Skew-flavored dark matter

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Skew-Flavored Dark Matter

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We explore a novel flavor structure in the interactions of dark matter with the Standard Model. We consider theories in which both the dark matter candidate, and the particles that mediate its interactions with the Standard Model fields, carry flavor quantum numbers. The interactions are skewed in flavor space, so that a dark matter particle does not directly couple to the Standard Model matter fields of the same flavor, but only to the other two flavors. This framework respects Minimal Flavor Violation, and is therefore naturally consistent with flavor constraints. We study the phenomenology of a benchmark model in which dark matter couples to right-handed charged leptons. In large regions of parameter space the dark matter can emerge as a thermal relic, while remaining consistent with the constraints from direct and indirect detection. The collider signatures of this scenario include events with multiple leptons and missing energy. These events exhibit a characteristic flavor pattern that may allow this class of models to be distinguished from other theories of dark matter.

I. INTRODUCTION

It is now well established that about four-fifths of the matter density of the universe is made up of some form of dark matter (DM) that is neutral under both the color and electromagnetic interactions, and that lies outside the Standard Model (SM) of particle physics. However, the precise nature of the particles of which DM is composed continues to remain a mystery. One well-motivated possibility is that DM is composed of "Weakly Interacting Massive Particles" (WIMPs), particles with masses of order the weak scale that have interactions of weak scale strength with the Standard Model (SM) fields. The WIMP scenario is rather appealing because, provided the WIMPs were in equilibrium with the SM at early times, just enough of them survive today as thermal relics to account for the observed density of DM.

An attractive feature of the WIMP framework is that the weak scale strength interaction of DM with the SM fields can be probed at current experiments. Nevertheless, efforts to produce DM at high energy colliders have thus far proven unsuccessful [1, 2]. Likewise, direct detection experiments, which seek to observe DM in the laboratory through its scattering off nucleons, have also been fruitless [3]. Indirect detection experiments do offer some tantalizing hints of signals that may originate from the annihilation of DM [4–7], but these have not been confirmed so far.

New physics at the weak scale is severely constrained by flavor experiments. Since any WIMP DM candidate is required to have interactions of order weak scale strength with the SM fields, any flavor violating couplings of DM with the SM fields are constrained to be extremely small. This constitutes a severe restriction on this class of theories. We shall refer to this as the "WIMP Flavor Problem". In the class of theories in which the relic abundance of DM is set by annihilation into the weak gauge bosons of the SM as, for example, in Minimal Dark Matter [8], or through the Higgs portal [9–11], this problem can naturally be avoided. However, in theories in which the relic abundance is set by direct couplings of the DM candidate to the SM matter fields, these interactions are required to be closely aligned with the SM Yukawa couplings.

In supersymmetric theories with neutralino or sneutrino DM, the WIMP Flavor Problem is generally subsumed into the well-known "Supersymmetric Flavor Problem" [12]. Solutions to the Supersymmetric Flavor Problem, such as gauge mediation [13–19], anomaly mediation [20, 21] and gaugino mediation [22, 23] then automatically resolve the WIMP Flavor Problem. The WIMP Flavor Problem may be thought of as the generalization of the Supersymmetric Flavor Problem to the larger class of theories of WIMP DM.

The phenomenology of a WIMP DM model depends sensitively on the flavor structure associated with the couplings of the DM candidate to the SM, which in turn on how the WIMP Flavor Problem is solved. It is therefore very important to identify flavor structures that naturally resolve the WIMP Flavor Problem. One convenient framework that is sufficient, although not necessary, to suppress flavor violation is Minimal Flavor Violation (MFV) [24–28]. Within this framework, the flavor structure of the entire theory is set by the SM Yukawa couplings. This automatically ensures that the flavor violation pattern conforms to that of the SM, making it compatible with experiment. A simple way to implement MFV is to elevate the SM Yukawa couplings to spurions that transform under the flavor group and require the theory to be invariant under these spurious flavor symmetries. Most commonly, the DM has been assumed to be a singlet under the SM flavor symmetries. More recently, realizations of MFV in which the DM particle carries flavor quantum numbers and transforms under the flavor group have been explored [29–31].

At present, the status of experimental observations provides additional motivation for considering theories in which DM comes in multiple flavors [29–46], or has flavor-specific couplings to the SM [47–50]. The absence of signals in direct detection implies that the couplings of DM to the first generation SM quarks must be small. Theories in which the DM particle couples preferentially to the heavier quark flavors [30, 33, 49, 51] can naturally satisfy this bound, while remaining consistent with the relic abundance constraint. In addition, flavored DM has been proposed as an explanation of the gamma ray excess observed emanating from the galactic center [36, 37], and also the observed 3.5 keV line in the X-ray spectrum [41].

In this paper, we explore a novel flavor structure for the coupling of DM to the SM that is consistent with MFV. We focus on theories in which the DM has renormalizable contact interactions with SM matter and a mediator. If all three fields transform as the fundamental representation of the SU(3) flavor group associated with the SM field, it is possible to construct flavor invariants using the completely antisymmetric ϵ_{ijk} contraction, leading to interactions with a “skewed texture”.

As an example, consider the case in which the DM particle, a SM singlet Dirac fermion which we label as χ, and the mediator, a complex scalar which we label as ϕ interact with the right-handed SM leptons, with all three fields transforming in the fundamental representation of $\mathrm{SU}(3)_E$, the flavor symmetry of the right-handed leptons. The interaction term has the form

$$\lambda^{ijk}\chi_i E^c_j \phi_k \quad + \mathrm{h.c.} \tag{1}$$

In this expression i, j and k represent $\mathrm{SU}(3)_E$ quantum numbers and define the flavor labels of the DM and the mediator with respect to charged leptons. Then, if the theory is to be consistent with MFV, the flavor structure associated with this interaction must respect the $\mathrm{SU}(3)_E$ flavor symmetry, up to effects associated with the SM Yukawa couplings.

If we write the lepton Yukawa couplings of the SM as

$$y_A{}^i L^A E^c_i H \quad + \mathrm{h.c.}, \tag{2}$$

the Yukawa matrix $y_A{}^i$ can be thought of as a spurion transforming as $(3, \bar{3})$ under the $\mathrm{SU}(3)_L\times$ $\mathrm{SU}(3)_E$ flavor symmetry. Then, if the theory respects MFV the matrix λ is restricted to be of the form

$$\lambda^{ijk} = \alpha\epsilon^{ijk} + \delta\lambda^{ijk} \tag{3}$$

where $\delta\lambda^{ijk}$ is given by

$$\beta_1 \left(y^\dagger y\right)_{i'}{}^{i} \epsilon^{i'jk} + \beta_2 \left(y^\dagger y\right)_{j'}{}^{j} \epsilon^{ij'k} + \beta_3 \left(y^\dagger y\right)_{k'}{}^{k} \epsilon^{ijk'} \, . \tag{4}$$

Here the α and β parameters are constants, and we are keeping only the leading terms in an expansion in powers of the SM Yukawa couplings. We see from this that the couplings of the DM particle are skewed in flavor space, so that, for example, χ_τ couples to the electron and the muon, but not to the tau. Nevertheless, because this construction respects MFV, it is consistent with the bounds on flavor violating processes.

We can write the DM mass term schematically as

$$\left[m_\chi\right]{}_i{}^j \bar{\chi}^i \chi_j \, . \tag{5}$$

In this case MFV restricts m_χ to be of the form

$$\left[m_\chi\right]{}_i{}^j = \left(m_0 \mathbb{1} + \Delta m \; y^\dagger y\right)_i{}^j \, , \tag{6}$$

where m_0 and Δm are constants. Since the SM Yukawa couplings are small, the various DM flavors are expected to have small splittings. Either the tau flavored or the electron flavored state will be the lightest, depending on the sign of Δm.

Similarly, we can write the mediator mass term schematically as

$$\left[\hat{m}^2_\phi\right]{}_i{}^j \phi^{\dagger i} \phi_j \, . \tag{7}$$

As before, MFV restricts $\hat{m}^2_\phi$ to be of the form

$$\left[\hat{m}^2_\phi\right]{}_i{}^j = \left(m^2_\phi \mathbb{1} + \Delta m^2_\phi \; y^\dagger y\right)_i{}^j \, , \tag{8}$$

where m^2_ϕ and Δm^2_ϕ are constants. Once again, we expect that the splittings will be small.

In the next section we consider in detail a simple benchmark model that realizes the skew-flavored DM scenario, in which DM couples to the right-handed leptons of the SM. We determine the range of parameters that leads to the observed abundance of DM, and study the implications for direct detection, indirect detection and for the LHC. We then briefly consider alternative realizations of skew-flavored DM, in which DM couples to the left-handed leptons or quarks, before concluding.

II. A BENCHMARK MODEL

In this section we consider in detail a benchmark DM model that exhibits skewed flavor structure.[1] We restrict the interaction term to be of the form

$$\lambda\, \epsilon^{ijk} \chi_i E^c_j \phi_k \quad + \text{h.c.} \tag{9}$$

This corresponds to the limit in which the flavor non-universal terms in Eq. (4) are small, and can be neglected. Expanding this out in the language of 4-component Dirac fermions, the couplings of the electron flavor of DM take the form,

$$\mathcal{L} \supset \lambda \left[\bar{\chi}_e \frac{1+\gamma_5}{2} \left(\mu\, \phi_\tau - \tau\, \phi_\mu \right) \right] + \text{h.c.} \tag{10}$$

The couplings of the μ and τ flavors of DM may be obtained by cyclically permuting the e, μ and τ flavors in the expression above. This is to be contrasted with the form of the coupling in the more conventional realization of flavored DM, where the mediator ϕ is a flavor singlet,

$$\lambda\, \chi^i E^c_i \phi \quad + \text{h.c.} \tag{11}$$

As regards the masses of the DM particles, we work in the limit that the e and μ flavors of DM are very nearly degenerate, so that their splitting can be neglected. However, because of the much larger τ Yukawa coupling, we allow for the possibility that the τ flavor of DM is somewhat split from the other two. Accordingly, we write the DM mass term as

$$m_0 \left(\bar{\chi}_e \chi_e + \bar{\chi}_\mu \chi_\mu + \bar{\chi}_\tau \chi_\tau \right) + \Delta m \bar{\chi}_\tau \chi_\tau \ . \tag{12}$$

The sign of Δm determines which flavor of DM is the lightest. In the limit that Δm is very small, all three DM flavors are nearly degenerate. It is important to note, however, that even fairly small splittings Δm cannot always be neglected, since the lifetimes of the heavier flavors depend on this splitting.

Small splittings in the mediator masses, however, do not significantly affect the phenomenology. Therefore, for simplicity, we take all the different flavors of mediator to have a common mass m_ϕ. In the rest of this paper, we will focus our attention on two mass hierarchies, one where χ_τ is significantly lighter than $\chi_{e,\mu}$ such that it freezes out after the other two have already decayed away, and one where all mass splittings are below an MeV so that all three χ flavors are long-lived on cosmological time scales and the relic abundance of DM today consists of all three flavors.

[1] In accordance with the WIMP nature of our model, we will take the mass scale of the DM particles χ and mediators ϕ to be in the GeV-TeV range, with $m_\chi < m_\phi$.

A. Relic Abundance

If DM is a thermal WIMP, its relic abundance is set by its annihilation rate to SM states. The primary annihilation mode is through t-channel ϕ exchange to two leptons. We wish to determine the region of parameter space that is consistent with the observed abundance of DM.

We first consider the case in which χ_τ is the lightest DM flavor, and constitutes all of DM. We assume that the mass splitting between χ_τ and the other flavors is large enough that these states decay at early times and play no role in the relic abundance calculation.

Since the DM particle is non-relativistic at freeze-out, the annihilation processes $\chi_\tau \chi_\tau \to e^+e^-$, $\mu^+\mu^-$ proceed through the lowest partial wave. For each of these final states, only one flavor of ϕ is relevant, and therefore the cross sections add up, leading to

$$\langle \sigma v \rangle_{relic} = \frac{2\lambda^4 m_\chi^2}{32\pi (m_\chi^2 + m_\phi^2)^2} \equiv 2 \langle \sigma v \rangle_0 . \tag{13}$$

Here we have neglected the masses of the final state leptons, and defined $\langle \sigma v \rangle_0$ as the annihilation cross section to just the e^+e^- (or $\mu^+\mu^-$) final state. Note that the annihilation cross section for the skew-flavored case is twice that of the conventional flavored DM case, Eq. (11), since in the latter case the only annihilation channel is $\chi_\tau \chi_\tau \to \tau^+\tau^-$.

We next consider the case where all three χ are degenerate and long-lived on cosmological time sales. Taking coannihilations into account, we find that the Boltzmann equation for the number density of χ_e is given by,

$$\begin{aligned} \frac{dN_{\chi,e}}{dt} + 3H\, N_{\chi,e} = &-2 \langle \sigma v \rangle_0 (N_{\chi,e}^2 - n_{eq}^2) \\ &- \langle \sigma v \rangle_0 (N_{\chi,e} N_{\chi,\mu} - n_{eq}^2) \\ &- \langle \sigma v \rangle_0 (N_{\chi,e} N_{\chi,\tau} - n_{eq}^2) \\ &- [\chi_e \to \chi_{\mu,\tau}] \ , \end{aligned} \tag{14}$$

where n_{eq} represents the equilibrium number density for any one flavor of DM. The last line includes interactions such as $\chi_e e \to \chi_\mu \mu$. These interactions are rapid since the lepton number density is not Boltzmann suppressed, and ensure that the number density of each flavor of DM is equal. We note that the annihilation cross section for two DM particles of the same flavor (such as $\bar{\chi}_e \chi_e$) is twice as large as for a different flavor channel (such as either one of $\bar{\chi}_e \chi_\mu$ or $\bar{\chi}_\mu \chi_e$). Similar equations apply for the number densities of χ_μ and χ_τ.

We can sum the Boltzmann equations for each of the three flavors of χ to track the total number density of DM, ($N_\chi \equiv N_{\chi,e} + N_{\chi,\mu} + N_{\chi_\tau}$),

$$\frac{dN_\chi}{dt} + 3H\, N_\chi = -\frac{4}{3} \langle \sigma v \rangle_0 \left(N_\chi^2 - (3n_{eq})^2 \right) \ . \tag{15}$$

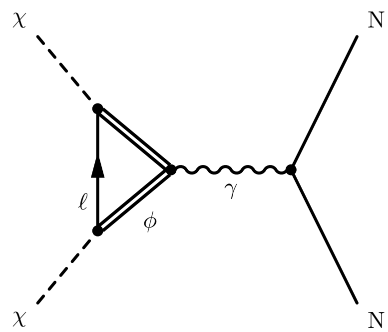

FIG. 1. Feynman diagram contributing to direct detection of dark matter. The diagram where the photon attaches to the lepton line also contributes.

This equation makes it clear that the effective annihilation cross section in this case is

$$\langle \sigma v \rangle_{relic} = \frac{4}{3} \langle \sigma v \rangle_0 \ . \tag{16}$$

This result will also be relevant when we discuss indirect detection.

In Fig. 2, we show the parameter space in the m_χ vs. λ parameter space where the correct relic abundance is obtained. We present results for ϕ masses of $\{200, 350, 500\}$ GeV and the two mass hierarchies considered above.

B. Direct Detection

We now turn our attention to direct detection constraints. Skew-flavored DM can scatter off nuclei through loop diagrams involving the SM leptons, as shown in Fig. 1. In particular, for any flavor of χ there will be two sets of diagrams that contribute to direct detection. These must be added at the amplitude level and then squared to obtain the total cross section. The calculation of each set proceeds in a manner that is identical to the case of conventional flavored DM, Eq. (11). Therefore, in this paper we limit ourselves to writing down the final result and we refer the interested reader to [30] for additional details of the calculation.

In the case when χ_τ is the lightest flavor, the WIMP–nucleon cross section for direct detection is given by

$$\sigma_n = \frac{\mu_n^2 Z^2}{A^2 \pi} \left(\frac{\lambda^2 e^2}{32 \pi^2 m_\phi^2} X[e, \mu] \right)^2 , \tag{17}$$

where μ_n is the reduced mass of the DM–nucleon system, and Z and A are the atomic and mass number of the nucleus. Since the dark matter dominantly scatters off protons, the WIMP–nucleon cross section scales differently for different target nuclei. $X[i, j]$ is defined for two flavors i and j as

$$X[i, j] \equiv \left[1 + \frac{1}{3} \log \frac{\Lambda_i^2}{m_\phi^2} + \frac{1}{3} \log \frac{\Lambda_j^2}{m_\phi^2} \right] , \tag{18}$$

where Λ_ℓ represents the infrared cutoff in the loop calculation for the effective DM-photon coupling. This cutoff is well approximated by m_ℓ, the mass of the corresponding lepton, unless m_ℓ is smaller than the momentum exchange in the process, which is of order 10 MeV. We therefore use $\Lambda_\tau = m_\tau$ and $\Lambda_\mu = m_\mu$, but $\Lambda_e = 10$ MeV.

For the case where all three flavors of χ are degenerate and the DM relic abundance today is made up of equal numbers of them, the direct detection cross section is given by the average of their individual scattering cross sections,

$$\sigma_n = \frac{\mu_n^2 Z^2}{A^2 \pi} \left(\frac{\lambda^2 e^2}{32 \pi^2 m_\phi^2} \right)^2 \times \left(\frac{X[e, \mu]^2 + X[e, \tau]^2 + X[\mu, \tau]^2}{3} \right) . \tag{19}$$

For $m_\phi = \{200, 350, 500\}$ GeV, we illustrate in Fig. 2 the region excluded by the LUX constraints [3] for the two mass hierarchies of interest.

C. Indirect Detection

We now turn our attention to the limits from indirect detection, in particular from the AMS experiment for positrons [52] and the FERMI experiment [53] for gamma rays. As in ref. [41], we will make the simplifying assumption that the γ-ray flux is dominated by the decays of neutral pions $\pi^0 \to \gamma\gamma$ produced after annihilation to $\tau^\pm$ pairs, and that photons that arise from the bremsstrahlung of electrons and muons can be neglected. We further assume that for a given χ mass, the positron bounds are dominantly sensitive to direct annihilation into positrons rather than to the secondary positrons that are produced in the decays of muons or taus, which exhibit a softer energy spectrum. While these approximations can certainly be improved upon, our results in Fig. 2 indicate that direct detection bounds always dominate over indirect detection bounds in this scenario, and therefore a full calculation of the positron and γ-ray fluxes would not affect the region of parameter space that is allowed.

Since DM annihilation proceeds dominantly through s-wave, the annihilation cross sections relevant for indirect detection are the same as those for relic abundance. When χ_τ is the lightest flavor, the annihilation cross section is $\langle \sigma v \rangle_{relic} = 2 \langle \sigma v \rangle_0$ from Eq. (13), and e and μ pairs are produced with equal probabilities in each annihilation event. With the assumptions outlined above, we can then write down effective annihilation cross

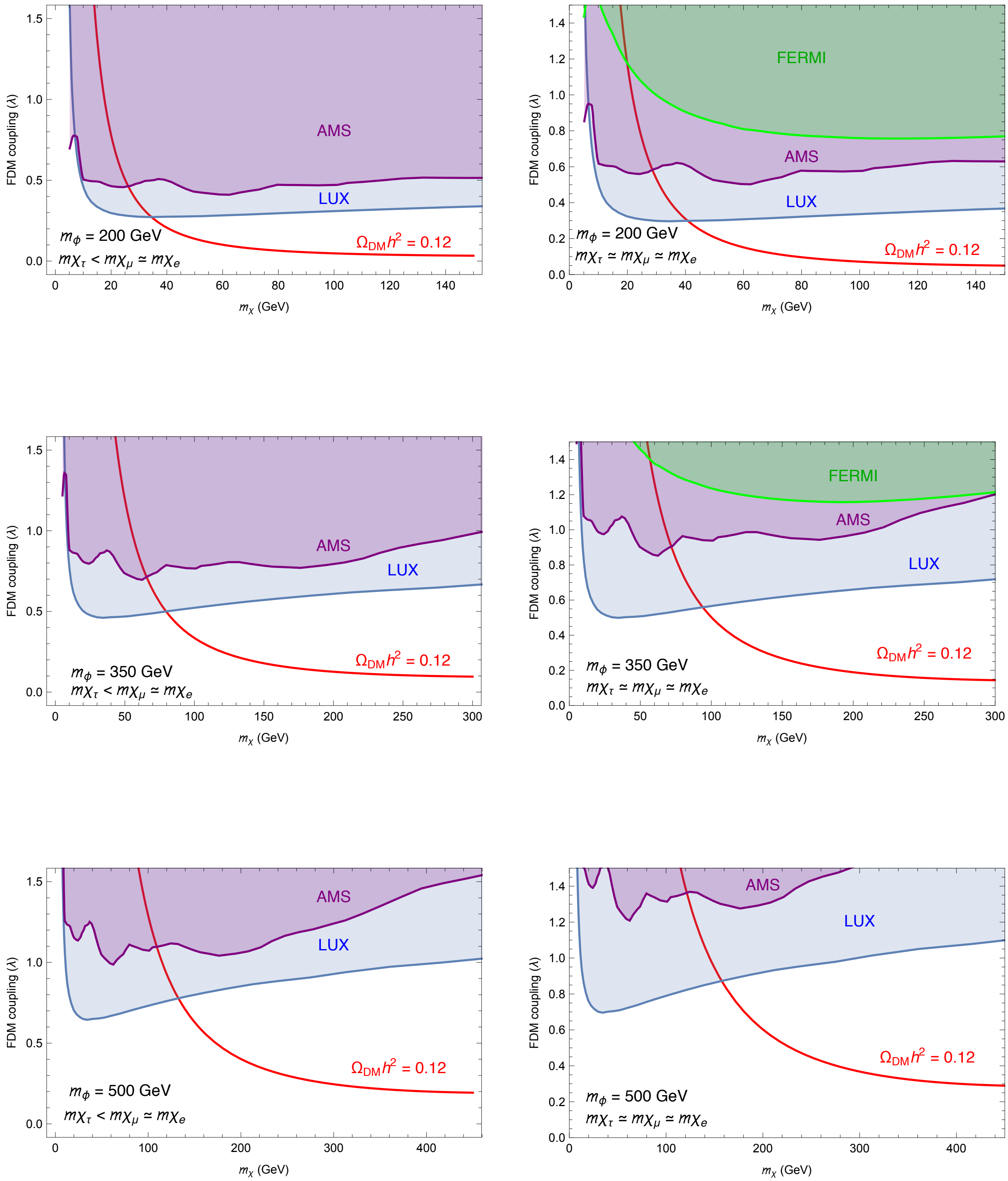

FIG. 2. For the cases of χ_τ being the lightest flavor (left plots), and for all three flavors degenerate (right plots), and taking $m_\phi = \{200, 350, 500\}$ GeV (top to bottom), we illustrate the region in m_χ vs. λ parameter space where the correct relic abundance is obtained (red curve), the direct detection exclusion region from LUX [3] (blue shaded region), the indirect detection exclusion region due to AMS [52] (purple shaded region) and the exclusion region due to FERMI gamma ray constraints [53] (green shaded region).

sections that can be compared to the limits set by the FERMI and AMS experiments

$$\langle\sigma v\rangle_{e^+ eff} = \frac{1}{2}\langle\sigma v\rangle_{relic},$$
$$\langle\sigma v\rangle_{\gamma,eff} \approx 0\ . \tag{20}$$

Here $\langle\sigma v\rangle_{relic}$ is as defined in Eq. (13).

When all three flavors of χ are degenerate, and contribute equally to the total energy density, a similar analysis yields

$$\langle\sigma v\rangle_{e^+,eff} = \frac{1}{3}\langle\sigma v\rangle_{relic}$$
$$\langle\sigma v\rangle_{\gamma,eff} = \frac{1}{3}\langle\sigma v\rangle_{relic}\ . \tag{21}$$

Here $\langle\sigma v\rangle_{relic} = \frac{4}{3}\langle\sigma v\rangle_0$ is the annihilation rate defined in Eq. (16). As noted earlier, the annihilation cross section for two DM particles of the same flavor yields two possible final states with equal probabilities. For a different flavor channel we obtain a unique final state. For example, a $\bar{\chi}_e\chi_e$ initial state gives rise to equal amounts of $\mu\mu$ and $\tau\tau$ final states, while annihilations of χ_e with χ_μ lead to $e\mu$ final states only. All these considerations have been taken into account in deriving Eq. (21).

For $m_\phi = \{200, 350, 500\}$ GeV, we illustrate in Fig. 2 the region excluded by positron and γ-ray constraints in the two mass hierarchies of interest. It should be pointed out that the limits quoted by AMS and FERMI are calculated for a Majorana fermion, therefore in plotting Fig. 2 we include the necessary factor of 2 to compare with predictions for χ, which is a Dirac fermion.

D. Other constraints

There are other potential constraints that arise from the interaction in Eq. (9). For example, this interaction can lead to corrections to the anomalous magnetic moment of the muon [54–56]. However, the $(g-2)$ bound constrains the mediator masses $m_\phi \sim 100$ GeV for coupling $\lambda \sim 1$. We see from Fig. 2 that direct detection constraints are more stringent than those from $(g-2)$ of the muon. There are also potential constraints from monophoton production at LEP [57]. Again, as shown in [56], these bounds are weaker than the limits from direct detection.

For very light masses $m_\chi \lesssim 5$ GeV, the direct and indirect detection constraints are substantially weakened, and the $(g-2)$ and monophoton constraints might play a role in this region. However, as we see from Fig.2, this region is not compatible with dark matter relic abundance, and hence would require a more complicated cosmological history to be viable.

E. Collider Signals

We now consider the collider signatures associated with this class of models at the LHC. Since χ_e and χ_μ are expected to be highly degenerate, decays from one to the other may not be kinematically allowed. Even in a scenario where these decays are allowed, the resulting charged leptons are extremely soft, and would be challenging to detect in an LHC environment. For the purposes of the following discussion, we will therefore assume that these leptons are not detected.

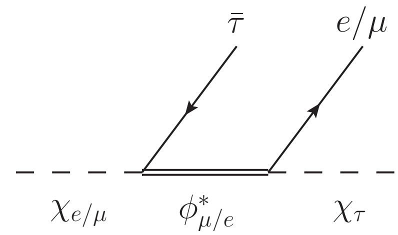

FIG. 3. Feynman diagram for the decay of $\chi_{e,\mu}$ to χ_τ.

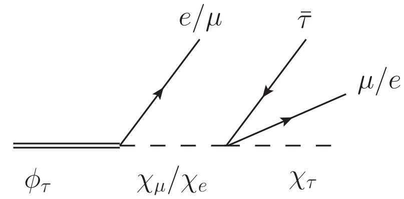

FIG. 4. Feynman diagram for the decay of ϕ_τ.

On the other hand, in the case when χ_τ is sufficiently split from the other two flavors, the leptons produced in the decays can indeed be detected. As shown in figure 3, if χ_τ is the lightest flavor, χ_e and χ_μ will decay down to it, these decays being accompanied by a tau and an electron in the case of of χ_e, and by a tau and a muon in the case of χ_μ.

With this in mind, let us consider the scenario in which χ_τ is the lightest flavor. The mediators ϕ_e, ϕ_μ and ϕ_τ can be pair-produced in colliders through an off-shell photon or Z. As shown in figure 4, each ϕ_τ decays either to $\chi_e + \mu$ or to $\chi_\mu + e$, followed by the decay of χ_e or χ_μ to χ_τ. We see that each ϕ_τ eventually decays down to χ_τ accompanied by an electron, a muon and a tau. It follows that events where ϕ_τ is pair-produced are characterized by two electrons, two muons, two taus and missing energy.

Each ϕ_e, on the other hand, can decay directly to χ_τ accompanied by a single muon. Alternatively, it can decay down to $\chi_\mu + \tau$, followed by the decay of χ_μ to χ_τ, which is accompanied by a muon and a tau. We label the direct decay to χ_τ as the short chain, and the cascade decay as the long chain. These are shown in figure 5. It follows that when ϕ_e is pair-produced, we can obtain an event with two short chains, with a short chain and a long chain, or with two long chains, each containing two muons and missing energy, and zero, two or four taus, respectively. Similarly, when ϕ_μ is pair-

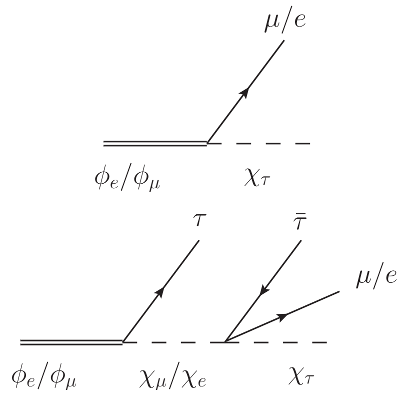

FIG. 5. Feynman diagrams for the short and long decay modes of $\phi_{e,\mu}$.

produced, we can obtain an event with two electrons and missing energy, and zero, two or four taus.

Since all these final states are produced with comparable branching fractions, the more spectacular ones will dominate in setting the discovery potential, since the corresponding backgrounds will be negligible for all intents and purposes. In particular, a search strategy can be set up to look for the $2e$-2μ + MET final state, with the additional requirement that at least one good τ candidate be present in the event. Given the smallness of SM backgrounds for such a final state, as long as the signal results in $\mathcal{O}(10)$ events after detector and analysis efficiencies are taken into account, discovery-level significance should be easy to obtain. Furthermore, once an excess of this kind is observed, the additional 2ℓ-4τ final state with comparable numbers of signal events can be used as a cross-check to not only bolster the discovery significance, but as a smoking gun to distinguish skew-flavored DM from any other potential explanation of the excess.

The best existing constraints on the 4ℓ final states come from the multilepton searches by ATLAS and CMS [58, 59]. Note that the 4ℓ states are populated by ϕ_τ pair production, and always result in two opposite-sign same flavor pairs (which may have the same or different flavors), plus τ's. Thus they populate the OSSF2 category in CMS' notation. Since there is no significant anomalous excess in these categories, the mass of ϕ_τ should be heavy enough such that the expected number of events with 20 fb^{-1} of luminosity at 8 TeV is less than one. This pushes the ϕ_τ mass to roughly 500 GeV. As can be seen in figure 2 (lower left plot), there is a region of parameter space where all constraints can be satisfied. Note that at 13 TeV the luminosity function for a q-$\bar{q}$ initial state at these masses is larger than that at 8 TeV by a factor of 5 or so, and since the backgrounds are so low, even a small number of events observed in run II may quickly become significant.

When all three flavors are degenerate and long-lived on cosmological scales, the collider phenomenology is much simpler. In particular, any flavor of ϕ, once produced, will have a 50% chance to decay to one of the other two flavors of χ along with a SM lepton. Any χ so produced will simply leave the detector as missing energy without further decaying. Therefore, once the contributions from the three ϕ flavors are added up, this means that any event will result in a pair of opposite sign, flavor uncorrelated leptons, and additional missing energy. While these final states are not as background-free as the ones discussed above, they are similar to the final states that occur in other extensions of the Standard Model, such as chargino pair production followed by $\chi^\pm \to \ell^\pm \nu \chi^0$ in supersymmetric models. As in those theories, the existence of additional missing energy in the final state makes it possible for kinematic cuts such as $m_{T2} > m_W$ to be used to enhance the signal to background ratio. We therefore expect that discovery is still possible as long as the ϕ masses are low enough to result in observable production cross sections.

Note that even in the degenerate case where multi-lepton final states do not arise, there is still something unique about the flavor correlations that could in principle be used as a smoking gun signature to identify the underlying skew-flavored DM model. In particular, since any given ϕ flavor can decay to two, but not all three possible lepton (and χ) flavors, and since pair production always starts with a same-flavor ϕ-pair, the ratio of the number of same-flavor over different-flavor dilepton events in the final state is 1 (of course, within the same-flavor and the different-flavor final states, all flavor combinations are equally likely as long as the ϕ flavors are degenerate). This is in contrast to both SM backgrounds such as W^+W^- and t-$\bar{t}$, as well as to flavor-uncorrelated beyond-the-SM signals such as chargino pair production in SUSY with decays to the LSP. In all those cases, since all three lepton flavors can be produced on either side of the event, the same-flavor to different-flavor ratio in the final state lepton pairs is 1/2. Therefore, if the signal can be purified by cutting on a kinematic variable such as m_{T2}, then this ratio can be used to check the skew-flavored DM hypothesis.

For the degenerate case, the best existing constraints come from ATLAS and CMS searches for supersymmetry with two opposite sign leptons [60, 61]. Since this is a less exotic state than $4\ell+\tau$'s, the backgrounds are larger, and even though there is no statistically significant excess, the data can accommodate $\mathcal{O}(10)$ events, see for instance table 5 of the ATLAS reference. Considering that all three flavors of ϕ-pairs can contribute to this final state, this results in mass bounds on the ϕ particles of roughly 350 GeV. As can be seen in the middle right plot of figure 2, there is again a region of parameter space that is consistent with all constraints. Similar to the degenerate case, the cross section at 13 TeV is larger than that at 8 TeV by roughly a factor of 5, so if the ϕ masses are not far above the bound, signal events should be observable with a moderate luminosity in run II. Of course, unlike the 4ℓ final state where due to the low backgrounds kinematic cuts can be very low in searches, for the 2ℓ+MET channel one has to rely on cuts on variables such as m_{T2}, and therefore to get precise bounds or to map out discovery regions one has to evaluate signal efficiencies using Monte Carlo simulation and reconstruct the statistical procedures used in the ATLAS and CMS analyses. This is beyond the scope of this paper which aims to describe the general characteristics of the skew-FDM scenario, but it will be taken up in future work.

III. ALTERNATIVE REALIZATIONS OF SKEW-FLAVORED DM

Although our primary focus has been on the case in which DM couples to the right-handed leptons of the SM, it is straightforward to construct theories of skew-flavored DM in which the χ fields couple to the left-handed leptons, or to the quarks. Consider first the case in which the DM particles couple to the left-handed leptons. The interaction term then takes the form

$$\lambda_{ABC}\chi^A L^B \phi^C \quad + \text{h.c.}\,, \tag{22}$$

where A, B and C represent $\mathrm{SU}(3)_L$ flavor indices. The χ fields are taken to be SM singlets, while the mediator fields ϕ transform as doublets under the SM $\mathrm{SU(2)_L}$ gauge symmetry.

This scenario gives rise to signals that are qualitatively quite similar to those we have studied. However, since the mediators are now charged under the weak interactions, their production cross section at the LHC is significantly larger. In addition, some of the final state particles produced in the decay chains will now be neutrinos rather than charged leptons. Therefore, although the characteristic signatures still involve leptons and missing energy, a typical signal event is expected to have larger missing energy, but fewer charged leptons in the final state, than in the scenario we have focused on.

Theories in which the DM fields couple to the SM quarks tend to be more severely constrained, both from direct detection experiments and from existing searches at the LHC. The interaction term takes the form

$$\lambda^{ijk}\chi_i D^c_j \phi_k \quad + \text{h.c.} \tag{23}$$

for the case of coupling to the right-handed down-type quarks, and

$$\lambda^{ijk}\chi_i U^c_j \phi_k \quad + \text{h.c.} \tag{24}$$

for the case of coupling to the right-handed up-type quarks. Here i, j and k represent $\mathrm{SU}(3)_D$ or $\mathrm{SU}(3)_U$ flavor indices respectively. In the case of coupling to left-handed quarks, the interaction term becomes

$$\lambda_{ABC}\chi^A Q^B \phi^C \quad + \text{h.c.}\,, \tag{25}$$

where A, B and C represent $\mathrm{SU}(3)_Q$ flavor indices. The χ fields are once again taken to be SM singlets, while the

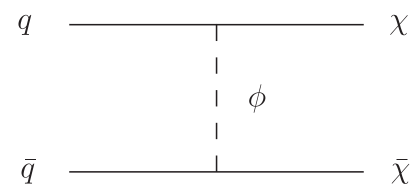

FIG. 6. Feynman diagram for pair production of DM particles through ϕ-exchange. Flavor indices have been suppressed.

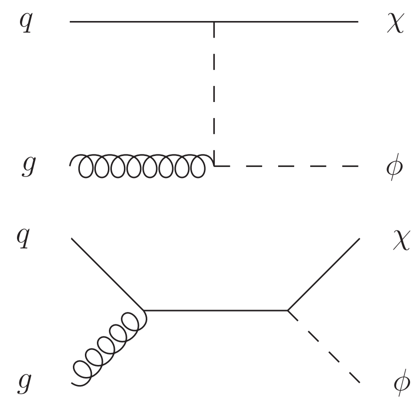

FIG. 7. Feynman diagrams for associated χ-ϕ production. Flavor indices have been suppressed.

mediator fields ϕ are now charged under the SM color group.

If the lightest DM particle carries the flavor quantum numbers of any of the down, strange or bottom quarks, the skewed flavor structure admits scattering at tree level off nuclei, leading to stringent bounds from direct detection. Similar considerations apply to the top- and charm-flavored scenarios. The lone exception is the scenario in which the lightest DM particle carries up-flavor. Since the nucleon has no significant charm or top content, in this case the dominant direct detection signal is loop suppressed.

The collider phenomenology of the quark-flavored scenario is also very different from the lepton-flavored case. In particular, qualitatively distinct types of production mechanisms can now give rise to signal events. Since the mediators now carry SM color, their pair production cross section at the LHC is much larger than in the case we have studied, and the corresponding limits from searches for jet events with missing energy are expected to be very strong. In addition, there are now events involving direct pair production of DM particles through ϕ exchange, as shown in Fig. 6. Provided the mass splittings are large enough, decays of the heavier DM flavors will result in observable signatures involving jets and missing energy. In regions of parameter space in which the mediators are much heavier than the DM fields, these events are expected to give rise to the dominant signal. It is now also possible to directly produce a DM particle in association with a mediator, as shown in Fig. 7. This class of events also gives rise to jets plus missing energy signatures. Overall, the bounds on quark-flavored scenarios are expected to be much stronger than in the lepton-flavored case we have focused on.

IV. CONCLUSIONS

Flavored DM is a simple possibility consistent with the WIMP miracle and the non-observation of flavor violation beyond the SM. Null results in current direct detection experiments further motivate flavor-specific couplings of the DM with SM matter. In this paper we presented a novel skewed flavor structure in flavored DM models that is consistent with MFV. We studied the phenomenology of a benchmark model in which the DM has contact interactions with right-handed leptons, and the interactions are fully antisymmetric in flavor space. Unlike the conventional flavored DM scenario, the skew-flavored setup includes three flavors of the mediator. Depending on the mass splittings between the DM flavors, the cosmological relic abundance today may be due to a single flavor, or a mixture of two or even three nearly-degenerate flavors.

We have found that in large regions of parameter space the DM can arise as a thermal relic while remaining consistent with the null results of direct and indirect detection experiments. This allowed parameter space also includes regions where the mediator is light enough to be pair-produced at the LHC with a potentially observable cross section. When that happens, the mediators decay to the lightest DM flavor, frequently resulting in cascade decays, and the associated collider signatures involve multi-lepton final states with additional missing energy. An order one fraction of the signal events can therefore produce final states with essentially vanishing SM backgrounds, making discovery a possibility even for low production cross sections. Furthermore, the flavor pattern in the signal events is quite distinctive, and can potentially be used to distinguish this class of theories from other flavored and unflavored DM models. The detailed collider phenomenology of this scenario will be the subject of a future study.

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