ISS Heavy Neutrino production @LHC

Xabier Marcano
in collaboration with E. Arganda, M.J. Herrero and C. Weiland
Instituto de Física Teórica, Universidad Autónoma de Madrid/CSIC
xabier.marcano@uam.es

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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, ...
- 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 di-lepton signals**

The Inverse Seesaw Model

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

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

- 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: three light neutrinos and six heavy neutrinos with masses of $m_N \sim M_R \sim \mathcal{O}(\text{TeV})$.
- Accommodate successfully 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 $\Longrightarrow$ New Phenomenoly

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 has found a 2.4σ excess

$$\mathrm{BR}(H \to \tau\mu) = 0.84^{+0.39}_{-0.37}\% \ (95\% CL)$$

Approximate formulas in the large Y_ν limit

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

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

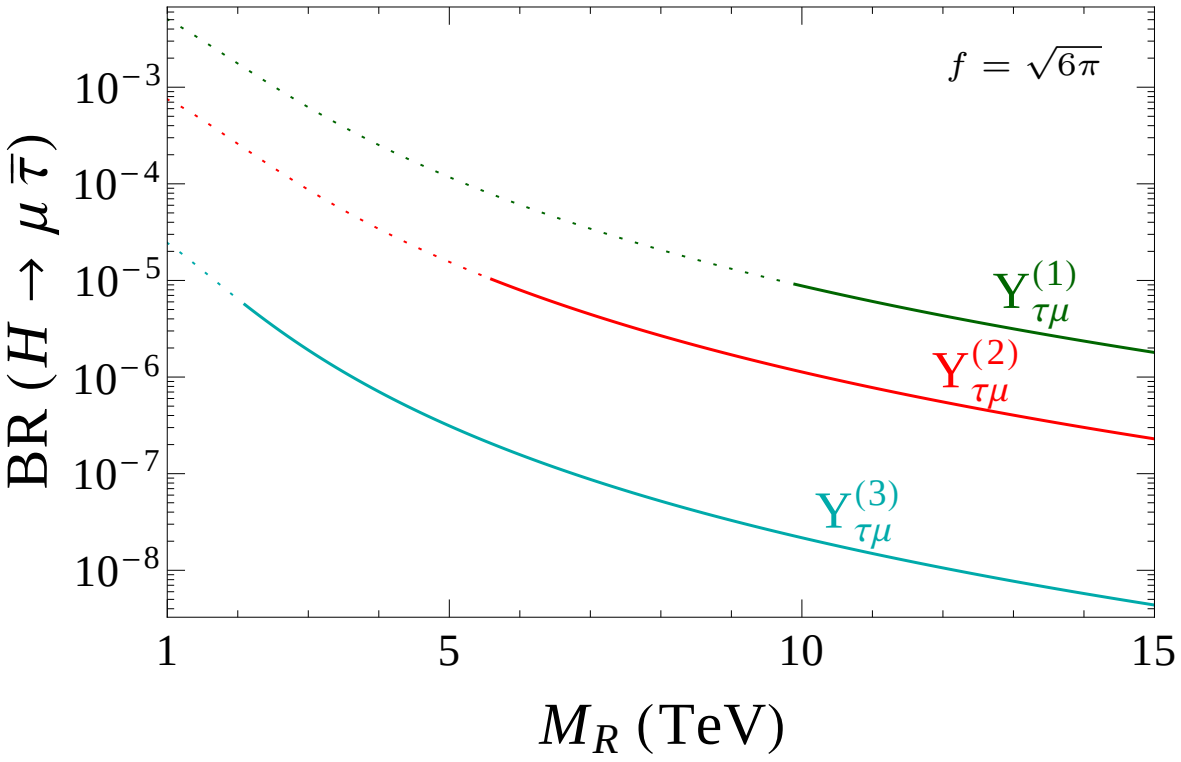
They behave differently. Large rates, $\mathrm{BR}(H \to \mu\bar{\tau}) \sim 10^{-4}$, nevertheless they are bounded by the upper limits on radiative decays, especially by $\mu \to e\gamma$

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

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

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

$$\mathrm{BR}(H \to \mu\overline{\tau})^{\mathrm{ISS}}_{\mathrm{max}} \sim 10^{-5}$$



Examples suppressing μe mixing

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

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

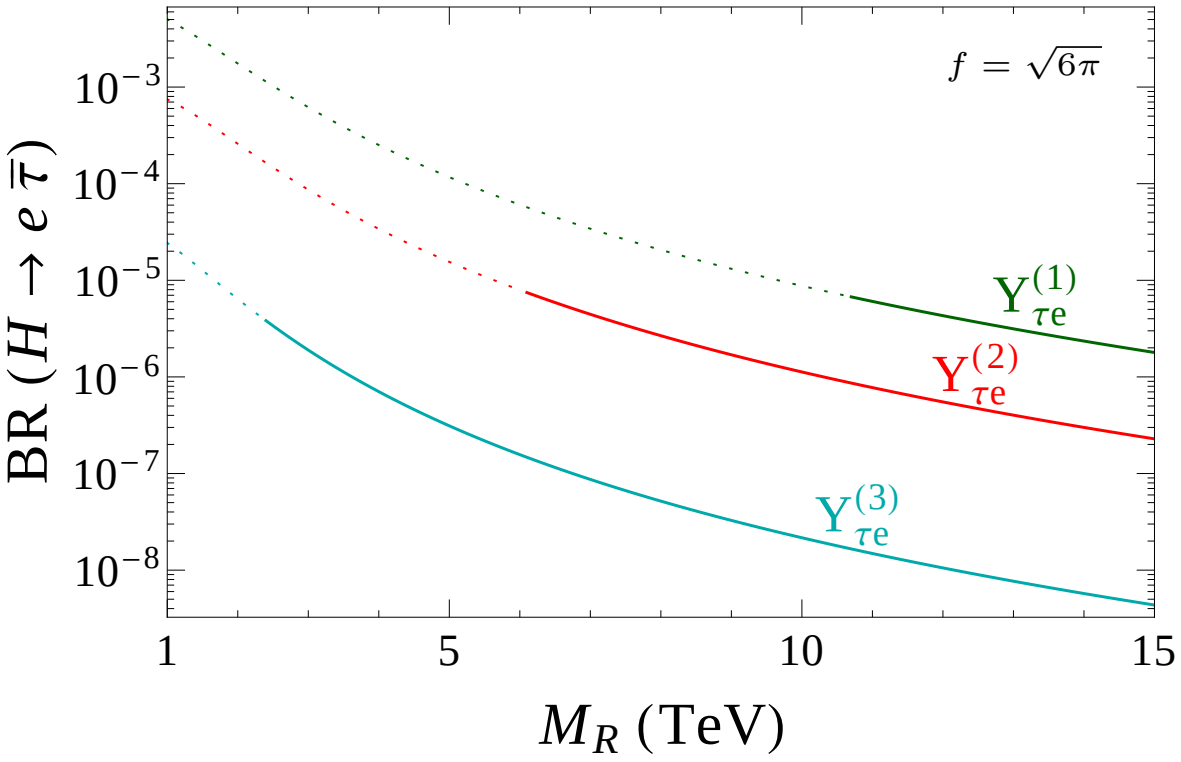
$$Y^{(3)}_{\tau\mu} = f \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix}$$

Solid lines: allowed by all radiative decays

Maximum allowed LFV τe in the ISS

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

$$\mathrm{BR}(H \to e\overline{\tau})^{\mathrm{ISS}}_{\mathrm{max}} \sim 10^{-5}$$



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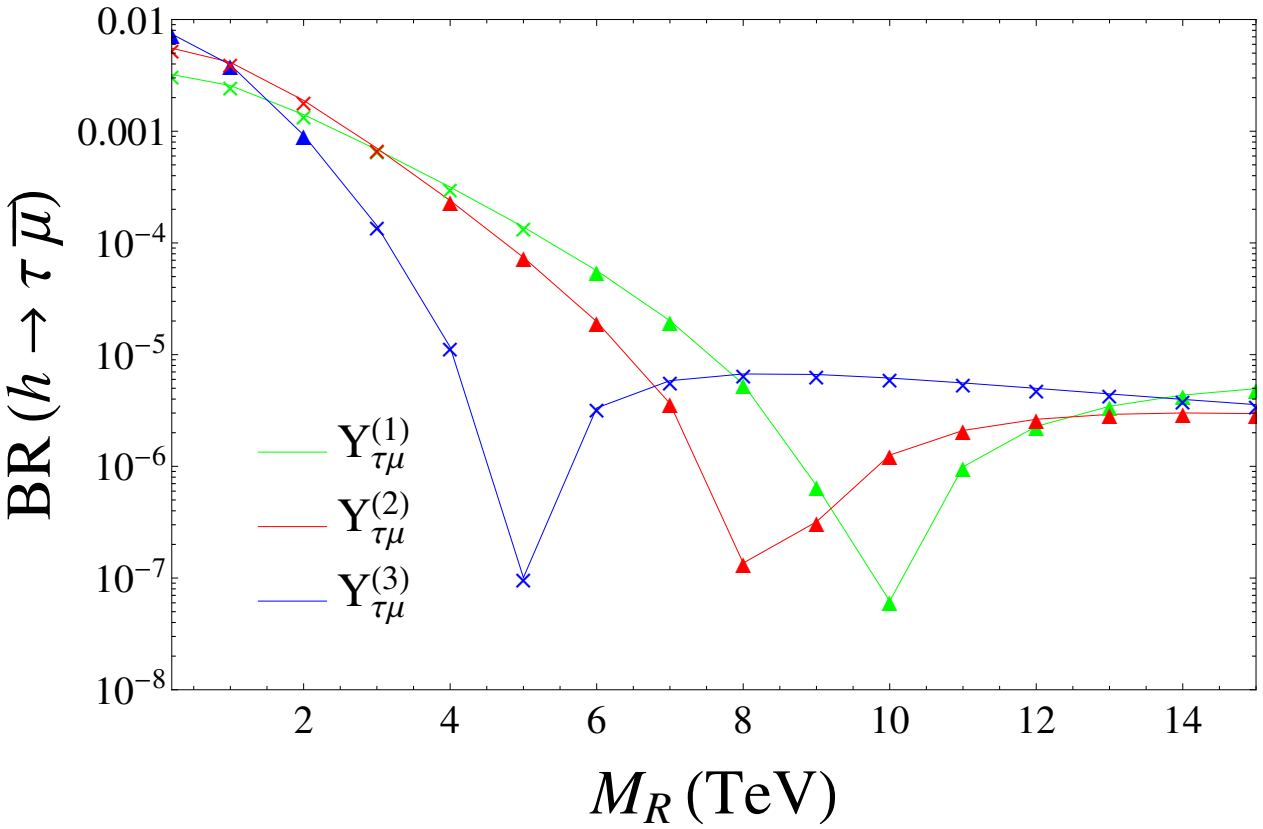
Solid lines: allowed by all radiative decays

$H \to \tau\mu$ in the MSSM-ISS

- The rates can be enhanced if SUSY is considered.
- The SUSY contributions can reach $\mathcal{O}(10^{-2})$ being allowed by $\tau \to \mu\gamma$.
- Work in progress



$\tan\beta = 10$

$m_0 = 1$ TeV

$A_\nu = 2.5$ TeV

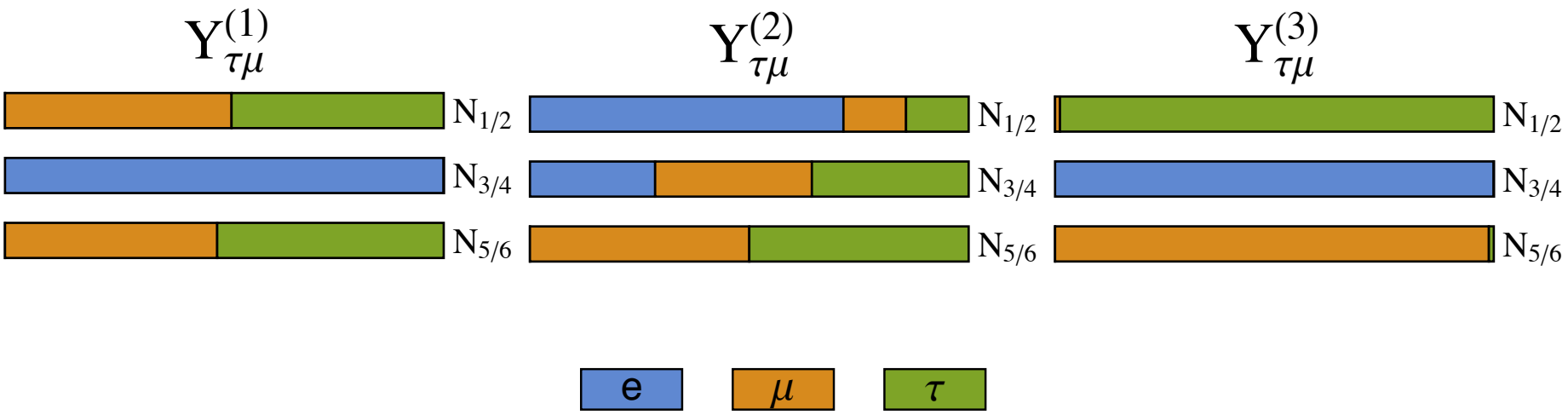
$m_A = 800$ GeV

$m_{\tilde{\nu}_R} = 1$ TeV

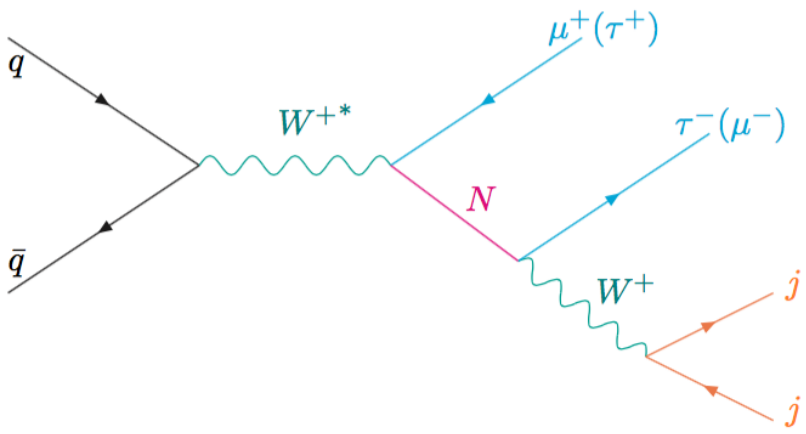
$m_{\tilde{X}} = 1$ TeV

The Flavor of the Heavy Neutrinos

- 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

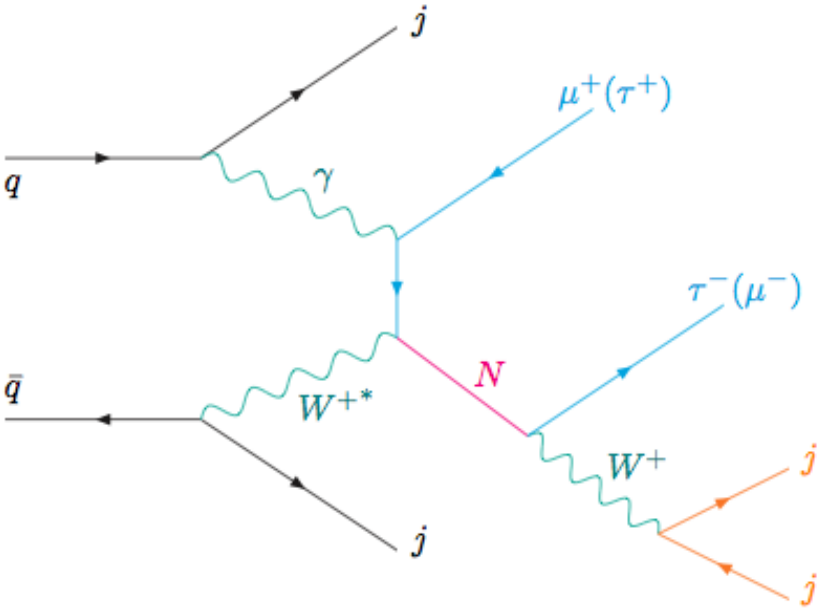


Dominant production: Drell-Yan

Exotic $\mu^\pm\tau^\mp jj$ signal with no $\not{E}_T$

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,

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

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

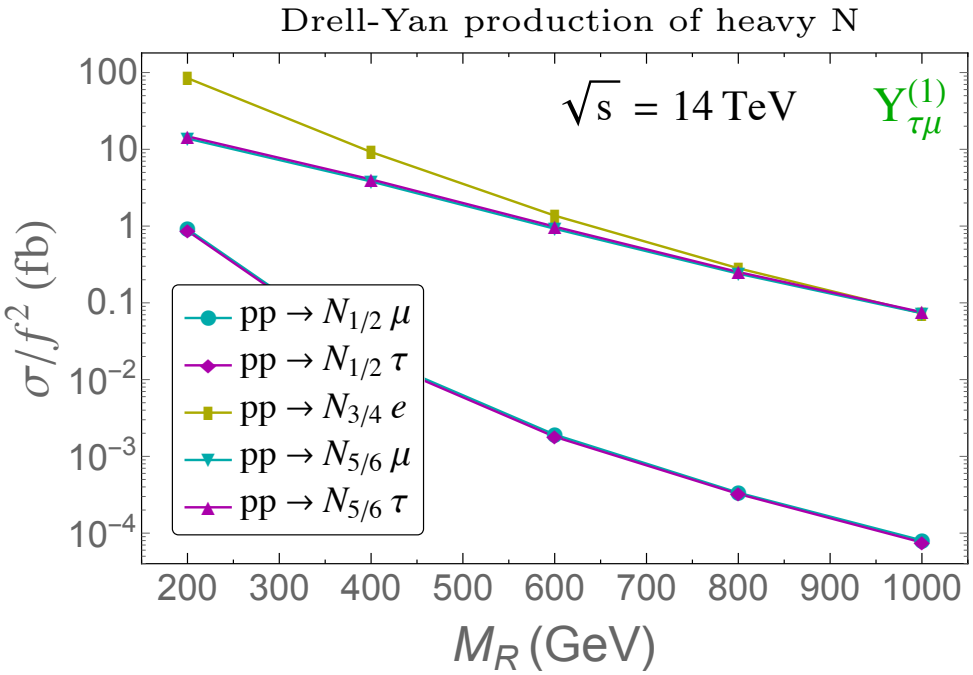
Heavy neutrino production and decay @LHC: scenario 1

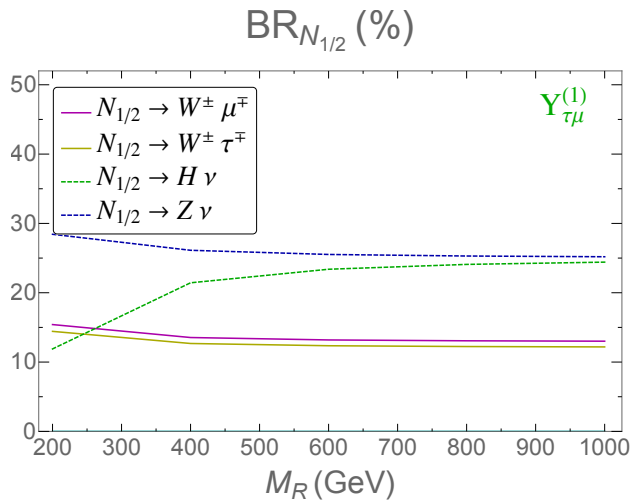
Large production $\sigma \sim \mathcal{O}(fb)$,
reachable @LHC for $M_R \leq 500$GeV

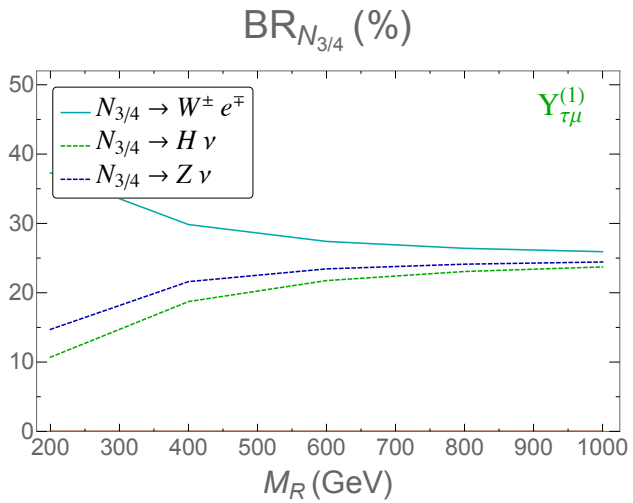
Distinct rates for diff flavors
For $Y^{(1)}_{\tau\mu}$, max. couplings between:

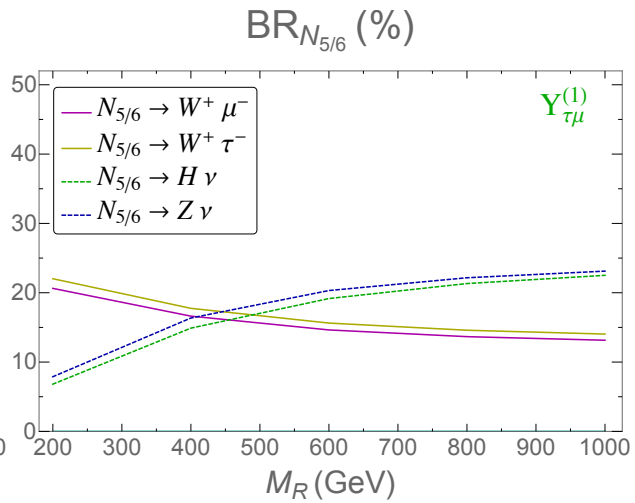
$$N_{1/2} \longleftrightarrow \mu, \tau$$
$$N_{3/4} \longleftrightarrow e$$
$$N_{5/6} \longleftrightarrow \mu, \tau$$

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









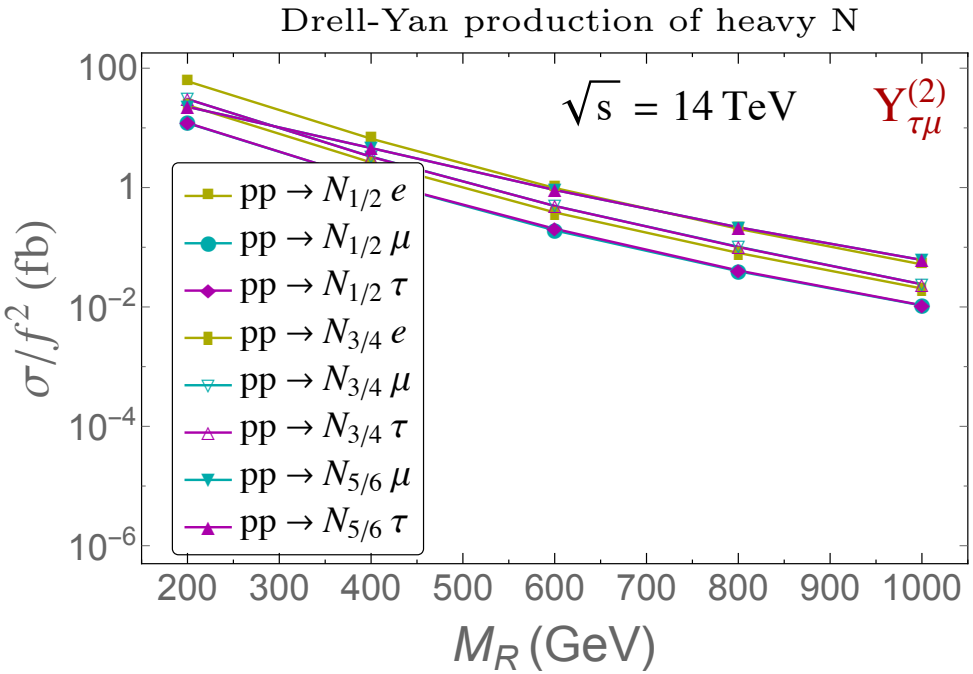
Heavy neutrino production and decay @LHC: scenario 2

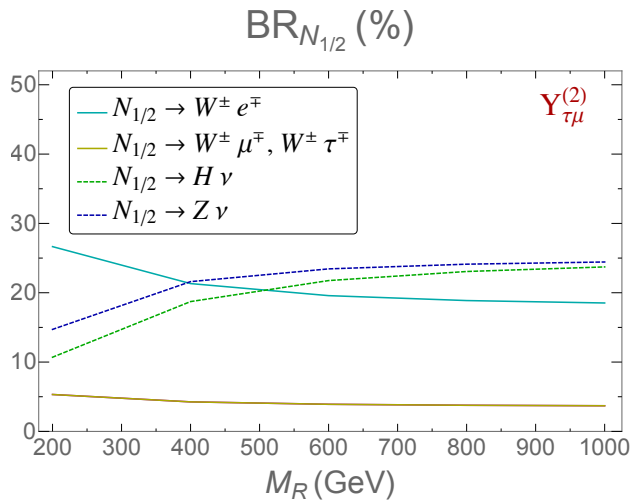
Large production $\sigma \sim \mathcal{O}(fb)$,
reachable @LHC for $M_R \leq 500$GeV

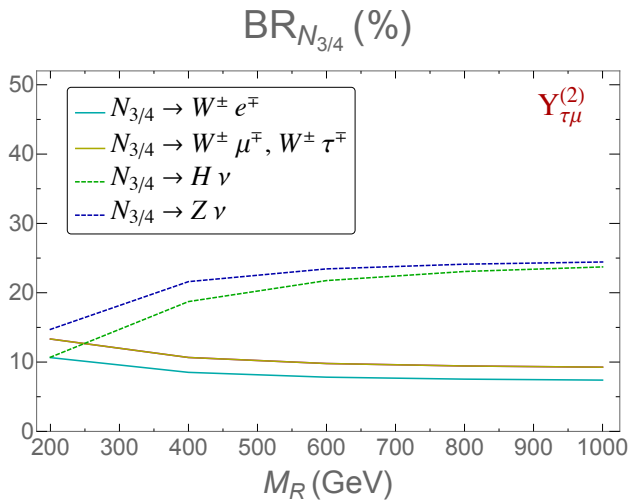
Distinct rates for diff flavors
For $Y^{(2)}_{\tau\mu}$, max. couplings between:

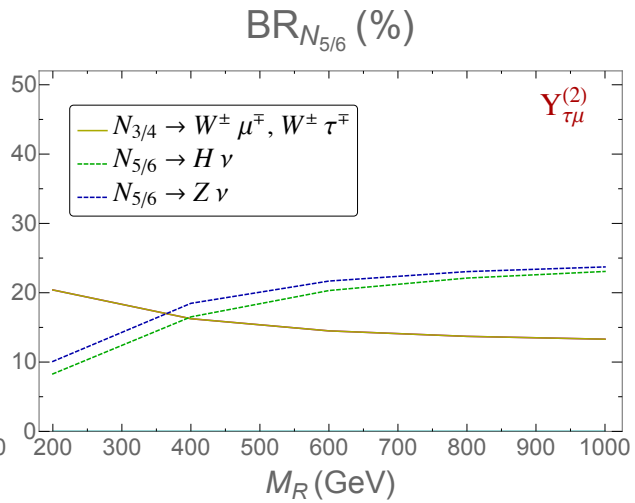
$$N_{1/2} \longleftrightarrow e, \mu, \tau$$
$$N_{3/4} \longleftrightarrow e, \mu, \tau$$
$$N_{5/6} \longleftrightarrow \mu, \tau$$

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









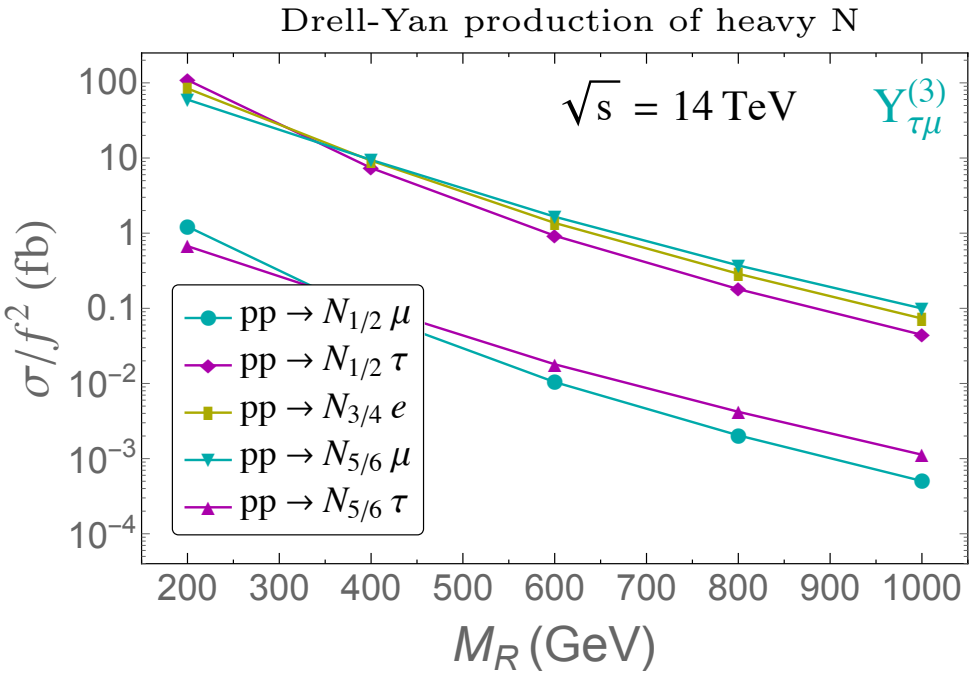
Heavy neutrino production and decay @LHC: scenario 3

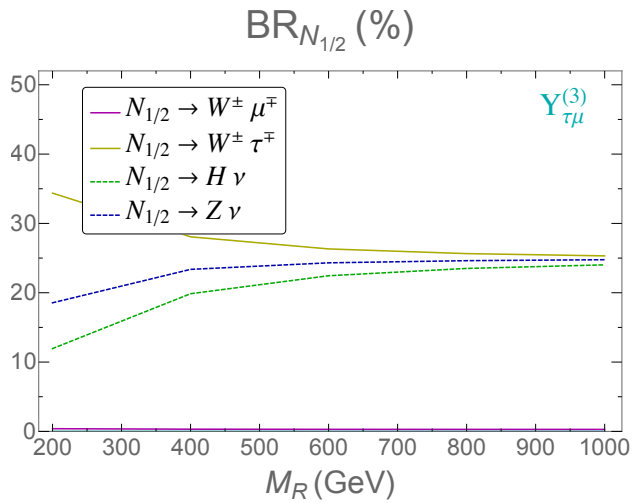
Large production $\sigma \sim \mathcal{O}(fb)$,
reachable @LHC for $M_R \leq 500$GeV

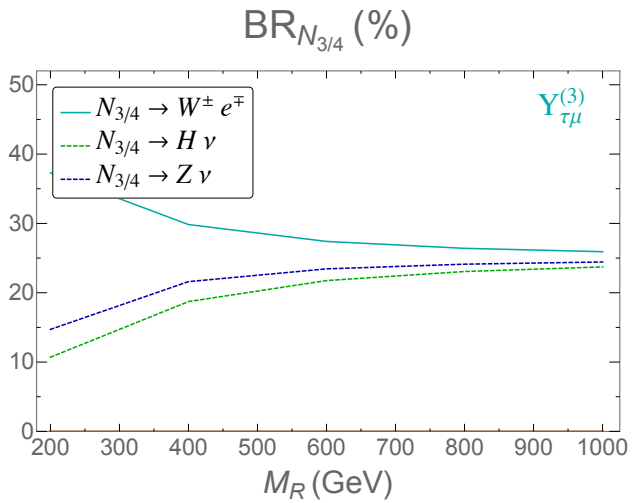
Distinct rates for diff flavors
For $Y^{(3)}_{\tau\mu}$, max. couplings between:

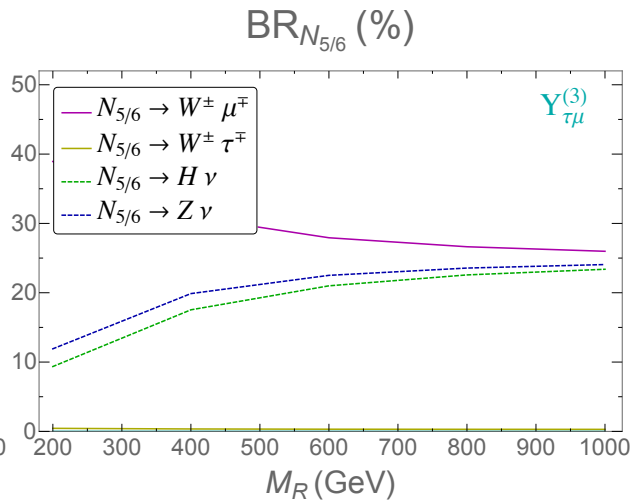
$$N_{1/2} \longleftrightarrow \tau$$
$$N_{3/4} \longleftrightarrow e$$
$$N_{5/6} \longleftrightarrow \mu$$

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

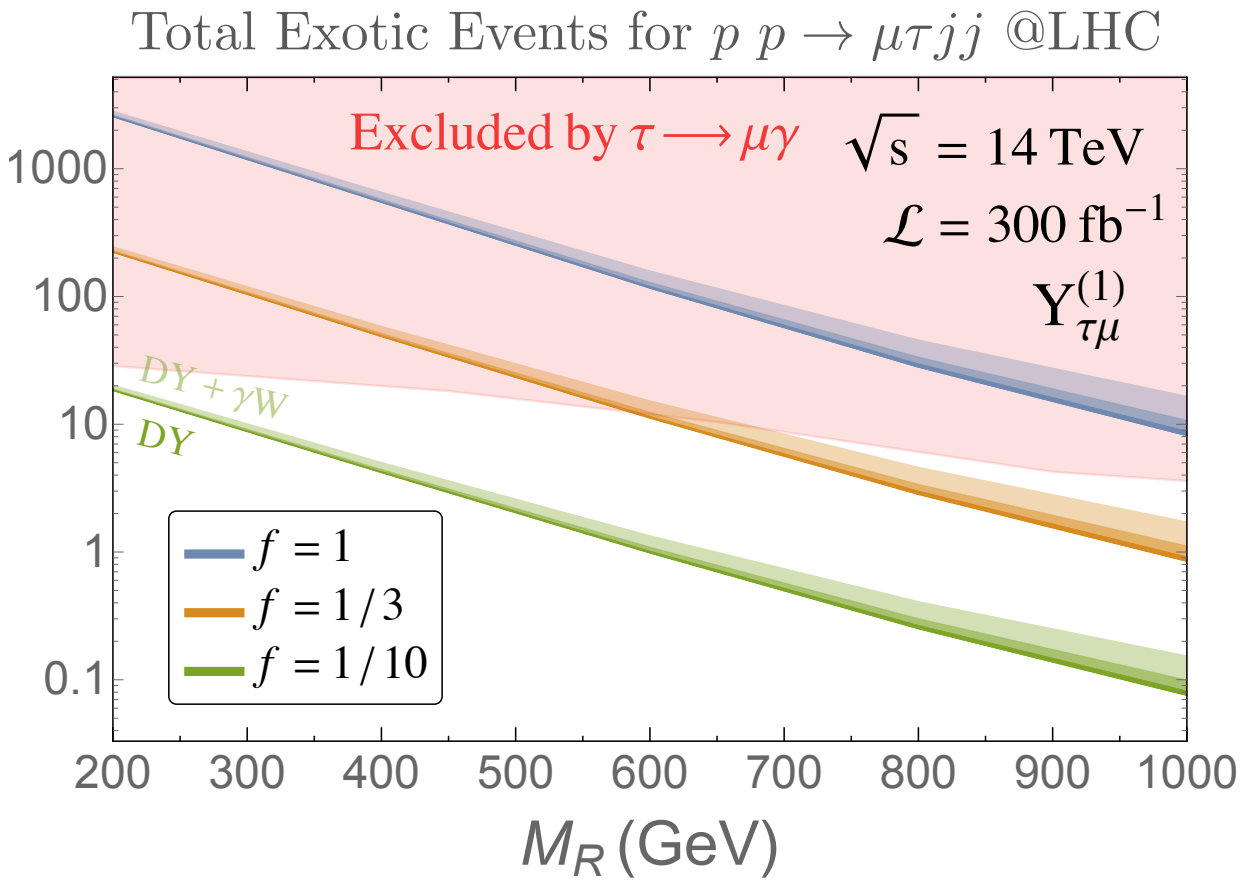








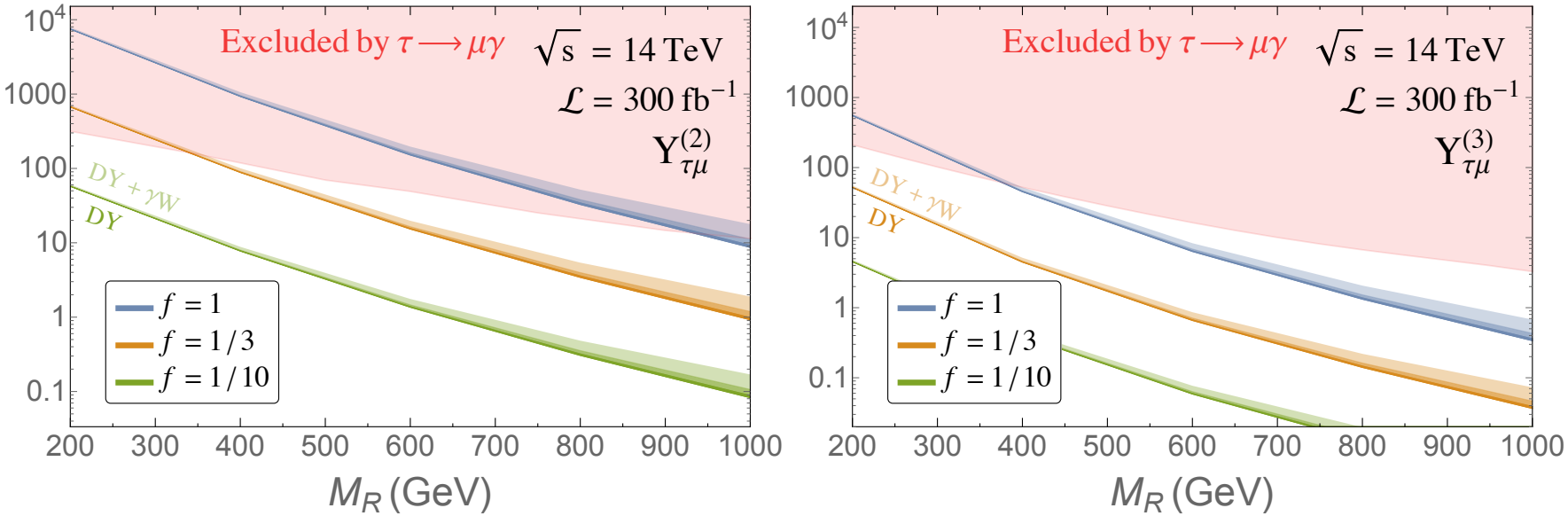
Exotic events at LHC: $p\,p \to l^- l'^+ jj,\ l \neq l'$, Scenario 1



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

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

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



- Scenarios 2 and 3 also lead to detectable number of events.
- In all the scenarios we obtain $\mathcal{O}(10-500)$ exotic events.

Conclusions

- Heavy neutrinos can carry flavor information
- We found scenarios with enhanced branching ratios for LFV H decays
- SUSY contributions alone could explain the CMS excess
- This kind of scenarios with large LFV could lead to exotic LFV signals at the LHC
- We predict a detectable number of singular events with no $\not{E}_T$, two different lepton flavors and two jets with $M_{jj} \sim M_W$, naively background free

Work in progress:

- Explore other singular signals: $pp \to e^{\pm}\tau^{\mp}jj$ or $pp \to e^{\pm}\mu^{\mp}jj$
- 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,

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

The other two light masses are obtained from:

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

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

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

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
$\lvert(Y_\nu Y_\nu^\dagger)_{23}\rvert$	0.8	8.0	1.4
$\lvert(Y_\nu Y_\nu^\dagger)_{12}\rvert$	0.2	1.7	0.3
$\lvert(Y_\nu Y_\nu^\dagger)_{13}\rvert$	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:

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

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

$$B_{l_i n_j} = U_{ij}^{\nu *}\,, \tag{5}$$

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

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]:

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

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

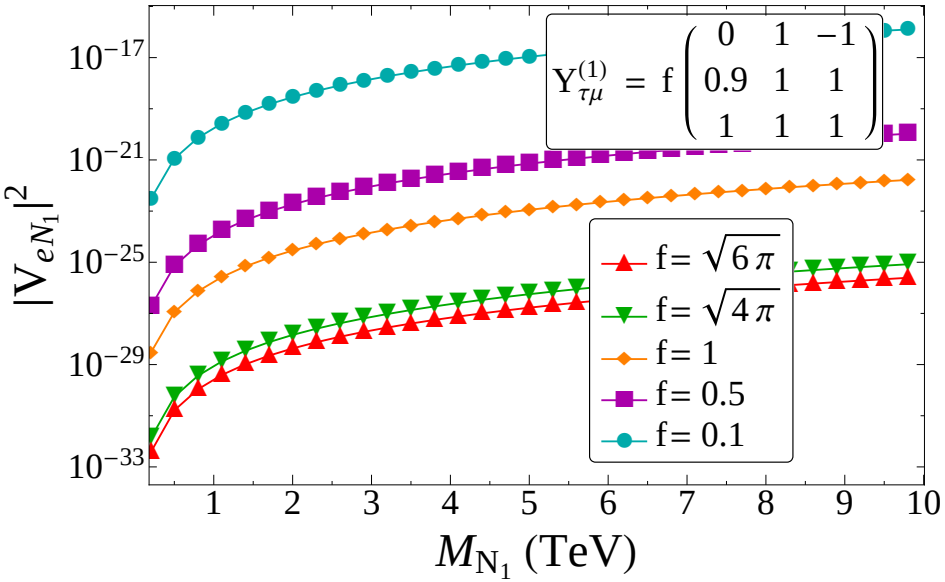
Case II: More general case with non-diagonal μ_X matrix

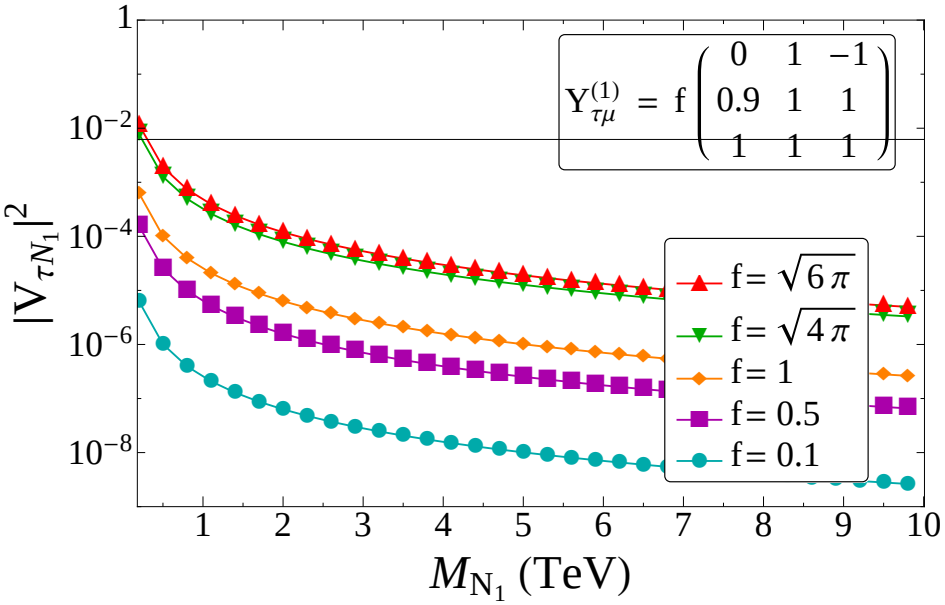
- Look for Yukawa matrices which lead to large LFVHD
- Accomodate neutrino data setting

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

- Input parameters: M_R and Y_ν $(m_\nu, U_{\rm PMNS})$

Constraints from EWPO





Active sterile mixing is controlled by $vY_\nu M_R^{-1}$

Limits at 90% C.L.:

del Aguila et al., 2008

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