Lepton-Flavored Scalar Dark Matter with Minimal Flavor Violation

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Abstract

We explore scalar dark matter that is part of a lepton flavor triplet satisfying symmetry requirements under the hypothesis of minimal flavor violation. The dark-matter candidate couples to standard-model particles via Higgs-portal renormalizable interactions as well as to leptons through dimension-six operators, all of which have minimal flavor violation built-in. With the simplest parameter choices, we investigate the constraints and implications from a series of experimental data to test the validity of our model. Future high-energy e^+e^- machines, such as the International Linear Collider, are well suited to probe various aspects of our model more stringently.

Introduction

0.1 Motivation

(1) Dark matter (DM) exists in the Universe. ⇒ Beyond SM

(2) Neutrino Oscillation ⇒ Neutrino masses ⇒ Beyond SM

(3) Flavor-changing neutral currents (FCNC) of leptons ⇒ Probing New Physics

(4) Recent Experimental Data: Flavor-Violating Higgs Decay

1 Framework of MFV and Type-I Seesaw Mechanism

1.1 MFV hypothesis [1]:

All sources of flavor and CP violation reside in renormalizable Yukawa couplings defined at tree level

1.2 Type-I Seesaw Mechanism

$$\begin{aligned}\mathcal{L}_{\rm m} &= -(Y_\nu)_{kl}\,\bar L_{k,L}\,\nu_{l,R}\,\tilde H - (Y_e)_{kl}\,\bar L_{k,L}\,E_{l,R}\,H - \tfrac12 (M_\nu)_{kl}\,\overline{\nu^c_{k,R}}\,\nu_{l,R} + \text{H.c.}\,,\\ &\supset \frac{-1}{2}\left(\overline{\nu_L}\;\overline{(\nu_R)^c}\right)\begin{pmatrix}0 & \frac{v}{\sqrt2}Y_\nu\\ \frac{v}{\sqrt2}Y_\nu^T & M_\nu\end{pmatrix}\begin{pmatrix}\nu_L^c\\ \nu_R\end{pmatrix} + \text{H.c.}\\ \Rightarrow m_\nu &= -\frac{v^2}{2}Y_\nu M_\nu^{-1}Y_\nu^{\rm T} = U_{\rm PMNS}\,\hat m_\nu\,U_{\rm PMNS}^{\rm T}\quad,\quad |m_\nu\times M_\nu|\sim|v^2Y_\nu^2|\quad (\text{"Seesaw"})\end{aligned}$$

1.3 Flavor Groups and Spurions [2]

$\mathrm{U}(3)_L\times\mathrm{U}(3)_\nu\times\mathrm{U}(3)_E = G_\ell\times\mathrm{U}(1)_L\times\mathrm{U}(1)_\nu\times\mathrm{U}(1)_E$, with $G_\ell=\mathrm{SU}(3)_L\times\mathrm{SU}(3)_\nu\times\mathrm{SU}(3)_E$

$$L_L\to V_L L_L\,,\qquad \nu_R\to V_\nu\nu_R\,,\qquad E_R\to V_E E_R\,,\qquad V_{L,\nu,E}\in\mathrm{SU}(3)_{L,\nu,E}\,,$$

Treat the Yukawa couplings as spurion fields

$$Y_\nu\to V_L Y_\nu V_\nu^\dagger\,,\qquad Y_e\to V_L Y_e V_E^\dagger\,.$$

Simple Choice: $M_\nu=\mathcal{M}\mathbb{1}$, $SU(3)_\nu\to O(3)_\nu$

$\Rightarrow\ G_\ell=\mathbf{SU(3)}_{\boldsymbol L}\times\mathbf{SU(3)}_{\boldsymbol E}\times\mathrm{O}(3)_\nu$

Building Blocks $A=Y_\nu Y_\nu^\dagger\sim(8,1)$, $B=Y_eY_e^\dagger\sim(8,1)$, $Y_e\sim(3,\bar3)$, $Y_\nu\sim(3,1)$

Explicit form of the spurions (Yukawa couplings)

$$Y_e=\frac{\sqrt2}{v}\,\mathrm{diag}\big(m_e,m_\mu,m_\tau\big)\,,\ \boldsymbol{Y_\nu^{(M)}=\frac{i\sqrt2}{v}U_{\rm PMNS}\hat m_\nu^{1/2}OM_\nu^{1/2}}\,,\ Y_\nu^{(D)}=\frac{\sqrt2}{v}U_{\rm PMNS}\hat m_\nu\,,$$

Double matrix expansion series [3]

$\Delta=\sum\xi_{jkl\ldots}\mathsf{A}^j\mathsf{B}^k\mathsf{A}^l\cdots$ with $\xi_{jkl\ldots}\lesssim\mathcal{O}(1)$, $\&\,Im(xi_{jkl\ldots})=0$ (MFV assumption)

$$\begin{aligned}\Delta={}&\xi_1\mathbf{1}+\xi_2\mathsf{A}+\xi_3\mathsf{B}+\xi_4\mathsf{A}^2+\xi_5\mathsf{B}^2+\xi_6\mathsf{AB}+\xi_7\mathsf{BA}+\xi_8\mathsf{ABA}+\xi_9\mathsf{BA}^2+\xi_{10}\mathsf{BAB}\\&+\xi_{11}\mathsf{AB}^2+\xi_{12}\mathsf{ABA}^2+\xi_{13}\mathsf{A}^2\mathsf{B}^2+\xi_{14}\mathsf{B}^2\mathsf{A}^2+\xi_{15}\mathsf{B}^2\mathsf{AB}+\xi_{16}\mathsf{AB}^2\mathsf{A}^2+\xi_{17}\mathsf{B}^2\mathsf{A}^2\mathsf{B}\,,\end{aligned}$$

We choose the largest eigenvalue of $\mathsf{A}=Y_\nu Y_\nu^\dagger$ to be unity. Hence terms with B can be neglected.

2 Lepton-flavored dark matter

Include additional flavor triplet (SM gauge singlet), imposed Z_2 symmetry for stability

$$\tilde s=\begin{pmatrix}\tilde s_1\\ \tilde s_2\\ \tilde s_3\end{pmatrix}\sim(3,1)\ \text{where}\ \mathcal{G}_\ell=\mathrm{SU}(3)_L\times\mathrm{SU}(3)_E,$$

2.1 Renormalizable Interaction Terms

$$\begin{aligned}\mathcal{L}^{ren}&=(\mathcal{D}^\eta H)^\dagger\mathcal{D}_\eta H+\partial^\eta\tilde s^\dagger\partial_\eta\tilde s-\Big[\mu_H^2H^\dagger H+\tilde s^\dagger\mu_s^2\tilde s+\lambda_H(H^\dagger H)^2+2H^\dagger H\,\tilde s^\dagger\Delta_{HS}\tilde s+\big(\tilde s^\dagger\Delta_{SS}\tilde s\big)^2\Big]\\&\supset\tilde s^\dagger\big(\mu_{s0}^2\mathbb{1}+\mu_{s1}^2\mathsf{A}+\mu_{s2}^2\mathsf{A}^2\big)\tilde s+2H^\dagger H\,\tilde s^\dagger\big(\lambda_{s0}\mathbb{1}+\lambda_{s1}\mathsf{A}+\lambda_{s2}\mathsf{A}^2\big)\tilde s+\big[\tilde s^\dagger\big(\lambda'_{s0}\mathbb{1}+\lambda'_{s1}\mathsf{A}+\lambda'_{s2}\mathsf{A}^2\big)\tilde s\big]^2\,,\end{aligned}$$

$$m_{S_k}^2=\mu_k^2+\lambda_kv^2\,,\qquad\mu_k^2=\mu_{s0}^2+\mu_{s1}^2\hat{\mathsf{A}}_k+\mu_{s2}^2\hat{\mathsf{A}}_k^2\,,\qquad\lambda_k^{(\prime)}=\lambda_{s0}^{(\prime)}+\lambda_{s1}^{(\prime)}\hat{\mathsf{A}}_k+\lambda_{s2}^{(\prime)}\hat{\mathsf{A}}_k^2\,.$$

With the parameter choices:

$O=\mathbb{1}$, $M_\nu=\mathcal{M}\mathbb{1}$, Inverted Hierarchy neutrino spectrum with $m_3=0$

$$m_{S_3}^2=\mu_{s0}^2+\lambda_{s0}v^2=\mu_{s1}^2+\lambda_{s1}v^2=\mu_{s2}^2+\lambda_{s2}v^2$$

$$m_{S_1}^2=m_{S_3}^2\big(1+\frac{2\mathcal{M}m_1}{v^2}+\frac{4\mathcal{M}^2m_1^2}{v^4}\big)$$

$$m_{S_2}^2=m_{S_3}^2\big(1+\frac{2\mathcal{M}m_2}{v^2}+\frac{4\mathcal{M}^2m_2^2}{v^4}\big)$$

2.2 Dimension-Six Effective Operators

$$\mathcal{L}'=\frac{C^L_{bdkl}}{\Lambda^2}O^L_{bdkl}+\frac{C^R_{bdkl}}{\Lambda^2}O^R_{bdkl}+\left(\frac{C^{LR}_{bdkl}}{\Lambda^2}O^{LR}_{bdkl}+\text{H.c.}\right),$$

$$\begin{aligned}C^L_{bdkl}&=(\Delta_{LL})_{bd}(\Delta_{SS})_{kl}+(\Delta_{LS})_{bl}(\Delta_{SL})_{kd}+(\Delta_{LS})_{kd}(\Delta_{SL})_{bl} & O^L_{bdkl}&=i\bar L_{b,L}\gamma^\rho L_{d,L}\,\tilde s_k^*\overleftrightarrow{\partial}_\rho\tilde s_l\\ C^R_{bdkl}&=\delta_{bd}\,(\Delta'_{SS})_{kl} & O^R_{bdkl}&=i\bar E_{b,R}\gamma^\rho E_{d,R}\,\tilde s_k^*\overleftrightarrow{\partial}_\rho\tilde s_l\\ C^{LR}_{bdkl}&=(\Delta_{LY}Y_e)_{bd}\big(\Delta''_{SS}\big)_{kl}+\big(\Delta'_{LS}\big)_{bl}(\Delta_{SY}Y_e)_{kd} & O^{LR}_{bdkl}&=\bar L_{b,L}E_{d,R}\,\tilde s_k^*\tilde s_l\,H\end{aligned}$$

This is in analogy to the case of quark-flavored scalar DM [4].
For simplicity, we adopt the following choices

$$C^L_{bdkl}=2\kappa_L\delta_{bl}\delta_{dk}\,,\qquad C^R_{bdkl}=\kappa_R\delta_{bd}\delta_{kl}\,,\qquad C^{LR}_{bdkl}=\frac{\sqrt2\,\kappa_{LR}m_{\ell_d}}{v}\delta_{bl}\delta_{dk}\,,$$

3 Phenomenology Aspects

3.1 Renormalizable Higgs-portal interactions

Constraints from DM annihilation, DM-nucleon scattering and Higgs invisible decay data

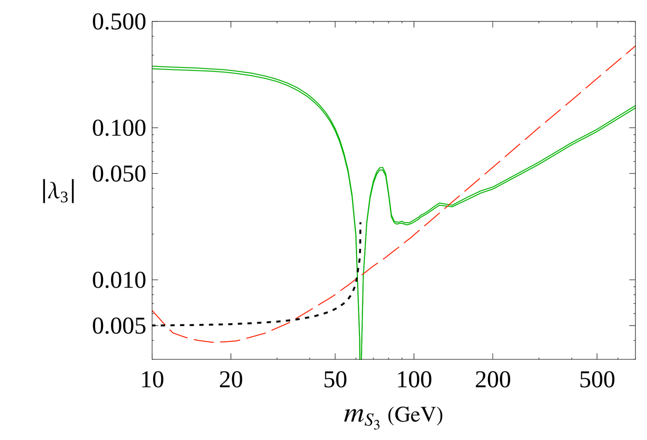


Figure 1: Values of $|\lambda_3|$ consistent with the relic density data (green solid curve), compared to upper limits on $|\lambda_3|$ from Higgs measurements (black dotted curve) and from null results of DM direct searches (red dashed curve). The numbers we used here are $\mathcal{B}\big(h\to S^*S\big)<0.19$, $\Omega\hat h^2=0.1198\pm0.0026$. Direct search data is from LUX.

3.2 Non-Renormalizable Effective couplings

(1) The DM annihilates to leptons $S_3S_3^*\to\ell_b^-\ell_d^+,\nu_b\nu_d$

(2) Constraints from LEP II data on the monophoton production process $e^+e^-\to\gamma\not{E}$ with missing energy $\not{E}$ in the final state.

$$\sigma_{e\bar e\to\gamma S\bar S'\to\gamma\not{E}}=\sum_{k,l=1}^{3}\sigma_{e\bar e\to\gamma S_k\bar S_l}\mathcal{B}_{k3}\mathcal{B}_{l3}$$

with the branching ratios

$$\mathcal{B}_{13}=\mathcal{B}(S_1\to\nu\nu'S_3)\,,\qquad\mathcal{B}_{23}=\mathcal{B}(S_2\to\nu\nu'S_3)+\mathcal{B}(S_2\to\nu\nu'S_1)\,\mathcal{B}_{13}\,,\qquad\mathcal{B}_{33}=1\,,$$

(3) The International Linear Collider(ILC) can test this process more stringently in the future.

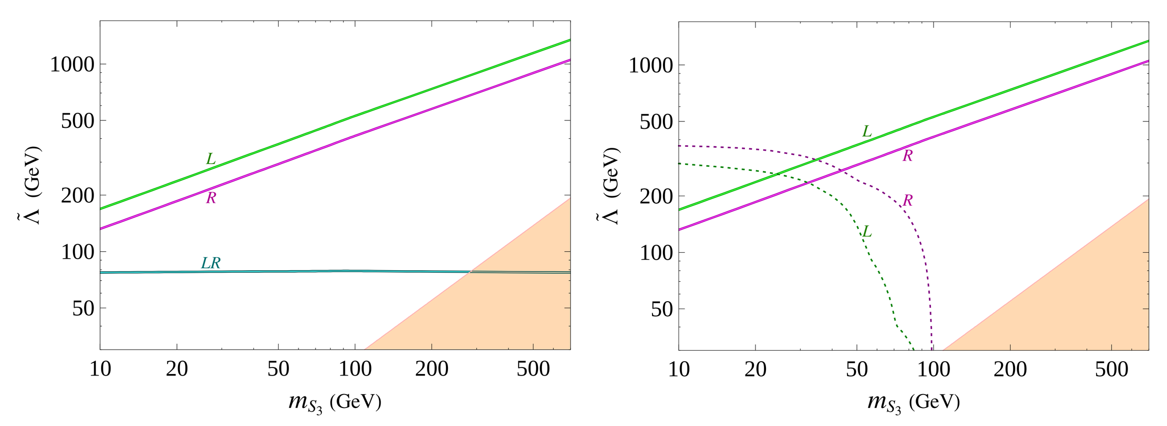


Figure 2: Values of $\tilde\Lambda=\Lambda/|\kappa_\epsilon|^{1/2}$ for $\epsilon=L,R,LR$ fulfilling the relic density constraint. The orange region depicts region where the EFT approach breaks down. The dotted curves represent restraints from $e^+e^-\to\gamma\not{E}$ at LEP II.

3.3 Constraints from Lepton Flavor Violating Rare Decay $\ell_a^-\to\ell_b^-\ell_c^-\ell_d^+$

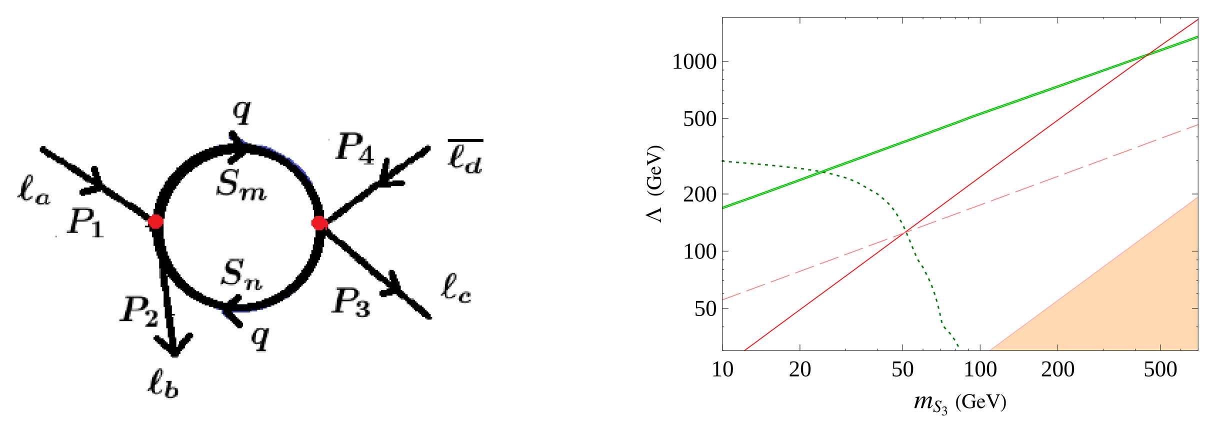
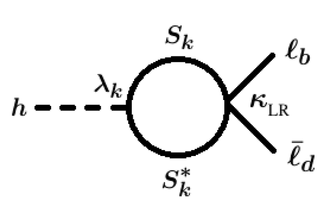


Figure 3: Constraints from lepton flavor violating rare decay:
$\mu^-\to e^-e^-e^+$ (red solid curve) and $\tau^-\to\mu^-\mu^-e^+$ (pink dashed curve)

3.4 Flavor-violating Higgs Decay $h\to\mu\tau$



$$\Gamma_{h\to\ell_b\bar\ell_d}=\frac{m_h\big|y_{bd}^{\rm SM}+y_{bd}^{\rm new}\big|^2}{16\pi v^2}\big(m_{\ell_b}^2+m_{\ell_d}^2\big)$$

The CMS Collaboration has recently detected a slight excess of $h\to\mu^\pm\tau^\mp$ events with a significance of 2.5σ. As a statistical fluctuation it translates into a limit of
$\mathcal{B}(h\to\mu\tau)<1.57\,\%$ at 95% CL
ATLAS and CMS recent data also suggest $0.7<\frac{\Gamma_{h\to\tau\bar\tau}}{\Gamma^{\rm SM}_{h\to\tau\bar\tau}}<1.8\,,\quad\frac{\Gamma_{h\to\mu\bar\mu}}{\Gamma^{\rm SM}_{h\to\mu\bar\mu}}<6.7\,,$

Our model can accommodate this $h\to\mu\tau$ hint. Select sample point from blue curve in Figure 2

$$(m_{S_3},\Lambda)=(200,78)\text{GeV}\underset{(h\to\mu\tau)}{\Longrightarrow}-2.9<\lambda_1<-2.4\underset{\text{Prediction}}{\Longrightarrow}\begin{cases}1.6<\Gamma_{h\to\tau\bar\tau}/\Gamma^{\rm SM}_{h\to\tau\bar\tau}<1.8\\ 1.8<\Gamma_{h\to\mu\bar\mu}/\Gamma^{\rm SM}_{h\to\mu\bar\mu}<2.0\end{cases}$$

4 Summary

(1) We apply the MFV principle to a lepton-flavored scalar DM model supplemented with the type-I seesaw mechanism.

(2) In addition to Higgs-portal renormalizable interaction terms, we can construct three possible effective couplings which conform the SM gauge symmetry and the flavor symmetry from the effective field theory point of view.

(3) The MFV framework allows us to make interesting phenomenological connections between the evidence and searches for DM, Higgs collider measurements, and available data on lepton-flavor-violating processes. The future experiments at the LHC and ILC can probe various aspects of our model in greater detail.

References

[1] G. D'Ambrosio, G.F. Giudice, G. Isidori, and A. Strumia, Nucl. Phys. B **645**, 155 (2002) [hep-ph/0207036].

[2] V. Cirigliano, B. Grinstein, G. Isidori, and M.B. Wise, Nucl. Phys. B **728**, 121 (2005) [hep-ph/0507001].

[3] L. Mercolli and C. Smith, Nucl. Phys. B **817**, 1 (2009) [arXiv:0902.1949 [hep-ph]].

[4] B. Batell, J. Pradler, and M. Spannowsky, JHEP **1108**, 038 (2011) [arXiv:1105.1781 [hep-ph]].