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Beyond minimal lepton-flavored Dark Matter

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Abstract: We consider a class of flavored dark matter (DM) theories where dark matter interacts with the Standard Model lepton fields at the renormalizable level. We allow for a general coupling matrix between the dark matter and leptons whose structure is beyond the one permitted by the minimal flavor violation (MFV) assumption. It is assumed that this is the only new source of flavor violation in addition to the Standard Model (SM) Yukawa interactions. The setup can be described by augmenting the SM flavor symmetry by an additional $SU(3)_\chi$, under which the dark matter χ transforms. This framework is especially phenomenologically rich, due to possible novel flavor-changing interactions which are not present within the more restrictive MFV framework. As a representative case study of this setting, which we call "beyond MFV" (BMFV), we consider Dirac fermion dark matter which transforms as a singlet under the SM gauge group and a triplet under $SU(3)_\chi$. The DM fermion couples to the SM lepton sector through a scalar mediator ϕ. Unlike the case of quark-flavored DM, we show that there is no $\mathbb{Z}_3$ symmetry within either the MFV or BMFV settings which automatically stabilizes the lepton-flavored DM. We discuss constraints on this setup from flavor-changing processes, DM relic abundance as well as direct and indirect detections. We find that relatively large flavor-changing couplings are possible, while the dark matter mass is still within the phenomenologically interesting region below the TeV scale. Collider signatures which can be potentially searched for at the lepton and hadron colliders are discussed. Finally, we discuss the implications for decaying dark matter, which can appear if an additional stabilizing symmetry is not imposed.

Keywords: Dark Matter and Double Beta Decay, Beyond Standard Model, Flavor physics

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1 Introduction

With the natural interpretation of dark matter (DM) in terms of new particles and forces, its existence [1] is among one of the striking indications of new physics beyond the Standard Model (SM). While it is now known that DM constitutes around 85% of the matter in the universe [2], we are still lacking a comprehensive understanding of its identity and properties. Many theories of dark matter have been put forward, where the DM candidate is identified with a neutralino, axion, sterile neutrino or some other new exotic (see [3] for a review). Since the DM interactions as well as its mass remain unknown, it is important to explore possible new signatures as well as constrains on various models. A very motivated scenario is for dark matter to be a weakly interacting massive particle (WIMP), since it was found that weakly interacting DM with a mass of around 100 GeV reproduces the observed

relic abundance ("WIMP-miracle"). Such possibility has been extensively studied within the context of low-scale supersymmetry (SUSY), where there are natural DM candidates with the desired features [4]. However, with LHC strongly constraining minimal low-scale SUSY extensions of the SM [5, 6], the above scenario becomes somewhat less appealing and it is imperative to investigate more general or alternative frameworks. A popular approach for analyzing generic phenomenological features of classes of theories is to study "simplified models". The simplified models constitute minimal extensions of the SM in terms of their particle content and interactions. Such approach allows for a more direct comparison between the model predictions and constraints from the experimental DM searches [7–9].

An interesting class of simplified DM models is associated with flavored dark matter (see [10] for a review). Motivated by the approximate global SU(3) flavor symmetries present in the SM, in these theories DM is charged under the flavor symmetry, comes in multiple copies and couples to quarks or leptons. While there are also other scenarios where sizable flavor violating effects can occur, such as models of sneutrino DM [11–15], neutrino DM within the context of extra dimensions [16] or even more exotic possibilities [17], flavor effects are not their main focus. Many studies of the flavored dark matter have concentrated on quark-flavored DM [8, 18–20], which leads to interesting LHC phenomenology and which usually has enhanced direct detection potential, since a tree level coupling of DM to the target nuclei is possible. Lepton-flavored DM [18, 21], on the other hand, leads to very different phenomenology, whose consequences have been less explored.

Since new contributions to flavor violating processes are very constrained, flavored DM has been typically considered within the context of minimal flavor violation (MFV) [22]. Within the MFV framework the only source of flavor violation are the SM Yukawa couplings, hence, flavor changing neutral currents (FCNC) are automatically suppressed. While this scenario is safe and by construction is in agreement with the experimental constraints, it is overly restrictive for exploring new phenomenology. Since all forms of matter in the SM have flavor, it is worthwhile to explore the possibility that dark matter also has its own notion of flavor. Starting with an unrestricted flavor structure in the DM coupling to SM fermions will allow us to quantitatively study how much freedom in flavor transformations does the dark matter has. In a recent work of [23], the SM flavor symmetries have been extended by an additional global $SU(3)_\chi$ symmetry. Within the model, Dirac fermion DM χ transforms as a triplet under the $SU(3)_\chi$ and as a singlet under the SM group. The DM χ couples to the quark fields with a new Yukawa-like coupling λ through a scalar mediator ϕ, which carries electroweak charge and is a triplet under the SM color $SU(3)_C$ group. The main assumption of the model is that aside from the Yukawa couplings, the only new source of flavor violation is λ. This generalizes the setup beyond that of MFV (BMFV).[1] The coupling λ is a priori not constrained and allows for large flavor violating effects. On the other hand, lepton-flavored DM within BMFV has not been studied.

In this work, we consider lepton-flavored dark matter within the BMFV framework. Specifically, the SM flavor symmetries are extended by an additional global $SU(3)_\chi$, under which the DM transforms. As we will show, while the lepton flavor violating processes are

[1]The authors of [23] call this Dark MFV (DMFV).

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strongly constrained, there exists viable parameter space for DM to be within the several hundred GeV range. We will also demonstrate that, contrary to the case of quark-flavored DM within the MFV or the BMFV, there is no $\mathbb{Z}_3$ symmetry available within the model to stabilize the lepton-flavored DM. Additionally, we will discuss how direct and indirect detection limits the parameter space and how DM in our scenario can naturally account for the 511 keV γ-ray excess. Then, we comment on several possible new signatures at the lepton and hadron colliders. As we shall see, the lepton e^+e^- colliders provide one of the more stringent constraints for both MFV and the BMFV scenarios. Finally, we discuss the implications for decaying dark matter, which can occur if an additional stabilizing symmetry is not imposed.

This manuscript is organized as follows. Section 2 reviews the framework of minimal flavor violation. We then extend it to BMFV and present a minimal model which satisfies this hypothesis. We comment on the assumptions of the model, what will constitute the MFV limit and also discuss how dark matter is stabilized within this setup. In section 3, we study the constraints on the model from lepton flavor violating processes and discuss which structure of the new Yukawa coupling λ will satisfy them, if the DM mass is to be kept in the phenomenologically interesting region of few hundred GeV. We then discuss constraints from direct and indirect detection and comment on lepton and hadron collider signatures in MFV and BMFV models. The possibility of decaying dark matter is also considered. In section 4, we present combined plots that include all experimental constraints and summarize the work.

2 Lepton-flavored dark matter

2.1 Minimal Flavor Violation

We start by reviewing the framework of minimal flavor violation (MFV) [22]. In the SM, there exists an approximate global $G_F = \mathrm{U}(3)^5$ symmetry [24], with the group factors $\mathrm{U}(3)_Q, \mathrm{U}(3)_U, \mathrm{U}(3)_D$ acting on quark fields Q, U^c, D^c and the factors $\mathrm{U}(3)_L$, $\mathrm{U}(3)_E$ acting on the lepton fields L, E^c. The symmetry breaking is induced by the SM Yukawa couplings, which provide different masses to different generations of quarks and leptons. The G_F symmetry can be decomposed[2] into

$$G_F \equiv \mathrm{SU}(3)_q^3 \times \mathrm{SU}(3)_l^2 \times \mathrm{U}(1)_B \times \mathrm{U}(1)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{PQ} \times \mathrm{U}(1)_{E_R}, \tag{2.1}$$

where

$$\mathrm{SU}(3)_q^3 = \mathrm{SU}(3)_Q \times \mathrm{SU}(3)_U \times \mathrm{SU}(3)_D, \tag{2.2}$$
$$\mathrm{SU}(3)_l^2 = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_E. \tag{2.3}$$

Here, the individual U(1) factors have been combined into the more familiar linear combinations of $\mathrm{U}(1)_B$, $\mathrm{U}(1)_L$, $\mathrm{U}(1)_Y$, $\mathrm{U}(1)_{PQ}$ and $\mathrm{U}(1)_{E_R}$ which are identified with baryon

[2]Recall, that a unitary group $\mathrm{U}(N)$ can be separated into non-Abelian and Abelian components with a group product $\mathrm{U}(N) \simeq \mathrm{SU}(N) \times \mathrm{U}(1)$.

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	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(3)_Q$	$SU(3)_U$	$SU(3)_D$	$SU(3)_L$	$SU(3)_E$	$SU(3)_\chi$
Q_L	**3**	**2**	1/6	**3**	**1**	**1**	**1**	**1**	**1**
u_R	**3**	**1**	2/3	**1**	**3**	**1**	**1**	**1**	**1**
d_R	**3**	**1**	-1/3	**1**	**1**	**3**	**1**	**1**	**1**
L_L	**1**	**2**	-1/2	**1**	**1**	**1**	**3**	**1**	**1**
e_R	**1**	**1**	-1	**1**	**1**	**1**	**1**	**3**	**1**
H	**1**	**2**	1/2	**1**	**1**	**1**	**1**	**1**	**1**
ϕ	**1**	**1**	-1	**1**	**1**	**1**	**1**	**1**	**1**
χ	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**3**
Y_U	**1**	**1**	0	**3**	$\overline{\mathbf{3}}$	**1**	**1**	**1**	**1**
Y_D	**1**	**1**	0	**3**	**1**	$\overline{\mathbf{3}}$	**1**	**1**	**1**
Y_E	**1**	**1**	0	**1**	**1**	**1**	**3**	$\overline{\mathbf{3}}$	**1**
λ	**1**	**1**	0	**1**	**1**	**1**	**1**	**3**	$\overline{\mathbf{3}}$

Table 1. Field content of the minimal lepton-flavored BMFV model.

(B) number, lepton (L) number, global hypercharge, Peccei-Quinn and the right handed rotation symmetries.[3] Neglecting the U(1) factors, we are left with a global $G_f = \mathrm{SU}(3)^5$ "flavor symmetry". In the absence of the Yukawa interactions, the flavor symmetry is exact. The breaking of the flavor symmetry is solely parametrized by the Yukawa couplings, which is the only source of flavor violation within the framework of MFV.

2.2 Beyond the MFV

Going beyond the MFV framework, the BMFV setup adds an additional "flavor" $\mathrm{SU}(3)_\chi$. In our analysis we shall focus on the lepton-flavored dark matter. The dark matter χ, which we assume to be a Dirac fermion, transforms as a triplet under the $\mathrm{SU}(3)_\chi$ symmetry and is a singlet under the SM gauge group. The χ field interacts with the SM fermions through a mediator ϕ, with a new Yukawa-like coupling λ. The mediator is charged under the electroweak symmetry and transforms as a color singlet. The coupling λ is a priori unconstrained and large flavor violating couplings are possible.

In principle, the DM χ can interact with either the left-handed SM $\mathrm{SU}(2)_L$ doublet l field or with the right-handed SM singlet e_R. For simplicity, we will concentrate on the latter case. Below, we present the full minimal model. The field content of the model is provided in table 1, where we have also included the quark sector for completeness. Since a Majorana DM mass term would violate the $\mathrm{SU}(3)_\chi$ symmetry, it is forbidden.

The complete renormalizable Lagrangian of our model is given by

$$\begin{aligned}\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + i\overline{\chi}\partial\!\!\!/\chi - m_\chi\overline{\chi}\chi - (\lambda_{ij}\overline{e}_{R_i}\chi_j\phi + \mathrm{h.c.}) \\ + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi + \lambda_{H\phi}(\phi^\dagger\phi)(H^\dagger H) + \lambda_{\phi\phi}(\phi^\dagger\phi)^2,\end{aligned} \tag{2.4}$$

[3]The global $\mathrm{U}(1)_Y$ factor coincides with the gauged $\mathrm{U}(1)_Y$ in the SM. Hence, the "true" U(1) factor in the SM global symmetry is $\mathrm{U}(1)^4$.

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where in order to systematically account for the flavor violating effects, the SM charged lepton Yukawa coupling Y_E as well as λ have been treated as spurion fields, which also transform under the symmetry group (see table 1).

2.3 Model assumptions, structure of λ and the MFV limit

We will now specify what constitutes the "MFV limit" within the BMFV framework. For the case of lepton-flavored DM, to recover the MFV from BMFV, one simply has to identify the $\mathrm{SU}(3)_\chi$ with either of the SM leptonic flavor symmetries, $\mathrm{SU}(3)_E$ or the $\mathrm{SU}(3)_L$. The parameters of the model will be restricted, in order to enforce consistency with the MFV assumptions [18].

First, consider the case where $\mathrm{SU}(3)_\chi$ is identified with $\mathrm{SU}(3)_E$. The MFV expansion of the DM coupling matrix λ and the χ mass matrix m, is given in terms of the SM charged lepton Yukawa couplings Y_E as,

$$\lambda_{ij}^{\mathrm{MFV}} = (\alpha \mathbf{1} + \beta\, [Y_E^\dagger Y_E])_{ij}, \tag{2.5}$$

$$m_{ij}^{\mathrm{MFV}} = (m_\chi \mathbf{1} + \Delta_m\, [Y_E^\dagger Y_E])_{ij}, \tag{2.6}$$

where we have kept only the lowest order term in the expansion and α, β, m_χ and Δ_m are the expansion parameters. On the other hand, if $\mathrm{SU}(3)_\chi$ is identified with $\mathrm{SU}(3)_L$, then $\lambda_{ij}^{\mathrm{MFV}}$ will simply reduce to the charged lepton Yukawa coupling $\lambda_{ij}^{\mathrm{MFV}} = Y_e$, while the mass term expansion will stay the same as above. It is assumed that any such expansions are convergent.

To make the discussion concrete, one may choose the basis where the observed flavor mixing in the SM is attributed to the flavor rotation in one sector only. For example, in the quark sector, a common choice for the Yukawa matrices constitutes $Y_D = \lambda_D$ and $Y_U = V_{CKM}\lambda_U$, which automatically satisfies the more stringent flavor constraints in the down quark sector. Here, $\lambda_D = (y_d, y_s, y_b)$ and $\lambda_U = (y_u, y_c, y_t)$ are diagonal and V_{CKM} is the CKM matrix. In this parametrization, flavor violating contributions will only appear through the off-diagonal CKM components, which will be present in the MFV expansion of the model parameters due to the $[Y_U^\dagger Y_U]$ terms. Similarly, in the lepton sector, it is commonly chosen that the charged lepton Yukawa coupling Y_E is diagonal, with $Y_E = \lambda_E = (y_e, y_\mu, y_\tau)$. Hence, Y_E will not provide any flavor violating contributions in the MFV expansion. Thus far, due to large uncertainty, we have omitted mentioning neutrino masses. Assuming that neutrinos are Dirac fermions, the above discussion of quark Yukawas will directly translate to the lepton sector. With a diagonal Y_E, all the lepton flavor violating contributions will come from the off-diagonal elements of the PMNS mixing matrix, which will appear in the MFV expansion through the $[Y_\nu^\dagger Y_\nu]$ terms. The situation is slightly different if neutrinos are Majorana, generally discussed within the context of the see-saw mechanism [25]. For the remainder of this work, we will neglect the possible flavor violating contributions from the lepton sector, since their size is negligible compared to the possible contributions from the new DM coupling λ.

In the case of BMFV, unlike the MFV, coupling λ is a priori not restricted in its form. Hence, both the diagonal (flavor-preserving) and the off-diagonal (flavor-changing)

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coefficients, can potentially be of $\mathcal{O}(1)$. Neglecting the SM Yukawa contributions, the mass term expansion is now given in terms of λ_{ij} as

$$m_{ij}^{\rm BMFV} = (m_\chi \mathbf{1} + \Delta_m \, [\lambda^\dagger \lambda])_{ij}. \tag{2.7}$$

Further, since there will be induced mass-splitting among the components in the DM multiplet induced by the RGEs, Δ_m is estimated to be [23]

$$\Delta_m \sim \frac{1}{16\pi^2} \log\left(\frac{m_\chi^2}{\Lambda^2}\right), \tag{2.8}$$

where Λ is the UV-scale at which $\mathrm{SU}(3)_\chi$ gets broken. Detailed discussion regarding possible UV-completions of such scenario is beyond the scope of this work. Throughout our analysis, unless otherwise stated, we will assume that the three components in the DM triplet χ are highly degenerate in mass with $m_a \simeq m_\chi$ for $a = 1, 2, 3$.

2.4 Dark matter stability

To ensure DM stability, it is common to impose an additional symmetry which forbids DM from decaying. In [26], it was pointed out that within the MFV framework, assuming quark-flavored DM, there is a residual $\mathbb{Z}_3$ symmetry which automatically stabilizes the DM.[4] The argument was later extended [23] to the BMFV framework assuming quark-flavored DM. It is then natural to wonder, if there is an analogous argument, in the context of either MFV or the BMFV framework, for the case of lepton-flavored DM. As we will show below, there is no residual discrete symmetry to automatically stabilize the DM for either of the two of lepton-flavored DM scenarios.

Let us first discuss the more general BMFV framework. For the lepton-flavored DM, the most general invariant operator involving the DM triplet χ, mediator ϕ as well as the SM fields and the Yukawa spurions, which parametrize flavor symmetry breaking, is

$$\mathcal{O}_{\rm DM} \sim \; \chi \ldots \overline{\chi} \ldots \phi \ldots \phi^\dagger \ldots L \ldots \overline{L} \ldots e_R \ldots \overline{e}_R \ldots Y_E \ldots Y_E^\dagger \ldots \lambda \ldots \lambda^\dagger \ldots G, \tag{2.9}$$

where the dots signify an arbitrary number of insertions of a given field type and G schematically denotes the field combination which is itself invariant under the color $\mathrm{SU}(3)_c$ and which renders $\mathcal{O}_{\rm DM}$ invariant under the electroweak symmetry. Since the fields transform in fundamental and anti-fundamental representations of the flavor SU(3) symmetries, the product[5] $\mathcal{O}_{\rm DM}$ results in an SU(3) singlet only if the number of the corresponding SU(3) triplets $\mathbf{3}$ minus the number of the corresponding anti-triplets $\overline{\mathbf{3}}$ is 0 modulo 3. This results in a set of conditions, one for each SU(3) symmetry, which must hold for $\mathcal{O}_{\rm DM}$ to be an invariant

$$(N_L - N_{\overline{L}} + N_{Y_E} - N_{Y_E^\dagger}) \mod 3 = 0, \quad \text{for SU}(3)_L, \tag{2.10}$$

$$(N_E - N_{\overline{E}} - N_{Y_E} + N_{Y_E^\dagger} + N_\lambda - N_{\lambda^\dagger}) \mod 3 = 0, \quad \text{for SU}(3)_E, \tag{2.11}$$

$$(N_\chi - N_{\overline{\chi}} - N_\lambda + N_{\lambda^\dagger}) \mod 3 = 0, \quad \text{for SU}(3)_\chi, \tag{2.12}$$

[4] Recall that $\mathbb{Z}_N$ is the center of the $\mathrm{SU}(N)$ group. The residual $\mathbb{Z}_3$ symmetry in the quark-flavored DM case is thus related to the centers of the SU(3)'s present in the model.

[5] Recall, the SU(3) singlets can be formed from the fundamental $\mathbf{3}$ and anti-fundamental $\overline{\mathbf{3}}$ representations via multiples of $\mathbf{3} \times \mathbf{3} \times \mathbf{3}$, $\overline{\mathbf{3}} \times \overline{\mathbf{3}} \times \overline{\mathbf{3}}$ or $\mathbf{3} \times \overline{\mathbf{3}}$.

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where N_j denotes the number of insertions of the field j. Canceling the dependency on Y_E and λ, we obtain

$$(N_\chi - N_{\overline{\chi}} + N_L - N_{\overline{L}} + N_E - N_{\overline{E}}) \mod 3 = 0, \tag{2.13}$$

which can be interpreted as a condition on the field charges transforming under a $\mathbb{Z}_3$ symmetry.

Consider now the case with $N_\chi = 1$, $N_{\overline{\chi}} = N_\phi = N_{\phi^\dagger} = 0$, which corresponds to operators that lead to dark matter decay. Since the $\mathbb{Z}_3$ invariance condition (2.13) can still be satisfied, provided an appropriate combination of the lepton fields, the dark matter stability is not ensured. This argument applies identically in the MFV framework, where $\mathrm{SU}(3)_\chi$ is identified with either $\mathrm{SU}(3)_E$ or $\mathrm{SU}(3)_L$. Since in the quark-flavored case of [23, 26] there was an extra condition coming from the additional color $\mathrm{SU}(3)_c$, the final equation for $\mathbb{Z}_3$ was further reduced. In that case, the above condition only has dependency on the DM χ and mediator ϕ fields and not on the SM fermions, enabling the $\mathbb{Z}_3$ to stabilize the dark matter.

Thus, we have shown that the $\mathbb{Z}_3$ symmetry which stabilizes quark-flavored DM, in the MFV and BMFV settings, is not available for the lepton-flavored DM case. Hence, we will assume that there is an additional $\mathbb{Z}_2$ which stabilizes the DM. Under this $\mathbb{Z}_2$ symmetry the χ and ϕ fields are odd while the SM fields are even and the dark matter decay operators are consequently forbidden. The case of decaying dark matter will be discussed in section 3.5.

3 Constraints and signals

Below, we discuss constraints as well as possible signals from the various sources related to lepton BMFV as specified in section 2.2.

3.1 Flavor constraints

3.1.1 Lepton flavor violating processes

As the structure of λ in the BMFV is a priori unrestricted, unlike the case of MFV, unsuppressed lepton flavor-violating (LFV) processes are possible and will occur through the off-diagonal elements of λ. Assuming the flavor violating couplings $\lambda_{ij\ (i\neq j)}$ are sizable, there are strong constraints on mediator mass m_ϕ and dark matter mass m_χ from the LFV processes. As we will see, these LFV processes give rise to the most severe constraints on our model in some parameter space. Lepton flavor violating processes have been extensively studied, as shown by the stringency of the current experimental limits as well as the expected sensitivities of future experiments, which can be found in [27–37]. Within BMFV, processes such as $\mu \to e\gamma$ will arise at the 1-loop level, as displayed in figure 1. The effective amplitude for this process can be expressed as

$$\mathcal{M}_{\mu\to e\gamma} = \frac{e}{2m_\mu}\epsilon^{*\alpha}\overline{u}_e[i\sigma_{\beta\alpha}q^\beta(a_R^{(\mu e\gamma)}P_L + a_L^{(\mu e\gamma)}P_R)]u_\mu, \tag{3.1}$$

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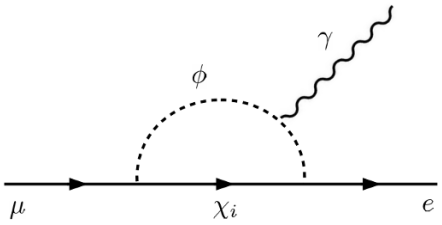

Figure 1. Contributing diagram for $\mu \to e\gamma$.

where $P_{R,L} = (1 \pm \gamma_5)/2$ are the projection operators, $\sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu]$, the $\overline{u}_e, u_\mu$ are the spinors that satisfy the Dirac equation, e is the electric charge, ϵ is the photon polarization vector and the indices L, R in $a_L^{(\mu e\gamma)}, a_R^{(\mu e\gamma)}$ refer to the electron chirality.[6] This leads to the branching ratio of

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\pi^2 e^2}{G_F^2 m_\mu^4}(|a_L^{\mu e\gamma)}|^2 + |a_R^{(\mu e\gamma)}|^2). \tag{3.2}$$

With the current 90% C.L. experimental limit on the branching ratio being

$$\mathcal{B}(\mu \to e\gamma) \equiv \Gamma(\mu \to e\gamma)/\Gamma(\mu_{\text{total}}) < 5.7 \times 10^{-13}, \tag{3.3}$$

$\mu \to e\gamma$ is one of the most constrained processes among various LFV channels. We will thus focus our attention on this decay mode.

Within the SM [39, 40], various LFV processes are extremely suppressed, with the predicted rate for $\mu \to e\gamma$ being of the order of 10^{-56} and arising through neutrino mixing. On the other hand, going beyond the SM, sizable contributions to these channels often are present. This is also the case for the MSSM, within the context of which $\mu \to e\gamma$ has been extensively studied [41]. As we discuss, the analytic result for $\mu \to e\gamma$ for the BMFV setting can be obtained directly from the MSSM, if the couplings are appropriately identified between the two frameworks. The contributing $\mu \to e\gamma$ diagrams in the MSSM come from loops that involve sfermions and charginos/neutralinos. For the BMFV scenario, we are interested in the sfermion-neutralino loop, which contains a neutral fermion and a charged scalar and which we can interpret in terms of χ and ϕ. We note, that in order to obtain the flavor violation within the MSSM, mass insertion terms must be present in the loop (see for example [42]). This is also the case for the MFV, where the couplings are nearly flavor diagonal. On the other hand, in the BMFV, the off-diagonal λ couplings mediate this process directly. Taking the MSSM sfermion-neutralino loop and neglecting the mass insertion term [38], the amplitude is

$$a_R^{(\mu e\gamma)} = -\frac{m_\mu^2}{192\pi^2 m_\phi^2}\left[\sum_{i=1}^{3}(\lambda_{1i}^*\lambda_{2i})\right] F_1(x), \tag{3.4}$$

[6] We use the notation of [38], which has indices interchanged compared to the usual notation (see for example textbook of Cheng and Li).

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where $x = m_\chi^2/m_\phi^2$ and $\lambda_{1i}^*, \lambda_{2i}$ correspond to the electron and muon couplings of χ_i running in the loop. The form factor $F_1(x)$ is given by

$$F_1(x) = \frac{2}{(1-x)^4}\Big[1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x\Big]. \tag{3.5}$$

Labeling the components of the triplet field as χ_1, χ_2, χ_3, the first two particles contribute to the amplitude above with one diagonal and one off-diagonal coupling. On the other hand, the χ_3 contribution originates from purely flavor-violating off-diagonal λ elements.

If all λ couplings are taken to be 1,

$$\lambda_0 = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} ,$$

the lower limits on the DM mass m_χ and the mediator mass m_ϕ from the experimental constraint on $\mu \to e\gamma$ will lie in the uninteresting region of 10–50 TeV (see figure 2). In order to have DM mass within the phenomenologically interesting parameter space of several hundred GeV, some of the couplings will have to be suppressed. One possible choice, is to assume that the diagonal λ couplings are dominant and are equal to 1, which will allow to make a more direct comparison to the MFV scenario. In this case, to maximize the LFV contributions, we set $\lambda_{12} = \lambda_{21} = 0$. This ensures that only χ_3 mediates the process. Taking the LFV couplings of χ_3 to be $\lambda_{23} = \lambda_{13} = 10^{-\frac{3}{2}}$, places the DM mass below the TeV scale as desired.

Thus far, we have discussed six of the nine λ couplings, which are involved in $\mu \to e\gamma$. We can similarly restrict the remaining three couplings, which describe the τ lepton, by looking at the constraints on $\tau \to e\gamma$ and $\tau \to \mu\gamma$. Requiring that the DM mass is in the range of a few hundred GeV, the remaining τ couplings are set to be $10^{-\frac{1}{2}}$ while satisfying experimental constraints on all LFV processes. The full structure of matrix λ for these constraints is then given by

$$\lambda_1 = \begin{pmatrix} 1 & 0 & 10^{-\frac{3}{2}} \\ 0 & 1 & 10^{-\frac{3}{2}} \\ 10^{-\frac{1}{2}} & 10^{-\frac{1}{2}} & 1 \end{pmatrix} .$$

In figure 2, we show the constraints from LFV processes for two representative choices for the structure of λ, the case $\lambda = \lambda_0$, where all λ couplings are taken to be 1, as well as the case of $\lambda = \lambda_1$. We stress, that the above choice of λ_1 is not unique. Suppressing the diagonal elements would allow to enlarge the off-diagonal LFV couplings. As an example, consider the coupling matrix λ_2, whose structure is given by

$$\lambda_2 = \begin{pmatrix} 0 & 1 & 10^{-\frac{3}{2}} \\ 1 & 0 & 10^{-\frac{3}{2}} \\ 10^{-\frac{1}{2}} & 10^{-\frac{1}{2}} & 0 \end{pmatrix} .$$

The matrix λ_2 is a variation of λ_1, but with the diagonal entries set to 0 and off-diagonal λ_{12} and λ_{21} terms set to 1. The structure of λ_2 is manifestly non-MFV. Since constraints on λ_2 are similar to those on λ_1, we will focus only on λ_1 for the remainder of this work.

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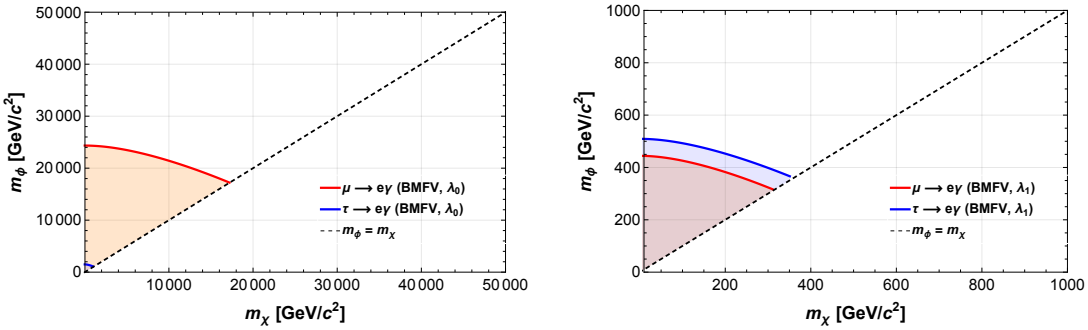

Figure 2. The unshaded region above the dashed line indicates the allowed parameter space on the $m_\phi - m_\chi$ plane by the LFV constraints, for the choice of DM coupling matrix $\lambda = \lambda_0$ (left) and $\lambda = \lambda_1$ (right).

3.1.2 Muon $(g-2)$

The measured value [43] of the magnetic moment of electron is in a good agreement with the SM predictions [44]. On the other hand, the measured value of the muon's magnetic moment [45, 46]

$$a_\mu^{\text{exp}} \equiv \frac{g_\mu - 2}{2} \equiv \frac{\mu_\mu}{(e\hbar/2m_\mu)} - 1 = (11659208.9 \pm 6.3) \times 10^{-10}, \tag{3.6}$$

differs from the SM calculations [47, 48] of $a_\mu^{\text{SM}} = (11659182.8 \pm 4.9) \times 10^{-10}$ by

$$a_\mu^{\text{diff}} = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0) \times 10^{-10}, \tag{3.7}$$

which corresponds to around 3σ deviation. Proposed future experiments [49] aim at improving the precision to 1.6×10^{-10} (0.14 ppm).

While one cannot make a definite statements about this discrepancy at present, it can still be of interest to explore it further by interpreting it as a possible sign of new physics. This issue has been extensively studied in the MSSM [50–53], with the sfermion or gaugino running in the loop. Its effective amplitude is obtained by identifying $a_L^{(\mu e\gamma)} = a_R^{(\mu e\gamma)} = a_\mu$ in the effective amplitude for $\mu \to e\gamma$ in equation (3.4),

$$\mathcal{M}_\mu = \frac{e}{2m_\mu} \epsilon^\alpha \overline{u}_\mu [i\sigma_{\beta\alpha} q^\beta a_\mu] u_\mu. \tag{3.8}$$

It is worthy to note, that while the loop form factor will stay the same for both the magnetic moment and $\mu \to e\gamma$, in the MSSM the two amplitudes are distinct. In MSSM, a mass insertion terms is required to be present for the flavor-changing process, $\mu \to e\gamma$, but not for the magnetic moment as it is flavor-conserving. This statement also holds for the case of flavored DM models with the MFV assumption. On the other hand, within BMFV, the results for the two processes will have the same general analytic structure, differing only in the couplings. Hence, by properly replacing the coupling constants in the MSSM loop contribution due to slepton and neutralino [52], the muon magnetic moment in our model with BMFV can be obtained,

$$\delta a_\mu = -\frac{m_\mu^2}{192\pi^2 m_\phi^2} \left[\sum_{i=1}^{3} (\lambda_{2i}^* \lambda_{2i}) \right] F_1(x), \tag{3.9}$$

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where x and $F_1(x)$ are the same as in equation (3.4). Since in the BMFV case with a general coupling matrix $\lambda = \lambda_0$, all three components χ_i can couple to the muon, there will be multiplied contributions to the muon magnetic moment compared to the MFV case [23] or its "lepto-philic" DM [54] variation. However, all the extra contributions will come with a negative sign and cannot account for the a_μ^{diff} and the discrepancy only increases. Thus, we shall not discuss this process further.

3.2 Relic abundance

Assuming that χ is a thermal WIMP dark matter, the relic abundance is found from the annihilation rate to the SM particles. The dominant contribution comes from the t-channel, through a mediator ϕ exchange, resulting in two leptons. The relic abundance calculation in the case of MFV was already described in [18, 21]. Since in the BMFV case, each of the DM particles χ_i can couple to the e, μ and τ leptons, additional contributions become possible.

For a general case with multiple DM species of distinct masses, the relic density is determined by the self-annihilation process, $\chi_a \overline{\chi}_a \to l_i \bar{l}_j$, where i, j label the lepton generation and a labels the DM type. Following the MFV calculation [18, 21] the s- and p-wave annihilation cross-section is given by

$$\begin{aligned}\frac{1}{2}\langle\sigma v\rangle_{\chi_a\overline{\chi}_a} &= \frac{1}{2}\left[\frac{(\lambda^*_{ia}\lambda_{ja}\lambda_{ia}\lambda^*_{ja})m^2_{\chi_a}}{32\pi(m^2_{\chi_a}+m^2_\phi)^2}\right. \\ &\quad \left. + v^2\frac{(\lambda^*_{ia}\lambda_{ja}\lambda_{ia}\lambda^*_{ja})m^2_{\chi_a}(-5m^4_\chi - 18m^2_{\chi_a}m^2_\phi + 11m^4_\phi)}{768\pi(m^2_{\chi_a}+m^2_\phi)^4}\right] \\ &= s + pv^2,\end{aligned} \tag{3.10}$$

where v is relative velocity of DM particles ($\sim 0.3c$ at freeze-out). We review the standard procedure for calculating the relic abundance in appendix A. Since within the BMFV the flavor-violating off-diagonal couplings $\lambda_{ij\ (i\neq j)}$ can contribute, the total annihilation cross-section will be enhanced. Due to the velocity suppression, we consider only the s-wave contribution at the freeze-out.

On the other hand, in the case where the masses of the DM triplet components are highly degenerate, with $m_{\chi_a} \simeq m_{\chi_b} \simeq m_{\chi_c}$, co-annihilation contributions become important. This is the scenario assumed within this work. If the species-transforming processes $\chi_a l_i \to \chi_b l_j$ occur fast, all DM species are present at the freeze-out, and co-annihilation dominates. As described in the appendix A, the effective annihilation cross-section, to a good approximation [55], will then be

$$\langle\sigma v\rangle_{\text{eff}} = \frac{1}{18}\sum_{i,j=e,\mu,\tau}\left[\sum_{a,b=1,2,3}\langle\sigma v\rangle_{\chi_a\overline{\chi}_b\to l_i\bar{l}_j}\right], \tag{3.11}$$

where the sum is performed over the s-wave contributions of each channel. This result is in agreement with [23], where quark-flavored DM with BMFV was considered. Equation (3.11) will apply for both BMFV and MFV. The difference between the two scenarios

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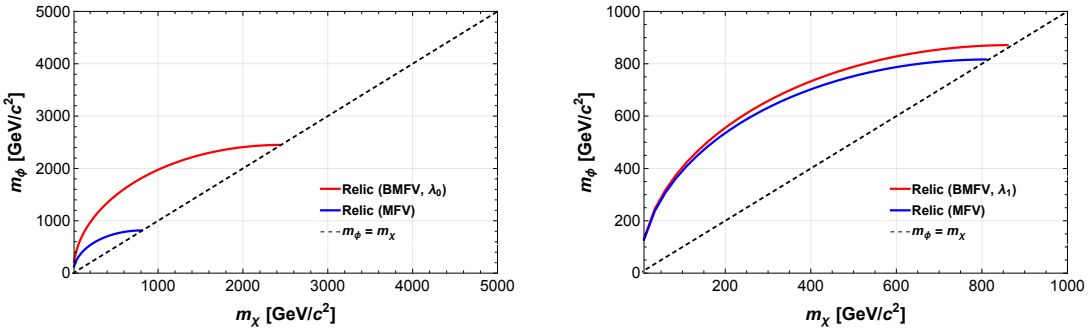

Figure 3. The solid curves correspond to values of m_ϕ and m_χ that give rise to the correct relic abundance, for the choice of DM coupling matrix $\lambda = \lambda_0$ (left) and $\lambda = \lambda_1$ (right). For both cases, comparison with MFV is also shown.

will come from the additional BMFV contributions in the sum, from the terms $\langle\sigma v\rangle_{\chi_a\overline{\chi}_b\to l_i\bar{l}_j}$ with $a \neq i, b \neq j$. With the effective cross-section taken to be

$$\langle\sigma v\rangle_{\text{eff}} = 2.2 \times 10^{-26}\text{cm}^3/\text{s}, \tag{3.12}$$

which approximately gives the correct observed relic abundance [56], the $m_\chi - m_\phi$ parameter space can be constrained through equation (3.11). For simplicity, we have also assumed that the regime of interest does not lie in the degenerate $m_\chi - m_\phi$ parameter space region, where $\Delta_{\chi\phi} \equiv (m_\phi - m_\chi)/m_\chi \ll 1$ and that $\Delta_{\chi\phi}$ is near or below the freeze-out temperature x_F. To ensure DM stability, unless stated otherwise, we have assumed that $m_\phi > m_\chi$.

In figure 3, we show the relic abundance constraints for the coupling matrix λ choices of λ_0 and λ_1. For a comparison, results for the case of MFV are also overlaid. As expected, since λ_1 has a similar structure as the flavor-diagonal MFV case, the relic abundance constraints are comparable between the two. On the other hand, the λ_0 scenario shows that relic abundance constraints are greater than those of MFV, which is a direct consequence of the increased number of open channels in the BMFV case where all the flavor-violating λ couplings significantly contribute. We note that both MFV and BMFV cases considered above are different from the setting of lepton MFV in [57], which focused on the region of non-degenerate DM masses without the co-annihilation effects and which considered the coupling to only one flavor at a time.

3.3 Detection

3.3.1 Direct detection

In the direct detection experiments, dark matter interactions with ordinary matter are studied. For the case of lepton-flavored dark matter, unlike the case of quark-flavored DM [18, 57], there is no direct tree-level coupling to the target nucleus. The only interactions which may occur for lepton-flavored DM are the scattering from the target electron [58] or through the photon exchange with the target nucleus which is a loop level process. As the scattering from the target electrons is highly suppressed, we will consider only the scattering off the target nucleus, which can occur in our model through the depicted diagram shown in figure 4.

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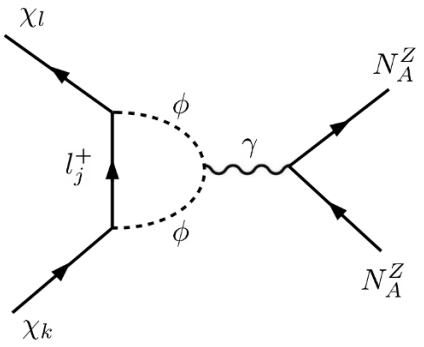

Figure 4. Contributing diagram for the direct detection.

In principle, both spin-dependent (SD) and spin-independent (SI) DM interactions can contribute, through a dipole-dipole coupling and a charge-charge/charge-dipole coupling, respectively. For the lepton-flavored DM, the SI charge-charge contribution dominates [18, 21]. The resulting DM-nucleon cross-section[7] is

$$\sigma_\chi^N = \sum_{j=e,\mu,\tau} c_j^2 e^2 \left(\frac{Z}{A}\right)^2 \frac{\mu^2}{\pi}, \tag{3.13}$$

where Z is the charge of the nucleus, A is the atomic number, e is the electromagnetic coupling and μ is the reduced DM-nucleon mass.[8] The coefficients c_j are given by [18]

$$c_j = -\frac{e}{(64\pi^2 m_\phi^2)} \left[\sum_{k,l=1}^{3} (\lambda_{jk}^* \lambda_{jl})\right] \left[1 + \frac{2}{3}\log\left(\frac{m_{l_j}^2}{m_\phi^2}\right)\right], \tag{3.14}$$

with m_{l_j} being the mass of the lepton j running in the loop. For the total cross-section we have summed over the possible e, μ, τ contributions. Using the current result from LUX[9] [59], the constraints on the $m_\phi - m_\chi$ parameter space is shown in figure 5 for $\lambda = \lambda_0$ and $\lambda = \lambda_1$.

3.3.2 Indirect detection (A): electron-positron fluxes

Indirect detection constraints for lepton-flavored DM originate predominantly from the electron-positron flux. The AMS-02 measured [60] an excess in the position flux at high energies, which is difficult to explain from purely astrophysical sources since they typically produce electron-dominant flux. On the other hand, in DM scenarios such lepton-flavored DM with either MFV or BMFV assumption, electrons and positrons are produced in equal amounts and thus could potentially explain the excess. The main contribution to the AMS-02 spectrum will come from DM annihilation into positrons, $\chi_a \overline{\chi}_b \to e^+ e^-$. The secondary positron production from μ^+ or τ^+ decays will result in a smeared momentum distribution of the positrons and is thus weaker, especially given that majority of this region is already

[7] The DM-nucleus cross-section σ_χ^{T} is found from $\sigma_\chi^{\mathrm{T}} = \sigma_\chi^{\mathrm{N}} \cdot A^2$.
[8] Reduced mass is given by $\mu = m_\chi m_N/(m_\chi + m_N)$, where m_N is the mass of a nucleon.
[9] For Xenon, $Z = 54$ and $A = 129$.

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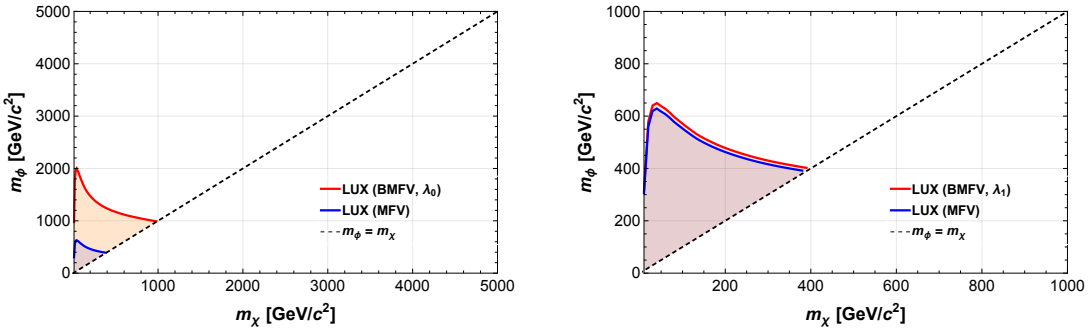

Figure 5. Allowed parameter space by the direct detection constraints from LUX for the choice of DM coupling matrix $\lambda = \lambda_0$ (left) and $\lambda = \lambda_1$ (right).

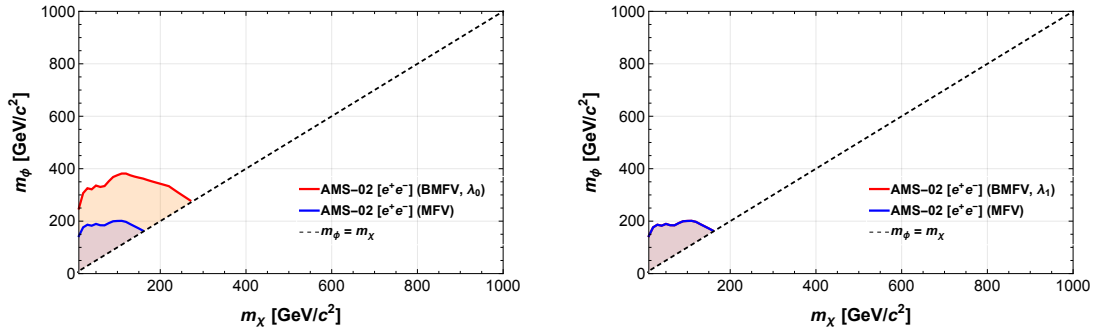

Figure 6. Allowed parameter space by the indirect detection constraints from electron-positron fluxes for the choice of DM coupling matrix $\lambda = \lambda_0$ (left) and $\lambda = \lambda_1$ (right).

restricted from direct detection which is more sensitive than indirect detection. Thus, we will only consider the channels with direct decays into e^+e^-. Following [61], the $m_\phi - m_\chi$ parameter space in our model with BMFV is constrained by the AMS-02 data similar to the way where the constraint on SUSY DM decaying into e^+e^- is derived, after properly taking into account the factor of 2 difference between the Dirac (as in our model) vs Majorana (as in SUSY case) fermions in the annihilation cross section. The results are shown in figure 6, for the two choices of coupling matrix λ_0 and λ_1. For this figure, we have used the e^+e^- data of [62] and considered only the $\chi_a\overline{\chi}_b \to e^+e^-$ channels.

3.3.3 Indirect detection (B): γ rays

In addition to the position flux, the annihilation cross section is also bounded by the limits on the γ-ray sources. The γ-rays can arise from various processes. These include the annihilation channel through lepton-anti-lepton intermediate state, $\chi_a\overline{\chi}_b \to l_i^+ l_j^- \to \gamma$. The production of photons can also arise through the hadronic τ decay channels such as $\tau \to \pi^+\pi^0\nu$,[10] followed by $\pi^0 \to \gamma\gamma$, which turns out to be the dominant contribution. In figure 7, we present the constraints from the γ-ray flux on the $\chi_a\overline{\chi}_b \to \tau^+\tau^-$ channel, which are based on simulations [63] consistent with Fermi-LAT data. We show results for both λ_0 and λ_1, which turns out to be less stringent than those from the direct detection.

[10]This is the main τ decay channel, with a branching ratio of 25.52%.

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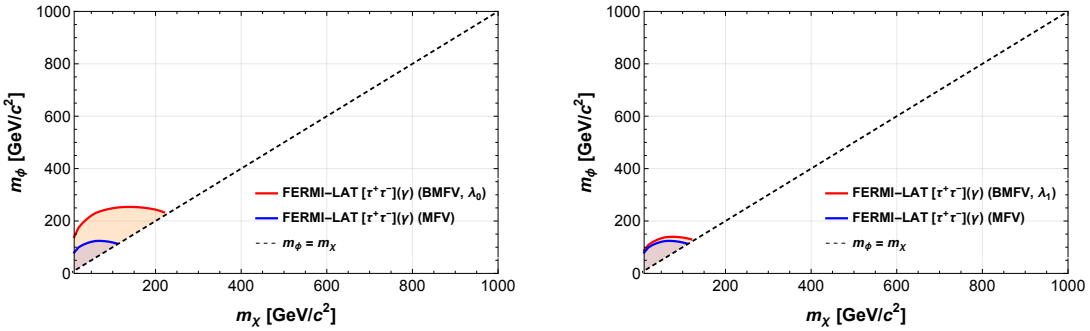

Figure 7. Allowed parameter space by the indirect detection constraints from γ-ray fluxes, for the choice of DM coupling matrix $\lambda = \lambda_0$ (left) and $\lambda = \lambda_1$ (right).

While the γ-ray constraints are not overly stringent, there have been several (potential) observations of γ-ray line excesses which may be interpreted in the context of DM. Many proposals have been put forward as a potential explanation for the recently observed galactic 3.5 keV X-ray excess [64, 65]. Within the lepton-flavored dark matter framework [61], one possibility is to consider the energy release after one DM species decays to another through a flavor changing process $\chi_a \to \chi_b \gamma$ at one loop, with the energy of γ identified with the mass splitting of the species $\Delta m_{ab} = m_a - m_b$. Another possibility is the decay $\chi_a \to \chi_b l_i \bar{l}_j$ due to flavor preserving couplings, where the lepton is identified with a neutrino if the mass splitting Δm_{ab} is smaller than $2m_e$. Generally, the former dominates over the latter, given that the latter case is further suppressed by the 3-body decay phase space as well as additional powers of loop lepton masses. The mass splitting required to explain the 3.5 keV γ-ray line can be generated within the lepton-flavored DM framework with MFV [61]. At the leading order the χ_a masses are degenerate due to the flavor symmetry both in the MFV and BMFV cases. On the other hand, the splitting among the χ_a masses is induced at the one-loop level through wave-function renormalization, which will depend on the loop charged fermion masses. This will induce several γ-ray lines with closely spaced frequencies proportional to mass splitting, given by

$$\delta w = w(\chi_\tau \to \chi_e) - w(\chi_\tau \to \chi_\mu) \approx w_0(m_\mu^2/m_\tau^2), \tag{3.15}$$

where $w(\chi_\tau \to \chi_e)$ and $w(\chi_\tau \to \chi_\mu)$ are the frequencies for the transitions $\chi_\tau \to \chi_\mu$ and $\chi_\tau \to \chi_\mu$, respectively. The parameter w_0 is the average χ_τ line frequency, which if taken to be 3.5 keV to explain the excess will result in $\delta w \simeq 12.4\,\text{eV}$. Hence, not only will the excess be explained but there will be an eV level line splitting at 3.5 keV.

Similarly, we can use the same argument to address the long standing 511 keV γ-ray excess observed by SPI/INTEGRAL [66, 67] in the Galactic Center. By setting $w_0 = 511$ keV in (3.15), there will be an induced splitting $\delta w \simeq 1.82$ keV, which is still consistent with the observed broadening of several keV around the 511 keV line [67] and will require future experiments to settle the question if such features are indeed present.

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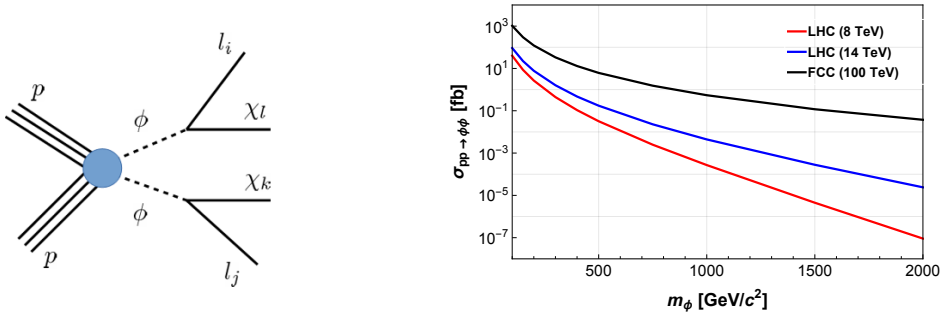

Figure 8. (left) Mediator pair production at hadron colliders. (right) Production cross-section as a function of the mediator mass for LHC as well as FCC.

3.4 Collider searches

We will now comment on hadron (pp) and lepton (e^+e^-) collider searches, emphasizing the difference between MFV and BMFV scenarios. For our studies, we have estimated cross-sections at the parton level using `MadGraph5` [68], with the flavored DM models implemented via `FeynRules` [69]. Since the final states of interest are associated with leptons, hadronization and associated showers can be neglected. We will mention possible backgrounds only in passing, with a detailed background estimates and analysis for various scenarios left for future work. In the simulations, unless stated otherwise, we have used the extreme case of λ_0 to represent BMFV, in order to highlight the difference with MFV.

3.4.1 Hadron colliders

The most sensitive hadron collider signals for the lepton-flavored DM come from Drell-Yan production of the mediator pair through Z and γ with $\chi\overline{\chi}l^+l^-$ final state, giving a signature of same flavor, opposite sign di-lepton plus missing energy (l^+l^- + MET). The general sensitivity of these searches can be seen from the mediator production cross-section, as shown in figure 8, which is the same for both MFV and BMFV. The results for LHC ($\sqrt{s} = 8$ and 14 TeV), in the mass region below 1 TeV, are in agreement with [18, 21]. For potential future studies, we have extended the considered mass region and also shown the results for the proposed far future circular collider (FCC) operating at $\sqrt{s} = 100$ TeV.

In general, BMFV will have enhanced di-lepton signal over that in the MFV case, due to the existence of additional contributing χ channels. Note that l^+l^-+ MET is also the standard signature for SUSY slepton searches. Hence, based on slepton search analyses from ATLAS [70] and CMS [71], the constraints on the flavored DM model can be obtained [18, 21, 54]. As an illustration, in figure 9 we display both MFV and BMFV cases for the simplest final state of e^+e^- at LHC (14 TeV), assuming two representative scenarios of $m_\chi = 10$ GeV and $m_\chi = 50$ GeV. We anticipate that the upcoming LHC 14 TeV run will provide additional constrains on the parameter space in this region. Results for other lepton final states are similar.

On the other hand, the multi-flavor lepton final state (e.g. $e^\pm\mu^\mp$) in SUSY result from chargino production. Since the event topologies for the chargino production and flavored-

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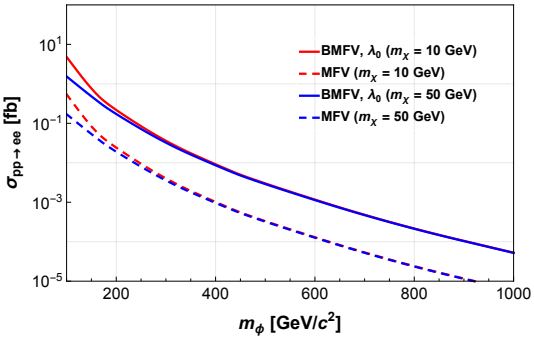

Figure 9. Comparison of MFV and BMFV cross sections for $pp \to e^+e^-$ production at the LHC (14 TeV), assuming $m_\chi = 10$ GeV and $m_\chi = 50$ GeV.

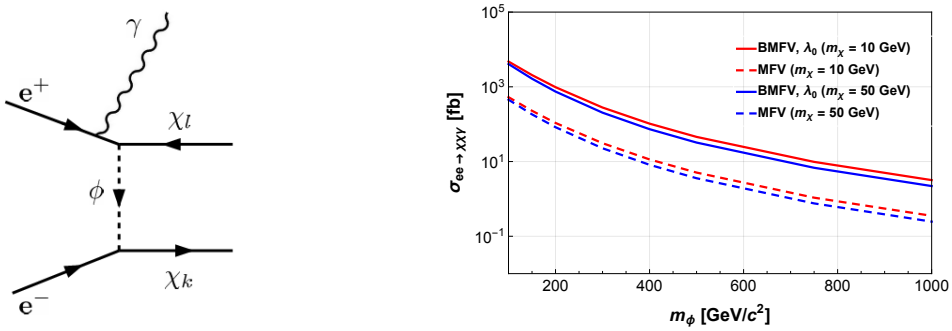

Figure 10. (left) Contributing diagram for e^+e^- collider mono-photon channel. (right) LEP mono-photon channel cross-section.

DM differ, the two cannot be mapped directly to each other. The main background in these searches comes from di-boson (WW, ZW, ZZ) as well as top production. Additional signatures could come from taus in the final state, and these would be the main collider search channels which could discriminate between BMFV (with λ_1 or λ_2) and MFV, due to large off-diagonal couplings involving τ. These channels, however, are less sensitive than the others, due to high background contamination and lower efficiency [72].

3.4.2 Lepton colliders

For e^+e^- lepton collider at LEP ($\sqrt{s} = 200$ GeV), one of the best discovery channels is $e^+e^- \to \chi\overline{\chi}\gamma$ with search signature of a mono-photon plus missing energy (γ+ MET). A possible contributing diagram as well as general parton-level cross sections are shown in figure 10. While proper comparison without detailed analysis is difficult, from figure 9 and 10, it is evident that constraints from lepton collider are more significant. In fact, it has been pointed out that using effective field theory (EFT) approach [73], in the context of lepto-philic DM with a charged scalar mediator, similar to MFV and BMFV models we consider, the LEP DELPHI experiment results [74] restrict the DM mass to be $\gtrsim 100$ GeV and mediator mass to be above several hundred GeV. The dominant background for this search, is the $e^+e^- \to Z\gamma$ process, with Z decaying invisibly via $Z \to \nu\overline{\nu}$.

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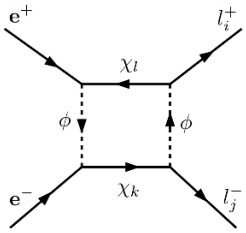

Figure 11. Contributing diagram for e^+e^- collider fermion pair production channel.

Aside from the mono-photon searches, for the case of lepton-flavored DM with a charged scalar mediator, the fermion pair production is important. A diagram that can lead to fermion pair production is shown in figure 11. In fact, recent EFT analysis [75] shows that LEP fermion pair production constraints [76] are competitive with mono-photon searches and limit the mediator mass in the region of several hundred GeV and DM mass below 100–200 GeV. Additional advantage of searching in these channels is that it provides a way to test the flavor violating couplings, which is not possible in the mono-photon channel as this channel only probes DM coupling to electrons. In BMFV one can expect processes with multi-flavor lepton final state such as $e^+e^- \to \mu^+e^-$, with χ and ϕ running in the loop. The scenario can thus be tested by searching for multi-flavor lepton final state. Past experimental searches mainly focused on single flavor lepton final state and thus these channels are not as constrained.

Looking into the future, the proposed International Linear Collider (ILC) with the collision energy of $\sqrt{s} = 500\,\text{GeV}$ is expected to probe [75] the TeV region in m_ϕ, m_χ parameter space, thus putting stringent bounds on the model.

3.5 Decaying dark matter

Having investigated the constraints and signals for the case of stable dark matter, we will also briefly discuss decaying dark matter. As we have shown in section 2.4, there is no "natural" stabilizing symmetry for dark matter present within the lepton-flavored MFV or BMFV scenarios. Hence, if one is to ensure DM stability, an extra symmetry such as the $\mathbb{Z}_2$ symmetry mentioned in section 2.4 must be imposed ad hoc. On the other hand, without such stabilizing symmetry, our framework provides an interesting setup for studying decaying dark matter. As has been stressed in the recent literature, decaying dark matter can lead to novel experimental signatures, especially for indirect detection [77].

To obtain effective operators for decaying DM, we have scanned for gauge invariant terms which obey the constraints of equations from section 2.4, using a custom `Mathematica` code. The smallest operators which contain a single DM χ field ($N_\chi = 1$) are 4-fermion dimension-6 terms with one lepton. We found four combinations of such operators, corresponding to decays

$$\chi \to \text{lepton} + \text{meson} \tag{3.16}$$

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to which many combinations of couplings can be added to make them invariant. Assuming a minimal combination of couplings, these are:

$$\left(\frac{\lambda Y_D Y_U^\dagger}{\Lambda^2}\right)\chi\overline{e_R}d_R\overline{u_R} \implies \chi \to e^+\pi^- \tag{3.17}$$

$$\left(\frac{\lambda Y_E Y_D}{\Lambda^2}\right)\chi d_R\overline{LQ} = \left(\frac{\lambda Y_E Y_D}{\Lambda^2}\right)\chi d_R\{\overline{\nu_L}\overline{d_L} - \overline{e_L u_L}\} \implies \chi \to \overline{\nu}\pi^0\,,\ \chi \to e^+\pi^- \tag{3.18}$$

$$\left(\frac{\lambda Y_E Y_U^\dagger}{\Lambda^2}\right)\chi\overline{u_R}\overline{L}Q = \left(\frac{\lambda Y_E Y_U^\dagger}{\Lambda^2}\right)\chi\overline{u_R}\{\overline{\nu_L}d_L - \overline{e_L}u_L\} \implies \chi \to \overline{\nu}\pi^0\,,\ \chi \to e^+\pi^- \tag{3.19}$$

$$\left(\frac{\lambda Y_E^\dagger}{\Lambda^2}\right)\chi e_R\overline{LL} = \left(\frac{\lambda Y_E^\dagger}{\Lambda^2}\right)\chi e_R\{\overline{\nu_L e_L} - \overline{e_L\nu_L}\} \implies \chi \to \overline{\nu}e^+e^- \tag{3.20}$$

where we have suppressed the flavor indices and taking for illustrative purposes first generation particles, displayed the possible processes on the right. Since there exists a similarity between our DM χ and SUSY neutralino, the channels which appear above are analogous to those of decaying neutralino [78] in R-parity violating (RPV) MSSM. Namely, with lepton number (L) violating RPV operators $LQ\overline{d}$ and $LL\overline{e}$, neutralino could also decay via $\chi \to \overline{\nu}d\overline{d}, \chi \to \overline{e}d\overline{u}$ and $\chi \to \overline{\nu}e\overline{e}$.

For the decaying DM to be consistent with observation, its lifetime must be longer than the age of the Universe, $\tau_{\rm univ.} \sim 4.3 \times 10^{17}$s. For the above 4-fermion operators, the lifetime is given by [79]

$$\tau_\chi \sim 10^{26}\text{s}\left(\frac{1}{f(\lambda,\lambda^\dagger,Y,Y^\dagger)}\right)^2\left(\frac{\text{TeV}}{m_\chi}\right)^5\left(\frac{\Lambda}{10^{15}\text{ GeV}}\right)^4 \tag{3.21}$$

where we have included the couplings using a function $f(\lambda,\lambda^\dagger,Y,Y^\dagger)$, which denotes the appropriate combination of λ's and Yukawa's such that a given operator is rendered invariant.

In general, decaying dark matter can lead to indirect detection signals coming from gamma rays [80–83], neutrinos [84–87], electrons/positrons [88–92] and anti-protons/anti-deuterons [93–97]. From the above channels, if m_χ is not very high ($m_\chi \sim$ GeV), the χ decay will result in a prompt hard lepton as well as several softer leptons or gammas coming from the meson decay. If $m_\chi \gg$ GeV, energetic quarks will lead to hadronizing jets resulting in a platitude of even softer leptons or gammas.[11] Decaying DM with a hard charged lepton can in principle be used to explain (for example, see [77, 98]) the positron flux excess observed by Pamela [99] and AMS-02 [60]. On the other hand, very heavy ($m_\chi \sim 100$ TeV) DM with a prompt energetic neutrino, which can also appear within our setup, can have implications for neutrino observatories such as IceCube or Super-Kamiokande [100]. Additionally, gamma ray signals have already been extensively analyzed by the Fermi LAT [101] and HESS [102] experiments. Future experiments, such as CTA [103], will allow to further investigate the parameter space for heavier DM. Analyses of decaying DM with such signatures already exist in the literature [104–106]. The constraints that we have obtained from the previous sections, especially those from flavor, restrict the

[11] In this case, there will also be additional constraints from astrophysics, such as those from the anti-proton flux. We would like to thank Tim Tait for stressing this point.

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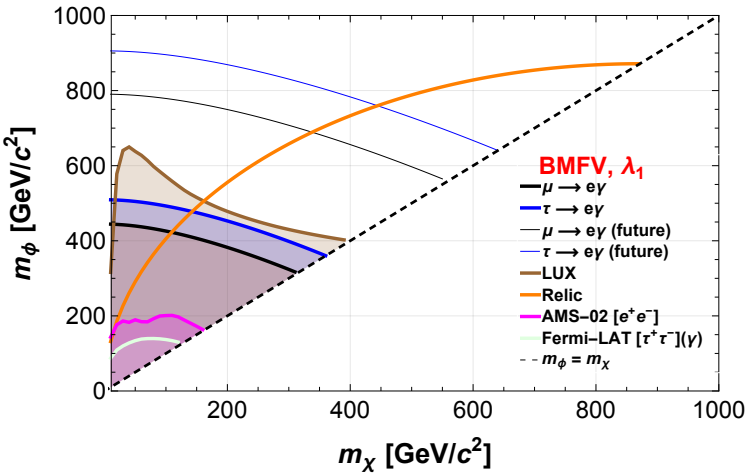

Figure 12. Allowed parameter space for the coupling choice of λ_1, after the constraints from LFV, relic abundance, direct and indirect detection have been combined.

allowed structure in the coupling λ. Hence, an astrophysical analysis will result in the allowed parameter space for m_χ and Λ. A detailed study of decaying dark matter and the implications of astrophysics, however, is beyond the scope of the present work and is left for future analysis.

4 Summary

In summary, BMFV lepton-flavored DM which transforms under additional flavor $SU(3)_\chi$ symmetry, provides an interesting possibility to explore and contrast with MFV. In the literature it has been pointed out that for quark-flavored MFV and BMFV scenarios there is a readily available $\mathbb{Z}_3$ symmetry which stabilizes the dark matter. We have shown, that for lepton-flavored MFV and BMFV scenarios this is not the case, and one needs to impose an additional symmetry, such as $\mathbb{Z}_2$, to stabilize it. Unlike the case of MFV, in BMFV, large flavor-violating effects are possible. We have considered flavor, direct and indirect detection as well as relic abundance constraints and on figure 12 show the combined result for a representative BMFV model based on λ_1 couplings, which allows us to have m_χ, m_ϕ in the several hundred GeV range. The most stringent constraints are those from the flavor-violating processes, and we can see that near term new experiments will have the possibility to eliminate a large region of parameter space below TeV for the BMFV model with λ_1, while keeping MFV-based scenario safe. We have also noted that if we are to assume that lepton-flavored DM MFV based scenario can explain the 511 keV line splitting, following the explanation of the 3.5 keV line in the recent literature, it is expected that there will be a sizable ($\sim$ keV) line-splitting induced near 511 keV. In the BMFV case, due to the lack of constraints on the coupling matrix λ, the predicted splitting is not as definite. This splitting may be of interest for the future indirect-detection experiments. Finally, the previous works on MFV based lepton-flavored DM mainly considered hadron collider di-lepton signals. On the other hand, our parton-level cross-section simulations as well as EFT considerations in

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the recent literature, show, that lepton e^+e^- collider constraints from mono-photon and fermion pair production are stronger and are competitive among each other. Finally, we have outlined possible implications for decaying DM, if an additional stabilizing symmetry has not been imposed.

A Calculating the relic abundance

We briefly review relic abundance calculation (see [107] for details) and comment on co-annihilation effects. Consider several DM species χ_a, χ_b with distinct masses m_{χ_a}, m_{χ_b}. For χ_a, the relic abundance is determined by the self-annihilation process, $\chi_a \overline{\chi}_a \to l_i \bar{l}_j$, where l_i is SM lepton of generation i. This is done by solving the Boltzman equation for evolution of the DM number density n_a

$$\frac{dn_a}{dt} = -3Hn_a - \langle \sigma v \rangle_{aa} [n_a^2 - (n^{eq})^2], \tag{A.1}$$

where H is the Hubble parameter governing expansion of the universe is equal to $H = (8\pi\rho/3M_{\rm Pl})^{1/2}$, n^{eq} is the χ_a number density at equilibrium, $\langle \sigma v \rangle_{aa}$ is the thermally averaged annihilation cross-section times the relative velocity. In the non-relativistic approximation, n^{eq} is given by

$$n^{eq} \approx g \left(\frac{m_{\chi_a} T}{2\pi} \right)^{3/2} e^{-m_\chi/T}, \tag{A.2}$$

where T is the temperature and g the number of degrees of freedom ($g = 4[2]$ for Dirac [Majorana] fermion). Before the thermal averaging, in the non-relativistic limit one can expand the cross-section $\sigma = s + pv^2$, thus separating $\langle \sigma v \rangle_{aa}$ into the non-relativistic (s-wave) and relativistic (p-wave) components.

For a single DM species present at the freeze-out, the relic abundance in terms of s- and p-wave components is approximately

$$\Omega_\chi h^2 \approx \frac{1.07 \times 10^9}{\rm GeV} \frac{1}{M_{pl}\sqrt{g^*}} \left(\frac{x_F}{s + 3(p - s/4)/x_F} \right), \tag{A.3}$$

where Ω_χ is the present-day mass density divided by the critical density ρ_c,[12] h is the normalized expansion rate and x_F is the freeze-out temperature. Here, x_F is given by

$$x_F = \left[\frac{5}{8} \sqrt{\frac{45}{8}} \left(\frac{g}{\sqrt{g^*}} \right) \frac{M_{pl}}{\pi^3} \frac{m_{\chi_a}(s + 6p/x_F)}{\sqrt{x_F}} \right], \tag{A.4}$$

where in the above M_{pl} is the Planck scale given by $M_{pl} = 1.22 \times 10^{19}\,\text{GeV}$ and g^* is the temperature-dependent number of relativistic degrees of freedom at the freeze-out, taken here to be $g^* = 86.25$ (as in [57]). Fitting the relic abundance to the observed value of $\Omega_\chi h^2 = 0.1199 \pm 0.0027$ from WMAP [108] and Planck [109], we obtain the allowed dark matter parameter space.

[12] The critical mass density, which corresponds to a flat universe, is given by $\rho_c = 3H_0^2 M_{\rm Pl}^2/8\pi = 1.0539 \times 10^{-5} h^2 \text{GeV cm}^{-3}$, where $H_0 = 100h$ km s^{-1}Mpc^{-1} is the normalization of the expansion rate.

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For several DM species χ_a and χ_b with semi-degenerate masses, where $m_{\chi_b} \gtrsim m_{\chi_a}$, the relic density can be dominantly controlled by the co-annihilation process, $\chi_a\overline{\chi}_b \to l_i\bar{l}_j$ (i,j = generation). Then, all χ_b decay into the stable DM candidate χ_a, giving rise to the relic density in the universe today.

On the other hand, if the mass splitting between the species is very small, $(m_{\chi_a} - m_{\chi_b}) < x_F/20$, co-annihilation effects become important. Assuming small splitting and that flavor changing processes $x_a l_i \to x_b l_j$ occur fast, all of the states are present in the freeze-out and co-annihilation dominates.[13] The Boltzman equation has the same form as for single DM species and the relic abundance will not be strongly affected. At this point it is useful to define the effective cross-section, which for Dirac fermion DM as considered within this work, reads [112]

$$\langle\sigma v\rangle_{\rm eff} = \frac{1}{2}\langle\sigma v\rangle. \tag{A.5}$$

Then, the effects of co-annihilation are taken into account [55] (see also [16]) as

$$\sigma_{\rm eff} = \sum_{i,j}^{N} \sigma_{ij}\left(\frac{g_i g_j}{g_{\rm eff}^2}\right)\Big[1+\Delta_i\Big]^{3/2}\Big[1+\Delta_j\Big]^{3/2} e^{-x(\Delta_i+\Delta_j)}, \tag{A.6}$$

where $\Delta_i = (m_i - m_1)/m_1$ is the mass difference between the 1^{st} and i'th DM particle, g_i are i'th relativistic d.o.f and $g_{\rm eff}$ are the effective d.o.f., given by

$$g_{\rm eff} = \sum_{i=1}^{N} g_i\Big[1+\Delta_i\Big]^{3/2} e^{-x\Delta_i}. \tag{A.7}$$

From the above, for highly degenerate DM with $m_i \approx m_j$, as we have assumed for out model, we can take $\Delta_i = 0$, resulting in

$$\sigma_{\rm eff} = \sum_{i,j}^{N} \sigma_{ij}\left(\frac{g_i g_j}{\sum_a g_a^2}\right). \tag{A.8}$$

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[13] See [110, 111] for co-annihilation effects within SUSY-based settings with neutralino DM.

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