Probing scotogenic models via SM $Z-$ and Higgs boson decays

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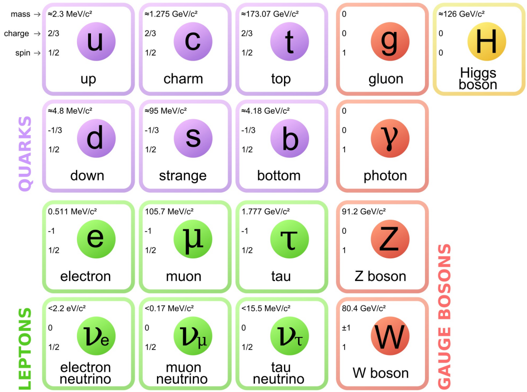
1. Introduction

The Standard Model explains many phenomena to a high precision.



Limitations of the SM:

- Neutrino masses
- Dark Matter (DM) and Dark Energy (DE)
- Baryon asymmetry
- flavor puzzle: hierarchy in fermion masses and mixing pattern
- flavor puzzle: muon anomalous magnetic moment

Main motivations for this work read:

1. Offer an unified, simple framework to explain smallness of ν masses (and oscillation data) and put forward viable DM candidate $\rightarrow$ scotogenic models.
2. Possibly address tension in $(g-2)_{\mu}$.
3. Explain CLFV correlations as means to test model.
4. Explain prospects of CLFV Z and H decays
5. Further test with "precision observables $R_{\tau\mu}^{Z,H}$, ...

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2. Model setup

The extended scotogenic model under consideration features (2301.08485):

Field	η	S	F_1	F_2	Ψ_1	Ψ_2
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	1	0	0	0	-1	1

Table 1: The fields are odd under Z_2 discrete symmetry.

The Lagrangian with this field assignment reads (All g couplings are source of LNV):

$$\mathcal{L}_{\text{fermion}} = i(\overline{\Psi}_j \sigma^\mu D_\mu \Psi_j + \frac{1}{2}\overline{F}_j \sigma^\mu \partial_\mu F_j) - \frac{1}{2} M_{F_{ij}} F_i F_j - M_\Psi \Psi_1 \Psi_2$$
$$- y_{1i} \Psi_1 H F_i - y_{2i} \Psi_2 \tilde{H} F_i - g_\Psi^k \Psi_2 L_k S - g_{F_j}^K \eta L_k F_j - g_R^k e_k^c \tilde{\eta} \Psi_1 + \text{h.c.}$$

And the scalar potential reads:

$$V = \frac{1}{2} M_S^2 S^2 + \frac{1}{2}\lambda_{4S} S^4 + M_\eta^2 |\eta|^2 + \lambda_{4\eta} |\eta|^4 + \frac{1}{2}\lambda_S S^2 |\Phi|^2 + \frac{1}{2}\lambda_{S\eta} S^2 |\eta|^2$$
$$+ \lambda_\eta |\eta|^2 |\Phi|^2 + \lambda_\eta' |\eta \Phi^\dagger|^2 + \frac{1}{2}\lambda_\eta'' \left[\left(\Phi \eta^\dagger \right)^2 + \text{H.c.} \right] + \alpha S \left[\Phi \eta^\dagger + \text{H.c.} \right],$$

The fermion and scalar sectors are diagonalized as follows:

$$U_\chi^* M_\chi U_\chi^\dagger = M_\chi^{\text{diag}} \, (F_1, F_2, \Psi_1^0, \Psi_2^0), \qquad U_\phi M_H^2 U_\phi^\dagger = m_H^{\text{diag},2} \, (S, \eta^0, A^0)$$

2. Model setup

2.1 Neutrino masses at one-loop level

The diagrams for active neutrinos at one-loop level read (Z_2 symmetry forbids tree-level ν mass generation):

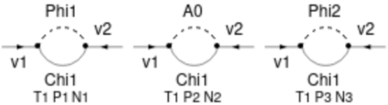

Figure 1: Neutrino masses at one-loop

The Majorana mass term for one-loop neutrino can be written using Casas-Ibarra parameterization:

$$\mathcal{M}_\nu = \mathcal{G}^T M_L \mathcal{G}$$

where M_L is a complex symmetric 3×3 matrix which encodes loop functions and scalalr and fermion mixing matrices. The $\mathcal{G}$ is a 3×3 coupling matrix:

$$\mathcal{G} = \begin{pmatrix} g_\Psi^1 & g_\Psi^2 & g_\Psi^3 \\ g_{F_1}^1 & g_{F_1}^2 & g_{F_1}^3 \\ g_{F_2}^1 & g_{F_2}^2 & g_{F_2}^3 \end{pmatrix} = U_L D_L^{-1/2} R D_\nu^{1/2} U^*_{\mathrm{PMNS}}$$

2. Model setup

2.2 Relevant form factors = radiative decay & transition

The diagrams for the Wilson coefficient, required for muon $g-2$ and $\mu \to e\gamma$ decay, read:

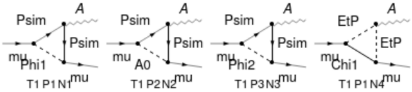

Figure 2: Diagrams for the Wilson coefficient required for muon $g-2$ and $\mu \to e\gamma$ decay

Then, the Wilson coefficient can be parameterized as follows:

$$c_R^{ij} = \frac{e}{16\pi^2}\left[\Gamma_L^{i*}\Gamma_R^{j} M_\Psi \frac{f(x)+Qg(x)}{M_\Phi^2} + \left(m_{l_j}\Gamma_L^{i*}\Gamma_L^{j} + m_{l_i}\Gamma_R^{i*}\Gamma_R^{j}\right)\frac{\tilde{f}(x)+Q\tilde{g}(x)}{M_\Phi^2}\right]$$

where $x = M_\Psi^2/M_\Phi^2$. Then, the anomalous magnetic moment and branching ratios of $l_i \to l_j\gamma$ can be written like:

$$\Delta a_i = -4\frac{m_{l_i}}{e}\,\mathrm{Re}\left(c_R^{ij}\right)$$

$$\mathrm{BR}\left(l_i \to l_j\gamma\right) = \frac{m_i^3}{4\pi\Gamma_{l_i}}\left[|c_R^{ij}|^2 + |c_R^{ji}|^2\right]$$

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3. Constraints

3.1 A flowchart of this work

Schematic outline:

1. Model implemented in both **SARAH** and **FeynRules**.
2. **SARAH** generates **SPheno** module to calculate observables of interest.
   - Neutrino masses and mixing matrix (at 1σ), normal hierarchy
   - flavor observables

$$\Delta a_\mu = [10.7, 24.9] \times 10^{-10} \text{ with an error bar of } 4.8 \times 10^{-10}$$

$$\mathrm{BR}\,(\mu \to e\gamma) < 3.1 \times 10^{-13}, \qquad \mathrm{BR}\,(\mu \to 3e) < 1.0 \times 10^{-12}$$

$$\mathrm{BR}\,(\tau \to \mu\gamma) < 4.2 \times 10^{-8}, \qquad \mathrm{BR}\,(\tau \to 3\mu) < 2.1 \times 10^{-8}$$

   - Dark Matter abundance $\Omega h^2 = (0.12 \pm 0.012)$

3. We implement observables which require renormalization in **FeynCalc** analytically (e.g. oblique S, T, U parameters, $Z \to l_i l_j$, $H \to l_i l_j$)
4. And then we carry out numerical studies based on MCMC setup in **Python**.

$$\chi^2 = \exp\left[-\frac{\left(\mathcal{O}_i^{\rm pred} - \mathcal{O}_i^{\rm exp}\right)^2}{2\sigma_i^2}\right] \qquad (1)$$

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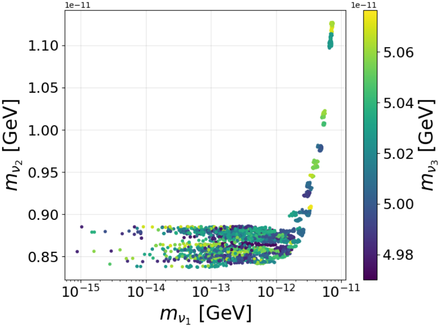
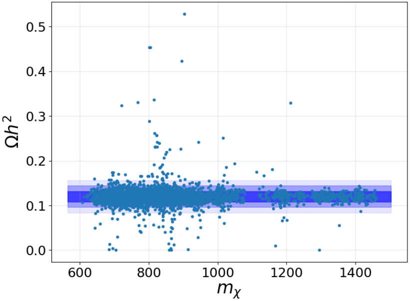
4. Numerical analysis (Preliminary)

4.1 Neutrino masses and DM relic density



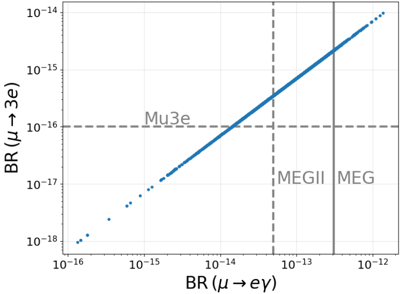
(a) Neutrino masses

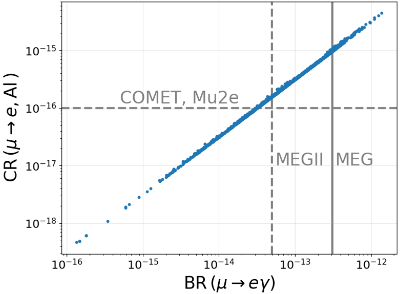


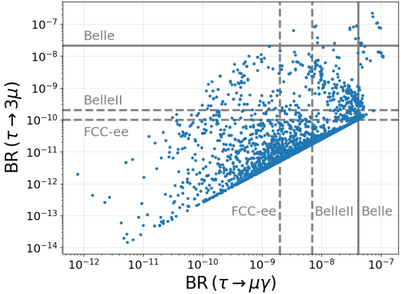
(b) DM relic abundance = fermionic candidate

4. Numerical analysis (Preliminary)

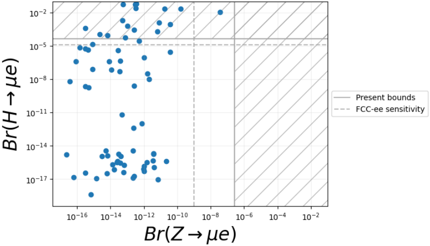
4.2 CLFV $\mu \to e\gamma$, $\mu \to 3e$, $\tau \to \mu\gamma$ and $\tau \to 3\mu$ decays

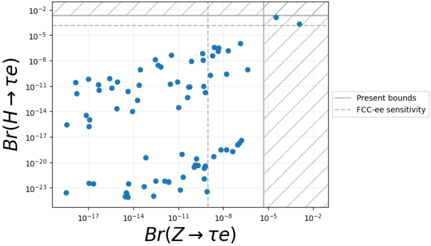


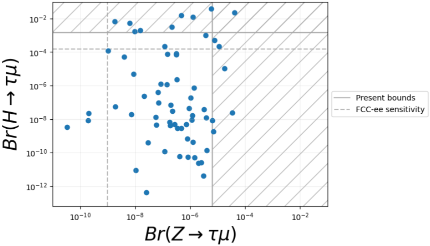




1. A strong correlation among $\mu \to e\gamma$, $\mu \to 3e$ and $\mu - e$ conversion rate is found, within the reach of future sensitivity.
2. A strong correlation does not appear between the $\tau \to \mu\gamma$ and $\tau \to 3\mu$ decays, as contributions from their penguin diagrams can dominate. However, many points still lie within the reach of the future sensitivity.



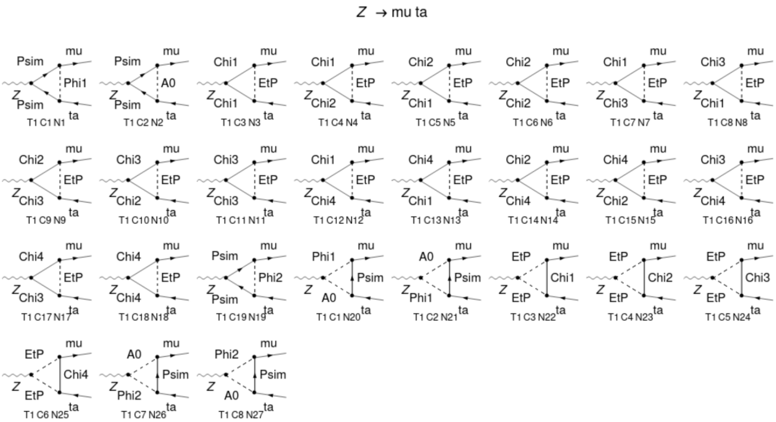


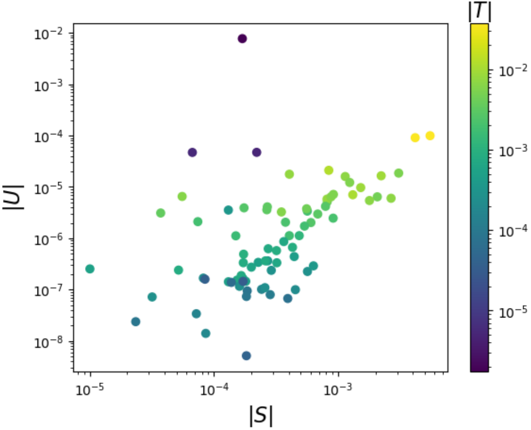


1. The flavor violating decays $(Z, H \to l_i l_j)$ are also within the reach of future experimental sensitivity.

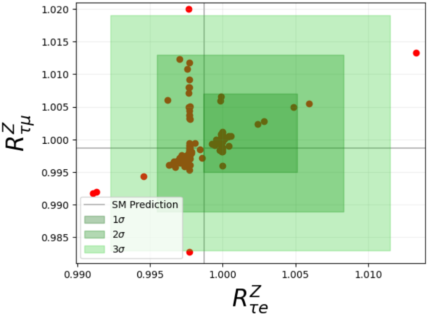
4. Numerical analysis (Preliminary)

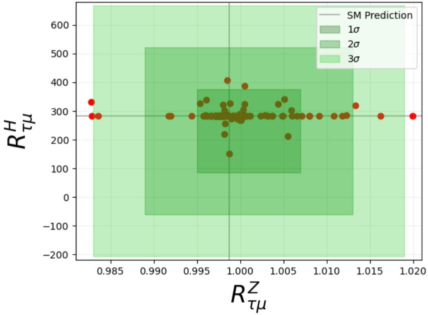
4.3 Flavor violating $Z-$ and Higgs decays





1. All the oblique parameters S, T, U are under control.





1. The ratio R is defined:

$$R^Z_{\tau\mu} = \frac{\mathrm{BR}\,(Z \to \tau\tau)}{\mathrm{BR}\,(Z \to \mu\mu)} \tag{2}$$

2. The ratio between $Z, H \to l_i l_i$ decays are within the SM prediction, however we can enhance the predicted order of flavor violating $Z \to l_i l_j$ decays as the coupling g^2_Ψ drives this enhancement.

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5. Conclusion

1. Minimal framework to address SM observational issues: m_ν, DM and potentially $(g-2)_\mu$ (if needed)
2. Testability of CLFV observables
3. Additionally explored $Z, H \to l_i l_j$
4. Work in progress