Lepton-Flavored Scalar Dark Matter with Minimal Flavor Violation

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[arXiv:1410.6803 [hep-ph]]

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Outline

- Minimal Flavor Violation (MFV) Hypothesis
- Stability Requirement
- Operators-Renormalizable & Non-renormalizable
- Phenomenology Aspects
- Summary and conclusion

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Minimal Flavor Violation (MFV)

- Def: SM Yukawa couplings are the only sources for the breaking of flavor and CP symmetries. [hep-ph/0207036]
- For quarks: The implementation is straightforward .
- For leptons: Some Ambiguity (neutrino mass)

- Another major mystery is the identity of the constituents of dark matter.

- Neutrino mass+ Flavor physics(FCNC)+ Dark matter

  -> Cook these ingredients together

Mass terms of SM fermions +3 RH neutrinos

$$\mathcal{L}_{\mathrm{m}} = -(Y_\nu)_{kl}\,\bar{L}_{k,L}\,\nu_{l,R}\,\tilde{H} - (Y_e)_{kl}\,\bar{L}_{k,L}\,E_{l,R}\,H - \tfrac{1}{2}(M_\nu)_{kl}\,\overline{\nu^{\mathrm{c}}_{k,R}}\,\nu_{l,R} + \mathrm{H.c.}\,,$$

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

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

$$Y_e = \frac{\sqrt{2}}{v}\,\mathrm{diag}\big(m_e, m_\mu, m_\tau\big)\,,\; Y_\nu = \frac{\sqrt{2}}{v}\,U_{\mathrm{PMNS}}\,\hat{m}_\nu\,, \quad \hat{m}_\nu = \mathrm{diag}\big(m_1, m_2, m_3\big)$$

$$\begin{pmatrix} \bar{\nu}_L & \overline{\nu^c_R} \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_\nu \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}\,,\; Y_\nu = \frac{i\sqrt{2}}{v}\,U_{\mathrm{PMNS}}\,\hat{m}_\nu^{1/2} O M_\nu^{1/2}\,,\; M_\nu = \mathrm{diag}(M_1, M_2, M_3)$$

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Guiding principle of stability of DM- [arXiv:1105.1781] Batell et. al

$$\mathcal{O}_{\rm decay} = \chi \underbrace{Q\ldots}_{A}\underbrace{\bar{Q}\ldots}_{B}\underbrace{u_R\ldots}_{C}\underbrace{\bar{u}_R\ldots}_{D}\underbrace{d_R\ldots}_{E}\underbrace{\bar{d}_R\ldots}_{F} \times \underbrace{Y_u\ldots}_{G}\underbrace{Y_u^\dagger\ldots}_{H}\underbrace{Y_d\ldots}_{I}\underbrace{Y_d^\dagger\ldots}_{J}\mathcal{O}_{\rm weak},$$

Denoting the irreducible representation of χ under G_q as

$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R}$,

where n_Q, m_Q, $0, 1, 2, \ldots$

$$n \equiv n_Q + n_u + n_d$$
$$m \equiv m_Q + m_u + m_d.$$

$\mathcal{O}_{\rm decay}$ to be allowed,

χ unstable $(n - m) \bmod 3 = 0$,

(n,m)	$SU(3)_Q \times SU(3)_{u_R} \times SU(3)_{d_R}$	Stable?
$(0,0)$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	
$(1,0)$	$(\mathbf{3},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{3},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{3})$	Yes
$(0,1)$	$(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$	Yes
(2,0)	$(\mathbf{6},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{6},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{6})$ $(\mathbf{3},\mathbf{3},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\mathbf{3},\mathbf{3})$	Yes
(0,2)	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\bar{\mathbf{6}},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\bar{\mathbf{6}})$ $(\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\bar{\mathbf{3}},\bar{\mathbf{3}})$	Yes
(1,1)	$(\mathbf{8},\mathbf{1},\mathbf{1})$, $(\mathbf{1},\mathbf{8},\mathbf{1})$, $(\mathbf{1},\mathbf{1},\mathbf{8})$ $(\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $(\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$, $(\mathbf{1},\mathbf{3},\bar{\mathbf{3}})$ $(\bar{\mathbf{3}},\mathbf{3},\mathbf{1})$, $(\bar{\mathbf{3}},\mathbf{1},\mathbf{3})$, $(\mathbf{1},\bar{\mathbf{3}},\mathbf{3})$	

MFV building blocks and Flavor scalar triplet

$$M_\nu = \mathcal{M}\mathbb{1} \qquad G_\ell = \mathcal{G}_\ell \times \mathrm{O}(3)_\nu, \text{ where } \mathcal{G}_\ell = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_E$$

$$A = Y_\nu Y_\nu^\dagger \sim (8,1), \; B = Y_e Y_e^\dagger \sim (8,1)$$

$$\Delta \;=\; \xi_1 \mathbb{1} + \xi_2 \mathsf{A} + \xi_3 \mathsf{B} + \xi_4 \mathsf{A}^2 + \xi_5 \mathsf{B}^2 + \xi_6 \mathsf{AB} + \xi_7 \mathsf{BA} + \xi_8 \mathsf{ABA} + \cdots$$

$$\Delta \sim (8,1)$$

$$\tilde{s} \;=\; \begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \\ \tilde{s}_3 \end{pmatrix} \sim \;(3,1)\,. \quad S \;=\; \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} \;=\; \mathcal{U}^\dagger \tilde{s}\,,$$

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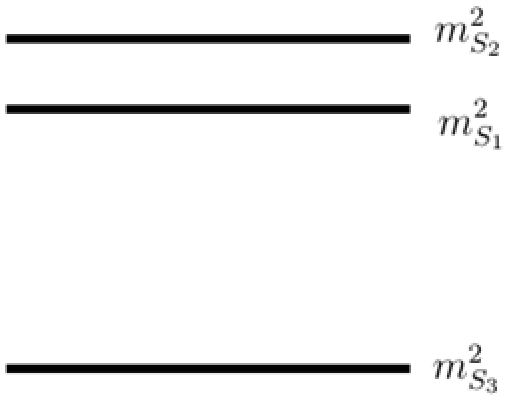
Mass spectrum and Dim-4 terms

Renormalizable interaction terms

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

$$
\begin{aligned}
m_{S_1}^2 &= m_{S_3}^2 \left(1 + \frac{2\mathcal{M} m_1}{v^2} + \frac{4\mathcal{M}^2 m_1^2}{v^4}\right) \\
m_{S_2}^2 &= m_{S_3}^2 \left(1 + \frac{2\mathcal{M} m_2}{v^2} + \frac{4\mathcal{M}^2 m_2^2}{v^4}\right)
\end{aligned}
$$



Non-Renormalizable Operators-Effective theory approach

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

$$O^{L}_{bdkl} = i\bar{L}_{b,L} \gamma^{\rho} L_{d,L} \, \tilde{s}^{*}_{k} \overleftrightarrow{\partial}_{\rho} \tilde{s}_{l} ,$$

$$O^{R}_{bdkl} = i\bar{E}_{b,R} \gamma^{\rho} E_{d,R} \, \tilde{s}^{*}_{k} \overleftrightarrow{\partial}_{\rho} \tilde{s}_{l} ,$$

$$O^{LR}_{bdkl} = \bar{L}_{b,L} E_{d,R} \, \tilde{s}^{*}_{k} \tilde{s}_{l} H ,$$

$$C^{L}_{bdkl} = (\Delta_{LL})_{bd} (\Delta_{SS})_{kl} + (\Delta_{LS})_{bl} (\Delta_{SL})_{kd} + (\Delta_{LS})_{kd} (\Delta_{SL})_{bl} ,$$

$$C^{R}_{bdkl} = \delta_{bd} \left(\Delta'_{SS}\right)_{kl} ,$$

$$C^{LR}_{bdkl} = (\Delta_{LY} Y_e)_{bd} \left(\Delta''_{SS}\right)_{kl} + \left(\Delta'_{LS}\right)_{bl} (\Delta_{SY} Y_e)_{kd} ,$$

$$\Delta \sim (8,1)$$

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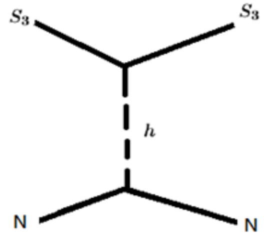
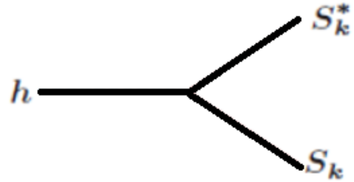
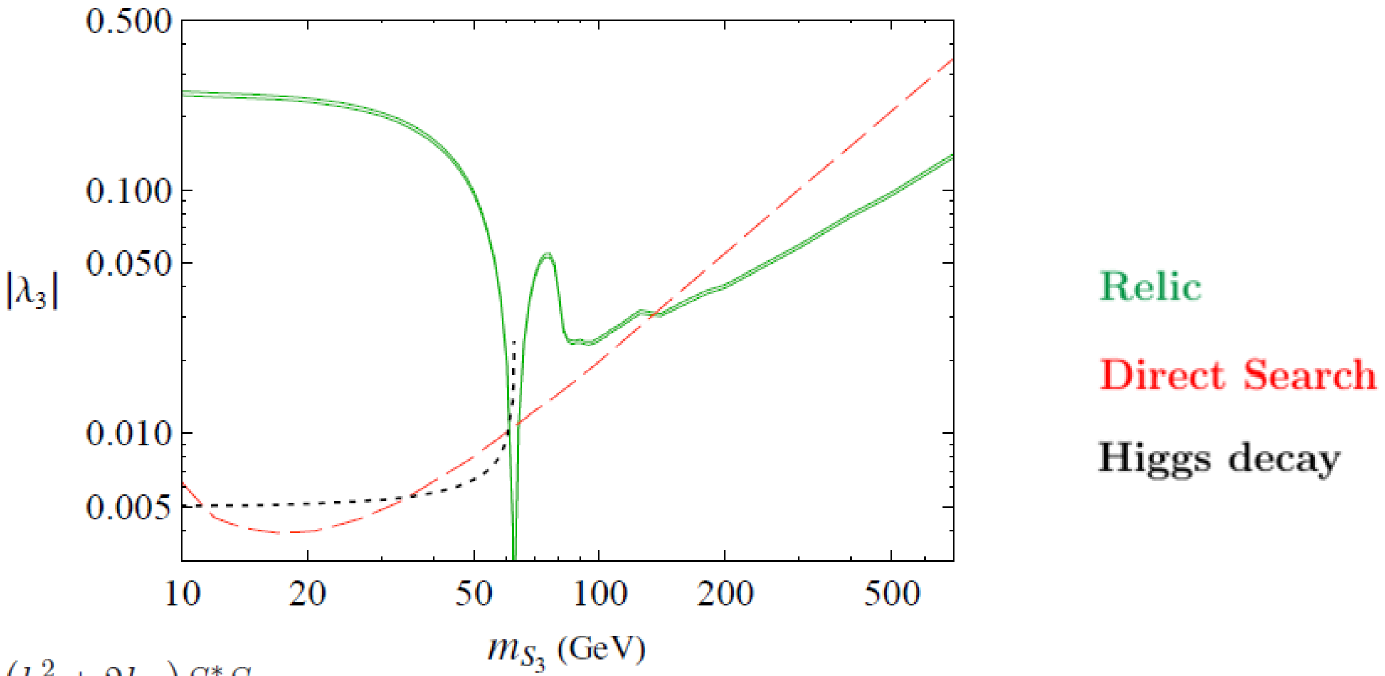
The constraints from EXP

- Cosmological Relic density
- Direct Search
- Higgs Invisible Decay

$$\Omega \hat{h}^2 = 0.1198 \pm 0.0026$$







$$\mathcal{L} \supset -\lambda_k \left(h^2 + 2hv\right) S_k^* S_k$$

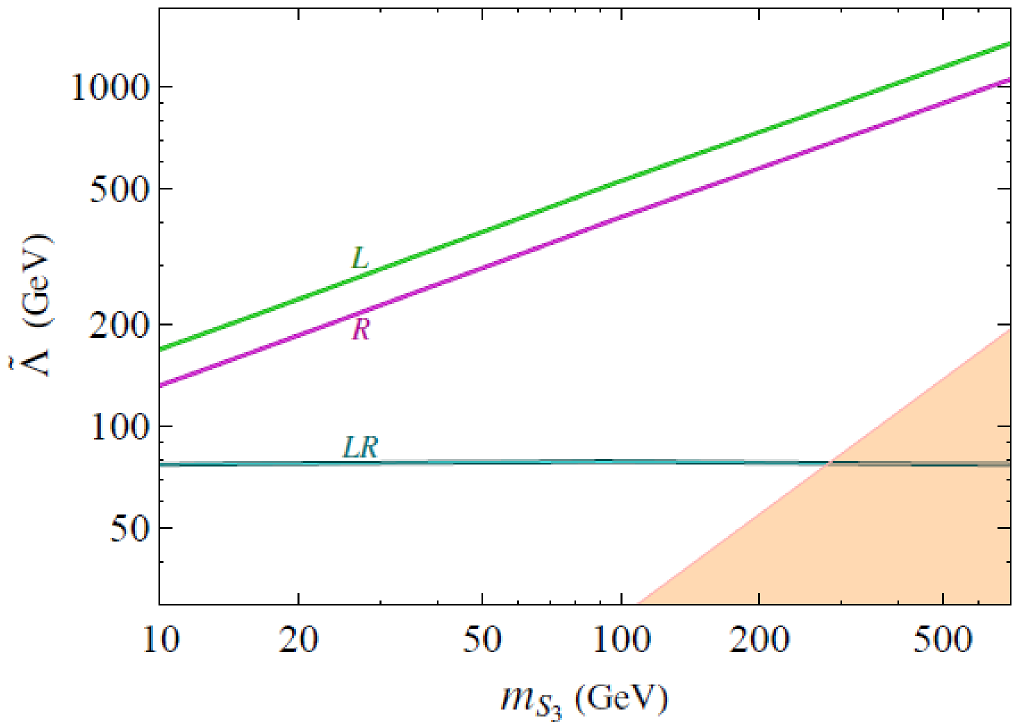
Effective interactions –DM Relic Abundance

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

$$O^L_{bdkl} = i\bar{L}_{b,L}\gamma^\rho L_{d,L}\,\tilde{s}^*_k \overset{\leftrightarrow}{\partial}_\rho \tilde{s}_l\,, \qquad C^L_{bdkl} = 2\kappa_L \delta_{bl}\delta_{dk}\,,$$

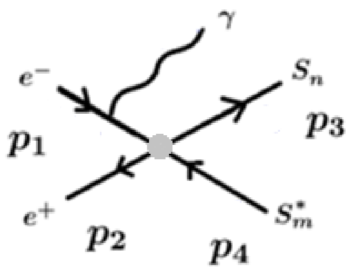
$$O^R_{bdkl} = i\bar{E}_{b,R}\gamma^\rho E_{d,R}\,\tilde{s}^*_k \overset{\leftrightarrow}{\partial}_\rho \tilde{s}_l\,, \qquad C^R_{bdkl} = \kappa_R \delta_{bd}\delta_{kl}\,,$$

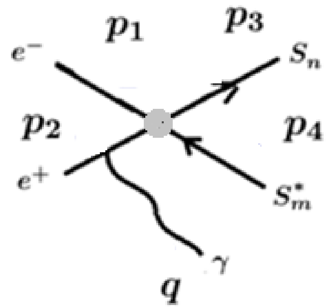
$$O^{LR}_{bdkl} = \bar{L}_{b,L} E_{d,R}\,\tilde{s}^*_k \tilde{s}_l H\,, \qquad C^{LR}_{bdkl} = \frac{\sqrt{2}\,\kappa_{LR} m_{\ell_d}}{v}\delta_{bl}\delta_{dk}$$



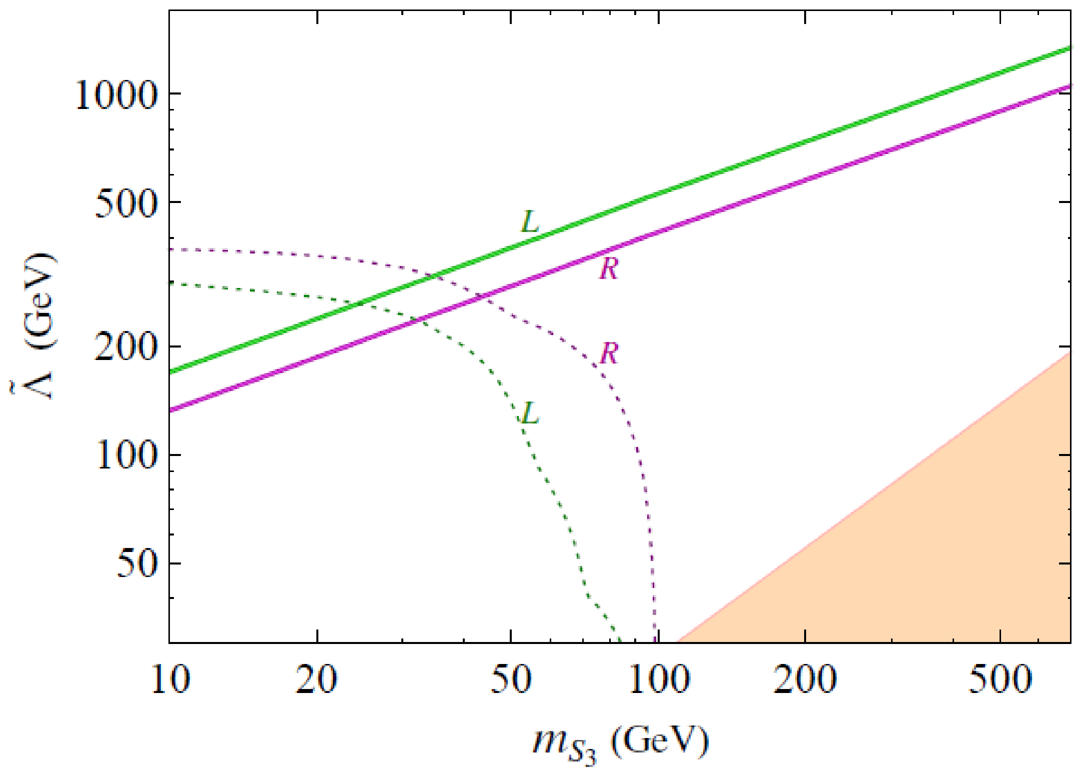
LEP II experiments $e^+e^- \to \gamma \not{E}$

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





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

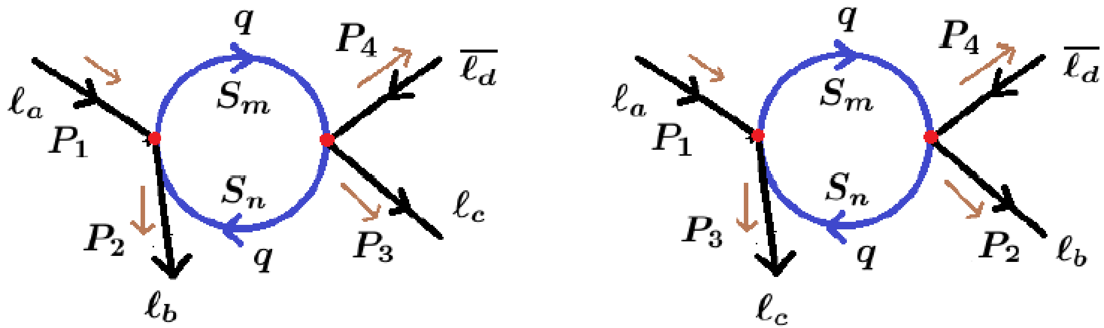


Flavor violation decay of lepton and higgs(?)

$$C^{LR}_{bdkl} = \frac{\sqrt{2}\,\kappa_{LR} m_{\ell_d}}{v}\delta_{bl}\delta_{dk}\,,$$
$$C^{L}_{bdkl} = 2\kappa_L \delta_{bl}\delta_{dk}\,,$$
$$C^{R}_{bdkl} = \kappa_R \delta_{bd}\delta_{kl}\,,$$

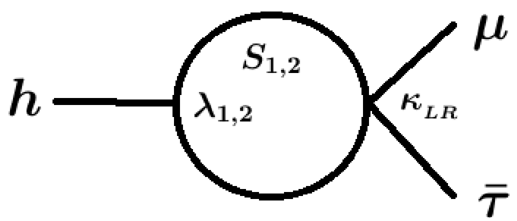
$$\mathcal{B}(\tau^- \to \mu^-\mu^-\mu^+)_{\rm exp} < 2.1\times 10^{-8}$$
$$\tilde{\Lambda} > 11\ \mathrm{GeV}$$

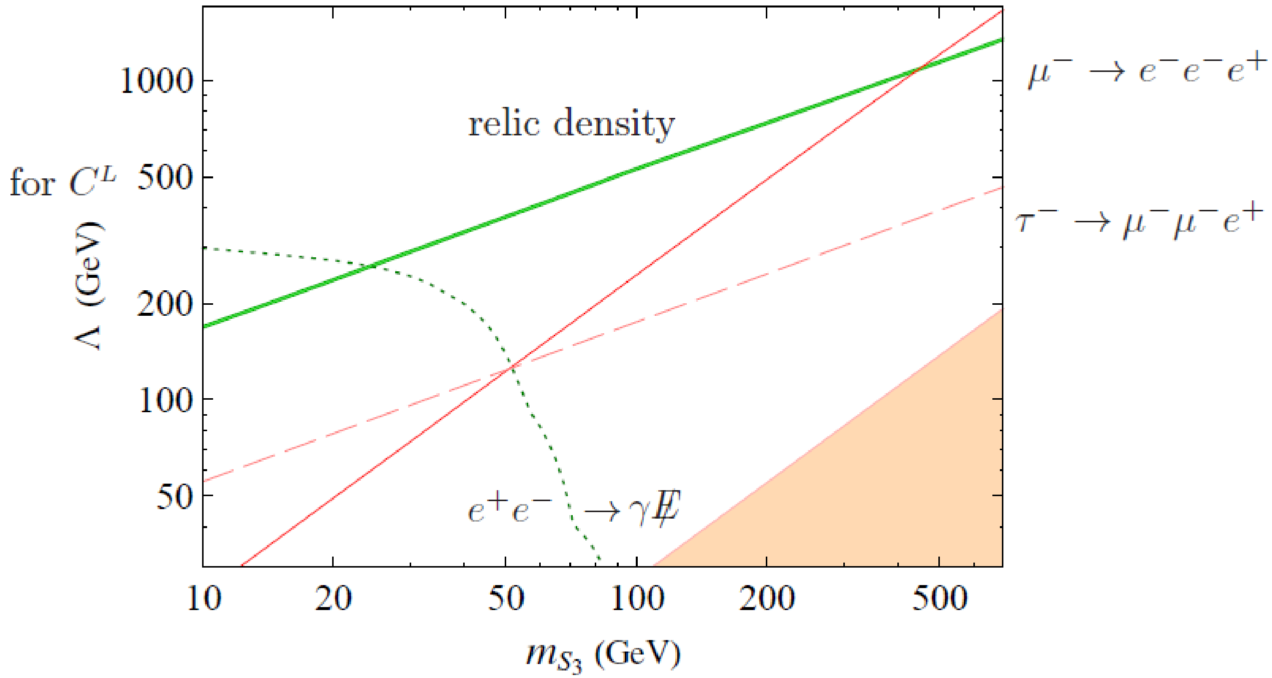
$\ell \to \ell_1 \ell_2 \bar{\ell}_3$



CMS: $h \to \mu\bar{\tau}$ 2.5σ

$$\mathcal{B}(h \to \mu\tau) = (0.89^{+0.40}_{-0.37})\%$$





Summary

- MFV assumption and seesaw mechanisms
- The new scalars couple to SM particles via renormalizable interactions and to leptons through effective dim-6 operators.
- Through the dim-6 operators , we demonstrate a simple way to make phenomenological connections between neutrino, dark matter, higgs and FCNC of leptons.

Thanks for your attention

Back up Materials

Stability of DM

The most general operator that induces the decay of χ

$$\mathcal{O}_{\text{decay}} = \chi \underbrace{Q\ldots}_{A}\underbrace{\bar{Q}\ldots}_{B}\underbrace{u_R\ldots}_{C}\underbrace{\bar{u}_R\ldots}_{D}\underbrace{d_R\ldots}_{E}\underbrace{\bar{d}_R\ldots}_{F} \times \underbrace{Y_u\ldots}_{G}\underbrace{Y_u^\dagger\ldots}_{H}\underbrace{Y_d\ldots}_{I}\underbrace{Y_d^\dagger\ldots}_{J}\,\mathcal{O}_{\text{weak}},$$

A : the number of Q fields

B : the number of $\bar{Q}$ fields

...

$\mathcal{O}_{\text{weak}}$: electroweak operator s.t $\mathcal{O}_{\text{decay}}$ is invariant under $SU(2)_L \times U(1)_Y$.

$\mathcal{O}_{\text{decay}}$ requires to be color and flavor singlet.

Condition:

$$t_i \equiv (p-q)_i \bmod 3 = 0, \quad i = c,\, Q,\, u_R,\, d_R.$$

triality t_i of each $SU(3)_i$ tensor

product $(p,q)_i$ with p factors of $\mathbf{3}_i$ and q factors of $\bar{\mathbf{3}}_i$,

color and flavor symmetry

$$t_i \equiv (p-q)_i \bmod 3 = 0, \quad i = c,\, Q,\, u_R,\, d_R.$$

the decay operator $\mathcal{O}_{\rm decay}$ will be forbidden if $t_i \neq 0$ for at least one i.

Denoting the irreducible representation of χ under G_q as

$$\chi \sim (n_Q, m_Q)_Q \times (n_u, m_u)_{u_R} \times (n_d, m_d)_{d_R},$$

where n_Q, m_Q, etc. can take values $0, 1, 2, \ldots$

the triality conditions

$$
\begin{aligned}
t_c &= (A-B+C-D+E-F) \bmod 3 = 0, \\
t_Q &= (n_Q-m_Q+A-B+G-H+I-J) \bmod 3 = 0, \\
t_{u_R} &= (n_u-m_u+C-D-G+H) \bmod 3 = 0, \\
t_{d_R} &= (n_d-m_d+E-F-I+J) \bmod 3 = 0.
\end{aligned}
$$

$\mathcal{O}_{\text{decay}}$ to be allowed, χ unstable $(n - m) \bmod 3 = 0,$

where $n \equiv n_Q + n_u + n_d$ $m \equiv m_Q + m_u + m_d.$

It follows that that $\mathcal{O}_{\text{decay}}$ is forbidden and χ is stable if $(n - m) \bmod 3 \neq 0.$

For lepton sector, there is no extra internal symmetry like $SU(3)_c$ group,

therefore the number of conditions reduce to 3

$$t_L = (n_L - m_L + A - B + G - H + I - J) \bmod 3 = 0,$$
$$t_{\nu_R} = (n_\nu - m_\nu + C - D - G + H) \bmod 3 = 0,$$
$$t_{e_R} = (n_e - m_e + E - F - I + J) \bmod 3 = 0.$$

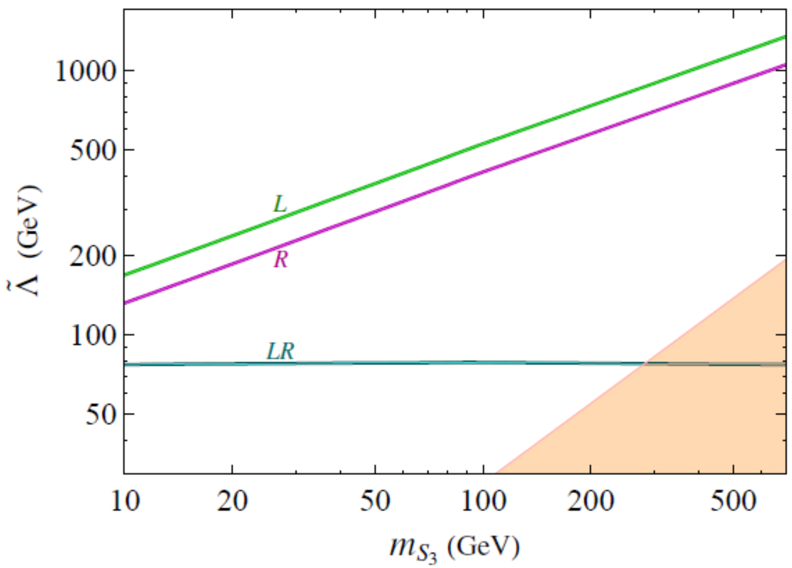
$$n' \equiv n_L + n_\nu + n_e + (A + C + E)$$
$$m' \equiv m_L + m_\nu + m_e + (B + D + F)$$

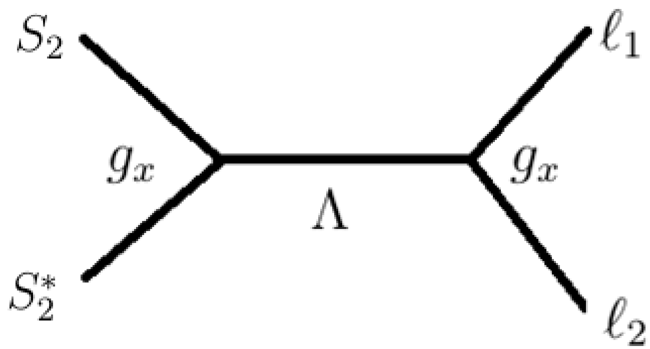
$$(n' - m')\ mod\ 3 \neq 0$$

- Decay operator without Z2 protection

$$\epsilon_{bdk}\,\overline{(\Delta_1 L_L)^{c}_{b}}\,\tilde{H}^{*}\,\tilde{H}^{\dagger}(\Delta_2 L_L)_d\,(\Delta_3 \tilde{s})_k$$

- EFT Break





$$\frac{g_x^2}{\Lambda^2} < \frac{(4\pi)^2}{(2m_{S_2})^2}$$

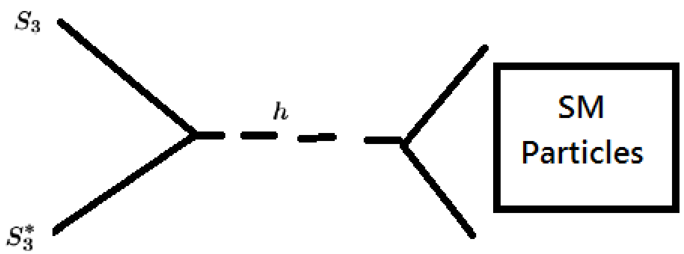
$$\frac{\Lambda}{\sqrt{g_x}} = \tilde{\Lambda} > \frac{m_{S_2}}{2\pi}$$

Renormalizable interactions- DM Relic Abundance

$$\sigma_{\rm ann} v_{\rm rel} = \hat{a} + \hat{b} v_{\rm rel}^2 \qquad \Omega \hat{h}^2 = 0.1198 \pm 0.0026$$

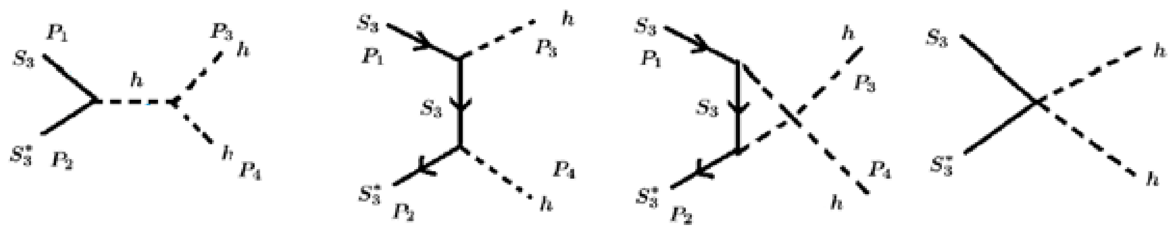
$$\Omega \hat{h}^2 = \frac{2.14 \times 10^9 \, x_f \ {\rm GeV}^{-1}}{\sqrt{g_*}\, m_{\rm Pl} \left(\hat{a} + 3\hat{b}/x_f\right)} \,, \quad x_f = \ln \frac{0.038\, m_{S_3}\, m_{\rm Pl} \left(\hat{a} + 6\hat{b}/x_f\right)}{\sqrt{g_* x_f}} \,,$$

$$\sigma_{\rm ann} v_{\rm rel} \simeq \hat{a} = \frac{4\lambda_3^2 v^2 m_{S_3}^{-1} \sum_i \Gamma(\tilde{h} \to X_i)}{\left(4m_{S_3}^2 - m_h^2\right)^2 + \Gamma_h^2 m_h^2} \qquad \tilde{h} \ \text{invariant mass} = 2m_{S_3}$$



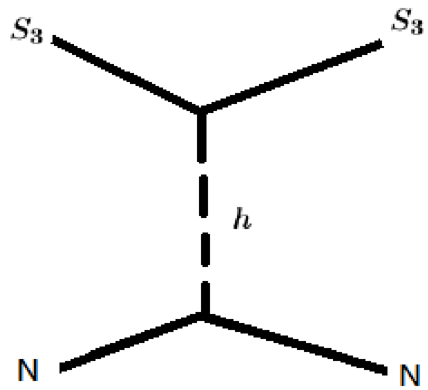
$m_{S_3} > m_h$,

$S_3 S_3^* \to hh$



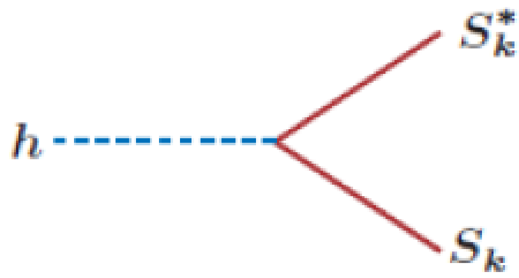
Renormalizable Operators-
Direct Search and Higgs Invisible Decay

$$S_3^{(*)} N \to S_3^{(*)} N \qquad \sigma_{\rm el} = \frac{\lambda_3^2\, g_{NNh}^2\, m_N^2\, v^2}{\pi\,(m_{S_3} + m_N)^2 m_h^4}$$



$$2m_{S_k} < m_h$$

$$\Gamma_{h\to S_k^* S_k} = \frac{\lambda_k^2 v^2}{4\pi\, m_h}\sqrt{1 - \frac{4m_{S_k}^2}{m_h^2}}\,.$$



$$\mathcal{B}(h \to S^* S) = \frac{\sum_k \Gamma_{h\to S_k^* S_k}}{\Gamma_h^{\rm SM} + \sum_k \Gamma_{h\to S_k^* S_k}}\,.$$

Non-Renormalizable Operators-Effective theory approach

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

$$O^{L}_{bdkl} = i\bar{L}_{b,L}\gamma^{\rho} L_{d,L}\, \tilde{s}^{*}_{k} \overset{\leftrightarrow}{\partial}_{\rho} \tilde{s}_{l}\,,\ O^{R}_{bdkl} = i\bar{E}_{b,R}\gamma^{\rho} E_{d,R}\, \tilde{s}^{*}_{k} \overset{\leftrightarrow}{\partial}_{\rho} \tilde{s}_{l}\,,$$

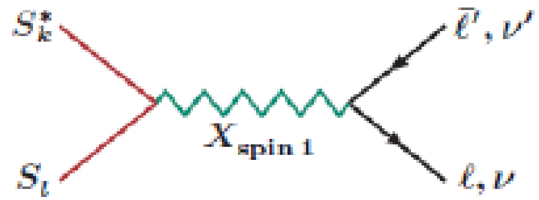
$$O^{LR}_{bdkl} = \bar{L}_{b,L} E_{d,R}\, \tilde{s}^{*}_{k} \tilde{s}_{l} H\,,$$

$$C^{L}_{bdkl} = (\Delta_{LL})_{bd}(\Delta_{SS})_{kl} + (\Delta_{LS})_{bl}(\Delta_{SL})_{kd} + (\Delta_{LS})_{kd}(\Delta_{SL})_{bl}\,,$$

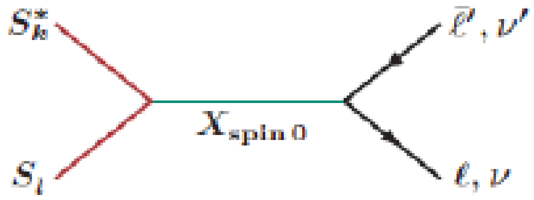
$$C^{R}_{bdkl} = \delta_{bd}\left(\Delta'_{SS}\right)_{kl}\,,$$

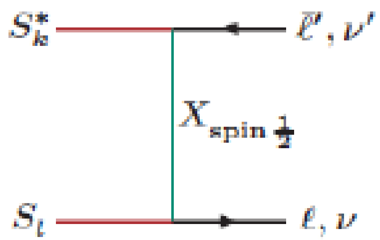
$$C^{LR}_{bdkl} = (\Delta_{LY} Y_e)_{bd}\left(\Delta''_{SS}\right)_{kl} + \left(\Delta'_{LS}\right)_{bl}(\Delta_{SY} Y_e)_{kd}\,,$$

Possible mechanisms that can induce $O_{1,2}$:



O_3:





Potential Implication for $\boldsymbol{h \to \mu\tau}$

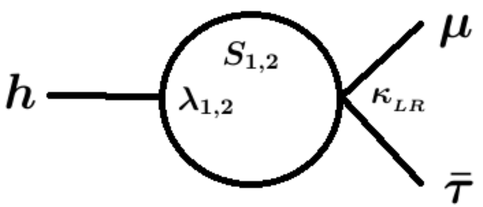
CMS recently observed a slight excess of $h \to \mu\tau$ at 2.5σ

If a signal, $\mathcal{B}(h \to \mu\tau) = (0.89^{+0.40}_{-0.37})\%$

If a statistical fluctuation, $\mathcal{B}(h \to \mu\tau) < 1.57\%$ at 95% CL.

Other data from ATLAS & CMS, respectively:

$$0.7 < \frac{\Gamma_{h\to\tau\bar{\tau}}}{\Gamma^{\rm SM}_{h\to\tau\bar{\tau}}} < 1.8\,, \qquad \frac{\Gamma_{h\to\mu\bar{\mu}}}{\Gamma^{\rm SM}_{h\to\mu\bar{\mu}}} < 6.7$$



$$\Gamma_{h\to\ell_b\bar{\ell}_d} = \frac{m_h\left|y^{\rm SM}_{bd} + y^{\rm new}_{bd}\right|^2}{16\pi v^2}\left(m^2_{\ell_b} + m^2_{\ell_d}\right)$$

Choose a set of data $(m_{S_3}, \Lambda) \xRightarrow[h\to\mu\tau \text{ constraint}]{} \lambda_{1,2}$ range

$\xRightarrow[\text{Prediction}]{} Br(h \to \mu\mu), Br(h \to \tau\tau)$