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Discovering dark matter through flavor violation at the LHC

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We show that the discovery channel for dark matter (DM) production at colliders can be through flavor violating interactions resulting in a novel signature of a single top and large missing transverse energy. We discuss several examples where the production of DM is dominated by flavor violating couplings: minimal flavor violating models with a large bottom Yukawa, models with horizontal symmetries, and DM in nontrivial flavor group representations. Discovery at the 7 TeV LHC with a few fb^{-1} may already be possible.

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I. INTRODUCTION

The matter fields of the standard model (SM) come in three generations, leading to distinct flavors of quarks and leptons. The gauge interactions do not distinguish between different generations and are flavor blind. The Yukawa interactions, on the other hand, are flavor violating. In the quark sector, the eigenvalues of the Yukawa matrices—the quark masses—are very hierarchical and span 5 orders of magnitude. Similar hierarchical structure is seen in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, where the smallest off-diagonal element is $V_{ub} \simeq 3 \times 10^{-3}$.

A distinguishing feature of the SM gauge and matter structure is that no flavor changing neutral currents (FCNCs) are generated at the leading perturbative order. They are further suppressed also by the smallness of the relevant CKM matrix elements. The agreement of predicted small FCNCs with the precision flavor experiments requires any new physics (NP) at the TeV scale to have a highly nontrivial flavor structure. Only small amount of flavor violation is allowed phenomenologically. The flavor violation cannot be completely absent, however. If nothing else, the flavor symmetry is broken already by the SM Yukawas. At least at loop level (and thus also from RG running) these will then feed into the interactions between NP and the SM sector. Thus, some amount of flavor violation in the interactions between NP and SM sector is unavoidable.

In this Letter, we explore the consequences of the above insight for the detection of dark matter (DM) at colliders. We will show that large effects are likely, leading to a prominent signal of a single top plus missing transverse energy (MET). A $t + \not{E}_T$ final state is an experimentally readily accessible channel. Since in the SM the production is both loop and CKM suppressed, an observation of a $t + \not{E}_T$ signal above the background would be a clear indication of NP at LHC. In fact, the $t + \not{E}_T$ could even be a discovery channel of DM for a large set of NP models. For instance, the cross section for $t + \not{E}_T$ can be orders of magnitude larger then the monojet cross section even in the case of minimal flavor violation (MFV), if the interactions are chirality flipping. Somewhat surprisingly, DM would then be discovered through flavor violating interactions. While this paper was being finalized, an analysis of $t + \not{E}_T$ experimental reach at LHC appeared in [1], where a name *monotop* was coined for the $t + \not{E}_T$ signature.

II. EFFECTIVE FIELD THEORY DESCRIPTION

We want to compare the flavor violating production of DM at colliders with the flavor conserving one. The comparison crucially depends on the size of flavor violation in the NP sector that contains DM. Let us start with a general discussion by using the simplifying assumption that all the NP states apart from DM are heavy enough so that we can integrate them out at a large scale Λ (we will later relax this assumption). We can then write down an effective field theory (EFT) for DM interactions with the SM quark matter sector [2]

$$\mathcal{L}_{\mathrm{int}} = \sum_a \frac{C_a}{\Lambda^{n_a}} \mathcal{O}_a. \tag{1}$$

The sum above runs over the full set of SU(2) gauge invariant operators $\mathcal{O}_a$ that are bilinear in quark fields. For simplicity, we assume that DM is not charged under SM gauge group, so that to $\mathcal{O}(n_a \leq 3)$

$$\begin{aligned} &\mathcal{O}_{1a}^{ij} = (\bar{Q}_L^i \gamma_\mu Q_L^j)\mathcal{J}_a^\mu, \qquad \mathcal{O}_{2a}^{ij} = (\bar{u}_R^i \gamma_\mu u_R^j)\mathcal{J}_a^\mu,\\ &\mathcal{O}_{3a}^{ij} = (\bar{d}_R^i \gamma_\mu d_R^j)\mathcal{J}_a^\mu, \qquad \mathcal{O}_{4a}^{ij} = (\bar{Q}_L^i H u_R^j)\mathcal{J}_a,\\ &\mathcal{O}_{5a}^{ij} = (\bar{Q}_L^i \tilde{H} d_R^j)\mathcal{J}_a, \end{aligned} \tag{2}$$

and we do not write down additional tensor operators (contractions of Lorentz tensors $\mathcal{J}_a^{\mu\nu}$) for which the same

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discussion as for $\mathcal{O}_{4a,5a}$ will apply. Here Q_L, u_R, and d_R are, respectively, the left-handed quark doublets, and right-handed up- and down- quarks, i, j are the generational indices, H is the SM Higgs doublet (with $\tilde{H} = i\sigma_2 H^*$), while $\mathcal{J}_a$ are the DM currents. Throughout this paper we assume that DM is odd under an exact Z_2. For fermionic DM χ, we then have $\mathcal{J}^\mu_{V,A} = \bar{\chi}\gamma^\mu\{1,\gamma_5\}\chi$, $\mathcal{J}_{S,P} = \bar{\chi}\{1,\gamma_5\}\chi$, (for Majorana fermion $\mathcal{J}^\mu_V = 0$), leading to $n_a = 2$ for $\mathcal{O}_{1a,\ldots,3a}$ in Eq. (1), while for $\mathcal{O}_{4a,5a}$ we have $n_a = 3$. For scalar DM $\mathcal{J} = \chi^\dagger\chi$, $\mathcal{J}^\mu = \chi^\dagger\partial^\mu\chi$, so that $n_a = 2$ for all operators in (2).

If DM is light enough the above operators can lead to FCNC decays of top [3], b [4], and even lighter quarks [5]. Then, there are contributions to $B_{d,s} - \bar{B}_{d,s}$ and $K - \bar{K}$ mixing with DM running in the loop and two insertions of operators $\mathcal{O}_{1a,3a,5a}$. This gives the bounds for couplings to the third generation [6] $\Lambda/\sqrt{C^{13}_{1a}} \gtrsim 2$ TeV and $\Lambda/\sqrt{C^{23}_{1a}} \gtrsim 0.3$ TeV, and bounds of similar size for $C^{13,23}_{3a,5a}$. The bounds on $C^{13,23}_{2a,4a}$ on the other hand, come from top decays but the EFT description breaks down before they are saturated. This indicates that large $t + \not{E}_T$ production signals from flavor violating couplings are possible at LHC and Tevatron. It would be interesting to see whether the more constrained (and thus more likely to come from flavor conserving operators) $b + \not{E}_T$ signal can be picked out from the background of (mistagged) jet+invisibly decaying Z events. From now on, we focus on the more promising $t + \not{E}_T$ channel and estimate its size in a number of models of flavor.

A. Minimal flavor violation

Let us first assume that the interactions of the mediators with the SM are minimally flavor violating, i.e. that the flavor is only broken by the SM Yukawas $Y_{u,d}$. Using the spurion analysis [7] the Wilson coefficients take the form

$$C_{2a} = b_1^{(2a)} + b_2^{(2a)} Y_u^\dagger Y_u + b_3^{(2a)} Y_u^\dagger Y_d Y_d^\dagger Y_u + \cdots, \qquad (3a)$$

$$C_{4a} = (b_1^{(4a)} + b_2^{(4a)} Y_d Y_d^\dagger + \cdots) Y_u. \qquad (3b)$$

In the up-quark mass eigenstate basis $Y_d = V_{\rm CKM}{\rm diag}(y_d, y_s, y_b)$ and $Y_u = {\rm diag}(y_u, y_c, y_t)$. In the following, let us assume that $b_1^a \sim b_2^a \sim b_3^a$ are all of the same order. The Wilson coefficient C_{2a} is then flavor diagonal and universal to a good approximation and flavor violating interactions for all practical purposes are negligible.

The situation is different for the chirality flipping operator C_{4a} that is proportional to Yukawa matrix Y_u. In this case, DM couples most strongly to the third generation, while the couplings to the first two generations are parametrically suppressed by $y_{u,c}/y_t$. This has important implications for the detection of DM at colliders. The flavor violating $qg \to t\chi\chi$ cross section is enhanced over the conserving one by (see also Fig. 1)

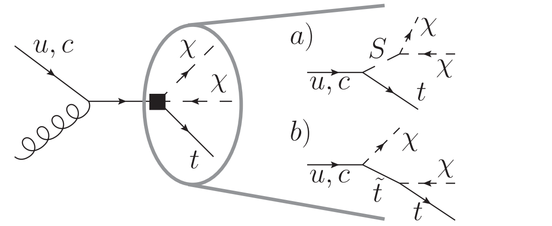

FIG. 1. Flavor violating DM production at collider in the EFT description (left) and for two on-shell models, (a) with a SM gauge singlet S, and (b) with a color triplet $\tilde{t}$ as a mediator.

$$\frac{\hat{\sigma}(ug \to t + 2\chi)}{\hat{\sigma}(ug \to u + 2\chi)} \sim \left(\frac{y_t |V_{ub}| y_b^2}{y_u}\right)^2 \sim 5 \times 10^5 y_b^4, \qquad (4a)$$

$$\frac{\hat{\sigma}(cg \to t + 2\chi)}{\hat{\sigma}(cg \to c + 2\chi)} \sim \left(\frac{y_t |V_{cb}| y_b^2}{y_c}\right)^2 \sim 50 y_b^4. \qquad (4b)$$

The $t + \not{E}_T$ signal can be significantly enhanced over the monojet signal even in the case of MFV, if two conditions are fulfilled, i) bottom Yukawa is large, preferably $y_b \sim O(1)$, and ii) DM couples to quarks through scalar interactions. We note in passing that DM coupling only through the SM Higgs portal would not lead to flavor violating effects. The above MFV counting thus assumes additional scalar interactions. Such interactions are, for instance, needed for isospin violating models proposed to explain CoGeNT and DAMA excesses [8] (see, however, also [9]).

In the rough estimates (4a) and (4b) we have neglected phase space effects and the role of pdfs. A more quantitative analysis using MADGRAPHV4 and CTEQ6L1 pdfs is shown on Fig. 2, where the ratio of production cross sections $\sigma(t + 2\chi)/\sigma(j + 2\chi)$ as a function of m_χ is shown for Tevatron and 7 TeV LHC assuming MFV sizes of flavor violating couplings with $b_i = 1$ and $y_b = 1$. We used $\not{E}_T > 80(120)$ GeV cuts at the partonic level for the Tevatron (LHC) cross sections, following [10,11]. We work in the EFT limit so that the mediator masses drop

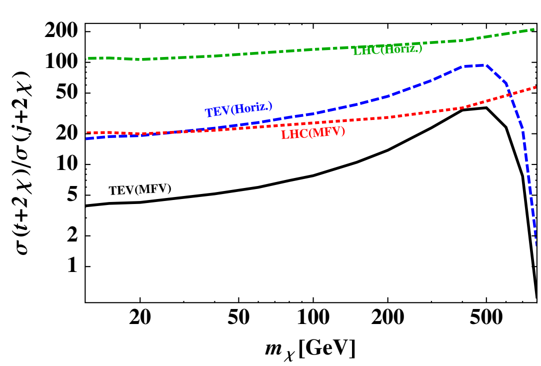

FIG. 2 (color online). The ratio $\sigma(t + 2\chi)/\sigma(j + 2\chi)$ as a function of DM mass at Tevatron with $\not{E}_T > 80$ GeV (black solid, blue dashed) and at 7 TeV LHC with $\not{E}_T > 120$ GeV (red dotted, green dot-dashed) for MFV (4a) and (4b) and horizontal (7) couplings denoted by (MFV) and (Horiz.), respectively, in the EFT limit.

out in the ratio. The monojet signal is predominantly produced from charm-gluon initial state resulting in a charm jet in the final state [2], while in MFV monotop production, the charm-gluon and up-gluon initial state contributions are comparable in magnitude. The monotop signal clearly dominates both at the Tevatron and the LHC. We note in passing that, assuming MFV, present LHC monojet searches give $\Lambda > 40$ GeV, as can be easily derived from results of Ref. [12] (assuming horizontal flavor symmetries, to be discussed below, one gets $\Lambda > 60$ GeV).

B. Beyond minimal flavor violation

The above effect is not specific to MFV, and can in fact be much larger for concrete models of flavor. For instance, in warped extra dimensional models of flavor the coupling of DM to quarks will depend on the localization of the quark zero modes with respect to the zero mode of the mediator. Both large $u_R - t_R$–DM and $c_R - t_R$–DM couplings are possible without violating low energy bounds [13]. Similarly, the $u - t$–DM and $c - t$–DM couplings can be enhanced above their MFV estimates in flavor models with abelian or nonabelian horizontal symmetries.

As an illustration, let us assume that the structure of quark Yukawas is due to spontaneously broken horizontal symmetries [14], i.e. that they are generated through a Froggatt-Nielsen type mechanism [15]. The quark fields carry horizontal charges $H(\bar{u}_R^i)$, $H(\bar{d}_R^i)$, $H(Q_L^i)$ so that the Yukawas are given by

$$(Y_u)_{ij} \sim \lambda^{|H(\bar{u}_R^j)+H(Q^i)|}, \qquad (Y_d)_{ij} \sim \lambda^{|H(\bar{d}_R^j)+H(Q^i)|}, \quad (5)$$

and we assume that the expansion parameter is $\lambda \simeq \sin\theta_C = 0.23$, with θ_C the Cabibbo mixing angle. The quark mass matrices after electroweak symmetry breaking are $(M_{d,u})_{ij} = v(Y_{d,u})_{ij}$, where we assumed a single Higgs with vacuum expectation value v. An assignment of horizontal charges leading to phenomenologically satisfactory quark masses and CKM matrix, is $H(\{Q_L^1, Q_L^2, Q_L^3; \bar{u}_R^1, \bar{u}_R^2, \bar{u}_R^3; \bar{d}_R^1, \bar{d}_R^2, \bar{d}_R^3\}) = \{3, 2, 0; 3, 1, 0; 3, 2, 2\}$ [14].

The horizontal symmetries then also fix the sizes of DM–quark couplings. Assuming that $J_{\rm DM}$ does not carry a horizontal charge (an assumption that we will relax below) the Wilson coefficients are

$$C_2^{ij} \sim \lambda^{|H(\bar{u}_R^i)-H(\bar{u}_R^j)|}, \qquad C_4^{ij} \sim \lambda^{|H(Q_L^i)+H(\bar{u}_R^j)|}, \quad (6)$$

or explicitly,

$$C_2 \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^3 \\ \lambda^2 & 1 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}, \qquad C_4 \sim \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda & 1 \end{pmatrix}. \quad (7)$$

The constraints from $D - \bar{D}$ mixing require that the mediator masses are $\Lambda \gtrsim 5$ TeV for C_2 (vector case) and $\Lambda \gtrsim 200$ GeV for C_4 (scalar mediator). For the case of scalar mediators close to the bound, the EFT description is not adequate. The mediators are produced on-shell, a situation that we will cover shortly. Nevertheless, note that the flavor violating couplings in C_4 are quite large, $\sim\lambda$ for $\bar{c}_L t_R \chi^\dagger \chi$, instead of $\sim\lambda^2 y_b^2$ that one would obtain in the MFV counting. The flavor conserving DM production is suppressed compared to flavor violating one. For instance, the partonic cross section for $c_R g \to c_L + 2\chi$ is $(\lambda^2)^2 \sim \mathcal{O}(10^{-3})$ suppressed compared to $c_R g \to t_L + 2\chi$ (see also Fig. 2).

Comparing the flavor conserving and flavor violating DM production can give a handle on distinguishing different flavor models. The size of the flavor violating couplings could in addition be measured from associated production of $c + t + \not{E}_T$, if charm jet-tagging can be performed. Additional information would come from meson mixing, $\Delta F = 1$ processes, and electric dipole moments, where DM would contribute in loops, and from indirect detection data where for instance annihilation do $t\bar{t}$ could be compared to annihilation to light quarks.

C. Flavorful dark matter

So far, we have assumed that DM does not carry a flavor quantum number. Let us next relax this assumption and consider a case where DM carries a nonzero horizontal charge. For simplicity let us assume that DM is a scalar. In this case, we have two distinct cases for the DM current $\mathcal{J}_{\rm DM}^{(0)} = \chi^\dagger \chi$ and $\mathcal{J}_{\rm DM}^{(1)} = \chi^2$. The current $\mathcal{J}_{\rm DM}^{(0)}$ is neutral under horizontal symmetries so that the same analysis as above applies. The second current, $\mathcal{J}_{\rm DM}^{(1)}$, on the other hand, carries a nonzero horizontal charge. This can have striking phenomenological implications for the DM production signals at colliders. For instance, if the DM horizontal charge $H(\chi)$ equals $1/2(H(t_L) - H(u_R))$ the $\bar{t}_L u_R \chi^2$ would have a coupling constant $C_4^{31} \sim O(1)$, with $t + 2\chi$ the largest production channel. Note that in this case the flavor violation in the production is only apparent since DM carries away a nonzero horizontal charge.

Another interesting example is DM that is part of a flavor multiplet [16–18]. This might be because the underlying flavor symmetry is non-Abelian and χ is a part of the flavor multiplet. This can again lead to production of DM through seemingly flavor violating signatures with $t + 2\chi$ (one of) the dominant production channels. As a concrete example consider the case of MFV, where DM is in $(3, \bar{3}, 1)$ of the flavor $SU(3)_Q \times SU(3)_U \times SU(3)_D$ and the flavor conserving interaction Lagrangian $\epsilon^{ijk}\epsilon^{abc}\bar{u}_R^i Q_L^a H \chi^{jb} \chi^{kc}$ leads to both $j + \not{E}_T$ and $t + \not{E}_T$ signatures that are unsuppressed.

Yet another possibility that can lead to the same type of DM collider signature is a case of composite DM. Let us assume that DM is the lowest lying state of a strongly coupled sector that gets most of its mass from new strong interactions, not from the Yukawa interaction (in the same way as low lying resonances in QCD). In this way, one can have an approximately degenerate multiplet of dark states (the lowest being the DM), but each carrying a different horizontal charge despite mass degeneracy.

III. ON-SHELL PRODUCTION OF MEDIATORS

The largest $t + \not{E}_T$ signal can be expected, if the mediators can be produced on-shell. There are two classes of models that can lead to large $t + 2\chi$ signals of DM production at colliders: i) models with a Z_2 even SM gauge singlet state S (either scalar of vector) coupling to both DM and quarks; and ii) color triplet Z_2 odd mediators $\tilde{t}$ that are scalars (fermions) if DM is a fermion (scalar). Each leads to a different topology, shown on Fig. 1 (if $\tilde{t}$ are Z_2 even and χ carries baryon number, also a topology with s-channel resonant production is possible [1,19]). If the mediators are light enough to be produced on-shell, the cross section for $t + 2\chi$ will be phase space enhanced compared to our EFT discussion so far, where we had a three-body final state to start with.

For illustration, we present a toy model example from each of the two classes. First let us consider the case where S and χ are both scalars, and S has the SM gauge quantum numbers of a Higgs. A model of this sort was considered in [3], where FCNC decays of the top were discussed. The relevant part of the interaction Lagrangian after electroweak symmetry breaking (EWSB) is

$$\mathcal{L}_{\rm int} = g_L^u \bar{u}_R t_L S + g_L^c \bar{c}_R t_L S + g_R^u \bar{t}_R u_L S + g_R^c \bar{t}_R c_L S + \lambda v S \chi\chi + \text{H.c.}, \qquad (8)$$

where the last term arises from $SH^\dagger \chi^2$, and we are intermittently using S for the weak doublet field and its neutral component. On Fig. 3 we show the $t + \chi\chi$ production cross section for two cases, $g_L^u = 1$ and $g_L^c = 1$, while all the other couplings are taken to zero in each case and χ is taken massless for simplicity. The results are easily rescaled for the discussed flavor models. With the horizontal charge assignments in (6), we would have $g_L^u \sim \lambda^3$, $g_L^c \sim \lambda$, $g_R^u \sim \lambda^3$, $g_R^c \sim \lambda^2$. Taking $g_L^c = \lambda = 0.23$ the production of top in association with DM can be discovered at the 7 TeV LHC. Using the results of [1] the significance would be $S/\sqrt{S+B} \sim 5$, 3 for $m_S = 200$, 400 GeV with 5 fb^{-1}. Since the irreducible background $3j + Z(\to \nu\bar{\nu})$ can be well understood from leptonic Z decays, further improvements with increased statistics can be expected. Note that, if χ is lighter than the top quark, then the decay $t \to j + 2\chi$ is also possible. The expected 14 TeV LHC reach for $\text{Br}(t \to j + 2\chi)$ was estimated in [3] to be $\text{Br}(t \to j + 2\chi) \sim \mathcal{O}(10^{-4})$. Since the branching ratio for $t \to j + 2\chi$ drops very quickly with increased m_S as soon as S in the top decay is forced to be off-shell (cf. Fig. 3), the monotop is the preferred search channel for this model above $m_S \sim 200$ GeV.

A toy example from the second class of models has a Z_2 odd majorana fermion h, with SM gauge quantum numbers of the Higgs, and two Z_2 odd color triplet scalars $\tilde{t}_{R,L}$ with gauge quantum numbers of right-handed and left-handed up-quarks. The neutral component of h is DM χ. After EWSB the relevant part of the interaction Lagrangian is

$$\mathcal{L}_{\rm int} = g_L^u \bar{\chi} u_R \tilde{t}_1^* + g_L^c \bar{\chi} c_R \tilde{t}_1^* + g_L^t \bar{\chi} t_R \tilde{t}_1^* + (L \leftrightarrow R) + \text{H.c.}, \qquad (9)$$

where $\tilde{t}_{R,L}$ mix into mass eigenstates $\tilde{t}_{1,2}$ after EWSB, and we only keep the lowest lying state for simplicity. An example of this model is the minimal supersymmetric standard model (MSSM) where we only keep the lightest stop and a neutralino which needs to have a large Higgsino component (the impact of flavor violation on neutralino DM within the MSSM has recently been discussed in [20]). An alternative model realization with a SM singlet DM leading to the same interaction Lagrangian has recently been shown to produce a large forward-backward asymmetry in $t\bar{t}$ pair production at the Tevatron [21]. Since $\tilde{t}_1$ is colored, it can be pair produced, leading to $t\bar{t} + 2\chi$ signal. Taking $g_L^t = 1$, $g_L^c = \lambda$, $g_L^u = \lambda^3$ we compare on Fig. 4 the $t + 2\chi$ and $t\bar{t} + 2\chi$ cross sections at the 7 TeV and 14 TeV LHC as a function of $m_{\tilde{t}}$, taking χ again massless for simplicity. For this choice of parameters, pair production yields an order of magnitude larger signals, which,

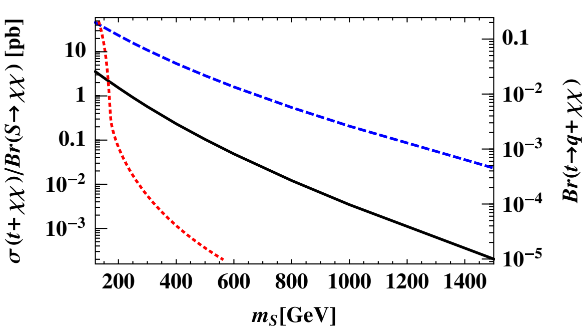

FIG. 3 (color online). The m_S dependence of $\text{Br}(t \to j + \chi\chi)$ (red dotted) and of $\sigma(t + 2\chi)$ at 7 TeV LHC in model (9) for $g_L^u = 1$ (blue dashed) and $g_L^c = 1$ (black solid), keeping all other $g_i = 0$ in each case.

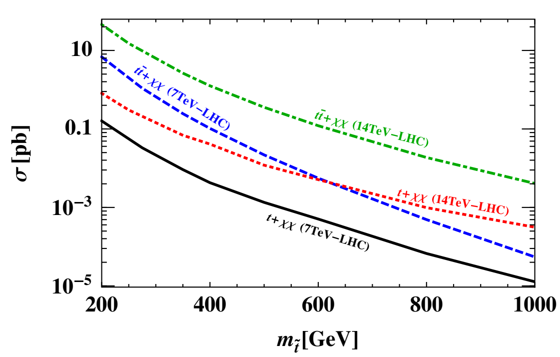

FIG. 4 (color online). Cross sections for single and pair produced $\tilde{t}_1$ (9) taking $g_L^{c(u)} = \lambda^{1(3)}$ resulting in $t + \not{E}_T$ and $t\bar{t} + \not{E}_D$ signal at 7 TeV and 14 TeV LHC.

however, are still below the present limits from $t\bar{t} + \not{E}_T$ searches at the Tevatron [21,22] and the LHC [23]. The hierarchy between $t + 2\chi$ and $t\bar{t} + 2\chi$ cross sections can change if $g_L^{c,u}$ are larger in reality, or if $\mathrm{Br}(\tilde{t}_1 \to t\chi) < 100\%$ since the pair production $t\bar{t} + 2\chi$ signal scales as this branching ratio squared. In either case the cross sections are large enough that a discovery is possible at the LHC with increased statistics.

An important part of the experimental program, once a MET signal is found, will be to check whether the hypothesized production of DM agrees with DM being a thermal relic. In the calculation of DM thermal relic abundance the flavor violating interactions are subdominant. They are always smaller than the diagonal couplings to the quarks light enough to be in the thermal bath at a particular temperature. For concreteness, consider couplings of DM to top quarks through operator $\mathcal{O}_4$ in (7). If the temperature of the universe is large enough, so that top quarks are present in significant numbers in the thermal bath, then the diagonal coupling $\chi\chi\bar{t}t$, being $\mathcal{O}(1)$, is much more important than the λ suppressed $\chi\chi\bar{t}c$ coupling. The same reasoning applies to other quark flavors. Therefore the EFT results for relic abundance calculations from [2] apply, up to λ^2 corrections that one can safely neglect. Experimentally, it will thus be important to measure the diagonal couplings of DM to quarks. While DM may be discovered through flavor violating monotop channel, a subsequent measurement of the monojets will be essential for the calculation of the expected thermal relic abundance.

IV. CONCLUSIONS

We have shown that flavor violating interactions of DM with SM quark fields naturally lead to a novel $t + \not{E}_T$ collider signature. This is an interesting search channel for DM production at the LHC, where with reasonable size of flavor violation the discovery can be made already at the 7 TeV LHC with a few fb^{-1} of data. For light DM, $t \to j + \not{E}_T$ decays offer another interesting search mode. Comparing the sizes of monotop signal and the monojet signal one could then learn about the underlying flavor structure of dark matter interactions with the visible matter, with monotops offering a rare opportunity to explore flavor violating interactions of dark matter.

ACKNOWLEDGMENTS

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