Lepton flavor violation in SUSY left-right symmetric theories

Avelino Vicente
IFIC - CSIC/U. Valencia

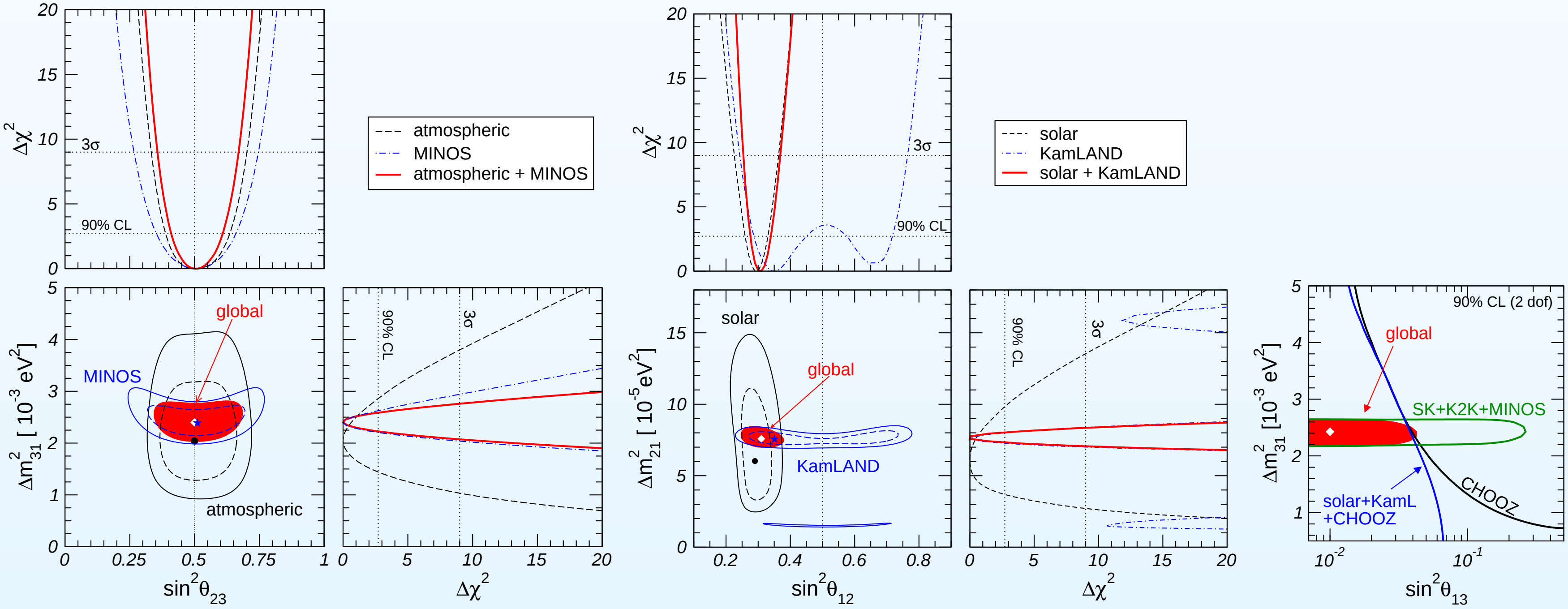
Based on work in progress with
J. Esteves, M. Hirsch, W. Porod, J. Romão and F. Staub

SUSY 10
August 24, 2010

Introduction

Introduction

Oscillation experiments have demonstrated that neutrinos have non-zero masses and mixing angles.



Taken from Schwetz *et al*, New J. Phys. 10 (2008) 113011 *[arXiv:0808.2016v2]*

This reference is updated continuosly with recent experimental data.

Introduction

The most popular explanation for the smallness of neutrino masses is the **seesaw mechanism**.

- Usual example : **Type I**

$$\mathcal{L} \supset Y_\nu L H \nu_R + M_R \nu_R \nu_R$$

$$M_{\nu_L \nu_R} = \begin{pmatrix} 0 & Y_\nu v \\ Y_\nu^T v & M_R \end{pmatrix}$$

$$m_{\text{light}} = -v^2 Y_\nu^T M_R^{-1} Y_\nu$$

Only **indirect tests** are possible, due to the high energy seesaw scale.

Introduction

In addition to neutrino masses, the Standard Model has some open theoretical questions that need be addressed. The most popular solution to these problems is **Supersymmetry**.

However, the most general superpotential allowed by gauge symmetry is

$$W = W^{MSSM} + W^{\not R_p}$$

$W^{\not R_p}$ violates baryon and lepton numbers

Conventional solution: A new symmetry that forbids all terms in $W^{\not R_p}$

R-parity

$$\boldsymbol{R_p = (-1)^{3(B-L)+2s}}$$

Introduction

However . . . R-parity is usually introduced **by hand**, without any theoretical argument supporting it.

Idea: R-parity is the remnant subgroup after the breaking of a continuous $U(1)_{B-L}$ gauge symmetry

Introduction

However . . . R-parity is usually introduced **by hand**, without any theoretical argument supporting it.

Idea: R-parity is the remnant subgroup after the breaking of a continuous $U(1)_{B-L}$ gauge symmetry

- Minimal $U(1)_{B-L}$ extensions

Introduction

However . . . R-parity is usually introduced **by hand**, without any theoretical argument supporting it.

Idea: R-parity is the remnant subgroup after the breaking of a continuous $U(1)_{B-L}$ gauge symmetry

- Minimal $U(1)_{B-L}$ extensions
- **Left-Right symmetry :** $\mathbf{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$
  - ⋆ Restoration of parity at high energies
  - ⋆ Natural framework for the seesaw mechanism $\rightarrow$ neutrino masses
  - ⋆ Provides technical solutions to SUSY and strong CP problems
  - ⋆ Gives an understanding for the $U(1)$ charges
  - ⋆ Can be easily embedded in $SO(10)$ GUTs

The model

How to break the LR symmetry

$$\mathbf{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$$
$$\downarrow$$
$$\mathbf{SU(3)_c \times SU(2)_L \times U(1)_Y}$$

Requirements:

- Automatic conservation of R-parity
- Parity conservation
- Seesaw mechanism
- Cancellation of anomalies

Case 1: Doublet models

R. N. Mohapatra and G. Senjanovic, Phys. Rev. D 12, 1502 (1975)

In the **first LR models** doublets were chosen to break the LR symmetry.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
χ	1	2	1	1
χ^c	1	1	2	-1

Case 1: Doublet models

R. N. Mohapatra and G. Senjanovic, Phys. Rev. D 12, 1502 (1975)

In the **first LR models** doublets were chosen to break the LR symmetry.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
χ	1	2	1	1
χ^c	1	1	2	-1

However . . .

- R-parity gets broken unless additional discrete symmetries are imposed by hand
- There is no seesaw mechanism

Case 2: MSUSYLR

M. Cvetic and J. C. Pati, Phys. Lett. 135, 57 (1984)

The so-called **Minimal SUSY Left-Right** (MSUSYLR) model breaks the LR symmetry with **triplets** instead of doublets.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
Δ	1	3	1	2
Δ^c	1	1	3	-2
$\bar{\Delta}$	1	3	1	-2
$\bar{\Delta}^c$	1	1	3	2

Case 2: MSUSYLR

M. Cvetic and J. C. Pati, Phys. Lett. 135, 57 (1984)

The so-called **Minimal SUSY Left-Right** (MSUSYLR) model breaks the LR symmetry with **triplets** instead of doublets.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	
Δ	1	3	1	2	
Δ^c	1	1	3	-2	$\Rightarrow f L^c \Delta^c L^c$
$\bar{\Delta}$	1	3	1	-2	$\Downarrow$
$\bar{\Delta}^c$	1	1	3	2	$\mathbf{f\, v_{BL}\, \nu^c \nu^c}$

RH neutrinos mass

Seesaw mechanism

Case 2: MSUSYLR

M. Cvetic and J. C. Pati, Phys. Lett. 135, 57 (1984)

The so-called **Minimal SUSY Left-Right** (MSUSYLR) model breaks the LR symmetry with **triplets** instead of doublets.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	
Δ	1	3	1	2	
Δ^c	1	1	3	-2	$\Rightarrow \; f L^c \Delta^c L^c$
$\bar{\Delta}$	1	3	1	-2	$\Downarrow$
$\bar{\Delta}^c$	1	1	3	2	$\mathbf{f \, v_{BL} \, \nu^c \nu^c}$

RH neutrinos mass

Seesaw mechanism

However . . .

- A detailed analysis of the scalar potential shows that **R-parity gets broken by** $\langle \tilde{\nu}^c \rangle \neq 0$. Kuchimanchi, Mohapatra, PRD 48, 4352 (1993).

  $\rightarrow$ This is **controversial** : 1-loop corrections must be taken very seriously.

Case 3: Omega LR

Aulakh *et al*, Phys. Rev. Lett. 79, 2188 (1997)
Aulakh *et al*, Phys. Rev. D 58, 115007 (1998)

New $B - L = 0$ triplets contribute to the scalar potential and allow for **R-parity conservation**.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
Δ	1	3	1	2
Δ^c	1	1	3	-2
$\bar{\Delta}$	1	3	1	-2
$\bar{\Delta}^c$	1	1	3	2
$\mathbf{\Omega}$	**1**	**3**	**1**	**0**
$\mathbf{\Omega}^c$	**1**	**1**	**3**	**0**

Case 3: Omega LR

Aulakh *et al*, Phys. Rev. Lett. 79, 2188 (1997)
Aulakh *et al*, Phys. Rev. D 58, 115007 (1998)

New $B - L = 0$ triplets contribute to the scalar potential and allow for **R-parity conservation**.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	
Δ	1	3	1	2	
Δ^c	1	1	3	-2	$\Rightarrow f L^c \Delta^c L^c$
$\bar{\Delta}$	1	3	1	-2	$\Downarrow$
$\bar{\Delta}^c$	1	1	3	2	$\mathbf{f\ v_{BL}\ \nu^c \nu^c}$
$\mathbf{\Omega}$	**1**	**3**	**1**	**0**	RH neutrinos mass
$\mathbf{\Omega}^c$	**1**	**1**	**3**	**0**	**Seesaw mechanism**

Case 3: Omega LR

Aulakh *et al*, Phys. Rev. Lett. 79, 2188 (1997)
Aulakh *et al*, Phys. Rev. D 58, 115007 (1998)

New $B-L=0$ triplets contribute to the scalar potential and allow for **R-parity conservation**.

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	
Δ	1	3	1	2	
Δ^c	1	1	3	-2	$\Rightarrow \; f L^c \Delta^c L^c$
$\bar{\Delta}$	1	3	1	-2	$\Downarrow$
$\bar{\Delta}^c$	1	1	3	2	$\mathbf{f \, v_{BL} \, \nu^c \nu^c}$
$\boldsymbol{\Omega}$	**1**	**3**	**1**	**0**	RH neutrinos mass
$\boldsymbol{\Omega^c}$	**1**	**1**	**3**	**0**	**Seesaw mechanism**

All the requirements are fulfilled.

Symmetry breaking

$$\mathbf{SU(2)_R \times U(1)_{B-L}}$$

$$\downarrow$$

$$\langle \Omega^c \rangle = \frac{v_R}{\sqrt{2}}$$

Parity breaking scale

$$\mathbf{U(1)_R \times U(1)_{B-L}}$$

$$\downarrow$$

$$\langle \Delta^c \rangle = \langle \bar{\Delta}^c \rangle = \frac{v_{BL}}{\sqrt{2}}$$

Seesaw scale

$$\mathbf{U(1)_Y}$$

Slepton decays and LFV

Basic setup

F. Borzumati and A. Masiero, Phys. Rev. Lett. 57, 961 (1986)

Lepton flavor violation is a good **indirect test** of physics at high energies.

- Flavor diagonal soft terms at the GUT scale
  - ⋆ mSUGRA boundary conditions : $m_L^2 = m_E^2 = m_0^2 \, \mathcal{I}_3$
- RGE running from GUT to SUSY/EW scale
  - ⋆ Leptons couple to heavy fields with flavor violating couplings
  - ⋆ RGE running induces LFV
  - ⋆ Off-diagonal entries in m_L^2 and m_E^2 at the SUSY/EW scale
  - ⋆ Flavor violating slepton decays
- After the heavy fields decouple no more LFV is induced
  - ⋆ Indirect hint of the intermediate scales

Basic setup

- mSUGRA boundary conditions
- 2-loop RGEs
  - ⋆ Analytical computation with *Sarah*

    F. Staub, Comput. Phys. Commun. 181, 1077 (2010)
  - ⋆ Numerical implementation with *SPheno*

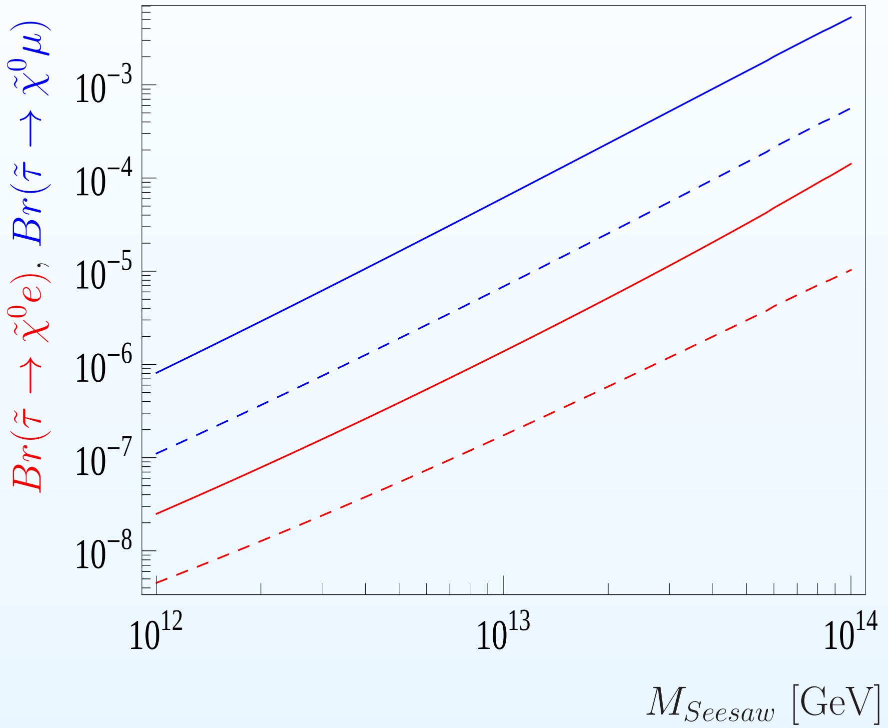
    W. Porod, Comput. Phys. Commun. 153, 275 (2003)
- Threshold corrections at intermediate scales
- Yukawa fit to neutrino oscillation parameters

Seesaw scale determination

SPS3 benchmark point

Degenerate right-handed neutrinos

$v_{BL} = 10^{15}$ GeV and $v_R = 5 \cdot 10^{15}$ GeV



$$m_\nu = -\frac{v_u^2}{2} Y_\nu^T \cdot M_R^{-1} \cdot Y_\nu$$

The absolute value of LFV BR's is linked to the Seesaw scale.

Left vs Right

In minimal seesaw models LFV is generated **only for the left-handed sleptons**.

- ⋆ **Example:** Type-I seesaw. e^c only couples through the flavor diagonal charged lepton Yukawa Y_e.
- ⋆ No chances to observe LFV in right-handed slepton decays.

However, in a LR extended version of the seesaw, $L^c = (e^c, \nu^c)$ couples exactly like the left-handed doublet $L = (\nu, e)$.

GUT scale : $\mathbf{m_L^2 = m_E^2 = m_0^2 \, \mathcal{I}_3}$

$\downarrow$

$\mathbf{v_R}$ **scale :** $\mathbf{m_L^2 = m_E^2}$ **due to parity conservation**

off-diagonal m_E^2 stop running

$\downarrow$

$\mathbf{v_{BL}}$ **scale :** $\mathbf{m_L^2 \neq m_E^2}$

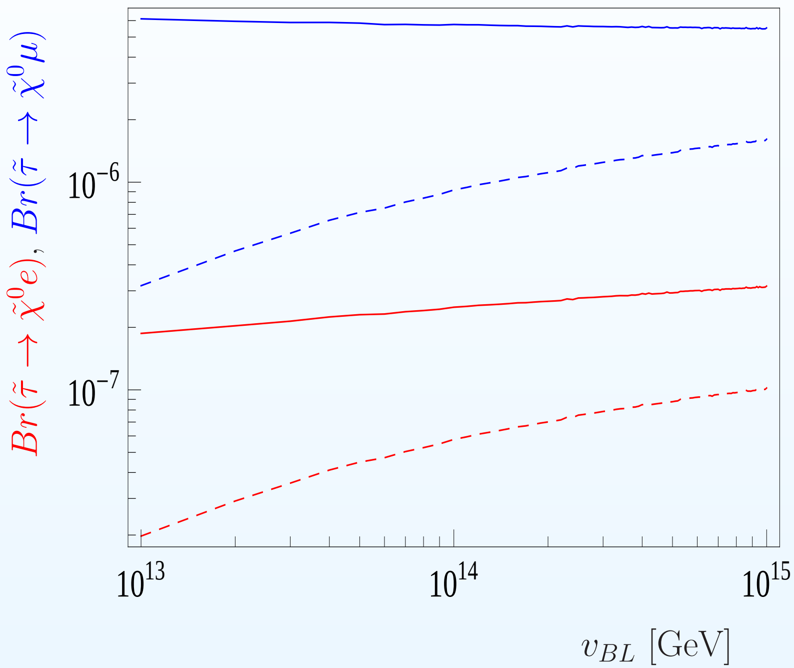
off-diagonal m_L^2 stop running

$\downarrow$

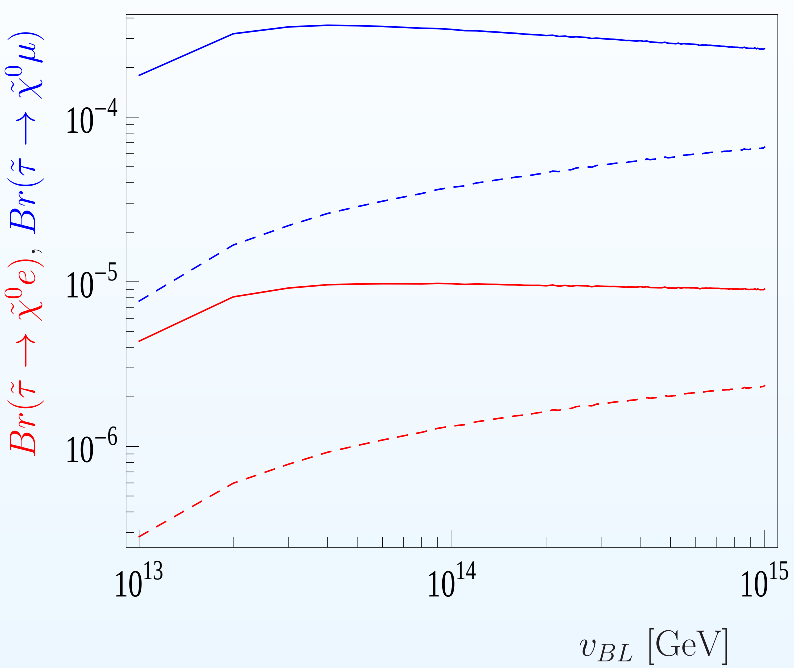
SUSY scale : $\mathbf{m_L^2 \neq m_E^2}$

Left vs Right

SPS3 benchmark point
Degenerate right-handed neutrinos
$v_R = 3 \cdot 10^{15}$ GeV



$\mathbf{M_{Seesaw} = 10^{12}}$ **GeV**



$\mathbf{M_{Seesaw} = 10^{13}}$ **GeV**

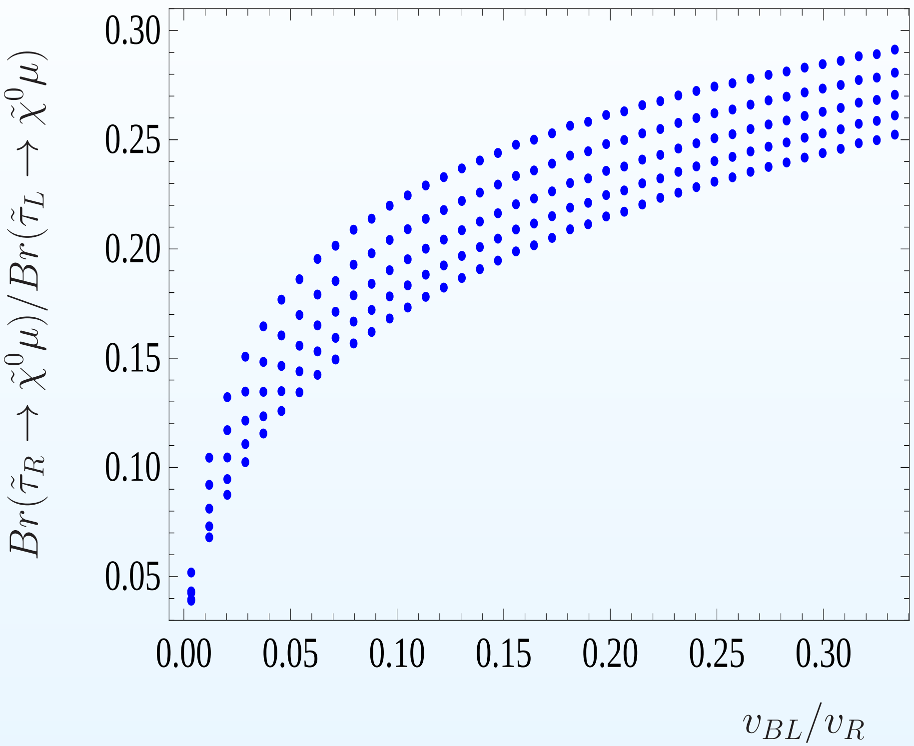
- There are regions of parameter space with observable rates for LFV in the right-handed slepton sector
- Closer $v_{BL} - v_R$ implies closer $Br(\tilde{\tau}_L) - Br(\tilde{\tau}_R)$
- Is it possible to determine the ratio v_{BL}/v_R?

Left vs Right

SPS3 benchmark point

Degenerate right-handed neutrinos

$v_R = 3 \cdot 10^{15}$ GeV



- By measuring **left- and right-handed LFV** the ratio v_{BL}/v_R can be constrained
- However, there is a slight dependence on M_{Seesaw} and m_{GUT}
- More information (e.g. other LFV decays) is required

$\tilde{e} - \tilde{\mu}$ mass splitting

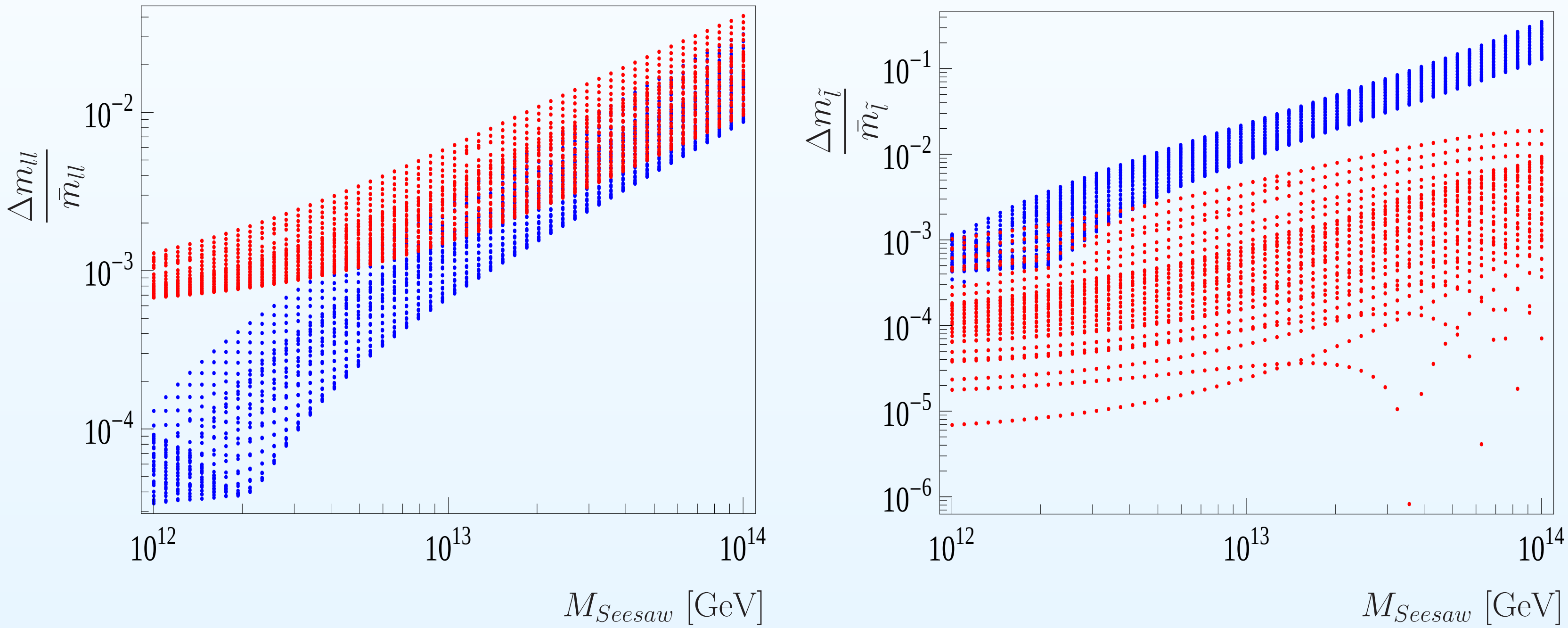
SPS1a' benchmark point

Degenerate right-handed neutrinos

$v_{BL} = 10^{15}$ GeV , $v_R \in [10^{15}, 10^{16}]$ GeV

$$\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^{\pm} l^{\mp}$$

Abada et al. arXiv:1007.4833, see talk by Ana M. Teixeira (Phenomenology 24-1)



- Large splittings $m_{\tilde{e}} - m_{\tilde{\mu}}$ are produced by RGE running in the **L** and **R** sectors.
- Sensitivities around 10^{-4} can be reached at the LHC for both observables (See Allanach et al. PRD 77 (2008) 076006).
- Deviations from the mSUGRA prediction ($m_{\tilde{e}} \simeq m_{\tilde{\mu}}$) are measurable.

Other signatures

Other things to look at:

- Correlations with neutrino oscillation parameters
  - ⋆ Non-negligible right-handed slepton contributions
  - ⋆ Other flavor sources
- Impact on the SUSY spectrum
  - ⋆ Main changes from the standard expectation
  - ⋆ Invariant sparticle mass combinations
- Dark matter relic density
- Other low-energy lepton flavor violating processes ($\mu \to e\gamma$, $\mu \to 3e \ldots$)

Summary

Summary

- ⋆ SUSY Left-Right models are well motivated extensions of the MSSM, with automatic R-parity conservation and seesaw mechanism.
- ⋆ Assuming flavor blind soft terms at the GUT scale, lepton flavor violating entries are generated at the SUSY scale due to RGE running. This makes LFV a window to the high energy scales.
- ⋆ Contrary to minimal seesaw implementations, there are regions of parameter space where LFV decays of right-handed sleptons have measurable rates. Such observation would clearly point to an underlying Left-Right symmetry.
- ⋆ In addition, by measuring ratios $Br(\tilde{l}_{L\,i} \to \tilde{\chi}^0 l_j)/Br(\tilde{l}_{R\,i} \to \tilde{\chi}^0 l_j)$ one can constrain the ratio v_{BL}/v_R, providing valuable information about the symmetry breaking pattern.
- ⋆ Many distinctive features not present in the standard mSUGRA scenarios. More observables to study!

Backup slides

Superpotential and soft terms

$$
\begin{aligned}
\mathcal{W} &= Y_Q Q \Phi Q^c + Y_L L \Phi L^c - \frac{\mu}{2}\Phi\Phi + f L \Delta L + f^* L^c \Delta^c L^c \\
&+ a \Delta \Omega \bar{\Delta} + a^* \Delta^c \Omega^c \bar{\Delta}^c + \alpha \Omega \Phi \Phi + \alpha^* \Omega^c \Phi \Phi \\
&+ M_\Delta \Delta \bar{\Delta} + M_\Delta^* \Delta^c \bar{\Delta}^c + M_\Omega \Omega \Omega + M_\Omega^* \Omega^c \Omega^c
\end{aligned}
$$

$$
\begin{aligned}
-\mathcal{L}_{soft} &= m_Q^2 \tilde{Q}^\dagger \tilde{Q} + m_{Q^c}^2 \tilde{Q^c}^\dagger \tilde{Q}^c + m_L^2 \tilde{L}^\dagger \tilde{L} + m_{L^c}^2 \tilde{L^c}^\dagger \tilde{L}^c \\
&+ m_\Delta^2 \Delta^\dagger \Delta + m_{\bar{\Delta}}^2 \bar{\Delta}^\dagger \bar{\Delta} + m_{\Delta^c}^2 \Delta^{c\dagger} \Delta^c + m_{\bar{\Delta}^c}^2 \bar{\Delta}^{c\,\dagger} \bar{\Delta}^c \\
&+ m_\Phi^2 \Phi^\dagger \Phi + m_\Omega^2 \Omega^\dagger \Omega + m_{\Omega^c}^2 \Omega^{c\dagger} \Omega^c \\
&+ \frac{1}{2}\Big[M_1 \tilde{B}^0 \tilde{B}^0 + M_2 (\tilde{W}_L \tilde{W}_L + \tilde{W}_R \tilde{W}_R) + M_3 \tilde{g}\tilde{g} + h.c.\Big] \\
&+ \Big[T_Q \tilde{Q} \Phi \tilde{Q}^c + T_L \tilde{L} \Phi \tilde{L}^c + T_f \tilde{L} \Delta \tilde{L} + T_f^* \tilde{L}^c \Delta^c \tilde{L}^c + T_a \Delta \Omega \bar{\Delta} \\
&+ T_a^* \Delta^c \Omega^c \bar{\Delta}^c + T_\alpha \Omega \Phi \Phi + T_\alpha^* \Omega^c \Phi \Phi + B_\mu \Phi \Phi \\
&+ B_{M_\Delta} \Delta \bar{\Delta} + {B_{M_\Delta}}^* \Delta^c \bar{\Delta}^c + B_{M_\Omega} \Omega \Omega + {B_{M_\Omega}}^* \Omega^c \Omega^c + h.c.\Big]
\end{aligned}
$$

A comment on bidoublets

In LR models the MSSM Higgses are introduced as **bidoublets**

$$\Phi = \begin{bmatrix} H_d^0 & H_u^+ \\ H_d^- & H_u^0 \end{bmatrix} \quad : \quad (2,2,0) \text{ under } SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

However, at least **two bidoublets** are needed to produce a non-trivial V_{CKM} at tree-level.

$$Y_Q^{(i)} Q \Phi_i Q^c \;\Rightarrow\; \text{The misalignment } Y_Q^{(1)} - Y_Q^{(2)} \text{ generates } V_{CKM}$$

At the v_R scale one of these two bidoublets dicouples while the orthogonal combination leads to the MSSM two Higgs doublets. Therefore, the **low-energy Yukawa parameters** are rotations of the original ones. In the leptonic sector:

$$\begin{aligned} Y_e &= Y_L^1 \cos\theta_1 - Y_L^2 \sin\theta_1 \\ Y_\nu &= -Y_L^1 \cos\theta_2 + Y_L^2 \sin\theta_2 \end{aligned}$$

Renormalization Group Equations

- **From the GUT scale to the $\mathbf{v_R}$ scale**

$$16\pi^2 \frac{d}{dt} m_L^2 = 6 f f^\dagger m_L^2 + 12 f m_L^2 f^\dagger + 6 m_L^2 f f^\dagger + 12 m_\Delta^2 f f^\dagger$$
$$+2 Y_L^{(k)} Y_L^{(k)\,\dagger} m_L^2 + 2 m_L^2 Y_L^{(k)} Y_L^{(k)\,\dagger} + 4 Y_L^{(k)} m_{L^c}^2 Y_L^{(k)\,\dagger}$$
$$+4 (m_\Phi^2)_{mn} Y_L^{(m)} Y_L^{(n)\,\dagger} + 12 T_f T_f^\dagger + 4 T_L^{(k)} T_L^{(k)\,\dagger}$$
$$-(3 g_{BL}^2 |M_1|^2 + 6 g_2^2 |M_2|^2 + \frac{3}{2} g_{BL}^2 S_1) \mathcal{I}_3$$

$$16\pi^2 \frac{d}{dt} m_{L^c}^2 = 6 f^\dagger f m_{L^c}^2 + 12 f^\dagger m_{L^c}^2 f + 6 m_{L^c}^2 f^\dagger f + 12 m_{\Delta^c}^2 f^\dagger f$$
$$+2 Y_L^{(k)\,\dagger} Y_L^{(k)} m_{L^c}^2 + 2 m_{L^c}^2 Y_L^{(k)\,\dagger} Y_L^{(k)} + 4 Y_L^{(k)\,\dagger} m_L^2 Y_L^{(k)}$$
$$+4 (m_\Phi^2)_{mn} Y_L^{(m)\,\dagger} Y_L^{(n)} + 12 T_f^\dagger T_f + 4 T_L^{(k)\,\dagger} T_L^{(k)}$$
$$-(3 g_{BL}^2 |M_1|^2 + 6 g_2^2 |M_2|^2 - \frac{3}{2} g_{BL}^2 S_1) \mathcal{I}_3$$

Renormalization Group Equations

- **From the $\mathbf{v_R}$ scale to the $\mathbf{v_{BL}}$ scale**

$$
\begin{aligned}
16\pi^2 \frac{d}{dt} m_L^2 \quad = \quad & 2 Y_e m_{\tilde{e}^c}^2 Y_e^\dagger + 2 m_{H_d}^2 Y_e Y_e^\dagger + 2 m_{H_u}^2 Y_\nu Y_\nu^\dagger + m_L^2 Y_e Y_e^\dagger \\
& + Y_e Y_e^\dagger m_L^2 + m_L^2 Y_\nu Y_\nu^\dagger + Y_\nu Y_\nu^\dagger m_L^2 + 2 Y_\nu m_{\tilde{\nu}^c}^2 Y_\nu^\dagger \\
& + 2 T_e T_e^\dagger + 2 T_\nu T_\nu^\dagger - (3 g_{BL}^2 |M_1|^2 + 6 g_L^2 |M_L|^2 + \frac{3}{4} g_{BL}^2 S_2) \mathcal{I}_3
\end{aligned}
$$

$$
\begin{aligned}
16\pi^2 \frac{d}{dt} m_{\tilde{e}^c}^2 \quad = \quad & 2 Y_e^\dagger Y_e m_{\tilde{e}^c}^2 + 2 m_{\tilde{e}^c}^2 Y_e^\dagger Y_e + 4 m_{H_d}^2 Y_e^\dagger Y_e + 4 Y_e^\dagger m_L^2 Y_e \\
& + 4 T_e^\dagger T_e - (3 g_{BL}^2 |M_1|^2 + 2 g_R^2 |M_R|^2 - \frac{3}{4} g_{BL}^2 S_2 - \frac{1}{2} g_R^2 S_3) \mathcal{I}_3
\end{aligned}
$$

RGEs: Approximated expressions

- **From the GUT scale to the $\mathbf{v_R}$ scale**

$$\Delta m_L^2 = -\frac{1}{4\pi^2}\left(3 f f^\dagger + Y_L^{(k)} Y_L^{(k)\,\dagger}\right)(3 m_0^2 + A_0^2)\ln\left(\frac{m_{GUT}}{v_R}\right)$$
$$\Delta m_{L^c}^2 = -\frac{1}{4\pi^2}\left(3 f^\dagger f + Y_L^{(k)\,\dagger} Y_L^{(k)}\right)(3 m_0^2 + A_0^2)\ln\left(\frac{m_{GUT}}{v_R}\right)$$

- **From the $\mathbf{v_R}$ scale to the $\mathbf{v_{BL}}$ scale**

$$\Delta m_L^2 = -\frac{1}{8\pi^2} Y_\nu Y_\nu^\dagger (3 m_0^2 + A_0^2)\ln\left(\frac{v_R}{v_{BL}}\right)$$
$$\Delta m_{\tilde{e}^c}^2 = 0$$

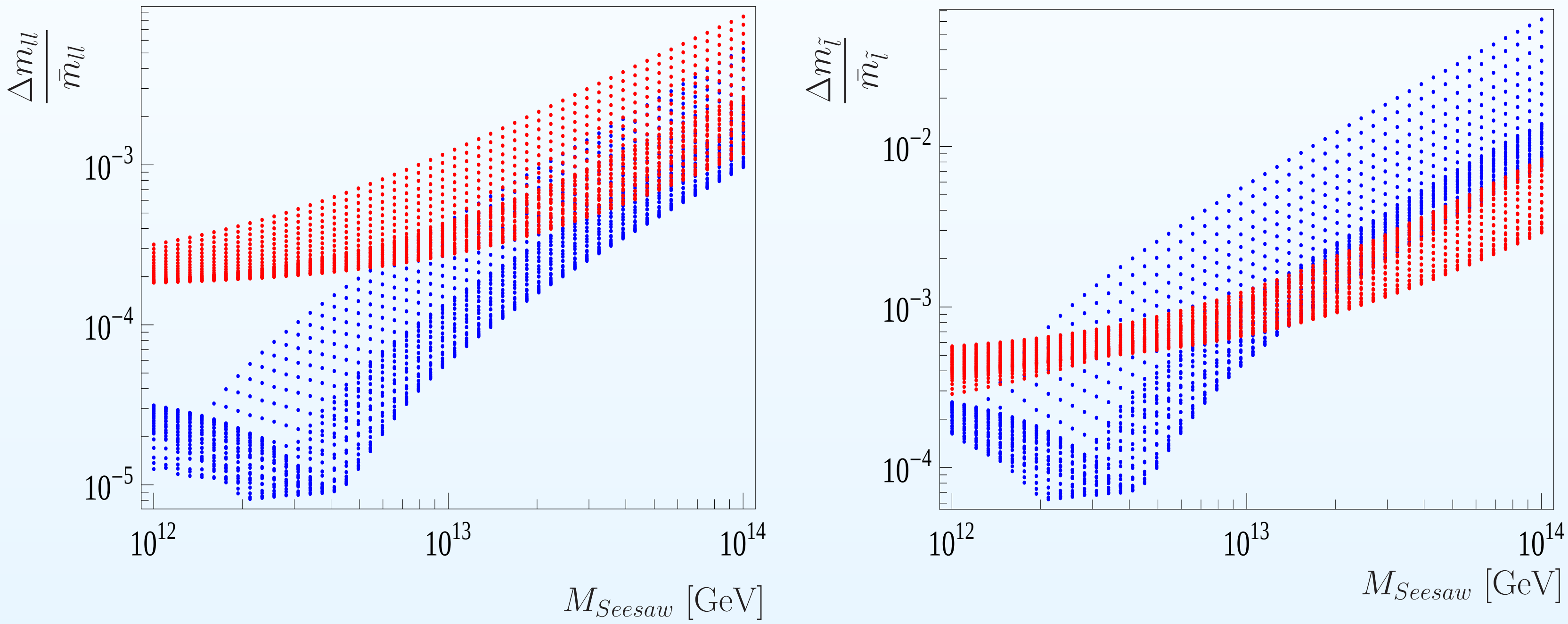
$\tilde{e} - \tilde{\mu}$ mass splitting

SPS3 benchmark point

Degenerate right-handed neutrinos

$v_{BL} = 10^{15}$ GeV , $v_R \in [10^{15}, 10^{16}]$ GeV

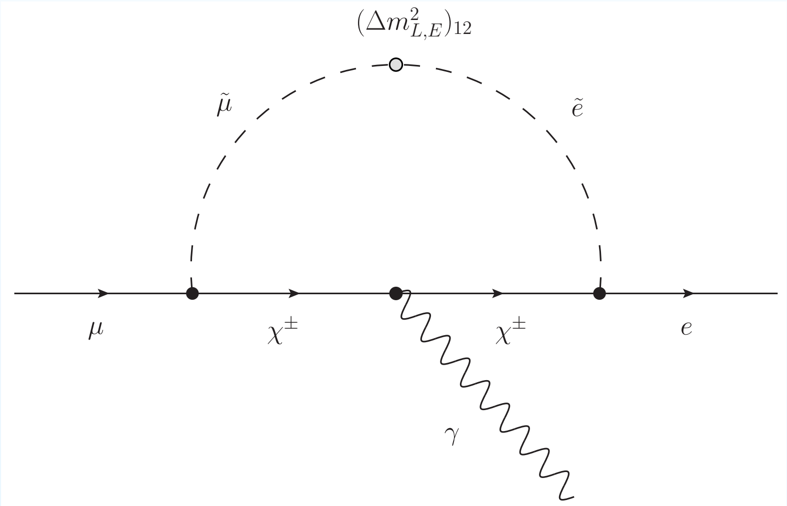
$$\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^{\pm} l^{\mp}$$

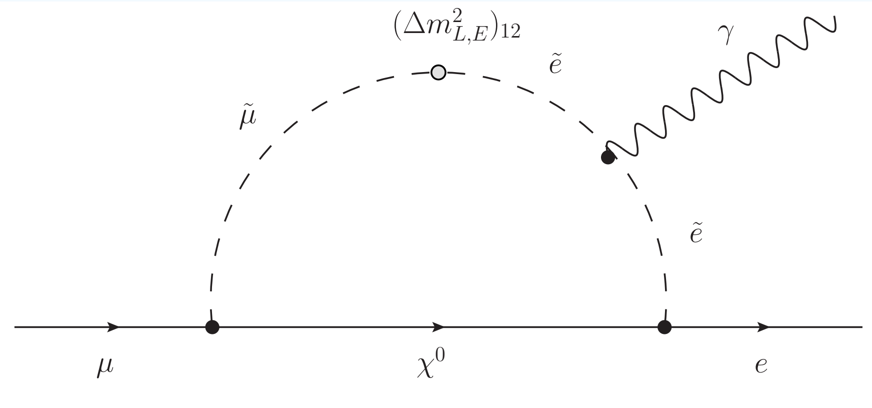


Large splittings $m_{\tilde{e}} - m_{\tilde{\mu}}$ are produced by RGE running in the **L** and **R** sectors.

$l_i \to l_j\gamma$

$l_i \to l_j\gamma$ processes are enhanced by **off-diagonal Δm_L^2 and Δm_E^2**. For example, in the case of $\mu \to e\gamma$:

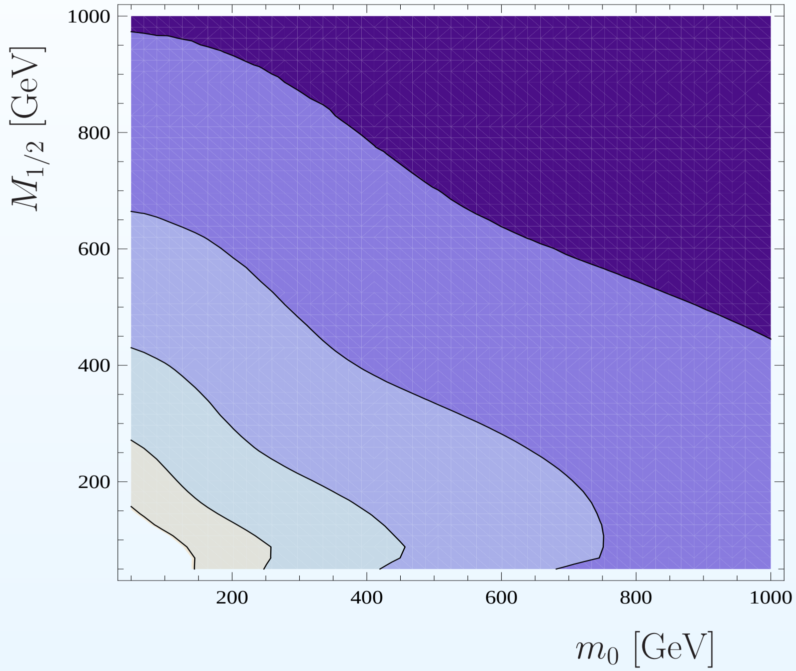




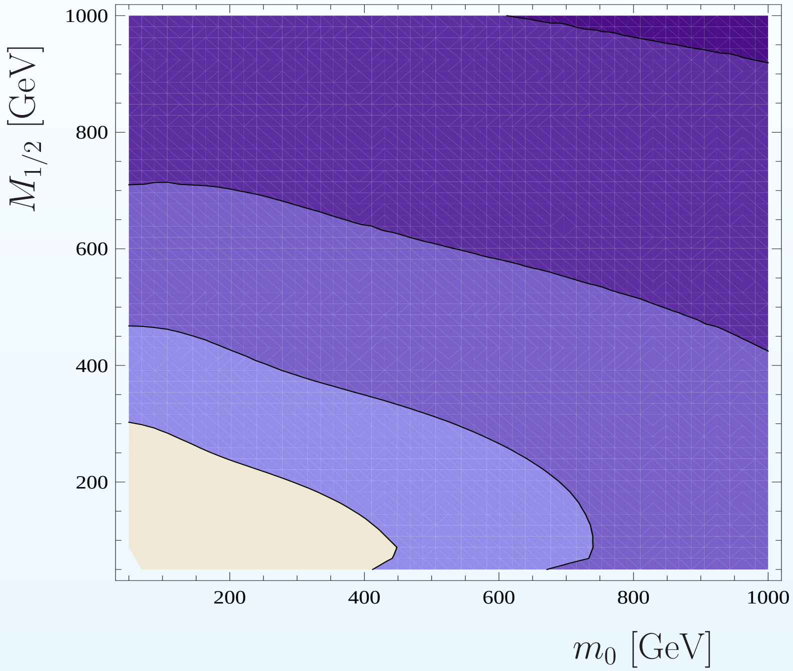
$$Br(\mu \to e\gamma) \propto \Delta(m^2_{L,E})^2_{12}$$

$l_i \to l_j \gamma$

$\boldsymbol{\mu \to e\gamma}$



$\mathbf{M_{Seesaw} = 10^{12}}$ **GeV**



$\mathbf{M_{Seesaw} = 10^{13}}$ **GeV**

Contours shown for Br$(\mu \to e\gamma) = 10^{-11}, 10^{-12}, 10^{-13}, 10^{-14}$ and 10^{-15}.

Non-negligible right-handed contribution

$\Rightarrow$ **Larger Br's w.r.t. stardard seesaw**