Enhancing lepton flavour violation in the (SUSY) inverse seesaw

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Neutrino oscillations

- $P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \neq 0$ only if $\Delta m^2_{kj} = m^2_k - m^2_j$ and $U_\nu \neq \mathbb{1}$
- Best fit (nu-fit.org)

solar	$\theta_{12} \simeq 33^\circ$	$\Delta m^2_{12} \simeq 7.5 \times 10^{-5}\text{eV}^2$
atmospheric	$\theta_{23} \simeq 49^\circ$	$\lvert\Delta m^2_{23}\rvert \simeq 2.4 \times 10^{-3}\text{eV}^2$
reactor	$\theta_{13} \simeq 8.5^\circ$	

- Different mixing pattern from CKM, ν lightness $\overset{?}{\longleftarrow}$ Majorana ν
- SM: no ν mass term, lepton flavour is conserved
  $\Rightarrow$ need new Physics
  - Radiative models
  - Extra dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanism $\rightarrow$ BAU through leptogenesis ?
- Neutrino oscillations = Neutral lepton flavour violation
  What about charged lepton flavour violation (cLFV) ?

cLFV

- 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...

cLFV

- Radiative decays, e.g. $\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]
- 3-body lepton decays,
  e.g. $\tau \to 3\mu < 2.1 \times 10^{-8}$ [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. $B_d^0 \to e\mu < 2.8 \times 10^{-9}$ [LHCb, 2013]
- Z decays, e.g. $Z^0 \to e\mu < 1.7 \times 10^{-6}$ [OPAL, 1995]

Higgs boson: discovery to precision measurements

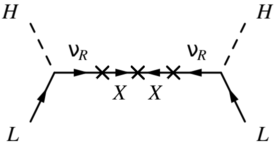
- Discovery of a Higgs boson at the LHC in 2012, with properties compatible with the SM Higgs [ATLAS, 2012; CMS, 2012]
- Evidence for $H \to \tau^+\tau^-$ (CMS: 3.2σ, ATLAS: 4.5σ)
  Active searches of $H \to \mu^-\mu^+$ and $H \to e^+e^-$
- CMS search for $H \to \tau\mu$ [CMS, 2015]: 2.4σ signal excess (best fit: $\mathrm{Br} = 0.84^{+0.39}_{-0.37}\%$, UL: $\mathrm{Br} < 1.51\%$ at 95% CL)
- Timely to consider LFV Higgs decays, e.g. $H \to \bar{\tau}\mu$

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



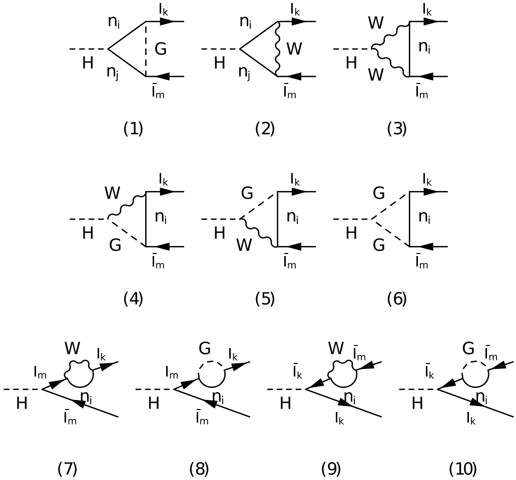
$$m_\nu \approx \frac{m_D^2\mu_X}{m_D^2 + M_R^2}$$

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

2 scales: μ_X (LNV) and M_R (LNC)

Diagrams

- 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

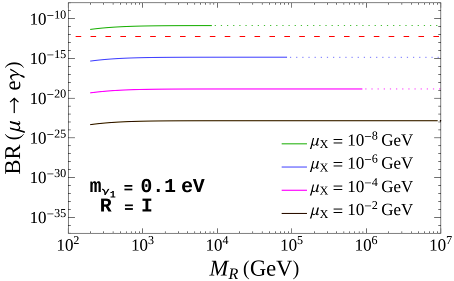
Constraints

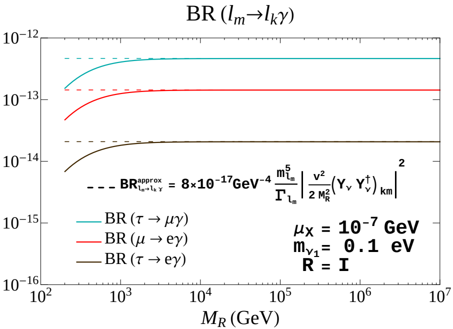
- Neutrino data → Use specific parametrizations (modified Casas-Ibarra [Casas and Ibarra, 2001] or μ_X parametrization)

$$vY_\nu^T = V^\dagger \text{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3})\, R\, \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) U_{PMNS}^\dagger$$
$$M = M_R \mu_X^{-1} M_R^T$$
$$\text{OR}$$
$$\mu_X = M_R^T\, m_D^{-1}\, U_{\text{PMNS}}^* m_\nu U_{\text{PMNS}}^\dagger\, m_D^{T\,-1} M_R$$

- Charged lepton flavour violation → Most constraining: $\text{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [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

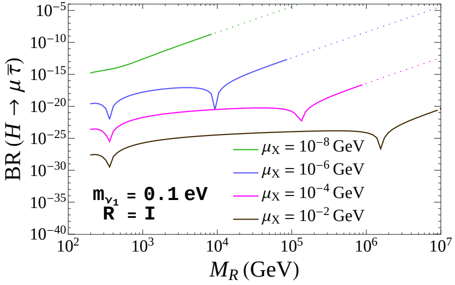
Constraints: focus on $\mu \to e\gamma$

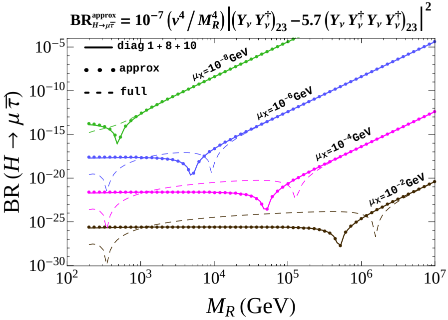




- M_R and μ_X real and degenerate
- Constrains μ_X
- Perturbativity $\to \left|\frac{Y_\nu^2}{4\pi}\right| < 1.5$ (Dotted line = non-perturbative couplings)
- Good agreement between the full calculation and the approximate formula

Dependence on ISS parameters





- M_R and μ_X degenerate and real, $R = I$
- Perturbativity $\to \left|\frac{Y_\nu^2}{4\pi}\right| < 1.5$ (Dotted line = non-perturbative couplings)
- Dips from interferences between diagrams
- Good agreement with the approximate formula
- Can be understood using the mass insertion approximation
- $\mathrm{Br}(H \to \bar{\tau}\mu) \lesssim 10^{-9} - 10^{-10}$

Scenarios with large LFV Higgs decay rates

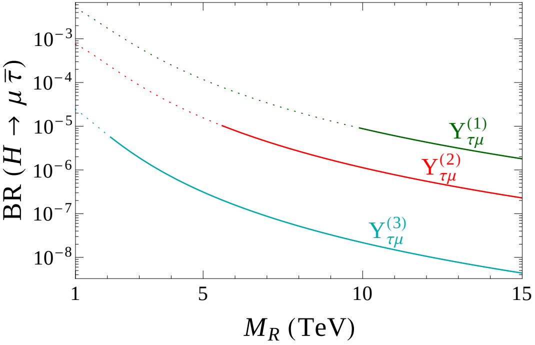
- Strongest experimental constraint: $\mu \to e\gamma$

$$
\begin{aligned}
BR^{\rm approx}_{\mu\to e\gamma} &= 8\times 10^{-17}{\rm GeV}^{-4}\frac{m_\mu^5}{\Gamma_\mu}\left|\frac{{\rm v}^2}{2M_R^2}(Y_\nu Y_\nu^\dagger)_{12}\right|^2 \\
BR^{\rm approx}_{H\to\mu\bar\tau} &= 10^{-7}\frac{{\rm v}^4}{M_R^4}\left|(Y_\nu Y_\nu^\dagger)_{23} - 5.7(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23}\right|^2 \\
&\underset{(Y_\nu Y_\nu^\dagger)_{12}=0}{=} 10^{-7}\frac{{\rm v}^4}{M_R^4}\left|1 - 5.7[(Y_\nu Y_\nu^\dagger)_{22} + (Y_\nu Y_\nu^\dagger)_{33}]\right|^2 \left|(Y_\nu Y_\nu^\dagger)_{23}\right|^2
\end{aligned}
$$

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

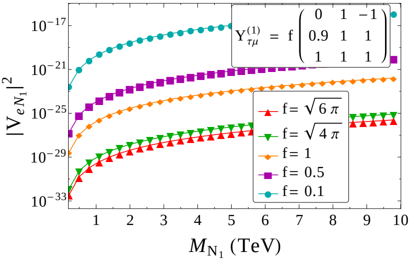
$$
Y_{\tau\mu}^{(1)} = \sqrt{6\pi}\begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix},\;
Y_{\tau\mu}^{(2)} = \sqrt{6\pi}\begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix},\;
Y_{\tau\mu}^{(3)} = \sqrt{6\pi}\begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}
$$

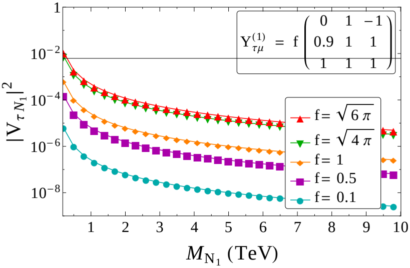
Scenarios with large LFV Higgs decay rates



- Numerics done with the full one-loop formulas
- Dotted: excluded by $\tau \to \mu\gamma$
  Solid: allowed by LFV, LUV, etc
- $\text{Br}^{\text{max}}(H \to \mu\bar{\tau}) \sim 10^{-5}$
- Same maximum branching ratio with hierarchical heavy N
- Similarly, $\text{Br}^{\text{max}}(H \to e\bar{\tau}) \sim 10^{-5}$ for $Y^{(i)}_{\tau e}$ (=$Y^{(i)}_{\tau\mu}$ with rows 1 and 2 exchanged)

Constraints from EWPO (work in progress)





- Active sterile mixing is controlled by $\theta \sim m_D M_R^{-1}$
- Large mixing → possible conflict with EWPO
- Limits taken from [del Aguila et al., 2008] at 90% C.L. :

$$|V_{eN}|^2 < 3.0 \times 10^{-3}$$
$$|V_{\mu N}|^2 < 3.2 \times 10^{-3}$$
$$|V_{\tau N}|^2 < 6.2 \times 10^{-3}$$

- See X. Marcano's poster

Another possibility: SUSY inverse seesaw

- MSSM extended by singlet chiral superfields $\widehat{N}_i$ and $\widehat{X}_i$ $(i = 1, 2, 3)$ with respectively $L = -1$ and $L = +1$
- Defined by the superpotential:

$$\mathcal{W} \quad = \quad W_{MSSM} + \varepsilon_{ab}\widehat{N}Y_\nu \widehat{H}_u^b \widehat{L}^a + \widehat{N}M_R\widehat{X} + \frac{1}{2}\widehat{X}\mu_X\widehat{X}$$

- New couplings, e.g.

$$\tilde{\nu}_R^\dagger (A_\nu Y_\nu)\tilde{\nu}_L H_u^0 + \text{h.c.} \in -\mathcal{L}$$

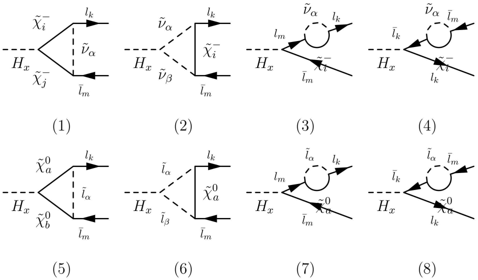
- Light right-handed sneutrinos:

$$M_{\tilde{N}}^2 \simeq m_{\tilde{\nu}_R}^2 + M_R^2 + m_D^2 \sim (1\text{TeV})^2$$

- Could generate large $\text{Br}(h \to \mu\tau)$ [Abada et al., 2012]

LFV Higgs decays in the SUSY ISS

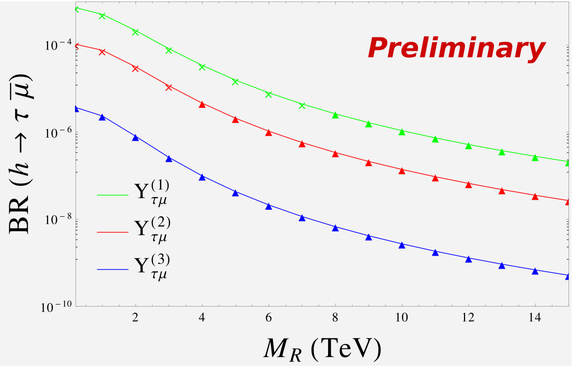
- Work in progress, focus on the supersymmetric contributions



- Chargino contributions induced by $Y^{\nu}_{ij} \neq 0$

- Neutralino contributions require $(\Delta m^2_{\tilde{L}})_{ij} \neq 0$
  $\rightarrow$ from RGE [Hisano et al., 1996]
  $(\Delta m^2_{\tilde{L}})_{ij} \propto (Y^{\dagger}_{\nu} Y_{\nu})_{ij} \ln \frac{M_{GUT}}{M_R}$

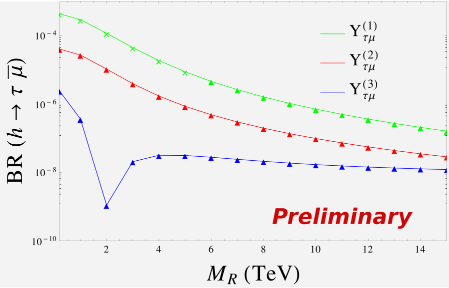
No charged slepton mixing

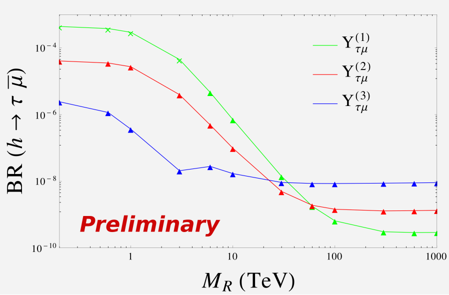


- $\triangle$: Allowed by $\tau \to \mu\gamma$
  $\times$: Excluded
- Dominated by the chargino contributions
- Behaviour similar to the non-SUSY case

- $m_{\tilde{L}} = m_{\tilde{\nu}_R} = m_{\tilde{X}} = 1\,\text{TeV}$, $A_\nu = 0$, $\tan\beta = 10$, $m_{A^0} = 800\,\text{GeV}$

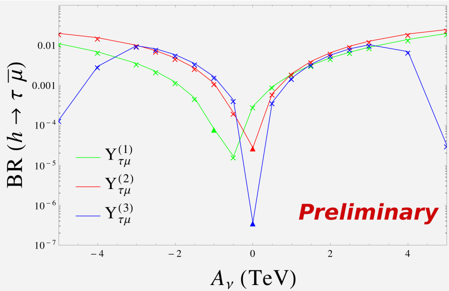
Full SUSY contribution

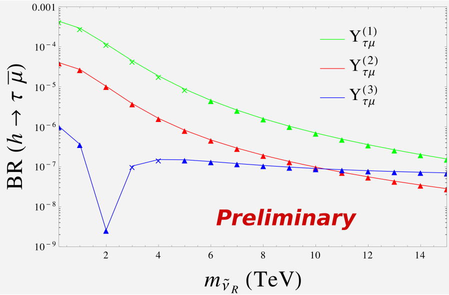




- △: Allowed by $\tau \to \mu\gamma$
  ×: Excluded
- $(\Delta m^2_{\tilde{L}})_{ij} \propto (Y^\dagger_\nu Y_\nu)_{ij} \ln \frac{M_{GUT}}{M_R}$
- Dip for $Y^{(3)}_{\tau\mu}$ → cancellation between chargino and neutralino contributions
- Low M_R : chargino-loops dominate
  High M_R : neutralino-loops dominate
- $m_{\tilde{L}} = m_{\tilde{\nu}_R} = m_{\tilde{X}} = 1\,\text{TeV}$,
  $A_\nu = 0$, $\tan\beta = 10$,
  $m_{A^0} = 800\,\text{GeV}$

Full SUSY contribution





- △: Allowed by $\tau \to \mu\gamma$
  ×: Excluded
- Very sensitive to A_ν
- Low $m_{\tilde{\nu}_R}$: chargino-loops dominate
  High $m_{\tilde{\nu}_R}$: neutralino-loops dominate
- Dip for $Y^{(3)}_{\tau\mu}$ → cancellation between chargino and neutralino contributions
- $m_{\tilde{L}} = 1\,\text{TeV}$, $\tan\beta = 10$,
  $m_{A^0} = 800\,\text{GeV}$
  when not varied $A_\nu = 0$ and
  $m_{\tilde{\nu}_R} = m_{\tilde{X}} = 1\,\text{TeV}$

Conclusions

- cLFV $\Rightarrow$ Clear evidence of new physics
- LFV Higgs decays: complementary to other cLFV searches
- Enhancement from the inverse seesaw
  $\text{Br}(H \to \bar{\tau}\mu) \leqslant 10^{-5}$
  $\text{Br}(H \to \bar{\tau}e) \leqslant 10^{-5}$
- Enhancement from the SUSY inverse seesaw
  $\text{Br}(H \to \bar{\tau}\mu) \simeq 10^{-4} - 10^{-5}$ possible (work in progress)
- In the (SUSY) ISS, $H \to \bar{\tau}\mu$ is within the reach of future colliders
- If CMS signal is confirmed, very strong constraints on the inverse seesaw parameter space

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