

Lepton-flavour violation in a Pati-Salam model with gauged flavour symmetry

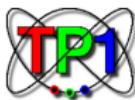
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Theoretische Physik 1
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Outline:

- Introduction
- The model
- LFV in Pati-Salam models



Charged Lepton-Flavour Violation

- Charged radiative lepton decays

$$\mu \rightarrow e\gamma \text{ & } \tau \rightarrow \mu\gamma \dots$$

- Decay into three leptons

$$\mu \rightarrow 3e \text{ & } \tau \rightarrow 3\mu \dots$$

- Lepton conversion in nuclei

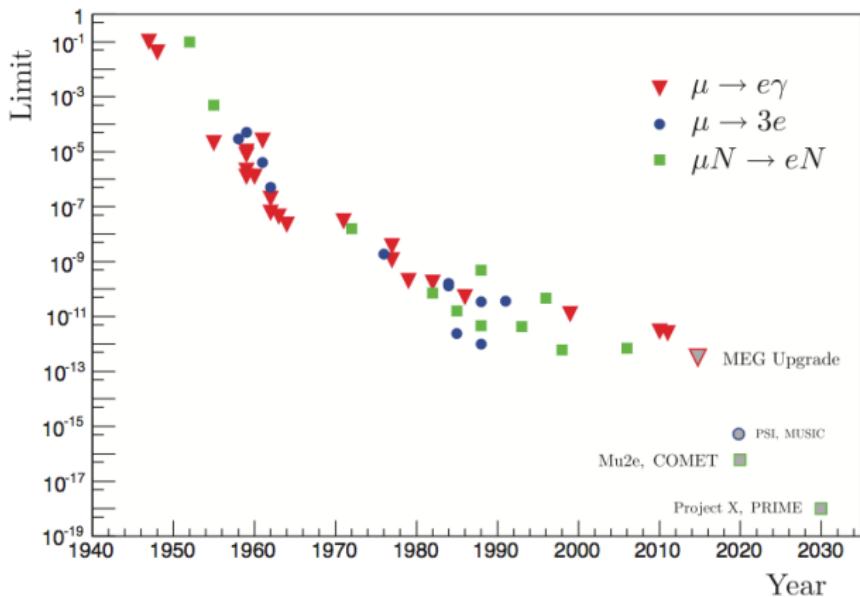
$$N\mu \rightarrow Ne$$

Tiny Branchingratios after neutrino mass inclusion into the SM

$$\text{BR}(\mu \rightarrow e\gamma)_{\text{theo}} \sim 10^{-54} \quad \text{BR}(\mu \rightarrow e\gamma)_{\text{exp}} < 4.2 \cdot 10^{-13}$$

Experimental signal → high indication of beyond SM physics

65 Years Of Searches



- Future upgrades with measurement starting dates around 2020 will allow multi TeV scans for additional signs of new physics.

Strategy: Effective Field Theory

- New physic model with distinct hierarchy $\Lambda_{\text{NP}} \gg v \gg \underbrace{m_\ell}_{IR}$
- Integrate out the NP degrees of freedom by matching onto an $SU(3) \times SU(2) \times U(1)_Y$ invariant Lagrangian at a scale $\Lambda_{\text{NP}} \gg \mu \gg v$:
- Relevant dim. six operators for $\mu \rightarrow e\gamma$ include

$$\mathcal{L}_{\text{NP}} \rightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}^2} \sum_i C_i \mathcal{O}_i$$

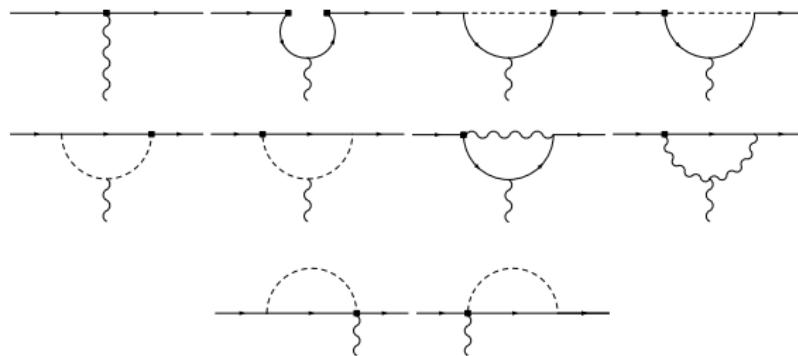
$$\begin{aligned} \sum_i C_i \mathcal{O}_i \supset & a_{B,ij} \bar{L}_i \Phi \sigma_{\mu\nu} E_j B^{\mu\nu} + a_{W,ij} \bar{L}_i \tau^a \Phi \sigma_{\mu\nu} E_j W^{a,\mu\nu} && \text{Dipole Operators} \\ & + b_{LE,ij} (\bar{L}_i \gamma^\mu L_i) (\bar{E}_j \gamma_\mu E_j) + c_{1,i} (\bar{E}_i \gamma_\mu E_i) (\Phi^\dagger i D^\mu \Phi) \\ & + c_{2,i} (\bar{L}_i \gamma_\mu L_i) (\Phi^\dagger i D^\mu \Phi) + c_{3,i} (\bar{L}_i \gamma^\mu \tau^a L_i) (\Phi^\dagger i \overleftrightarrow{\tau^a D_\mu} \Phi) && \text{Tree Operators} \\ & + \dots \end{aligned}$$

[W. Buchmüller, D. Wyler]

EFT After EWSB(Lepton Sector)

$$\Phi \rightarrow \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\nu + H + iG) \end{pmatrix} \quad E \rightarrow V\psi_R, \quad L \rightarrow U \begin{pmatrix} \nu_L \\ \psi_L \end{pmatrix}$$

- Diagram set for radiative charged lepton decay



- Find lower bounds on Wilson coefficients [A. Crivellin, M. Hoferichter, M. Procura (2014)]
- Determine the Wilson coefficients with specific NP models

Pati-Salam Models: Introduction

Flavour symmetry of the standard model:

without Yukawas

- only “kinetic” terms for quarks and leptons
 $\bar{\psi}_i \mathcal{D}_\mu \gamma^\mu \psi_i \quad (i = 1, 2, 3)$
- invariant under global unitary transformations in flavour space

$$G_F = U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R} \times U(3)_{L_L} \times U(3)_{E_R}$$

promote Yukawas as matrix-valued fields

- Yukawas transform as bi-triplets of G_F
e.g. $\frac{1}{\Lambda} H \bar{Q}_L Y_u U_R \rightarrow Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1})$
- standard model Yukawa matrices given by the VEV
e.g. $y_u = \frac{1}{\Lambda} \langle Y_u \rangle$

→ Minimal flavour violation [Grinstein, Redi, Villadoro (2010)]

Pati-Salam Models: Introduction

- Yukawa terms non-renormalisable
 - e.g. $\frac{1}{\Lambda} H \bar{Q}_L Y_u U_R$
- UV completion requires new particles

- spontaneous breaking of G_F yields massless Goldstone modes . . .

. . . unless flavour symmetry is gauged

- constraints from gauge anomalies
- phenomenology of extra fermions, scalars and flavour gauge bosons

Motivation for Pati-Salam GUT

$$SU(4) \times SU(2) \times SU(2)'$$

- Possible formulation in a manifestly left-right symmetric way.
- Leptons as 4th colour.– Right-handed neutrinos.
- PS scenarios with extended field content may realise gauge-coupling unification in a non-trivial way, without invoking SUSY.

Symmetries

- Pati-Salam Gauge Group(contains SM)

$$\begin{array}{ccc} SU(4) \times \underbrace{SU(2) \times SU(2)'}_{\downarrow} & & \\ & & \downarrow \\ & & SU(3)_c \times SU(2)_L \times U(1)_Y \end{array}$$

- Flavour Symmetry (gauged):

$$SU(3)_I \times SU(3)_{II}$$

- Explicit Left-Right Symmetry:

$$\mathbb{Z}_2 : \begin{cases} SU(2) \leftrightarrow SU(2)' \\ SU(3)_I \leftrightarrow SU(3)_{II} \end{cases}$$

Scalars and VEVs

- Higgs Bi-Doublet(flavour-neutral)

$$H \quad \text{VEVs} : v_u, v_d \sim \mathcal{O}(100 \text{ GeV})$$

- PS Singlets and Triplets(flavour bi- triplets)

$$S, T \quad \text{VEVs} : sM, tM \gg \mathcal{O}(500 \text{ GeV})$$

$$T' \quad \text{VEVs} : t'M \sim 0$$

- $SU(4)$ Adjoints(flavour bi- triplets)

$$S_{15}, T'_{15} \quad \text{VEVs} : sM, t'M \gg \mathcal{O}(500 \text{ GeV})$$

$$T_{15} \quad \text{VEVs} : t_{15}M \sim 0$$

- Scalars for the Majorana Sector $\sim \mathcal{O}(M_{\text{GUT}})$

- Dirac Mass term $M \sim \mathcal{O}(500 \text{ GeV})$

The Yukawa Lagrangian

- Quarks and charged leptons:

$$\begin{aligned}\mathcal{L}_{\text{Yuk}}^{q,\ell} = & \bar{q}_L \lambda \textcolor{red}{H} \Sigma_R + \bar{\Sigma}_L (\textcolor{blue}{S} + T + T' + T'_{15}) \Sigma_R + \textcolor{red}{M} \bar{\Sigma}_L q_R + \text{h.c.} \\ & \bar{q}_L \lambda \textcolor{red}{H} \Sigma'_L + \bar{\Sigma}'_L (\textcolor{blue}{S} + T + T' + T'_{15}) \Sigma_R + \textcolor{red}{M} \bar{\Sigma}_L q_R + \text{h.c.}\end{aligned}$$

- For charged fermions $\rightarrow 9 \times 9$ mass matrices in 3×3 block form:

$$M^u = \begin{pmatrix} 0 & \lambda \epsilon_u & 1 \\ 1 & (s + t')_u & 0 \\ \lambda_u & 0 & s_u \end{pmatrix} M$$

with $\epsilon_{u,d}(\ell) = v_{u,d}/M$ and

$$(s + t')_{u,d} = (s + t') \pm (t' + t'_{15}), \quad (s + t')_\ell = (s - 3s_{15}) - (t' - 3t_{15})$$

- Up-and down-type quarks distinguished by sign of $SU(2)'$ triplet VEVs.
- Charged leptons and quarks distinguished by pre-factor of $SU(4)$ 15-plets

Effective Yukawa Matrices for charged Fermions

First approximation: Neglect mixing between heavy fermions.

- Quarks

$$Y_U \sim -\lambda \left[\frac{1}{(s+t)_u} + \frac{1}{s_u} \right] \quad Y_D \sim -\lambda \left[\frac{1}{(s+t)_d} + \frac{1}{s_d} \right]$$

- Charged Leptons

$$Y_L \sim -\lambda \left[\frac{1}{(s+t)_l} + \frac{1}{s_l} \right]$$

- Relation between the Y_x and the s_i, t_i not invertible

Numerical solution non-trivial due to large hierachies in eigenvalues and mixing angles.

→ Sophisticated Numerical Scan

Features/Comments

- Generic breaking of the Flavour and Pati-Salam symmetries near the GUT scale
New heavy bosons negligible for low- energy phenomenology!
- Scalar potential not **specified explicitly written**. (Ongoing project with simpler Flavour gauge groups)
- low- energy phenomenology dominated by contributions of the new heavy fermions (**$m > \text{LHC reach}$**)

$$\begin{aligned}\mathcal{L}_{\text{LFV}} = & \frac{g}{2 c_W} \left(\Delta g_{Z\bar{\ell}_L \ell_L}^{ij} Z^\mu (\bar{\ell}_i \gamma_\mu P_L \ell_j) - \Delta g_{Z\bar{\ell}_R \ell_R}^{ij} Z^\mu (\bar{\ell}_i \gamma_\mu P_R \ell_j) \right) \\ & - \frac{g}{\sqrt{2}} \Delta g_{W\bar{\nu}_L \ell_L}^{ij} W^{+\mu} (\bar{\nu}_i \gamma_\mu P_L \ell_j) + \text{h.c.} \\ & + \frac{3}{2} \Delta g_{h\bar{\ell}\ell}^{ij} \frac{h}{\sqrt{2}} (\bar{\ell}_i P_R \ell_j) + \frac{1}{2} \Delta g_{h\bar{\ell}\ell}^{ij} \frac{v}{\sqrt{2}} (\bar{\ell}_i P_R \ell_j) + \text{h.c.}\end{aligned}$$

- NP effects suppressed by $\epsilon_{u,d} = \frac{v_{u,d}}{M}$

Low-energy Phenomenology in the Lepton Sector: Parameters

- All anomalous couplings analytic functions of the matrix $\textcolor{blue}{s}_\ell$

$$\Delta g_{Z\bar{\ell}_L \ell_L} = \left[\frac{\sqrt{2}\hat{M}^\ell}{\lambda v_d} + \textcolor{blue}{s}_l^{-1} \right] \left[\frac{\sqrt{2}\hat{M}^\ell}{\lambda v_d} + \textcolor{blue}{s}_l^{-1} \right]^\dagger \lambda^2 \epsilon_d^2 ,$$

$$\Delta g_{Z\bar{\ell}_R \ell_R} = [\textcolor{blue}{s}_l^{-1}]^\dagger [\textcolor{blue}{s}_l^{-1}] \lambda^2 \epsilon_d^2 ,$$

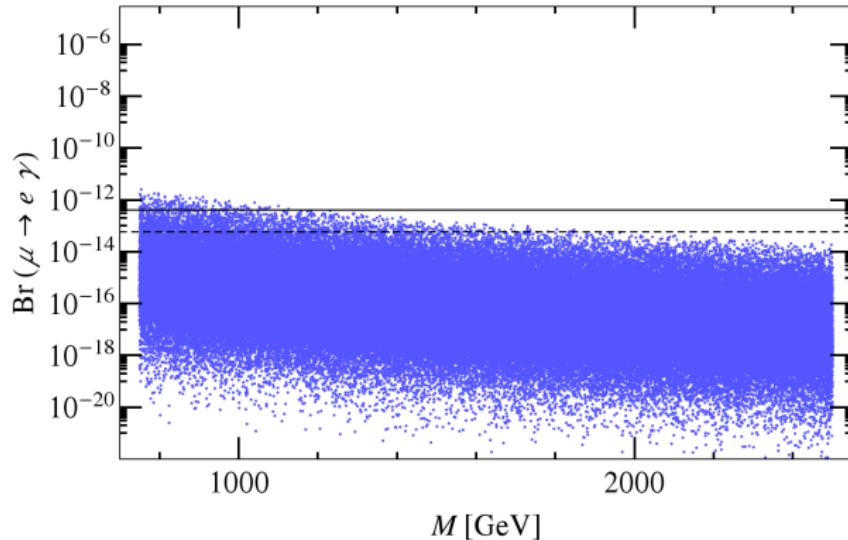
$$\Delta g_{W\bar{\nu}_L \ell_L} = \frac{1}{2} \left[\frac{\sqrt{2}\hat{M}^\ell}{\lambda v_d} + \textcolor{blue}{s}_l^{-1} \right] \left[\frac{\sqrt{2}\hat{M}^\ell}{\lambda v_d} + \textcolor{blue}{s}_l^{-1} \right]^\dagger \lambda^2 \epsilon_d^2 .$$

- All anomalous couplings are hermitian up to order ϵ_d^2
→ contributions to the electron EDM parametrically suppressed.

Low-energy Phenomenology in the Lepton Sector: Parameter Scan

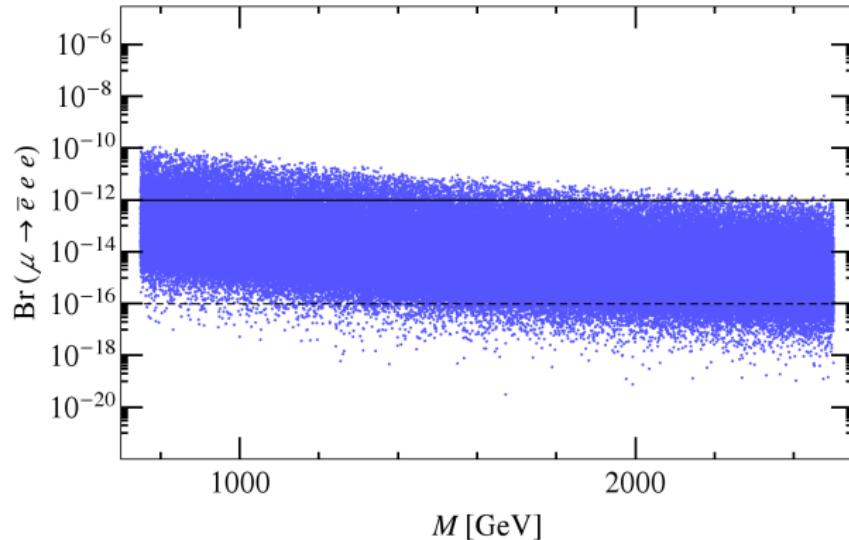
- Scan 1:
 - Choose again $\beta \in [1, 15]$, $\lambda \in [1.5, 3]$, $M \in [750, 2000]$ GeV.
 - Restrict singular values of flavon matrix s_ℓ to avoid fine-tuned solutions.
 - Arbitrary mixing angles and phases for rotation matrices.
- Scan 2:
 - Fix $M = 1$ TeV and define two parameter sets:
 1. Arbitrary mixing angles.
 2. Small mixing angles in rotation matrices (smaller than $\pi/6$ for standard CKM convention).
 - $\mathcal{O}(200.000)$ parameter points for each scan strategy.

Lepton Flavour Violation: $\mu \rightarrow e\gamma$



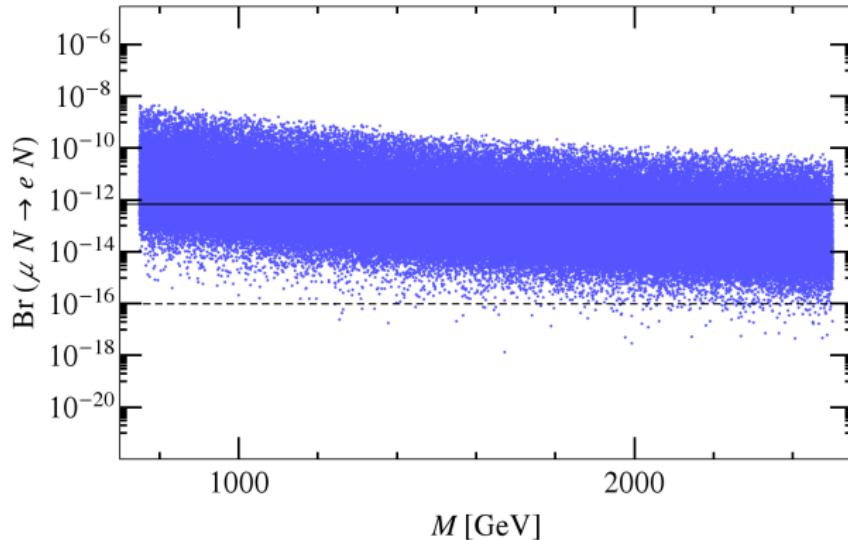
- Most parameter points compatible with present and future bounds.

Lepton Flavour Violation: $\mu \rightarrow 3e$



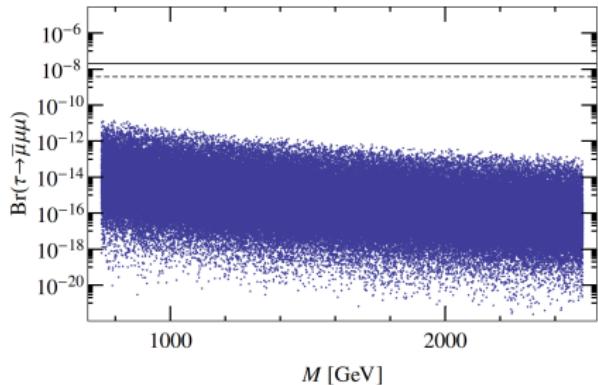
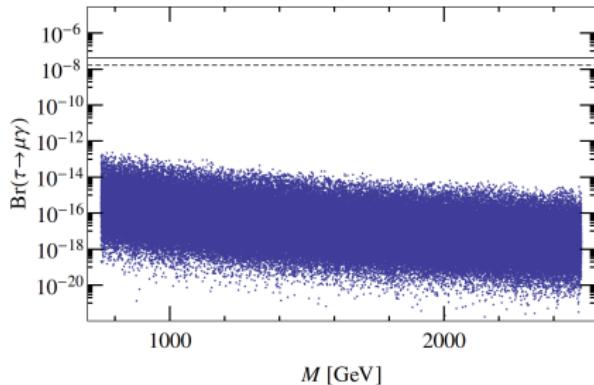
- Possible LFV signals at future experiments.

Lepton Flavour Violation: $\mu N \rightarrow e N$



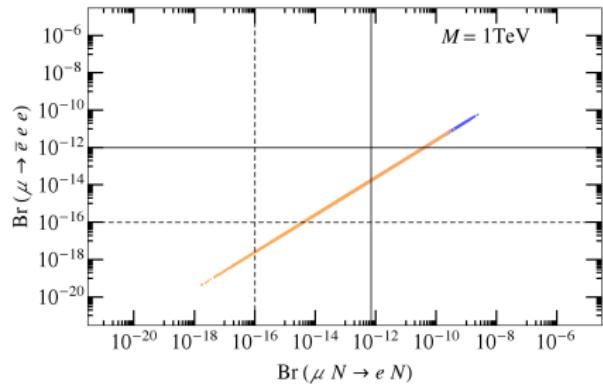
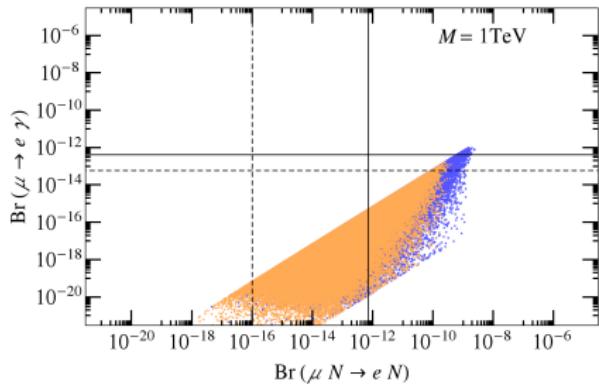
- Possible LFV signals at future experiments

Lepton Flavour Violation: $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow 3\mu$



- Signals not expected for $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow 3\mu$ at CEPC.

Lepton Flavour Violation: Correlations for $M = 1 \text{ TeV}$



- $\mu \rightarrow 3e$ and $N \mu \rightarrow N \mu$ strongly correlated, due to similar tree-level contributions.
- Orange points represent models with lower flavour changing mixing angle contributions in the generation of mass matrices.

Conclusions

$$[SU(4) \times SU(2) \times SU(2)'] \times [SU(3)_I \times SU(3)_{II}]$$

- Horizontal and vertical unification with dynamical symmetry breaking
- Future charged LVF signals possible for muonic decays mediated via tree-level decays
- Charged LVF via similar τ decays at least three magnitudes below current limits
- Muon g-2 and electric dipole moments contributions of the Pati-Salam model too small

Current Project

- Simplified flavour model with a distinguished third generation using bottom up approach.