

LFV signatures of heavy neutrinos at the LHC

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Motivations

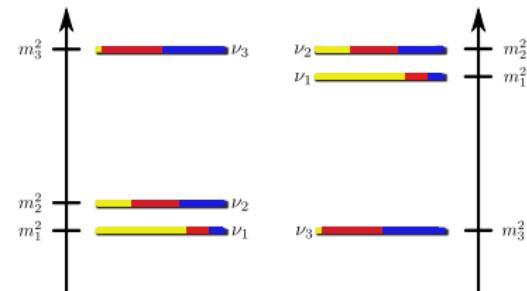
- Neutrino oscillations (best fit from nu-fit.org):

solar $\nu_e \rightarrow \nu_{\text{others}}$: $\theta_{12} \simeq 33^\circ$, $\Delta m_{21}^2 \simeq 7.5 \times 10^{-5} \text{ eV}^2$

atmospheric $\overset{(-)}{\nu_\mu} \rightarrow \overset{(-)}{\nu_\tau}$: $\theta_{23} \simeq 49^\circ$, $|\Delta m_{23}^2| \simeq 2.4 \times 10^{-3} \text{ eV}^2$

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

accelerator $\nu_\mu \rightarrow \nu_{\text{others}}$



- Different mixing pattern from CKM, ν lightness $\xleftarrow{?}$ Majorana ν
- SM: no ν mass term, lepton flavour is conserved
⇒ need new Physics
 - Radiative models
 - Extra dimensions
 - R-parity violation in supersymmetry
 - Seesaw mechanism → ν mass at tree-level
 - + BAU through leptogenesis
- Low-scale seesaw mechanisms
→ no naturalness problem from heavy neutrinos

The inverse seesaw mechanism

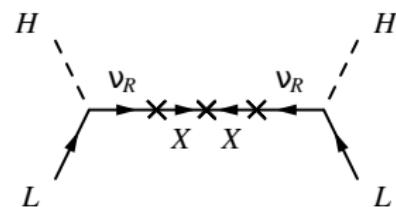
- Inverse seesaw \Rightarrow Consider fermionic gauge singlets ν_{Ri} ($L = +1$) and X_i ($L = -1$) [Mohapatra and Valle, 1986]

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

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

A rich phenomenology

- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1 \text{ TeV}$
⇒ testable at the LHC and low energy experiments
- LHC/LC signatures
 - single lepton + dijet + missing energy [Das and Okada, 2013]
 - di-lepton + missing p_T [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013]
 - LFV di-lepton + dijet [PLB752(2016)46]
 - 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 (LFV) [Bernabéu et al., 1987]...
 - neutrinoless double beta decay [Awasthi et al., 2013]...
 - charged lepton anomalous magnetic moment [Abada et al., 2014]

An aside on LFV Higgs decays

- $h \rightarrow \tau\mu$: 2.4 σ excess in CMS, $\text{Br} = 0.84^{+0.39\%}_{-0.37\%}$ [PLB749(2015)337]
1.3 σ excess in ATLAS, $\text{Br} = 0.77 \pm 0.62\%$ [JHEP1511(2015)211]
- Very stringent constraints from other LFV processes, e.g.

$$\text{BR}(\mu \rightarrow e\gamma) \leq 5.7 \times 10^{-13} \quad [\text{MEG, 2013}]$$

$$\text{BR}(\tau \rightarrow e\gamma) \leq 3.3 \times 10^{-8} \quad [\text{BaBar, 2010}]$$

$$\text{BR}(\tau \rightarrow \mu\gamma) \leq 4.4 \times 10^{-8} \quad [\text{BaBar, 2010}]$$

- Approximate formulas for the ISS with large Y_ν

[Arganda, Herrero, Marcano and CW, PRD91(2015)015001]

$$\text{BR}_{l_m \rightarrow l_k \gamma} \simeq 8 \times 10^{-17} \frac{m_{l_m}^5}{\Gamma_{l_m}} \left| \frac{v^2}{2M_R^2} (Y_\nu Y_\nu^\dagger)_{km} \right|^2$$

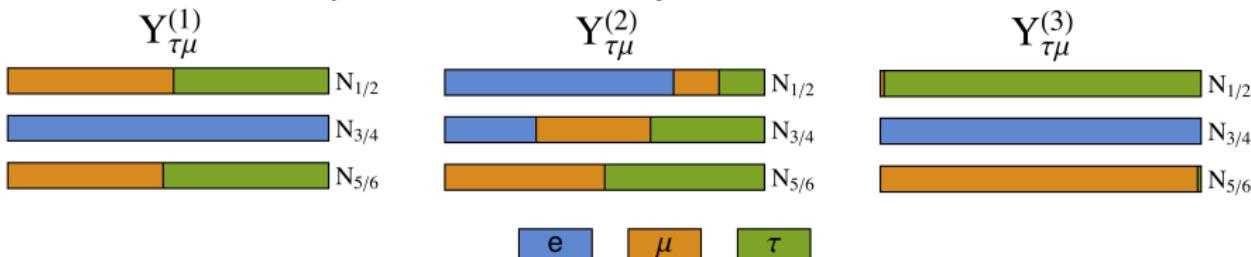
$$\text{BR}_{h \rightarrow \mu \bar{\tau}} \simeq 10^{-7} \frac{v^4}{M_R^4} \left| (Y_\nu Y_\nu^\dagger)_{23} - 5.7 (Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23} \right|^2$$

Producing large $h \rightarrow \tau\mu$ rates

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

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

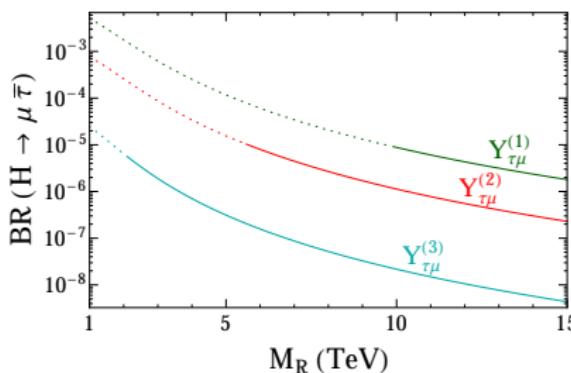
- Flavour composition of the heavy neutrinos:



- 3 very different flavour patterns
- Heavy neutrino mixing of $\tau - \mu$ type is always present

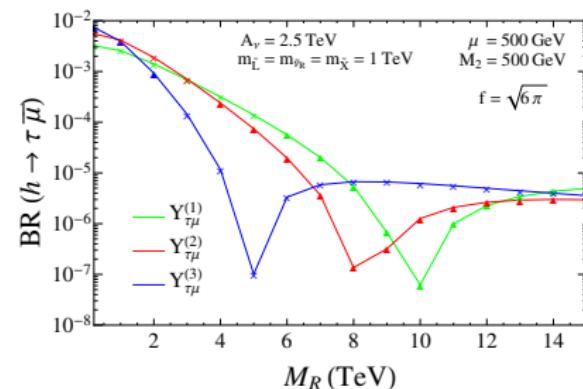
$h \rightarrow \tau\mu$ in the (SUSY) ISS

- $f = \sqrt{6\pi}$, M_R real, degenerate, ν oscillations reproduced by μ_X



[PRD91(2015)015001]

- Dotted: excluded by $\tau \rightarrow \mu\gamma$
Solid: allowed by LFV, LUV...
- $\text{Br}^{\max}(h \rightarrow \mu\bar{\tau}) \sim 10^{-5}$
- Can be probed at the HL-LHC and future colliders



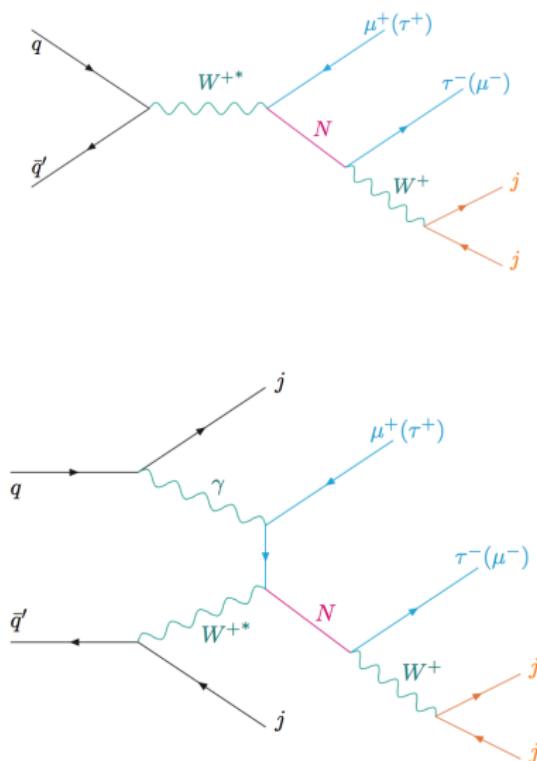
[arXiv:1508.04623]

- \times : excluded by $\tau \rightarrow \mu\gamma$
 \blacktriangle : allowed
- $\text{Br}^{\max}(h \rightarrow \mu\bar{\tau}) = \mathcal{O}(1\%)$
- SUSY loops could explain the CMS and ATLAS excesses



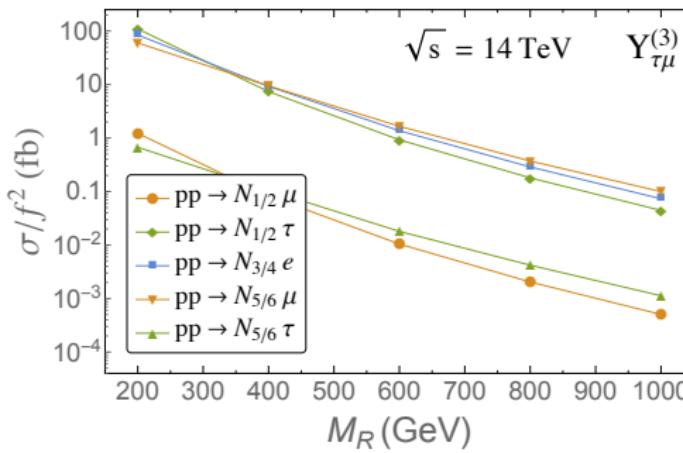
Heavy neutrinos production and decays at the LHC

[PLB752(2016)46]

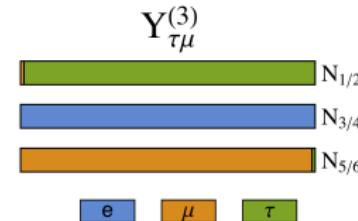


- Main production channel: Drell-Yan
 - $\tau - \mu$ mixing in N
 $\Rightarrow \mu^\pm \tau^\mp jj$ with $M_{jj} = M_W$
 - $W\gamma$ fusion relevant at large M_R [Dev et al., 2014, Alva et al., 2015]
 - Contribute to $\mu^\pm \tau^\mp jj$ signal if extra-jets are soft or collinear
 $\rightarrow p_T < p_T^{\max}$
 - Numerics done with MadGraph5 and NNPDFQED, M_R real and degenerate
 - Similar results with CTEQ PDF set

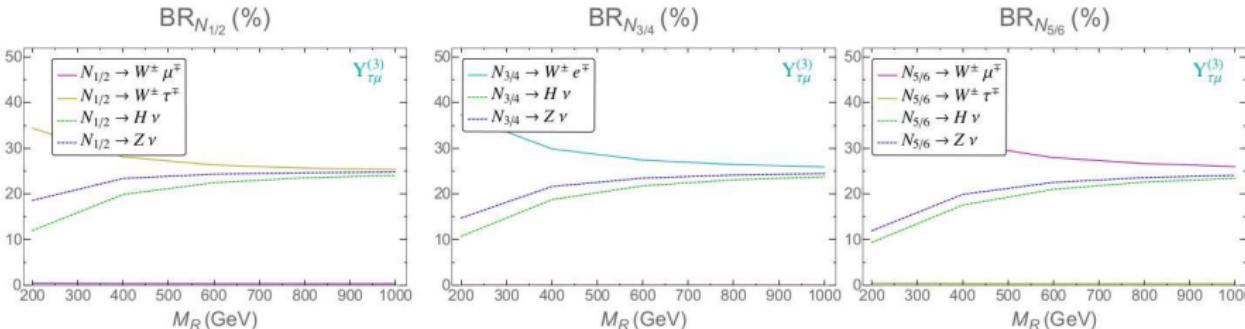
Production and decays at LHC14



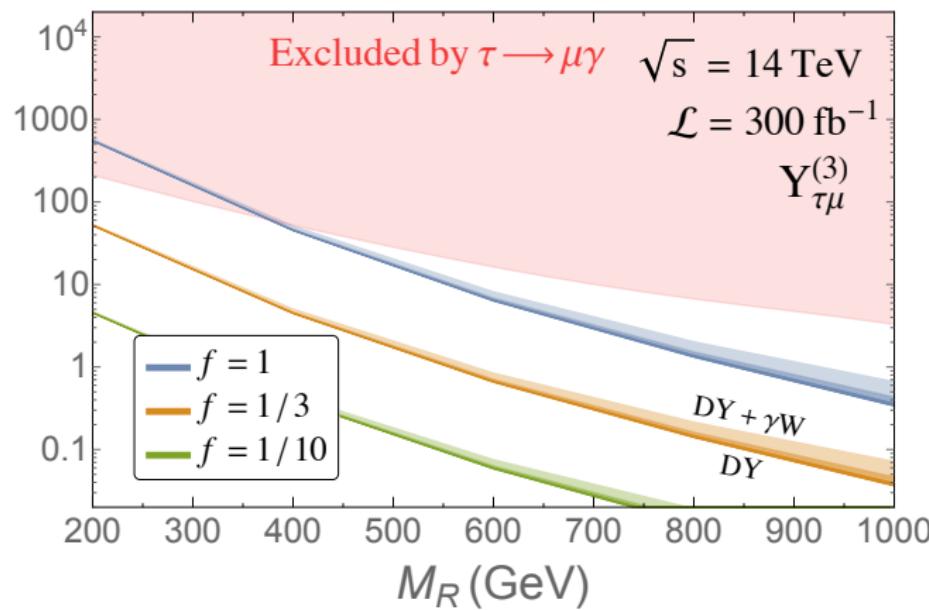
- Large production at LHC14:
 $\sigma \sim 0.1 - 100\text{fb}$
- Associated lepton depends on N_i



- Decays behave similarly

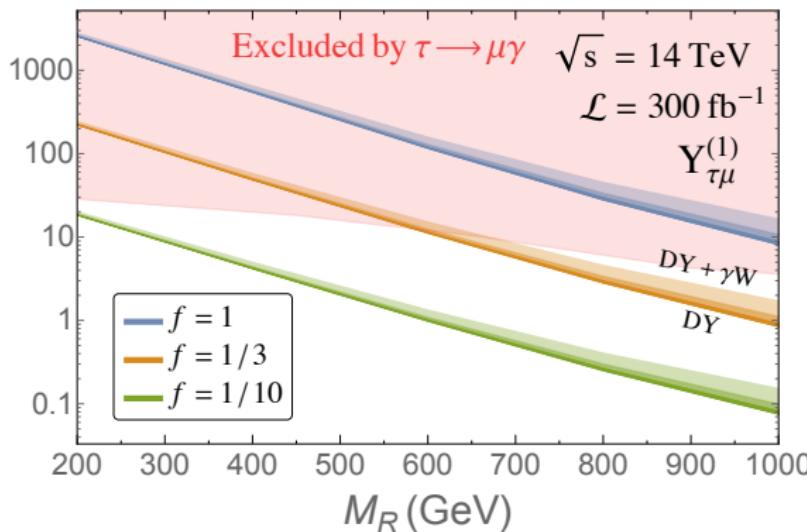
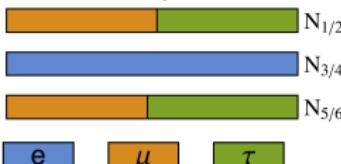


$pp \rightarrow \mu\tau jj$ events at LHC14 for $Y_{\tau\mu}^{(3)}$



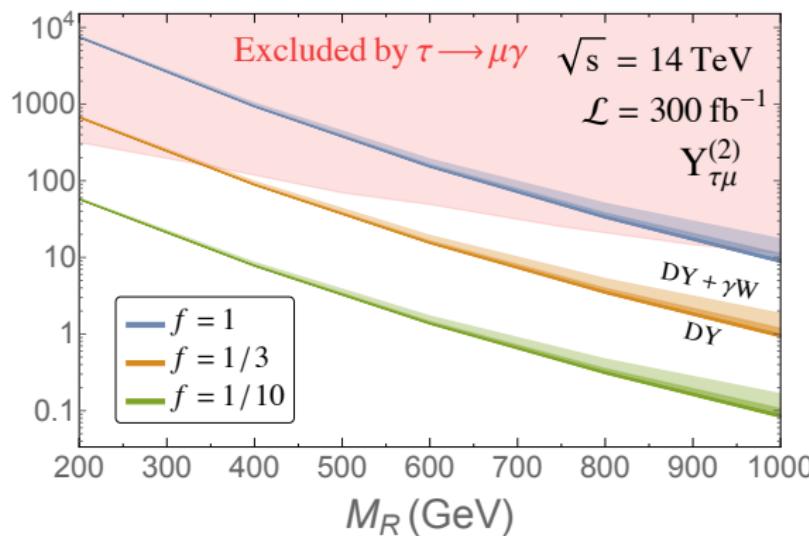
- Lower line: production only from Drell-Yan
Shaded regions: $W\gamma$ fusion added with $p_T^{\max} = 10, 20, 40 \text{ GeV}$
(darker to lighter)
- Up to $\mathcal{O}(100)$ events

$pp \rightarrow \mu\tau jj$ events at LHC14 for $Y_{\tau\mu}^{(1)}$

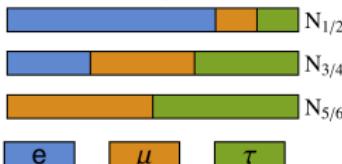

 $Y_{\tau\mu}^{(1)}$


- Lower line: production only from Drell-Yan
Shaded regions: $W\gamma$ fusion added with $p_T^{\max} = 10, 20, 40 \text{ GeV}$ (darker to lighter)
- Up to $\mathcal{O}(10)$ events

$pp \rightarrow \mu\tau jj$ events at LHC14 for $Y_{\tau\mu}^{(2)}$



$Y_{\tau\mu}^{(2)}$



- Lower line: production only from Drell-Yan
Shaded regions: $W\gamma$ fusion added with $p_T^{\max} = 10, 20, 40$ GeV (darker to lighter)
- Up to $\mathcal{O}(200)$ events

Conclusions

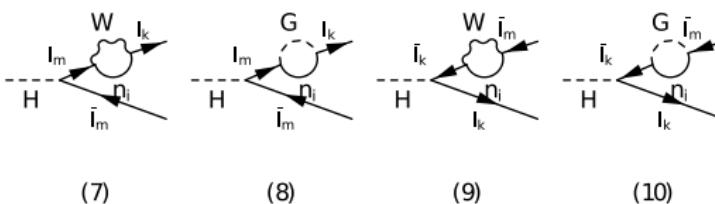
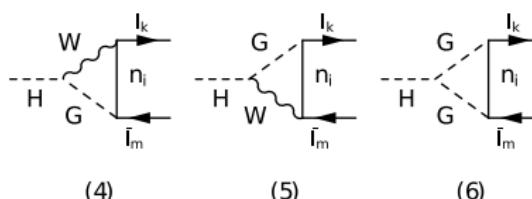
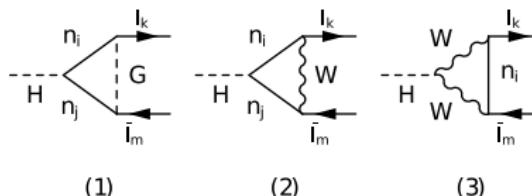
- (SUSY) Inverse seesaw: specific examples of low-scale seesaw mechanisms
- New physics at the TeV scale with large couplings: rich phenomenology
- SUSY loops could explain the CMS and ATLAS excess in $h \rightarrow \tau \mu$
- Exotic LFV $\mu\tau jj$ signal with $M_{jj} = M_W$, expected to be easily distinguishable from the background
- 10-200 events would be expected at LHC14
- Next step: - Consider $e\tau jj$ and $e\mu jj$ final states
 - Estimate the signal/background ratio via detector level studies

Backup slides

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)

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

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

OR

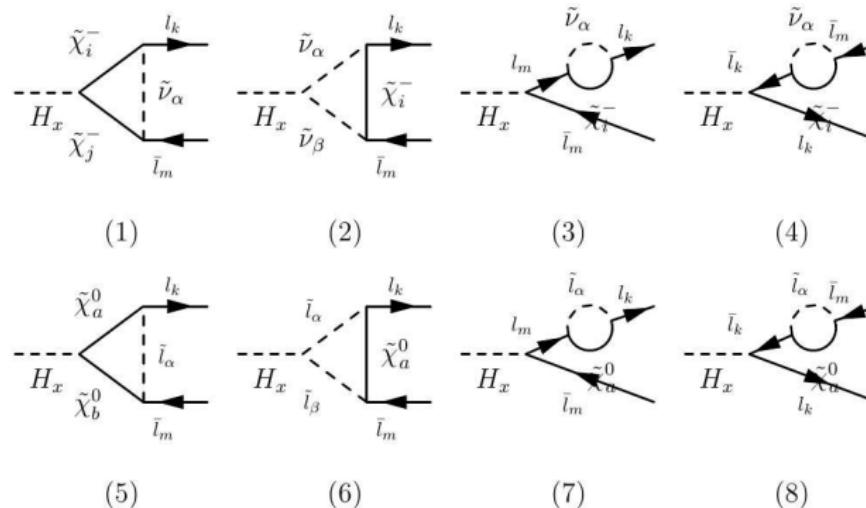
$$\mu_X = M_R^T m_D^{-1} U_{PMNS}^* m_\nu U_{PMNS}^\dagger m_D^{T^{-1}} M_R$$

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

cLFV Higgs decays from SUSY loops

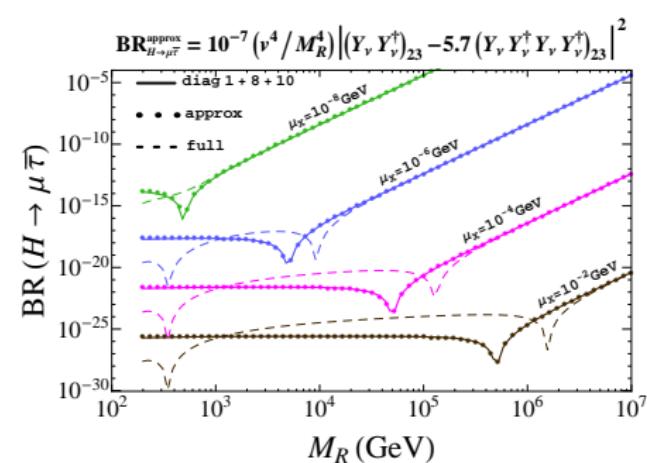
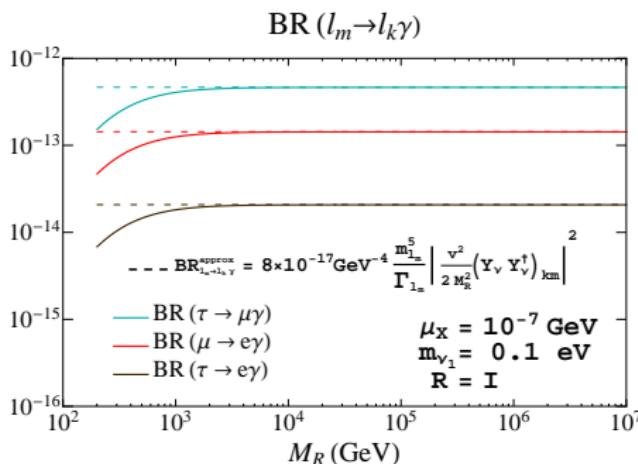
(arXiv:1508.04623)

- 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 $\tilde{\nu}$

Approximate formulas for LFV in the ISS



- M_R and μ_X real and degenerate

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

