Charged Lepton Flavor Violation from Low Scale Seesaw Neutrinos

Francesca Scarcella

Instituto de Física Teórica, Universidad Autónoma de Madrid/CSIC

francesca.scarcella@studio.unibo.it

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Based on: V. De Romeri, M.J. Herrero, X. Marcano, F. Scarcella

arXiv: 1607.05257

Motivation

The Standard Model predicts zero lepton flavor violation

Lepton Flavor Violation = New Physics

Neutral LFV observed in neutrino oscillations!

neutrino oscillations $\Longrightarrow$ BSM neutrino masses

This NP can induce charged LFV

$$nLFV \xrightarrow{\text{New Neutrino Physics}} cLFV$$

cLFV not seen yet. Intense program (I).

LFV transitions	LFV Present Bounds (90%CL)	Future Sensitivities
BR($\mu \to e\gamma$)	4.2×10^{-13} (MEG 2016)	4×10^{-14} (MEG-II)
BR($\tau \to e\gamma$)	3.3×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
BR($\tau \to \mu\gamma$)	4.4×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
BR($\mu \to eee$)	1.0×10^{-12} (SINDRUM 1988)	10^{-16} Mu3E (PSI)
BR($\tau \to eee$)	2.7×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
BR($\tau \to \mu\mu\mu$)	2.1×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
BR($\tau \to \mu\eta$)	2.3×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
CR($\mu - e$, Au)	7.0×10^{-13} (SINDRUM II 2006)	
CR($\mu - e$, Ti)	4.3×10^{-12} (SINDRUM II 2004)	10^{-18} PRISM (J-PARC)
CR($\mu - e$, Al)		3.1×10^{-15} COMET-I (J-PARC)
		2.6×10^{-17} COMET-II (J-PARC)
		2.5×10^{-17} Mu2E (Fermilab)

Strongest present constraints on LFV - μe sector

cLFV not seen yet. Intense program (II)

Upper bounds on LFV Z and H decays ($95\% CL$):

	LEP	ATLAS	CMS
$BR(Z \to \mu e)$	1.7×10^{-6}	7.5×10^{-7} PRD90(2014)072010	
$BR(Z \to \tau e)$	9.8×10^{-6}		
$BR(Z \to \tau \mu)$	1.2×10^{-5}	1.69×10^{-5} arXiv:1604.07730	
$BR(H \to \mu e)$	-		3.6×10^{-3} CMS-PAS-HIG-14-040
$BR(H \to \tau e)$	-	1.04×10^{-2} arXiv:1604.07730	0.7×10^{-2} CMS-PAS-HIG-14-040
$BR(H \to \tau \mu)$	-	1.43×10^{-2} arXiv:1604.07730	1.51×10^{-2} PLB749(2015)337-362

cLFV signal???:

CMS 2.4σ excess: $BR(H \to \tau\mu) = 0.84^{+0.39}_{-0.37}\%\ (95\% CL)$ PLB749(2015)337-362
ATLAS $\sim 1\sigma$ excess: $BR(H \to \tau\mu) = 0.53 \pm 0.51\%\ (95\% CL)$ arXiv:1604.07730

Type-I Seesaw Model

Modelling neutrino masses m_ν : Add ν_R to the SM

- Dirac mass: $m_D = vY_\nu$
- ν_R is a SM singlet $\Rightarrow$ Majorana mass: M_R (violates Lepton Number $U(1)_L$)

Type-I Seesaw Model: $m_D \ll M_R$

$$\mathcal{L}_{\text{type-I}} = -Y_\nu^{ij}\overline{L_i}\tilde{\phi}\nu_{R_j} - M_R^{ij}\overline{\nu^c_{R_i}}\nu_{R_j} + h.c. \quad i,j = 1..3$$

$$\mathcal{L}^{mass}_{\text{type-I}} = -\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu^c_R}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D^T & M_R\end{pmatrix}\begin{pmatrix}\nu^c_L \\ \nu_R\end{pmatrix} + h.c.$$

Type-I Seesaw Model - Continued

Diagonalize the mass matrix $\longrightarrow$ Physical states

$$U_\nu{}^T \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} U_\nu = \begin{pmatrix} m^{light} & 0 \\ 0 & M^{heavy} \end{pmatrix} \qquad \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = U_\nu^* P_L \begin{pmatrix} n \\ N \end{pmatrix}$$

For $m_D \ll M_R$:

$$m_\nu^{light} \sim \frac{m_D^2}{M_R}$$

$$M_\nu^{heavy} \sim M_R$$

Large coupling $Y_\nu \sim 1 \Longleftrightarrow$ heavy $M \sim 10^{14}$ GeV
Low $M \sim 1$ TeV $\Longleftrightarrow$ small $Y_\nu \ll 1$
} Suppressed Pheno

The Inverse Seesaw Model [Mohapatra and Valle, 1986]

Use symmetry arguments to lower M_R yet keeping the coupling Y_ν large:

Approximate Lepton Number consevation: $U(1)_L$

Smallness of neutrino masses $\longleftrightarrow$ small violation of $U(1)_L$

SM extended with 3 pairs of fermion singlets: $\nu_R(L=1)$ & $X(L=-1)$

$$\mathcal{L}_{\rm ISS} = -Y_\nu^{ij}\overline{L_i}\tilde{\Phi}\nu_{R_j} - M_R^{ij}\overline{\nu_{R_i}^C}X_j - \frac{1}{2}\mu_X^{ij}\overline{X_i^C}X_j + h.c. \quad i,j = 1..3$$

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

$$m_\nu^{light} \sim m_D M_R^{T-1}\mu_X M_R^{-1} m_D^T$$

$$M_\nu^{heavy} \sim M_R$$

Low heavy masses $M \sim 1$ TeV
Large coupling $Y_\nu \sim 1$
} Enhanced Pheno

The Inverse Seesaw Model - Parameters

Maximum allowed LFV Z decay rates?

Use μ_X to accommodate low energy neutrino data. Arganda et al., PRD91(2015)1,015001

$$\mu_X = M_R^T m_D^{-1} U^*_{\text{PMNS}} m_\nu U^\dagger_{\text{PMNS}} m_D^{T^{-1}} M_R$$

it allows to choose Intuitive Input Parameters

$M_R \longrightarrow$ Masses of the 6 heavy Majorana neutrinos (3 pseudo-Dirac pairs)

$Y_\nu \longrightarrow$ Yukawa interaction between ν_L-ν_R-H

Geometrical parametrization for Y_ν

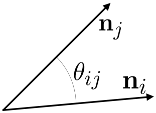
E. Arganda, M.J. Herrero, XM, C. Weiland, PRD91(2015)1,015001

Assuming $M_{R_{ij}} = M_R \delta_{ij}$ and real Y_ν matrix:

$$\boxed{\mathrm{LFV}_{ij} \longleftrightarrow \left(Y_\nu Y_\nu^T\right)_{ij}}$$

Y_ν 9 d.o.f $\longrightarrow$ 3 vectors (global strength f):

$$Y_\nu \equiv f \begin{pmatrix} \boldsymbol{n}_e \\ \boldsymbol{n}_\mu \\ \boldsymbol{n}_\tau \end{pmatrix} \left\{ \begin{array}{l} \text{3 moduli} : |\boldsymbol{n}_e|, |\boldsymbol{n}_\mu|, |\boldsymbol{n}_\tau| \\ \text{3 relative flavor angles:} \, \theta_{\mu e}, \theta_{\tau e}, \theta_{\tau\mu} \\ \text{global rotation } O(\theta_1, \theta_2, \theta_3), \; OO^T = 1 \end{array} \right.$$



$$Y_\nu Y_\nu^T = f^2 \begin{pmatrix} |\boldsymbol{n}_e|^2 & \boldsymbol{n}_e \cdot \boldsymbol{n}_\mu & \boldsymbol{n}_e \cdot \boldsymbol{n}_\tau \\ \boldsymbol{n}_e \cdot \boldsymbol{n}_\mu & |\boldsymbol{n}_\mu|^2 & \boldsymbol{n}_\mu \cdot \boldsymbol{n}_\tau \\ \boldsymbol{n}_e \cdot \boldsymbol{n}_\tau & \boldsymbol{n}_\mu \cdot \boldsymbol{n}_\tau & |\boldsymbol{n}_\tau|^2 \end{pmatrix}$$

Fully determined by $(c_{ij} \equiv \cos\theta_{ij})$
$(f, |\boldsymbol{n}_e|, |\boldsymbol{n}_\mu|, |\boldsymbol{n}_\tau|, c_{\mu e}, c_{\tau e}, c_{\tau\mu})$

Independent of O

Exp. Searches: $\mathrm{LFV}_{\mu e}$ very suppressed $\Longrightarrow$ $\boxed{\mathrm{LFV}_{\mu e} = 0 \rightarrow \boldsymbol{n}_e \cdot \boldsymbol{n}_\mu = 0 \leftrightarrow c_{\mu e} = 0}$

We choose $Y_\nu = A \cdot O$ with $A = f \begin{pmatrix} |\boldsymbol{n}_e| & 0 & 0 \\ 0 & |\boldsymbol{n}_\mu| & 0 \\ |\boldsymbol{n}_\tau| c_{\tau e} & |\boldsymbol{n}_\tau| c_{\tau\mu} & |\boldsymbol{n}_\tau| \sqrt{1 - c_{\tau e}^2 - c_{\tau\mu}^2} \end{pmatrix}$

Results for LFV radiative decays in the ISS with $\not{\text{LFV}}_{\mu e}$

E. Arganda, M.J. Herrero, XM, C. Weiland, PRD91(2015)1,015001
V. De Romeri, M.J. Herrero, XM, F. Scarcella, arXiv: 1607.05257

Dominant contributions:

$$\text{BR}(\tau \to e\gamma) \sim \frac{f^4}{M_R^4}\ c_{\tau e}^2$$

$$\text{BR}(\tau \to \mu\gamma) \sim \frac{f^4}{M_R^4}\ c_{\tau \mu}^2$$

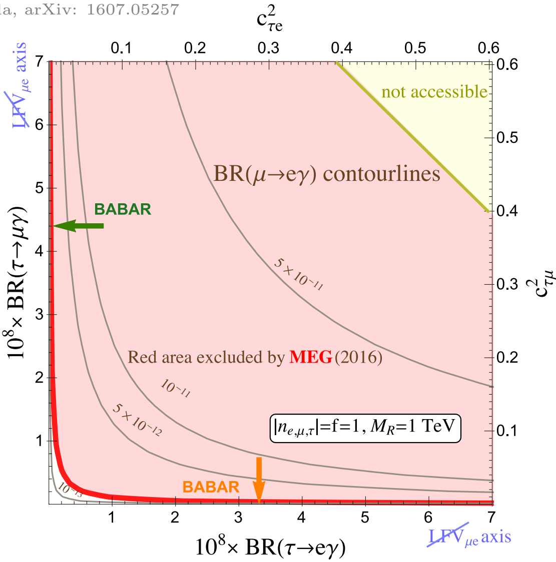
$\text{LFV}_{\mu e}$ highly suppressed :
(occurs at next order)

$$\text{BR}(\mu \to e\gamma) \sim \frac{f^8}{M_R^8}\ c_{\tau e}^2 c_{\tau\mu}^2$$

Focus on just one of the two axes:

– $\text{LFV}_{\tau\mu}$ with $\not{\text{LFV}}_{\tau e,\mu e}$

– $\text{LFV}_{\tau e}$ with $\not{\text{LFV}}_{\tau\mu,\mu e}$



ISS scenarios with highly suppressed LFV$_{\mu e}$

We study different **classes of scenarios** with ~~LFV~~$_{\mu e}$ in the LFV$_{\tau\mu}$ direction ($\equiv$ TM):

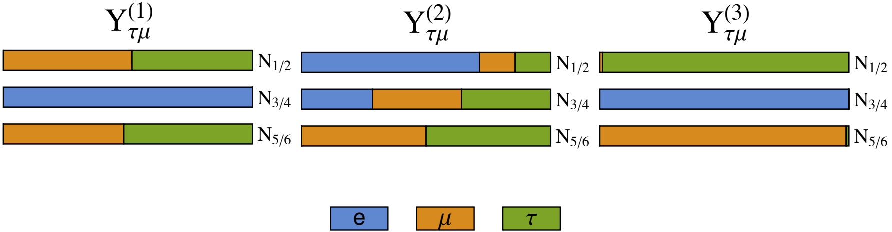
Scenario Name	$c_{\tau\mu}$	$\lvert\boldsymbol{n}_e\rvert$	$\lvert\boldsymbol{n}_\mu\rvert$	$\lvert\boldsymbol{n}_\tau\rvert$	Example
TM-1	$1/\sqrt{2}$	1	1	1	$Y_\nu = f \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$
TM-2	1	1	1	1	$Y_\nu \simeq f \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{pmatrix}$
TM-3	$1/\sqrt{2}$	0.1	1	1	$Y_\nu = f \begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$
TM-4	1	0.1	1	1	$Y_\nu \simeq f \begin{pmatrix} 0.1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{pmatrix}$
TM-5	1	$\sqrt{2}$	1.7	$\sqrt{3}$	$Y_\nu = f \begin{pmatrix} 0 & 1 & -1 \\ 0.9 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \equiv Y_{\tau\mu}^{(1)}$
TM-6	1/3	$\sqrt{2}$	$\sqrt{3}$	$\sqrt{3}$	$Y_\nu = f \begin{pmatrix} 0 & 1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & -1 \end{pmatrix} \equiv Y_{\tau\mu}^{(2)}$
TM-7	0.1	$\sqrt{2}$	$\sqrt{3}$	1.1	$Y_\nu = f \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & 1 \\ 0.8 & 0.5 & 0.5 \end{pmatrix} \equiv Y_{\tau\mu}^{(3)}$

And equivalent ones for the LFV$_{\tau e}$ direction ($\equiv$ TE) (Replace $\mu \longleftrightarrow e$ in all the above)

The flavor of the Heavy Neutrinos

E. Arganda, M.J. Herrero, XM, C. Weiland, PLB752(2016)46-50

- All the above scenario share the property of suppressing LFV$_{\mu e}$
- The **flavor of the heavy neutrinos** is different in each scenario.
- Some of the neutrinos carry both μ and τ flavors.



LFV $Z \to \tau\mu$ and $Z \to \tau e$ in the ISS with ~~LFV~~$_{\mu e}$

V. De Romeri, M.J. Herrero, XM, F. Scarcella, About to appear

LFV Z decays: a promising window to Low scale Seesaw neutrinos!!

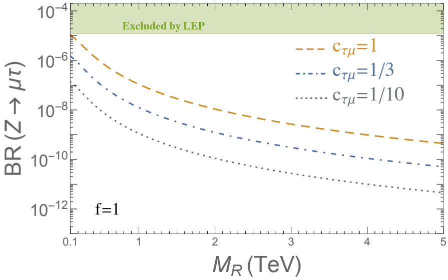
Bounds from LEP: $\text{BR}(Z \to \tau\mu) < 1.2 \times 10^{-5}, \text{BR}(Z \to \tau e) < 9.8 \times 10^{-6}$

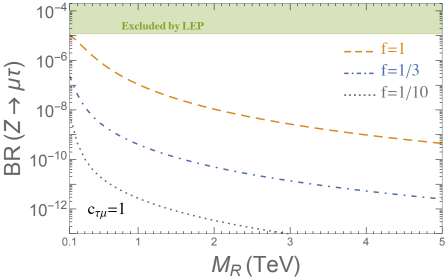
Present searches by LHC: $\text{BR}(Z \to \tau\mu) < 1.69 \times 10^{-5}$ (ATLAS, April'16)

LFV Z decays in the ISS-~~LFV~~$_{\mu e}$

Formulas from Illana et al. arXiv:hep-ph/0001273

Large rates within present experimental sensitivities†



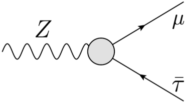


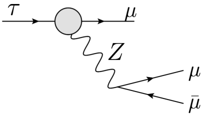
†Similar results for $\text{BR}(Z \to \tau e)$

$Z \to \tau\mu$ vs $\tau \to \mu\mu\mu$

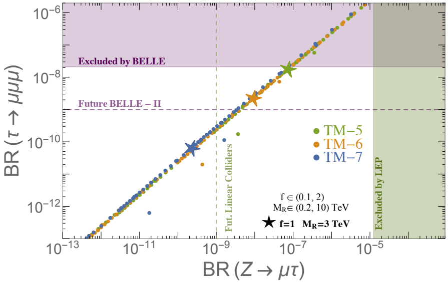
We find **Strong correlation** between $Z \to \tau\mu$ and $\tau \to \mu\mu\mu$
in agreement with Abada et al.JHEP1504(2015)051

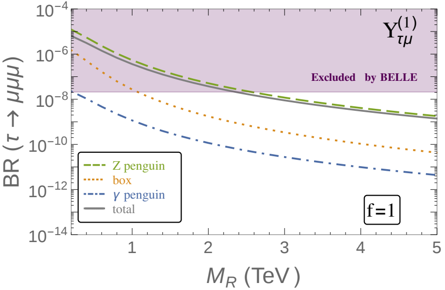
We have checked it is due to the dominance of the Z penguin in $\tau \to \mu\mu\mu$





ISS-~~LFV~~$_{\mu e}$: Bounds on $\mathrm{BR}(\tau \to \mu\mu\mu)$ suggest $\mathrm{BR}(Z \to \tau\mu)_{\max} \sim 10^{-7}$





Full study of the ISS-$\not{\text{LFV}}_{\mu e}$: Constraints

We consider the following subset of most constraining observables:

- **LFV transitions:** formulas from Ilakovac,Pilaftsis NPB437(1995)491

$$\text{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \quad \text{(BABAR'10)}$$
$$\text{BR}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8} \quad \text{(BELLE'10)}$$

- **Lepton flavor Universality:** formulas from Abada et al. JHEP1402(2014)091

$$\Delta r_k{}^{3\sigma} \equiv \frac{R_K}{R_K^{SM}} - 1 = (4 \pm 12) \times 10^{-3} \ \text{(NA62)} \quad \text{with} \quad R_K \equiv \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

- **Lepton flavor Conserving observables**

  Z invisible width: formulas from Abada et al. JHEP1402(2014)091

$$\Gamma(Z \to \text{inv.})^{3\sigma} = 499.0 \pm 4.5 \text{ MeV} \quad \text{(LEP)}$$

  EWPO: S, T, U parameters formulas from Akhmedov et al. JHEP1305(2013)081

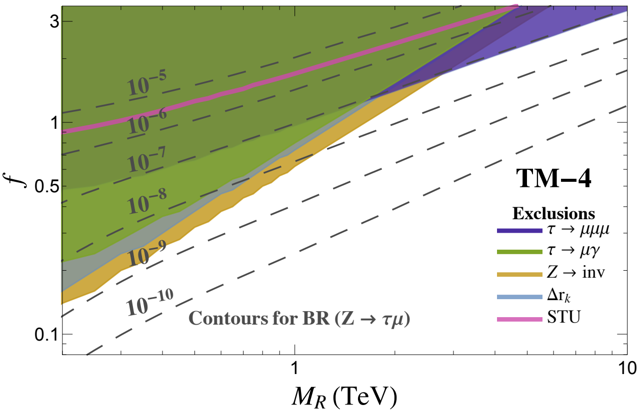
$$S^{3\sigma} = -0.03 \pm 0.30, \quad T^{3\sigma} = 0.01 \pm 0.12, \quad U^{3\sigma} = 0.05 \pm 0.10 \ \text{(PDG'14)}$$

- **Theoretical constraints:**

  Perturbativity imposed by constraining heavy neutrino widths: $\Gamma_N/M_N < 1/2$

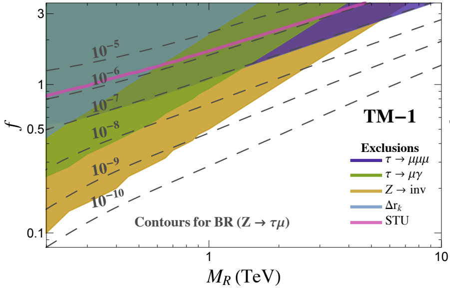
  Agreement with **light neutrino data**: validity of the μ_X parametrization

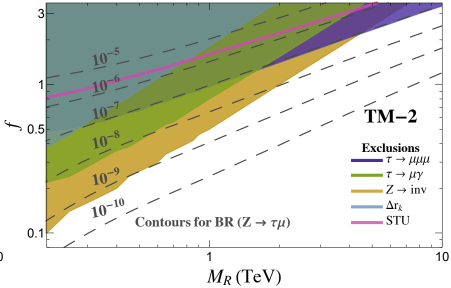
Full study of the ISS-$\not{LFV}_{\mu e}$: Results

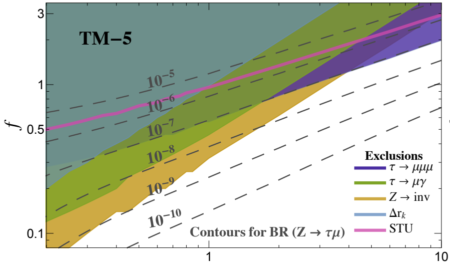


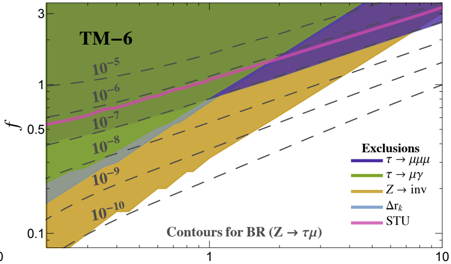
$\mathrm{BR}(Z \to \tau\mu)_{\max} \sim 10^{-7}$ allowed by all the constrains for masses $M_R \sim 2 - 3$ TeV

Similar results for other scenarios









Conclusions

- The Inverse Seesaw is an appealing Model for explaining light neutrino data.
- Heavy neutrinos from the ISS model can have important implications for charged lepton flavor violation.
- Strong experimental bounds motivate scenarios with suppressed $\text{LFV}_{\mu e}$
- Studying the $\text{LFV}_{\tau\mu}$ sector within the ISS-~~LFV~~$_{\mu e}$ (similar for $\text{LFV}_{\tau e}$).:
  - **LFV Z decays:** We found ratios, as large as $\text{BR}(Z \to \tau\mu) \sim 10^{-7}$, potentially measurable at Future Linear Colliders and FCCee.

LFV is a promising window to Low scale Seesaw neutrinos

Thank you!

I warmly thank my advisor M.J. Herrero and my colleague X. Marcano for his valuable help in preparing this presentation

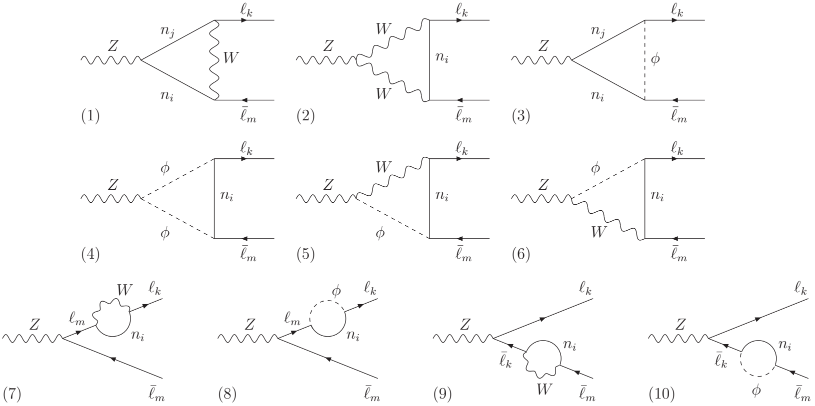
Backup slides

Other results

Studying the $\text{LFV}_{\tau\mu}$ sector within the ISS-$\not{\text{LFV}}_{\mu e}$ (similar for $\text{LFV}_{\tau e}$).:

- **LFV Z decays:** We found ratios, as large as $\text{BR}(Z \to \tau\mu) \sim 10^{-7}$, potentially measurable at Future Linear Colliders and FCCee.
- **LFV H decays:** large ratios for $\text{BR}(h \to \tau\mu)$, specially in the SUSY-ISS with contributions of the order of the CMS excess.
- **Production at colliders:** We predicted detectable number of singular LFV events $\mu^{\pm}\tau^{\mp}jj$ for heavy neutrino masses reachable at the LHC.

LFV Z decays



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_{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
$\|(Y_\nu Y_\nu^\dagger)_{23}\|$	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:

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

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]:

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

- 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

$$\mu_X = M_R^T m_D^{-1} U^*_{\rm PMNS} m_\nu U^\dagger_{\rm PMNS} m_D^{T^{-1}} M_R$$

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

Constraints from EWPO

Active sterile mixing

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

Controlled by $vY_\nu M_R^{-1}$

Limits at 90% C.L.:

del Aguila et al., 2008

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

The flavor of the Heavy Neutrinos

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

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