# SUSY Seesaw and Lepton Flavor Violation at the LHC and ILC

**Frank Deppisch**
**frank.deppisch@desy.de**

**DESY Hamburg**

**in collaboration with**
**S. Albino (Hamburg), D.K. Ghosh (Delhi), R. Rückl (Würzburg)**

3rd Vienna Central European Seminar on
Particle Physics and Quantum Field Theory
December 1-3, 2006

# Overview

- SUSY
- Neutrinos
- SUSY Seesaw
- Rare decays
- LFV at the ILC
- LFV at the LHC
- Conclusion

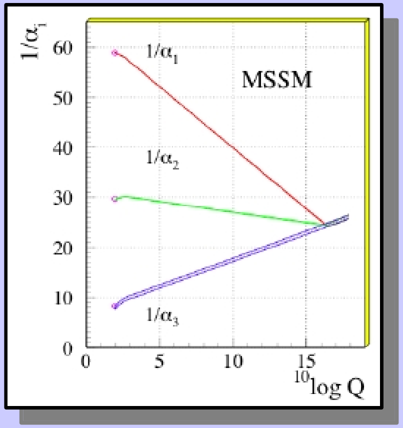
# Supersymmetry

**SUSY** relates bosonic and fermionic degrees of freedom

$$Q|\text{Boson}| \rightarrow |\text{Fermion}|, Q|\text{Fermion}| \rightarrow |\text{Boson}|$$

$\Rightarrow$ Every Standard Model particle has a SUSY partner

- Solution to hierarchy problem
- Radiative EW symmetry breaking
- Gauge coupling unification
- Cold Dark Matter




**MSSM** Minimal extension of the Standard Model with two Higgs doublets and conserved R-parity

Superpotential:

$$\begin{aligned} W = & \hat{u}^{cT} Y_u \hat{Q} \cdot \hat{H}_u \\ & - \hat{d}^{cT} Y_d \hat{Q} \cdot \hat{H}_d \\ & - \hat{e}^{cT} Y_e \hat{Q} \cdot \hat{H}_d \\ & + \mu \hat{H}_u \cdot \hat{H}_d \end{aligned}$$

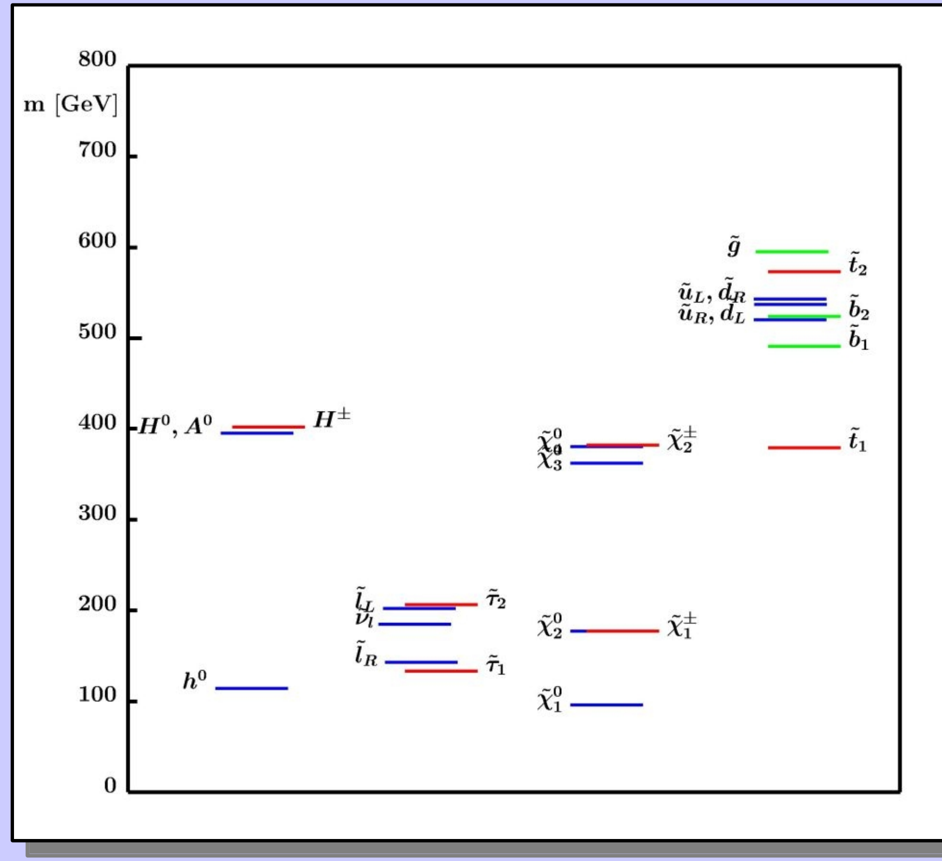
| Boson | Fermion | Description |
|---|---|---|
| $g$ | $\tilde{g}$ | gluon/gluino |
| $W$ | $\tilde{W}$ | W boson/wino |
| $B$ | $\tilde{B}$ | B boson/bino |
| $(\tilde{\nu}, \tilde{e})_L$ | $(\nu, e)_L$ | L (s)leptons |
| $\tilde{e}_R^*$ | $e_L^c$ | R (s)leptons |
| $(\tilde{u}, \tilde{d})_L$ | $(u, d)_L$ | L (s)quarks |
| $\tilde{u}_R^*$ | $u_L^c$ | R up-(s)squarks |
| $\tilde{d}_R^*$ | $d_L^c$ | R down-(s)squarks |
| $(h_u^+, h_u^0)_L$ | $(\tilde{h}_u^+, \tilde{h}_u^0)_L$ | up-Higgs(inos) |
| $(h_d^0, h_d^-)_L$ | $(\tilde{h}_d^0, \tilde{h}_d^-)_L$ | down-Higgs(inos) |

# mSUGRA

Phenomenology demands breaking of exact SUSY

$\Rightarrow$ Additional terms in Lagrangian

$\Rightarrow$ 100+ free parameters




Scenario SPS1a:
$m_0$ = 100 GeV, $m_{1/2}$ = 250 GeV,
$A_0$ = -100 GeV, $\tan\beta$ = 10, sign$\mu$ = +

**mSUGRA**

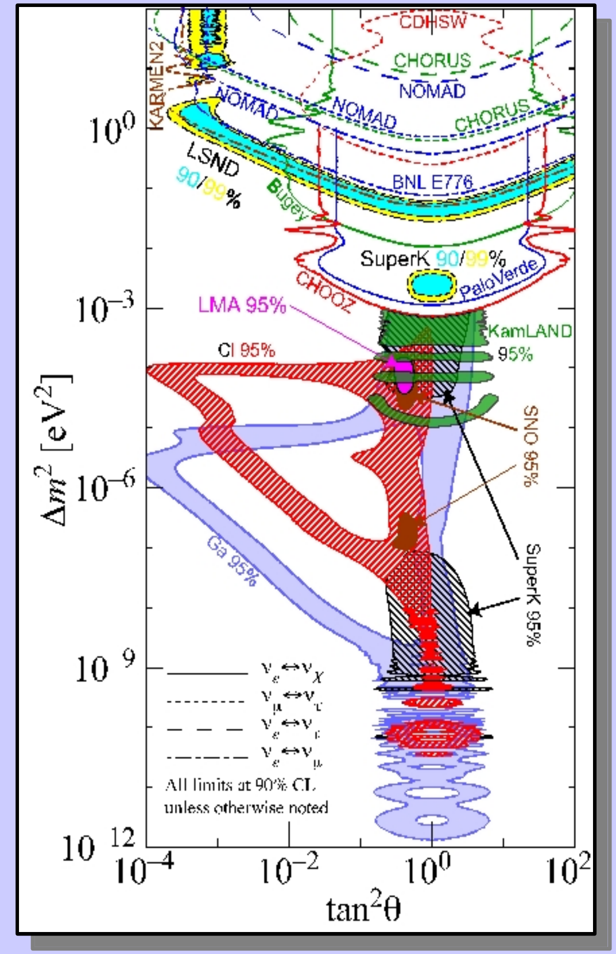
- Theoretical framework for SUSY breaking
- Universality at $M_{\text{GUT}}$
- Five free parameters
  - $m_0$ common scalar mass
  - $m_{1/2}$ common gaugino mass
  - $A_0$ common trilinear coupling
  - $\tan\beta$ ratio of Higgs VEVs
  - sign$\mu$ sign of Higgs mixing

# Neutrinos

- Standard Model: Neutrinos are massless
- But: Experimental observation of neutrino flavor oscillations
- $\Rightarrow$ Neutrinos have masses and neutrino flavor is violated

$$U^T m_\nu U = diag\left(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\right)$$

$$U = \begin{pmatrix} c_{13} c_{12} & s_{12} c_{13} & s_{13} \\ -s_{12} c_{23} - s_{23} s_{13} c_{12} & c_{23} c_{12} - s_{23} s_{13} s_{12} & s_{23} c_{13} \\ s_{23} s_{12} - s_{13} c_{23} c_{12} & -s_{23} c_{12} - s_{13} s_{12} c_{23} & c_{23} c_{13} \end{pmatrix}$$




- Best fit values for mixing angles and mass differences

$$\sin^2\theta_{12} = 0.30, \sin^2\theta_{23} = 0.50, \sin^2\theta_{13} = 0.00,$$
$$\Delta m_{12}^2 = 7.9 \cdot 10^{-5}\,\mathrm{eV}^2, \Delta m_{13}^2 = 2.2 \cdot 10^{-3}\,\mathrm{eV}^2$$

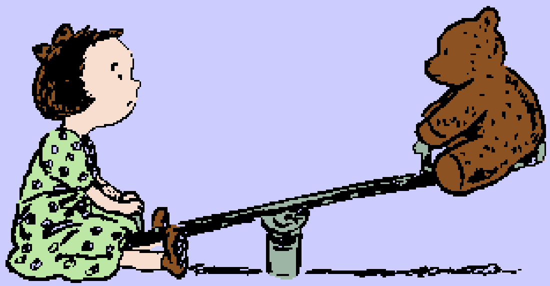
- Unknown absolute mass scale $m_{\nu_1} = 0 \ldots 0.3\,\mathrm{eV}$

# SUSY Seesaw

## Mechanism

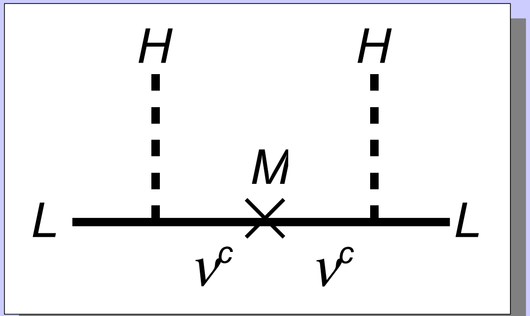
- Add heavy right-handed neutrinos to (MS)SM particle content

$$W = W_{\mathrm{MSSM}} - \frac{1}{2}\hat{\nu}_R^{cT} M \hat{\nu}_R^c + \hat{\nu}_R^{cT} Y_\nu \hat{L}\cdot\hat{H}_u$$



- Diagonalize seesaw matrix assuming super-heavy right-handed neutrinos

$$\begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \quad \text{with} \quad m_D = Y_\nu \langle H_u^0 \rangle \ll M_R$$



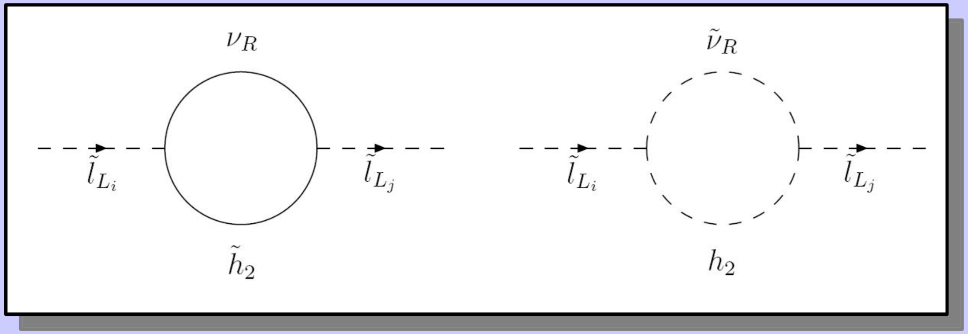

- Effective light neutrino mass matrix at low energies

$$m_\nu = m_D^T M^{-1} m_D \quad \text{for} \quad m_D \ll M_R \qquad m_\nu \approx 0.1\,\mathrm{eV}\left(\frac{m_D}{100\,\mathrm{GeV}}\right)^2 \left(\frac{M_R}{10^{14}\,\mathrm{GeV}}\right)^{-1}$$

# SUSY Seesaw

## Sleptons

- Neutrino flavor mixing radiatively induces slepton flavor mixing from $M_{\mathrm{GUT}}$ to the right-handed neutrino mass scales




Slepton mass matrix (6x6):

$$m_{\tilde{l}}^2 = \begin{pmatrix} m_{\tilde{L}}^2 & (m_{\tilde{L}R}^2)^+ \\ m_{\tilde{L}R}^2 & m_{\tilde{R}}^2 \end{pmatrix}$$

- Slepton off-diagonal mass corrections determined by neutrino Yukawa coupling

$$(\delta m_{\tilde{L}}^2)_{ij} = \frac{-1}{8\pi^2}(3m_0 + A_0)(Y_\nu^+ L Y_\nu)_{ij}$$

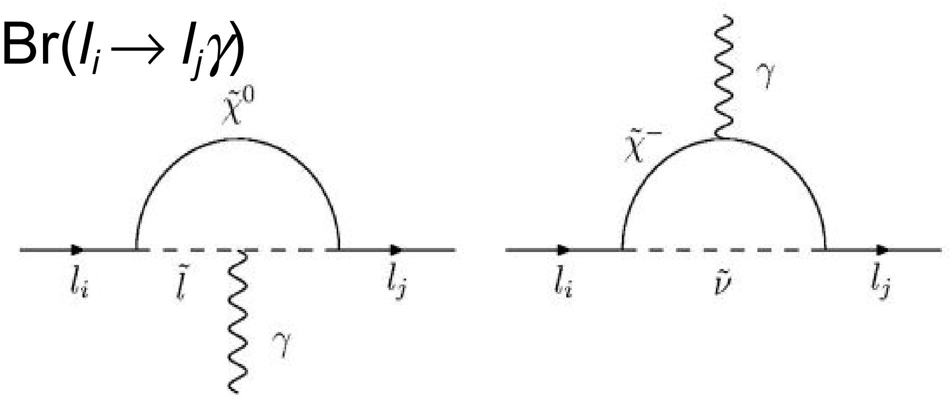
$$(\delta m_{\tilde{R}}^2)_{ij} = 0 \qquad L = \log\left(\frac{M_{GUT}}{M_{\nu_{Ri}}}\right)\delta_{ij}$$

$$(\delta m_{\tilde{L}R}^2)_{ij} = \frac{-3A_0}{8\pi^2} Y_e (Y_\nu^+ L Y_\nu)_{ij}$$

⇒ Origin of charged LFV

# Rare LFV Decays

- Current bounds and future sensitivities
  - Br($\mu\to e\gamma$) < $1.2\cdot10^{-11}$($10^{-13}$, MEG@PSI)
  - Br($\tau\to\mu\gamma$) < $3.1\cdot10^{-7}$ ($10^{-8}$, LHC?)
  - Br($\tau\to e\gamma$) < $3.7\cdot10^{-7}$
  - $\mu\to eee$, $\mu$-$e$ conversion in nuclei, etc.
- SUSY Seesaw: Br($l_i\to l_j\gamma$)

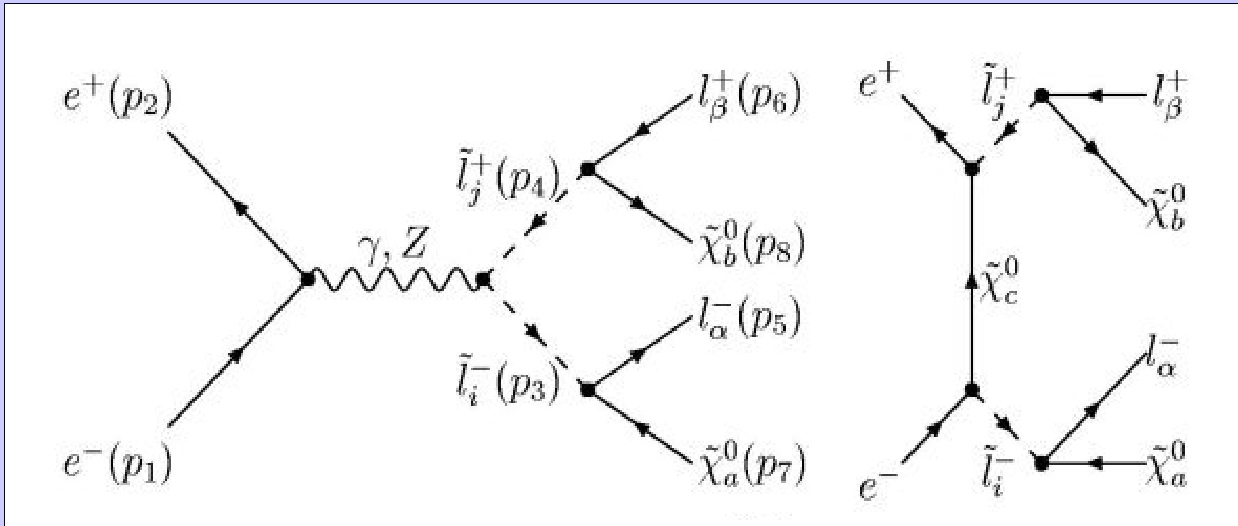



$$Br(l_i\to l_j\gamma)\approx\frac{\alpha^3\tan^2\beta}{\tilde{m}^8}\frac{m_{l_i}^5}{\Gamma_{l_i}}\left|\left(\delta m_{\tilde{L}}^2\right)_{ij}\right|^2\propto\left(Y_\nu^+LY_\nu\right)_{ij}^2$$

# LFV at the ILC

## Process

- Slepton-pair production at $e^+e^-$ collider (Krasnikov, Arkani-Hamed et al.)

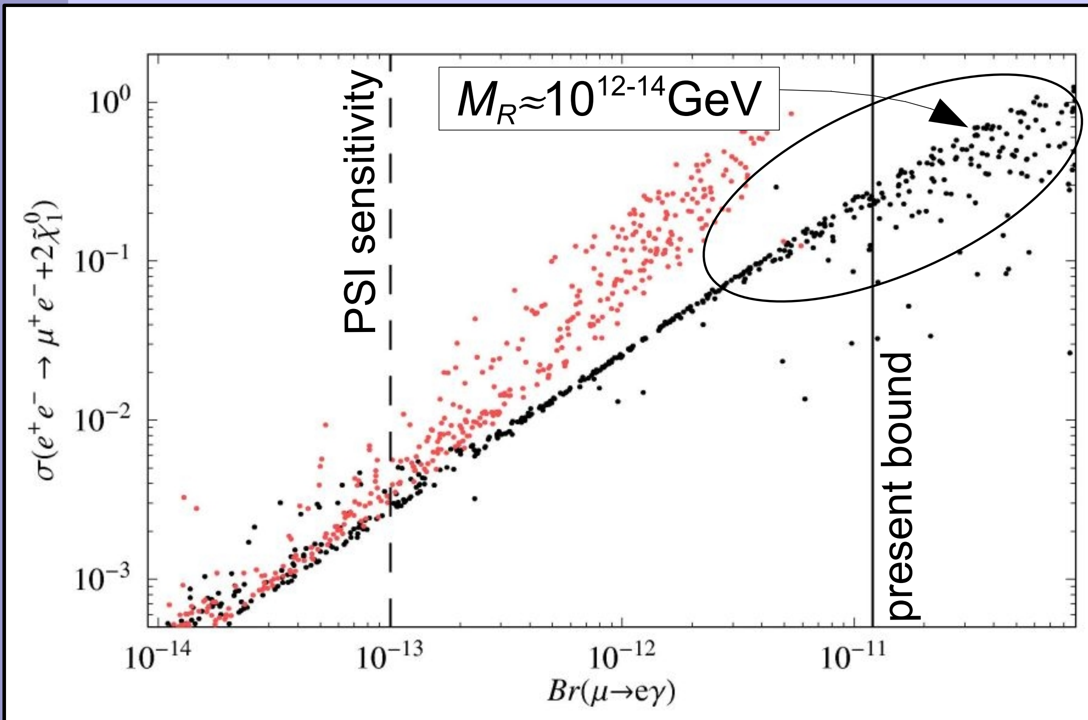



$$\sigma(e^+ e^- \to l_i^- l_j^+ + 2\tilde{\chi}_1^0) \propto \frac{\left|\left(\delta m_{\tilde{L}}^2\right)_{ij}\right|^2}{m_{\tilde{l}}^2 \Gamma_{\tilde{l}}^2} \sigma(e^+ e^- \to l_i^- l_i^+ + 2\tilde{\chi}_1^0)$$

Main background: $W^+W^-$ production
1fb signal $\to$ $5\sigma$ effect
(SPS1a, $L$=500fb$^{-1}$, Martyn et al.)

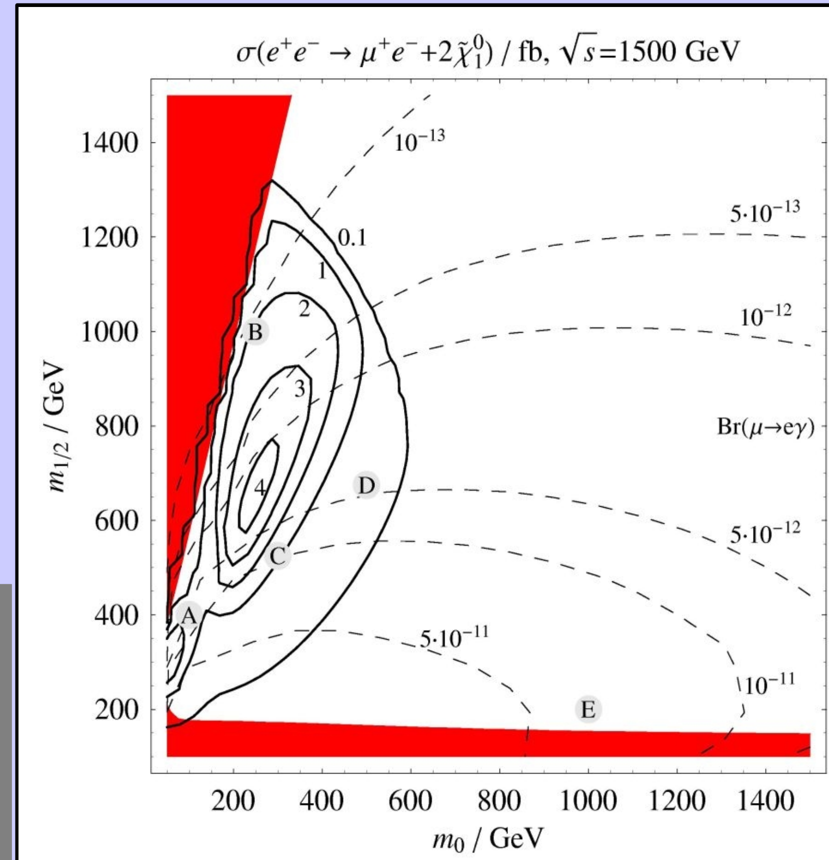
# LFV at the ILC

## Model parameter variation




Correlation with $Br(\mu \to e\gamma)$

- Fixed mSUGRA scenario: SPS1a
- Variation of neutrino parameters, **hier** and **deg** light neutrinos, deg heavy neutrinos




Comparing sensitivity reach

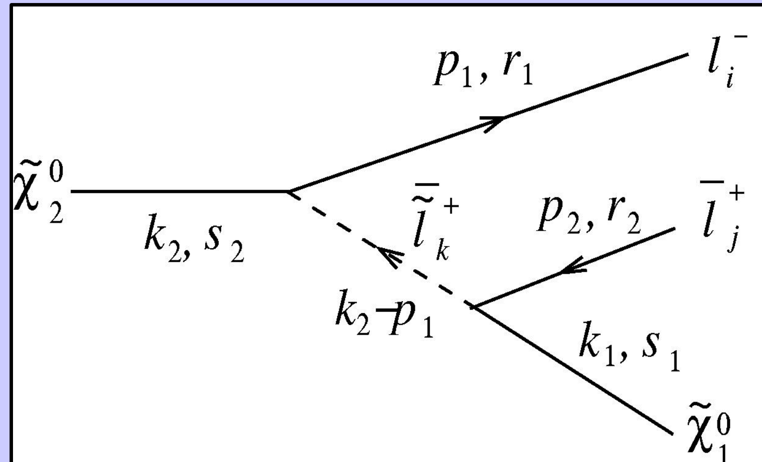
- Fixed neutrino parameters: hierarchical light, degenerate heavy: $M_R = 10^{14}$ GeV
- Variation of $m_{1/2}$, $m_0$ ($A_0 = 0$, $\tan\beta = 10$, sign$\mu$ = +)

# LFV at the LHC

## Process

- Squark and gluino production followed by cascade decays via neutralinos and sleptons (Agashe/Graesser, Hisano et al., Bartl et al.)

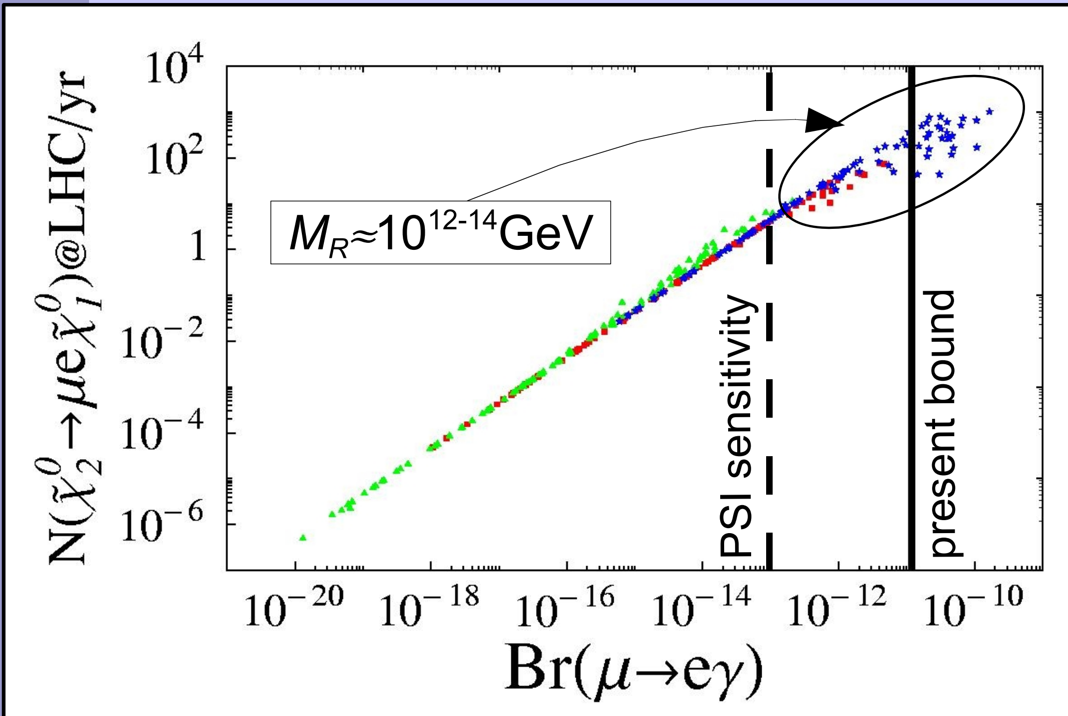
$$pp \to \tilde{q}\,\tilde{q}\,,\ \tilde{g}\,\tilde{q}\,,\ \tilde{g}\,\tilde{g}$$
$$\tilde{q} \to \tilde{\chi}^0_2\, q$$
$$\tilde{g} \to \tilde{\chi}^0_2\, g$$
$$\tilde{\chi}^0_2 \to l_i^-\, l_j^+\, \tilde{\chi}^0_1$$




$$Br(\tilde{\chi}^0_2 \to l_i^-\, l_j^+\, \tilde{\chi}^0_1) \propto \frac{\left|\left(\delta\, m^2_{\tilde{L}}\right)_{ij}\right|^2}{m^2_{\tilde{l}}\, \Gamma^2_{\tilde{l}}}\, Br(\tilde{\chi}^0_2 \to l_i^-\, l_i^+\, \tilde{\chi}^0_1)$$

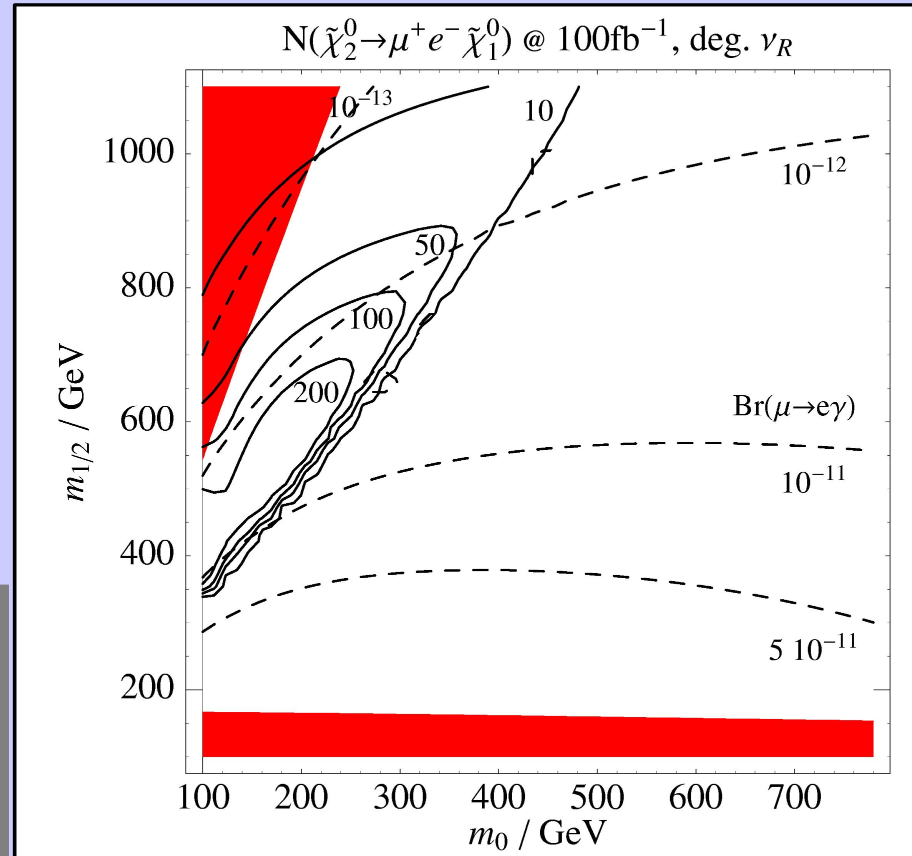
# LFV at the LHC

## Model parameter variation




Correlation with Br($\mu \to e\gamma$)

- Fixed mSUGRA scenario: SPS1a
- Variation of neutrino parameters, **deg L/R**, **hier L/R** and **hier L/deg R** neutrinos




Comparing sensitivity reach

- Fixed neutrino parameters: hierarchical light, degenerate heavy: $M_R = 10^{14}$ GeV
- Variation of $m_{1/2}$, $m_0$ ($A_0 = 0$, $\tan\beta = 10$, sign$\mu = +$)

# Conclusion

- SUSY Seesaw induces charged LFV processes
  - Rare decays, e.g. $Br(\mu \to e\gamma)$
  - Slepton pair production at the ILC
  - Decays of second lightest neutralino at the LHC
- Strong correlations among different processes
  - Allowing predictions
  - In general: $\mu \to e\gamma$ has superior sensitivity,
    Colliders can be superior in large $m_{1/2}$ – small $m_0$ region
  - Colliders provide more information:
    slepton masses, LFV in left- or right-handed slepton sector
- Determination of model parameters
  - e.g. $Br(\mu \to e\gamma) = 10^{-11} \Rightarrow M_R \approx 10^{12\text{-}14}$ GeV