Theories of lepton flavor violation

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Nufact@London, July 1-7, 2002

Introduction

Lepton Flavor is violated in physics beyond the SM

- GUTs (SU(5), SO(10) ...)
  (quarks and leptons are unified)
- right-handed neutrinos
  (neutrino oscillations)

LFV processes in charged-lepton sector ($\mu \to e\gamma$, *etc*)
can be important clues to search for beyond the SM

Experimental bounds

	Current	Near Future
$B(\tau \to \mu\gamma)$	1.0×10^{-6}	$\sim 10^{-7}$
$B(\mu \to e\gamma)$	1.2×10^{-11}	2×10^{-14}
$B(\mu \to 3e)$	1.0×10^{-12}	
$R(\mu^- ;\text{Al} \to e^-;\text{Al})$	6.1×10^{-13}	5×10^{-17}

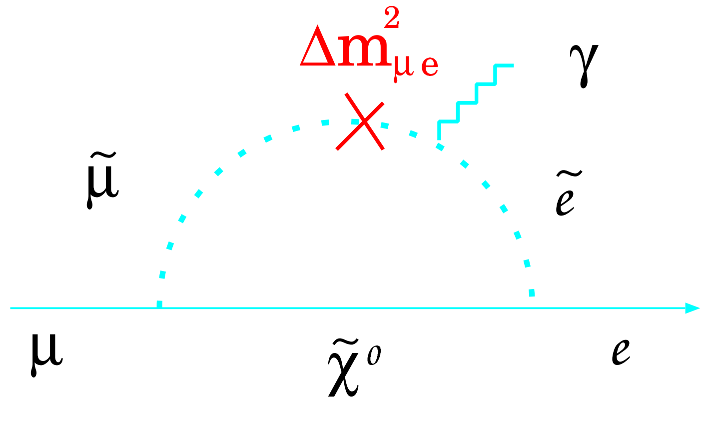
PRISM, NuFACT may lower the bounds further

For SM with right-handed neutrinos

$$B(\mu \to e\gamma) < 10^{-50}$$

LFV in the MSSM

Sleptons have LFV masses



$$B(\mu \to e\gamma) \simeq 10^{-5} \left(\frac{(\Delta m^2_{\tilde{L}})_{12}}{m^2_{\tilde{L}}} \right)^2 \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{L}}} \right)^4$$

$$B(\tau \to \mu\gamma) \simeq 10^{-6} \left(\frac{(\Delta m^2_{\tilde{L}})_{23}}{m^2_{\tilde{L}}} \right)^2 \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{L}}} \right)^4$$

SU(5) SUSY GUT

Leptons and quarks are unified

$$\mathbf{10_i} = (Q_i, \overline{U}_i, \overline{E}_i) \qquad \mathbf{\overline{5}_i} = (L_i, \overline{D}_i)$$

$$\begin{aligned} W &= \mathbf{10}_i (Y_U)_{ij} \mathbf{10}_j H_5 + \mathbf{10}_i (Y_D)_i \overline{5}_i H_{\overline{5}} \\ &= Q_i (Y_U)_{ij} \overline{U}_j H_2 + Q_i (Y_D)_i \overline{D}_i H_1 + \overline{E}_i (Y_D)_i L_i H_1 \\ &+ \overline{E}_i (Y_U)_{ij} \overline{U}_j H_C \ldots \end{aligned}$$

$$Y_U = V_{\mathrm{KM}}^T Y_U^{(diag)} V_{\mathrm{KM}}$$

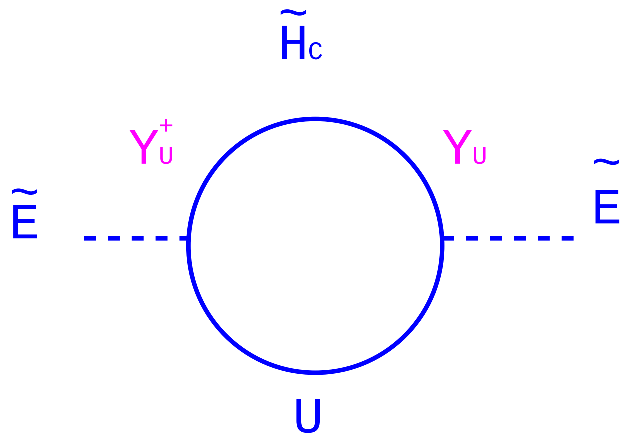
Right-handed leptons have flavor mixing interactions

Origin of LFV in slepton masses

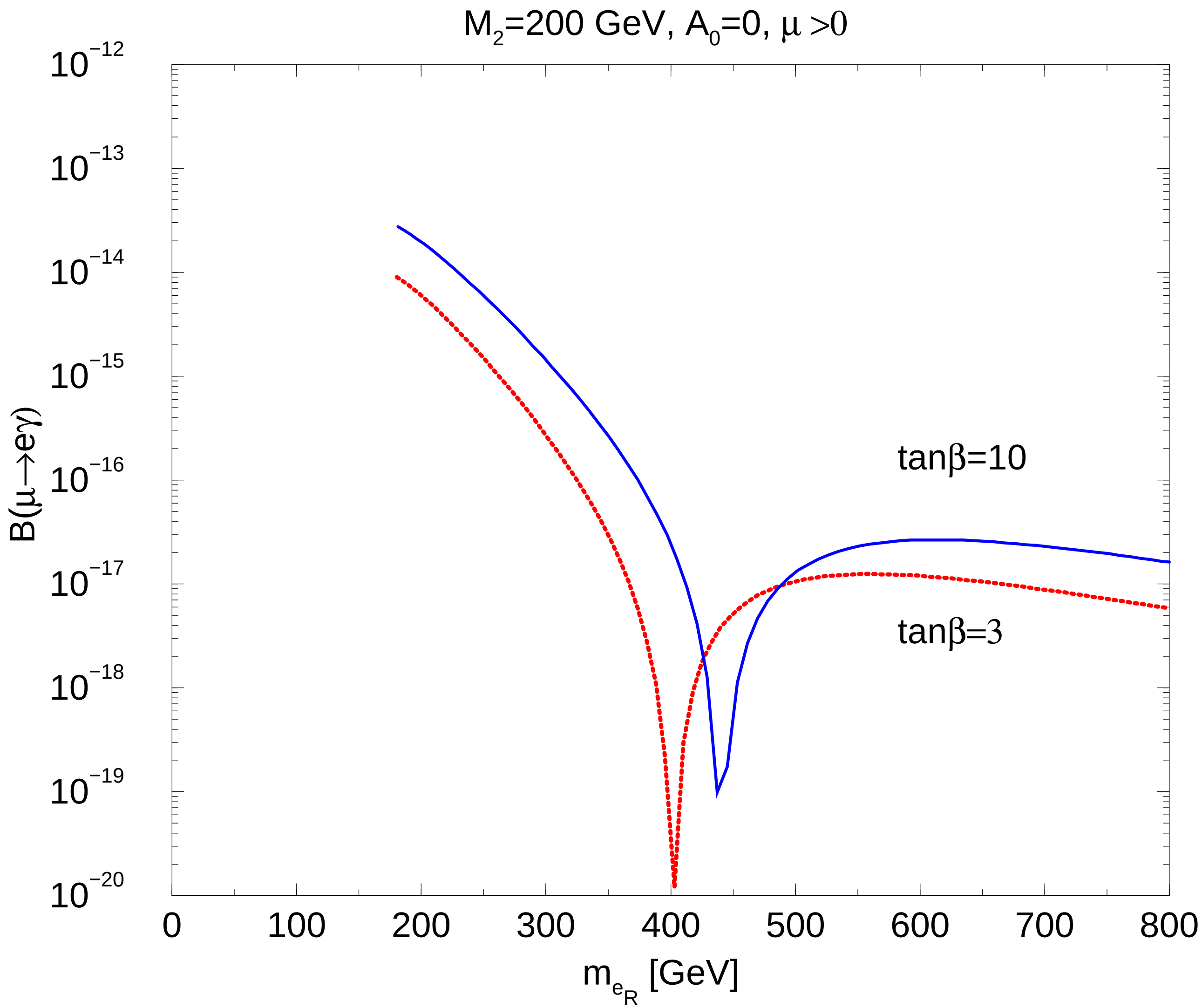
In minimal supergravity scenario

$$(m_{\tilde{E}})_{ij} = m_0^2\,\delta_{ij} \quad @M_{pl}$$

LFV masses are induced to right-handed sleptons



$$(\Delta m^2_{\tilde{E}})_{ij} \approx -\frac{3Y_t^2}{8\pi^2}(3m_0^2 + A_0^2)(V_{\rm KM})_{3i}(V_{\rm KM})^*_{3j} \log\frac{M_{pl}}{M_{GUT}}$$


M2=200 GeV, A0=0, μ >0
10−12
10−13
10−14
10−15
10−16
10−17
10−18
10−19
10−20
B(μ→eγ)
0
100
200
300
400
500
600
700
800
meR [GeV]
tanβ=10
tanβ=3

MSSM with right-handed neutrinos

$$W = \overline{N}_i (Y_N)_{ij} L_j H_2 + \overline{E}_i (Y_E)_i L_j H_1 + \frac{1}{2} \overline{N}_i (M_N)_i \overline{N}_i$$

$\overline{N}_i$: right-handed neutrinos

L_i: left-handed leptons

$$(Y_N)_{ij} = Z_{ik} \hat{Y}_k^N X_{kj}^\dagger$$

- mixing angles — 6
- CP phases — 6

Seesaw mechanism for light neutrino mass matrix

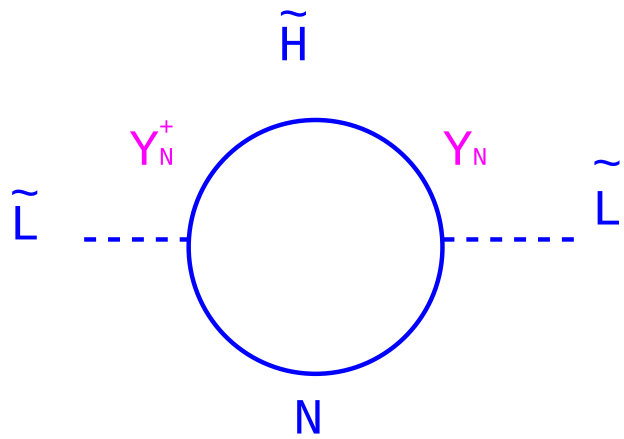
$$Y_N^{\mathrm{T}} \frac{1}{M_N} Y_N v^2 \sin^2 \beta \quad \equiv \quad U_{\mathrm{MNS}}^* m_\nu U_{\mathrm{MNS}}^\dagger$$

Origin of LFV in slepton masses

In minimal supergravity scenario

$$(m_{\tilde{L}})_{ij} = m_0^2 \, \delta_{ij} \;\; @M_{pl}$$

LFV masses are induced to left-handed sleptons



$$(\Delta m^2_{\tilde{L}})_{ij} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)(Y_\nu^\dagger)_{ik}(Y_\nu)_{kj} \log \frac{M_{pl}}{M_{N_k}}$$

No structure in Majorana masses ($Z = 1$)

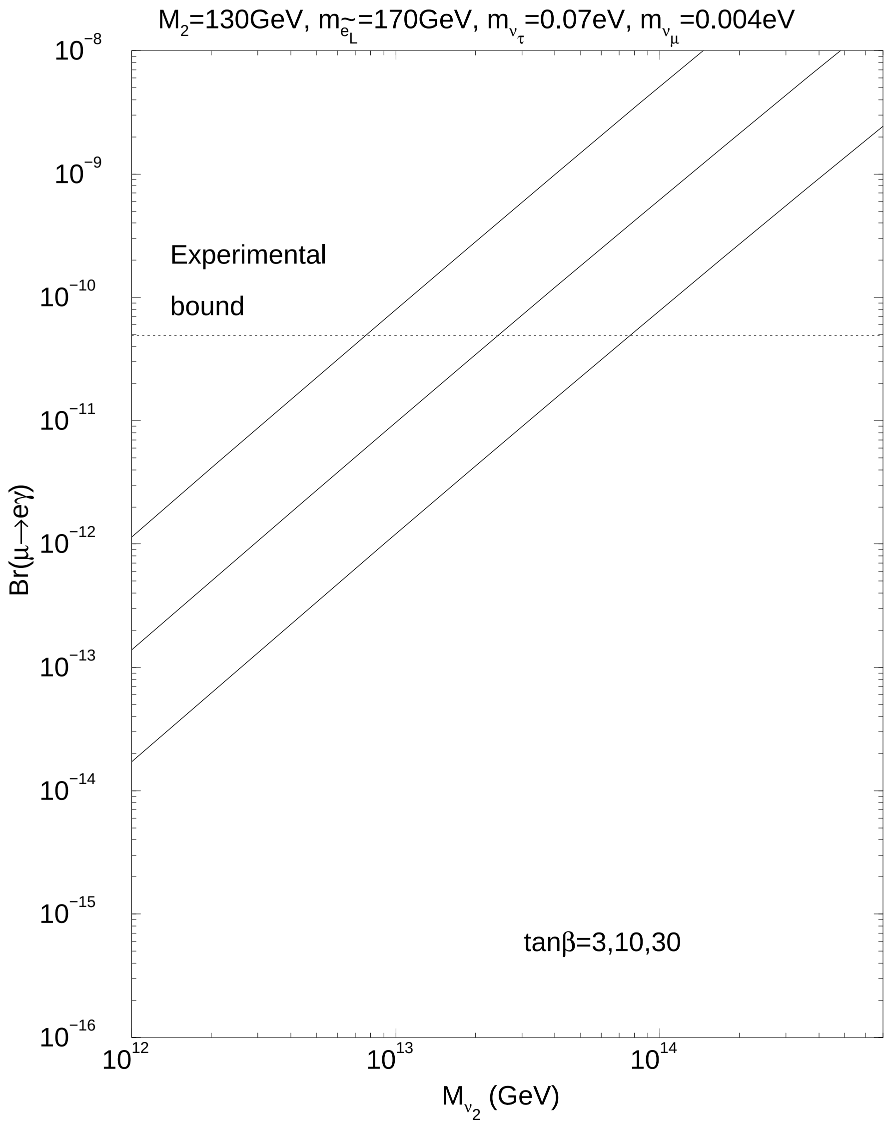
$$m_\nu = Y_N^{\mathrm{T}} \frac{1}{M_N} Y_N v^2 \sin^2\beta = X^{\mathrm{T}} \frac{\hat{Y}^N \hat{Y}^N}{\hat{M}_N} X$$

$$(\Delta m^2_{\tilde{L}})_{ij} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2) X_{ik} (\hat{Y}_k^N)^2 X_{kj}^* \log \frac{M_{pl}}{\hat{M}_N}$$

Slepton mixing is also determined by the MNS matrix ($X = U^\dagger_{MNS}$)

- atmospheric ν $(U_{23}) \cdots$ $\tau \to \mu\gamma$
- solar ν(LMA) $(U_{12}) \cdots \mu \to e\gamma$

μ→eγ in the MSSMRN with the MSW large angle solution



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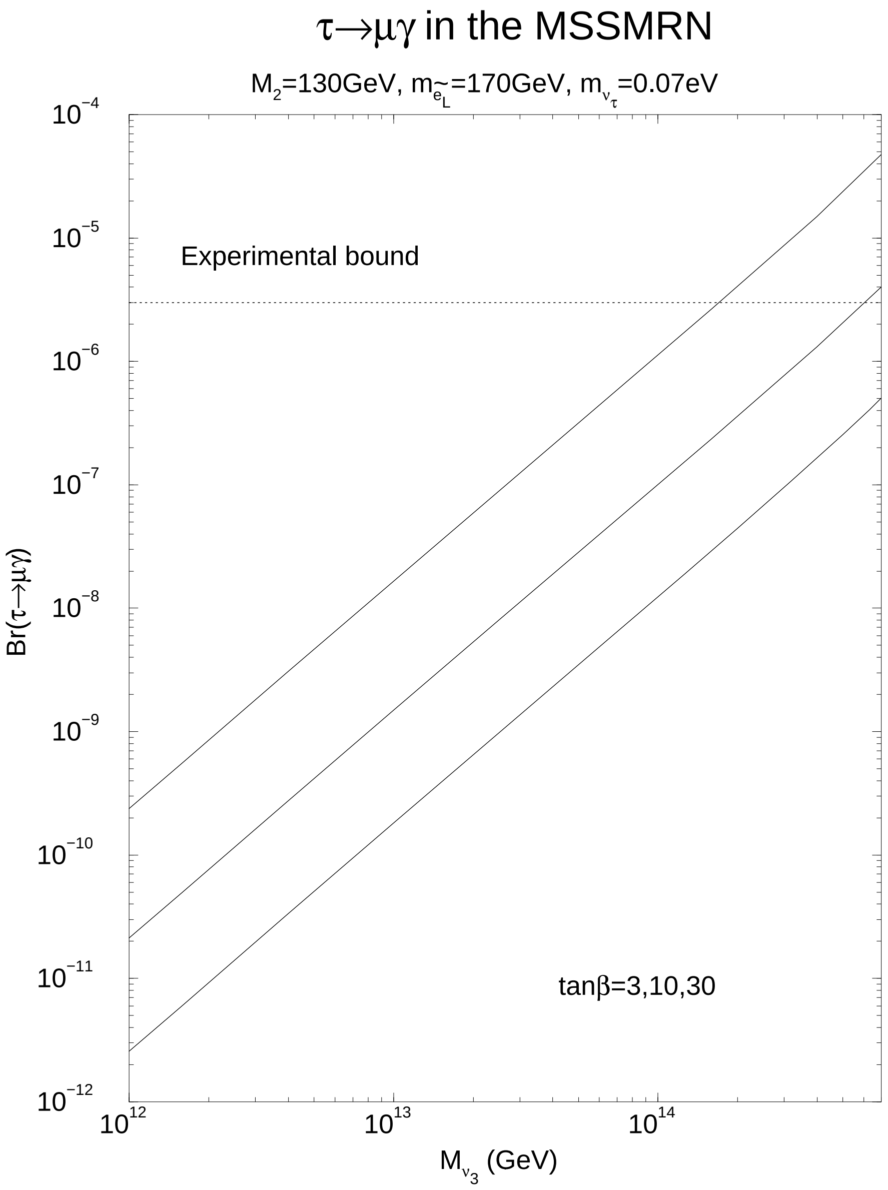

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General Majorana neutrinos

No direct relation between slepton and neutrino mixings

Parameters in seesaw models

- 3 Dirac neutrino masses
- 3 Majorana neutrino masses
- 6 mixings — total 18
- 6 CP phases

low energy observable of neutrinos

- 3 light neutrino masses
- 3 neutrino mixings — total 9
- 3 CP phases

Need 9 more inputs (Ellis, Hisano, Raidal, Y.S)

$$H_{ij} \equiv (Y_\nu^\dagger)_{ik}(Y_\nu)_{kj} \log \frac{M_{pl}}{M_{N_k}}$$

- H contains 9 parameters
- charged LFV is proportional to H

$$(\Delta m^2_{\tilde{L}})_{ij} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)H_{ij}$$

For example

$$H = \begin{pmatrix} a & 0 & 0 \\ 0 & b & d \\ 0 & d^\dagger & c \end{pmatrix}$$

How to reconstruct Y_ν and M_N from H

$$Y_\nu = \frac{\sqrt{M_N} R \sqrt{\mathcal{M}_\nu} U^\dagger}{v \sin\beta}$$

R: complex orthogonal matrix (Casas, Ibarra)

$$H = \frac{1}{v^2 \sin^2\beta} U \sqrt{\mathcal{M}_\nu} R^\dagger \overline{M_N} R \sqrt{\mathcal{M}_\nu} U^\dagger$$

$\overline{M_{N_i}} \equiv M_{N_i} \log(M_G/M_{N_i})$. R can be obtained as

$$H' = \sqrt{\mathcal{M}_\nu}^{-1} U^\dagger H U \sqrt{\mathcal{M}_\nu}^{-1} v^2 \sin^2\beta$$

$$H' = R^\dagger \overline{M_N} R$$

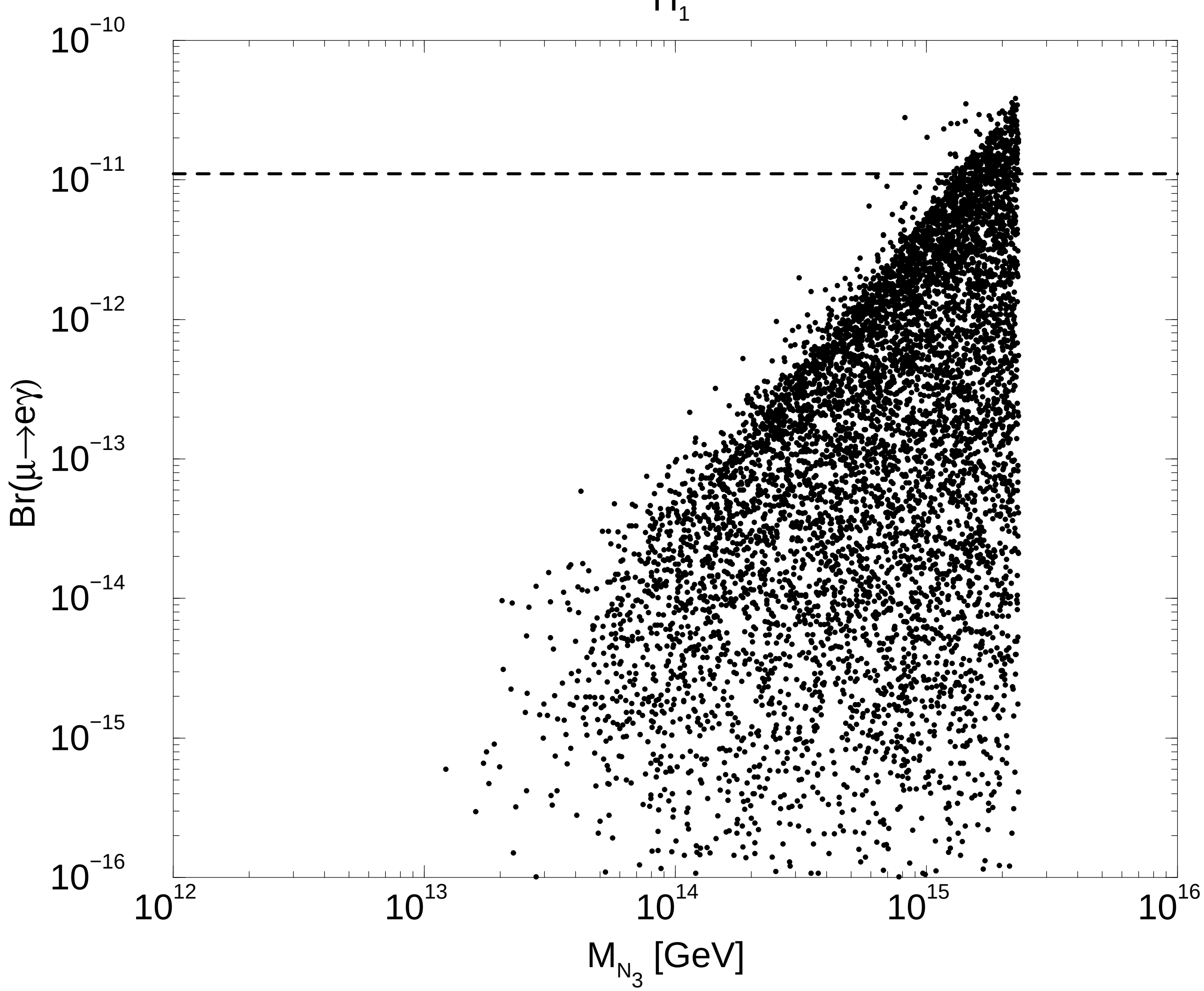
R does not always exist

Input

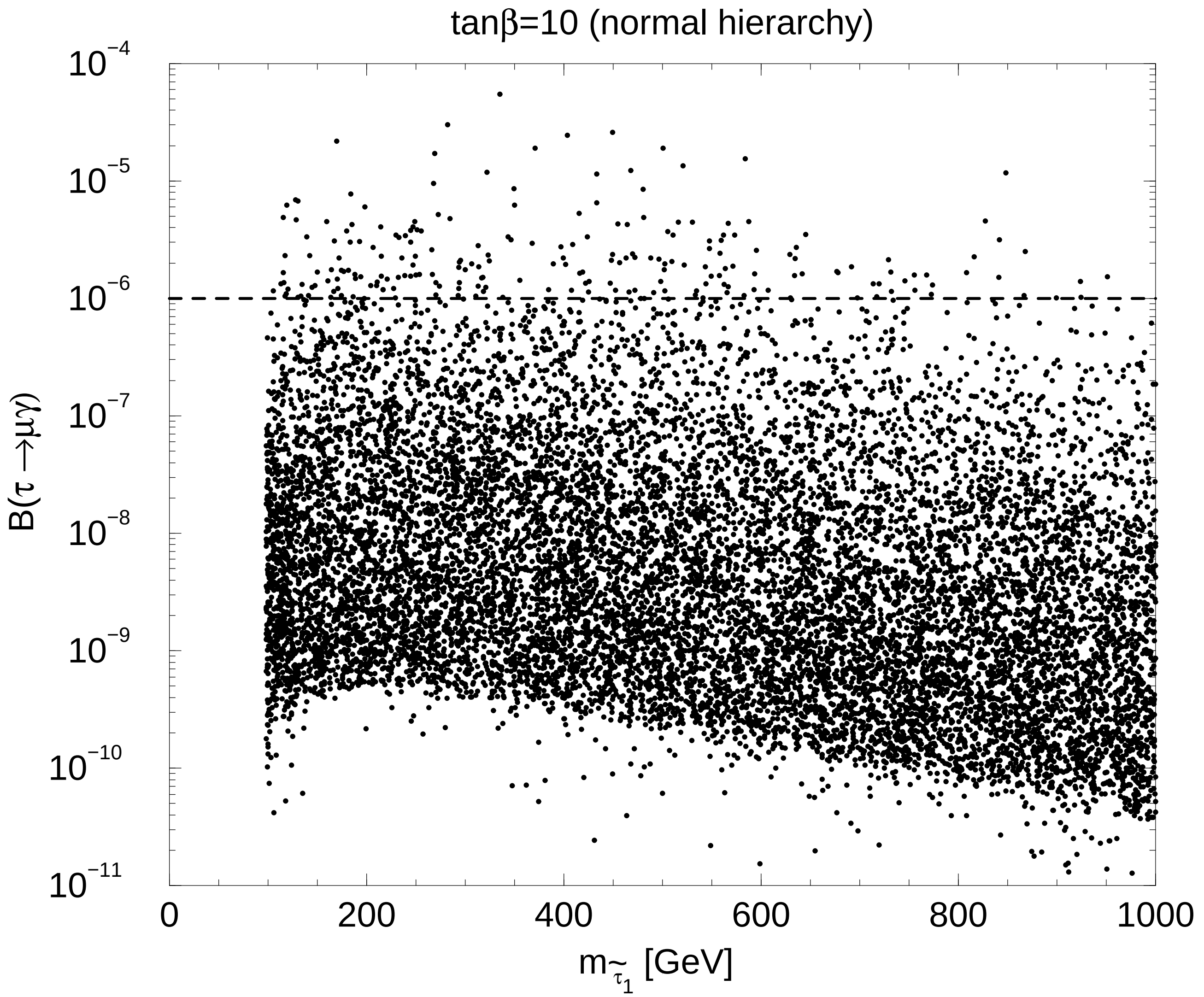
$$\begin{aligned}
\Delta m^2_{32} &= 3 \times 10^{-3} \mathrm{eV}^2 \,, \\
\tan^2 2\theta_{23} &= 1.0 \,, \\
\Delta m^2_{21} &= 4.5 \times 10^{-5} \mathrm{eV}^2 \,, \\
\tan^2 \theta_{12} &\simeq 0.4 \,, \\
\sin \theta_{13} &= 0.1 \,, \\
\delta &= \pi/2 \,, \\
m_1 &= (10^{-4} - 0.3)\,\mathrm{eV}
\end{aligned}$$

$$10^{-2} < a, b, c, |d| < 10$$

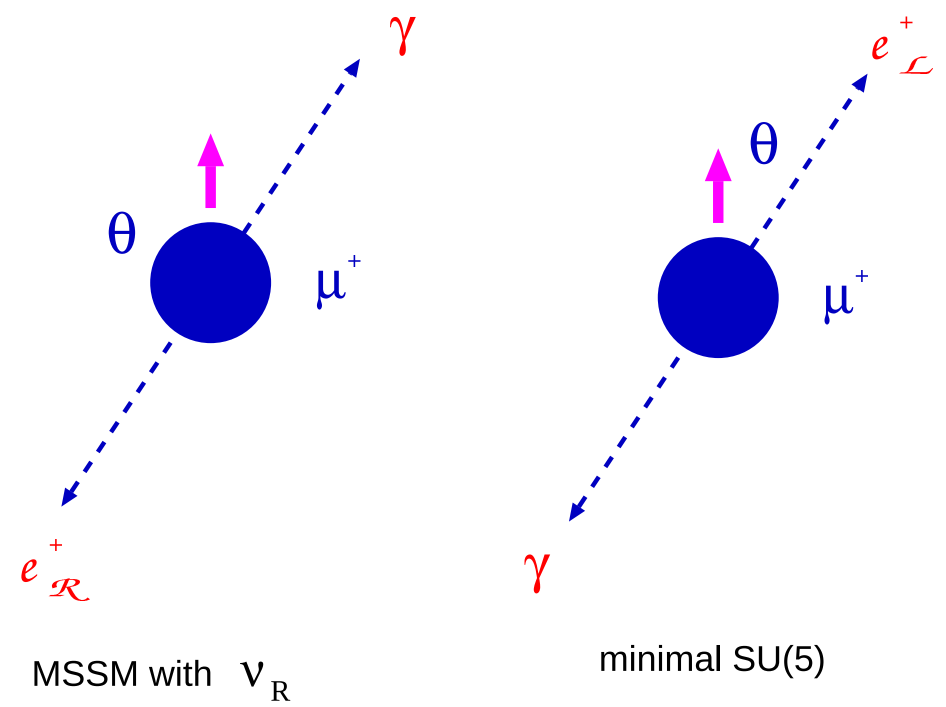
$\tan\beta = 10,\ M_2 = 200\ \mathrm{GeV},\ A = 0\ \mathrm{GeV},\ \mu > 0$



$$\tan\beta = 10,\ M_2 = 200\ \mathrm{GeV},\ A = 0\ \mathrm{GeV},\ \mu > 0$$



Angular distribution in $\mu \to e\gamma$ (Kuno, Okada)



Angular distribution may discriminate SUSY models

$\mu \to 3e$, $\mu - e$ conversion

Photon penguin diagram dominates in most parameter regions

- $\mathrm{B}(\mu \to 3e) \simeq 10^{-3}\ \mathrm{B}(\mu \to e\gamma)$
- $\mathrm{R}(\mu - e \text{ conversion}) \simeq 10^{-3}\ \mathrm{B}(\mu \to e\gamma)$

EDMs

Current and future experimental bounds

$$d_e < 1.6 \times 10^{-27} \quad \longrightarrow \quad 10^{-(32-33)} e\,\mathrm{cm}$$
$$d_\mu = (3.7 \pm 3.4) \times 10^{-19} \quad \longrightarrow \quad 10^{-26} e\,\mathrm{cm}$$

- Degenerate Majorana neutrinos $\cdots$ suppressed

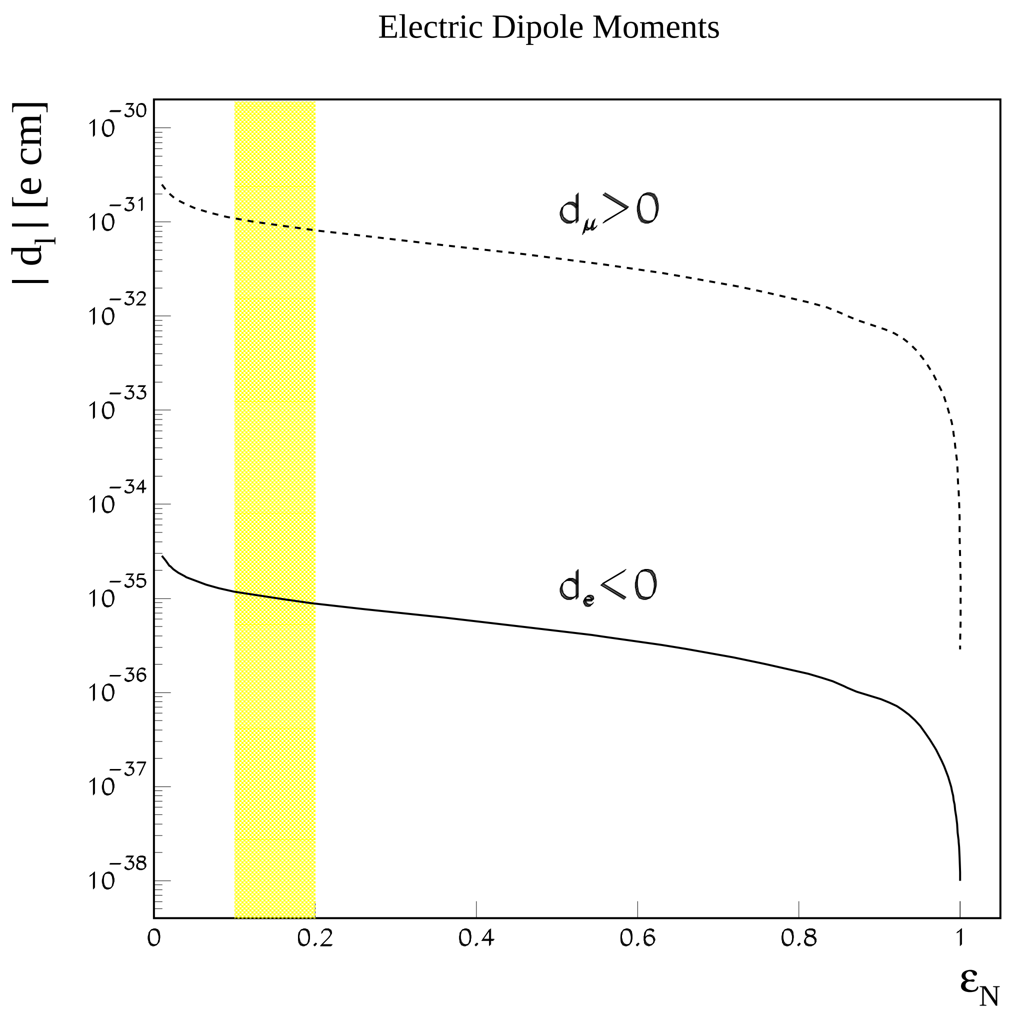
  $$d_i \sim \mathrm{Im}\left[\left[Y_E Y_N^\dagger Y_N \left[Y_E^\dagger Y_E,\ Y_N^\dagger Y_N\right] Y_N^\dagger Y_N\right]_{ii}\right] \times \log^3 M_{pl}/M_N$$

- Non degenarate Majorana neutrinos $\cdots$ enhanced

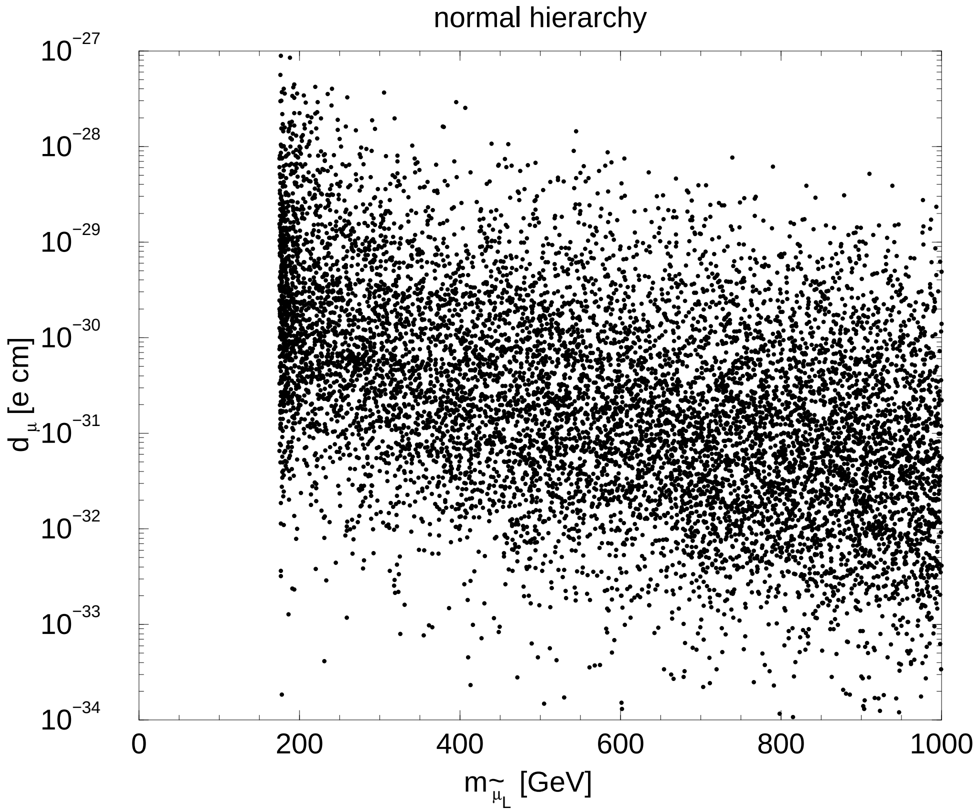
  $$d_i \sim \mathrm{Im}[X_j, X_k]_{ii} \log M_{N_k}/M_{N_j},$$

  where $\quad (X_k)_{ij} = (Y_N^*)_{ki}(Y_N)_{kj}$

$$M_{N_3} : M_{N_2} : M_{N_1} = 1 : \epsilon_N^4 : \epsilon_N^6$$



$$\tan\beta = 10,\ M_2 = 200\ \text{GeV},\ A = -600\ \text{GeV},\ \mu > 0$$



Summary

- Sizable charged LFV are induced in various SUSY models
- LMA solar $\nu \rightarrow$ large $\mu \rightarrow e\gamma$
- charged LFV may help to obtain information on neutrino sector
- EDMs are enhanced for non-degenerate Majonara neutrino
- d_μ can reach $10^{-(26-27)}$ e cm which may be accessible in future experiments