τ - Physics and Lepton Flavour Violation

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Plan:
- Looking for LFV τ decays: LFV in the SUSY seesaw - a unique scenario
- Theoretical prospects: relevant parameters and experimental implications
- Learning from ν data and LFV ?

In collaboration with **M. J. Herrero**, E. Arganda and S. Antusch

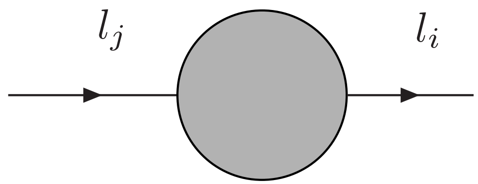
Detailed discussion in **PRD 73** (2006) 055003 (Arganda, Herrero)

and **JHEP 0611** (2006) 090 (Antusch, Arganda, Herrero, AMT)

Lepton flavour violation in charged lepton decays

Flavour violated in neutral leptons ($\nu_i \leftrightarrow \nu_j$ oscillations)

Extend SM to accommodate massive neutrinos: **SM+ν_R**



What about **charged lepton flavour violation??**

LFV process	**Present** bound	**Future** sensitivity
BR($\mu \to e\,\gamma$)	1.2×10^{-11}	1.3×10^{-13}
BR($\tau \to e\,\gamma$)	$\mathbf{1.1 \times 10^{-7}}$	$\mathcal{O}(10^{-8})$
BR($\tau \to \mu\,\gamma$)	$\mathbf{6.8 \times 10^{-8}}$	$\mathcal{O}(10^{-8})$
BR($\mu \to 3\,e$)	1.0×10^{-12}	$\mathcal{O}(10^{-13} - 10^{-14})$
BR($\tau \to 3\,e$)	$\mathbf{2.0 \times 10^{-7}}$	$\mathcal{O}(10^{-8})$
BR($\tau \to 3\,\mu$)	$\mathbf{1.9 \times 10^{-7}}$	$\mathcal{O}(10^{-8})$
CR($\mu \to e$ in Ti)	4.3×10^{-12}	$\mathcal{O}(10^{-18})$

Huge experimental effort

Running & Upcoming:

BABAR, Belle, MEG

Future:

SuperKEKB (2011),

PRISM/PRIME (next decade),

Super Flavour factory (?)

SM+ν_R: $l_j^- \to l_i^-$ transitions via $\nu_k - W^\pm$ loops are **strongly suppressed**

$$\text{BR}(l_j^- \to l_i^-\,\gamma)|_{\text{SM}_R} \approx (m_\nu/M_W)^2 \sim \mathcal{O}(10^{-54}) \;\Rightarrow\; \text{forever invisible..}$$

Measurement of LFV, e.g. BR($l_j^- \to l_i^-\,\gamma$) $\Rightarrow$ indication of New Physics!

LFV and New Physics

⋆ Seesaw mechanism ⇝ If **Majorana** ν, a natural explanation for small m_ν

New scale - m_R; additional **heavy singlet states** N **[Leptogenesis?]**

$$\boxed{m_\nu \approx \frac{(Y_\nu\, v)^2}{m_R}}$$

New **parameters** (masses + mixings) **unreachable (?)**

$Y_\nu \sim \mathcal{O}(1)$ (model-dependent)

⋆ Supersymmetry ⇝ One of the most appealing **extensions of the SM!**

dark matter candidates, hierarchy problem, **testable in the near future**, ...

LFV: very sensitive to SUSY

Large Y_ν, via **SUSY** loops ⇒ sizable **slepton flavour mixing** $(l_i \not\leftrightarrow \tilde{l}_i, \tilde{\nu}_i)$

potentially **large LFV rates!**

If **no LFV** found ⇒ **Restrictions** on SUSY seesaw parameters

If **LFV measured** ⇒ **Important hints on SUSY seesaw parameters**

How does this interplay originate?

Minimal Supersymmetric Standard Model (MSSM) + 3 ν_R

Superfields	Boson Fields	Fermionic Partners	$SU(2)_L \times U(1)_Y \times SU(3)_c$
Gauge Multiplets			
$\hat{G}$	g	$\tilde{g}$	$(1, 0, 8)$
$\hat{V}$	W	$\tilde{W}$	$(3, 0, 1)$
$\hat{B}$	B	$\tilde{B}$	$(1, 0, 1)$
Matter Multiplets			
$\hat{L}$	$\tilde{L} = (\tilde{\nu}, \tilde{e}^-)_L^T$	$(\nu, e^-)_L^T$	$(2, -1, 1)$
$\hat{E^c}$	$\tilde{E} = \tilde{e}_R^+$	e_L^c	$(1, +2, 1)$
$\hat{N^c}$	$\tilde{N} = \tilde{\nu}_R$	ν_L	$(1, 0, 1)$
$\hat{Q}$	$\tilde{Q} = (\tilde{u}_L, \tilde{d}_L)^T$	$(u, d)_L^T$	$(2, 1/3, 3)$
$\hat{U^c}$	$\tilde{U} = \tilde{u}_R^*$	u_L^c	$(1, -4/3, 3^*)$
$\hat{D^c}$	$\tilde{D} = \tilde{d}_R^*$	d_L^c	$(1, 2/3, 3^*)$
$\hat{H}_1$	$(H_1^0, H_1^-)^T$	$(\tilde{H}_1^0, \tilde{H}_1^-)^T$	$(2, -1, 1)$
$\hat{H}_2$	$(H_2^+, H_2^0)^T$	$(\tilde{H}_2^+, \tilde{H}_2^0)^T$	$(2, +1, 1)$

Mixings: neutral Higgsinos, Binos, neutral Winos $\longrightarrow$ Neutralinos $(\tilde{\chi}^0)$;

charged Higgsinos, charged Winos $\longrightarrow$ Charginos $(\tilde{\chi}^{\pm})$;

$$\boldsymbol{W} = Y_u \hat{H}_2 \hat{Q} \hat{U}^c + Y_d \hat{H}_1 \hat{Q} \hat{D}^c + Y_e \hat{H}_1 \hat{L} \hat{E}^c + \boldsymbol{Y_\nu \hat{H}_2 \hat{L} \hat{N}^c + \frac{1}{2} \hat{N}^c m_N \hat{N}^c} - \mu H_1 H_2$$

And soft-breaking terms for scalars and gauginos! $\mathcal{L}^{\text{soft}}\{M^i_{1/2}, (M_0^{\tilde{\phi}})_{ij}, (A_0^{\tilde{\phi}})_{ij}, B\mu\}$

SUSY Seesaw (Type I)

MSSM + 3 $\hat{\nu}_R$ $\quad W^{\text{lepton}} = Y_e\, L\, e^c\, H_1 + Y_\nu\, L\, \nu^c\, H_2 + m_R\, \nu^c\, \nu^c$

$$\begin{pmatrix} \nu_{R_i} \\ \tilde{\nu}_{R_i} \end{pmatrix}$$

- Slepton terms in $\mathcal{L}^{\text{soft}}$

$$m_{\tilde{R}} = m_{\tilde{L}} = m_{\tilde{E}} = M_0 \quad , \quad A_\nu = A_l = A_0$$

- Enriched s-spectrum: 3 light and 3 heavy sneutrinos!

Assumptions: basis where $Y_e = Y_e^{\text{diag}}$ and $m_R = m_R^{\text{diag}}$

$$M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

$m_D \to$ Dirac mass matrix; $m_D = v_2 Y_\nu \quad (\ll m_R)$

$m_R \to$ Heavy neutrino mass matrix - diag (m_{N_i})

In the limit $m_R \gg v$, and to lowest order in $(m_D/m_R)^n$

Seesaw equation: $m_\nu = -m_D\, m_R^{-1}\, m_D^T$

$\Rightarrow$ **find** m_D **(i.e.** Y_ν**) compatible** with

$$\begin{cases} U_{\text{MNS}}^T\, m_\nu\, U_{\text{MNS}} = m_\nu^{\text{diag}} \\ U_{\text{MNS}}(\theta_{12}, \theta_{23}, \theta_{13}) \\ m_\nu^{\text{diag}}(\Delta m^2_{\text{sol}}, \Delta m^2_{\text{atm}}, \sum m_{\nu_i}) \end{cases}$$

SUSY Seesaw (Type I)

Solve Seesaw equation for m_D (Y_ν) $\Rightarrow$ **Casas-Ibarra parameterisation** ('01)

Solution:
$$\boxed{m_D = v_u Y_\nu = i \sqrt{m_N^{\text{diag}}}\, R \sqrt{m_\nu^{\text{diag}}}\, U_{\text{MNS}}^\dagger} \qquad (\text{at } m_R)$$

R encodes possible mixings in the right-handed sector (in addition to U_{MNS})

$$R = \begin{pmatrix} c_2\, c_3 & -c_1\, s_3 - s_1\, s_2\, c_3 & s_1\, s_3 - c_1\, s_2\, c_3 \\ c_2\, c_3 & c_1\, c_3 - s_1\, s_2\, s_3 & -s_1\, c_3 - c_1\, s_2\, s_3 \\ s_2 & s_1\, c_2 & c_1\, c_2 \end{pmatrix}$$

$R^T R = 1$

$c_i = \cos\theta_i\,;\, s_i = \sin\theta_i$

θ_i **complex angles**

Parameterise Y_ν while in agreement with low-energy ν-data

Y_ν strongly reflects the chosen values of θ_i, m_N and θ_{13} !

Notice that **additional constraints** on Y_ν can be obtained from

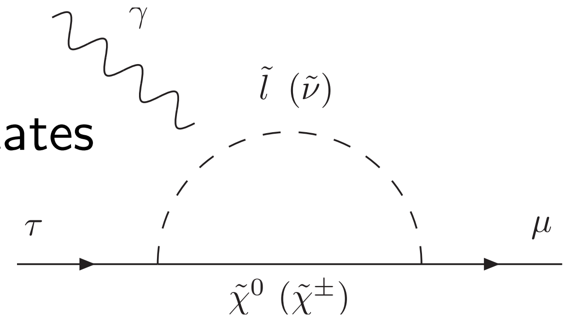
- **BAU (leptogenesis)** constraints on R-angles and on m_{N_1}
- Potential **contributions** to e, μ and τ **electric dipole moments**

Origin of large LFV in SUSY Seesaw

Focus on the **SUSY contributions** to $\tau \to \mu\gamma$

Like in SM, SUSY LFV relies on **misalignement** of eigenstates

$\Rightarrow$ **How does** $\tau \not\leftrightarrow \tilde{\tau}, \tilde{\nu}_\tau$; $\mu \not\leftrightarrow \tilde{\mu}, \tilde{\nu}_\mu$; **originate?**



LFV originates from large size and non-trivial structure of Y_ν!

Borzumati, Masiero (86); Hisano et al (96);...

- If Majorana νs, $\boldsymbol{Y_\nu}$ can be $\boldsymbol{\mathcal{O}(1)}$
- To accommodate **data on ν-oscillations**, $\boldsymbol{Y_\nu}$ cannot be **diagonal**!
- Even for **universal** soft-breaking terms @ M_{GUT},

  RGE running of Y_ν from M_{GUT} down to **Seesaw scale m_R**

  induces flavour-violating terms in slepton soft-breaking masses

  $M^2_{L\,ij} \neq 0$, $M^2_{LR\,ij} \neq 0$, etc $\Rightarrow$ **slepton-lepton misalignment**

Flavour violation in the charged slepton sector!

Large LFV decay rates $(l_j \to l_i\,\gamma,\, l_j \to 3\,l_i)$ **within experimental reach!**

On the computation of LFV observables

All processes: **Full one-loop computation** (full-vertex, physical eigenstates)

All relevant one-loop SUSY **diagrams included**

▶ **Radiative decays $l_j \to l_i\,\gamma$**: $\text{BR}(l_j \to l_i\,\gamma) \,=\, \frac{e^2}{16\,\pi}\,\frac{m_{l_j}^5}{\Gamma_{l_j}}\,\left(|A_2^L|^2 \,+\, |A_2^R|^2\right)$

Loops: chargino-sneutrino and charged slepton-neutralino

▶ **Decays into 3 leptons $l_j \to 3\,l_i$**: photon-, Z-, Higgs-penguins; box diagrams

Dominant photon-penguin: $\text{BR}(l_j \to 3 l_i) \,=\, \frac{\alpha}{3\,\pi}\,\left(\log\frac{m_{l_j}^2}{m_{l_i}^2} \,-\, \frac{11}{4}\right) \times \text{BR}(l_j \to l_i\,\gamma)$

Useful analytical insight: **Leading Log Approximation & MIA**

$$\begin{array}{ll} l & \\ \not{l} & \\ \tilde{l} & \end{array} \begin{cases} (M^{\tilde{l}}_{LL})^2_{ij} \,\propto\, (3\,M_0^2 + A_0^2)\,(Y_\nu^*\,L\,Y_\nu^T)_{ij} \\ (M^{\tilde{l}}_{LR})^2_{ij} \,\propto\, A_0\,v_1\,Y_i^e\,(Y_\nu^*\,L\,Y_\nu^T)_{ij} \\ (M^{\tilde{l}}_{RR})^2_{ij} \,=\, 0\,; \quad L_i \,=\, \log(\frac{M_X}{m_{N_i}}) \end{cases}$$

BRs $\begin{cases} \tan^2\beta \ \blacktriangle \\ |m_{N_3}\,\log m_{N_3}|^2 \ \blacktriangledown \end{cases}$

LLog & MIA $\Rightarrow$ $\text{BR}(\tau \to \mu\gamma) \approx \frac{\alpha^3\tan^2\beta}{G_F^2\,m_{\text{SUSY}}^8}\left|\frac{1}{8\pi^2}(3M_0^2 + A_0^2)(Y_\nu^\dagger L Y_\nu)_{32}\right|^2$

Not always good approximations...

Our approach

- Work in **MSSM + 3$\hat{\nu}_R$**, universal conditions at $M_{\text{GUT}} \approx 2 \times 10^{16}$ GeV

CMSSM: SPS benchmark points SPS$_X(M_0, M_{1/2}, A_0, \tan\beta, \text{sign}\,\mu)$

- Compatibility with neutrino data (assume **hierachical heavy neutrinos**)

$$m_{\nu_i} \begin{cases} \Delta m^2_{\text{sol}} = 8 \times 10^{-5}\,\text{eV}^2 \\ \Delta m^2_{\text{atm}} = 2 \times 10^{-3}\,\text{eV}^2 \\ \text{Hierarchical } \boldsymbol{m_{\nu_i}} \end{cases} \qquad U_{\text{MNS}} \begin{cases} \theta_{12} = 30^o\,;\theta_{23} = 45^o \\ \delta = \phi_1 = \phi_2 = 0 \\ \text{Impact of } 0 \lesssim \boldsymbol{\theta_{13}} \lesssim 10^o \end{cases}$$

- Require "viable" BAU: $n_{\text{B}}/n_\gamma \in [10^{-10}, 10^{-9}]$ (WMAP $\sim 6.1 \times 10^{-10}$, '06)

- Compatibility EDM$_{e\mu\tau} \lesssim (6.9 \times 10^{-28}, 3.7 \times 10^{-19}, 4.5 \times 10^{-17})$ e.cm

- Theoretical **predictions for LFV decay rates:**

`SPheno 2.2.2`: Numerical integration of two-loop RGEs from M_X to M_Z

Additionally: Neutrino RGEs, LFV decays (full 1-loop), Leptogenesis, EDMs

- Compare with present and future LFV bounds!

The Constrained MSSM

Assume (well-motivated) relations between soft-breaking parameters

universality of soft gaugino masses: $M_i = M_{1/2}$

universality of soft breaking scalar masses: $(M_0^{\tilde{\phi}})_{ij} = M_0$

universality of soft breaking trilinear couplings: $(A_0^{\tilde{\phi}})_{ij} = A_0$

at a common scale, **gauge-coupling unification scale**, $M_X \approx 10^{16}$ GeV

CMSSM (mSUGRA-like): $M_{1/2}$, M_0, A_0, $\tan\beta$, sign(μ)

Predictions for the low-energy spectrum: solve **RGEs !**

Further simplify: consider benchmark points (**S**nowmass **P**oints and **S**lopes):

SPS 1a, 1b	typical mSUGRA points, bulk cosmological region, med-large $\tan\beta$
SPS 2	light gauginos, focus point region for relic density
SPS 3	small $\tilde{l} - \tilde{\chi}^0$ mass difference, coannihilation region
SPS 4, 5	extreme $\tan\beta$: high and low

Similar analysis for any other (reconstructed) SUSY model

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Predictions for LFV within the type I SUSY Seesaw

- Dependence on CMSSM parameters

- Dependence on the size of the Yukawa couplings

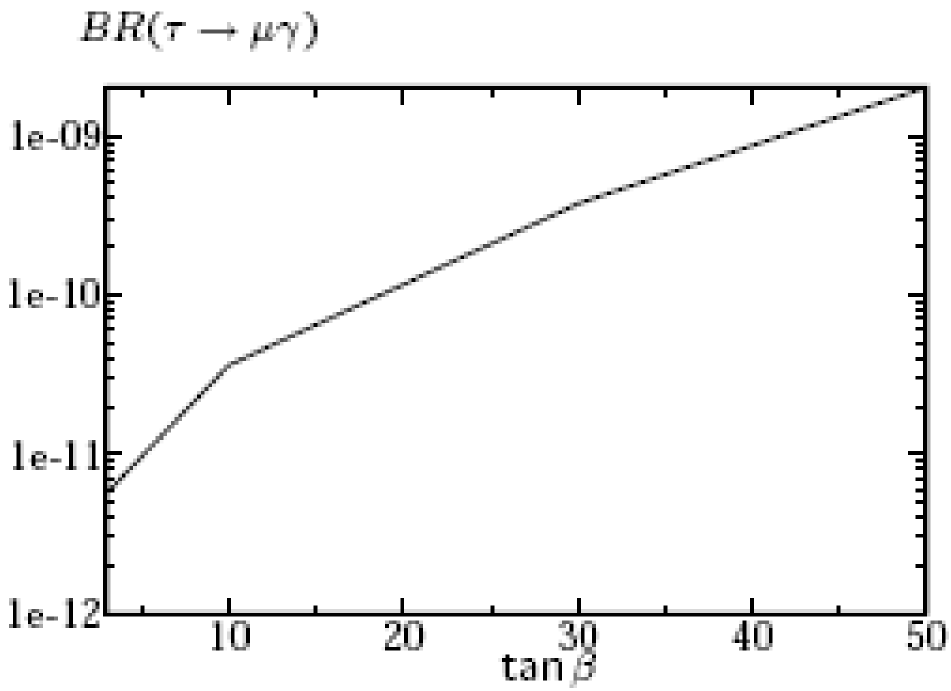
- Impact of a measurement of θ_{13}

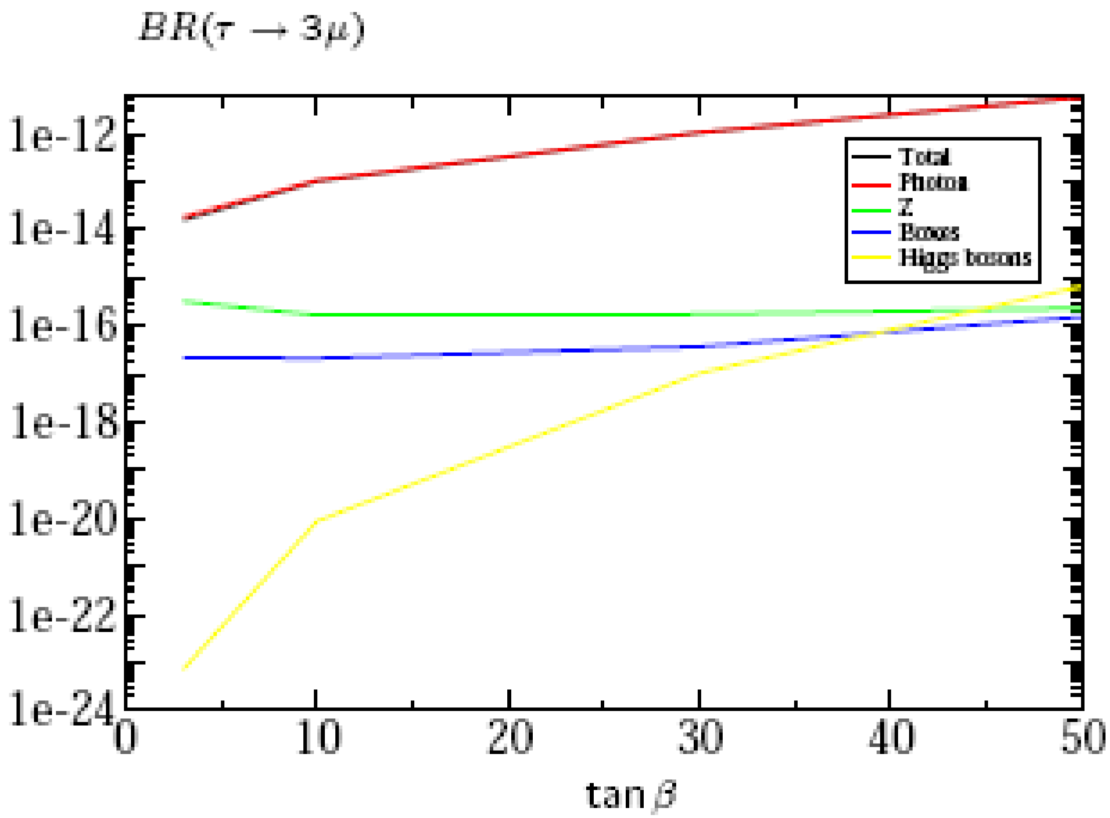
$$\text{BRs (@EW)} \longrightarrow \text{affected by } Y_\nu \begin{array}{l} \nearrow \quad m_N\,,\,\theta_i \\ \searrow \quad U_{\text{MNS}}\,,\,m_\nu \end{array} \quad (@m_R)$$

CMSSM parameters: $\tan\beta$

$M_0 = 400$ GeV, $M_{1/2} = 300$ GeV, $A_0 = 0$, $m_N = 10^{14}$ GeV (degen.), $\theta_i = 0$

From Arganda and Herrero, PRD 73 (2006)





★ **BRs** dependence on $\tan\beta$: BR($\tau \to 3\, l_i$), BR($\tau \to l_j\, \gamma$) grow as $\tan^2\beta$

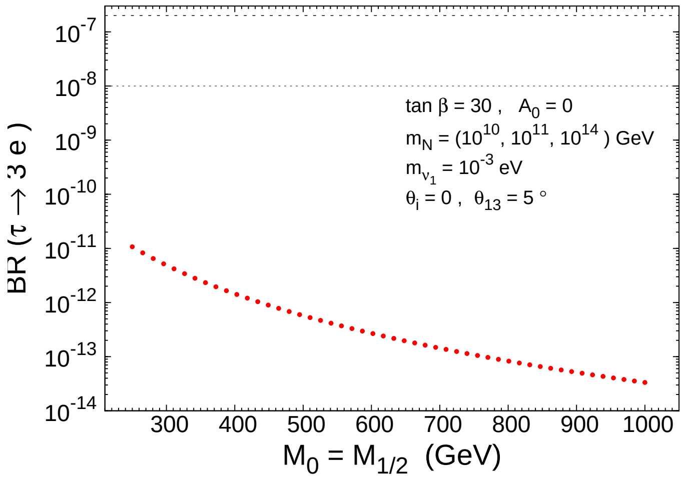
★ BR($\tau \to \mu\, \mu\, \mu$)/ BR($\tau \to \mu\, \gamma$) $\approx 1/440$

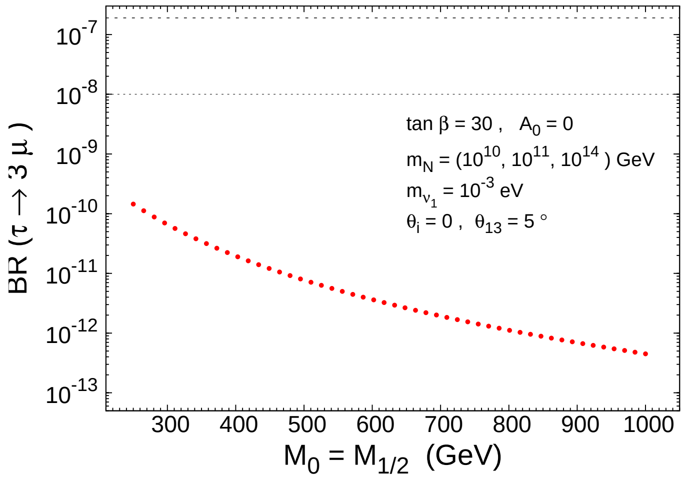
$\Rightarrow$ reflects **strong γ-penguin dominance** (all $\tan\beta$)

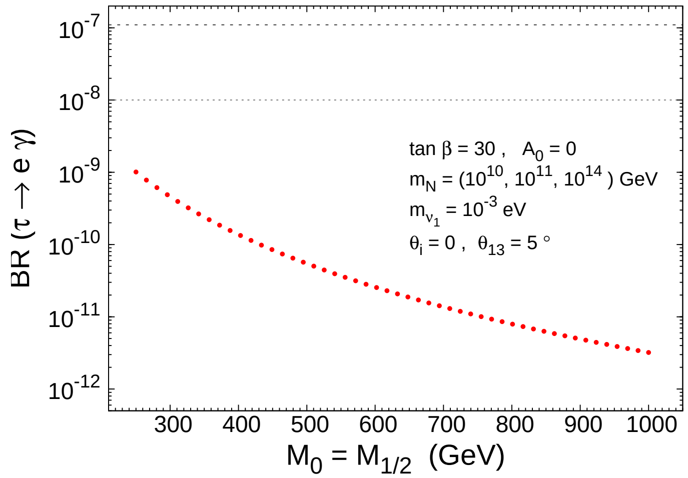
★ Degenerate N_i: typically **lower BRs** than **hierarchical** N_i

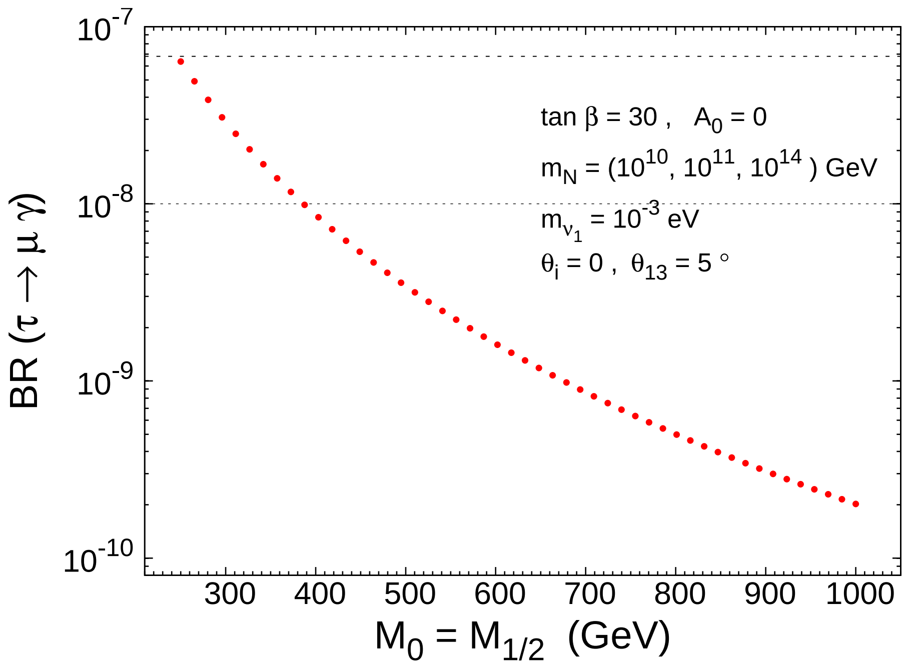
CMSSM parameters: M_0 and $M_{1/2}$

$M_0 = M_{1/2}$, $\tan\beta = 30$, $A_0 = 0$, $m_N = (10^{10}, 10^{11}, 10^{14})$ GeV, $\theta_{13} = 5°$, $\theta_i = 0$









- ★ **Important dependence** on M_0 and $M_{1/2}$
- ★ **Larger BRs** obtained for low M_0 $(M_{1/2})$
- ★ Comparative analysis:

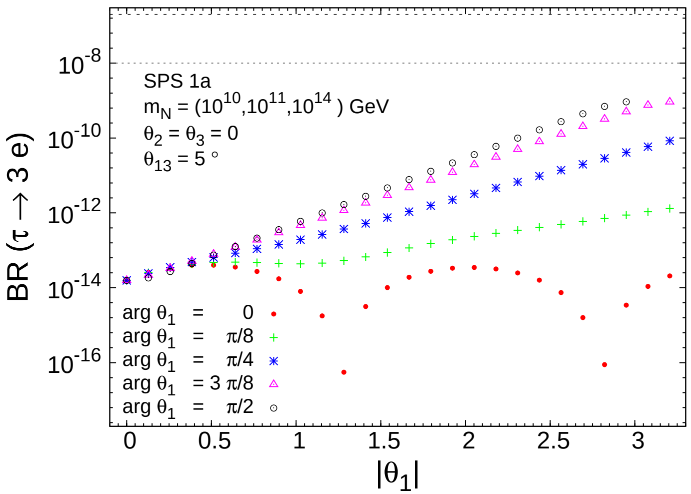
  $\tau \to \mu\gamma$ **most challenging** channel

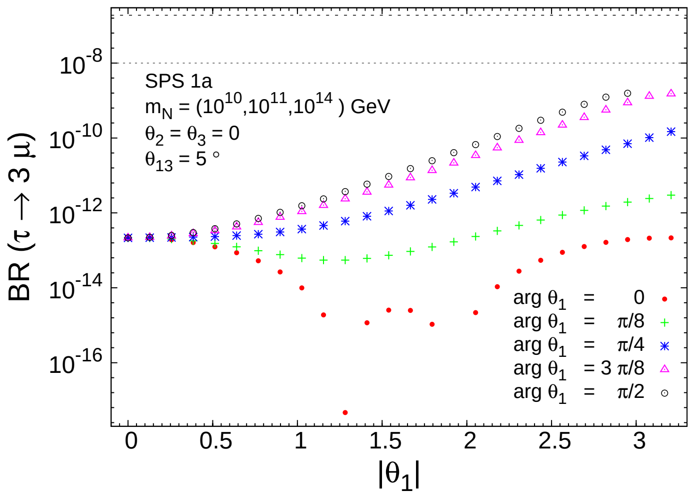
  $\tan\beta = 30$, BR$(\tau \to \mu\gamma)$ within **exp. reach!**

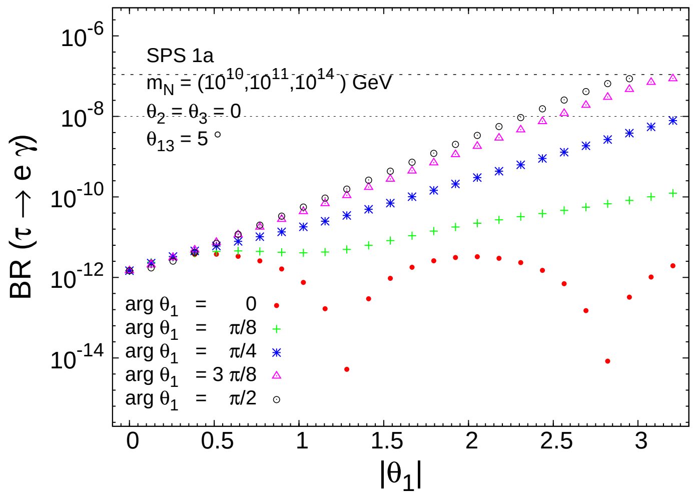
  $\Rightarrow$ **Disfavouring** M_0 $(M_{1/2}) \lesssim 300$ GeV

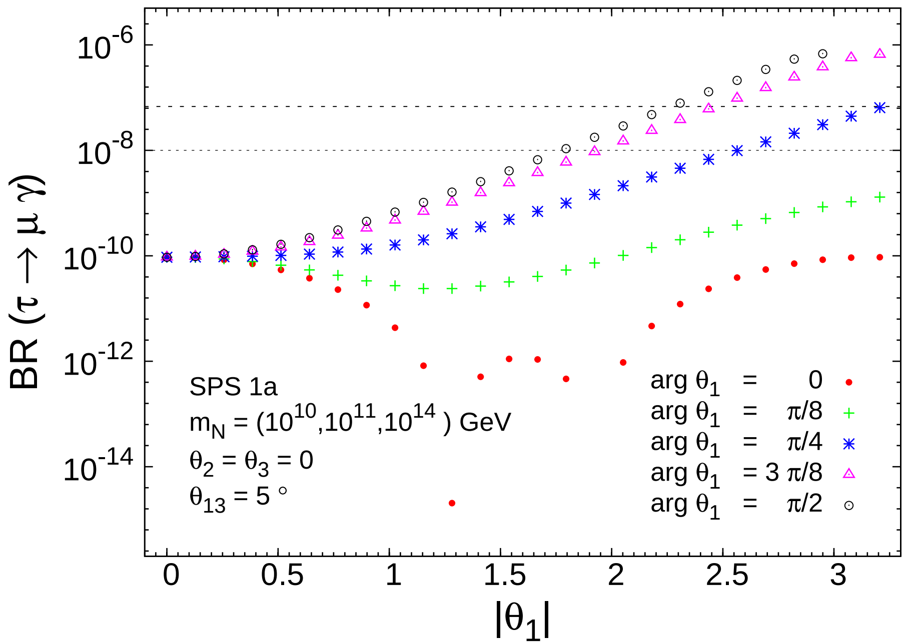
Large Yukawa couplings: role of θ_1

SPS 1a ($\tan\beta = 10$), $m_N = (10^{10}, 10^{11}, 10^{14})$ GeV, $\theta_{13} = 5°$, $\theta_2 = \theta_3 = 0$









★ ***R*-matrix** complex **angles** strongly **affect Y_ν**

$\arg\theta_1 = 0,\ \pi/8,\ \pi/4,\ 3\pi/8,\ \pi/2$

★ **BRs** closely **follow pattern** of $Y_\nu(\theta_1)$

★ **Large, complex θ_1** can induce

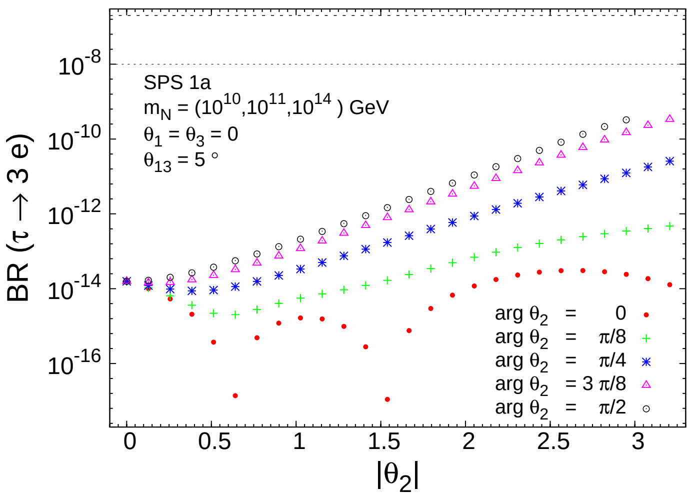
$\mathcal{O}(10^4)$ **enhancement in BRs**

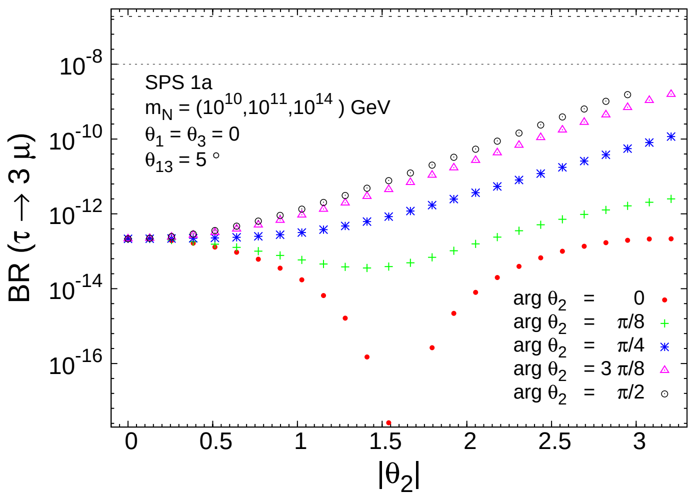
$\Rightarrow$ For **SPS 1a**, BR($\tau \to \mu\gamma$)

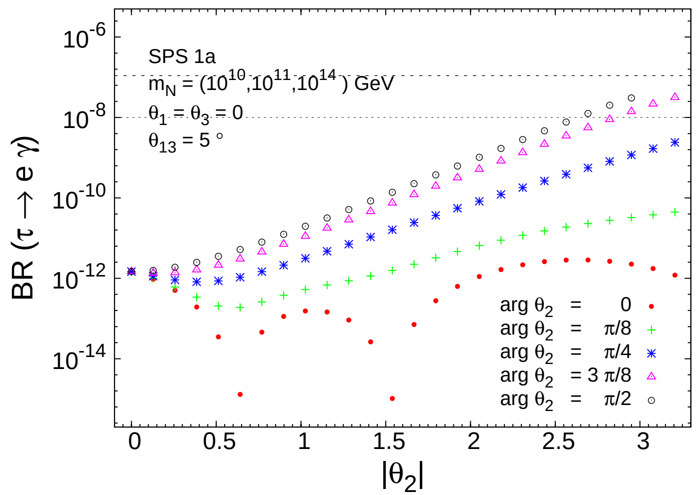
already constrains values of θ_1

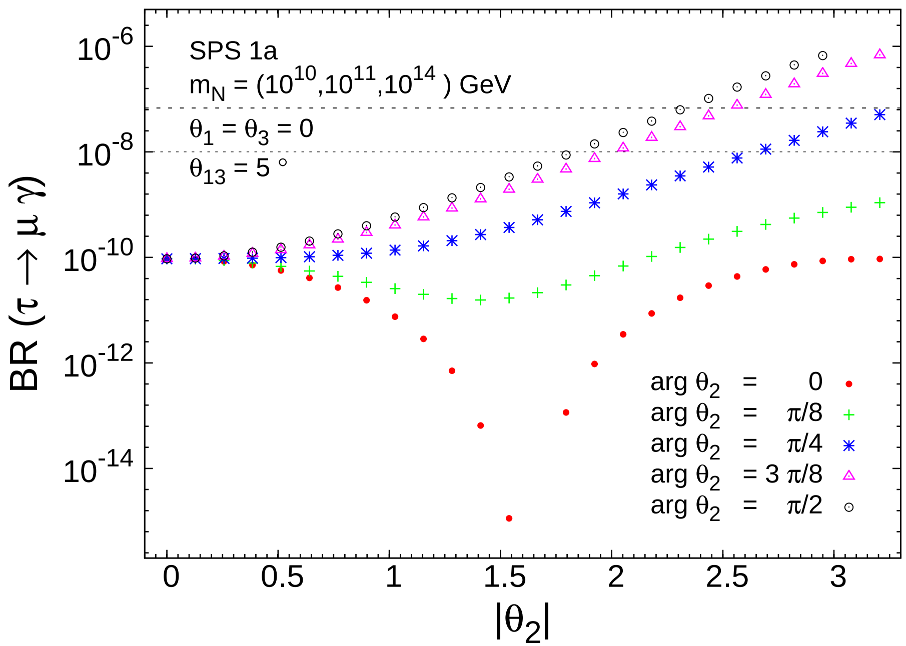
Large Yukawa couplings: role of θ_2

SPS 1a ($\tan\beta = 10$), $m_N = (10^{10}, 10^{11}, 10^{14})$ GeV, $\theta_{13} = 5°$, $\theta_1 = \theta_3 = 0$









★ Similar role played by $\boldsymbol{\theta_2}$

$$\arg\theta_2 = 0,\ \pi/8,\ \pi/4,\ 3\pi/8,\ \pi/2$$

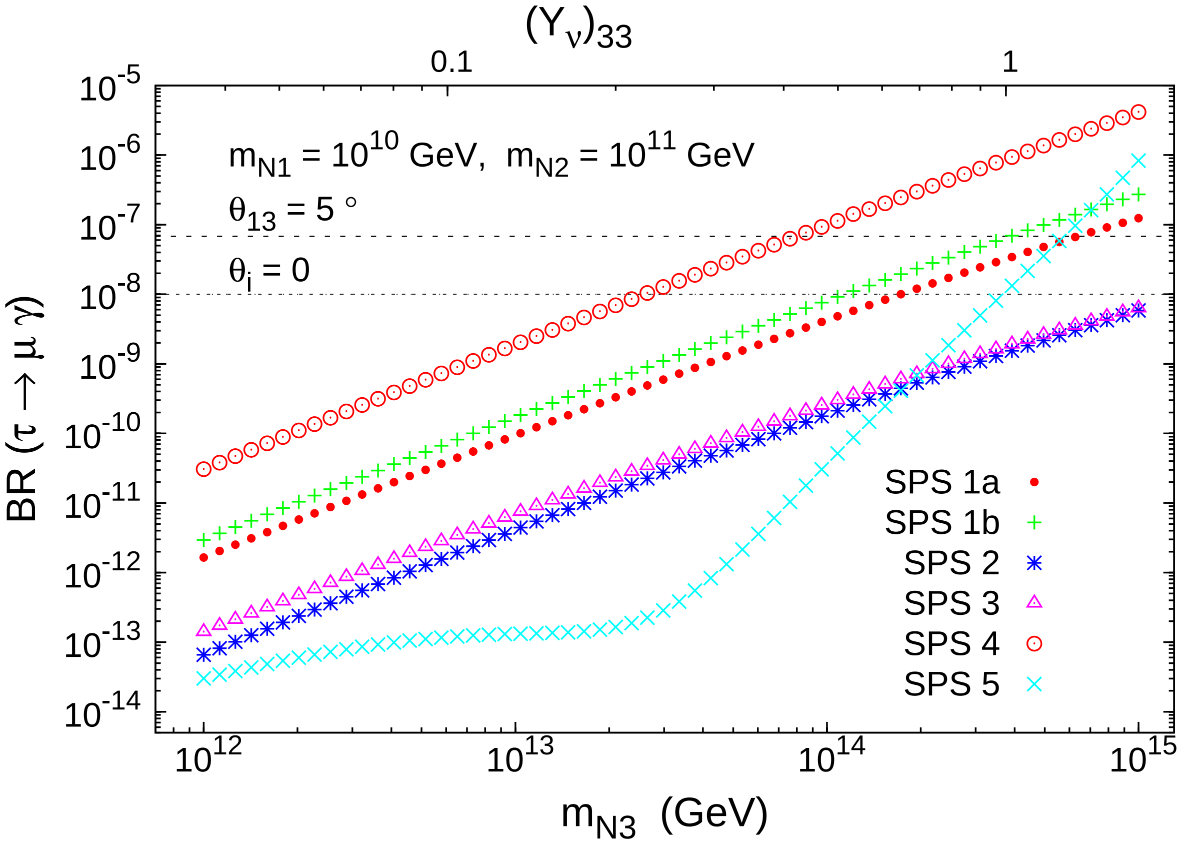
★ BR($\tau \to \mu\gamma$) also **constrains** values of θ_2

★ **Baryon Asymmetry of the Universe:**

Leptogenesis requires $\theta_1, \theta_2\ (\arg\theta_{1,2}) \neq 0 \ldots$

θ_3 does not play a relevant role for BRs

Large Yukawa couplings: m_{N_3}



★ m_{N_3} drives Y_ν:

hierarchical N_i, $m_D \propto \sqrt{m_N^{\text{diag}}}$

strongly **affects** BR$(\tau \to \mu\,\gamma)$

and all other BRs!

★ Without predictive framework

$m_{N_3} \in [10^{10},\, 10^{15}]$ GeV

(indirect lower bound - Leptogenesis)

★ SUSY seesaw scenario ⇒ **indirect bounds** via BRs: $\begin{cases} m_{N_3} \lesssim 10^{14}\ \text{GeV (SPS 4)} \\ m_{N_3} \lesssim 5 \times 10^{14}\ \text{GeV (1a,1b)} \end{cases}$

▶ **SPS 1a, SPS 1b, SPS 2, SPS 3, SPS 4** - Good **agreement** with LLog

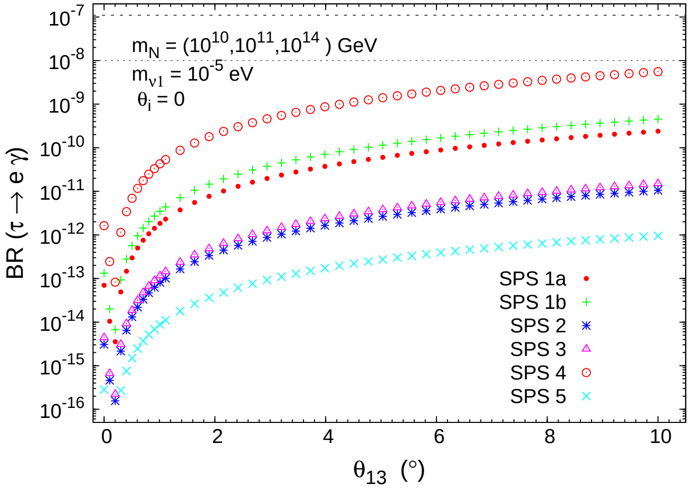
BR $\propto \tan^2\beta$: BR$_4$ > BR$_{1b}$ $\gtrsim$ BR$_{1a}$ > BR$_3$ $\gtrsim$ BR$_2$ > BR$_5$ BR $\propto |m_{N_3}\ \log m_{N_3}|^2$

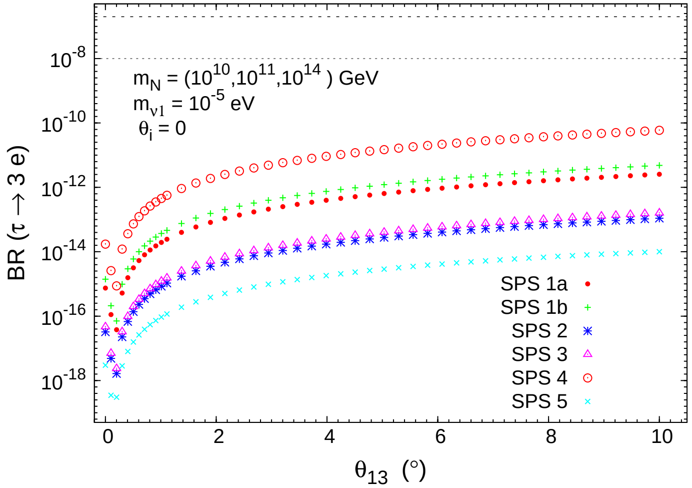
▶ **SPS 5:** LLog not good approximation!

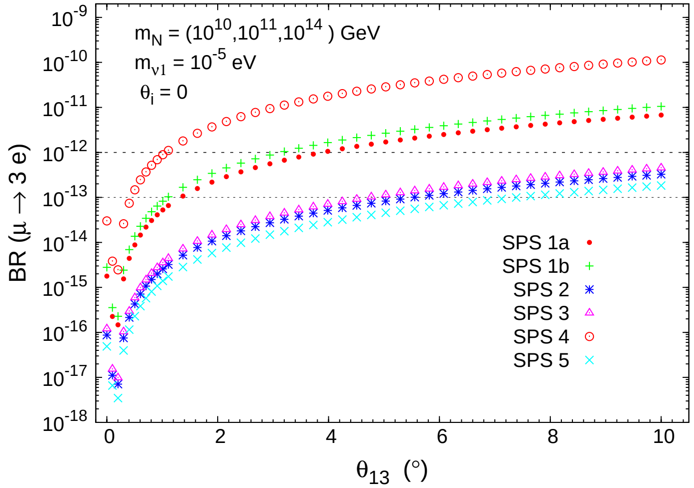
Useful hints on m_{N_3} from potential BR and θ_{13} measurement!!

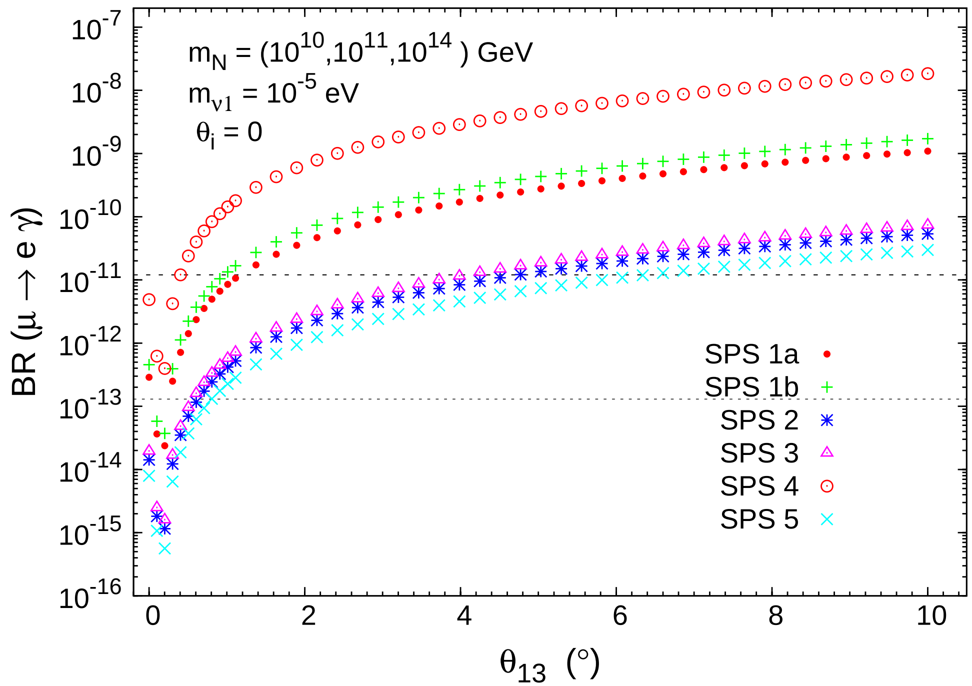
Sensitivity to θ_{13}: τ and μ decays

SPS X, $m_N = (10^{10}, 10^{11}, 10^{14})$ GeV, $\theta_i = 0$









- ⋆ $\boldsymbol{\mu, \tau \to e\,\gamma}$ and $\boldsymbol{\mu, \tau \to 3\,e}$ exhibit

  large **sensitivity** to $\boldsymbol{\theta_{13}}$ (for small θ_i)

  $\tau \to \mu\gamma$ and $\tau \to 3\mu$: **no** θ_{13} **dependence**

- ⋆ **Measurement** of θ_{13} is crucial!

  Maximal impact for $\boldsymbol{\mu \to e\gamma}$

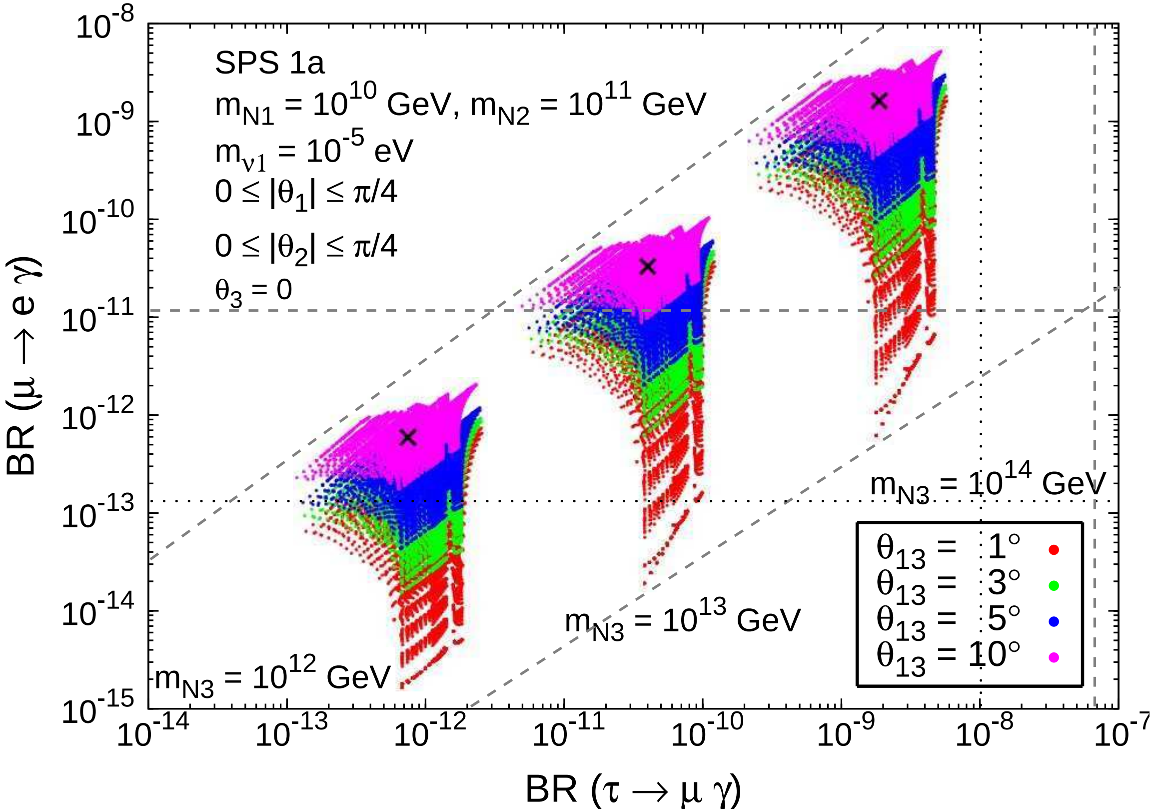
- ▶ **Experimentally:** SUSY & Seesaw scenarios,

  $\boldsymbol{\theta_{13} \gtrsim 2^o}$ within **MEG reach**

Impact of θ_{13} on LFV observables: hints on m_{N_3}

Experimental **measurement of θ_{13}** in a near future! **SUSY @ LHC??**

Correlations of BR($\mu \to e\,\gamma$) and BR($\tau \to \mu\,\gamma$) $\Rightarrow$ Optimises impact of θ_{13}^{exp}



- $\star$ Other m_{N_3} within "corridor"
- $\star$ Conclude on impact of θ_{13} measurement on allowed/excluded m_{N_3}
- $\star$ BR($\mu \to e\,\gamma$)$|_{'06}$ + $\boldsymbol{\theta_{13} = 1°}$ $\Rightarrow$ $m_{N_3} < 10^{14}$ **GeV**
- $\star$ BR($\mu \to e\,\gamma$)$|_{\text{MEG}}$ + $\boldsymbol{\theta_{13} = 1°}$ $\Rightarrow$ $m_{N_3} < 3 \times 10^{12}$ **GeV**

Discovery of SUSY (LHC, Tevatron)

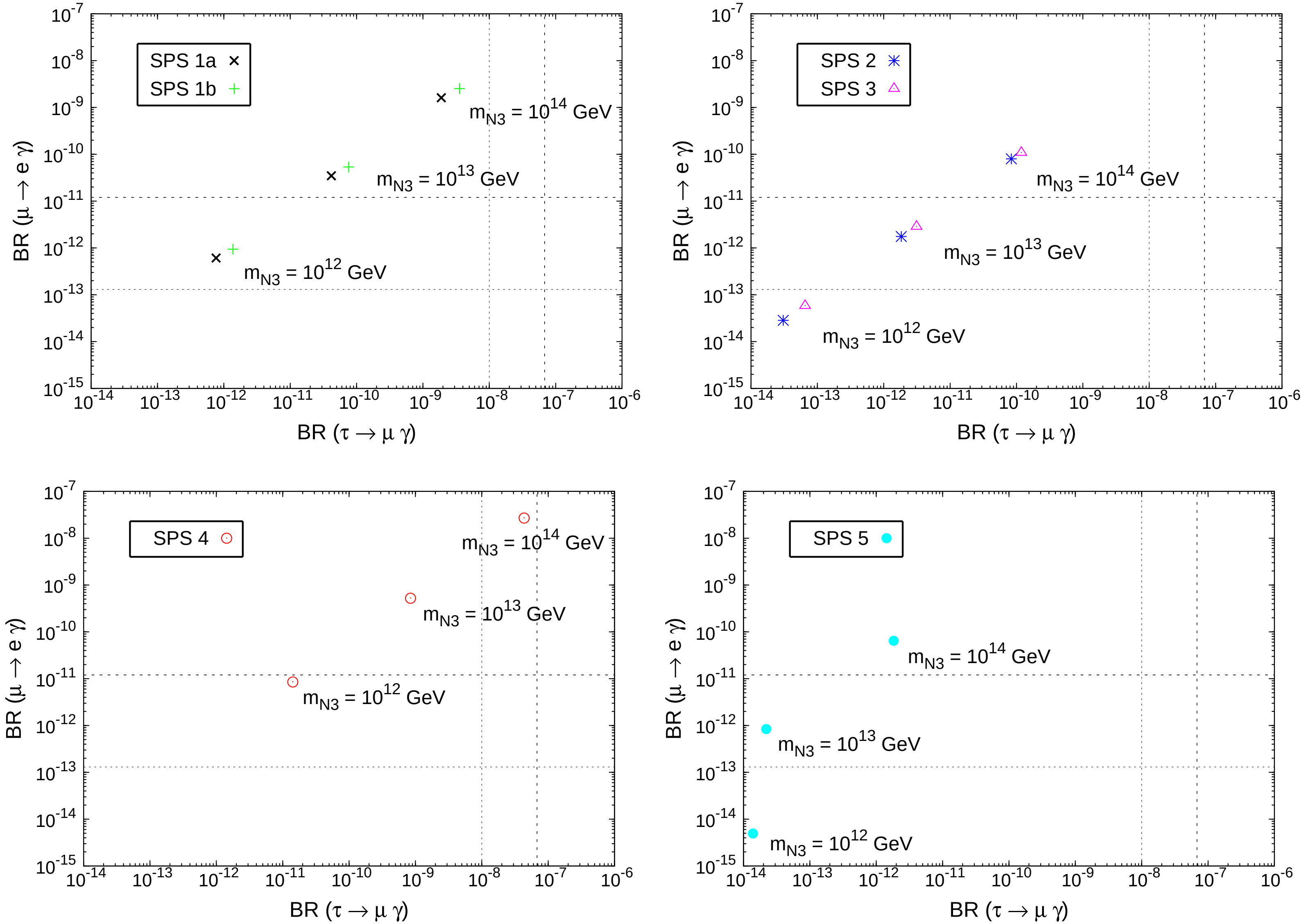
Measurement of θ_{13}

Observation of LFV τ, μ decays

$\Rightarrow$ **Window to higher scales!**

Insight into Seesaw parameters

Impact of θ_{13} on LFV observables: hints on m_{N_3}



⋆ Similar conclusions for other **SPS points**: **SPS 4 most stringent**

$\theta_{13} \approx 10^\circ \Rightarrow m_{N_3} \lesssim 2 \times 10^{12}$ **GeV**

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

Final remarks

▶ **Framework:**

Lepton flavour violation may provide first **evidence** of New Physics!

LFV in SUSY Seesaw: obtain large BR($l_j \to l_i\,\gamma$) and BR($l_j \to 3\,l_i$)

Consistency with low-energy ν-data, EDMs (and BAU via thermal leptogenesis)

Studied **BR dependence** on θ_{13} and other key parameters (m_{N_i}, θ_i, $\tan\beta$)

▶ **Results:**

$\tau \to \mu\,\gamma$, $\mu \to e\,\gamma$ and $\mu \to 3\,e$ within present experimental reach

for SPS 4 and $m_{N_3} = 10^{14}$ GeV

For $R \approx 1$, important **impact** of θ_{13} (factor 10^5 for $\theta_{13} \in [0, 10^o]$)

Sensitivity manifest in $\mu \to e\,\gamma$, $\mu \to 3\,e$, $\tau \to e\,\gamma$ and $\tau \to 3\,e$

Possible **interplay** of future experimental measurements in

hinting towards SUSY and Seesaw parameters via **LFV!**

If SUSY is present at low scale ($\lesssim$ 1 TeV)

If ν masses are originated by a type-I Seesaw mechanism

LFV τ and μ decays offer a unique laboratory

that together with low-energy ν data can provide

insight into the heavy neutrino sector,

and into Seesaw parameters

Additional transparencies

Implications of ν-oscillations

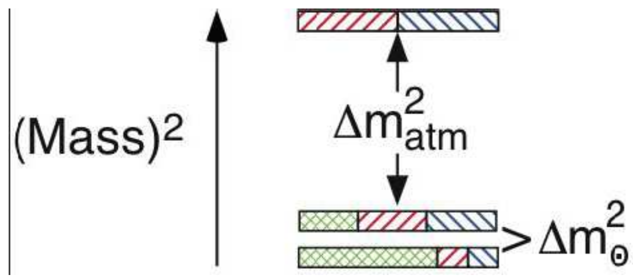
▶ Neutrinos are massive (very light); large mixing in the lepton sector

⋆ Experimentally (June '06): **three mass eigenstates** (possibly $m_{\nu_1} = 0$)

$\Delta m^2_{\text{sol}} = m^2_{\nu_2} - m^2_{\nu_1} \approx 8 \times 10^{-5}$ eV^2

$\Delta m^2_{\text{atm}} = m^2_{\nu_3} - m^2_{\nu_1} \approx 2 \times 10^{-3}$ eV^2

$\sum m_{\nu_i} \lesssim 0.7$ eV (Cosmological)



also Tritium β-decays and $0\nu2\beta$ decays

⋆ And **three mixing angles** (and CP violating phases??): U_{MNS}

$$\left.\begin{array}{l} \sin^2\theta_{12} \approx 0.3 \\ \sin^2\theta_{23} \approx 0.5 \\ \sin^2\theta_{13} \leq 0.04 \end{array}\right\} \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta} & c_{23}\,c_{13} \end{pmatrix} \cdot P(\phi_{1,2})$$

▶ Extend SM! Add right-handed neutrinos ν_R ! **Dirac** or **Majorana** νs ??

Neutrino masses

▶ **Dirac ν:** Only "standard" Dirac neutrino mass term: $Y_\nu \, H \, \bar{\nu}_L \, \nu_R$

EWBS: $m_\nu \; = \; Y_\nu \, v$; $\quad m_\nu \ll v \Rightarrow Y_\nu \sim \mathcal{O}(10^{-11}) \longrightarrow$ Naturalness problem

▶ **Majorana ν** $\leftrightsquigarrow$ **Seesaw mechanism**

Type-I Seesaw: [Minkowski; Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanović]

New scale - m_R; additional **heavy singlet states** N $\quad < m_N > \sim \mathcal{O}(m_R)$

$$\mathcal{L}_R^{\text{Maj}} \sim m_R \, \bar{\nu}_R^c \, \nu_R \qquad \boxed{m_\nu \; \approx \; \frac{(Y_\nu \, v)^2}{m_R}} \qquad (Y_\nu \; \sim \mathcal{O}(1), \text{ model-dependent})$$

New **parameters** (masses + complex mixings) - Experimentally **unreachable**

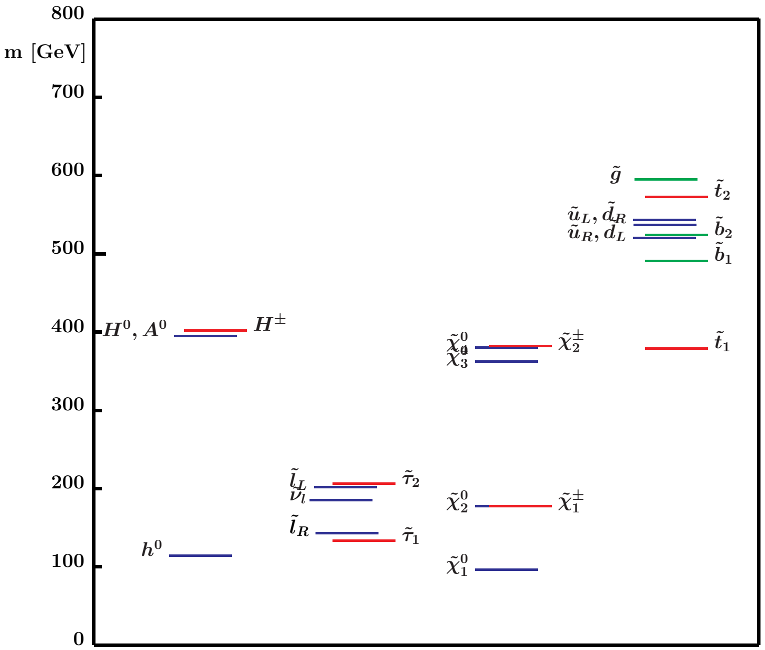
Opens the possibility of generating **Baryogenesis via Leptogenesis**

Type-II Seesaw: [Barbieri et al; Marshak, Mohapatra; Cheng, Li; Magg, Wetterich; Schechter, Valle; Mohapatra, Senjanović]

$$\mathcal{L}_L^{\text{Maj}} \sim Y_\nu^\Delta \, \Delta_H \, \bar{l}_L^c \, l_L \qquad \leftrightarrow \qquad \textbf{triplet Seesaw}$$

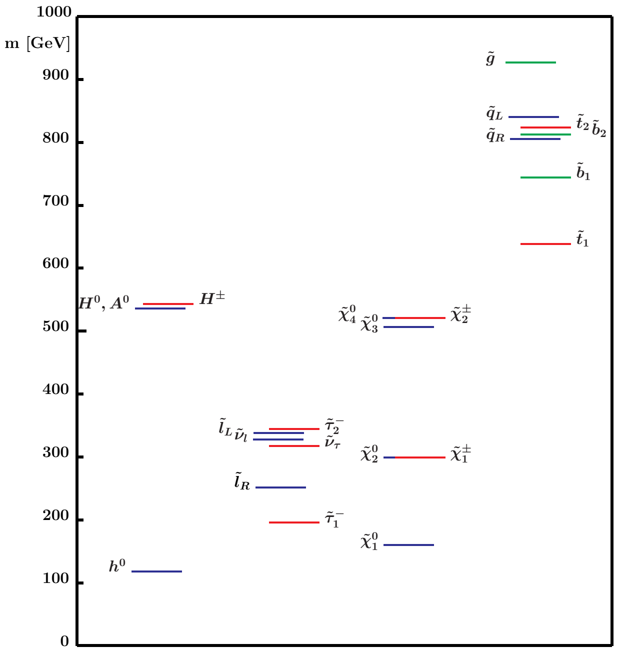
We will not pursue this here..

SPS points



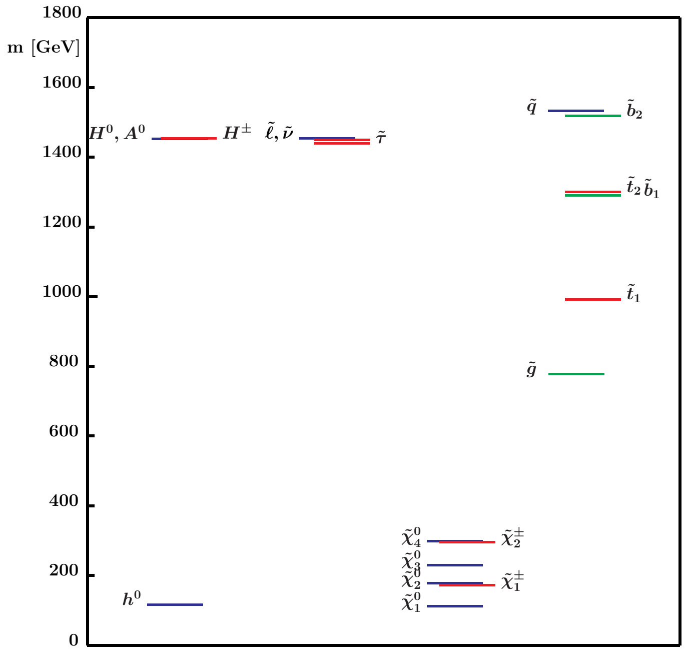
SPS 1a

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



SPS 1b

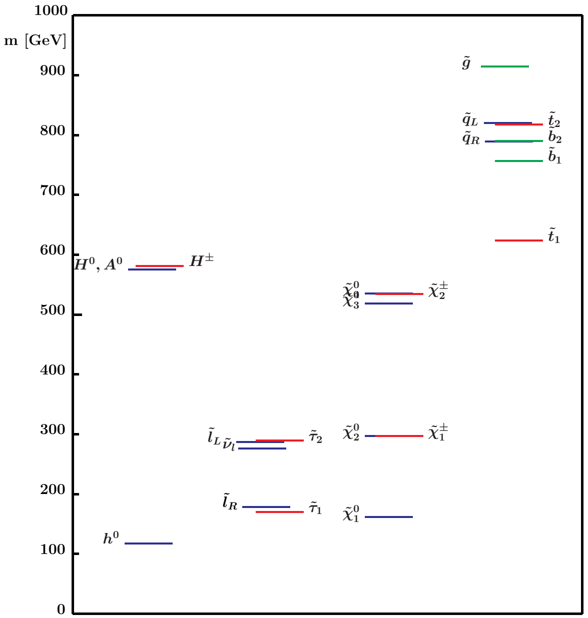
$$M_0 = 200\,\text{GeV}$$
$$M_{1/2} = 400\,\text{GeV}$$
$$A_0 = 0\,\text{GeV}$$
$$\tan\beta = 30$$
$$\mu > 0$$



SPS 2

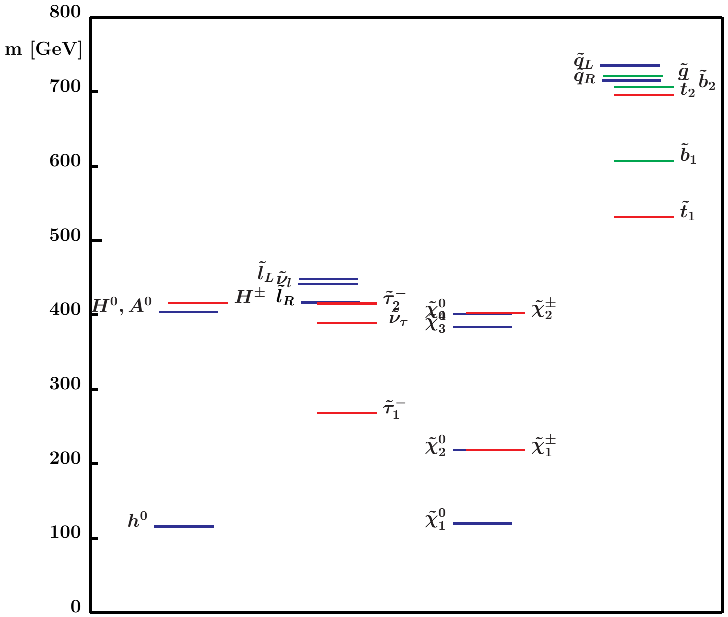
$$M_0 = 1450\,\text{GeV}$$
$$M_{1/2} = 300\,\text{GeV}$$
$$A_0 = 0\,\text{GeV}$$
$$\tan\beta = 10$$
$$\mu > 0$$

SPS points



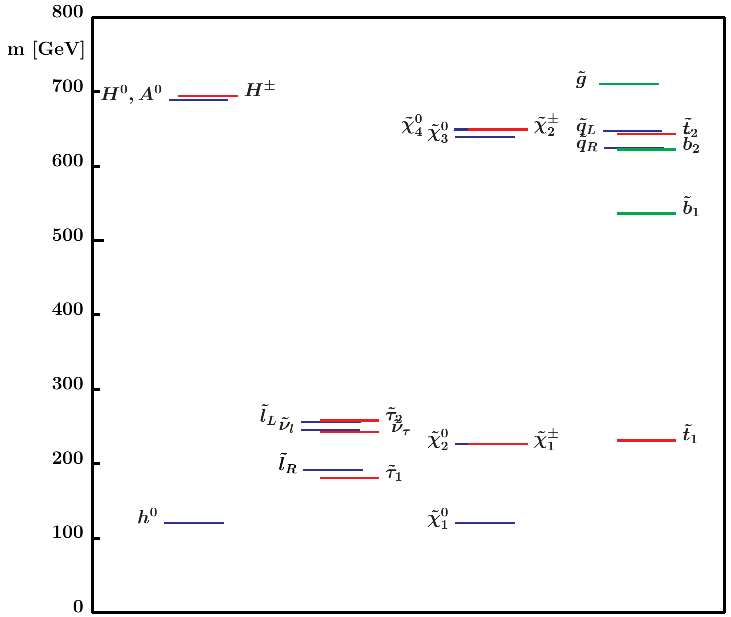
SPS 3

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



SPS 4

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



SPS 5

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

BAU via Thermal Leptogenesis

Seesaw mechanism: $\begin{cases} \text{smallness of neutrino masses} \\ \textbf{Baryogenesis via Leptogenesis} \end{cases}$

Lepton asymmetry dynamically generated via out-of-equilibrium,

CP violating decay of lightest RH neutrino N_1 [Fukujita,Yanaguida ('86)]

- Correct treatment: **flavour matters!** (CP violation from U_{MNS} and R !)

[Barbieri et al, Abada et al, ...]

- **Here:** "one-flavour" *approximation*... (to be improved! CP only from R)

Lepton asymmetry: $Y_{\mathsf{B\text{-}L}}^{\mathsf{MSSM}} \approx -\eta \left[\frac{1}{2}(\varepsilon_1 + \tilde{\varepsilon}_1) Y_{N_1}^{\mathsf{eq}} + \frac{1}{2}(\varepsilon_{\tilde{1}} + \tilde{\varepsilon}_{\tilde{1}}) Y_{\tilde{N}_1}^{\mathsf{eq}} \right]$

$\Downarrow$ efficiency factor $\nearrow$ $\searrow$ decay asymmetry $\Rightarrow$ ($R \in$)

Baryon asymmetry: $Y_{\mathsf{B}} = \alpha(N_H)\, Y_{\mathsf{B\text{-}L}}$

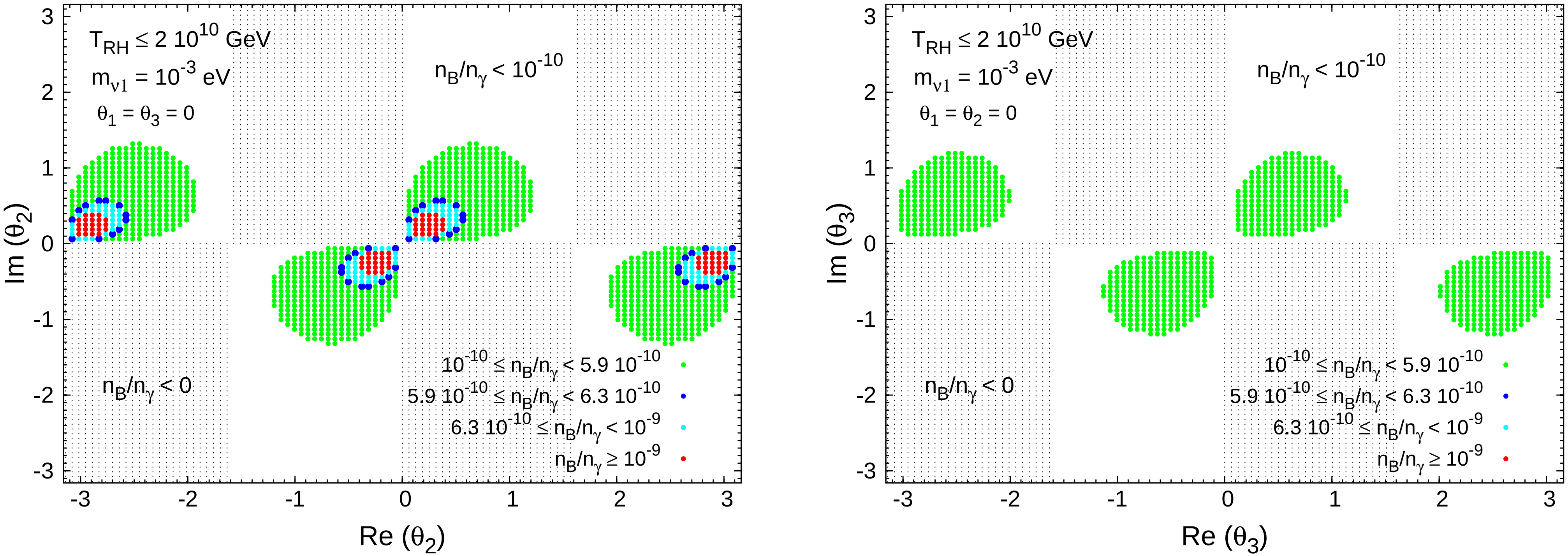
(partial sphaleron conversion [Kuzmin,Rubakov,Shaposnikov ('85)])

BAU in agreement with WMAP ('06): $n_{\mathsf{B}}/n\gamma \approx (6.10 \pm 0.21) \times 10^{-10}$

First constraints on Seesaw parameters

▶ **BAU constraints on R-angles:** $\begin{cases} |\theta_2|\,,\ |\theta_3| \ : \ \textbf{small, but non-zero} \\ |\theta_1| \ : \ \text{generically not constrained} \end{cases}$

(no U_{MNS} - one-flavour approx.)



Notice: different favoured regions in **flavour dependent treatment!** [Antusch, AT ('06)]

First constraints on Seesaw parameters

- **BAU constraints on R-angles:** $\begin{cases} |\theta_2|\,,\ |\theta_3| \ : \ \textbf{small, but non-zero} \\ |\theta_1| \ : \ \text{generically not constrained} \end{cases}$

(no U_{MNS} - one-flavour approx.)

- Additional **BAU constraints** on m_{N_1}: $\boxed{m_{N_1} \sim \mathcal{O}(T_{\text{RH}}) \sim 10^{10}\text{GeV}}$

Dramatic efficiency loss for $m_{N_1} \gg T_{\text{RH}}$ [Giudice et al ('03)]

BBN gravitino problem: constraints on T_{RH} depending on $m_{3/2}$

Gravitino decay and non-thermal LSP production: $T_{\text{RH}} \lesssim 2 \times 10^{10}$ GeV
($m_{\text{LSP}} \sim 100$ GeV)

- Contributions to **EDMs**:

Even for CP-conserving U_{MNS}, CP violating phases in R, thus **complex** Y_ν

Potential **contributions** to e, μ and τ electric dipole moments

Ensure **compatibility** with current **bounds:**

$$\text{EDM}_{e\mu\tau} \lesssim (6.9 \times 10^{-28}, 3.7 \times 10^{-19}, 4.5 \times 10^{-17})\ \text{e.cm}$$