Charged LFV in a low-energy see-saw mSUGRA model

Amon Ilakovac

Department of Physics, University of Zagreb, 10002 Zagreb pp332, Croatia

Based on : Apostolos Pilaftsis, Luka Popov, A.I., PRD 87 (2013) 053014

- We study CLFV in a CMSSM (mSUGRA) model with large neutrino Yukawas and low scale heavy neutrinos: two sources of LFV: soft-SUSY breaking sector; neutrino Yukawa sector: supersymmetric.
- On-mass-shell $\ell \to \ell' \gamma$ amplitude suppressed, Z and box amplitudes enhanced.
- Comparison with experiment : $\mu \to e$ conversion, $\mu \to 3e$, $\tau \to 3e/e + 2\mu \ldots$

Motivation

Experiment

No.	Observable	Upper Limit	Future Sensitivity
1.	$B(\mu \to e\gamma)$	2.4×10^{-12} [1]	$1 - 2 \times 10^{-13}$ [6], 10^{-14} [6]
2.	$B(\mu \to eee)$	10^{-12} [2]	10^{-16} [8], 10^{-17} [7]
3.	$R_{\mu e}^{\mathrm{Ti}}$	4.3×10^{-12} [3],	$3 - 7 \times 10^{-17}$ [10, 9], 10^{-18} [11, 7]
4.	$R_{\mu e}^{\mathrm{Au}}$	7×10^{-13} [4]	$3 - 7 \times 10^{-17}$ [10, 9], 10^{-18} [11, 7]
5.	$B(\tau \to e\gamma)$	3.3×10^{-8} [5]	$1 - 2 \times 10^{-9}$ [13, 12]
6.	$B(\tau \to \mu\gamma)$	4.4×10^{-8} [5]	2×10^{-9} [13, 12]
7.	$B(\tau \to eee)$	2.7×10^{-8} [5]	2×10^{-10} [13, 12]
8.	$B(\tau \to e\mu\mu)$	2.7×10^{-8} [5]	10^{-10} [12]
9.	$B(\tau \to \mu\mu\mu)$	2.1×10^{-8} [5]	2×10^{-10} [13, 12]
10.	$B(\tau \to \mu ee)$	1.8×10^{-8} [5]	10^{-10} [12]

Table 1: Current upper limits and future sensitivities of CLFV observables under study.

[1] J. Adam, PRL (MEG) 107 (2011) 171801
[2] U. Bellgart, (SINDRUM) NPB 299 (1988) 1

[3] C. Dohmen, (SINDRUM II) PLB 317 (1993) 631

[4] W. Bertl, EPJ C47 (2006) 337

[5] See A.I., arXiv:1212.5939, Ref. [11]

[6] B.A. Golden (MEG) PhD 2012, J. Adam (MEG) PhD 2012

[7] J.L. Hewett, arXiv:1205.2671

[8] N. Berger, (μ3e) JPCS 408, 122070 (2013)

[9] A. Kurup (COMET) NPPS 218, 38 (2011)

[10] R.J. Abrams (Mu2e) arXiv:1211.7019; E.C. Dukes NPPS 218 (2011) 44

[11] Y. Kuno (PRISM) NPPS 149 (2005) 376; R.J. Barow (PRISM) , NPPS 218 (2011) 44

[12] K. Hayasaka, JPCS 171 (2009) 012079

[13] M. Bona (SuperB), arXiv:0709.0451

Theory

- LFV: found in neutrino oscillations only;
- CLFV: would be independent sign for a physics beyond SM
- information on a scale of new physics

Standard MSSM+3N LFV

Leptonic part of the superpotential

$$W = h_e^{ij} E_{iR}^c H_{dL} \cdot L_{jL} + h_\nu^{ij} N_{iR}^c H_{uL} \cdot L_{jL} + \frac{1}{2} M_M^{ij} N_{iR}^c N_{jR}^c$$

LFV : Borzumati, Masiero PRL (1986) 961;

$$\mathcal{M}_{\tilde{e}}^2 = \begin{pmatrix} M_{\tilde{L}}^2 + (m_e m_e^\dagger) + D_1 \mathbf{1} & m_e(A_e^* - \mu t_\beta \mathbf{1}) \\ (A_e^T - \mu^* t_\beta \mathbf{1}) m_e^\dagger & M_{\tilde{e}}^2 + (m_e^\dagger m_e) + D_2 \mathbf{1} \end{pmatrix}$$

$$(\Delta M_{\tilde{L}}^2)_{ij} \approx -\frac{1}{8\pi^2}(3m_0^2 + A_0^2) h_\nu^\dagger h_\nu \log \frac{M_X}{M_N},$$

$$(A_e)_{ij} \approx -\frac{3}{8\pi^2} A_0 h_e h_\nu^\dagger h_\nu \log \frac{M_X}{M_N},$$

Since recently : all SUSY LFV studies : LFV induced by soft-SUSY breaking

LFV in low-scale see-saw models (ν_RMSSM)

- **New SUSY mechanism: $\mathbf{m_N \gtrsim 1}$ TeV**

- LFV parameters in N sector:

$$\Omega_{\ell\ell'} = \frac{v_u^2}{2m_N^2}(h_\nu^\dagger h_\nu)_{\ell\ell'} = B^*_{\ell N_i} B_{\ell' N_i}$$

- Neutrino mass matrix (m_e diagonal basis; at scale m_N)

$$M_\nu = \begin{pmatrix} 0 & m_D^T \\ m_D & M_M \end{pmatrix}, \qquad \begin{aligned} M_\nu B^{\nu\dagger} &= 0, \quad m_{n_i} \approx m_{n_j}, \quad i,j > 3, \\ m_D &= \sqrt{2} M_W s_\beta g^{-1} h_\nu^\dagger \end{aligned}$$

$$h_\nu = \begin{pmatrix} 0 & 0 & 0 \\ ae^{-\frac{i\pi}{4}} & be^{-\frac{i\pi}{4}} & ce^{-\frac{i\pi}{4}} \\ ae^{\frac{i\pi}{4}} & be^{\frac{i\pi}{4}} & ce^{\frac{i\pi}{4}} \end{pmatrix} \qquad h_\nu = \begin{pmatrix} a^* & b^* & c^* \\ a^* e^{-\frac{2\pi i}{3}} & b^* e^{-\frac{2\pi i}{3}} & c^* e^{-\frac{2\pi i}{3}} \\ a^* e^{\frac{2\pi i}{3}} & b^* e^{\frac{2\pi i}{3}} & c^* e^{\frac{2\pi i}{3}} \end{pmatrix}$$

· $\nu_\ell^{SM} = (Bn)_\ell = (B^\nu \nu)_\ell + (B^N N)_\ell$: B diagonalizes M_ν

· ν masses : sym. breaking; radiatively induced

- Sneutrino mass matrix

$$M_{\tilde\nu}^2 \quad = \quad \begin{pmatrix} H_1 & N & 0 & M \\ N^\dagger & H_2^T & M^T & 0 \\ 0 & M^* & H_1^T & N^* \\ M^\dagger & 0 & N^T & H_2 \end{pmatrix}, \qquad M_{\tilde\nu}^2 \xrightarrow{SUSY} \begin{pmatrix} M_\nu M_\nu^\dagger & 0_{6\times 6} \\ 0_{6\times 6} & M_\nu^\dagger M_\nu \end{pmatrix}$$

$$H_1 \quad = \quad m_{\tilde L}^2 + (\frac{1}{2} M_Z^2 c_{2\beta} \mathbf{1}) + (m_D m_D^\dagger)$$

$$H_2 \quad = \quad m_{\tilde\nu}^2 + (m_D^\dagger m_D) + (M_M^\dagger M_M)$$

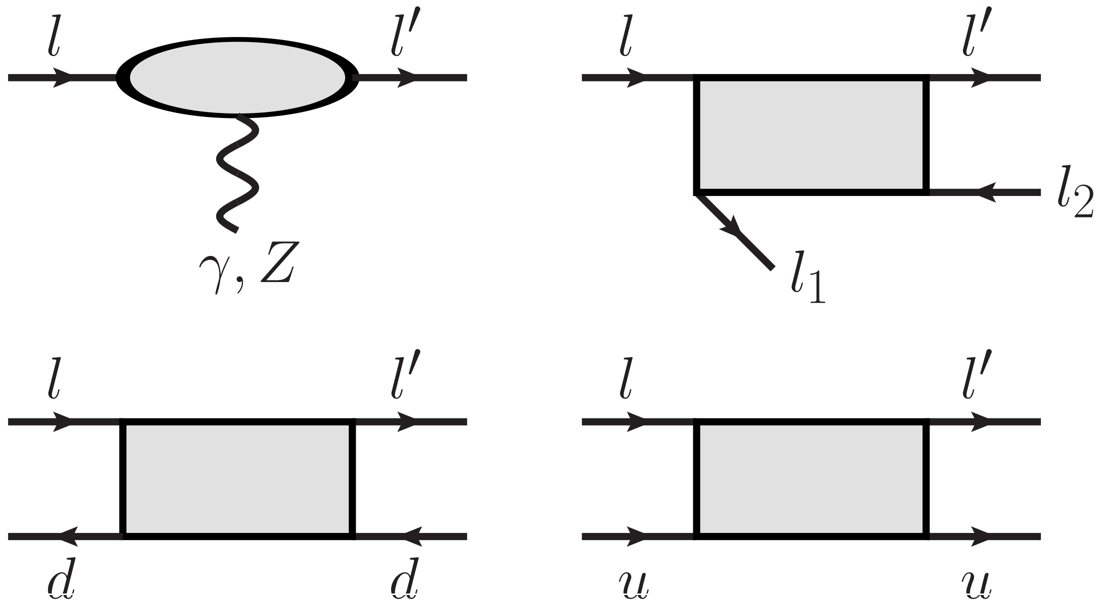
$$M \quad = \quad m_D (A_\nu - \mu\, ct_\beta)$$

$$N \quad = \quad m_D M_M^\dagger, \qquad M_B \;\equiv\; \frac{1}{2} B_{IJ} (M_\nu)_{IJ} \;\rightarrow\; 0$$

- N-$\tilde N$ sector nearly supersymmetric if $m_N > m_{SUSY}$ and $h_\nu \leq 0.2$

Amplitudes

Amplitudes : diagrams



We took $\tan\beta < 20$. Neutral Higgs (h, H, A) contr. not taken into account

Amplitudes : structure

$$\mathcal{T}_\mu^{\gamma l' l} = \frac{e\,\alpha_w}{8\pi M_W^2}\,\bar{l}'[(F_\gamma^L)_{l'l}\,(q^2\gamma_\mu - \not{q}q_\mu)P_L + (F_\gamma^R)_{l'l}\,(q^2\gamma_\mu - \not{q}q_\mu)P_R$$

$$+(G_\gamma^L)_{l'l}\,i\sigma_{\mu\nu}q^\nu P_L + (G_\gamma^R)_{l'l}\,i\sigma_{\mu\nu}q^\nu P_R]\,l,$$

$$\mathcal{T}_\mu^{Z l' l} = \frac{g_w\,\alpha_w}{8\pi\cos\theta_w}\,\bar{l}'[(F_Z^L)_{l'l}\,\gamma_\mu P_L + (F_Z^R)_{l'l}\,\gamma_\mu P_R]\,l,$$

$$\mathcal{T}_\gamma^{l l' l_1 l_2} = \frac{\alpha_w^2 s_w^2}{2M_W^2}\{\delta_{l_1 l_2}\,\bar{l}'\,[(F_\gamma^L)_{l'l}\,\gamma_\mu P_L + (F_\gamma^R)_{l'l}\,\gamma_\mu P_R$$

$$+\frac{(\not{p}-\not{p}')}{(p-p')^2}((G_\gamma^L)_{l'l}\,\gamma_\mu P_L + (G_\gamma^R)_{l'l}\,\gamma_\mu P_R)]\,l\;\;\bar{l}_1\gamma^\mu l_2^C \;-\; [l' \leftrightarrow l_1]\}\;,$$

$$\mathcal{T}_Z^{l l' l_1 l_2} = \frac{\alpha_w^2}{2M_W^2}[\delta_{l_1 l_2}\,\bar{l}'((F_Z^L)_{l'l}\,\gamma_\mu P_L + (F_Z^R)_{l'l}\,\gamma_\mu P_R)l$$

$$\times\;\bar{l}_1(g_L^l\,\gamma^\mu P_L + g_R^l\,\gamma^\mu P_R)l_2^C - (l' \leftrightarrow l_1)]\;,$$

$$
\begin{aligned}
\mathcal{T}_{\text{box}}^{ll'l_1l_2} &= -\frac{\alpha_w^2}{4M_W^2}\Big(B_{\ell V}^{LL}\,\bar{l}'\gamma_\mu P_L l\;\bar{l}_1\gamma^\mu P_L l_2^C + B_{\ell V}^{RR}\,\bar{l}'\gamma_\mu P_R l\;\bar{l}_1\gamma^\mu P_R l_2^C \\
&\quad + B_{\ell V}^{LR}\,\bar{l}'\gamma_\mu P_L l\;\bar{l}_1\gamma^\mu P_R l_2^C + B_{\ell V}^{RL}\,\bar{l}'\gamma_\mu P_R l\;\bar{l}_1\gamma^\mu P_L l_2^C \\
&\quad + B_{\ell S}^{LL}\,\bar{l}' P_L l\;\bar{l}_1 P_L l_2^C + B_{\ell S}^{RR}\,\bar{l}' P_R l\;\bar{l}_1 P_R l_2^C \\
&\quad + B_{\ell S}^{LR}\,\bar{l}' P_L l\;\bar{l}_1 P_R l_2^C + B_{\ell S}^{RL}\,\bar{l}' P_R l\;\bar{l}_1 P_L l_2^C \\
&\quad + B_{\ell T}^{LL}\,\bar{l}'\sigma_{\mu\nu} P_L l\;\bar{l}_1\sigma^{\mu\nu} P_L l_2^C + B_{\ell T}^{RR}\,\bar{l}'\sigma_{\mu\nu} P_R l\;\bar{l}_1\sigma^{\mu\nu} P_R l_2^C\Big) \\
&\equiv -\frac{\alpha_w^2}{4M_W^2}\sum_{X,Y=L,R}\;\sum_{A=V,S,T} B_{\ell A}^{XY}\;\bar{l}'\Gamma_A^X l\;\bar{l}_1\Gamma_A^Y l_2^C\;,
\end{aligned}
$$

$\mathcal{T}_{\text{box}}^{ll'dd}$ and $\mathcal{T}_{\text{box}}^{ll'uu}$ have the same structure as $\mathcal{T}_{\text{box}}^{ll'l_1l_2}$

- form factors
- new form factors

Form factors

Contributions

1. γ, Z, l-box, sl-box; h, H, A not included
2. Each form factor in principle has heavy neutrino (N), sneutrino ($\tilde{N}$) and soft SUSY breaking SB contributions, for instance

$$(F_\gamma^L)_{l'l} \quad = \quad F^N_{l'l\gamma} + F^{L,\tilde{N}}_{l'l\gamma} + F^{L,\mathrm{SB}}_{l'l\gamma}$$

A.I., A. Pilaftsis, PRD80 (2009) 091902 : N, $\tilde{N}$; γ, Z, l-box, sl-box; $\nu_R MSSM$

M. Hirsch, F. Staub, A. Vicente, Phys.Rev. D85 (2012) 113013, A. Abada, D. Das, A. Vicente, C. Weiland: N, $\tilde{N}$, SB; γ, Z, higgs, l-box, sl-box, but no N-box, MSISM

A.I., A. Pilaftsis, L. Popov, arXiv:1212.5939: N, $\tilde{N}$, SB; γ, Z, l-box, sl-box but no higgs; $\nu_R MSSM$

SUSY limit; cancelations:

- $\tilde{m}^2_{\tilde{\chi}_{1,2}} \stackrel{SL}{\longrightarrow} M_W^2, \quad t_\beta \stackrel{SL}{\longrightarrow} 1, \quad \mu \stackrel{SL}{\longrightarrow} 0$ (Barbieri, Giudice PLB309)
- $(G_\gamma^{\ell\ell'})^N + (G_\gamma^{\ell\ell'})^{\tilde{N}} \stackrel{SL}{=} 0$: Ferrara, Remiddi PLB53 (1974) 347

mSUGRA Framework

Boundary conditions and RGEs:

1. SM parameters at M_Z scale (Fusaoka and Koide PRD57 (1998) 3986).

2. Neutrino Yukawa and heavy neutrino masses at heavy neutrino scale m_N,
(Pilaftsis PRL95 (081602) 2005, PRD72 (2005) 113001, PRD83 (2011) 076007;
J. Kersten, A.Y. Smirnov, PRD76 (2007) 073005)

$$
\begin{aligned}
m_{N_i} &= m_N, \\
h_\nu &= \begin{pmatrix} 0 & 0 & 0 \\ a e^{-\frac{i\pi}{4}} & b e^{-\frac{i\pi}{4}} & c e^{-\frac{i\pi}{4}} \\ a e^{\frac{i\pi}{4}} & b e^{\frac{i\pi}{4}} & c e^{\frac{i\pi}{4}} \end{pmatrix} \qquad h_\nu = \begin{pmatrix} a^* & b^* & c^* \\ a^* e^{-\frac{2\pi i}{3}} & b^* e^{-\frac{2\pi i}{3}} & c^* e^{-\frac{2\pi i}{3}} \\ a^* e^{\frac{2\pi i}{3}} & b^* e^{\frac{2\pi i}{3}} & c^* e^{\frac{2\pi i}{3}} \end{pmatrix}
\end{aligned}
$$

3. mSUGRA conditions at gauge unification scale $g_1 = g_2 = g_3$,

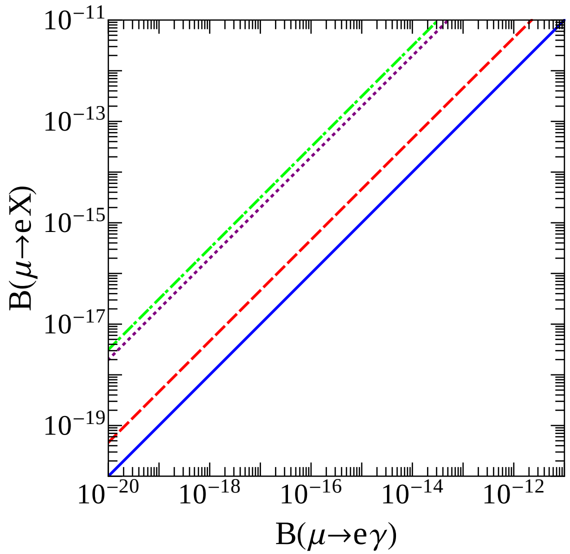
$$
\begin{aligned}
m^2_{H_1,H_2} &= m_0^2, \qquad & m^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{n}} &= m_0^2\,\mathbf{1} \\
M_{1,2,3} &= M_0, \qquad & A_{u,d,e,n} &= A_0\, h_{u,d,e,n}\ .
\end{aligned}
$$

4. MSSM+$3N$ RGE equations (P. Chankowski and S. Pokorski, IJMP A17 (2002) 575,
S. Petcov et al. NPB676 (2004) 453).

Numerical results

Choice of parameters

1. $m_0 = 1000$ GeV, $A_0 = -3000$ GeV, $M_{1/2} = 1000$ GeV
   consistent with $m_h \approx 126$ GeV
   consistent with $m_{\tilde{g}},\ m_{\tilde{q}} > 1$ GeV
   in agreement with lightest neutralino as a dark matter candidate
2. $sign(\mu) > 0$
3. $\tan\beta = 10$ in most of calculations
4. Yukawa parameters:
   model 1: $a = b$, $c = 0$; $a = c$, $b = 0$; $b = c$, $a = 0$
   model 2: $a = b = c$
   Pertubativity condition $Trh_\nu^\dagger h_\nu < 4\pi$:
   model 1: $a < 0.34$
   model 2: $a < 0.23$
5. $m_N < 10$ TeV: consistency with resonant leptogenesis



$B(\mu \to e\gamma)$ $B(\mu \to eee)$ $R_{\mu e}^{Ti}$ $R_{\mu e}^{Au}$

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -3$ TeV

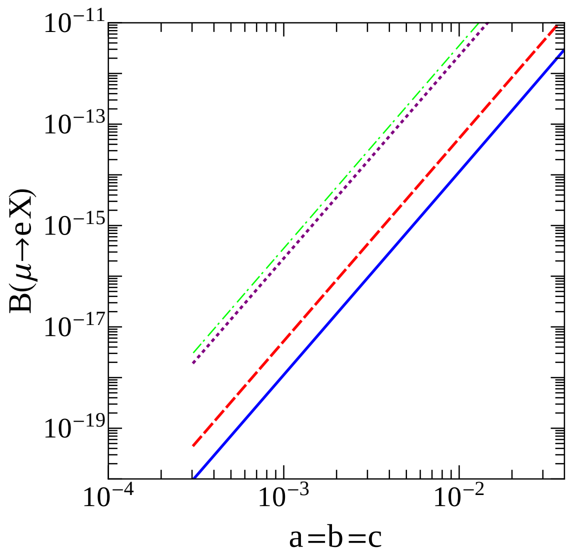
$m_N = 1$ TeV, $\tan\beta = 10$

model 2: $a = b = c$

pertubativity condition $Trh_\nu^\dagger h_\nu < 4\pi$

quadratic Yukawa dependence

$R_{\mu e}^{Au},\ R_{\mu e}^{Ti}, B(\mu \to eee) > B(\mu \to e\gamma)$



$B(\mu \to e\gamma)$ $B(\mu \to eee)$ $R_{\mu e}^{Ti}$ $R_{\mu e}^{Au}$

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -3$ TeV

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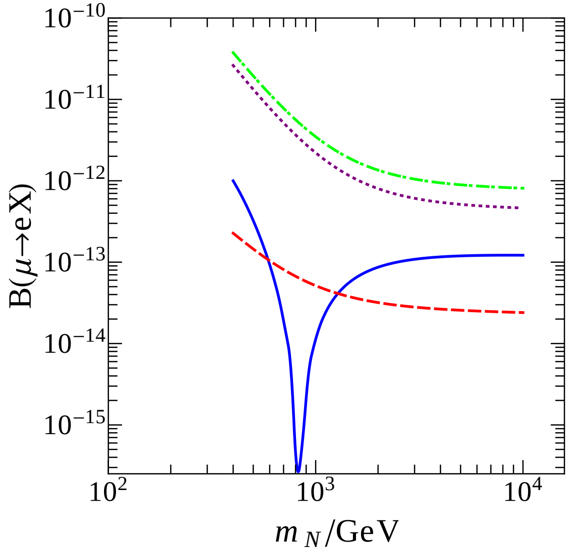


$B(\mu \to e\gamma)$ $B(\mu \to eee)$ $R^{Ti}_{\mu e}$ $R^{Au}_{\mu e}$

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -3$ TeV

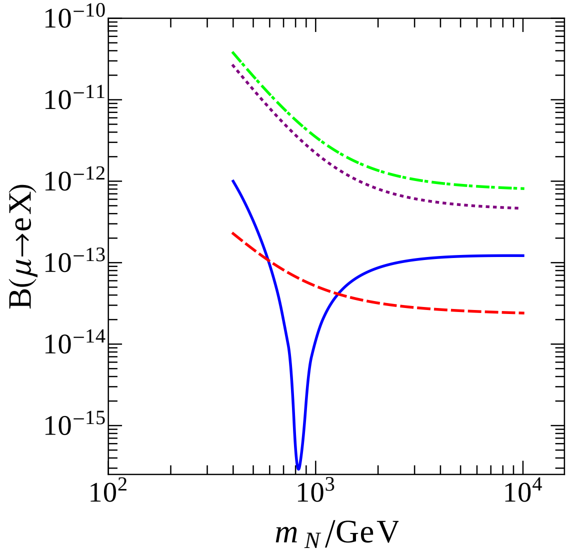
a: $B(\mu \to eee) = 10^{-12}$ for $m_N = 400$ GeV

$\tan\beta = 10$

model 2: $a = b = c$

$B(\mu \to e\gamma)$: cancelation of N, $\tilde{N}$ and SB contributions

$R^{Au}_{\mu e},\ R^{Ti}_{\mu e} > B(\mu \to e\gamma)$



$B(\mu \to e\gamma)$ $B(\mu \to eee)$ $R^{Ti}_{\mu e}$ $R^{Au}_{\mu e}$

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -3$ TeV

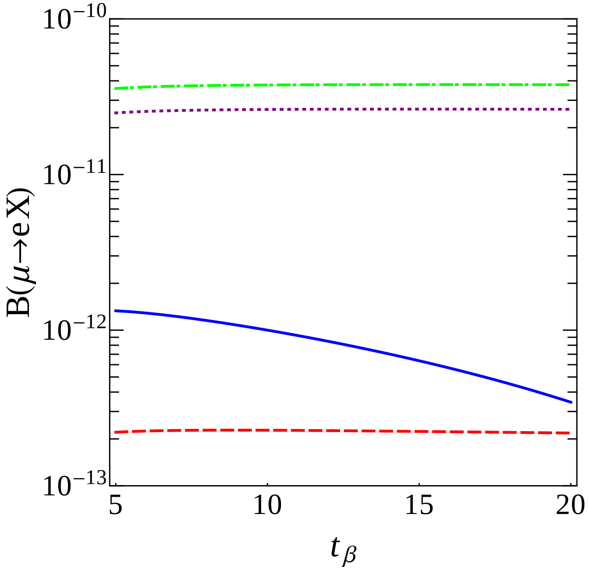
a: $B(\mu \to eee) = 10^{-12}$ for $m_N = 400$ GeV

$\tan\beta = 10$

model 1: $a = b$, $c = 0$

$B(\mu \to e\gamma)$: cancelation of N, $\tilde{N}$ and SB contributions

$R^{Au}_{\mu e},\ R^{Ti}_{\mu e} > B(\mu \to e\gamma)$



$B(\mu \to e\gamma)$ $B(\mu \to eee)$ $R_{\mu e}^{Ti}$ $R_{\mu e}^{Au}$

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -3$ TeV

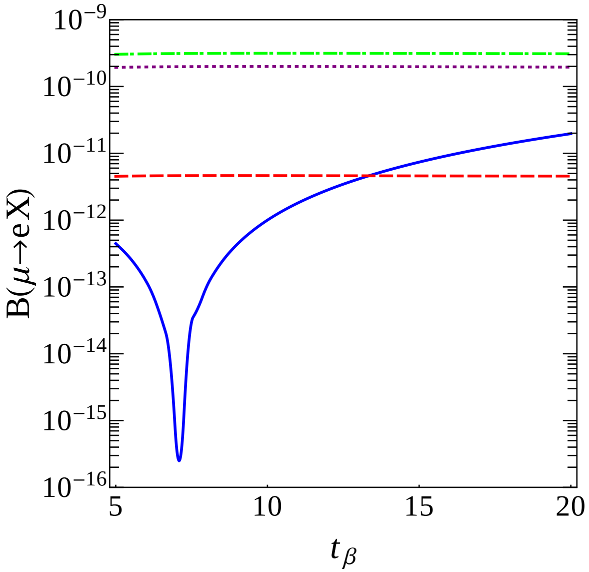
$m_N = 400$ GeV

a: $B(\mu \to eee) = 10^{-12}$ for $\tan\beta = 10$

model 2: $a = b = c$

weak dependence on $\tan\beta$

$R_{\mu e}^{Au},\ R_{\mu e}^{Ti} > B(\mu \to e\gamma)$



$B(\mu \to e\gamma)$ $B(\mu \to eee)$ $R_{\mu e}^{Ti}$ $R_{\mu e}^{Au}$

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -3$ TeV

$m_N = 1$ TeV

a: $B(\mu \to eee) = 10^{-12}$ for $m_N = 1$ TeV

model 2: $a = b = c$

$B(\mu \to e\gamma)$: cancelation of N, $\tilde{N}$ and SB contributions

$R_{\mu e}^{Au},\ R_{\mu e}^{Ti} > B(\mu \to e\gamma)$

$$R_1 \equiv \frac{B(l \to l' l_1 l_1^c)}{B(l \to l'\gamma)} \to \frac{\alpha}{3\pi}\left(\ln\frac{m_l^2}{m_{l'}^2} - 3\right)$$

$$R_2 \equiv \frac{B(l \to l' l' l'^c)}{B(l \to l'\gamma)} \to \frac{\alpha}{3\pi}\left(\ln\frac{m_l^2}{m_{l'}^2} - \frac{11}{4}\right)$$

$$R_3 \equiv \frac{R_{\mu e}^J}{B(\mu \to e\gamma)}$$

$$\to 16\alpha^4 \frac{\Gamma_\mu}{\Gamma_{\text{capture}}} Z Z_{eff}^4 |F(-\mu^2)|^2$$

$(G_\gamma^L)_{l'l}$, $(G_\gamma^R)_{l'l}$ only:

$R_1(\tau \to e\mu\mu) = 1/90$,

$R_1(\tau \to e\mu\mu) = 1/419$

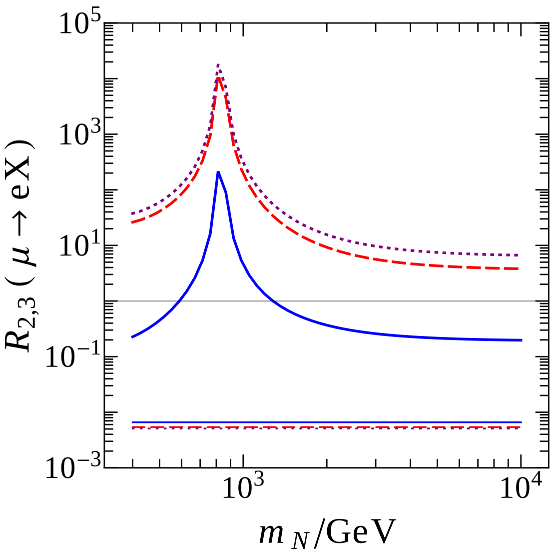
$R_2(\mu \to eee) = 1/159$,

$R_2(\tau \to eee) = 1/91$,

$R_2(\tau \to \mu\mu\mu) = 1/460$

$R_3^{Ti} = 1/198$,

$R_3^{Au} = 1/188$



$R_2(\mu \to eee)$, R_3^{Ti}, R_3^{Au}

$m_0 = M_{1/2} = 1$ TeV, $A_0 = -3$ TeV

$m_N = 400$ GeV, $\tan\beta = 10$

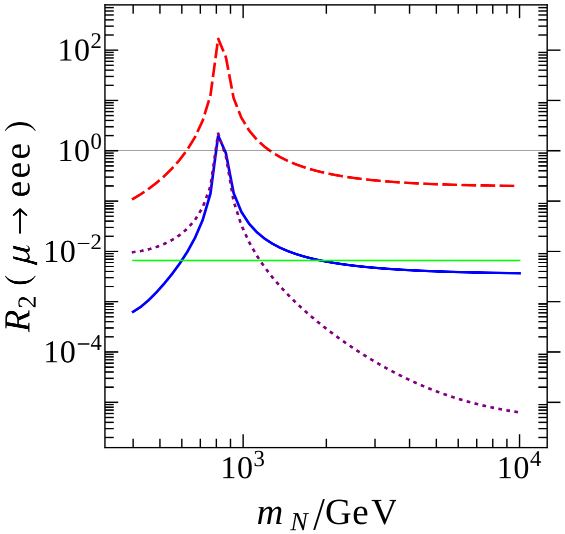
model 1 : $a = b$, $c = 0$

$R_2(\mu \to eee)$: full: $0.2 - 10^2$, $(G_\gamma^{L,R})_{l'l}$ only: $1/159$

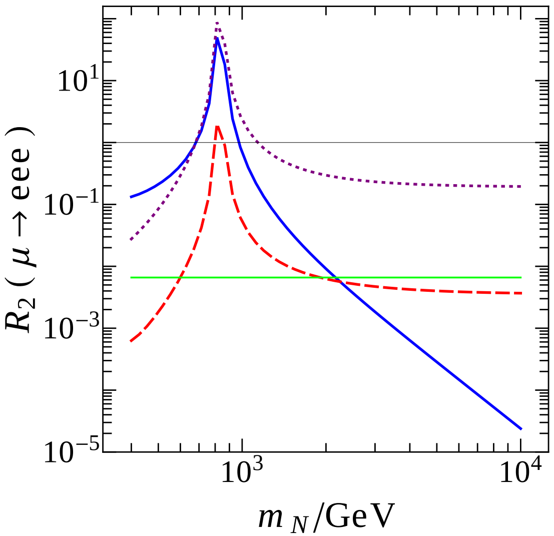
R_3^{Ti}: full: $3 - 10^4$, $(G_\gamma^{L,R})_{l'l}$ only: $1/198$

R_3^{Au}: full: $6 - 2 \times 10^2$, $(G_\gamma^{L,R})_{l'l}$ only: $1/188$

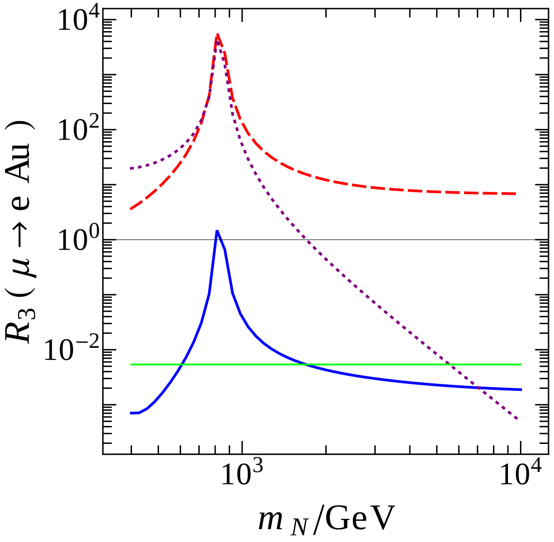
- source of strong enhancement?



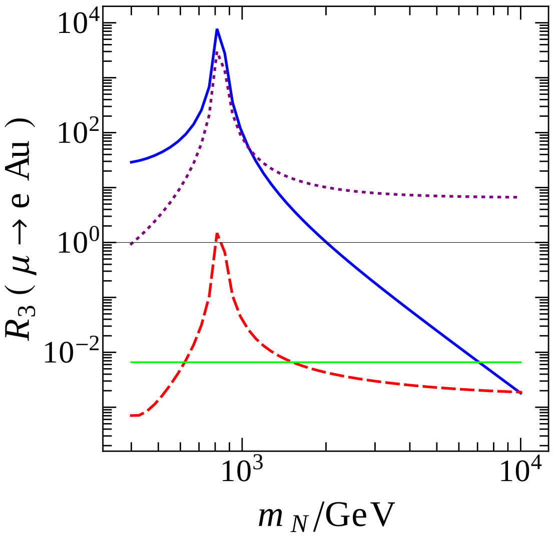
$R_2(\mu \longrightarrow eee)$: form factor contributions
G_γ and F_γ, F_Z, box, $G_\gamma^{L,R}$ only
$\tan\beta = 10$
a : $B(\mu \to e\gamma) = 10^{12}$ for $m_N = 400$ GeV
- dominance of the F_Z contribution



$R_2(\mu \longrightarrow eee)$: N, $\tilde{N}$, SB, $G_\gamma^{L,R}$ only
$\tan\beta = 10$
a : $B(\mu \to e\gamma) = 10^{12}$ for $m_N = 400$ GeV
- dominance of N for $m_N < 1$ TeV,
- dominance of SB for $m_N > 1$ TeV



R_3^{Au} : form factor contributions
G_γ and F_γ, F_Z, box, $G_\gamma^{L,R}$ only
$\tan\beta = 10$
a : $B(\mu \to e\gamma) = 10^{12}$ for $m_N = 400$ GeV
- dominance of F_Z cont. for $m_N < 1$ TeV
- dominance of box cont. for $m_N > 1$ TeV



R_3^{Au}: N, $\tilde{N}$, SB, $G_\gamma^{L,R}$ only
$\tan\beta = 10$
a : $B(\mu \to e\gamma) = 10^{12}$ for $m_N = 400$ GeV
- dominance of N cont. for $m_N < 1$ TeV,
- dominance of SB cont. for $m_N > 1$ TeV

Summary

- We have carefully studied the N, $\tilde{N}$ and soft SB contributions to LFV. For the first time complete set of box diagrams is included. Complete set of chiral amplitudes is included ($B^{LR}_{\ell S}$, $B^{RL}_{\ell S}$) - this decomposition is valid for any model.

- We have shown that in $\mu \to eee$ N Z-boson-mediated graphs dominate for $m_N < 1$ TeV and soft SB Z-boson-mediated graphs dominate for $m_N > 1$ TeV. In $\mu \to e$ conversion in nuclei N box graphs dominate for $m_N < 1$ TeV and soft SB Z-boson-mediated graphs dominate for $m_N > 1$ TeV. It is interesting that the low-scale see saw model setup strongly influences soft SB part of the amplitude.

- Due to partial cancelation of N and $\tilde{N}$ contributions in magnetic dipole amplitudes the $l \to l'\gamma$ amplitudes are suppressed relative to other CLFV amplitudes.

- Due to pertubativity condition on Yukawa couplings, the CLFV amplitudes are dominated by quadratic Yukawa contributions, while quartic contributions are small.

- The dependence of LFV amplitudes on $\tan\beta$ for $5 \leq \tan\beta \leq 20$ is weak, except for $l \to l'\gamma$ processes. $(B_s \to \mu\mu)$

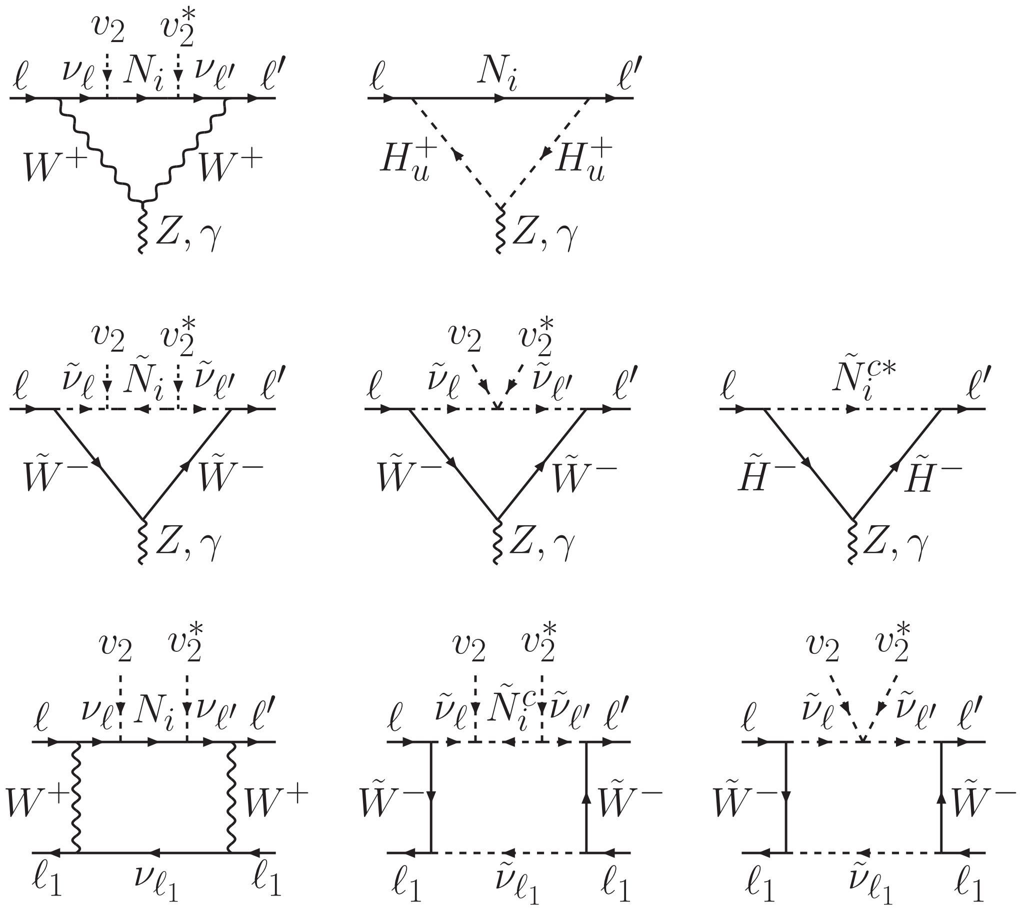
- Relative to the MSSM with ordinary see saw mechanism, $l \to l'l_1l_2$ and $\mu \to e$ conversion branching ratios are enhanced $2-3$ orders of magnitude in the region of parametric space where are no accidental cancelations of amplitudes. Opposed to the high-scale see saw MSSM models, in the low-scale see saw MSSM models $l \to l'l_1l_2$ and $\mu \to e$ may give stronger constraint to the model parameters than $l \to l'\gamma$ processes.

Thank you

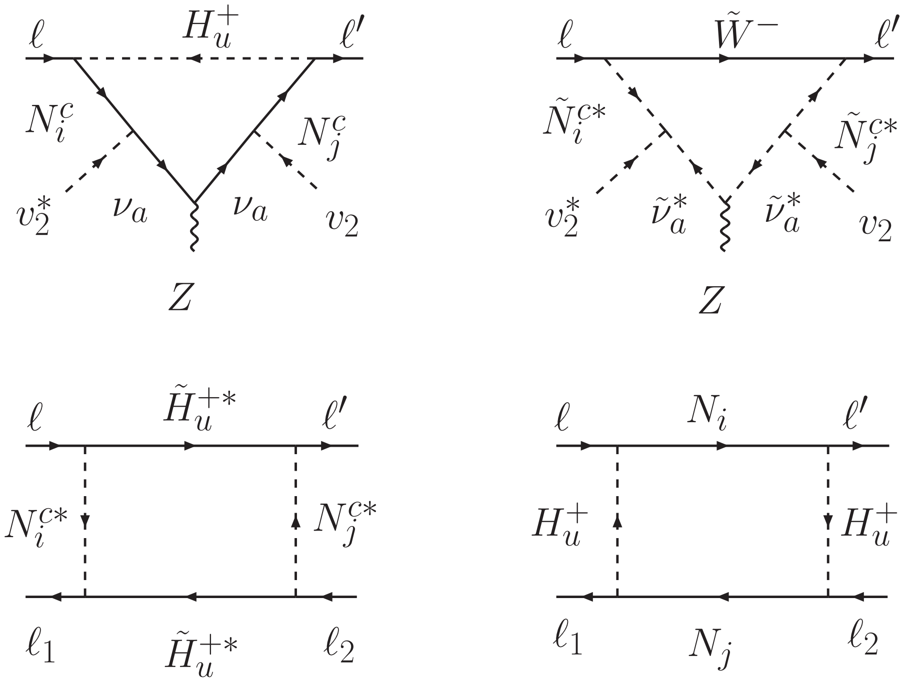
Amplitudes : Dominant contributions

- dominant terms in lowest order in g_W and v_u (Y_ν)

Two Yukawas



Four Yukawas



Form factors

$$(F_\gamma^{\ell\ell'})^N = \frac{\Omega_{\ell\ell'}}{6s_\beta^2} \ln \underbrace{\frac{m_N^2}{M_W^2}}_{=\lambda_N},$$

$$(F_\gamma^{\ell\ell'})^{\tilde{N}} = \frac{\Omega_{\ell\ell'}}{3s_\beta^2} \sum_{k=1}^{2} \mathcal{V}_{k1}^2 \ln \frac{m_N^2}{\tilde{m}_{\tilde{\chi}_k^2}},$$

$$(G_\gamma^{\ell\ell'})^N = -\Omega_{\ell\ell'}(\frac{1}{6s_\beta^2} + \frac{5}{6})$$

$$(G_\gamma^{\ell\ell'})^{\tilde{N}} = \Omega_{\ell\ell'}(\frac{1}{6s_\beta^2} + g_\gamma)$$

$$g_\gamma = -\sum_{k=1}^{2} \left[\mathcal{V}_{k1}^2 \frac{2M_W^2}{m_{\tilde{\chi}_i}^2} g_{\gamma,1}(\frac{m_{\tilde{\nu}}^2}{m_{\tilde{\chi}_i}^2}) + \mathcal{V}_{k1}\mathcal{U}_{k1} \frac{\sqrt{2}}{c_\beta} \frac{M_W^2}{m_{\tilde{\chi}_i}^2} g_{\gamma,2}(\frac{m_{\tilde{\nu}}^2}{m_{\tilde{\chi}_i}^2}) \right]$$

$$
\begin{aligned}
(F_Z^{\ell\ell'})^N &= -\frac{3\Omega_{\ell\ell'}}{2}\ln\frac{m_N^2}{M_W^2} - \frac{\Omega_{\ell\ell'}^2}{2s_\beta^2}\frac{m_N^2}{M_W^2}, \\
(F_Z^{\ell\ell'})^{\tilde{N}} &= \frac{\Omega_{\ell\ell'}}{2}\ln\frac{m_N^2}{\tilde{m}_1^2}\Big(-\frac{1}{2} + 2s_W^2 + \frac{1}{s_\beta^2}f_Z\Big) \\
f_Z &= \sum_{k,l=1}^{2}\frac{m_{\tilde{\chi}_k}m_{\tilde{\chi}_l}}{M_W^2}(\mathcal{V}_{k2}\mathcal{U}_{k1}\mathcal{U}_{l1}\mathcal{V}_{l2} + \frac{1}{2}\mathcal{V}_{k2}\mathcal{U}_{k2}\mathcal{U}_{l2}\mathcal{V}_{l2} - s_W^2\delta_{kl}\mathcal{V}_{k2}\mathcal{V}_{l2}) \\
(F_{box}^{\ell\ell'\ell_1\ell_2})^N &= -(\Omega_{\ell\ell'}\delta_{\ell_2\ell_1} + \Omega_{\ell\ell_1}\delta_{\ell_2\ell'}) + \frac{1}{4s_\beta^4}(\Omega_{\ell\ell'}\Omega_{\ell_2\ell_1} + \Omega_{\ell\ell_1}\Omega_{\ell_2\ell'})\frac{m_N^2}{M_W^2} \\
(F_{box}^{\ell\ell'\ell_1\ell_2})^{\tilde{N}} &= (\Omega_{\ell\ell'}\delta_{\ell_2\ell_1} + \Omega_{\ell\ell_1}\delta_{\ell_2\ell'})\ f_{box}^{\ell} + \frac{1}{4s_\beta^4}(\Omega_{\ell\ell'}\Omega_{\ell_2\ell_1} + \Omega_{\ell\ell_1}\Omega_{\ell_2\ell'})\frac{m_N^2}{M_W^2} \\
f_{box}^{\ell} &= \sum_{k,l=1}^{2}\mathcal{V}_{k1}^2\mathcal{V}_{l1}^2 f_{box,1}^{\ell}(\lambda_{\tilde{\chi}_k}, \lambda_{\tilde{\chi}_l}, \lambda_{\tilde{\nu}}, \lambda_N) + \mathcal{V}_{k2}\mathcal{V}_{k1}\mathcal{V}_{l2}\mathcal{V}_{l1}f_{box,2}^{\ell}()
\end{aligned}
$$

$$(F_{box}^{\ell\ell' uu})^{N} = -4(F_{box}^{\ell\ell' dd})^{N} = 4\Omega_{e\mu}$$

$$(F_{box}^{\ell\ell' uu})^{\tilde{N}} = \sum_{k,l=1}^{2} \mathcal{V}_{k1}^{2}\mathcal{V}_{l1}^{2} f_{box}^{u}(\lambda_{\tilde{\chi}_k}, \lambda_{\tilde{\chi}_l}, \lambda_{\tilde{d}}, \lambda_N)$$

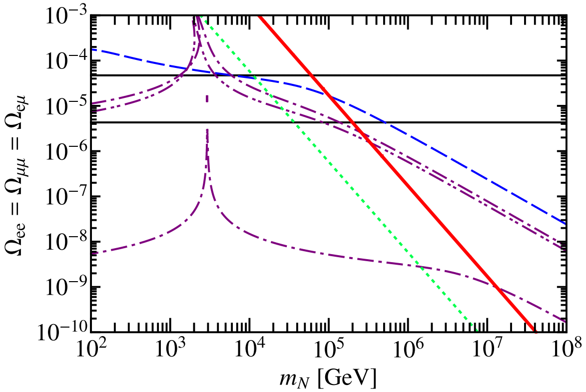
$$(F_{box}^{\ell\ell' dd})^{\tilde{N}} = \sum_{k,l=1}^{2} \mathcal{V}_{k1}^{2}\mathcal{V}_{l1}^{2} f_{box}^{d}(\lambda_{\tilde{\chi}_k}, \lambda_{\tilde{\chi}_l}, \lambda_{\tilde{u}}, \lambda_N)$$

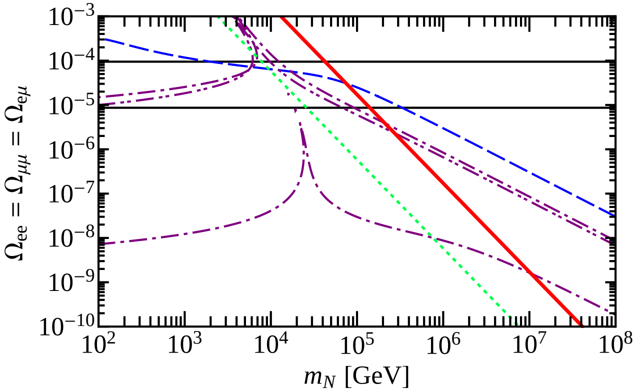
SUSY limit; cancelations, enhancements:

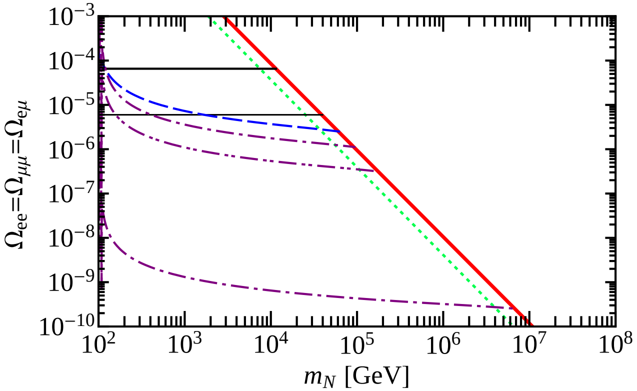
- $\tilde{m}^2_{\tilde{\chi}_{1,2}} \stackrel{SL}{\rightarrow} M_W^2, \quad t_\beta \stackrel{SL}{\rightarrow} 1, \quad \mu \stackrel{SL}{\rightarrow} 0$ (Barbieri, Giudice PLB309)
- $(G_\gamma^{\ell\ell'})^{N} + (G_\gamma^{\ell\ell'})^{\tilde{N}} \stackrel{SL}{=} 0$: Ferrara, Remiddi PLB53 (1974) 347
- box form factors : positive interference
- Y_ν^4 terms : become important when $Y_\nu / g_W \sim 1$ $\left(\Omega_{\ell\ell'} \frac{m_N^2}{M_W^2} = 2(Y^\dagger Y)_{\ell\ell'}/g_W^2\right)$

  (A. Pilaftsis, A.I, NPB437 (1995) 491)

Numerical estimates







$\tan\beta = 3$

$m_0 = 100$ GeV, $M_0 = 250$ GeV

$A_0 = 100$ GeV

$\Omega_{\mu e} = \Omega_{ee} = \Omega_{\mu\mu}$, other $\Omega_{\ell\ell'} = 0$

Upper bounds

$B(\mu^- \to e^- \gamma)$	1.2×10^{-11}	[1]
	1×10^{-13}	[2]
$B(\mu^- \to e^- e^- e^+)$	1×10^{-12}	[1]
$R_{\mu e}^{Ti}$	4.3×10^{-12}	[3]
	1×10^{-18}	[4]
$R_{\mu e}^{Au}$	7×10^{-13}	[5]

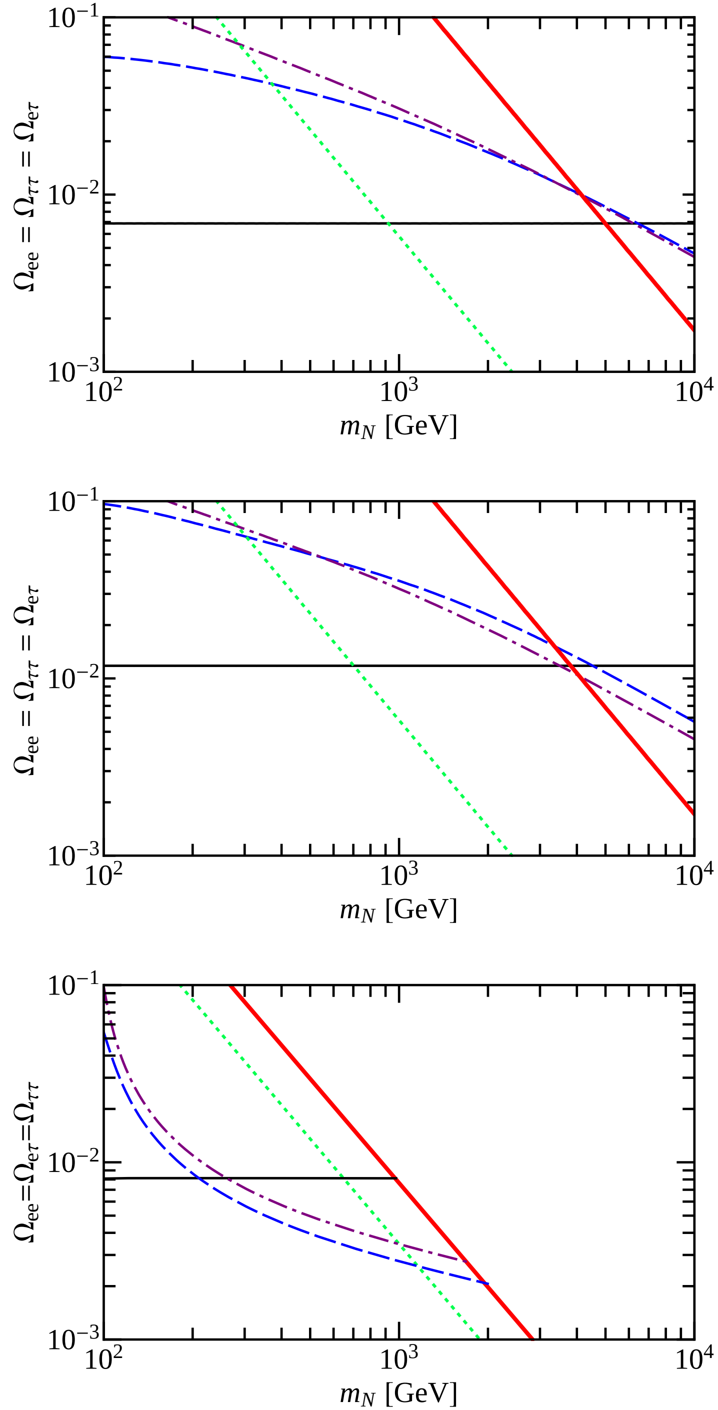
[1] Amsler, PLB 667 (2008) 1

[2] Ritt, NPBPS 162 (2006) 279

[3] Dohmen, PLB 317 (1993) 631

[4] Kuno, NPBPS 149 (2005) 376

[5] Bertl, EPJC 47 (2006) 337



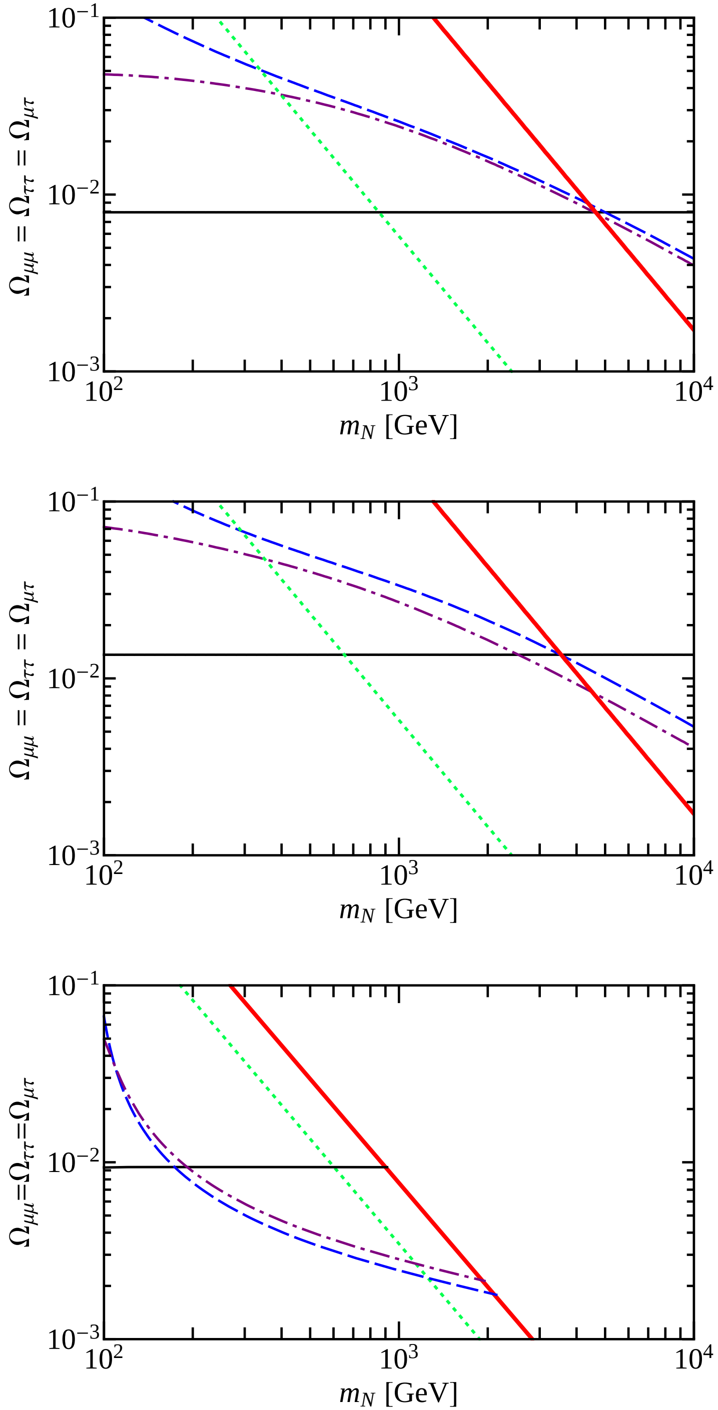
$\Omega_{\tau e} = \Omega_{ee} = \Omega_{\tau\tau}$, other $\Omega_{\ell\ell'} = 0$

Upper bounds

$B(\tau^- \to e^-\gamma)$	3.3×10^{-8}	[1]
$B(\tau^- \to e^-e^-e^+)$	2.7×10^{-8}	[2]
$B(\tau^- \to e^-\mu^-\mu^+)$	2.7×10^{-8}	[2]

[1] Aubert, PRL 104 (2010) 021802

[2] Hayasaka, PRL 687 (2010) 139



$\Omega_{\tau\mu} = \Omega_{\mu\mu} = \Omega_{\tau\tau}$, other $\Omega_{\ell\ell'} = 0$

Upper bounds

$B(\tau^- \to \mu^- \gamma)$	4.4×10^{-8}	[1]
$B(\tau^- \to \mu^- \mu^- \mu^+)$	2.1×10^{-8}	[2]
$B(\tau^- \to \mu^- e^- e^+)$	1.8×10^{-8}	[2]

[1] Aubert, PRL 104 (2010) 021802

[2] Hayasaka, PRL 687 (2010) 139

Summary

- We have shown that in the low-scaled supersymmetric see-saw models sneutrinos might give large effects indenpenent of SUSY breaking mechanism.
- Due to SUSY the $\ell \to \ell'\gamma$ are suppressed.
- That makes $\mu \to e$ conversion especially interesting candidate for finding LFV. $\mu \to 3e$ and $\tau \to 3e$ give complementary information on LFV.
- Inclusion of the mSUGRA boundary conditions strongly influences te final results of the model. Particularly it leads to lo larger theoretical prediction for LFV observables $R_{\mu e}$, $\mu \to 3e$ and $\tau \to 3$ leptons by up to factor of 25. The branching fractions for $\ell \to \ell'\gamma$ variation show smaller variation – they are slightly larger than those obtained in in MSSM+3N without mSUGRA boundary condition, but larger than results obtained in non-supersymmetric version of the model.