LFV lepton decays in the inverse seesaw: SUSY and non-SUSY contributions

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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

Supersymmetric seesaw models

- The SM doesn't only lack neutrino masses, e.g. the hierarchy problem
- 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

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

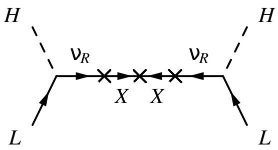
- To distinguish the several seesaw mechanisms, either
  - Directly produce the heavy states (LHC, future collider)
  - Look for dimension $\geqslant 6$ operators effects $\rightarrow$ cLFV

The inverse seesaw mechanism

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

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

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 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, CMSSM-like boundary conditions
- Right-handed sneutrino mass:

$$M^2_{\tilde{N}} = m^2_{\tilde{N}} + M^2_R + Y^\dagger_\nu Y_\nu v^2_u \sim (1\text{TeV})^2$$

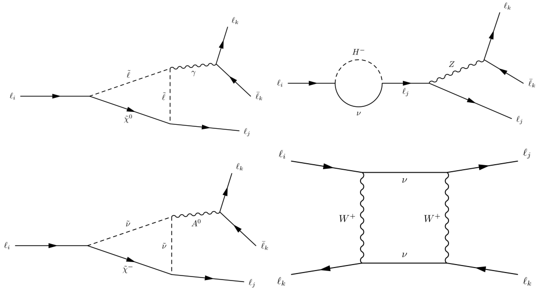
$\Rightarrow$ Large Yukawa couplings with a TeV new Physics scale

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., 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]

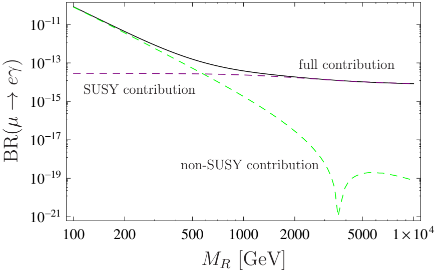
Diagrams

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

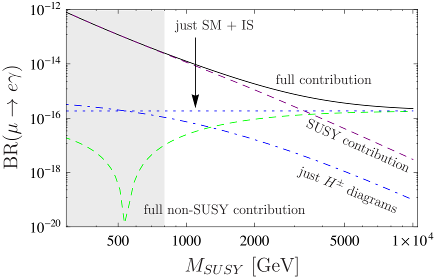


- γ, Z, h_i, A_i-penguins and boxes
- Formulas computed using the `FlavorKit` interface
- Checked against the literature when possible
- Numerics done with `SARAH/Spheno` using 2 loops RGEs
- Enhancement from:
  -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale ν_R, $\widetilde{N}$

Radiative cLFV decays



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

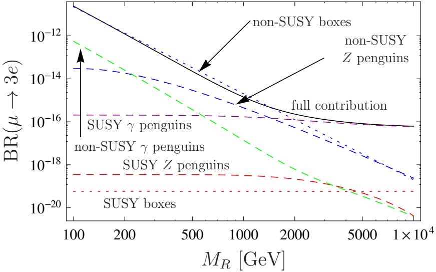


$M_R = 2\text{TeV}\mathbb{1},$
$M_{SUSY} = m_0 = M_{1/2} = -A_0$

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

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

3-body cLFV decays



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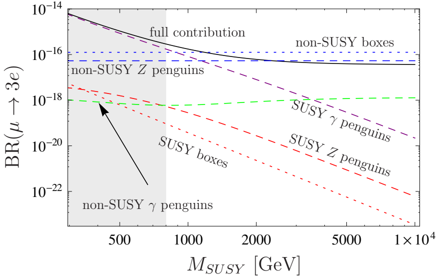
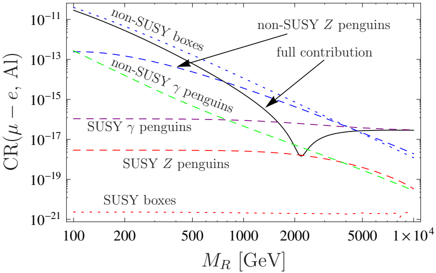


$M_R = 2\text{TeV}\mathbb{1},$
$M_{SUSY} = m_0 = M_{1/2} = -A_0$

- 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 sub-dominant, except at $\tan\beta \gtrsim 50$ ($\tan^6\beta$ enhanced)

Neutrinoless $\mu - e$ conversion



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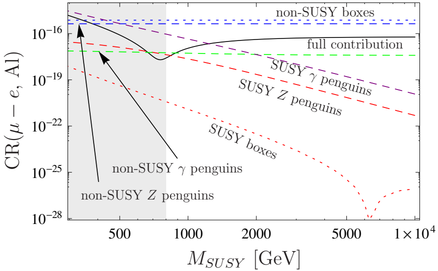
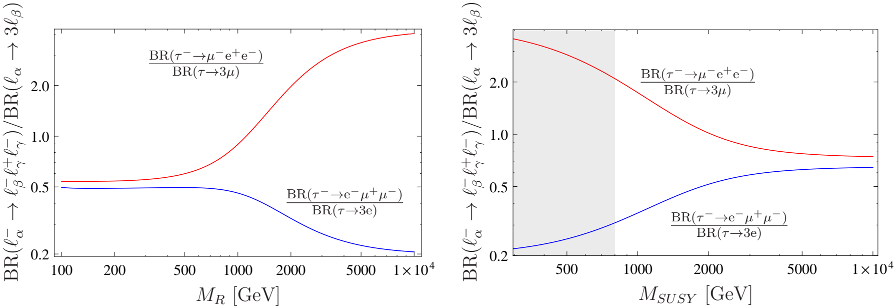


$M_R = 2\text{TeV}\mathbb{1},$
$M_{SUSY} = m_0 = M_{1/2} = -A_0$

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

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

Backup slides

Modified Casas-Ibarra parameters and neutrino input

- Casas-Ibarra parametrization adapted to the inverse seesaw:

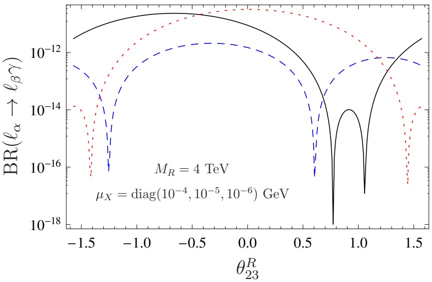
$$Y_\nu = \frac{\sqrt{2}}{v_u} V^\dagger D_{\sqrt{X}} R D_{\sqrt{m_\nu}} U^\dagger_{\text{PMNS}}$$

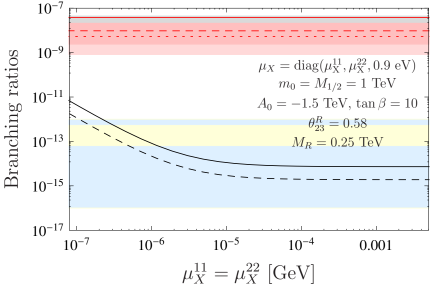
- Input parameters: $M_R = 2$ TeV, $\mu_X = 10^{-5}$ GeV, $m_{\nu_1} = 10^{-4}$ eV, R matrix

- Neutrino oscillation best-fit values [Forero et al., 2014]:

$$\Delta m^2_{21} = 7.60 \cdot 10^{-5}\ \text{eV}^2\,,\ \blacksquare\mathrm{m}^2_{31} = 2.48 \cdot 10^{-3}\ \text{eV}^2\,,$$
$$\sin^2\theta_{12} = 0.323\,,\ \sin^2\theta_{23} = 0.467\,,\ \sin^2\theta_{13} = 0.0234$$

Impact of active-sterile neutrino misalignment





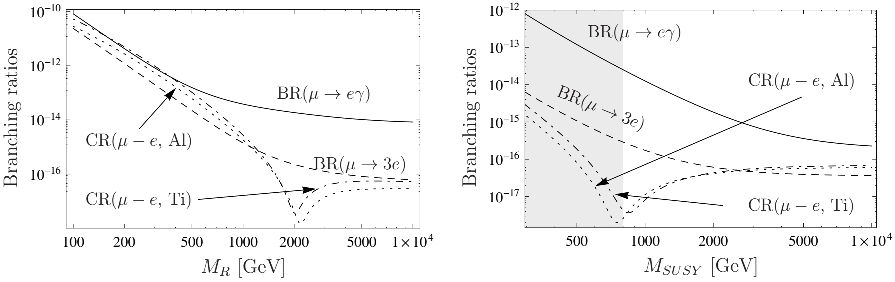
$m_0 = M_{1/2} = 1\,\mathrm{TeV},\ A_0 = -1.5\,\mathrm{TeV}$

$\mu \to e\gamma$ $\tau \to e\gamma$ $\tau \to \mu\gamma$

$\mu \to e\gamma$ (full), $\mu \to 3e$ (dashed)
$\tau \to \mu\gamma$ (full), $\tau \to 3\mu$ (dashed),
$\tau^- \to \mu^- e^+ e^-$ (dotted)

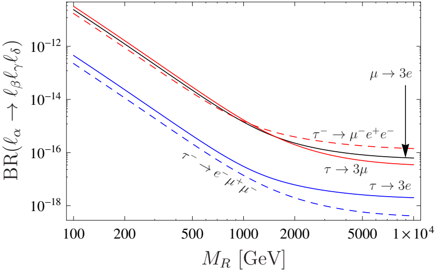
- Shaded areas: Expected sensitivities of future experiments
- $R \neq \mathbb{1}$ impacts relative size of Br
- Large enhancement of cLFV τ decays

Comparison of cLFV decays



- $\mu \to e\gamma$: largest Br and the lowest current UL (5.7×10^{-13})
  → Most constraining observable today
- $\mu \to 3e$: 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.

3-body cLFV decays



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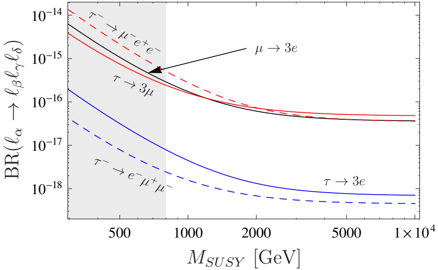

$M_R = 2\text{TeV}\mathbb{1},$
$M_{SUSY} = m_0 = M_{1/2} = -A_0$

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