Perspectives for Detecting Lepton Flavour Violation in Left-Right Symmetric Models

Toby Opferkuch

Based on arXiv:1611.07025

in collaboration with Cesar Bonilla, Manuel E. Krauss and Werner Porod

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universitätbonn

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Why Left-right Symmetric Models?

Motivation

1. Automatic neutrino masses
   - Combination both type-I and II seesaw

[R. Mohapatra & G. Senjanovic (1979), ...]

2. GUT origin of gauge symmetries

[H. Fritzsch & P. Minkowski (1975), J. Pati & A. Salam (1973), C. Aulakh, et. al. (hep-ph/9712551), ...]

   - $\mathrm{SO}(10) \xrightarrow{M_{\mathrm{GUT}}} (\mathcal{G}_{\mathrm{PS}} \longrightarrow) \, \mathcal{G}_{\mathrm{LR}} \xrightarrow{v_R} \mathcal{G}_{\mathrm{SM}}$

$$\mathcal{G}_{\mathrm{PS}} = \mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$$
$$\mathcal{G}_{\mathrm{LR}} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$$

3. Strong-CP problem

[A. Maiezza & M. Nemevšek (arXiv:1407.3678), ...]

   - Potentially solved by $\mathcal{C}$ & $\mathcal{P}$ restoration

So, what's the plan?

1. Preliminaries
2. Parametrising the neutrino sector
   - Casas-Ibarra parametrisation
   - Our parametrisation
3. Lepton flavour violation results
   - Current and future bounds
   - (Effect of δ_{CP})

Preliminaries

Field content, Yukawa sector and all that jazz!

Quick-fire recap from last time:

$$\mathscr{L}_Y = \mathscr{L}_Y^{\Phi} + \mathscr{L}_Y^{\Delta} + \text{h.c.}$$

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$$-\mathscr{L}_Y^{\Phi} = \overline{Q_L}\left(Y_{Q_1}\Phi + Y_{Q_2}\tilde{\Phi}\right)Q_R + \overline{L_L}\left(Y_{L_1}\Phi + Y_{L_2}\tilde{\Phi}\right)L_R$$

Field	Gen.	$\mathcal{G}_{LR}$
Q_L	3	$(\mathbf{3},\mathbf{2},\mathbf{1},\frac{1}{3})$
Q_R	3	$(\mathbf{3},\mathbf{1},\mathbf{2},\frac{1}{3})$
L_L	3	$(\mathbf{1},\mathbf{2},\mathbf{1},-1)$
L_R	3	$(\mathbf{1},\mathbf{1},\mathbf{2},-1)$
Φ	1	$(\mathbf{1},\mathbf{2},\mathbf{2},0)$

$$\tilde{\Phi} \equiv -\sigma_2\Phi^*\sigma_2$$

$$\overline{\Psi^C} = \Psi^T C\,, \qquad C = i\gamma_2\gamma_0$$

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$\hookrightarrow$ `SARAH` model file publicly available

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Determining the Neutrino Sector

Neutrino Masses

Neutrino mass matrix from $\mathscr{L}_Y$

$$\mathcal{M}_\nu = \begin{pmatrix} M_L^* & M_D \\ M_D^T & M_R \end{pmatrix}$$

$$M_{L/R} = \sqrt{2}\, Y_{\Delta_{L/R}} v_{L/R}$$

$$M_D = \frac{1}{\sqrt{2}} \left(Y_{L_1} v_1 + Y_{L_2} v_2 \right)$$

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In the seesaw approximation

$$m_\nu^{\text{light}} = U^*_{\text{PMNS}} \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) U^\dagger_{\text{PMNS}} \stackrel{!}{=} \left(M_L^* - M_D\, M_R^{-1}\, M_D^T \right)$$

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How to determine model parameters?

- Casas-Ibarra parametrisation
- Brute force fits
- Our parametrisation

Casas-Ibarra parametrisation

Simple procedure to find M_D:

$$M_D = f(m_\nu^{\text{light}}, M_L, M_R, R)$$

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$$\Rightarrow \quad \mathbb{1} = \underbrace{\left[i D_{X_\nu}^{-1/2} V^T M_D O D_{M_R}^{-1/2} \right]}_{\equiv R} \underbrace{\left[i D_{M_R}^{-1/2} O^T M_D^T V D_{X_\nu}^{-1/2} \right]}_{\equiv R^T}$$

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Using the above expression we can than determine M_D as required

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Implications:

- R is an unknown matrix $\in \mathrm{O}(3;\mathbb{C})$
- Unrelated to model parameters
- Potentially violates $\mathcal{C}$ & $\mathcal{P}$
- Results in an infinite number of degenerate solutions

Discrete symmetries

Parity $\mathcal{P}$:

$$\left.\begin{array}{l} L_L \leftrightarrow L_R \\ \Delta_L \leftrightarrow \Delta_R \\ \Phi \leftrightarrow \Phi^\dagger \end{array}\right\} \xrightarrow{\mathscr{L}\text{ inv.}} \left\{\begin{array}{l} Y_{Q_i} = Y_{Q_i}^\dagger \\ Y_{L_i} = Y_{L_i}^\dagger \\ Y_{\Delta_L} = Y_{\Delta_R} \end{array}\right.$$

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Charge-conjugation $\mathcal{C}$:

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Consequence:

$$m_\nu^{\text{light}} \overset{\mathcal{P}}{=} \left(\frac{v_L}{v_R} M_R^* - M_D\, M_R^{-1}\, M_D^*\right)$$

$$m_\nu^{\text{light}} \overset{\mathcal{C}}{=} \left(\frac{v_L}{v_R} M_R - M_D\, M_R^{-1}\, M_D\right)$$

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Direct algebraic solutions

$$Y_\Delta \equiv Y_{\Delta_L}^{(*)} = Y_{\Delta_R} = f(M_D, v_L, v_R)$$

[E. Akhmedov and M. Frigerio (hep-ph/0509299)]

Our parametrisation

$\mathcal{C}$-conserving case re-written as:

$$\begin{aligned} B &= \alpha A - A^{-1} \\ &= V^* \left(\alpha D_A - D_A^{-1} \right) V^\dagger \end{aligned}$$

$$B \equiv M_D^{-1/2} m_\nu^{\text{light}} M_D^{-1/2}, \quad \alpha \equiv \frac{v_L}{v_R}$$

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Diagonalise and solve resulting diagonal polynomial matrix equations

$$D_A^{(i,i)} = \frac{D_B^{(i,i)} \pm \sqrt{\left(D_B^{(i,i)}\right)^2 + 4\alpha}}{2\alpha}$$

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Result

$$Y_\Delta^{(\pm\pm\pm)} = \frac{1}{2\sqrt{2}v_L} M_D^{1/2} V^* \text{diag}\left(D_B^{(i,i)} \pm \sqrt{\left(D_B^{(i,i)}\right)^2 + 4\alpha}\right) V^\dagger M_D^{1/2}$$

Advantages:

1. Eightfold degenerate solutions
2. Function only of model parameters

Lepton Flavour Violation

Lepton flavour observables

Calculated observables:

- $\ell_\alpha \to \ell_\beta \gamma$
- $\ell_\alpha \to 3\ell_\beta$
- $\ell_\alpha \to \ell_\beta \ell_\gamma \ell_\delta$
- $\mu - e$ conversion

Including all tree and one-loop contributions

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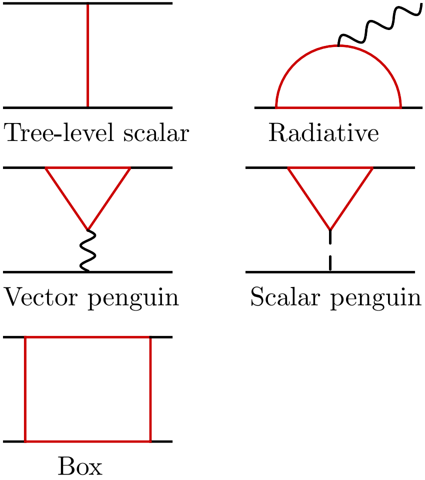
Example Topologies



Lepton flavour observables

Key Parameters (As a result of the parametrisation)

- v_L
- δ_{CP}
- M_D
  - (*i*) $x\mathbb{1}$ GeV
  - (*ii*) $xM_{\text{up-type}}$
  - (*iii*) $xV^{\dagger}_{\text{CKM}}M_{\text{up-type}}V^{*}_{\text{CKM}}$
- Y_{Δ}
  - (*i*) $Y_{\Delta}^{(+++)}$
  - (*ii*) $Y_{\Delta}^{(+-+)}$

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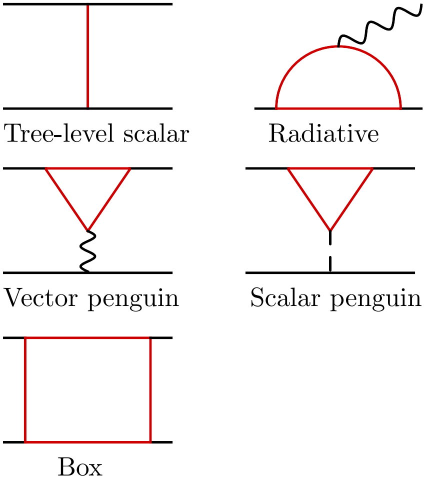
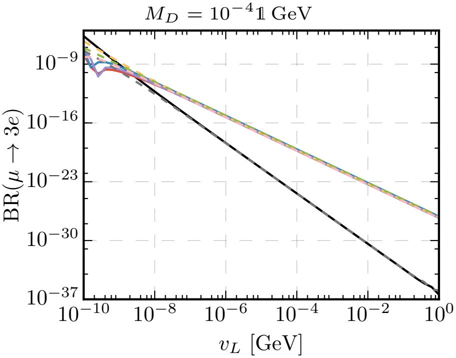
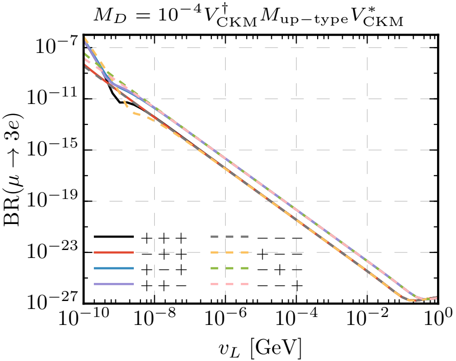


Triplet-Yukawa sign-choice

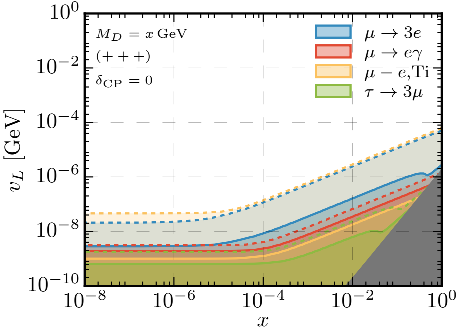




- Sufficient to consider **only** two choices

Current and Future Bounds

Diagonal M_D



LFV Process	Present Bound	Future Sensitivity
$\mu \to e\gamma$	4.2×10^{-13}	6×10^{-14}
$\mu \to 3e$	1.0×10^{-12}	$\sim 3 \times 10^{-16}$
$\tau \to 3\mu$	2.1×10^{-8}	$\sim 4 \times 10^{-10}$
$\mu^- \to e^-$, Ti	4.3×10^{-12}	$\sim 10^{-18}$

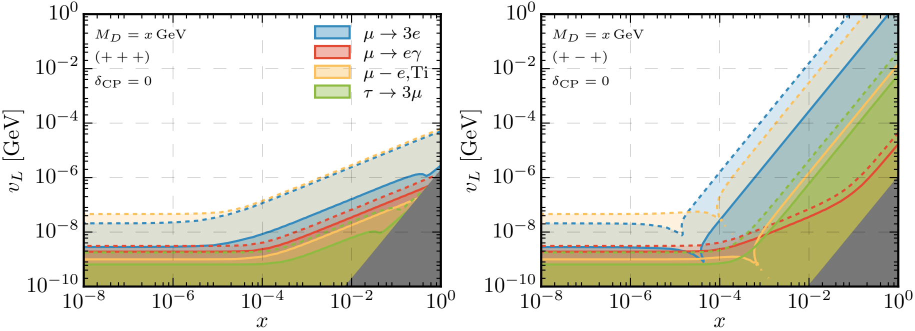
- Scalar tree-level contributions dominate
- Off-diagonal Y_Δ vanish at LO

$$D_B = \frac{m_\nu^{\rm light}}{M_D} \ll \mathcal{O}\left(\sqrt{\alpha}\right)$$

$$\Rightarrow \; D_A \simeq \pm\alpha^{-1/2}$$

$$\hookrightarrow A^{(+++)} = V D_A V^T = D_A$$

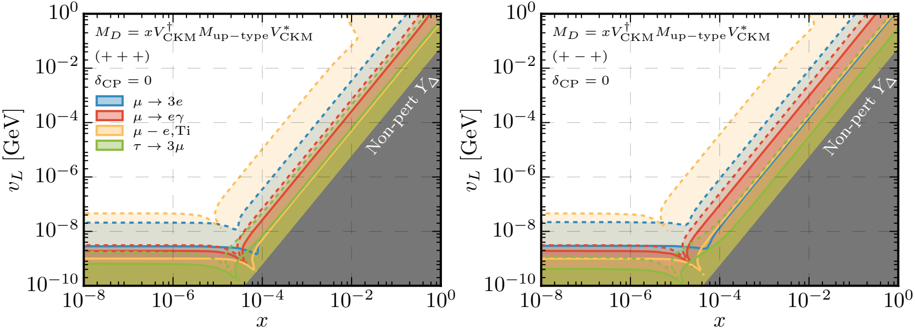
Diagonal M_D



- Scalar tree-level contributions again dominate
- Off-diagonal Y_Δ **<u>do not</u>** vanish at LO

$$A^{(+-)} = V \begin{pmatrix} \alpha^{-1/2} & 0 \\ 0 & -\alpha^{-1/2} \end{pmatrix} V^T = \alpha^{-1/2} \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \neq D_A$$

$M_D = V_{\text{CKM}}^{\dagger} M_{\text{up-type}} V_{\text{CKM}}^{*}$



- Additonal flavour violation from CKM elements
- Large hierarchy in Y_Δ
- Interplay between γ-penguins and tree-level scalar contributions
  Example $\mu \to 3e$:

$$\mathcal{M}_{\text{tree-level}} \propto Y_\Delta^{(2,1)} Y_\Delta^{(1,1)} \qquad \mathcal{M}_{\gamma-\text{peng}} \propto \frac{1}{16\pi^2} \sum_i Y_\Delta^{(2,i)} Y_\Delta^{(i,1)}$$

Conclusions

1. Exploited discrete left-right symmetries to simplify neutrino sector

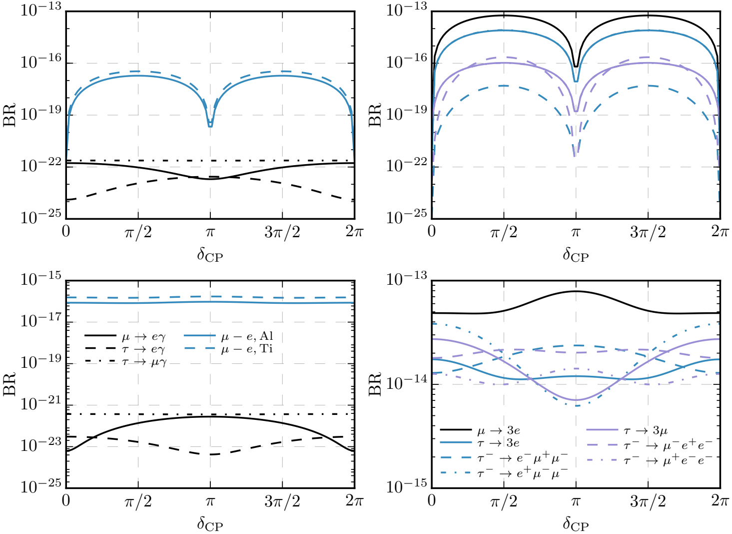
2. Examined current constraints and prospects of probing low-scale left-right symmetries using LFV observables

   Also investigated:

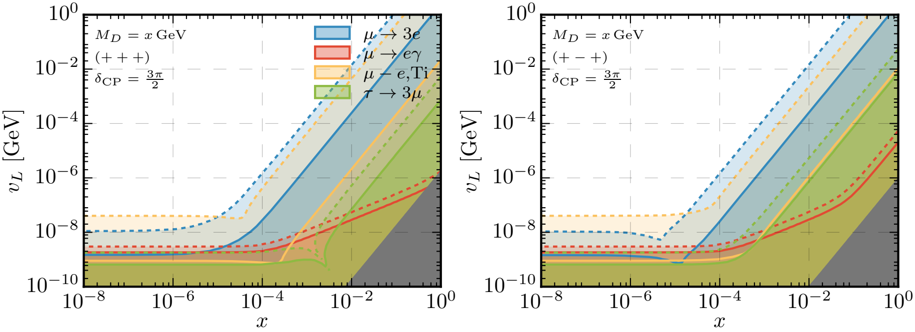
   - Varying scalar masses
   - Neutrino hierarchy & mass scale
   - Varying δ_{CP}

Backup Slides

Effect of δ_{CP}



EFFECT OF δ_{CP}



- For both sign choices off-diagonal Y_Δ **do not** vanish at LO

$$A^{(+-)} = V^* D_A V^\dagger \neq D_A$$

Scalar Sector

Field content

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} \qquad \Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix} \qquad \Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix}$$

with VEVs

$$\phi_1^0 = \frac{1}{\sqrt{2}}\left(v_1 + \sigma_1 + i\varphi_1\right) \qquad \delta_L^0 = \frac{1}{\sqrt{2}}\left(v_L + \sigma_L + i\varphi_L\right)$$

$$\phi_2^0 = \frac{1}{\sqrt{2}}\left(v_2 + \sigma_2 + i\varphi_2\right) \qquad \delta_R^0 = \frac{1}{\sqrt{2}}\left(v_R + \sigma_R + i\varphi_R\right)$$

Scalar Masses

Bi-doublet/SM-like masses

$$m_h^2 \simeq 2\lambda_1 v^2 - \frac{8\lambda_4^2 v^4}{\alpha_3 v_R^2} \qquad m_H^2 \simeq 2(2\lambda_2 + \lambda_3)v^2 + \frac{\alpha_3}{2} v_R^2$$

$$m_A^2 \simeq 2\alpha_3 v_R^2 + 2(\lambda_3 - 2\lambda_2)v^2 \qquad m_{H^\pm}^2 \simeq \frac{1}{4}\alpha_3(v^2 + 2v_R^2)$$

Left/right triplet masses

$$m_{H_L}^2 \simeq \frac{1}{2}\left(\rho_3 - 2\rho_1\right) v_R^2 \qquad m_{H_R}^2 \simeq 2\rho_1 v_R^2$$

$$m_{A_L}^2 \simeq \frac{1}{2}(\rho_3 - 2\rho_1)v_R^2 \qquad m_{H_L^\pm}^2 \simeq \frac{1}{2}v_R^2(\rho_3 - 2\rho_1)\,,$$

$$m_{H_1^{\pm\pm}}^2 \simeq 2\rho_2 v_R^2 + \frac{1}{2}\alpha_3 v^2 \qquad m_{H_2^{\pm\pm}}^2 \simeq \frac{1}{2}\left((\rho_3 - 2\rho_1)v_R^2 + \alpha_3 v^2\right)$$

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$\tau \to eee$	2.7×10^{-8}	$\sim 5 \times 10^{-10}$
$\tau \to \mu\mu\mu$	2.1×10^{-8}	$\sim 4 \times 10^{-10}$
$\tau^- \to e^-\mu^+\mu^-$	2.7×10^{-8}	$\sim 5 \times 10^{-10}$
$\tau^- \to \mu^-e^+e^-$	1.8×10^{-8}	$\sim 3 \times 10^{-10}$
$\tau^- \to \mu^+e^-e^-$	1.5×10^{-8}	$\sim 3 \times 10^{-10}$
$\tau^- \to e^+\mu^-\mu^-$	1.7×10^{-8}	$\sim 3 \times 10^{-10}$
$\mu^- \to e^-, \mathrm{Ti}$	4.3×10^{-12}	$\sim 10^{-18}$
$\mu^- \to e^-, \mathrm{Au}$	7×10^{-13}	-
$\mu^- \to e^-, \mathrm{Al}$	-	$10^{-16} - 3 \times 10^{-17}$
$\mu^- \to e^-, \mathrm{SiC}$	-	10^{-14}

Model Parameters and Mass Spectrum

Model Parameters			
λ_1	0.13	v_L	10^{-10}... 1 GeV
λ_2	1.0	v_R	20 TeV
λ_3	1.0	$\tan\beta$	10^{-4}
λ_4	0	α_1	0
ρ_1	3.2×10^{-4}	α_2	0
ρ_2	2.5×10^{-4}	α_3	2.0
ρ_3	1.8×10^{-3}	β_1	0
ρ_4	0	β_2	3.83×10^{-4}
μ_1^2	7.87×10^3 GeV^2	β_3	0
μ_2^2	-2.00×10^4 GeV^2	μ_3^2	1.28×10^5 GeV^2
Resulting Mass Spectrum			
m_h	125.5 GeV	m_H	20 TeV
m_A	20 TeV	$m_{H^\pm}$	20 TeV
m_{H_L}	482 GeV	m_{H_R}	506 GeV
m_{A_L}	482 GeV	$m_{H_L^\pm}$	512 GeV
$m_{H_1^{\pm\pm}}$	511 GeV	$m_{H_2^{\pm\pm}}$	541 GeV
M_{W_R}	9.37 TeV	M_{Z_R}	15.7 TeV