Lepton Flavor Violation in the singlet-triplet scotogenic model

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(in colab. with Avelino Vicente)

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Outline

1. Introduction
2. The singlet-triplet scotogenic model
3. Phenomenological analysis of LFV observables
4. Conclusions

[1] E. Ma, Phys. Rev. D73, 077301 (2006)

- **The scotogenic model**[1] is a simple extension of the SM which correlates neutrino masses (induced at 1-loop level) and the existence of dark matter.
  - ▸ SM extended: a second scalar doublet and N_N ($N_N \geq 2$) singlet fermions all of them odd under $\mathbb{Z}_2$ discrete symmetry.
  - ▸ $\mathbb{Z}_2$ symmetry forbids tree-level contribution to neutrino masses, and gives rise to a stable state, a WIMP dark matter candidate.
- A mechanism for neutrino mass generation will induce Lepton Flavor Violating (LFV) processes.

∗ LFV experiments provide the most promising way to test such models!

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The singlet-triplet scotogenic model (TTTDM)

[2] M. Hirsch, R. A. Lineros, S. Morisi, J. Palacio, N. Rojas, and J. W. F. Valle, JHEP 10, 149 (2013), 1307.8134

Matter content and $SU(2)_L$, $U(1)_Y$, $\mathbb{Z}_2$ charge assignment of the model [2]

	Standard Model			Fermions		Scalars	
	L	e	ϕ	Σ	N	η	Ω
generations	3	3	1	1	1	1	1
$SU(2)_L$	2	1	2	3	1	2	3
$U(1)_Y$	$-1/2$	-1	$1/2$	0	0	$1/2$	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$-$	$-$	$-$	$+$

Yukawa Lagrangian for the new couplings

$$-\mathcal{L}_Y = Y_N^\alpha \, \overline{L}_\alpha \, \tilde{\eta} \, N + Y_\Sigma^\alpha \, \overline{L}_\alpha \, \tilde{\eta} \, \Sigma + \underbrace{Y_\Omega \, \Sigma \, \Omega \, N}_{\Sigma^0 - N \text{ mixing}} + \text{h.c.} \,. \tag{1}$$

The scalar potential

$$\mathcal{V} = -m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta - \frac{m_\Omega^2}{2} \Omega^\dagger \Omega + \mu_1 \, \phi^\dagger \, \Omega \, \phi + \mu_2 \, \eta^\dagger \, \Omega \, \eta + \text{quartic couplings} \tag{2}$$

The singlet-triplet scotogenic model (TTTDM)

- Σ and N fermions have Majorana mass terms.
- The vacuum expectation value of the scalars are

$$\langle \phi^0 \rangle = \frac{v_\phi}{\sqrt{2}} \,, \quad \langle \Omega^0 \rangle = v_\Omega \,, \quad \langle \eta^0 \rangle = 0 \,, \tag{3}$$

  The VEVs are determined by the tadpole equations.
- v_ϕ and v_Ω break the electroweak symmetry and induce masses for the gauge bosons,

$$m_W^2 = \frac{1}{4} g^2 \left(v_\phi^2 + 4\, v_\Omega^2 \right) , \quad m_Z^2 = \frac{1}{4} \left(g^2 + g'^2 \right) v_\phi^2 . \tag{4}$$

$\frac{m_W}{m_Z} \rightarrow$ electroweak precision test constraint v_Ω value $<$ few GeV

The scalar spectrum

The model contains the $\mathbb{Z}_2$-even scalars ϕ^0, Ω^0, $\phi^\pm$ and $\Omega^\pm$

- The eigenstates of ϕ^0-Ω^0 mixing are
  S_1 = SM Higgs,
  S_2 = a new heavy Higgs boson.
- For the mixing of $\phi^\pm$-$\Omega^\pm$ we have:
  $H_1^\pm$ = a Goldstone boson,
  $H_2^\pm$ = a physical charged scalar.

- The $\mathbb{Z}_2$-odd scalars $\eta^{0,\pm}$ have the following masses,

$$m^2_{\eta^R} = m^2_\eta + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)\, v^2_\phi + \frac{1}{2}\lambda^\eta v^2_\Omega - \frac{1}{\sqrt{2}} v_\Omega\, \mu_2 \quad (5)$$

$$m^2_{\eta^I} = m^2_\eta + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)\, v^2_\phi + \frac{1}{2}\lambda^\eta v^2_\Omega - \frac{1}{\sqrt{2}} v_\Omega\, \mu_2 \quad (6)$$

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$\eta^{R,I,\pm}$ fields do not mix with the rest of scalars.

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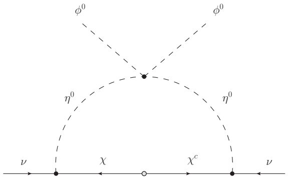
Raditative neutrino masses

The $\mathbb{Z}_2$-odd fields Σ^0 and N are mixed such that

$$\begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \Sigma^0 \\ N \end{pmatrix} = V(\alpha) \begin{pmatrix} \Sigma^0 \\ N \end{pmatrix}, \quad (8)$$

where $\tan(2\alpha) = \frac{2\, Y_\Omega v_\Omega}{M_\Sigma - M_N}$

Majorana neutrino masses are generated at 1-loop level through $\eta^0 \equiv (\eta^R, \eta^I)$ and $\chi \equiv (\chi_1, \chi_2)$ loops.



- Resulting neutrino mass matrix

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_{\sigma=1}^{2} \frac{h_{\alpha\sigma}\, h_{\beta\sigma}\, M_{\chi_\sigma}}{2\,(4\pi)^2} \left[\frac{m^2_{\eta^R} \ln\left(\frac{M^2_{\chi_\sigma}}{m^2_{\eta^R}}\right)}{M^2_{\chi_\sigma} - m^2_{\eta^R}} - \frac{m^2_{\eta^I} \ln\left(\frac{M^2_{\chi_\sigma}}{m^2_{\eta^I}}\right)}{M^2_{\chi_\sigma} - m^2_{\eta^I}} \right], \quad (9)$$

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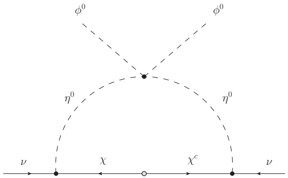

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where h is a 3×2 matrix defined as

$$h = \begin{pmatrix} \frac{Y_\Sigma^1}{\sqrt{2}} & Y_N^1 \\ \frac{Y_\Sigma^2}{\sqrt{2}} & Y_N^2 \\ \frac{Y_\Sigma^3}{\sqrt{2}} & Y_N^3 \end{pmatrix} \cdot V^T(\alpha)\,, \tag{10}$$

Type-I seesaw relation

$$\mathcal{M}_\nu = h\,\Lambda\,h^T \longrightarrow h = U^* \sqrt{\widehat{\mathcal{M}_\nu}}\,R\,\sqrt{\Lambda}^{-1} \quad \text{Casas-Ibarra Parametrization}\,, \tag{11}$$

$R(\gamma)$ is a 3×2 complex matrix such that $RR^T = \mathbb{I}_3$,
$\widehat{\mathcal{M}_\nu}$ is the diagonalized neutrino mass matrix $\rightarrow U^T\,\mathcal{M}_\nu\,U = \widehat{\mathcal{M}_\nu}$

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LFV phenomenology

[3] Porod, Werner et al. Eur.Phys.J. C74 (2014) no.8, 2992

Computation of LFV observables SARAH $\downarrow$ FlavorKit[3] $\Rightarrow$ SPheno

- Dominant Wilson coefficients: Monopole K_1^L and Dipole K_2^R .

$$D^0, M^0(m_{\chi_{1,2}}, m_{\eta^+}) \qquad D^-, M^-(m_{\chi^-}, m_{\eta^0})$$

$$K_2^R = \frac{1}{16\pi^2}\left(D^0 + D^-\right), \quad K_1^L = \frac{1}{16\pi^2}\left(M^0 + M^-\right),$$

- Sizable contributions A_{LL}^V, B_{LL}^V, $C_{LL}^V \ll K_1^L$, K_2^R

Limit $M_\Sigma \to \infty$ in agreement with the scotogenic model

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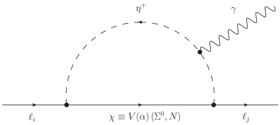
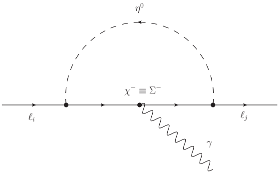


$D^-, M^-(m_{\chi^-}, m_{\eta^0})$



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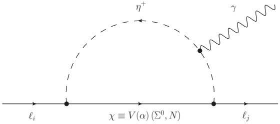

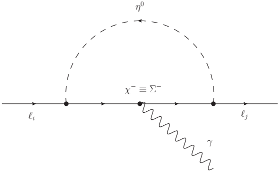

$$K_2^R = \frac{1}{16\pi^2}\left(D^0 + D^-\right), \quad K_1^L = \frac{1}{16\pi^2}\left(M^0 + M^-\right),$$

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Limit $M_\Sigma \to \infty$ in agreement with the scotogenic model

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Phenomenological analysis

- Solve tadpole eqs. for m_H^2 and m_Ω^2.
- Compute Yukawa couplings Y_N and Y_Σ
  - $\hookrightarrow$ Adapted Casas-Ibarra Parametrization (eq. 11)
  - $\hookrightarrow$ Neutrino oscillation data.
- Fix the scalar potential parameters
  - $\hookrightarrow$ $\lambda_{2,3,4} = \lambda_{1,2}^{\Omega} = \lambda^{\eta} = 0.1,\ \lambda_5 = 10^{-8},\ \lambda_1 = 0.26,$
  - $\hookrightarrow$ $\mu_1 = 50$ GeV , $\mu_2 = 1$ TeV , $v_\Omega = 1$ GeV.

$\Rightarrow$ Four free model parameters,

$$Y_\Omega\,, \quad m_\eta^2\,, \quad M_N\,, \quad M_\Sigma\,.$$

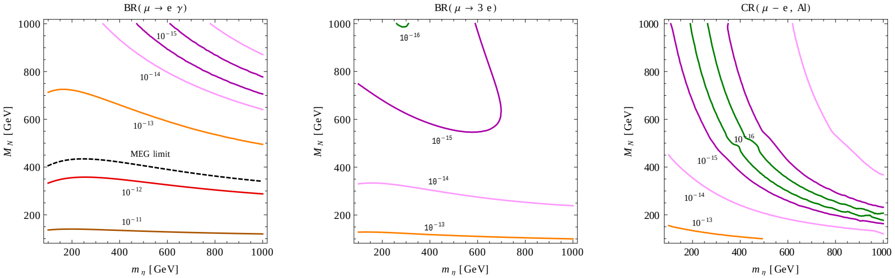
Free choices:

- R matrix angle γ
- Dirac CP-violating phase δ,
- Normal/Inverted Hierarchy for the light neutrino spectrum.

Contours in the m_η-M_N plane

[4] D. V. Forero, et al. Phys. Rev. D90, 093006 (2014), 1405.7540

- $Y_\Omega = 0.1,\ M_\Sigma = 500$ GeV
- Normal Hierarchy
- $\gamma = \delta = 0$
- Best-fit neutrino osc. param.[4]

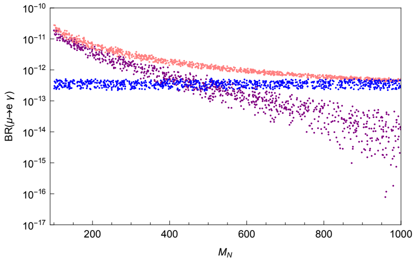


LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	5.7×10^{-13} *	6×10^{-14}
$\mu \to eee$	1.0×10^{-12}	$\sim10^{-16}$
$\mu^-,\mathrm{Al} \to e^-,\mathrm{Al}$		10^{-15}–10^{-18}

* arXiv:1605.05081 New upper limit 4.2×10^{-13}

The BR($\mu \to 3\,e$)/BR($\mu \to e\gamma$) ratio

$BR(\mu \to e\gamma) \gg BR(\mu \to 3\,e)$ for most points in the selected m_η-M_N plane.
This is not a general prediction of the model.



$Y_\Omega = 0.1$,
$m_\eta^2 = 2.5 \cdot 10^5$ GeV^2
$M_\Sigma = 500$ GeV.

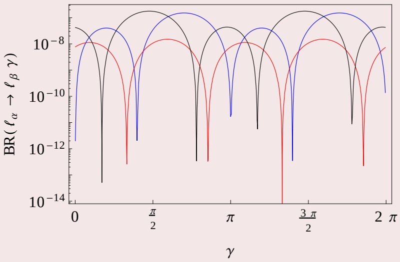
- Total BR($\mu \to e\gamma$)
- D^0 contribution
- D^- contribution

- $M_\Sigma < M_N$. Dominant Feynman diagrams are those with Σ^0-Σ^- loops.
- If $\alpha \simeq 0 \to D^0$ and D^- cancellation $\to$ total BR drops.
- For low M_N the singlet contribution to D^0 dominates, irrelevant triplet cancellation.
- Similar cancellation in K_1^L with little impact on the LFV observables

LFV τ decays

The results above were obtained with a vanishing γ (R matrix angle).
$\Rightarrow \gamma$ has a direct impact on Y_N and Y_Σ, and can lead to cancellations in the amplitudes of specific flavor violating transitions.

BR$(\ell_\alpha \to \ell_\beta \gamma)$ as a function of γ, $M_\Sigma = 300$ GeV, $\lambda_5 = 10^{-10}$



$-(\alpha, \beta) = (\mu, e)$
$-(\alpha, \beta) = (\tau, e)$
$-(\alpha, \beta) = (\tau, \mu)$

Outline

Conclusions

- The model will be probed in the next generation of LFV experiments.
- The operators with the largest contributions to the LFV amplitudes are the monopole and dipole ones, induced by photon penguin diagrams with scotogenic states running in the loop. Box diagrams have a subdominant role.
- One naturally finds points of the parameter space with BR($\mu \to 3\,e$), CR($\mu - e$, Nucleus) $\gg$ BR($\mu \to e\gamma$). Caused by cancellations in the dipole coefficient
- The singlet-triplet scotogenic model can also be probed via τ observables, but the scenarios where these have values close to the current or near future sensitivities require a certain tuning of the Yukawa parameters. Nevertheless, this can be achieved by properly choosing the γ angle of the Casas-Ibarra matrix R.

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