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

M. Zeleny-Mora[†], R. Gaitán-Lozano[†], R. Martinez[*]

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[†]Departamento de Física, FES-Cuautitlán, UNAM
[*]Departamento de Física, Universidad Nacional de Colombia

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Outline

Theory:

- Introduction
- The Doublet Left-Right Symmetric Model
- Inverse Seesaw Mechanism

Phenomenology:

- Lepton Flavor Violation

Results:

- Numerical Analysis and Results

Summary:

- Conclusions

Motivation

Standard Model Limitations:

- Origin of neutrino masses
- Nature of parity violation
- Lepton flavor violation (LFV)

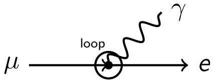
Left-Right Symmetric Models (LRSM):

- Gauge group:
  $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$[1, 2]
- Restores left-right symmetry at high energies
- Natural framework for neutrino masses

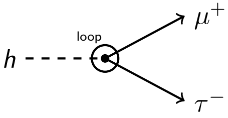
Doublet LRSM:

- More economical than canonical triplet LRSM
- Avoids doubly charged scalars
- Requires additional mechanism for neutrino masses
  $\Rightarrow$ **Inverse Seesaw**

LFV Processes



$\mathcal{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$



$\mathcal{BR}(h \to \mu\tau) < 0.18\%$

One-loop induced processes

Model Construction: Gauge and Matter Content

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

Particle Content:

Field	Representation	Type
$L_{iL} = \begin{pmatrix} \nu_i' \\ \ell_i' \end{pmatrix}_L$	$(2, 1, -1)$	Fermion
$L_{iR} = \begin{pmatrix} \nu_i' \\ \ell_i' \end{pmatrix}_R$	$(1, 2, -1)$	Fermion
S_i	$(1, 1, 0)$	Fermion
Φ	$(2, 2, 0)$	Scalar
χ_L	$(2, 1, 1)$	Scalar
χ_R	$(1, 2, 1)$	Scalar

Symmetry Breaking:

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$v_R \sim$ TeV $\quad \downarrow \; \langle \chi_R \rangle = \frac{v_R}{\sqrt{2}}$

$$SU(2)_L \otimes U(1)_Y$$

$k_1 = 246$ GeV $\quad \downarrow \; \langle \Phi \rangle = \frac{k_1}{\sqrt{2}}$

$$U(1)_{EM}$$

Parity Transformation:

$$L_L \leftrightarrow L_R, \quad S \leftrightarrow S^c, \quad \chi_L \leftrightarrow \chi_R$$

Scalar Sector and Vacuum Structure

VEV Configuration:

$$\langle \chi_R \rangle = \frac{v_R}{\sqrt{2}}, \quad \langle \chi_L \rangle = v_L$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}$$

Minimal Case: $k_2 = v_L = 0$

Physical Higgs States:

- **CP-even:** $H^0_{1,2,3,4}$
- **CP-odd:** $A^0_{1,2}$
- **Charged:** $H^{\pm}_{L,R}$

Mass Hierarchy Spectrum:

Mass

$\sim v_R^2$

$$m^2_{H_R^\pm} = (\alpha_2 - \alpha_3)\left(k_1^2 + v_R^2\right)$$

$$m^2_{H_L^\pm} = k_1^2\,(\alpha_2 - \alpha_3) + v_R^2\,(\rho_2 - 2\rho_1)$$

$$m^2_{H_4^0} = 2\,(\rho_2 - 2\rho_1)\,v_R^2$$

$$m^2_{H_3^0} = 2\,(\alpha_2 - \alpha_3)\,v_R^2 + 4\,(-\lambda_2 + 4\lambda_3 + \lambda_5 + \lambda_6)\,k_1^2$$

$\sim v_R^2$

$$m^2_{H_2^0} \approx 8\rho_1 v_R^2 + \frac{4}{\rho_1}\,(\alpha_1 + \alpha_3)^2\,k_1^2$$

v_R scale

EW scale

$\sim k_1^2$

$$m^2_{H_1^0} \approx 8\left(\lambda_1 + \lambda_2 - \frac{(\alpha_1+\alpha_3)^2}{4\rho_1}\right) k_1^2$$

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

Charged Gauge Bosons:

- Physical states: $W^{\pm}$, $W'^{\pm}$
- Small mixing: $\sin\xi \approx \frac{2k_1k_2}{v_R^2}$
- Masses:

$$m_W^2 \approx \frac{g^2 k_1^2}{4}$$

$$m_{W'}^2 \approx \frac{g^2 v_R^2}{4}$$

Neutral Gauge Bosons:

- Physical states: γ, Z, Z'
- $Z - Z'$ mixing suppressed
- Mass relation:

$$m_Z^2 = \frac{m_W^2}{\cos^2\theta_W}$$

New Physics Scale:

- v_R controls masses of W', Z', $H_R^{\pm}$, and heavy neutrinos
- Experimental bounds: $m_{W'} > 5.4$ TeV $\Rightarrow v_R > 16.5$ TeV[9]

Yukava Lagrangian and Mass Terms

Lepton Yukawa Lagrangian:[3, 4]

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

Left-Right Symmetry:

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

Charged leptons:

$$M_\ell = \frac{k_1}{\sqrt{2}} \tilde{Y} \quad \hat{M}_\ell = V_L^{\ell\dagger} M_\ell V_R$$

Dirac/Majorana terms:

$$m_D = \frac{k_1}{\sqrt{2}} Y \qquad M_D = \frac{v_R}{\sqrt{2}} Y_R \qquad \mu$$

Neutrino Mass Matrix and Inverse Seesaw

Neutrino Mass Matrix in basis (ν_L, ν_R^c, S^c):

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_D^T \\ 0 & M_D & \mu \end{pmatrix}$$

Light Neutrino Mass (limit $v_L = 0$, $k_2 = 0$) $|\mu| \ll |m_D| \ll |(M_D)|$:

$$m_\nu \approx m_D^T M_D^{-1} \mu (M_D^T)^{-1} m_D = m_D^T \mathcal{M}^{-1} m_D; \qquad \mathcal{M} = M_D \mu^{-1} M_D^\top$$

Heavy Neutrino Masses:

$$M_i^\pm \approx M_{D_i} \pm \frac{\mu_{ii}}{2}$$

Key Features:

- Heavy neutrinos at TeV scale: $M_i^\pm \sim v_R$
- Sizable mixing between active and sterile neutrinos

Neutrino Mixing Structure

Total Mixing Matrix:

$$\mathcal{U} \approx \begin{pmatrix} U_\nu & -\frac{i}{\sqrt{2}} m_D^T M_D^{-1} & \frac{1}{\sqrt{2}} m_D^T M_D^{-1} \\ M_D^{-1} \mu M_D^{-1} m_D U_\nu & \frac{i}{\sqrt{2}} \mathbb{I} & \frac{1}{\sqrt{2}} \mathbb{I} \\ -M_D^{-1} m_D U_\nu & -\frac{i}{\sqrt{2}} \mathbb{I} & \frac{1}{\sqrt{2}} \mathbb{I} \end{pmatrix} = \begin{pmatrix} U_L \\ U_R \\ U_S \end{pmatrix}$$

where U_ν is the PMNS matrix diagonalizing m_ν.

Casas-Ibarra Parametrization:[5]

$$m_D = V^\dagger \mathrm{diag}(\sqrt{\mathcal{M}_1}, \sqrt{\mathcal{M}_2}, \sqrt{\mathcal{M}_3}) R \,\mathrm{diag}(\sqrt{m_{\nu_1}}, \sqrt{m_{\nu_2}}, \sqrt{m_{\nu_3}}) U_\nu^\dagger$$

Simplified Case:

- Diagonal $M_D = \mathrm{diag}(M_{D1}, M_{D2}, M_{D3})$
- Universal $\mu = \mu_X \mathbb{I}$
- Orthogonal matrix $R = \mathbb{I}$

Neutrino Mass Basis and Physical States

Rotation to Physical Basis:

$$n'_L = \mathcal{U} n_L, \qquad n'_R = \mathcal{U}^* n_R$$

$$n_L = \left(\nu_L, \nu_R^c, S^c\right), \qquad n'_L = \left(\nu, N_i^-, N_i^+\right)_L$$

Block Matrix Structure:

$$\mathcal{U} = \begin{pmatrix} U_L \\ U_R \\ U_S \end{pmatrix}, \qquad \text{with } 3 \times 9 \text{ blocks}$$

Unitarity Conditions:

$$U_X U_Y^\dagger = \begin{cases} \mathbb{I} & X = Y \\ 0 & X \neq Y \end{cases}; \qquad X, Y = L, R, S$$

Mass Matrix Relations:

$$m_D = U_R^* \hat{\mathcal{M}} U_L^\dagger \qquad \mu = U_S^* \hat{\mathcal{M}} U_S^\dagger$$

$$M_D = U_S^* \hat{\mathcal{M}} U_R^\dagger \qquad \hat{\mathcal{M}} = \mathcal{U}^\top \mathcal{M} \mathcal{U} = \text{diag}(m_i, M_i^-, M_i^+)$$

LFV Process: $\mu \to e\gamma$

Amplitude:

$$\mathcal{A}(\mu \to e\gamma) = i\bar{u}_e(p-q)\epsilon^*_\nu \sigma^{\nu\mu} q_\mu [B_L P_L + B_R P_R] u_\mu(p)$$

Branching Ratio:

$$\mathcal{BR}\left(\ell \to \ell'\gamma\right) = \frac{\Gamma\left(\ell \to \ell'\gamma\right)}{\Gamma\left(\ell \to \ell'\nu_\ell\overline{\nu}_{\ell'}\right) + \Gamma\left(\ell \to \ell'\gamma\right)}, \qquad \Gamma\left(\ell \to \ell'\gamma\right) = \frac{m_\ell^3}{16\pi^2}\left(|B_L|^2 + |B_R|^2\right)$$

Contributions in DLRSM:

$H_R^\pm$ contribution:

$$B_R^{H_R^\pm} = \frac{e m_\mu}{16\pi^2 m^2_{H_R^\pm}} \sum_{i=1}^{9} \mathcal{K}_{ai}\mathcal{K}^*_{bi} G\left(\frac{m^2_{n_i}}{m^2_{H_R^\pm}}\right)$$

where $\mathcal{K} = V_R^{\ell\dagger} Y U_L$

Loop function:

$$G(t) = \frac{1}{12(t-1)^4}(2t^3 - 6t^2 \log t + 3t^2 - 6t + 1)$$

Limits:

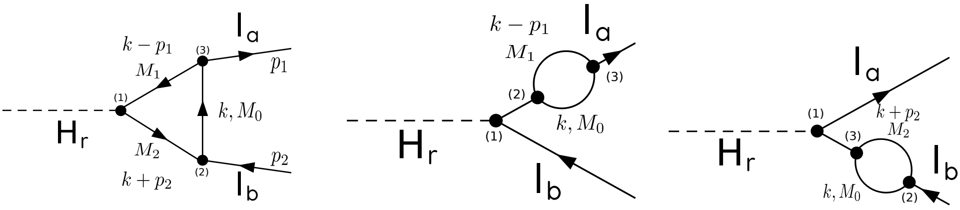
- $t \to 1$: $G(t) \approx \frac{7}{120}$ (constant)
- $t \ll 1$: $G(t) \approx \frac{1}{12}$

W' contribution: Suppressed due to block-diagonal structure of $Q_R = V_R^{\ell\dagger} U_R^*$

Amplitude:

$$\mathcal{M}(h \to \ell_a \ell_b) = -\bar{u}(p_1)[A_L P_L + A_R P_R] v(p_2)$$

One-Loop Topologies:



Contributing Diagrams in DLRSM:

- 28 different one-loop diagrams
- Mediated by: $W^{\pm}$, $W'^{\pm}$, $G^{\pm}_{L,R}$, $H^{\pm}_R$, and neutrinos n_i
- Form factors computed exactly using LoopTools

ATLAS bound: $\mathcal{BR}(h \to \mu\tau) < 0.18\%$[7]

Computational Framework and Parameters

Computational Tools:

- **SARAH:** DLRSM model implementation (available on GitHub)
- **SPheno:** Mass spectrum calculation
- **hep-aid:** MCMC parameter space scan
- **LoopTools:** One-loop integral evaluation

Scalar Potential Benchmark:

$$\rho_1 = 0.6641, \quad \lambda_1 = 6.7478 \qquad \alpha_2 = 4.6905, \quad \alpha_3 = 1.5826$$

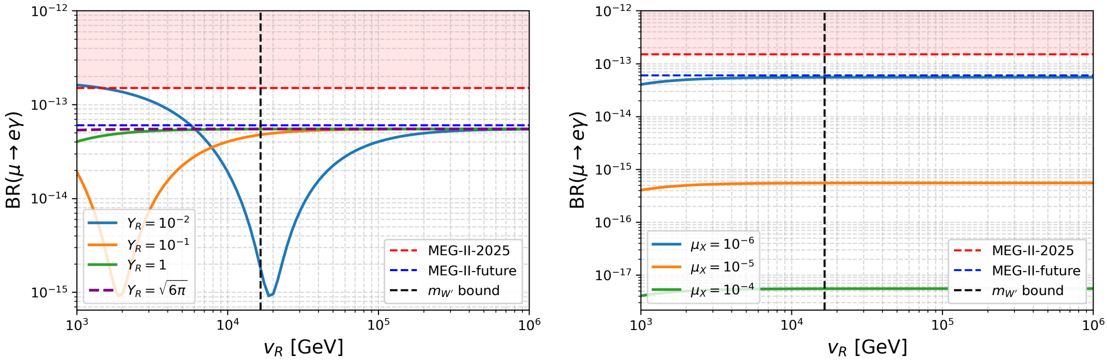
$$\lambda_2 = 3.3884, \quad \alpha_1 = 3.5455 \qquad \Rightarrow m_{H_1^0} \approx 125.20 \pm 0.11 \text{ GeV}$$

Neutrino Parameters:

- Mixing angles and mass differences from NuFIT (Normal Ordering)[8]
- Lightest neutrino: $m_{\nu_1} = 10^{-3}$ eV
- Degenerate heavy neutrinos: $M_i^- \approx M_i^+ = M = \frac{Y_R}{\sqrt{2}} v_R$

Free Parameters: v_R, Y_R, μ_X

Results: $\mu \to e\gamma$ Branching Ratios



Left plot: Fixed $\mu_X = 10^{-6}$ GeV

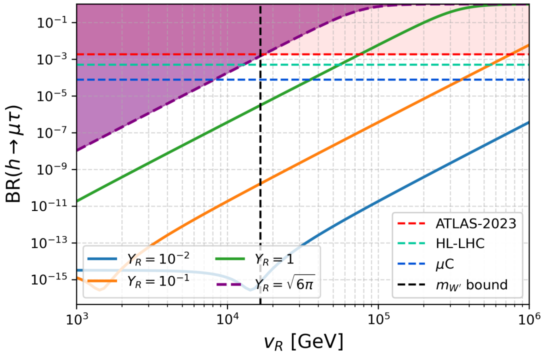
- $\mathcal{BR}$ approaches constant for large v_R (loop saturation)
- Large $Y_R \sim \sqrt{6\pi}$ reaches MEG-II sensitivity

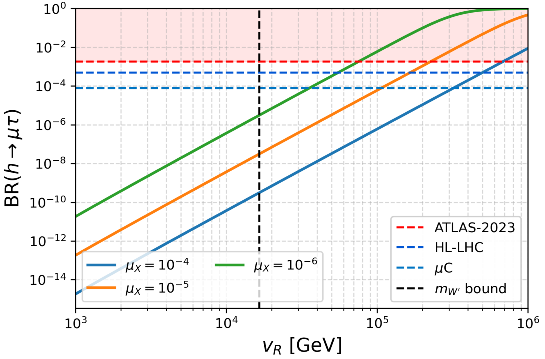
Right plot: Fixed $Y_R = 1$

- Strong dependence on μ_X parameter
- $\mu_X = 10^{-6}$ GeV approaches projected MEG-II sensitivity

Constraint: Vertical line shows CMS bound $m_{W'} > 5.4$ TeV $\Rightarrow v_R > 16.5$ TeV

Results: $h \to \mu\tau$ Branching Ratios





Left plot: Fixed $\mu_X = 10^{-6}$ GeV

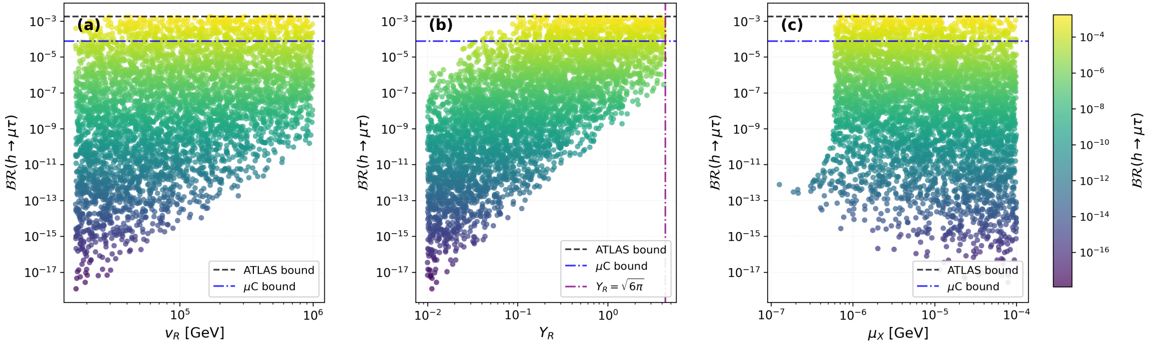
- Highly sensitive to Y_R
- $Y_R = \sqrt{6\pi}$ exceeds HL-LHC and muon collider sensitivities

Right plot: Fixed $Y_R = 1$

- Smaller μ_X significantly enhances $\mathcal{BR}$
- $\mu_X = 10^{-6}$ GeV reaches HL-LHC sensitivity

Reference: Current ATLAS bound and future sensitivities shown for comparison

Parameter Space Correlations



Allowed Parameter Space:

- Constrained by: $\mathcal{BR}(h \to \mu\tau)$, $\mathcal{BR}(\mu \to e\gamma)$, perturbativity ($Y_R < \sqrt{6\pi}$), and $m_{W'} > 5.4$ TeV
- Strong correlation with Y_R (heavy neutrino mass M)
- Moderate correlations with v_R and μ_X

Summary and Outlook

Main Results:

- **Model:** DLRSM + Inverse Seesaw provides minimal framework for LFV
  - More economical than triplet LRSM
  - TeV-scale heavy neutrinos accessible at colliders
- **LFV Signatures:**
  - $\mu \to e\gamma$: Dominated by $H_R^\pm$ loops, sensitive to Y_R and μ_X
  - $h \to \mu\tau$: 28 one-loop diagrams, strong dependence on Y_R
  - Both processes approach experimental sensitivities in viable parameter space
- **Phenomenology:**
  - Experimental bounds: $v_R > 16.5$ TeV from W' searches
  - MEG-II, HL-LHC and μC can probe significant parameter space
  - Complementarity between radiative and Higgs decays

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"

Code available: github.com/moiseszeleny/DLRSM

Backup: Scalar Potential (Minimal Case)

Complete Scalar Potential:

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

Minimal case: $k_2 = v_L = 0$

Backup: Charged Current Interactions

Charged Scalar-Lepton-Neutrino Interactions:

$$
\begin{aligned}
-\mathcal{L}_Y^{\pm} = & \frac{\sqrt{2}}{k_1} G_L^- \bar{\ell}_i \left(T^*_{RL,ji} P_R - m_{\ell_i} Q_{L,ij} P_L \right) n_j \\
& + \frac{\sqrt{2}}{v_R} G_R^+ \bar{n}_j \left[Q^*_{R,ij} m_{\ell_i} P_L - J^*_{ij} P_R \right] \ell_i \\
& + \frac{\sqrt{2}}{k_1} H_R^- \bar{\ell}_i \left(K_{ij} P_L - m_{\ell_i} Q_{R,ij} P_R \right) n_j + \text{h.c.}
\end{aligned}
$$

Key Matrices:

- $K = S_{RL} \approx V_R^{\ell\dagger} m_D U_L \propto k_1$
- $J = T_{SR}^{\dagger} + S_{RL}$ with $T_{SR} \propto v_R$
- LFV couplings arise from neutrino mixing

Backup: Heavy Neutrino Mass Spectrum

Degenerate Case:

$$M_i^- \approx M_i^+ = M = \frac{Y_R}{\sqrt{2}} v_R$$

Non-degenerate Case:

$$M_i^\pm = M_{D_i} \pm \frac{\mu_{ii}}{2}$$

where $M_{D_i} = \frac{v_R}{\sqrt{2}}(Y_R)_{ii}$

Mass Scale:

- For $v_R = 10$ TeV and $Y_R = 1$: $M \approx 7$ TeV
- Perturbativity bound: $Y_R < \sqrt{6\pi} \approx 4.3$
- Heavy neutrinos accessible at future colliders

References

[1] J.C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974).

[2] R.N. Mohapatra and J.C. Pati, Phys. Rev. D **11**, 566 (1975).

[3] P.-H. Gu et al., Phys. Rev. D **81**, 095002 (2010).

[4] V. Brdar and A.Yu. Smirnov, JHEP **02**, 045 (2019).

[5] J.A. Casas and A. Ibarra, Nucl. Phys. B **618**, 171 (2001).

[6] MEG Collaboration, Eur. Phys. J. C **76**, 434 (2016).

[7] ATLAS Collaboration, Phys. Lett. B **800**, 135069 (2020).

[8] I. Esteban et al., JHEP **09**, 178 (2020) [NuFIT].

[9] CMS Collaboration, JHEP **06**, 128 (2018).