Slepton Flavor Violation

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LCWS04, Paris

- MSSM + right-handed neutrino singlet fields ν_R
- superpotential $W \subset W_\nu = -\frac{1}{2}\nu_R^{cT} M \nu_R^c + \nu_R^{cT} Y_\nu L \cdot H_2$
- EWSB $\rightarrow$ Dirac mass $m_D = Y_\nu \langle H_2 \rangle \ll$ Majorana mass scale M_R
- neutrino mass matrix $-\begin{pmatrix} \bar{\nu}_L & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$

light neutrinos: $M_\nu = m_D^T M^{-1} m_D$

heavy neutrinos: $M \sim M_R$

- diagonalization in flavor space

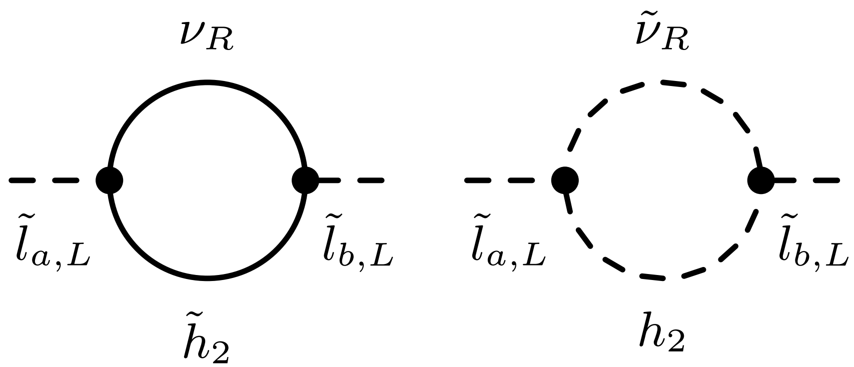
$$U^T M_\nu U = \mathrm{diag}\,(m_1, m_2, m_3)$$
$$U = \mathrm{diag}(e^{i\phi_1}, e^{i\phi_2}, 1) V\,(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$$

masses and mixing parameters from experiment

Slepton Mass Matrix

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

flavor non-diagonal terms generated by RG-running from M_{GUT} to M_R



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

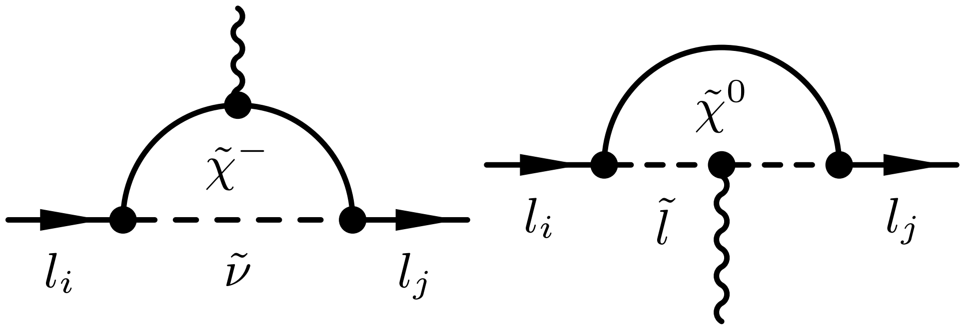
where

$Y_\nu = \frac{1}{v \sin\beta} \mathrm{diag}\left(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}\right) R \, \mathrm{diag}\left(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}\right) U^\dagger$ and $L_{ab} = \ln\left(\frac{M_{GUT}}{M_a}\right)\delta_{ab}$

in general $R = R^T$ undetermined complex matrix, for degenerate M_a and real R

$$Y_\nu^\dagger L Y_\nu = \frac{M_R}{v^2 \sin^2\beta} V \cdot \mathrm{diag}(m_1, m_2, m_3) \cdot V^\dagger \ln\frac{M_{GUT}}{M_R}$$

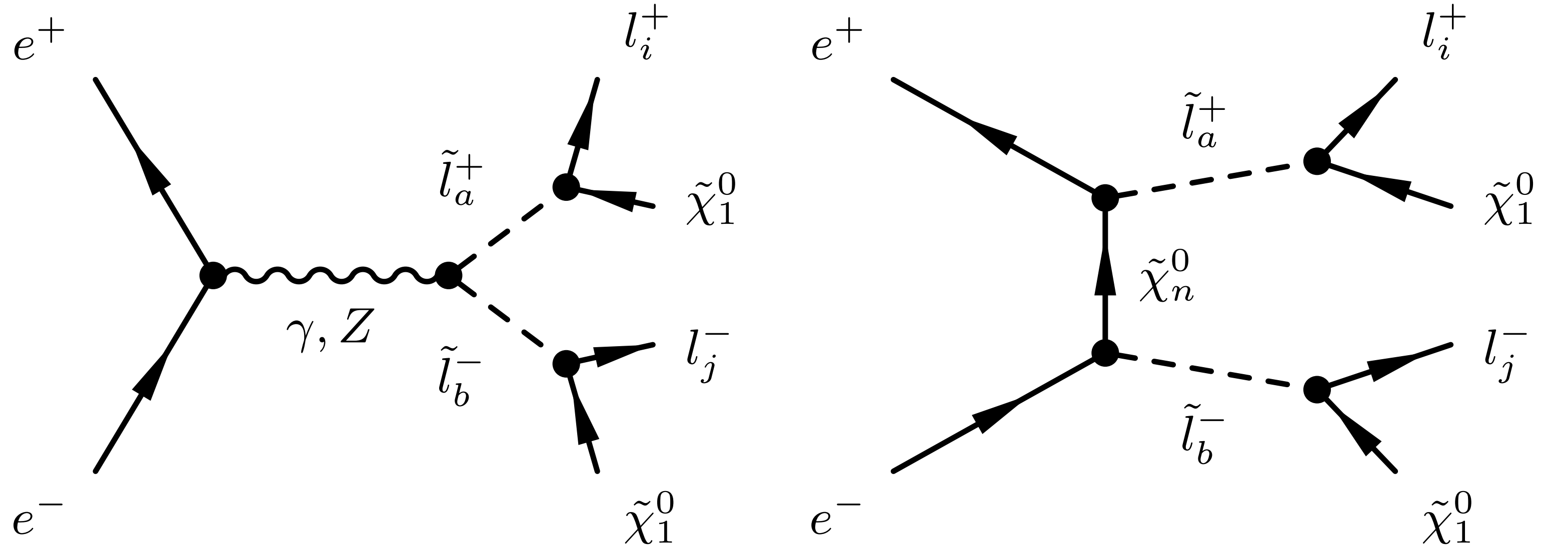
$$\mu \to e\gamma, \tau \to \mu\gamma$$



for small Yukawa couplings, i.e., sufficiently small Majorana mass scale

$$\Gamma\left(l_i^- \to l_j^- \gamma\right) \propto \alpha^3 m_{l_i}^5 \frac{|\,(\delta m_L)_{ij}^2\,|^2}{\tilde{m}^8} \tan^2\beta \propto \; M_R^2$$

$$e^{\pm}e^{-} \rightarrow \tilde{l}_a^{\pm}\tilde{l}_b^{-} \rightarrow l_i^{\pm}l_j^{-} + 2\tilde{\chi}_1^0$$



$$\sigma(l_i^+ l_j^-) \propto \frac{|(\delta m_L)_{ij}^2|^2}{\tilde{m}^2\Gamma_{\tilde{l}}^2}\,\sigma(e^+e^- \rightarrow \tilde{l}_a^+\,\tilde{l}_b^-)Br(\tilde{l}_a^+ \rightarrow l_j^+\,\tilde{\chi}_1^0)Br(\tilde{l}_b^- \rightarrow l_i^-\,\tilde{\chi}_1^0)$$

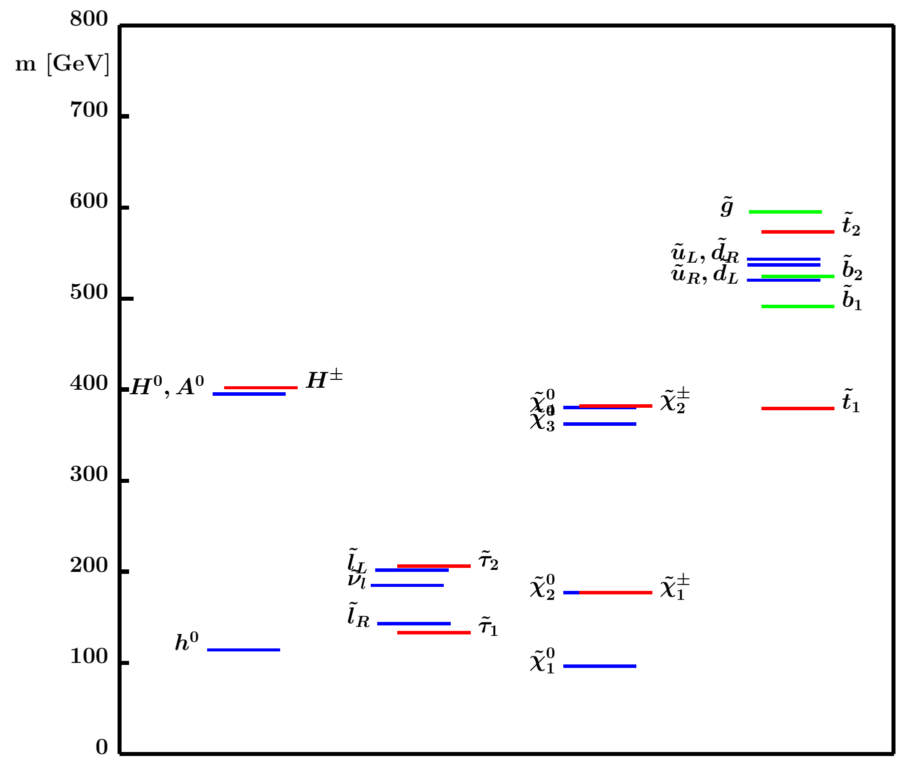
- SM background:
  W-production: $e^+e^- \rightarrow W^+W^- \rightarrow l_a^+ l_b^- \bar{\nu}_b \nu_a$ (+non-resonant contributions)
- MSSM background:
  Slepton/chargino production: $e^+e^- \rightarrow l_a^+ l_b^- + 2\tilde{\chi}_1^0 + 2(4)\nu$

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 scenarios

- B', C', G', I': M. Battaglia et al., arXiv:hep-ph/0306219
- SPS1a: Study of Sleptons, H.-U. Martyn, LC-PHSM-2003-071

SPS1a spectrum



neutrino input

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

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

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

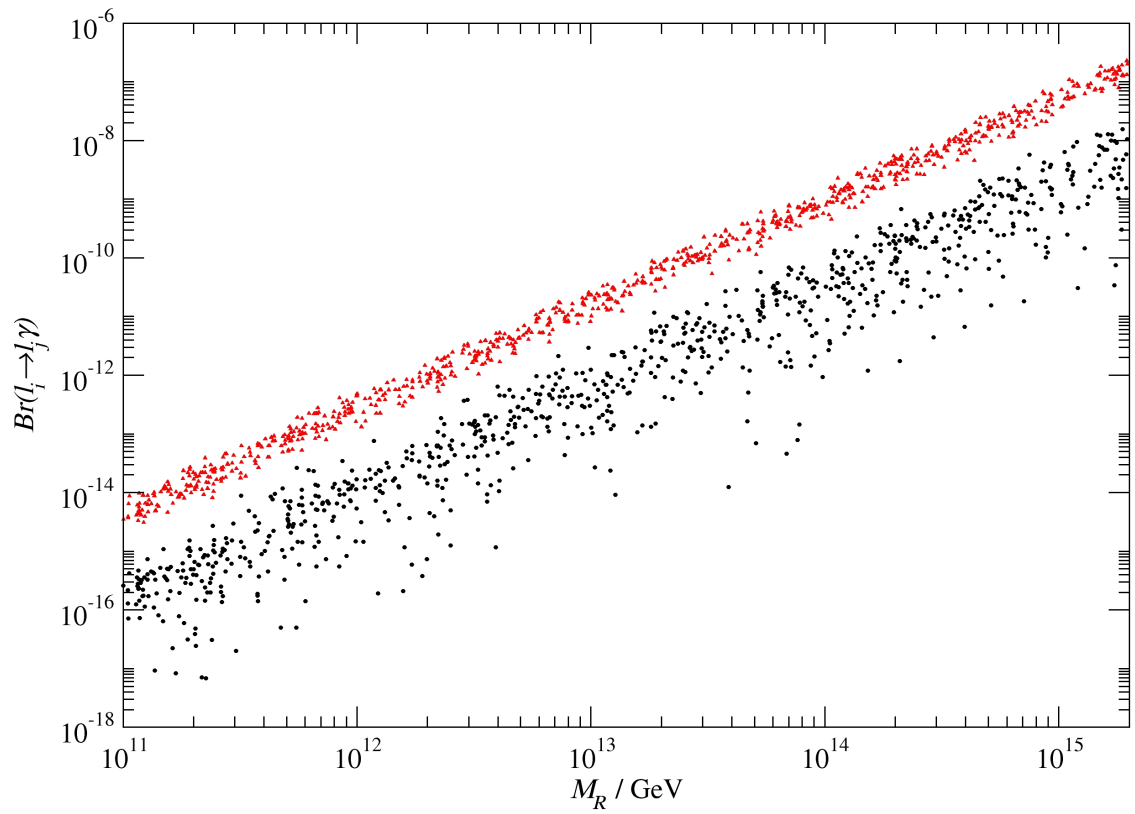
$$\tan^2\theta_{23} = 1.10^{+1.39}_{-0.60}$$

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

- central values from M. Maltoni at al., Phys. Rev. **D68** (2003) 113010
- 90% C.L. errors as anticipated for running/proposed experiments
- degenerate Majorana masses, real R-matrix

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

SUSY scenario SPS1a

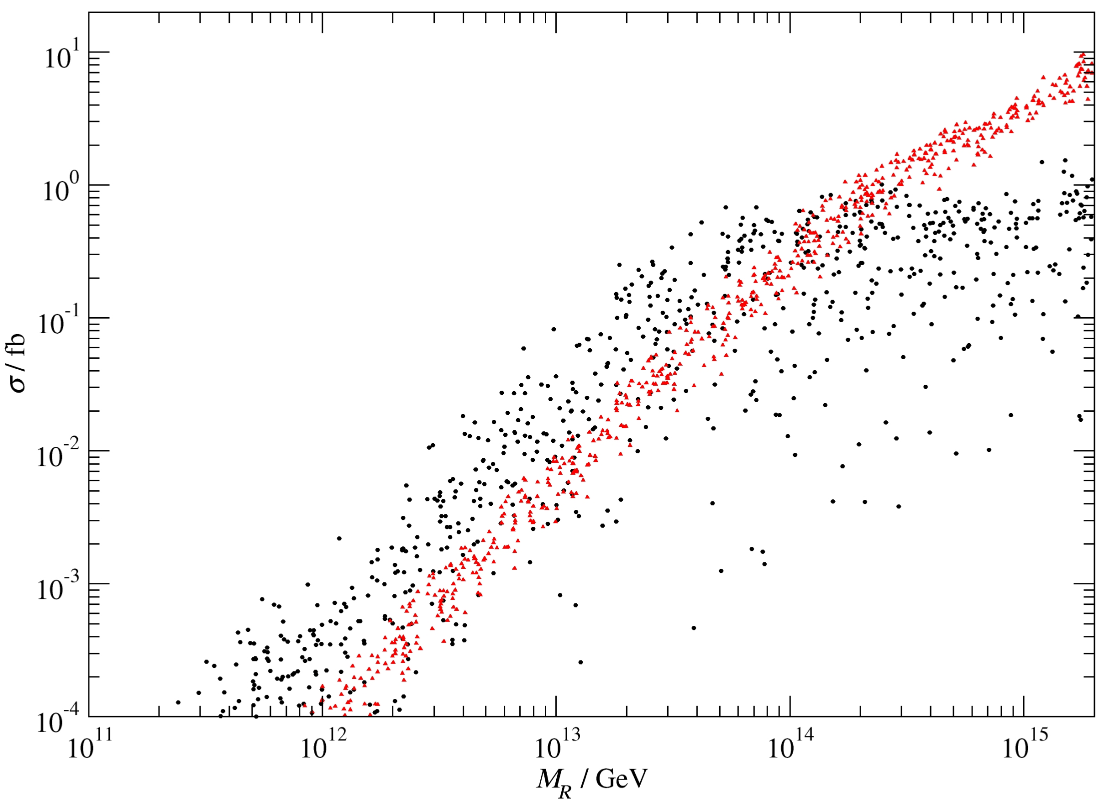


PDG: $Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$ $(90\%\, C.L.)$

$Br(\tau \to \mu\gamma) < 1.1 \cdot 10^{-6}$ $(90\%\, C.L.)$

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

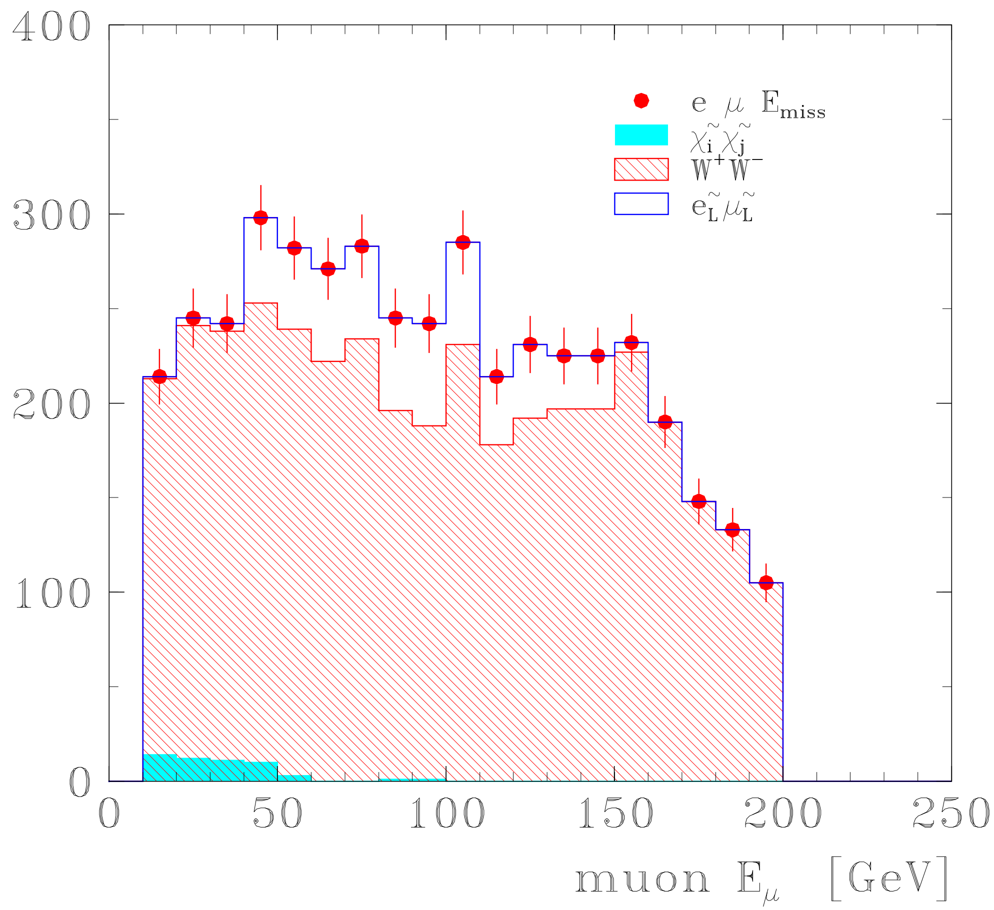
SUSY scenario SPS1a, $\sqrt{s} = 500$ GeV, unpolarized



scatter plots: impact of uncertainties in neutrino data

simulation: $e\mu$ final states

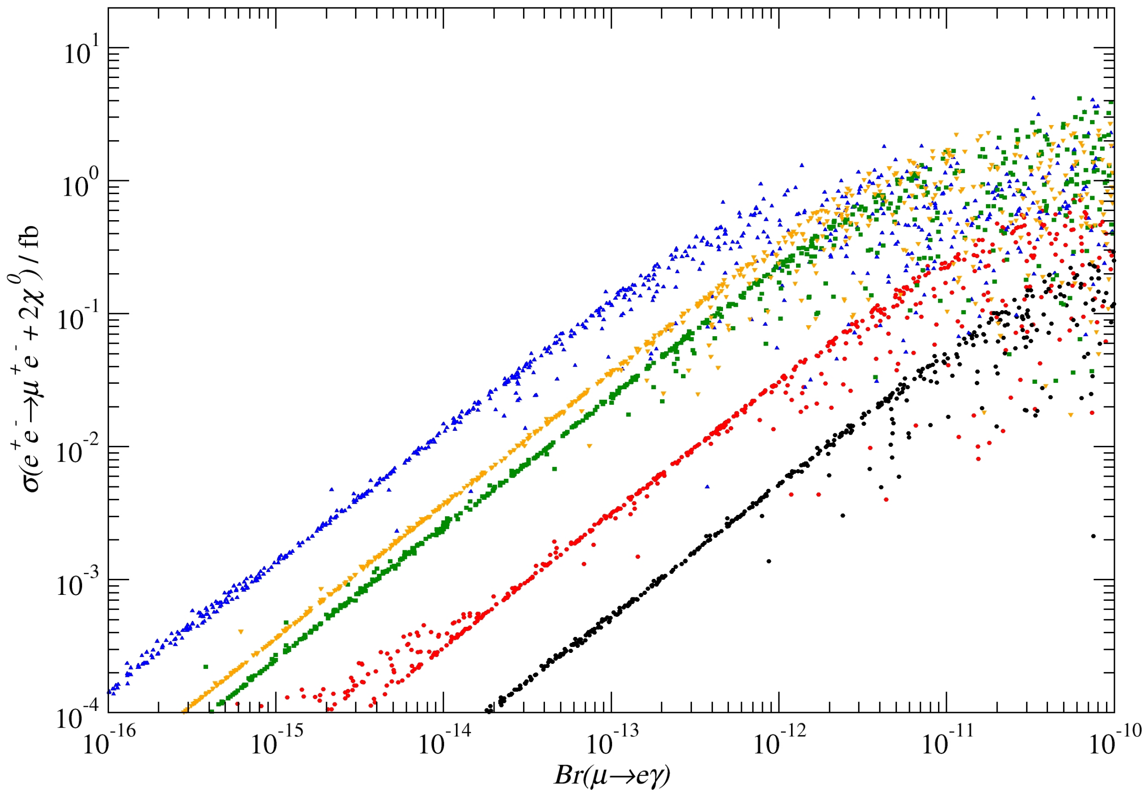
SUSY scenario SPS1a, $\sqrt{s} = 500$ GeV, unpolarized, 500 fb^{-1}



- 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)

correlation of high- and low-energy signals: $e\mu$-channel

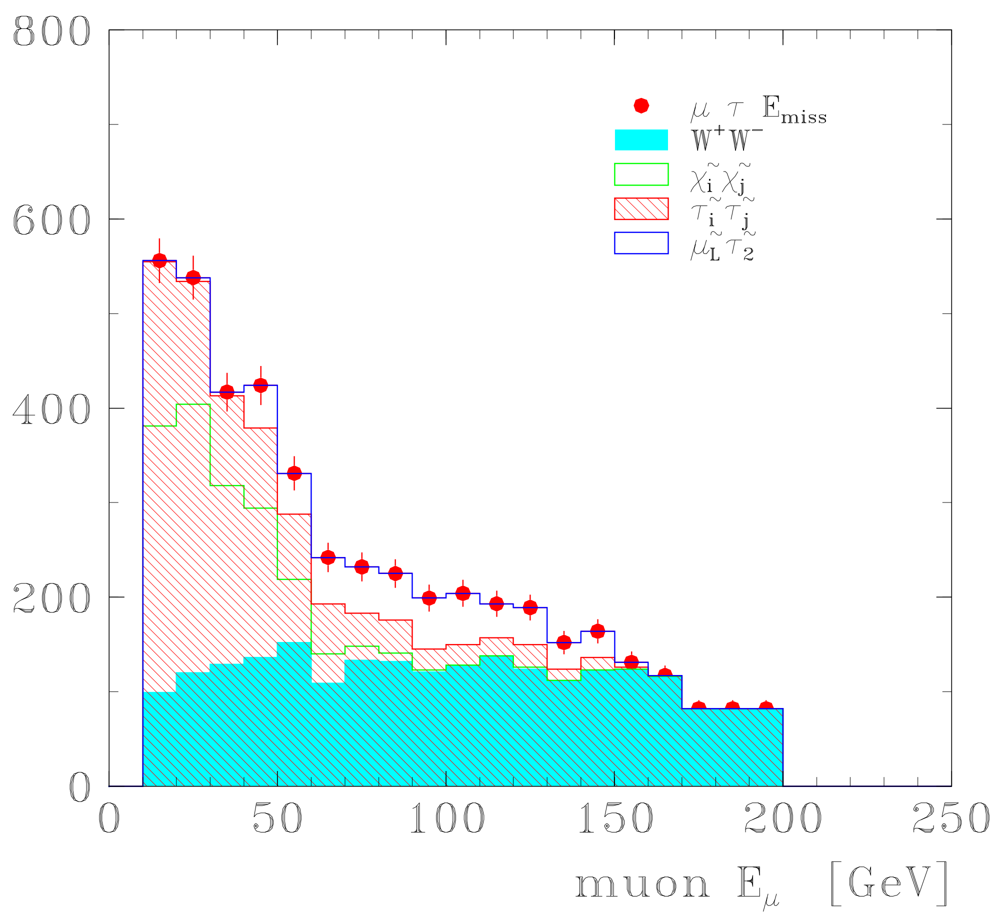
SUSY scenarios C', G', B', SPS1, I', $\sqrt{s} = 800$ GeV



SPS1a: $\sigma(e\mu + 2\tilde{\chi}^0_1) = 0.1$ fb $\equiv Br(\mu \to e\gamma) = 4 \times 10^{-12}$

simulation: $\tau\mu$ final states

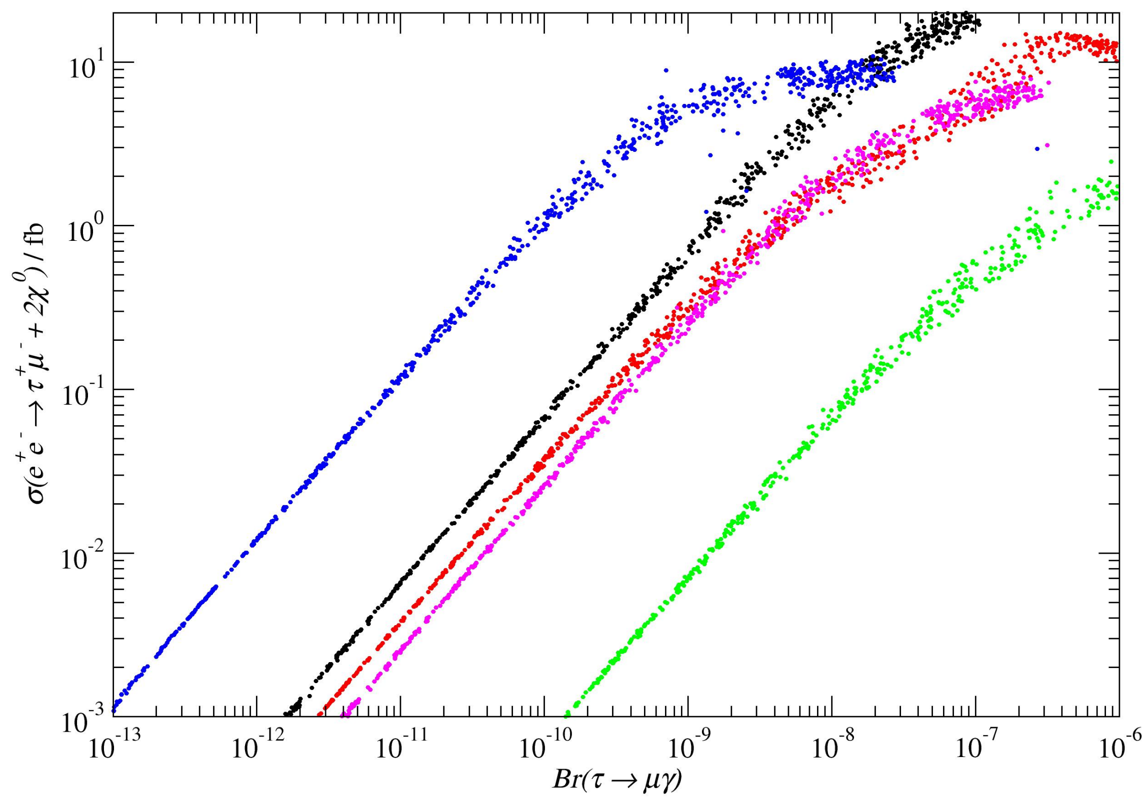
SUSY scenario SPS1a, $\sqrt{s} = 500$ GeV, unpolarized, 500 fb^{-1}



- 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

correlation of high- and low-energy signals: $\tau\mu$-channel

SUSY scenarios C', B', SPS1, G', I', $\sqrt{s} = 800$ GeV



SPS1a: $\sigma(\tau\mu + 2\tilde{\chi}_1^0) = 1$ fb $\equiv Br(\tau \to \mu\gamma) = 5 \times 10^{-9}$

- LFV in slepton-pair production ($\sqrt{s} = 500$ GeV, SPS1, $M_R = 10^{13} - 10^{15}$ GeV)

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

  $\sigma(e^+e^- \to \tau^+\mu^- + 2\tilde{\chi}_1^0) \approx 10^{-3} - 3$ fb

- correlation with searches for radiative decays ($\sqrt{s} = 800$ GeV, SPS1)

  $Br(\tau \to \mu\gamma) = 10^{-8}$ (LHC) $\to \sigma(e^+e^- \to \tau^+\mu^- + 2\tilde{\chi}_1^0) \approx 1.5 - 3$ fb

  $Br(\mu \to e\gamma) < 10^{-13}$ (PSI) $\to \sigma(e^+e^- \to \tau^+\mu^- + 2\tilde{\chi}_1^0) < 10^{-2}$ fb

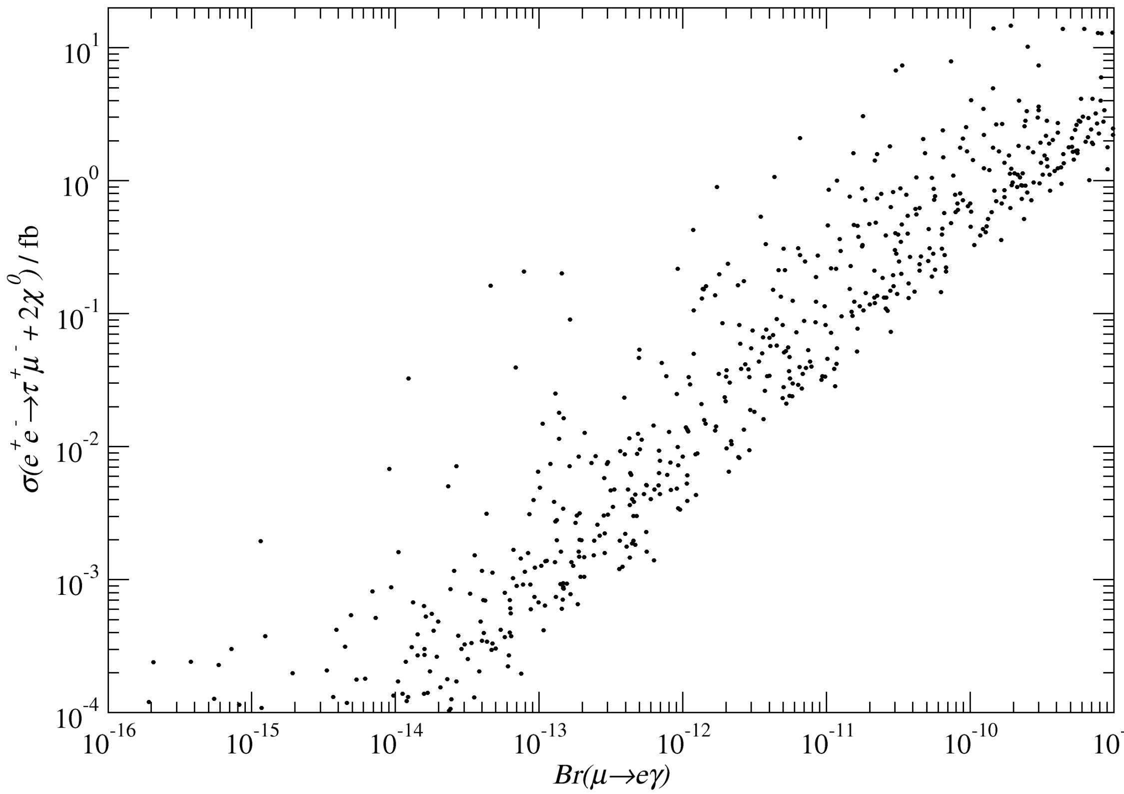
- strong dependence on SUSY and neutrino parameters
  $e\mu$-channel strongly affected by uncertainties in neutrino data

- beam polarization important (background supression, probing individual vertices)

F. Deppisch, H. Päs, A. Redelbach, R.R., Y. Shimizu
hep-ph/0206122 (Eur. Phys. J. C)
hep-ph/0310053 (Phys. Rev. D)
simulation by H.-U. Martyn

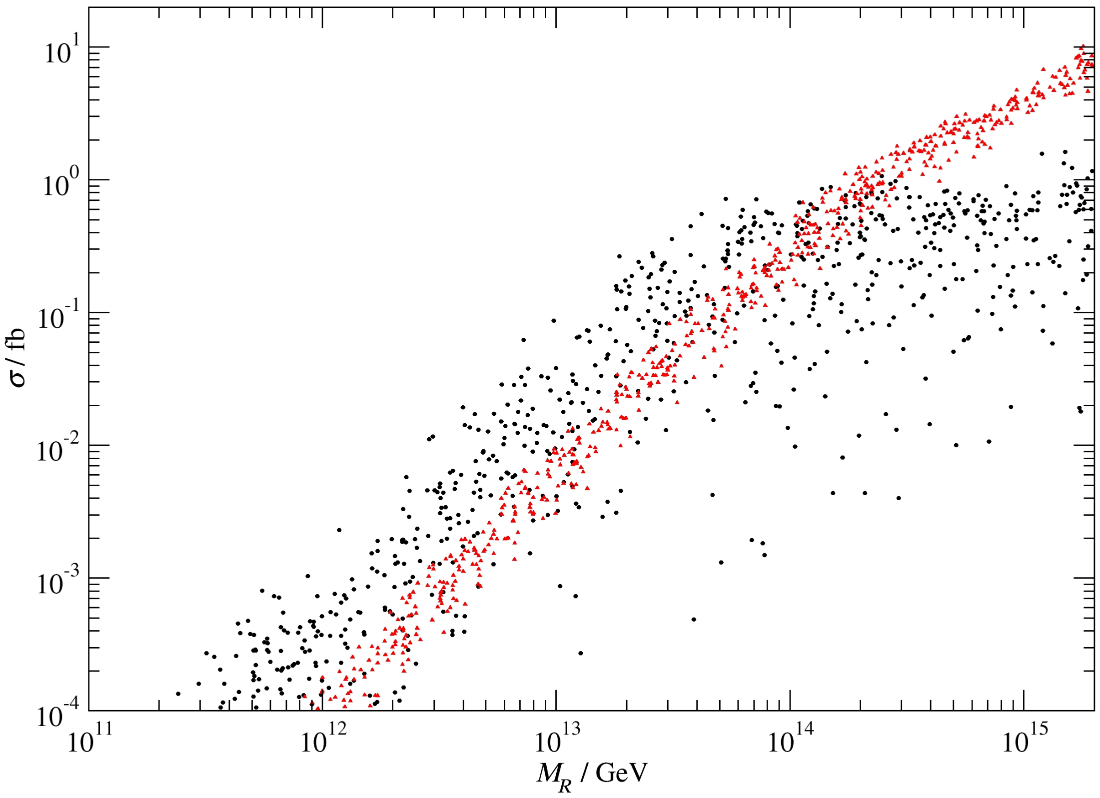
correlation of signals in $\tau\mu$ and $e\mu$-channels

SUSY scenario SPS1, $\sqrt{s} = 800$ GeV



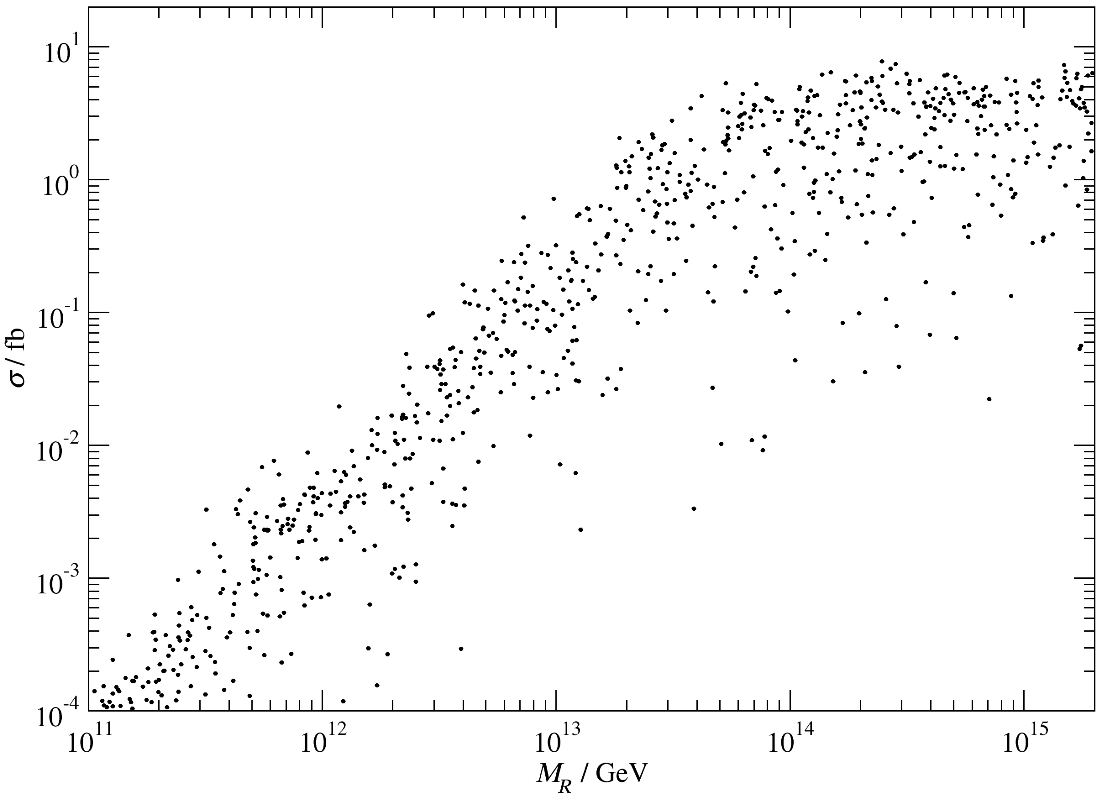
$$\sigma(e^+e^- \rightarrow \mu^+e^-(\tau^+\mu^-) + 2\tilde{\chi}_1^0)$$

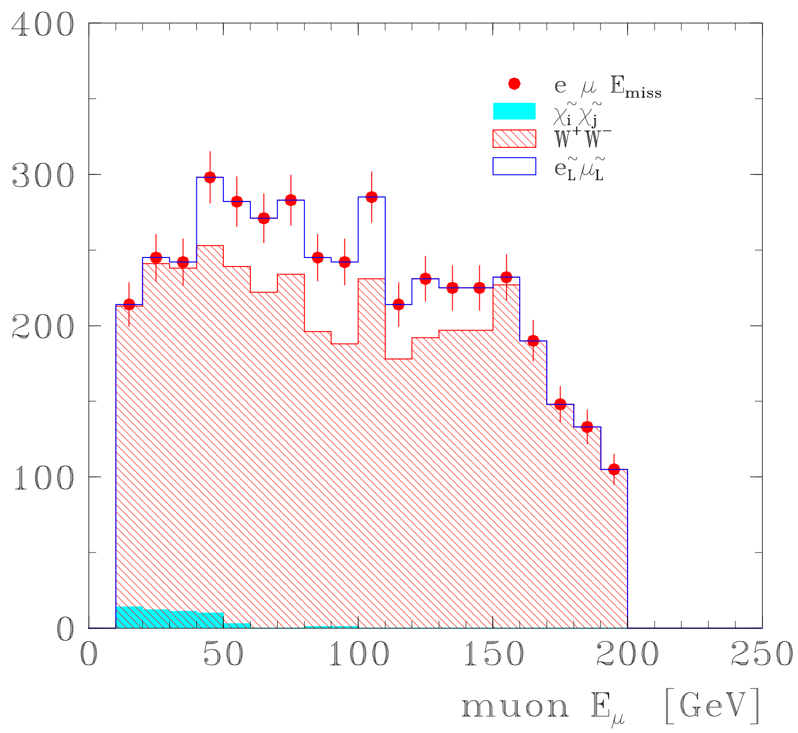
SUSY scenario SPS1, $\sqrt{s} = 800$ GeV

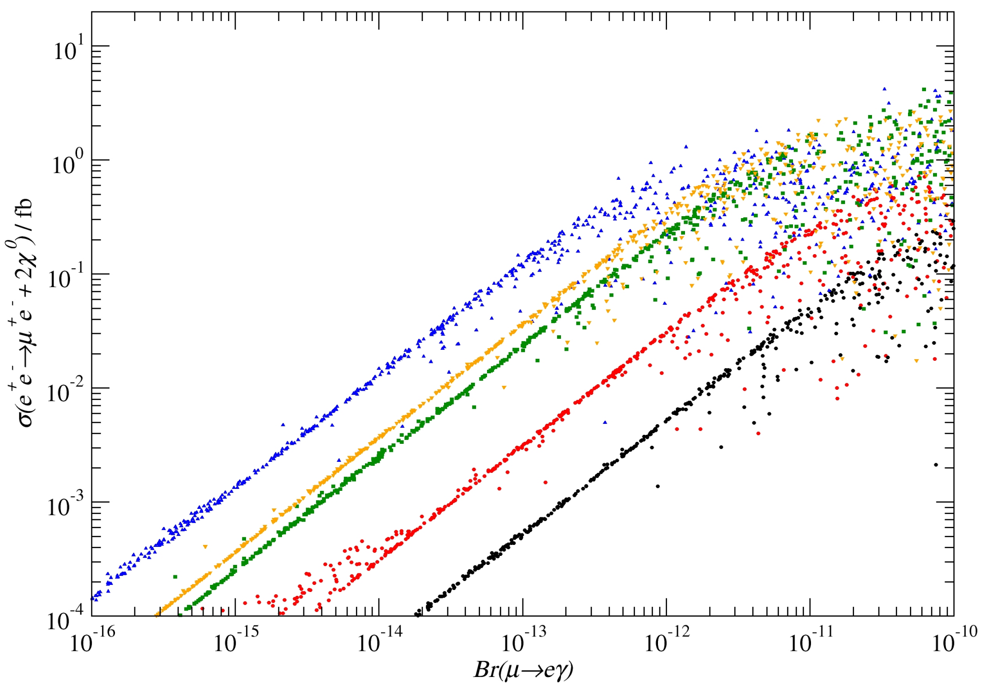


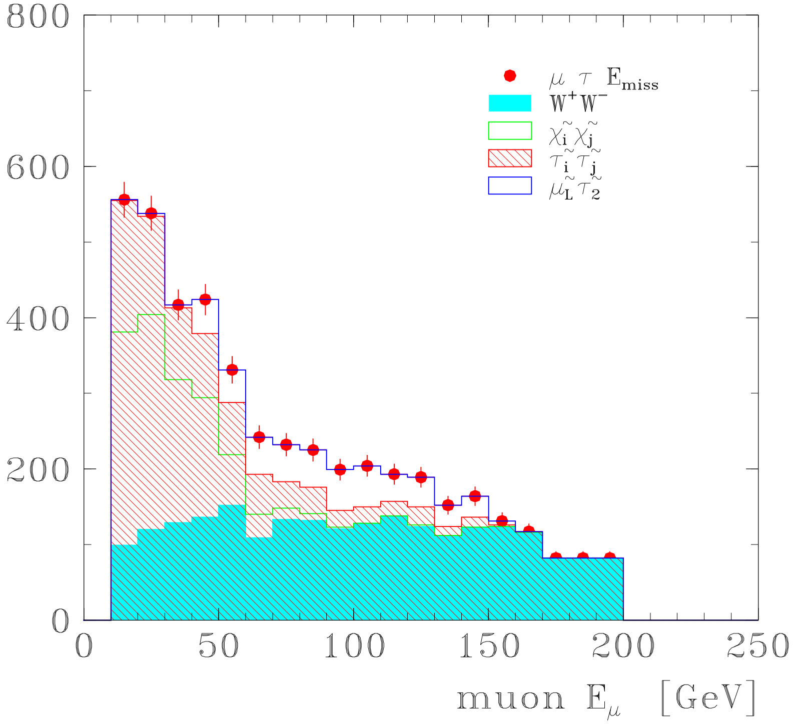
$$\sigma(e^-e^- \to \mu^-e^-(\tau^-\mu^-) + 2\tilde{\chi}_1^0)$$

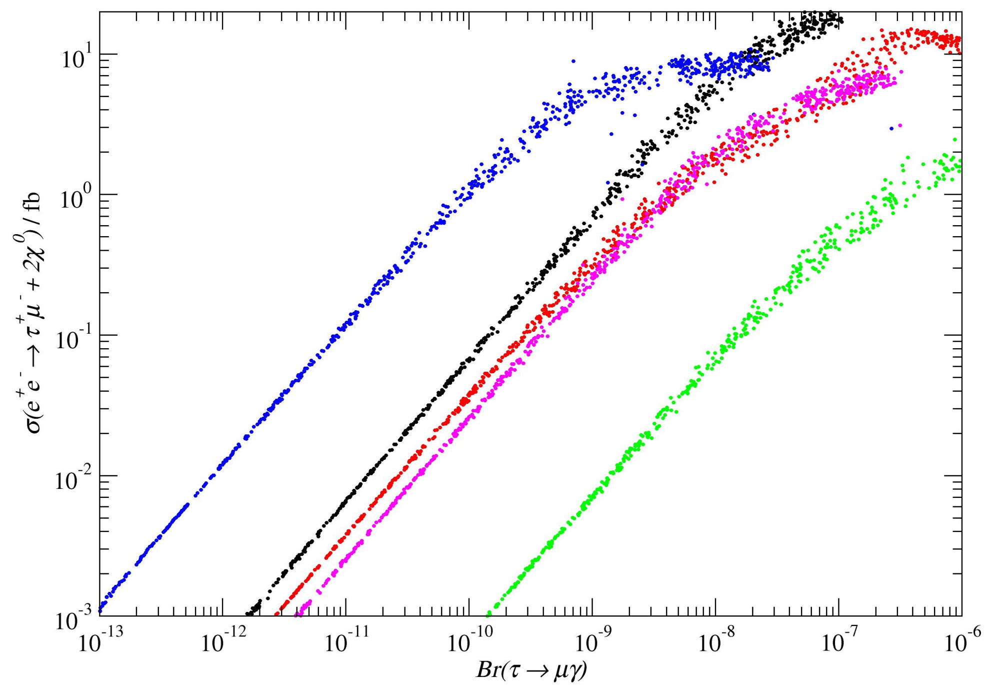
SUSY scenario SPS1, $\sqrt{s} = 800$ GeV




400
300
200
100
0
0
50
100
150
200
250
muon E_μ [GeV]
e μ E_miss
χ̃_i χ̃_j
W⁺W⁻
ẽ_L μ̃_L


σ(e⁺e⁻→μ⁺e⁻+2χ⁰) / fb
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻¹⁶
10⁻¹⁵
10⁻¹⁴
10⁻¹³
10⁻¹²
10⁻¹¹
10⁻¹⁰
Br(μ→eγ)


800
600
400
200
0
0
50
100
150
200
250
muon E$_\mu$ [GeV]
μ τ E$_{miss}$
W$^+$W$^-$


σ(e$^+$e$^-$ → τ$^+$μ$^-$ + 2χ^0) / fb
Br(τ → μγ)

ratios od branching ratios

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

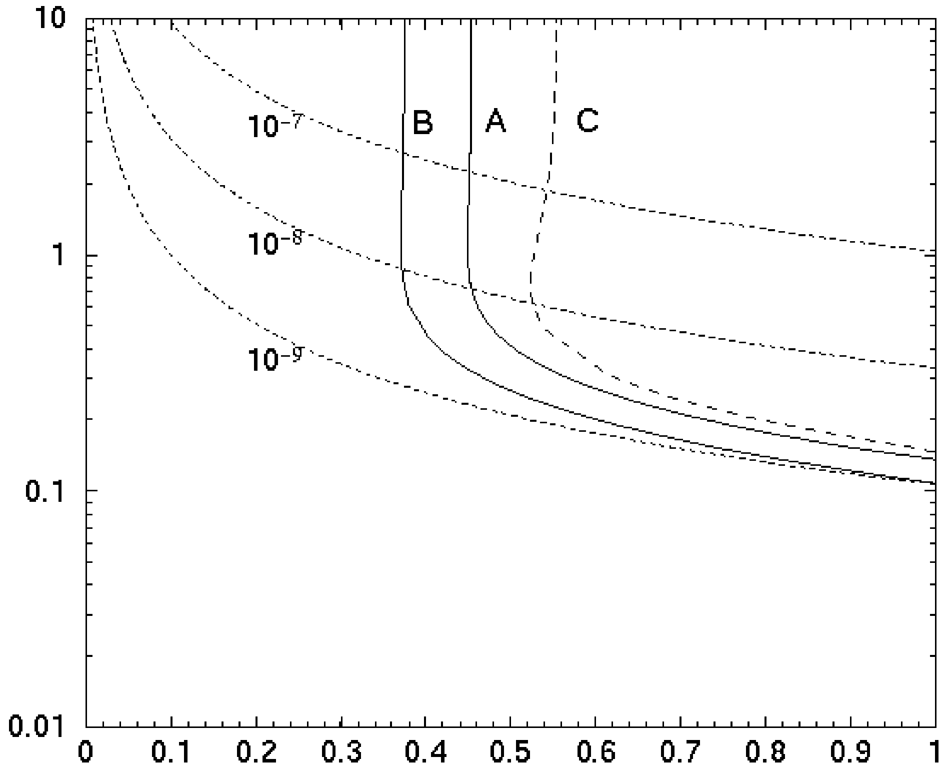
Example:

- hierarchical light neutrinos, central best-fit values for neutrino parameters
- vanishing Dirac/Majorana phases, $R = 1$
- 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

$$m_0 = 100\,\mathrm{GeV},\ m_{1/2} = 200\,\mathrm{GeV},$$
$$A_0 = 0\,\mathrm{GeV},\ \tan\beta = 3,\ \mathrm{sgn}\mu = +,$$
$$\sqrt{s} = 500\,\mathrm{GeV}$$

$\Delta\tilde{m}_{23}$/GeV



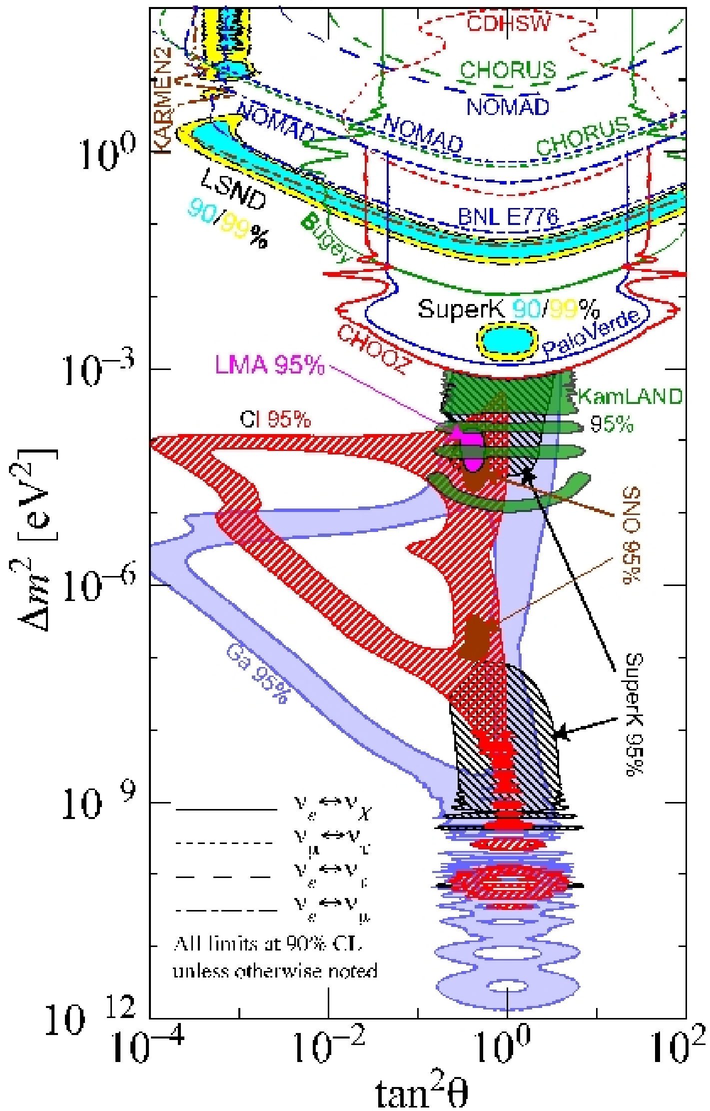
$\sin 2\tilde{\theta}_{23}$

Kalinowski et al.:
hep-ph/0103161, hep-ph/0207051

- sneutrino mass difference $\Delta\tilde{m}_{23} = m_{\tilde{\nu}_3} - m_{\tilde{\nu}_2}$
- sneutrino mixing angle $\tilde{\theta}_{23}$
- 3σ significance contours of
  - A: $e^+e^- \to \tilde{\nu}_i\tilde{\nu}_j^c(\tilde{\chi}_2^+\tilde{\chi}_1^-) \to \tau^\pm\mu^\pm\tilde{\chi}_1^+\tilde{\chi}_1^-$ for 500 fb^{-1}
  - B: as above for 1000 fb^{-1}
  - C: separate $\tilde{\nu}\tilde{\nu}^c$ contribution for 500 fb^{-1}
  - dotted lines:

    Br$(\tau \to \mu\gamma) = 10^{-7}\ldots 10^{-9}$

(*H. Murayama, http://hitoshi.berkeley.edu/*)



global 3-neutrino analysis (3 σ)

- $\Delta m^2_{12} = 6.9^{+2.6}_{-1.5} \times 10^{-5}\ \mathrm{eV}^2$
- $\Delta m^2_{23} = 2.6^{+1.1}_{-1.2} \times 10^{-3}\ \mathrm{eV}^2$
- $\tan^2\theta_{12} = 0.43^{+0.20}_{-0.14}$
- $\tan^2\theta_{23} = 1.08^{+1.49}_{-0.64}$
- $\tan^2\theta_{13} = 0.006^{+0.051}_{-0.006}$

(*M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, PRD68 (2003) 113010)*