Lepton Flavor Violation

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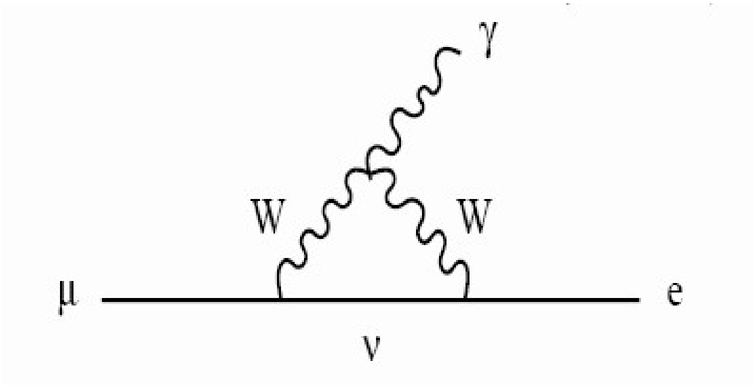
Why Lepton Flavour Violation (LFV) ?

⋆ LFV occurs in Nature: LFV observed in neutral sector
$\nu_i - \nu_j$ oscillations DO NOT conserve Lepton Flavour Number
Does LFV happen in the charged sector?: Not seen yet

⋆ Challenging exp. bounds in the charged sector : present/future (see next)
MEGA, SINDRUM, BaBar, Belle /MEG, SuperB, PRISM/PRIME

⋆ In SM: no LFV if $m_\nu = 0$; extremely small if $m_\nu \neq 0$. For example:



$$\mathrm{BR}(\mu \to e\gamma) \sim \frac{3\alpha}{32\pi} \sum_i U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{m^2_W} \leq 10^{-54}$$

Highly suppressed by small neutrino masses

Any observation of LFV points to New Physics Beyond SM

Where to look for LFV ?

- Decays of standard leptons: (the most studied ones)
  τ: BaBar, Belle, SuperB, μ: MEGA/MEG, SINDRUM
  $\star$ Radiative LFV decays: $l_j \to l_i \gamma$ $(i \neq j)$ $l_{3,2,1} = \tau, \mu, e$
  $\star$ Leptonic LFV decays: $l_j \to l_i l_k l_k$ ($\tau \to 3\mu$ maybe also at LHC)
  $\star$ Semileptonic LFV tau decays
  $\tau \to \mu\eta$, $\tau \to \mu f_0$, $\tau \to \mu V$ $(V = \rho, \phi, \omega, K^*)$
  $\tau \to \mu PP$ $(PP = \pi\pi, KK, \pi K)$
- Other decays considered in the literature:
  $D_0 \to l_j l_i$, $Z \to l_j l_i$, $H \to l_j l_i$, $B \to \mu e$, $K \to \mu\nu$ / $K \to e\nu$, ...
- $\mu - e$ conversion in heavy nuclei $\mu^- N \to e^- N$: SINDRUM-II
  Coherent process (enhanced by $\sim Z^5$ $Z =$ protons in N)
  Clear signal: single mono-energetic e
- New LFV process propossed in a muonic atom (Kolke et al PRL 2010):
  $\mu^- e^- N \to e^- e^- N$, is a 2-body decay, larger PS than $\mu^+ \to e^+ e^+ e^-$
  overwrap between μ^- and e^- enhanced by $\sim Z^3$ over muonium.
- Decays of non standard particles: SUSY etc
  One example: LFV stau decays $\tilde{\tau} \to \mu\chi$ could be seen at LHC.

Experimental Status on LFV

(I thank Simon Eidelman for help in the update)

Present experimental bounds and future sensitivity to LFV decays:

I) radiative $l_i \to l_j \gamma$ and leptonic $l_i \to l_j l l$

LFV decay	Current best UL ($90\% CL$)	Future sensitivity (?)
BR($\mu \to e\gamma$)	1.2×10^{-11} (MEGA 1999)	
	2.8×10^{-11} (MEG 2010)	$10^{-13} - 10^{-14}$ MEG
BR($\tau \to e\gamma$)	3.3×10^{-8} (BaBar 2010)	3×10^{-9} SuperB
BR($\tau \to \mu\gamma$)	4.4×10^{-8} (BaBar 2010)	2.4×10^{-9} SuperB
BR($\mu \to e\,e\,e$)	1×10^{-12} (SINDRUM 1988)	$10^{-13} - 10^{-14}$ MEG
BR($\tau \to e\,e\,e$)	2.7×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
BR($\tau \to \mu\,\mu\,\mu$)	2.1×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
BR($\tau \to e\,\mu\,\mu$)	2.7×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
BR($\tau \to \mu\,e\,e$)	1.8×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB

(?) = Future sensitivities are under discussion

SuperB potential for LFV also to be discussed here, at Bensaque....

II) Semileptonic tau decays

competitive with leptonic modes

LFV decay	Current best UL $(90\% CL)$	Future sensitivity (?)
$BR(\tau \to \mu\eta)$	5.1×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu f_0)$	3.4×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu\pi)$	5.8×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu\rho)$	1.2×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu\phi)$	8.4×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu\omega)$	4.7×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu K^{*0})$	7.2×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu \bar{K}^{*0})$	7.0×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu\pi^+\pi^-)$	3.3×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu K^+ K^-)$	6.8×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu\pi^+ K^-)$	16×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB
$BR(\tau \to \mu K^+ \pi^-)$	10×10^{-8} (Belle 2010)	$10^{-9} - 10^{-10}$ SuperB

Similar bounds for $\tau \to e$ semileptonic modes

(?) = Future sensitivities are under discussion

III) $\mu - e$ conv. in nuclei

(From PDG2010 and Kuno's talk at NOW2010 conf.)

LFV process	Current best UL (90%CL)	Fut. sensitivity (?)
CR($\mu - e$, Au)	7.0×10^{-13} (SINDRUM2 2004)	10^{-16} Mu2E
CR($\mu - e$, Al)		10^{-16} COMET
CR($\mu - e$, Ti)	4.3×10^{-12} (SINDRUM2 2004)	10^{-18} PRISM

SINDRUM2 (PSI), Mu2E (Fermilab), COMET (COherent Muon to Electron Transition) (JPARC), PRISM/PRIME (JPARC)

(?) = Future sensitivities are under discussion

LFV Beyond SM

- Many models BSM produce sizeable LFV rates
  - ⋆ SM + heavy (but not too heavy) neutrinos $m_N \sim \mathcal{O}(TeV)$
  - ⋆ SUSY + SeesawI with heavy neutrinos $m_N \sim 10^{13-15} GeV$
  - ⋆ SUSY + SeesawII with heavy scalar Triplets $m_T \sim 10^{13-15} GeV$
  - ⋆ SUSY + RPV
  - ⋆ Models with extended Higgs sector:

  Little Higgs Models, Additional doblets, triplets etc.
  - ⋆ Models with extra generations
  - ⋆ Models with extra dimensions, etc....

- Most models produce too much LFV

  $\longrightarrow$ Flavour problem of BSM

  $\longrightarrow$ Usually some extra condition is required to reduce Flavour mixing. For instance in SUSY: some universality conditions on soft SUSY breaking mass parameters at the GUT scale

  $\longrightarrow$ Models with Minimal Lepton Flavour Violation (MLFV)

- SUSY usually preferred due to the Hierachy Problem of BSM

General Theoret. Description of LFV

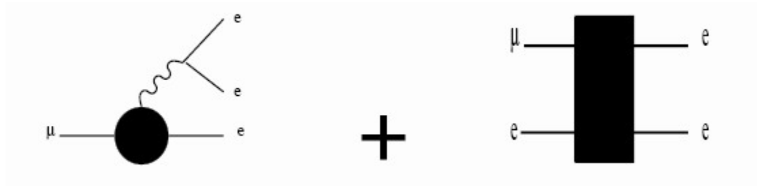
(see, for example, review by Kuno and Okada 2001)

General Lagrangian for $\mu - e$ transitions (similar for $\tau - \mu$, $\tau - e$):

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}}(m_\mu A_R \bar{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L \bar{\mu}\sigma^{\mu\nu}P_R e F_{\mu\nu})$$

$$-\frac{4G_F}{\sqrt{2}}\sum_f (g_{L,\alpha,f}\bar{e}\mathcal{O}^\alpha P_L \mu + g_{R,\alpha,f}\bar{e}\mathcal{O}^\alpha P_R \mu)(\bar{f}\mathcal{O}_\alpha f) + h.c$$

dipole (photonic diag) + contact int.



where $\alpha = S, P, V, A, T$ and $f = l_i, q_i$

the values of the form factors A_L, A_R, and $g_{L/R,\alpha,f}$ depend on model

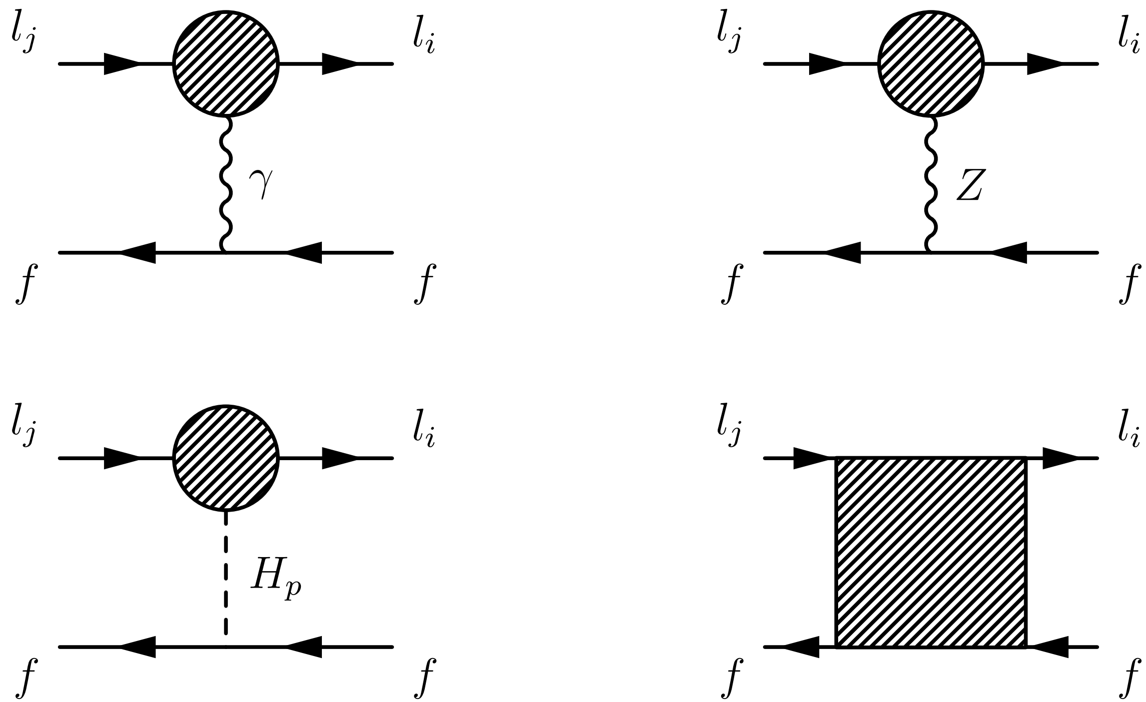
If photonic diagram dominates $\longrightarrow$ correlations among LFV processes
ex.: BR$(\mu \to eee) \sim \alpha \times$ BR$(\mu \to e\gamma)$; CR$(\mu - e, N) \sim \alpha \times$ BR$(\mu \to e\gamma)$

$(l_j \to l_i\gamma)$ explore less types of new physics than $(l_j \to l_i l_k l_k)$, $(\mu - e, N)$, LFV τ decays (lep and semilep)

$\longrightarrow$ ex.: $(l_j \to l_i\gamma)$ not sensitive to NP in Higgs neutral sector

Generic diagrams in LFV

Applies to : $l_j \to l_i l_k l_k$, $\tau \to \mu P$ $\tau \to \mu PP$, $\tau \to \mu V$, $\mu - e$ conv. in nucl.



New Physics can enter in: 1) shaded areas (via loops),
2) different mediators, ex.: Z' (Bernabeu 1993), Higgs bosons..(tree)

Ex.: If Higgs-mediated diag. dominates over the photon-mediated one, the correlations with $l_j \to l_i\gamma$ are lost: this is a clear signal of New Physics. Different models give different ratios:
BR($l_j \to l_i l_k l_k$)/BR($l_j \to l_i\gamma$), CR($\mu - e, N$)/BR($\mu \to e\gamma$), etc.

Ratios of LFV rates in different BSM scenarios

Different LFV models predict different ratios

(Ex.: table from Buras et al. 2010)

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{BR(\mu^-\to e^-e^+e^-)}{BR(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 6\cdot10^{-3}$	$\sim 6\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{BR(\tau^-\to e^-e^+e^-)}{BR(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{BR(\tau^-\to \mu^-\mu^+\mu^-)}{BR(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots0.1$	$0.06\ldots2.2$
$\frac{BR(\tau^-\to e^-\mu^+\mu^-)}{BR(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.02\ldots0.04$	$0.03\ldots1.3$
$\frac{BR(\tau^-\to \mu^-e^+e^-)}{BR(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{BR(\tau^-\to e^-e^+e^-)}{BR(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots2$	~ 5	$0.3\ldots0.5$	$1.5\ldots2.3$
$\frac{BR(\tau^-\to \mu^-\mu^+\mu^-)}{BR(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots1.6$	~ 0.2	$5\ldots10$	$1.4\ldots1.7$
$\frac{CR(\mu\mathrm{Ti}\to e\mathrm{Ti})}{BR(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$0.08\ldots0.15$	$10^{-12}\ldots26$

LHT= Littlest Higgs model with T-parity (Blanke(2009),delAguila(2009)) Z-dominance

MSSM (dipole)= MSSM without Higgs (Ellis(2002),Brignole(2004)) γ-dominance

MSSM (Higgs)= MSSM with Higgs (Paradisi(2006)) γ, H competition

SM4= SM + 4th generation (Buras(2010))

In models with γ-dominance, ratios fixed to:

$\frac{BR(l_j\to 3l_i)}{BR(l_j\to l_i\gamma)} = \frac{\alpha}{3\pi}(\log\frac{m_{l_j}^2}{m_{l_i}^2} - \frac{11}{4}) = 6.10^{-3}, 1.10^{-2}, 2.10^{-3}$ for $(l_j l_i) = (\mu e), (\tau e), (\tau\mu)$.

The most popular scenario for LFV:

SUSY + Seesaw with heavy ν_R

How to generate LFV via SUSY loops

(A. Masiero and F. Borzumati 1986)

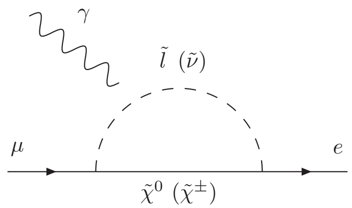
- 1.- Need flavour off-diagonal slepton mass entries

Y_ν generate at one-loop (for instance via **RGE-running**)
flavour off diagonal $M_{\tilde{l}}^{ij}$ and $M_{\tilde{\nu}}^{ij}$ $(i \neq j)$

- 2.- Flavour changing slepton propagators into loops then generate LFV

Example: $\mu \longrightarrow e\gamma$

$M_{\tilde{l}}^2 = \begin{pmatrix} M_{LL}^{ij\,2} & M_{LR}^{ij\,2} & M_{RR}^{ij\,2} \end{pmatrix} \Rightarrow$



BR simple in LLog and MIA

$$
\begin{aligned}
M_{LL}^{ij2} &= = -\frac{1}{8\pi^2}(3M_0^2 + A_0^2)\,;\,(i \neq j)(Y_\nu^+ L Y_\nu)_{ij} \\
M_{LR}^{ij2} &= -\frac{3}{16\pi^2} A_0 \frac{v_1}{\sqrt{2}} Y_{l_i}(Y_\nu^+ L Y_\nu)_{ij} \\
M_{RR}^{ij2} &= 0\,;\, L_{ii} \equiv \log\left(\frac{M_X}{m_{N_i}}\right)
\end{aligned}
$$

$$
\mathrm{BR}(\mu \to e\gamma) \simeq \frac{\alpha^3 \tan^2\beta}{G_F^2 M_{SUSY}^4} \left|\delta_{LL}^{21}\right|^2 ;\ \delta_{XY}^{ij} \equiv \frac{M_{XY}^{ij2}}{M_{SUSY}^2} ;\ XY = LL, LR, RR ;\ ij = 21, 31, 32
$$

LFV need: large Y_ν, large $\tan\beta \equiv \frac{<H_2>}{<H_1>}$ and not too large m_{SUSY}

Why seesaw mechanism for m_ν generation

* The seesaw is the simplest mechanism explaining small m_ν
* If Majonana ν, the seesaw allows for large Y_ν couplings
* If Majorana ν, L not preserved, viable BAU via Leptogenesis

$$-\mathcal{L}_{Y+M} = Y^e \bar{l}_L e_R H_1 + Y^\nu \bar{l}_L \nu_R H_2 + \frac{1}{2} m_M \nu_R^T C \nu_R + h.c.$$

$$m_e = Y_e < H_1 >,\ m_D = Y_\nu < H_2 >,\ < H_{1,2} >= 174\, GeV \times (\cos\beta, \sin\beta)$$

Both Dirac mass m_D and Majorana mass m_M involved $\longleftrightarrow$ $M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix}$

$m_D << m_M \Rightarrow$ seesaw: $m_\nu = -m_D m_M^{-1} m_D^T$ (light), $m_N = m_M$ (heavy)

For $Y_\nu \sim \mathcal{O}(1)$, $m_M \sim 10^{14}$ GeV $\Rightarrow$

For 1 gen. $\rightarrow$ 2 mass eigenstates $\begin{cases} m_\nu \sim 0.1\,\text{eV (OK with data)} \\ m_N \sim 10^{14}\,\text{GeV} \end{cases}$

Generalization to three generations also OK with data

Seesaw parameters versus neutrino data

SeeSaw equation: $m_\nu = -m_D m_N{}^{-1} m_D^T \; ; m_N = m_M \; ; m_D = Y_\nu < H_2 >$

Solution: $\boxed{m_D = i \sqrt{m_N^{diag}}\, R \sqrt{m_\nu^{diag}}\, U^\dagger_{\text{PMNS}}}$ [Casas, Ibarra ('01)]

R is a 3×3 complex matrix and orthogonal

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

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 : $m^2_{\nu_1} << m^2_{\nu_2} = \Delta m^2_{\text{sol}} + m^2_{\nu_1} << m^2_{\nu_3} = \Delta m^2_{\text{atm}} + m^2_{\nu_1}$

2 Scenarios

- Degenerate N's

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

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

Connection between LFV and Neutrino Physics

In the MIA the LFV is parameterized by $\delta^{ij}_{XY} \equiv \frac{M^{ij2}_{XY}}{M^2_{SUSY}}$.

Within SUSY-Seesaw and in the LLog aprox. δ^{ij}_{LL} dominate.

For instance, in the tau-mu sector:

$$\delta^{32}_{LL}|_{\mathrm{LLog}} \equiv \delta_{32} = -\frac{1}{8\pi^2}\frac{(3\,M_0^2 + A_0^2)}{M^2_{\mathrm{SUSY}}}\left(Y_\nu^\dagger\, L\, Y_\nu\right)_{32}$$

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

The relation with neutrino physics comes in,

$$\begin{aligned}
v_2^2\left(Y_\nu^\dagger\, L\, Y_\nu\right)_{32} = \;& L_{33}\, m_{N_3}\left[\left(\sqrt{m_{\nu_3}}c_1c_2c_{13}c_{23} - \sqrt{m_{\nu_2}}s_1c_2c_{12}s_{23}\right)\right. \\
& \left.\left(\sqrt{m_{\nu_3}}c_1^*c_2^*s_{23} + \sqrt{m_{\nu_2}}s_1^*c_2^*c_{12}c_{23}\right)\right] \\
+ \;& L_{22}\, m_{N_2}\left[\left(\sqrt{m_{\nu_3}}(-s_1c_3 - c_1s_2s_3)c_{23} + \sqrt{m_{\nu_2}}(s_1s_2s_3 - c_1c_3)c_{12}s_{23}\right)\right. \\
& \left.\left(\sqrt{m_{\nu_3}}(-s_1^*c_3^* - c_1^*s_2^*s_3^*)s_{23} + \sqrt{m_{\nu_2}}(c_1^*c_3^* - s_1^*s_2^*s_3^*)c_{12}c_{23}\right)\right] \\
+ \;& L_{11}\, m_{N_1}\left[\left(\sqrt{m_{\nu_3}}(s_1s_3 - c_1s_2c_3)c_{12}c_{23} + \sqrt{m_{\nu_2}}(s_1s_2c_3 + c_1s_3)c_{12}s_{23}\right)\right. \\
& \left.\left(\sqrt{m_{\nu_3}}(s_1^*s_3^* - s_1^*s_2^*s_3^*)c_{12}s_{23} - \sqrt{m_{\nu_2}}(s_1^*s_2^*c_3^* + c_1^*s_3^*)c_{12}c_{23}\right)\right]
\end{aligned}$$

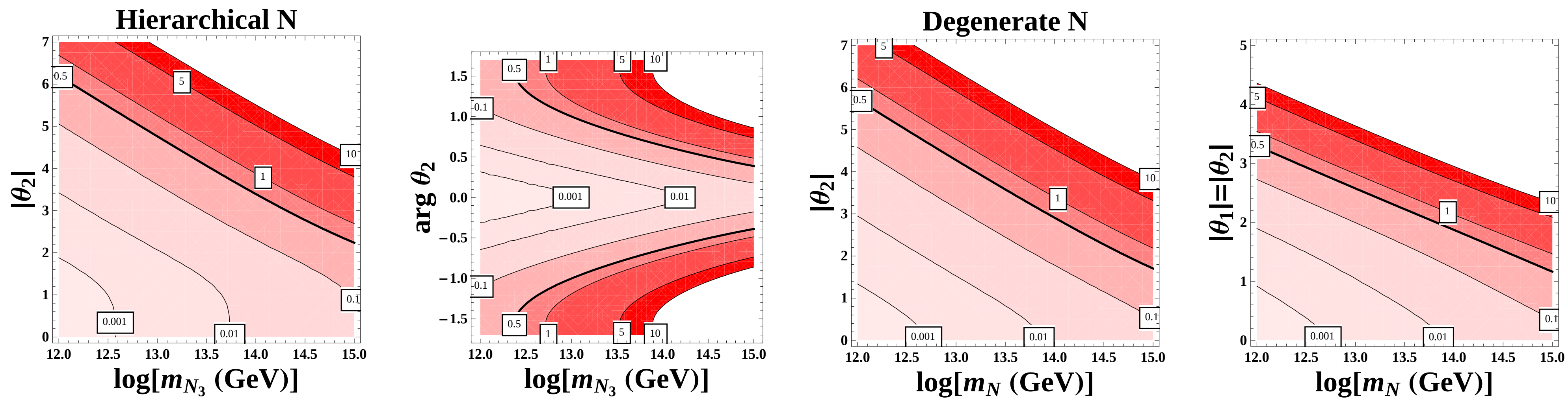
The size of m_{N_i} and θ_i drive the size of δ_{ij}, hence the LFV rates

Within SUSY-Seesaw $\delta_{32} > \delta_{21}$, δ_{31}, hence, larger $\tau - \mu$ rates

Size of δ_{32} in Constrained SUSY-Seesaw models

(Plots from Herrero(2009))

Hierarchical N / Degenerate N



$\arg\theta_2 = \pi/4$ | $|\theta_2|$=4 | $\arg\theta_2 = \pi/4$ | $\arg\theta_2 = \arg\theta_1 = \pi/4$

- Large size of $|\delta_{32}|$ for large $\theta_{1,2}$ and/or large m_N if degenerate heavy neutrinos (large m_{N_3} if hierarchical. Nearly independent on $m_{N_{1,2}}$)
- Complex $\theta_{1,2}$, with large: mod ($2 < |\theta_{1,2}| < 3$); arg ($\pi/4 < \arg\theta_{1,2} < 3\pi/4$); large $m_N \sim 10^{14} - 10^{15}$ GeV $\Rightarrow |\delta_{32}| \sim 0.1 - 10$
- In contrast to $|\delta_{21}|, |\delta_{31}| < 10^{-3}$

Next: Our contribution to LFV in SUSY-Seesaw Models

From several papers in collaboration with:

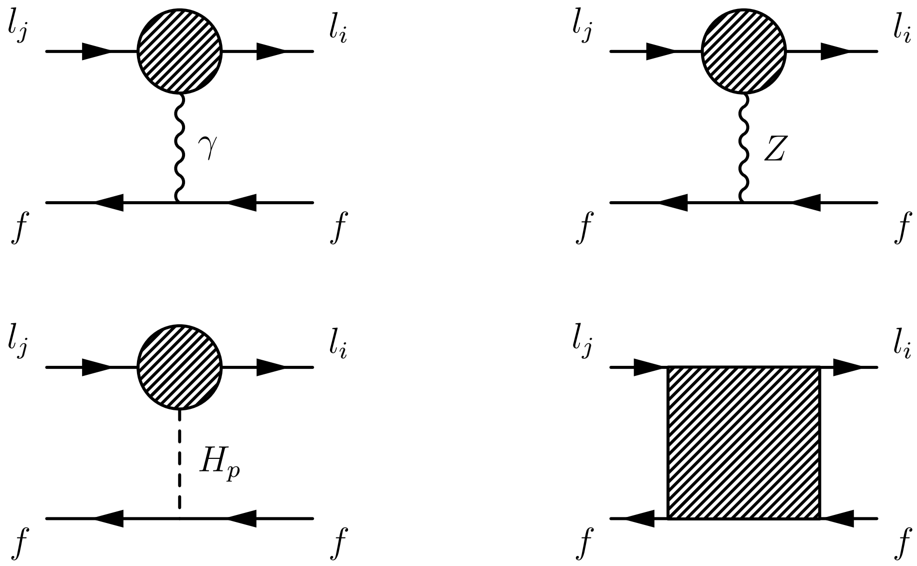
various coleagues and PhD students

E.Arganda, A.Curiel, M.H. and D.Temes PRD71,035011(2005) Higgs
E.Arganda and M.H. PRD73,055003(2006) $l_j \to 3l_i$, $l_j \to l_i\gamma$
S.Antusch, E.Arganda, M.H. and A.Teixeira JHEP11(2006)090 θ_{13}
E.Arganda, M.H. and A.Teixeira JHEP10(2007)104 $\mu - e$ conv. nuclei
E.Arganda, M.H. and J.Portolés JHEP06(2008)079 semilep. τ decays
M.H.,J.Portolés, A.Rodríguez-Sánchez PRD80,015023(2009) $\tau \to \mu f_0$

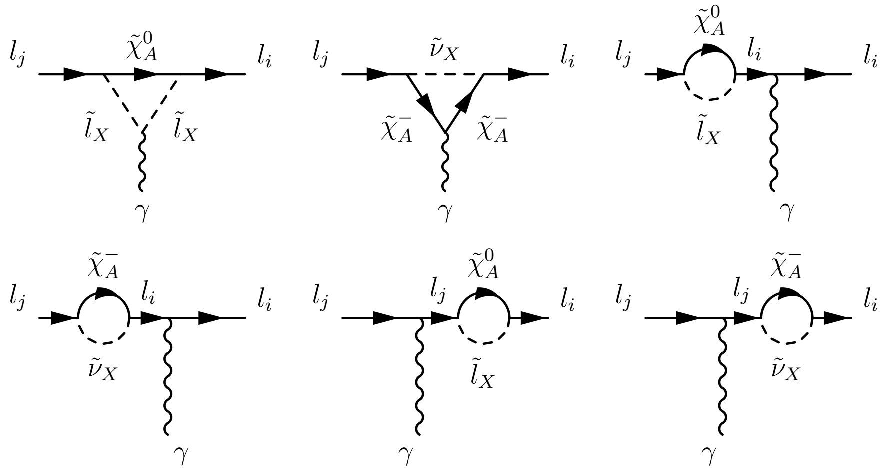
Summary of our Work

- **Predictions of LFV rates in SUSY-Seesaw**
  - ⋆ $l_j \to l_i\gamma$; $l_j \to 3l_i$; $h^0, H^0, A^0 \to l_j\bar{l}_i$
  - ⋆ $\tau \to \mu P$ $(P = \eta, \pi)$ and $\tau \to \mu f_0$
  - ⋆ $\tau \to \mu PP$ $(PP = \pi^+\pi^-, \pi^0\pi^0, K^+K^-, K_0\bar{K}_0)$
  - ⋆ $\tau \to \mu V$ $(V = \rho, \phi$, 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 predictions with LFV bounds**
- **Explore sensitivity to SUSY, Higgs and heavy ν_R**
- **Provide a set of simple formulas that approximate well the full result and are usefull for comparison with data and with other authors**

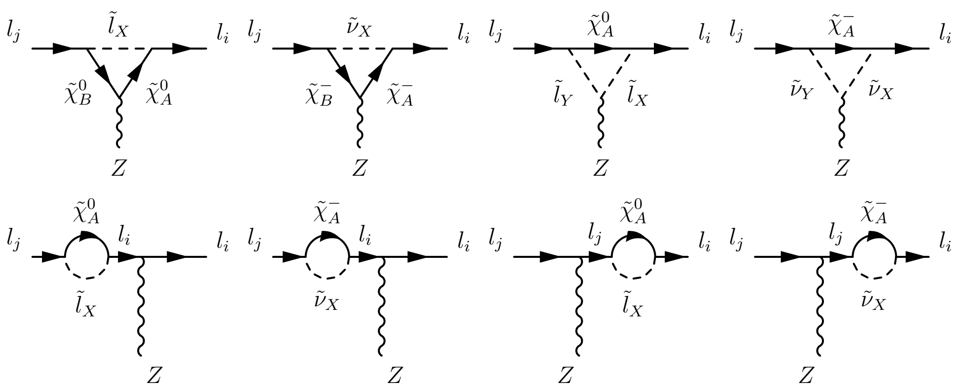
Full 1-loop in $l_j \to 3l_i$, $\tau \to \mu P$ $\tau \to \mu PP$, $\tau \to \mu V$, $\mu - e$ conv. in nucl.



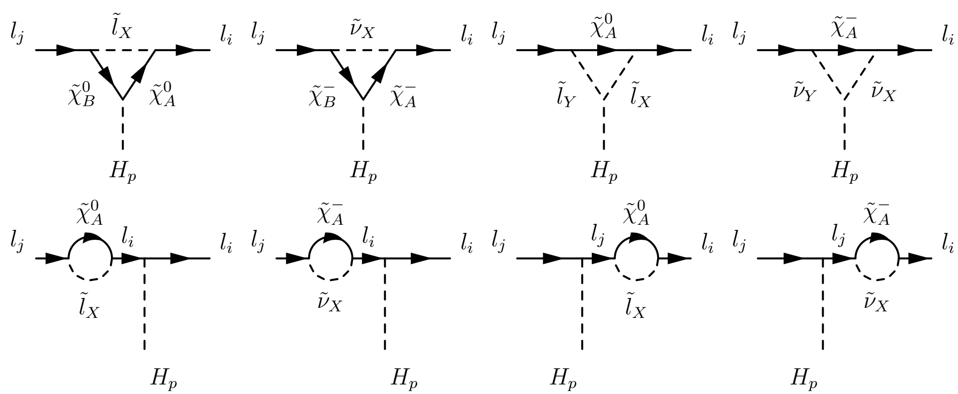
Generic



γ-mediated (also $l_j \to l_i\gamma$)



Z-mediated (also $Z \to l_j\bar{l}_i$)

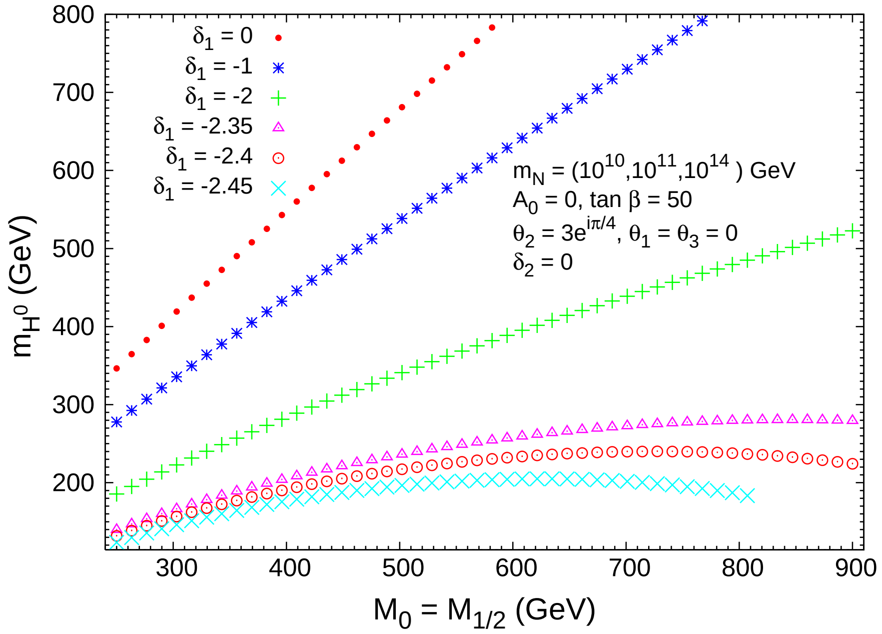


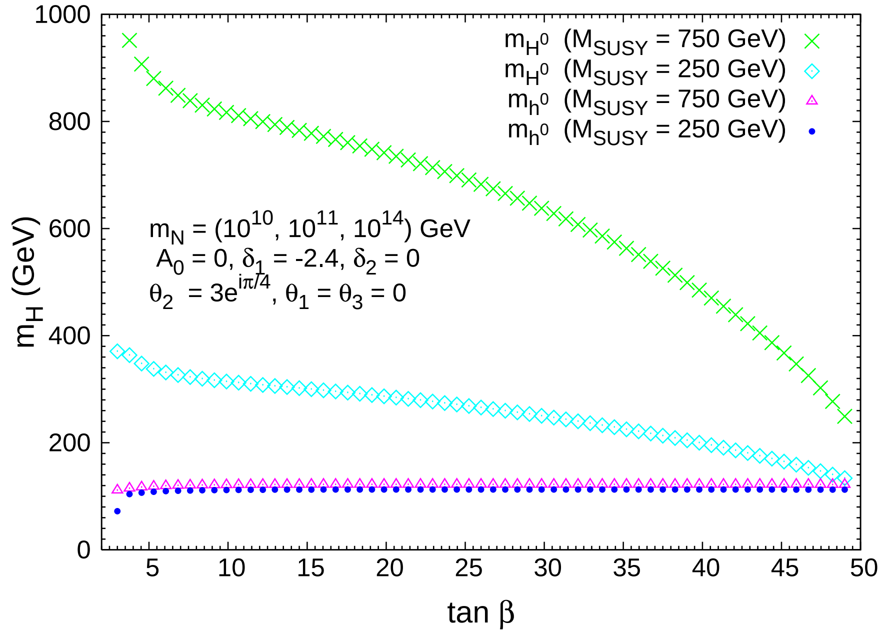
H-mediated (also $H \to l_j\bar{l}_i$)

Our framework for computation of LFV rates

- **Use seesaw (Type I) for ν mass generation**
- **Within SUSY-seesaw (MSSM content$+3\nu_R+$ $3\tilde{\nu}_R$)**
  Two simple scenarios for soft parameters at $M_X = 2 \times 10^{16}$ GeV:
  - ⋆ Universal soft parameters: CMSSM-seesaw
    $(M_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu))$
  - ⋆ Non-universal soft Higgs masses: NUHM-seesaw
    $(M_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu), M_{H_1} = M_0\sqrt{1+\delta_1}, M_{H_2} = M_0\sqrt{1+\delta_2})$
- 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 SUSY, neutrinos and Higgs (No MI approx)
- **Numerical estimates:**
  - ⋆ SPheno (W.Porod) for int. of RGEs and SUSY spectrum
  - ⋆ Additional subroutines for all LFV processes (by us)
    Also subroutines for checks of BAU, EDM and $(g-2)_\mu$

Lighter H in NUHM than in CMSSM ⇒ larger LFV





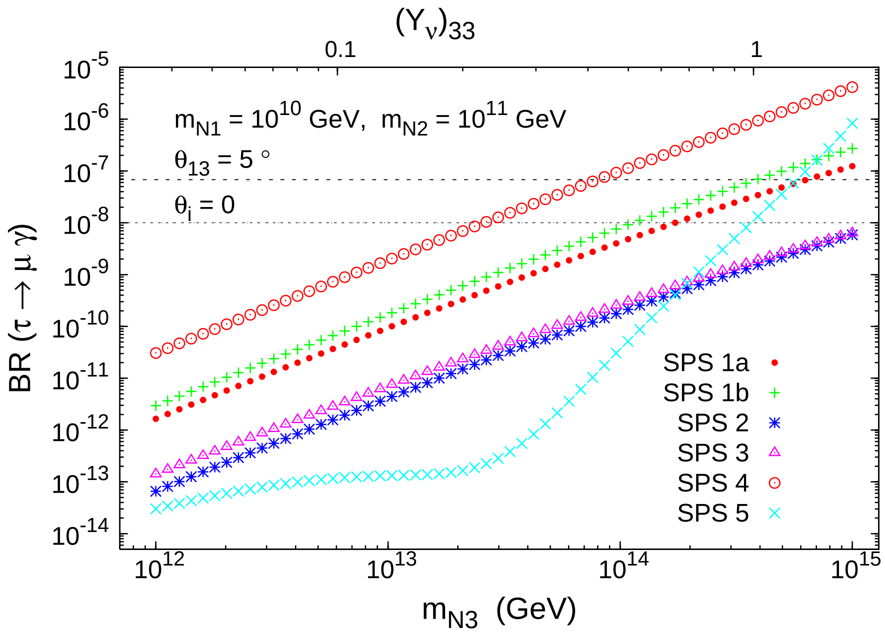
- In CMSSM ($\delta_{1,2} = 0$) a heavy SUSY spectrum (large M_0, $M_{1/2}$) ⇒ heavy H^0 and A^0.
- In NUHM, a proper choice of δ_1 and δ_2, even for very large SUSY masses of $\mathcal{O}(1\text{ TeV})$, can lead to light H^0 and A^0, $m_{H^0,A^0} \lesssim 200$ GeV
  H^0 and A^0 become lighter with the increase of $\tan\beta$.
- h^0 remains always light (for all $\tan\beta$ and M_{SUSY}), $m_{h_0} < 150$ GeV.
- H^0 and/or A^0 relevant Higgses in H-mediated LFV processes:
  Their couplings to $I = -1/2$ fermions are enhanced at large $\tan\beta$.

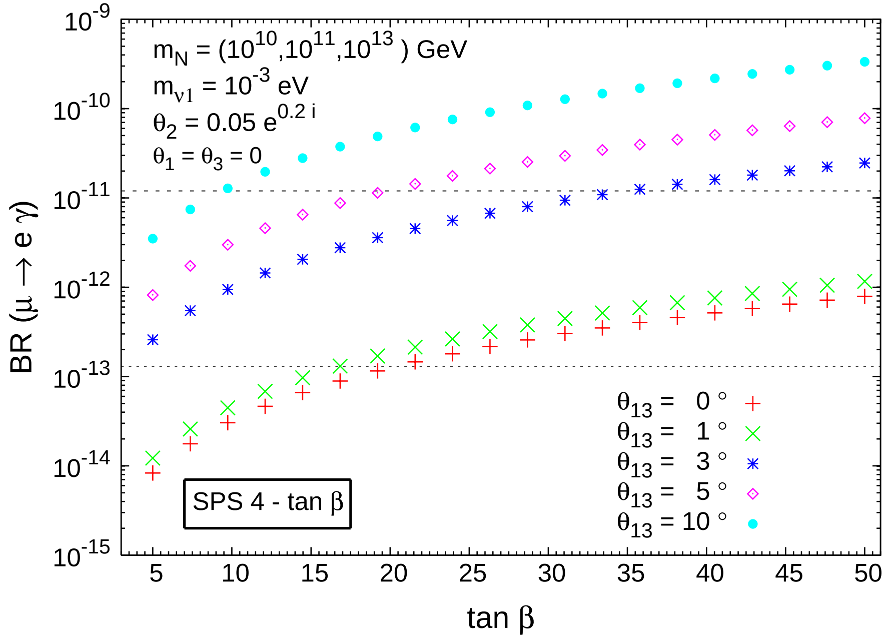
Other works on LFV from SUSY loops (etc..)

- **Seminal:** Masiero, Borzumati (86): LFV in $\mu - e$, MSSM-seesaw
- **Improved:** Hisano, Moroi, Tobe, Yamaguchi (96):
  $l_j \to l_i \gamma$, $l_j \to 3 l_i$ (without Higgs), $\mu - e$ (without Higgs)
- **SUSYGUT-Seesaw, lepton-quark relations:**
  Barbieri, Hall; Barbieri, Hall, Strumia; Hisano, Nomura, Yanagida; Hisano, Nomura; Hisano, Moroi, Tobe, Yamaguchi; Fukuyama, Kikuchi, Okada; Bi, Dai, Qi; Masiero, Vempati, Vives; Carvalho, Ellis, Gomez, Lola; Calibbi, Faccia, Masiero, Vempati.
- **CMSSM-Seesaw: Without Higgs**
  Casas, Ibarra; Lavignac, Masina, Savoy; Blazek, King; Kuno, Okada; Ellis, Hisano, Raidal, Shimizu; Petcov, Rodejohann, Shindou, Takanishi; Deppisch, Pas, Redelbach, Rueckl, Shimizu; Petcov, Profumo, Takanisi, Yaguna; Illana, Masip.
- **Higgs-Mediated LFV:**
  Babu, Kolda; Sher; Kitano, Koike, Komine, Okada; Dedes, Ellis, Raidal; Brignole, Rossi; Paradisi.
- **muon-electron conversion in nuclei:**
  Hisano, Moroi, Tobe, Yamaguchi; Kitano, Koike, Komine, Okada; Kuno, Okada; Calibbi, Faccia, Masiero, Vempati.
- **semileptonic LFV tau decays:**
  Sher; Brignole, Rossi; Cheng, Geng; Fukuyama, Illakovac, Kikuchi.

Results for LFV radiative and leptonic decays

Predictions for $\tau \to \mu\gamma$ and $\mu \to e\gamma$ in CMSSM-seesaw





⋆ Most relevant seesaw param.: m_{N_3} if ν_R hierarchical (m_N if degenerate)

BR $\sim |m_{N_3} \log m_{N_3}|^2$. Next θ_i; Ex.: BR $\times 10-100$ if θ_2: $0 \to 3e^{i\pi/4}$

⋆ Relevant SUSY parameters: $\tan\beta$ and M_{SUSY} (explains BR$_{SPS}$)

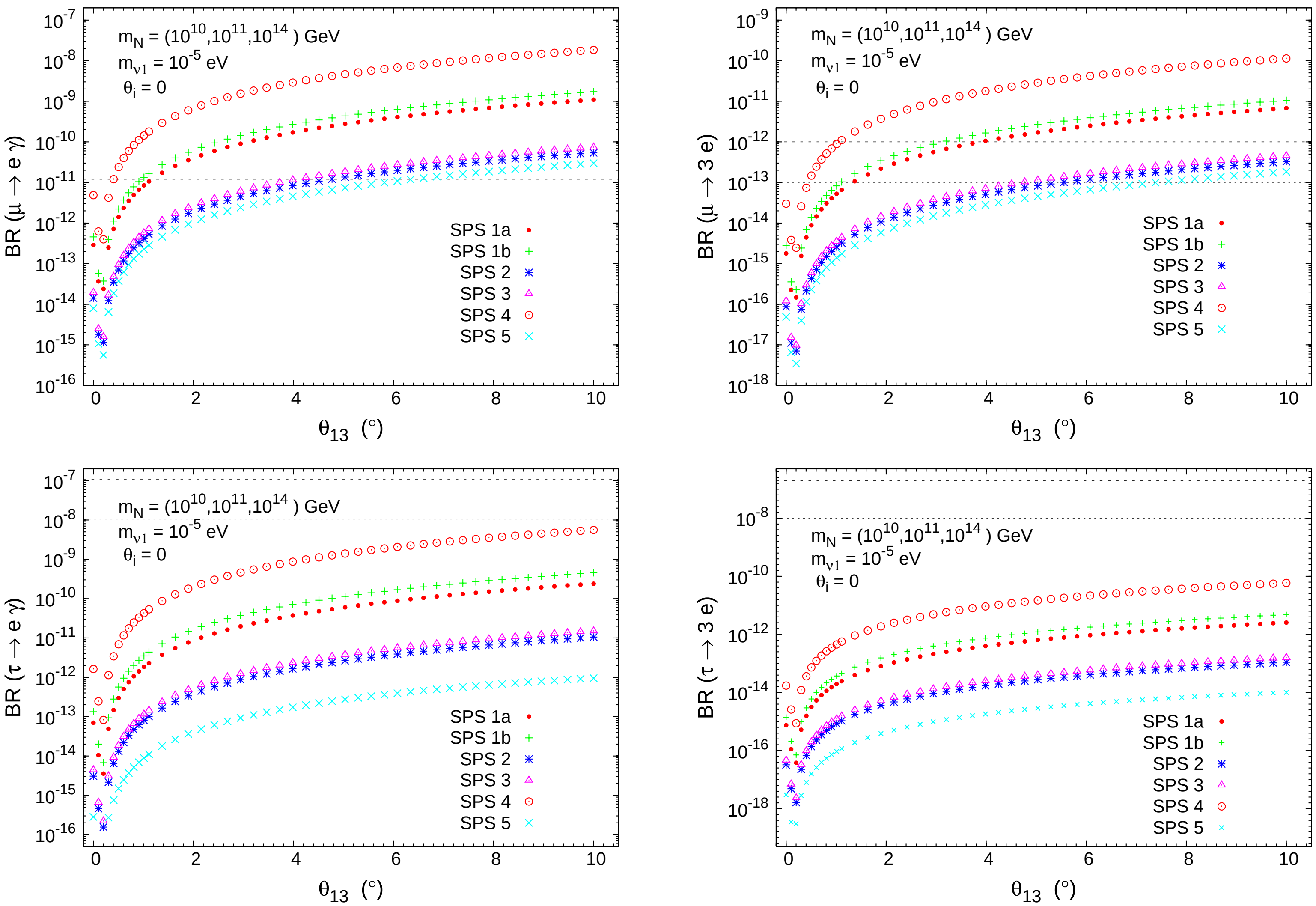
$BR(\mu \to e\gamma) \simeq 0.1|\delta_{21}|^2(\frac{100}{M_{SUSY}})^4(\frac{\tan\beta}{60})^2$; $BR(\tau \to \mu\gamma) \simeq 0.015|\delta_{32}|^2(\frac{100}{M_{SUSY}})^4(\frac{\tan\beta}{60})^2$

$BR(\mu \to e\gamma)/BR(\tau \to \mu\gamma)$ ratio nearly independent on SUSY parameters.

It depends just on neutrino parameters: correlations fixed by seesaw (see next)

⋆ BR($\mu \to e\gamma$), BR($\tau \to \mu\gamma$) reach exp. lim. at large (m_{N_3}, $\tan\beta$, θ_i)

Sensitivity to θ_{13}

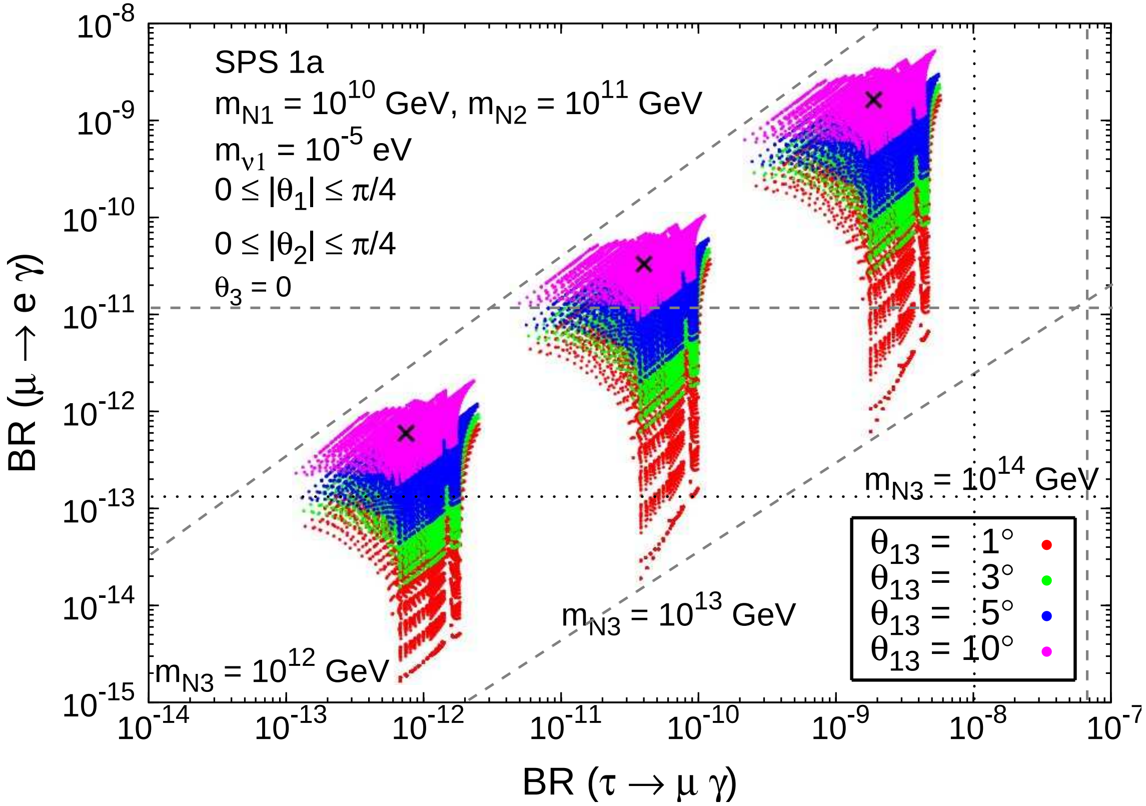


- ⋆ $\mu \to e\gamma$ very sensitive to θ_{13} (see also Masiero et al 04) Ordrs of mag change!!
- ⋆ $\mu \to 3e$, $\tau \to e\gamma$ and $\tau \to 3e$ also very sensitive to θ_{13} ($\tau \to \mu\gamma$, $\tau \to 3\mu$ are not!!)
- ⋆ Sensitivity of $\mu \to e\gamma$, $\mu \to 3e$ clearly **within exp. reach**
- ⋆ $\mathrm{BR}_4 > \mathrm{BR}_{1b} \gtrsim \mathrm{BR}_{1a} > \mathrm{BR}_3 \gtrsim \mathrm{BR}_2 > \mathrm{BR}_5$ (all $> \mathrm{BR}^{\mathrm{present}}_{\mathrm{exp}}$ in $\mu \to e\gamma$ for $\theta_{13} \gtrsim 5^o$!!)

Correlated study of $\mu \to e\gamma$ and $\tau \to \mu\gamma$

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

(SP1a: $M_0 = 100$ GeV, $M_{1/2} = 250$ GeV, $A_0 = -100$ GeV, $\tan\beta = 10$, $\mu > 0$)



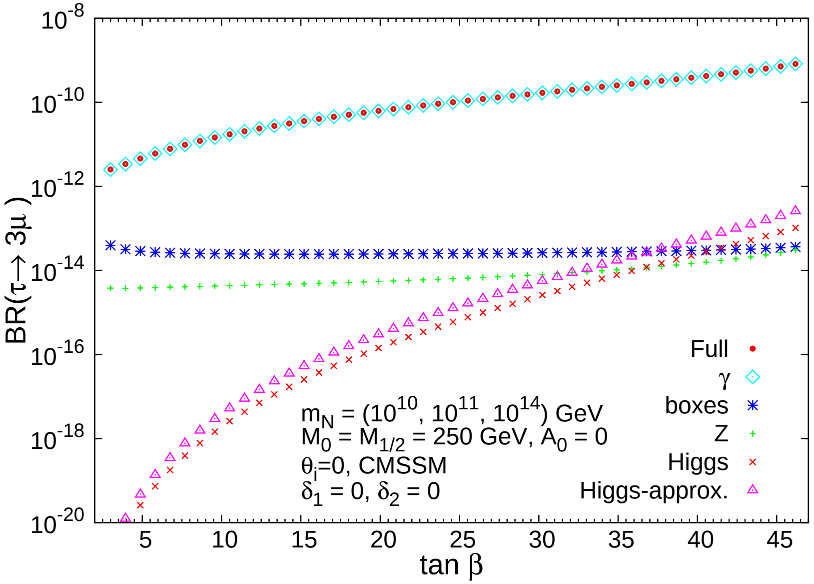
Present: $\mu \to e\gamma$ still more competitive than $\tau \to \mu\gamma$, unless very small $\theta_{13} < 3^o$.
MEGA bound, BR($\mu \to e\gamma$) $< 10^{-11}$, already excludes $m_{N_3} \gtrsim 10^{14}$ GeV (for SPS 1a)

Future: Assume θ_{13} is measured. Planned SuperB sensitivity BR($\tau \to \mu\gamma$) $\sim 10^{-9}$ will compete and even set better upper bounds on m_{N_3}. Planned MEG 10^{-13} will reach further.

BUT: both are insensitive to Higgs! Some LFV semileptonic tau decays do! (see next)

The $\tau \to 3\mu$ channel: fully dominated by photon diagram

CMSSM



the three h^0, H^0, A^0 participate

h^0 contrib. negligible

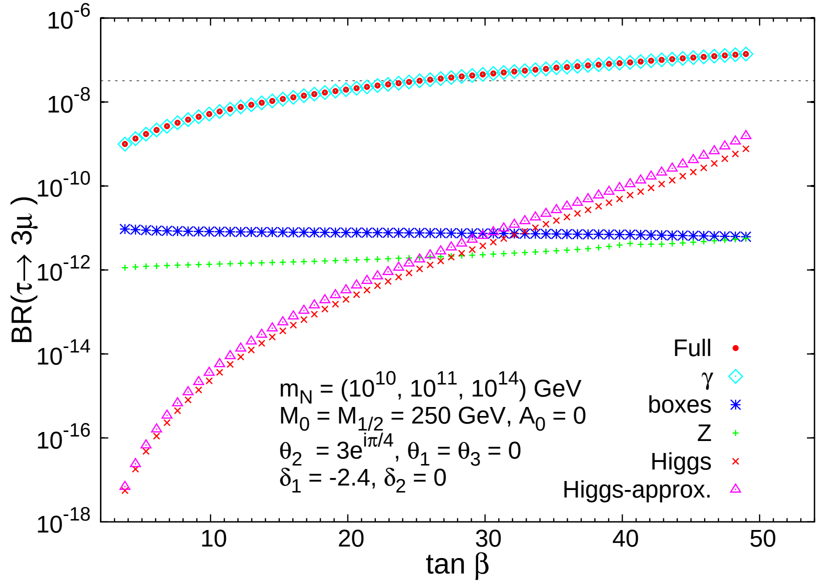
$$\mathrm{BR}|_{H^0,A^0} \sim (\tan\beta)^6$$

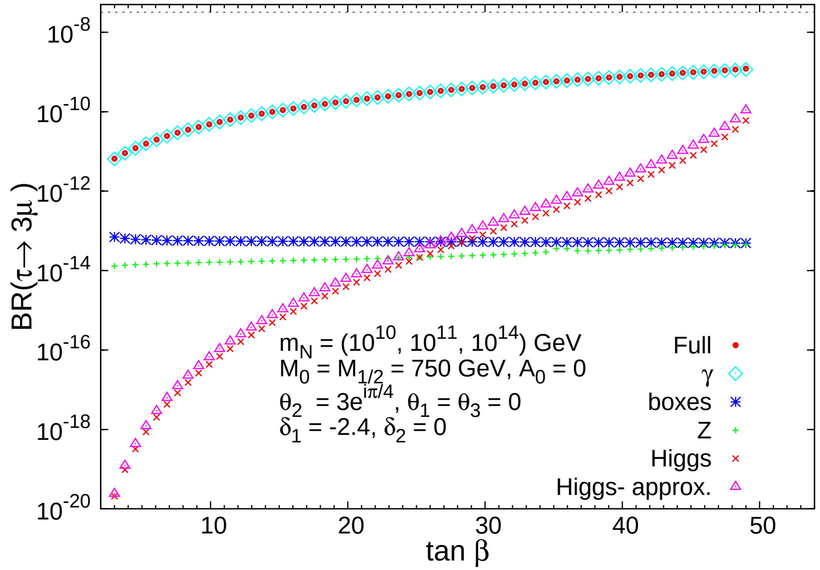
H-contrib. overwhelmed by γ-contrib. even at large

$\tan\beta \sim 50$ and large $M_0, M_{1/2} \sim \mathcal{O}(1\ \mathrm{TeV})$

Even if $m_{A^0,H^0} \lesssim 200$ GeV (as in NUHM)

NUHM





There is NOT sensitivity to Higgs in $\tau \to 3\mu$ in CMSSM nor NUHM

Comparison between $l_j \to l_i l_k l_k$ and $l_j \to l_i \gamma$

For this comparison, better use the approximate formulas (work well, see our papers)

$$\mathrm{BR}(\tau \to 3\mu)_{\gamma_{\mathrm{approx}}} = 3.4 \times 10^{-5} \left[|\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})} \right)^4 \left(\frac{\tan\beta}{60} \right)^2 \right]_1$$

$$\mathrm{BR}(\tau \to 3\mu)_{H_{\mathrm{approx}}} = 1.2 \times 10^{-7} \left[|\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})} \right)^4 \left(\frac{\tan\beta}{60} \right)^6 \right]_2$$

$$\mathrm{BR}(\tau \to \mu\gamma)_{\mathrm{approx}} = 1.5 \times 10^{-2} \left[|\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})} \right)^4 \left(\frac{\tan\beta}{60} \right)^2 \right]_1$$

For instance: for typical $\delta_{32} = 0.1$, ($m_{N_3} = 10^{14}\,\mathrm{GeV}, \theta_2 = 2e^{i\pi/4}$),
SPS 4 ($\tan\beta = 50, M_{\mathrm{SUSY}} \sim 500\,\mathrm{GeV}, m_{A^0} \sim 400\,\mathrm{GeV}$), $[\mathrm{factor}]_{1,2} \sim 10^{-5}$,
CMSSM maximum rates: $\mathrm{BR}(\tau \to \mu\gamma) \sim 10^{-7}$, $\mathrm{BR}(\tau \to 3\mu) \sim 2 \times 10^{-10}$ (SuperB?)

BR	SPS 1a	SPS 1b	SPS 2	SPS 3	SPS 4	SPS 5
$\tau \to \mu\gamma$	4.2×10^{-9}	7.9×10^{-9}	1.8×10^{-10}	2.6×10^{-10}	9.7×10^{-8}	1.9×10^{-11}
$\tau \to 3\mu$	9.4×10^{-12}	1.8×10^{-11}	4.1×10^{-13}	5.9×10^{-13}	2.2×10^{-10}	4.3×10^{-14}

Conclussion 1: $\mathrm{BR}(\tau \to 3\mu)$ dominated by γ contrib. in both CMSSM and NUHM,
unless extremely light, $m_{A^0} \sim 100$ GeV, NUHM: $[\mathrm{factor}]_2 \sim 3 \times 10^{-3}$

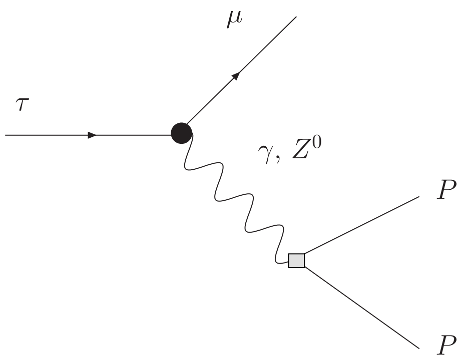
Conclussion 2: **$\tau \to \mu\gamma$ still more competitive than $\tau \to 3\mu$ for LFV searches**

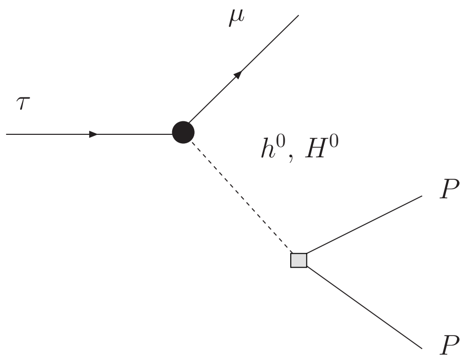
Conclussion 3: Due to γ-dominance (even for $\tau \to 3\mu$), **fixed predicted ratios:**

$$\frac{BR(l_j \to 3l_i)}{BR(l_j \to l_i\gamma)} = \frac{\alpha}{3\pi}\left(\log\frac{m_{l_j}^2}{m_{l_i}^2} - \frac{11}{4}\right) = 6.10^{-3}, 1.10^{-2}, 2.10^{-3} \text{ for } (l_j l_i) = (\mu e), (\tau e), (\tau\mu)$$

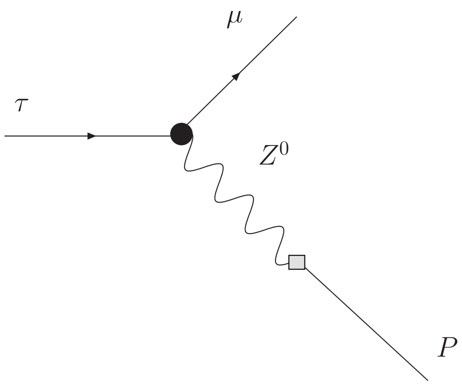
Results for LFV semileptonic tau decays

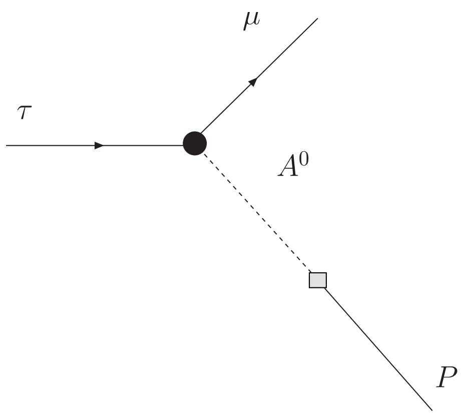
(Framework for hadronization: we use ChPT, see our papers for details)



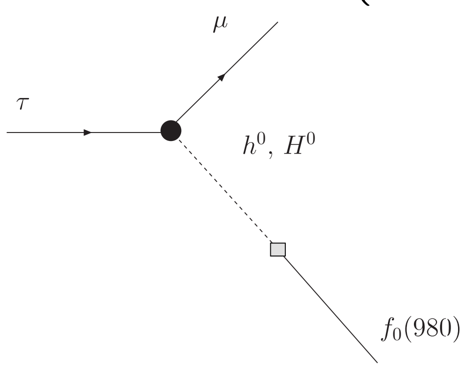


$(PP = \pi\pi, KK)$



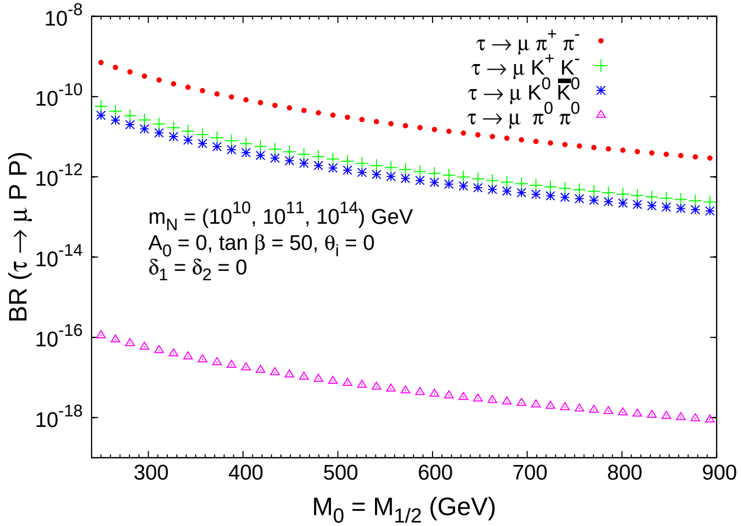


$(P = \pi, \eta, \eta')$

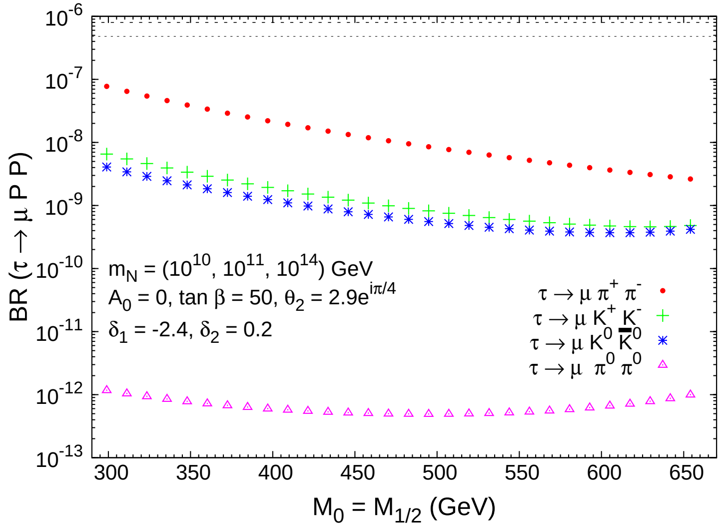


Enhanced H coupl. to hadrons with s quark component, $g_{Ass} \sim m_s \tan\beta$, $g_{H^0ss} \sim m_s \frac{\cos\alpha}{\cos\beta}$,
Are semileptonic decays into KK, η, f_0 sensitive to Higgs? (see next)

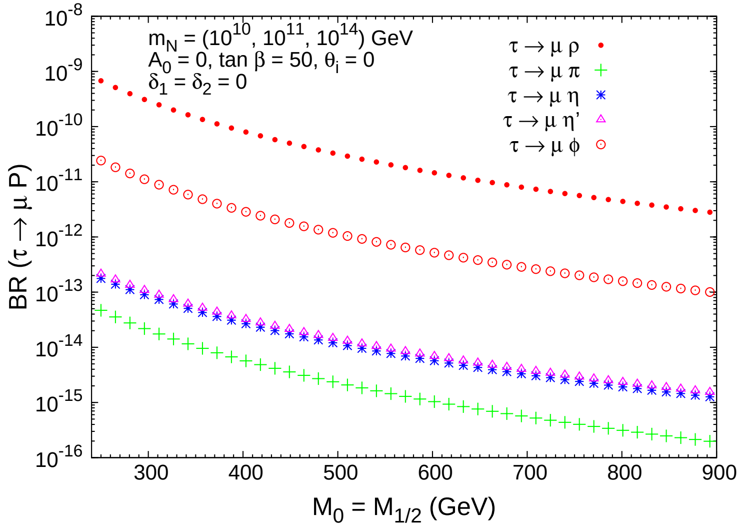
LFV tau semileptonic decay rates

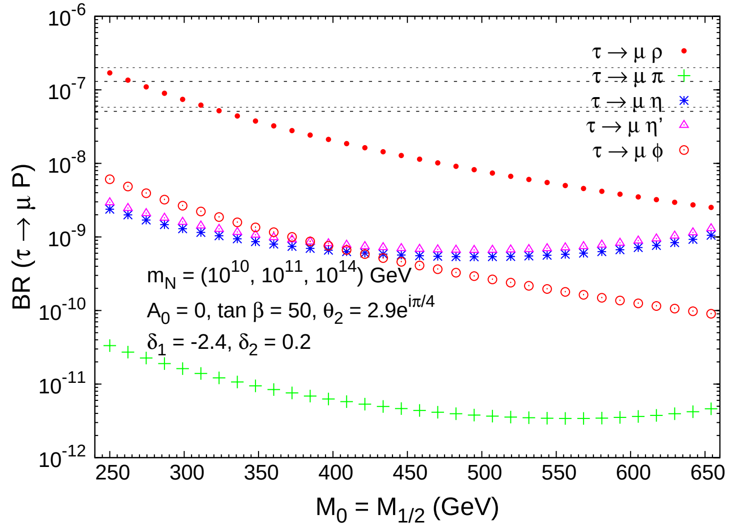


CMSSM: No sensitivity to Higgs



NUHM: H^0 enters at large $M_{\rm SUSY}$





- ⋆ In scenarios with light H and heavy SUSY (NUHM) we find sensitivity to Higgs
- ⋆ Largest rates in CMSSM are for BR($\tau \to \mu\rho$), BR($\tau \to \mu\pi^+\pi^-$) (γ-dom).

In NUHM also BR($\tau \to \mu\eta$),BR($\tau \to \mu f_0$) (H-dom). At the present exp.reach 10^{-8}

Approx. rates for LFV semilep. τ decays in SUSY-seesaw

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

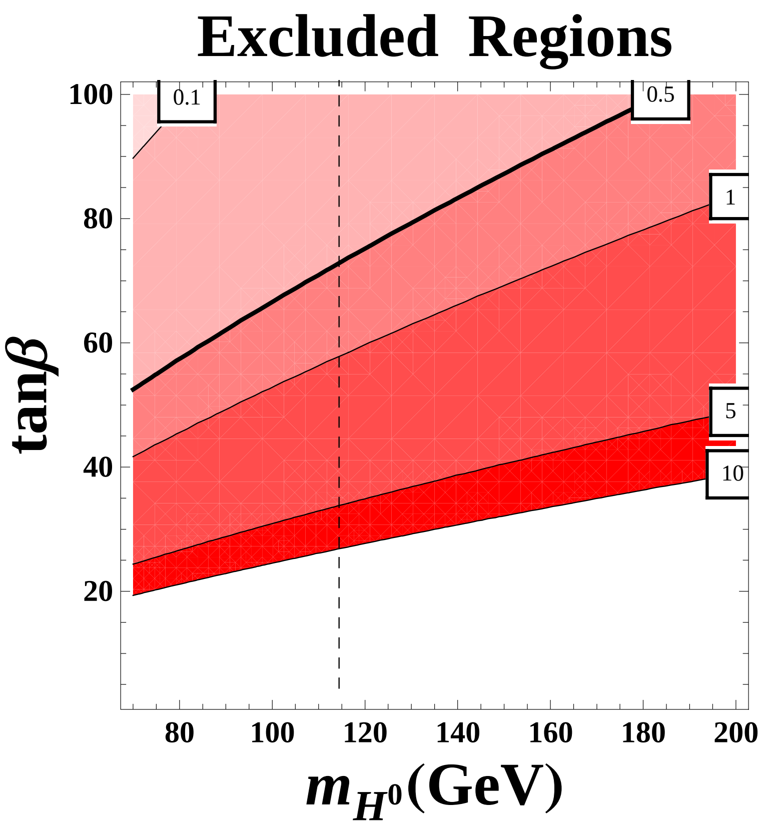
$$\begin{aligned}
\mathrm{BR}(\tau \to \mu\eta)_{H_{\mathrm{approx}}} &= 1.2\times 10^{-7}\,|\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
\mathrm{BR}(\tau \to \mu f_0)_{H_{\mathrm{approx}}} &= \left(\begin{array}{c} 7.3\times 10^{-8}\ (\theta_S = 7^\circ) \\ 4.2\times 10^{-9}\ (\theta_S = 30^\circ) \end{array}\right) |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
\mathrm{BR}(\tau \to \mu\pi)_{H_{\mathrm{approx}}} &= 3.6\times 10^{-10}\,|\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
\mathrm{BR}(\tau \to \mu\rho)_{\gamma_{\mathrm{approx}}} &= 3.4\times 10^{-5}\,|\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \\
\mathrm{BR}(\tau \to \mu\phi)_{\gamma_{\mathrm{approx}}} &= 1.3\times 10^{-6}\,|\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \\
\mathrm{BR}(\tau \to \mu\pi^+\pi^-)_{\gamma_{\mathrm{approx}}} &= 3.7\times 10^{-5}\,|\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \quad \gamma \text{ dominates} \\
\mathrm{BR}(\tau \to \mu\pi^+\pi^-)_{H_{\mathrm{approx}}} &= 2.6\times 10^{-10}\,|\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \\
\mathrm{BR}(\tau \to \mu K^+K^-)_{\gamma_{\mathrm{approx}}} &= 3.0\times 10^{-6}\,|\delta_{32}|^2 \left(\frac{100}{M_{\mathrm{SUSY}}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2 \quad \gamma \text{ and H compete} \\
\mathrm{BR}(\tau \to \mu K^+K^-)_{H_{\mathrm{approx}}} &= 2.8\times 10^{-8}\,|\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6
\end{aligned} \tag{1}$$

Predicted fixed ratios: $BR(\tau\to\mu\rho)/BR(\tau\to\mu\gamma)$, $BR(\tau\to\mu\pi^+\pi^-)/BR(\tau\to\mu\gamma) \sim 2\times 10^{-3}$ (γ-dom)

Better sensitivity to new physics in: $BR(\tau\to\mu\eta)/BR(\tau\to\mu\gamma)$, $BR(\tau\to\mu f_0)/BR(\tau\to\mu\gamma)$

Constraining the model parameters from $\tau \to \mu f_0$

(Similarly for $\tau \to \mu\eta$, replacing H^0 by A^0)



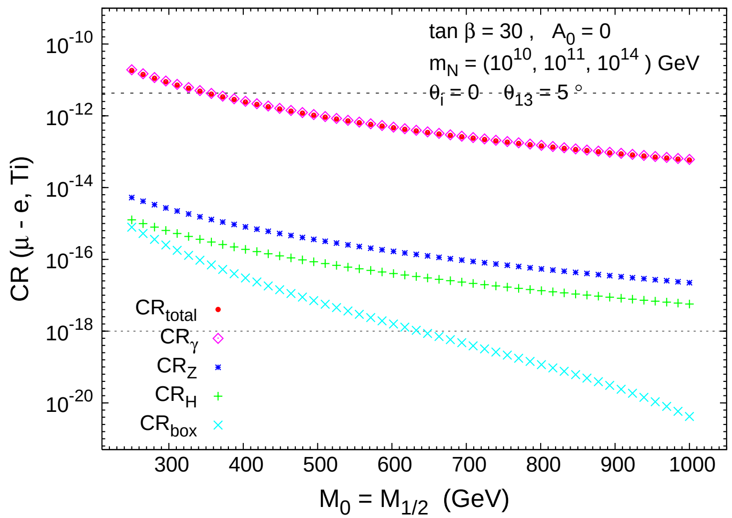
- Sensitivity to Higgs sector $\Rightarrow$ constraining mainly $\tan\beta$ and m_{H^0}
- For fixed $|\delta_{32}|$, comparison with present exp. bound $\Rightarrow$ limits on large $\tan\beta$ and light m_{H^0}.
  For ex., if $|\delta_{32}| = 1 \Rightarrow \tan\beta \gtrsim 50$, $m_{H^0} \lesssim 115$ GeV excluded.

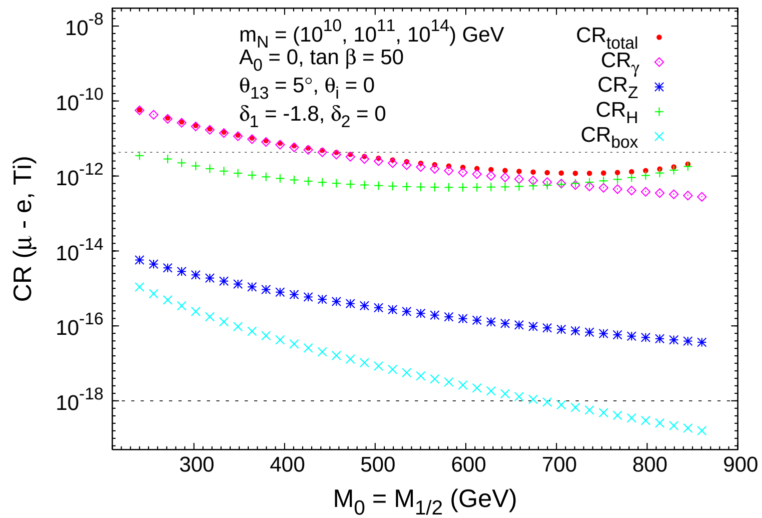
Results for $\mu - e$ conversion in nuclei

We follow the general parameterisation and approxs of Kuno & Okada Review (2001). See our papers for details

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

First estimates of CR($\mu - e$, Nuclei) did not include H-contrib. (Hisano et al PRD53(1996)2442)





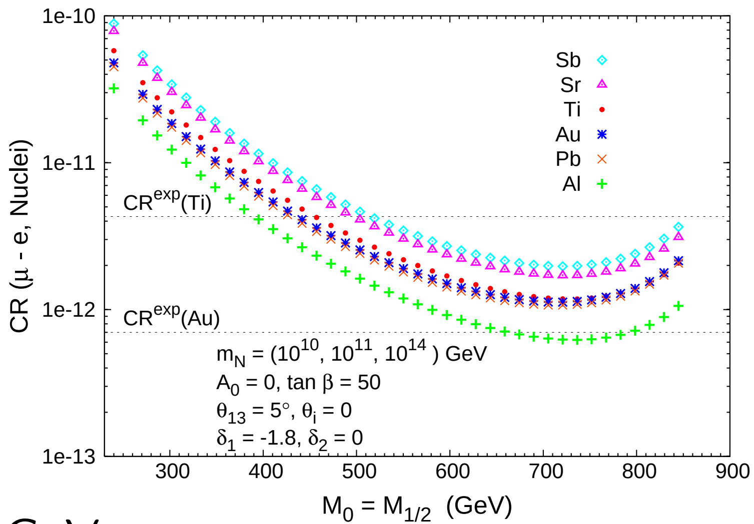
CMSSM: γ dominance for all M_{SUSY}

CR$(\mu - e, \text{Ti})/BR(\mu \to e\gamma) \sim 5.10^{-3}$

NUHM: H^0 dominance if H^0 light

NUHM:

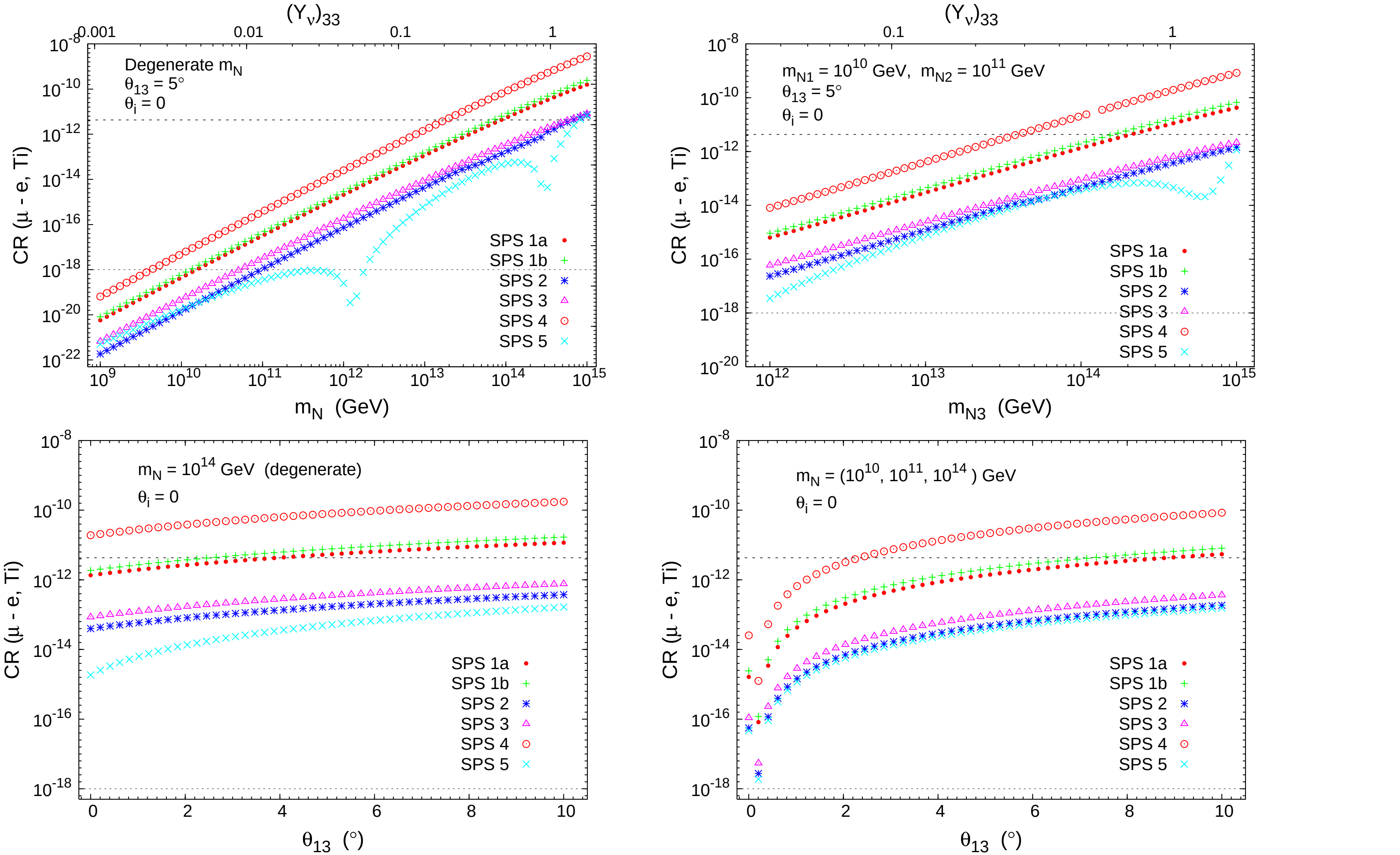
$$\text{CR}(\mu - e, \text{Ti})_H \simeq 10^{-12} \left(\frac{115}{m_{H^0}(\text{GeV})}\right)^4 \left(\frac{\tan\beta}{50}\right)^6$$



- ⋆ CMSSM rates above exp. bound if $M_{\text{SUSY}} < 400$ GeV
- ⋆ NUHM: CR($\mu - e$, Au) above exp. bound, 7.10^{-13} even for heavy SUSY

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
Full coverage of SUSY parameter space.

⋆ 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

- At present, if θ_{13} is not very small, $\mu \to e\gamma$ is still the most competitive channel to search for LFV signals within Constrained MSSM-Seesaw scenarios
- If $\theta_{13} < 3^o$, $\tau \to \mu\gamma$ is better than $\mu \to e\gamma$ and $\mu \to 3e$
- Semileptonic tau decays complement nicely the searches for LFV in $\tau - \mu$ sector
- The most competitive semileptonic channels to search for Higgs sector signals are $\tau \to \mu\eta$ (sensitive to A^0) and $\tau \to \mu f_0$ (sensitive to H^0)
- The future prospects for $\mu - e$ conversion in Ti are the most challenging for LFV. With sensitivity 10^{-18} will cover the full SUSY parameter space and be able to explore the Higgs sector
- Future prospects for SuperB are the most challenging for $\tau - \mu$ and $\tau - e$ transitions via tau decays. Sensitivity up to $10^{-9} - 10^{-10}$ needed to explore Higgs sector. Mainly via semileptonic decays
- Work in progress to constrain the model parameters from a global study of all LFV channels

Additional transparencies

Why Majorana neutrinos are prefered

Massive neutrinos ($Q_\nu = 0$) could be either Dirac or Majorana fermions

- **Dirac neutrinos:**

neutrino $\neq$ anti-neutrino. Four degrees of freedom, ν_L, ν_R

Lepton number is preserved ($m\bar{\nu}\nu$, $\Delta L = 0$). ν are like other SM fermions

$-\mathcal{L}_Y = Y^e \bar{l}_L e_R H + Y^\nu \bar{l}_L \nu_R \tilde{H} + h.c.$, $\bar{l}_L = (\bar{\nu}_L \bar{e}_L)$, H doublet, $\tilde{H} = i\tau_2 H^*$

$m_e = Y^e < H >$, $m_\nu = Y^\nu < H >$, $< H >= 174 GeV$

$m_\nu \sim 0.1 eV \Rightarrow Y^\nu \sim 10^{-12}$!!!

- **Majorana neutrinos:**

neutrino=anti-neutrino. Two degrees of freedom, ν_L ($\nu_R = (\nu_L)^c$)

Lepton number is violated ($M\nu^c\nu$, $\Delta L \neq 0$). ν different than other fermions.

It allows for Leptogenesis: Generation of Lepton asymmetry in the Universe by particle interactions ($\Rightarrow$ may induce successful Baryon asymmetry)

Both allow for Lepton Flavor Violation (LFV) ($\Delta L_e \neq 0$,..) but it is more relevant in the Majorana case due to the potential larger size of Y_ν

MSSM spectrum and experimental constraints

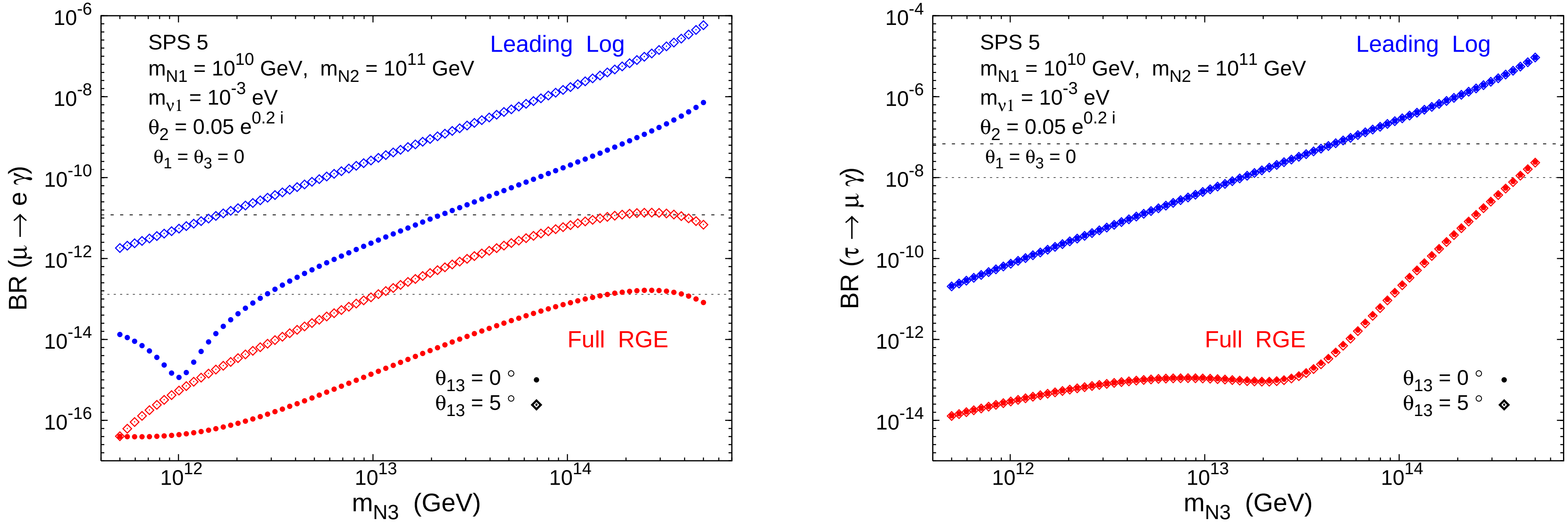
Extended Standard Model spectrum	SUSY particles: $SU(3)_C \times SU(2)_L \times U(1)_Y$ interaction eigenstates – Notation	Name	Mass eigenstates – Notation	Name
$q = u, d, s, c, b, t$ $l = e, \mu, \tau$ $\nu = \nu_e, \nu_\mu, \nu_\tau$	$\tilde{q}_L, \tilde{q}_R$ $\tilde{l}_L, \tilde{l}_R$ $\tilde{\nu}$	squarks sleptons sneutrino	$\tilde{q}_1, \tilde{q}_2$ $\tilde{l}_1, \tilde{l}_2$ $\tilde{\nu}$	squarks sleptons sneutrino
g	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$ $H_1^+ \supset H^+$ $H_2^- \supset H^-$	$\tilde{W}^\pm$ $\tilde{H}_1^+$ $\tilde{H}_2^-$	wino higgsino higgsino	$\tilde{\chi}_i^\pm$ $(i{=}1,2)$	charginos
γ Z $H_1^o \supset h^0,\ H^0,\ A^0$ $H_2^o \supset h^0,\ H^0,\ A^0$ W^3 B	$\tilde{\gamma}$ $\tilde{Z}$ $\tilde{H}_1^o$ $\tilde{H}_2^o$ $\tilde{W}^3$ $\tilde{B}$	photino zino higgsino higgsino wino bino	$\tilde{\chi}_j^o$ $(j{=}1,\ldots,4)$	neutralinos

- Mass bounds (95% C.L.) from direct searches (PDG 2008) in GeV

$m_{h^0} > 92.8$, $m_{A^0} > 93.4$, $m_{H^\pm} > 79.3$, $m_{\tilde{b}} > 89$, $m_{\tilde{t}} > 95.7$, $m_{\tilde{q}} > 379$, $m_{\tilde{g}} > 308$,

$m_{\tilde{e}} > 73$, $m_{\tilde{\mu}} > 94$, $m_{\tilde{\tau}} > 81.9$, $m_{\tilde{\nu}} > 94$,$m_{\tilde{\chi}_1^0} > 46$, $m_{\tilde{\chi}_1^\pm} > 94$

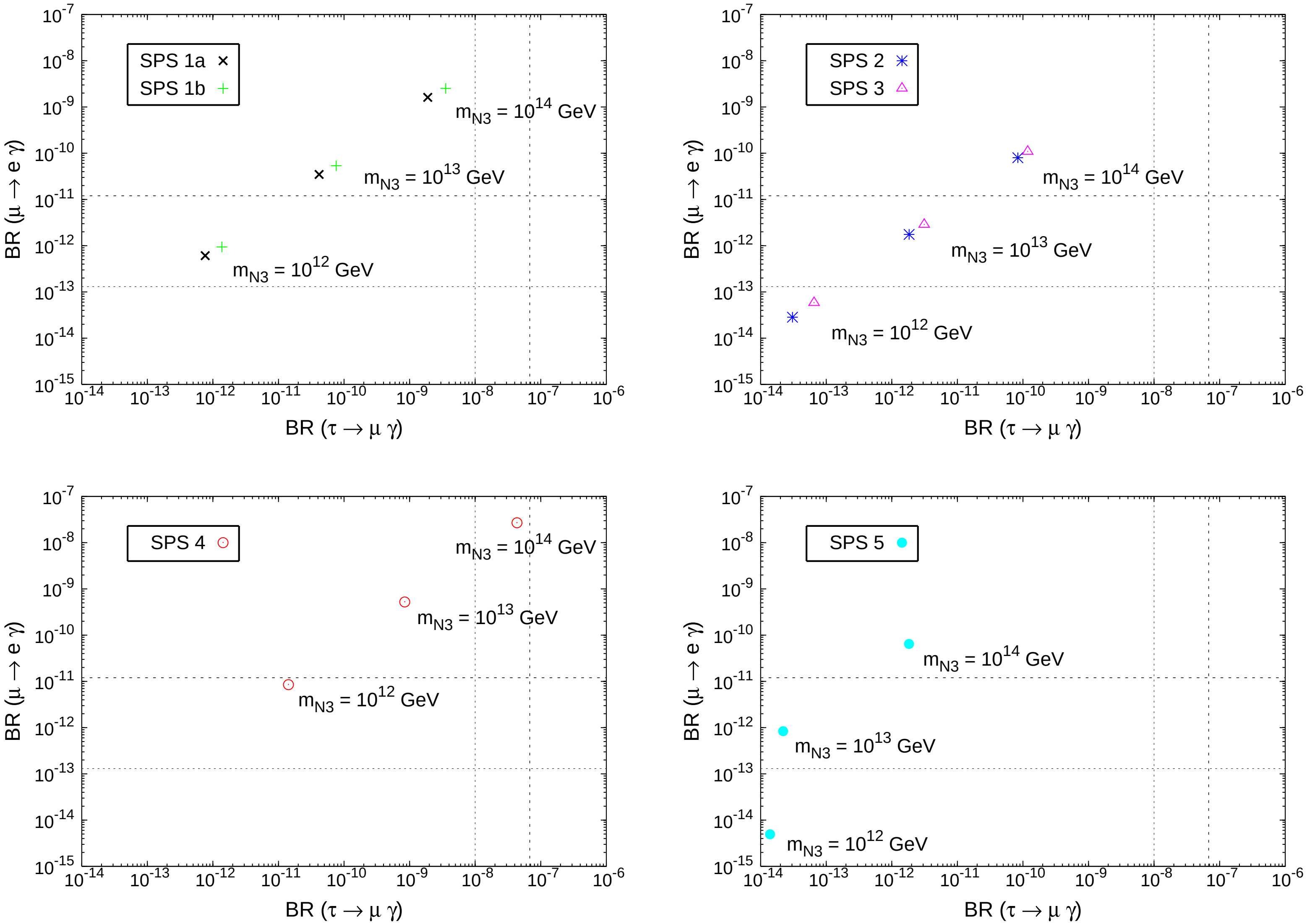
Full RGE vs Leading Log



$$\mathrm{BR}(l_j \to l_i\, \gamma)_{\mathrm{MIA}} = \frac{\alpha^3}{14400\pi^2} \frac{m_{l_j}^5}{\Gamma_{l_j} \sin^4\theta_W} \frac{\tan^2\beta}{m_{\mathrm{SUSY}}^4} \, |\delta_{ji}|^2; \; \delta_{ji}^{\mathrm{LLog}} = \frac{-1}{8\,\pi^2} \frac{(3\,M_0^2 + A_0^2)}{m_{\mathrm{SUSY}}^2} (Y_\nu^\dagger \, L \, Y_\nu)_{ji}; \; L_{kl} = \log\left(\frac{M_X}{m_{N_k}}\right) \delta_{kl}$$

- ⋆ **LLog approximation** fails: $\mathrm{BR}^{\mathrm{LLog}} \approx 10^4 \times \mathrm{BR}^{\mathrm{full}}$ for SPS 5
- ⋆ **Scaling** of $\mathrm{BR}^{\mathrm{full}}$ with m_{N_3} **is not** $|m_{N_3} \log m_{N_3}|^2$ for SPS 5
- ⋆ Checked: **divergence** of $\mathrm{BR}^{\mathrm{full}}$ vs $\mathrm{BR}^{\mathrm{LLog}}$ **enhanced** for **large** A_0
  LLog also fails for low M_0 and large $M_{1/2}$, as in SPS 3
- ⋆ Generically: LLog works better for $A_0 = 0$ and not small M_0
  (Full vs LLog: see also Petcov et al 04; Chankowski et al 04)
  (Full vs MIA: see Paradisi 06, departures of up to $\sim 50\%$ found for $|\delta_{ji}| \sim 1$)

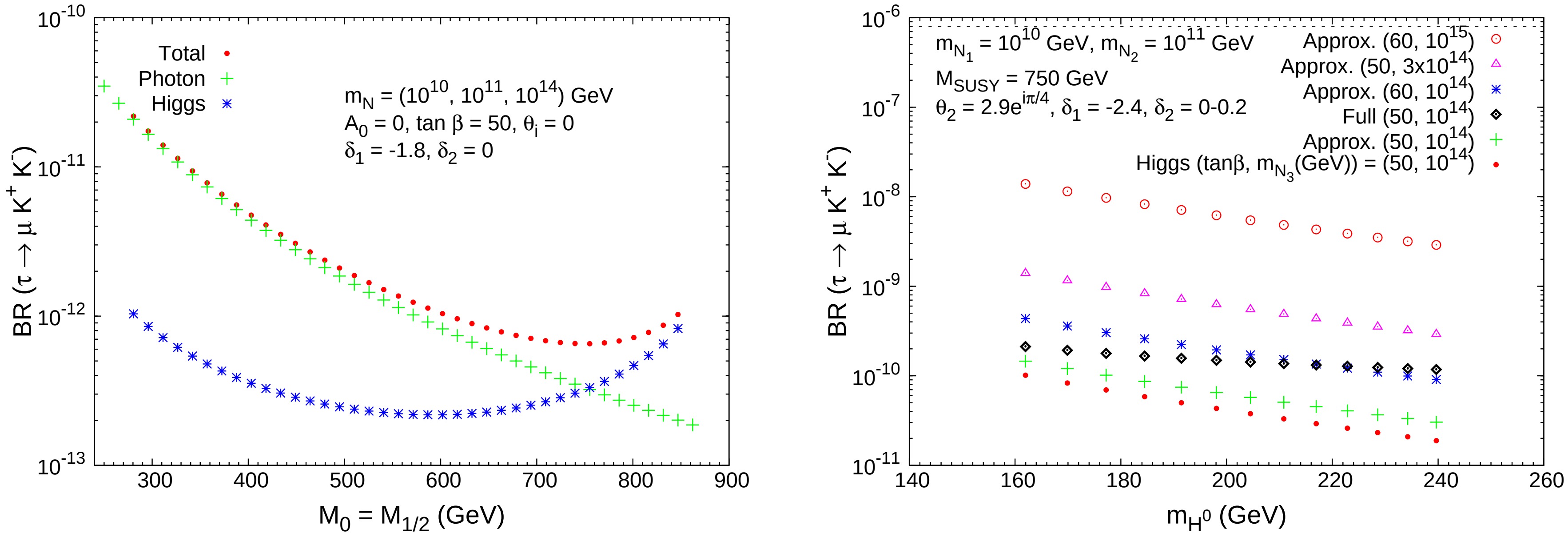
Predictions for other SPS points



Similar results for SPS1b. Slightly worse prospects for SPS2,3. SPS5 the worst.

SPS4 the most restrictive one (due to $\tan\beta = 50$): $m_{N_3} \gtrsim 10^{13}$ GeV disfavoured!!

Not enough sensitivity to Higgs in $\tau \to \mu K K$



γ-dominated at low $M_{\rm SUSY}$, H^0-dominated at large $M_{\rm SUSY}$: SUSY non-decoupling

★ The Higgs contribution is important at large $\tan\beta \gtrsim 50$

Within χPT, and for large $\tan\beta$:

$$g_{HKK} \sim m_K^2 \tan\beta, \text{ since } g_{Hss} \sim m_s \tan\beta \text{ and } B_0 m_s = m_K^2 - \tfrac{1}{2} m_\pi^2$$

★ However, BR below present exp. bound at 6.4×10^{-8} (Prelim,tau08) if $M_{\rm SUSY} \sim \mathcal{O}(1\text{TeV})$

★ Provided usefull approximate formulas at large $\tan\beta$ which work pretty well

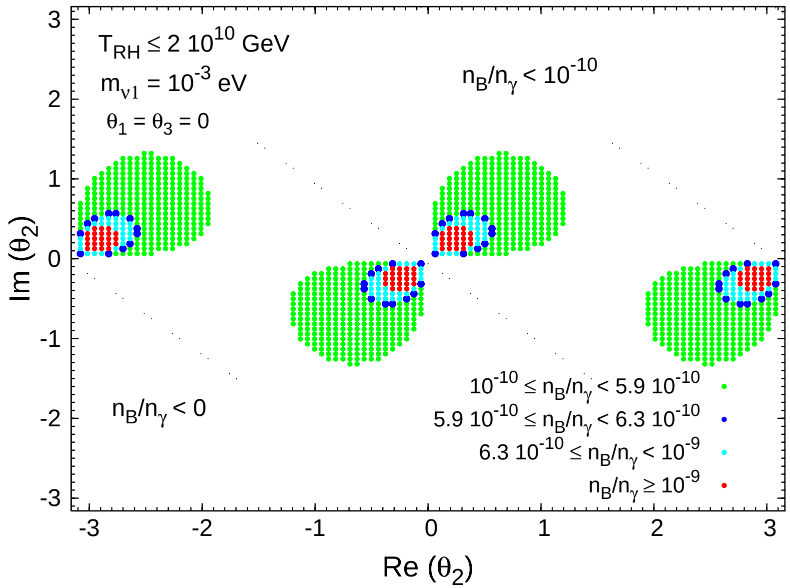
$$\text{BR}(\tau \to \mu K^+ K^-)_{H_{\rm approx}} = 2.8\times10^{-8}\,|\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\text{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim \frac{1}{50}\times \text{BR}_{\text{Cheng-Geng(2006)}}$$

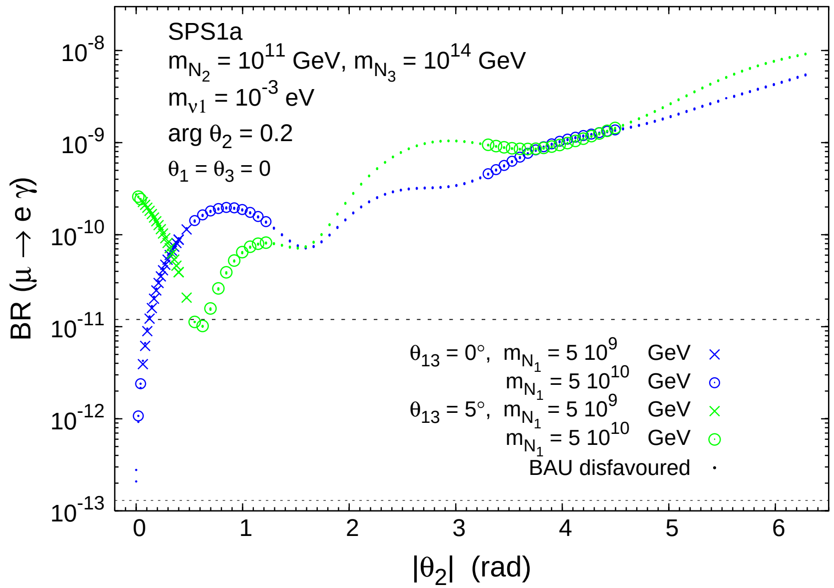
$$\text{BR}(\tau \to \mu K^+ K^-)_{\gamma_{\rm approx}} = 3.0\times10^{-6}\,|\delta_{32}|^2 \left(\frac{100}{M_{\rm SUSY}(\text{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^2$$

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 $\Rightarrow$ (Re(θ_2), Im(θ_2)) $\in$ area ('ring') (WMAP in darkest ring)





Implications for LFV

⋆ **'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 ($\neq 0$) $|\theta_2| \lesssim 1.5$

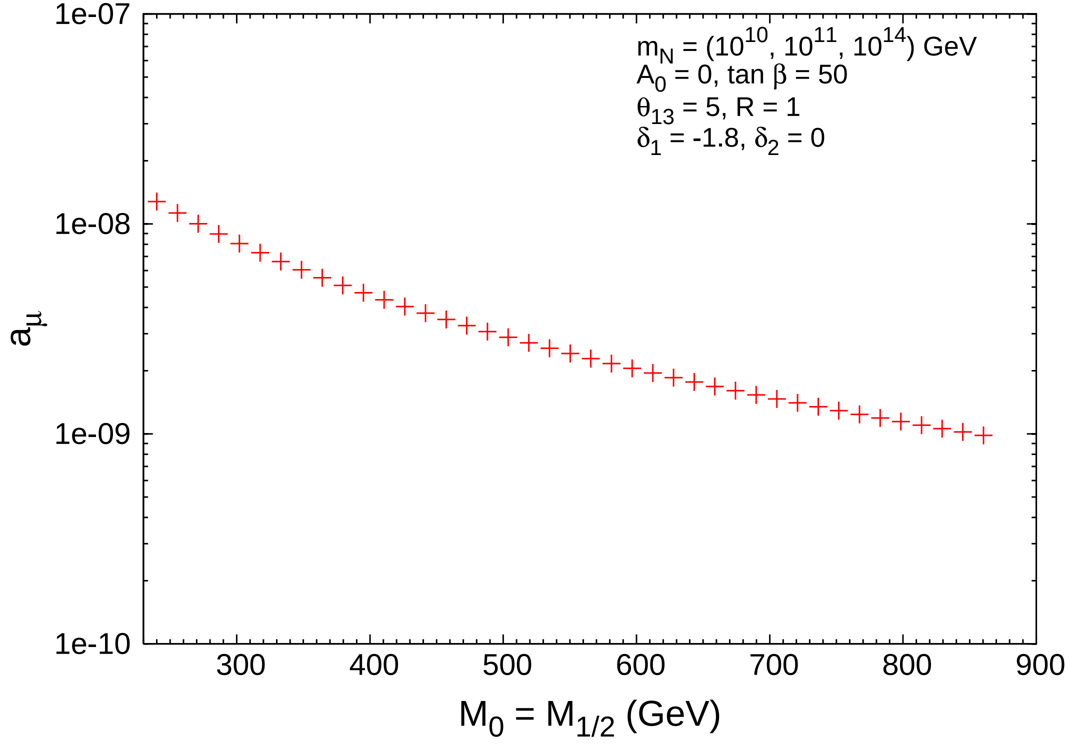
⋆ **smaller** $|\theta_2|$ $\Rightarrow$ **smaller LFV rates**

⋆ 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 $|\theta_2| \sim O(5 \times 10^{-1})$

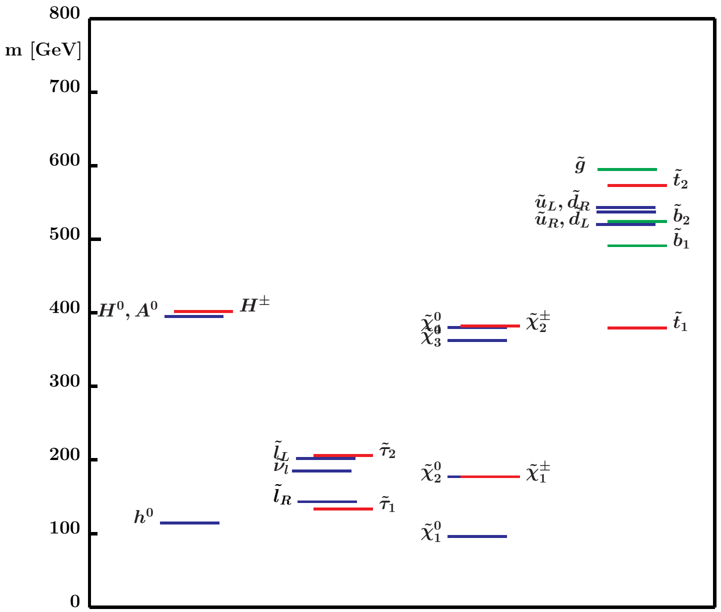
Contributions to $\Delta a_\mu^{\text{SUSY}}$



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

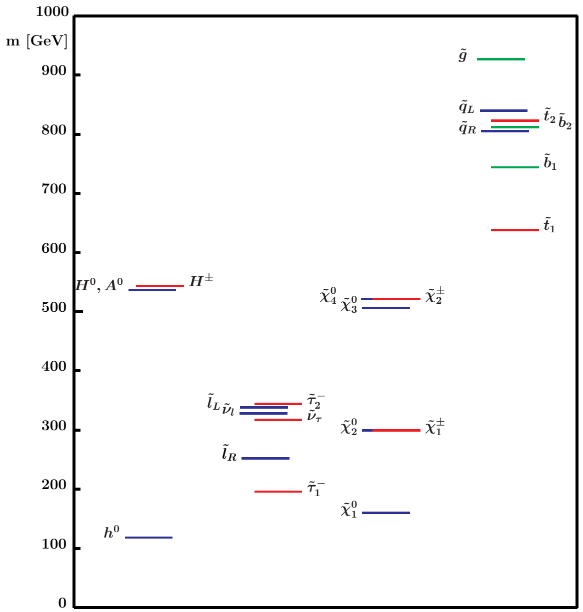
SPS	$M_{1/2}$ (GeV)	M_0 (GeV)	A_0 (GeV)	$\tan\beta$	μ
1 a	250	100	-100	10	> 0
1 b	400	200	0	30	> 0
2	300	1450	0	10	> 0
3	400	90	0	10	> 0
4	300	400	0	50	> 0
5	300	150	-1000	5	> 0

SUSY SPS points (I)



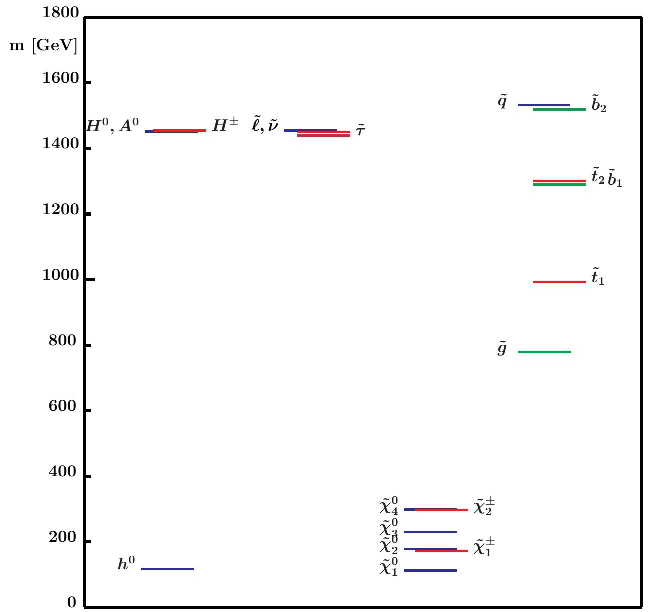
SPS1a

$M_0 = 100$ GeV
$M_{1/2} = 250$ GeV
$A_0 = -100$ GeV
$\tan\beta = 10$
$\mu > 0$



SPS1b

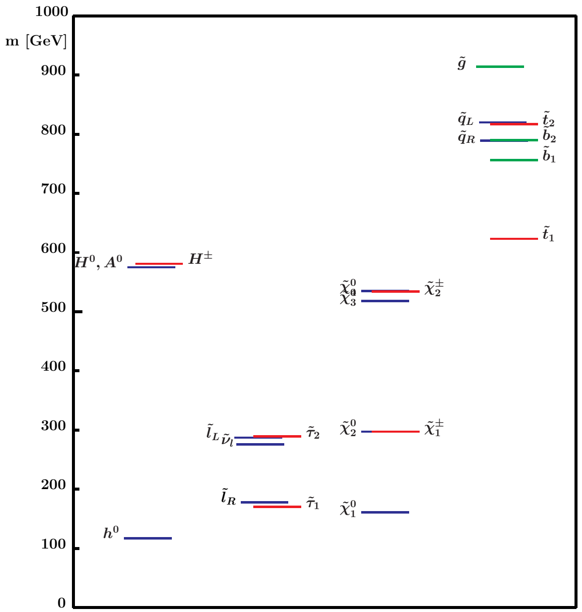
$M_0 = 200$ GeV
$M_{1/2} = 400$ GeV
$A_0 = 0$ GeV
$\tan\beta = 30$
$\mu > 0$



SPS2

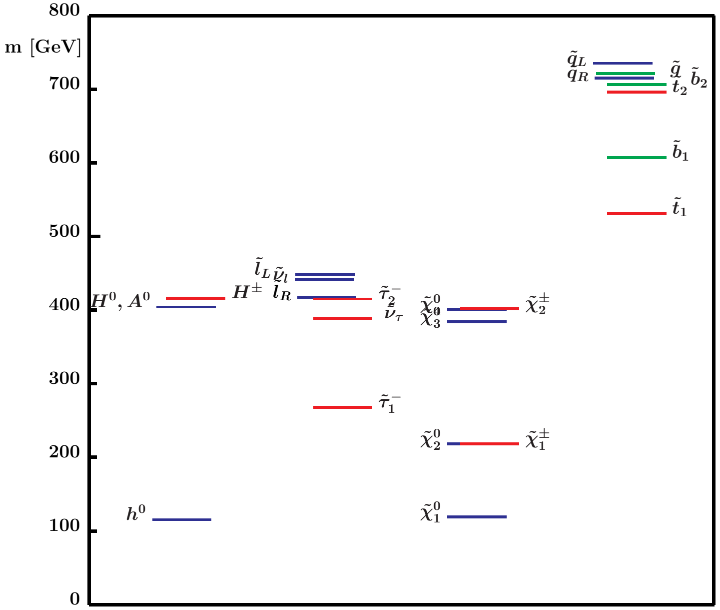
$M_0 = 1450$ GeV
$M_{1/2} = 300$ GeV
$A_0 = 0$ GeV
$\tan\beta = 10$
$\mu > 0$

SUSY SPS points (II)



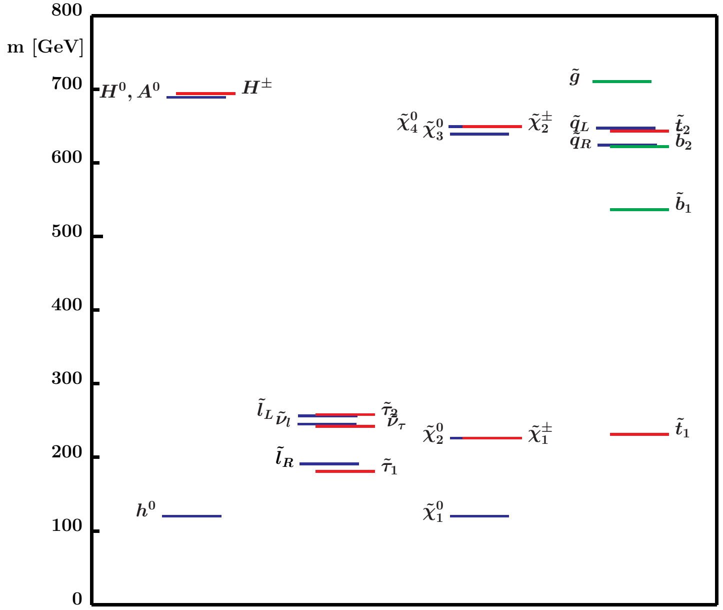
SPS3

$$M_0 = 90 \text{ GeV}$$
$$M_{1/2} = 300 \text{ GeV}$$
$$A_0 = 0 \text{ GeV}$$
$$\tan\beta = 10$$
$$\mu > 0$$



SPS4

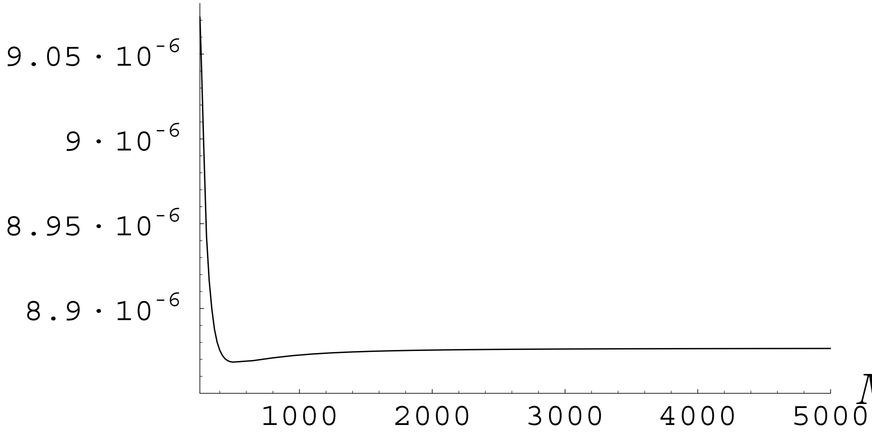
$$M_0 = 400 \text{ GeV}$$
$$M_{1/2} = 300 \text{ GeV}$$
$$A_0 = 0 \text{ GeV}$$
$$\tan\beta = 50$$
$$\mu > 0$$

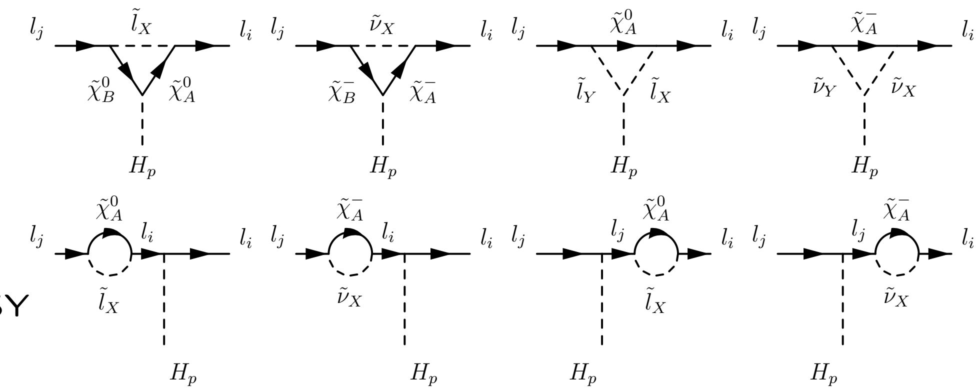


SPS5

$$M_0 = 150 \text{ GeV}$$
$$M_{1/2} = 300 \text{ GeV}$$
$$A_0 = -1000 \text{ GeV}$$
$$\tan\beta = 5$$
$$\mu > 0$$

Non-Decoupling of SUSY in LFV Higgs vertex





$(\delta_{32} = -0.4$, $\tan\beta = 50$, $m_{H_0} = 340\,GeV)$

Large $M_{\rm SUSY} = M_0 = M_{1/2} >> m_Z$, large $\tan\beta$, m_{H^0} fixed (with $\delta_{1,2}$)

$$F_{L(\chi^\pm\tilde{\nu})}^{H^0\tau\mu} \longrightarrow \frac{g^3}{16\pi\sin^2}\frac{m_\tau}{12m_W}\delta_{32}\tan^2\beta$$

$$F_{L(\chi^0\tilde{l})}^{H^0\tau\mu} \longrightarrow \frac{g^3}{16\pi\sin^2}\frac{m_\tau}{24m_W}(1-3\tan^2\theta_W)\delta_{32}\tan^2\beta$$

⋆ The effective Hl_jl_i vertex tends to a **non-vanishing constant at large** $M_{\rm SUSY}$

$\Downarrow$

Non-decoupling of SUSY in Higgs mediated LFV processes: $H \to \tau\bar{\mu}$, $\tau \to 3\mu$, $\tau \to \mu\eta$....

⋆ In contrast to $BR(\tau \to \mu\gamma) \sim (M_W/M_{\rm SUSY})^4$

⋆ Higgs decay rates up to $\sim 10^{-5}$, even for large $M_{\rm SUSY}$ (See also Brignole and Rossi 03)

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 ($F \simeq F_\pi \simeq$ 92.4 MeV, $B_0 F^2 = - < \overline{\psi}\psi >$)

  ⋆ 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)

$$
\begin{aligned}
F_V^{\pi\pi}(s) &= F(s)\ \exp\left[2\, Re\left(\tilde{H}_{\pi\pi}(s)\right) + Re\left(\tilde{H}_{KK}(s)\right)\right] \\
F(s) &= \frac{M_\rho^2}{M_\rho^2 - s - iM_\rho\Gamma_\rho(s)}\left[1 + \left(\delta\,\frac{M_\omega^2}{M_\rho^2} - \gamma\,\frac{s}{M_\rho^2}\right)\frac{s}{M_\omega^2 - s - iM_\omega\Gamma_\omega}\right] \\
&\quad - \frac{\gamma\, s}{M_{\rho'}^2 - s - iM_{\rho'}\Gamma_{\rho'}(s)}\,, \\
\tilde{H}_{PP}(s) &= \frac{s}{F_\pi^2}\left[\frac{1}{12}\left(1 - 4\frac{m_P^2}{s}\right)J_P(s) - \frac{k_P(M_\rho)}{6} + \frac{1}{288\pi^2}\right]\,, \sigma_P(s) = \sqrt{1 - 4\frac{m_P^2}{s}} \\
J_P(s) &= \frac{1}{16\pi^2}\left[\sigma_P(s)\ \ln\frac{\sigma_P(s) - 1}{\sigma_P(s) + 1} + 2\right]\,, k_P(\mu) = \frac{1}{32\pi^2}\left(\ln\frac{m_P^2}{\mu^2} + 1\right)
\end{aligned}
$$

The $\eta(548)$ and $f_0(980)$ mesons

We define $\eta(548)$ via mixing between the octet, η_8, and singlet, η_0, components of the $P(0^-)$ nonet of pseudoscalar Goldstone bosons in χPT

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix} \qquad (2)$$

θ ranges from $\sim -12^\circ$ to $\sim -20^\circ$. We take $\theta \sim -18^\circ$ (Ecker et al)

$$\eta = \frac{1}{2B_0F}\{(\frac{\sqrt{3}}{3}\cos\theta - \frac{\sqrt{6}}{3}\sin\theta)(\overline{u}i\gamma_5 u + \overline{d}i\gamma_5 d) + (-2\frac{\sqrt{3}}{3}\cos\theta - \frac{\sqrt{6}}{3}\sin\theta)\overline{s}i\gamma_5 s\}$$

s most relevant, $g_{Ass} \sim m_s \tan\beta$. Expected large A^0-η mixing at large $\tan\beta$

We define $f_0(980)$ via mixing between the octet, R_8, and singlet, R_0, components of the $R(0^+)$ nonet of resonances in RχT

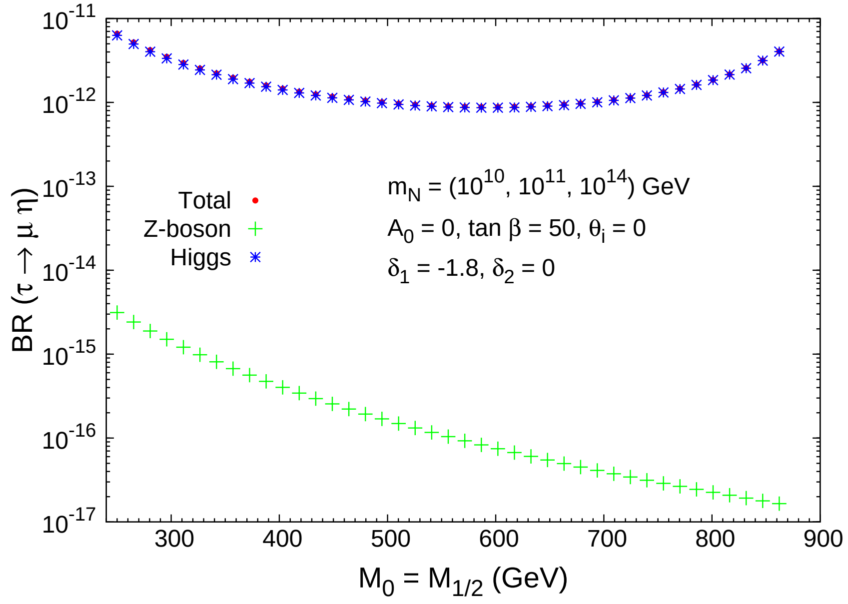
$$\begin{pmatrix} f_0(1500) \\ f_0(980) \end{pmatrix} = \begin{pmatrix} \cos\theta_S & -\sin\theta_S \\ \sin\theta_S & \cos\theta_S \end{pmatrix} \begin{pmatrix} R_8 \\ R_0 \end{pmatrix} \qquad (3)$$

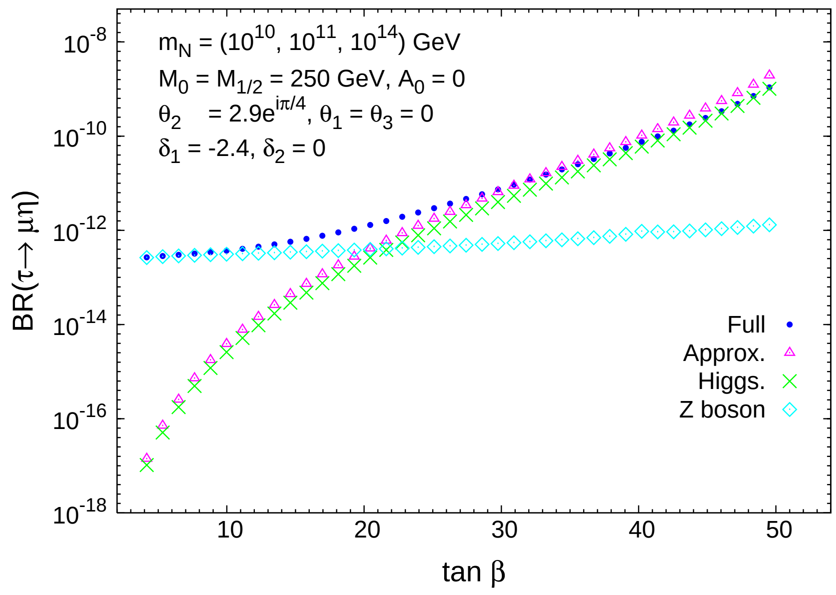
θ_S quite uncertain. We take $\theta_S \sim 7^\circ$ and $\theta_S \sim 30^\circ$ (Cirigliano et al)

$$f_0 = \frac{1}{2\sqrt{2}B_0F}\{(-\frac{\sqrt{6}}{3}\cos\theta_S - \frac{\sqrt{3}}{3}\sin\theta_S)(\overline{u}u + \overline{d}d) + (-\frac{\sqrt{6}}{3}\cos\theta_S + 2\frac{\sqrt{3}}{3}\sin\theta_S)\overline{s}s\}$$

s most relevant: $g_{H^0ss} \sim m_s\frac{\cos\alpha}{\cos\beta}$. Expected large H^0-f_0 mix. at large $\tan\beta$

The $\tau \to \mu\eta$ channel





Z-dominated at $\tan\beta \lesssim 15$, A^0-dominated at $\tan\beta \gtrsim 30$. Not much dependent on M_{SUSY}

- ⋆ Provided usefull approximate formulas, valid at large $\tan\beta \gtrsim 30$

$$\text{BR}(\tau \to \mu\eta)_{H_{\text{approx}}} = \frac{1}{8\pi m_\tau^3}\left(m_\tau^2 - m_\eta^2\right)^2 \left| \frac{g}{2m_W}\frac{F}{m_{A^0}^2} B_L^{(A^0)}(\eta)\, H_{L,c}^{(A^0)} \right|^2 \frac{1}{\Gamma_\tau}$$

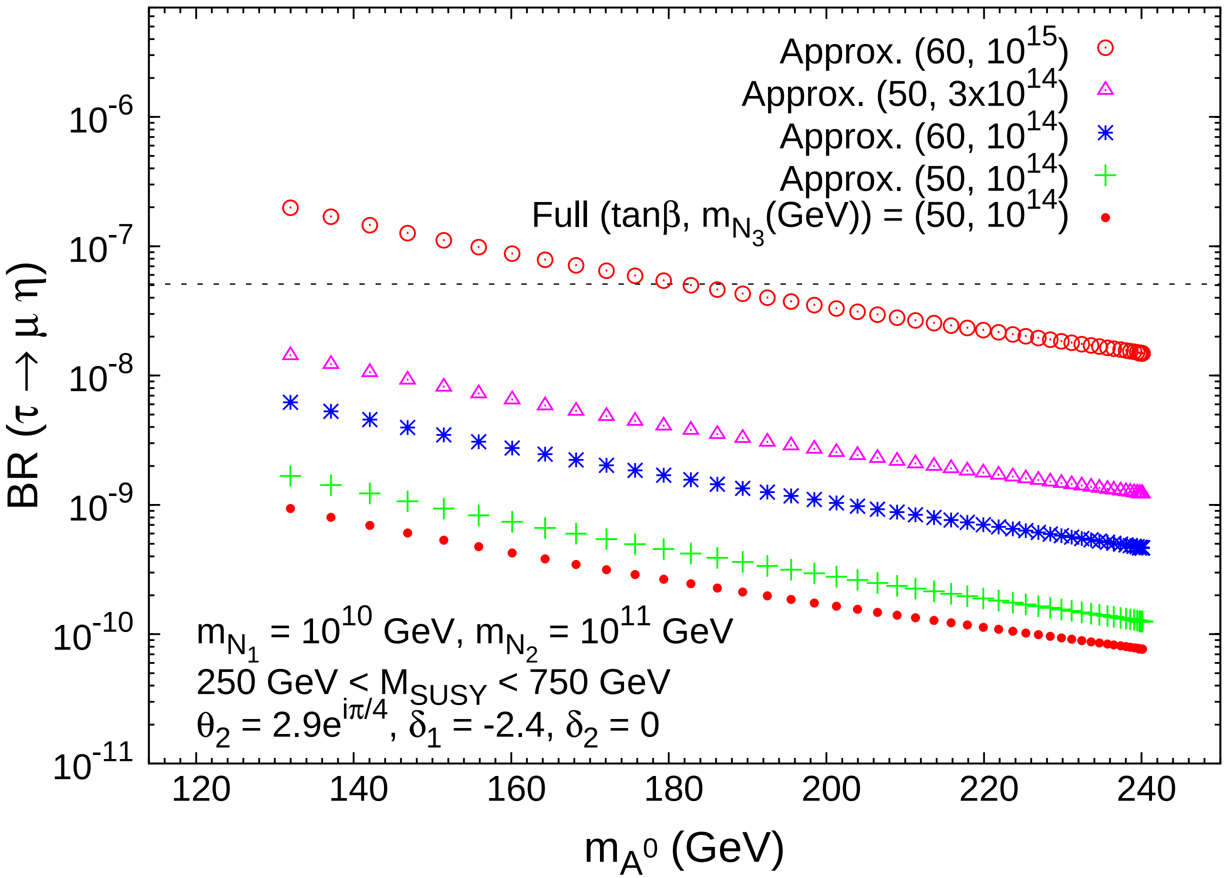
$$= 1.2 \times 10^{-7} \, |\delta_{32}|^2 \left(\frac{100}{m_{A^0}(\text{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim \frac{1}{7} \times \text{BR}_{\text{Sher(2002)}}$$

$$H_{L,c}^{(A^0)} = i\,\frac{g^3}{16\pi^2}\frac{m_\tau}{12 m_W}\,\delta_{32}\tan^2\beta\,, \quad \text{LFV form factor}$$

$$B_L^{(A^0)}(\eta) = -i\frac{1}{4\sqrt{3}}\tan\beta\left[(3m_\pi^2 - 4m_K^2)\cos\theta - 2\sqrt{2}m_K^2\sin\theta\right]\,, \quad \text{hadronic form factor}$$

- ⋆ The χPT mass relation $B_0 m_s = m_K^2 - \frac{1}{2}m_\pi^2$ (and $F \simeq F_\pi$) is used everywhere

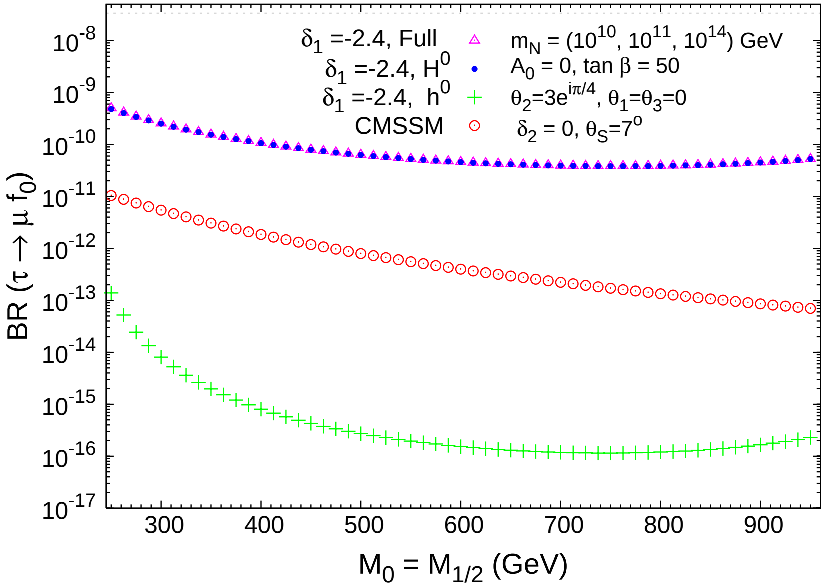
Sensitivity to Higgs in $\tau \to \mu\eta$ within NUHM

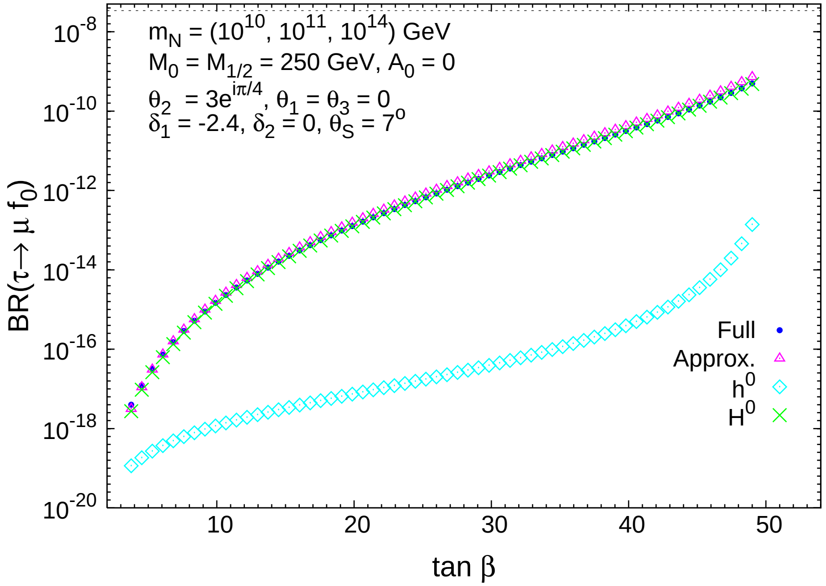


⋆ Great sensitivity to A^0 found in $\tau \to \mu\eta$ within NUHM
BR($\tau \to \mu\eta$) at exp. bound for $m_{N_3} = 10^{15}$ GeV, $\tan\beta = 60$, $\theta_2 = 3e^{i\pi/4}$

⋆ The approximate formula works quite well (within a factor 1.5-2)

Results for $\tau \to \mu f_0$ (new)





Totally dominated by H^0 at all $\tan\beta$ and $M_{\rm SUSY}$, h^0 negligible. Not much dependent on $M_{\rm SUSY}$

★ Provided approximate formulas, valid at all studied $\tan\beta$. They work pretty well

$$\mathrm{BR}(\tau \to \mu f_0(980))_{\rm approx} = \frac{1}{16\pi m_\tau^3}\left(m_\tau^2 - m_{f_0}^2\right)^2 \left| \frac{g}{2m_W}\frac{1}{m_{H^0}^2} J_L^{(H^0)} H_{L,c}^{(H^0)}\right|^2 \frac{1}{\Gamma_\tau}$$

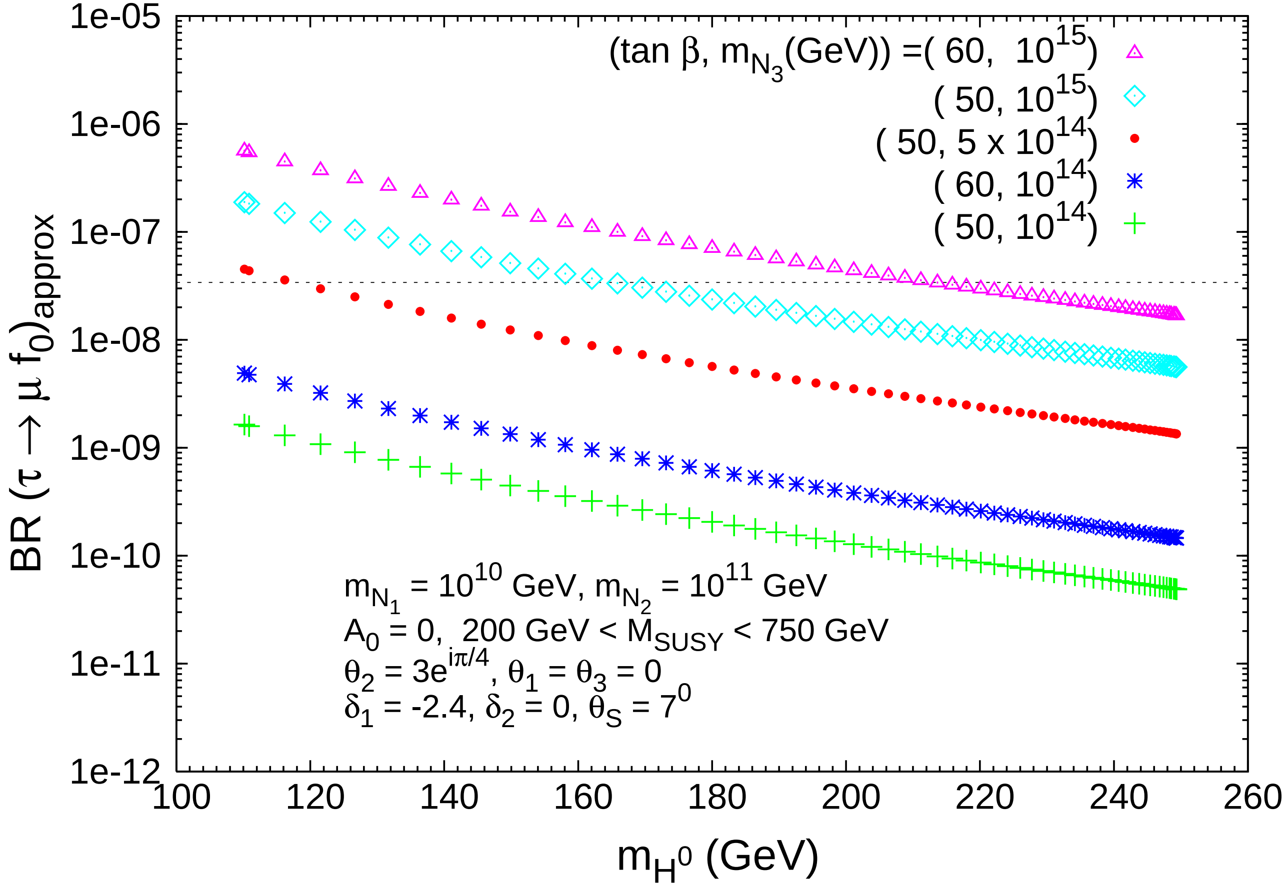
$$= \begin{pmatrix} 7.3\times 10^{-8}\ (\theta_S = 7^\circ) \\ 4.2\times 10^{-9}\ (\theta_S = 30^\circ)\end{pmatrix} |\delta_{32}|^2 \left(\frac{100}{m_{H^0}(\mathrm{GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim \frac{1}{20}\mathrm{BR}_{\rm Chen-Geng(2006)}$$

$$H_{L,c}^{(H^0)} = \frac{g^3}{16\pi^2}\frac{m_\tau}{12 m_W}\delta_{32}\tan^2\beta\,, \quad \text{LFV form factor}$$

$$J_L^{(H^0)} = \frac{F}{2\sqrt{3}}\tan\beta\left[\frac{3}{\sqrt{2}}\sin\theta_S\, m_\pi^2 + (\cos\theta_S - \sqrt{2}\sin\theta_S)2m_K^2\right]\,, \quad \text{hadronic form factor}$$

★ Large BR are found for light $m_{H^0} \sim 115 - 250$ GeV within NUHM

Sensitivity to Higgs in $\tau \to \mu f_0$ within NUHM



⋆ We find great sensitivity to H^0 in this channel within NUHM

For large $m_{N_3} \sim 5 \times 10^{14} - 10^{15}$ GeV and large $\tan\beta \sim 50 - 60$ the rates are at the present experimental reach

(Note: In the comparison with present exp bound we are assuming $\text{BR}(f_0 \to \pi^+\pi) \simeq 1$)

Framework for $\mu - e$ conversion in nuclei

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

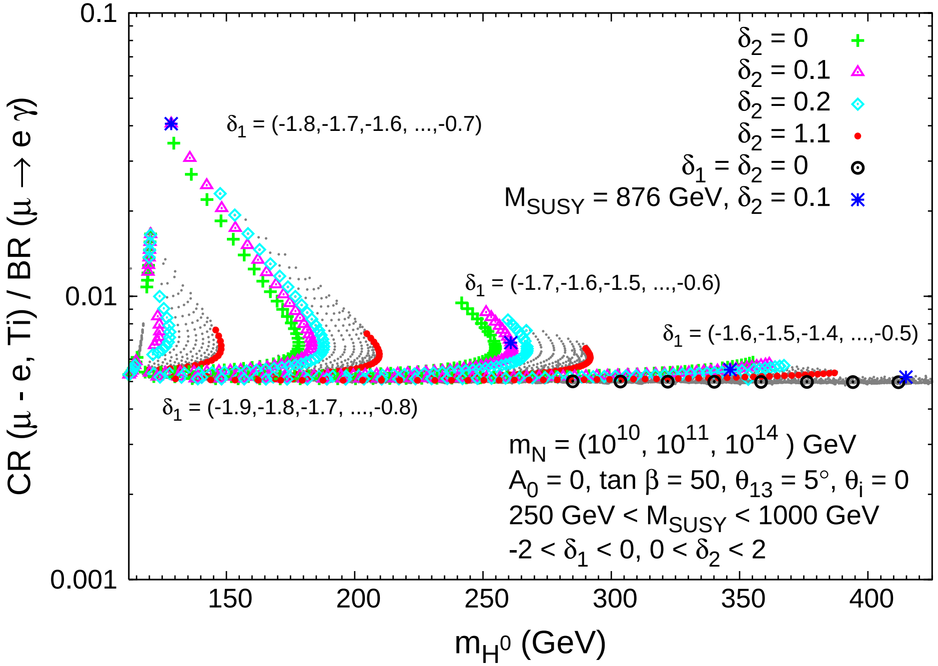
  ⋆ Equal proton and neutron densities in the nucleus; non-relativistic μ wave function for the 1s state; neglect momentum dependence of nucleon form factors

  ⋆ $\mu - e$ 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.

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

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 $\mu \to e\gamma$ 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

Approx. formulae for LFV semilep. τ decays

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

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

$$BR(\tau \to \mu\eta')_{H_{\rm approx}} = 1.5 \times 10^{-7}\, |\delta_{32}|^2 \left(\frac{100}{m_{A^0}({\rm GeV})}\right)^4 \left(\frac{\tan\beta}{60}\right)^6 \sim BR_{\rm Brignole-Rossi} {\rm NPB701(04)3}$$

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

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

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

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

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

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

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

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

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

Seesaw mechanism with $3\,\nu_R$

For 3 generations $\Rightarrow$ 6 physical neutrinos: 3 ν light, 3 N heavy

$$U^{\nu T} M^{\nu} U^{\nu} = \widehat{M}^{\nu} = diag(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_{N_1}, m_{N_2}, m_{N_3}).$$

$$m_D \ll m_M,\; m_D = Y_\nu < H_2 > \Rightarrow$$

$$m_\nu^{diag} = U_{\text{PMNS}}^T m_\nu U_{\text{PMNS}}$$
$$m_N^{diag} = m_N$$

$$\begin{cases} m_\nu \approx -m_D {m_M}^{-1} m_D^T \text{ (light)} \\ m_N \approx m_M \text{ (heavy)} \end{cases}$$

All, Y_ν, m_D, m_M, U_{PMNS}, are 3×3 matrices; $c_{ij} \equiv \cos(\theta_{ij})$, $s_{ij} \equiv \sin(\theta_{ij})$

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times diag(1, e^{i\alpha}, e^{i\beta})$$

Pontecorvo-Maki-Nakagawa-Sakata matrix: θ_{12}, θ_{13}, θ_{23}, δ, α, β

Our choice of input parameters

Spectra= MSSM content $+3\nu_R + 3\tilde{\nu}_R$

- CMSSM:

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

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

Choose $M_0 = M_{1/2},\ M^2_{H_1} = M^2_0(1+\delta_1),\ M^2_{H_2} = M^2_0(1+\delta_2)$

- 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:

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

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

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

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

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