Lepton Flavor Violation, Leptogenesis and the LHC

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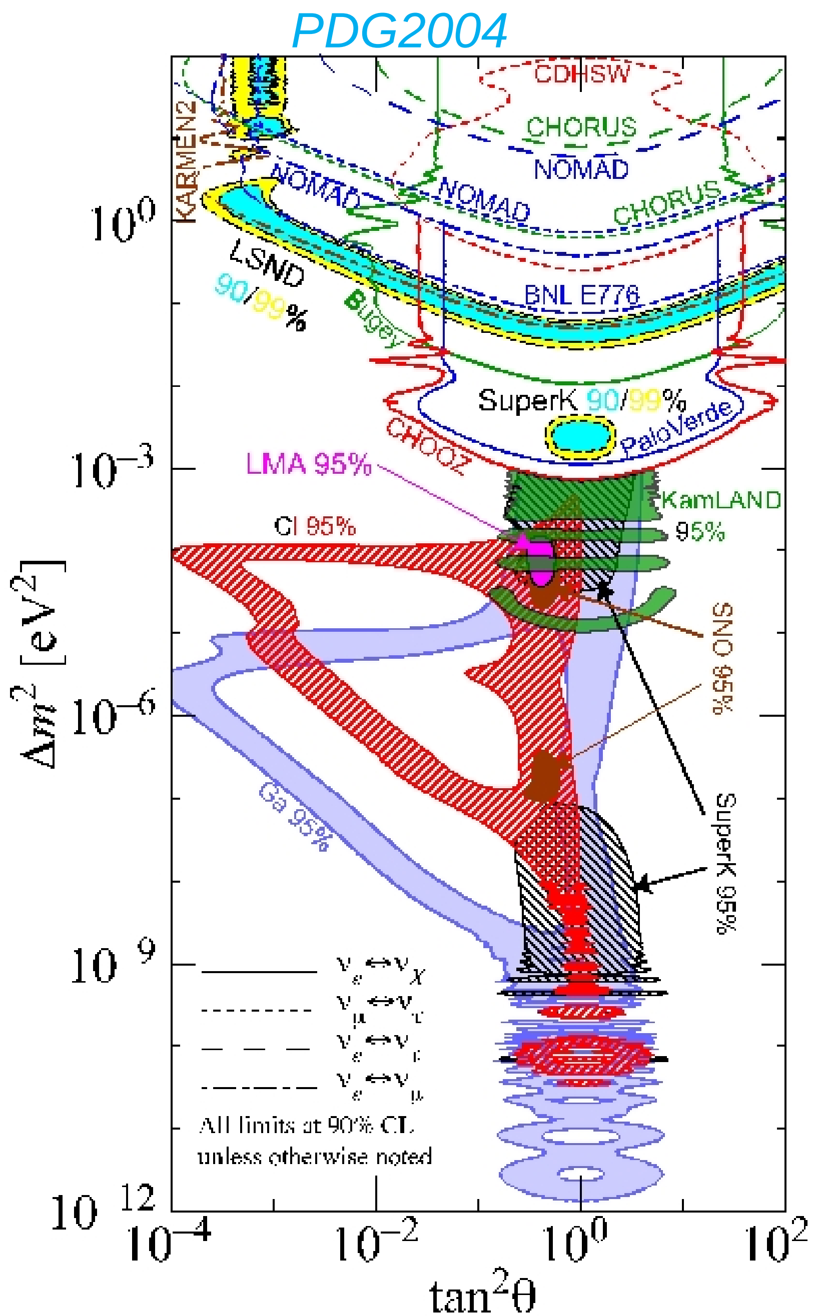
2004 LHC Days, Split



neutrino masses and mixing

physics beyond the standard model

- heavy Majorana neutrinos
- grand unification
- lepton flavor violation
- leptogenesis

role of collider searches?

- MSSM + 3 right-handed neutrino singlet fields ν_R
- superpotential $W \supset W_\nu = \frac{1}{2}\nu_R^{cT} M \nu_R^c + \nu_R^{cT} Y_\nu L \cdot H_2$
- EWSB $\rightarrow$ Dirac mass $m_D = Y_\nu \langle H_2 \rangle \ll$ Majorana mass scale M_R
- neutrino mass matrix $\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L{}^c \\ \nu_R \end{pmatrix}$

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

heavy neutrinos: $M \sim M_R$

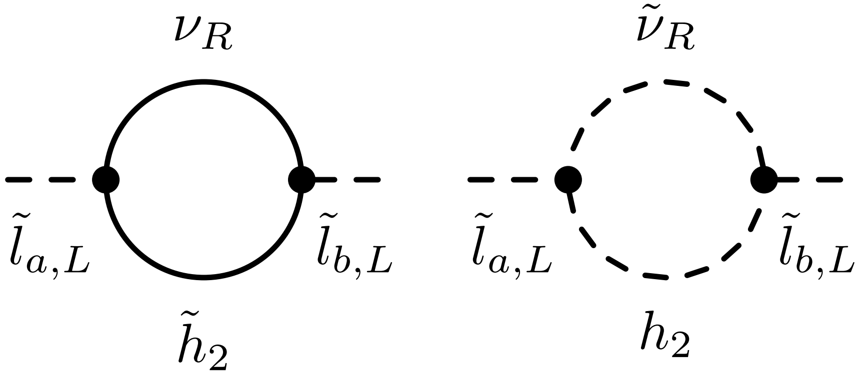
- diagonalization in flavor space

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

masses and mixing angles from experiment

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

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



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

with $L = D\left(\ln(\frac{M_{GUT}}{M_i})\right)$ and

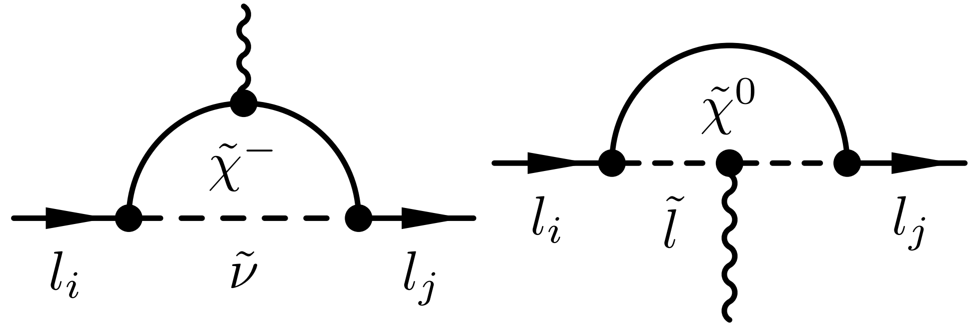
neutrino Yukawa coupling matrix ($R = R^T$ undetermined complex matrix)

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

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

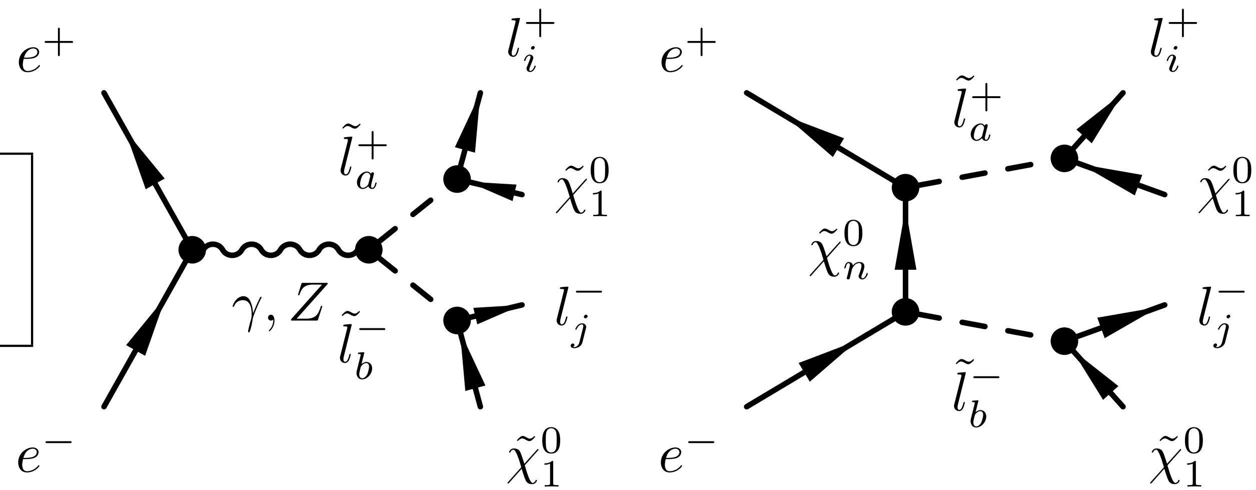
Charged Lepton Flavor Violation

$$\boxed{\mu \to e\gamma, \tau \to \mu\gamma}$$



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

$$\boxed{e^+e^- \to l_i^+ l_j^- + 2\tilde{\chi}_1^0}$$

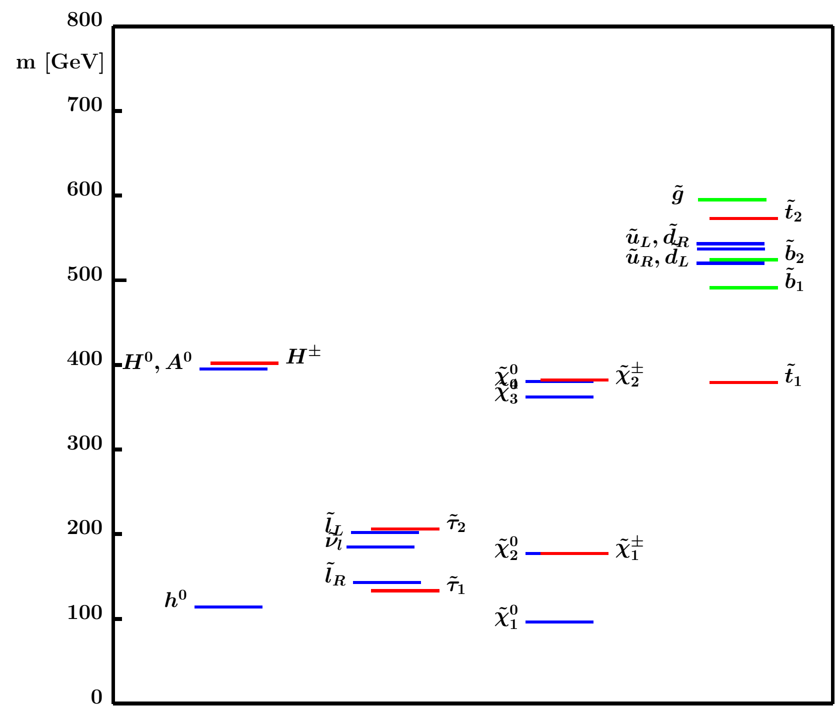


$$\sigma(l_i^+ l_j^-) \; \propto \; \frac{|(\delta m_L)^2_{ij}|^2}{\tilde{m}^2 \Gamma^2_{\tilde{l}}} \, \sigma(e^+e^- \to \tilde{l}_a^+\, \tilde{l}_b^-) Br(\tilde{l}_a^+ \to l_j^+\, \tilde{\chi}_1^0) Br(\tilde{l}_b^- \to l_i^-\, \tilde{\chi}_1^0) \propto \; M_R^2$$

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’, C’, G’, I’:
  M. Battaglia et al., hep-ph/0306219
- SPS1a:
  H.-U. Martyn, LC-PHSM-2003-071



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

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

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

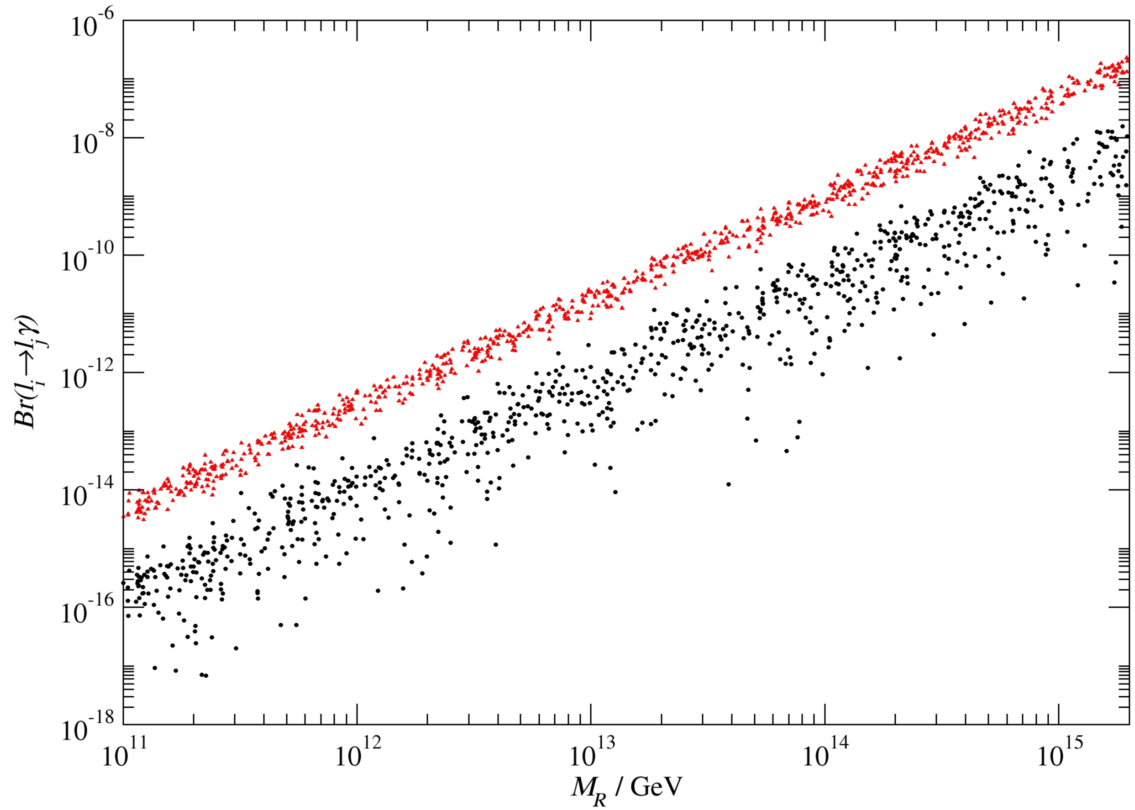
$$\tan^2\theta_{23} = 1.10^{+1.39}_{-0.60}$$

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

- central values from *M. Maltoni et al., PRD68(2003)113010*
- 90% C.L. errors as anticipated for running/proposed experiments
- Dirac phase unconstrained
- absolute mass scale $m_1 \leq 0.03$ eV
- degenerate Majorana masses, real R-matrix
  $18 \rightarrow 8$ parameters $(m_i, \theta_i, \delta, M_R)$

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

SUSY scenario SPS1a

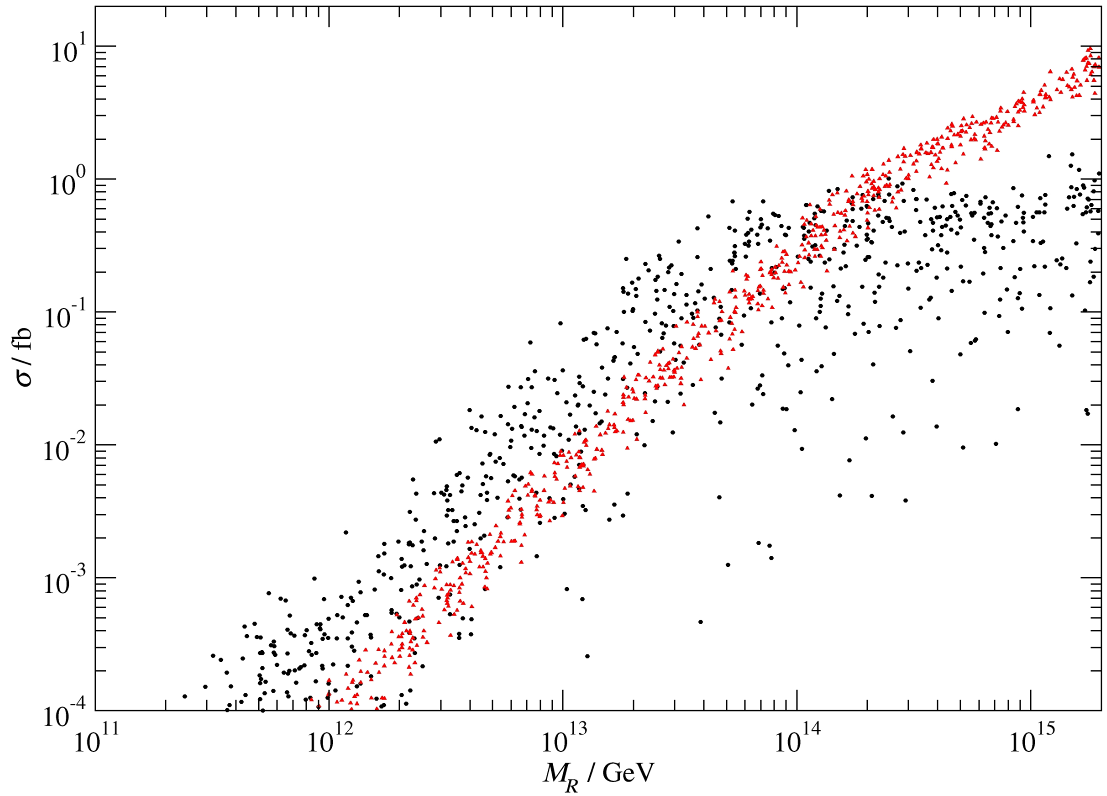


PDG2004:

$$Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11} \quad (90\%\, C.L.)$$
$$Br(\tau \to \mu\gamma) < 1.1 \cdot 10^{-6} \quad (90\%\, C.L.)$$

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

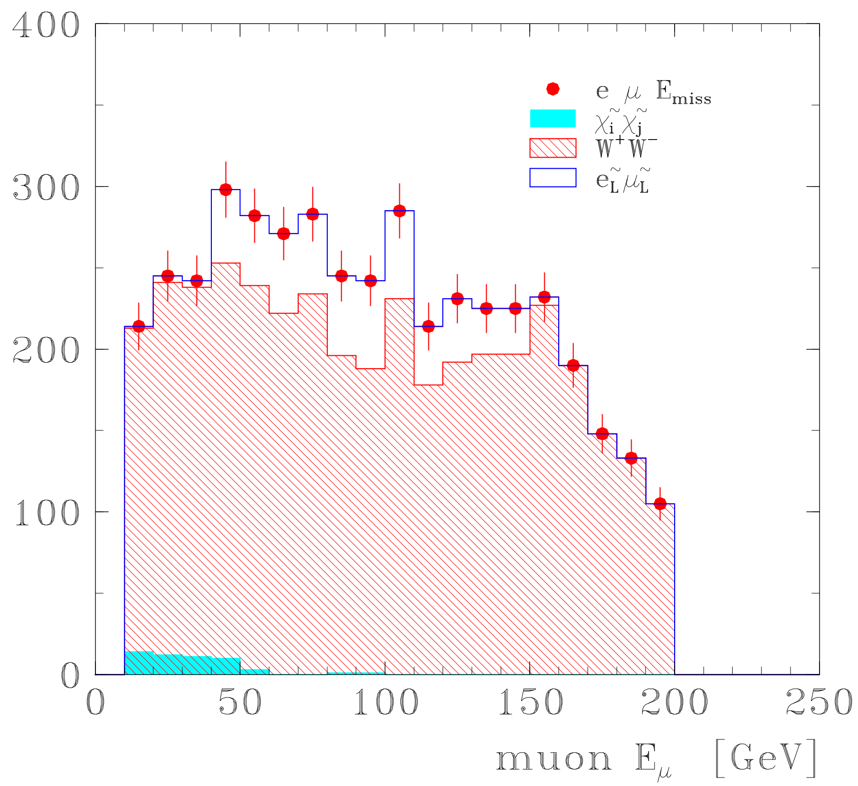
SUSY scenario SPS1a, $\sqrt{s} = 500$ GeV, unpolarized



scatter plots: impact of uncertainties in neutrino data

$e\mu$ final states

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

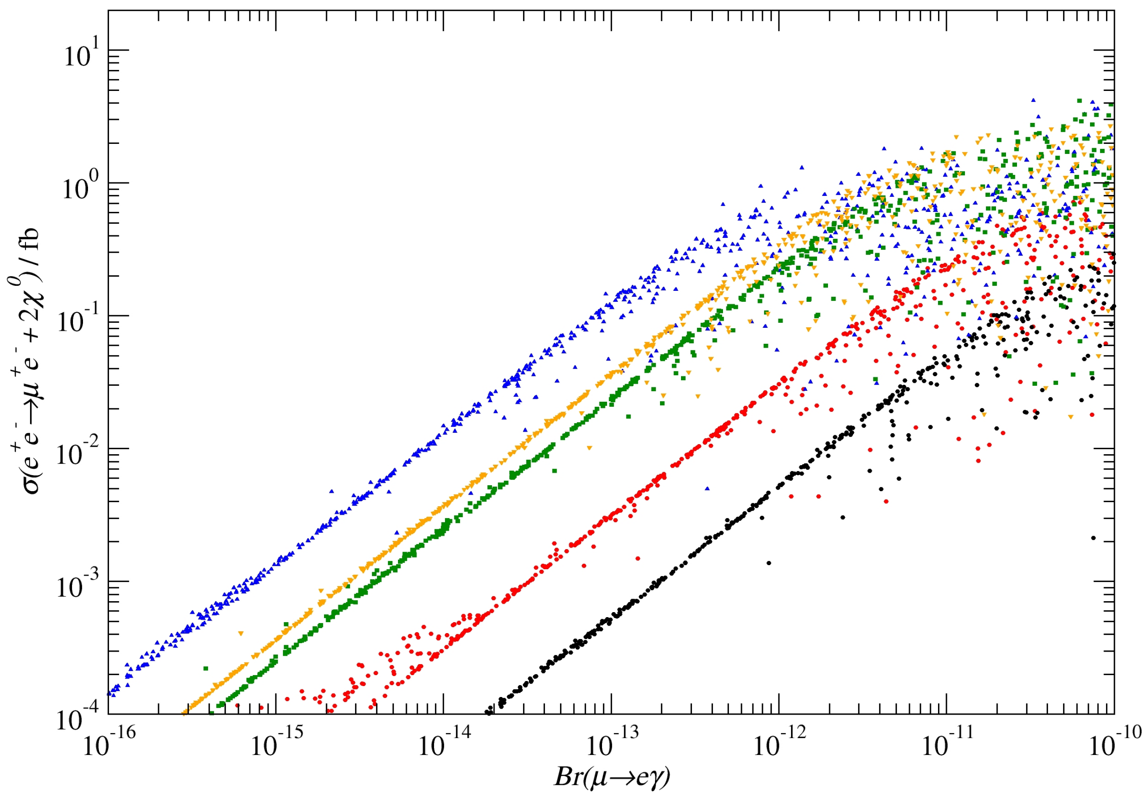


- 2 fb signal cross section (flat lepton energy spectrum)
- SM+MSSM background
- standard selection criteria (50% efficiency)
- $\sigma(\tilde{e}_L \tilde{\mu}_L) = 1$ fb $\rightarrow 5\sigma$ effect
- improvements possible (E_e spectrum, polarization)

H.-U. Martyn (2004)

correlation of signals

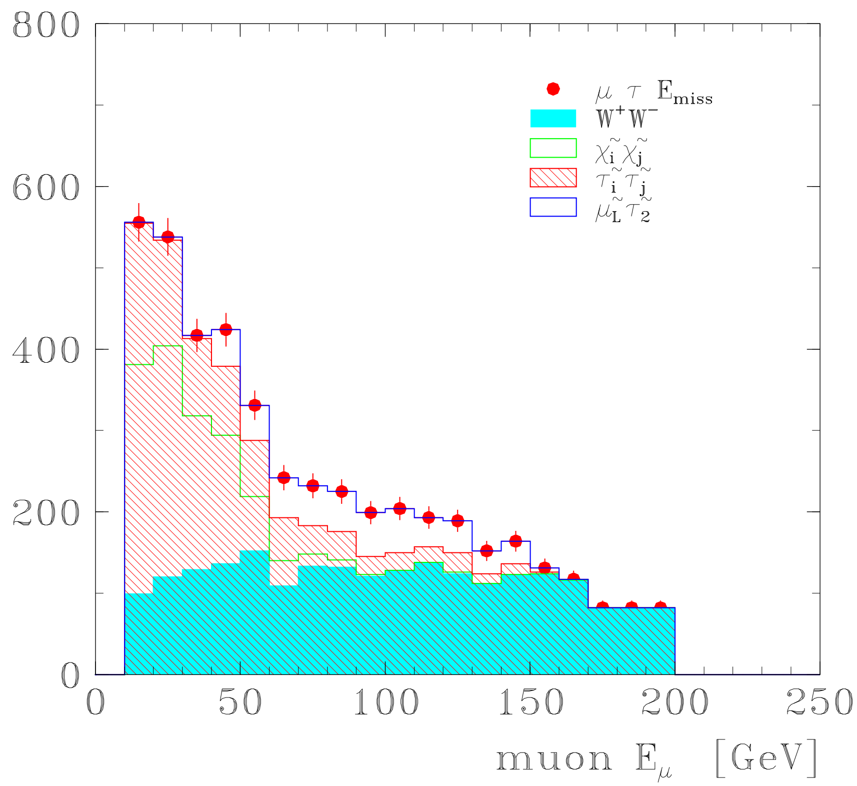
SUSY scenarios C', G', B', SPS1a, I', $\sqrt{s} = 800$ GeV



for SPS1a: $Br(\mu \to e\gamma) = 10^{-13}$ (PSI expt.) $\Rightarrow \sigma(e\mu + 2\tilde{\chi}_1^0) = 3 \cdot 10^{-3}$ fb

$\tau\mu$ final states

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

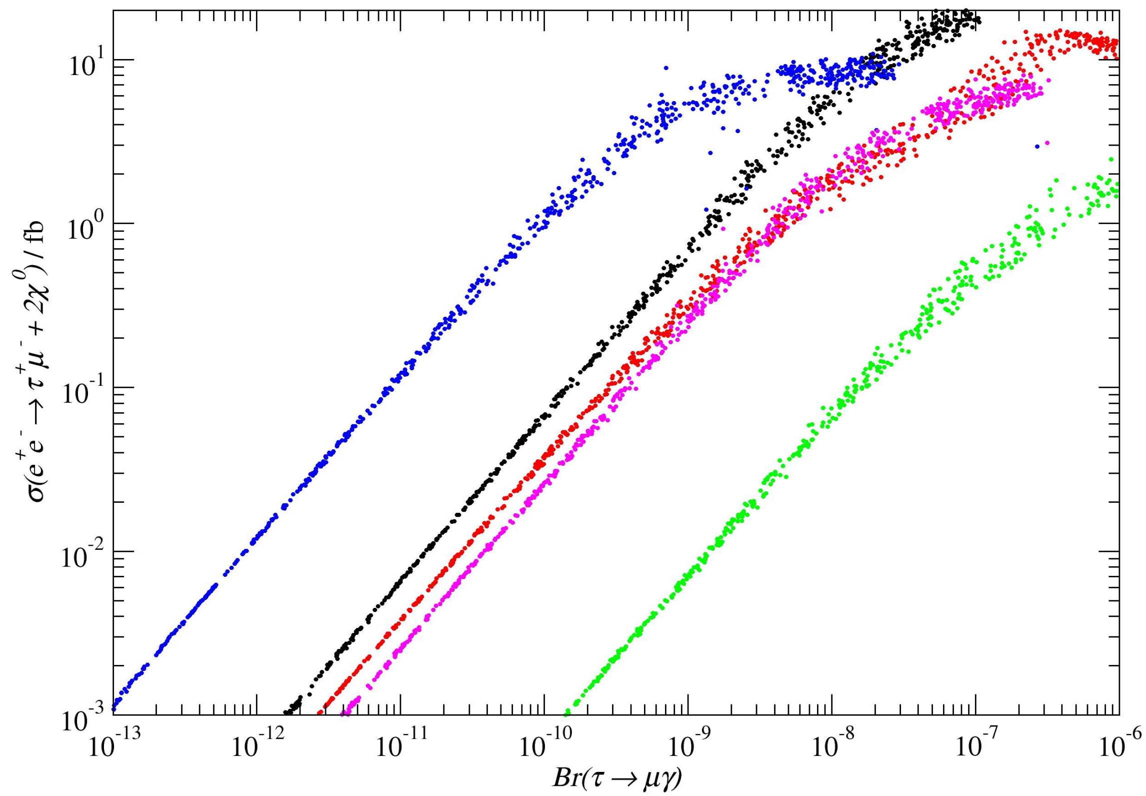


- 4 fb signal cross section (flat lepton energy spectrum)
- SM+MSSM background (soft E_μ spectrum)
- standard selection criteria (τ identification via hadronic decays, 25% efficiency)
- $\sigma(\tilde{\tau}_2\tilde{\mu}_L) = 2$ fb $\rightarrow 5\sigma$ effect

H.-U. Martyn (2004)

correlation of signals

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



for SPS1a: $\sigma(\tau\mu + 2\tilde{\chi}_1^0) = 1$ fb (LC expt.) $\Rightarrow Br(\tau \to \mu\gamma) = 5 \cdot 10^{-9}$

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

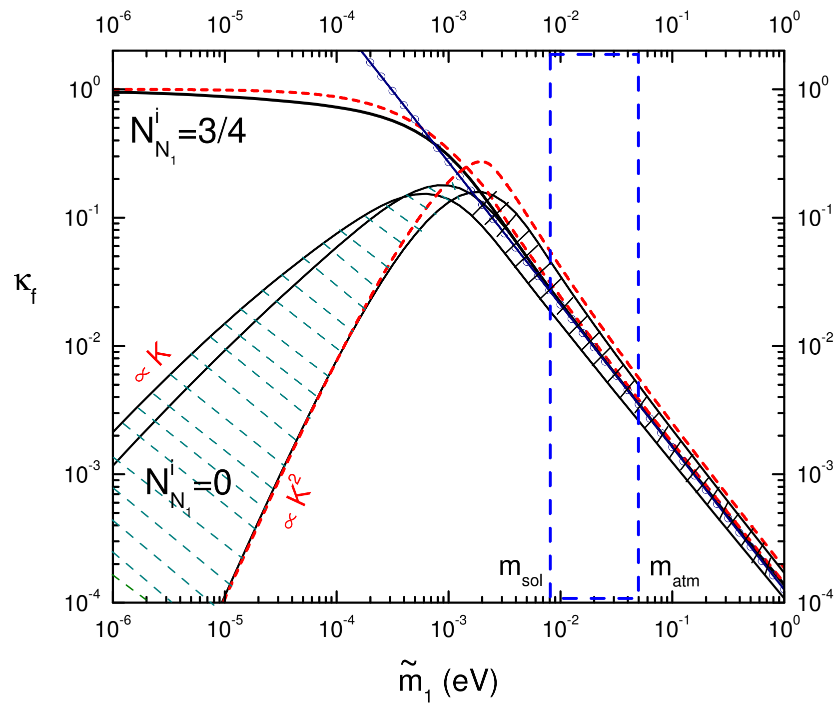
later on conversion to baryon asymmetry via sphaleron processes

$$\boxed{\eta_B = d\, a_{sph} \epsilon\, \kappa_f = (6.3 \pm 0.3) \times 10^{-10} \text{ from CMB}}$$

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

- $M_1 \ll M_2 \ll M_3$, i.e. L-violation in N_1 decays •

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



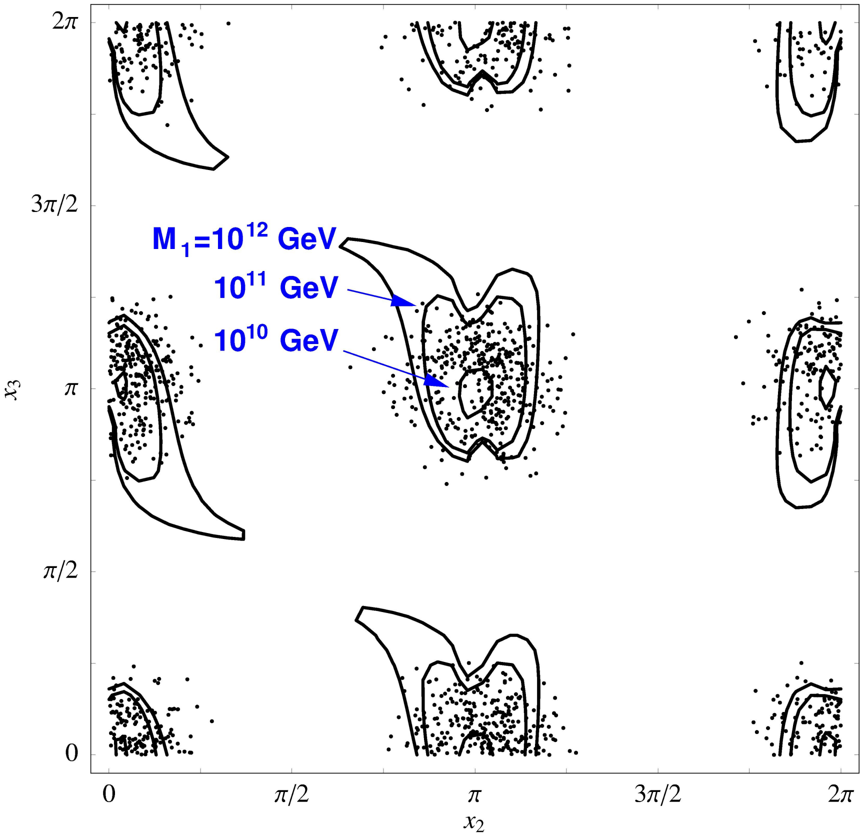
Buchmüller, Di Bari, Plümacher, hep-ph/0406014

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

successfull baryogenesis with $M_1 < 10^{11}$ GeV to avoid overabundance of gravitinos

gravitino problem in big bang nucleosynthesis requires $T_R < 10^9$ GeV

$\Rightarrow M_1 < 10\, T_R < 10^{10}$ GeV for $m_{3/2} = 1$ TeV

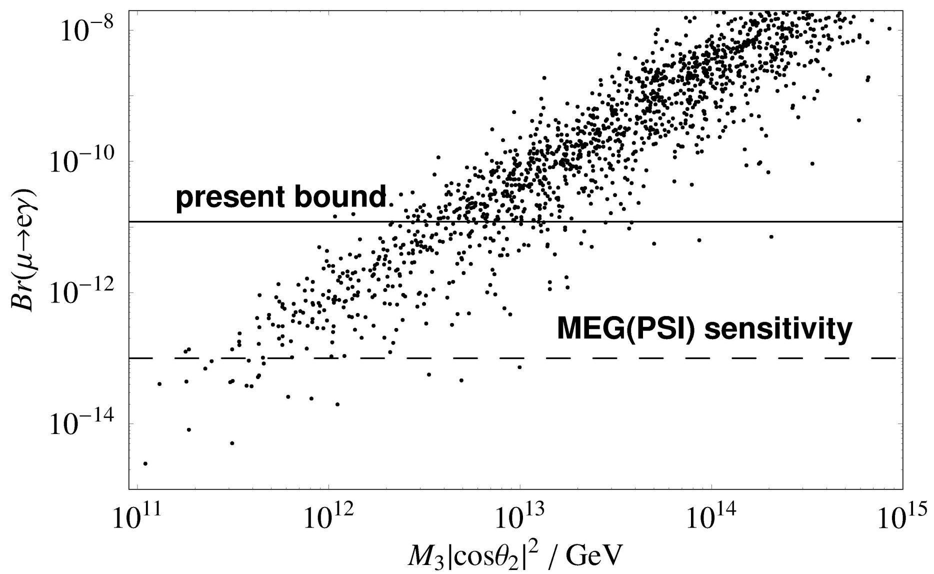


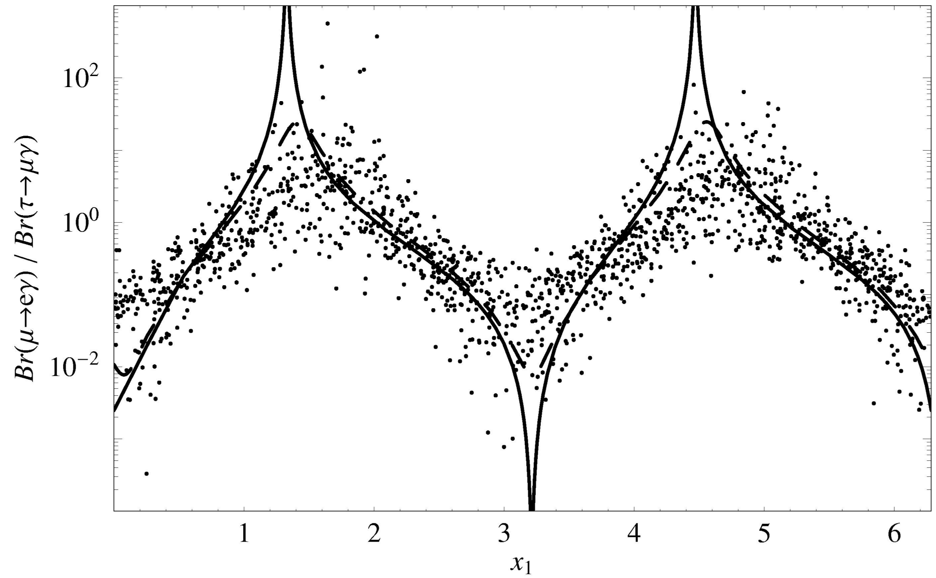
$$R = \begin{pmatrix} c_2c_3 & -c_1s_3 - s_1s_2c_3 & s_1s_3 - c_1s_2c_3 \\ c_2s_3 & c_1c_3 - s_1s_2s_3 & -s_1c_3 - c_1s_2s_3 \\ s_2 & s_1c_2 & c_1c_2 \end{pmatrix}$$

$c_j = \cos(x_j + iy_j)$

- $0 \leq x_1 \leq 2\pi$
- $10^{-3} < y_i < \mathcal{O}(1)$ $(y_i = 0.1)$

$\Rightarrow x_2, x_3 \simeq n\pi$





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

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

- $x_{2,3} = n\pi$
- $10^{-3} < y < \mathcal{O}(1)$
- successfull baryogenesis
- solid (dashed): $y_i = 0.01(0.1)$

$\Rightarrow x_1$

searches for lepton flavor violation?

- rare radiative decays $Br(\tau \rightarrow \mu\gamma) \simeq 10^{-8}$
  Serin, Stroynowski, ATLAS Internal Note (1997)
- slepton production $\tilde{g} \rightarrow \tilde{q} \rightarrow \chi_2 \rightarrow \tilde{l}l \rightarrow \chi_1 + \tau\mu$
  Carvalho, Ellis et al., hep-ph/0206148
  Hisano et al.,PRD65(2002)
  Hinchliffe, Paige, PRD63(2001), hep-ph/0010086
  Agashe, Graesser, hep-ph/9904422

Conclusion:
Observation of LFV may be possible at the LHC
largest signal probably in $\tau - \mu$ channel
urge more detailed study