Neutrino Oscillations, SUSY Seesaw Mechanism and Charged Lepton Flavor Violation

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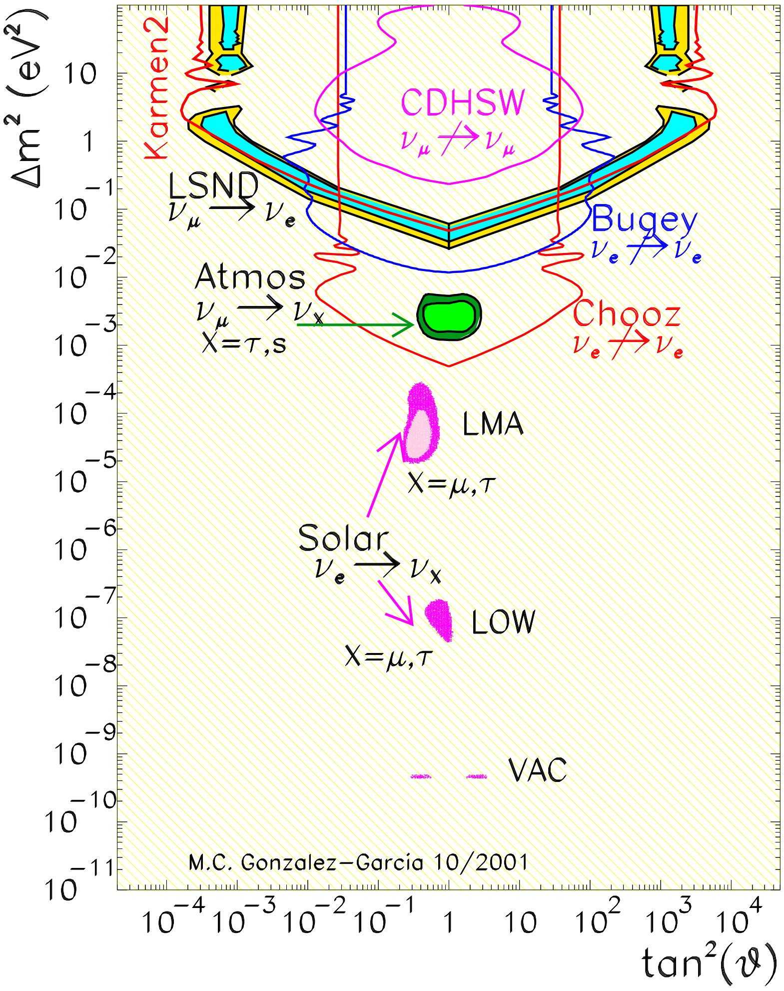
Neutrino Oscillations

experimental evidence

- solar neutrinos
- atmospheric neutrinos
- LSND(?)



mass squared differences

- $\Delta m^2_{12} \simeq \begin{cases} 6 \times 10^{-5}\ \text{eV}^2 & LMA \\ 10^{-7}\ \text{eV}^2 & LOW \\ 4 \times 10^{-10}\ \text{eV}^2 & VAC \end{cases}$

- $\Delta m^2_{23} \simeq 3 \times 10^{-3}\ \text{eV}^2$

mixing matrix

- $s_{13} \approx 0, s_{23} = c_{23} = \frac{1}{\sqrt{2}}$

$$V \approx \begin{pmatrix} c_{12} & s_{12} & 0 \\ -\frac{s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- $s_{12} = c_{12} = \frac{1}{\sqrt{2}}$ (bimaximal mixing)

$$V \approx \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

experimental evidence: $c_{12} \approx 0.86$ (LMA)

SUSY Seesaw Mechanism

neutrinos

superpotential:

$$W \subset W_\nu = -\frac{1}{2}\nu_R^{cT} M \nu_R^c + \nu_R^{cT} Y_\nu L \cdot H_2$$

neutrino mass terms:

$$-\left(\bar{\nu}_L \quad \overline{\nu_R{}^c} \right) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L{}^c \\ \nu_R \end{pmatrix}$$

Dirac mass $m_D = Y_\nu \langle H_2 \rangle \ll$ Majorana mass scale M_R

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

diagonalization in flavor space:

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

masses and mixing parameters from experiment

renormalization group running:

- M_ν, Y_ν from $M_{exp} \to M_R \to M_{GUT}$
- LFV through loops in slepton sector

sleptons

charged slepton (mass)^2 matrix:

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

$$\begin{aligned} (m^2_{\tilde{l}_L})_{ab} &= (m^2_L)_{ab} + \delta_{ab}\left(m^2_{l_a} + m^2_Z \cos 2\beta \left(-\frac{1}{2} + \sin^2\theta_W\right)\right) \\ (m^2_{\tilde{l}_R})_{ab} &= (m^2_R)_{ab} + \delta_{ab}(m^2_{l_a} - m^2_Z \cos 2\beta \sin^2\theta_W) \\ (m^2_{\tilde{l}_{LR}})_{ab} &= A_{ab} v \cos\beta - \delta_{ab} m_{l_a} \mu \tan\beta \end{aligned}$$

mSUGRA scenario (with universality conditions at M_{GUT})

$$\begin{aligned} m^2_L &= m^2_0 \mathbf{1} + (\delta m^2_L)_{\mathrm{MSSM}} + \delta m^2_L \\ m^2_R &= m^2_0 \mathbf{1} + (\delta m^2_R)_{\mathrm{MSSM}} + \delta m^2_R \\ A &= A_0 Y_l + \delta A_{\mathrm{MSSM}} + \delta A \end{aligned}$$

LFV terms generated in RG-running $M_{GUT} \to M_R$

$$\begin{aligned} \delta m^2_L &\simeq -\frac{1}{8\pi^2}(3m^2_0 + A^2_0) Y^\dagger_\nu Y_\nu \ln\left(\frac{M_{GUT}}{M_R}\right) \\ \delta m^2_R &\simeq 0 \\ \delta A &\simeq -\frac{3A_0}{16\pi^2} Y_l Y^\dagger_\nu Y_\nu \ln\left(\frac{M_{GUT}}{M_R}\right) \end{aligned}$$

neutrino input

$$Y_\nu = \frac{1}{v \sin\beta} \mathrm{diag}\left(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}\right) R\, \mathrm{diag}\left(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}\right) U^\dagger$$

$$\mathrm{Y}^\dagger_\nu Y_\nu = \frac{M_R}{v^2 \sin^2\beta} V \cdot \mathrm{diag}(m_1, m_2, m_3) \cdot V^\dagger \quad \text{for } M_i = M_R, \ \text{real } R$$

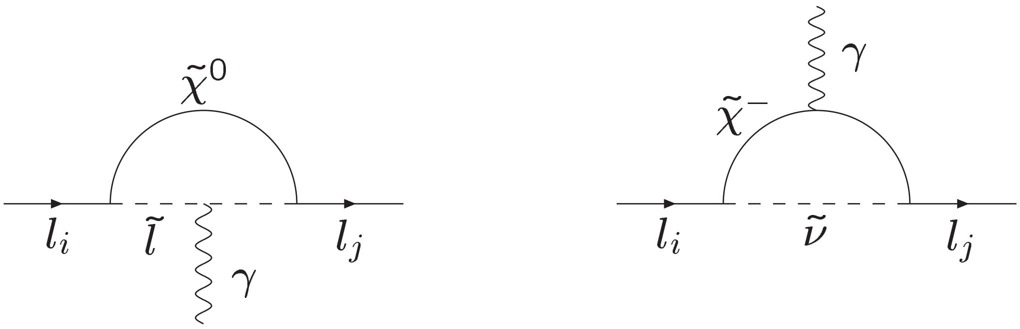
Charged Lepton Flavor Violation

low-energy rare processes

- $\boxed{\mu \to e\gamma, \tau \to \mu\gamma, \text{ etc.}}$

in SM $+\ \nu_R$ unobservable

in MSSM:



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

due to dominance of $\mu \to e\gamma$ penguin contributions related to

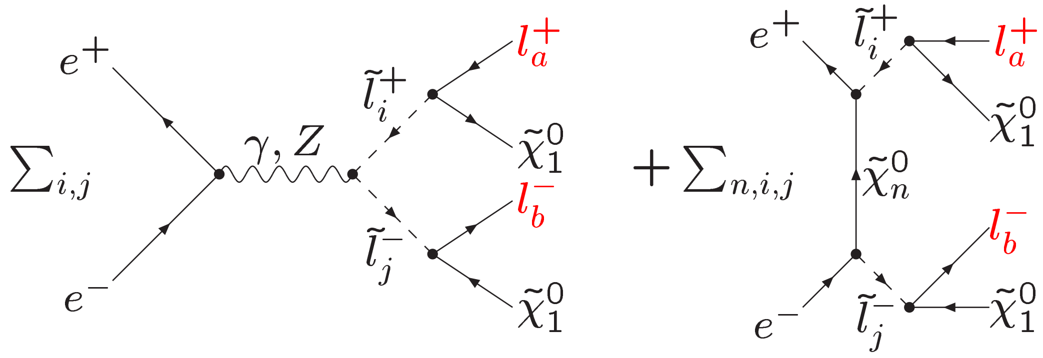
- $\boxed{\mu \to 3e}$

$$\frac{Br(\mu \to 3e)}{Br(\mu \to e\gamma)} \approx \frac{\alpha}{8\pi}\frac{8}{3}\left(\ln\frac{m_\mu^2}{m_e^2} - \frac{11}{4}\right) \approx (6-7)\cdot 10^{-3}$$

- $\boxed{\mu^- N \to e^- N}$

$$\frac{R(\mu^- N \to e^- N)}{Br(\mu \to e\gamma)} \approx \frac{\Gamma_\mu}{\Gamma_{cap}} 16\alpha^4 Z_{eff}^4 Z |F(q^2)|^2 \approx (5{-}7)\cdot 10^{-3}\ (\text{Ti})$$

high-energy $e^+e^-(e^-e^-)$ collisions



- $\boxed{e^+e^- \to l_a^+ l_b^- + \text{ missing energy}}$

$$|M|^2 \;\propto\; \alpha^4 \sum_{ijkl} |(\delta m_L)^2_{ij}(\delta m_L)^2_{kl}|$$
$$\times \quad \frac{\pi}{2(m_i\Gamma_i + m_k\Gamma_k + i\Delta m^2_{ik})}\frac{\pi}{2(m_j\Gamma_j + m_l\Gamma_l + i\Delta m^2_{jl})}$$

- SM background:
  W-production: $e^+e^- \to l_a^+ l_b^- \bar{\nu}_b \nu_a$
  $\sigma(e\mu) \approx 80$ fb at $\sqrt{s} = 800$ GeV

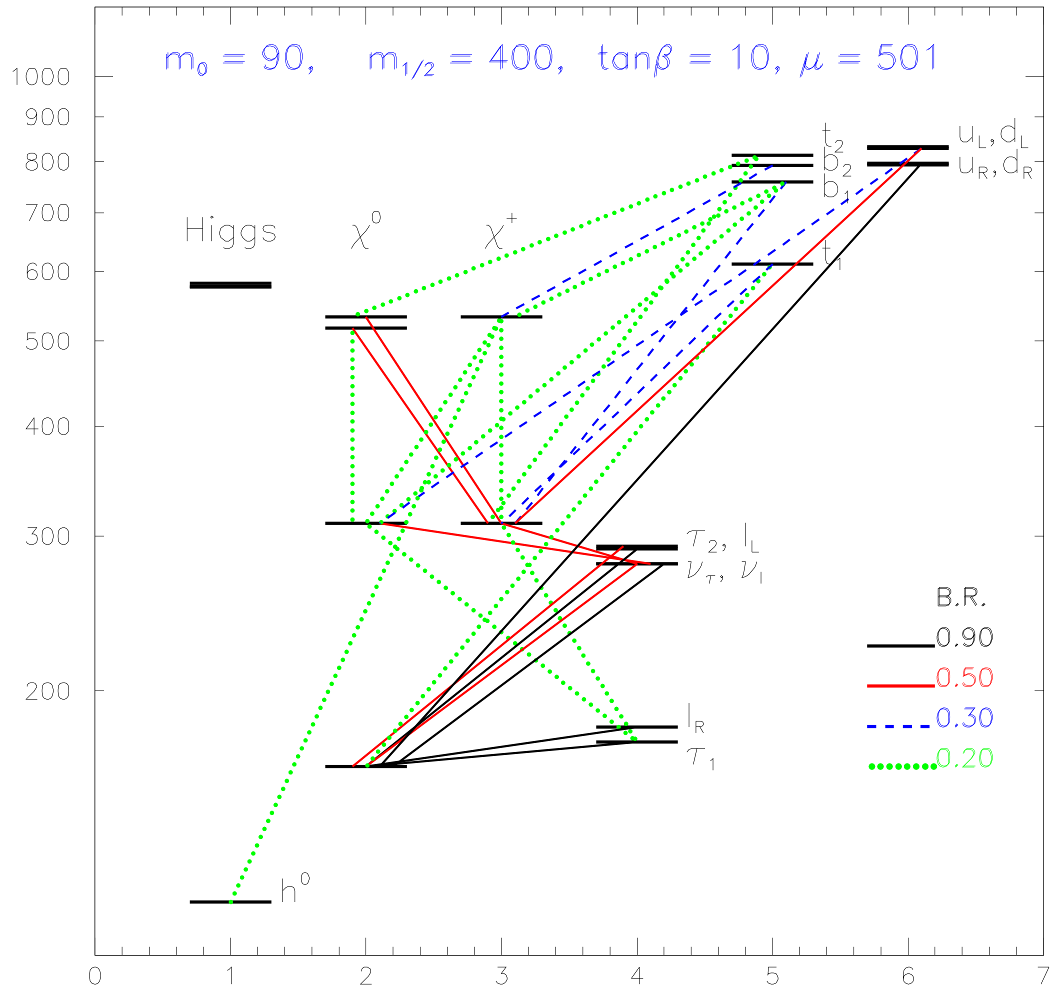
- MSSM background:
  Slepton/chargino production: $e^+e^- \to l_a^+ l_b^- + 2\tilde{\chi}_1^0 + 2(4)\nu$
  $\sigma(e\mu) \approx 0.1 - 5$ fb at $\sqrt{s} = 800$ GeV

Numerical analysis

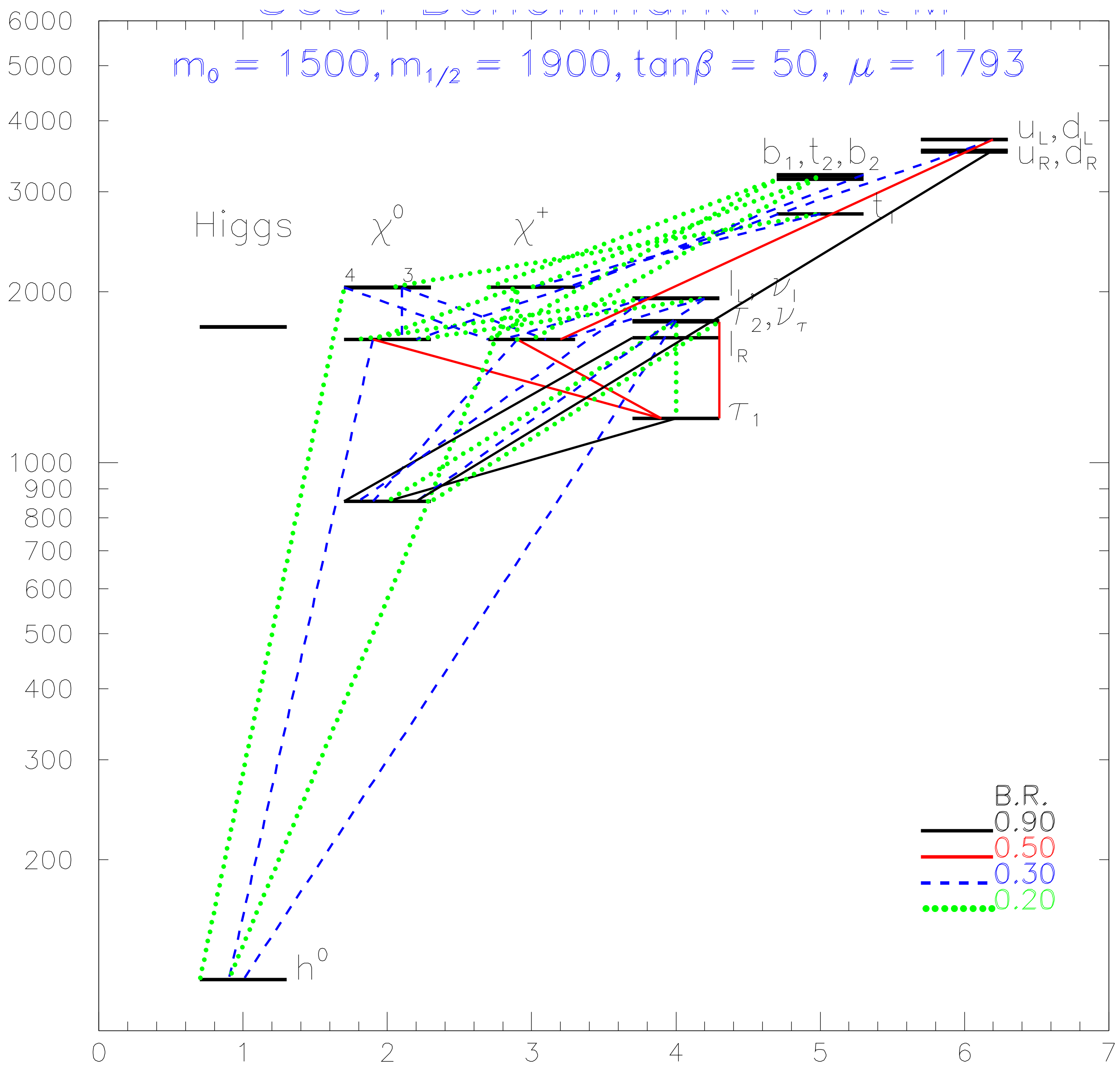
mSUGRA benchmark scenarios

- proposed for Linear Collider studies (Battaglia et al., hep-ph/0106204)
- consistent with direct searches, $b \to s\gamma$, Higgs searches, cosmology

Scenario C



Scenario M



$m_0 = 1500, m_{1/2} = 1900, \tan\beta = 50, \ \mu = 1793$
Higgs
χ^0
χ^+
4
3
h^0
l_L, ν_l
τ_2, ν_τ
l_R
τ_1
b_1, t_2, b_2
t_1
u_L, d_L
u_R, d_R
B.R.
0.90
0.50
0.30
0.20
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
0
1
2
3
4
5
6
7

MSUGRA parameters

- m_0: common scalar mass at M_{GUT}

$$90 \text{ GeV} \leq m_0 \leq 3450 \text{ GeV}$$

- $m_{1/2}$: common gaugino mass at M_{GUT}

$$250 \text{ GeV} \leq m_{1/2} \leq 1900 \text{ GeV}$$

- A_0: common trilinear coupling at M_{GUT}

$$A_0 = 0$$

- $\tan\beta$: ratio of Higgs VEVs at EW scale $\left(\tan\beta = \frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle}\right)$

$$5 \leq \tan\beta \leq 50$$

- signμ: sign of Higgs mixing term

$$\text{sign}(\mu) = \pm 1$$

neutrino input

oscillation parameters (90% CL):

- present best fit (LMA)
- solar $\nu_1 - \nu_2$ (KAMLAND)
- atmospheric $\nu_2 - \nu_3$ (MINOS)
- $\nu_1 - \nu_3$ (neutrino factory/galactic supernova)

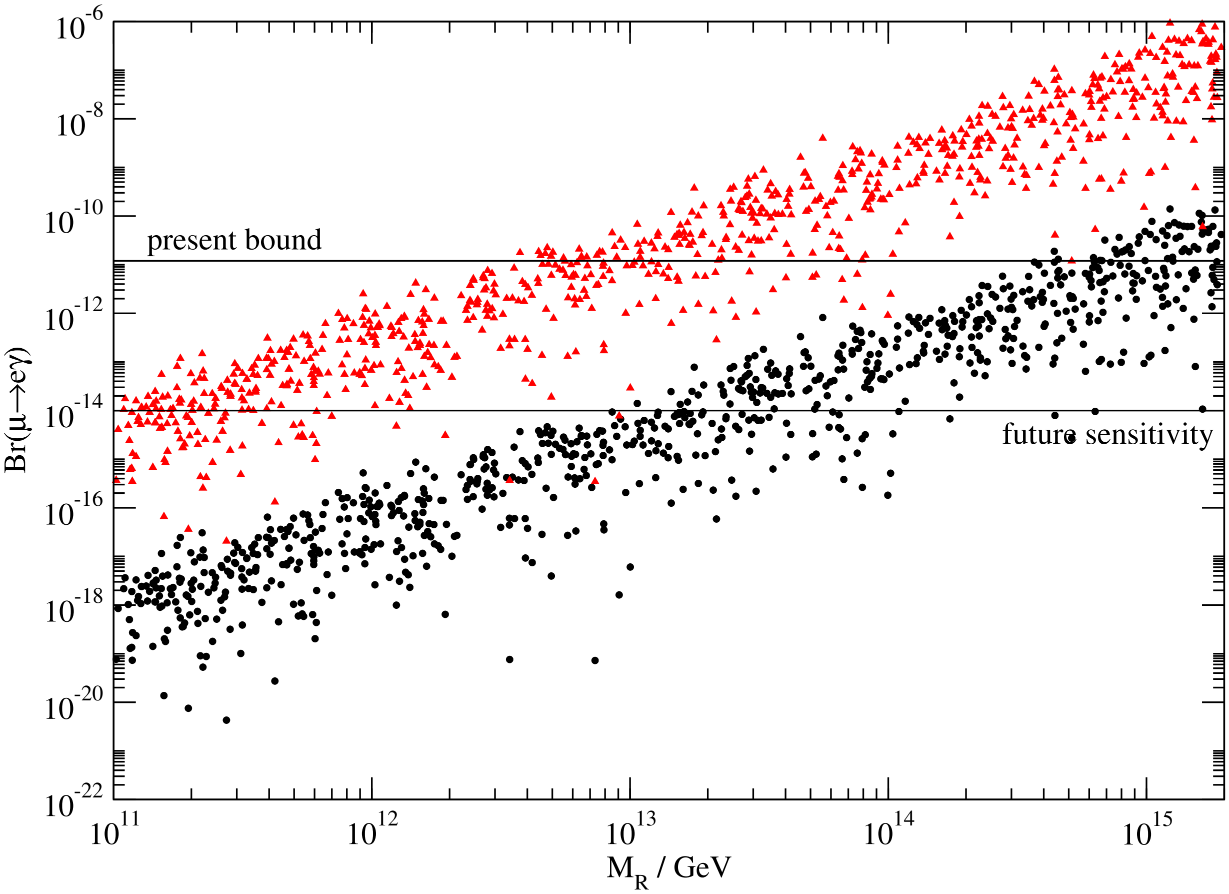
absolute neutrino mass scale:

- $U_{1i}^2 m_i$ from $0\nu\beta\beta$ (e.g. GENIUSI)
- m_1 from Tritium β-decay (KATRIN)

parameter	best fit	present	future
$\tan^2\theta_{23}$	1.40	${}^{+1.64}_{-1.01}$	${}^{+1.37}_{-0.66}$
$\tan^2\theta_{13}$	0.005	${}^{+0.050}_{-0.005}$	${}^{+0.001}_{-0.005}$
$\tan^2\theta_{12}$	0.36	${}^{+0.65}_{-0.16}$	${}^{+0.35}_{-0.16}$
$\Delta m_{12}^2/10^{-5}$ eV^2	3.30	${}^{+66.7}_{-2.3}$	${}^{+0.3}_{-0.3}$
$\Delta m_{23}^2/10^{-3}$ eV^2	3.10	${}^{+3.0}_{-1.7}$	${}^{+1.0}_{-1.0}$
φ/rad	0 to 2π		
m_1/eV	0 to 0.03 ($0.3^{+0.11}_{-0.16}$)		

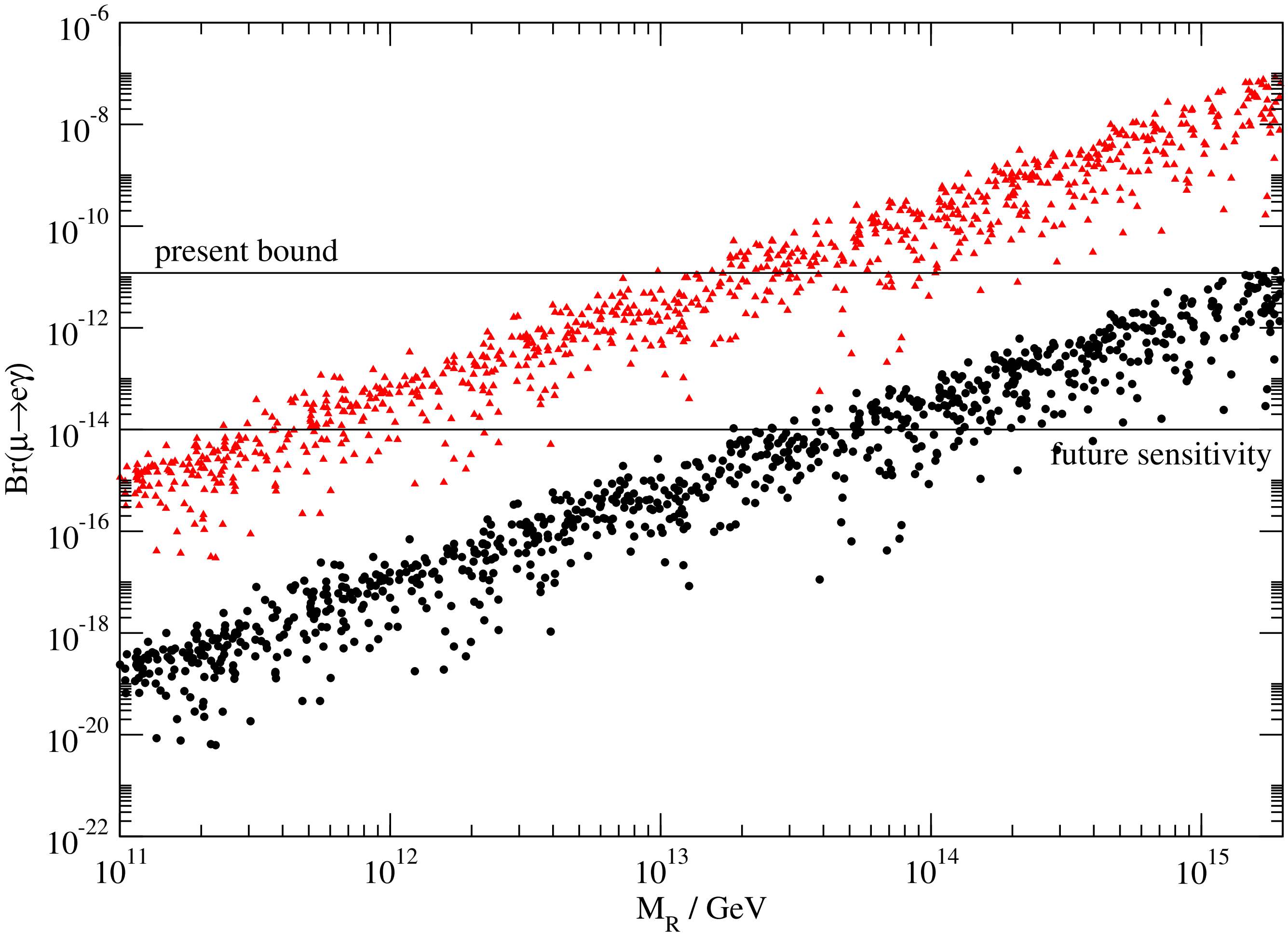
Results

$Br(\mu \to e\gamma)$, hierar. ν_L



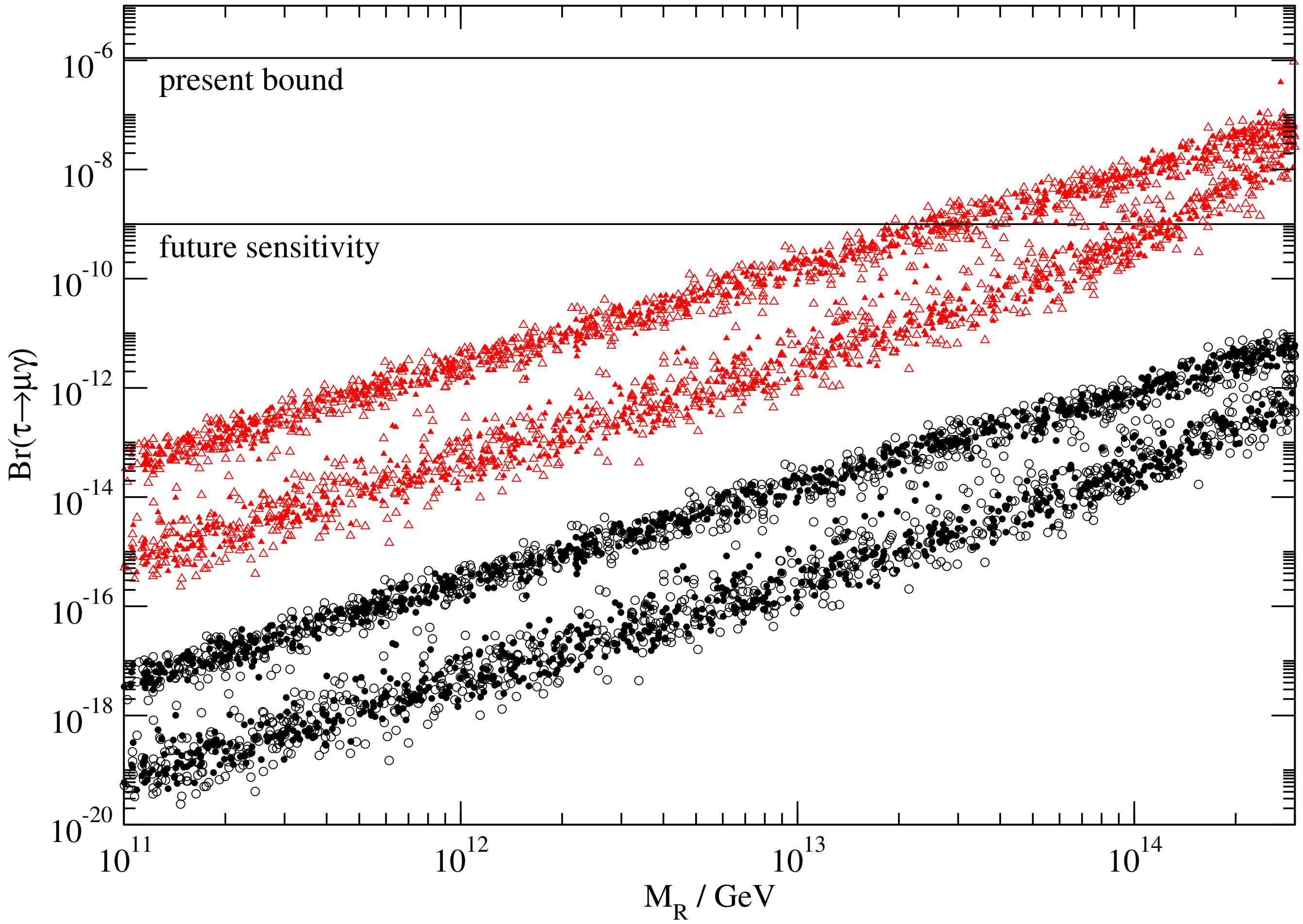
- MSUGRA scenarios leading to largest (L) and smallest (H) branching ratios
- uncertainties of present ν-experiments

$Br(\mu \to e\gamma)$, hierar. ν_L



- MSUGRA scenarios leading to largest (L) and smallest (H) branching ratios
- uncertainties of future ν-experiments

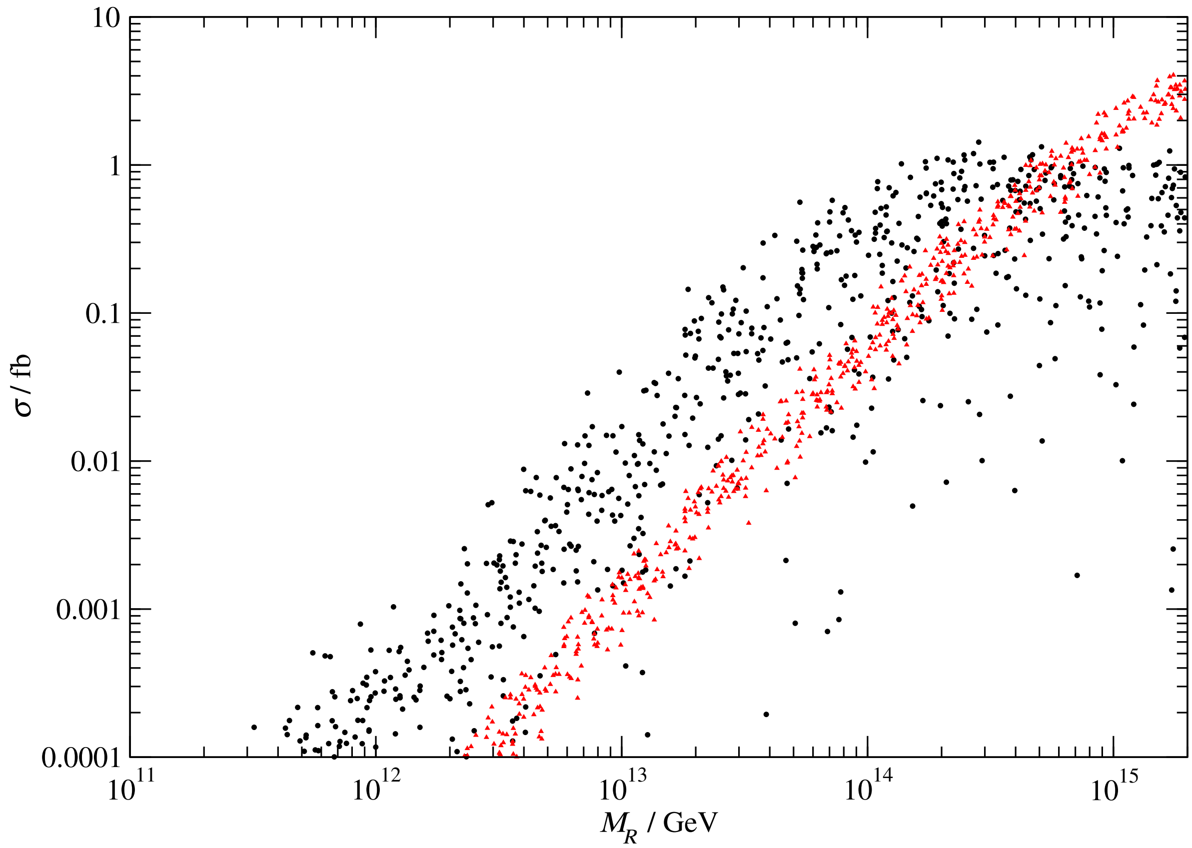
$Br(\tau \to \mu\gamma)$



- MSUGRA scenarios leading to largest (L) and smallest (H) branching ratio
- uncertainties of present ($\triangle, \bullet$) and future ($\triangle, \circ$) ν-experiments
- Br(deg. ν spectrum) $< Br$(hier. ν spectrum)

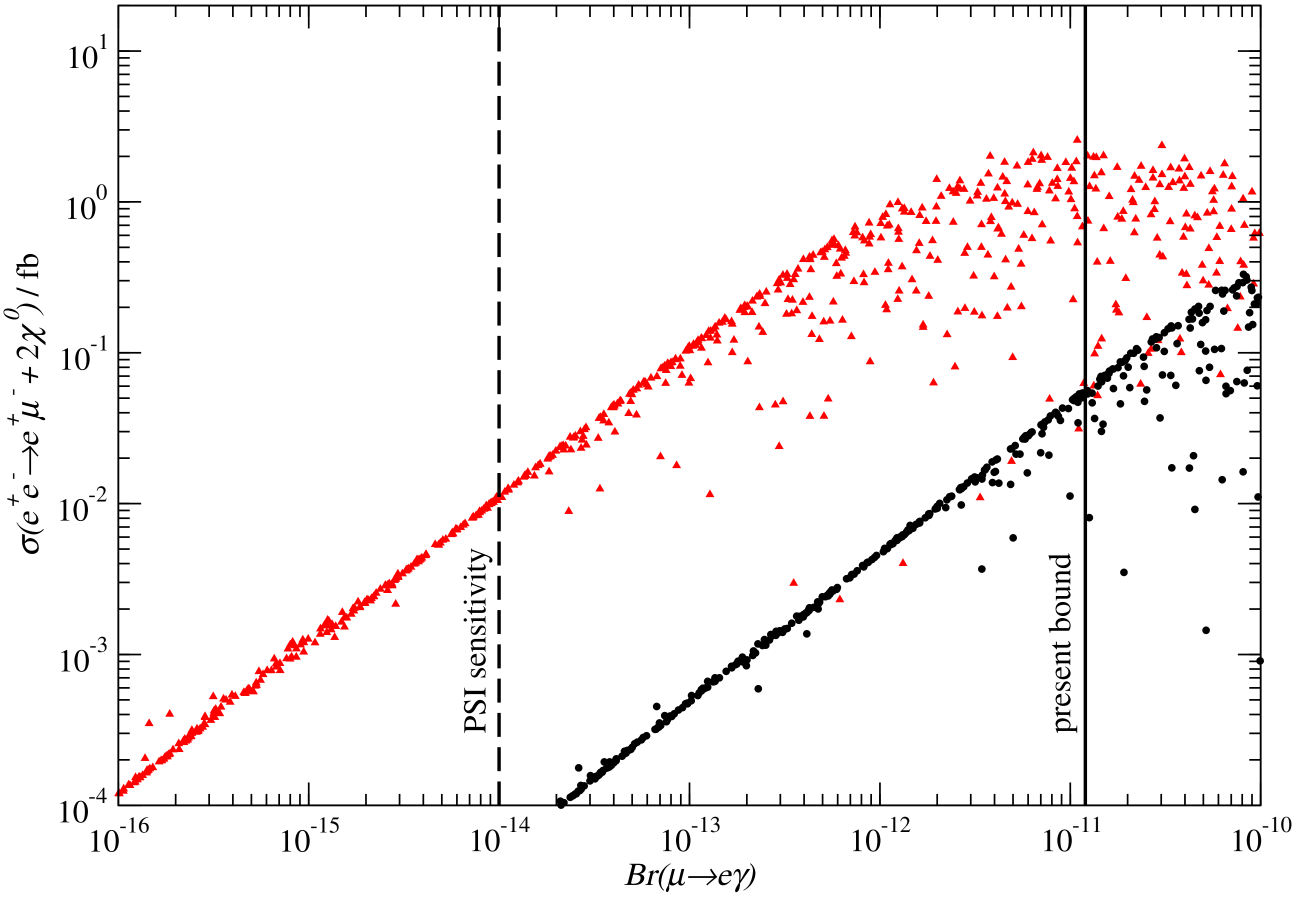
$$\sigma(e^+e^- \to e^+\mu^-(\mu^+\tau^-) + 2\tilde{\chi}_1^0)$$

$$\sqrt{s} = 500 \text{ GeV}$$



- MSUGRA scenario B, hierarchical neutrino masses
- uncertainties of future ν-experiments

correlation of high- and low-energy signals



- scenarios C and I; hierarchical neutrino masses
- uncertainties of future ν-experiments
- $\sqrt{s} = 800$ GeV

Conclusions

SUSY seesaw mechanism can be tested by LFV processes involving charged leptons

strong dependence on mSUGRA scenario

impact of uncertainties in neutrino sector

- $\underline{Br(\mu \to e\gamma) \approx 10^{-14}}$ (PSI)
  - $M_R > \begin{cases} 10^{11} - 10^{13} \text{ GeV, hier. spectrum} \\ 10^{12} - 10^{14} \text{ GeV, deg. spectrum} \end{cases}$
  - determination of M_R within factor 10 in a given mSUGRA scenario

- $\underline{Br(\tau \to \mu\gamma) \approx 10^{-9}}$ (SUPERKEKB, LHC)
  - hierarchical spectrum: $M_R > 10^{13}$ GeV
  - determination of M_R within factor 2 in a given mSUGRA scenario

- $\underline{Br(\mu \to e\gamma) \approx 10^{-14} - 10^{-11}}$
  - implies $\sigma(e^+e^- \to e^+\mu^- + 2\tilde{\chi}_1^0) \approx 10^{-4} - 1$ fb at $\sqrt{s} = 800$ GeV

Appendix

$$Y_\nu = \frac{1}{v \sin\beta} \mathrm{diag}\left(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}\right) R \, \mathrm{diag}\left(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}\right) U^\dagger$$

i) degenerate $M_1 = M_2 = M_3 = M_R$ and real R

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

ii) hierarchical spectrum:

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

iii) degenerate spectrum:

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