Minimal flavor violating realizations of minimal seesaw models

Diego Aristizabal

IFPA Group, AGO Department, University of Liege, Belgium

Based on:

arXiv:1205.5547 (submitted to JHEP)

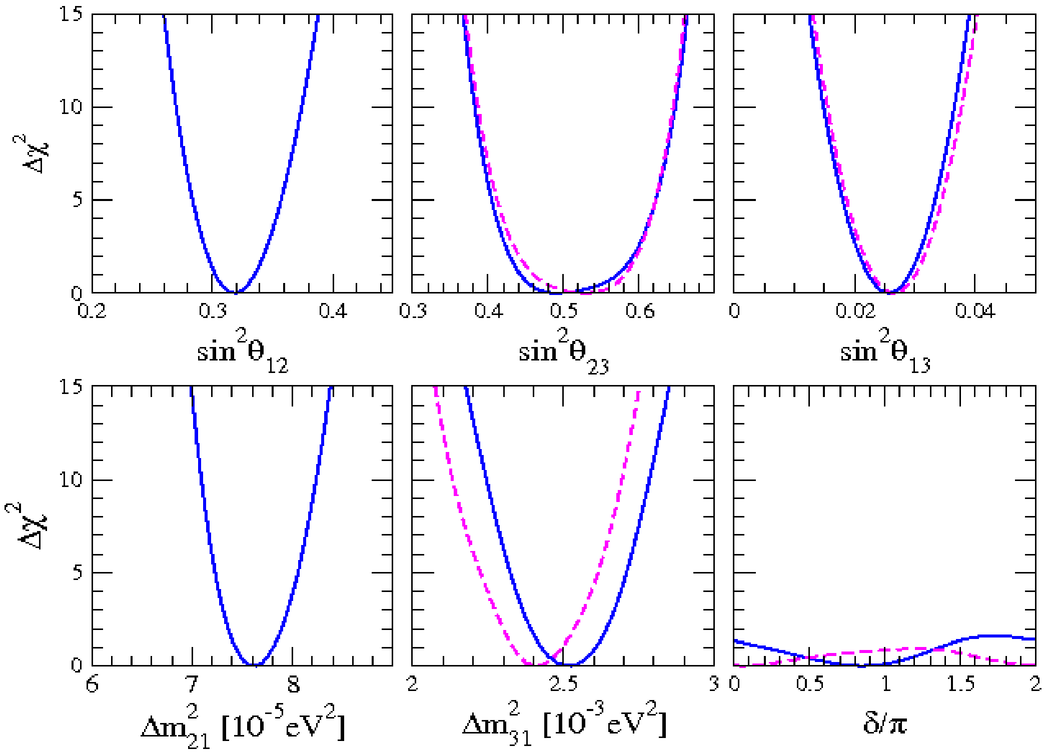
Audrey Degee (Liege) and Jernej Kamenik (JSI)

Motivation

Neutrino experimental status

Neutrino oscillation experiments

Parameters are extracted from solar, atmospheric, reactor and long-baseline experiments:



Forero, Tortola, Valle [1205.4018]

Normal spectrum

Parameter	2σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	7.27-8.01
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$	2.34-2.69
$\sin^2\theta_{12}$	0.29-0.35
$\sin^2\theta_{23}$	0.41-0.62
$\sin^2\theta_{13}$	0.019-0.033
δ	0-2π

$\theta_{13}=0$ **excluded @** 8σ

Neutrinos are massive with non-vanishing mixing angles

Prove of lepton flavor violation (LFV) in the neutral sector

Can charged LFV effects be expected in current or near future experiments?

Neutrino masses $\Rightarrow$ **Charged LFV processes**

No definitive mechanism for neutrino mass generation

charge LFV effects are model dependent

Effective approach **[Weinberg, 1979]**

$$\mathcal{L}^{\rm eff} = \mathcal{O}_5 + \mathcal{O}_6 = \underbrace{\frac{1}{2}\frac{c_{ij}}{\Lambda}\bar{\ell}_i^c \tilde{H}^* \ \tilde{H}^\dagger \ell_j}_{\Delta L \neq 0} + \underbrace{\frac{c'_{ij}}{\Lambda'}\bar{\ell}_i \tilde{H} i \not{\partial} \ \tilde{H}^\dagger \ell_j}_{\Delta L = 0, \Delta F \neq 0} + \text{h.c.}$$

✔ $\mathcal{O}_5$ constrained by low-energy neutrino data

✘ Flavor structure of $\mathcal{O}_6$ not related with $\mathcal{O}_5$

Make assumptions to relate c'_{ij} with c_{ij}

MFV: effective approach

The only sources of flavor violation in the SM Lagrangian

are the only sources of flavor violation also beyond the SM

Chivukula & Georgi (1987)

Hall & Randall (1990)

D'Ambrosio, Giudice, Isidori & Strumia (2002)

Quark sector Y_u and Y_d sources of FV $\Rightarrow$ MFV uniquely implemented

Lepton sector Y_e only source $\Rightarrow$ LFV effects can be rotated away

Neutrino masses $\Rightarrow$ new LFV couplings $\Rightarrow$ LFV effects can not be rotated away anymore

➥ Fix a scheme e.g. type-I seesaw: **Cirigliano** *et. al.* **(2005,2006), Alonso** *et. al.* **(2011)**

$$\mathcal{L}_{\text{kin}} \xrightarrow{G} \mathcal{L}_{\text{kin}} \qquad G = U(3)_e \times U(3)_\ell \times U(3)_N$$

$$G = U(1)_L \times U(1)_Y \times U(1)_R \times SU(3)^3$$

$$\mathcal{L}_Y \xrightarrow{G} \mathcal{L}'_Y \qquad SU(3)^3 \text{ broken by } Y\text{'s}$$

- ❒ Recover formal invariance of $\mathcal{L}^{\text{full}}$ by $Y \xrightarrow{G} Y$
- ❒ Construct a tower of effective operators with Y's
- ❒ Choose $G' \subset G_F$ s.t. the flavor structure is entirely determined by ν data.

LFV observables entirely determined by low-energy data

MLFV: Explicit models

Add fermionic electroweak singlets (right-handed neutrinos), N_a, to the SM Lagrangian

$$\mathcal{L} = -\bar{\ell}\,\boldsymbol{\lambda}^*\,N\tilde{H} - \mu\frac{1}{2}\bar{N}^T C\,\hat{\mathbf{Y}}_{\boldsymbol{N}}\,N$$

$$(SU(3)_\ell, SU(3)_N)$$
$$\boldsymbol{\lambda} \sim (\mathbf{3}, \bar{\boldsymbol{n}}), \quad \boldsymbol{Y_N} \sim (\mathbf{1}, \bar{\boldsymbol{n}})$$

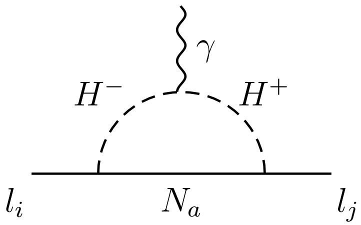
Key point: $\boldsymbol{\mathcal{P}} = \{\lambda_{ia}, M_{N_a}\}$ compared with $\boldsymbol{\mathcal{O}} = \{\theta_{ij}, \delta, \phi_{1,2}, m_{\nu_k}\}$

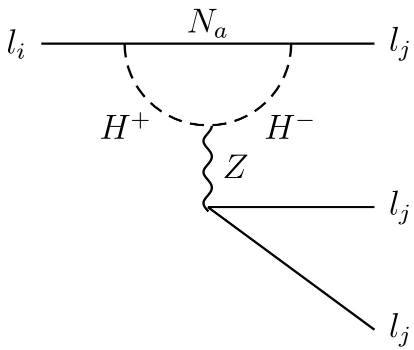
- $\boldsymbol{\mathcal{P}} > \boldsymbol{\mathcal{O}}$:

$$G' \subset G_F \begin{cases} SU(3)_N \longrightarrow SO(3) \times \text{CP} \Longrightarrow \boldsymbol{\lambda}^\dagger = \boldsymbol{\lambda}^T \\ SU(3)_\ell \times SU(3)_N \longrightarrow SU(3)_{\ell+N} \Longrightarrow \boldsymbol{\lambda}\boldsymbol{\lambda}^\dagger = \boldsymbol{I} \end{cases} \Longrightarrow \quad \boldsymbol{\lambda} \text{ determined by } \boldsymbol{\mathcal{O}}$$

- $\boldsymbol{\mathcal{P}} \simeq \boldsymbol{\mathcal{O}} \Rightarrow \lambda_{ia} = f(\theta_{kj}, m_{\nu_k})$ **Gavela,Hambye,D. Hernandez,P. Hernandez (2009)**

The new d.o.f mediate LFV processes:





$\cdots$

LFV processes entirely determined by $\mathcal{O}$ due to MLFV hypothesis

MLFV in minimal realizations

General setups

➢ Minimal models consistent with data $\Longrightarrow$ 2 RH neutrinos.

➢ Flavor group decomposition $G = U(1)_Y \times U(1)_L \times \boldsymbol{U(1)_R} \times G_F$

GOAL

In that context study the implications of $U(1)_R$ for LFV

Strategy

- Consider different SM fields and RH neutrinos R charge assignments.
- Consider models with slightly broken $U(1)_R$.
- Derive consequences for LFV processes.

Generic models

Type A models: $R(N_a) = +1$ and $R(\ell_i, e_i, H) = 0$

Type B models: $R(N_1, \ell_i, e_i) = +1$ and $R(N_2) = -1$ $R(H) = 0$

$$\mathcal{L} = -\bar{\ell}\hat{\boldsymbol{Y}}_{\boldsymbol{e}}\, eH - \epsilon\,\bar{\ell}\,\boldsymbol{\lambda}^*\, N\tilde{H} - \frac{1}{2}\epsilon^2\,\mu N^T\, C\,\hat{\boldsymbol{Y}}_{\boldsymbol{N}}\, N + \text{h.c.}\,.$$

$$\boldsymbol{\mathcal{M}} = \begin{pmatrix} 0 & \epsilon\, v\boldsymbol{\lambda} \\ \epsilon\, v\boldsymbol{\lambda} & \epsilon^2\,\mu\hat{\boldsymbol{Y}}_{\boldsymbol{N}} \end{pmatrix}$$

$$\boldsymbol{m}_{\boldsymbol{\nu}}^{\text{eff}} = -\frac{v^2}{\mu}\sum_{a=1,2}\frac{\boldsymbol{\lambda_a}\otimes\boldsymbol{\lambda_a}}{Y_{N_a}} \quad\Rightarrow\quad \boldsymbol{U}^T\,\boldsymbol{m}_{\boldsymbol{\nu}}^{\text{eff}}\,\boldsymbol{U} = \hat{\boldsymbol{m}}_{\boldsymbol{\nu}}^{\text{eff}}$$

$$\boldsymbol{\lambda_a} = (\lambda_{ea}, \lambda_{\mu a}, \lambda_{\tau a})$$

$$\hat{\boldsymbol{M}}_{\boldsymbol{N}} = \epsilon^2\,\mu\,\hat{\boldsymbol{Y}}_{\boldsymbol{N}}$$

μ scale $\quad \hat{\boldsymbol{Y}}_{\boldsymbol{N}}, \boldsymbol{\lambda} \lesssim \mathcal{O}(1);\ \sqrt{\Delta m^2_{31}} \sim 0.05$ eV $\quad\Rightarrow\quad \mu \sim 10^{15}$ GeV

M_N scale $\quad \epsilon \sim 10^{-6} \Rightarrow\quad \mathcal{O}(M_N) \sim$ TeV

Sizable CLFV effects?

$$\text{BR}(l_i \to l_j\gamma) \simeq \frac{\alpha}{4096\pi^4}\frac{m_i^5}{\mu^4\epsilon^4}\frac{1}{\Gamma^{l_i}_{\text{Tot}}}\left|\left(\boldsymbol{\lambda}\,\boldsymbol{Y_N}^{-2}\boldsymbol{\lambda}^\dagger\right)_{ij}\right|^2 \quad\Rightarrow\quad \text{BR}(\mu \to e\gamma) \simeq 10^{-30}$$

ν mass suppression "propagates" to LFV observables

Type-B models

$$\mathcal{L} = -\bar{\ell}\,\boldsymbol{\lambda_1}^*\,N_1\tilde{H} - \epsilon_\lambda\,\bar{\ell}\,\boldsymbol{\lambda_2}^*\,N_2\tilde{H} - \frac{1}{2}N_1^T\,CM\,N_2 - \frac{1}{2}\epsilon_N N_a^T\,CM_{aa}\,N_a + \text{h.c.}\,.$$

$$\boldsymbol{M_N} = \begin{pmatrix} \epsilon_N M_{11} & M \\ M & \epsilon_N M_{22} \end{pmatrix}$$

Diagonalization of $\boldsymbol{M_N}$:

$$M_{N_{1,2}} = M \mp \frac{M_{11}+M_{22}}{2}\epsilon_N$$

$$\lambda_{ka} \to -\frac{(i)^a}{\sqrt{2}}\left[\lambda_{k1} + (-1)^a\epsilon_\lambda\lambda_{k2}\right]$$

$$\boldsymbol{m_\nu^{\text{eff}}} = -\frac{v^2\epsilon_\lambda}{M}|\boldsymbol{\lambda_1}||\boldsymbol{\Lambda}|\left(\hat{\boldsymbol{\lambda}}_1^*\otimes\hat{\boldsymbol{\Lambda}}^* + \hat{\boldsymbol{\Lambda}}^*\otimes\hat{\boldsymbol{\lambda}}_1^*\right)$$

$$\boldsymbol{\lambda_1} = |\boldsymbol{\lambda_1}|\hat{\boldsymbol{\lambda}}_1$$

$$\boldsymbol{\Lambda} = |\boldsymbol{\Lambda}|\hat{\boldsymbol{\Lambda}}$$

MLFV due to the structure of the $\boldsymbol{m_\nu^{\text{eff}}}$

Gavela,Hambye,D.Hernandez,P.Hernandez, (2009)

$$\boldsymbol{\lambda_1} = |\boldsymbol{\lambda_1}|\,\hat{\boldsymbol{\lambda}}_1 = \frac{|\boldsymbol{\lambda_1}|}{\sqrt{2}}\left(\sqrt{1+\rho}\,\boldsymbol{U_3}^* + \sqrt{1-\rho}\,\boldsymbol{U_2}^*\right)$$

$$\boldsymbol{\Lambda} = |\boldsymbol{\Lambda}|\,\hat{\boldsymbol{\Lambda}} = \frac{|\boldsymbol{\Lambda}|}{\sqrt{2}}\left(\sqrt{1+\rho}\,\boldsymbol{U_3}^* - \sqrt{1-\rho}\,\boldsymbol{U_2}^*\right)$$

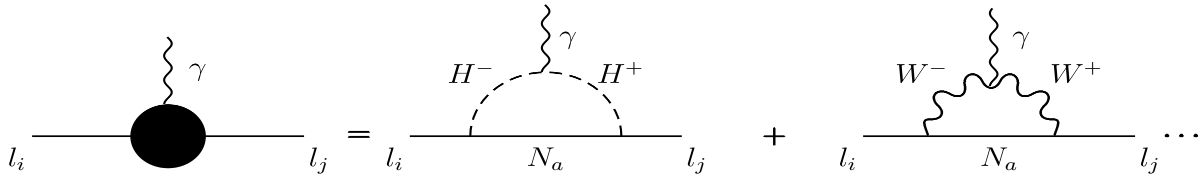
$$\rho = \rho(r)$$

$$\rho = \frac{m_{\nu_2}^2}{m_{\nu_3}^2 - m_{\nu_2}^2}$$

$\boldsymbol{m_\nu^{\text{eff}}} \propto \epsilon_\lambda$ $\Longrightarrow$ **Large Y's, light M_N**

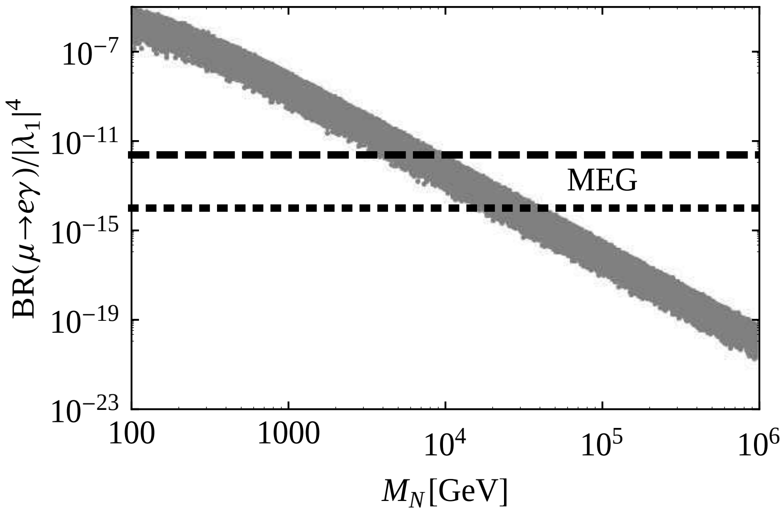
Potentially large LFV!!

Implications for LFV processes



Ilakovac & Pilaftsis (1994)

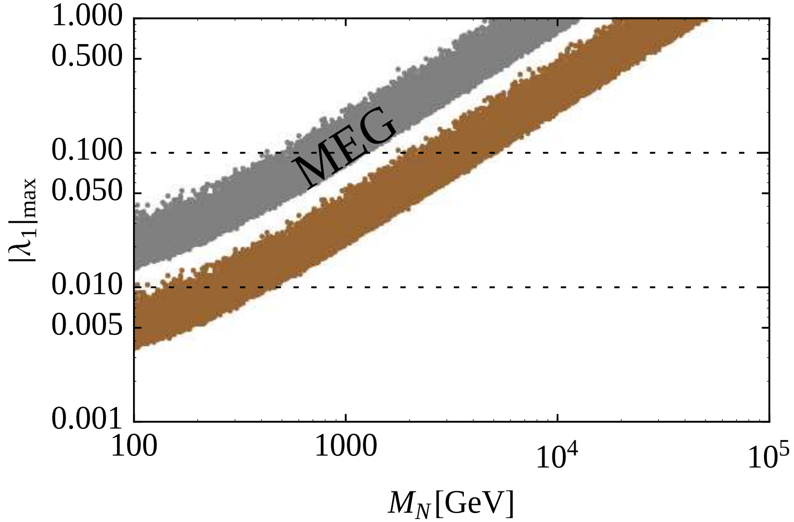
$$\mathrm{BR}(l_i \to l_j\gamma) = \frac{\alpha}{1024\pi^4}\frac{m_i^5}{M_W^4\Gamma_{\rm Tot}^{l_i}}\left|\left(\boldsymbol{\lambda}\,\boldsymbol{G_\gamma}\,\boldsymbol{\lambda}^\dagger\right)_{ij}\right|^2 \simeq \frac{\alpha}{1024\pi^4}\frac{m_i^5}{M^4}\frac{|\boldsymbol{\lambda_1}|^4}{\Gamma_{\rm Tot}^{l_i}}\underbrace{\left|\hat{\lambda}_{i1}\,\hat{\lambda}^*_{j1}\right|^2}_{\{m_\nu,\theta_{ij}\}}$$

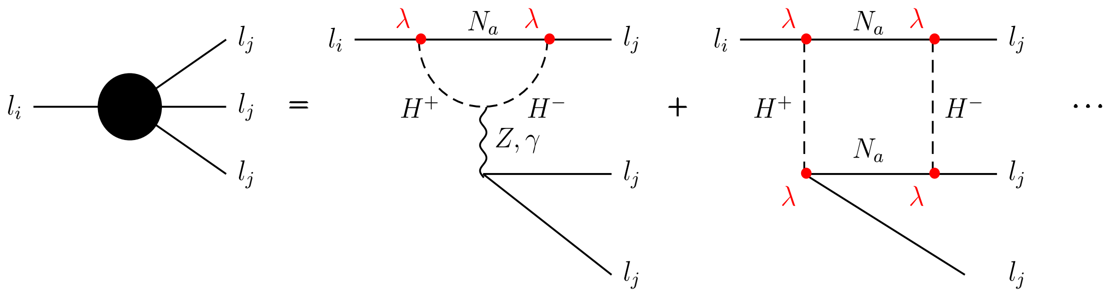


τ LFV decays are suppressed

Upper bounds on $|\boldsymbol{\lambda_1}|$:

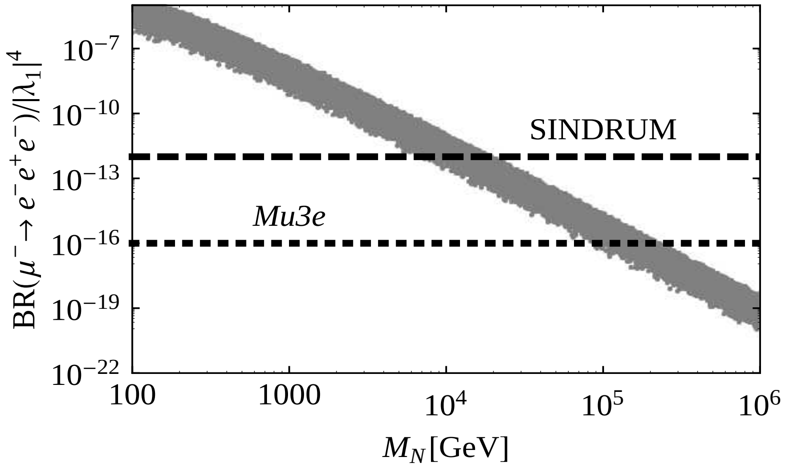
$$\frac{|\boldsymbol{\lambda_1}|^4}{M^4} \simeq \frac{1024\,\pi^4}{\alpha}\frac{\Gamma_{\rm Tot}^{l_i}}{m_i^5}\frac{\mathrm{BR}^{\rm Fix}_{\mu\to e\gamma}}{\left|\hat{\lambda}_{i1}\,\hat{\lambda}^*_{j1}\right|^2}$$





Ilakovac & Pilaftsis (1994)

BRs$(\lambda, M_N) \xrightarrow{MLFV}$ BRs$(m_\nu, \theta_{ij}, |\boldsymbol{\lambda_1}|, M_N)$

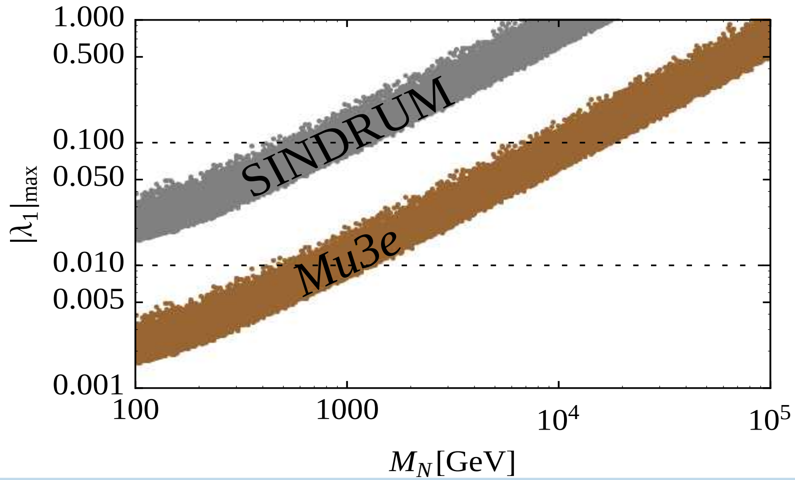


Future sensitivities $\Rightarrow$ Heavier M_N

τ LFV decays are suppressed

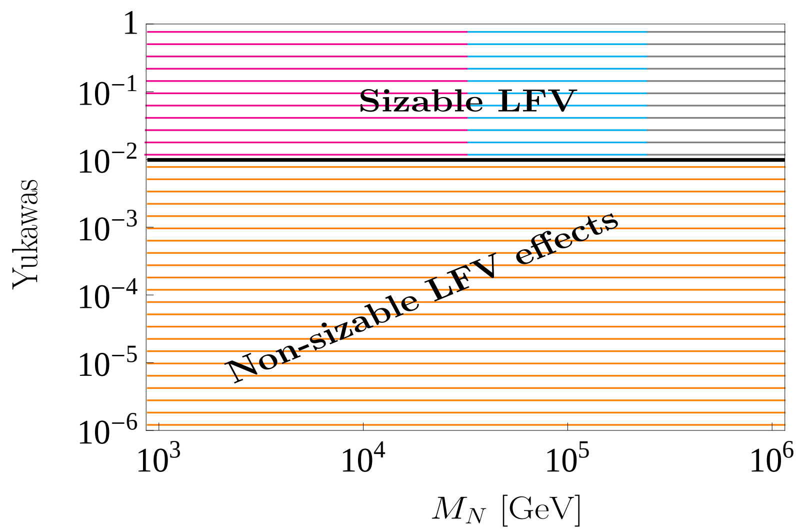
Upper bounds on $|\boldsymbol{\lambda_1}|$:

$$\frac{|\boldsymbol{\lambda_1}|^4}{M^4} = f(\theta_{ij}, m_\nu)\mathrm{BR}^{\mathrm{Fix}}_{\mu\to 3e}$$



Implications for primordial $B-L$ asymmetries

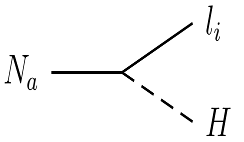
RHN washout dynamics



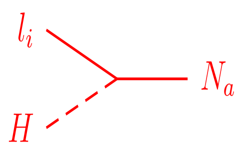
Are there any relevant RHN processes

in the region $\boldsymbol{Y} \lesssim 10^{-2}$?

At high temperature the RHN dynamics has implications:



- Baryogenesis via leptogenesis



- Erasing of primordial $B - L$ asymmetries ($\boldsymbol{Y_{\Delta_i}}$)

Boltzmann equations

$$\frac{dY_{\Delta_i}}{dz} = -\frac{\kappa_i}{4} \sum_{j=e,\mu,\tau} C_{ij}^{(\ell)}\, Y_{\Delta_j}\, K_1(z) z^3$$

$$\kappa_i \propto \frac{|\boldsymbol{\lambda_1}|^2}{M_N} \underbrace{|\hat{\lambda}_{i1}|^2}_{\{\boldsymbol{\theta_{ij}},\mathbf{m}_\nu\}}$$

$$Y_{\Delta_B} = \frac{12}{37}\, Y_{\Delta_{B-L}}^{(\text{in})}\, e^{-3\pi\kappa/8}$$

Large κ ($Y \gtrsim 10^{-2}$) $\Rightarrow Y_{\Delta_B} \ll Y_{\Delta_B}^{\text{Exp}}$

In the region of non-sizable LFV effects

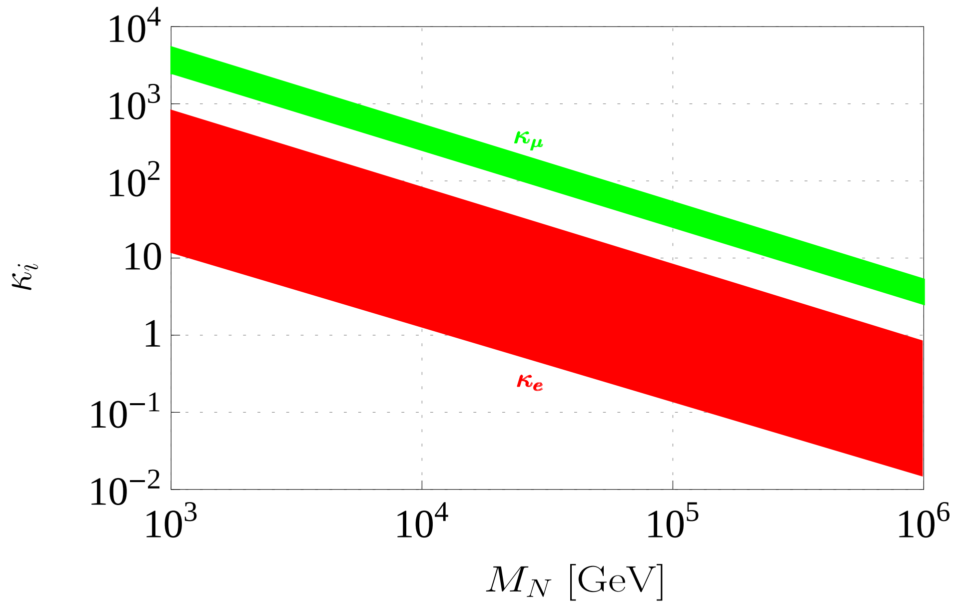
a primordial $Y_{\Delta_{B-L}}$ may be preserved

Results

Parameter space splitted in two regions: Large Yukawa and small Yukawa regions

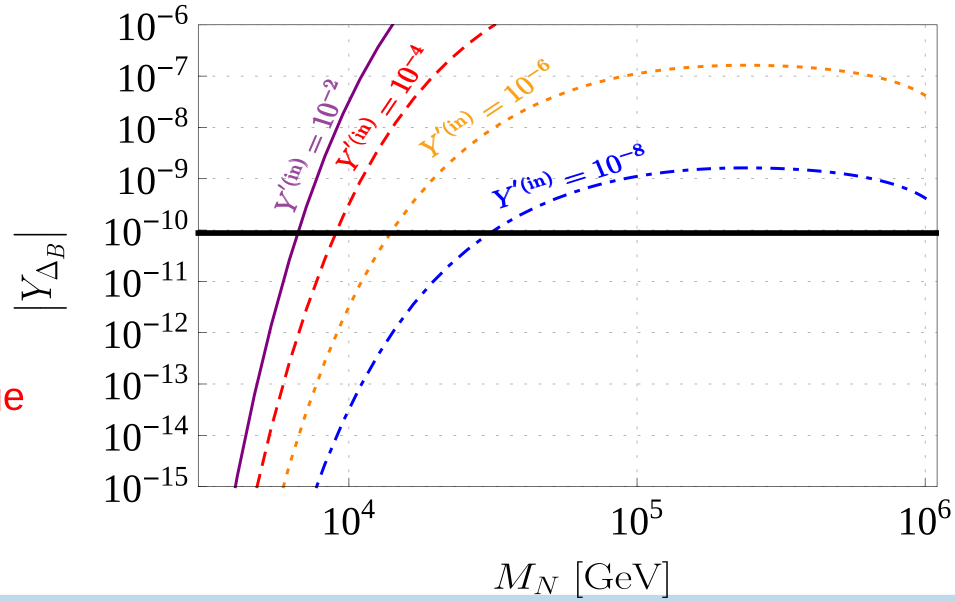
- $|\boldsymbol{\lambda_1}| = 10^{-5}$
- experimental ν-data @ 2σ

An asymmetry stored in e flavor



- $|\boldsymbol{\lambda_1}| = 10^{-5}$
- ν-data best fit point values

A baryon asymmetry in the correct range can always be obtained!



Conclusions

Final Remarks

- MLFV is a guide for constructing “predictive” models in which charged lepton flavor violating (CLFV) effects are determined by low-energy data.

- The G decomposition contains a $U(1)_R$ that allows the definition of two kind of generic models:
  - **Models A**: the neutrino mass suppression mechanism “propagates” to the LFV observables $\Rightarrow$ and therefore CLFV effects are suppressed
  - **Models B**: the suppression mechanism “decouples” from the LFV observables and CLFV effects become sizable

- In type-B models the parameter space can be splitted in two non-overlapped portions with their own physical implications:
  - Regions of large Y’s where $\mu \to e\gamma$, $\mu \to 3e$ and $\mu - e$ conversion are within experimental reach.
  - Regions of small Y’s where CLFV effects are negligibly small and $B - L$ asymmetries can survive the washouts induced by N_a