Minimal lepton flavor violating realizations of minimal seesaw models

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based on JHEP 1207 (2012) 135

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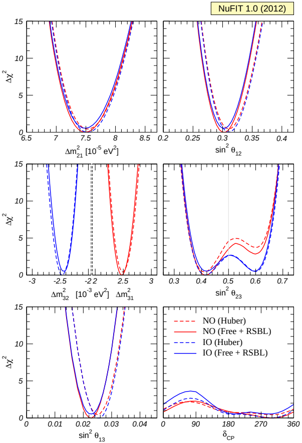
April 17, Portoroz 2013

Evidence of neutrino oscillations



M. C. Gonzalez-Garcia, Michele Maltoni, Jordi Salvado, Thomas Schwetze (2011) [JHEP 1212 (2012) 123], [arXiv :1209.3023]

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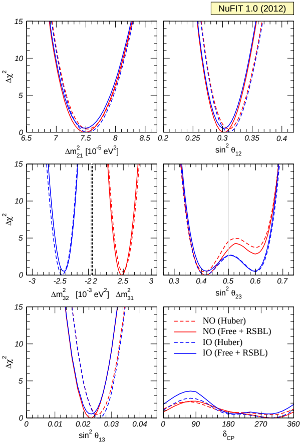


M. C. Gonzalez-Garcia, Michele Maltoni, Jordi Salvado, Thomas Schwetze (2011) [JHEP 1212 (2012) 123], [arXiv :1209.3023]

For normal spectrum :

Parameter	2σ
Δm^2_{12} [$10^{-5} eV^2$]	7.27 - 8.01
$\lvert\Delta m^2_{31}\rvert$ [$10^{-3} eV^2$]	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

Neutrino flavor oscillations

$\rightarrow$ **nondegenerate neutrino masses and mixings**

$\rightarrow$lepton flavor violation in the neutral sector

Lepton flavor violating (LFV) signals

Neutrino masses $\rightarrow$ Charged LFV processes

No signal for LFV in the charged lepton sector has been observed yet.

No definitive model for neutrino masses $\rightarrow$ no definitive predictions for LFV processes.

- Detection $\rightarrow$ new physics scale $\sim$ TeV
- Predictions $\rightarrow$LFV signals determined by low-energy neutrino data

Model + flavor structure :

We study the lepton flavor violation (LFV) related phenomenology of the type-I seesaw assuming minimal flavor violation (MFV).

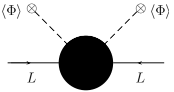
Outline

1. Generalities
   - Seesaw mechanism
   - MFV and $U(1)_R$ symmetry
2. Models
   - First model
   - Second model
3. Results
   - $l_i \to l_j \gamma$
   - $l_i^- \to l_j^- l_j^- l_j^+$
   - $\mu - e$ conversion in nuclei
4. Conclusion

Seesaw mechanism

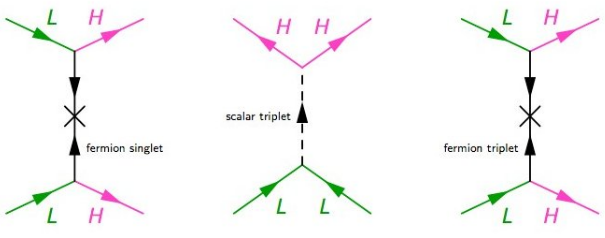
Majorana neutrino ($\bar{\nu} = \nu$) mass term violates lepton number with

the dimension 5 effective operator $\mathbf{Y_{ij}} \frac{\mathbf{L_i \Phi \Phi L_j}}{\mathbf{M}}$:



Weinberg, 1979

3 tree-level realizations :



Type I — P.Minkowski (1997) ; R.N. Mohapatra (1980)...

Type II — J.Schechter and J.W.F.Valle (1980)...

Type III — R.Foot, H.Lew, X.G.He and G.C.Joshi (1989).

Type-I seesaw

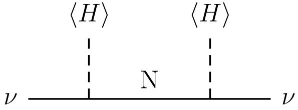
SM + **n $\mathbf{SU(2)_L}$ singlets neutrinos $\mathbf{N_R}$ with heavy Majorana masses**.

$$-\mathcal{L} = \bar{l}_L \lambda^* N \tilde{H} + \frac{1}{2} \bar{N} C M_R \bar{N}^T + H.C..$$

The $(3+n) \times (3+n)$ neutral fermion mass matrix :

$$M = \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix}, \quad m_D = v\lambda.$$

The light neutrino mass matrix in the seesaw limit $m_D \ll M_R$:



$$\mathbf{m_\nu^{eff} = m_D^T (M_R^{-1}) m_D}.$$

LFV signals and type-I seesaw

Neutrino mass ($m_\nu = v^2 \lambda M_R^{-1} \lambda^T$) constraints require either :

- $M_R >> \Lambda_{\text{EW}}$ (if $\lambda \sim 1$, $M_R \sim 10^{14}$ GeV to have $m_\nu \sim 10^{-1}$eV)
- $\lambda << 1$ (if $M_R \sim 1$ TeV, $\lambda \sim 10^{-6}$ to have $m_\nu \sim 10^{-1}$eV)

The simple seesaw neutrino model does not induce experimentally observable rates for lepton flavor violating processe, such as $\mu \to e\gamma$:

$\Gamma(\mu \to e\gamma) \propto \lambda^2 \frac{m_\mu^5}{M_R^4}$ is very suppressed.

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Minimal flavor violation hypothesis (MFV)

The **global flavor symmetry group** of the SM without the Yukawa couplings is :

$$G_F = U(3)_{Q_L} \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E .$$

In MFV model, G_F is taken to be a symmetry of the full Lagrangian **promoting the Yukawa mass matrices to spurion fields** with definite group transformations.

MFV hypothesis :

- The Yukawa couplings are the only sources of flavour violation.
- Spurions are entirely determined by low energy data.

R. S. Chivukula and H. Georgi, Phys (1987) ; L. J. Hall and L. Randall (1990) ; G. DAmbrosio, G. F. Giudice, G. Isidori and A. Strumia (2002) [Nucl.Phys. B645 (2002) 155-187].

Quark sector : Y_u and Y_d sources of FV $\rightarrow$ MFV uniquely implemented.

Lepton sector : Y_e only source of FV $\rightarrow$ LFV effects can be rotated away.

MFV seesaw and $U(1)_R$ symmetry

The kinetic Lagrangian of the SM extended with n RH neutrinos exhibits the global :

$$G = U(3)_E \times U(3)_L \times U(n)_N = U(1)_L \times U(1)_Y \times \mathbf{U(1)_R} \times G_F,$$

where E, L, N denotes triplets in flavor space.

G_F determines the flavor symmetry which is explicitly broken in the Yukawa sector.

$U(1)_{Y,L}$ = global phase rephasing of hypercharge and lepton number.

$\mathbf{U(1)_R}$ = global rephasing of lepton sector.

A. Strumia (2002)[Nucl.Phys. B645 (2002) 155-187] ; R. Alonso, G. Isidori, L. Merlo, L. A. Munoz and E. Nardi [JHEP 1106 :037,2011]

$\rightarrow$ arbitrary R charge assignment $\rightarrow$ 2 classes of generic models.

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First type$-I$ seesaw model with $U(1)_R$ symmetry

Type$-I$ seesaw model with 2 right-handed neutrinos N_1, N_2 and R assignments :

Charge	N_1	N_2	l	e
L	1	1	1	1
R	1	1	0	0

$\Delta R = 0$: $\Delta L = 0, \quad M = 0, \quad m_\nu = 0.$

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$\Delta R = 0$: $\Delta L = 0, \quad M = 0, \quad m_\nu = 0.$

$$\Delta R \neq 0: \ \Delta L \neq 0, \quad M = \begin{pmatrix} 0 & \epsilon v \lambda \\ \epsilon v \lambda & \epsilon^2 \mu Y_N v \lambda \end{pmatrix}, \quad m_\nu^{eff} = -\frac{v^2}{\mu} \lambda . Y_N^{-1} . \lambda^T$$

$$(\ \mathcal{O}(Y_N, \lambda) \sim 1, \quad m_\nu \sim 10^{-1}\text{eV} \quad \rightarrow \quad \boldsymbol{\mu} \sim \mathbf{10^{14}GeV})$$

First type$-I$ seesaw model with $U(1)_R$ symmetry

$$\hat{M}_N = \epsilon^2 \mu \hat{Y}_N$$

is decoupled from μ as long as $\epsilon << 1$, (e.g. :$\epsilon \sim 10^{-5}, M_N \sim 1$TeV)

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Does O(M_N)$\sim$TeV imply sizable LFV ?

The Yukawa couplings

$$\tilde{\lambda} = \epsilon \lambda$$

So,

$$\text{Br}(\mu \to e\gamma) \sim \frac{\alpha}{1024\pi^4} \frac{m_\mu^5}{\Gamma_{\text{tot}}^\mu} \frac{\tilde{\lambda}^4}{M_N^4}$$

Same R charge for N_1 and N_2 doesn't produce sizable LFV effect :

$$\text{Br}(\mu \to e\gamma) \sim 10^{-54}$$

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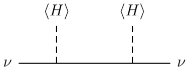
Second type$-I$ seesaw model with $U(1)_R$ symmetry

Type$-I$ seesaw with 2 right-handed neutrinos N_1 and N_2 and R-charge assignments :

Charge	N_1	N_2	l	e
L	1	1	1	1
R	1	-1	1	1

$$-\mathcal{L} = \bar{l}\lambda^* N\tilde{H} + \frac{1}{2}N^T C M_N N + H.C.,$$

$$\lambda^* = \begin{pmatrix} \lambda^*_{11} & 0 \\ \lambda^*_{21} & 0 \\ \lambda^*_{31} & 0 \end{pmatrix}, \quad M_N = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}.$$

$\Delta R = 0:$ $\Delta L \neq 0 \rightarrow$  but $m_\nu = 0$

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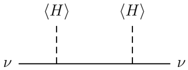
$$-\mathcal{L} = \bar{l}\lambda^* N\tilde{H} + \frac{1}{2}N^T C M_N N + H.C.,$$

$$\lambda^* = \begin{pmatrix} \lambda^*_{11} & \epsilon_\lambda \lambda^*_{12} \\ \lambda^*_{21} & \epsilon_\lambda \lambda^*_{22} \\ \lambda^*_{31} & \epsilon_\lambda \lambda^*_{32} \end{pmatrix}, \quad M_N = \begin{pmatrix} M_{11}\epsilon_N & M \\ M & M_{22}\epsilon_N \end{pmatrix}.$$

$\Delta R = 0$: $\Delta L \neq 0 \rightarrow$ 

but $m_\nu = 0$

$\Delta R \neq 0$: $\Delta L \neq 0$, $m_\nu \propto \frac{v^2 \epsilon_\lambda}{M}(\vec{\lambda}_1 \otimes \vec{\lambda}_2 + \vec{\lambda}_2 \otimes \vec{\lambda}_1)$,

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

Second type$-I$ seesaw model with $U(1)_R$ symmetry

light $\mathbf{m}_\nu$ due to $\epsilon_{\boldsymbol{\lambda}} \ll \mathbf{1} \rightarrow \boldsymbol{\lambda}$ large and O(M) $\sim$TeV.

Potentially large LFV.

MLFV realized due to the structure of m_ν^{eff} :

$$\lambda_{i1} = |\boldsymbol{\lambda_1}|(\sqrt{1+\rho}U_{i3}^* + \sqrt{1-\rho}U_{i2}^*)$$

$$\rho = \frac{\sqrt{1+r} - \sqrt{r}}{\sqrt{1+r} + \sqrt{r}}, \quad r = \frac{\Delta m_{12}^2}{\Delta m_{23}^2}$$

M. B. Gavela, T. Hambye, D. Hernandez and P. Hernandez (2009)[JHEP 0909 (2009) 038]

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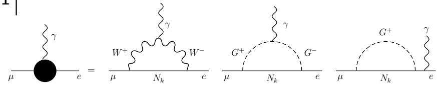
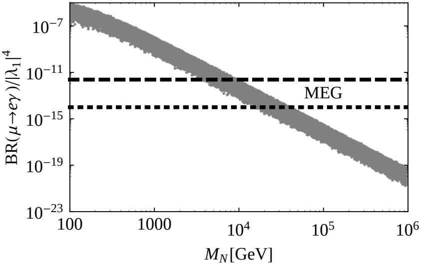
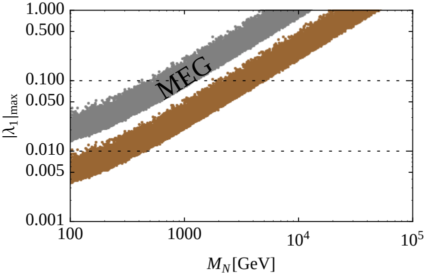
Br($\mu \to e\gamma$) in the normal spectrum (NS)

$$\mathrm{BR}(l_i \to l_j\gamma) \sim \frac{\alpha}{1024\pi^4}\frac{m_i^5}{M^4}\frac{|\boldsymbol{\lambda_1}|^4}{\Gamma^{l_i}_{\mathrm{Tot}}}\left|\hat{\lambda}_{i1}\ \hat{\lambda}^*_{j1}\right|^2$$

Ilakovac and Pilaftsis (1994)







- Br($\mu \to e\gamma$) $\leq 2.4 \times 10^{-12}$(current) - 10^{-14}(future) at 90% level.

J. Adam et al. [MEG Collaboration] (2011)[Phys.Rev.Lett. 107 (2011) 171801]

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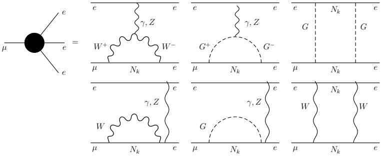
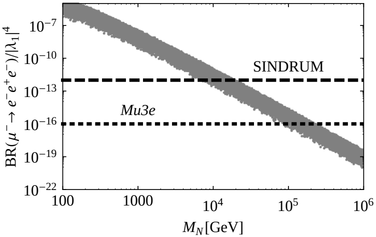
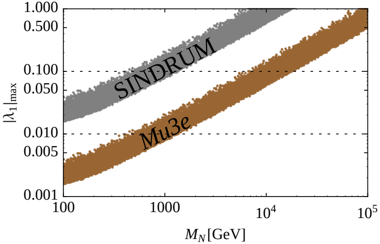
Br($\mu^- \to e^- e^+ e^-$) in the normal spectrum (NS)



Ilakovac and Pilaftsis (1994)





- Bounds from SINDRUM : Br($\mu^- \to e^+ e^+ e^-$) $\leq 10^{-12}$ at 90% level.
- Mu3e/PSI expects 10^{-16}.

U. Bellgardt et al. [SINDRUM Collaboration] (1988)

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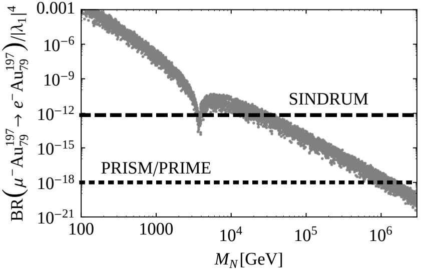
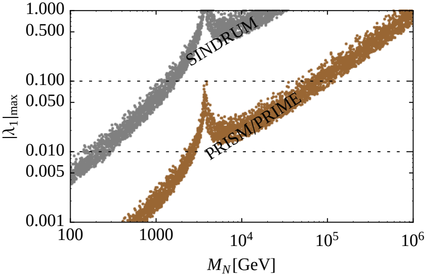
Br(μ-e conversion) in the NS for Au





- Bound on $\mu - e$ conversion from SINDRUM on Ti is 4.3×10^{-12} at 90% level. C. Dohmen et al. [SINDRUM II Collaboration.] (1993)
- Bound on $\mu - e$ conversion from SINDRUM on Au is 7×10^{-13} at 90% level. W. Bertl et al. [SINDRUM II Collaboration] (2006)
- PRISM/PRIME expects 10^{-16}-10^{-18}. C. Ankenbrandt et al.[physics/0611124].

Conclusion

We have studied the **implications of a slightly broken** $U(1)_R$ **symmetry in the minimal Type-I seesaw model**.

Two classes of generic models can be identified, models in which :

- $R(N_1) = R(N_2)$:
  - charged lepton flavor violating decay branching ratios are negligible.
- $R(N_1) = -R(N_2)$:
  - the intrinsic structure leads to a **flavor structure completely determined by low-energy neutrino observables**.
  - **sizable** $\mu \to e\gamma$**,** $\mu \to 3e$ **and** $\mu - e$ **processes.**

Thank you !

Neutrino data

For normal spectrum :

Parameter	Best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{12} $[10^{-5} eV^2]$	$7.59^{+0.20}_{-0.18}$	7.24 - 7.99	7.09 - 8.19
$\|\Delta m^2_{31}\|$ $[10^{-3} eV^2]$	2.45 ± 0.09	2.28 - 2.64	2.18 - 2.73
$Sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28 - 0.35	0.27 - 0.36
$Sin^2\theta_{23}$	0.51 ± 0.06	0.41 - 0.61	0.39 - 0.64
$Sin^2\theta_{13}$	$0.01^{+0.009}_{-0.006}$	$\leq$ 0.027	$\leq$ 0.035

J.W.F. Valle arXiv :1103.0734

Seesaw model conserving L : inverse seesaw

Models in which **lepton flavour (LF) violating scale (λ) can be disconnected from the lepton number (LN) violating one ($\mathbf{M_R}$)** :

- we assume $\Delta L = 0$, $M_N \sim 100$ GeV -100 TeV and $\lambda \sim 10^{-2} - 1$

  $\rightarrow$ Br($\mu \rightarrow e\gamma$)$\sim 10^{-12}$ (experimental limit) but $m_\nu \sim 0$;

- we assume $\Delta L \neq 0$ slightly by a small perturbation ϵ

  $\rightarrow$ $m_\nu \propto \epsilon$ rather than MR^{-1} and Br($\mu \rightarrow e\gamma$)$\sim 10^{-12}$.

M. B. Gavela, T. Hambye, D. Hernandez and P. Hernandez (2009) arXiv :0906.1461

LN and LF

Distinguish :

- **lepton number (LN)** violating interactions : LN is $U(1)$ symmetry such as $L(\text{leptons}) = 1 \rightarrow$ **Majorana breaks LN.**
- **lepton flavor (LF)** violating interactions : LF is an $SU(3)$ symmetry, mixing different flavors $\rightarrow$ **Yukawa breaks LF.**

MFV in the quark and lepton sectors

- **Quark sector** in SM : in absence of masses :

$$G_{F,quarks} = U(3)^3 = SU(3)^3 \times U(1)^3.$$

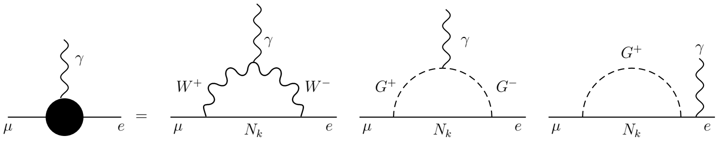
  MFV hypothesis :

  - All breaking of G_F must transform as the Yukawa interactions.
  - In the mass eigenstate basis, **all mixings are parametrized by CKM.**

- **Lepton sector** in SM : since $m_\nu = 0$, MLFV cannot be uniquely implemented in the lepton sector.

  $\rightarrow$ depends on the new physics responsible for neutrino masses.

Radiative lepton flavor violating decays : $l_i \to l_j\gamma$



For $m_j << m_i$:

$$\mathrm{Br}(l_i \to l_j\gamma) = \frac{\alpha\alpha_W^2}{256\pi^2}\frac{m_i^5}{M_W^4}\frac{1}{\Gamma_{Tot}^{l_i}}|(\lambda G_\gamma \lambda^\dagger)_{ij}|^2$$

A. Ilakovac and A. Pilaftsis (1995)

Parametrization in the second model and bounds

For the normal spectrum (NS) :

$$\lambda_{i1} = |\vec{\lambda}_1|(\sqrt{1+\rho}U^*_{i3} + \sqrt{1-\rho}U^*_{i2})$$

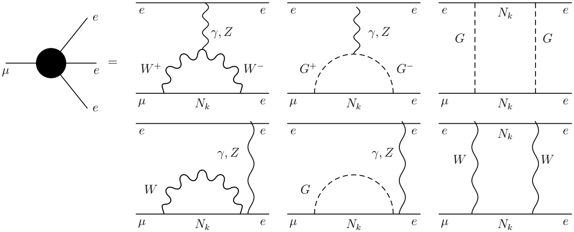
$$\rho = \frac{\sqrt{1+r}-\sqrt{r}}{\sqrt{1+r}+\sqrt{r}}, \quad r = \frac{\Delta m^2_{12}}{\Delta m^2_{23}}$$

M. B. Gavela, T. Hambye, D. Hernandez and P. Hernandez (2009) : arXiv :0906.1461

Bounds from MEG :

- $Br(\mu \to e\gamma) \leq 2.4 \times 10^{-12}$(current) - 10^{-14}(future) at 90% level.
- $Br(\tau \to e\gamma) \leq 3.3 \times 10^{-8}$(current) - $10^{-?}$(future) at 90% level.
- $Br(\tau \to \mu\gamma) \leq 4.4 \times 10^{-8}$(current) - $10^{-?}$(future) at 90% level.

$l_i^- \to l_j^- l_j^- l_j^+$



$$T(l_i^- \to l_j^- l_j^- l_j^+) = T_{\gamma-penguin} + T_{Z-penguin} + T_{Boxes}$$

$$\mathrm{BR}(l_i^- \to l_j^+ l_j^- l_j^+) = \frac{\alpha_W^4}{24576\pi^3} \frac{m_i^5}{M_W^4} \frac{1}{\Gamma_{\mathrm{Total}}^{l_i}}$$

$$\left\{ 2 \left| \frac{1}{2} F_{\mathrm{Box}}^{l_i 3 l_j} + F_Z^{l_i l_j} - 2 s_W^2 \left(F_Z^{l_i l_j} - F_\gamma^{l_i l_j} \right) \right|^2 \right.$$

$$+ 4 s_W^4 \left| F_Z^{l_i l_j} - F_\gamma^{l_i l_j} \right|^2 + 16 s_W^2 \mathrm{Re} \left[\left(F_Z^{l_i l_j} + \frac{1}{2} F_{\mathrm{Box}}^{l_i 3 l_j} \right) G_\gamma^{l_i l_j *} \right]$$

$$\left. - 48 s_W^4 \mathrm{Re} \left[\left(F_Z^{l_i l_j} - F_\gamma^{l_i l_j} \right) G_\gamma^{l_i l_j *} \right] + 32 s_W^4 \left| G_\gamma^{l_i l_j} \right|^2 \left(\ln \frac{m_i^2}{m_j^2} - \frac{11}{4} \right) \right\}$$

A. Ilakovac and A. Pilaftsis (1995)

$\mu - e$ conversion in nuclei

Currently the best bound comes from the search for coherent $\mu^- \to e^-$ conversions in the field of a nucleus, $\mu^- N \to e^- N$.

$$\mathrm{Br}(\mu^- \to e\gamma) = \frac{\Gamma_{\mathrm{conversion}}}{\Gamma_{\mathrm{capture}}} = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu N)}$$

$$\Gamma_{\mathrm{conversion}} = 2G_F^2 |A_R^* D + (2g_{LV}^{(u)} + g_{LV}^{(d)})V^{(p)} + (g_{LV}^{(u)} + 2g_{LV}^{(d)})V^{(n)}|^2$$

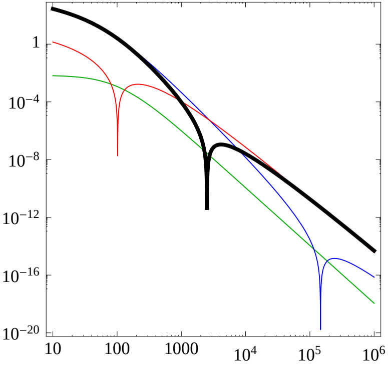
$$A_R = \frac{\sqrt{2}}{8G_F M_W^2} \frac{\alpha_W}{8\pi} e G_\gamma^{\mu e}$$

$$g_{LV}^{(u)} = \frac{\sqrt{2}\alpha_W^2}{8G_F M_W^2} \left((F_Z^{\mu e} + 2F_{Box}^{\mu 3e(1)}) - 4Q_u S_W^2 (F_Z^{\mu e} - F_\gamma^{\mu e}) \right)$$

$$g_{LV}^{(d)} = -\frac{\sqrt{2}\alpha_W^2}{8G_F M_W^2} \left((F_Z^{\mu e} + \frac{1}{2} F_{Box}^{\mu 3e(1)}) + 4Q_d S_W^2 (F_Z^{\mu e} - F_\gamma^{\mu e}) \right)$$

R. Kitano, M. Koike and Y. Okada(2002) arXiv :hep-ph/0203110

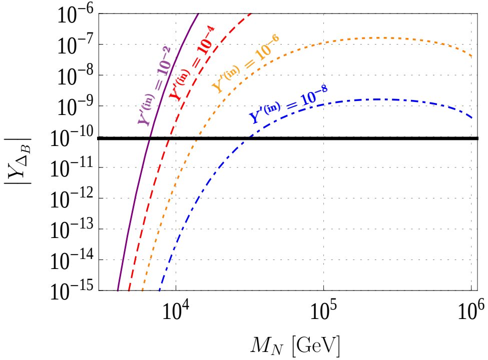
Plot $\mu - e$ conversion



Primordial lepton asymmetries

Sizable charged lepton flavor violating effects and generating/erasing a B-L asymmetry are mutually exclusive.

For $|\boldsymbol{\lambda_1}| = 10^{-5}$:



$$Y_{\Delta_B} = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

Moreover, we've studied the consequences of these setups for models of high scale baryogenesis.

- The phenomenological requirements of **sizable charged lepton flavor violating effects and the generation of a B-L asymmetry (or of not erasing a preexisting one) are therefore mutually exclusive.**