Lepton Flavor Violation at the LHC

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Overview

- Supersymmetry
- Neutrino Physics
- Seesaw Mechanism
- Low Energy Experiments
- LHC Signals
- Outlook: Slepton mass measurements at ILC
- Conclusion

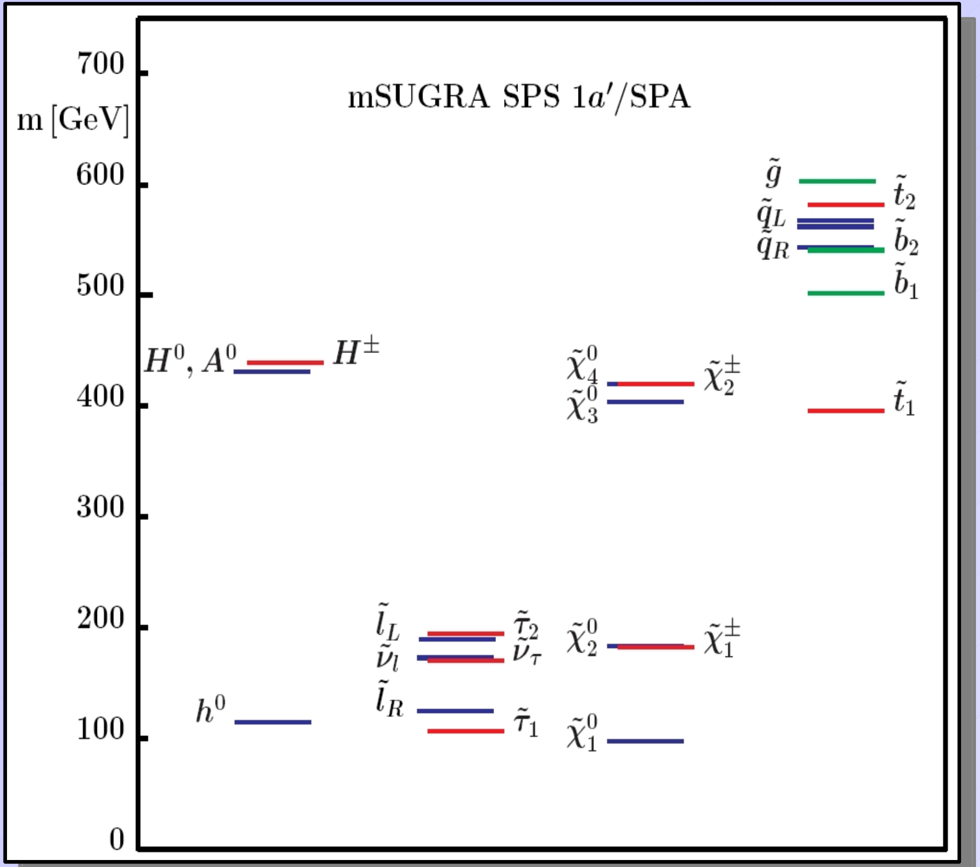
mSUGRA

MSSM

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

mSUGRA

- Theoretical framework for SUSY breaking
- Universality at M_{GUT}
- No FCNC / CP Violation
- 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
  - signμ sign of Higgs mixing
- SUSY particle spectrum generated by RG running



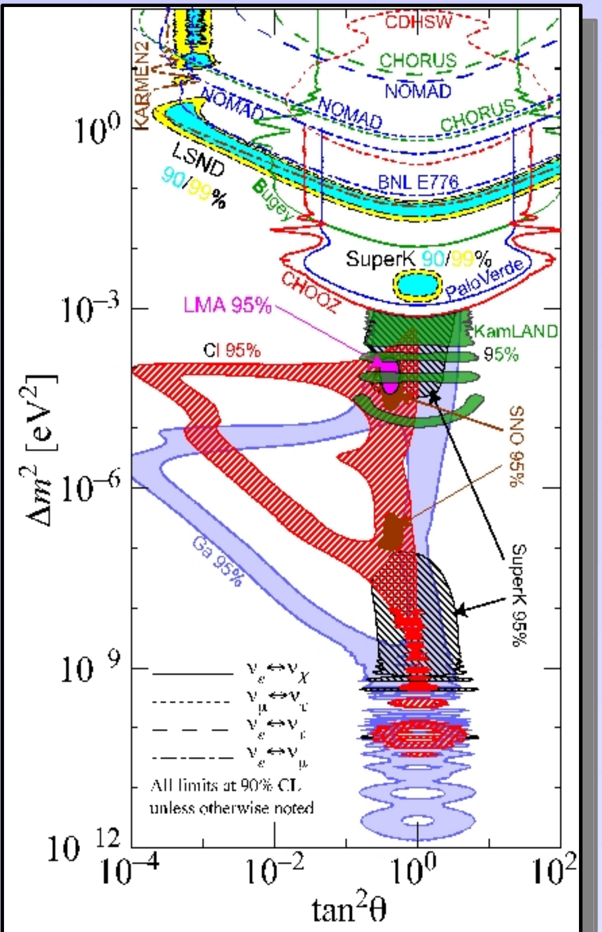
Scenario SPS1a':
m_0 = 100 GeV, $m_{1/2}$ = 250 GeV,
A_0 = -100 GeV, $\tan\beta$ = 10, signμ = +

Neutrinos

- Experimental observation of neutrino flavor oscillations
- $\Rightarrow$ Neutrinos have masses and neutrino flavor is violated

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

$$U = \begin{pmatrix} c_{13} c_{12} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - s_{23} s_{13} c_{12} & c_{23} c_{12} - s_{23} s_{13} s_{12} & s_{23} c_{13} \\ s_{23} s_{12} - s_{13} c_{23} c_{12} & -s_{23} c_{12} - s_{13} s_{12} c_{23} & c_{23} c_{13} \end{pmatrix} \times diag\left(e^{i\phi_1}, e^{i\phi_2}, 1\right)$$



- Measured mixing angles and mass differences

$$\sin^2\theta_{12} = 0.30^{+0.04}_{-0.05}, \sin^2\theta_{23} = 0.50^{+0.14}_{-0.12}, \sin^2\theta_{13} = 0.000^{+0.028}_{-0.000},$$
$$\Delta m^2_{12} = \left(8.1^{+0.6}_{-0.6}\right)\cdot 10^{-5}\,\mathrm{eV}^2, \Delta m^2_{13} = \left(2.2^{+0.7}_{-0.5}\right)\cdot 10^{-3}\,\mathrm{eV}^2$$

$\Rightarrow$ Nearly bi-maximal mixing $\neq$ Quark mixing

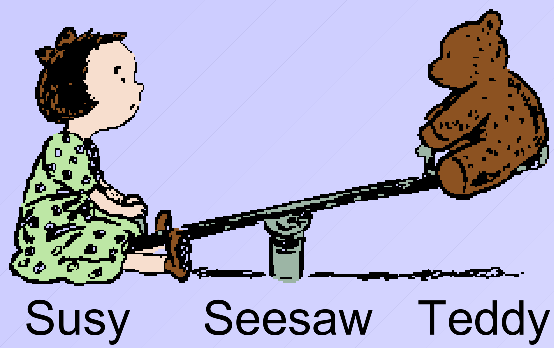
- Absolute neutrino mass $m_{\nu_1} = 0\ldots0.5\,\mathrm{eV}$ (Cosmology, $0\nu\beta\beta$)
  $\Rightarrow$ much lighter than other fermions

SUSY Seesaw

Mechanism

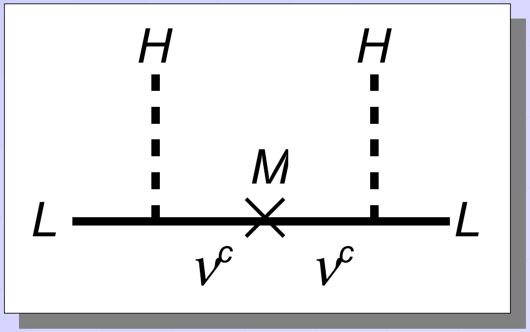
- Add right-handed neutrinos to (MS)SM particle content, Seesaw Type I:

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



- 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

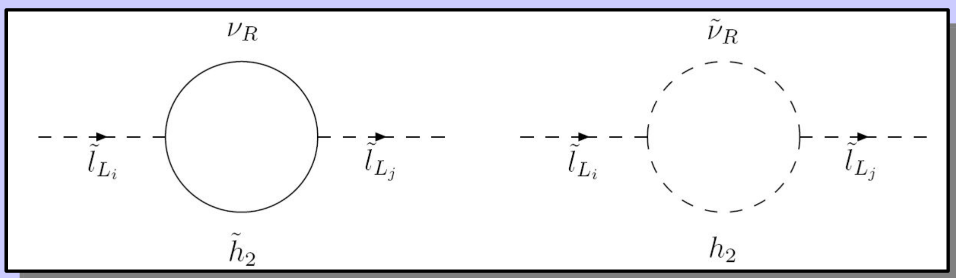
$$m_\nu = m_D^T M^{-1} m_D \quad \text{for} \quad m_D \ll M_R \qquad m_\nu \approx 0.1\,\mathrm{eV} \left(\frac{m_D}{100\,\mathrm{GeV}} \right)^2 \left(\frac{M_R}{10^{14}\,\mathrm{GeV}} \right)^{-1}$$

Non-SUSY Seesaw

- Ch. LFV is extremely suppressed by tiny ν masses, e.g. Br($\mu \to e\gamma$) = 10^{-34}

SUSY Seesaw

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



Slepton mass matrix (6x6)

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

- Correlation between slepton and neutrino flavor mixing

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

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

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

Charged LFV

Additional observables lifting ambiguities in the neutrino sector, see e.g. Talk by F. Plentinger (Plentinger, Seidl, Winter, arXiv:0707.2379)

Rare LFV Decays

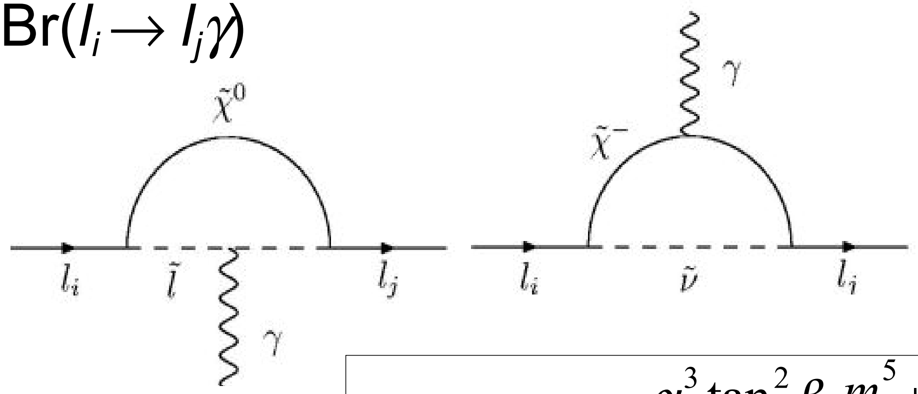
- Current bounds and future sensitivities

Process	Current bound		Future sensitivity	
$Br(\mu \to e\gamma)$	$< 1.2 \cdot 10^{-11}$	(MEGA)	10^{-13} (MEG)	
$Br(\tau \to \mu\gamma)$	$< 3.1 \cdot 10^{-7}$	(Belle)	10^{-8} (Super-B Factory, LHC?)	
$Br(\tau \to e\gamma)$	$< 3.7 \cdot 10^{-7}$	(BaBar)	10^{-8} (Super-B Factory)	
$R(\mu N \to e N)$	$< 7 \cdot 10^{-13}$	(Sindrum)	10^{-18} (PRIME)	($\mu - e$ conversion in nuclei)

- $\mu \to 3e$, $\tau \to 3\mu$ (LHC), etc.

- SUSY Seesaw

$Br(l_i \to l_j \gamma)$



$$Br(\mu \to e\gamma) \approx \frac{\alpha^3 \tan^2\beta}{\tilde{m}^8} \frac{m_\mu^5}{\Gamma_\mu} \left| \left(\delta m_{\tilde{L}}^2 \right)_{12} \right|^2 \propto \left(Y_\nu^+ L Y_\nu \right)_{12}^2$$

LFV at the LHC

Process

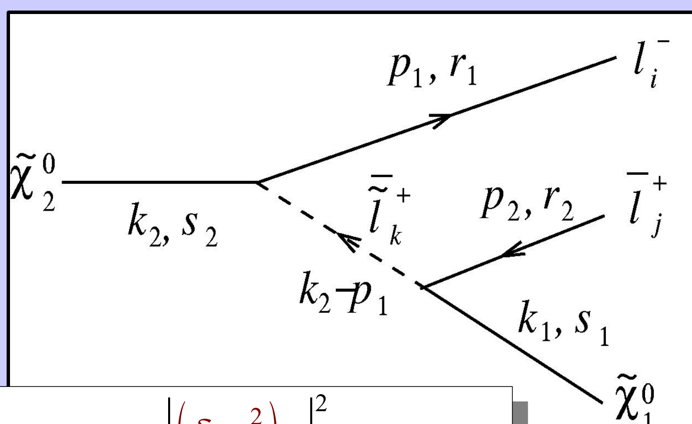
- Squark and gluino production

$$pp \to \tilde{q}\,\tilde{q}\,,\,\tilde{g}\,\tilde{q}\,,\,\tilde{g}\,\tilde{g}$$

- ... followed by cascade decays via second lightest neutralino

$$\tilde{q}(\tilde{g}) \to \tilde{\chi}_2^0\, q(g)$$

- ... followed by LFV decay via sleptons (Agashe/Graesser, Hisano et al., Bartl et al.)

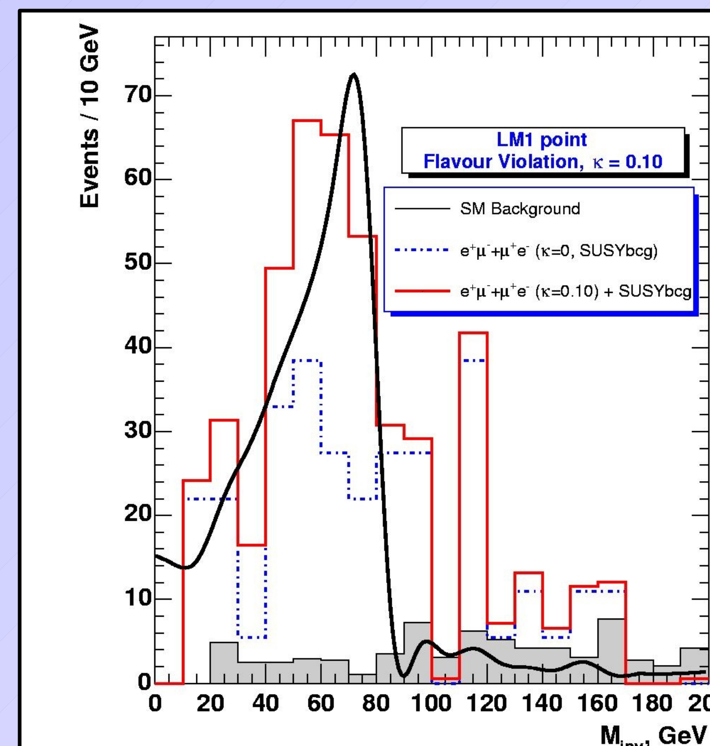


$$Br(\tilde{\chi}_2^0 \to \mu^- e^+ \tilde{\chi}_1^0) \propto \frac{\left|\left(\delta m_{\tilde{L}}^2\right)_{12}\right|^2}{m_{\tilde{l}}^2 \Gamma_{\tilde{l}}^2} Br(LFC)$$

- Possible signal signatures

$$pp \to l_i l_j + 2j + E_T^{\text{miss}}$$
$$l_i l_j + 3j + E_T^{\text{miss}}$$
$$l_i l_j l_k l_k + 2j + E_T^{\text{miss}}$$

- Exploit edge structure of signal invariant mass distribution

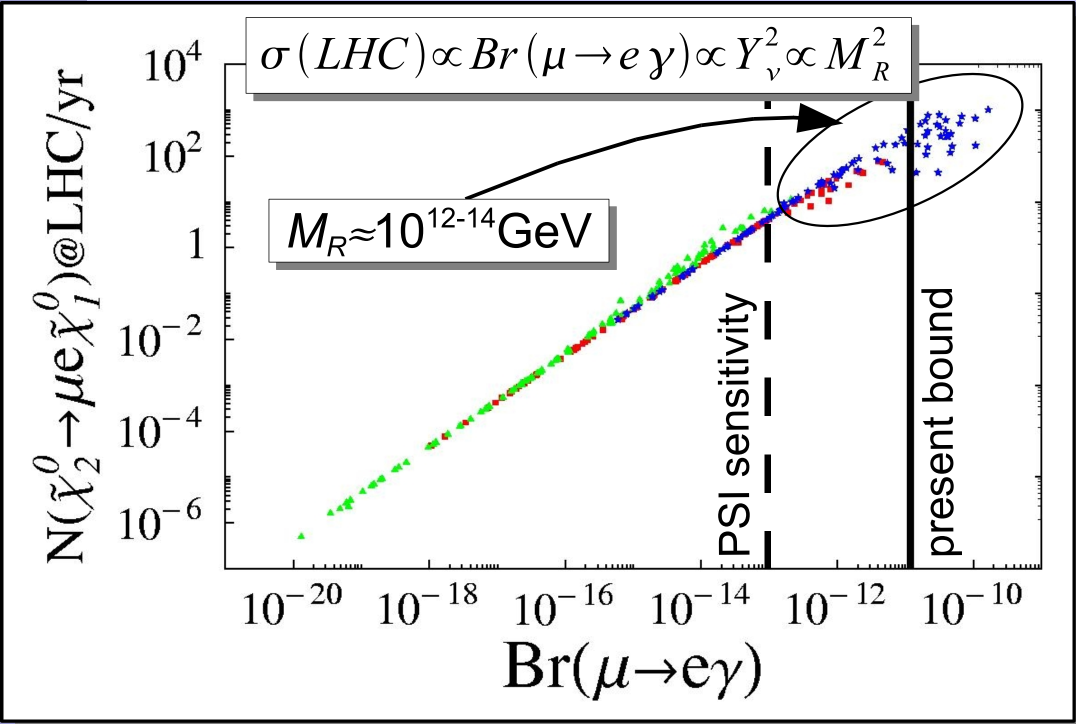


Andreev et al, hep-ph/0608176

- Rough estimate:

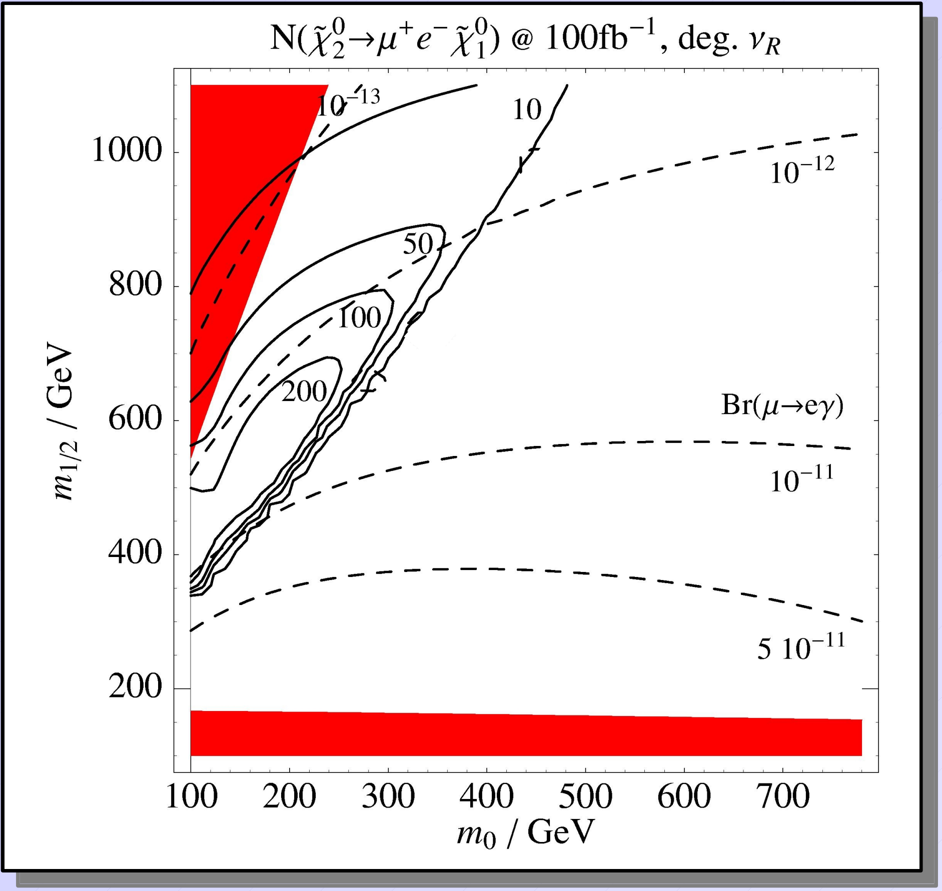
$$N(\tilde{\chi}_2^0 \to \mu\, e\, \tilde{\chi}_1^0) = 200 \;\Rightarrow\; 5\sigma\, @\, L = 100\,\text{fb}^{-1}$$

Results



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

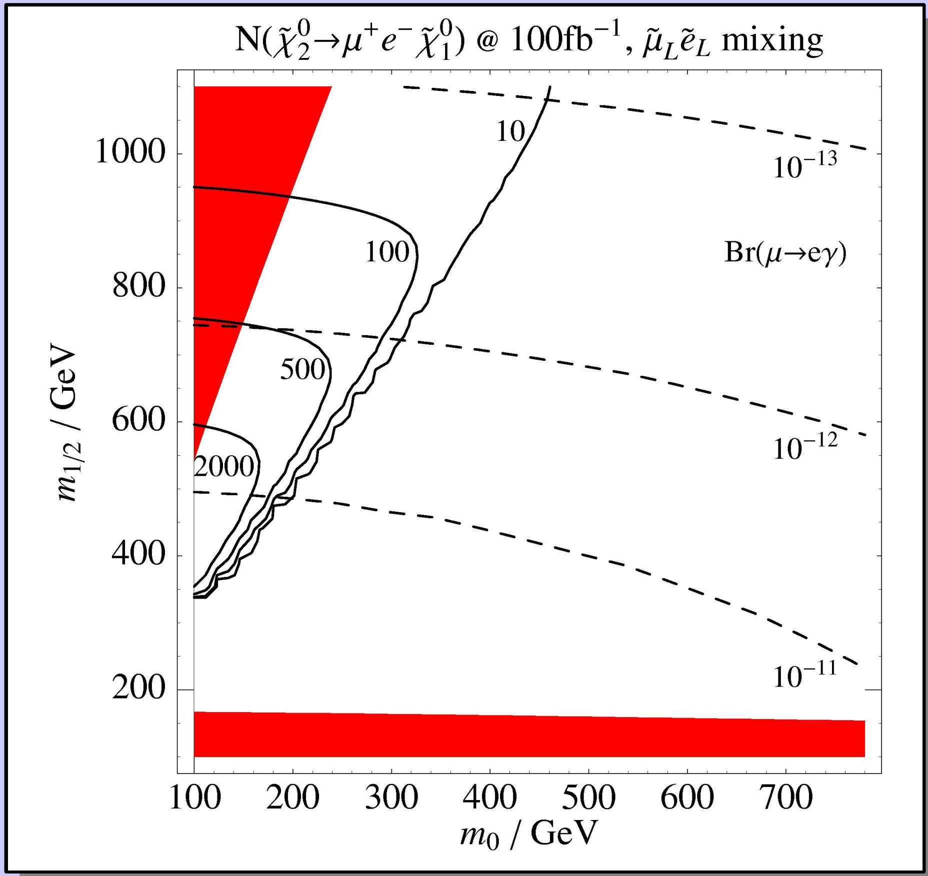


Comparing sensitivity reach

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

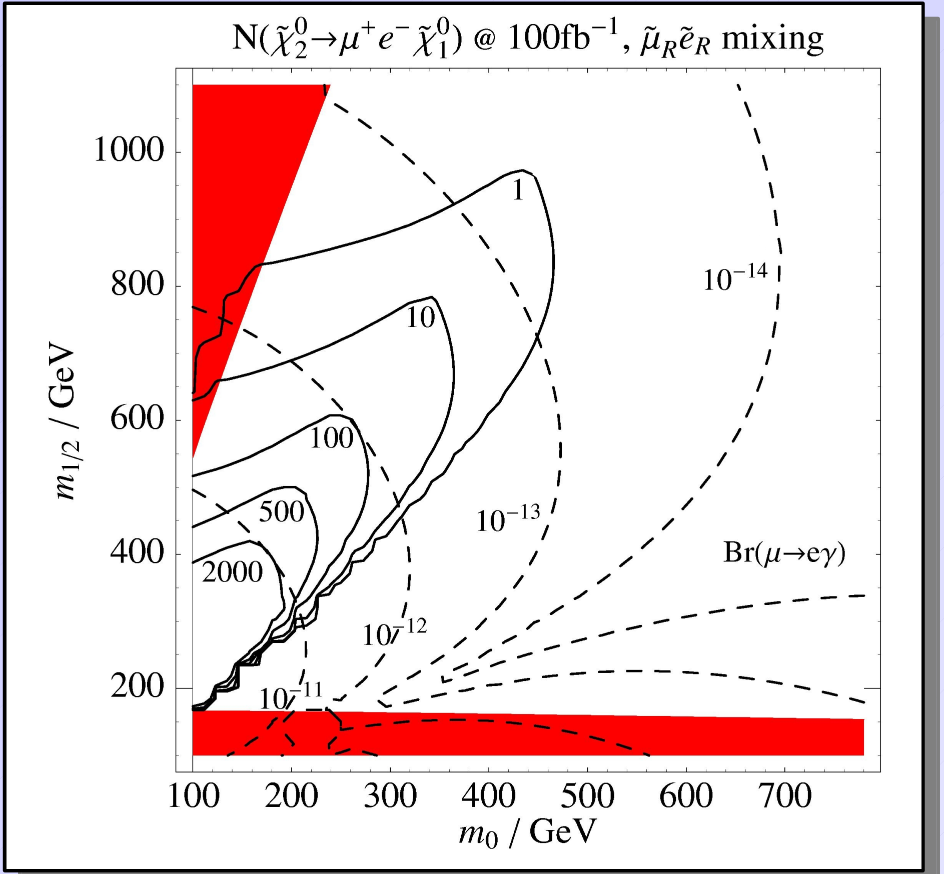
LFV at the LHC

General Slepton Mixing (2 Flavor)



Maximal left-handed slepton mixing

$$\begin{pmatrix}\tilde l_1\\ \tilde l_2\end{pmatrix} = \begin{pmatrix} c_{\theta_L} & s_{\theta_L} \\ -s_{\theta_L} & c_{\theta_L}\end{pmatrix} \cdot \begin{pmatrix}\tilde e_L \\ \tilde\mu_L\end{pmatrix}, \theta_L = \frac{\pi}{4}, \Delta\tilde m = 1\,\text{GeV}$$



Maximal right-handed slepton mixing

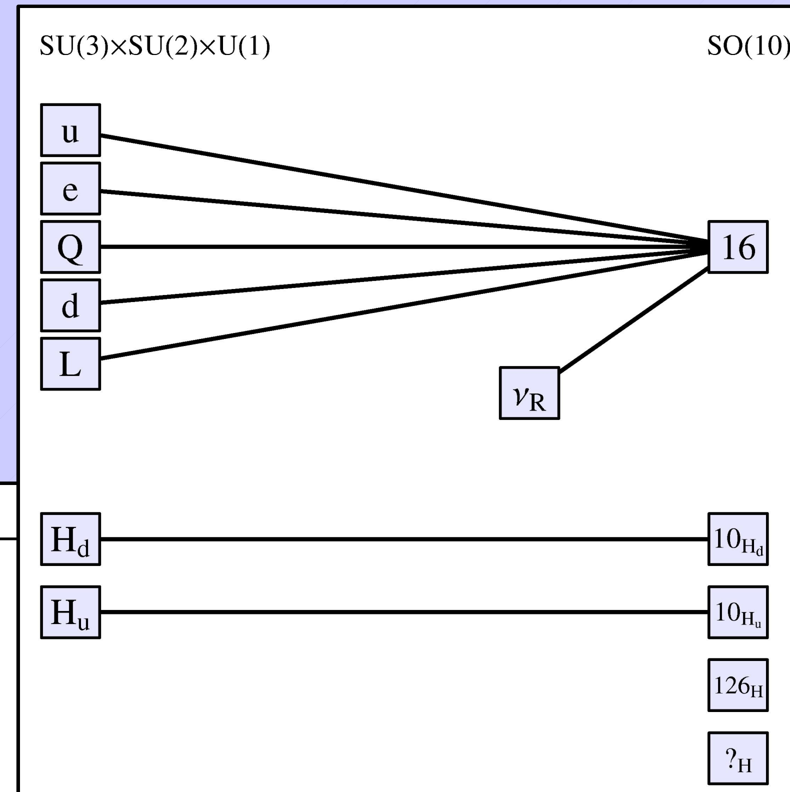
$$\theta_R = \frac{\pi}{4}, \Delta\tilde m = 1\,\text{GeV}$$

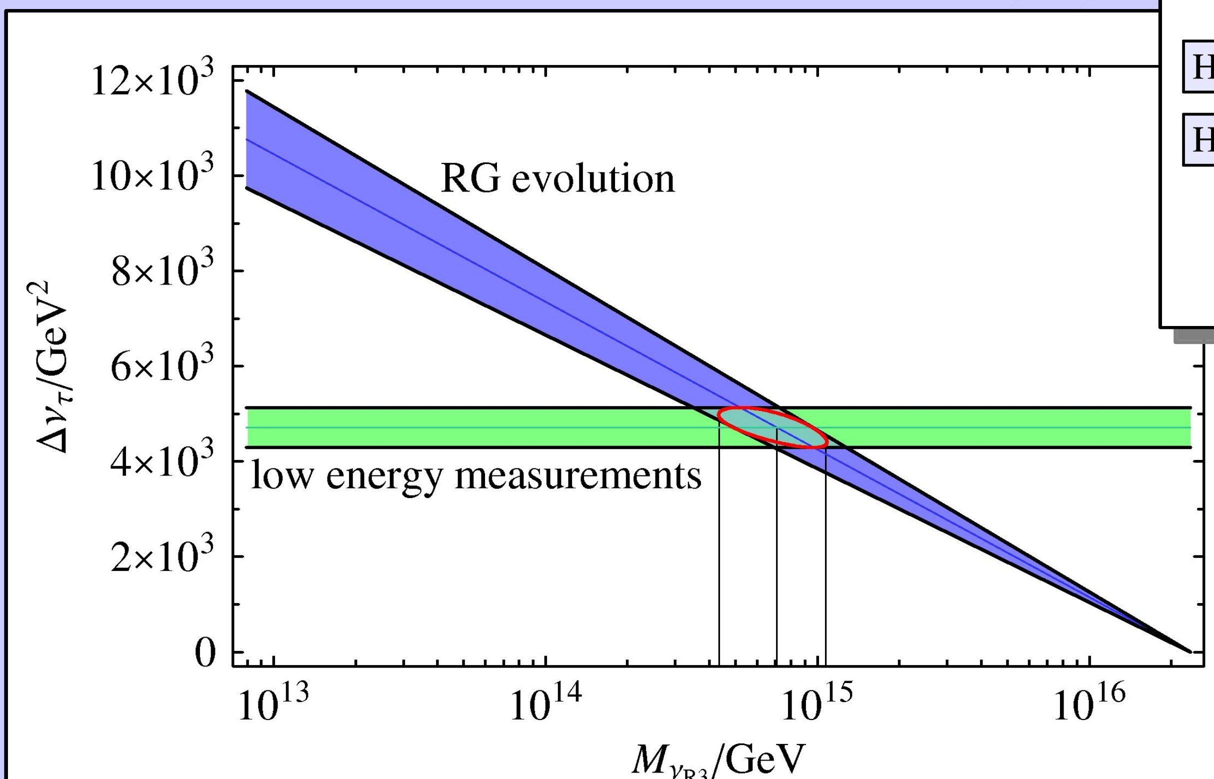
Outlook: Determination of $M_{\nu R3}$ and $m_{\nu 1}$ at ILC

- SUSY Seesaw Loops also generate a shift in third generation L-slepton mass

$$\Delta_{\nu_\tau} \approx \frac{m_t^2(\Lambda_U)}{4\pi^2 v_u^2}(3m_{16}^2 + A_0^2)\log\frac{\Lambda_U^2}{M_{\nu_{R3}}^2}$$

- Precision mass measurements at ILC in a SUSY SO(10) model (FFD, Freitas, Porod, Zerwas)





- Heavy neutrino mass

$$M_{\nu R_3} = 10^{14.9\pm0.2}\,\mathrm{GeV}$$

- Light neutrino mass

$$m_{\nu_1} = 10^{-2.5\pm0.3}\,\mathrm{eV}$$

Conclusion

- SUSY Seesaw induces charged LFV processes
  - Rare decays, e.g. $Br(\mu \to e\gamma)$, and other low energy processes
  - Decays of second lightest neutralino at the LHC
  - Correlations among these processes and neutrino parameters
- Sensitivity comparison
  - Complementary sensitivity of low and high energy processes
  - Radiative processes have higher mass reach
  - Collider provide more information (sparticle masses etc.)
- Determination of model parameters
  - SUSY observables can lift neutrino parameter ambiguities
  - e.g. $Br(\mu \to e\gamma) = 10^{-11}$, N(LHC) = 200 $\Rightarrow M_R \approx 10^{12\text{-}14}$ GeV
  - Implications for SUSY GUT Models