Lepton Flavour Violation in charged leptons

within SUSY-seesaw

María J. Herrero

Dpt. Física Teórica/IFT, Universidad Autónoma, Madrid

From works

E.Arganda, M.H. and J.Portolés

JHEP06(2008)079 LFV semilep. τ decays

E.Arganda, M.H. and A.Teixeira

JHEP10(2007)104 $\mu - e$ conv. in nuclei

Tau08, Novosibirsk, Russia, 22-25 Sept. 2008

Motivation

⋆ Lepton Flavour Violation (LFV) occurs in Nature: $\nu_i - \nu_j$ oscill.

⋆ LFV is very sensitive to SUSY: if m_ν from seesaw with Majorana ν_R $\Rightarrow Y_\nu$ can be $\mathcal{O}(1)$. Large Y_ν induce, via SUSY loops, large LFV rates

⋆ We focus here on LFV semilep τ decays, $\tau \to \mu PP$ and $\tau \to \mu P$, and $\mu - e$ conv. in nuclei which 1) complement previous studies of LFV leptonic τ and μ decays and 2) have more sensitivity to Higgs sector

⋆ Exp. bounds for the processes of interest here (Belle-BABAR,SINDRUM):

BR$(\tau \to \mu\eta)$	$<$	$\mathbf{5.1 \times 10^{-8}}$	BR$(\tau \to \mu\pi^+\pi^-)$	$<$	4.8×10^{-7}
BR$(\tau \to \mu\eta')$	$<$	$\mathbf{5.3 \times 10^{-8}}$	BR$(\tau \to \mu\pi^0\pi^0)$		(no bound)
BR$(\tau \to \mu\pi)$	$<$	5.8×10^{-8}	BR$(\tau \to \mu K^+ K^-)$	$<$	8×10^{-7}
BR$(\tau \to \mu\rho)$	$<$	2×10^{-7}	BR$(\tau \to \mu K^0 \bar{K}^0)$		(no bound)
BR$(\tau \to \mu\phi)$	$<$	1.3×10^{-7}			
CR$(\mu - e, \text{Au})$	$<$	7×10^{-13}	CR$(\mu - e, \text{Ti})$	$<$	4.3×10^{-12}

Present: Some LFV semilep. decays already competitive with lep. ones
Future: $\mu - e$ conv. in Ti, the most challenging $\mathbf{10^{-18}}$ (PRISM/PRIME)

⋆ Few predictions of these processes in the previous literature:
Some not in the SUSY-seesaw context (i.e no connection with ν physics);
Others not complete (i.e not all loops); Hadronisation treated differently

Our work presented here:

- **Predictions of LFV rates within SUSY-seesaw for:**

  - ⋆ $\tau \to \mu P$, $P = \eta, \eta', \pi$

  - ⋆ $\tau \to \mu PP$, $PP = \pi^+ \pi^-, \pi^0 \pi^0, K^+ K^-, K_0 \bar{K}_0$

  - ⋆ $\tau \to \mu V$, $V = \rho, \phi$ (related to $\tau \to \mu PP$)

  - ⋆ $\mu - e$ conversion in different nuclei: Ti, Au,...

- **Full one-loop computation of LFV rates**

- **Require compatibility with ν data**

- **Compare with present LFV bounds**

- **Explore sensitivity to SUSY, and seesaw parameters**

- **Found higher sensitivity to Higgs sector in these processes than in LFV lep. decays, $\tau \to 3\mu$,..**

- **Found a set of simple formulas that approximate well the full result and are usefull for comparison with data**

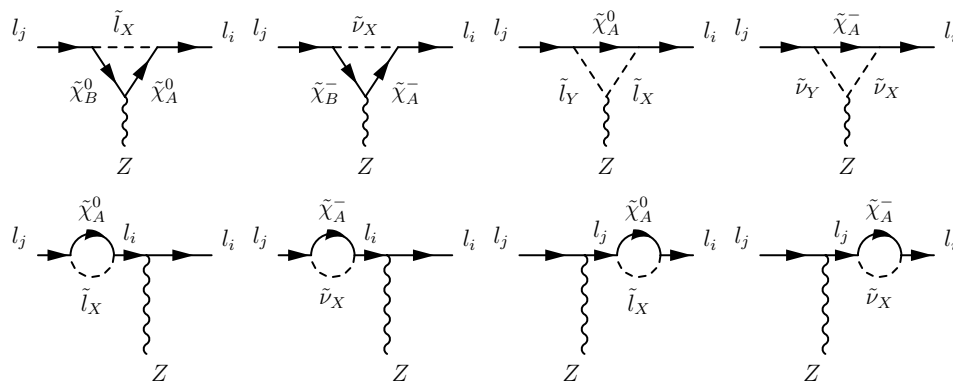# 1-loop diagrams in $\tau \to 3\mu$, $\tau \to \mu P$ $\tau \to \mu PP$, $\tau \to \mu V$, $\mu - e$
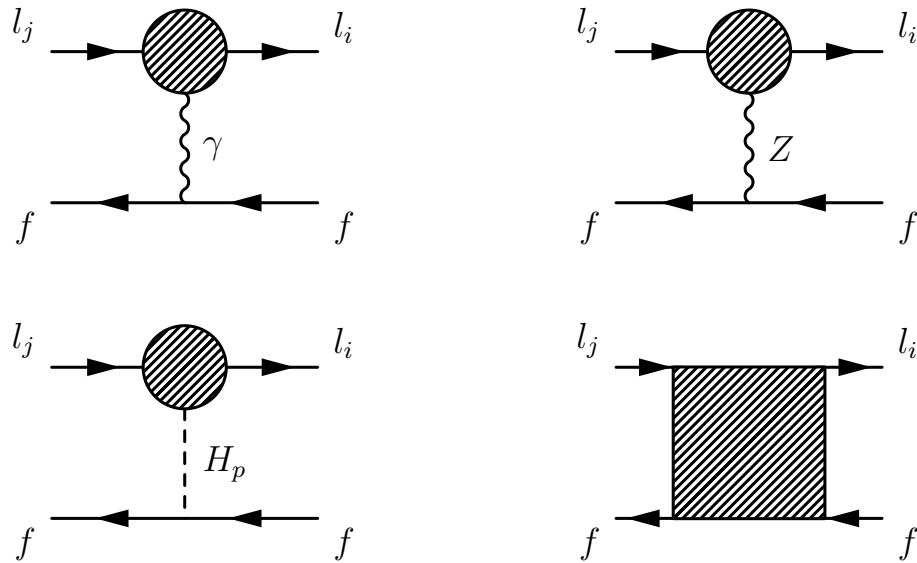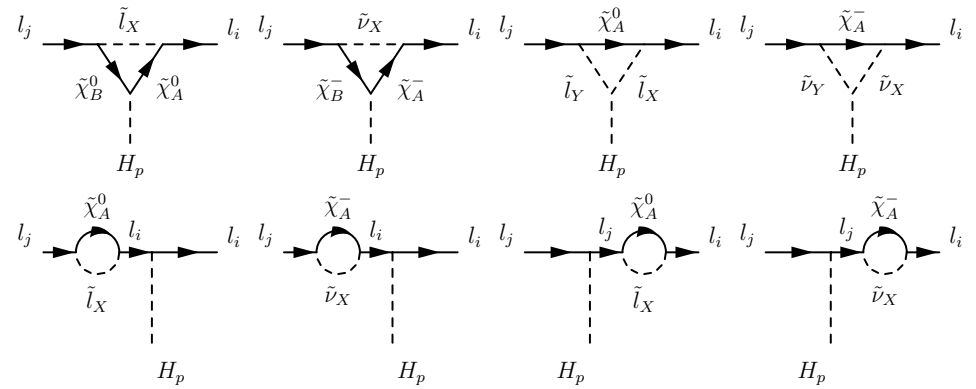

Generic
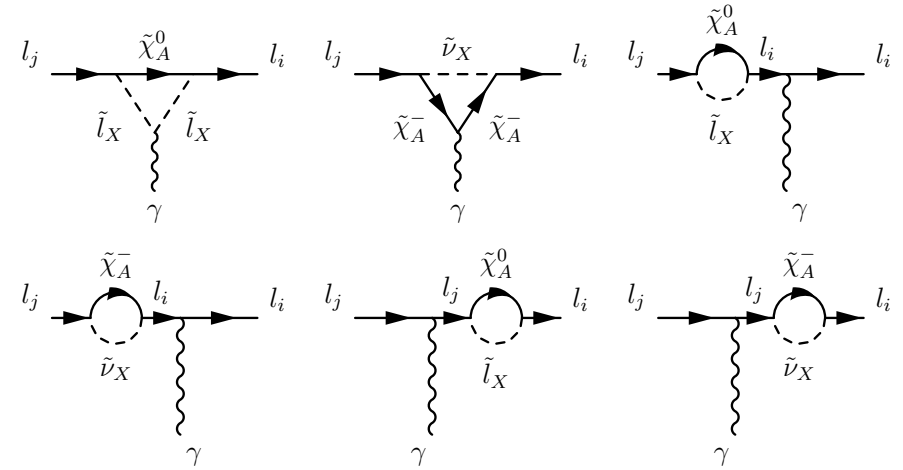
Photon-mediated

Z boson-mediated

H boson-mediated

Framework for LFV

- **Use seesaw (Type I) for ν mass generation**

- **Within Constrained MSSM $+ \, 3\nu_R$ (Majorana) $+ \, 3\tilde{\nu}_R$**
  Two scenarios for soft parameters at $M_X = 2 \times 10^{16}$ GeV:

  - $\star$ Universal soft parameters: CMSSM-seesaw
    $(M_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu))$; $\tan\beta = v_2/v_1$

  - $\star$ Non-universal soft Higgs masses: NUHM-seesaw
    $(M_0, M_{1/2}, M_{H_1}, M_{H_2}, A_0, \tan\beta, \text{sign}(\mu))$

- LFV generated by 1-loop running from M_X to M_Z
  Full RGEs including ν and $\tilde{\nu}$ sectors (No Llog approx)

- Mass eigenstates for all SUSY and Higgs particles (No MI approx)

- **Numerical estimates:**

  - $\star$ SPheno 2.2.2 (W.Porod) for int. of RGEs and SUSY spectrum

  - $\star$ Additional subroutines for all LFV processes (by us)
    Also subroutines for checks of BAU, EDM and $(g-2)_\mu$

Framework for Hadronisation

- **We use Chiral Perturbation Theory (χPT)**
  It realizes nicely the large N_C expansion of $SU(N_C)$ QCD and is the appropriate scheme to describe strong ints of PG Bosons $P = \pi, K, \eta$.

  - ⋆ BR($\tau \to \mu P$), $P = \pi, \eta, \eta'$, from leading $\mathcal{O}(p^2)$ χPT. Results in terms of F_π and m_P (assume $\eta_8 - \eta_0$ mix. ang. $\theta \simeq -18^o$ for $P = \eta, \eta'$).

  - ⋆ BR($\tau \to \mu PP$), $PP = \pi^+\pi^-, K^+K^-, K_0\bar{K}_0$ from χPT plus contributions from resonances (RχT). Results in terms of F_π, m_P and well established form factors $F_V^{PP}(s)$,(G.Ecker et al. PLB223(1989)425).

$$
F_V^{\pi\pi}(s) = F(s) \, \exp\left[2\,Re\left(\tilde{H}_{\pi\pi}(s)\right) + Re\left(\tilde{H}_{KK}(s)\right)\right]
$$

$$
F(s) = \frac{M_\rho^2}{M_\rho^2 - s - iM_\rho\Gamma_\rho(s)}\left[1 + \left(\delta\frac{M_\omega^2}{M_\rho^2} - \gamma\frac{s}{M_\rho^2}\right)\frac{s}{M_\omega^2 - s - iM_\omega\Gamma_\omega}\right]
$$
$$
- \frac{\gamma\,s}{M_{\rho'}^2 - s - iM_{\rho'}\Gamma_{\rho'}(s)} \, ,
$$

$$
\tilde{H}_{PP}(s) = \frac{s}{F_\pi^2}\left[\frac{1}{12}\left(1 - 4\frac{m_P^2}{s}\right)J_P(s) - \frac{k_P(M_\rho)}{6} + \frac{1}{288\pi^2}\right], \sigma_P(s) = \sqrt{1 - 4\frac{m_P^2}{s}}
$$

$$
J_P(s) = \frac{1}{16\pi^2}\left[\sigma_P(s)\ln\frac{\sigma_P(s) - 1}{\sigma_P(s) + 1} + 2\right], k_P(\mu) = \frac{1}{32\pi^2}\left(\ln\frac{m_P^2}{\mu^2} + 1\right)
$$

Framework for $\mu - e$ conversion in nuclei

- **We follow the general parameterisation and approxs of Kuno & Okada Rev.Mod.Phys.73(01)151**

  ⋆ Equal proton and neutron densities in the nucleus; non-relativistic μ wave function for the 1s state; neglect momentum dependence of nucleon form factors

  ⋆ $\mu - e$ conv. rate compared to muon capture rate, as a function of: Z, N number of p and n in nucleus; Z_{eff} effective atomic charge, F_p nuclear matrix element. We compute isoscalar and isovector couplings $g^{(0)}$, $g^{(1)}$ from the full set of 1-loop diagrams. Z_{eff}, F_p, Γ_{capt} for various nuclei from Kitano, Koike, Okada, PRD66(02)096002.

$$
\begin{aligned}
\text{CR}(\mu - e, \text{Nucleus}) \;=\; & \frac{m_\mu^5\, G_F^2\, \alpha^3\, Z_{\text{eff}}^4\, F_p^2}{8\,\pi^2\, Z} \\
\times \;\; & \left\{ \left| (Z+N)\left(g_{LV}^{(0)} + g_{LS}^{(0)}\right) + (Z-N)\left(g_{LV}^{(1)} + g_{LS}^{(1)}\right) \right|^2 + \right. \\
& \left. \left| (Z+N)\left(g_{RV}^{(0)} + g_{RS}^{(0)}\right) + (Z-N)\left(g_{RV}^{(1)} + g_{RS}^{(1)}\right) \right|^2 \right\} \frac{1}{\Gamma_{\text{capt}}}
\end{aligned}
$$

Seesaw parameters versus neutrino data

SeeSaw eq.: $m_\nu = -m_D^T m_N^{-1} m_D$; 3 light ν $(\sim \nu_L)$, 3 heavy N $(\sim \nu_R)$

Solution: $\boxed{m_D = Y_\nu\, v_2 = i\,\sqrt{m_N^{diag}}\,R\,\sqrt{m_\nu^{diag}}\,U_{MNS}^\dagger}$ [Casas, Ibarra ('01)]

R is a 3×3 complex matrix and orthogonal

$$R = \begin{pmatrix} c_2 c_3 & -c_1 s_3 - s_1 s_2 c_3 & s_1 s_3 - c_1 s_2 c_3 \\ c_2 s_3 & c_1 c_3 - s_1 s_2 s_3 & -s_1 c_3 - c_1 s_2 s_3 \\ s_2 & s_1 c_2 & c_1 c_2 \end{pmatrix}$$, $c_i = \cos\theta_i$, $s_i = \sin\theta_i$, $\theta_{1,2,3}$ complex

Parameters: $\theta_{ij}, \delta, \alpha, \beta, m_{\nu_i}, m_{N_i}, \theta_i$ **(18)** ; m_{N_i}, θ_i drive the size of Y_ν

Hierarchical ν's : $m_{\nu_1}^2 << m_{\nu_2}^2 = \Delta m_{\text{sol}}^2 + m_{\nu_1}^2 << m_{\nu_3}^2 = \Delta m_{\text{atm}}^2 + m_{\nu_1}^2$

2 Scenarios

- Degenerate N's

  $m_{N_1} = m_{N_2} = m_{N_3} = m_N$
- Hierarchical N's

  $m_{N_1} << m_{N_2} << m_{N_3}$

Our choice of **input** parameters

Constrained MSSM $+3\nu_R + 3\tilde{\nu}_R +$ seesaw

- CMSSM:

$$\left\{ \begin{array}{l} M_0, M_{1/2}, A_0 \text{ (at } M_X \sim 2 \times 10^{16} \text{ GeV)} \\ \tan\beta = <H_2>/<H_1> \text{ (at EW scale)} \\ \text{sign}(\mu) \text{ (}\mu \text{ derived from EW breaking)} \end{array} \right\}$$

- NUHM: $(M_0, M_{1/2}, M_{H_1}, M_{H_2}, A_0, \tan\beta, \text{sign}(\mu))$

Choose $M_0 = M_{1/2}$, $M_{H_1}^2 = M_0^2(1+\delta_1)$, $M_{H_2}^2 = M_0^2(1+\delta_2)$

- Seesaw parameters $\left\{ \begin{array}{l} m_{\nu_{1,2,3}} \text{ (set by data)} \\ m_{N_{1,2,3}} \text{ (input)} \\ U_{MNS} \text{ (set by data)} \\ R(\theta_1, \theta_2, \theta_3) \text{ (input)} \end{array} \right.$

- For numerical estimates:

$$(\triangle m^2)_{12} = \triangle m^2_{\text{sol}} = 8 \times 10^{-5} \text{ eV}^2$$

$$(\triangle m^2)_{23} = \triangle m^2_{\text{atm}} = 2.5 \times 10^{-3} \text{eV}^2$$

$$\theta_{12} = 30^o; \ \theta_{23} = 45^o; \ \delta = \alpha = \beta = 0; \ 0 \le \theta_{13} \le 10^o$$

$$250 \text{ GeV} < M_0, M_{1/2} < 1000 \text{ GeV}, \ -500 \text{ GeV} < A_0 < 500 \text{ GeV}$$

$$5 < \tan\beta < 50, \ -2 < \delta_{1,2} < 2$$

Competing LFV $\tau \to \mu + ...$ decays:

$$\tau \to \mu\gamma, \; \tau \to 3\mu, \; \tau \to \mu PP, \; \tau \to \mu P, \; \tau \to \mu V, ...$$

I) Common/Non-common aspects

II) Comments on $\tau \to \mu\gamma$ and $\tau \to 3\mu$

Phenomenological parameter for LFV in the tau-muon sector: δ_{32}

Within the Mass Insertion (MI) approx.,

$$\mathrm{BR}(\tau \to \mu + ...) \propto |\delta_{32}|^2$$

In SUSY-Seesaw scenarios, the contributions from neutrinos and sneutrinos to the slepton mass matrix entry 32, in the Leading Logarithmic Approximation (Llog) are parameterized by:

$$\delta_{32} = \frac{\Delta \tilde{M}^2_{32}}{M^2_{\mathsf{SUSY}}} = -\frac{1}{8\pi^2}\frac{(3\,M^2_0 + A^2_0)}{M^2_{\mathsf{SUSY}}} \left(Y^\dagger_\nu\,L\,Y_\nu\right)_{32}$$

$$L_{ii} = \log(M_X/m_{N_i}); \ M_{\mathsf{SUSY}} \text{ is an average SUSY mass}$$

The relation with neutrino physics comes in,

$$
\begin{aligned}
v^2_2 \left(Y^\dagger_\nu\,L\,Y_\nu\right)_{32} &= L_{33}\,m_{N_3}\left[\left(\sqrt{m_{\nu_3}}c_1c_2c_{13}c_{23} - \sqrt{m_{\nu_2}}s_1c_2c_{12}s_{23}\right)\right.\\
&\qquad \left.\left(\sqrt{m_{\nu_3}}c^*_1c^*_2s_{23} + \sqrt{m_{\nu_2}}s^*_1c^*_2c_{12}c_{23}\right)\right]\\
&+ L_{22}\,m_{N_2}\left[\left(\sqrt{m_{\nu_3}}(-s_1c_3 - c_1s_2s_3)c_{23} + \sqrt{m_{\nu_2}}(s_1s_2s_3 - c_1c_3)c_{12}s_{23}\right)\right.\\
&\qquad \left.\left(\sqrt{m_{\nu_3}}(-s^*_1c^*_3 - c^*_1s^*_2s^*_3)s_{23} + \sqrt{m_{\nu_2}}(c^*_1c^*_3 - s^*_1s^*_2s^*_3)c_{12}c_{23}\right)\right]\\
&+ L_{11}\,m_{N_1}\left[\left(\sqrt{m_{\nu_3}}(s_1s_3 - c_1s_2c_3)c_{12}c_{23} + \sqrt{m_{\nu_2}}(s_1s_2c_3 + c_1s_3)c_{12}s_{23}\right)\right.\\
&\qquad \left.\left(\sqrt{m_{\nu_3}}(s^*_1s^*_3 - s^*_1s^*_2s^*_3)c_{12}s_{23} - \sqrt{m_{\nu_2}}(s^*_1s^*_2c^*_3 + c^*_1s^*_3)c_{12}c_{23}\right)\right]
\end{aligned}
$$

Large BRs in LFV tau decays within SUSY-seesaw
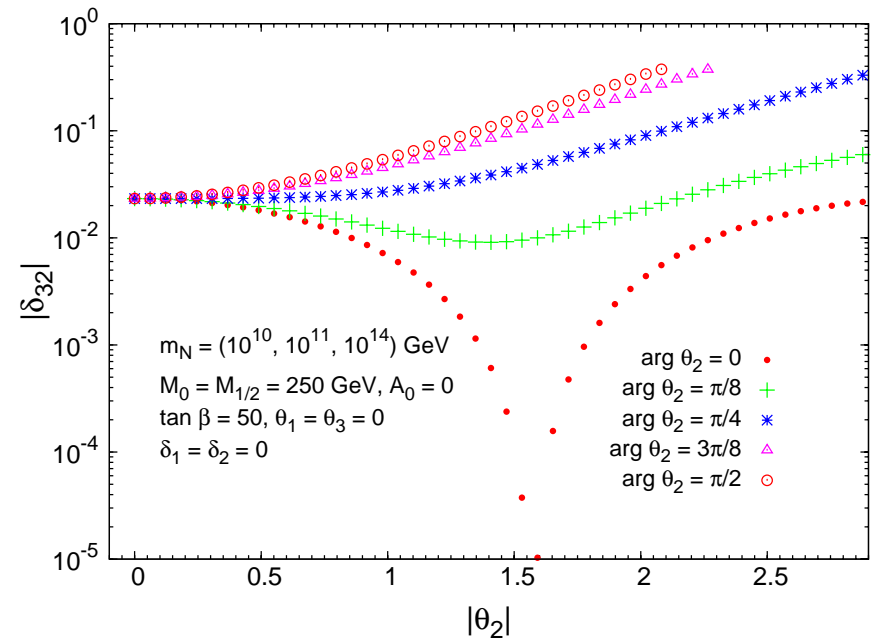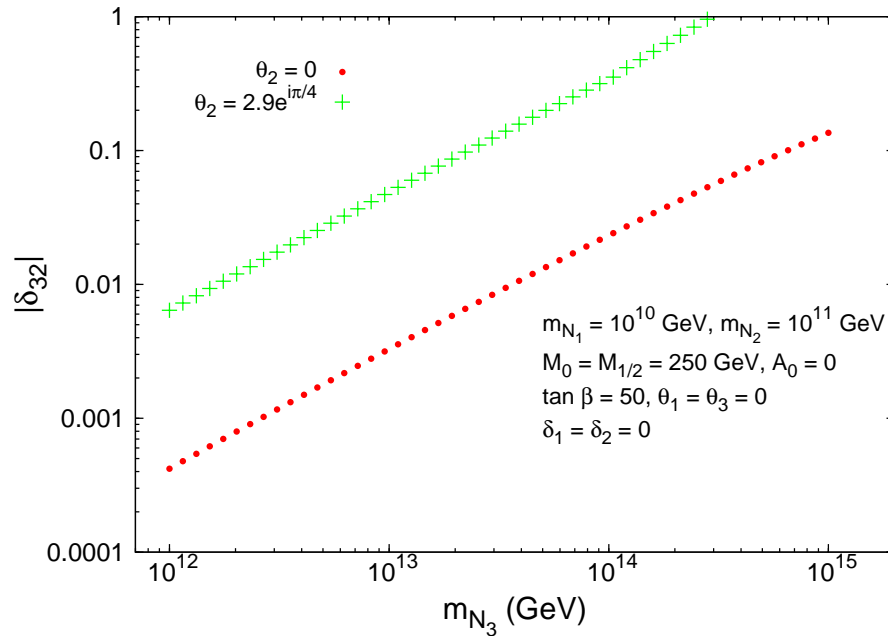
- ★ Most relevant seesaw param.: m_{N_3} if ν_R hierarchical (m_N if degenerate)

  BR $\sim |\delta_{32}|^2 \sim |m_{N_3} \log m_{N_3}|^2$ (larger BRs than for deg.) (same all decays)

- ★ Next relevant seesaw parameter: θ_i (same all decays)

  Ex.: BR $\times 10 - 100$ if θ_2: $0 \to 2.9 e^{i\pi/4}$; $|\delta_{32}| \sim \mathcal{O}(1)$; $Y_\nu \sim \mathcal{O}(1)$

- ★ Most relevant SUSY parameter: $\tan\beta$ (same all decays)

  BR$\sim (\tan\beta)^2$ if γ-dominated; $\sim (\tan\beta)^6$ if H-dominated (not same all dec.)

- ★ Some BRs reach exp. lim. at large m_{N_3}, large $\tan\beta$ and large θ_i

The most competitive LFV tau decay: $\tau \to \mu\gamma$

From our previous study, JHEP11(2006)090, presented at Tau06, Pisa

$(-\pi/4 \lesssim \arg\theta_1 \lesssim \pi/4,\ 0 \lesssim \arg\theta_2 \lesssim \pi/4)$,

(SP1a: $M_0 = 100$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan\beta = 10$, $\mu > 0$)
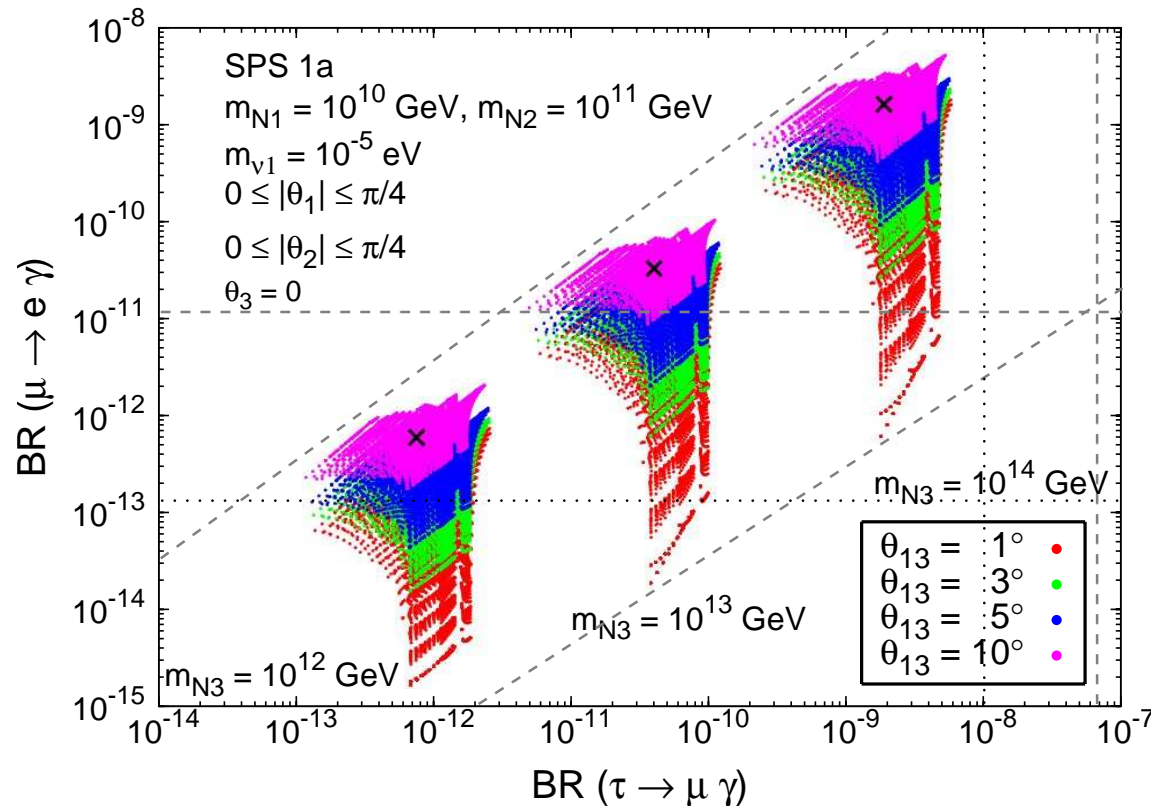
Present: $\mu \to e\gamma$ more competitive than $\tau \to \mu\gamma$, except if very small θ_{13}

MEGA bound, $BR(\mu \to e\gamma) < 10^{-11}$, already disfavours $m_{N_3} \gtrsim 10^{14}$ GeV

Conclusion: For a given SPS, $\tau \to \mu\gamma$ sets upper bounds on m_{N_3} that, if small θ_{13}, are competitive with those from $\mu \to e\gamma$.

BUT: both are insensitive to Higgs!!. Next: Some LFV semileptonic tau decays do!!

Sensitivity to Higgs if and only if: light Higgs and heavy SUSY
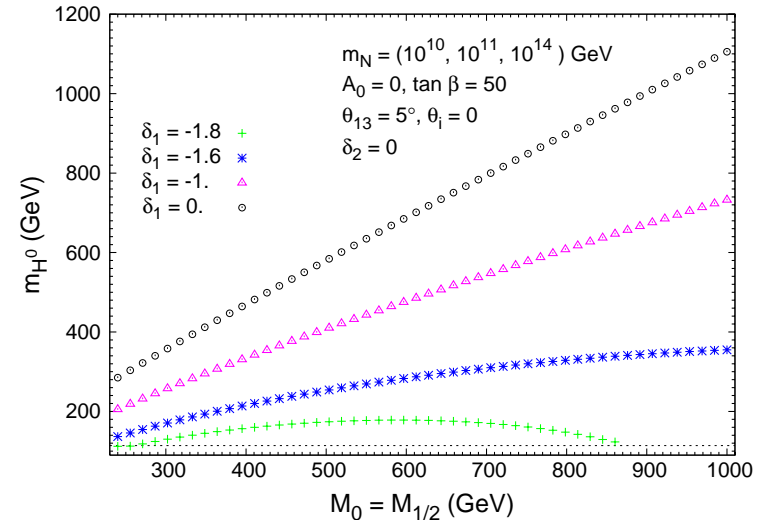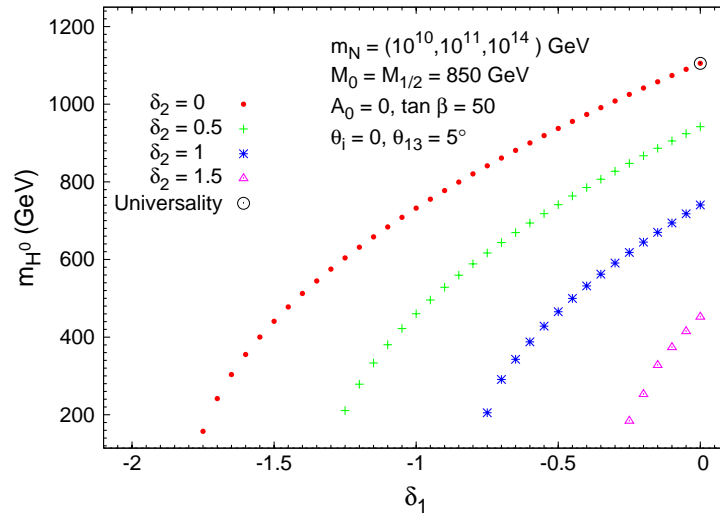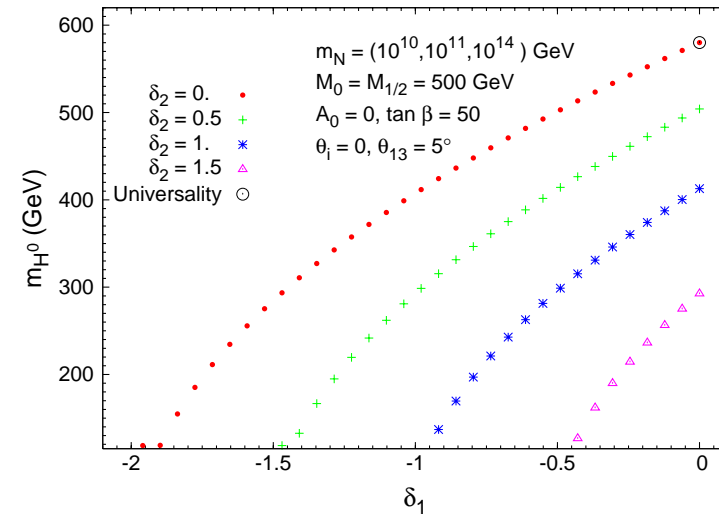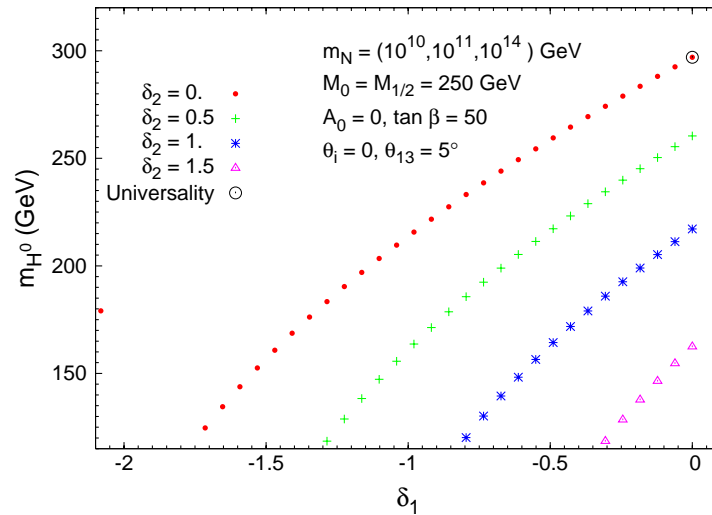
* NUHM-seesaw predicts **light Higgs particles** even for large $M_0 = M_{1/2} = M_{SUSY}$
* Ex.: for $M_{SUSY} = 850$ GeV, $\tan\beta = 50$, $A_0 = 0$, $\delta_1 = -1.8$, $\delta_2 = 0$, we find:
  light Higgs: $m_{H^0} = 127$ GeV, $m_{h^0} = 123$ GeV, $m_{A^0} = 127$ GeV, $m_{H^+} = 155$ GeV
  heavy SUSY: $m_{\tilde{l}_1} = 734$ GeV, $m_{\tilde{\nu}_1} = 971$ GeV, $m_{\tilde{\chi}_1^-} = 687$ GeV, $m_{\tilde{\chi}_1^0} = 362$ GeV

We find no sensitivity to Higgs in $\tau \to 3\mu$ either
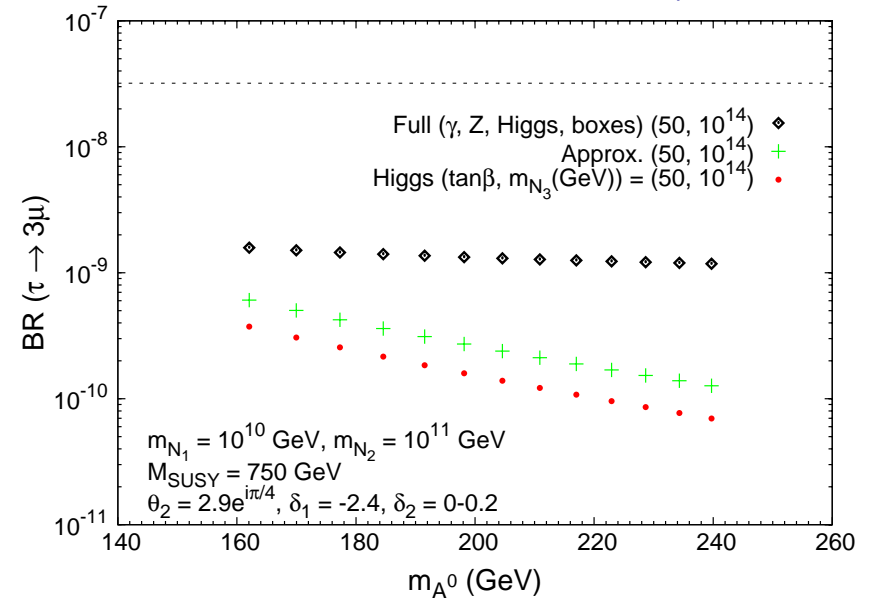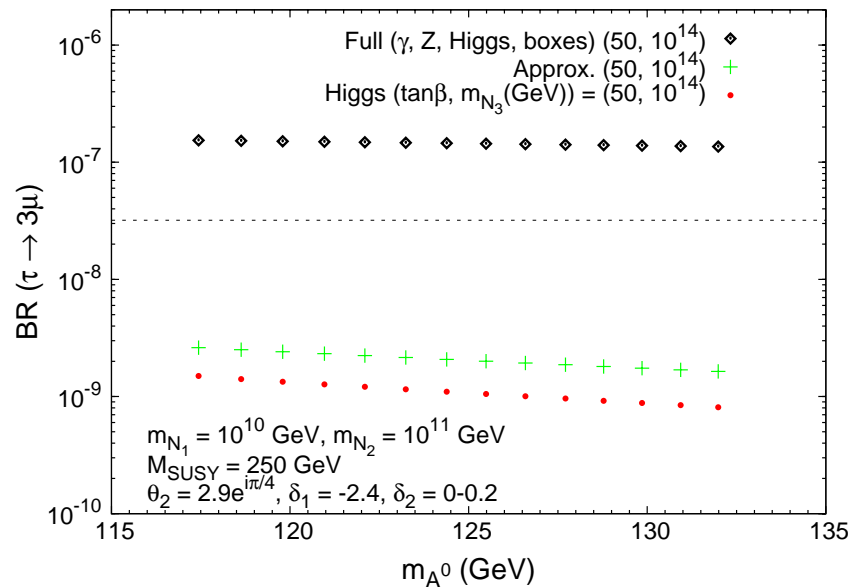
$\star$ $\tau \to 3\mu$ is highly dominated by γ diags., even at low m_{A^0} and large M_{SUSY}

Present bound on BR($\tau \to 3\mu$) disfavours $m_{N_3} \gtrsim 10^{14}$ GeV, $\tan\beta \gtrsim 50$, $M_{\text{SUSY}} \lesssim 300$ GeV
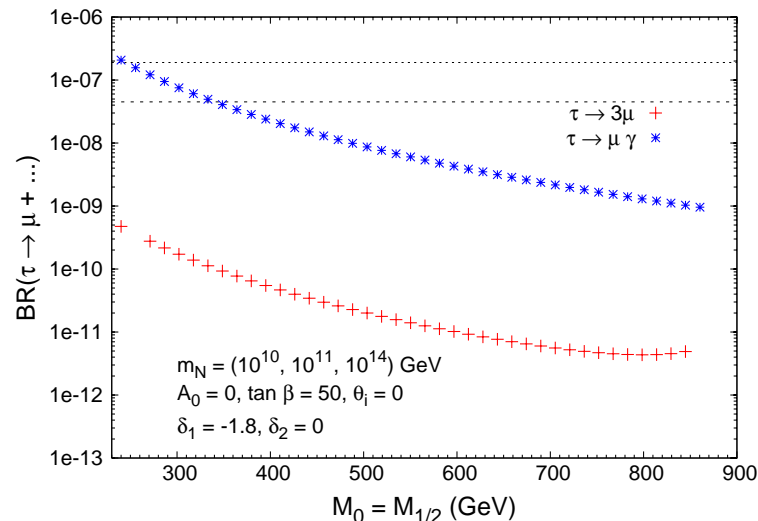
$\star$ $\tau \to \mu\gamma$ still more competitive than $\tau \to 3\mu$; BR($\tau \to 3\mu$) $\simeq 2 \times 10^{-3}$ BR($\tau \to \mu\gamma$)

Results for LFV semilep. tau decays
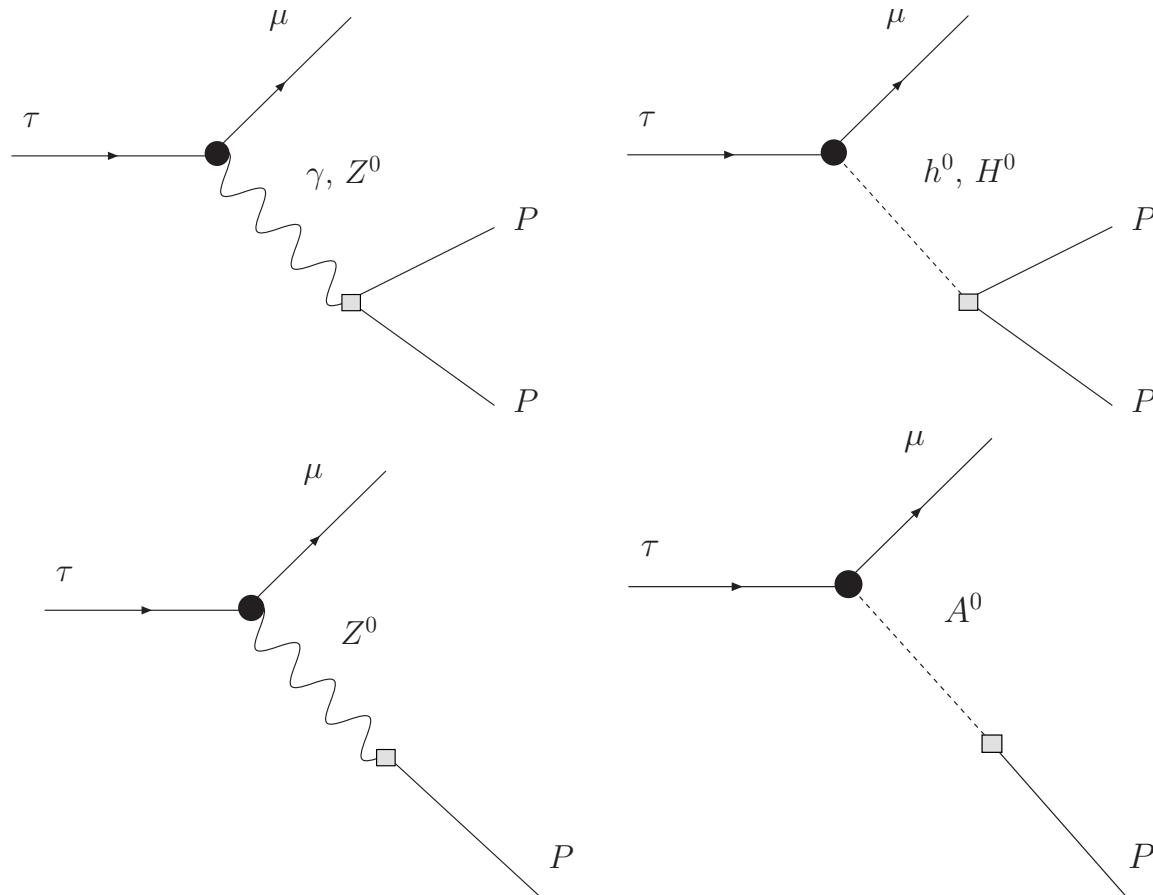
Relevant contributions to $\tau \to \mu PP$ in NUHM
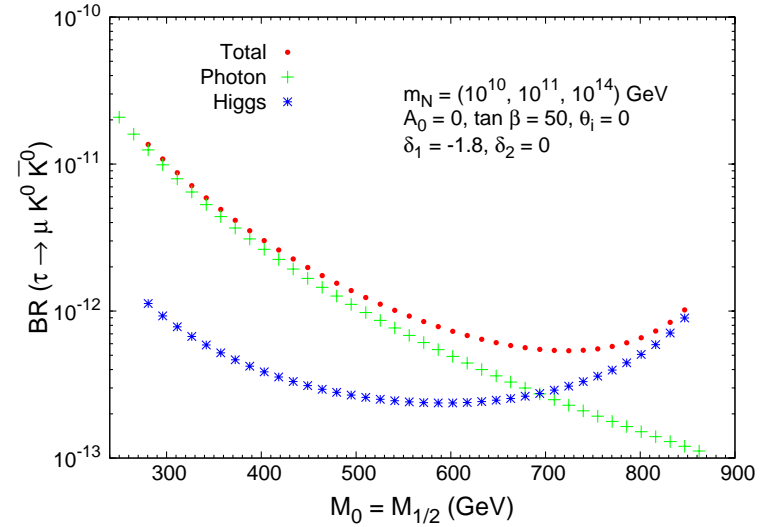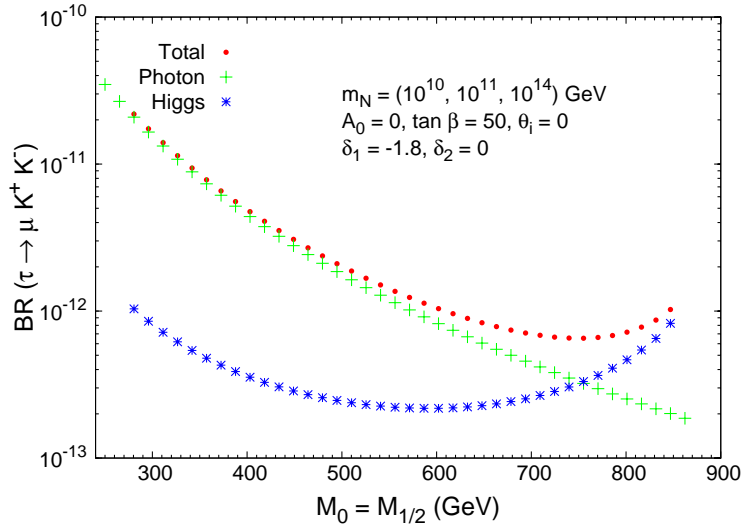
★ $\tau \to \mu K^+ K^-$, $\tau \to \mu K^0 \bar{K}^0$: HKK coup. large $\sim m_K^2$ (χPT: $B_0 m_s = m_K^2 - \frac{1}{2} m_\pi^2$)
Both KK channels γ-dominated at low M_{SUSY}, H-dominated at large M_{SUSY}
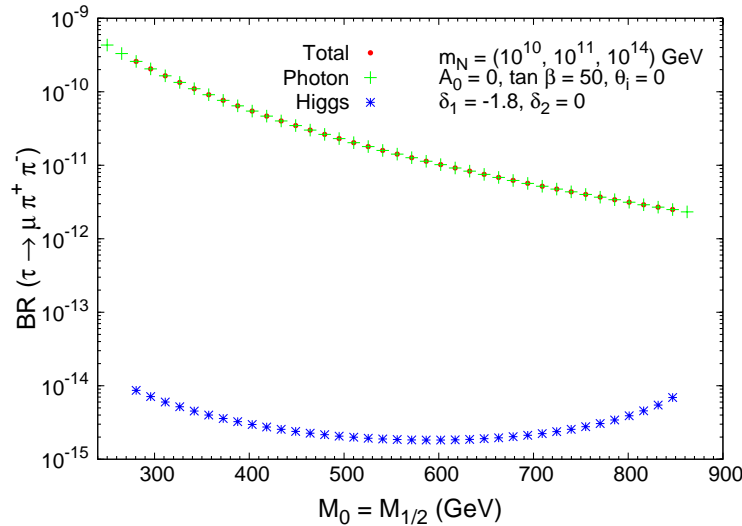
★ $\tau \to \mu \pi^+ \pi^-$: γ-dominated ; $\tau \to \mu \pi^0 \pi^0$: only H contributes.
$H\pi\pi$ coup. small $\sim m_\pi^2$ (χPT: $B_0 m_{u,d} = \frac{1}{2} m_\pi^2$)

$\tau \to \mu PP$: CMSSM versus NUHM
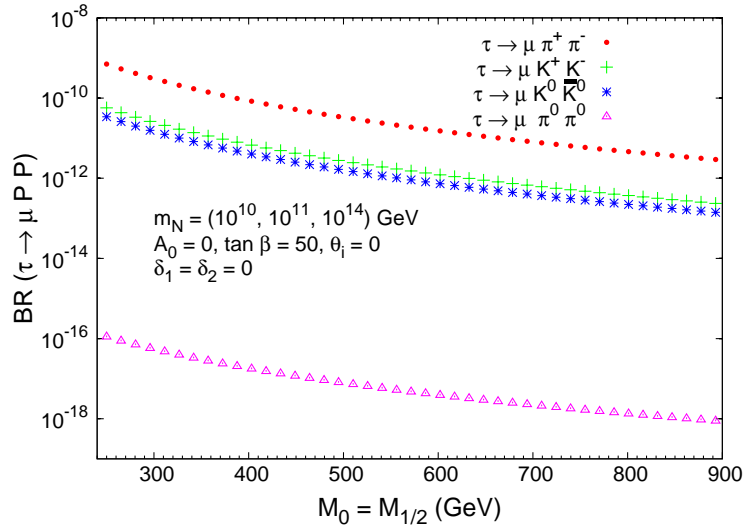
CMSSM: γ dominance at all M_{SUSY}
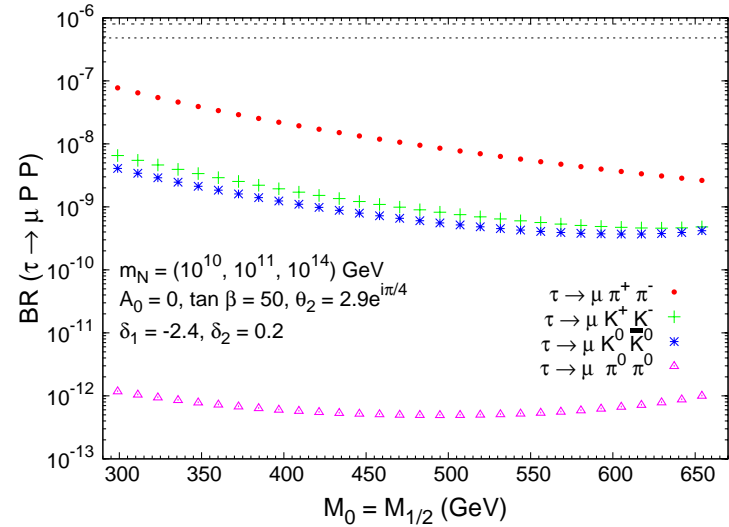
NUHM: H^0 enters at large M_{SUSY}
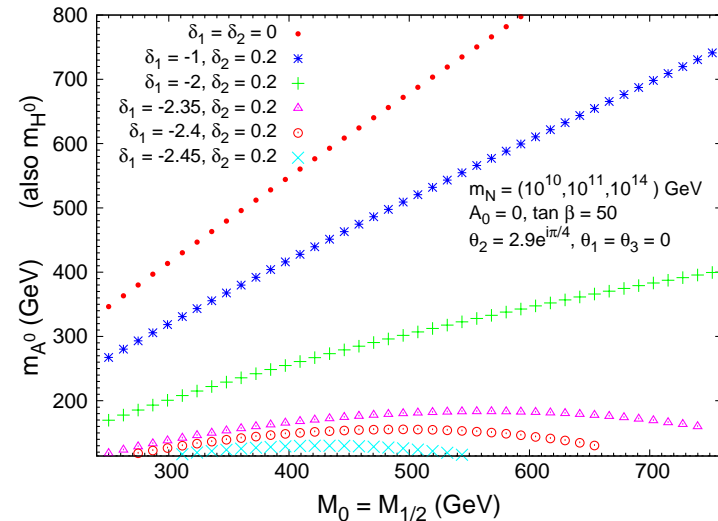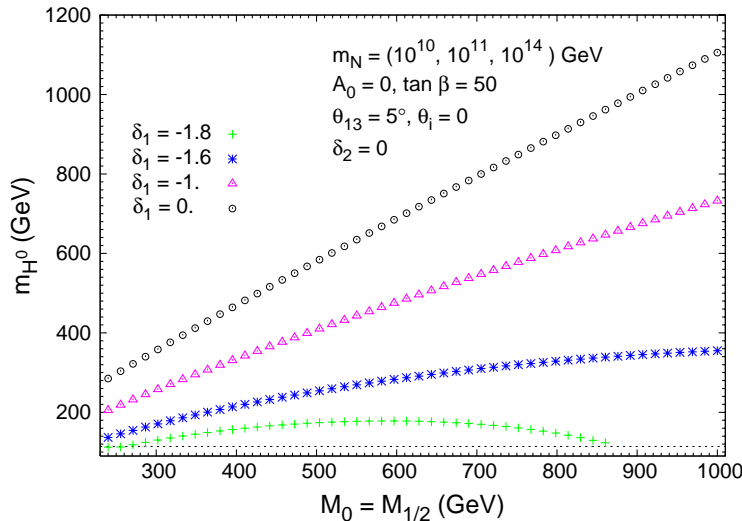
★ In scenarios with light H and heavy SUSY (NUHM) we find SUSY non-decoupling

★ $BR(\tau \to \mu\pi^+\pi^-) \sim$ exp.bound $> BR(\tau \to \mu K^+K^-) \gtrsim BR(\tau \to \mu K^0\bar{K}^0) \gg BR(\tau \to \mu\pi^0\pi^0)$
hierarchy from dominant electromag. contrib. and relative phase space suppression

$\tau \to \mu P$ $(P = \eta, \eta', \pi)$ and $\tau \to \mu V$ $(V = \rho, \phi)$
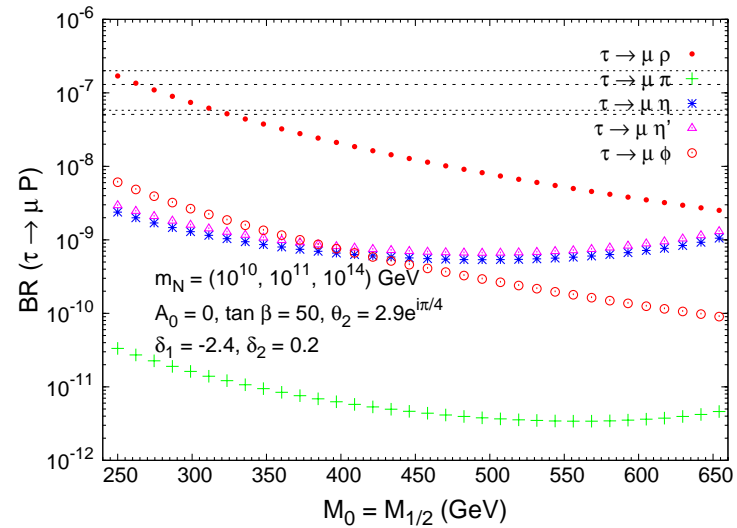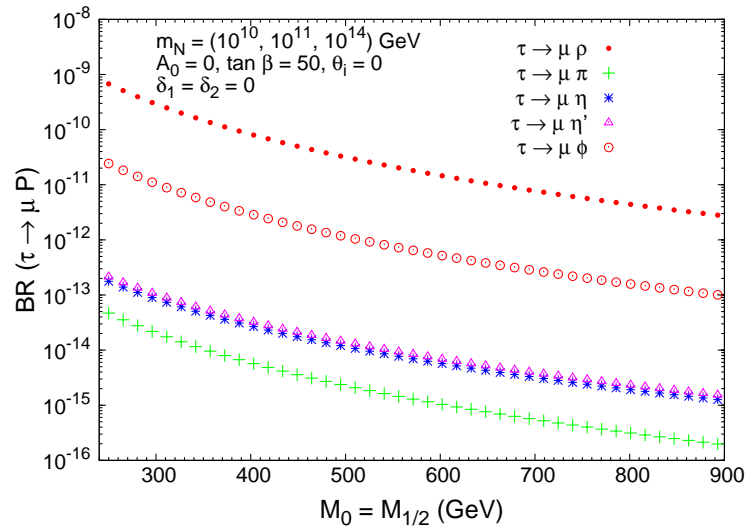
CMSSM: SUSY decoupling

NUHM: SUSY non-decoupling in $\tau \to \mu P$

★ Large BR($\tau \to \mu \rho$) ($\sim$ exp. bound). Next $\tau \to \mu \phi$. Also $\tau \to \mu \eta(\eta')$ in NUHM
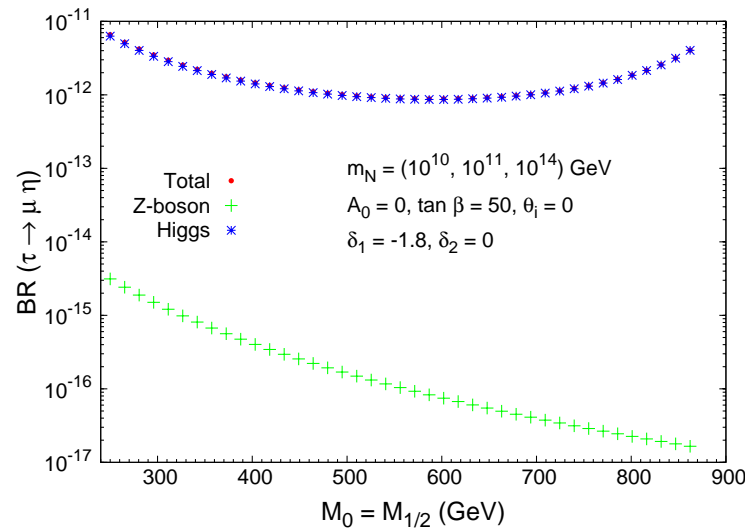
★ $\tau \to \mu \eta$ and $\tau \to \mu \eta'$ largely dominated by A^0 Higgs contribution

Approx. formulae for LFV semilep. τ decays

Valid at large $\tan\beta$ and MI: agreement with full results within a factor of 2

$$\mathrm{BR}(\tau \to \mu\eta)_{H_{\mathrm{approx}}} = 1.2 \times 10^{-7} |\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim \frac{1}{7} \times \mathrm{BR}_{\mathrm{Sher}} \ \mathrm{PRD66(2002)57301}$$

$$\mathrm{BR}(\tau \to \mu\eta')_{H_{\mathrm{approx}}} = 1.5 \times 10^{-7} |\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim 100 \times \mathrm{BR}_{\mathrm{Brignole-Rossi}} \mathrm{NPB701(04)}$$

$$\mathrm{BR}(\tau \to \mu\pi)_{H_{\mathrm{approx}}} = 3.6 \times 10^{-10} |\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim \mathrm{BR}_{\mathrm{Brignole-Rossi}}$$

$$\mathrm{BR}(\tau \to \mu\pi^0\pi^0)_{H_{\mathrm{approx}}} = 1.3 \times 10^{-10} |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6$$
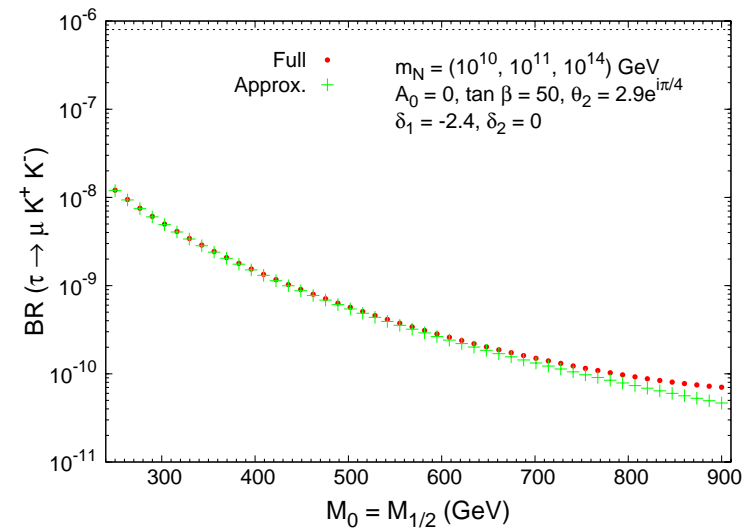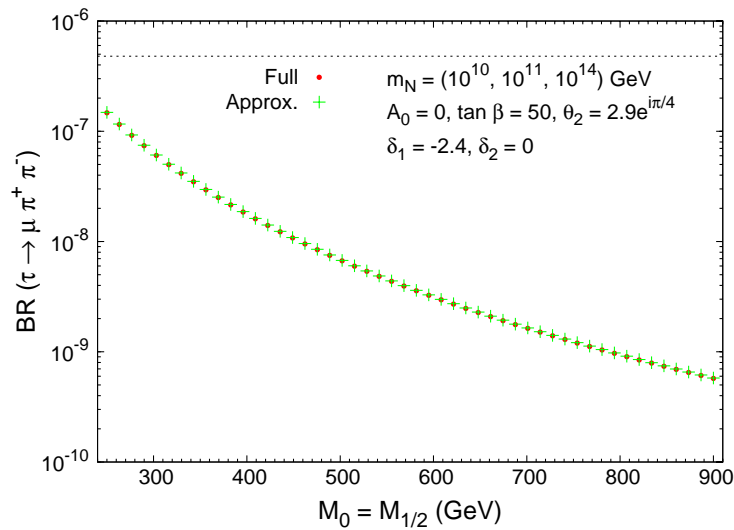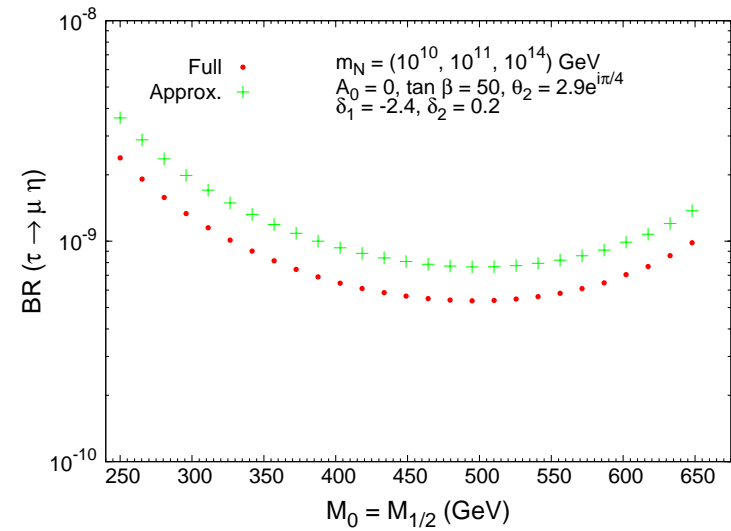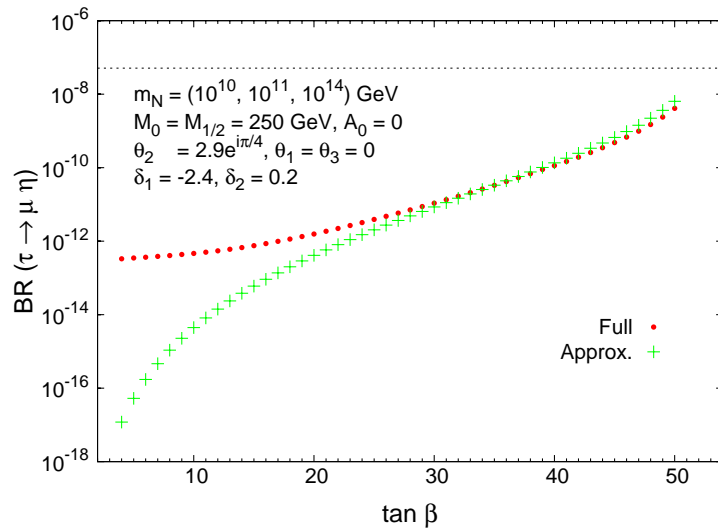
$$\mathrm{BR}(\tau \to \mu\pi^+\pi^-)_{H_{\mathrm{approx}}} = 2.6 \times 10^{-10} |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6$$

$$\mathrm{BR}(\tau \to \mu K^+ K^-)_{H_{\mathrm{approx}}} = 2.8 \times 10^{-8} |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim \frac{1}{50} \times \mathrm{BR}_{\mathrm{Chen-Geng}} \ \mathrm{PRD74(2006)}$$

$$\mathrm{BR}(\tau \to \mu K^0 \bar{K}^0)_{H_{\mathrm{approx}}} = 3.0 \times 10^{-8} |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6$$

$$\mathrm{BR}(\tau \to \mu\pi^+\pi^-)_{\gamma_{\mathrm{approx}}} = 3.7 \times 10^{-5} |\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \quad \text{dominant for all } \mathbf{M_{SUSY}}$$

$$\mathrm{BR}(\tau \to \mu K^+ K^-)_{\gamma_{\mathrm{approx}}} = 3.0 \times 10^{-6} |\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \text{dominant if } \mathbf{M_{SUSY} \leq 300 \ GeV}$$
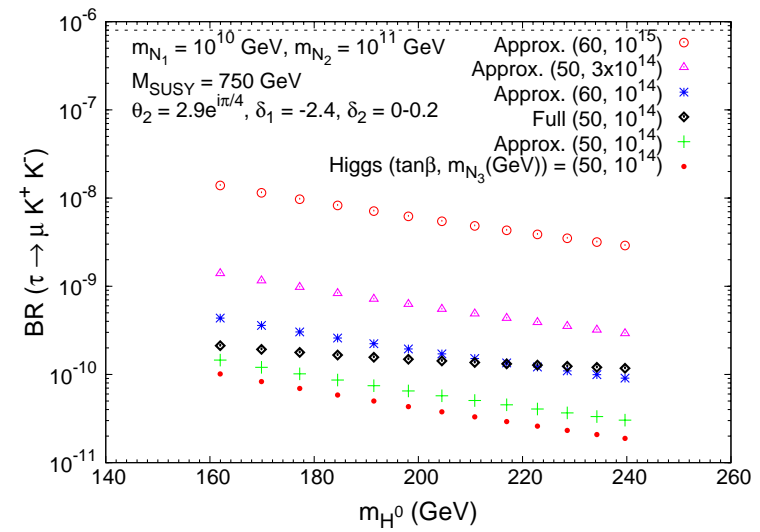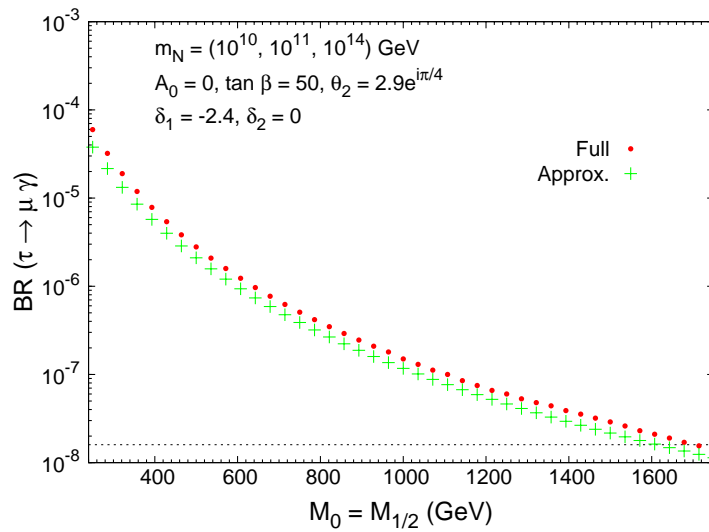
$$\mathrm{BR}(\tau \to \mu K^0 \bar{K}^0)_{\gamma_{\mathrm{approx}}} = 1.8 \times 10^{-6} |\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \text{dominant if } \mathbf{M_{SUSY} \leq 250 \ GeV}$$

$$\text{Compare to } \mathrm{BR}(\tau \to \mu\gamma)_{\mathrm{approx}} = 1.5 \times 10^{-2} |\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 > \text{semil if} M_{\mathrm{SUSY}} < 1500 \mathrm{GeV}$$
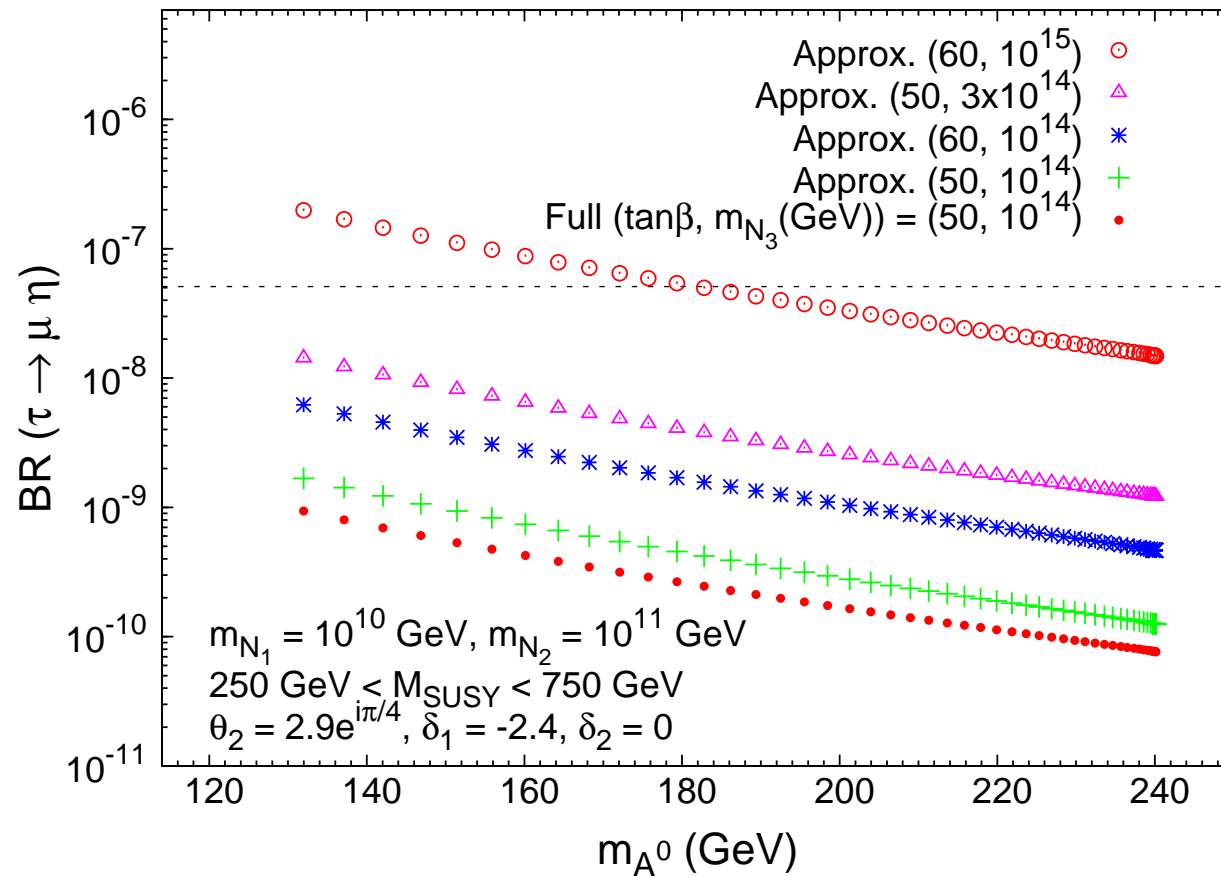
Comparison approximate/full results (I)

Comparison approximate/full results (II)

Left plot:

$m_N = (10^{10}, 10^{11}, 10^{14})$ GeV
$A_0 = 0$, $\tan\beta = 50$, $\theta_2 = 2.9e^{i\pi/4}$
$\delta_1 = -2.4$, $\delta_2 = 0$

Full
Approx.

y-axis: BR $(\tau \to \mu\,\gamma)$
x-axis: $M_0 = M_{1/2}$ (GeV)

Right plot:

$m_{N_1} = 10^{10}$ GeV, $m_{N_2} = 10^{11}$ GeV
$M_{SUSY} = 750$ GeV
$\theta_2 = 2.9e^{i\pi/4}$, $\delta_1 = -2.4$, $\delta_2 = 0\text{-}0.2$

Approx. (60, 10^{15})
Approx. (50, 3×10^{14})
Approx. (60, 10^{14})
Full (50, 10^{14})
Approx. (50, 10^{14})
Higgs ($\tan\beta$, m_{N_3}(GeV)) = (50, 10^{14})

y-axis: BR $(\tau \to \mu\,K^+K^-)$
x-axis: m_{H^0} (GeV)

Sensitivity to Higgs in LFV semilep. τ decays

★ Maximum sensitivity to Higgs sector found in $\tau \to \mu\eta$ and $\tau \to \mu\eta'$
BR($\tau \to \mu\eta$) at exp. bound for $m_{N_3} = 10^{15}$ GeV, $\tan\beta = 60$, $\theta_2 = 2.9e^{i\pi/4}$
★ Next relevant channel in sensitivity to Higgs sector is $\tau \to \mu K^+ K$
(but still below exp. bound)

Results for $\mu - e$ conversion in nuclei

$\mu - e$ conversion in nuclei: CMSSM versus NUHM

First estimates of CR$(\mu - e, \text{Nuclei})$ did not include H-contrib. (Hisano et al PRD53(1996)2442)
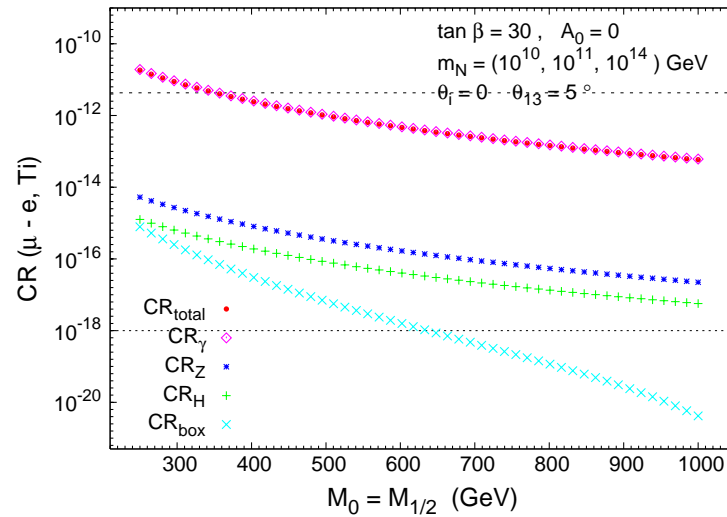
CMSSM: γ dominance for all M_{SUSY} NUHM: H^0 dominance if H^0 light
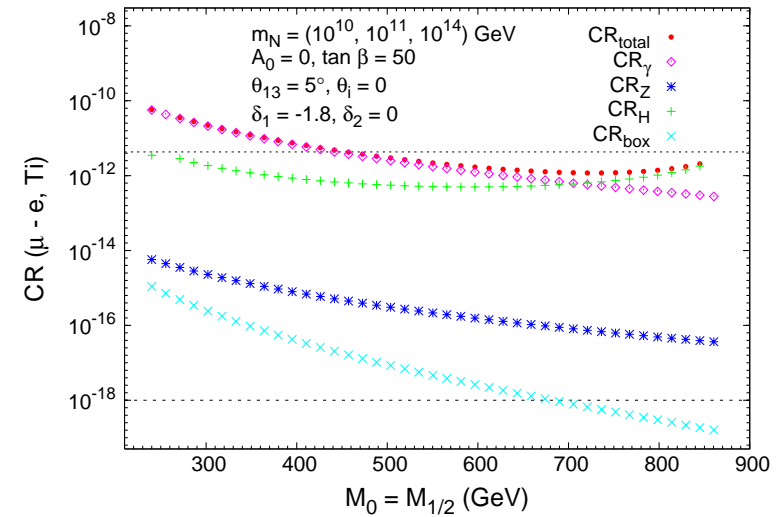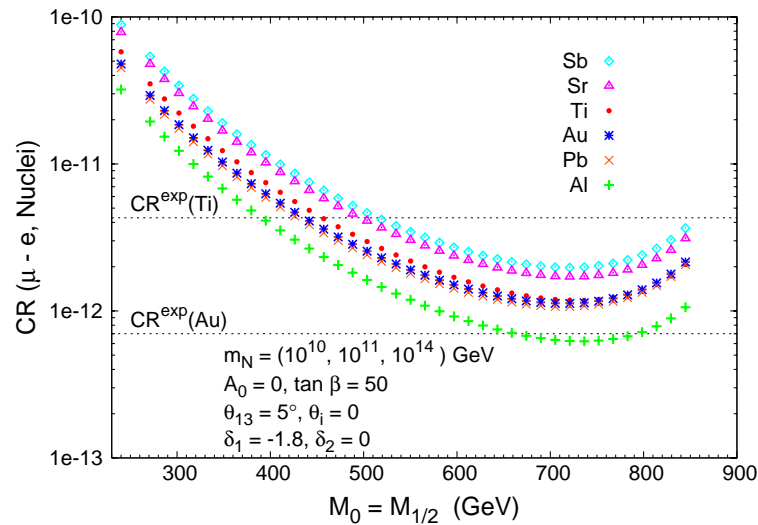
★ NUHM $\Rightarrow$ heavy SUSY spectra do not decouple in $\mu - e$ conversion due to H

CR$(\mu - e, \text{Au})$ above present experimental bound even for heavy SUSY

Sensitivity to Higgs sector in $\mu - e$ conv. in nuclei

★ NUHM: Noticeable sensitivity to the Higgs sector if H_0 is light, due to

large couplings of Higgs to strange quarks in nucleon/nuclei ($\propto m_s$)
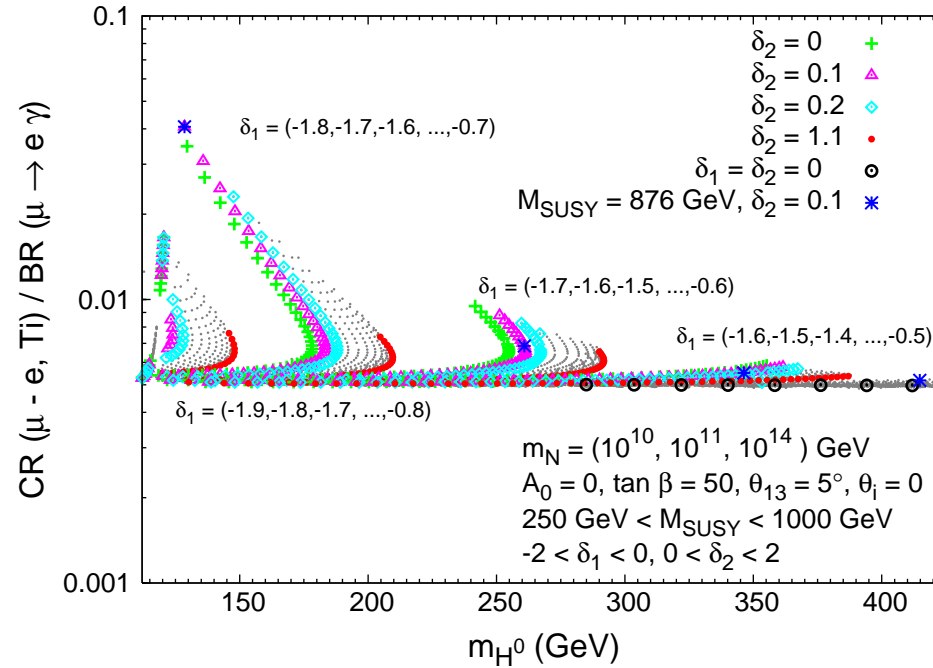
★ Ratio of $\mu - e$ to $\mu \rightarrow e\gamma$ can be a factor 10 larger in NUHM than in CMSSM

★ Found useful approximate formula, if H-dominated, valid at large $\tan\beta$ and MI approx.

$$\text{CR}(\mu - e, \text{Nucleus})|_{H\text{approx}} \; \simeq \; \frac{m_\mu^5 \, G_F^2 \, \alpha^3 \, Z_{\text{eff}}^4 \, F_p^2}{8\pi^2 \, Z} \, (Z+N)^2 \left| g_{LS}^{(0)} \right|^2 \frac{1}{\Gamma_{\text{capt}}},$$

$$g_{LS}^{(0)} \; = \; \frac{g^2}{48\pi^2} G_S^{(s,p)} \frac{m_\mu m_s}{m_{H^0}^2} \delta_{21} (\tan\beta)^3$$

Numerical estimates of $\text{CR}(\mu - e, \text{Ti})|_{H\text{approx}}$ OK with Kitano et.al. PLB575(2003)300

Future prospects for $\mu - e$ conversion in nuclei
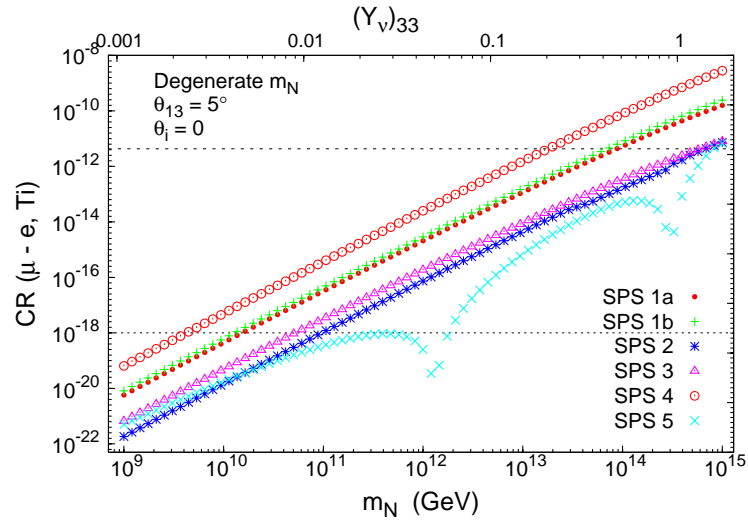
Degenerate ν_R Hierarchical ν_R
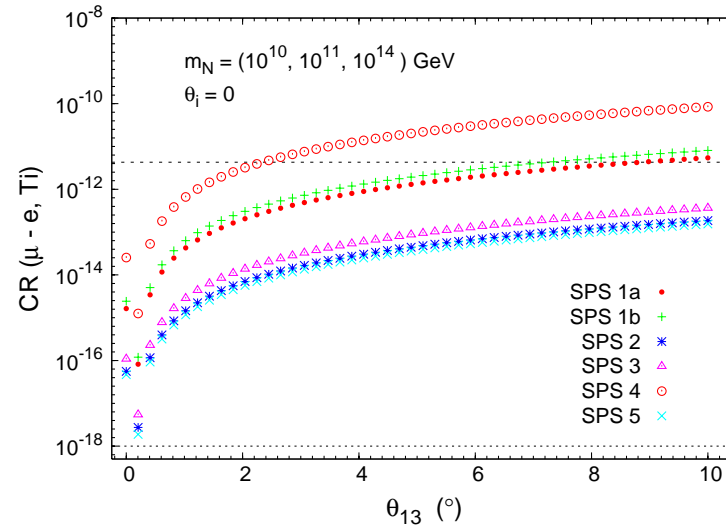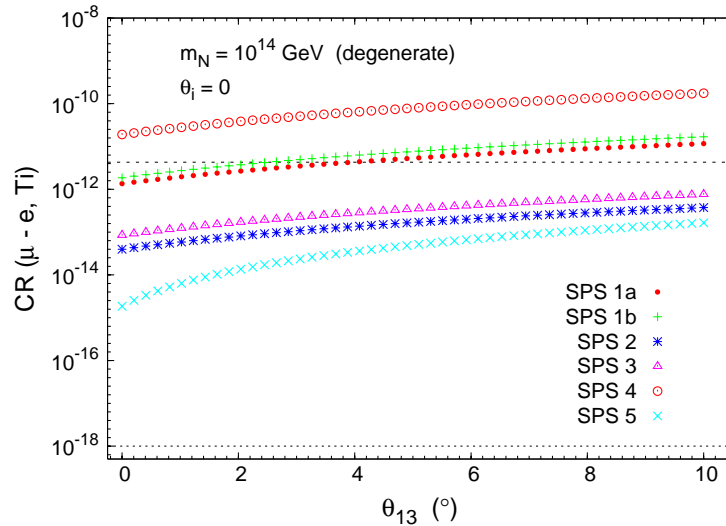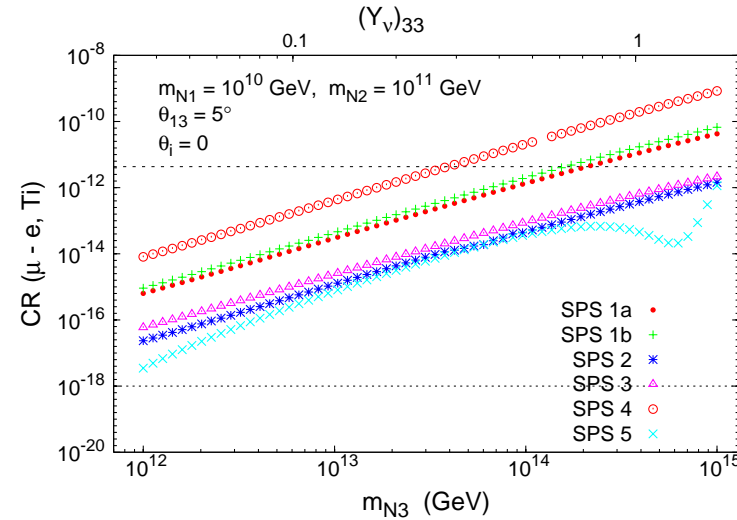
★ Challenging: if sensitivity $\sim 10^{-18}$ reached: m_N down to 10^{12} GeV will be tested

★ CR($\mu - e$) very sensitive to θ_{13}, mainly for hierarchical ν_R (as $\mu \to e\gamma$ and $\mu \to 3e$)

A future meassurement of θ_{13} can help in searches of LFV in $\mu - e$ sector

CONCLUSIONS

Semileptonic tau decays complement nicely the searches for LFV in $\tau - \mu$ sector, in addition to $\tau \to \mu\gamma$. The future prospects for $\mu - e$ conversion in Ti are the most challenging for LFV. Both processes allow to test the Higgs sector (better than $\tau \to 3\mu$), besides the **SUSY** and seesaw sectors.

Additional transparencies

Predictions for other SPS points
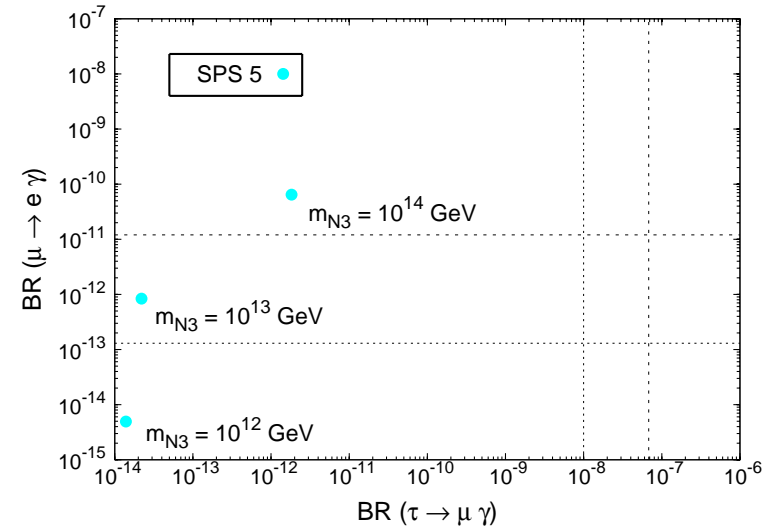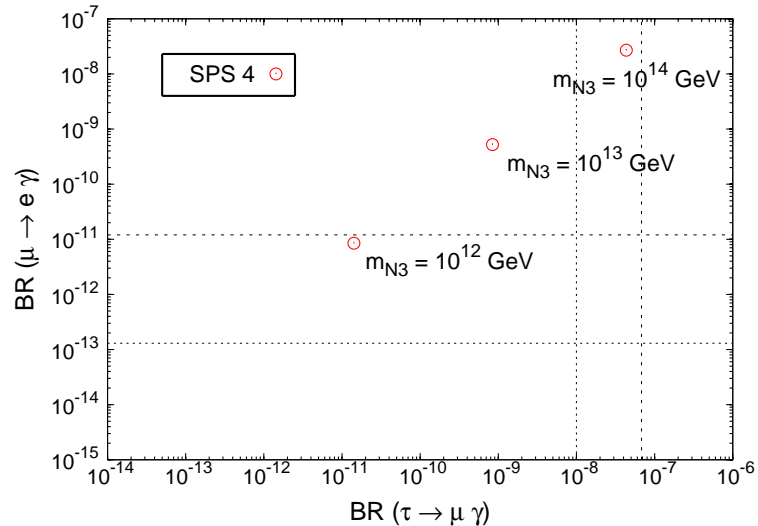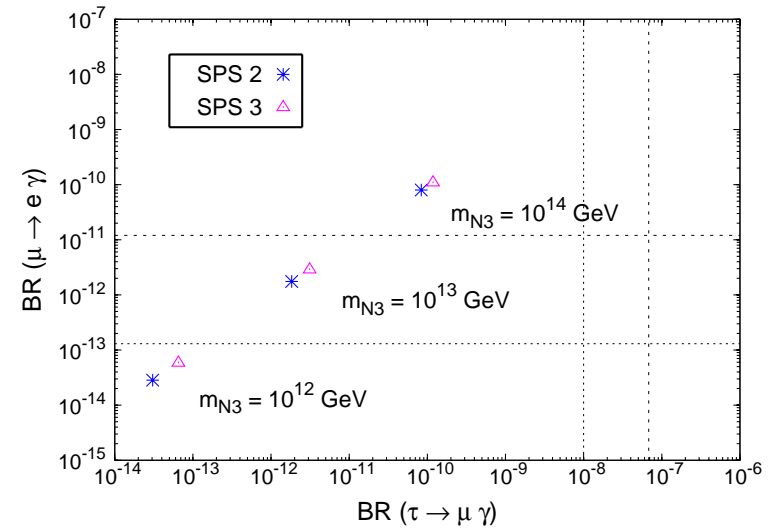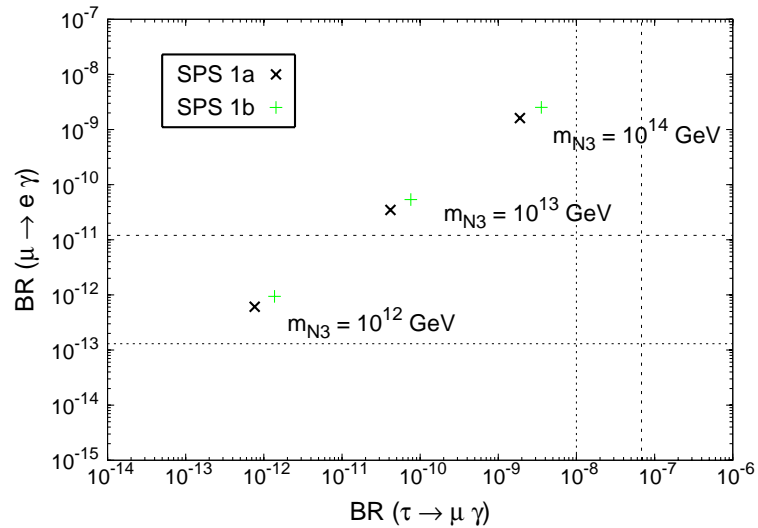
Similar for SPS1a,1b. Slightly worse prospects for SPS2,3. SPS5 the worst.

SPS4 the most restrictive one (due to $\tan\beta = 50$):

Present bounds from $\mu \to e\gamma$ and $\tau \to \mu\gamma$ already exclude $m_{N_3} \gtrsim 10^{14}$ GeV!!

Comparing predictions for various LFV decays

Hierarchical m_{N_i} and complex θ_i

$(m_{N_1}, m_{N_2}, m_{N_3}) = (10^8, 2 \times 10^8, 10^{14})$ GeV, $\arg(\theta_1) = 0, \pi/10, \pi/8, \pi/6, \pi/4$ $(\theta_2 = \theta_3 = 0)$

SPS 4
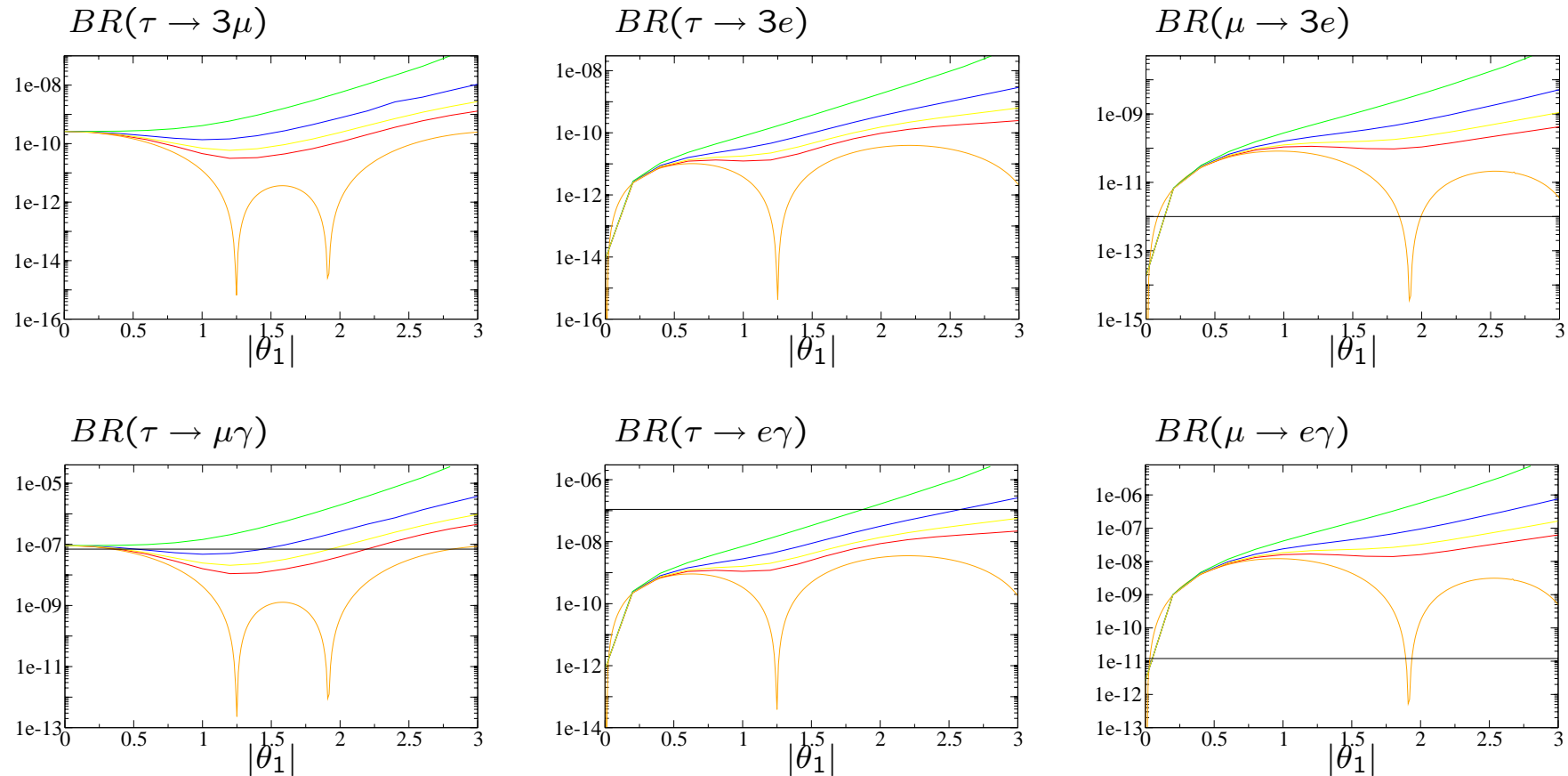
- ★ BRs for $0 < |\theta_i| < \pi$, $0 < \arg\theta_i < \pi/2$ can increase up to $10^2 - 10^4$ respect to $\theta_i = 0$

- ★ **BRs above present experimental bounds**: mainly $\mu \to e\gamma$, $\mu \to 3e$ and $\tau \to \mu\gamma$

- ★ Similar results for θ_2. BRs nearly constant with θ_3 in the case of hier. N's

# Constraints from 'viable' BAU

BAU requires complex $R \neq 1 \Rightarrow$ complex $\theta_i \neq 0$. Most relevantly θ_2

$n_B/n_\gamma \in$ interval $\Rightarrow (\text{Re}(\theta_2), \text{Im}(\theta_2)) \in$ area ('ring') (WMAP in darkest ring)
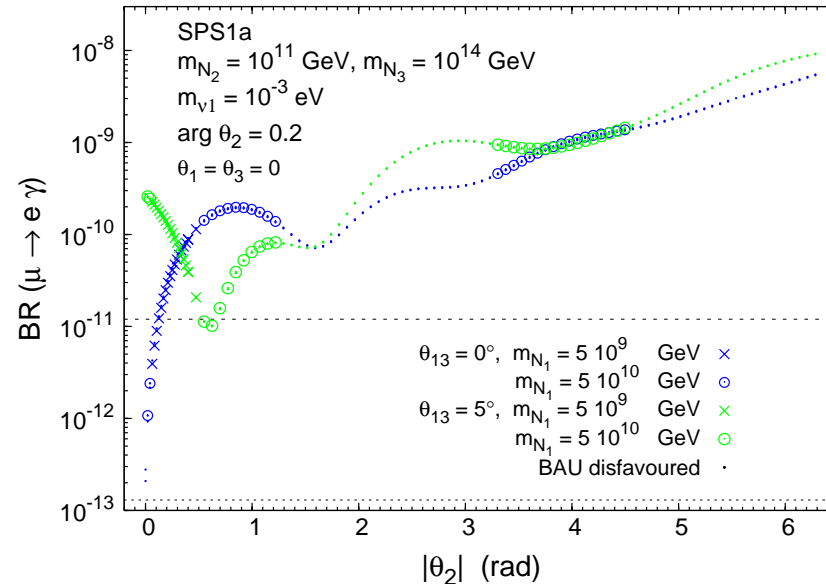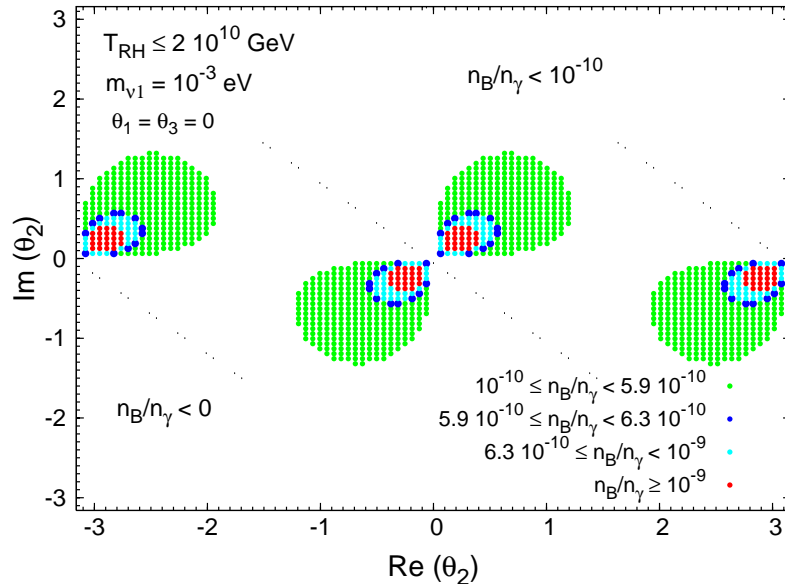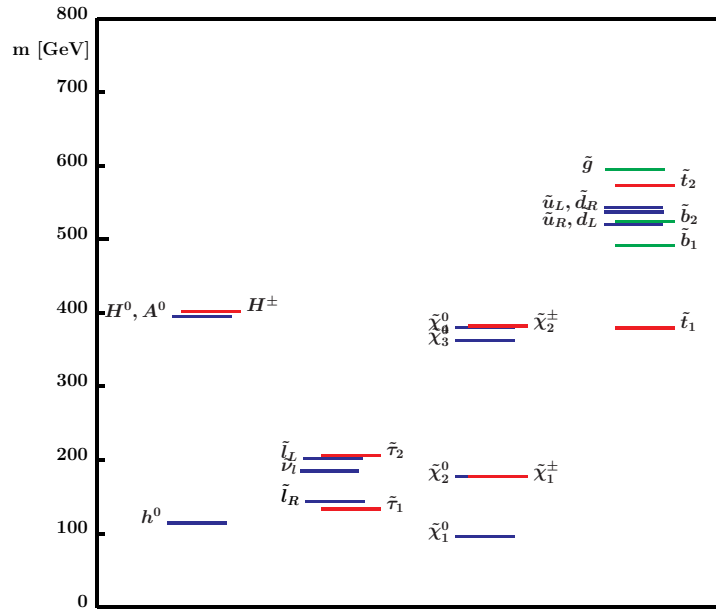

Implications for LFV

$\star$ **'viable' BAU** $\leftrightarrow n_b/n_\gamma \in [10^{-10}, 10^{-9}]$ (WMAP $\sim 6.1 \times 10^{-10}$,'06)

BAU [disfav]-[fav]-[disfav]-[fav]-[disfav] pattern in $0 < |\theta_2| < 3$

The BAU [fav] windows occur at small $(\neq 0)$ $|\theta_2| \lesssim 1.5$

$\star$ **smaller $|\theta_2| \Rightarrow$ smaller LFV rates**

$\star$ The existence, location and size of the windows depend on m_{N_1}

$m_{N_1} \sim O(10^{10})$ GeV BAU [fav] windows at $|\theta_2| \sim O(1)$ and $|\theta_2| \sim O(10^{-2})$

$m_{N_1} \sim O(10^9)$ GeV only one window at $|\theta_2| \sim O(5 \times 10^{-1})$

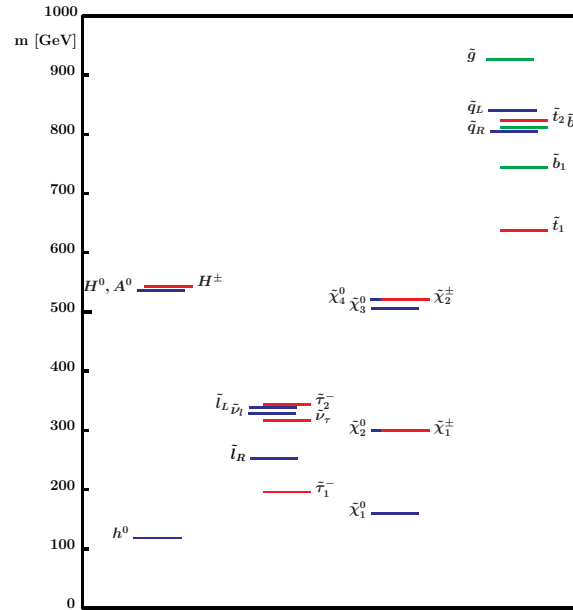# Contributions to $\Delta a_\mu^{\text{SUSY}}$
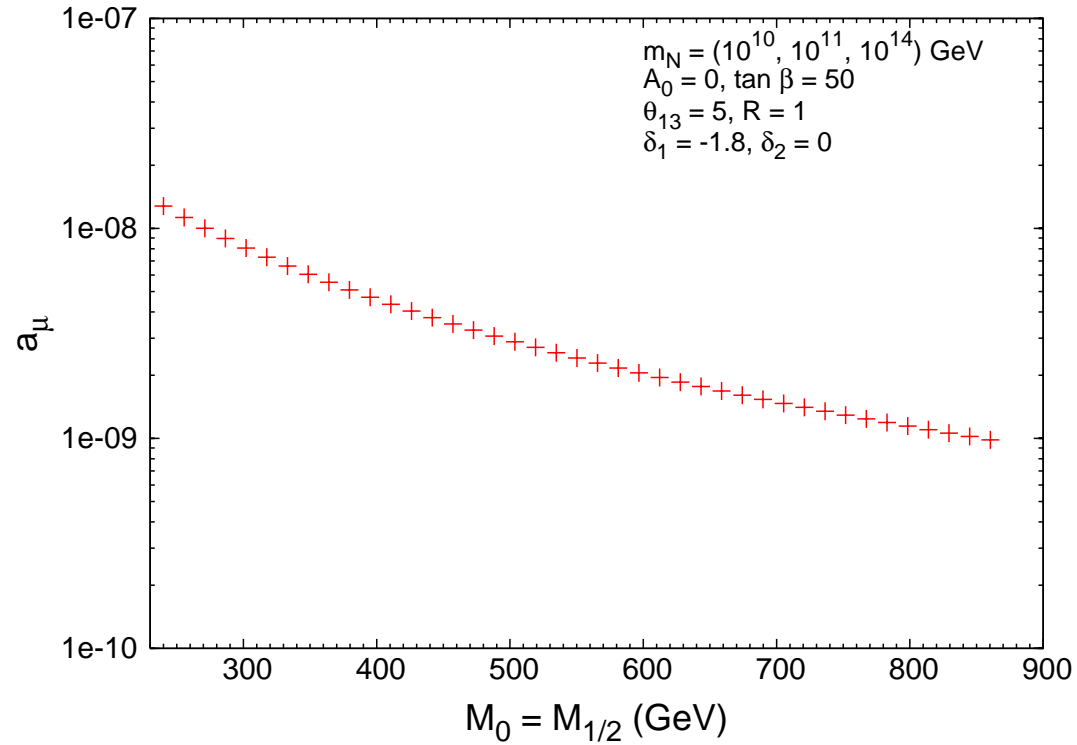
$$\Delta a_\mu^{\text{SUSY}} \in \left[10^{-8}, 10^{-9}\right]: \text{ compatible with } a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = 3.32 \times 10^{-9} \ (3.8\sigma)$$

SUSY SPS points (I)

SPS1a

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

$M_{1/2} = 250\,\text{GeV}$

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

$\tan\beta = 10$

$\mu > 0$

SPS1b

$M_0 = 200\,\text{GeV}$

$M_{1/2} = 400\,\text{GeV}$

$A_0 = 0\,\text{GeV}$

$\tan\beta = 30$

$\mu > 0$
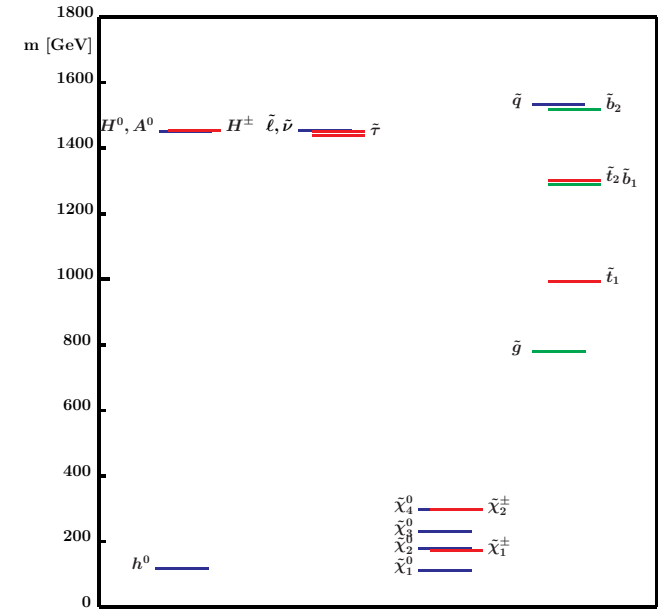
SPS2

$M_0 = 1450\,\text{GeV}$

$M_{1/2} = 300\,\text{GeV}$

$A_0 = 0\,\text{GeV}$

$\tan\beta = 10$

$\mu > 0$

SUSY SPS points (II)
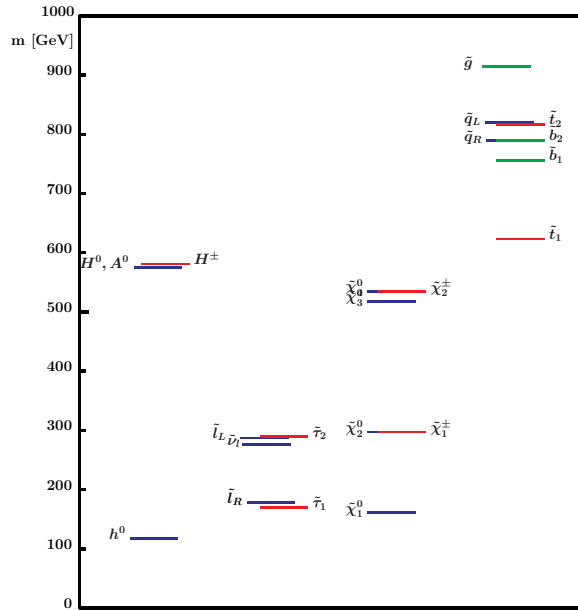
SPS3

$M_0 = 90\,\text{GeV}$

$M_{1/2} = 300\,\text{GeV}$

$A_0 = 0\,\text{GeV}$

$\tan\beta = 10$

$\mu > 0$
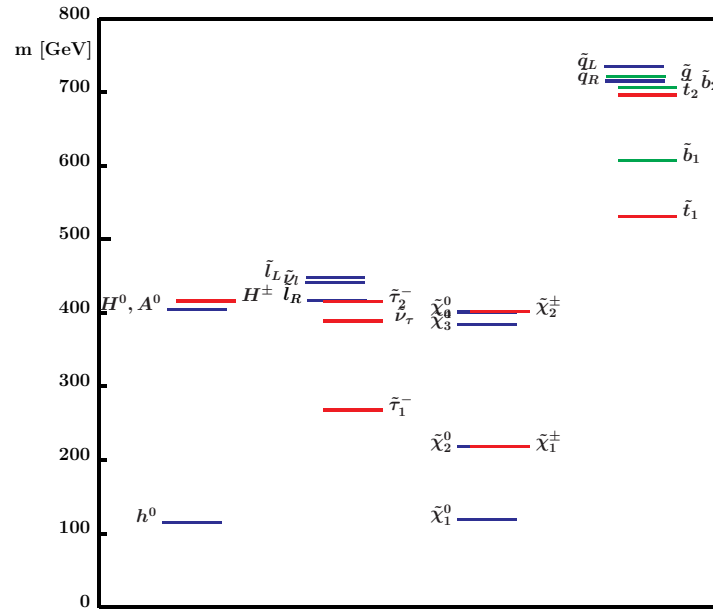
SPS4

$M_0 = 400\,\text{GeV}$

$M_{1/2} = 300\,\text{GeV}$

$A_0 = 0\,\text{GeV}$

$\tan\beta = 50$

$\mu > 0$
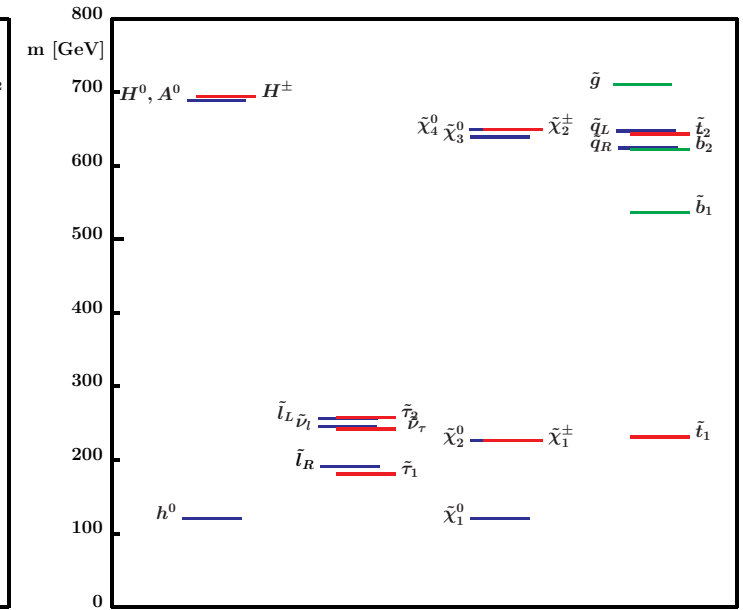
SPS5

$M_0 = 150\,\text{GeV}$

$M_{1/2} = 300\,\text{GeV}$

$A_0 = -1000\,\text{GeV}$

$\tan\beta = 5$

$\mu > 0$