LFV Higgs decays in the 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	$\theta_{12} \simeq 34^\circ$	$\Delta m^2_{12} \simeq 7.5 \times 10^{-5} \mathrm{eV}^2$
atmospheric	$\theta_{23} \simeq 42^\circ$	$\lvert\Delta m^2_{23}\rvert \simeq 2.4 \times 10^{-3} \mathrm{eV}^2$
reactor	$\theta_{13} \simeq 8.8^\circ$	

- Different mixing pattern, ν lightness $\stackrel{?}{\longleftarrow}$ Majorana nature
- 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
  Why not 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

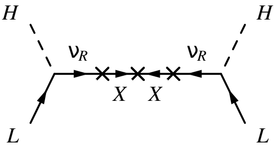
- Discovery of a Higgs boson at LHC in 2012, with properties compatible with the SM Higgs [ATLAS, 2012; CMS, 2012]
- Evidence for $H \to \tau^+\tau^-$ (CMS: 3.2σ, ATLAS: 4.1σ)
  Active searches of $H \to \mu^-\mu^+$ and $H \to e^+e^-$
- Timely to consider LFV Higgs decays, e.g. $H \to \bar{\tau}\mu$
- LHC sensitivity to $\mathrm{Br}(H \to \bar{\tau}\mu)$:
  4.5×10^{-3} with $20\mathrm{fb}^{-1}$ [Davidson and Verdier, 2012]
  8.6×10^{-3} with $20\mathrm{fb}^{-1}$ [Bressler et al., 2014]

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

Effective approach to seesaw mechanisms

- Seesaw mechanism: New fields with a mass $M_R >$ EW scale and Majorana mass terms
  $\Rightarrow$ Generate m_ν in a renormalizable theory and at tree-level
- Notice that lepton number conservation is accidental in the SM
- Unique dimension 5 operator for all seesaw mechanisms
  $\rightarrow$ Violates lepton number L $\Rightarrow$ Majorana neutrinos

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

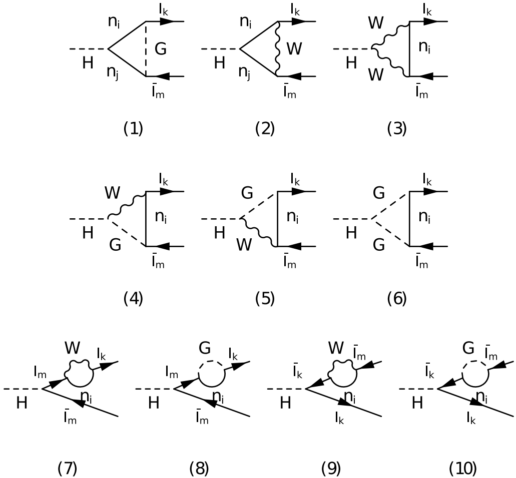
- To distinguish the several seesaw mechanisms, either
  - Directly produce the heavy states (LHC, ILC)
  - Look for dimension $\geqslant 6$ operators effects $\rightarrow$ cLFV, precision test measurements, etc

Inverse seesaw experimental tests

- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1\,\mathrm{TeV}$
  $\Rightarrow$ testable at the LHC and low energy experiments
- LHC/ILC signatures
  - single lepton + dijet + missing energy [Das and Okada, 2012]
  - di-lepton + missing p_T [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013]
  - tri-lepton + missing E_T [Das and Okada, 2012, Mondal et al., 2012]
  - 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, Deppisch et al., 2006]
  - neutrinoless double beta decay
    [Awasthi et al., 2013, Abada and Lucente, 2014]

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 of a modified Casas-Ibarra parametrization [Casas and Ibarra, 2001]

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

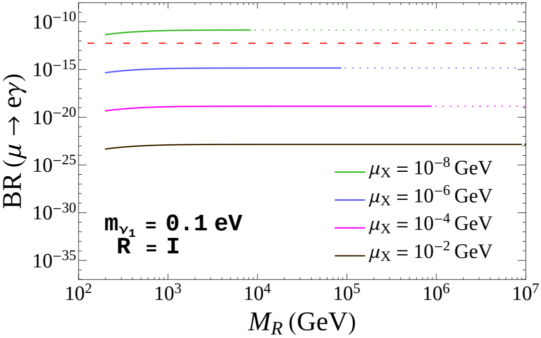
- Charged lepton flavour violation
→ Most constraining: $\text{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ [MEG, 2013]

- 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

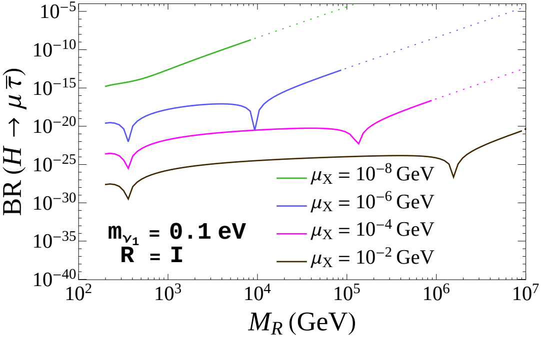
Constraints: focus on $\mu \to e\gamma$



- M_R and μ_X real and degenerate
- Constrains μ_X
- Perturbativity $\to \left|\frac{Y_\nu^2}{4\pi}\right| < 1.5$

- $$\frac{v^2 (Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} \approx \frac{1}{\mu_X} \frac{(U_{\text{PMNS}} \Delta m^2 \; U_{\text{PMNS}}^T)_{km}}{2 m_{\nu_1}}$$

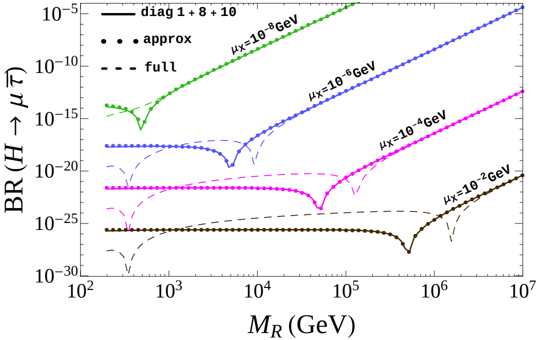
Dependence on ISS parameters



- M_R and μ_X degenerate and real
- Perturbativity $\to \left|\frac{Y_\nu^2}{4\pi}\right| < 1.5$
- Dips come from interferences between diagrams

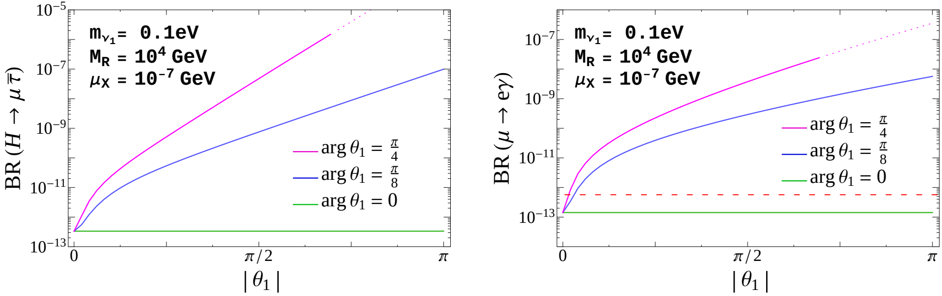
Dependence on ISS parameters

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



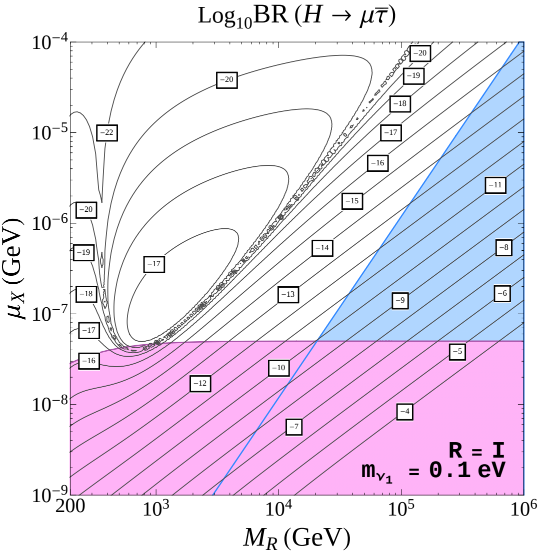
- M_R and μ_X degenerate and real, $R = I$
- $\dfrac{v^2 (Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} \approx \dfrac{1}{\mu_X} \dfrac{(U_{\mathrm{PMNS}} \Delta m^2\ U_{\mathrm{PMNS}}^T)_{km}}{2 m_{\nu_1}}$
- $\dfrac{v^2 (Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{km}}{M_R^2} = \dfrac{M_R^2 (U_{\mathrm{PMNS}} \Delta m^2\ U_{\mathrm{PMNS}}^T)_{km}}{v^2 \mu_X^2}$
- Can be understood using the mass insertion approximation

Dependence on ISS parameters



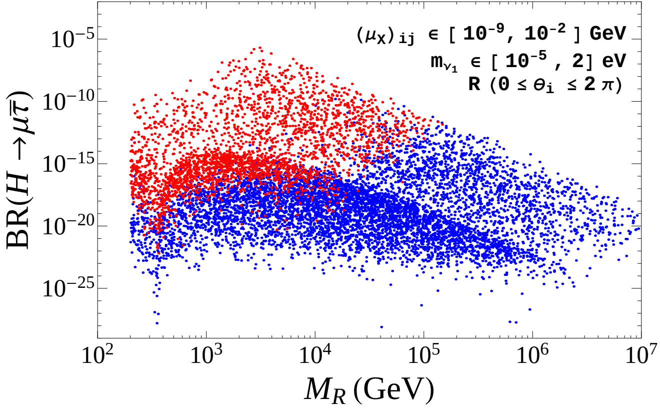
- M_R and μ_X degenerate and real
- Independent of R for real mixing angles
- Increase with complex angles, but increase limited by $\mu \to e\gamma$
  $\Rightarrow$ Complex R matrix doesn't change our results

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



- M_R and μ_X degenerate and real
- Excluded by $\mu \to e\gamma$
  Non-perturbative Y_ν
- $\mathrm{Br}(H \to \bar{\tau}\mu) \lesssim 10^{-10}$

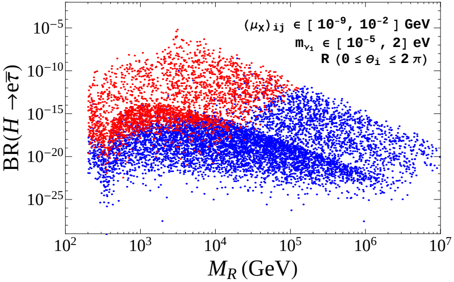
Full scan: $H \to \bar{\tau}\mu$

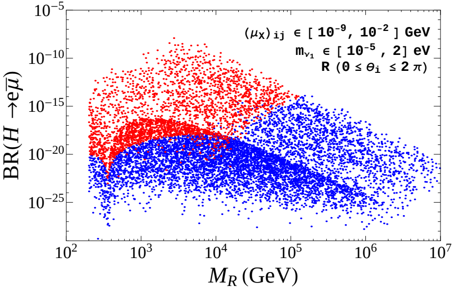


- M_R and μ_X real and random
- No gain in a complex scenario

- Excluded by constraints
  Agree with all constraints
- $\mathrm{Br}(H \to \bar{\tau}\mu) \lesssim 10^{-10}$

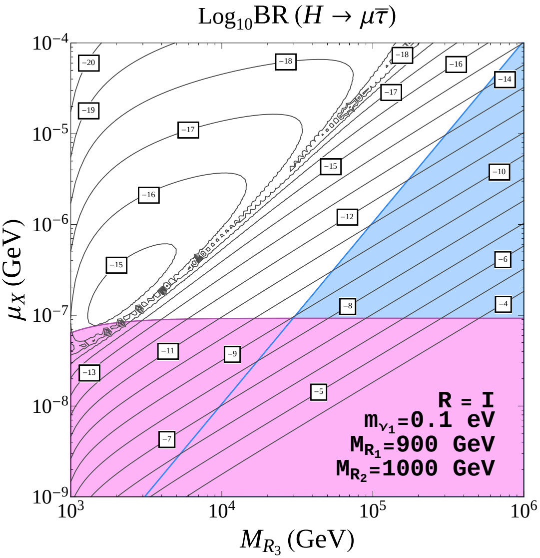
Full scan: $H \to \bar{\tau} e$ and $H \to e \bar{\mu}$





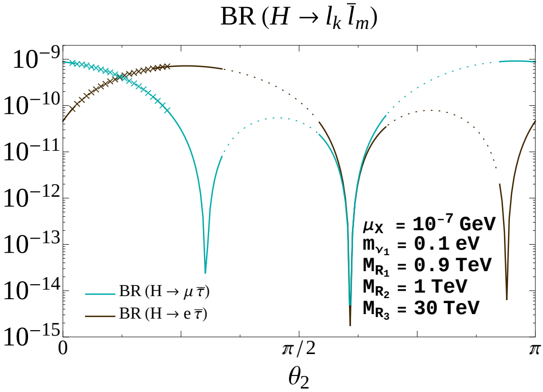
- μ_X real and random
  M_R diagonal and degenerate
- Excluded by constraints
  Agree with all constraints
- $\mathrm{Br}(H \to \bar{\tau} e) \leqslant 10^{-10}$
  $\mathrm{Br}(H \to \bar{\mu} e) \leqslant 10^{-13}$
- No gain in a complex scenario

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
- $\mathrm{Br}(H \to \bar{\tau}\mu) \lesssim 10^{-9}$

Impact of the R matrix



- Contrary to degenerate case, R dependence
- Varying θ_1: Same conlusions as before
- $\theta_2 \sim \pi/4$: $\text{Br}(H \to e\bar{\tau}) > \text{Br}(H \to \mu\bar{\tau})$
- Results quite insensitive to θ_3

Conclusions

- cLFV $\Rightarrow$ Clear evidence of new physics
- LFV Higgs decays: complementary to other cLFV searches
- Enhancement from the inverse seesaw
  but largest values excluded by $\mu \to e\gamma$
- $\mathrm{Br}(H \to \bar{\tau}\mu) \leqslant 10^{-9} - 10^{-10}$
  $\mathrm{Br}(H \to \bar{\tau}e) \leqslant 10^{-9} - 10^{-10}$
  $\mathrm{Br}(H \to \bar{\mu}e) \leqslant 10^{-13} - 10^{-14}$
- In the inverse seesaw, LFV Higgs decays allowed by radiative LFV bounds seem not to be reachable at LHC

Backup slides

Scan method

- Inverse seesaw as an illustrative example, only one among other possibilities
- Random scan on M_R and μ_X entries
- Y_ν obtained from neutrino data via the Casas-Ibarra parametrization [Casas and Ibarra, 2001]

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

where R is a complex orthogonal matrix and V a unitary matrix that decompose $M = M_R \mu_X^{-1} M_R^T$ according to $M = V^\dagger \mathrm{diag}(M_1\,, M_2\,, M_3) V^*$.

- Apply the constraints

Leptogenesis

- Generate the baryonic (leptonic) asymmetry → Sakharov conditions [Sakharov, 1967]
  - Out of equilibrium process
  - Baryon (lepton) number violation
  - C and CP violation

- Impossible in the Standard Model: not enough CP violation [Gavela et al., 1994]

- Use the leptonic sector
  - Majorana mass term violates lepton number conservation ⇒ Passed to the baryonic sector via sphalerons ($B-L$ conserving)
  - Neutrinos mass matrix ⇒ Extra sources of CP violation ($\delta_{13}, \alpha_{1,2}$)