Exotic LFV events at the LHC

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Motivations

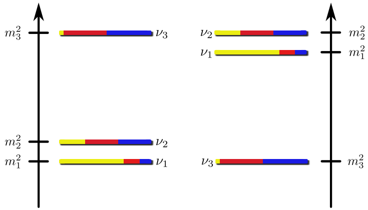
- Neutrino oscillations (best fit from nu-fit.org):

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

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

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

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



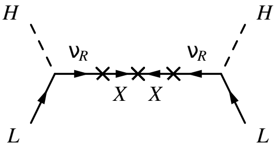
- Different mixing pattern from CKM, ν lightness $\overset{?}{\longleftarrow}$ Majorana ν
- SM: no ν mass term, lepton flavour is conserved
  $\Rightarrow$ need new Physics
  - Radiative models
  - Extra dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanism $\to$ ν mass at tree-level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

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

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

A rich phenomenology

- 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/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 [1508.05074]
  - 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

- $h \to \tau\mu$: 2.4σ excess in CMS, $\mathrm{Br} = 0.84^{+0.39}_{-0.37}\%$ [Khachatryan et al., 2015]
  1.3σ excess in ATLAS, $\mathrm{Br} = 0.77 \pm 0.62\%$ [1508.03372]
- Very stringent constraints from other LFV processes, e.g.

$$\mathrm{BR}(\mu \to e\gamma) \leqslant 5.7 \times 10^{-13} \quad [\mathrm{MEG}, 2013]$$
$$\mathrm{BR}(\tau \to e\gamma) \leqslant 3.3 \times 10^{-8} \quad [\mathrm{BaBar}, 2010]$$
$$\mathrm{BR}(\tau \to \mu\gamma) \leqslant 4.4 \times 10^{-8} \quad [\mathrm{BaBar}, 2010]$$

- Approximate formulas for the ISS with large Y_ν

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

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

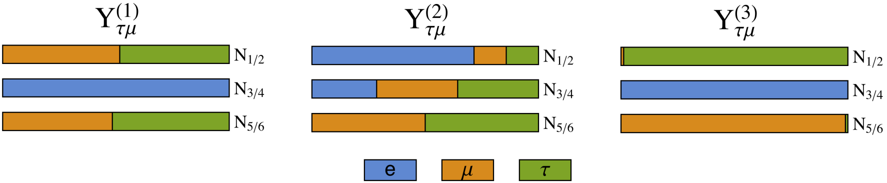
$$\mathrm{BR}_{h \to \mu\bar{\tau}} \simeq 10^{-7} \frac{v^4}{M_R^4} \left| (Y_\nu Y_\nu^\dagger)_{23} - 5.7 (Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23} \right|^2$$

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

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

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

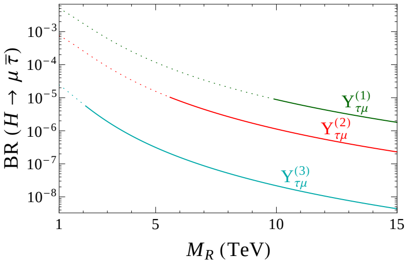
- Flavour composition of the heavy neutrinos:



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

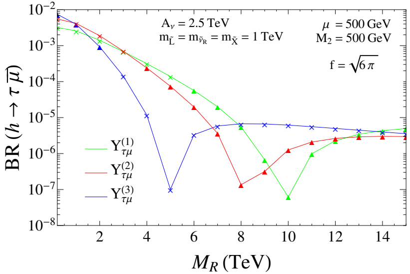
$h \to \tau\mu$ in the (SUSY) ISS

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



[PRD91(2015)015001]

- Dotted: excluded by $\tau \to \mu\gamma$
  Solid: allowed by LFV, LUV...
- $\mathrm{Br}^{\max}(h \to \mu\bar{\tau}) \sim 10^{-5}$
- Same with hierarchical heavy neutrinos

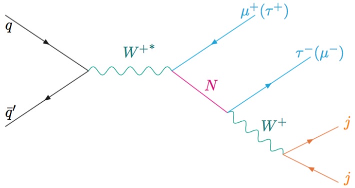


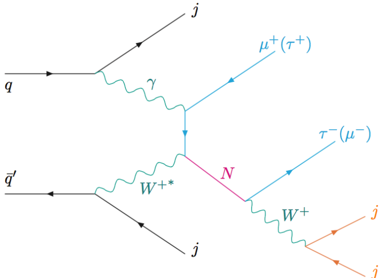
[arXiv:1508.04623]

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

Heavy neutrinos production and decays at the LHC

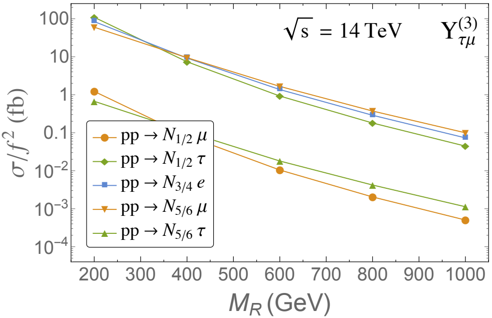
[1508.05074]



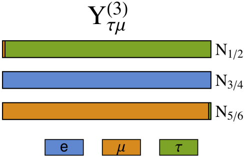


- Main production channel: Drell-Yan
- $\tau - \mu$ mixing in N $\Rightarrow \mu^\pm\tau^\mp jj$ signal with no $\not{E}_T$
- $W\gamma$ fusion relevant at large M_R [Dev et al., 2014, Alva et al., 2015]
- Contribute to $\mu^\pm\tau^\mp jj$ signal if extra-jets are soft or collinear $\to p_T < p_T^{\max}$
- Numerics done with MadGraph5 and NNPDFQED, M_R real and degenerate
- Similar results with other PDF sets

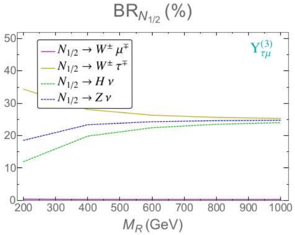
Production and decays at LHC14

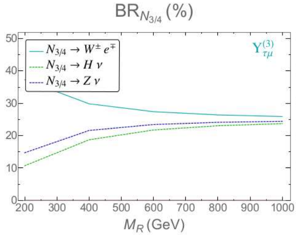


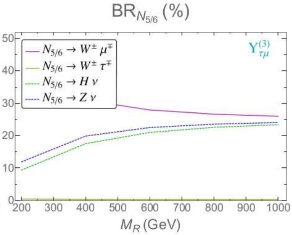
- Large production at LHC14: $\sigma \sim 0.1 - 100$fb
- Associated lepton depends on N_i



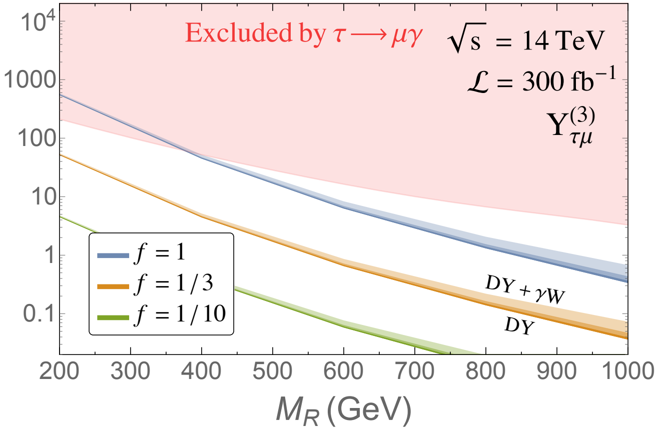
- Decays behave similarly





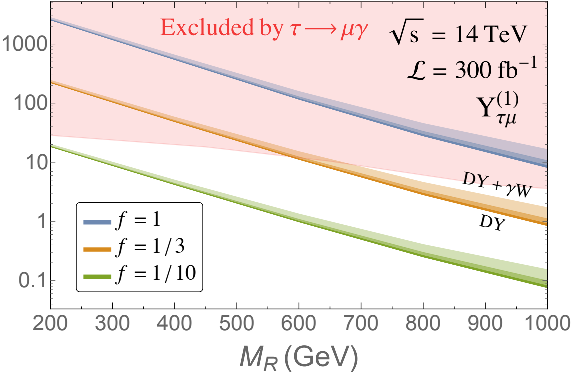


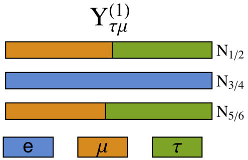
$pp \to \mu\tau jj$ events at LHC14 for $Y^{(3)}_{\tau\mu}$



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

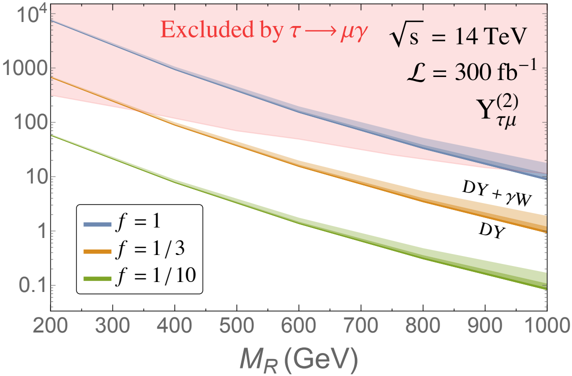
$pp \to \mu\tau jj$ events at LHC14 for $Y^{(1)}_{\tau\mu}$

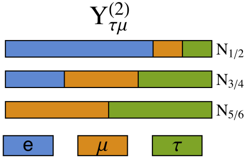




- Lower line: production only from Drell-Yan
  Shaded regions: $W\gamma$ fusion added with $p_T^{max} = 10\,, 20\,, 40\,\mathrm{GeV}$ (darker to lighter)
- Up to $\mathcal{O}(10)$ events, naively background free

$pp \to \mu\tau jj$ events at LHC14 for $Y^{(2)}_{\tau\mu}$





- 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, naively background free

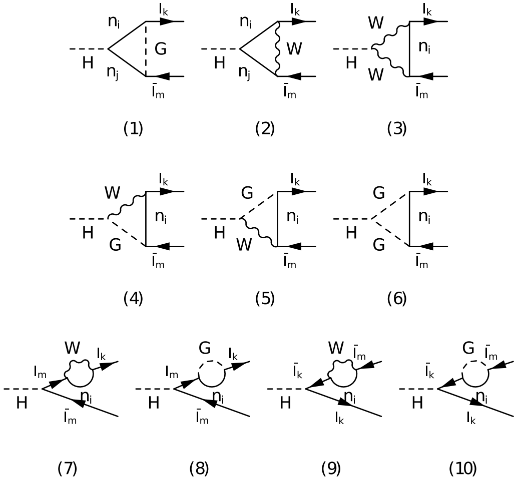
Conclusions

- (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 $h \to \tau\mu$
- Exotic LFV $\mu\tau jj$ signal with no $\not{E}_T$ and $M_{jj} = M_W$, naively background free
- 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)

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

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

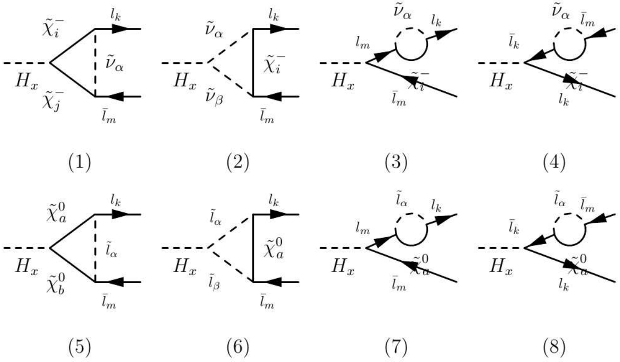
$$\text{OR}$$

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

- Charged lepton flavour violation → 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

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 $\tilde{\nu}$