Lepton Flavour Violation in SUSY-seesaw: an update

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From works

E.Arganda and M.H. PRD73,055003(2006)

S.Antusch, E.Arganda, M.H. and A.Teixeira JHEP 0611(2006)090

E.Arganda, M.H. and A.Teixeira hep-ph/0707.2955

E.Arganda, M.H. and J.Portolés IFT-UAM/CSIC-07-27

SUSY07, Karlsruhe, 27-July-2007

Motivation

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

⋆ In SM: no LFV if $m_\nu = 0$; very suppresed if $m_\nu \neq 0$

⋆ Many exp. bounds (present/future sensitivities):

MEGA, SINDRUM, BABAR, Belle / MEG,...PRISM/PRIME

$\text{BR}(\mu \to e\gamma)$	$<$	$1.2 \times 10^{-11}/10^{-13}$	$\text{BR}(\tau \to \mu\eta)$	$<$	6.5×10^{-8}
$\text{BR}(\tau \to \mu\gamma)$	$<$	$4.5 \times 10^{-8}/10^{-8}$	$\text{BR}(\tau \to \mu\eta')$	$<$	1.3×10^{-7}
$\text{BR}(\tau \to e\gamma)$	$<$	$1.2 \times 10^{-7}/10^{-8}$	$\text{BR}(\tau \to \mu\pi)$	$<$	1.2×10^{-7}
$\text{BR}(\mu \to 3e)$	$<$	$1.0 \times 10^{-12}/10^{-13}$	$\text{BR}(\tau \to \mu\rho)$	$<$	2×10^{-7}
$\text{BR}(\tau \to 3\mu)$	$<$	$1.9 \times 10^{-7}/10^{-8}$	$\text{CR}(\mu - e, \text{Au})$	$<$	7×10^{-13}
$\text{BR}(\tau \to 3e)$	$<$	$2.0 \times 10^{-7}/10^{-8}$	$\text{CR}(\mu - e, \text{Ti})$	$<$	$4.3 \times 10^{-12}/\mathbf{10^{-18}}$
.....			....		

⋆ Measurement of LFV ⇒ Window for new physics

⋆ Very sensitive to SUSY: if Majorana ν, Y_ν can be $\mathcal{O}(1)$

Large Y_ν induce, via SUSY loops, large LFV rates

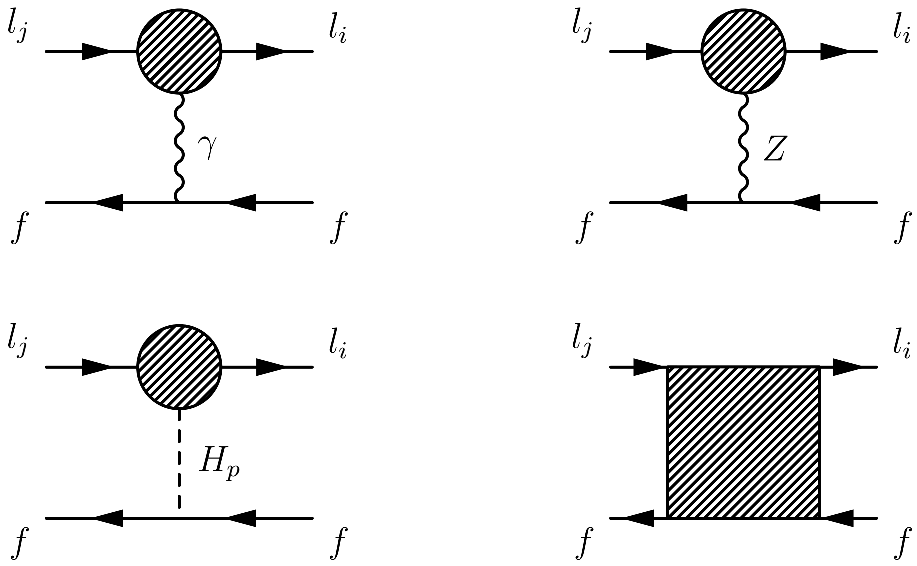
⋆ If no LFV found ⇒

Restrictions on SUSY and/or seesaw parameters

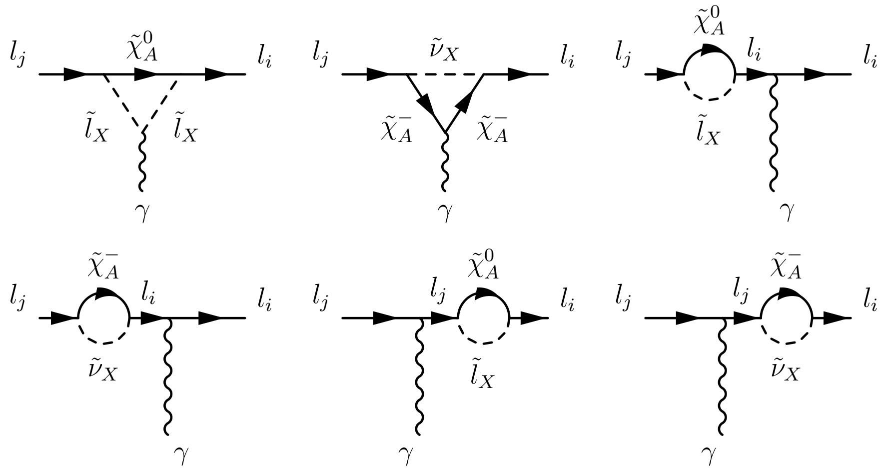
Our Work

- **Prediction of LFV rates within SUSY-seesaw:**
  - ⋆ all $l_j \to l_i \gamma$
  - ⋆ all $l_j \to 3 l_i$
  - ⋆ some semileptonic tau decays: $\tau \to \mu\eta$, $\tau \to \mu\pi$, $\tau \to \mu\rho$...
  - ⋆ $\mu - e$ conversion in nuclei: Ti, Au,...
- **Full one-loop computation of LFV BRs**
- **Require compatibility with ν data**
- **Compare with present/future LFV bounds/sensitivities**
- **Explore sensitivity to SUSY and seesaw parameters**
- **Study impact of θ_{13} on LFV, specially $\mu - e$**
- **Study of correlated/un-correlated processes: competing future sensitivities?**

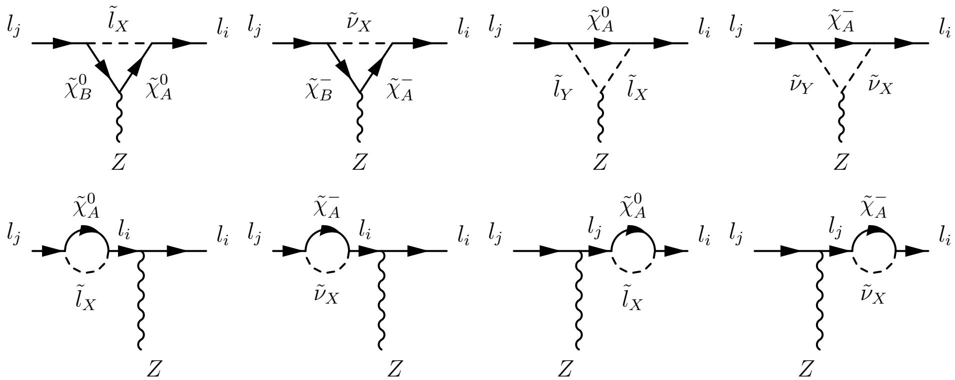
1-loop diagrams in $l_j \to 3l_i$, $\tau \to \mu$ hadrons, $\mu - e$ conversion



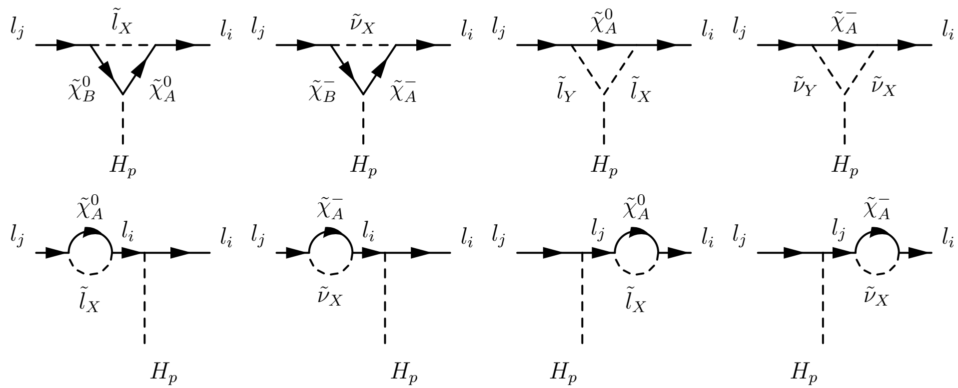
Generic



Photon-mediated



Z boson-mediated



H boson-mediated

Framework

- **Use seesaw (Type I) for ν mass generation**
- **Work within CMSSM + $3\nu_R$ (Majorana) + $3\tilde{\nu}_R$**

  Two scenarios for soft parameters at $M_X = 2 \times 10^{16}$ GeV:

  ⋆ Universal soft Higgs masses: CMSSM-seesaw
  $(M_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu))$

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

- 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 MIA approx)

- **Numerical estimates:**

  ⋆ SPheno 2.2.2 (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 $(g-2)_\mu$

Seesaw parameters versus neutrino data

SeeSaw equation: $m_\nu = -m_D^T {m_N}^{-1} m_D$

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

R is a 3×3 complex matrix and orthogonal

$$R = \begin{pmatrix} c_2c_3 & -c_1s_3 - s_1s_2c_3 & s_1s_3 - c_1s_2c_3 \\ c_2s_3 & c_1c_3 - s_1s_2s_3 & -s_1c_3 - c_1s_2s_3 \\ s_2 & s_1c_2 & c_1c_2 \end{pmatrix}, \; c_i = \cos\theta_i \,,\; s_i = \sin\theta_i \,,\; \theta_{1,2,3} \text{ complex}$$

Parameters: θ_{ij},δ,α,β,m_{ν_i},m_{N_i},θ_i **(18)** ; m_{N_i}, θ_i drive the size of Y_ν

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

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:

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

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

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

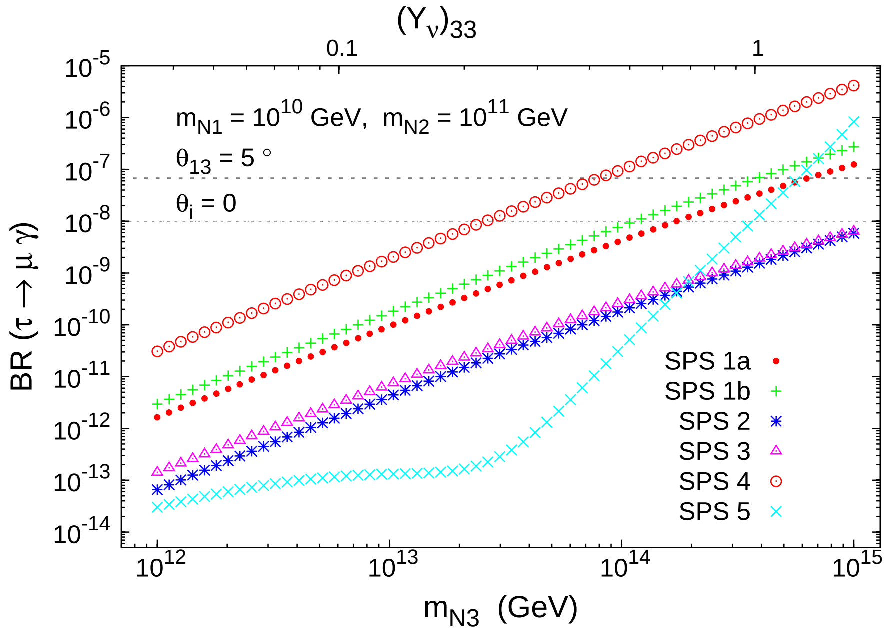
- Seesaw parameters $\left\{\begin{array}{l} m_{\nu_{1,2,3}} \text{ (set by data)} \\ m_{N_{1,2,3}} \text{ (input)} \\ U_{MNS} \text{ (set by data)} \\ R(\theta_1,\ \theta_2,\ \theta_3) \text{ (input)} \end{array}\right.$

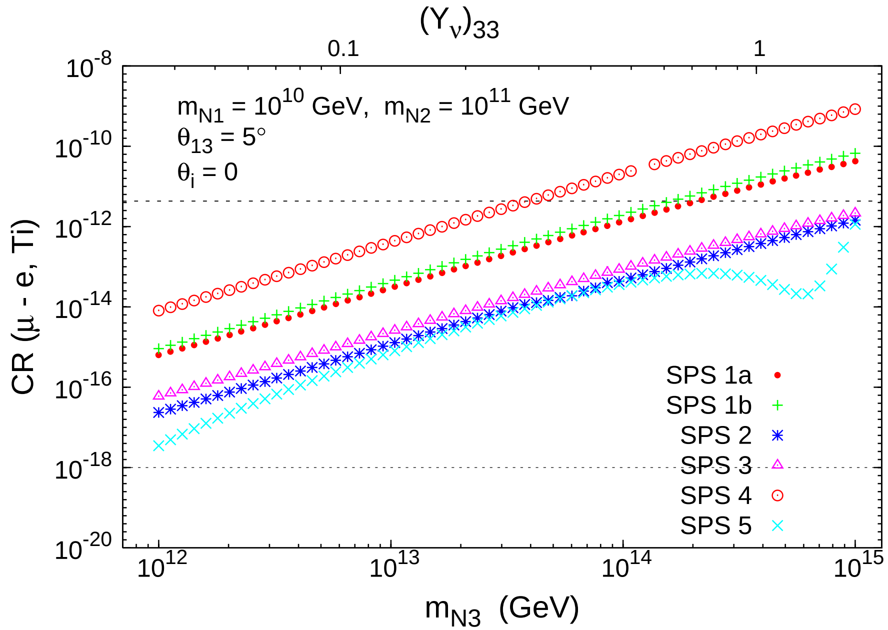
- For numerical estimates:

$$(\Delta m^2)_{12} = \Delta m^2_{\text{sol}} = 8\times 10^{-5}\ \text{eV}^2$$
$$(\Delta m^2)_{23} = \Delta m^2_{\text{atm}} = 2.5\times 10^{-3}\text{eV}^2$$
$$\theta_{12} = 30^o;\ \theta_{23} = 45^o;\ \delta = \alpha = \beta = 0;\ \ 0 \leq \theta_{13} \leq 10^o$$
$$250\text{ GeV} < M_0, M_{1/2} < 1000\text{ GeV},\ -500\text{ GeV} < A_0 < 500\text{ GeV}$$
$$5 < \tan\beta < 50,\ -2 < \delta_{1,2} < 2$$

Results for CMSSM-seesaw

The most relevant paramenter:
Hierarchical: m_{N_3} / Degenerate: m_N





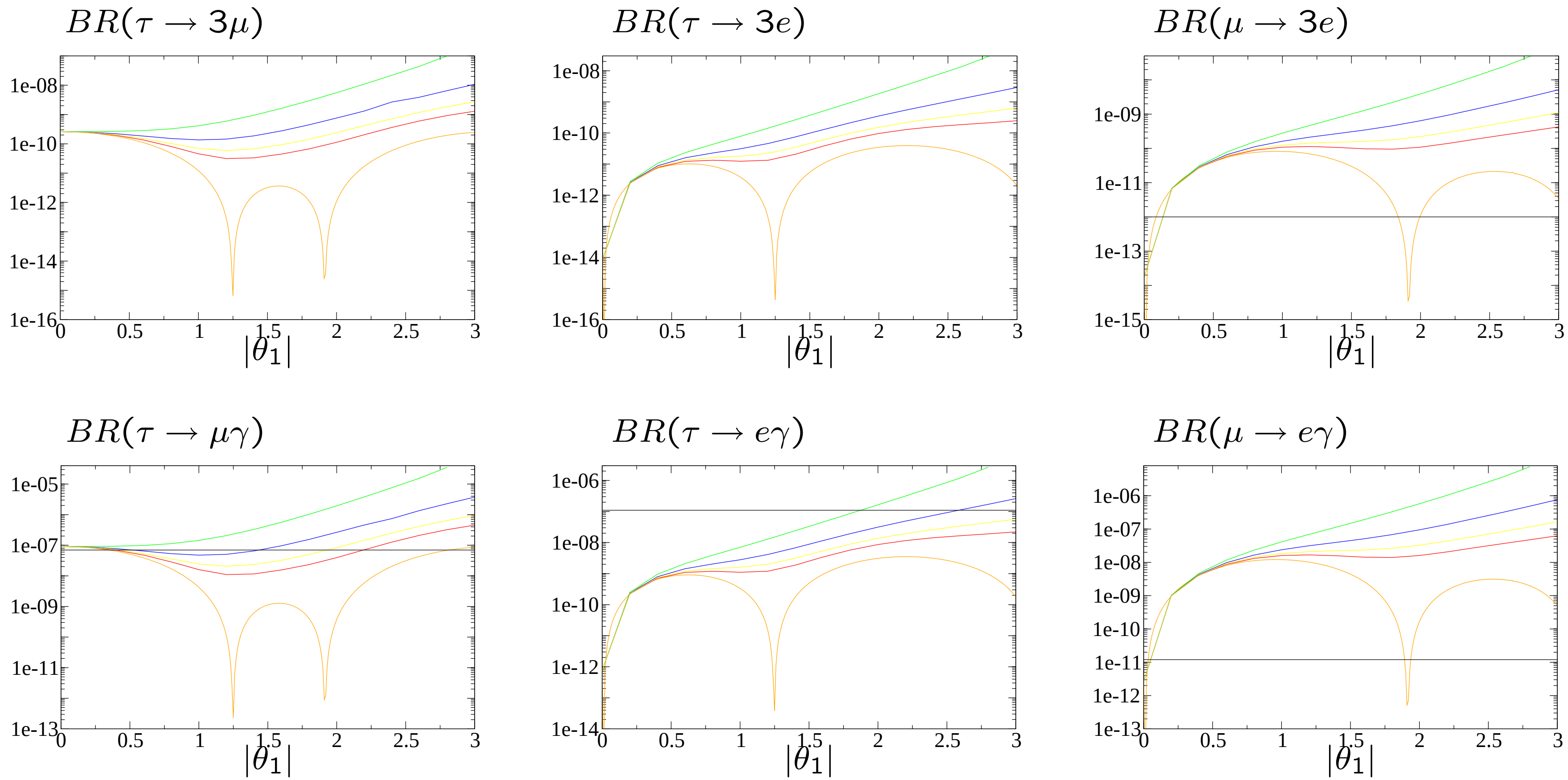
- ⋆ Most obs. reach exp. lim. at $m_{N_3} \in \left[10^{13}, 10^{15}\right]$ GeV,$(Y_\nu)_{33,32} \sim 0.1 - 1$
- ⋆ BR_4 $(\tan\beta = 50)$ $> \mathrm{BR}_{1b} \gtrsim \mathrm{BR}_{1a}$ $> \mathrm{BR}_3 \gtrsim \mathrm{BR}_2 > \mathrm{BR}_5$
- ⋆ BR$\sim |m_{N_3} \log m_{N_3}|^2$ except for SPS5: Llog fails in $\sim 10^4$!!
- ⋆ Present: the most restrictive one is $\mu \to e\gamma$ (if $\theta_{13} \neq 0$)
  Bounds for SPS1a $m_{N_3} < 10^{13} - 10^{14}$ GeV
  Next are $\mu - e$, $\mu \to 3e$; $\tau \to \mu\gamma$ competitive if $\theta_{13} \simeq 0$ and N's hier.
- ⋆ Future: $\mu - e$ conversion the best: sensitive to $m_{N_3} > 10^{12}$ GeV

Large Yukawa couplings: role of θ_i

Hierarchical m_{N_i} and complex θ_i

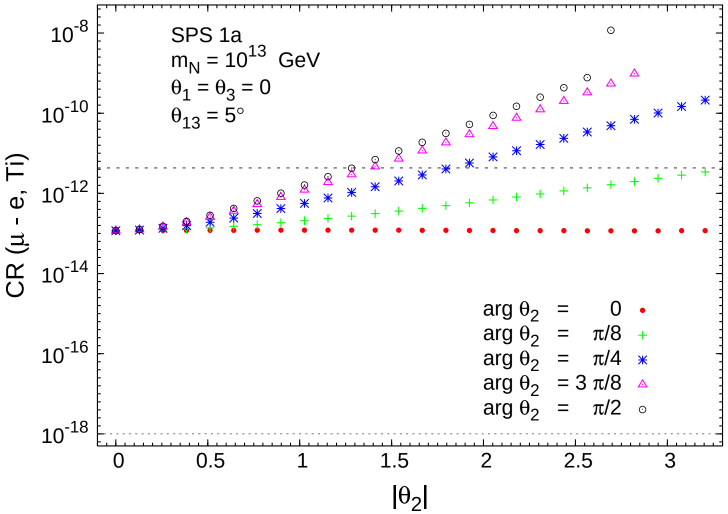
$(m_{N_1}, m_{N_2}, m_{N_3}) = (10^8, 2 \times 10^8, 10^{14})$ GeV, $\arg(\theta_1) = 0, \pi/10, \pi/8, \pi/6, \pi/4 \; (\theta_2 = \theta_3 = 0)$

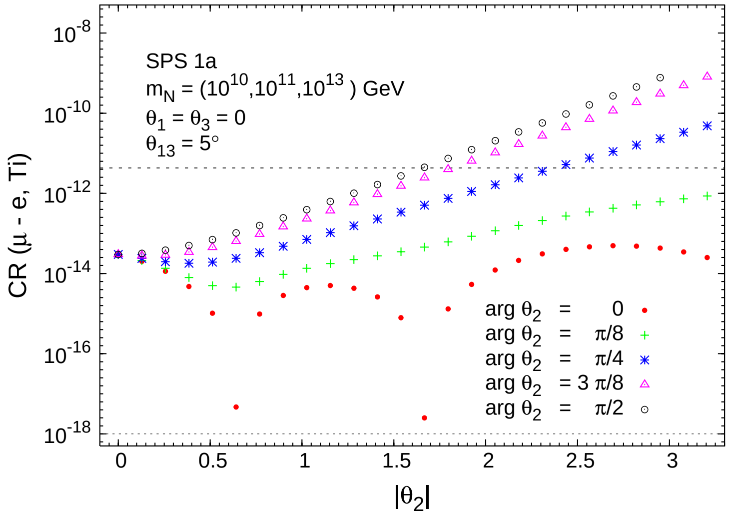
SPS 4



- ⋆ 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

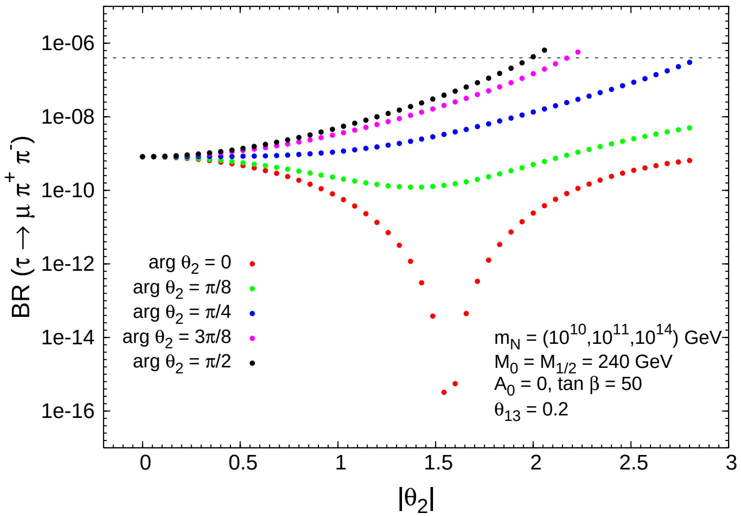
Role of θ_i (cont.)





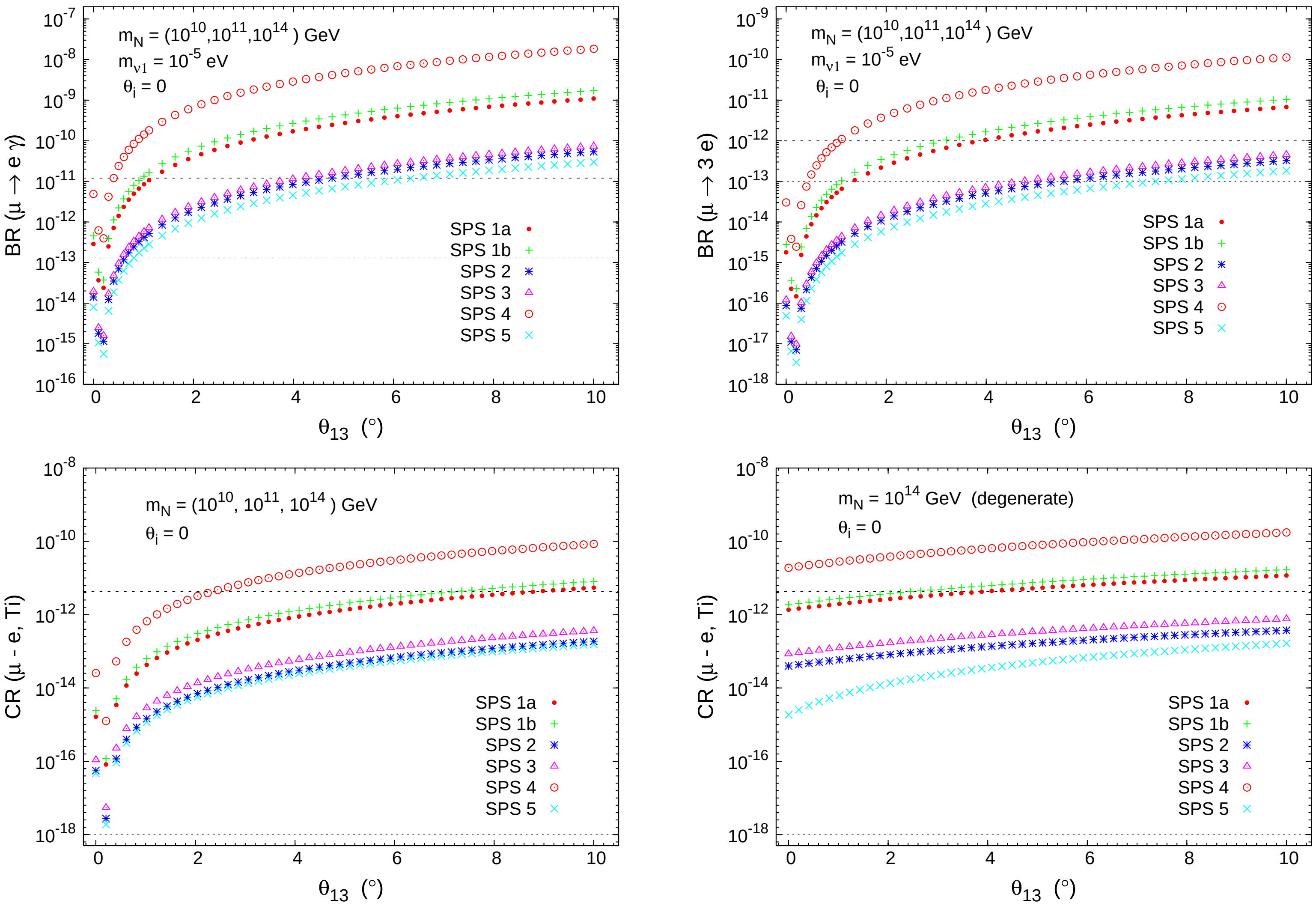
N's Deg. Eq. dep. all θ_i — N's Hier. relevant: $\theta_{1,2}$

★ CR($\mu - e$) reach exp. bound even for $m_N = 10^{13}$ GeV if complex $\theta_i \neq 0$



★ BR($\tau \to \mu\pi^+\pi^-$) reach exp. bound at high $m_{N_3} \sim 10^{14}$ GeV and large complex $\theta_{1,2}$

High sensitivity to θ_{13}: the case $\theta_i = 0$

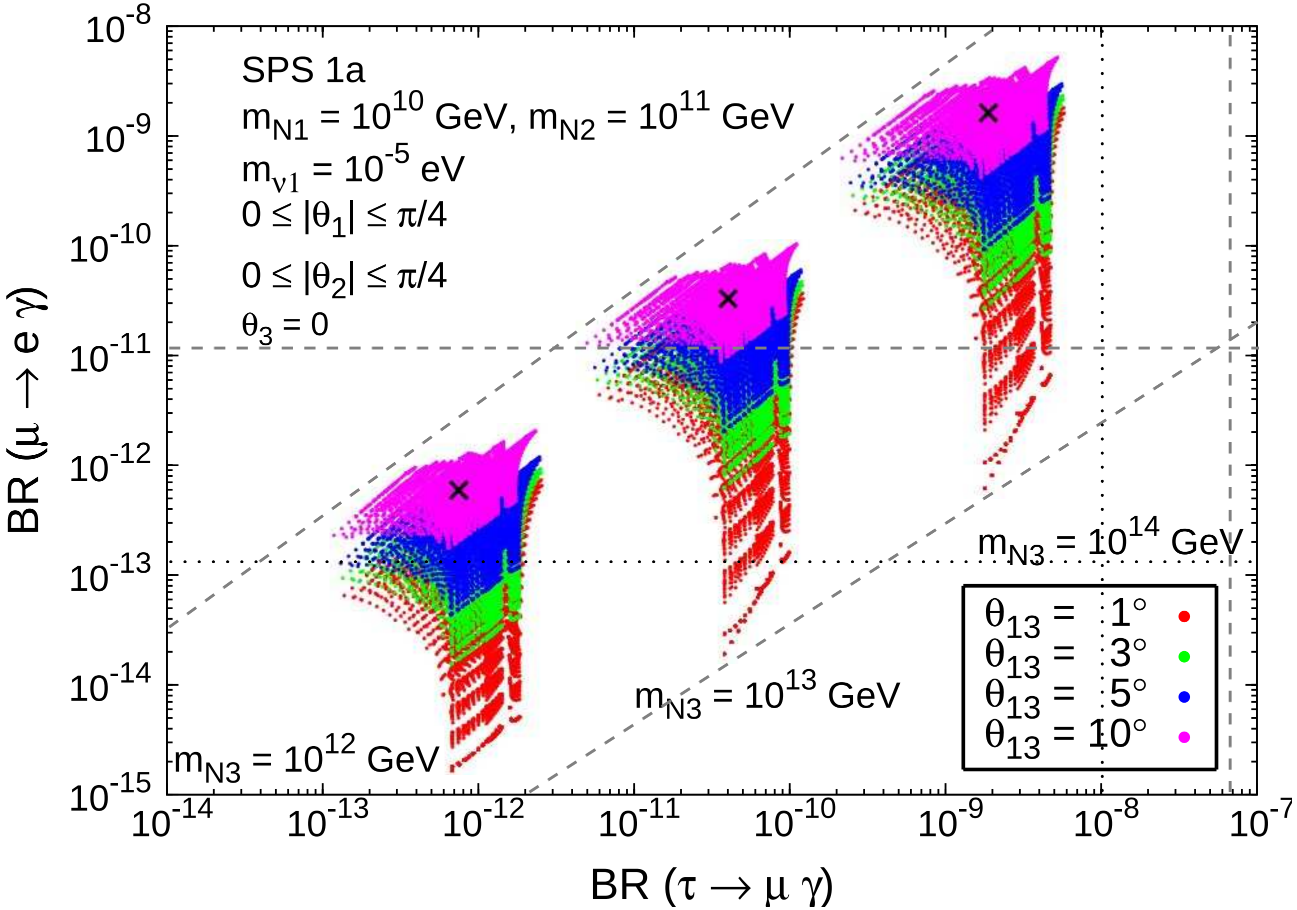


- ⋆ $\mu \to e\gamma$, $\mu \to 3e$, $\mu - e$ extremely sensitive to θ_{13} if Hier.N's: BRs $\times 10^5$ in $0^\circ < \theta_{13} < 10^\circ$
- ⋆ $\tau \to e\gamma$, $\tau \to 3e$ also, but not within exp.reach ($\tau \to \mu\gamma$, $\tau \to 3\mu$ are not!!)
- ⋆ Sensitivity of $\mu \to e\gamma$ clearly **within exp. reach**: $\text{BR}_{\text{all SPS}} > \text{BR}_{\text{exp}}^{\text{present}}$ for $\theta_{13} \gtrsim 5^o$!!

Impact of θ_{13} on LFV processes

(All plotted points lead to 'viable BAU', respect EDM bounds, OK with $(g-2)_\mu$)

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



Correlations in LFV BRs help: similar dependence on m_{N_3} and $\tan\beta$

MEGA bound already disfavours $\theta_{13} \gtrsim 10^o(2^o)$ for $m_{N_3} \gtrsim 10^{13}(10^{14})$ GeV

A measurement of BRs and θ_{13} will provide some insight into m_{N_3} !!

Results for NUHM-seesaw

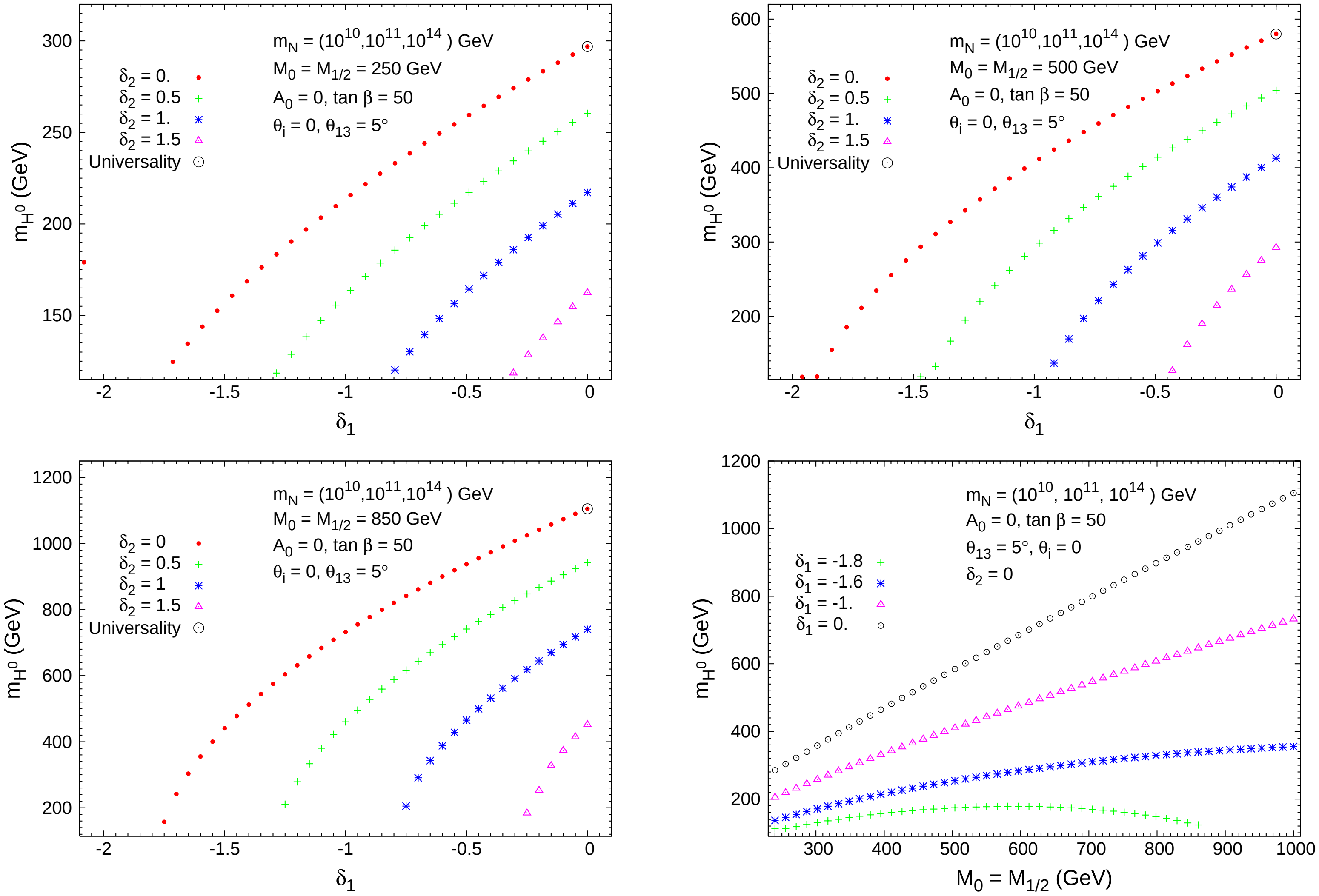
- Looking for solutions with light Higgs sector as functions of non-universal soft parameters: $M^2_{H_{1,2}} = M_0^2(1+\delta_{1,2})$, $-2 < \delta_{1,2} < 2$

- Study of correlation loss between related LFV observables due to Higgs-mediated contributions that can dominate the photon-mediated ones
  Relevant for:
  - ⋆ $\mu - e$ conversion in nuclei versus $\mu \to e\gamma$
  - ⋆ $\tau \to \mu\eta$ versus $\tau \to \mu\gamma$
  - ⋆ $\tau \to \mu\eta$ versus $\tau \to \mu\rho$

  due to large Higgs couplings to strange quarks (not relevant for $l_j \to 3l_i$)

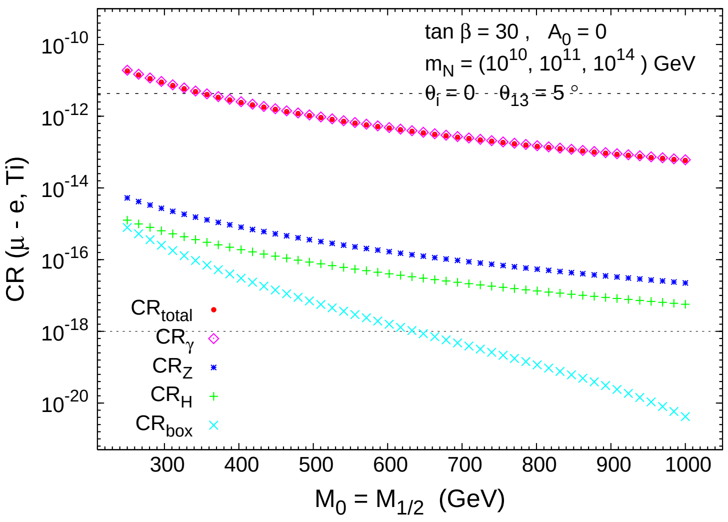
- Explore ratios of observables looking for enhacements respect to the universal case

Light Higgs sector in NUHM-seesaw

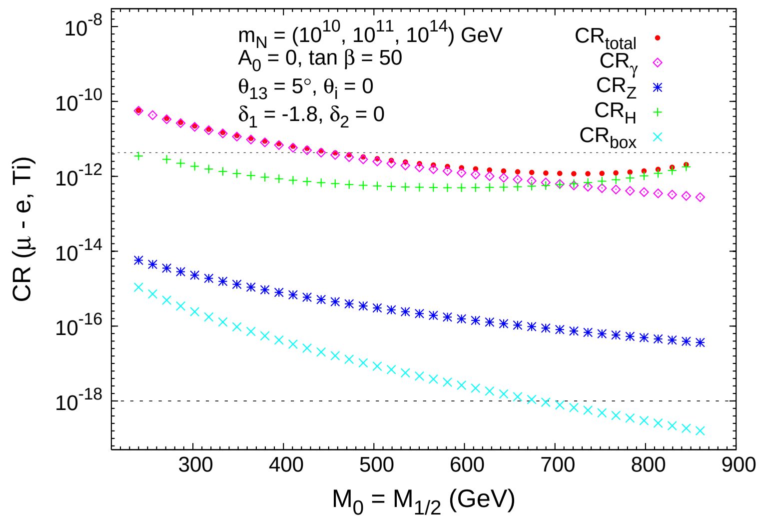


- ⋆ We find solutions with **light Higgs particles** even for large $M_0 = M_{1/2} = M_{\rm SUSY}$
- ⋆ Ex.: for $M_{\rm SUSY} = 850$ GeV, $\tan\beta = 50$, $A_0 = 0$, $\delta_1 = -1.8$, $\delta_2 = 0$, we find:
  light Higgs: $m_{H^0} = 127$ GeV, $m_{h^0} = 123$ GeV, $m_{A^0} = 127$ GeV, $m_{H^+} = 155$ 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

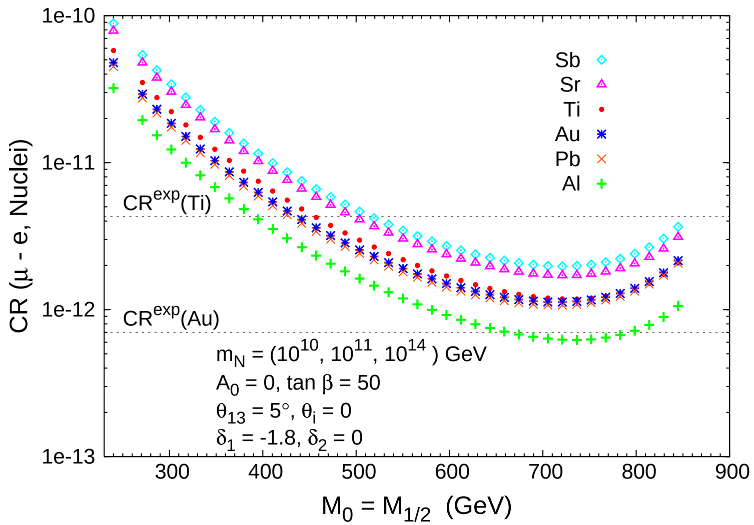
$\mu - e$ conversion in nuclei: universality versus non-universality



universality: γ dominance



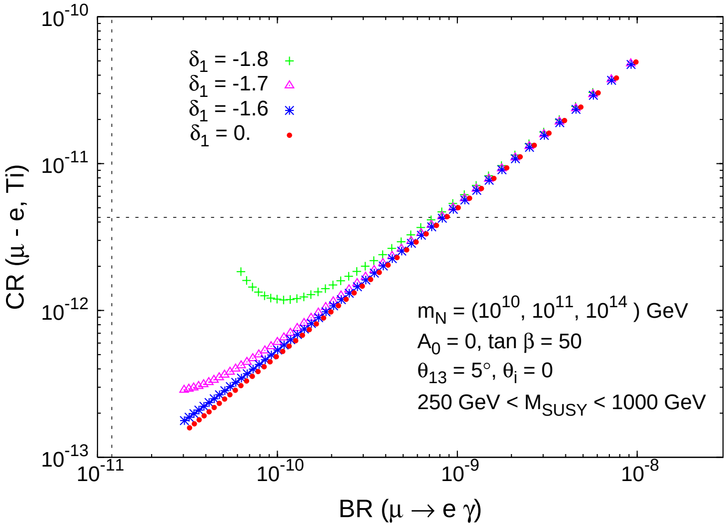
non-universality: H^0 dominance

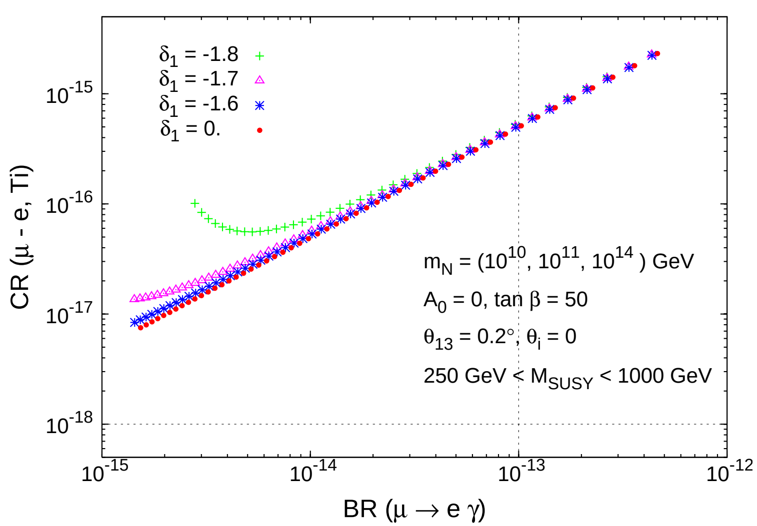


- ⋆ H^0 dominance $\Rightarrow$ heavy SUSY spectra do not decouple in $\mu - e$ conversion

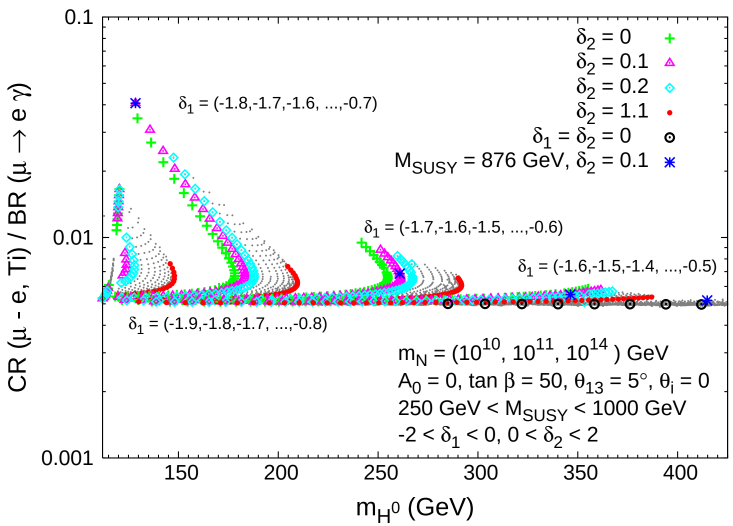
  CR($\mu - e$, Au) above present experimental bound even for heavy SUSY

Correlation loss between $\mu - e$ conv. and $\mu \to e\gamma$



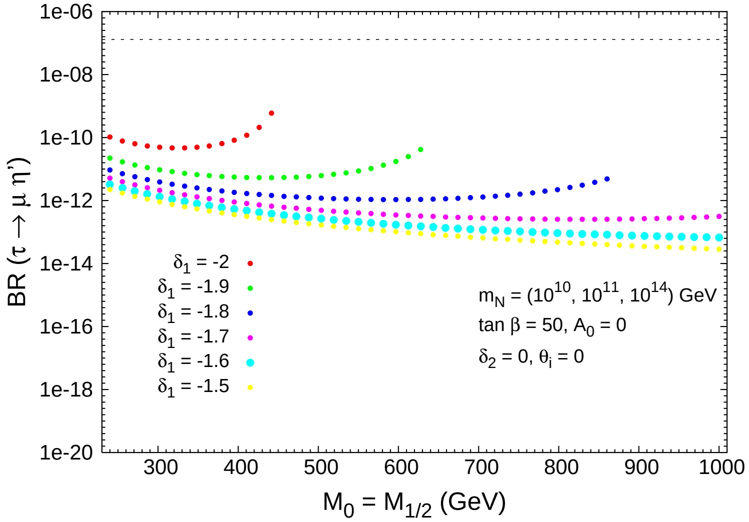


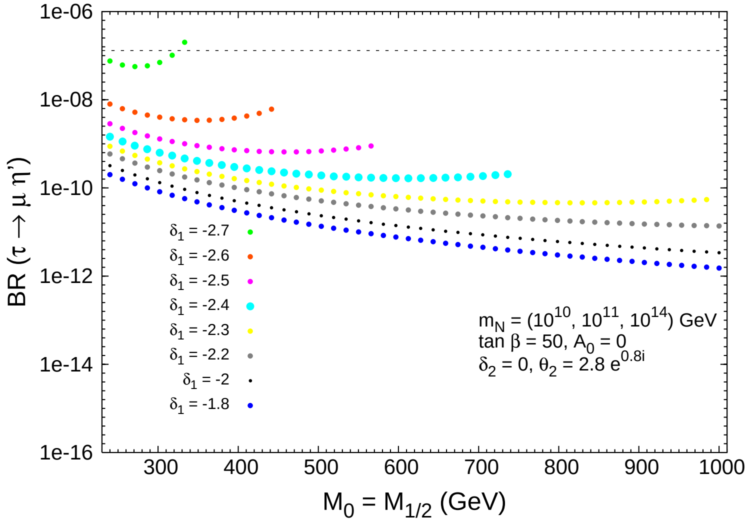
⋆ Deviation from linearity due to Higgs-dominated rates. Visible at future?



⋆ Ratio of $\mu - e$ to $\mu \to e\gamma$ can be a factor 10 larger than in photon-dominated scenarios like CMSSM (where this ratio is $\mathcal{O}(\alpha)$)

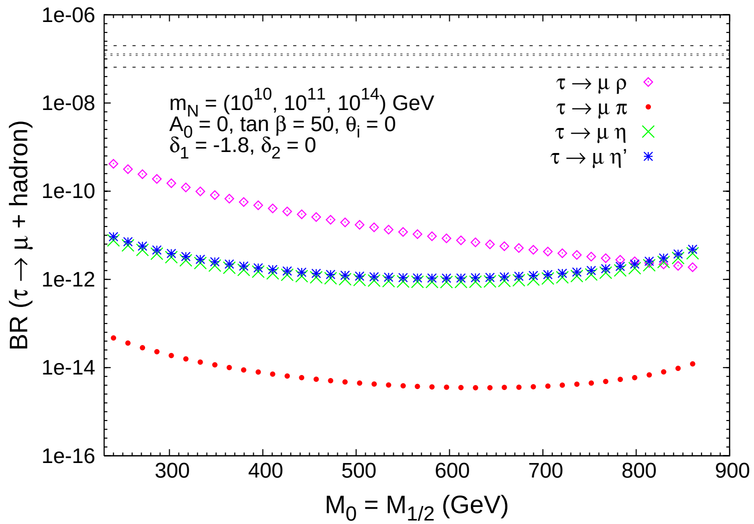
Higgs-dominance in semileptonic tau decays





⋆ Heavy SUSY do not decouple in $\tau \to \mu\eta'$ for scenarios with Higgs-dominance

$\tau \to \mu\eta'$ decay rates close to exp. bound if large θ_i



⋆ Ratio of $\tau \to \mu\eta$ to $\tau \to \mu\rho$ can be a factor 10 larger than in CMSSM

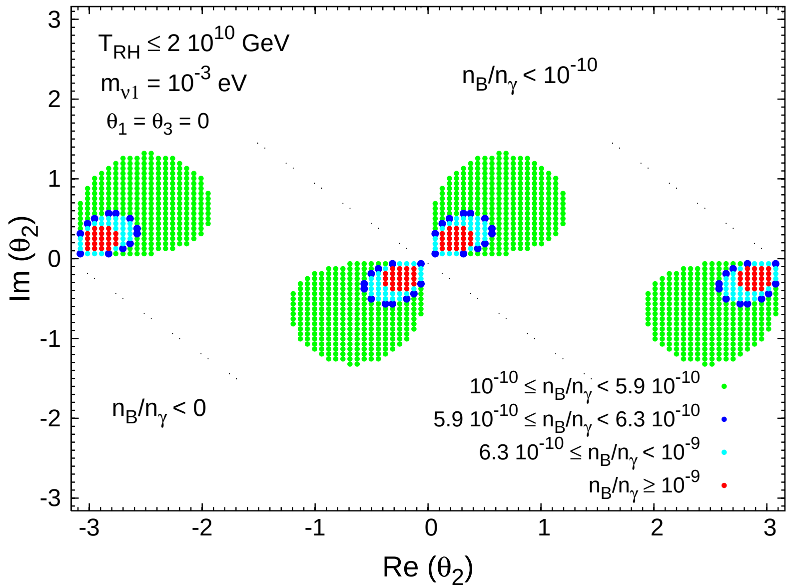
If SUSY exists:
LFV observables constitute an interesting lab that together with low-energy ν-data can provide some insight into the heavy neutrino sector and SeeSaw parameters. Also into Higgs sector if NUHM like scenarios

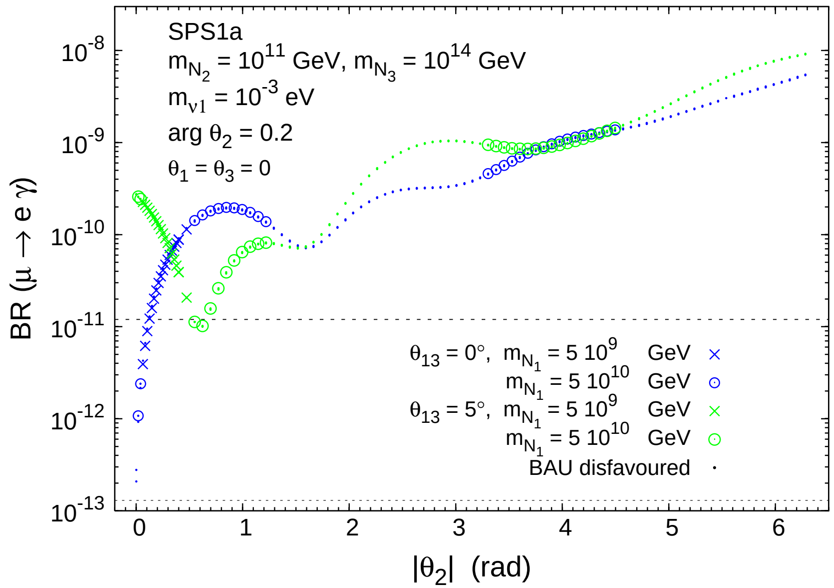
Additional transparencies

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)

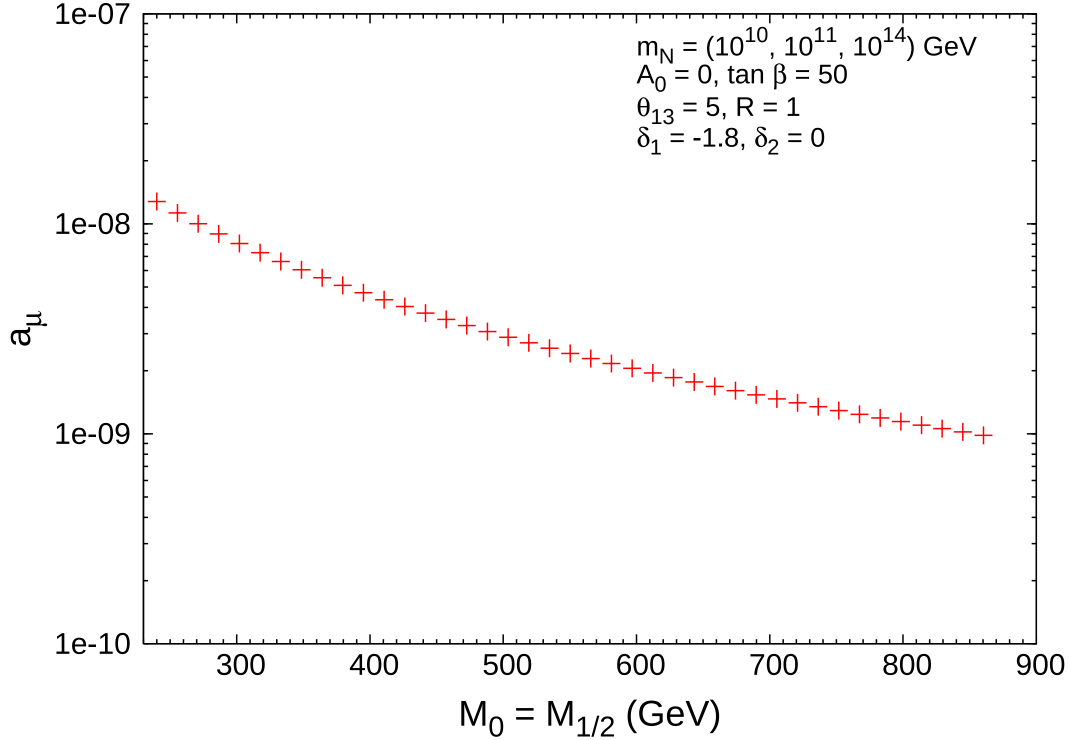
  BAU [disfav]-[fav]-[disfav]-[fav]-[disfav] pattern in $0 < |\theta_2| < 3$

  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 $|\theta_2| \sim O(10^{-2})$

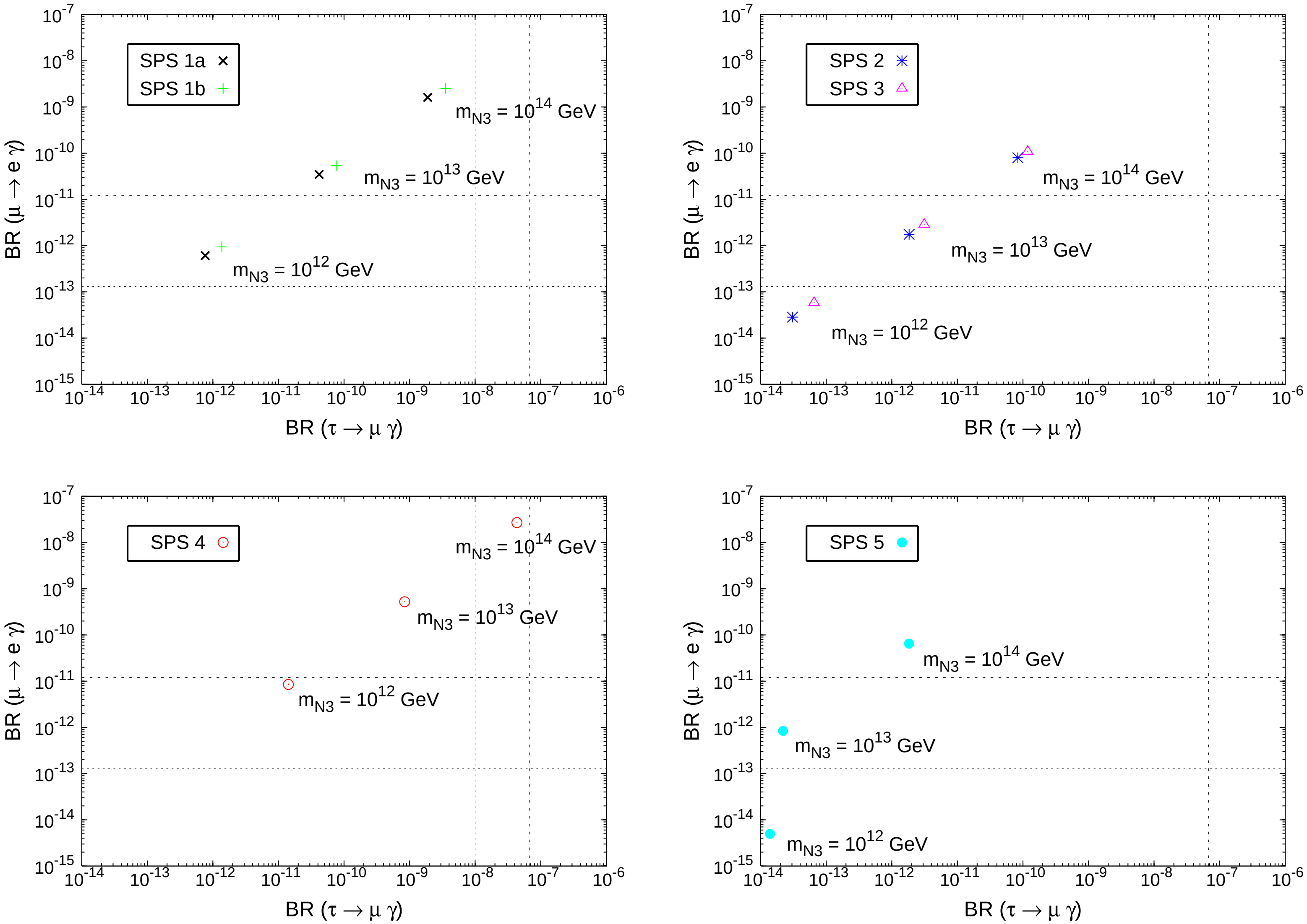
  $m_{N_1} \sim O(10^{9})$ GeV only one window at $|\theta_2| \sim O(5 \times 10^{-1})$

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



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

Impact of θ_{13} on LFV: Other SPS points

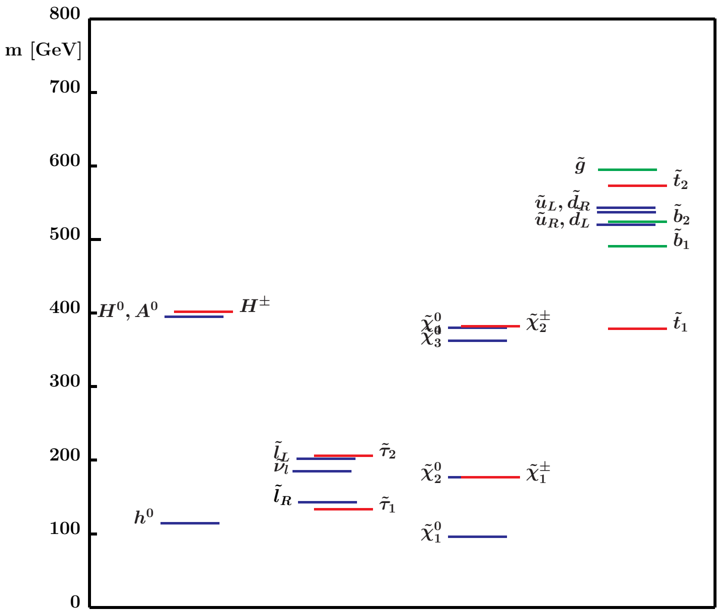


Similar for SPS1a,1b. Slightly worse prospects for SPS2,3. SPS5 the worst.

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

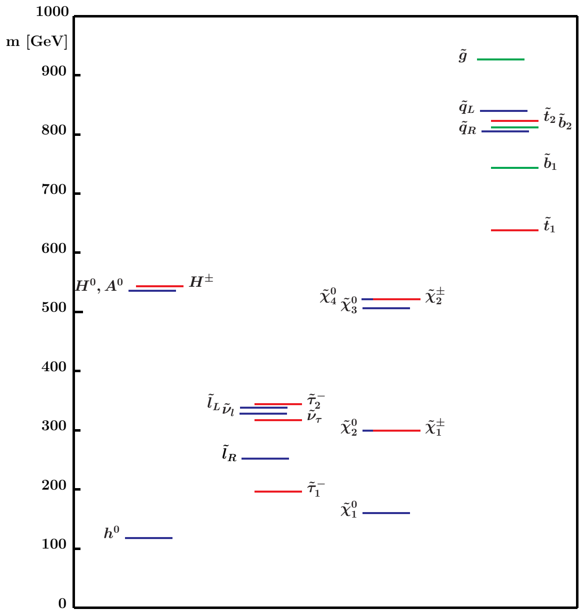
Present bounds from $\mu \to e\gamma$ and $\tau \to \mu\gamma$ already exclude $m_{N_3} \gtrsim 10^{14}$ GeV!!

SUSY SPS points (I)



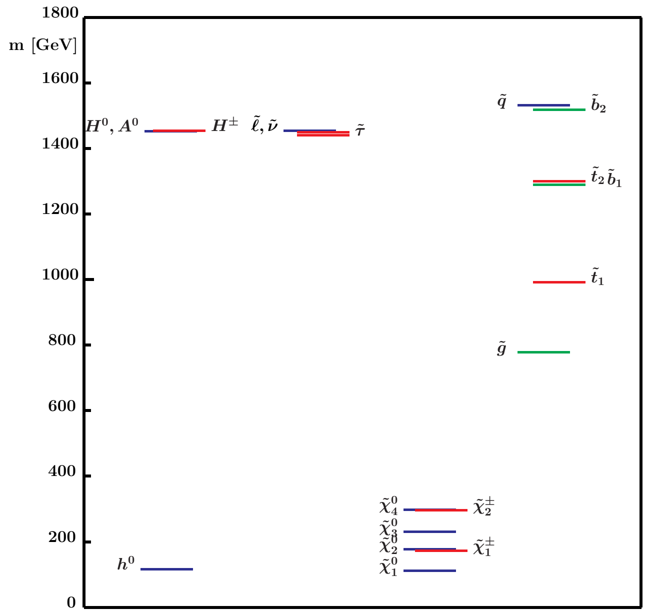
SPS1a

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



SPS1b

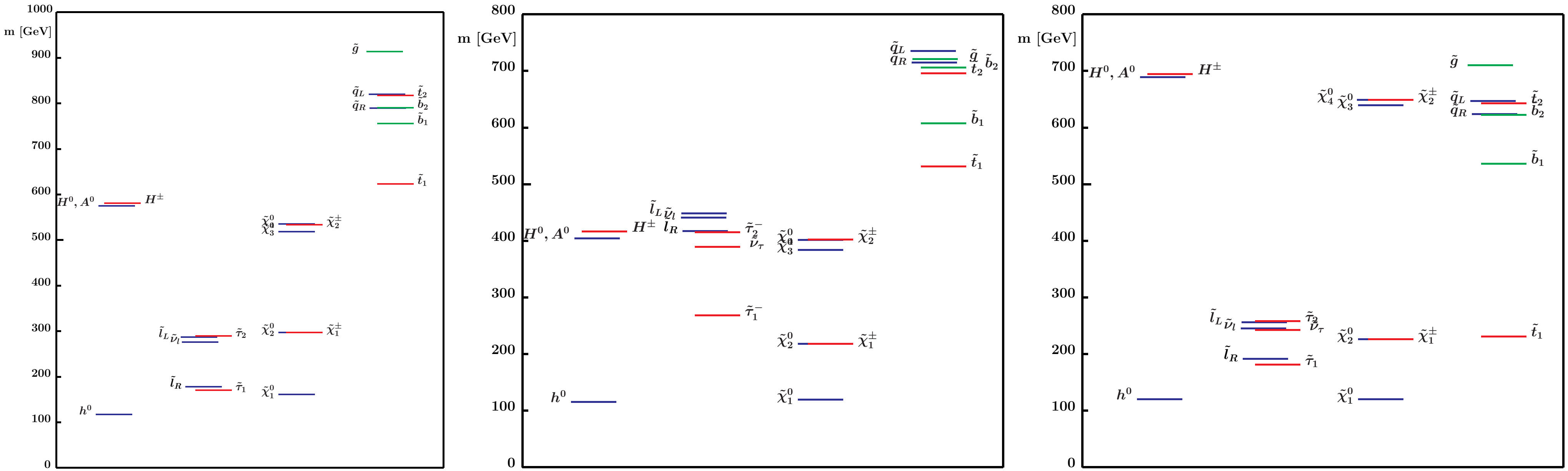
$M_0 = 200$ GeV
$M_{1/2} = 400$ GeV
$A_0 = 0$ GeV
$\tan\beta = 30$
$\mu > 0$



SPS2

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

SUSY SPS points (II)



SPS3	SPS4	SPS5
$M_0 = 90$ GeV	$M_0 = 400$ GeV	$M_0 = 150$ GeV
$M_{1/2} = 300$ GeV	$M_{1/2} = 300$ GeV	$M_{1/2} = 300$ GeV
$A_0 = 0$ GeV	$A_0 = 0$ GeV	$A_0 = -1000$ GeV
$\tan\beta = 10$	$\tan\beta = 50$	$\tan\beta = 5$
$\mu > 0$	$\mu > 0$	$\mu > 0$