

Lepton flavour violating lepton decays in the supersymmetric inverse seesaw

PRD90 (2014) 013008 and IFT-UAM/CSIC-14-061

Cédric Weiland

in collaboration with A. Abada, M. E. Krauss, W. Porod, F. Staub and A. Vicente

Instituto de Física Teórica, Universidad Autónoma de Madrid/CSIC, Spain

SUSY 2014

University of Manchester, July 25th, 2014



Neutrino masses and lepton flavour violation

- $P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} \neq 0$ only if $\Delta m_{kj}^2 = m_k^2 - m_j^2$ and $U_\nu \neq \mathbb{1}$
- SM: no ν mass term, lepton flavour is conserved
⇒ need new Physics, e.g. seesaw mechanism
- Neutrino oscillations ⇒ neutral lepton flavour violation. Why not charged lepton flavour violation (cLFV) ?
- cLFV arises from higher order processes:
negligible in the SM
- If observed:
 - Evidence of New Physics
 - Might probe the origin of lepton mixing
 - Might probe the origin of new physics



cLFV

- **Complementary** to other New Physics searches

- High energy: LHC
- High intensity:
 - B factories: Rare decays, etc
 - Neutrino dedicated experiments: U_{PMNS} non-unitarity, NSI, etc
 - Other low energy experiments: $(g-2)_\mu$, EDM, LUV, etc

- Can occur in many channels

- **Radiative decays**, e.g. $\text{Br}(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]
- **3-body lepton decays**, e.g. $\text{Br}(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8}$ [Belle, 2010]
- **$\mu - e$ conversion**, e.g. $\text{CR}(\mu \rightarrow e, \text{Au}) < 7 \times 10^{-13}$ [SINDRUM II, 2006]
- **Meson decays**, e.g. $\text{Br}(B_d^0 \rightarrow e\mu) < 2.8 \times 10^{-9}$ [LHCb, 2013]
- **Z decays**, e.g. $\text{Br}(Z^0 \rightarrow e\mu) < 1.7 \times 10^{-6}$ [OPAL, 1995]
- **Higgs decays**, e.g. $\text{Br}(H \rightarrow \tau\mu) < 1.57\%$ [CMS-PAS-HIG-14-005]

Why supersymmetry?

- The SM doesn't only lack neutrino masses, e.g. the hierarchy problem
- Extended frameworks to address SM issues:
 - Strongly coupled theories (e.g. Technicolor, Composite Higgs)
 - Extra-dimensions (e.g. Randall-Sundrum, Large extra dimension)
 - Extending the SM field content/gauge group (e.g. 2HDM, Little Higgs, GUT)
 - Supersymmetric extensions (e.g. [MSSM](#))
- Advantages of SUSY
 - Most general extension of the Poincaré algebra
 - Gauge coupling unification
 - Dark matter candidate
 - Graviton naturally appears in local supersymmetry



Supersymmetric seesaw models

- No ν_R in the MSSM \Rightarrow Massless neutrinos
 \rightarrow Implement a seesaw mechanism
- Seesaw mechanism: Consider new fields at this scale ($\sim M_R$) and Majorana mass terms \Rightarrow Generate m_ν in a **renormalizable** way
- **Unique** dimension 5 operator for all seesaw mechanisms
 \rightarrow Violates lepton number L \Rightarrow **Majorana neutrinos**

$$\delta\mathcal{L}^{d=5} = \frac{1}{2} c_{ij} \frac{\bar{L}_i \tilde{H} \tilde{H}^T L_j^C}{\Lambda} + \text{h.c.}$$

- To distinguish the several seesaw mechanisms, either
 - Directly produce the heavy states (LHC, future collider)
 - Look for dimension ≥ 6 operators effects \rightarrow **cLFV**



The inverse seesaw mechanism

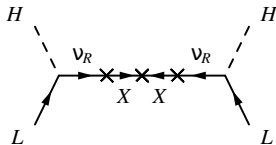
- Inverse seesaw \Rightarrow Consider fermionic gauge singlets ν_{Ri} ($L = +1$) and X_i ($L = -1$) [Mohapatra and Valle, 1986]

$$\mathcal{L}_{inverse} = -Y_{\nu}^{ij} \bar{L}_i \tilde{H} \nu_{Rj} - M_R^{ij} \bar{\nu}_{Ri}^C X_j - \frac{1}{2} \mu_X^{ij} \bar{X}_i^C X_j + \text{h.c.}$$

$$\text{with } m_D = Y_{\nu} v, M^{\nu} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

$$m_{\nu} \approx \frac{m_D^2 \mu_X}{m_D^2 + M_R^2}$$

$$m_{N_{1,2}} \approx \mp \sqrt{m_D^2 + M_R^2} + \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)}$$



2 scales: μ_X and M_R

The supersymmetric inverse seesaw model

- MSSM extended by singlet chiral superfields \hat{N}_i and \hat{X}_i with $L = -1$ and $L = +1$
- Superpotential:

$$\begin{aligned} \mathcal{W} = & Y_d \hat{Q} \hat{H}_d \hat{D} + Y_u \hat{Q} \hat{H}_u \hat{U} + Y_e \hat{L} \hat{H}_d \hat{E} - \mu \hat{H}_d \hat{H}_u \\ & + Y_\nu \hat{L} \hat{H}_u \hat{N} + M_R \hat{N} \hat{X} + \frac{1}{2} \mu_X \hat{X} \hat{X} \end{aligned}$$

- New couplings, e.g. $A_{Y_\nu} Y_\nu \tilde{L} \tilde{N} H_u + \text{h.c.}$
- Work with a flavour-blind mechanism for SUSY breaking, **CMSSM-like** boundary conditions
- Right-handed sneutrino mass:

$$M_N^2 = m_N^2 + M_R^2 + Y_\nu^\dagger Y_\nu v_u^2 \sim (1\text{TeV})^2$$

⇒ **Natural Yukawa couplings with a TeV new Physics scale**



cLFV in supersymmetric seesaw models

- Typically in SUSY, cLFV appears through RGE-induced **lepton mixing** $(\Delta m_L^2)_{ij}$

[Borzumati and Masiero, 1986, Hisano et al., 1996, Hisano and Nomura, 1999]

$$\Rightarrow (\Delta m_L^2)_{ij} \propto (Y_\nu^\dagger Y_\nu)_{ij} \ln \frac{M_{GUT}}{M_R}$$

- Contribute to **all cLFV observables**

→ Dominant in most of the SUSY seesaw models

- Type I seesaw ($Y_\nu \sim 1$, $M_R \sim 10^{14} \text{GeV}$) → $(\Delta m_L^2)_{ij} \propto 5$

- Inverse seesaw ($Y_\nu \sim 1$, $M_R \sim 1 \text{TeV}$) → $(\Delta m_L^2)_{ij} \propto 30$

→ **one-loop \tilde{N} -mediated processes are no longer suppressed**

[Deppisch and Valle, 2005, Hirsch et al., 2010, Abada et al., 2012, Ilakovac et al., 2012, Krauss et al., 2013]

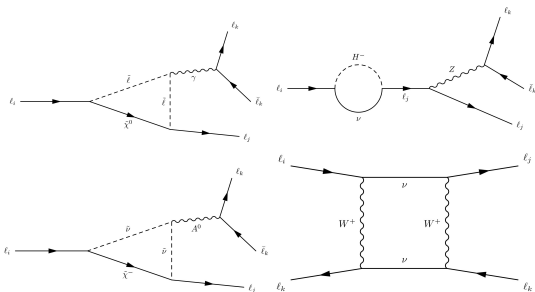
Similar enhancement in non-SUSY contributions

[Ilakovac and Pilaftsis, 1995, Deppisch et al., 2006, Forero et al., 2011, Alonso et al., 2013, Dinh et al., 2012]



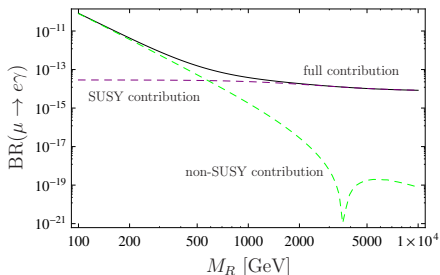
Diagrams

- In the Feynman-'t Hooft gauge, including both SUSY and non-SUSY: More than 100 classes of diagrams



- γ, Z, h_i, A_i -penguins and boxes
- Formulas computed using the FlavorKit interface
- Checked against the literature when possible
- Numerics done with SARAH/Spheno using 2 loops RGEs
- Enhancement** from:
 - $\mathcal{O}(1) Y_\nu$ couplings
 - TeV scale ν_R, \tilde{N}

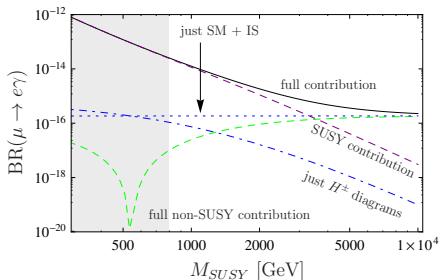
Radiative cLFV decays



$$m_0 = M_{1/2} = 1\text{TeV}, A_0 = -1.5\text{TeV}$$

$$\tan\beta = 10, \text{sign}(\mu) = +, \mu_X = 10^{-5}\text{GeV} \mathbb{1}, B_{\mu_X} = 100\mu_X, B_{M_R} = 100M_R$$

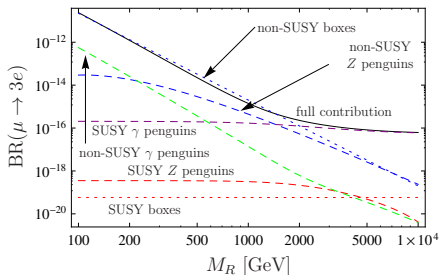
- **Reach the current upper limit:** $\text{Br}(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]
Expected sensitivity: 6×10^{-14} [MEG upgrade]
- Dominant contribution from the **lightest scale** (M_R or M_{SUSY})



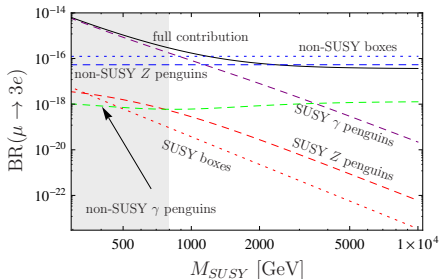
$$M_R = 2\text{TeV} \mathbb{1},$$

$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

3-body cLFV decays



$$m_0 = M_{1/2} = 1\text{TeV}, A_0 = -1.5\text{TeV}$$

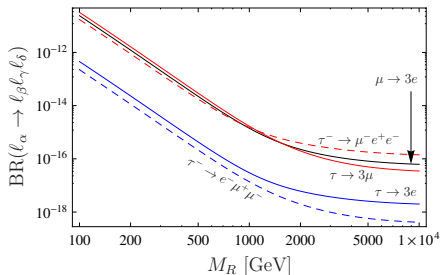


$$M_R = 2\text{TeV}\mathbb{1},$$

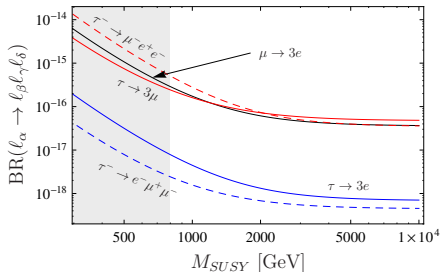
$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

- Saturate current UL: $\text{Br}(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ [SINDRUM, 1988]
Expected sensitivity: $10^{-15} - 10^{-16}$ [Mu3e proposal]
- Dominant non-SUSY contribution: boxes and Z-penguins
- Dominant SUSY contribution: γ -penguins
- Higgs-penguins sub-dominant, except at $\tan \beta \geq 50$ ($\tan^6 \beta$ enhanced)

3-body cLFV decays



$$m_0 = M_{1/2} = 1\text{TeV}, A_0 = -1.5\text{TeV}$$

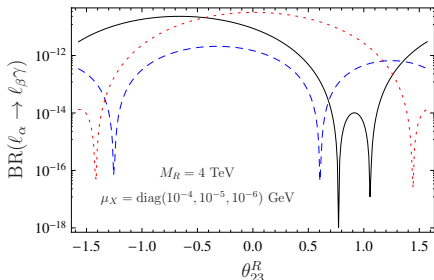


$$M_R = 2\text{TeV}\mathbb{1},$$

$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

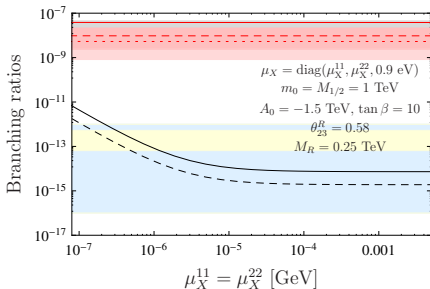
- Contributions with **similar behaviours** for both μ and τ decays
- $R = \mathbb{1}$, $\theta_{13} \ll \theta_{12}, \theta_{23}$
 → Similar Br for $\tau \rightarrow \mu$, $\mu \rightarrow e$ transitions, much smaller for $\tau \rightarrow e$
- **Strong suppression** of $\text{Br}(\tau \rightarrow e\mu^+e^-)$ and $\text{Br}(\tau \rightarrow \mu e^+\mu^-)$:
 2 LFV vertices are needed

Impact of active-sterile neutrino misalignment



$$m_0 = M_{1/2} = 1 \text{ TeV}, A_0 = -1.5 \text{ TeV}$$

$$\mu \rightarrow e\gamma \quad \tau \rightarrow e\gamma \quad \tau \rightarrow \mu\gamma$$



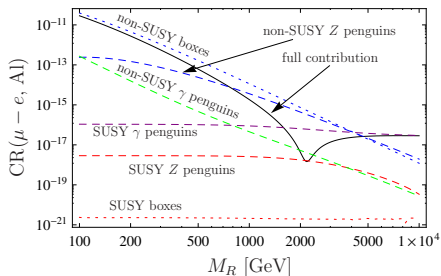
$$\mu \rightarrow e\gamma \text{ (full)}, \mu \rightarrow 3e \text{ (dashed)}$$

$$\tau \rightarrow \mu\gamma \text{ (full)}, \tau \rightarrow 3\mu \text{ (dashed)},$$

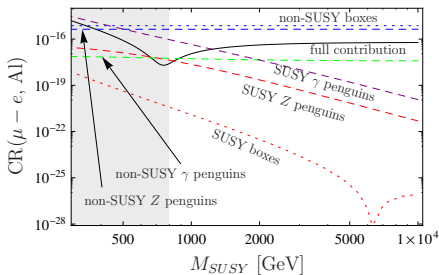
$$\tau^- \rightarrow \mu^- e^+ e^- \text{ (dotted)}$$

- Shaded areas: Expected sensitivities of future experiments
- $R \neq 1$ impacts relative size of Br
- Large enhancement of cLFV τ decays

Neutrinoless $\mu - e$ conversion



$$m_0 = M_{1/2} = 1\text{TeV}, A_0 = -1.5\text{TeV}$$

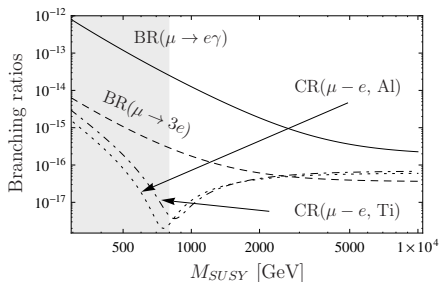
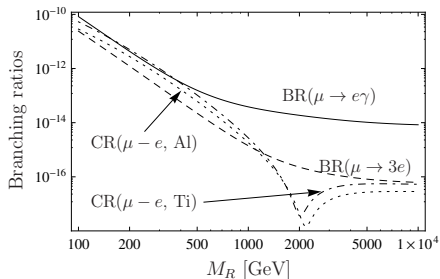


$$M_R = 2\text{TeV}\mathbb{1},$$

$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

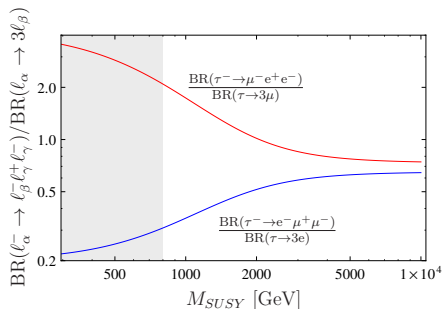
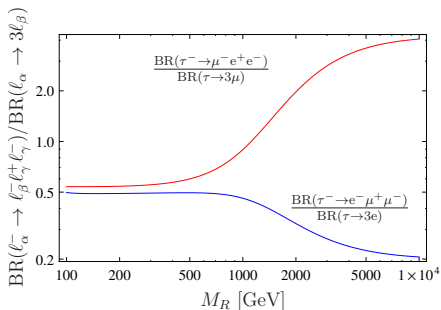
- Saturate current UL: $CR(\mu - e, Au) < 7.0 \times 10^{-13}$ [SINDRUM II, 2006]
Expected sensitivity: 10^{-14} [DeeMe], $10^{-17} - 10^{-18}$ [Mu2e, COMET/PRISM]
- Dips: partial cancellation between up quark and down quark contributions
- Otherwise similar to $\mu \rightarrow eee$

Comparison of cLFV decays



- $\mu \rightarrow e\gamma$: largest Br and the lowest current UL (5.7×10^{-13})
→ Most constraining observable **today**
- $\mu \rightarrow 3e$ conversion: best mid-term sensitivity ($\sim 10^{-15}$)
→ Should be the most constraining **by 2016**.
- $\mu - e$ conversion: best long-term sensitivity (down to 10^{-18})
→ Should be the most constraining **around 2020**.

Finding the dominant contribution



- LFV τ decays: factor 100 sensitivity improvement in Belle II
- **Ratios**: sensitive to the dominant contribution (SUSY or non-SUSY)

Conclusions

- **First complete calculation** with both SUSY and non-SUSY contributions
- At low M_R / high M_{SUSY} : dominant contributions from **non-SUSY boxes and Z-penguins**
- At low M_{SUSY} / high M_R : dominant contributions from **SUSY γ -penguins**
- **All observables** can already be used to **constrain** the parameter space
- **Most promising** observable: -short-term: $\mu \rightarrow e\gamma$
-mid-term: $\mu \rightarrow 3e$
-long-term: $\mu - e$ conversion
- Use **ratios** of τ decays to find the **dominant contribution**



Backup slides

Modified Casas-Ibarra parameters and neutrino input

- Casas-Ibarra parametrization adapted to the inverse seesaw:

$$Y_\nu = \frac{\sqrt{2}}{v_u} V^\dagger D_{\sqrt{X}} R D_{\sqrt{m_\nu}} U_{\text{PMNS}}^\dagger$$

- Input parameters: $M_R = 2 \text{ TeV}$, $\mu_X = 10^{-5} \text{ GeV}$, $m_{\nu_1} = 10^{-4} \text{ eV}$,
 R matrix
- Neutrino oscillation best-fit values [Forero et al., 2014]:

$$\Delta m_{21}^2 = 7.60 \cdot 10^{-5} \text{ eV}^2, \quad \blacksquare m_{31}^2 = 2.48 \cdot 10^{-3} \text{ eV}^2,$$

$$\sin^2 \theta_{12} = 0.323, \quad \sin^2 \theta_{23} = 0.467, \quad \sin^2 \theta_{13} = 0.0234$$



