

Heavy Neutrino LFV Phenomenology in the Inverse Seesaw Model

Xabier Marcano

Instituto de Física Teórica, Universidad Autónoma de Madrid/CSIC

xabier.marcano@uam.es

August, 28th 2015
SUSY 15, Lake Tahoe



Instituto de
Física
Teórica
UAM-CSIC



References

Work in collaboration with **E. Arganda, M.J. Herrero and C. Weiland**:

- E. Arganda, M.J. Herrero, XM, C. Weiland, PRD91(2015)1,05001
“Imprints of massive inverse seesaw model neutrinos in lepton flavor violating Higgs boson decays”
- E. Arganda, M.J. Herrero, XM, C. Weiland, arXiv:1508.04623
“Enhancement of the LFV Higgs decay rates from SUSY loops in the Inverse Seesaw Model”
- E. Arganda, M.J. Herrero, XM, C. Weiland, arXiv:1508.05074
“Exotic $\mu\tau jj$ events from heavy ISS neutrinos at the LHC”

Motivation

Low scale seesaw models

- Accommodate light neutrino data
- Allow large neutrino Yukawa couplings, $Y_\nu^2/4\pi \sim \mathcal{O}(1)$
- with heavy neutrino masses at $M_N \sim \mathcal{O}(1 \text{ TeV})$

New phenomenology

- Lepton Flavor Violation (LFV): radiative decays, H decays, ...
- **SUSY** could enhance the LFV rates even more
- Heavy neutrinos reachable at LHC

Usual Heavy neutrino searches at colliders

- Majorana neutrinos: same-sign di-lepton signals
- Dirac neutrinos: tri-lepton signals
- **We will focus on LFV opposite-sign di-lepton signals**

The Inverse Seesaw Model

[Mohapatra and Valle, 1986]

SM extended with 6 fermionic singlets: $3 \times \left\{ \nu_R(L = +1) \& X(L = -1) \right\}$

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

- M_R is lepton number conserving.
- μ_X is a lepton number violating Majorana mass matrix.

After EWSB, the 9×9 neutrino mass matrix reads

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

In the one generation case, the mass eigenvalues are given by:

$$m_\nu = \frac{m_D^2}{m_D^2 + M_R^2} \mu_X, \quad M_{N_1, N_2} = \pm \sqrt{M_R^2 + m_D^2} + \mathcal{O}(\mu_X)$$

Interesting features of the ISS

- Neutrino mass spectrum for 3 generations: 3 light neutrinos and 6 heavy neutrinos with masses of $m_N \sim M_R \sim \mathcal{O}(\text{TeV})$.
- Successfully accommodate low energy neutrino masses and oscillations.
- Smallness of light neutrino masses is associated with the smallness of lepton number violating parameter μ_X (in contrast to Type-I seesaw),

$$M_{\text{light}}^{\text{ISS}} \approx m_D M_R^{-1} \mu_X M_R^{-1} m_D^T$$

$$M_{\text{light}}^{\text{Type-I}} \approx m_D M^{-1} m_D^T$$

- The new scale μ_X decouples the LFV effects from low energy neutrino data.

New particle content \implies New Phenomenology

6 heavy Majorana neutrinos, quasi degenerate in (pseudo-Dirac) pairs

$$N_{1/2}, N_{3/4}, N_{5/6}$$

whose masses, driven by M_R , can be in the TeV range for $Y_\nu^2/4\pi \sim \mathcal{O}(1)$

LFV in the ISS

CMS found 2.4σ excess: $\text{BR}(H \rightarrow \tau\mu) = 0.84^{+0.39\%}_{-0.37\%} \text{ (95\%CL)}$ [PLB749(2015)337-362]
ATLAS found 1.3σ excess: $\text{BR}(H \rightarrow \tau\mu) = 0.77 \pm 0.62\% \text{ (95\%CL)}$ [arXiv:1508.03372]

Approximate formulas in the large Y_ν limit

E. Arganda, M.J. Herrero, XM, C. Weiland, PRD91(2015)1,05001

$$\begin{aligned}\text{BR}(l_m \rightarrow l_k \gamma) &\approx 4 \times 10^{-17} \frac{m_{l_m}^5 \text{ (GeV}^5)}{\Gamma_{l_m} \text{ (GeV)}} \frac{v^4}{M_R^4} \left| (Y_\nu Y_\nu^\dagger)_{km} \right|^2 \\ \text{BR}(H \rightarrow \mu \bar{\tau}) &\approx 10^{-7} \frac{v^4}{M_R^4} \left| (Y_\nu Y_\nu^\dagger)_{23} - 5.7 (Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{23} \right|^2\end{aligned}$$

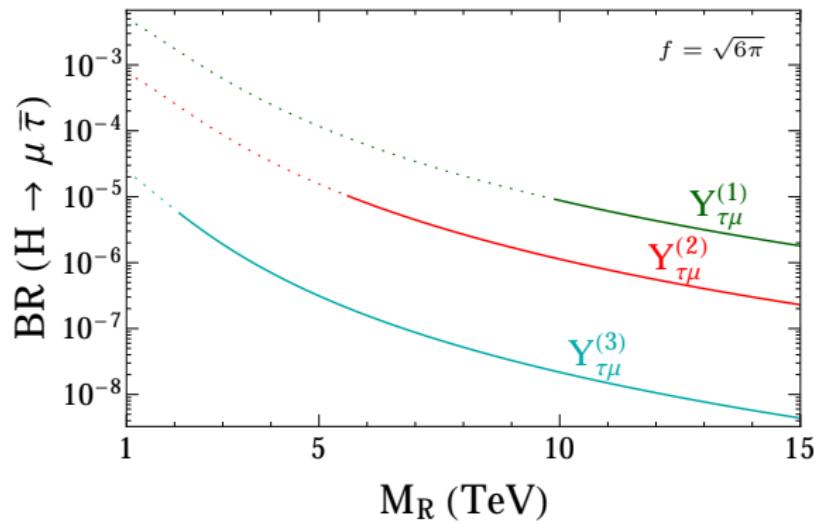
They behave differently. Large rates, $\text{BR}(H \rightarrow \mu \bar{\tau}) \sim 10^{-4}$ for $|Y_\nu|^2/4\pi \sim 1$ and $M_R \sim 1 \text{ TeV}$, nevertheless they are bounded by the upper limits on radiative decays, especially by $\mu \rightarrow e \gamma$

$$\begin{aligned}\text{BR}(\mu \rightarrow e \gamma) &\leq 5.7 \times 10^{-13} \text{ [MEG, 2013]} \\ \text{BR}(\tau \rightarrow e \gamma) &\leq 3.3 \times 10^{-8} \text{ [BABAR, 2010]} \\ \text{BR}(\tau \rightarrow \mu \gamma) &\leq 4.4 \times 10^{-8} \text{ [BABAR, 2010]}\end{aligned}$$

Maximum allowed LFV $H \rightarrow \tau\mu$ in the ISS

Scenarios in the ISS allowing for maximum LFVHD rates and being compatible with the LFV radiative decays

$$\text{BR}(H \rightarrow \mu\bar{\tau})_{\max}^{\text{ISS}} \sim 10^{-5}$$



Examples suppressing μe and τe mixing

$$Y_{\tau\mu}^{(1)} = f \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

$$Y_{\tau\mu}^{(2)} = f \begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix}$$

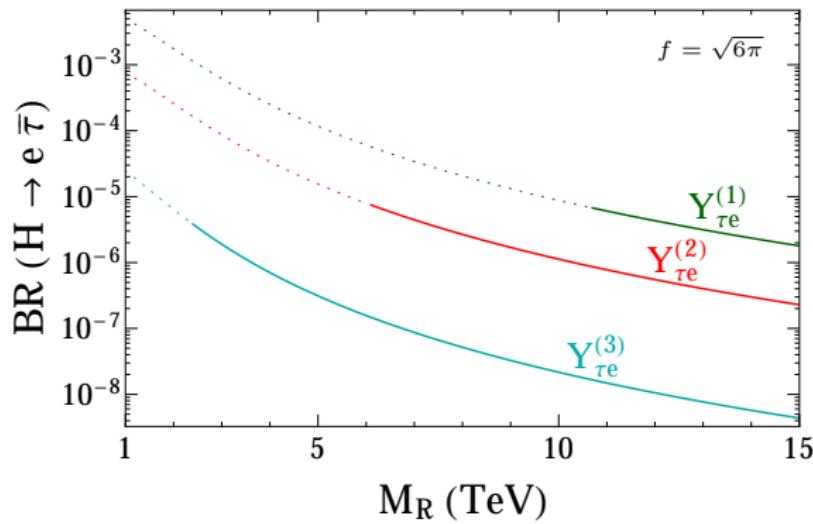
$$Y_{\tau\mu}^{(3)} = f \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$

Solid lines: allowed by all radiative decays

Maximum allowed LFV $H \rightarrow \tau e$ in the ISS

Scenarios in the ISS allowing for maximum LFVHD rates and being compatible with the LFV radiative decays

$$\text{BR}(H \rightarrow e\bar{\tau})_{\max}^{\text{ISS}} \sim 10^{-5}$$



Examples suppressing μe and $\tau \mu$ mixing

$$Y_{\tau e}^{(1)} = f \begin{pmatrix} 0.9 & 1 & 1 \\ 0 & 1 & -1 \\ 1 & 1 & 1 \end{pmatrix}$$

$$Y_{\tau e}^{(2)} = f \begin{pmatrix} 1 & 1 & -1 \\ 0 & 1 & 1 \\ -1 & 1 & -1 \end{pmatrix}$$

$$Y_{\tau e}^{(3)} = f \begin{pmatrix} -1 & 1 & 1 \\ 0 & -1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$

Solid lines: allowed by all radiative decays

We got large LFVHD rates in the SM-ISS, but they are still not testable at the present LHC run :(

Let's consider Supersymmetry

The SUSY-ISS model

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

$$W = W_{MSSM} + \varepsilon_{ab} \hat{N} \textcolor{orange}{Y}_{\nu} \hat{H}_2^b \hat{L}^a + \hat{N} \textcolor{red}{\tilde{M}}_R \hat{X} + \frac{1}{2} \hat{X} \textcolor{teal}{\tilde{\mu}}_X \hat{X}$$
$$\begin{aligned} -\mathcal{L}_{soft} = & -\mathcal{L}_{soft}^{MSSM} + \tilde{\nu}_R^T \textcolor{red}{m}_{\tilde{\nu}_R}^2 \tilde{\nu}_R^* + \tilde{X}^T \textcolor{teal}{m}_{\tilde{X}}^2 \tilde{X}^* \\ & + \tilde{\nu}_R^\dagger (\textcolor{orange}{A}_{\nu} \textcolor{orange}{Y}_{\nu}) \tilde{\nu}_L h_2^0 - \tilde{\nu}_R^\dagger (\textcolor{orange}{A}_{\nu} \textcolor{orange}{Y}_{\nu}) \tilde{e}_L h_2^+ + \text{h.c.} \\ & + \tilde{X}^\dagger (\textcolor{teal}{B}_X \textcolor{teal}{\tilde{\mu}}_X) \tilde{X}^* + \tilde{\nu}_R^\dagger (\textcolor{red}{B}_R \textcolor{red}{\tilde{M}}_R) \tilde{X}^* + \text{h.c.} \end{aligned}$$

Assumptions:

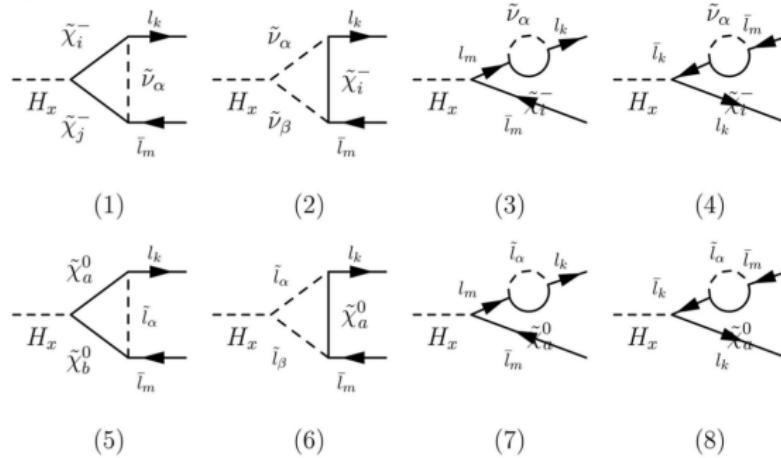
- Diagonal and degenerate $\textcolor{red}{M}_R$
- Accomodate light neutrino data adjusting $\textcolor{teal}{\mu}_X$
- Soft trilinear couplings proportional to $\textcolor{orange}{Y}_{\nu}$
- Flavor diagonal soft SUSY breaking masses
- Only exception RGE-induced corrections to $\Delta m_{\tilde{L}}^2$

$$(\Delta m_{\tilde{L}}^2)_{ij} = -\frac{1}{8\pi^2} (3M_0^2 + A_0^2) (\textcolor{orange}{Y}_{\nu}^\dagger \log \frac{M}{M_R} \textcolor{orange}{Y}_{\nu})_{ij}$$

Only sources of LFV: $\textcolor{orange}{Y}_{\nu}$

LFVHD in the SUSY-ISS

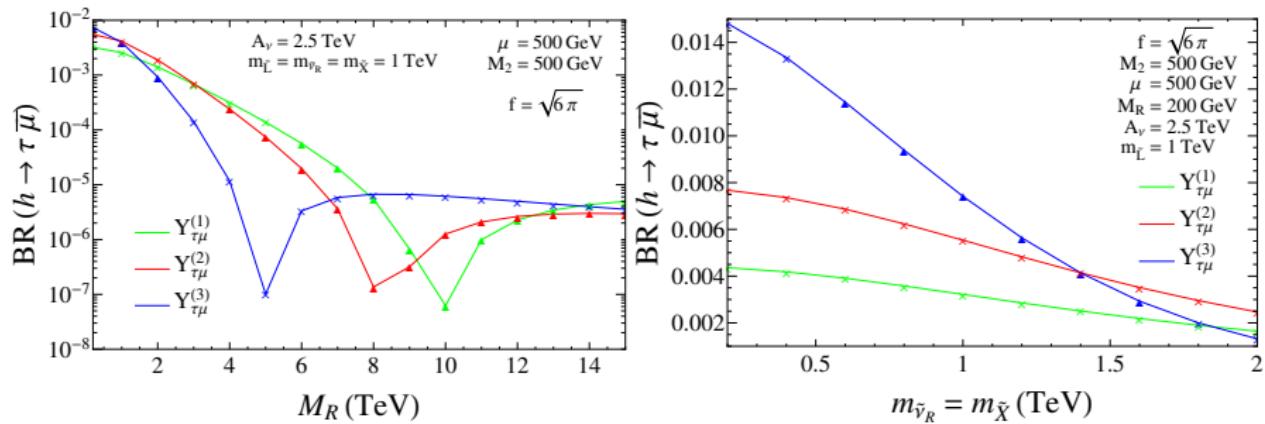
First step: focus on the SUSY contributions



- Contributions adapted from Arganda et al., PRD71(2005)035011
- Chargino-sneutrino contributions from Y_ν , A_ν and $\Delta m_{\tilde{L}}^2$
- Neutralino-slepton contributions from $\Delta m_{\tilde{L}}^2$

$h \rightarrow \tau\mu$ in the SUSY-ISS

E. Arganda, M.J. Herrero, XM, C. Weiland, 1508.04623



- \times : excluded by $\tau \rightarrow \mu\gamma$. \blacktriangle : allowed
- Different behavior as a function of the seesaw and SUSY scale if it is dominated by chargino or neutralino loops.
- $\text{BR}(h \rightarrow \tau\mu) \sim 10^{-2}$ allowed by LFV radiative decays
- Possible explanation of the CMS and ATLAS excess

Heavy Neutrino production considering LFV

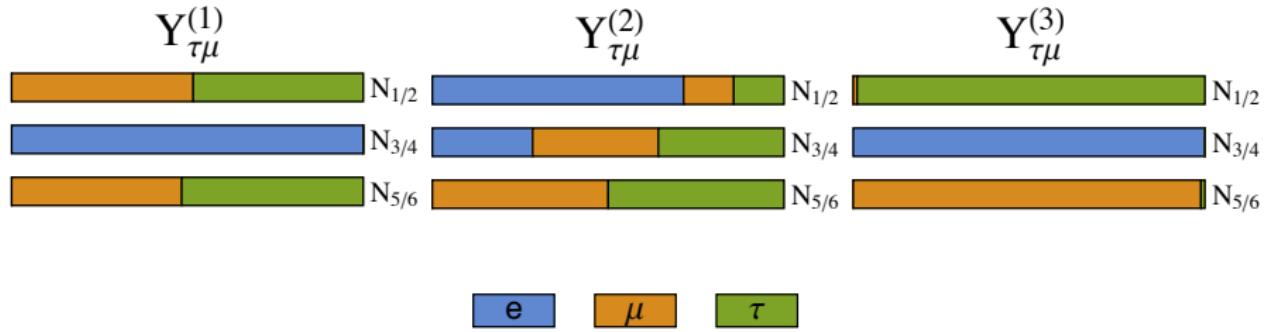
- Heavy neutrinos in the $\mathcal{O}(\text{TeV})$ range can be produced at LHC.
- Their production and decay in association with a charged lepton are governed by the mixing B_{lN} .
- LFV radiative and Higgs decays are sensitive to the combination $|B_{lN}B_{lN}^*|$, but not to the mixing B_{lN} itself.
- We have considered scenarios with $|B_{eN}B_{\mu N}^*| \sim |B_{eN}B_{\tau N}^*| \sim 0$ and maximal $|B_{\mu N}B_{\tau N}^*|$.

What is the flavor of the Heavy Neutrinos in these kind of scenarios?

The Flavor of the Heavy Neutrinos

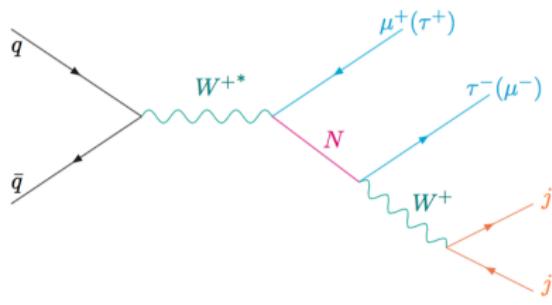
E. Arganda, M.J. Herrero, XM, C. Weiland, 1508.05074

- The flavor of the heavy neutrinos is different in each scenario.
- Some of the neutrinos carry both μ and τ flavors.
- Look for LFV exotic signals involving μ and τ leptons.

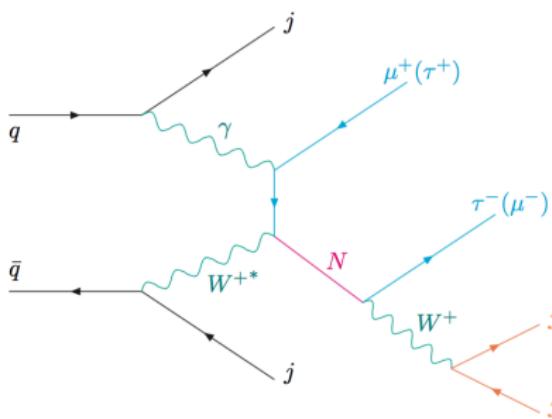


Heavy neutrino production and decay @LHC

E. Arganda, M.J. Herrero, XM, C. Weiland, 1508.05074



Dominant production: Drell-Yan
Exotic $\mu^\pm\tau^\mp jj$ signal with no \cancel{E}_T



We also consider γW fusion, relevant especially for large M_R values

Bhupal Dev et al. PRL112(2014)8,081801
Alva et al. JHEP1502(2015)072

In order to have the same signal, we ask the extra jets to be soft,

$$p_T^{\text{jet}} < p_T^{\max}$$

Computed with MadGraph5
Using NNPDFQED PDF set
Similar results for other PDF
Degenerate M_{R_i} entries

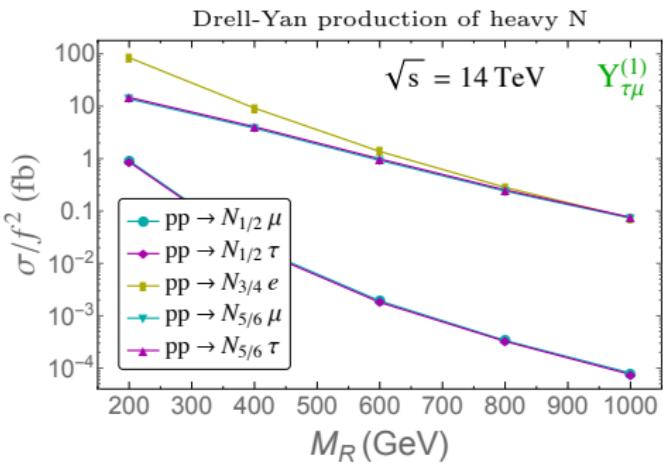
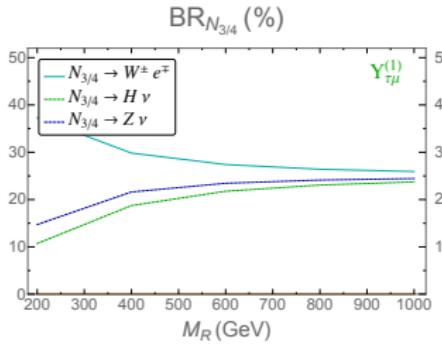
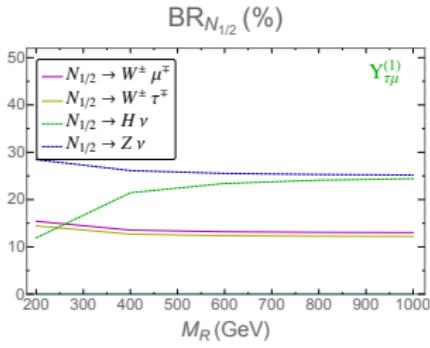
Heavy neutrino production and decay @LHC: scenario 1

Large production $\sigma \sim \mathcal{O}(fb)$,
reachable @LHC for $M_R \leq 500\text{GeV}$

Distinct rates for diff flavors
For $Y_{\tau\mu}^{(1)}$, max. couplings between:

$$\begin{array}{ccc} N_{1/2} & \longleftrightarrow & \mu, \tau \\ N_{3/4} & \longleftrightarrow & e \\ N_{5/6} & \longleftrightarrow & \mu, \tau \end{array}$$

We focus on the $N_j \rightarrow W l_i$ decay



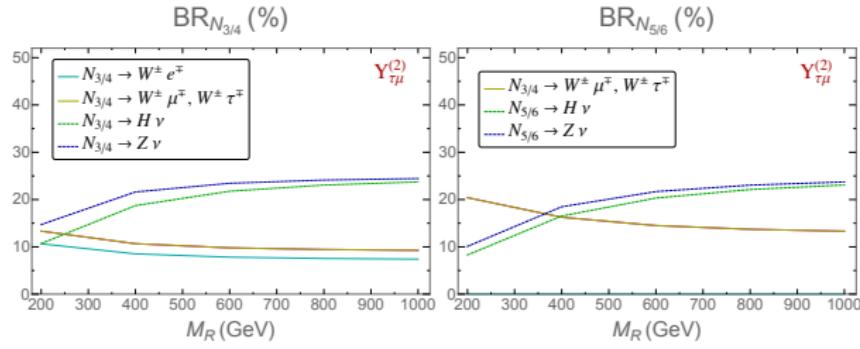
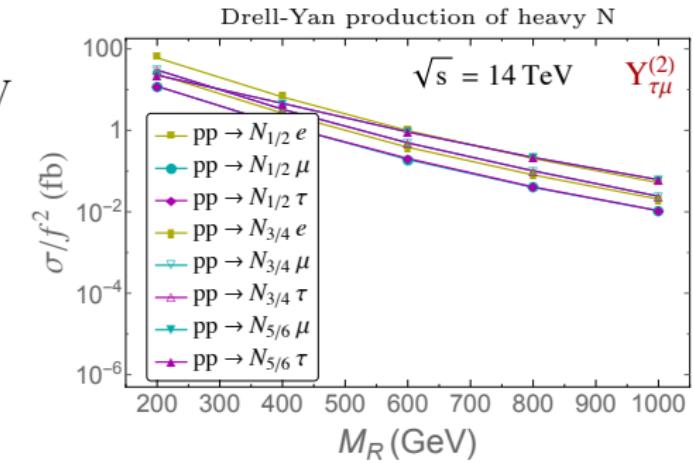
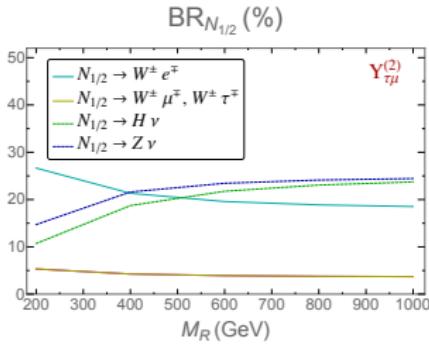
Heavy neutrino production and decay @LHC: scenario 2

Large production $\sigma \sim \mathcal{O}(fb)$,
reachable @LHC for $M_R \leq 500\text{GeV}$

Distinct rates for diff flavors
For $Y_{\tau\mu}^{(2)}$, max. couplings between:

$$\begin{aligned} N_{1/2} &\longleftrightarrow e, \mu, \tau \\ N_{3/4} &\longleftrightarrow e, \mu, \tau \\ N_{5/6} &\longleftrightarrow \mu, \tau \end{aligned}$$

We focus on the $N_j \rightarrow W l_i$ decay



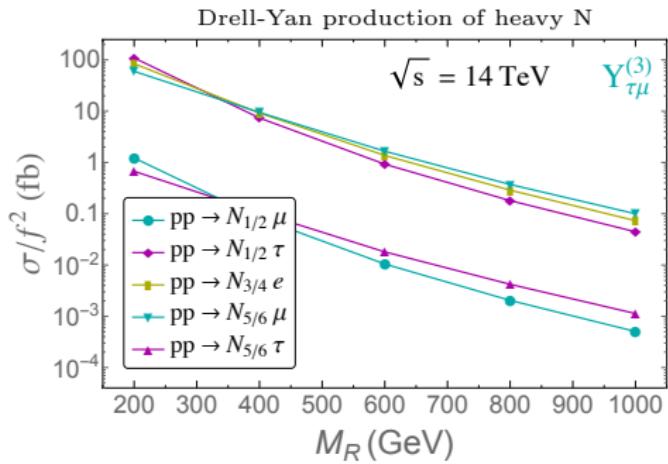
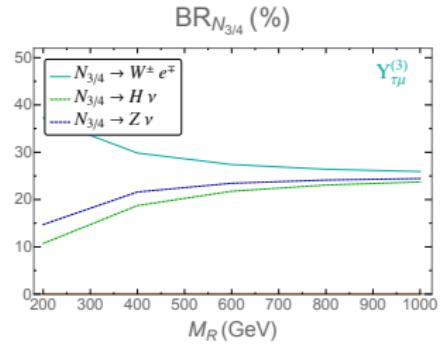
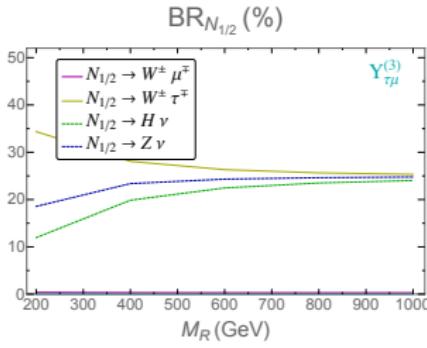
Heavy neutrino production and decay @LHC: scenario 3

Large production $\sigma \sim \mathcal{O}(fb)$,
reachable @LHC for $M_R \leq 500\text{GeV}$

Distinct rates for diff flavors
For $Y_{\tau\mu}^{(3)}$, max. couplings between:

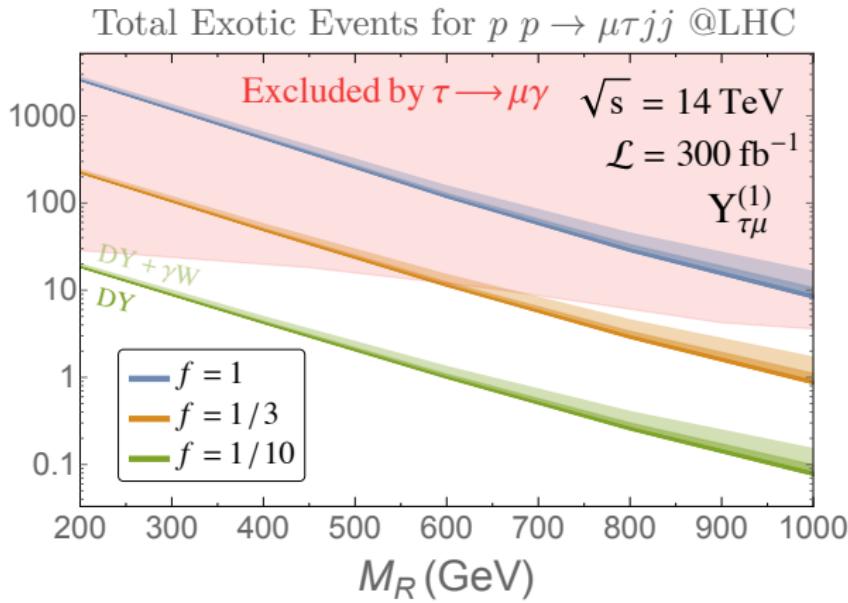
$$\begin{array}{ccc} N_{1/2} & \longleftrightarrow & \tau \\ N_{3/4} & \longleftrightarrow & e \\ N_{5/6} & \longleftrightarrow & \mu \end{array}$$

We focus on the $N_j \rightarrow Wl_i$ decay



Exotic events at LHC: $p\ p \rightarrow l^-l'^+jj$, $l \neq l'$, Scenario 1

E. Arganda, M.J. Herrero, XM, C. Weiland, 1508.05074

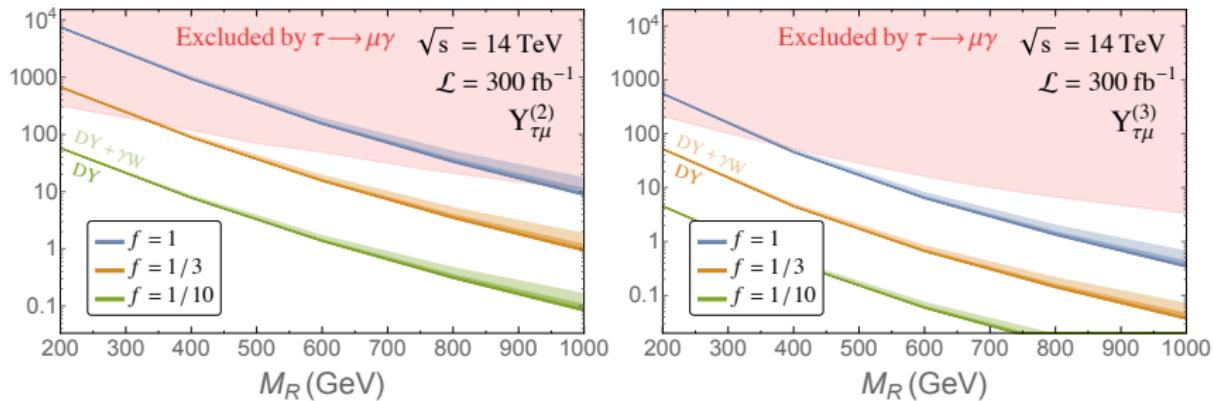


- Lower bound of the bands represents just DY production.
- Gradual decreasing areas correspond adding γW with $p_T^{\max} = 10, 20, 40 \text{ GeV}$.
- Red shadowed area is excluded by the upper bound on $\tau \rightarrow \mu\gamma$.
- $\mathcal{O}(10)$ events in the scenario 1 for masses $M_R \in (200, 1000) \text{ GeV}$.

Exotic events at LHC: $p\ p \rightarrow l^-l'^+jj$, other scenarios

E. Arganda, M.J. Herrero, XM, C. Weiland, 1508.05074

Total Exotic Events for $p\ p \rightarrow \mu\tau jj$ @LHC



- Scenarios 2 and 3 also lead to detectable number of events.
- In all the scenarios we obtain $\mathcal{O}(10 - 200)$ exotic events for masses $M_R \in (200, 1000)\text{GeV}$.

Conclusions

Heavy neutrinos have a lot to say about lepton flavor

LFV Higgs Decays:

- We found scenarios with enhanced branching ratios for LFVHD
- SUSY contributions alone could explain the CMS/ATLAS excess

Heavy N at LHC:

- This kind of scenarios with large LFV could lead to exotic LFV signals at the LHC
- We predict detectable number of singular events $\mu^\pm \tau^\mp jj$ with no \cancel{E}_T and $M_{jj} \sim M_W$, naively background free, for masses $M_R \in (200, 1000)\text{GeV}$

Work in progress:

- Full computation of LFVHD in the MSSM-ISS
- Explore other singular signals: $pp \rightarrow e^\pm \tau^\mp jj$ or $pp \rightarrow e^\pm \mu^\mp jj$
- Estimate realistic signal/background ratio

Conclusions

Heavy neutrinos have a lot to say about lepton flavor

LFV Higgs Decays:

- We found scenarios with enhanced branching ratios for LFVHD
- SUSY contributions alone could explain the CMS/ATLAS excess

Heavy N at LHC:

- This kind of scenarios with large LFV could lead to exotic LFV signals at the LHC
- We predict detectable number of singular events $\mu^\pm \tau^\mp jj$ with no \cancel{E}_T and $M_{jj} \sim M_W$, naively background free, for masses $M_R \in (200, 1000)\text{GeV}$

Work in progress:

- Full computation of LFVHD in the MSSM-ISS
- Explore other singular signals: $pp \rightarrow e^\pm \tau^\mp jj$ or $pp \rightarrow e^\pm \mu^\mp jj$
- Estimate realistic signal/background ratio

Thank you!

Backup slides

Neutrino data

The lightest neutrino mass m_{ν_1} is assumed as a free input parameter in agreement with the upper limit on the effective electron neutrino mass in β decays from the Mainz [C. Kraus *et al.*, 2005] and Troitsk [V. N. Aseev *et al.*, 2011] experiments,

$$m_\beta < 2.05 \text{ eV} \quad \text{at 95% CL.} \quad (1)$$

The other two light masses are obtained from:

$$m_{\nu_2} = \sqrt{m_{\nu_1}^2 + \Delta m_{21}^2}, \quad m_{\nu_3} = \sqrt{m_{\nu_1}^2 + \Delta m_{31}^2}. \quad (2)$$

For simplicity, we set to zero the CP-violating phase of the U_{PMNS} matrix and we have used the results of the global fit [M. C. Gonzalez-Garcia *et al.*, 2012] leading to:

$$\begin{aligned} \sin^2 \theta_{12} &= 0.306^{+0.012}_{-0.012}, & \Delta m_{21}^2 &= 7.45^{+0.19}_{-0.16} \times 10^{-5} \text{ eV}^2, \\ \sin^2 \theta_{23} &= 0.446^{+0.008}_{-0.008}, & \Delta m_{31}^2 &= 2.417^{+0.014}_{-0.014} \times 10^{-3} \text{ eV}^2, \\ \sin^2 \theta_{13} &= 0.0231^{+0.0019}_{-0.0019}, \end{aligned} \quad (3)$$

where we have assumed a normal hierarchy.

Examples of ISS neutrino mass spectrum

ISS examples	A	B	C
M_{R_1} (GeV)	1.5×10^4	1.5×10^2	1.5×10^2
M_{R_2} (GeV)	1.5×10^4	1.5×10^3	1.5×10^3
M_{R_3} (GeV)	1.5×10^4	1.5×10^4	1.5×10^4
$\mu_{X_{1,2,3}}$ (GeV)	5×10^{-8}	5×10^{-8}	5×10^{-8}
m_{ν_1} (eV)	0.1	0.1	0.1
$\theta_{1,2,3}$ (rad)	0, 0, 0	0, 0, 0	$\pi/4, 0, 0$
m_{n_1} (eV)	0.0998	0.0998	0.0998
m_{n_2} (eV)	0.1002	0.1002	0.1002
m_{n_3} (eV)	0.1112	0.1112	0.1112
m_{n_4} (GeV)	15014.99250747	150.1499250500	150.1499250500
m_{n_5} (GeV)	15014.99250752	150.1499250999	150.1499250999
m_{n_6} (GeV)	15015.04822299	1501.504822277	1501.587676006
m_{n_7} (GeV)	15015.04822304	1501.504822327	1501.587676056
m_{n_8} (GeV)	15016.70543659	15016.70543659	15015.87685358
m_{n_9} (GeV)	15016.70543664	15016.70543664	15015.87685363
$ (Y_\nu Y_\nu^\dagger)_{23} $	0.8	8.0	1.4
$ (Y_\nu Y_\nu^\dagger)_{12} $	0.2	1.7	0.3
$ (Y_\nu Y_\nu^\dagger)_{13} $	0.2	1.8	4.0

Relevant neutrino interactions for LFVHD

Following the notation in [A. Ilakovac and A. Pilaftsis, 1995] and [Arganda *et al.*, 2005], the relevant interactions are given in the mass basis by the following terms of the Lagrangian:

$$\begin{aligned}\mathcal{L}_{\text{int}}^{W^\pm} &= \frac{-g}{\sqrt{2}} W^{\mu -} \bar{l}_i B_{l_i n_j} \gamma_\mu P_L n_j + h.c., \\ \mathcal{L}_{\text{int}}^H &= \frac{-g}{2m_W} H \bar{n}_i C_{n_i n_j} [m_{n_i} P_L + m_{n_j} P_R] n_j, \\ \mathcal{L}_{\text{int}}^{G^\pm} &= \frac{-g}{\sqrt{2}m_W} G^- [\bar{l}_i B_{l_i n_j} (m_{l_i} P_L - m_{n_j} P_R) n_j] + h.c.,\end{aligned}\quad (4)$$

where the coupling factors $B_{l_i n_j}$ ($i = 1, 2, 3, j = 1, \dots, 9$) and $C_{n_i n_j}$ ($i, j = 1, \dots, 9$) are defined in terms of the U_ν matrix such that $U_\nu^T M_{\text{ISS}} U_\nu = \text{diag}(m_{n_1}, \dots, m_{n_9})$ by:

$$B_{l_i n_j} = U_{ij}^{\nu*}, \quad (5)$$

$$C_{n_i n_j} = \sum_{k=1}^3 U_{ki}^\nu U_{kj}^{\nu*}. \quad (6)$$

Accommodating light neutrino data: two different cases

Case I: simplest case with diagonal M_R and μ_X matrices

- Accommodate neutrino data using a modified Casas-Ibarra parametrization [Casas and Ibarra, 2001]:

$$m_D^T = V^\dagger \sqrt{M^{\text{diag}}} \ R \ \sqrt{m_\nu^{\text{diag}}} \ U_{\text{PMNS}}^\dagger, \quad \text{with } M \equiv M_R \mu_X^{-1} M_R^T$$

- Large Yukawa couplings for large M_R masses.
- Input parameters: $M_{R_i}, \mu_{X_i}, m_\nu, U_{\text{PMNS}}$ and R .

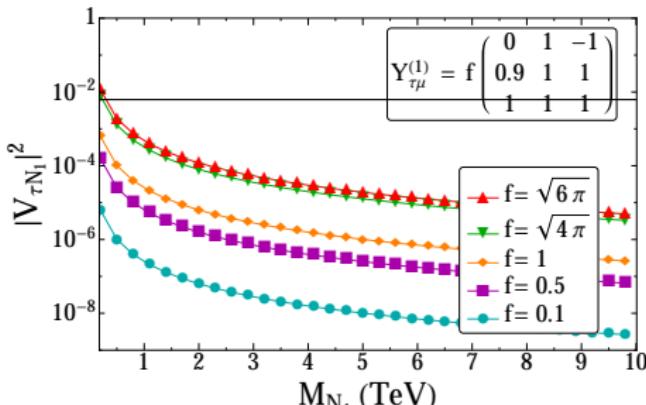
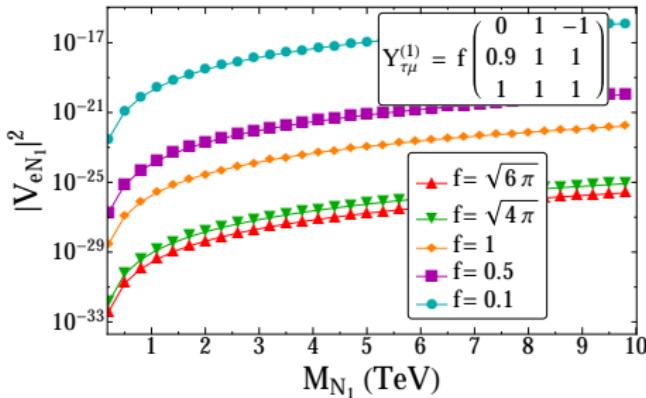
Case II: More general case with non-diagonal μ_X matrix

- Look for Yukawa matrices which lead to large LFVHD
- Accommodate neutrino data setting

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

- Input parameters: M_R and Y_ν (m_ν, U_{PMNS})

Constraints from EWPO



Active sterile mixing

$$V_{lN} \equiv B_{lN} = U_{lN}^{\nu*}$$

Controlled by $v Y_\nu M_R^{-1}$

Limits at 90% C.L.:

del Aguila et al., 2008

$$|V_{eN}|^2 < 3.0 \times 10^{-3}$$

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

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

The Flavor of the Heavy Neutrinos

Define the flavor of the heavy neutrino in terms of their coupling to W and charged leptons:

$$S_{lN_i} = \frac{|B_{lN_i}|^2}{\sum_{l=e,\mu,\tau} |B_{lN_i}|^2}$$

