The CMS excess and lepton flavour violation in the (supersymmetric) inverse seesaw

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Neutrino oscillations

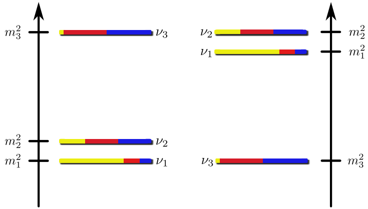
- Neutrino oscillations (best fit from nu-fit.org):

solar $\nu_e \to \nu_{\rm others}$: $\theta_{12} \simeq 33^\circ$, $\Delta m^2_{21} \simeq 7.5 \times 10^{-5}{\rm eV}^2$

atmospheric $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$: $\theta_{23} \simeq 49^\circ$, $|\Delta m^2_{23}| \simeq 2.4 \times 10^{-3}{\rm eV}^2$

reactor $\bar{\nu}_e \to \bar{\nu}_{\rm others}$: $\theta_{13} \simeq 8.5^\circ$

accelerator $\nu_\mu \to \nu_{\rm others}$



- Different mixing pattern from CKM, ν lightness $\overset{?}{\longleftarrow}$ Majorana ν

- Neutrino oscillations = Neutral lepton flavour violation
  What about charged lepton flavour violation (cLFV) ?

- Oscillations give no information on:
  - the absolute mass scale $\to \beta$ decays, cosmology
  - the Dirac or Majorana nature of neutrinos $\to 0\nu 2\beta$ decays

Massive neutrinos and New Physics

- Standard Model $L = \binom{\nu_L}{\ell_L}, \tilde{H} = \binom{H^{0*}}{H-}$
  - No right-handed neutrino $\nu_R \to$ No Dirac mass term

$$\mathcal{L}_{\text{mass}} = -Y_\nu \bar{L}\tilde{H}\nu_R + \text{h.c.}$$

  - No Higgs triplet $T \to$ No Majorana mass term

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} m \overline{L^C} T L + \text{h.c.}$$

- Necessary to go beyond the Standard Model for ν mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms $\to$ ν mass at tree-level
    + BAU through leptogenesis

Dirac neutrinos ?

- Add gauge singlet, right-handed neutrinos ν_R

$$\Rightarrow \nu = \nu_L + \nu_R$$

$$\mathcal{L}_{\text{mass}}^{\text{leptons}} = -Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L} \tilde{H} \nu_R + \text{h.c.}$$

$\Rightarrow$ After electroweak symmetry breaking $\langle H \rangle = \binom{0}{\text{v}}$

$$\mathcal{L}_{\text{mass}}^{\text{leptons}} = -\text{v} Y_\ell \bar{\ell}_L \ell_R - \text{v} Y_\nu \bar{\nu}_L \nu_R + \text{h.c.} = -m_\ell \bar{\ell}_L \ell_R - m_D \bar{\nu}_L \nu_R + \text{h.c.}$$

$\Rightarrow$ 3 light neutrinos: $m_\nu \lesssim 1\text{eV} \Rightarrow Y^\nu \lesssim 10^{-11}$

- Increase the hierarchy between Yukawa couplings

Majorana neutrinos ?

- Add gauge singlet, right-handed neutrinos ν_R
  $\mathcal{L}^{\text{leptons}}_{\text{mass}} = -Y_\ell \bar{L} H \ell_R - Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2} M_R \overline{\nu^C_R} \nu_R + \text{h.c.}$

  $\Rightarrow$ After electroweak symmetry breaking $\langle H \rangle = \binom{0}{\text{v}}$
  $\mathcal{L}^{\text{leptons}}_{\text{mass}} = -m_\ell \ell_L \ell_R - m_D \bar{\nu}_L \nu_R - \frac{1}{2} M_R \overline{\nu^C_R} \nu_R + \text{h.c.}$

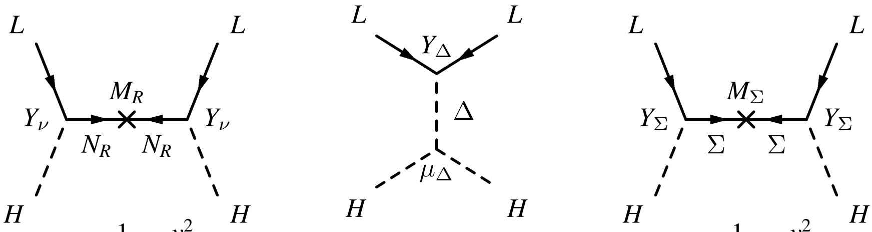
  $\Rightarrow$ 6 mass eigenstates: $\nu = \nu^C$

- ν_R gauge singlets
  $\Rightarrow$ M_R not related to SM dynamics, not protected by symmetries
  $\Rightarrow$ $M_R \overline{\nu^C_R} \nu_R$ is gauge and Lorentz invariant, renormalizable

- $M_R \overline{\nu^C_R} \nu_R$ violates lepton number conservation $\Delta L = 2$

The seesaw mechanisms

- Seesaw mechanism: New fields with a mass $M >$ EW scale (in general) and Majorana mass terms
  $\Rightarrow$ Generate m_ν in a renormalizable way and at tree-level
- 3 minimal tree-level seesaw models $\Rightarrow$ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets
  - type III: fermionic triplets



$$\mathrm{m}_\nu = -\frac{1}{2} Y_\nu^T \frac{v^2}{M_R} Y_\nu$$

$$\mathrm{m}_\nu = -2 Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}$$

$$\mathrm{m}_\nu = -\frac{1}{2} Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma$$

Distinguishing the seesaw models

- Notice that lepton number conservation is accidental in the SM (gauge group, field content and renormalizability)
- Unique dimension 5 operator for all seesaw mechanisms $\rightarrow$ Violates lepton number L $\Rightarrow$ Majorana neutrinos

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

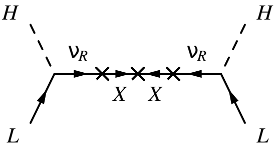
- To distinguish the several seesaw mechanisms, either
  - Directly produce the heavy states (LHC, LC, FCC)
  - Look for dimension $\geqslant 6$ operator effects $\rightarrow$ charged lepton flavour violation (cLFV), non-standard interactions, etc

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

Why supersymmetry?

- The SM doesn't only lack neutrino masses, e.g. no dark matter, 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 supersymmetric inverse seesaw model

- No ν_R in the MSSM $\Rightarrow$ Massless neutrinos
  $\rightarrow$ Implement a seesaw mechanism
- MSSM extended by singlet chiral superfields $\widehat{N}_i$ and $\widehat{X}_i$ with $L = -1$ and $L = +1$

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

- New couplings, e.g. $A_{Y_\nu} Y_\nu \widetilde{N}\widetilde{L}H_u + \mathrm{h.c.}$
- Work with a flavour-blind mechanism for SUSY breaking
  $\Rightarrow Y_\nu$ as the only source of cLFV
- Right-handed sneutrino mass:

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

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

(SUSY) Inverse seesaw experimental tests

- (SUSY) Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1\,\text{TeV}$
  $\Rightarrow$ testable at the LHC and low energy experiments
- LHC/ILC signatures
  - single lepton + dijet + missing energy [Das and Okada, 2013]
  - di-lepton + missing p_T [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013]
  - cLFV di-lepton + dijet [Arganda, Herrero, Marcano and CW, 2015]
  - tri-lepton + missing E_T [Mondal et al., 2012, Das et al., 2014]...
  - invisible Higgs decays [Banerjee et al., 2013]
- Low energy:
  - deviations from lepton universality [Abada, Teixeira, Vicente and CW, 2014]
  - charged lepton flavour violation [Bernabéu et al., 1987]...
  - neutrinoless double beta decay [Awasthi et al., 2013]...
  - charged lepton anomalous magnetic moment [Abada et al., 2014]
- Dark matter candidate: sterile neutrino [Abada et al., 2014] / sneutrino [De Romeri and Hirsch, 2012, Banerjee et al., 2013, Guo et al., 2014]...

Charged lepton flavour violation

- In the Standard Model: cLFV from higher order processes
  $\Rightarrow$ negligible
- If cLFV observed:
  - Clear evidence of physics at a higher scale
  - Probe the origin of lepton mixing
  - Probe the origin of New Physics
- Complementary to other New Physics searches
  - High energy: LHC
  - High intensity:
    - B factories: Rare decays, etc
    - Neutrino dedicated experiments: U_{PMNS} non-unitarity...
    - Other low energy experiments: $(g-2)_\mu$, EDM, LUV...

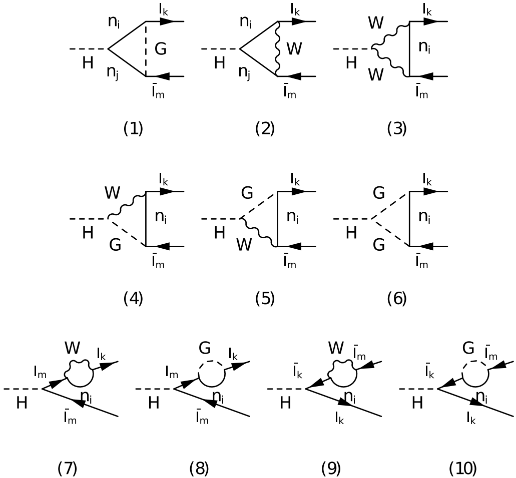
Experimental searches of cLFV

- Radiative decays, e.g. $\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]
- 3-body decays, e.g. $\mathrm{Br}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ [Belle, 2010]
- Neutrinoless muon conversion,
  e.g. $\mu^-, \mathrm{Au} \to e^-, \mathrm{Au} < 7 \times 10^{-13}$ [SINDRUM II, 2006]
- Meson decays, e.g. $\mathrm{Br}(B_d^0 \to e\mu) < 2.8 \times 10^{-9}$ [LHCb, 2013]
- Z decays, e.g. $\mathrm{Br}(Z^0 \to e\mu) < 1.7 \times 10^{-6}$ [OPAL, 1995]
- Higgs decays, e.g. $H \to \tau\mu$:
  CMS: 2.4σ signal excess with $\mathrm{Br} = 0.84^{+0.39}_{-0.37}\%$ [1502.07400]
  ATLAS: 1.3σ signal excess with $\mathrm{Br} = 0.77 \pm 0.62\%$ [1508.03372]

Diagrams for the ISS

(PRD91(2015)015001)

- In the Feynman-'t Hooft gauge, same as [Arganda et al., 2005]:



- Formulas adapted from [Arganda et al., 2005]
- Diagrams 1, 8, 10 → dominate at large M_R
- Enhancement from:
  -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale n_i

Most relevant constraints

- Neutrino data → Use specific parametrizations (modified Casas-Ibarra [Casas and Ibarra, 2001] or μ_X parametrization)

$$v Y_\nu^T = V^\dagger \mathrm{diag}(\sqrt{M_1}\,, \sqrt{M_2}\,, \sqrt{M_3})\; R\; \mathrm{diag}(\sqrt{m_1}\,, \sqrt{m_2}\,, \sqrt{m_3}) U_{PMNS}^\dagger$$

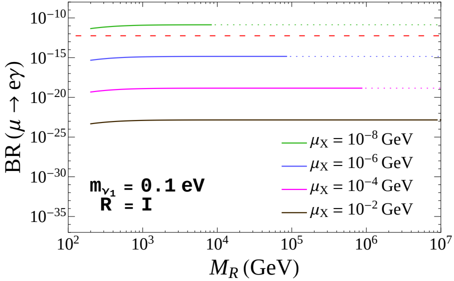
$$M = M_R \mu_X^{-1} M_R^T$$

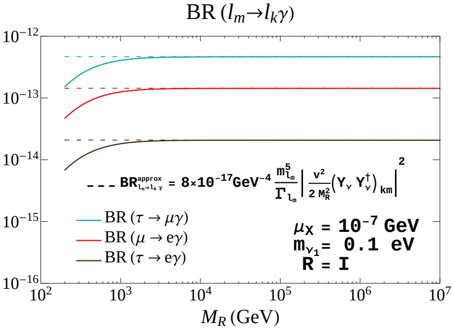
OR

$$\mu_X = M_R^T\, m_D^{-1}\; U_{\mathrm{PMNS}}^* m_\nu U_{\mathrm{PMNS}}^\dagger\; m_D^{T^{-1}} M_R$$

- Charged lepton flavour violation → For example: $\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]
- Lepton universality violation: less contraining than $\mu \to e\gamma$
- Electric dipole moment: 0 with real PMNS and mass matrices
- Invisible Higgs decays: $M_R > m_H$, does not apply

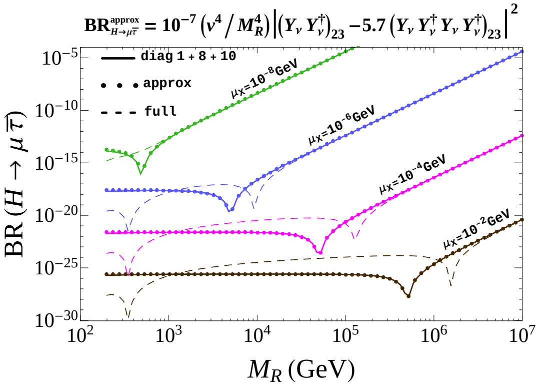
Constraints: focus on $\mu \to e\gamma$





- M_R and μ_X real and degenerate, Casas-Ibarra (C-I) parametrization
- Constrains μ_X
- Perturbativity $\to \left|\frac{Y_\nu^2}{4\pi}\right| < 1.5$ (Dotted line = non-perturbative couplings)
- $\frac{v^2 (Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} \approx \frac{1}{\mu_X} \frac{(U_{\text{PMNS}} \Delta m^2 \; U_{\text{PMNS}}^T)_{km}}{2 m_{\nu_1}}$

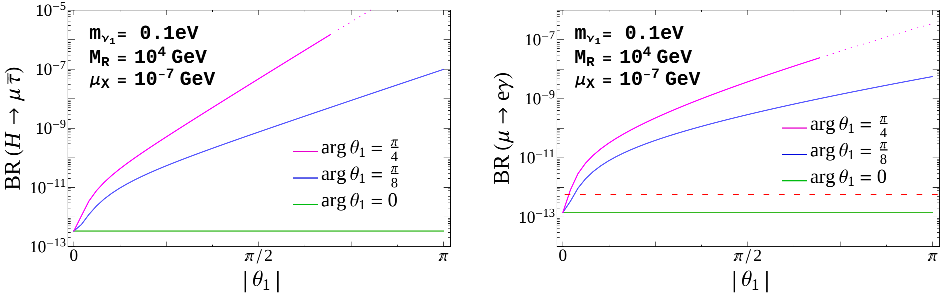
Dependence on ISS parameters: μ_X and M_R



- $R = \mathbb{1}$, M_R and μ_X degenerate and real, C-I parametrization
- Dips come from interferences between diagrams
- Can be understood using the mass insertion approximation

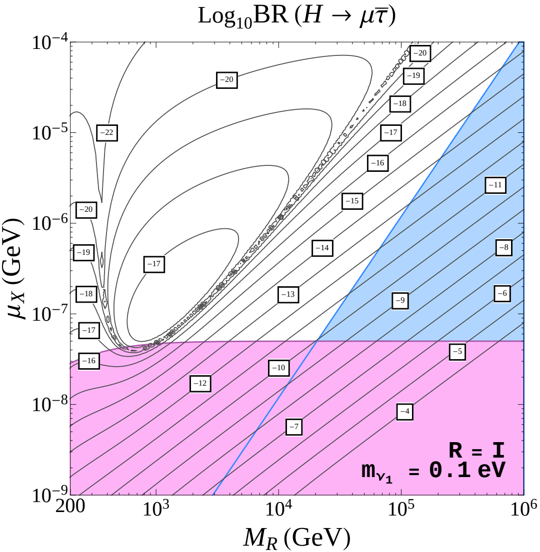
$$\frac{v^2 (Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} \approx \frac{1}{\mu_X}\frac{(U_{\mathrm{PMNS}}\Delta m^2\ U^T_{\mathrm{PMNS}})_{km}}{2m_{\nu_1}} \quad \text{and} \quad \frac{v^2 (Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} = \frac{M_R^2 (U_{\mathrm{PMNS}}\Delta m^2\ U^T_{\mathrm{PMNS}})_{km}}{v^2 \mu_X^2}$$

Dependence on ISS parameters: R matrix



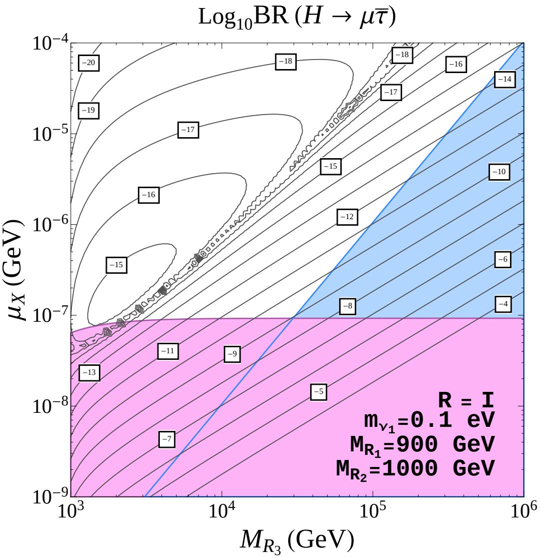
- M_R and μ_X degenerate and real
- Independent of R for real mixing angles
- Increase with complex angles, but increase limited by $\mu \to e\gamma$
  $\Rightarrow$ Complex R matrix doesn't change our results

Searching for maximal $\text{Br}(H \to \bar{\tau}\mu)$



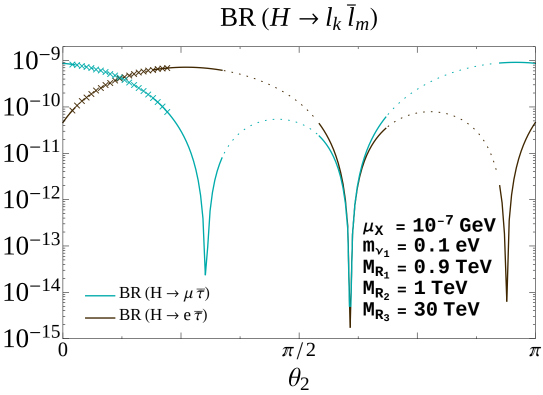
- M_R and μ_X degenerate and real
- Excluded by $\mu \to e\gamma$
  Non-perturbative Y_ν
- $\text{Br}(H \to \bar{\tau}\mu) \leqslant 10^{-10}$
- End of the story ?

Hierarchical heavy N



- Similar growth with M_{R_3} and μ_X as in the degenerate case with M_R and μ_X
- Excluded by $\mu \to e\gamma$
  Non-perturbative Y_ν
- $\text{Br}(H \to \bar{\tau}\mu) \leqslant 10^{-9}$

Impact of the R matrix



- Contrary to degenerate case, R dependence
- Varying θ_1: Same conclusions as before
- Dotted = non-perturbative couplings
  Cross = Excluded by $\mu \to e\gamma$
- $\theta_2 \sim \pi/4$:
  $\mathrm{Br}(H \to e\bar{\tau}) > \mathrm{Br}(H \to \mu\bar{\tau})$
- Results quite insensitive to θ_3

Large cLFV Higgs decay rates from textures I

- Strongest experimental constraint: $\mu \to e\gamma$

$$BR^{\text{approx}}_{\mu\to e\gamma} = 8\times 10^{-17}\text{GeV}^{-4}\frac{m_\mu^5}{\Gamma_\mu}\left|\frac{\text{v}^2}{2M_R^2}(Y_\nu Y_\nu^\dagger)_{12}\right|^2$$

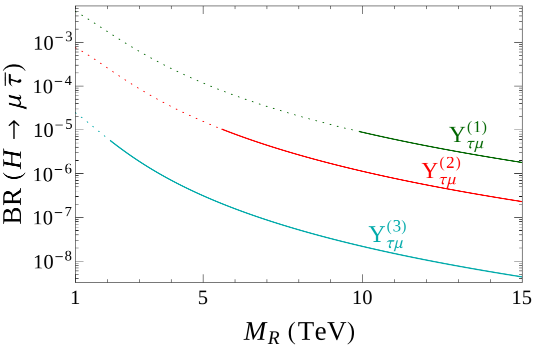
$$BR^{\text{approx}}_{H\to\mu\bar\tau} = 10^{-7}\frac{\text{v}^4}{M_R^4}\left|(Y_\nu Y_\nu^\dagger)_{23} - 5.7(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23}\right|^2$$

$$\underset{(Y_\nu Y_\nu^\dagger)_{12}=0}{=} 10^{-7}\frac{\text{v}^4}{M_R^4}\left|1-5.7[(Y_\nu Y_\nu^\dagger)_{22}+(Y_\nu Y_\nu^\dagger)_{33}]\right|^2\left|(Y_\nu Y_\nu^\dagger)_{23}\right|^2$$

- Solution: Textures with $(Y_\nu Y_\nu^\dagger)_{12} = 0$ and $\frac{|Y_\nu^{ij}|^2}{4\pi} < 1.5$
- Examples:

$$Y_{\tau\mu}^{(1)} = f\begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix},\; Y_{\tau\mu}^{(2)} = f\begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix},\; Y_{\tau\mu}^{(3)} = f\begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$

Large cLFV Higgs decay rates from textures II

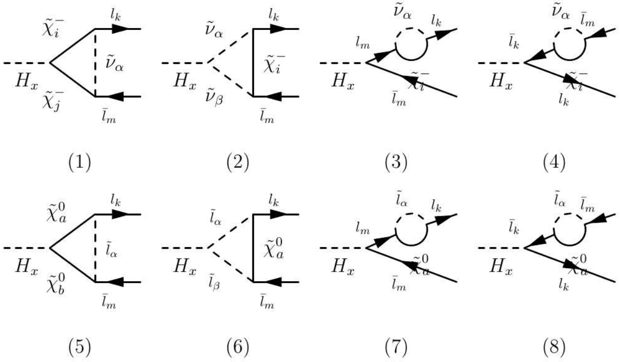


- Numerics done with the full one-loop formulas
- $f = \sqrt{6\pi}$, μ_X parametrization
- Dotted: excluded by $\tau \to \mu\gamma$ Solid: allowed by cLFV, LUV, etc
- $\mathrm{Br}^{\max}(H \to \mu\bar{\tau}) \sim 10^{-5}$
- Same maximum branching ratio with hierarchical heavy N

- Similarly, $\mathrm{Br}^{\max}(H \to e\bar{\tau}) \sim 10^{-5}$ for $Y_{\tau e}^{(i)}$ (=$Y_{\tau\mu}^{(i)}$ with rows 1 and 2 exchanged)

cLFV Higgs decays from SUSY loops (arXiv:1508.04623)

- In the Feynman-'t Hooft gauge, same as [Arganda et al., 2005]:

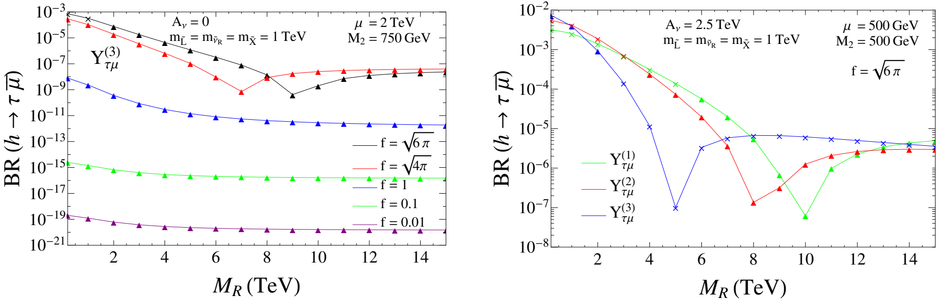


- Formulas adapted from [Arganda et al., 2005]
- Enhancement from: -$\mathcal{O}(1)$ Y_ν couplings
  -TeV scale $\tilde{\nu}$

cLFV in supersymmetric seesaw models

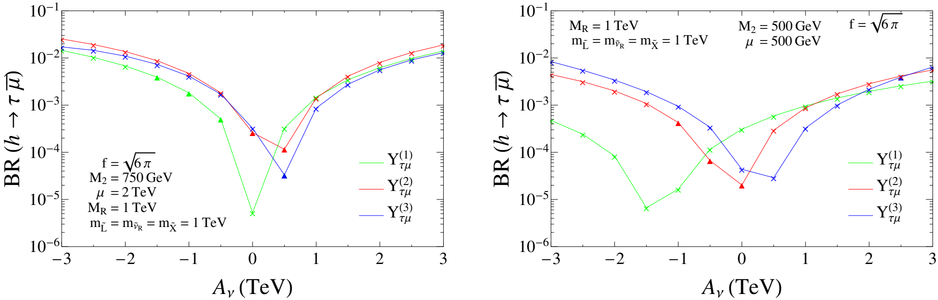
- Typically in SUSY, cLFV appears through RGE-induced slepton mixing $(\Delta m^2_{\tilde{L}})_{ij}$
  [Borzumati and Masiero, 1986, Hisano et al., 1996, Hisano and Nomura, 1999]
  $\Rightarrow (\Delta m^2_{\tilde{L}})_{ij} \propto (Y_\nu^\dagger Y_\nu)_{ij} \ln \frac{M_{GUT}}{M_R}$
- Contribute to all cLFV observables
  → Dominant in most of the SUSY seesaw models
- Type I seesaw ($Y_\nu \sim 1$, $M_R \sim 10^{14}$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., 2014]
  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]

Dependence on M_R



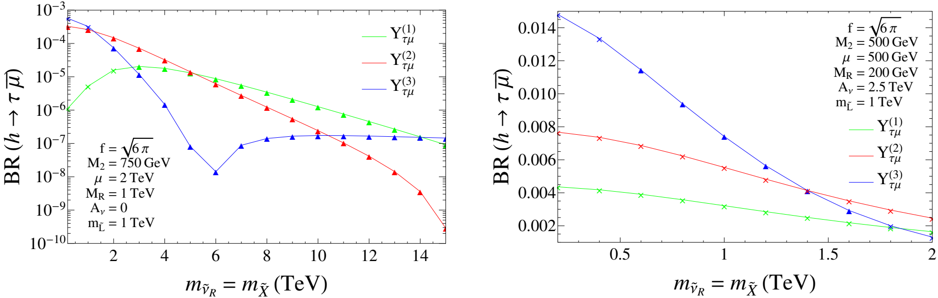
- M_R degenerate and real, $m_A = 800\,\mathrm{GeV}$,
  squark parameters safe from LHC (direct searches, Higgs mass)
- ▲: allowed by cLFV radiative decays, $\times$: excluded
- At low M_R: dominated by chargino-sneutrino loops
  At large M_R / small f: dominated by neutralino-slepton loops
- Can reach large $\mathrm{Br}(h \to \tau\bar{\mu}) = 0.7\%$

Dependence on A_ν



- M_R degenerate and real, $m_A = 800\,\mathrm{GeV}$, $M_R = m_{\tilde{L}} = m_{\tilde{\nu}_R} = m_{\tilde{X}} =$ 1 TeV
- ▲: allowed by cLFV radiative decays, $\times$: excluded
- A_ν in both $h^0 - \tilde{\nu}_L - \tilde{\nu}_R$ coupling and $\tilde{\nu}_L - \tilde{\nu}_R$ mixing
  $\to$ Dips when dominated by chargino loops
- Dips in BR($h \to \tau\bar{\mu}$) and BR($\tau \to \mu\gamma$) do not exactly coincide

Dependence on $m_{\tilde{\nu}_R}$ and $m_{\tilde{X}}$



- M_R degenerate and real, $m_A = 800\,\text{GeV}$
- ▲: allowed by cLFV radiative decays, $\times$: excluded
- At low $m_{\tilde{\nu}_R}$: dominated by chargino-sneutrino loops
  At large $m_{\tilde{\nu}_R}$: dominated by neutralino-slepton loops
- Can reach allowed values up to BR$(h \to \tau\bar{\mu}) = 1.1\%$

Summary of cLFV Higgs decays

- cLFV Higgs decays: complementary to other cLFV searches
- Enhancement from the inverse seesaw
  but largest values excluded by $\tau \to \mu\gamma$ / $\tau \to e\gamma$
- non-SUSY ISS: $\mathrm{Br}(H \to \bar{\tau}\mu) \lesssim 10^{-5}$
  $\mathrm{Br}(H \to \bar{\tau}e) \lesssim 10^{-5}$
- SUSY loops: $\mathrm{Br}(h \to \tau\bar{\mu}) \lesssim \mathcal{O}(1\%)$
- SUSY loops can explain the ATLAS and CMS excess
- $\tau\mu$ and τe will be probed at future LHC runs and future colliders

Diagrams

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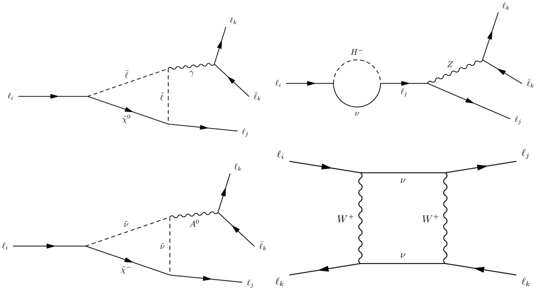
- In the Feynman-'t Hooft gauge, including both SUSY and non-SUSY: More than 100 classes of diagrams



- 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, $\widetilde{N}$

Modified Casas-Ibarra parameters and neutrino input for SUSY ISS study

- Casas-Ibarra parametrization adapted to the inverse seesaw:

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

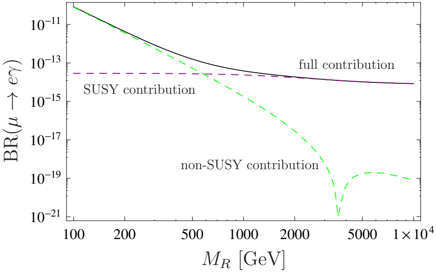
- Input parameters: $M_R = 2$ TeV, $\mu_X = 10^{-5}$ GeV, $m_{\nu_1} = 10^{-4}$ eV, R matrix

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

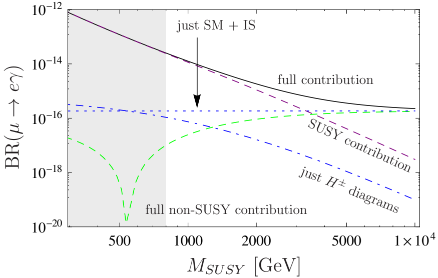
$$\Delta \mathrm{m}^2_{21} = 7.60 \times 10^{-5}\ \mathrm{eV}^2\,, \Delta \mathrm{m}^2_{31} = 2.48 \times 10^{-3}\ \mathrm{eV}^2\,,$$
$$\sin^2\theta_{12} = 0.323\,,\ \sin^2\theta_{23} = 0.467\,,\ \sin^2\theta_{13} = 0.0234$$

$\Rightarrow$ Give a specific texture that we keep fixed for the following scans

Radiative cLFV decays



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

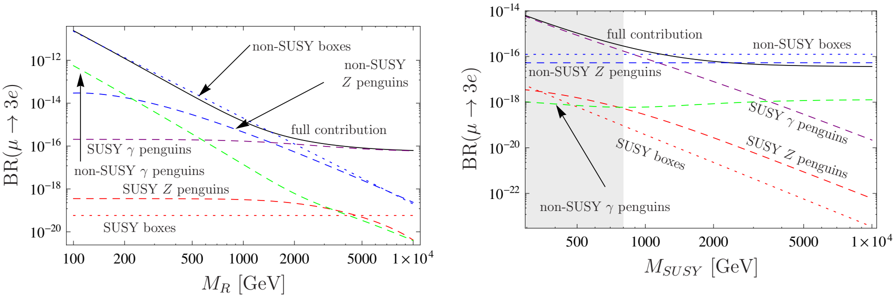


$$M_R = 2\text{TeV}\mathbb{1},$$
$$M_{SUSY} = m_0 = M_{1/2} = -A_0$$

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

- 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

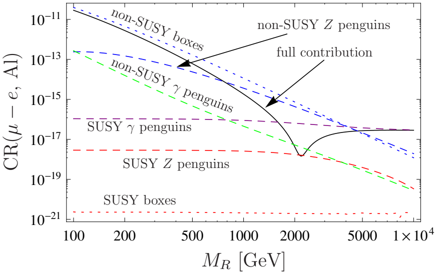


$m_0 = M_{1/2} = 1\text{TeV}, A_0 = -1.5\,\text{TeV}$

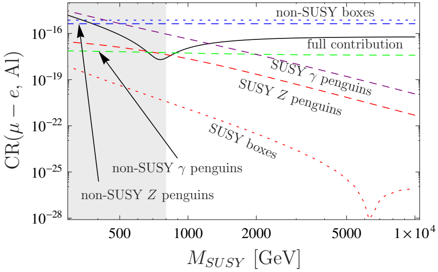
$M_R = 2\text{TeV}\mathbb{1}$,
$M_{SUSY} = m_0 = M_{1/2} = -A_0$

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

Neutrinoless $\mu - e$ conversion



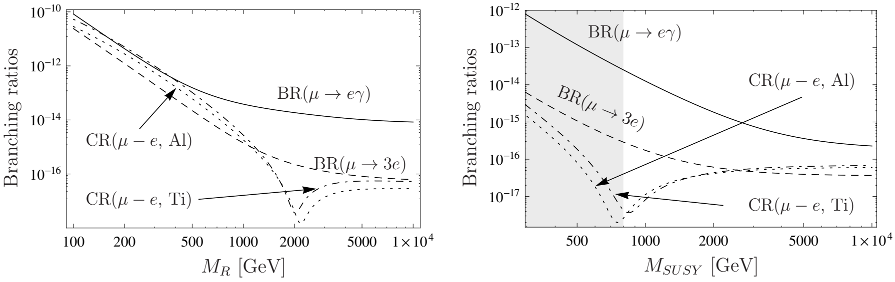
$m_0 = M_{1/2} = 1\text{TeV}, A_0 = -1.5\,\text{TeV}$



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

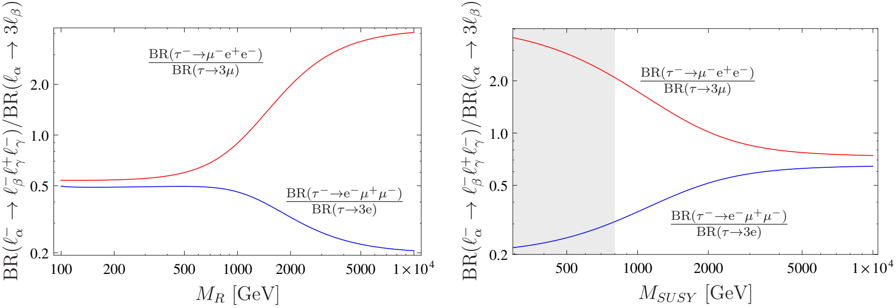
- Saturate current UL: $\text{CR}(\mu - e, \text{Au}) < 7.0 \times 10^{-13}$ [SINDRUM II, 2006]
  Expected sensitivity: 10^{-14} [DeeMe], $10^{-17} - 10^{-18}$ [Mu2e, COMET/PRISM]
- Dips: partial cancellation between up quark and down quark contributions
- Otherwise similar to $\mu \to eee$

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 2017–2018.
- $\mu - e$ conversion: best long-term sensitivity (down to 10^{-18})
  → Should be the most constraining after 2020.

Finding the dominant contribution



- Non-degenerate μ_X and $R \neq \mathbb{1}$: large $\tau - \mu$ rates and ok with $\mu - e$
- cLFV τ decays: factor 100 sensitivity improvement in Belle II
- Ratios: sensitive to the dominant contribution (SUSY or non-SUSY)

Summary of cLFV in the SUSY inverse seesaw

- 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

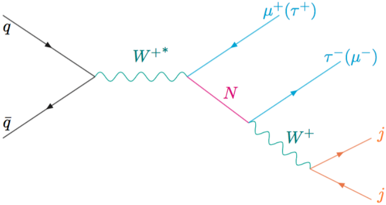
Conclusions

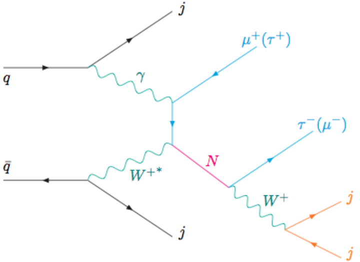
- (SUSY) Inverse seesaw: specific examples of low-scale seesaw mechanisms
- New physics at the TeV scale with large couplings: rich phenomenology
- Complementarity of cLFV lepton decays and Higgs decays because of their different dependence on the seesaw parameters
- Predictions for cLFV decays are already probed
- SUSY ISS could explain the CMS and ATLAS excess in $H \to \tau\mu$
- Next step: combine observables to try and discriminate models

Backup slides

Exotic $\mu\tau jj$ events at the LHC (1508.05074)

- Large Yukawa coupling → large production rate at the LHC
- Missing energy in most of the signals previously considered → background, difficulties to access heavy neutrino mass
- Could consider LFV opposite-sign dilepton signatures → no missing energy, naively background free





Exotic $\mu\tau jj$ events at the LHC (1508.05074)

- Heavy neutrino production: $\sigma \sim \mathcal{O}(1 - 100)\text{fb}$
- Textures $Y^{(1)}_{\tau\mu}$, $Y^{(2)}_{\tau\mu}$, $Y^{(3)}_{\tau\mu}$ enhances $\tau\mu$ final states: up to $\mathcal{O}(100)$ event at LHC run 2+3