

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

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**Acknowledgements** : Luka Popov, Krešimir Kumerički

- We present new SUSY mechanism for LFV in MSSM +3*N* (low scale heavy singlet neutrinos), independent of soft SUSY breaking in mSUGRA framework.
- On-mass-shell  $\ell \rightarrow \ell' \gamma$  amplitude suppressed/forbidden, other amplitudes enhanced.
- Comparison with experiment :  $\mu \rightarrow e$  conversion,  $\mu \rightarrow 3e$ ,  $\tau \rightarrow 3e/e + 2\mu \dots$   
The influence of mSUGRA soft breaking SUSY conditions is studied.

# Standard MSSM+3N LFV

## Leptonic part of the superpotential

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

**LFV** : Borzumati, Masiero PRL (1986) 961;

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

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

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

**All SUSY LFV studies** : LFV induced by soft-SUSY breaking

# LFV in low-scale see-saw models

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

- LFV parameters :

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

- Neutrino mass matrix ( $m_e$  diagonal basis)

$$M_\nu = \begin{pmatrix} 0 & m_D^T \\ m_D & M_M \end{pmatrix}, \quad \begin{aligned} M_\nu B^{\nu\dagger} &= 0, \\ m_{n_i} &\approx m_{n_j}, \quad i, j > 3 \end{aligned}$$

$$\cdot \nu_\ell^{SM} = (Bn)_\ell = (B^\nu \nu)_\ell + (B^N N)_\ell$$

•  $\nu$  masses radiatively induced

- Sneutrino mass matrix

$$\mathcal{M}_{\tilde{\nu}}^2 = \begin{pmatrix} H_1 & N & 0 & M \\ N^\dagger & H_2^T & M^T & 0 \\ 0 & M^* & H_1^T & N^* \\ M^\dagger & 0 & N^T & H_2 \end{pmatrix},$$

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

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

$$M = m_D (A_\nu - \mu c t_\beta)$$

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

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

• Pinpoint the SUSY LFV effects :

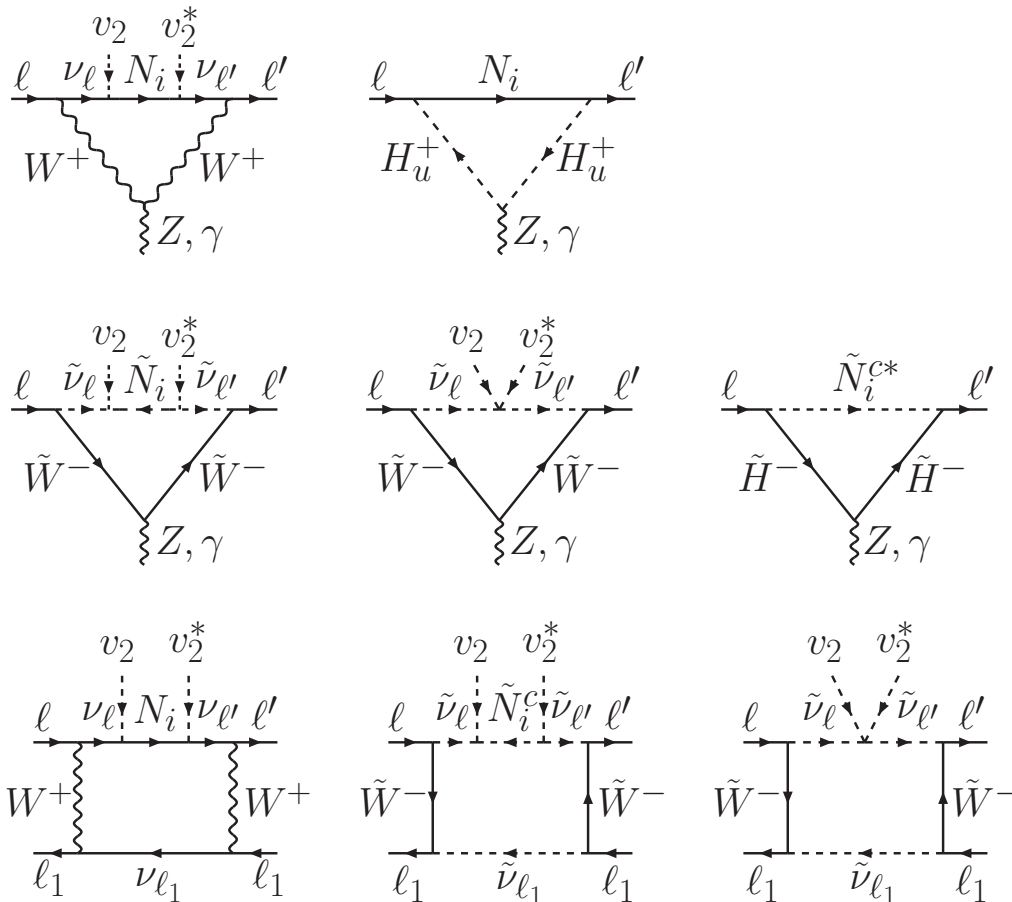
-  $\mu \ll M_N$

-  $\tilde{M}_L^2, \tilde{M}_e^2, A_e$  diagonal at  $M_N$  scale

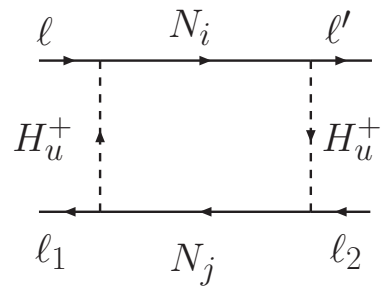
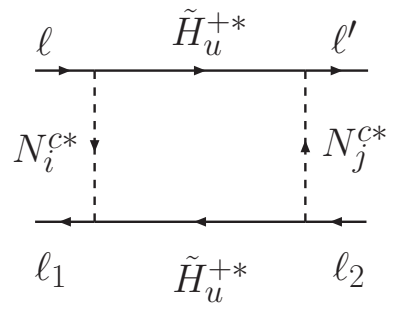
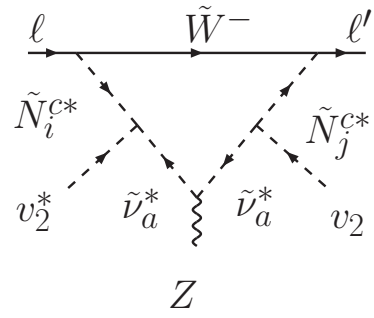
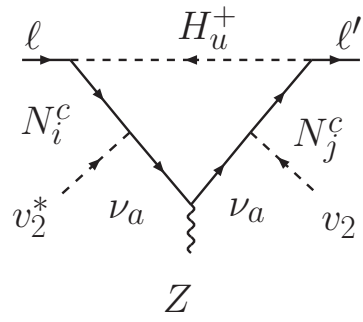
# Amplitudes : Dominant contributions

- dominant terms in lowest order in  $g_W$  and  $v_u$  ( $Y_\nu$ )

## Two Yukawas



# Four Yukawas



## Amplitudes : structure

$$\mathcal{T}_\mu^{\ell\ell'\gamma} = \frac{e\alpha_W}{8\pi M_W^2} \bar{\ell}' (F_\gamma^{\ell\ell'} (q^2 \gamma_\mu - \not{q} q_\mu) P_L + G_\gamma^{\ell\ell'} i\sigma_{\mu\nu} q^\nu m_\ell P_R) \ell,$$

$$\mathcal{T}_\mu^{\ell\ell'Z} = \frac{g_W \alpha_W}{8\pi c_W} \bar{\ell}' \gamma_\mu P_L \ell F_Z^{\ell'\ell}$$

$$\mathcal{T}_{box}^{\ell\ell'l_1l_2} = -\frac{\alpha_W^2}{4M_W^2} F_{box}^{\ell\ell'l_1l_2} \bar{\ell}' \gamma_\mu P_L \bar{\ell}_1 \gamma^\mu P_L \ell_2$$

$$\mathcal{T}_{box}^{\ell\ell'qq} = -\frac{\alpha_W^2}{4M_W^2} F_{box}^{\ell\ell'qq} \bar{\ell}' \gamma_\mu P_L \bar{q} \gamma^\mu P_L q, \quad q = u, d$$

## Form factors

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

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

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

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

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



$$(F_Z^{\ell\ell'})^N = -\frac{3\Omega_{\ell\ell'}}{2} \ln \frac{m_N^2}{M_W^2} - \frac{\Omega_{\ell\ell'}^2 m_N^2}{2s_\beta^2 M_W^2},$$

$$(F_Z^{\ell\ell'})^{\tilde{N}} = \frac{\Omega_{\ell\ell'}}{2} \ln \frac{m_N^2}{\tilde{m}_1^2} \left( -\frac{1}{2} + 2s_W^2 + \frac{1}{s_\beta^2} f_Z \right)$$

$$f_Z = \sum_{k,l=1}^2 \frac{m_{\tilde{\chi}_k} m_{\tilde{\chi}_l}}{M_W^2} (\mathcal{V}_{k2} \mathcal{U}_{k1} \mathcal{U}_{l1} \mathcal{V}_{l2} + \frac{1}{2} \mathcal{V}_{k2} \mathcal{U}_{k2} \mathcal{U}_{l2} \mathcal{V}_{l2} - s_W^2 \delta_{kl} \mathcal{V}_{k2} \mathcal{V}_{l2})$$

$$(F_{box}^{\ell\ell'l_1l_2})^N = -(\Omega_{\ell\ell'} \delta_{l_2l_1} + \Omega_{\ell l_1} \delta_{l_2l'}) + \frac{1}{4s_\beta^4} (\Omega_{\ell\ell'} \Omega_{l_2l_1} + \Omega_{\ell l_1} \Omega_{l_2l'}) \frac{m_N^2}{M_W^2}$$

$$(F_{box}^{\ell\ell'l_1l_2})^{\tilde{N}} = (\Omega_{\ell\ell'} \delta_{l_2l_1} + \Omega_{\ell l_1} \delta_{l_2l'}) f_{box}^\ell + \frac{1}{4s_\beta^4} (\Omega_{\ell\ell'} \Omega_{l_2l_1} + \Omega_{\ell l_1} \Omega_{l_2l'}) \frac{m_N^2}{M_W^2}$$

$$f_{box}^\ell = \sum_{k,l=1}^2 \mathcal{V}_{k1}^2 \mathcal{V}_{l1}^2 f_{box,1}^\ell(\lambda_{\tilde{\chi}_k}, \lambda_{\tilde{\chi}_l}, \lambda_{\tilde{\nu}}, \lambda_N) + \mathcal{V}_{k2} \mathcal{V}_{k1} \mathcal{V}_{l2} \mathcal{V}_{l1} f_{box,2}^\ell()$$

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

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

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

## SUSY limit; cancelations, enhancements:

-  $\tilde{m}_{\tilde{\chi}_{1,2}}^2 \xrightarrow{SL} M_W^2$ ,  $t_\beta \xrightarrow{SL} 1$ ,  $\mu \xrightarrow{SL} 0$  (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

-  $Y_\nu^4$  terms : become important when  $Y_\nu/g_W \sim 1$  ( $\Omega_{\ell\ell'} \frac{m_N^2}{M_W^2} = 2(Y^\dagger Y)_{\ell\ell'}/g_W^2$ )

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

# 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)

$$m_{N_i} = m_N, \quad Y_n^T = \begin{pmatrix} 0 & a e^{-i\pi/4} & a e^{-i\pi/4} \\ 0 & b e^{-i\pi/4} & b e^{-i\pi/4} \\ 0 & c e^{-i\pi/4} & c e^{-i\pi/4} \end{pmatrix} .$$

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

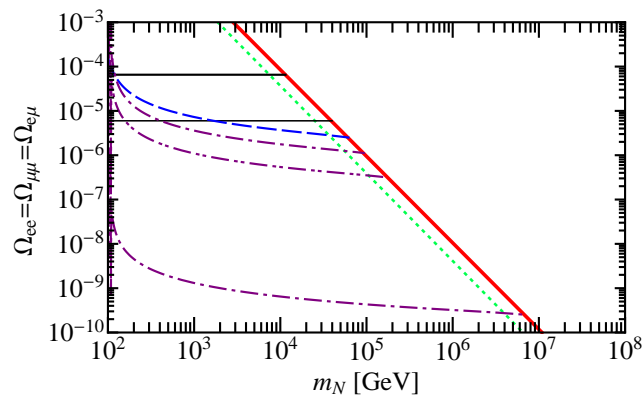
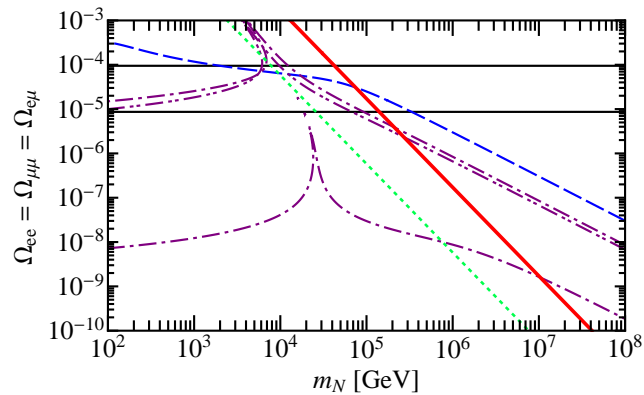
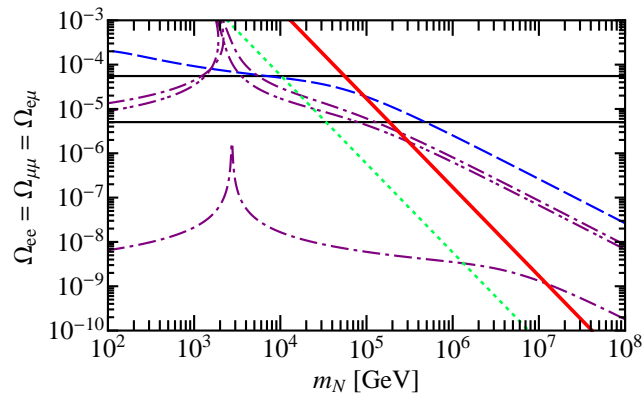
$$\begin{aligned} m_{H_1, H_2}^2 &= m_0^2, & m_{\tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}}^2 &= m_0^2 \mathbf{1} \\ M_{1,2,3} &= M_0, & A_{u,d,e,n} &= A_0 \mathbf{1} . \end{aligned}$$

We took

$$m_0 = 100 \text{ GeV}, \quad M_0 = 250 \text{ GeV}, \quad A_0 = 100 \text{ GeV} .$$

4. MSSM+3N RGE equations (Petcov NPB676 (2004) 453).

# Numerical estimates



$$\tan \beta = 3$$

$$m_0 = 100 \text{ GeV}, M_0 = 250 \text{ GeV}$$

$$A_0 = 100 \text{ GeV}$$

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

## Upper bounds

$$B(\mu^- \rightarrow e^- \gamma) \quad 1.2 \times 10^{-11} \quad [1]$$

$$1 \times 10^{-13} \quad [2]$$

$$B(\mu^- \rightarrow e^- e^- e^+) \quad 1 \times 10^{-12} \quad [1]$$

$$R_{\mu e}^{Ti} \quad 4.3 \times 10^{-12} \quad [3]$$

$$1 \times 10^{-18} \quad [4]$$

$$R_{\mu e}^{Au} \quad 7 \times 10^{-13} \quad [5]$$

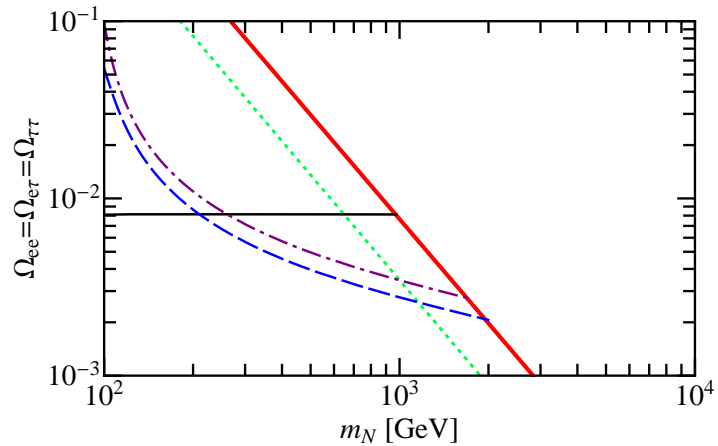
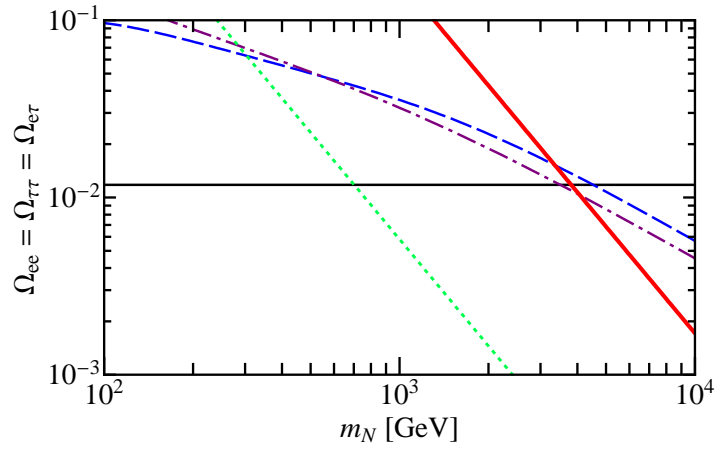
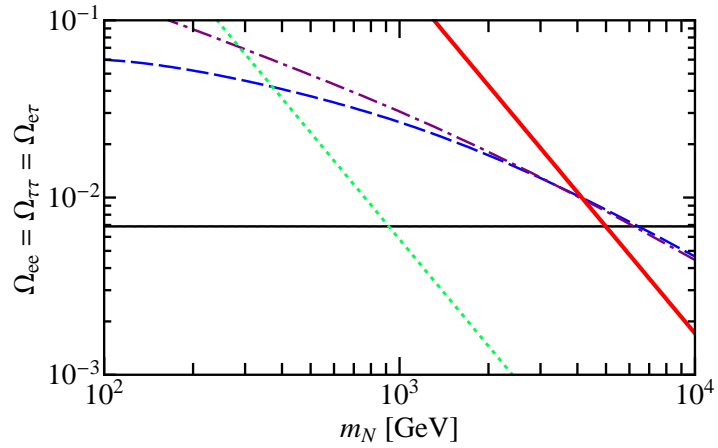
[1] Amsler, PLB 667 (2008) 1

[2] Ritt, NPBPS 162 (2006) 279 MEG

[3] Dohmen, PLB 317 (1993) 631

[4] Kuno, NPBPS 149 (2005) 376 PRIME

[5] Bertl, EPJC 47 (2006) 337



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

### Upper bounds

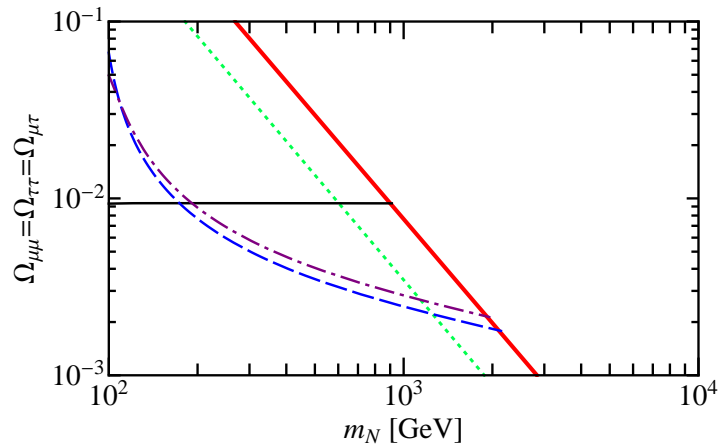
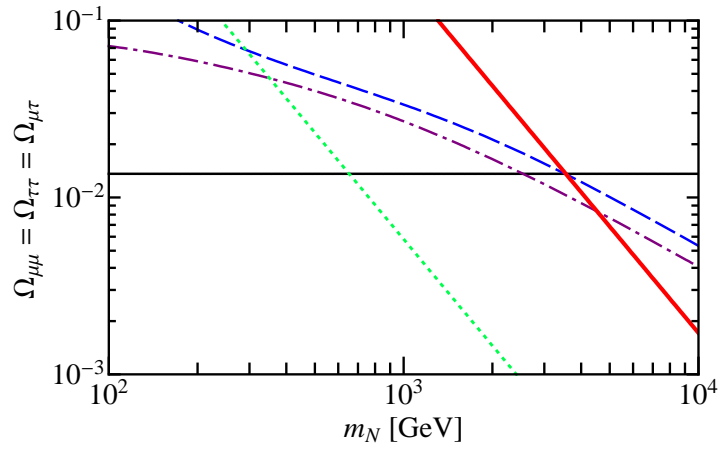
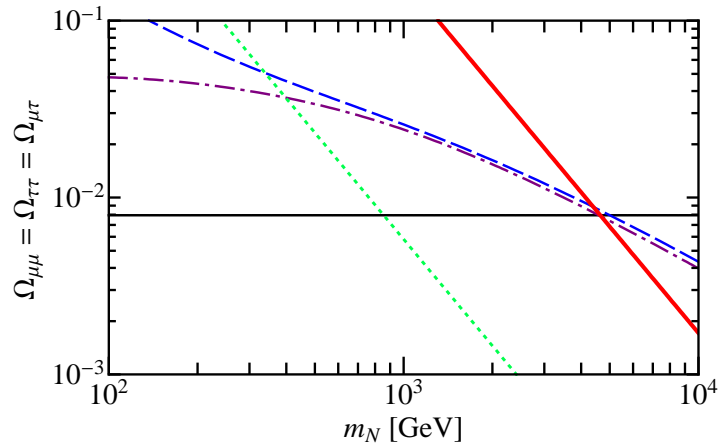
$$B(\tau^- \rightarrow e^- \gamma) \quad 3.3 \times 10^{-8} \quad [1]$$

$$B(\tau^- \rightarrow e^- e^- e^+) \quad 2.7 \times 10^{-8} \quad [2]$$

$$B(\tau^- \rightarrow e^- \mu^- \mu^+) \quad 2.7 \times 10^{-8} \quad [2]$$

[1] Aubert, PRL 104 (2010) 021802

[2] Hayasaka, PRL 687 (2010) 139



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

### Upper bounds

$$B(\tau^- \rightarrow \mu^- \gamma) \quad 4.4 \times 10^{-8} \quad [1]$$

$$B(\tau^- \rightarrow \mu^- \mu^- \mu^+) \quad 2.1 \times 10^{-8} \quad [2]$$

$$B(\tau^- \rightarrow \mu^- e^- e^+) \quad 1.8 \times 10^{-8} \quad [2]$$

[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 independent of SUSY breaking mechanism.
- Due to SUSY the  $\ell \rightarrow \ell' \gamma$  are suppressed.
- That makes  $\mu \rightarrow e$  conversion especially interesting candidate for finding LFV.  $\mu \rightarrow 3e$  and  $\tau \rightarrow 3e$  give complementary information on LFV.
- Inclusion of the mSUGRA boundary conditions strongly influences the final results of the model. It leads to larger theoretical prediction for LFV observables  $R_{\mu e}$ ,  $\mu \rightarrow 3e$  and  $\tau \rightarrow 3$  leptons. Particularly the BRs for  $\tau \rightarrow 3$  leptons can be larger than  $\tau \rightarrow \ell' \gamma$  by up to a factor of 25. The branching fractions for  $\ell \rightarrow \ell' \gamma$  variation show smaller variation – they are slightly larger than those obtained in MSSM+3N without mSUGRA boundary condition, but larger than results obtained in non-supersymmetric version of the model.