\Delta = 500$ GeV (purple). These two FCNC branching ratios scale as $|Y_q Y_t|^2$ and therefore higher values of $Y_q = Y_t$ will lead

to extremely large branching ratios especially for small M_χ and small Δ . We also show the experimental bounds reported on by ATLAS [34] and CMS [40] as horizontal solid (for $t \rightarrow uX$) and dashed (for $t \rightarrow cX$) lines. The strong bounds from the search of $t \rightarrow qZ$ imply that DM masses of order 400 GeV are excluded at the 95% CL if one assumes that $\Delta = 100$ GeV and $Y_q = 3$. Smaller values of the DM mass are still allowed if one considers $Y_q \approx 1$ and relatively large Δ . On the other hand, we can see that for heavy DM with mass $M_\chi \geq 1000$ GeV, the branching ratios become relatively independent of the choice of Δ .

4 Dark Matter

The relic density of the χ particles is mainly due to the freeze-out mechanism. The main process that leads to DM relic density within this model is through the annihilation into $q_\alpha \bar{q}_\beta$ where α and β are generation indices. This includes the case of same-flavor production ($u\bar{u}, c\bar{c}, t\bar{t}$) and of different-flavor production ($u\bar{c}, c\bar{u}, u\bar{t}, t\bar{u}, c\bar{t}, c\bar{u}$). The co-annihilation channels start to dominate for small mass splittings between the χ particle and the colored mediator S . The DM density of the χ particles can be obtained by solving the following Boltzmann equation assuming that the colored mediator has already decayed into $\chi + q_\alpha$:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v(x_f) \rangle (n^2 - n_{\text{eq}}^2), \quad (4.1)$$

with H being the Hubble parameter, $\langle \sigma_{\text{eff}} v(x_f) \rangle$ is the thermally-averaged annihilation cross section of DM with a velocity v at the freeze-out temperature x_f and n_{eq} is the equilibrium number density.

An approximate solution of the Boltzmann equation leads to the following expression for the DM relic density [58–60]

$$\Omega_\chi h^2 \simeq \frac{1.04 \times 10^9}{M_{\text{Planck}}} \frac{x_f}{\sqrt{g_*(x_f)}} \frac{1}{I_a + 3 \frac{I_b}{x_f}}, \quad (4.2)$$

with $M_{\text{Planck}} = 1.22 \times 10^{19}$ GeV being the Planck mass, g_* is the effective number of degrees of freedom and I_a and I_b are coefficients that depends on the effective cross section. Here, I_a is related to the velocity-independent and I_b is related to the velocity-dependent cross section (see e.g. ref. [60] for more details). We assume that the thermally-averaged cross section can be expanded as

$$\sigma_{\text{eff}} v = a_{\text{eff}} + b_{\text{eff}} v^2 + \mathcal{O}(v^4), \quad (4.3)$$

where the expression of a_{eff} and b_{eff} can be found in e.g. ref. [60]. In this analysis, we use MICROMEGAS version 5.3.41 [61] to solve numerically the Boltzmann equations and to calculate the relic density of the χ particles. We have cross checked the results of MICROMEGAS by comparing them with the results of MADDM version 3.1 [62] for various benchmark points. The results of the calculations are shown in fig. 4 where the couplings satisfying the condition $\Omega_\chi h^2 = 0.12$ are shown in the plane of M_χ and $\Delta = M_S - M_\chi$ in the case where co-annihilation is not included (left) and where co-annihilation is included

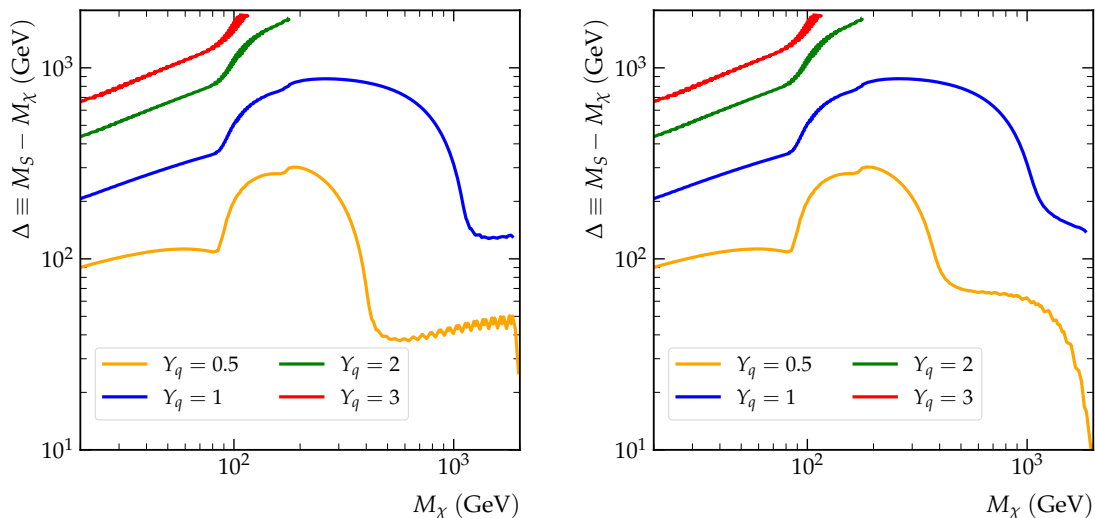


Figure 4. Parameter space satisfying $\Omega_\chi h^2 = 0.12$ shown in the (M_χ, Δ) plane. The thin solid curves are corresponding to contours of constant coupling $Y_q = 0.5$ (orange), $Y_q = 1$ (blue), $Y_q = 2$ (green) and $Y_q = 3$ (red) where $Y_q \equiv Y_u = Y_c = Y_t$. Here we show the results without co-annihilation (left) and with co-annihilation (right).

(right). We show the contours for $Y_q = 0.5$ (orange), $Y_q = 1$ (blue), $Y_q = 2$ (green) and $Y_q = 3$ (red). We can see that in order to fulfill the correct relic density, reasonably modest to large values of Y_q are required which increase with increasing mass splitting Δ . On the other hand, we can see that there is a wide peak for DM masses above ≈ 80 GeV for a given value of the DM coupling which indicates the opening of the annihilation channel $\chi\chi \rightarrow t\bar{t}$. Finally, we note that the effect of co-annihilation becomes very important for small Δ and large M_χ (see the right panel of fig. 4).

We close this section by commenting on the effects of DM direct detection searches on the model parameter space. In this model, the leading contribution to the DM-nucleus spin-independent cross section (σ_{SI}) occurs through the exchange of the scalar mediator. Further corrections can appear once we consider diagrams at NLO³. We, however, check the viability of the benchmark points presented in section 6 in what concerns the bounds from σ_{SI} reported on by the XENON1T collaboration [64] using calculations at LO only.

5 Bounds from the LHC searches

The model predicts the production of DM at the LHC through a variety of processes leading to various final-state signatures such as monoton ($t + E_T^{\text{miss}}$), $t\bar{t} + E_T^{\text{miss}}$, monojet, and

³The analysis of σ_{SI} is very involved and we do not consider it in this work. We refer the interested reader to refs. [47, 50, 63] for more detailed analyses of direct detection for more generalised models which involve three mediators or one mediator and one scalar leptoquark. We note that these constraints are not strong as long as couplings of order $\mathcal{O}(1)$ are considered.

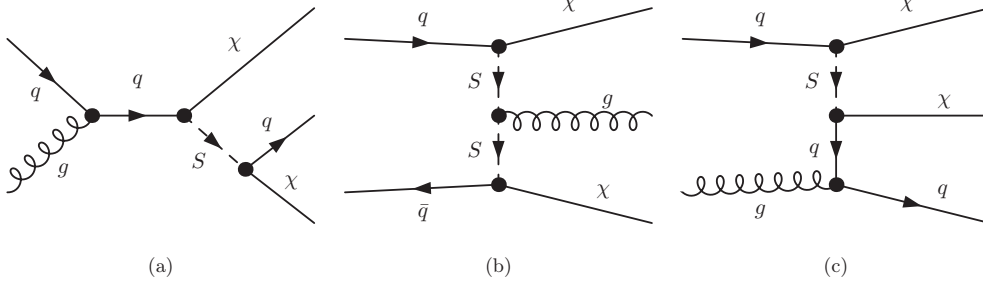


Figure 5. Representative Feynman diagrams for monojet production in this model. Here, we show the monojet production through resonant $S\chi$ production (a) and noresonant production (b-c).

multijet+ E_T^{miss} . There are several collider studies on the models with t -channel mediators [48, 49, 51]. In these analyses, the scalar mediator is assumed to couple to one generation of quarks only. Therefore constraints from multijet+ E_T^{miss} are found to be strong excluding a wide range of the parameter space [49]. In this model, the fact that the scalar mediator couples to all the three generations of quarks lead to weaker limits. We found that the strongest bound comes from the search of monojet (small number of jets and missing energy) which was carried by the ATLAS collaboration [65]⁴. Examples of Feynman diagrams for mono-jet production in this model at Leading Order (LO) are shown in fig. 5. In this model, one can distinguish between resonant production (fig. 5a) and non-resonant production through $q\bar{q}$ annihilation (fig. 5b) and through qg fusion (fig. 5c). The cross section of the mono-jet production can be generically expressed as follows:

$$\sigma(pp \rightarrow \chi\chi J) \equiv \sum_{i,j} \int dx_i dx_j f_{i/p}(x_i, Q^2) f_{j/p}(x_j, Q^2) \hat{\sigma}(ij \rightarrow \chi\chi J), \quad (5.1)$$

here $f_{i/p}(x_i, Q^2)$ is the PDF of a parton i within the proton to carry a momentum fraction x_i at a factorization scale Q , $\hat{\sigma}$ is the partonic cross section which scales in this process as $\hat{\sigma}(ij \rightarrow \chi\chi J) \propto Y_q^4$. Here Y_q is either Y_u or Y_c . Note that for all the diagrams, the contribution of the charm quark PDF is always smaller than the contribution of the up or down quarks. The analysis we consider in this study targeted the search of new physics beyond the Standard Model in final states consisting a small number of jets in association with missing energy using 139 fb^{-1} of data collected in the period of 2015-2018. In this analysis, events are required to have at least one jet with transverse momentum of 150 GeV and no reconstructed isolated 'Loose' electrons or muons with $p_T > 7 \text{ GeV}$ and $|\eta| < 2.5$, tau leptons with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$ or photons with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$. The missing transverse energy (E_T^{miss}) is required to be larger than 200 GeV. Twenty-six signal regions are defined depending on the cut on E_T^{miss} : 13 inclusive signal region (IM0-IM12) and 13 exclusive signal regions (EM0-EM12).

⁴A comprehensive analysis of all the existing collider searches at the LHC will be performed in a future study.

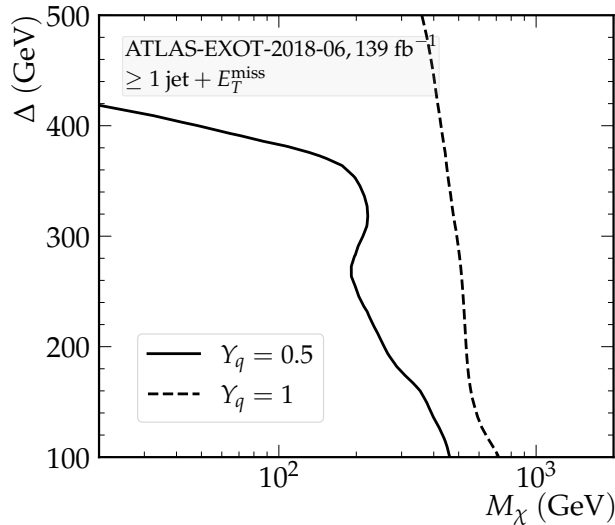


Figure 6. The 95% CL exclusion on the model projected on the plane of (M_χ, Δ) for $Y_q = 0.5$ (solid) and $Y_q = 1$ (dashed). For the two cases, the contours correspond to $\text{CL}_s^{95\%}$ which defines the exclusions at the 95% confidence level. Here, we assumed that $Y_q = Y_u = Y_c$ for simplicity.

To estimate the bounds on the model parameter space arising from this search, we use a validated implementation, which is denoted by ATLAS-EXOT-2018-06, in the MADANALYSIS 5 framework [66–69]. The link to the analysis code along with the validation material can be found in ref. [70]. Theory predictions for the signal have been done using MADGRAPH5_AMC@NLO version 3.5.0 [71] with Leading Order (LO) matrix elements. The matrix elements have been convoluted with the NNPDF31_lo_as_0130 PDF set with $\alpha_s(M_Z) = 0.130$ [72] which can be found in LHAPDF version 6.4.0 [73]. Note that our choice of α_s is adopted to capture some of the missing higher order corrections although the calculation is only accurate at LO. The generated events are then interfaced to PYTHIA 8 version 8309 [74] to add parton showering and hadronization. All the jets were clustered with the anti- k_t algorithm with a jet radius of $R = 0.4$ [75] using FASTJET version 3.40 [76]. Simplified detector modeling was achieved with the use of the Simplified Fast detector Simulation (SFS) module of MADANALYSIS 5 [77]. To estimate the exclusion bounds on the model we calculate the CL_s using Pyhf [78]. A point in the model parameter space is excluded at the 95% if $\text{CL}_s > 0.95$. In fig. 6 we show the 95% confidence level exclusions projected on the plane of (M_χ, Δ) for two assumptions on the coupling: $Y_q = 0.5$ (solid) and $Y_q = 1$ (dashed). We can see that for $Y_q = 1$ DM masses up to 800 GeV are excluded with very small dependence on the mass splitting (Δ). However, for the choice of $Y_q = 0.5$ the bounds get weaker given that total cross section behaves approximately as Y_q^4 . Note that further improvements on the bounds can be made if one consider calculations at NLO (see ref. [48] for more details). We plan to improve our results in a future work [79].

Benchmark point	Quantity	BP1	BP2	BP3	BP4
Parameters	Y_u	0.4	0.4	0.0	0.4
	Y_c	0.4	0.8	1.0	1.0
	Y_t	0.4	1.2	2.0	0.8
	λ_3	2.0	1.0	1.0	4.0
	M_χ (GeV)	500	200	100	600
	Δ (GeV)	57	650	500	250
	Λ_{pole} (TeV)	56	100	10	5.5
Branching ratios					
$\text{BR}(S \rightarrow q\chi)$	$\text{BR}(S \rightarrow u\chi)$	5.00×10^{-1}	7.60×10^{-2}	0.00×10^0	1.01×10^{-1}
	$\text{BR}(S \rightarrow c\chi)$	5.00×10^{-1}	3.03×10^{-1}	2.31×10^{-1}	6.32×10^{-1}
	$\text{BR}(S \rightarrow t\chi)$	0.00×10^0	6.21×10^{-1}	7.69×10^{-1}	2.67×10^{-1}
	Γ_S/M_S	1.18×10^{-4}	3.64×10^{-2}	8.31×10^{-2}	7.92×10^{-3}
$\text{BR}(t \rightarrow qX)$	$\text{BR}(t \rightarrow cH)$	1.02×10^{-8}	1.98×10^{-8}	3.69×10^{-7}	1.43×10^{-7}
	$\text{BR}(t \rightarrow uH)$	1.02×10^{-8}	4.95×10^{-9}	0.0	2.29×10^{-8}
	$\text{BR}(t \rightarrow cZ)$	1.50×10^{-8}	1.79×10^{-7}	3.49×10^{-6}	5.92×10^{-8}
	$\text{BR}(t \rightarrow uZ)$	1.50×10^{-8}	4.48×10^{-8}	0.0	9.48×10^{-9}

Table 2. Definition of the benchmark points. Here, we show the branching ratios $\text{BR}(S \rightarrow \chi q)$ along with the width-to-mass ratio (Γ_S/M_S) of S . The FCNC branching ratios of the top quark, $\text{BR}(t \rightarrow qH)$ and $\text{BR}(t \rightarrow qZ)$, are also shown. For each benchmark point we display the energy scale, denoted by Λ_{pole} , at which the perturbativity bound is violated at the one-loop order (more details about the renormalization group equation can be found in Appendix C).

6 Benchmark scenarios for future collider analyses

In this section, we present four benchmark points consistent with the current experimental bounds from LHC searches of new physics, top quark FCNC decays, Higgs boson couplings and cosmology. We also show the production rates for several processes which may be amenable to discovery at either the HL-LHC or the FCC-hh. The definition of the benchmark points is shown in Table 2 including the decay branching ratios of the colored scalar mediator and the top quark FCNC. Given the importance of the choice of λ_3 in our model, we also show the energy scale at which the perturbativity of the model is broken down (more details about the RGEs are shown in Appendix C). Some of the characteristics of the benchmark points are shown in Table 3. We give a few comments about the benchmark points:

BP1. This benchmark point is characterized by two main properties. First, all the Yukawa-type couplings (Y_q) are chosen to be equal, *i.e.* $Y_u = Y_c = Y_t = 0.4$. Second,

Benchmark point	Quantity	BP1	BP2	BP3	BP4
Dark matter	$\Omega_\chi h^2$	1.18×10^{-1}	6.42×10^{-2}	8.58×10^{-2}	1.05×10^{-1}
	σ_{SI}^p (pb)	4.74×10^{-11}	3.51×10^{-14}	4.57×10^{-13}	2.97×10^{-12}
Production cross sections [fb]					
13.6 TeV	$S\chi$	6.11×10^1	3.23×10^1	7.89×10^1	1.34×10^1
	SS^\dagger	1.56×10^2	1.19×10^1	1.06×10^2	1.16×10^1
	$SS + \text{h.c.}$	1.79×10^1	1.45×10^0	4.80×10^{-1}	5.47×10^0
	$\chi\chi H$	3.36×10^{-4}	2.65×10^{-4}	9.00×10^{-4}	4.94×10^{-4}
	$\chi\chi Z$	1.82×10^{-3}	1.25×10^{-2}	1.48×10^{-2}	2.08×10^{-3}
	χSH	5.35×10^{-2}	3.85×10^{-3}	1.11×10^{-2}	3.02×10^{-2}
	χSZ	4.44×10^{-2}	2.27×10^{-2}	3.88×10^{-2}	1.12×10^{-2}
	$SS^\dagger j$	2.19×10^2	1.64×10^1	1.46×10^2	1.63×10^1
	$SS^\dagger \gamma$	1.02×10^0	1.10×10^{-1}	7.40×10^{-1}	1.10×10^{-1}
	$SS^\dagger t$	8.21×10^{-2}	1.40×10^{-1}	1.01×10^0	4.50×10^{-2}
	$SS^\dagger H$	4.80×10^{-1}	6.42×10^{-3}	7.69×10^{-2}	1.00×10^{-1}
	$SS^\dagger Z$	2.40×10^{-1}	2.85×10^{-2}	1.80×10^{-1}	2.86×10^{-2}
	100 TeV	$S\chi$	3.41×10^3	2.32×10^3	6.53×10^3
SS^\dagger		28.82×10^3	4.63×10^3	21.36×10^3	4.61×10^3
$SS + \text{h.c.}$		2.25×10^2	4.94×10^1	5.39×10^1	2.31×10^2
$\chi\chi H$		1.61×10^{-2}	1.01×10^{-2}	5.09×10^{-2}	4.69×10^{-2}
$\chi\chi Z$		9.91×10^{-2}	5.03×10^{-1}	8.84×10^{-1}	2.04×10^{-1}
χSH		4.32×10^0	4.07×10^{-1}	1.39×10^0	5.06×10^1
χSZ		4.24×10^0	2.27×10^0	5.35×10^0	2.26×10^0
$SS^\dagger j$		58.65×10^3	10.36×10^3	43.92×10^3	10.32×10^3
$SS^\dagger \gamma$		1.38×10^2	2.48×10^1	8.91×10^1	2.75×10^1
$SS^\dagger t$		1.38×10^1	6.65×10^1	3.73×10^2	2.25×10^1
$SS^\dagger H$		1.28×10^2	3.64×10^0	2.24×10^1	5.84×10^1
$SS^\dagger Z$		2.65×10^1	6.66×10^0	2.16×10^1	6.70×10^0

Table 3. Some characteristics of the benchmark scenarios to be considered for future collider analyses.

we have chosen a small mass splitting between χ and S ; $\Delta = 57$ GeV. For this choice of M_χ , the dominant contribution to the relic abundance comes from the co-annihilation mechanism. We list the channels by their contribution to $(\Omega_\chi h^2)^{-1}$: $\chi S \rightarrow qg, qH, t$ contribute by about 65%, $\chi\chi \rightarrow q\beta\bar{q}_\alpha$ contributes by about 21% and $SS^\dagger \rightarrow W^+W^-, gg$ contribute by about 7%. Given that the mass splitting is smaller than the top quark mass, the main decay channel of S is into $u\chi$ and $c\chi$ with equal branching ratio of 50% for each

channel. The choice of $Y_u = Y_c$ leads to $\text{BR}(t \rightarrow uX) = \text{BR}(t \rightarrow cX)$ while the choice of $\lambda_3 = 2$ implies that $\text{BR}(t \rightarrow qZ) \approx 1.5 \times \text{BR}(t \rightarrow qH)$. For this benchmark point, we find that the best channels to look for are the production of $\chi\chi$ in association with jets: $S(\rightarrow j\chi)\chi$, $S(\rightarrow j\chi)S^\dagger(\rightarrow j\chi)$, $S(\rightarrow j\chi)S^\dagger(\rightarrow j\chi)j$ and $S(\rightarrow j\chi)S^\dagger(\rightarrow j\chi)H(\rightarrow b\bar{b})$ where $j = u, \bar{u}, c, \bar{c}$. There is also an important process to search for at hadron colliders which is the production of $SS^\dagger\gamma$ which leads to final states comprising of at least 2 jets, a high- p_T photon and large missing energy.

BP2. Here we choose a normal hierarchy for the couplings, *i.e.* $Y_t > Y_c > Y_u$. Large mass splitting ($\Delta = 650$ GeV) and a relatively light DM ($M_\chi = 200$ GeV) are chosen. Given this large mass splitting, the DM relic density is mainly due to the annihilation mechanism where annihilation into $t\bar{t}$ and $c\bar{c} + t\bar{c}$ contributes to the relic density by 55% and 34% respectively. In this benchmark scenario, the relic density of the χ particles form about 53% of the total DM relic density in the universe. On the other hand, the top quark FCNC branching ratios satisfy $\text{BR}(t \rightarrow cX) \approx 4 \times \text{BR}(\rightarrow uX)$ and $\text{BR}(t \rightarrow qZ) \approx 9.04 \times \text{BR}(t \rightarrow qH)$. Due to this choice of couplings, the S particle decays dominantly into $t\chi$ with BR of 62.1% followed by $S \rightarrow c\chi$ with BR of 30.3% while the decay $S \rightarrow u\chi$ is subleading with BR smaller than 10%. In this scenario, processes involving one top quark or more in association with large missing energy are the most prominent at hadron colliders. Here five processes may lead to interesting signatures: $S(\rightarrow t\chi)\chi$, $S(\rightarrow t\chi)S^\dagger(\rightarrow \bar{t}\chi)$, $S(\rightarrow t\chi)S(\rightarrow t\chi) + \text{h.c.}$ ⁵, $S(\rightarrow t\chi)S^\dagger(\rightarrow \bar{t}\chi)j$ and $S(\rightarrow t\chi)S^\dagger(\rightarrow \bar{t}\chi)t$. The latter channel is interesting as it leads to final states of 3 top quarks and missing energy. There are other channels that involve the production of one or two hard jets initiated by u and c quarks in association with one or two top quarks.

BP3. In this benchmark point, we specifically choose the coupling to the u quark to be exactly zero and assume the other couplings to be $Y_t = 2 \times Y_c = 2$ and $\lambda_3 = 1$. For the particle masses, we choose a DM of mass 100 GeV and a mediator with mass of 600 GeV. For this choice of mass and couplings, the most dominant decay of S is into $t\chi$ with a branching ratio of 76.9% followed by the decay into $c\chi$ with a branching ratio of 23.1%. The relic density of the χ particle in this benchmark point is about 71.5% of the total DM relic density and is mainly due to the annihilation of χ into $c\bar{c} + t\bar{c}$ with a contribution of 92%. In this scenario, the branching ratios of $t \rightarrow uZ$ and $t \rightarrow uH$ are exactly zero while the decays involving charm quarks satisfy: $\text{BR}(t \rightarrow cZ) \approx 9.46 \times \text{BR}(t \rightarrow cH)$. In addition to processes like the production of one or two top quarks and jets in association with missing energy, this BP can be probed using processes involving Higgs bosons as well, *i.e.* $S(\rightarrow t\chi)S^\dagger(\rightarrow \bar{c}\chi)H$ and $\chi S(\rightarrow t\chi)H$. These two processes are advantageous since they have smaller associated backgrounds and can be used to connect top FCNCs and DM at hadron colliders.

BP4. We select the couplings to satisfy $Y_c > Y_t > Y_u$ and $\lambda_3 = 4$. Moreover, we choose the DM to be quite heavy with a mass of 600 GeV and a mass splitting of 250 GeV. The

⁵Note that the production of SS always dominates over $S^\dagger S^\dagger$ since its rate is initiated by valence u quarks.

dominant decay of S is into $c\chi$ with a branching ratio of 62.3% followed by $t\chi$ and $u\chi$ with branching ratios of 26.7% and 10.1% respectively. The top FCNC decays into cX dominate over uX with branching ratios satisfying $\text{BR}(t \rightarrow cX) \approx 6.24 \times \text{BR}(t \rightarrow uX)$ where the proportionality factor is approximately equal to $(Y_c/Y_u)^2$. In this BP, the branching ratio of top FCNC decay into $H + q$ is larger than into $Z + q$ and satisfy $\text{BR}(t \rightarrow qH) \approx 2.41 \times \text{BR}(t \rightarrow qZ)$. The relic density in this BP is mainly due to the annihilation of χ into $c\bar{t}$, $t\bar{c}$, $t\bar{t}$ and $c\bar{c}$ with a combined contribution of about 86%. This choice leads to $\Omega_\chi h^2/\Omega_{\text{Planck}} h^2 \approx 87.1\%$. The heavy DM scenario in this BP leads to smaller cross sections for the production of χ and S in hadron colliders as compared to the rates for the other BPs.

7 Conclusions

In this work, we have suggested a minimal simplified model that simultaneously addresses the DM problem and generates *nonzero* rates for top quark FCNC decays. In this model, the SM is extended by two $SU(2)_L$ singlets: a colored scalar mediator (S) that carries the same quantum numbers as a right-handed up-type quark, and a Majorana fermion (χ) which plays the role of the DM candidate. The two extra states are odd under an ad-hoc Z_2 symmetry which is imposed to guarantee the stability of χ provided that $M_\chi \leq M_S$. Since the colored scalar mediator couples to all the quark generations, *nonzero* rates for top quark FCNC decays are induced through the loops of S and χ . Using examples of two interesting top quark FCNC decays, *i.e.* $t \rightarrow qH$ and $t \rightarrow qZ$, we have comprehensively analyzed the contribution of these two extra states on the corresponding branching ratios. First, we find that the top quark FCNC branching ratios do not depend on the light quark masses but only on their coupling to χ and S (denoted by Y_q). Second, we find that the branching ratios $\text{BR}(t \rightarrow qH)$ and $\text{BR}(t \rightarrow qZ)$ are related by phase space factors and the coupling of S to the SM Higgs boson doublet. We then analyzed the DM relic density in this model which is mainly due to the annihilation of the χ particles into quarks unless the mass splitting between χ and S is small in which case co-annihilation into SM particles starts to dominate. The bounds from the LHC searches of DM in monojet are analyzed. After analyzing all these constraints, we have defined four benchmark points that can lead to high discovery potential at the HL-LHC and FCC-hh. We discussed in details the characteristics of these benchmark points and the different methods to probe them at high-energy colliders. This work provides a novel interesting connection between top quark FCNC, the DM problem and collider searches of new physics BSM.

Acknowledgments

The work of A.J. is supported by the Institute for Basic Science (IBS) under the project code, IBS-R018-D1. The work of S. K. was supported by the JSPS KAKENHI Grant No. 20H00160 and No. 23K17691. A.J. would like to thank the CERN Theory Department for its hospitality where part of this work has been done.

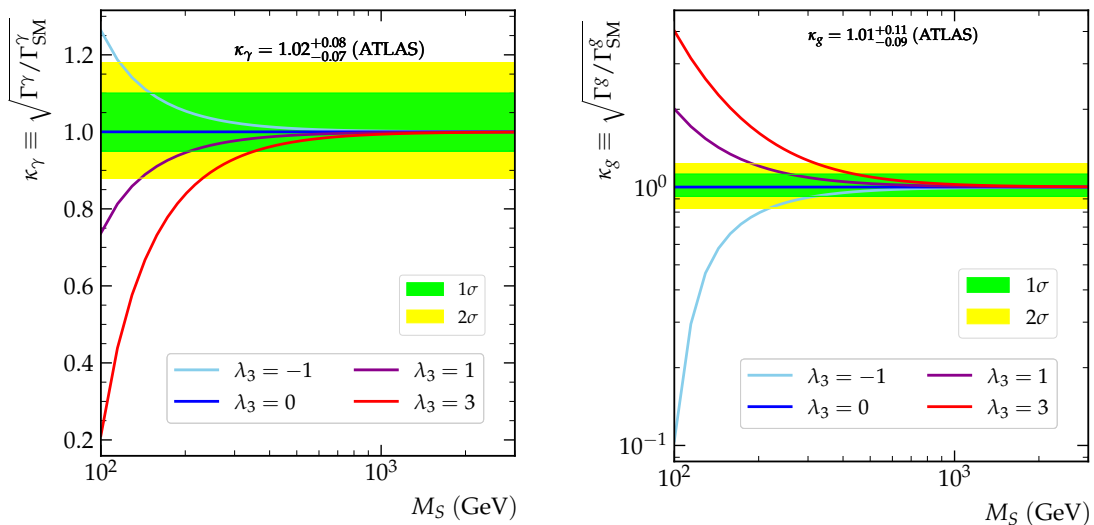


Figure 7. The dependence of κ_γ (left) and κ_g (right) on the colored scalar mass (M_S) for $\lambda_3 = -1$ (turquoise), $\lambda_3 = 0$ (blue), $\lambda_3 = 1$ (purple) and $\lambda_3 = 3$ (red). In the same plots we show the best-fit values of $\kappa_\gamma = 1.02^{+0.08}_{-0.07}$ and $\kappa_g = 1.01^{+0.11}_{-0.09}$ along with the 1σ (green) and 2σ (yellow) bands as was reported on by the ATLAS collaboration [80].

A Impact on Higgs boson couplings

As pointed out in section 2, the Higgs boson couplings get contributions from the parameters of this model. Here, we show explicitly the impact of the Higgs measurements on the allowed range of the model's parameters. There are two different categories of decay channels that can be affected by this model: bosonic decays into $\gamma\gamma$ and gg and fermionic decays into $u\bar{u}, c\bar{c}$. In this appendix, we do not consider the contribution to bosonic decay processes like ZZ^*, WW^* since it was found that they are small and do not go beyond a few percents, see refs. [81–83]. The main aim of this section is to evaluate the following ratio

$$\kappa_i = \sqrt{\frac{\Gamma(H \rightarrow i)}{\Gamma(H \rightarrow i)^{\text{SM}}}}, \quad (\text{A.1})$$

where $i = g, \gamma, u, c$. We start with the bosonic decay channels. In this model, the new contribution to these decay widths depends solely on the mass of the colored mediator (M_S) and the quartic coupling (λ_3). The partial decay widths for $\gamma\gamma$ and gg channels are given by

$$\begin{aligned} \Gamma(H \rightarrow \gamma\gamma) &= \frac{G_F \alpha_{\text{EM}}^2 m_H^3}{128 \sqrt{2} \pi^3} \left| \sum_f Q_f^2 N_{cf} A_{1/2}(\tau_f) + A_1(\tau_W) + N_{cS} Q_S^2 \frac{\lambda_3 v^2}{2M_S^2} A_0(\tau_S) \right|^2, \\ \Gamma(H \rightarrow gg) &= \frac{G_F \alpha_s^2 m_H^3}{64 \sqrt{2} \pi^3} \left| \sum_f A_{1/2}(\tau_f) + \frac{\lambda_3 v^2}{2M_S^2} A_0(\tau_S) \right|^2, \end{aligned} \quad (\text{A.2})$$

with $N_{cX} = 3$ being the number of colors for the quarks and the scalar mediator, $\tau_i = m_H^2/(4m_i^2)$, $A_{1/2}(\tau) = 2\tau^{-2}(\tau + (\tau - 1)f(\tau))$, $A_1(\tau) = -\tau^{-2}(2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau))$, $A_0(\tau) = -\tau^{-2}(\tau - f(\tau))$, and $f(\tau)$ is the one-loop function which can be found in e.g. ref. [84]. In the SM, the contribution of the W -boson to $\Gamma(H \rightarrow \gamma\gamma)$ is dominant as compared to the contribution of the top quark and it comes with an opposite sign. The contribution of the colored scalar is mainly controlled by the value of λ_3 . We can see that there are destructive (constructive) interference for positive (negative) values of λ_3 with the dominant W -boson contribution. The situation is different for the case of $H \rightarrow gg$ since the only dominant contribution in the SM is that of the top quark. The new scalar contribution comes with the same sign as the top quark contribution for $\lambda_3 > 0$ leading to enhancement while it reduces the rate of $H \rightarrow gg$ for negative λ_3 . These features can be clearly seen in fig. 7 where we show the dependence of κ_γ (left) and κ_g on M_S for different values of λ_3 . We can see that κ_g and κ_γ are anticorrelated in this model since for example the new scalar loops induce positive (negative) contributions to κ_γ (κ_g) when $\lambda_3 < 0$ ⁶. To compare with the experimental data, we also show the recent measurements of κ_γ and κ_g reported on by the ATLAS collaboration [80]. We can see that the recent measurements of κ_γ and κ_g do not prefer light scalars as masses of order 200–300 GeV are excluded for all but $\lambda_3 \approx 0$.

We turn now into a brief discussion of the contribution of the new states to the fermionic rates *i.e.*, $H \rightarrow u\bar{u}$ and $H \rightarrow c\bar{c}$. The partial width for these channels is given by

$$\Gamma(H \rightarrow q\bar{q}) \equiv \Gamma(H \rightarrow q\bar{q})_{\text{N3LO}} + \Delta\Gamma(H \rightarrow q\bar{q})_{\text{NP}}, \quad (\text{A.3})$$

where $\Gamma(H \rightarrow q\bar{q})_{\text{N3LO}}$ is the decay width in the SM calculated at N3LO including renormalized running quark masses [85, 86] and $\Delta\Gamma(H \rightarrow q\bar{q})_{\text{NP}}$ is the model contribution to the decay width which is given by

$$\Delta\Gamma(H \rightarrow q\bar{q})_{\text{NP}} = \frac{6m_H m_q}{16\pi v} \left[\text{Re}(f_L + \delta f_L) + \text{Re}(f_R + \delta f_R) \right], \quad (\text{A.4})$$

with $f_{L,R}$ being the one-loop form factors which depend on Y_q , λ_3 , M_χ and M_S and they are given by

$$\begin{aligned} f_L &= \frac{3\lambda_3 m_q v Y_q^2}{16\pi^2} C_2(m_q^2, m_H^2, m_q^2, M_\chi^2, M_S^2, M_S^2), \\ f_R &= \frac{3\lambda_3 m_q v Y_q^2}{16\pi^2} C_1(m_q^2, m_H^2, m_q^2, M_\chi^2, M_S^2, M_S^2). \end{aligned} \quad (\text{A.5})$$

δf_L and δf_R are the counterterms given by [87]

$$\begin{aligned} \delta f_L &= \frac{m_q e}{2s_W M_W} \left[1 + \delta Z_e - \frac{\delta s_W}{s_W} + \frac{\delta m_q}{m_q} - \frac{\delta M_W}{M_W} + \frac{1}{2}\delta Z_H + \frac{1}{2} \left(\delta Z_{qq}^R + \delta Z_{qq}^{L,\dagger} \right) \right], \\ \delta f_R &= \frac{m_q e}{2s_W M_W} \left[1 + \delta Z_e - \frac{\delta s_W}{s_W} + \frac{\delta m_q}{m_q} - \frac{\delta M_W}{M_W} + \frac{1}{2}\delta Z_H + \frac{1}{2} \left(\delta Z_{qq}^L + \delta Z_{qq}^{R,\dagger} \right) \right], \end{aligned} \quad (\text{A.6})$$

⁶The choice of a negative value of λ_3 may lead to vacuum configurations that break the color symmetry. Here we only show the results for comparison since an analysis of the color-breaking minima is beyond the scope of this work.

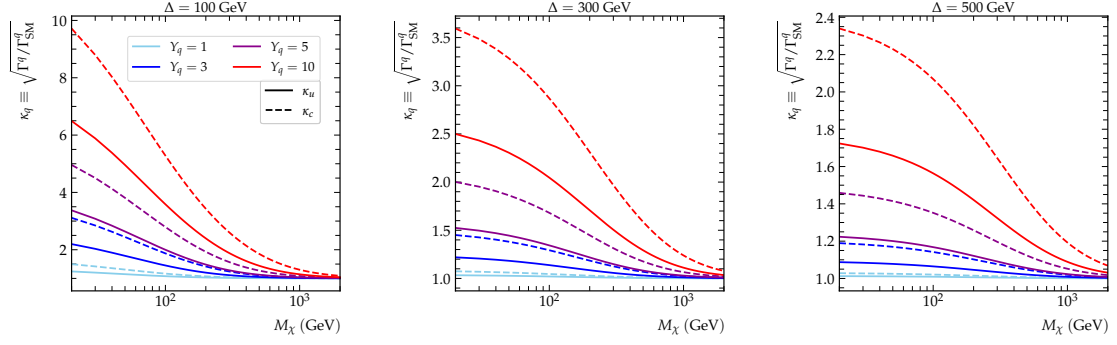


Figure 8. Dependence of κ_q on the dark-matter mass (M_χ) for $\Delta = 100$ GeV (left panel), $\Delta = 300$ GeV (middle panel) and $\Delta = 500$ GeV (right panel). Here, we show the results for κ_c (solid lines) and κ_u (dashed lines). For each panel, the results are shown for $Y_q = 1$ (purple), $Y_q = 3$ (blue), $Y_q = 5$ (purple) and $Y_q = 10$ (red).

the renormalization constants δZ are easily calculated:

$$\begin{aligned}
\delta M_Z^2 &= \frac{-\alpha s_W^2}{c_W^2 \pi} \left(\frac{-2}{3} A_0(M_S^2) + \frac{4}{3} B_{00}(M_Z^2, M_S^2, M_S^2) \right), \quad \delta M_W^2 = 0, \\
\delta Z_e &= \frac{1}{2} \left(-\delta Z_{\gamma\gamma} - \frac{s_W}{c_W} \delta Z_{Z\gamma} \right), \quad \delta s_W = \frac{c_W^2}{2s_W} \left(-\frac{\delta M_W^2}{M_W^2} + \frac{\delta M_Z^2}{M_Z^2} \right), \\
\delta Z_{\gamma\gamma} &= \frac{4\alpha}{3\pi} \frac{\partial}{\partial q^2} B_{00}(q^2, M_S^2, M_S^2) \Big|_{q^2=0}, \quad \delta Z_H = \frac{3\alpha \lambda_3^2 M_W^2}{\pi s_W^2} \frac{\partial}{\partial q^2} B_0(q^2, M_S^2, M_S^2) \Big|_{q^2=m_H^2}, \\
\delta Z_{Z\gamma} &= \frac{-2\alpha s_W}{c_W M_Z^2 \pi} \left(\frac{-2}{3} A_0(M_S^2) + \frac{4}{3} B_{00}(M_Z^2, M_S^2, M_S^2) \right), \tag{A.7} \\
\delta Z_{qq}^L &= \frac{m_q^2 Y_q^2}{16\pi^2} \frac{\partial}{\partial q^2} B_1(q^2, M_\chi^2, M_S^2) \Big|_{q^2=m_q^2}, \quad \delta m_q = \frac{-1}{32} \frac{m_q Y_q^2}{\pi^2} B_1(m_q^2, M_\chi^2, M_S^2), \\
\delta Z_{qq}^R &= \frac{Y_q^2}{16\pi^2} \left(B_1(m_q^2, M_\chi^2, M_S^2) + m_q^2 \frac{\partial}{\partial q^2} B_1(q^2, M_\chi^2, M_S^2) \Big|_{q^2=m_q^2} \right).
\end{aligned}$$

The numerical evaluation of the fermionic decay widths has been done using a customised `Python` code employing `PYCOLLIER` [88]⁷. The results of our calculations are shown in fig. 8 where we show κ_u (solid) and κ_c (dashed) as a function of M_χ for $\Delta = 100$ GeV (left), $\Delta = 300$ GeV (middle) and $\Delta = 500$ GeV (right). We can see that unless the couplings Y_q are very large, *i.e.* $Y_q > 5$ or so, the corrections to κ_q are always small. For large M_χ , all the corrections are decoupling and κ_q reach their SM values.

B Contribution to the ρ parameter

In this section, we demonstrate that our model give a zero contribution to the ρ parameter (this was mentioned in section 2). We explicitly calculate the contribution to the ρ

⁷`PYCOLLIER` is a `Python` wrapper of the `COLLIER` library [89].

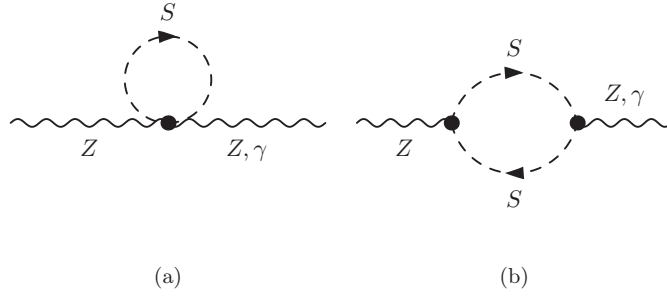


Figure 9. Examples of Feynman diagrams that contribute to ZZ and $Z\gamma$ self energies at the one-loop order.

parameter at the one-loop order where the leading order Feynman diagrams in this model are shown in fig. 9. The expression of $\Delta\rho$ is given by

$$\Delta\rho = \left(\frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2} - \frac{2s_W}{c_W} \frac{\Pi_{Z\gamma}(0)}{M_Z^2} \right), \quad (\text{B.1})$$

where $\Pi_{VV'}(q^2)$ is the contribution to the 1PI two-point function and $s_W = \sin^2 \theta_W$ is the sine of the Weinberg mixing angle. Since the colored scalar mediator is a singlet under $SU(2)_L$, its contribution to the W -boson self energy is exactly zero. Using FEYNARTS and FORMCALC, we have:

$$\begin{aligned} \Pi_{ZZ}(0) &= -\frac{g_1^2 s_W^2}{\pi^2} \left(\frac{1}{6} A_0(M_S^2) - \frac{1}{3} B_{00}(0, M_S^2, M_S^2) \right), \\ \Pi_{Z\gamma}(0) &= \frac{g_1^2 s_W c_W}{\pi^2} \left(\frac{1}{6} A_0(M_S^2) - \frac{1}{3} B_{00}(0, M_S^2, M_S^2) \right), \end{aligned} \quad (\text{B.2})$$

where $A_0(x)$ and $B_{00}(0, x, x)$ are the one- and two-point scalar loop functions and $g_1 = e/c_W$ is the $U(1)_Y$ gauge coupling. We get

$$\Delta\rho = -\frac{3g_1^2 s_W^2}{\pi^2 M_Z^2} \left(\frac{1}{6} A_0(M_S^2) - \frac{1}{3} B_{00}(0, M_S^2, M_S^2) \right). \quad (\text{B.3})$$

We must note that $\Delta\rho$ given above is free of UV divergences since the UV divergent part of the two Passarino-Veltman functions is

$$\text{Div}[A_0(m^2)] \equiv m^2 \Delta, \quad \text{Div}[B_{00}(p^2, m_1^2, m_2^2)] \equiv \left(\frac{m_1^2 + m_2^2}{4} - \frac{p^2}{2} \right) \Delta, \quad (\text{B.4})$$

where $\Delta = 2/\epsilon + \log(4\pi) - \gamma_E$. In our case the UV divergent part of A_0 and B_{00} satisfy $\text{Div}[A_0] = 2 \times \text{Div}[B_{00}]$ which imply that $\text{Div}[\Delta\rho] = 0$.

C Renormalization group equations and high-energy behavior

In this section we show the details of the renormalization group equations (RGEs) relevant for the analysis of section 6. The beta function for a parameter X is given by

$$\beta(X) \equiv \mu \frac{dX}{d\mu} \equiv \frac{1}{(4\pi)^2} \beta^{(1)}(X) + \frac{1}{(4\pi)^4} \beta^{(2)}(X) + \dots, \quad (\text{C.1})$$

where $\beta^{(1)}(X)$ and $\beta^{(2)}$ refer to the beta functions at the one-loop and two-order respectively. Higher order corrections are encoded in the \dots . The calculation of the beta functions was performed using `PyR@Te` version 3.0 [90]. Below we give the expression of the beta functions for the new parameters of the model at the one- and the two-loop orders. In what follows, $L_t = (Y_u, Y_c, Y_t)^T$.

C.1 Dark-matter couplings

$$\beta^{(1)}(L_t) = +Y_u^\dagger Y_u L_t + 4L_t L_t^\dagger L_t + 2\text{Tr}\left(L_t^\dagger L_t\right) L_t - \frac{4}{5}g_1^2 L_t - 4g_3^2 L_t,$$

$$\begin{aligned} \beta^{(2)}(L_t) = & -\frac{1}{4}Y_u^\dagger Y_u Y_u^\dagger Y_u L_t - \frac{1}{4}Y_u^\dagger Y_d Y_d^\dagger Y_u L_t - \frac{3}{2}L_t L_t^\dagger Y_u^\dagger Y_u L_t + 5L_t L_t^\dagger L_t L_t^\dagger L_t \\ & - \frac{9}{2}\text{Tr}\left(Y_u^\dagger Y_u\right) Y_u^\dagger Y_u L_t - 3\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger\right) L_t - \frac{9}{2}\text{Tr}\left(Y_d^\dagger Y_d\right) Y_u^\dagger Y_u L_t \\ & - \frac{3}{2}\text{Tr}\left(Y_e^\dagger Y_e\right) Y_u^\dagger Y_u L_t - 12\text{Tr}\left(L_t^\dagger L_t L_t^\dagger L_t\right) L_t - 12\text{Tr}\left(L_t^\dagger L_t\right) L_t L_t^\dagger L_t \\ & - 8\lambda_3 Y_u^\dagger Y_u L_t - 128\lambda_2 L_t L_t^\dagger L_t + 128\lambda_2^2 L_t + 4\lambda_3^2 L_t + \frac{49}{120}g_1^2 Y_u^\dagger Y_u L_t \\ & + \frac{51}{8}g_2^2 Y_u^\dagger Y_u L_t - \frac{16}{3}g_3^2 Y_u^\dagger Y_u L_t + \frac{268}{15}g_1^2 L_t L_t^\dagger L_t + \frac{124}{3}g_3^2 L_t L_t^\dagger L_t \\ & + \frac{4}{3}g_1^2 \text{Tr}\left(L_t^\dagger L_t\right) L_t + \frac{20}{3}g_3^2 \text{Tr}\left(L_t^\dagger L_t\right) L_t + \frac{232}{225}g_1^4 L_t - \frac{64}{15}g_1^2 g_3^2 L_t - \frac{181}{9}g_3^4 L_t. \end{aligned}$$

C.2 Quartic couplings

$$\begin{aligned} \beta^{(1)}(\lambda_1) = & +24\lambda_1^2 + 12\lambda_3^2 - \frac{9}{5}g_1^2 \lambda_1 - 9g_2^2 \lambda_1 + \frac{27}{200}g_1^4 + \frac{9}{20}g_1^2 g_2^2 + \frac{9}{8}g_2^4 + 12\lambda_1 \text{Tr}\left(Y_u^\dagger Y_u\right) \\ & + 12\lambda_1 \text{Tr}\left(Y_d^\dagger Y_d\right) + 4\lambda_1 \text{Tr}\left(Y_e^\dagger Y_e\right) - 6\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u\right) - 6\text{Tr}\left(Y_d^\dagger Y_d Y_d^\dagger Y_d\right) \\ & - 2\text{Tr}\left(Y_e^\dagger Y_e Y_e^\dagger Y_e\right), \end{aligned}$$

$$\begin{aligned} \beta^{(2)}(\lambda_1) = & -312\lambda_1^3 - 120\lambda_1 \lambda_3^2 - 96\lambda_3^3 + \frac{108}{5}g_1^2 \lambda_1^2 + 108g_2^2 \lambda_1^2 + \frac{128}{5}g_1^2 \lambda_3^2 + 128g_3^2 \lambda_3^2 \\ & + \frac{2063}{200}g_1^4 \lambda + \frac{117}{20}g_1^2 g_2^2 \lambda - \frac{73}{8}g_2^4 \lambda + \frac{24}{5}g_1^4 \lambda_3 - \frac{3747}{2000}g_1^6 - \frac{1789}{400}g_1^4 g_2^2 - \frac{289}{80}g_1^2 g_2^4 \\ & + \frac{305}{16}g_2^6 - 144\lambda_1^2 \text{Tr}\left(Y_u^\dagger Y_u\right) - 144\lambda_1^2 \text{Tr}\left(Y_d^\dagger Y_d\right) - 48\lambda_1^2 \text{Tr}\left(Y_e^\dagger Y_e\right) \\ & - 48\lambda_3^2 \text{Tr}\left(L_t^\dagger L_t\right) + \frac{17}{2}g_1^2 \lambda_1 \text{Tr}\left(Y_u^\dagger Y_u\right) + \frac{5}{2}g_1^2 \lambda_1 \text{Tr}\left(Y_d^\dagger Y_d\right) + \frac{15}{2}g_1^2 \lambda_1 \text{Tr}\left(Y_e^\dagger Y_e\right) \\ & + \frac{45}{2}g_2^2 \lambda_1 \text{Tr}\left(Y_u^\dagger Y_u\right) + \frac{45}{2}g_2^2 \lambda_1 \text{Tr}\left(Y_d^\dagger Y_d\right) + \frac{15}{2}g_2^2 \lambda_1 \text{Tr}\left(Y_e^\dagger Y_e\right) \\ & + 80g_3^2 \lambda_1 \text{Tr}\left(Y_u^\dagger Y_u\right) + 80g_3^2 \lambda_1 \text{Tr}\left(Y_d^\dagger Y_d\right) - \frac{171}{100}g_1^4 \text{Tr}\left(Y_u^\dagger Y_u\right) + \frac{9}{20}g_1^4 \text{Tr}\left(Y_d^\dagger Y_d\right) \\ & - \frac{9}{4}g_1^4 \text{Tr}\left(Y_e^\dagger Y_e\right) + \frac{63}{10}g_1^2 g_2^2 \text{Tr}\left(Y_u^\dagger Y_u\right) + \frac{27}{10}g_1^2 g_2^2 \text{Tr}\left(Y_d^\dagger Y_d\right) + \frac{33}{10}g_1^2 g_2^2 \text{Tr}\left(Y_e^\dagger Y_e\right) \end{aligned}$$

$$\begin{aligned}
& -\frac{9}{4}g_2^4\text{Tr}\left(Y_u^\dagger Y_u\right) - \frac{9}{4}g_2^4\text{Tr}\left(Y_d^\dagger Y_d\right) - \frac{3}{4}g_2^4\text{Tr}\left(Y_e^\dagger Y_e\right) - 3\lambda_1\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u\right) \\
& - 18\lambda_1\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger\right) - 42\lambda_1\text{Tr}\left(Y_u^\dagger Y_d Y_d^\dagger Y_u\right) - 3\lambda_1\text{Tr}\left(Y_d^\dagger Y_d Y_d^\dagger Y_d\right) \\
& - \lambda_1\text{Tr}\left(Y_e^\dagger Y_e Y_e^\dagger Y_e\right) - \frac{8}{5}g_1^2\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u\right) + \frac{4}{5}g_1^2\text{Tr}\left(Y_d^\dagger Y_d Y_d^\dagger Y_d\right) \\
& - \frac{12}{5}g_1^2\text{Tr}\left(Y_e^\dagger Y_e Y_e^\dagger Y_e\right) - 32g_3^2\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u\right) - 32g_3^2\text{Tr}\left(Y_d^\dagger Y_d Y_d^\dagger Y_d\right) \\
& + 30\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u Y_u^\dagger Y_u\right) + 12\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u L_t L_t^\dagger\right) - 6\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_d Y_d^\dagger Y_u\right) \\
& - 6\text{Tr}\left(Y_u^\dagger Y_d Y_d^\dagger Y_d Y_d^\dagger Y_u\right) + 30\text{Tr}\left(Y_d^\dagger Y_d Y_d^\dagger Y_d Y_d^\dagger Y_d\right) + 10\text{Tr}\left(Y_e^\dagger Y_e Y_e^\dagger Y_e Y_e^\dagger Y_e\right),
\end{aligned}$$

$$\begin{aligned}
\beta^{(1)}(\lambda_2) = & + 112\lambda_2^2 + 2\lambda_3^2 - \frac{16}{5}g_1^2\lambda_2 - 16g_3^2\lambda_2 + \frac{8}{75}g_1^4 + \frac{4}{15}g_1^2g_3^2 + \frac{13}{24}g_3^4 + 8\lambda_2\text{Tr}\left(L_t^\dagger L_t\right) \\
& - 2\text{Tr}\left(L_t^\dagger L_t L_t^\dagger L_t\right),
\end{aligned}$$

$$\begin{aligned}
\beta^{(2)}(\lambda_2) = & - 6144\lambda_2^3 - 80\lambda_2\lambda_3^2 - 16\lambda_3^3 + \frac{2816}{15}g_1^2\lambda_2^2 + \frac{2816}{3}g_3^2\lambda_2^2 + \frac{12}{5}g_1^2\lambda_3^2 + 12g_2^2\lambda_3^2 \\
& + \frac{5732}{225}g_1^4\lambda_2 + \frac{704}{45}g_1^2g_3^2\lambda_2 - \frac{212}{3}g_3^4\lambda_2 + \frac{4}{5}g_1^4\lambda_3 - \frac{5416}{3375}g_1^6 - \frac{2554}{675}g_1^4g_3^2 \\
& - \frac{398}{135}g_1^2g_3^4 + \frac{349}{27}g_3^6 - 448\lambda_2^2\text{Tr}\left(L_t^\dagger L_t\right) - 12\lambda_3^2\text{Tr}\left(Y_u^\dagger Y_u\right) - 12\lambda_3^2\text{Tr}\left(Y_d^\dagger Y_d\right) \\
& - 4\lambda_3^2\text{Tr}\left(Y_e^\dagger Y_e\right) + \frac{16}{3}g_1^2\lambda_2\text{Tr}\left(L_t^\dagger L_t\right) + \frac{80}{3}g_3^2\lambda_2\text{Tr}\left(L_t^\dagger L_t\right) - \frac{32}{225}g_1^4\text{Tr}\left(L_t^\dagger L_t\right) \\
& - \frac{16}{45}g_1^2g_3^2\text{Tr}\left(L_t^\dagger L_t\right) - \frac{13}{18}g_3^4\text{Tr}\left(L_t^\dagger L_t\right) - 12\lambda_2\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger\right) \\
& - 16\lambda_2\text{Tr}\left(L_t^\dagger L_t L_t^\dagger L_t\right) + 4\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger L_t L_t^\dagger\right) + 24\text{Tr}\left(L_t^\dagger L_t L_t^\dagger L_t L_t^\dagger L_t\right),
\end{aligned}$$

$$\begin{aligned}
\beta^{(1)}(\lambda_3) = & + 12\lambda_1\lambda_3 + 64\lambda_2\lambda_3 + 8\lambda_3^2 - \frac{5}{2}g_1^2\lambda_3 - \frac{9}{2}g_2^2\lambda_3 - 8g_3^2\lambda_3 + \frac{6}{25}g_1^4 + 6\lambda_3\text{Tr}\left(Y_u^\dagger Y_u\right) \\
& + 6\lambda_3\text{Tr}\left(Y_d^\dagger Y_d\right) + 2\lambda_3\text{Tr}\left(Y_e^\dagger Y_e\right) + 4\lambda_3\text{Tr}\left(L_t^\dagger L_t\right) - 4\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger\right),
\end{aligned}$$

$$\begin{aligned}
\beta^{(2)}(\lambda_3) = & - 144\lambda_1\lambda_3^2 - 768\lambda_2\lambda_3^2 - 60\lambda_1^2\lambda_3 - 1280\lambda_2^2\lambda_3 - 52\lambda_3^3 + \frac{72}{5}g_1^2\lambda_1\lambda_3 + 72g_2^2\lambda_1\lambda_3 \\
& + \frac{2048}{15}g_1^2\lambda_2\lambda_3 + \frac{2048}{3}g_3^2\lambda_2\lambda_3 + \frac{10}{3}g_1^2\lambda_3^2 + 6g_2^2\lambda_3^2 + \frac{32}{3}g_3^2\lambda_3^2 + \frac{12}{5}g_1^4\lambda + \frac{64}{5}g_1^4\lambda_2 \\
& + \frac{57487}{3600}g_1^4\lambda_3 + \frac{9}{8}g_1^2g_2^2\lambda_3 + \frac{32}{9}g_1^2g_3^2\lambda_3 - \frac{145}{16}g_2^4\lambda_3 - 44g_3^4\lambda_3 - \frac{2603}{750}g_1^6 - \frac{9}{10}g_1^4g_2^2 \\
& - \frac{8}{5}g_1^4g_3^2 - 72\lambda_1\lambda_3\text{Tr}\left(Y_u^\dagger Y_u\right) - 72\lambda_1\lambda_3\text{Tr}\left(Y_d^\dagger Y_d\right) - 24\lambda_1\lambda_3\text{Tr}\left(Y_e^\dagger Y_e\right) \\
& - 256\lambda_2\lambda_3\text{Tr}\left(L_t^\dagger L_t\right) - 24\lambda_3^2\text{Tr}\left(Y_u^\dagger Y_u\right) - 24\lambda_3^2\text{Tr}\left(Y_d^\dagger Y_d\right) - 8\lambda_3^2\text{Tr}\left(Y_e^\dagger Y_e\right) \\
& - 16\lambda_3^2\text{Tr}\left(L_t^\dagger L_t\right) + \frac{17}{4}g_1^2\lambda_3\text{Tr}\left(Y_u^\dagger Y_u\right) + \frac{5}{4}g_1^2\lambda_3\text{Tr}\left(Y_d^\dagger Y_d\right) + \frac{15}{4}g_1^2\lambda_3\text{Tr}\left(Y_e^\dagger Y_e\right)
\end{aligned}$$

$$\begin{aligned}
& + \frac{8}{3}g_1^2\lambda_3\text{Tr}\left(L_t^\dagger L_t\right) + \frac{45}{4}g_2^2\lambda_3\text{Tr}\left(Y_u^\dagger Y_u\right) + \frac{45}{4}g_2^2\lambda_3\text{Tr}\left(Y_d^\dagger Y_d\right) \\
& + \frac{15}{4}g_2^2\lambda_3\text{Tr}\left(Y_e^\dagger Y_e\right) + 40g_3^2\lambda_3\text{Tr}\left(Y_u^\dagger Y_u\right) + 40g_3^2\lambda_3\text{Tr}\left(Y_d^\dagger Y_d\right) \\
& + \frac{40}{3}g_3^2\lambda_3\text{Tr}\left(L_t^\dagger L_t\right) - \frac{38}{25}g_1^4\text{Tr}\left(Y_u^\dagger Y_u\right) + \frac{2}{5}g_1^4\text{Tr}\left(Y_d^\dagger Y_d\right) - 2g_1^4\text{Tr}\left(Y_e^\dagger Y_e\right) \\
& - \frac{4}{25}g_1^4\text{Tr}\left(L_t^\dagger L_t\right) - 16g_3^4\text{Tr}\left(Y_u^\dagger Y_u\right) - 16g_3^4\text{Tr}\left(Y_d^\dagger Y_d\right) - \frac{27}{2}\lambda_3\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u\right) \\
& + \lambda_3\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger\right) - 21\lambda_3\text{Tr}\left(Y_u^\dagger Y_d Y_d^\dagger Y_u\right) - \frac{27}{2}\lambda_3\text{Tr}\left(Y_d^\dagger Y_d Y_d^\dagger Y_d\right) \\
& - \frac{9}{2}\lambda_3\text{Tr}\left(Y_e^\dagger Y_e Y_e^\dagger Y_e\right) - 24\lambda_3\text{Tr}\left(L_t^\dagger L_t L_t^\dagger L_t\right) - \frac{8}{15}g_1^2\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger\right) \\
& - \frac{32}{3}g_3^2\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger\right) + 14\text{Tr}\left(Y_u^\dagger Y_u Y_u^\dagger Y_u L_t L_t^\dagger\right) + 44\text{Tr}\left(Y_u^\dagger Y_u L_t L_t^\dagger L_t L_t^\dagger\right) \\
& - 2\text{Tr}\left(Y_u^\dagger Y_d Y_d^\dagger Y_u L_t L_t^\dagger\right).
\end{aligned}$$

References

- [1] S. L. Glashow, J. Iliopoulos, and L. Maiani, *Weak Interactions with Lepton-Hadron Symmetry*, *Phys. Rev. D* **2** (1970) 1285–1292.
- [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, 039901 (1999)].
- [3] W.-S. Hou, *Tree level $t \rightarrow c h$ or $h \rightarrow t$ anti- c decays*, *Phys. Lett. B* **296** (1992) 179–184.
- [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, [[hep-ph/9609279](#)].
- [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, [[hep-ph/9702350](#)].
- [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, [[hep-ph/9705341](#)].
- [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, [[hep-ph/0102037](#)].
- [8] J. A. Aguilar-Saavedra, *Top flavor-changing neutral interactions: Theoretical expectations and experimental detection*, *Acta Phys. Polon. B* **35** (2004) 2695–2710, [[hep-ph/0409342](#)].
- [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, [[hep-ph/0410268](#)].
- [10] M. Frank and I. Turan, *$t \rightarrow cg, c\gamma, cZ$ in the left-right supersymmetric model*, *Phys. Rev. D* **72** (2005) 035008, [[hep-ph/0506197](#)].
- [11] S. Bejar, *Flavor changing neutral decay effects in models with two Higgs boson doublets: Applications to LHC Physics*, other thesis, 6, 2006.
- [12] 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, [[hep-ph/0606293](#)].

- [13] 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, [[hep-ph/0702264](#)].
- [14] 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, [[arXiv:0802.2622](#)].
- [15] K. Agashe and R. Contino, *Composite Higgs-Mediated FCNC*, *Phys. Rev. D* **80** (2009) 075016, [[arXiv:0906.1542](#)].
- [16] 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, [[arXiv:1303.0082](#)].
- [17] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho, and K. Tamvakis, *Rare Top-quark Decays to Higgs boson in MSSM*, *JHEP* **11** (2014) 137, [[arXiv:1409.6546](#)].
- [18] 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, [[arXiv:1503.06423](#)].
- [19] 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, [[arXiv:1508.05101](#)].
- [20] 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, [[arXiv:1602.03286](#)].
- [21] 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, [[arXiv:1603.08929](#)].
- [22] 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, [[arXiv:2103.07859](#)].
- [23] 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, [[arXiv:2204.05962](#)].
- [24] M. Frank, B. Fuks, S. K. Garg, and P. Poulose, *Flavour-changing top quark decays in the alternative left-right model*, [[arXiv:2312.12523](#)].
- [25] **ATLAS** Collaboration, G. Aad et al., *Search for flavour-changing neutral current top-quark decays to qZ in pp collision data collected with the ATLAS detector at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J. C* **76** (2016), no. 1 12, [[arXiv:1508.05796](#)].
- [26] **ATLAS** Collaboration, G. Aad et al., *Search for flavour-changing neutral current top quark decays $t \rightarrow Hq$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *JHEP* **12** (2015) 061, [[arXiv:1509.06047](#)].
- [27] **ATLAS** Collaboration, M. Aaboud et al., *Search for top quark decays $t \rightarrow qH$, with $H \rightarrow \gamma\gamma$, in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector*, *JHEP* **10** (2017) 129, [[arXiv:1707.01404](#)].
- [28] **ATLAS** Collaboration, M. Aaboud et al., *Search for flavour-changing neutral current top-quark decays $t \rightarrow qZ$ in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **07** (2018) 176, [[arXiv:1803.09923](#)].
- [29] **ATLAS** Collaboration, M. Aaboud et al., *Search for flavor-changing neutral currents in top quark decays $t \rightarrow Hc$ and $t \rightarrow Hu$ in multilepton final states in proton-proton collisions at*

- $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Rev. D* **98** (2018), no. 3 032002, [[arXiv:1805.03483](#)].
- [30] **ATLAS** Collaboration, M. Aaboud et al., *Search for top-quark decays $t \rightarrow Hq$ with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **05** (2019) 123, [[arXiv:1812.11568](#)].
- [31] **ATLAS** Collaboration, G. Aad et al., *Search for flavour-changing neutral currents in processes with one top quark and a photon using 81 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment*, *Phys. Lett. B* **800** (2020) 135082, [[arXiv:1908.08461](#)].
- [32] **ATLAS** Collaboration, G. Aad et al., *Search for flavour-changing neutral-current interactions of a top quark and a gluon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **82** (2022), no. 4 334, [[arXiv:2112.01302](#)].
- [33] **ATLAS** Collaboration, G. Aad et al., *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, [[arXiv:2205.02537](#)].
- [34] **ATLAS** Collaboration, G. Aad et al., *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, [[arXiv:2301.11605](#)].
- [35] **ATLAS** Collaboration, G. Aad et al., *Search for flavor-changing neutral tqH interactions with $H \rightarrow \gamma\gamma$ in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector*, [[arXiv:2309.12817](#)].
- [36] **CMS** Collaboration, S. Chatrchyan et al., *Search for Flavor-Changing Neutral Currents in Top-Quark Decays $t \rightarrow Zq$ in pp Collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev. Lett.* **112** (2014), no. 17 171802, [[arXiv:1312.4194](#)].
- [37] **CMS** Collaboration, V. Khachatryan et al., *Search for top quark decays via Higgs-boson-mediated flavor-changing neutral currents in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **02** (2017) 079, [[arXiv:1610.04857](#)].
- [38] **CMS** Collaboration, A. M. Sirunyan et al., *Search for associated production of a Z boson with a single top quark and for tZ flavour-changing interactions in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **07** (2017) 003, [[arXiv:1702.01404](#)].
- [39] **CMS** Collaboration, A. M. Sirunyan et al., *Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at $\sqrt{s} = 13$ TeV*, *JHEP* **06** (2018) 102, [[arXiv:1712.02399](#)].
- [40] **CMS** Collaboration, A. Tumasyan et al., *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, [[arXiv:2112.09734](#)].
- [41] S. Chang, R. Edezhath, J. Hutchinson, and M. Luty, *Effective WIMPs*, *Phys. Rev. D* **89** (2014), no. 1 015011, [[arXiv:1307.8120](#)].
- [42] H. An, L.-T. Wang, and H. Zhang, *Dark matter with t-channel mediator: a simple step beyond contact interaction*, *Phys. Rev. D* **89** (2014), no. 11 115014, [[arXiv:1308.0592](#)].
- [43] A. DiFranzo, K. I. Nagao, A. Rajaraman, and T. M. P. Tait, *Simplified Models for Dark Matter Interacting with Quarks*, *JHEP* **11** (2013) 014, [[arXiv:1308.2679](#)]. [Erratum: *JHEP* **01**, 162 (2014)].

- [44] A. Ibarra and S. Wild, *Dirac dark matter with a charged mediator: a comprehensive one-loop analysis of the direct detection phenomenology*, *JCAP* **05** (2015) 047, [[arXiv:1503.03382](#)].
- [45] M. Garny, A. Ibarra, and S. Vogl, *Signatures of Majorana dark matter with t -channel mediators*, *Int. J. Mod. Phys. D* **24** (2015), no. 07 1530019, [[arXiv:1503.01500](#)].
- [46] P. Ko, A. Natale, M. Park, and H. Yokoya, *Simplified DM models with the full SM gauge symmetry : the case of t -channel colored scalar mediators*, *JHEP* **01** (2017) 086, [[arXiv:1605.07058](#)].
- [47] 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, [[arXiv:1903.05650](#)]. [Erratum: *JHEP* **05**, 232 (2023)].
- [48] 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, [[arXiv:2001.05024](#)].
- [49] 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, [[arXiv:2010.07559](#)].
- [50] 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, [[arXiv:2203.04326](#)].
- [51] 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, [[arXiv:2307.10367](#)].
- [52] **Top Quark Working Group** Collaboration, K. Agashe et al., *Working Group Report: Top Quark*, in *Snowmass 2013: Snowmass on the Mississippi*, 11, 2013. [[arXiv:1311.2028](#)].
- [53] T. Hahn, *Generating Feynman diagrams and amplitudes with FeynArts 3*, *Comput. Phys. Commun.* **140** (2001) 418–431, [[hep-ph/0012260](#)].
- [54] T. Hahn, *A Mathematica interface for FormCalc-generated code*, *Comput. Phys. Commun.* **178** (2008) 217–221, [[hep-ph/0611273](#)].
- [55] T. Hahn, *Loop calculations with FeynArts, FormCalc, and LoopTools*, *Acta Phys. Polon. B* **30** (1999) 3469–3475, [[hep-ph/9910227](#)].
- [56] G. Passarino and M. J. G. Veltman, *One Loop Corrections for $e^+ e^-$ Annihilation Into $\mu^+ \mu^-$ in the Weinberg Model*, *Nucl. Phys. B* **160** (1979) 151–207.
- [57] 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, [[arXiv:1210.2808](#)].
- [58] K. Griest and D. Seckel, *Three exceptions in the calculation of relic abundances*, *Phys. Rev. D* **43** (1991) 3191–3203.
- [59] G. Servant and T. M. P. Tait, *Is the lightest Kaluza-Klein particle a viable dark matter candidate?*, *Nucl. Phys. B* **650** (2003) 391–419, [[hep-ph/0206071](#)].
- [60] K. Kong and K. T. Matchev, *Precise calculation of the relic density of Kaluza-Klein dark matter in universal extra dimensions*, *JHEP* **01** (2006) 038, [[hep-ph/0509119](#)].
- [61] G. Bélanger, F. Boudjema, A. Goudelis, A. Pukhov, and B. Zaldivar, *micrOMEGAs5.0 : Freeze-in*, *Comput. Phys. Commun.* **231** (2018) 173–186, [[arXiv:1801.03509](#)].

- [62] F. Ambrogio, C. Arina, M. Backovic, J. Heisig, F. Maltoni, L. Mantani, O. Mattelaer, and G. Mohlabeng, *MadDM v.3.0: a Comprehensive Tool for Dark Matter Studies*, *Phys. Dark Univ.* **24** (2019) 100249, [[arXiv:1804.00044](#)].
- [63] G. Belanger et al., *Leptoquark manoeuvres in the dark: a simultaneous solution of the dark matter problem and the $R_{D^{(*)}}$ anomalies*, *JHEP* **02** (2022) 042, [[arXiv:2111.08027](#)].
- [64] **XENON** Collaboration, E. Aprile et al., *Dark Matter Search Results from a One Ton-Year Exposure of XENON1T*, *Phys. Rev. Lett.* **121** (2018), no. 11 111302, [[arXiv:1805.12562](#)].
- [65] **ATLAS** Collaboration, G. Aad et al., *Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Rev. D* **103** (2021), no. 11 112006, [[arXiv:2102.10874](#)].
- [66] E. Conte, B. Fuks, and G. Serret, *MadAnalysis 5, A User-Friendly Framework for Collider Phenomenology*, *Comput. Phys. Commun.* **184** (2013) 222–256, [[arXiv:1206.1599](#)].
- [67] E. Conte, B. Dumont, B. Fuks, and C. Wymant, *Designing and recasting LHC analyses with MadAnalysis 5*, *Eur. Phys. J. C* **74** (2014), no. 10 3103, [[arXiv:1405.3982](#)].
- [68] B. Dumont, B. Fuks, S. Kraml, S. Bein, G. Chalons, E. Conte, S. Kulkarni, D. Sengupta, and C. Wymant, *Toward a public analysis database for LHC new physics searches using MADANALYSIS 5*, *Eur. Phys. J. C* **75** (2015), no. 2 56, [[arXiv:1407.3278](#)].
- [69] E. Conte and B. Fuks, *Confronting new physics theories to LHC data with MADANALYSIS 5*, *Int. J. Mod. Phys. A* **33** (2018), no. 28 1830027, [[arXiv:1808.00480](#)].
- [70] D. Agin, *Implementation of a search for new physics with jets and missing transverse energy (139/fb; 13 TeV; ATLAS-EXOT-2018-06)*, 2023.
- [71] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, [[arXiv:1405.0301](#)].
- [72] **NNPDF** Collaboration, R. D. Ball et al., *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017), no. 10 663, [[arXiv:1706.00428](#)].
- [73] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, *LHAPDF6: parton density access in the LHC precision era*, *Eur. Phys. J. C* **75** (2015) 132, [[arXiv:1412.7420](#)].
- [74] C. Bierlich et al., *A comprehensive guide to the physics and usage of PYTHIA 8.3*, *SciPost Phys. Codeb.* **2022** (2022) 8, [[arXiv:2203.11601](#)].
- [75] M. Cacciari, G. P. Salam, and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063, [[arXiv:0802.1189](#)].
- [76] M. Cacciari, G. P. Salam, and G. Soyez, *FastJet User Manual*, *Eur. Phys. J. C* **72** (2012) 1896, [[arXiv:1111.6097](#)].
- [77] J. Y. Araz, B. Fuks, and G. Polykratis, *Simplified fast detector simulation in MADANALYSIS 5*, *Eur. Phys. J. C* **81** (2021), no. 4 329, [[arXiv:2006.09387](#)].
- [78] L. Heinrich, M. Feickert, G. Stark, and K. Cranmer, *pyhf: pure-python implementation of histfactory statistical models*, *Journal of Open Source Software* **6** (2021), no. 58 2823.
- [79] A. Jueid and S. Kanemura, *In preparation*, .

- [80] **ATLAS** Collaboration, *Measurement of the properties of Higgs boson production at $\sqrt{s} = 13$ TeV in the $H \rightarrow \gamma\gamma$ channel using 139 fb^{-1} of pp collision data with the ATLAS experiment*, [arXiv:2207.00348](#).
- [81] A. Arhrib, R. Benbrik, J. El Falaki, and A. Jueid, *Radiative corrections to the Triple Higgs Coupling in the Inert Higgs Doublet Model*, *JHEP* **12** (2015) 007, [[arXiv:1507.03630](#)].
- [82] S. Kanemura, M. Kikuchi, and K. Sakurai, *Testing the dark matter scenario in the inert doublet model by future precision measurements of the Higgs boson couplings*, *Phys. Rev. D* **94** (2016), no. 11 115011, [[arXiv:1605.08520](#)].
- [83] S. Kanemura, M. Kikuchi, K. Sakurai, and K. Yagyu, *Gauge invariant one-loop corrections to Higgs boson couplings in non-minimal Higgs models*, *Phys. Rev. D* **96** (2017), no. 3 035014, [[arXiv:1705.05399](#)].
- [84] A. Djouadi, *The Anatomy of electro-weak symmetry breaking. I: The Higgs boson in the standard model*, *Phys. Rept.* **457** (2008) 1–216, [[hep-ph/0503172](#)].
- [85] K. G. Chetyrkin, *Correlator of the quark scalar currents and $\Gamma(\text{tot}) (H \rightarrow \text{hadrons})$ at $O(\alpha_s^3)$ in $p\text{QCD}$* , *Phys. Lett. B* **390** (1997) 309–317, [[hep-ph/9608318](#)].
- [86] K. G. Chetyrkin and M. Steinhauser, *Complete QCD corrections of order $O(\alpha_s^3)$ to the hadronic Higgs decay*, *Phys. Lett. B* **408** (1997) 320–324, [[hep-ph/9706462](#)].
- [87] A. Denner, *Techniques for calculation of electroweak radiative corrections at the one loop level and results for W physics at LEP-200*, *Fortsch. Phys.* **41** (1993) 307–420, [[arXiv:0709.1075](#)].
- [88] H. Bahl, J. Braathen, M. Gabelmann, and G. Weiglein, *anyH3: precise predictions for the trilinear Higgs coupling in the Standard Model and beyond*, [arXiv:2305.03015](#).
- [89] A. Denner, S. Dittmaier, and L. Hofer, *Collier: a fortran-based Complex One-Loop Library in Extended Regularizations*, *Comput. Phys. Commun.* **212** (2017) 220–238, [[arXiv:1604.06792](#)].
- [90] L. Sartore and I. Schienbein, *PyR@TE 3*, *Comput. Phys. Commun.* **261** (2021) 107819, [[arXiv:2007.12700](#)].