Flavour violating lepton decays in supersymmetric low-scale seesaws

arXiv:1312.5318(to appear in PRD) 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

ICHEP 2014
Valencia, July 4th, 2014

Neutrino masses and lepton flavour violation

- $P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \neq 0$ only if $\Delta m^2_{kj} = m^2_k - m^2_j$ and $U_\nu \neq \mathbb{1}$
- SM: no ν mass term, lepton flavour is conserved
  $\Rightarrow$ need new Physics, e.g. seesaw mechanism
- Neutrino oscillations $\Rightarrow$ 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. $\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]
  - 3-body lepton decays, e.g. $\mathrm{Br}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ [Belle, 2010]
  - $\mu - e$ conversion, e.g. $\mathrm{CR}(\mu \to e, \mathrm{Au}) < 7 \times 10^{-13}$ [SINDRUM II, 2006]
  - Meson decays, e.g. $\mathrm{Br}(B_d^0 \to e\mu) < 2.8 \times 10^{-9}$ [LHCb, 2013]
  - Higgs decays, e.g. $H \to \bar{\tau}\mu$

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

The seesaw mechanisms

- $m_\nu \neq 0 \Rightarrow$ New physics at a high scale ($>$ SM)
- 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 → Violates lepton number L $\Rightarrow$ Majorana neutrinos

$$\delta\mathcal{L}^{d=5} = \frac{1}{2} c_{ij} \frac{(H \cdot L_i)^\dagger (H \cdot L_j)}{\Lambda} + \text{h.c.}$$

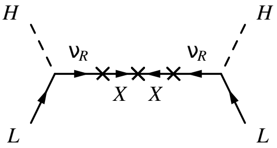
- To distinguish the several seesaw mechanisms, either
    - Directly produce the heavy states (LHC, ILC)
    - Look for dimension $\geqslant 6$ operators effects → cLFV

The inverse seesaw mechanism

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

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

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



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

$$m_{N_1,N_2} \approx \mp\sqrt{m_D^2+M_R^2} + \frac{M_R^2\mu_X}{2(m_D^2+M_R^2)}$$

2 scales: μ_X and M_R

The Minimal Supersymmetric Model (MSSM)

- Same gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ as the SM
- Field content $=$ SM fields and their SUSY partners
  Except for the Higgs sector → Up- and down-type Higgs
- More than 100 free parameters, most of them from soft SUSY breaking terms

$$\mathcal{L}_{\text{soft}} = (B\mathcal{S}\mathcal{S} + A\mathcal{S}\mathcal{S}\mathcal{S} + h.c.) - m_0^2 \mathcal{S}^\dagger \mathcal{S} - m_{1/2}\bar{\lambda}\lambda$$

$\Rightarrow$ Work in constrained frameworks

  - Constrained MSSM: 5 free parameters $m_{1/2}$, m_0, A_0, $\tan(\beta)$ and $\text{sign}(\mu)$

Supersymmetric seesaw models

- No ν_R in the MSSM ⇒ Massless neutrinos
  → Implement a seesaw mechanism

- Amount of cLFV proportional to the Yukawa couplings
  - From RGE-induced slepton mixing
    [Borzumati and Masiero, 1986, Hisano et al., 1996]

$$(\Delta m^2_{\tilde{L}})_{ij} \simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger Y_\nu)_{ij}\ln\frac{M_{GUT}}{M_R}$$

  - Type I seesaw: large scale to keep $\mathcal{O}(1)$ Yukawa couplings
  - Difficult to probe experimentally

- Embed the inverse seesaw in the MSSM
  ⇒ Natural Yukawa couplings with a TeV new Physics scale

The supersymmetric inverse seesaw model

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

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

- New couplings, e.g.

$$A_{Y_\nu} Y_\nu \widetilde{L}\widetilde{N} H_u + \text{h.c.}$$

- Work with a flavour-blind mechanism for SUSY breaking
- Right-handed sneutrino mass:

$$M^2_{\widetilde{N}} = m^2_{\widetilde{N}} + M_R^2 + Y_\nu^\dagger Y_\nu v_u^2 \sim (1\text{TeV})^2$$

cLFV in supersymmetric seesaw models

- Typically in SUSY, cLFV appears through RGE-induced slepton mixing $(\Delta m^2_{\tilde{L}})_{ij}$

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

  $\Rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto (Y^\dagger_\nu Y_\nu)_{ij} \ln\frac{M_{GUT}}{M_R}$
- Contribute to all cLFV observables

  → Dominant in most of the SUSY seesaw models
- Type I seesaw ($Y_\nu \sim 1$, $M_R \sim 10^{14}$GeV) → $(\Delta m^2_{\tilde{L}})_{ij} \propto 5$
- Inverse seesaw ($Y_\nu \sim 1$, $M_R \sim 1$TeV) → $(\Delta m^2_{\tilde{L}})_{ij} \propto 30$

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

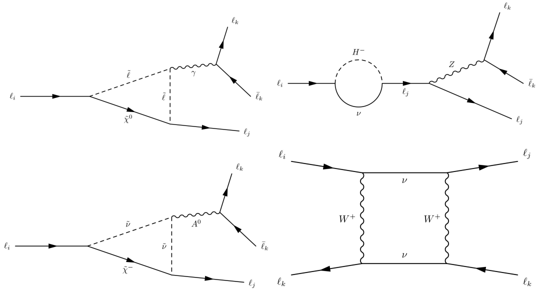
  [Deppisch and Valle, 2005, Hirsch et al., 2010, Abada et al., 2012b, Ilakovac et al., 2012, Krauss et al., 2013]

  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]

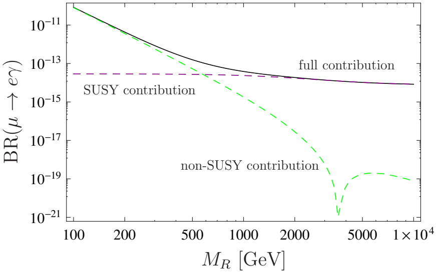
Diagrams

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

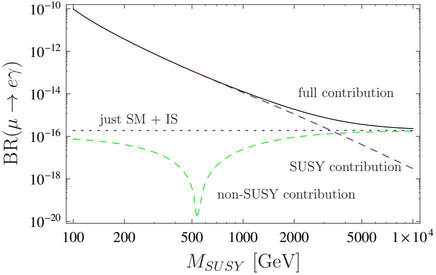


- γ, Z, h_i, A_i-penguins and boxes
- Formulas computed using the `FlavorKit` interface
- Checked against the literature when possible
- Numerics done with `SARAH/Spheno` using 2 loops RGEs
- Enhancement from:
  -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale ν_R, $\widetilde{N}$

Radiative cLFV decays



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

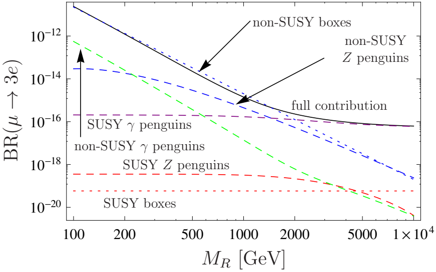


$$M_R = 2\text{TeV}\mathbb{1},$$
$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

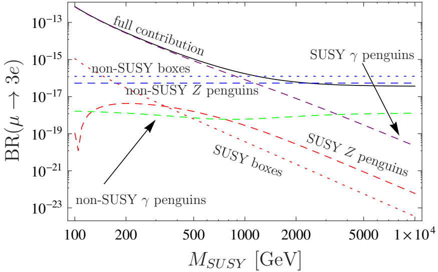
$$\tan\beta = 10,\ \mathrm{sign}(\mu) = +,\ \mu_X = 10^{-5}\text{GeV}\,\mathbb{1},\ B_{\mu_X} = 100\mu_X,\ B_{M_R} = 100 M_R$$

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

3-body cLFV decays



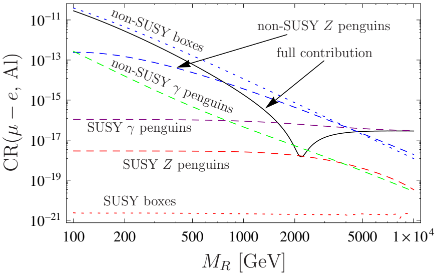
$$m_0 = M_{1/2} = 1\text{TeV}, A_0 = -1.5\,\text{TeV}$$



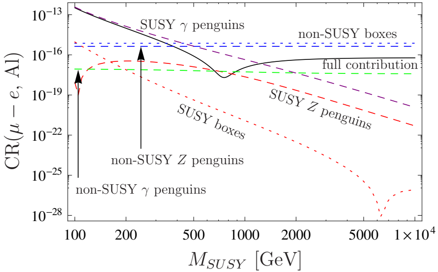
$$M_R = 2\text{TeV}\mathbb{1},$$
$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

- Saturate current UL: $\text{Br}(\mu \to eee) < 1.0 \times 10^{-12}$ [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 subdominant, except at $\tan\beta \gtrsim 50$ ($\tan^6\beta$ enhanced)

Neutrinoless $\mu - e$ conversion



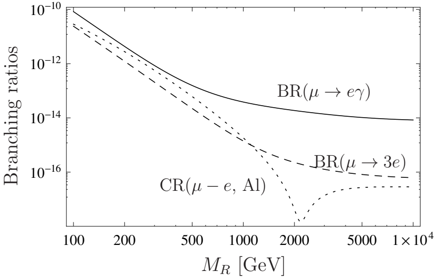
$$m_0 = M_{1/2} = 1\text{TeV},\ A_0 = -1.5\,\text{TeV}$$

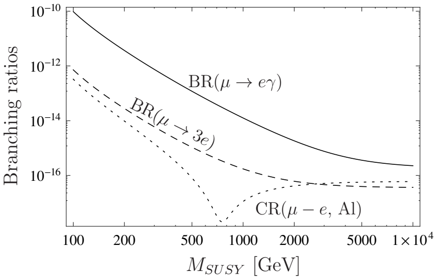


$$M_R = 2\text{TeV}\mathbb{1},$$
$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

- Saturate current UL: $\mathrm{CR}(\mu - e, \mathrm{Au}) < 7.0 \times 10^{-13}$ [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 $\mu \to eee$

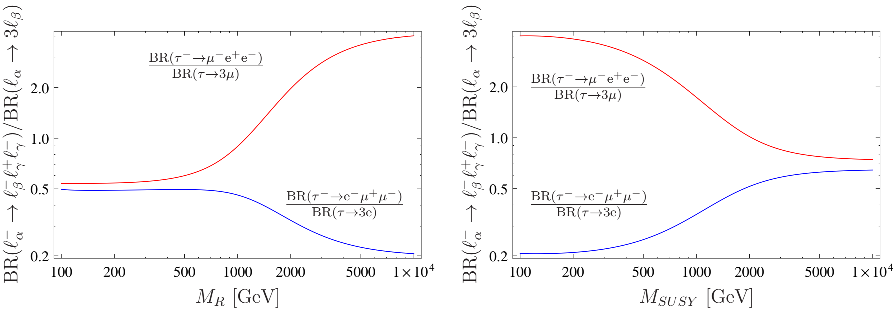
Comparison of cLFV decays





- $\mu \to e\gamma$: largest Br and the lowest current UL (5.7×10^{-13})
  → Most constraining observable today
- $\mu \to 3e$ 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: $\mu \to e\gamma$
  -mid-term: $\mu \to 3e$
  -long-term: $\mu - e$ conversion
- Use ratios of τ decays to find the dominant contribution