Lepton flavor violation in a Doublet Left-Right Symmetric Model with Inverse Seesaw

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Taller: "Más allá del Modelo Estándar y Astropartículas"
Instituto de Física, UNAM

Outline

Standard Model Limitations

- The Standard Model (SM) is remarkably successful but has open questions:
  - Origin of neutrino masses
  - Nature of parity violation
  - Possibility of lepton flavor violation (LFV)

- **Neutrino oscillations** $\Rightarrow$ neutrinos have mass
- In SM extended with neutrino masses:
  - LFV processes like $\mu \to e\gamma$ are highly suppressed
  - LFV Higgs decays (LFVHD) provide important probes

- **Current ATLAS bounds:**[8]
  - $\mathcal{BR}(h \to e\tau) < 0.20\%$
  - $\mathcal{BR}(h \to \mu\tau) < 0.18\%$

DLRSM: Gauge and Matter Content

Gauge Group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}[1,\ 2]$

Fermion Content:

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (2, 1, \frac{1}{3}) \tag{1}$$

$$q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \sim (1, 2, \frac{1}{3}) \tag{2}$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (2, 1, -1) \tag{3}$$

$$\ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \sim (1, 2, -1) \tag{4}$$

Scalar Content:

$$\Phi \sim (2, 2, 0) \quad \text{(bidoublet)} \tag{5}$$

$$\chi_L \sim (2, 1, 1) \quad \text{(left doublet)} \tag{6}$$

$$\chi_R \sim (1, 2, 1) \quad \text{(right doublet)} \tag{7}$$

Symmetry Breaking:

- Two-stage breaking
- $\langle \chi_R \rangle = v_R$ (new scale)
- $\langle \Phi \rangle$ gives EW scale

Gauge Sector: W, W', Z, and Z' Bosons

Charged Gauge Bosons:

- Mass matrix for $W^{\pm}_{L,R}$:

$$M^2_{W^\pm} = \begin{pmatrix} \frac{g^2(k_1^2+k_2^2+v_R^2)}{4} & -\frac{g^2 k_1 k_2}{2} \\ -\frac{g^2 k_1 k_2}{2} & \frac{g^2(k_1^2+k_2^2)}{4} \end{pmatrix} \quad (8)$$

- Mixing angle: $\sin\xi \approx \frac{2k_1k_2}{v_R^2}$
- Physical states:

$$W^{\pm}_{\mu} = W^{\pm}_{\mu L} + \frac{2k_1k_2}{v_R^2} W^{\pm}_{\mu R} \quad (9)$$

$$W'^{\pm}_{\mu} = W^{\pm}_{\mu R} - \frac{2k_1k_2}{v_R^2} W^{\pm}_{\mu L} \quad (10)$$

Neutral Gauge Bosons:

- Basis: $(W^3_{\mu L}, W^3_{\mu R}, B_\mu)$
- Diagonalization gives: A, Z, Z'
- Physical relations:

$$W^3_{\mu L} = A_\mu \sin\theta_W - Z_\mu \cos\theta_W \quad (11)$$

$$W^3_{\mu R} = A_\mu \sin\theta_W + Z_\mu \sin\theta_W \tan\theta_W \quad (12)$$

$$- Z'_\mu \frac{\sqrt{\cos(2\theta_W)}}{\cos\theta_W} \quad (13)$$

Masses (limit $k_2 = 0$, $k_1 \ll v_R$):

$$m_W^2 \approx \frac{g^2 k_1^2}{4} \quad (14)$$

$$m_{W'}^2 \approx \frac{g^2 v_R^2}{4} \quad (15)$$

Scalar Sector and Higgs Spectrum

$$
\begin{aligned}
V(\chi_L, \chi_R, \Phi) = & -\mu_1^2 \operatorname{Tr} \Phi^\dagger \Phi + \lambda_1 \left(\operatorname{Tr} \Phi^\dagger \Phi\right)^2 + \lambda_2 \operatorname{Tr} \Phi^\dagger \Phi \Phi^\dagger \Phi + \frac{1}{2}\lambda_3 \left(\operatorname{Tr} \Phi^\dagger \tilde{\Phi} + \operatorname{Tr} \tilde{\Phi}^\dagger \Phi\right)^2 \\
& + \frac{1}{2}\lambda_4 \left(\operatorname{Tr} \Phi^\dagger \tilde{\Phi} - \operatorname{Tr} \tilde{\Phi}^\dagger \Phi\right)^2 + \lambda_5 \operatorname{Tr} \Phi^\dagger \Phi \tilde{\Phi}^\dagger \tilde{\Phi} + \frac{1}{2}\lambda_6 \left[\operatorname{Tr} \Phi^\dagger \tilde{\Phi} \Phi^\dagger \tilde{\Phi} + \text{ h.c. }\right] \\
& - \mu_2^2 \left(\chi_\mathrm{L}^\dagger \chi_\mathrm{L} + \chi_\mathrm{R}^\dagger \chi_\mathrm{R}\right) + \rho_1 \left(\left(\chi_\mathrm{L}^\dagger \chi_\mathrm{L}\right)^2 + \left(\chi_\mathrm{R}^\dagger \chi_\mathrm{R}\right)^2\right) + \rho_2 \chi_\mathrm{L}^\dagger \chi_\mathrm{L} \chi_\mathrm{R}^\dagger \chi_\mathrm{R} \\
& + \alpha_1 \operatorname{Tr} \Phi^\dagger \Phi \left(\chi_\mathrm{L}^\dagger \chi_\mathrm{L} + \chi_\mathrm{R}^\dagger \chi_\mathrm{R}\right) + \alpha_2 \left(\chi_\mathrm{L}^\dagger \Phi \Phi^\dagger \chi_\mathrm{L} + \chi_\mathrm{R}^\dagger \Phi^\dagger \Phi \chi_\mathrm{R}\right) \\
& + \alpha_3 \left(\chi_\mathrm{L}^\dagger \tilde{\Phi} \tilde{\Phi}^\dagger \chi_\mathrm{L} + \chi_\mathrm{R}^\dagger \tilde{\Phi}^\dagger \tilde{\Phi} \chi_R\right).
\end{aligned}
$$

VEVs:

- $\langle \chi_R \rangle = \frac{v_R}{\sqrt{2}}$, $\langle \chi_L \rangle = 0$
- $\langle \Phi \rangle = \mathrm{diag}(k_1, k_2)/\sqrt{2}$
- $k_2 = 0$ in minimal case

Physical Higgs States:

- SM-like Higgs h (125 GeV)
- Heavy CP-even: H_i^0 iwth $i = 1, 2, 3$
- CP-odd: $A_{1,2}^0$
- Charged: $H_{L,R}^\pm$

Neutrino Mass Generation

$$-\mathcal{L}_Y = \overline{L}_{iR} Y_{ij} \Phi^\dagger L_{jL} + \overline{L}_{iR} \tilde{Y}_{ij} \tilde{\Phi}^\dagger L_{jL} + \overline{S}_i Y_{ijL} \tilde{\chi}_L^\dagger L_{ijL} + \overline{S}_i^c Y_{ijR} \tilde{\chi}_R^\dagger L_{jR} + \frac{1}{2} \overline{S}_i^c \mu_{ij} S_j + \text{h.c.}$$

Left-Right Symmetry:

$$Y_L = Y_R, \qquad Y = Y^\dagger, \qquad \tilde{Y} = \tilde{Y}^\dagger, \qquad \mu = \mu^\dagger$$

$$m_D = \frac{1}{\sqrt{2}} \left(k_1 Y + k_2 \tilde{Y} \right), \qquad m'_D = \frac{1}{\sqrt{2}} v_L Y_L, \qquad M_D = \frac{1}{\sqrt{2}} v_R Y_R$$

Neutrino Mass Matrix ($v_L = 0$):

$$m_\nu \approx m_D^\top M_D^{-1} \mu \left(M_D^\top \right)^{-1} m_D,$$

The Minimal Case: Diagonal Yukawa Structure

Simplifying Assumptions[7]:

- Diagonal Yukawa matrices: $Y = Y^{\text{diag}} = \text{diag}(Y_1, Y_2, Y_3)$
- Left-right symmetry: $Y_R = Y$

Light neutrino mass matrix:

$$m_\nu \approx \frac{k_1^2}{v_R^2} Y^T Y_R^{-1} \mu (Y_R^T)^{-1} Y = \epsilon^2 \mu \tag{17}$$

where $\epsilon = \frac{k_1}{v_R}$

Heavy neutrino masses:

$$M_i^- \approx M_{D_i} - \frac{\mu_{ii}}{2} \tag{18}$$

$$M_i^+ \approx M_{D_i} + \frac{\mu_{ii}}{2} \tag{19}$$

Diagonalization Structure:

$$\begin{aligned} \mathcal{U} &= \mathcal{U}_S \mathcal{U}_N \mathcal{U}_\nu O \\ &= \begin{pmatrix} c_\epsilon U_\nu^* & -i s_\epsilon \mathbf{S}_N & s_\epsilon \mathbf{C}_N \\ 0 & i\mathbf{C}_N & \mathbf{S}_N \\ -s_\epsilon U_\nu^* & -i c_\epsilon \mathbf{S}_N & c_\epsilon \mathbf{C}_N \end{pmatrix} \end{aligned} \tag{20}$$

Mixing Parameters:

$$s_N^i = \frac{\sqrt{M_i^-}}{\sqrt{M_i^- + M_i^+}} \tag{21}$$

LFV $\mu \to e\gamma$

Process: $\mu \to e\gamma$

- Mediated by neutrinos n_i, charged scalar $H_R^{\pm}$ and W, W' bosons

Amplitude:

$$\mathcal{A}(\mu \to e\gamma) = e\epsilon_\mu^* \bar{u}_e(p_e)[i\sigma^{\mu\nu} q_\nu (A_L P_L + A_R P_R)] u_\mu(p_\mu) \tag{22}$$

Branching Ratio:

$$\mathcal{BR}(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\gamma) + \Gamma(\mu \to e\nu_\mu \bar{\nu}_e)} \tag{23}$$

Current Limit: $\mathcal{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ (MEG Collaboration)[9]

One-loop topologies:

- Triangle diagrams (two types: one and two fermions in the loop)
- Bubble diagrams

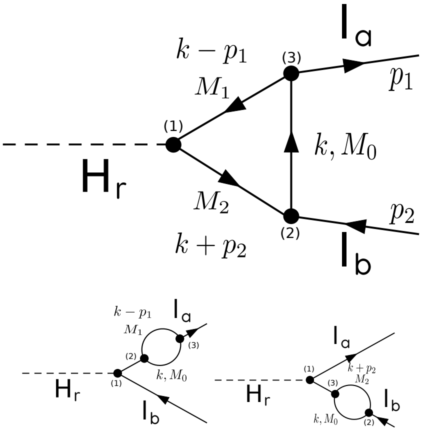
Amplitude:

$$\mathcal{A}(h \to \ell_a \ell_b) = \bar{u}_a(p_a)[A_L P_L + A_R P_R] v_b(p_b) \qquad (24)$$

Exact calculation:

- Finite results (divergences cancel)
- Numerical evaluation with LoopTools
- All loop contributions included

One-Loop Topologies



$$\mathcal{BR}(h \to \ell_a \ell_b) = \frac{\Gamma(h \to \ell_a \ell_b)}{\Gamma_h^{\text{total}} + \Gamma(h \to \ell_a \ell_b)} \qquad (25)$$

Computational Framework

Tools Used:

- **SARAH:** Model implementation
- **SPheno:** Spectrum calculation numerically
- **MCMC:** Parameter space scan (hep-aid library)
- **LoopTools:** One-loop integrals (Python wrapper)
- **Python scientific libraries:** NumPy, Matplotlib

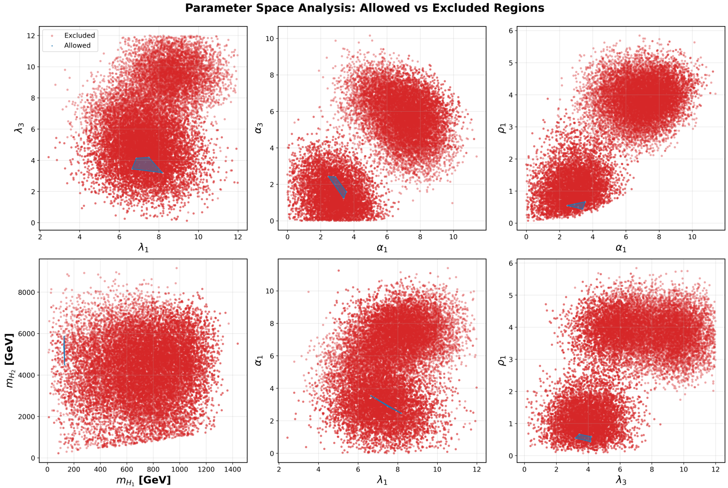
Key Parameters:

- v_R: Right-handed scale
- Y_R: Right-handed Yukawa couplings

Constraints Applied:

- Higgs mass: $m_h = 125.1 \pm 2.4$ GeV
- Perturbativity: $|Y_R| < \sqrt{4\pi}$

Scalar potential parameter Space



Higgs Mass Constraint:

- MCMC scan identifies viable regions
- Scalar potential parameters constrained
- Multiple solutions possible

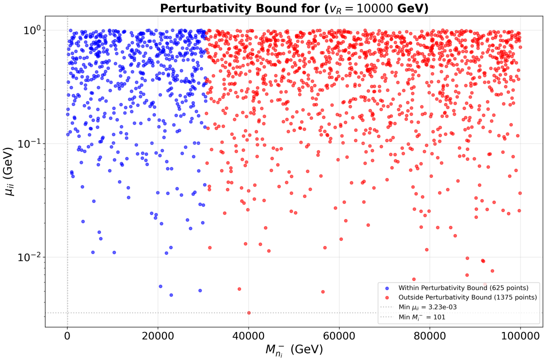
Key Observations:

- Viable parameter space exists
- Multiple benchmark points

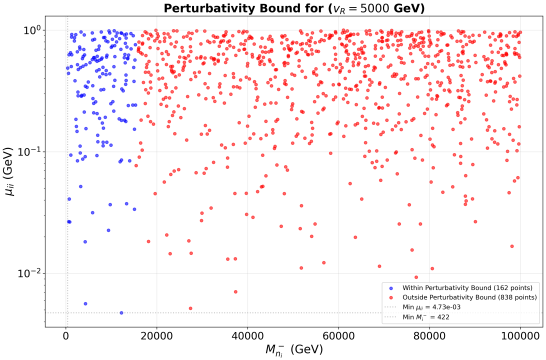
Perturbativity Constraints on Y_R

Impact of Perturbativity on Heavy Neutrino Masses

$v_R = 10$ **TeV**



$v_R = 5$ **TeV**

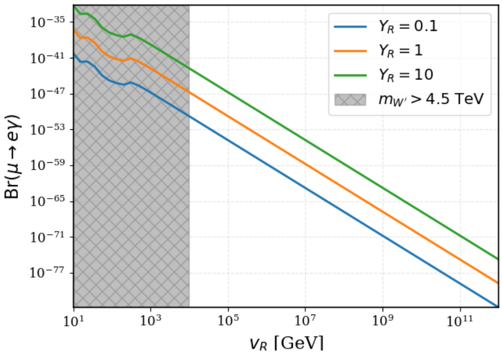


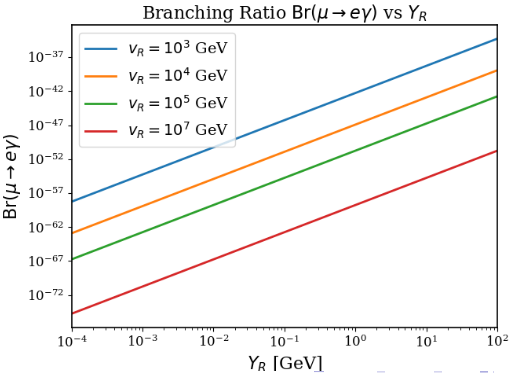
- **Perturbativity bound:** $|Y_R| < 6\pi$

$\mu \to e\gamma$ Branching Ratios

Degenerate Heavy Neutrino Masses:

$$M_i^- = M_i^+ = M_D = \frac{1}{\sqrt{2}} Y_R v_R$$

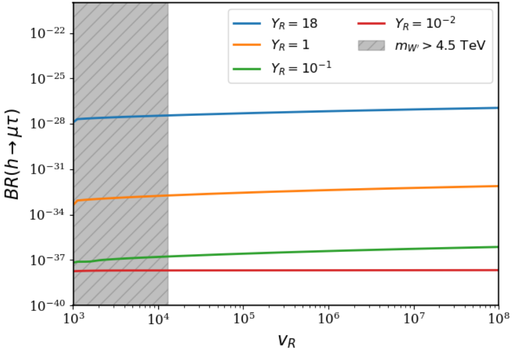


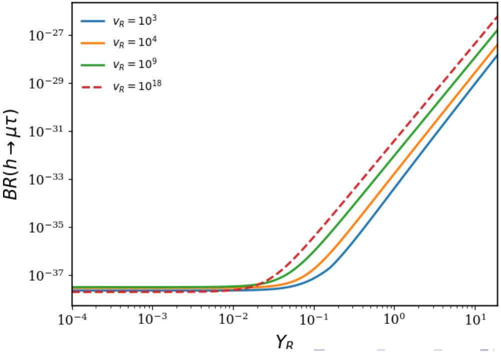


LFVHD Branching Ratios

Degenerate Heavy Neutrino Masses:

$$M_i^- = M_i^+ = M_D = \frac{1}{\sqrt{2}} Y_R v_R$$





Summary and Conclusions

- **Theoretical Framework:**
  - DLRSM + Inverse Seesaw provides natural LFV mechanism
  - More economical than triplet LRSM
- **Technical Achievements:**
  - Complete one-loop calculation of LFVHD
  - Exact form factors (finite results)
  - Extendible parameter space analysis
- **Phenomenological Results:**
  - $\mathcal{BR}(h \to \mu\tau)$ (below current bounds)
  - Viable parameter space with $m_h = 125$ GeV
- **Computational Achievements:**
  - New SARAH model files for DLRSM + ISS, available on DLRSM GitHub
  - Integrated SARAH, SPheno, hep-aid for parameter scans
  - LFVXD package for future studies, available on LFVXD GitHub with LoopTools (Python wrapper)

Future Directions

Theoretical Extensions:

- Include $k_2 \neq 0$, $v_L \neq 0$
- Consider $g_L \neq g_R$
- Extended scalar potential
- Other LFV processes

Phenomenological Studies:

- Collider signatures
- Direct heavy neutrino searches
- EDM constraints
- Precision EW tests

Model Building:

- Connection to dark matter
- Baryogenesis mechanisms

The DLRSM with ISS provides a rich framework for exploring physics beyond the Standard Model!

Thank You!

Questions?

M. Zeleny-Mora, R. Gaitán-Lozano, R. Martinez

"Lepton Flavor Violating Higgs Decays in a Minimal Doublet Left-Right Symmetric Model with an Inverse Seesaw"

Backup: Yukawa Lagrangian

Complete Yukawa Lagrangian:

$$-\mathcal{L}_Y = \overline{L}_{iR} Y_{ij} \Phi^\dagger L_{jL} + \overline{L}_{iR} \tilde{Y}_{ij} \tilde{\Phi}^\dagger L_{jL} + \overline{S}_i Y_{ijL} \tilde{\chi}_L^\dagger L_{ijL} + \overline{S}_i^c Y_{ijR} \tilde{\chi}_R^\dagger L_{jR} + \frac{1}{2} \overline{S}_i^c \mu_{ij} S_j + \text{h.c.} \tag{26}$$

Left-Right Symmetry Constraints:

$$Y_L = Y_R, \qquad Y = Y^\dagger, \qquad \tilde{Y} = \tilde{Y}^\dagger, \qquad \mu = \mu^\dagger \tag{27}$$

Field Definitions:

- $\tilde{X} \equiv i\sigma_2 X^*$ with $X = \chi_L, \chi_R$
- $S^c = C\overline{S}^\top$ and $\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$
- Y, $\tilde{Y}$, Y_L, Y_R: 3×3 Yukawa coupling matrices
- μ: Majorana mass matrix for fermionic singlets S_i

SM Higgs interactions with leptons and neutrinos:

$$-\mathcal{L}_{h\ell\ell} = \frac{\sqrt{2}}{k_1} m_\ell h^{SM} \overline{\ell} \ell \tag{28}$$

$$-\mathcal{L}_{hnn} = \frac{1}{\sqrt{2} k_1} h^{SM} \overline{n_i} \left[\left(\Gamma_{ij} + \Gamma_{ji} \right) P_L + \left(\Gamma^*_{ji} + \Gamma^*_{ij} \right) P_R \right] n_j \tag{29}$$

Charged scalar interactions:

$$\begin{aligned} -\mathcal{L}^{\pm}_{Y} = & \frac{\sqrt{2}}{k_1} G^{-}_{L} \overline{\ell}_i \left(T^*_{RL,ji} P_R - m_{\ell_i} Q_{L,ij} P_L \right) n_j \\ & + \frac{\sqrt{2}}{v_R} G^{+}_{R} \overline{n_j} \left[\left(Q^*_{R,ij} m_{\ell_i} P_L - J^*_{ij} P_R \right) \right] \ell_i \\ & + \frac{\sqrt{2}}{k_1} H^{-}_{R} \overline{\ell_i} \left(K_{ij} P_L - m_{\ell_i} Q_{R,ij} P_R \right) n_j + \text{h.c.} \end{aligned} \tag{30}$$

Key matrices:

- $\Gamma = G_{RL} \approx U_R^\top m_D U_L$ (LFV couplings)

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