SUSY Lepton Flavor Violation: Radiative Decays and Collider Searches

Reinhold Rückl

University of Würzburg

In collaboration with
S. Albino, F. Deppisch, H. Päs, A. Redelbach, Y. Shimizu
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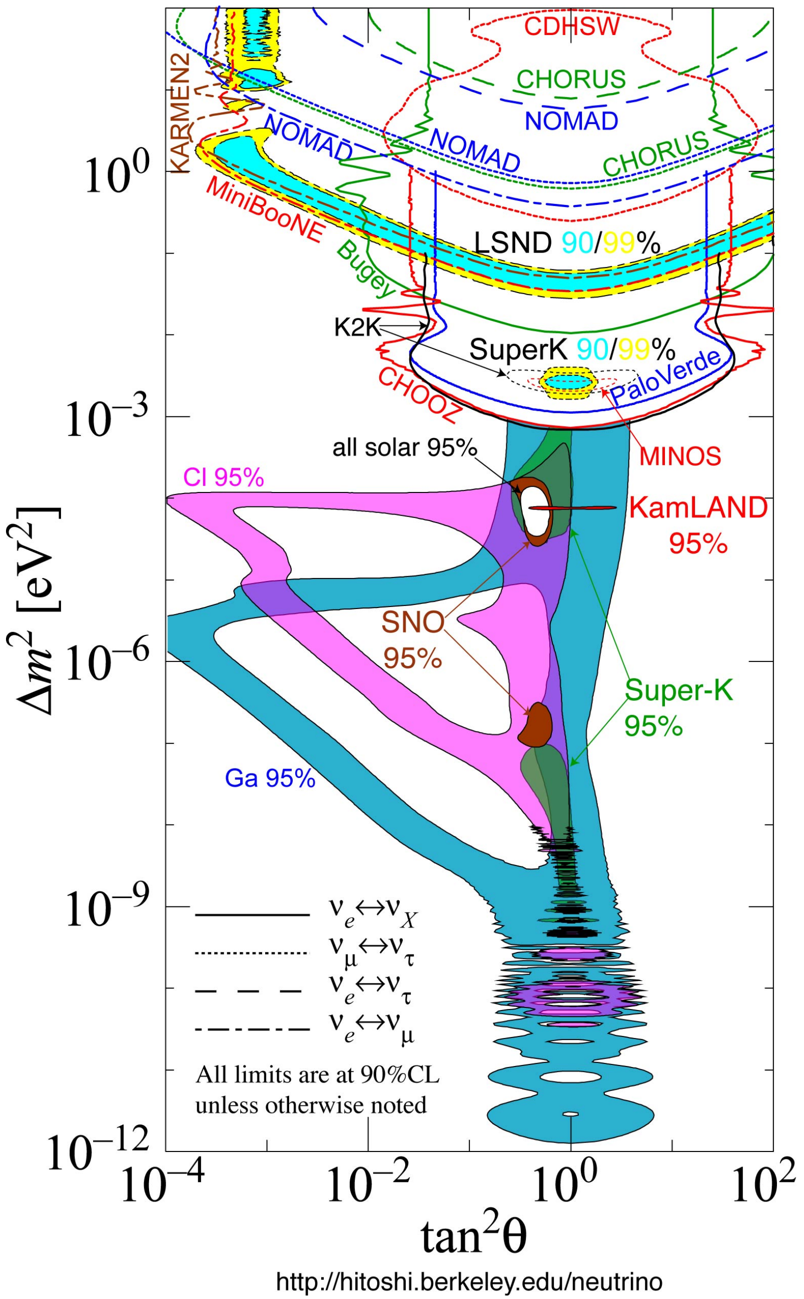


neutrino masses and mixing
give hints towards BSM physics

- lepton flavor violation
- leptonic CP violation
- Majorana mass and GUT scales
- lepton number violation

low-energy observables suppressed
by light neutrino masses unless
there is other new physics

e.g. **SUPERSYMMETRY**

minimal supersymmetric scenario

- MSSM + 3 families of right-handed neutrino singlet fields ν_R
- Majorana mass term: $\frac{1}{2}\nu_R^{cT} M \nu_R^c$
- Yukawa coupling to Higgs field (hypercharge $+\frac{1}{2}$): $\nu_R^{cT} Y_\nu L H_2$
- EWSB $\rightarrow$ Dirac mass term: $m_D = Y_\nu \langle H_2 \rangle$

diagonalization of neutrino mass matrix for $\langle H_2 \rangle \ll M_R$:

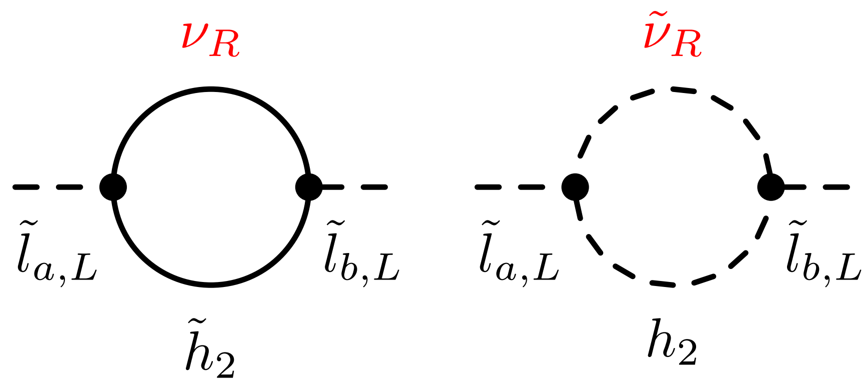
$$\frac{1}{2} \begin{pmatrix} \nu_L^T & \nu_R^{cT} \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

light neutrinos: $M_\nu = m_D^T M^{-1} m_D \sim \dfrac{\langle H_2 \rangle^2}{M_R}$

heavy neutrinos: $M_N \sim M_R$

Slepton Mass Matrix

virtual effects of heavy (s)neutrinos



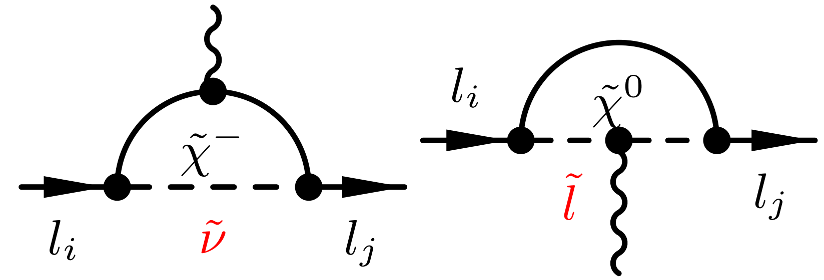
generate, via renormalization, **flavor non-diagonal terms** in

$$m^2_{\tilde{l}} = \begin{pmatrix} m^2_{\tilde{l}_L} & m^{2\dagger}_{\tilde{l}_{LR}} \\ m^2_{\tilde{l}_{LR}} & m^2_{\tilde{l}_R} \end{pmatrix} = \tilde{m}^2_{MSSM} + \begin{pmatrix} \delta m^2_L & \delta m^{2\dagger}_{LR} \\ \delta m^2_{LR} & \delta m^2_R \end{pmatrix}$$

e.g. **in MSUGRA** $[L = D(\ln(M_{GUT}/M_{N_i}))]$:

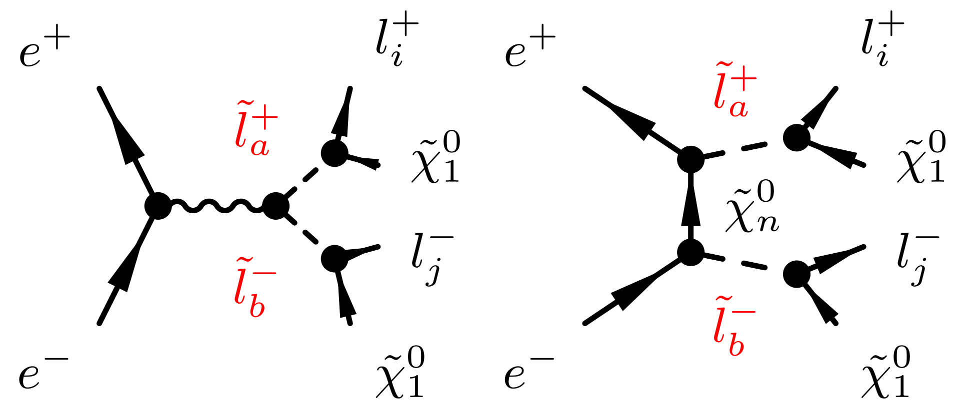
$$\begin{aligned} \delta m^2_L &\simeq -\frac{1}{8\pi^2}(3m_0^2 + A_0^2)\, Y_\nu^\dagger L Y_\nu \\ \delta m^2_R &\simeq 0 \\ \delta m^2_{LR} &\simeq -\frac{3}{16\pi^2} Y_l\, v \cos\beta\, A_0\, Y_\nu^\dagger L Y_\nu \end{aligned}$$

$$\mu \to e\gamma, \tau \to e\gamma, \tau \to \mu\gamma$$



$$\Gamma\,(l_i \to l_j\gamma) \propto \frac{|\delta m^2_{Lij}|^2}{\tilde{m}^4}\,\frac{\alpha^3 m^5_{l_i}}{\tilde{m}^4}\,\tan^2\beta, \qquad \frac{Br(l_i \to 3\,l_j)}{Br(l_i \to l_j\gamma)} \simeq O(10^{-3})$$

$$e^+e^- \to (\mu e/\tau e/\tau\mu) + 2\tilde{\chi}^0_1$$



$$\sigma(l_i^+ l_j^-) \propto \frac{|\delta m^2_{Lij}|^2}{\tilde{m}^2\Gamma^2_{\tilde{l}}}\,\sigma(e^+e^- \to \tilde{l}^+\,\tilde{l}^-)Br(\tilde{l}^+ \to l_i^+\,\tilde{\chi}^0_1)Br(\tilde{l}^- \to l_j^-\,\tilde{\chi}^0_1)$$

Casas, Ibarra, hep-ph/0103065 (NPB618)

$$\delta m_L^2 \propto Y_\nu^\dagger L Y_\nu, \quad Y_\nu = \frac{1}{v \sin\beta} D(\sqrt{M_i}) \cdot R \cdot D(\sqrt{m_j}) \cdot U^\dagger$$

- light and heavy neutrino **eigenmasses**: m_i (from experiment) and M_i
- mass diagonalization and **mixing**: θ_{ij} (from experiment) and ϕ_i, δ

$$\begin{aligned} U^T M_\nu U &= D\,(m_1, m_2, m_3) \\ U &= D(e^{i\phi_1}, e^{i\phi_2}, 1) V\,(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \end{aligned}$$

- **arbitrary complex matrix, $R^T R = \mathbf{1}$**:

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

$c(s)_i = \cos(\sin)\theta_i$, complex angles $\theta_i = x_i + I y_i$

$$\Delta m_{12}^2 = 6.9^{+0.36}_{-0.36} \cdot 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m_{13}^2 = 2.6^{+1.2}_{-1.2} \cdot 10^{-3}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.43^{+0.47}_{-0.22}$$

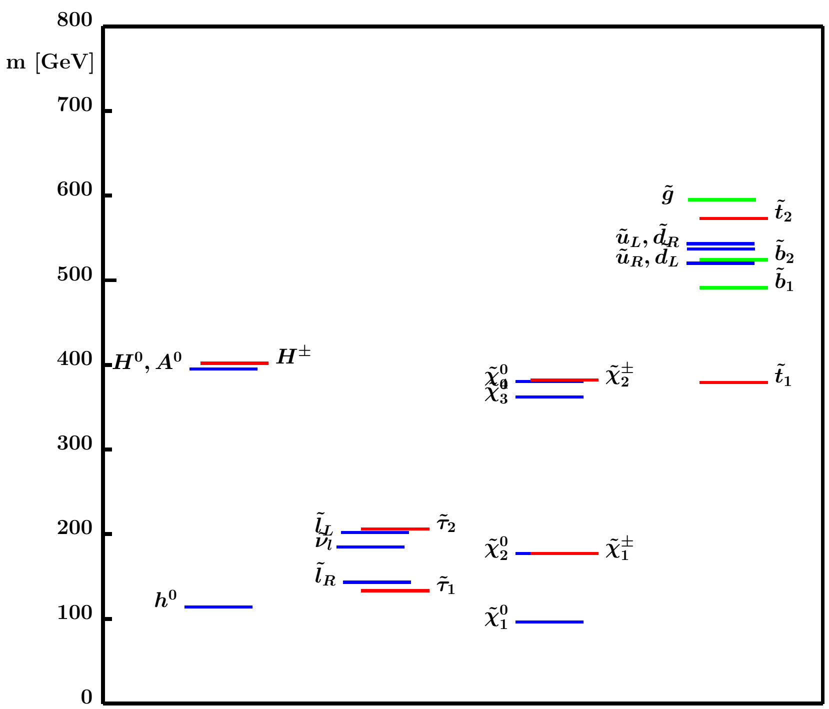
$$\tan^2\theta_{23} = 1.10^{+1.39}_{-0.60}$$

$$\tan^2\theta_{13} = 0.006^{+0.001}_{-0.006}$$

- central values from *Maltoni et al., hep-ph/0309130 (PRD68)*
- 90% C.L. errors as anticipated for running/proposed experiments
- Dirac and Majorana phases unconstrained
- hierarchical ($m_1 \leq 0.03$ eV) or degenerate ($m_1 \approx 0.3$ eV) spectrum

Scenario	$m_{1/2}$/GeV	m_0/GeV	$\tan\beta$	A_0/GeV	signμ
B’	250	60	10	0	+
C’	400	85	10	0	+
G’	375	115	20	0	+
I’	350	175	35	0	+
SPS1a	250	100	10	-100	+

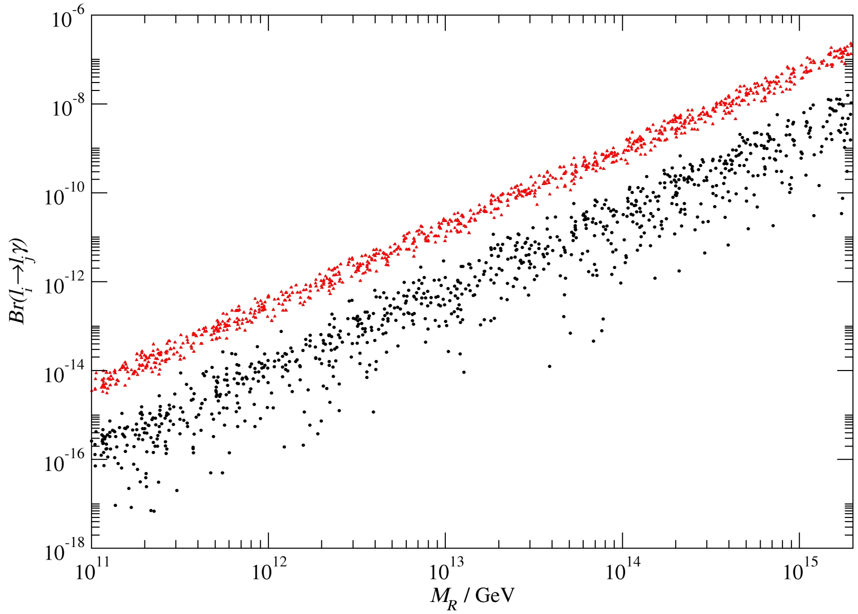
- MSUGRA benchmark models
  B’,..I’ *(Battaglia et al., hep-ph/0306219)*
  SPS1a *(http://spa.desy.de/spa)*
  consistent with experiment and CDM
- universal scalar masses keep LFV small



$Br(\mu \to e\gamma)$ and $Br(\tau \to \mu\gamma)$

degenerate $M_i = M_R$, real R: $Y_\nu^\dagger L Y_\nu = \frac{M_R}{v^2 \sin^2\beta} V \cdot D(m_i) \cdot V^\dagger L, \; L = \ln \frac{M_{GUT}}{M_R}$

degenerate m_i, SUSY point SPS1a, scatter: uncertainties from neutrino data



related LFV decays:

$$\frac{Br(\tau \to 3\mu)}{Br(\tau \to \mu\gamma)} \simeq 2 \cdot 10^{-3}$$

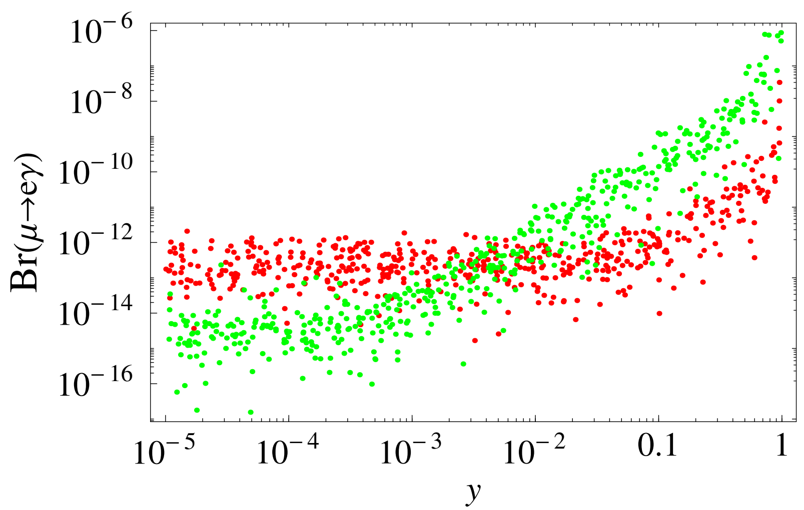
$$\frac{Br(\mu \to 3e)}{Br(\mu \to e\gamma)} \simeq 7 \cdot 10^{-3}$$

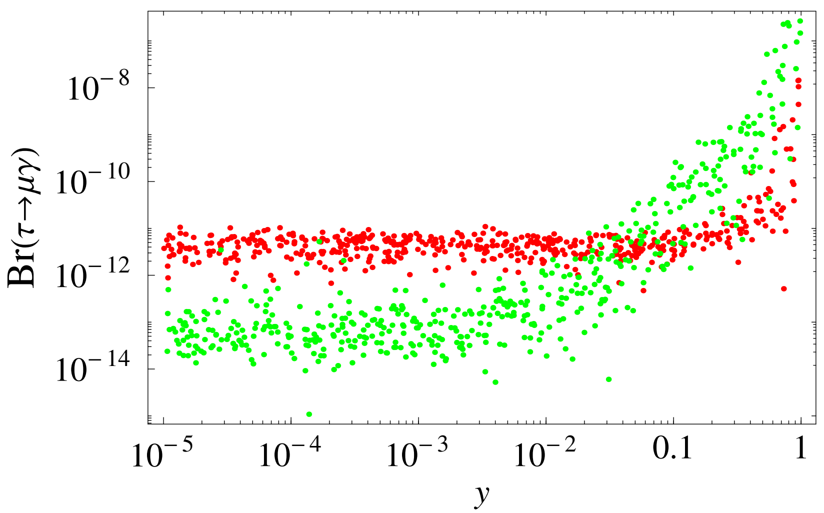
$Br(\tau \to \mu\gamma) < 6.8 \cdot 10^{-8}$ (90 % C.L., *BABAR 2005*)

$Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$ (90 % C.L., *PDG 2004*)

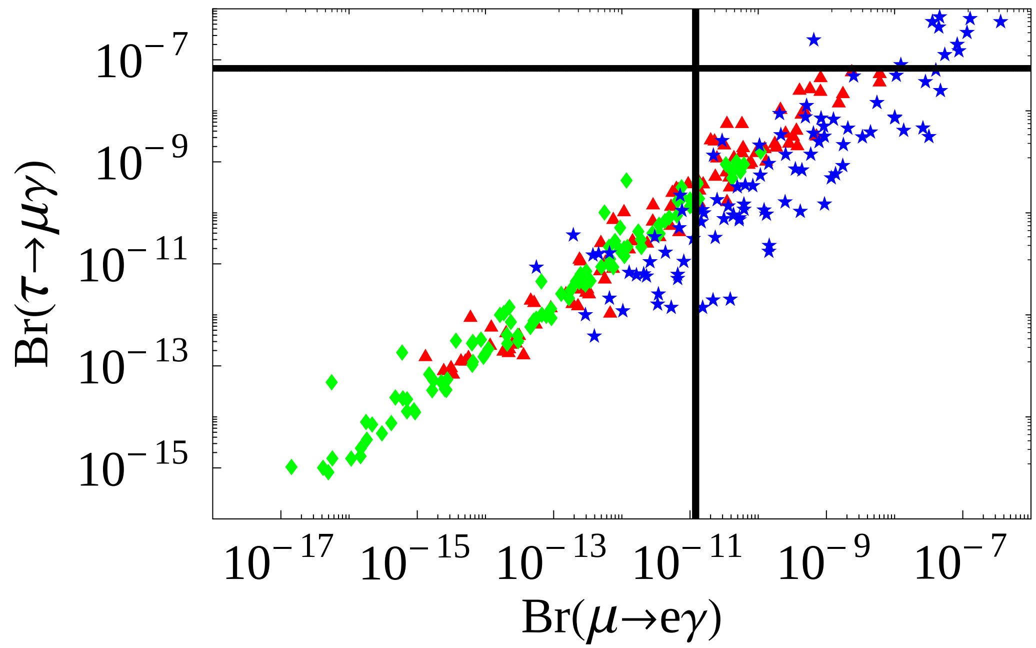
$$R(\cos\theta_i, \sin\theta_i) = R(\cos x_i \cosh y_i - I \sin x_i \sinh y_i, \sin x_i \cosh y_i + I \cos x_i \sinh y_i)$$

- $0 \leq x_i \leq 2\pi$, $y_i = y$
- degenerate heavy Majorana neutrinos $M_i = M_R = 10^{12}$ GeV
- hierarchical or degenerate light neutrinos and their mixing
- SUSY point SPS1a





complex R enhances LFV and generates lepton number violation in N decays seesaw parameters in preferred ranges ($M_i = 10^{10}$ to 10^{13} GeV), SUSY point SPS1a



deg. N, hier. ν, R real

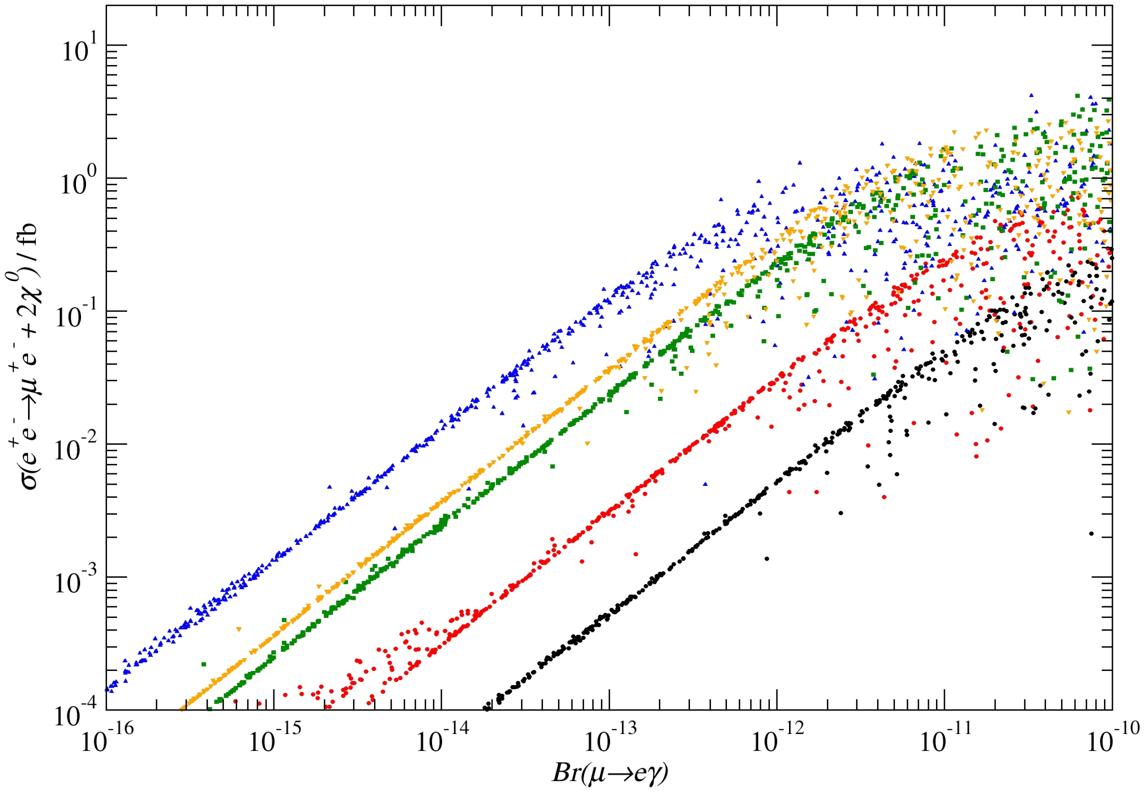
deg. N, deg. ν, R real

hier. N, hier. ν, R complex

yields model-dependent bound $Br(\tau \to \mu\gamma) < 10^{-9}$

$\sigma(e^+e^- \to \mu^+e^- + 2\tilde{\chi}_1^0)$, $\sqrt{s} = 800$ GeV

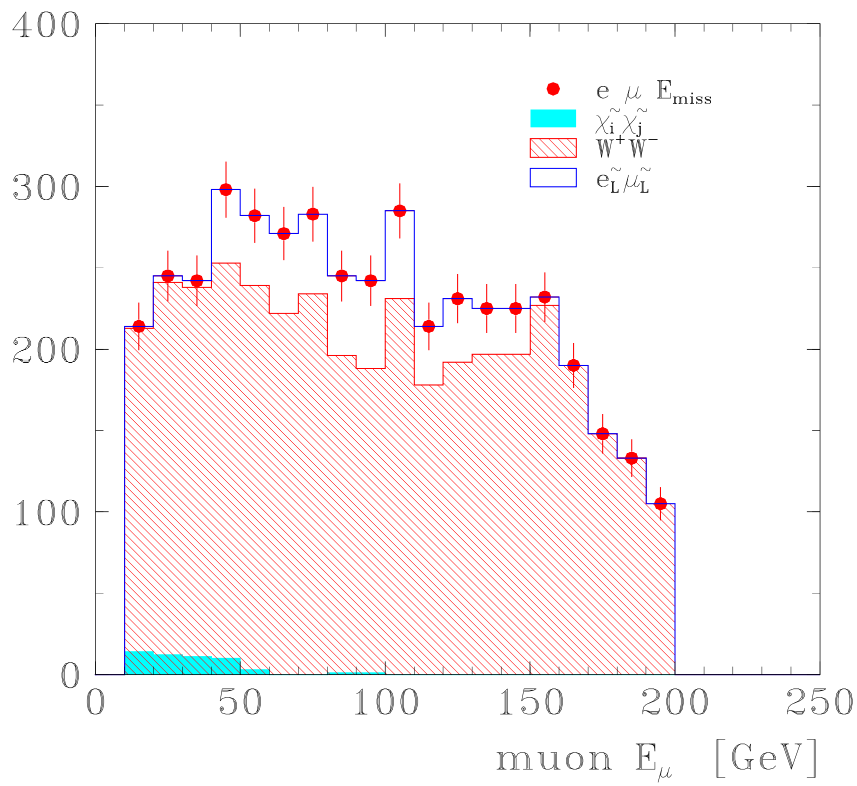
degenerate M_i and m_i, real R, SUSY points C', G', B', SPS1a, I'



$Br(\mu \to e\gamma) \approx 10^{-12}$ implies $\sigma(e^+e^- \to \mu e + 2\tilde{\chi}_1^0) \approx 0.01$ to 1 fb

$e\mu\, E_{miss}$ final states

MSUGRA point SPS1a, $\sqrt{s} = 500$ GeV, unpolarized, 500 fb^{-1}

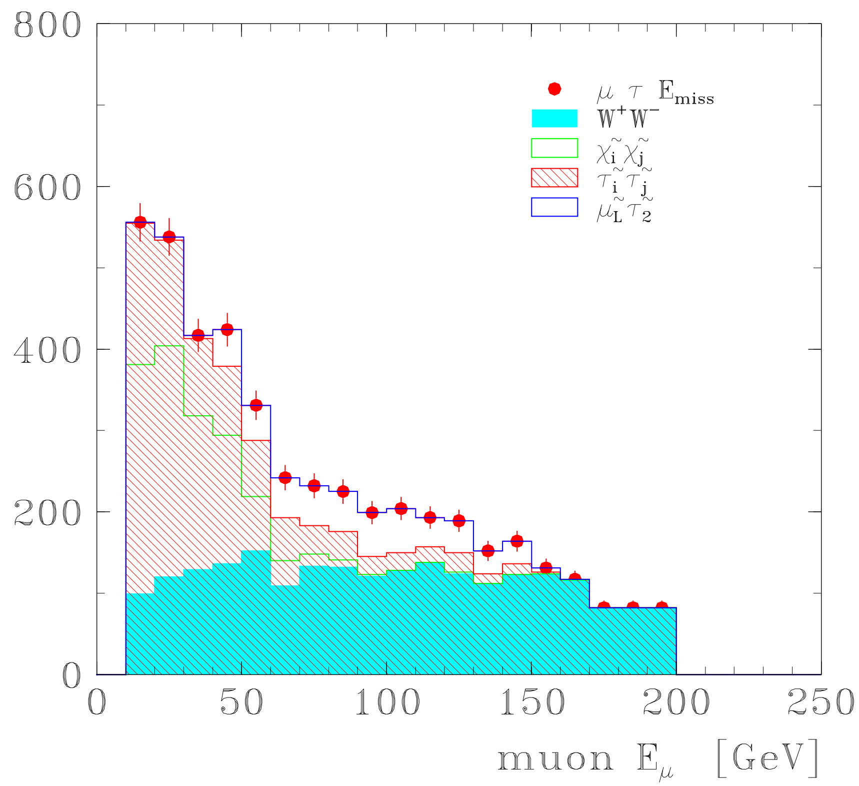


- 2 fb signal cross section (flat lepton energy spectrum)
- SM+MSSM background
- standard selection criteria (50% efficiency)
- $\sigma(\tilde{e}_L\tilde{\mu}_L) = 1$ fb $\rightarrow 5\sigma$ effect
- improvements possible (E_e spectrum, polarization)

Deppisch, Martyn, Päs, Redelbach, RR, hep-ph/0408140

$\tau\mu\, E_{miss}$ final states

MSUGRA point SPS1a, $\sqrt{s} = 500$ GeV, unpolarized, 500 fb^{-1}

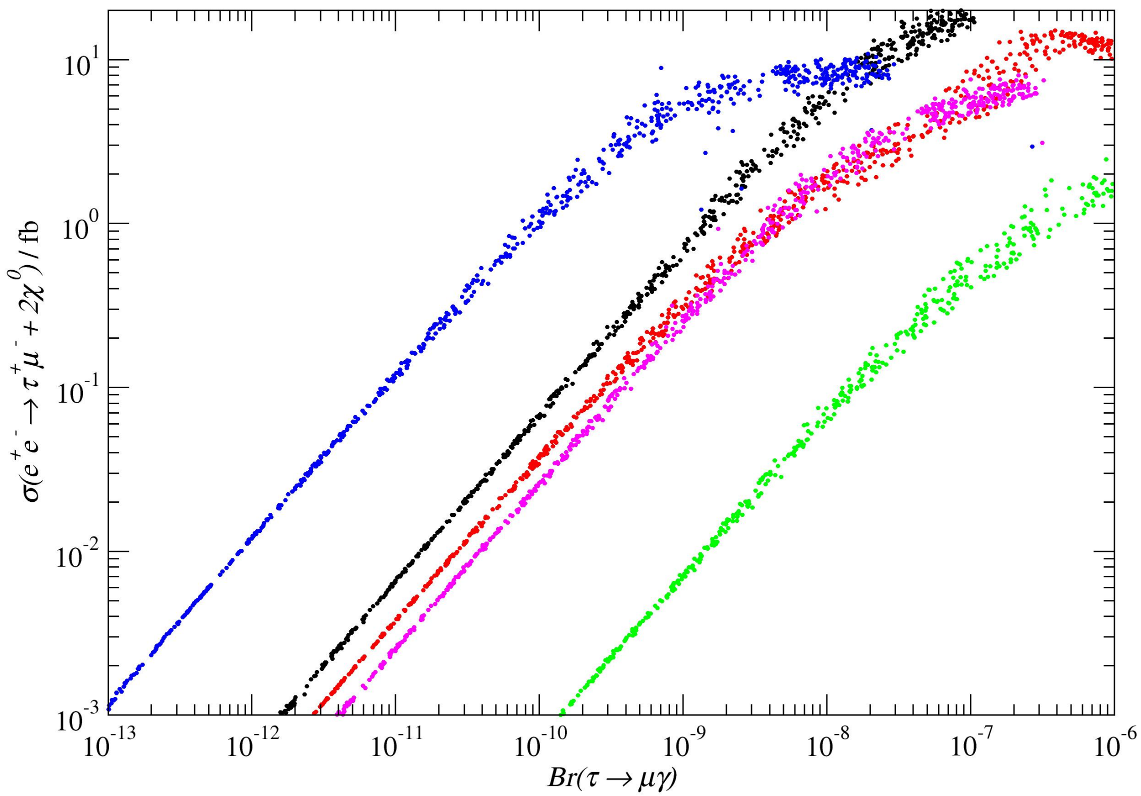


- 4 fb signal cross section (flat lepton energy spectrum)
- SM+MSSM background (soft E_μ spectrum)
- standard selection criteria (τ identification via hadronic decays, 25% efficiency)
- $\sigma(\tilde{\tau}_2\tilde{\mu}_L) = 2$ fb $\rightarrow 5\sigma$ effect

Deppisch, Martyn, Päs, Redelbach, RR, hep-ph/0408140

$$\sigma(e^+e^- \to \tau^+\mu^- + 2\tilde{\chi}_1^0),\ \sqrt{s} = 800 \text{ GeV}$$

degenerate M_i and m_i, real R, SUSY points C', B', SPS1a, G', I'



$\sigma(e^+e^- \to \tau\mu + 2\tilde{\chi}_1^0) \approx 2$ fb implies $Br(\tau \to \mu\gamma) \approx 10^{-6}$ to 10^{-10}

τ radiative decay: $W \to \tau\nu$, $\tau \to \mu\gamma$

Serin, Stroynowski, ATLAS Internal Note (1997)

- signal: $M(\mu\gamma) = m_\tau$
- background: QED radiation in production and decay
- reach (30 fb^{-1}): $Br(\tau \to \mu\gamma) \simeq 6 \cdot 10^{-7}$

direct DY production of sleptons: $\tilde{l}_i\tilde{l}_i \to l_j l_k 2\tilde{\chi}_1^0$

Bityukov,Krasniov, hep-ph/9712358
Agashe, Graesser, hep-ph/ 9904422

- signal: dileptons of different flavour and large missing p_T
- background: $t\bar{t}, W^+W^-, \tilde{\chi}^+\tilde{\chi}^-$
- generally very difficult

LFV neutralino and slepton decays: $\tilde{g}, \tilde{q} \to \tilde{\chi}_2^0 \to \tilde{l}_a l_j \to l_i l_j \tilde{\chi}_1^0$

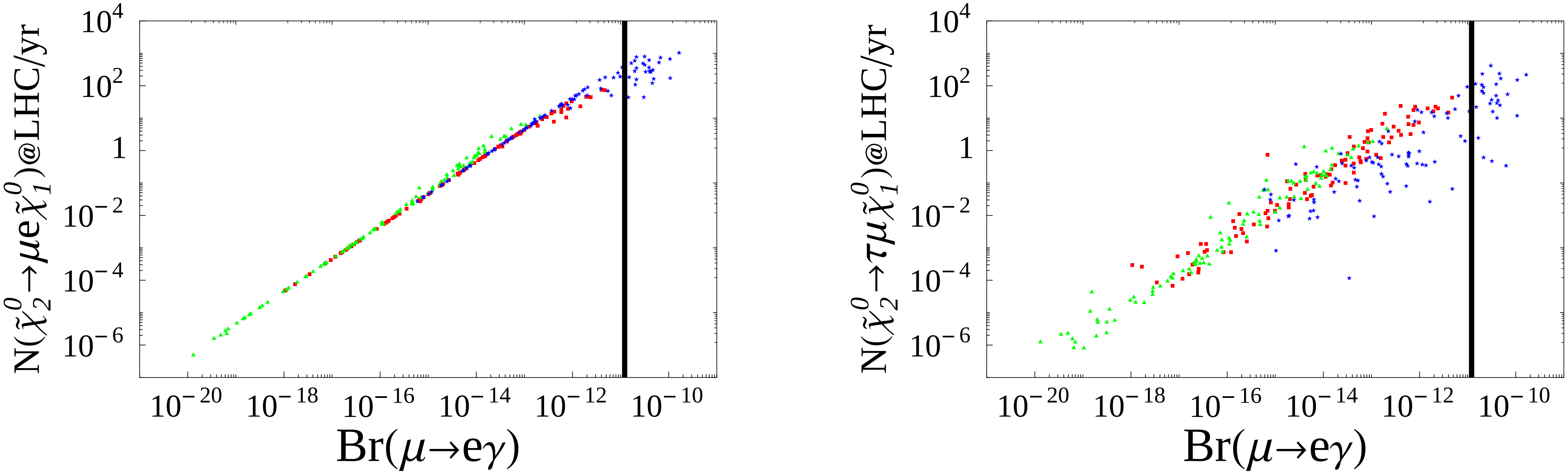
Agashe, Graesser, hep-ph/ 9904422
Hinchliffe, Paige, hep-ph/0010086
Hisano et al., PRD D65(2002)116002
Carvalho et al., hep-ph/0206148
Bartl et al., hep-ph/0510074

- signal: dilepton mass distribution
- background: $t\bar{t}$, SUSY channels
- reach (30 fb^{-1}): $Br(\tilde{\chi}_2^0 \to l_i l_j \tilde{\chi}_1^0) \simeq$ 2 to 4 %

$\tilde{\chi}_2^0 \to \mu^+ e^- \, (\tau^+ \mu^-) \, \tilde{\chi}_1^0$ vs. $BR(\mu \to e\gamma)$

$M_i = 10^{10}$ to 10^{13} and 100 fb^{-1}

MSUGRA point C' ($m_0 = 85$ GeV, $m_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$ GeV, sign$\mu = +$)

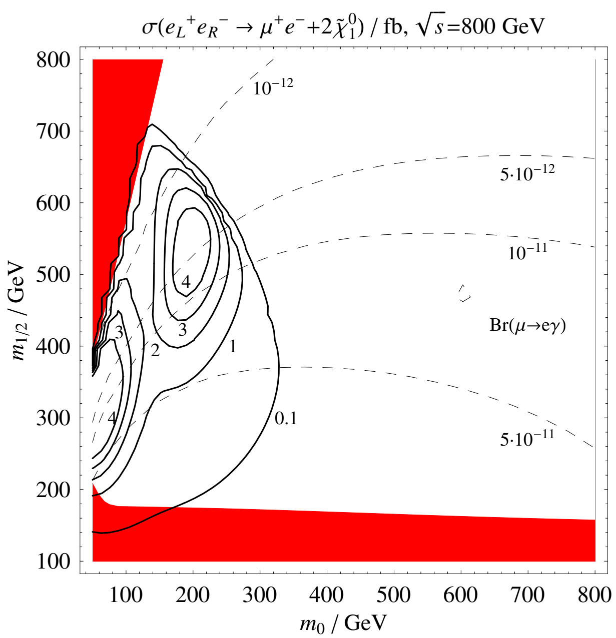


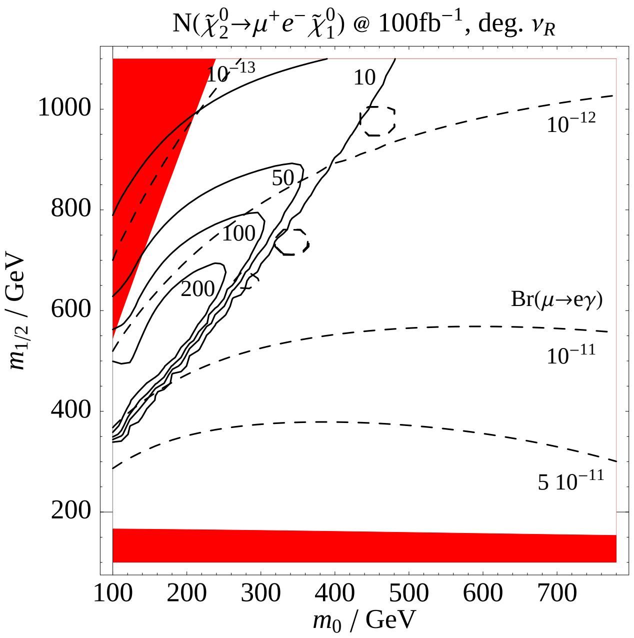
hierarch. N, hierarch. ν

degen. N, hierarch. ν

degen. N, degen. ν

- SUSY seesaw with $M_R = 10^{10}$ to 10^{14} GeV suggests sizeable charged LFV
- details model dependent, generically strong correlations in μe, τe, $\tau\mu$ channels
- for sufficiently small m_0 radiative decays and collider searches complementary
- BAU via CP violating out-of-equilibrium decays of heavy N_1 and sphaleron processes, i.e. leptogenesis





$A_0 = 0$, $\tan\beta = 5$, sign $\mu = +$,

$M_R = 10^{14}$ GeV, zero complex phases, central values of neutrino data, $m_1 = 0$

- evolution of neutrino mass matrix: $m_Z \to M_1$
  input: light neutrino data

$$16\pi^2 \frac{d}{dt} M_\nu = \left(-6g_2^2 - \frac{6}{5}g_1^2 + Tr(6Y_U^\dagger Y_U)\right) M_\nu + (Y_l^\dagger Y_l) M_\nu + M_\nu (Y_l^\dagger Y_l)^T$$

- inversion of $M_\nu = Y_\nu^T M^{-1} Y_\nu (v \sin\beta)^2$ and
  evolution of Yukawa coupling matrix: $M_1 \to M_2 \to M_3 \to M_{GUT}$

$$16\pi^2 \frac{d}{dt} Y_\nu = Y_\nu \left(-3g_2^2 - \frac{3}{5}g_1^2 + Tr(3Y_U^\dagger Y_U + Y_\nu^\dagger Y_\nu) + Y_l^\dagger Y_l + 3Y_\nu^\dagger Y_\nu\right)$$

- evolution of slepton mass matrix: $M_{GUT} \to m_Z$
  input: neutrino Yukawa couplings at M_{GUT}

$$16\pi^2 \frac{d\delta m_L^2}{d\ln\mu} = m_L^2 Y_\nu^\dagger Y_\nu + Y_\nu^\dagger Y_\nu m_L^2 + 2\left(Y_\nu^\dagger m_{\tilde{\nu}}^2 Y_\nu + m_{h_2}^2 Y_\nu^\dagger Y_\nu + A_\nu^\dagger A_\nu\right)$$

$$16\pi^2 \frac{d\delta m_R^2}{d\ln\mu} = 0$$

$$16\pi^2 \frac{d\delta A_e}{d\ln\mu} = 2Y_e Y_\nu^\dagger A_\nu + A_e Y_\nu^\dagger Y_\nu$$

general parametrization of Yukawa matrix: $Y_\nu = \frac{1}{v \sin\beta} D\left(\sqrt{M_i}\right) R\, D\left(\sqrt{m_i}\right) U^\dagger$

for degenerate Majorana masses $M_i = M_R$ and real R:

$$Y_\nu^\dagger L Y_\nu = \frac{M_R}{v^2 \sin^2\beta} V \cdot D(m_i) \cdot V^\dagger L, \;\; L = \ln \frac{M_{GUT}}{M_R}$$

- for hierarchical light ν spectrum:

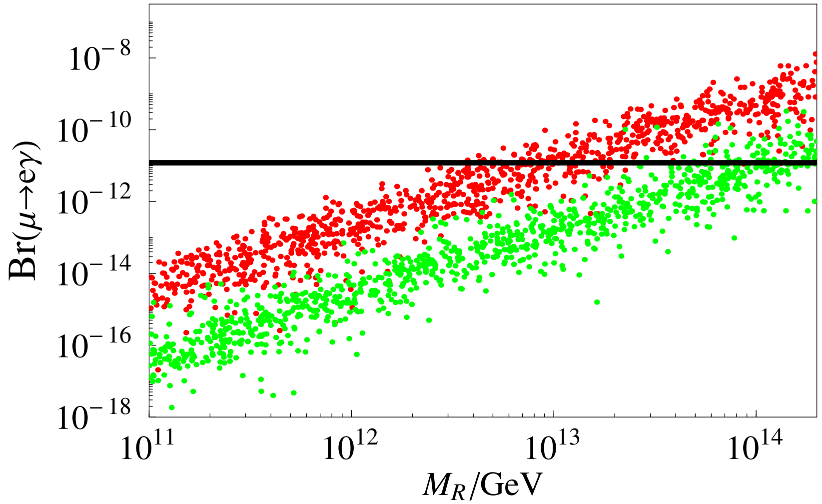
$$\left(Y_\nu^\dagger Y_\nu\right)_{ab} \approx \frac{M_R}{v^2 \sin^2\beta} \left(\sqrt{\Delta m_{12}^2} V_{a2} V_{b2}^* + \sqrt{\Delta m_{23}^2} V_{a3} V_{b3}^*\right)$$

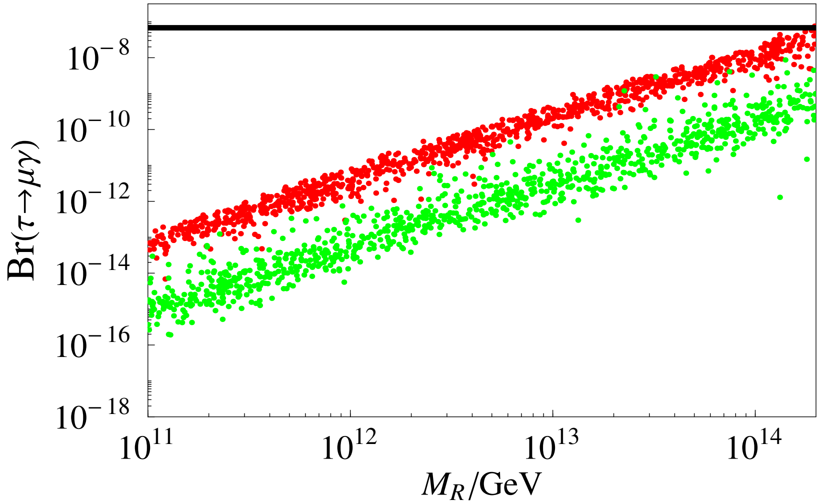
- for degenerate light ν spectrum:

$$\left(Y_\nu^\dagger Y_\nu\right)_{ab} \approx \frac{M_R}{v^2 \sin^2\beta} \left(m_1 \delta_{ab} + \frac{1}{2m_1}\left(\Delta m_{12}^2 V_{a2} V_{b2}^* + \Delta m_{23}^2 V_{a3} V_{b3}^*\right)\right)$$

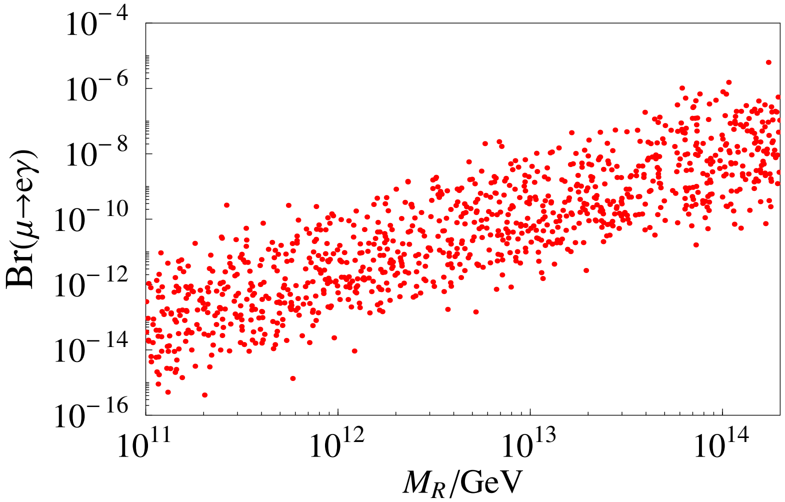
degenerate $M_{N_i} = M_R$, hierarch./degen. m_{ν_i}, SUSY point SPS1a

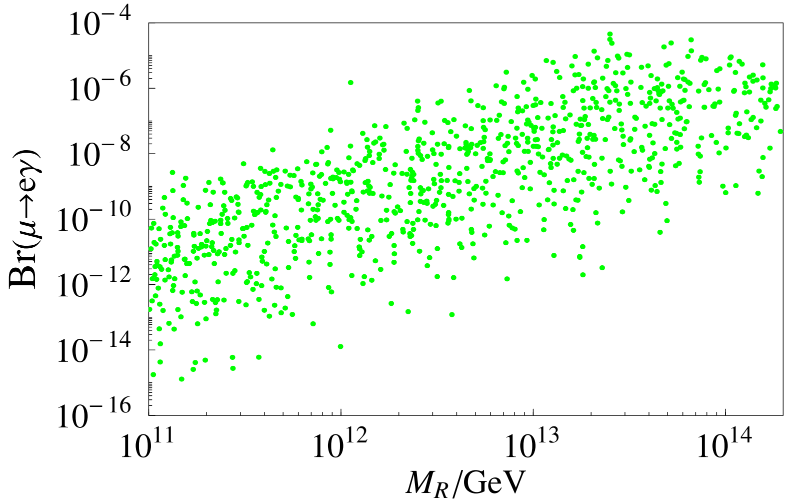
Real R: $\delta m_L^2 \sim Y_\nu^\dagger L Y_\nu \sim M_R \, \ln \frac{M_{\rm GUT}}{M_R} V \cdot D(m_j) \cdot V^\dagger$





Complex R: $\delta m_L^2 \sim Y_\nu^\dagger L Y_\nu, \; Y_\nu \sim \sqrt{M_R} \, R \cdot D(\sqrt{m_j}) \cdot U^\dagger$





ratios of branching ratios

$$\frac{Br\left(l_i \to l_j \gamma\right)}{Br\left(l_{i'} \to l_{j'} \gamma\right)} \sim \frac{m_{l_i}^5 \Gamma_{i'}}{m_{l'_i}^5 \Gamma_i} \frac{\left|\left(Y_\nu^\dagger L Y_\nu\right)_{ij}\right|^2}{\left|\left(Y_\nu^\dagger L Y_\nu\right)_{i'j'}\right|^2}$$

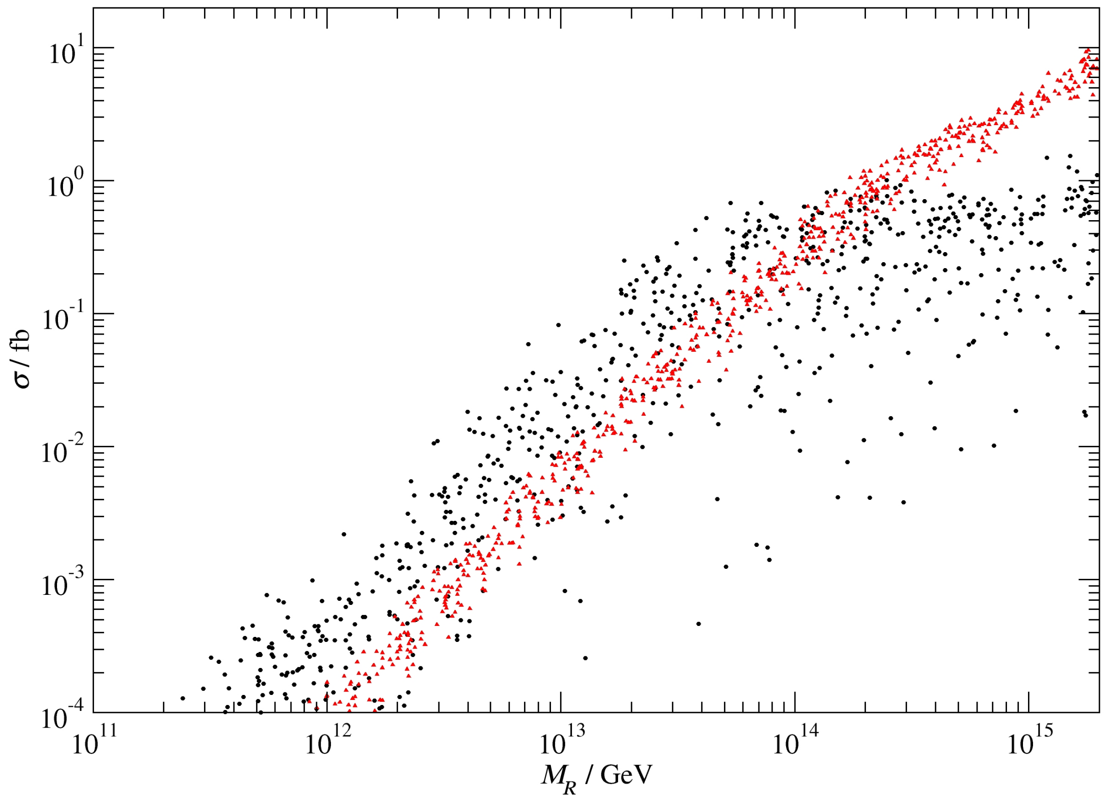
example:

- hierarchical light neutrinos, central best-fit values for neutrino parameters
- vanishing Dirac/Majorana phases
- SUSY scenario C

Majorana masses		
Ratios	$M_i = M_R$	$M_1 : M_2 : M_3 = 1 : 10 : 100$
$\tau \to \mu\gamma / \mu \to e\gamma$	4	12
$\tau \to \mu\gamma / \tau \to e\gamma$	2500	160
$\mu \to e\gamma / \tau \to e\gamma$	640	13

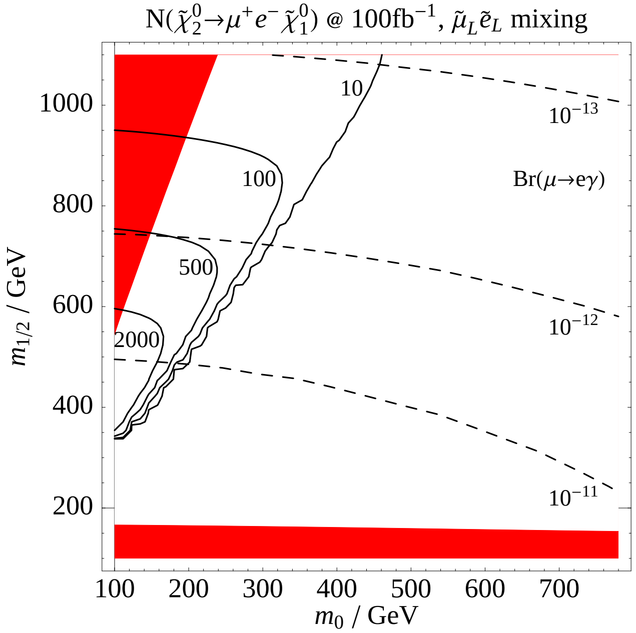
$$\sigma(e^+e^- \to \mu^+e^-(\tau^+\mu^-) + 2\tilde{\chi}_1^0)$$

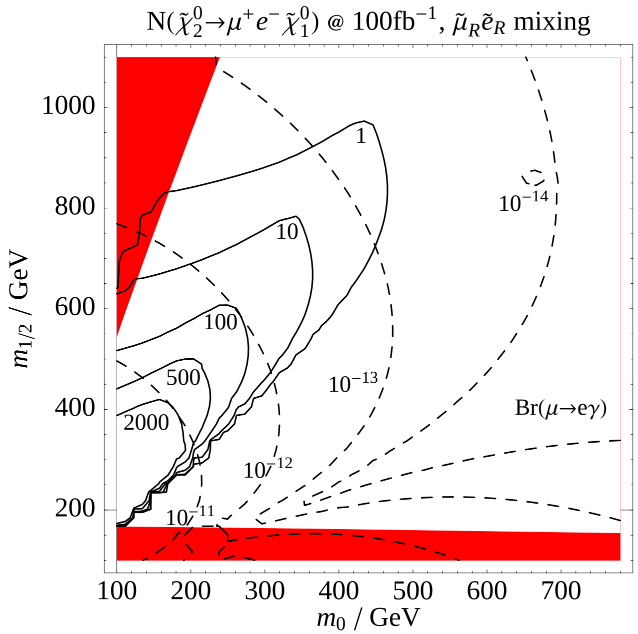
degenerate Majorana masses, real R, SUSY point SPS1a



direct production at $\sqrt{s} = 500$ GeV, neutralino and chargino cascades not included

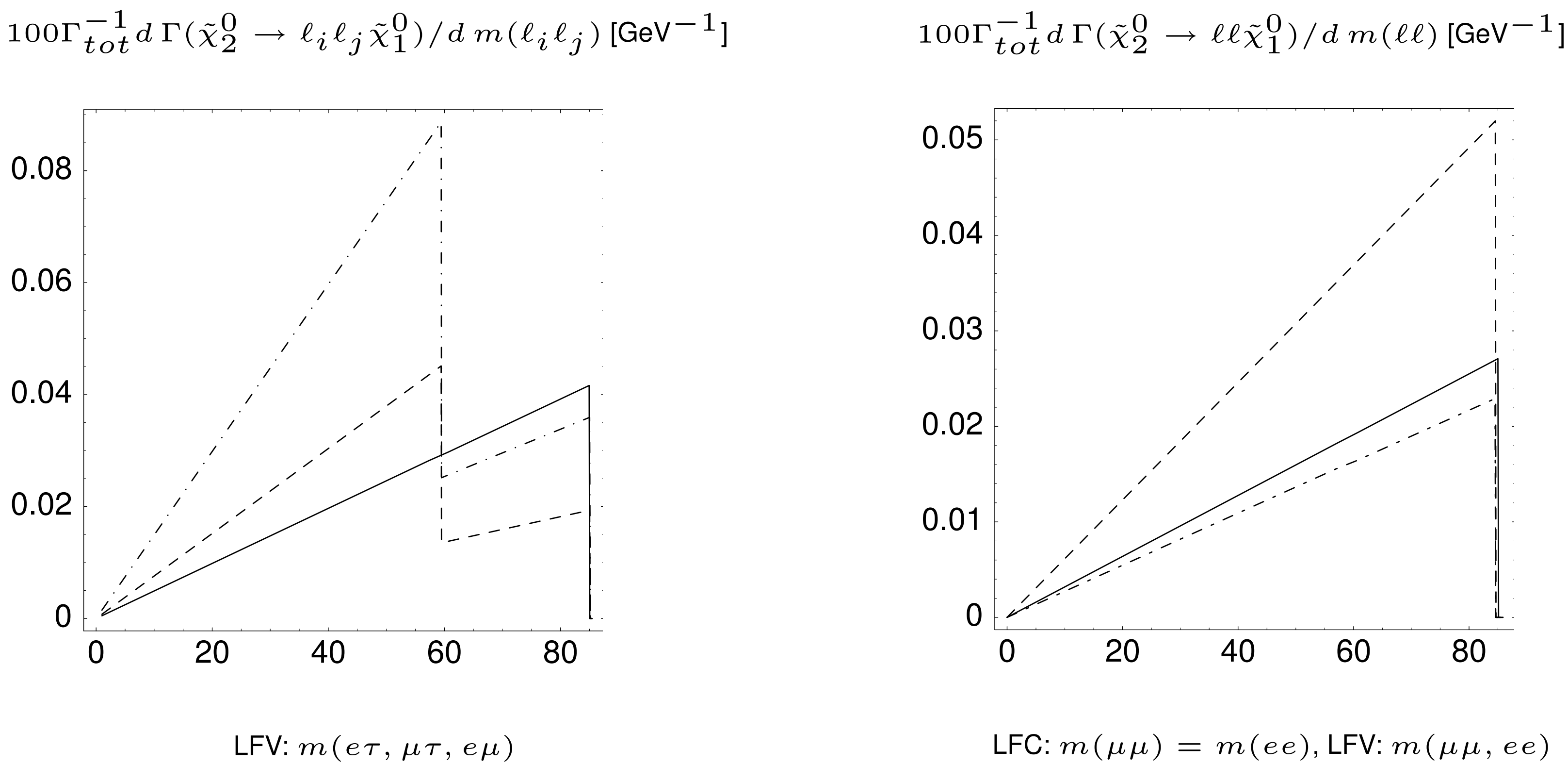
- two-flavor model with parameters $\theta_{L,R}$ and $\Delta\tilde{m}_{L,R}$
- LFV branching ratio:
  $$\mathrm{Br}(\tilde{\chi}_2^0 \to \mu^+ e^- \tilde{\chi}_1^0) = 2\sin^2\theta_{L,R}\cos^2\theta_{L,R}\frac{\Delta\tilde{m}_{L,R}^2}{\Delta\tilde{m}_{L,R}^2+\Gamma_{\tilde{l}}^2}\ \mathrm{Br}(\tilde{\chi}_2^0 \to e^+ e^- \tilde{\chi}_1^0)$$
- maximal mixing: $\theta_{L,R} = \pi/4$, $\Gamma_{\tilde{l}} \ll \Delta\tilde{m}_{L,R} = 0.5$ GeV





$$\tilde{\chi}_2^0 \to \tilde{l}_a l_j \to l_i l_j \tilde{\chi}_1^0: \quad m^2_{edge}(\ell\ell) = \frac{(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}_a})(m^2_{\tilde{\ell}_a} - m^2_{\tilde{\chi}_1^0})}{m^2_{\tilde{\ell}_a}}$$

MSUGRA point SPS1a’, mixing in the R-slepton sector



Bartl et al., hep-ph/0510074: double edge structure due to $m_{\tilde{l}_1} < m_{\tilde{l}_{2,3}}$

baryon asymmetry in the universe

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}$$ from CMB

generation of lepton asymmetry in out-of-equilibrium decays of N_1

later on transformation to baryon asymmetry via sphaleron processes

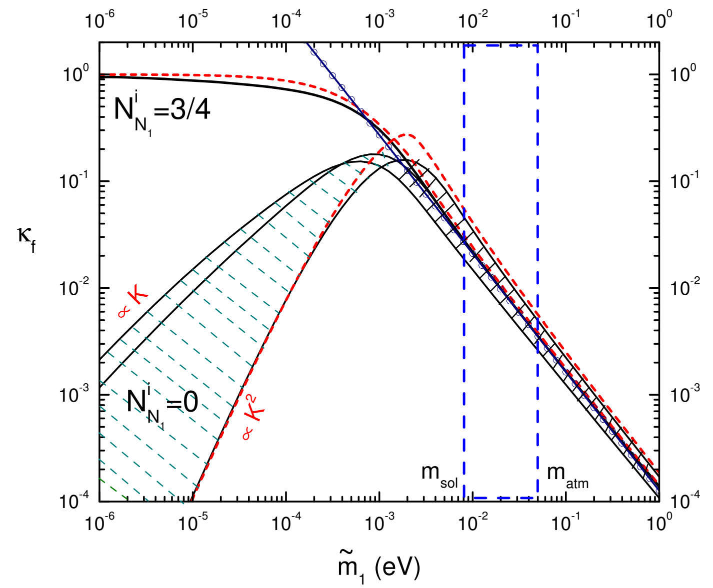
$$\boxed{\eta_B = \kappa_f \, d \, a_{sph} \, \epsilon_1}$$

- ϵ_1 = CP asymmetry = $\dfrac{\Gamma(N_1 \to h_2 + l) - \Gamma(N_1 \to \overline{h_2} + \bar{l})}{\Gamma(N_1 \to h_2 + l) + \Gamma(N_1 \to \overline{h_2} + \bar{l})}$
- a_{sph} = fraction of L-asymmetry converted to B-asymmetry = $\dfrac{8}{23}$
- d = dilution factor due to γ production $T_{\not{L}} \to T_{\rm rec}$ = $\dfrac{1}{78}$
- κ_f = efficiency factor (washout processes, Boltzmann equations)

Buchmüller, Di Bari, Plümacher, hep-ph/0406014

hierarchical neutrino spectra: $\epsilon_1 \simeq -\frac{3}{8\pi}\frac{M_1}{v_2^2}\frac{\sum_i m_i^2 \mathrm{Im}\left(R_{1i}^2\right)}{\sum_i m_i |R_{1i}|^2} < \frac{3}{8\pi}\frac{M_1}{v_2^2} m_3$

independence of initial conditions: $\sqrt{\Delta m_{12}^2} < \tilde{m}_1 = v_2 \frac{(Y_\nu Y_\nu^\dagger)_{11}}{M_1} < \sqrt{\Delta m_{23}^2}$



no gravitino problem for BBN: $M_1 \lesssim 10\ T_R \lesssim 10^{10}$ GeV for $m_{3/2} = 1$ TeV

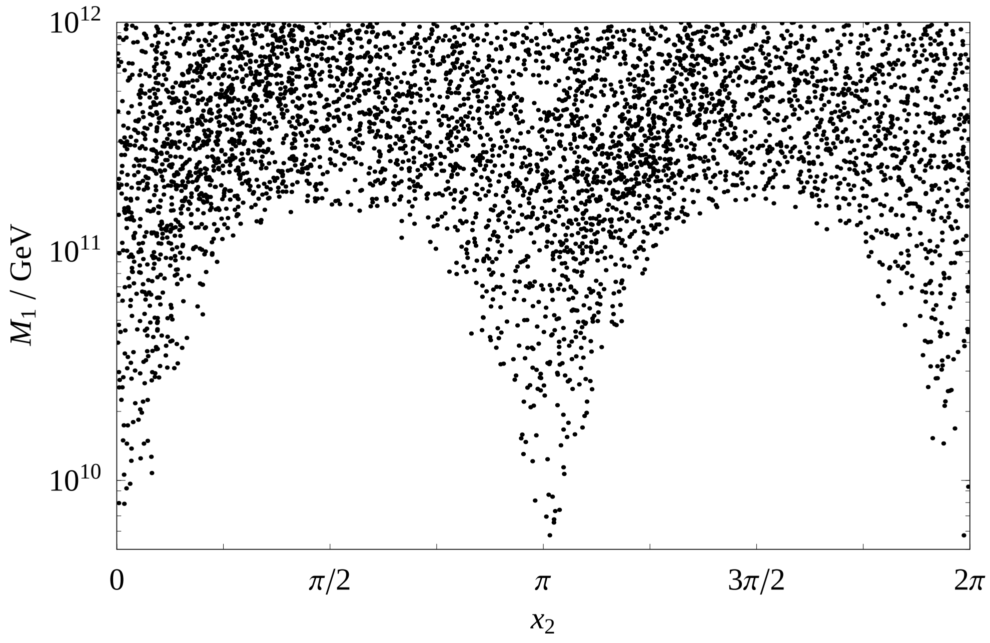
Abada et al., hep-ph/0605281: washout factors are flavor-dependent for $M_1 \lesssim 10^{12}$ GeV

$$Y_\nu = \frac{1}{v\sin\beta} D\left(\sqrt{M_i}\right) \; R(x_i + I y_i) \; D\left(\sqrt{m_j}\right) U^\dagger$$

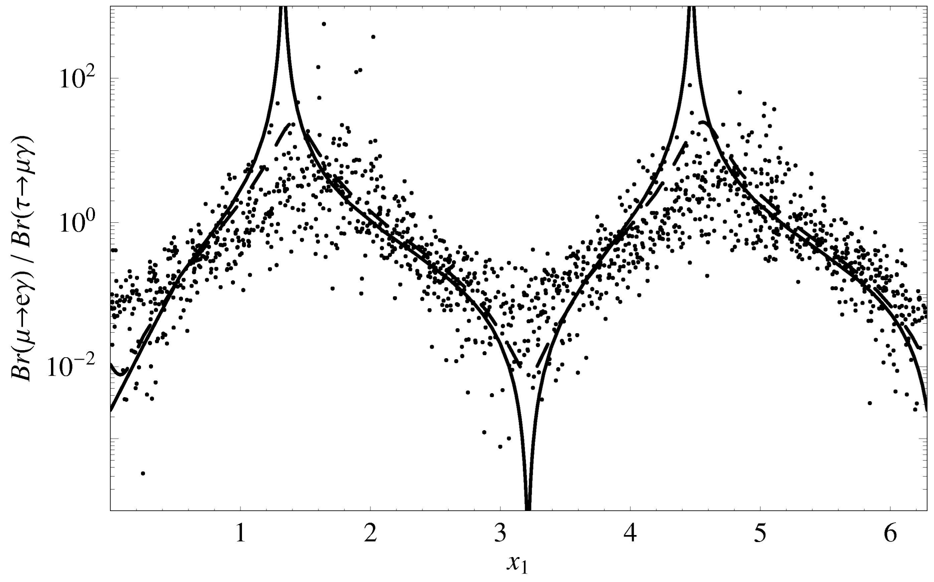
hierarchical heavy and light neutrino masses

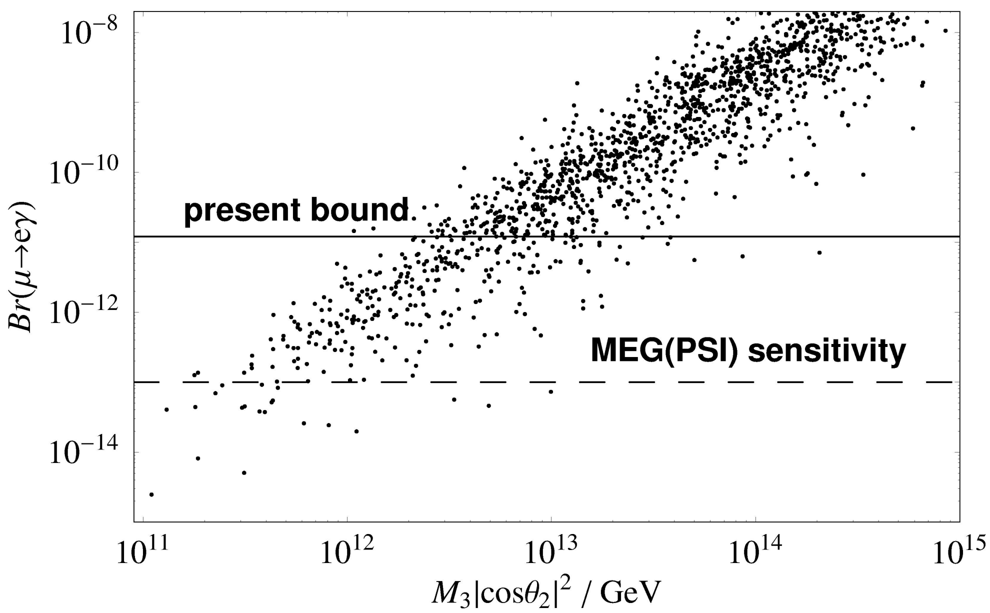
$$0 \leq x_{1,3} \leq 2\pi, \quad 10^{-3} < y_i < \mathcal{O}(1)$$

MSUGRA scenario SPS1a



$$\eta_B = 6.3 \cdot 10^{-10}, \quad M_1 < 10^{11} \text{ GeV} \;\Rightarrow\; \sin x_2 \simeq 0$$





$\Rightarrow x_1$

- $x_{2,3} \simeq n\pi$
- $0 \leq x_1 \leq 2\pi$
- $10^{-3} < y_i < \mathcal{O}(1)$

$y_i = 0.01$ (solid), 0.1 (dashed)

$\Rightarrow M_3 \lesssim 10^{13}$ GeV