SUSY Seesaw and LFV in the Era of the LHC

MANCHESTER 1824

The University of Manchester

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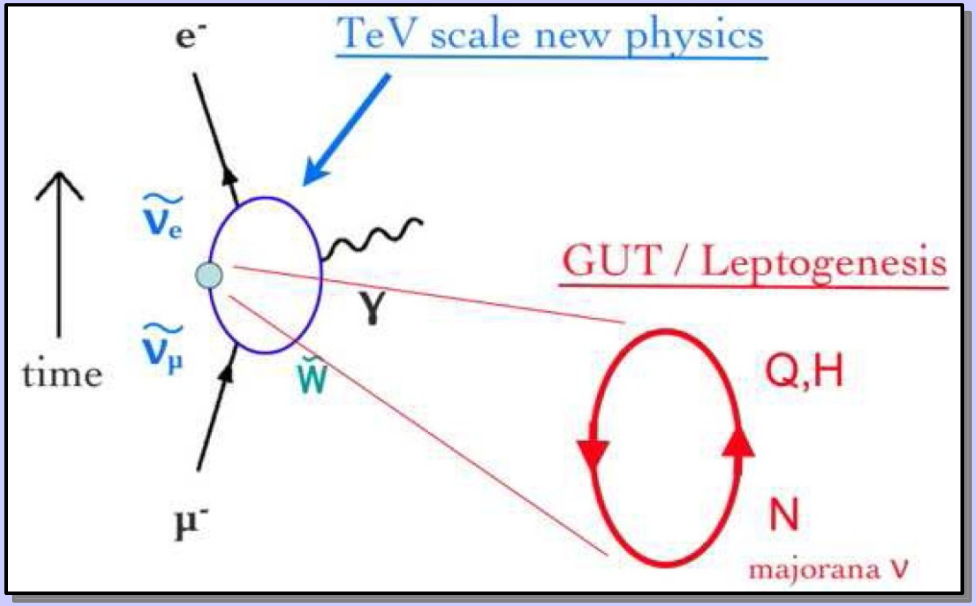
Overview

- **Introduction**
  - Lepton Flavor Violation
  - Supersymmetry
  - Neutrino Physics
- **SUSY Seesaw**
  - Mechanism
  - Rare LFV Processes
- **LFV Signals at LHC**
- **Precision Slepton Mass Measurements**
- **Conclusion**

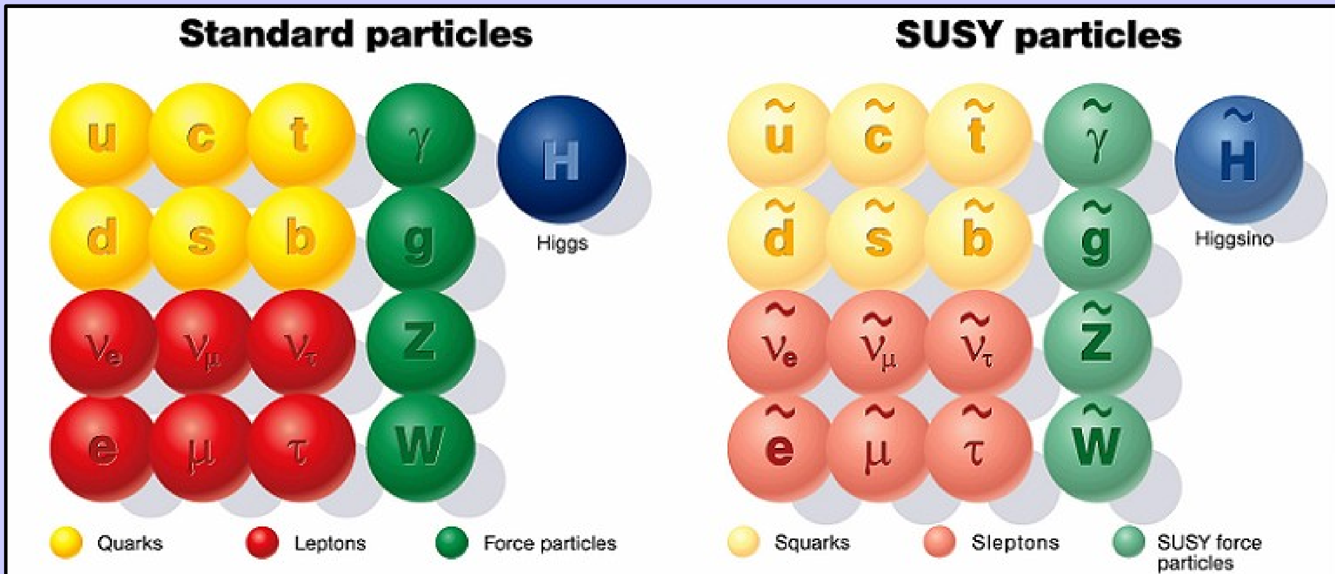
Lepton Flavor Violation

- **Lepton Flavor conserved in the Standard Model**
  ⇒ LFV is clear sign for BSM physics
- **Flavor Violation in quark and neutrino sector**
  ⇒ Strong case to look for charged LFV
- **LFV can shed light on**
  - Grand Unification Models, Connection to quark flavor violation
  - Flavor Symmetries
  - Origin of Flavor
- **Existing experimental bounds are stringent and will be improved in the near future**

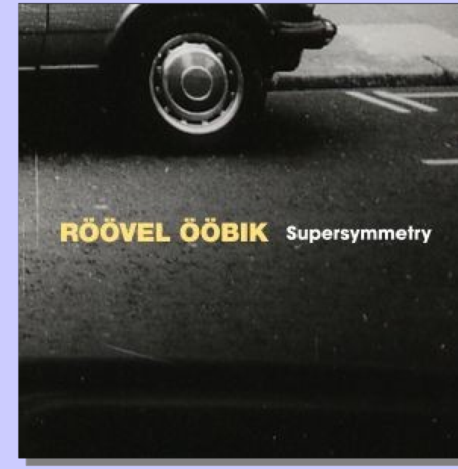


Supersymmetry

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



http://www.physics.gla.ac.uk/ppt/susy.htm



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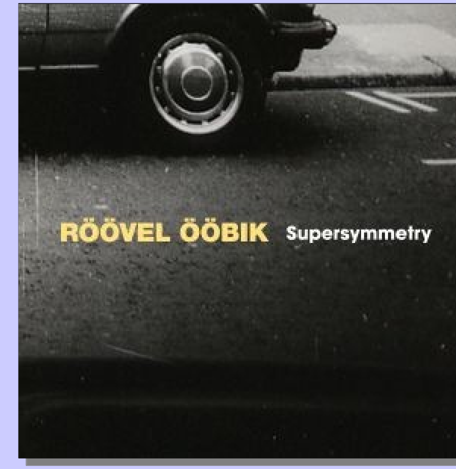
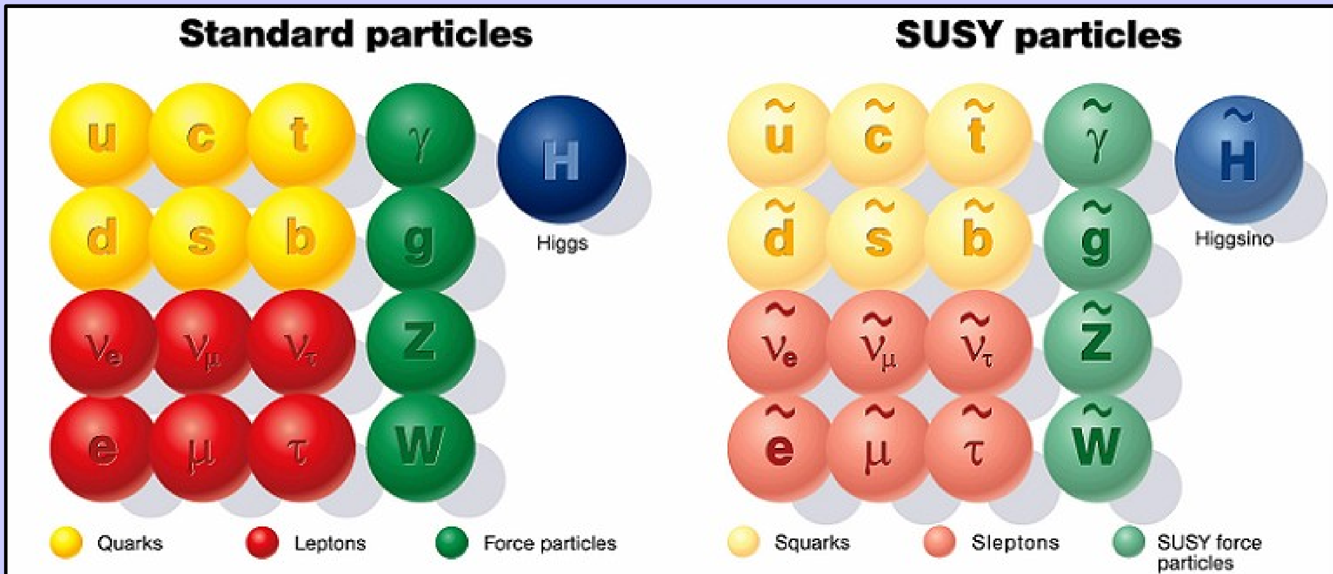




http://www.physics.gla.ac.uk/ppt/susy.htm

SUSY must be broken

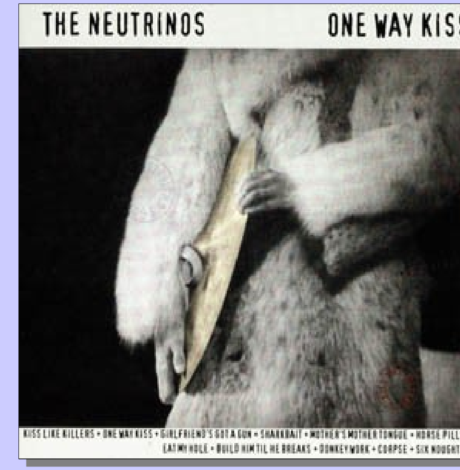
⇒ In general: Introduction of more than 100 free parameters

⇒ Required: Theoretical framework for SUSY breaking

⇒ **Minimal Supergravity (mSUGRA), Universality at GUT Scale**

Neutrinos

Oscillations



- **Standard Model: neutrinos are massless**
- **Neutrino Oscillations**

  $\Rightarrow$ Neutrinos have masses and flavors mix

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

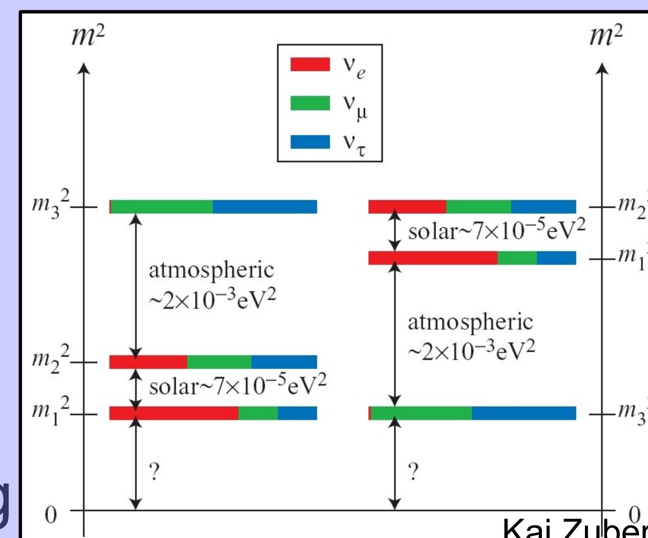
$$U = \begin{pmatrix} c_{13} c_{12} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - s_{23} s_{13} c_{12} & c_{23} c_{12} - s_{23} s_{13} s_{12} & s_{23} c_{13} \\ s_{23} s_{12} - s_{13} c_{23} c_{12} & -s_{23} c_{12} - s_{13} s_{12} c_{23} & c_{23} c_{13} \end{pmatrix} \times diag\left(e^{i\phi_1},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

- **Mixing angles and mass differences**

$$\sin^2\theta_{12} = 0.30^{+0.04}_{-0.05}, \sin^2\theta_{23} = 0.50^{+0.14}_{-0.12}, \sin^2\theta_{13} < 0.028$$

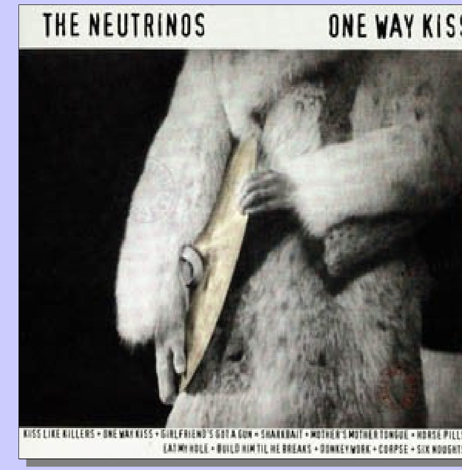
$$\Delta m^2_{12} = \left(8.1^{+0.6}_{-0.6}\right)\cdot 10^{-5}\,\mathrm{eV}^2, \Delta m^2_{13} = \pm\left(2.2^{+0.7}_{-0.5}\right)\cdot 10^{-3}\,\mathrm{eV}^2$$

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

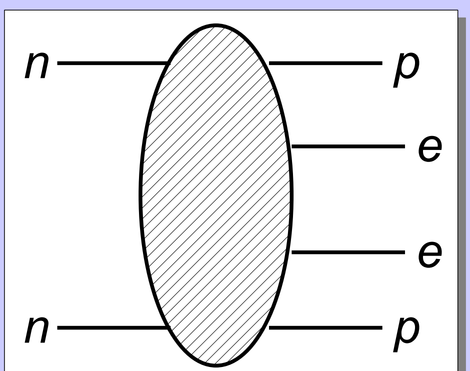


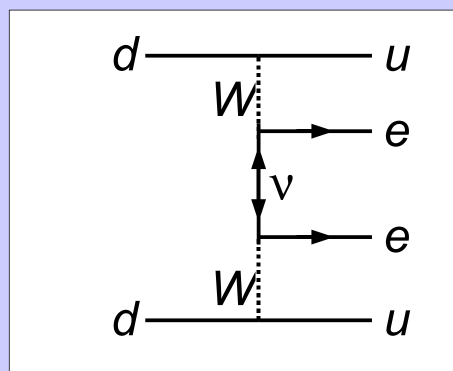
Neutrinos

Absolute Mass Scale

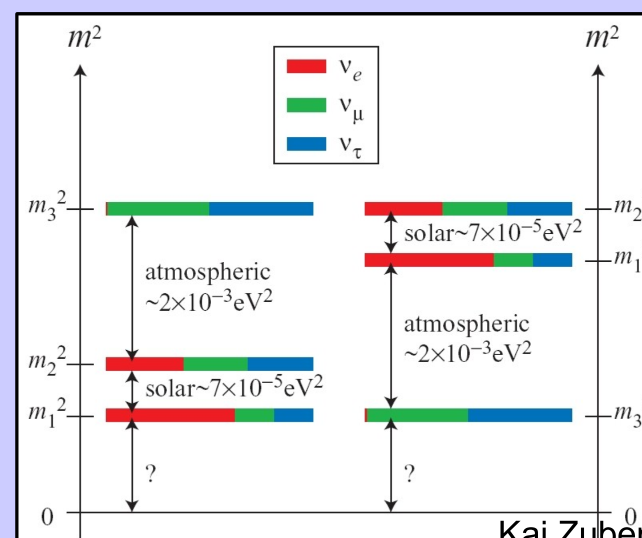


- **Oscillation experiments can not determine absolute neutrino masses**
- **Bounds from**
  - Cosmology (WMAP) $\sum m_{\nu_i} < 2\,\mathrm{eV}$
  - Tritium-Decay Endpoint (KATRIN)
  - Neutrinoless double beta decay (Heidelberg-Moscow, Evidence?)





$$m_{ee} = \sum U_{ei}^2 m_{\nu_i} = (0.24 - 0.58)\,\mathrm{eV}$$



- **Absolute mass scale** $m_{\nu_1} = 0 \ldots 0.5\,\mathrm{eV}$

SUSY Seesaw

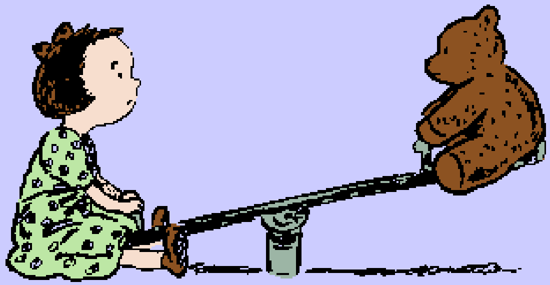
Collaboration with **H. Päs**, **A. Redelbach**, **R. Rückl**
Phys. Rev. D73 (2006) 033004 (hep-ph/0511062)
Phys. Rev. D69 (2004) 054014 (hep-ph/0310053)
Eur. Phys. J. C28 (2003) 365-374 (hep-ph/0206122)

SUSY Seesaw

Mechanism

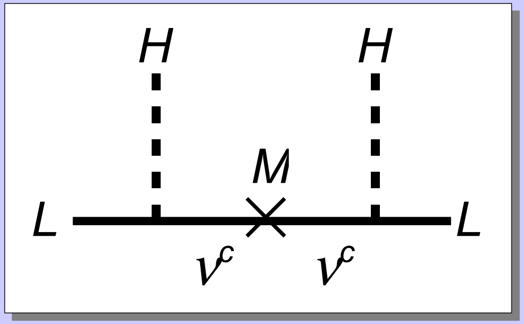
- Add right-handed neutrinos to (MS)SM particle content, Seesaw Type I

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



- 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

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

Seesaw Mechanism

Variations

Seesaw I	Seesaw II	Seesaw III
$\begin{pmatrix}\nu_i\\ e_i\end{pmatrix}, e_i^c, \nu_i^c$	$\begin{pmatrix}\nu_i\\ e_i\end{pmatrix}, e_i^c, \nu_i^c$	$\begin{pmatrix}\nu_i\\ e_i\end{pmatrix}, e_i^c, \nu_i^c, S_i$
$\begin{pmatrix}0 & m_D^T\\ m_D & M_R\end{pmatrix}$	$\begin{pmatrix}m_{LL} & m_D^T\\ m_D & M_R\end{pmatrix}$	$\begin{pmatrix}0 & m_D^T & 0\\ m_D & 0 & M_R^T\\ 0 & M_R & \mu\end{pmatrix}$
$m_D \ll M_R \Rightarrow$ $m_\nu = m_D^T M^{-1} m_D$	$m_D \ll M_R \Rightarrow$ $m_\nu = m_{LL} - m_D^T M^{-1} m_D$	$\mu, m_D \ll M_R \Rightarrow$ $m_\nu = m_D^T M_R^{T-1} \mu M_R^{-1} m_D$
$\frac{m_\nu}{0.1\text{eV}} = \frac{m_D^2}{(100\,GeV)^2} \frac{10^{14}\,GeV}{M_R}$		$\frac{m_\nu}{0.1\text{eV}} = \frac{m_D^2}{(100\,GeV)^2} \frac{\mu}{keV} \frac{(10^4\,GeV)^2}{M_R^2}$

- All three variations can emerge in SO(10) GUT models
- SUSY Seesaw as effective model of neutrino sector

Seesaw without SUSY

- Not testable, only effective light neutrino properties accessible (9 of 18 model parameters)
- Charged LFV is suppressed by tiny neutrino masses

SUSY Seesaw

Sleptons

Seesaw without SUSY

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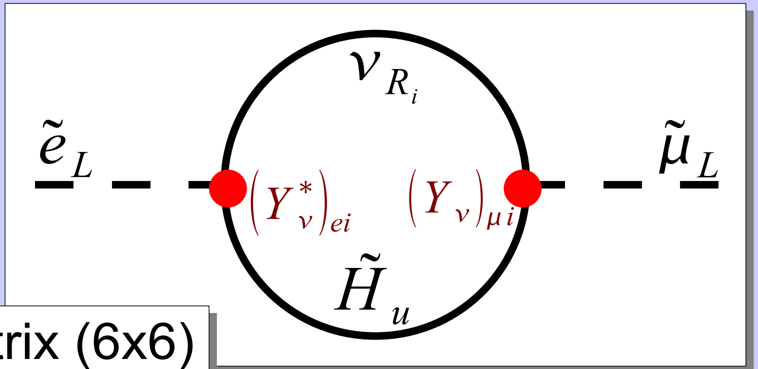
SUSY Seesaw

- Neutrino flavor mixing radiatively induces slepton flavor mixing between M_{GUT} and the right-handed neutrino mass scale
  (Masiero, Borzumati)



Slepton mass matrix (6x6)

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

SUSY Seesaw

Sleptons

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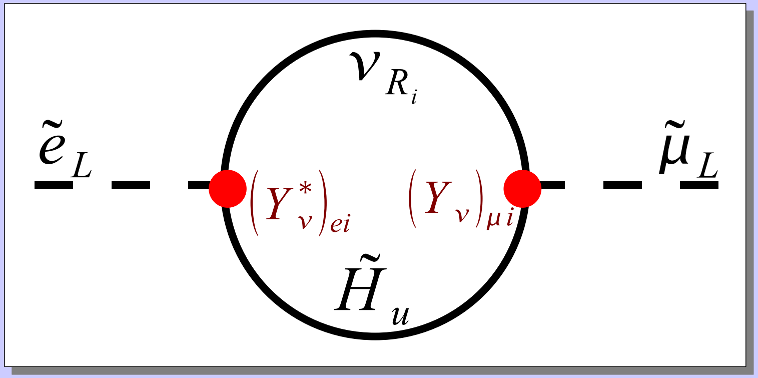

- Correlation between slepton and neutrino flavor mixing

$|\delta_{12}| \Rightarrow Br(\mu \to e\gamma)$, etc.

$$\delta m_{\tilde{L}}^2 = \begin{pmatrix} \delta_{11} & \delta_{12} & \delta_{13} \\ \delta_{12}^* & \delta_{22} & \delta_{23} \\ \delta_{13}^* & \delta_{23}^* & \delta_{33} \end{pmatrix} = \frac{-1}{8\pi^2}(3\mathrm{m}_0^2 + A_0^2) Y_\nu^+ \cdot Y_\nu \log\left(\frac{M_{\mathrm{GUT}}}{M_R}\right)$$

$\Im(\delta_{ij}) \Rightarrow$ EDMs d_e, d_μ

Slepton mass differences (Colliders)

$\Rightarrow$ 9 potential observables

$\Rightarrow$ SUSY Seesaw testable (in principle)

Rare LFV Processes

- **Current bounds** **and future sensitivities**
  - **Br($\mu \to e\gamma$) < $1.2 \cdot 10^{-11}$ (MEGA) 10^{-13} (MEG, 2009)**
  - Br($\tau \to \mu\gamma$) < $6.8 \cdot 10^{-8}$ (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), μ–e conversion in nuclei
  - $\mu \to 3e$, $\tau \to 3\mu$ (LHC), etc.

Rare LFV Processes

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  - **$Br(\mu\to e\gamma)$ < $1.2\cdot10^{-11}$ (MEGA) — 10^{-13} (MEG, 2009)**
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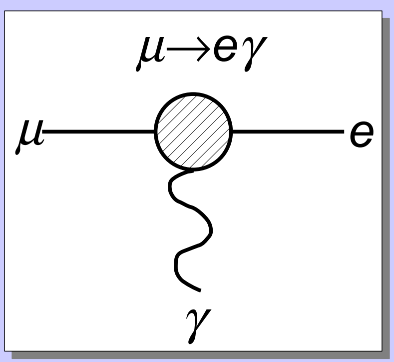
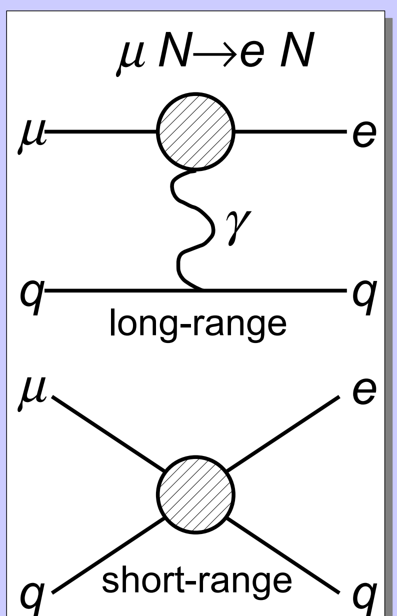
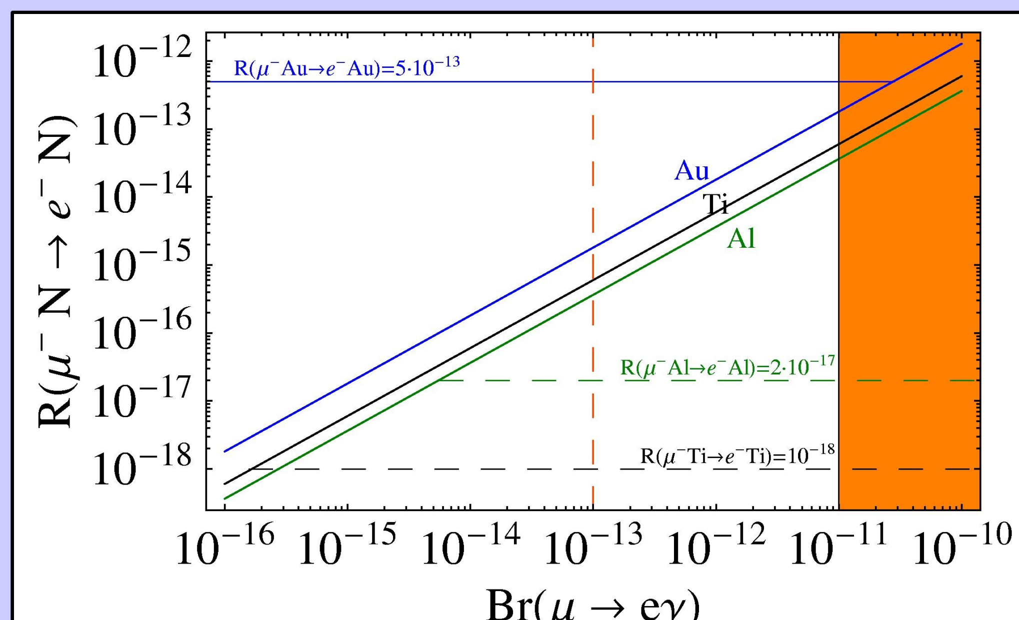
  - $\mu\to3e$, $\tau\to3\mu$ (LHC), etc.
- **SUSY Seesaw: Correlation between processes of same flavor transition**





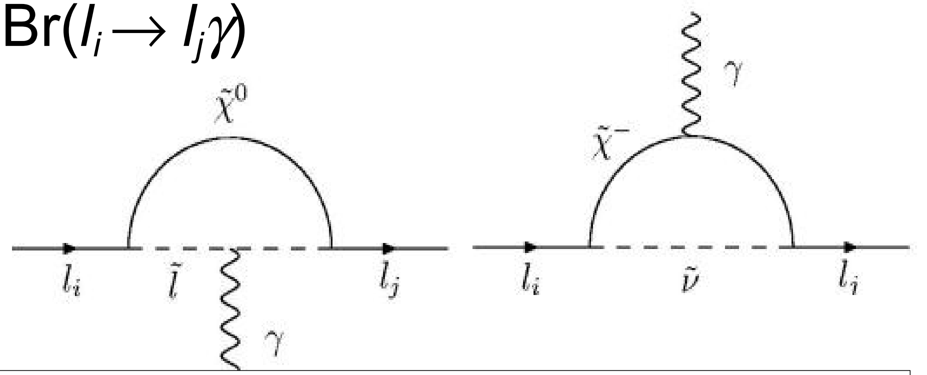


Rare LFV Decays

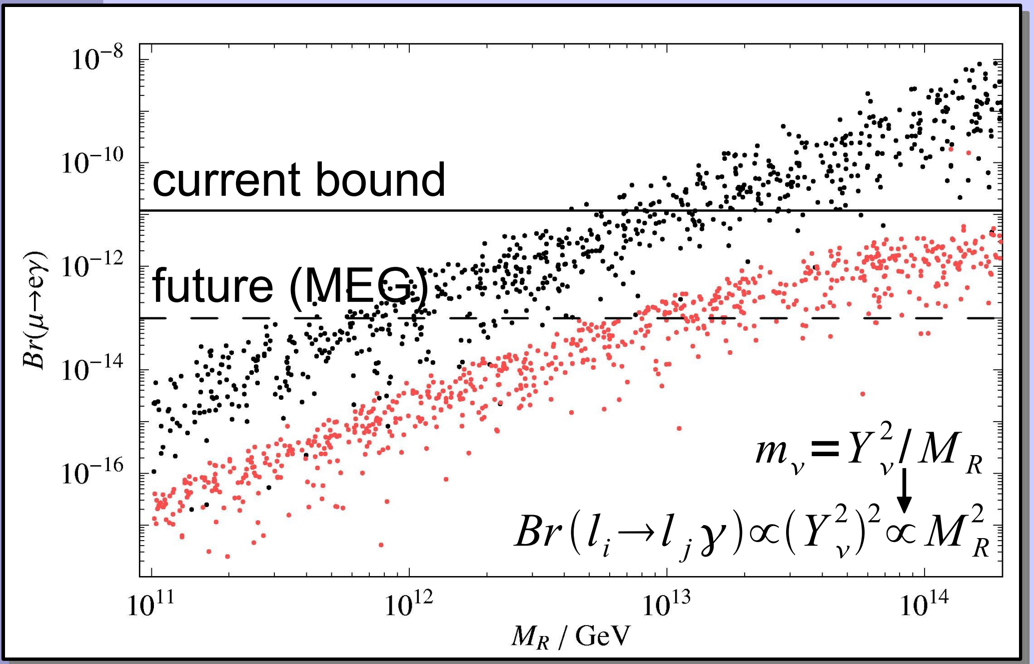
SUSY Seesaw

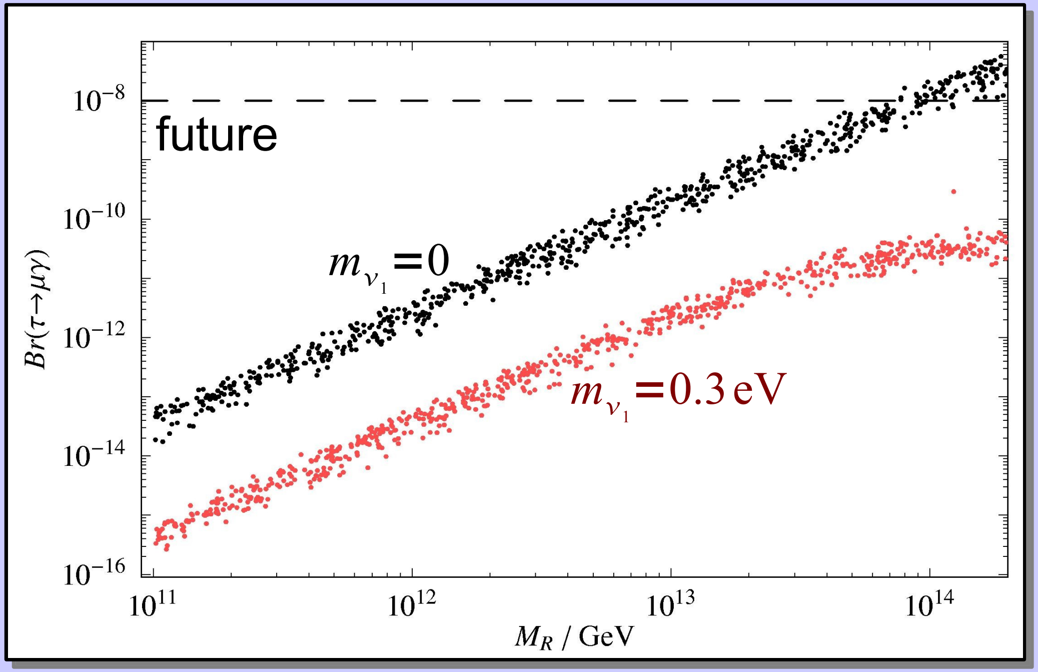
- Scattering of neutrino parameters
- Fixed SUSY scenario SPS1a
- Hierarchical (Degenerate) light neutrinos
- Degenerate heavy neutrinos $M_{\nu i} = M_R$
- Strong dependence with M_R

$Br(l_i \to l_j \gamma)$



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





LFV Signals at LHC

Collaboration with **S. Albino**, **D. Ghosh**, **R. Rückl**
Report of WG3 CERN Workshop 'Flavor in the era of the LHC' (arXiv:0801.1826)
Eur. Phys. J. C46 (2006) 43-60 (hep-ph/0511344)
Phys. Rept. 426 (2006) 47-358 (hep-ph/0410364)

LFV at LHC

LFV Neutralino and Slepton Decays

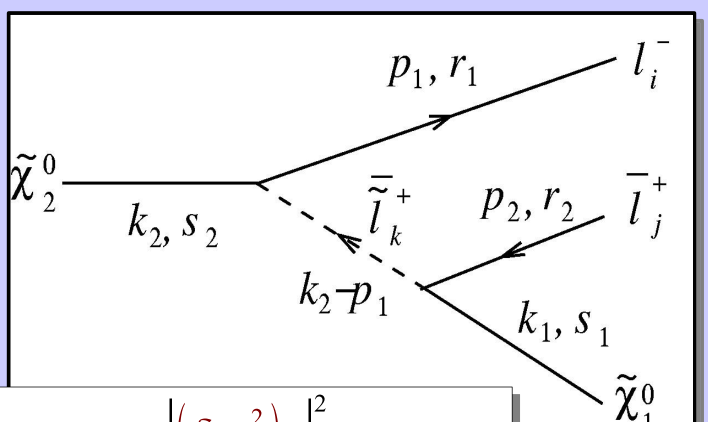
- Squark and gluino production

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

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

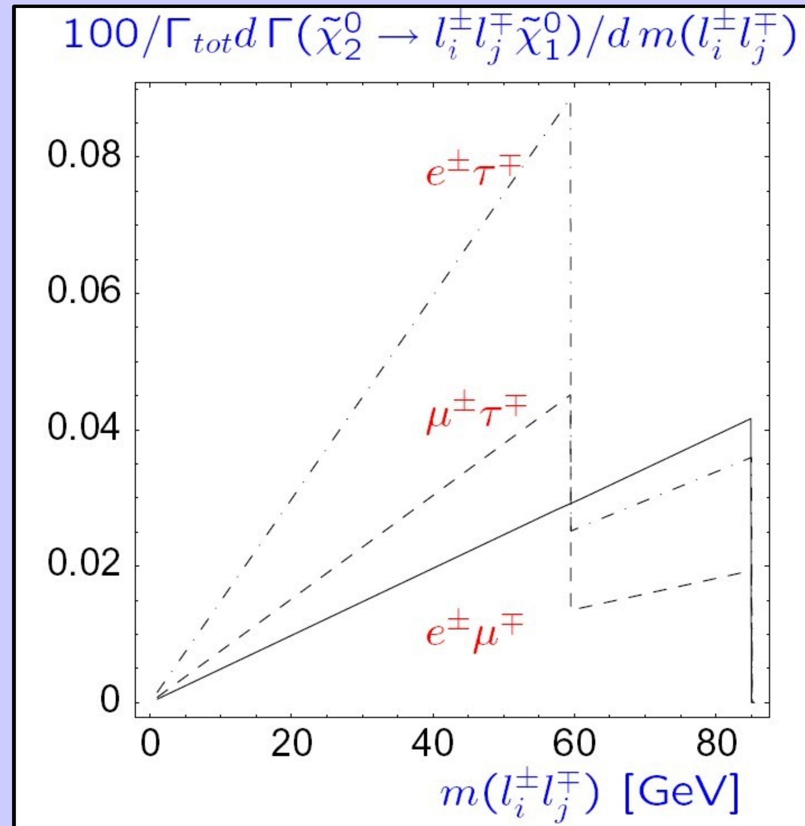
$$\tilde{q}\,(\tilde{g}) \to \tilde{\chi}^0_2\, q\,(g)$$

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



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

- Edge structure of di-lepton invariant mass distribution



Bartl et al, hep-ph/0510074

- Reach

$$Br(\tilde{\chi}^0_2 \to \mu\, e\, \tilde{\chi}^0_1) = 2 - 4\,\%\,,\; L = 30\,\text{fb}^{-1}$$

LFV at the LHC

Signals and Background

- Possible signal signatures

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

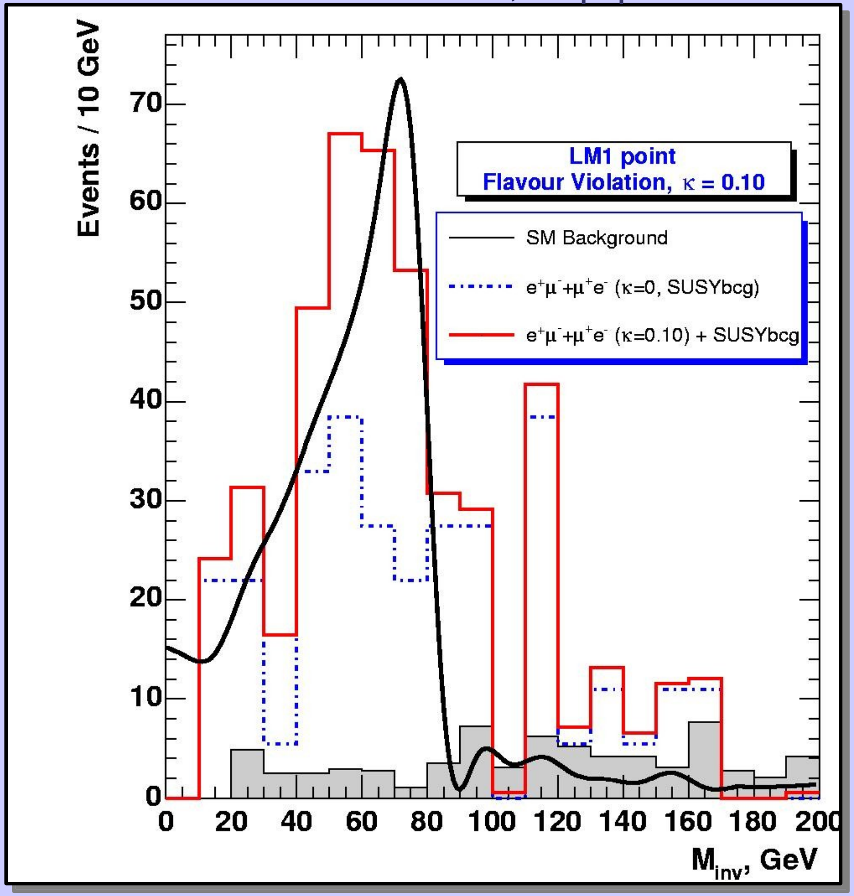
- Exploit edge structure of signal invariant mass distribution

$$\left(m_{\text{inv}}^{\max}(l_i^- l_j^+)\right)^2 = m_{\tilde{\chi}_2^0}^2 \left(1 - \frac{m_{\tilde{l}}^2}{m_{\tilde{\chi}_2^0}^2}\right)\left(1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}}^2}\right)$$

- Sensitivity estimate

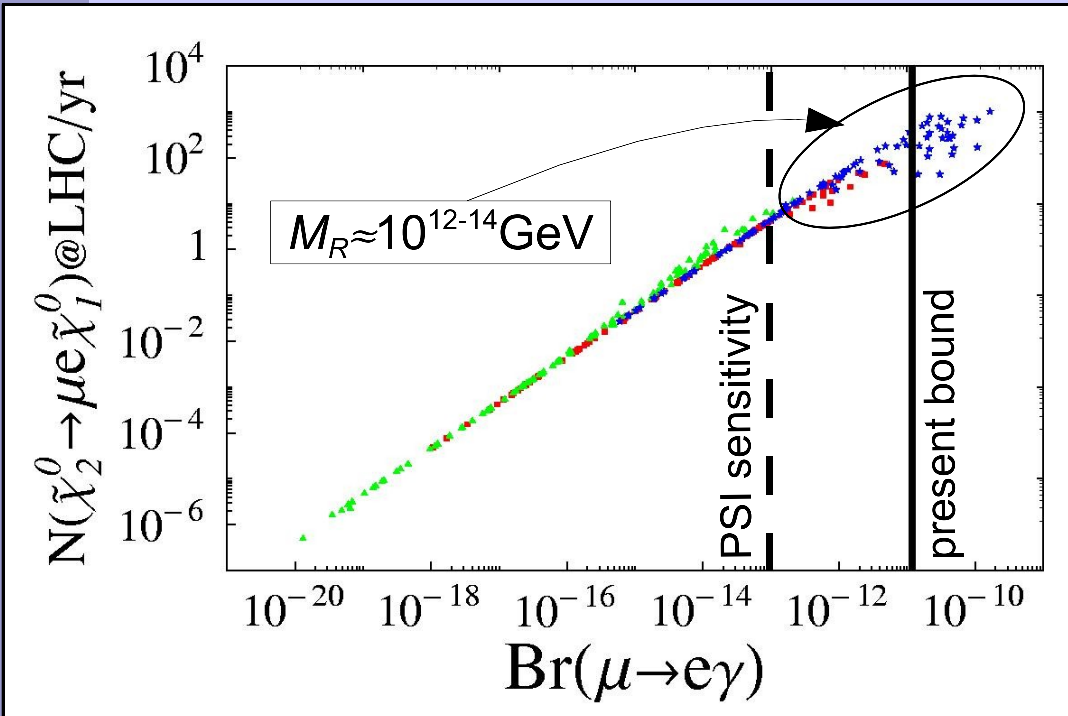
$$N(\tilde{\chi}_2^0 \to \mu e \tilde{\chi}_1^0) = 200 \;\Rightarrow\; 5\sigma\,@\,L = 100\,\text{fb}^{-1}$$

Andreev et al, hep-ph/0608176



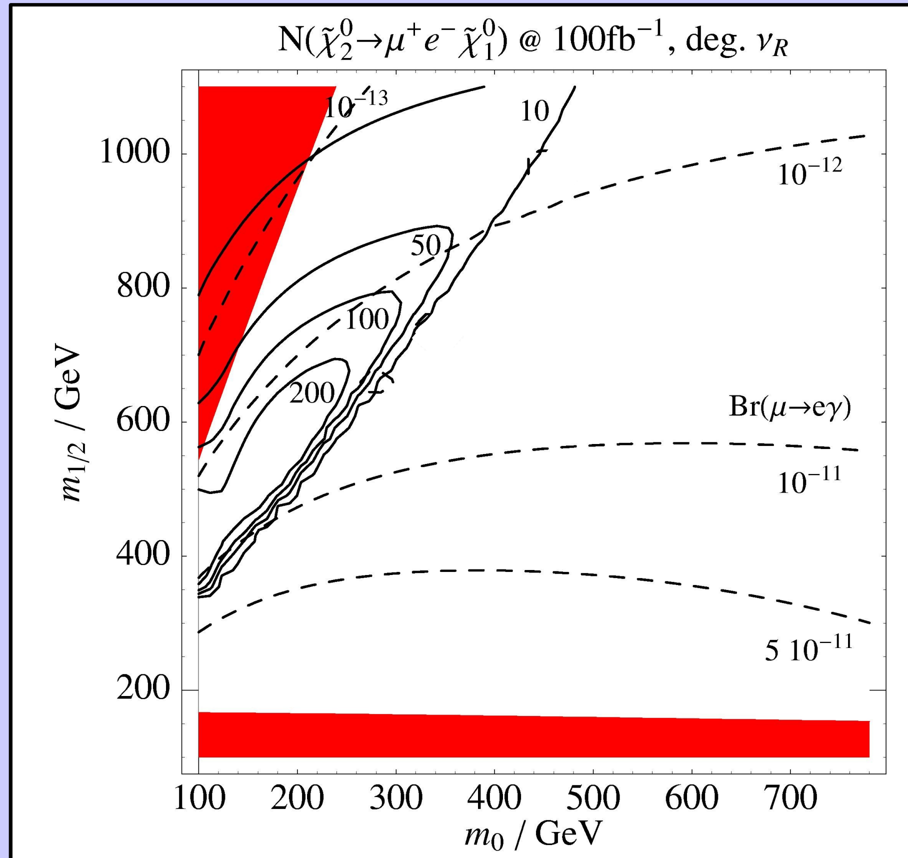
LFV at the LHC

SUSY Seesaw



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$\mu = +$)

Precision Slepton Mass Measurements

Collaboration with **A. Freitas**, **W. Porod**, **P. Zerwas**
Phys. Rev. D77 (2008) 075009 (arXiv:0712.0361)

Precision Mass Measurements

SO(10) GUT Model

- **SO(10)**
  - Favoured GUT group
  - Incorporates Seesaw

$$\mathbf{16}_F = \left(u_c, d_c, e, L, Q_c, \nu_R\right)$$

Precision Mass Measurements

SO(10) GUT Model

- **SO(10)**
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  - Incorporates Seesaw
- **Generic SO(10) Model**
  - Top unification $Y_\nu = Y_u$ (3rd gen.)
  - Two Higgs **10**-plets to avoid large tanβ
  - Dominance of $M^1{}_{126} \rightarrow$ **Seesaw Type I**
  - Realistic mass relations for all fermions are not our goal

$$\mathbf{16}_F = (u_c, d_c, e, L, Q_c, \nu_R)$$

$$\begin{aligned} W = & Y_d^{10}\,\mathbf{16}_F \cdot \mathbf{16}_F \cdot \mathbf{10}_{H_1} \\ & + Y_u^{10}\,\mathbf{16}_F \cdot \mathbf{16}_F \cdot \mathbf{10}_{H_2} \\ & + Y^{126}\,\mathbf{16}_F \cdot \mathbf{16}_F \cdot \mathbf{126}_H \end{aligned}$$

Breaking to SM

$$\begin{aligned} M^u &= \boldsymbol{M^5_{10_2}} + M^5_{126} \\ M^\nu_{LR} &= \boldsymbol{M^5_{10_2}} - 3\,M^5_{126} \\ M^d &= \boldsymbol{M^5_{10_1}} + M^{45}_{126} \\ M^e &= \boldsymbol{M^5_{10_1}} - 3\,M^{45}_{126} \\ M^\nu_{LL} &= M^{15}_{126} \\ M^\nu_{RR} &= \boldsymbol{M^1_{126}} \end{aligned}$$

Precision Mass Measurements

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  - Dominance of $M^1_{126} \rightarrow$ **Seesaw Type I**
  - Realistic mass relations for all fermions are not our goal
- **SO(10) Symmetry Breaking**
  - Direct: **SO(10)** $\rightarrow$ **SM**
  - Two-Step: **SO(10)** $\rightarrow$ **SU(5)** $\rightarrow$ **SM**

$$\mathbf{16}_F = (u_c, d_c, e, L, Q_c, \nu_R)$$

$$W = Y_d^{10}\,\mathbf{16}_F\cdot\mathbf{16}_F\cdot\mathbf{10}_{H_1} + Y_u^{10}\,\mathbf{16}_F\cdot\mathbf{16}_F\cdot\mathbf{10}_{H_2} + Y^{126}\,\mathbf{16}_F\cdot\mathbf{16}_F\cdot\mathbf{126}_H$$

Breaking to SM

$$\begin{aligned}
M^u &= \mathbf{M^5_{10_2}} + M^5_{126} \\
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M^e &= \mathbf{M^5_{10_1}} - 3\,M^{45}_{126} \\
M^\nu_{LL} &= M^{15}_{126} \\
M^\nu_{RR} &= \mathbf{M^1_{126}}
\end{aligned}$$

Precision Mass Measurements

Heavy Neutrino Mass Spectrum

- **Seesaw relation**

$Y_\nu = Y_u$ Yukawa unification (neglect small quark mixing)

$$M_{\nu_R} = Y_\nu \cdot m_\nu^{-1} \cdot Y_\nu^T v_u^2 \approx diag(m_{u_i}) \cdot U_\nu \cdot diag(m_{\nu_i}^{-1}) \cdot U_\nu^T \cdot diag(m_{u_i})$$

- **Strongly hierarchical masses**

$$M_{\nu_{R1}} : M_{\nu_{R2}} : M_{\nu_{R3}} \approx m_u^2 : m_c^2 : m_t^2$$

Precision Mass Measurements

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- **Strongly hierarchical masses**

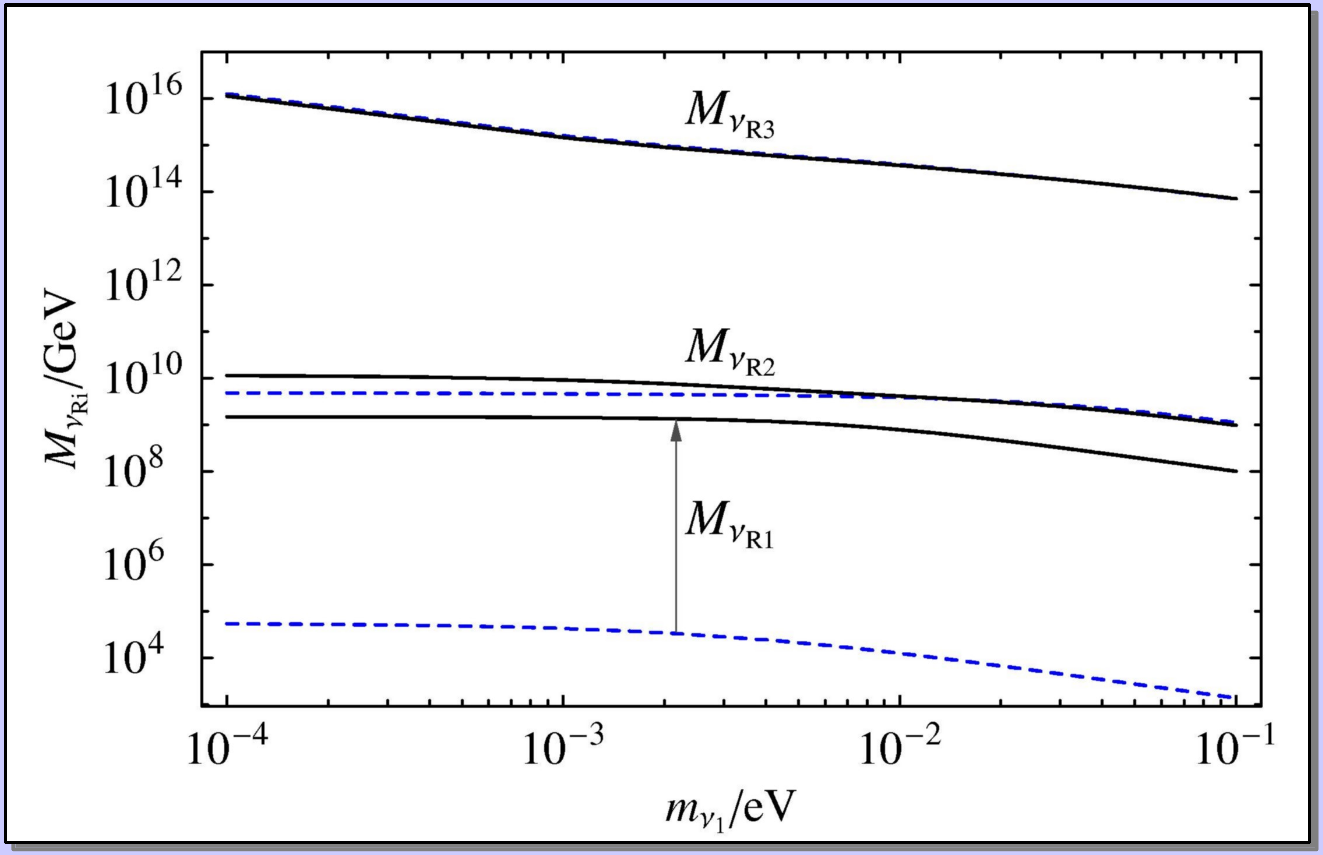
$$M_{\nu_{R1}} : M_{\nu_{R2}} : M_{\nu_{R3}} \approx m_u^2 : m_c^2 : m_t^2$$

- **Small violation of Yukawa unification**

$$Y_\nu = Y_u + O\left(\frac{m_c}{M_Z}\right)$$

→ Lifting of 1st and 2nd mass

- Realistic fermion mass relations
- Leptogenesis
- Does not affect our analysis



Precision Mass Measurements

Direct Breaking SO(10) → SM

- **Boundary Conditions at GUT scale Λ_U**

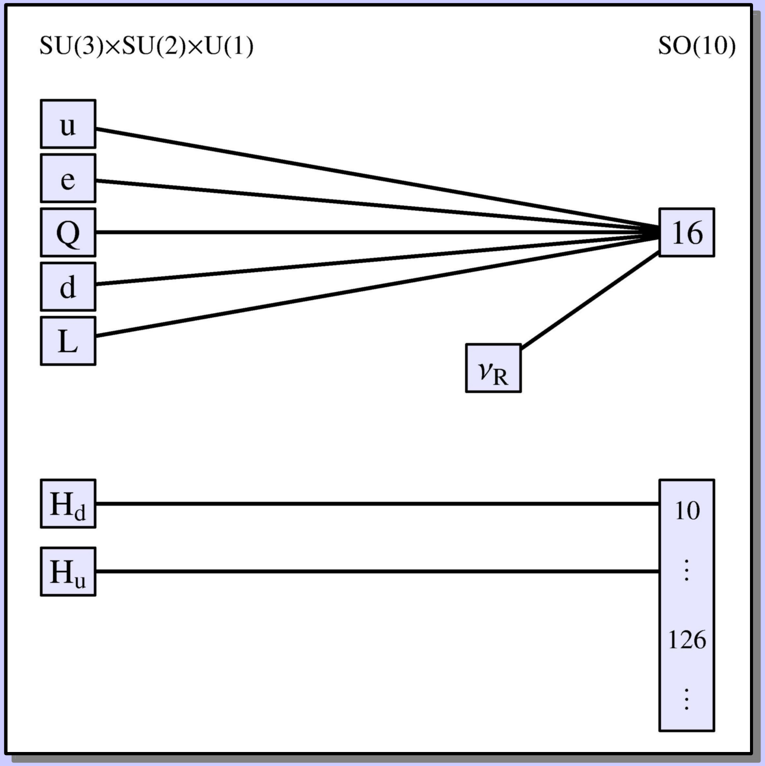
$$m_{16} = m_{10_1} = m_{10_2} \equiv M_0$$
$$M_{1/2}, A_0, \tan\beta, \text{sign}\,\mu$$
$$D_U$$

SSB masses at Λ_U

$$m_L^2 = m_{16}^2 - 3D_U$$
$$m_E^2 = m_{16}^2 + D_U$$

D-term associated with breaking rank-5 SO(10) to rank-4 SM

$$D_U \simeq g_U^2 O(m_{16}^2)$$



Precision Mass Measurements

Direct Breaking SO(10) → SM

- **Boundary Conditions at GUT scale Λ_U**

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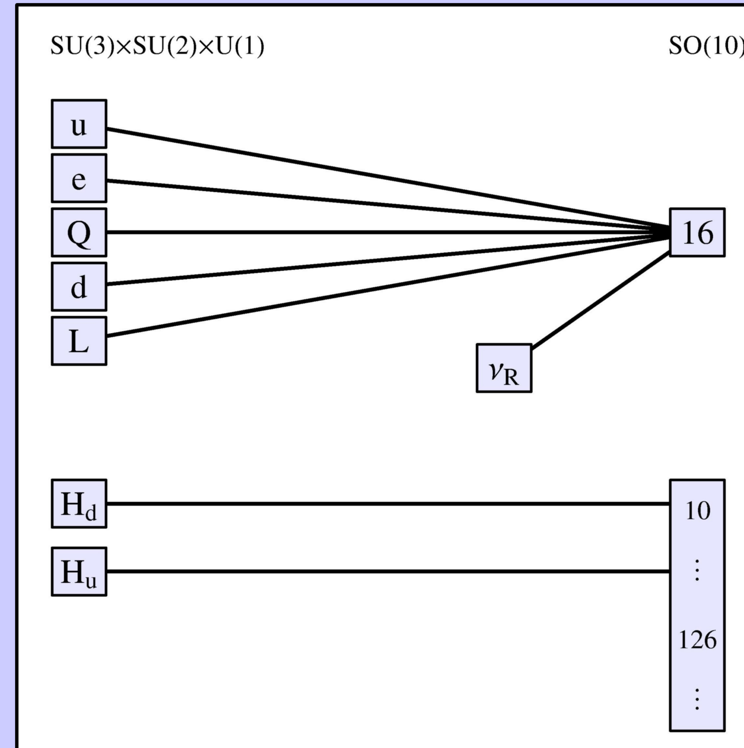


- **Solution to MSSM RGEs from Λ_U to M_Z**

1st and 2nd generation

$$m_{\tilde{e}_L}^2 = m_{16}^2 + 3D_U + \alpha_L M_{1/2}^2 - (1 - 2s_W^2) D_{EW}$$
$$m_{\tilde{\nu}_{eL}}^2 = m_{16}^2 + 3D_U + \alpha_L M_{1/2}^2 + D_{EW}$$
$$m_{\tilde{e}_R}^2 = m_{16}^2 + D_U + \alpha_R M_{1/2}^2 - 2s_W^2 D_{EW}$$

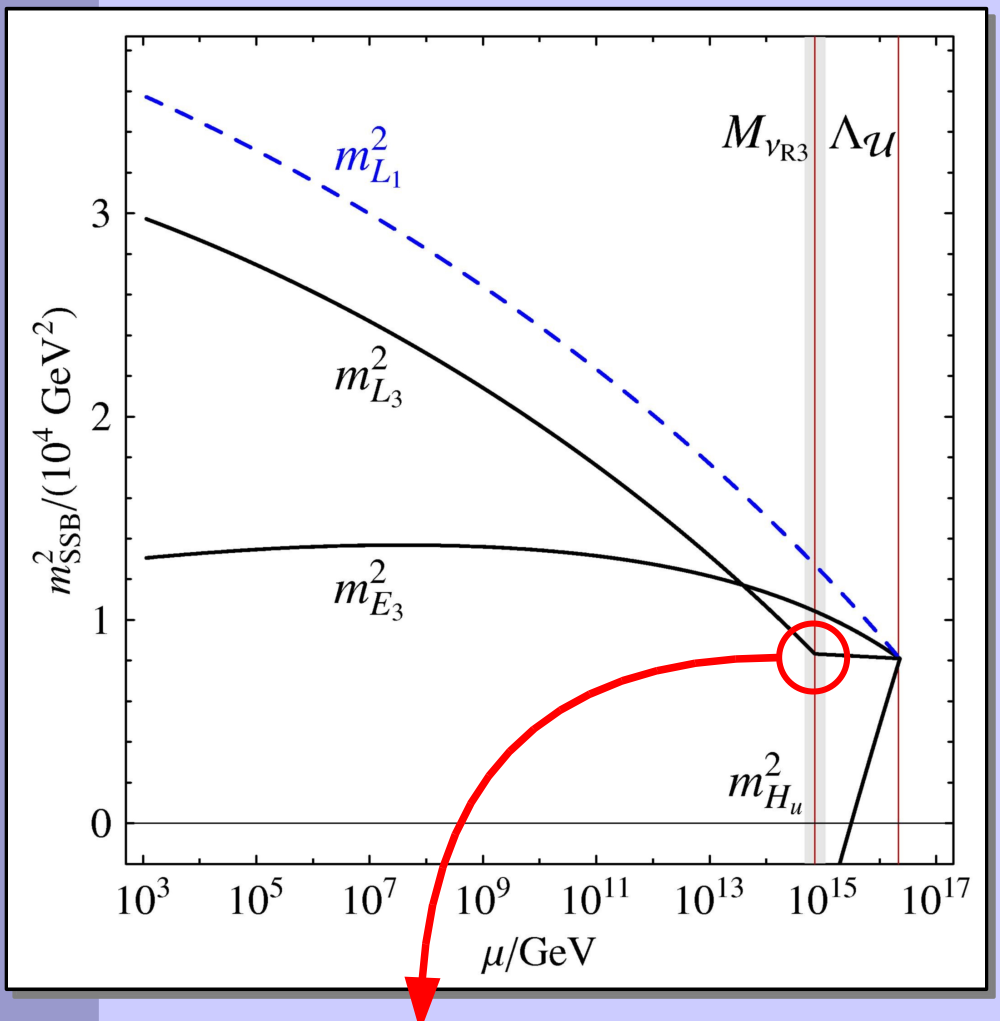
3rd gen. shifted due to strong Yukawa coupling

$$m_{\tilde{\tau}_L}^2 = m_{\tilde{e}_L}^2 + m_\tau^2 - \Delta_\tau - \Delta_{\nu_\tau}$$
$$m_{\tilde{\nu}_{\tau L}}^2 = m_{\tilde{\nu}_{eL}}^2 - \Delta_\tau - \Delta_{\nu_\tau}$$
$$m_{\tilde{\tau}_R}^2 = m_{\tilde{e}_R}^2 + m_\tau^2 - 2\Delta_\tau$$

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

Precision Mass Measurements

Slepton Mass Evolution



Different running of left-stau mass above and below the heavy neutrino mass scale

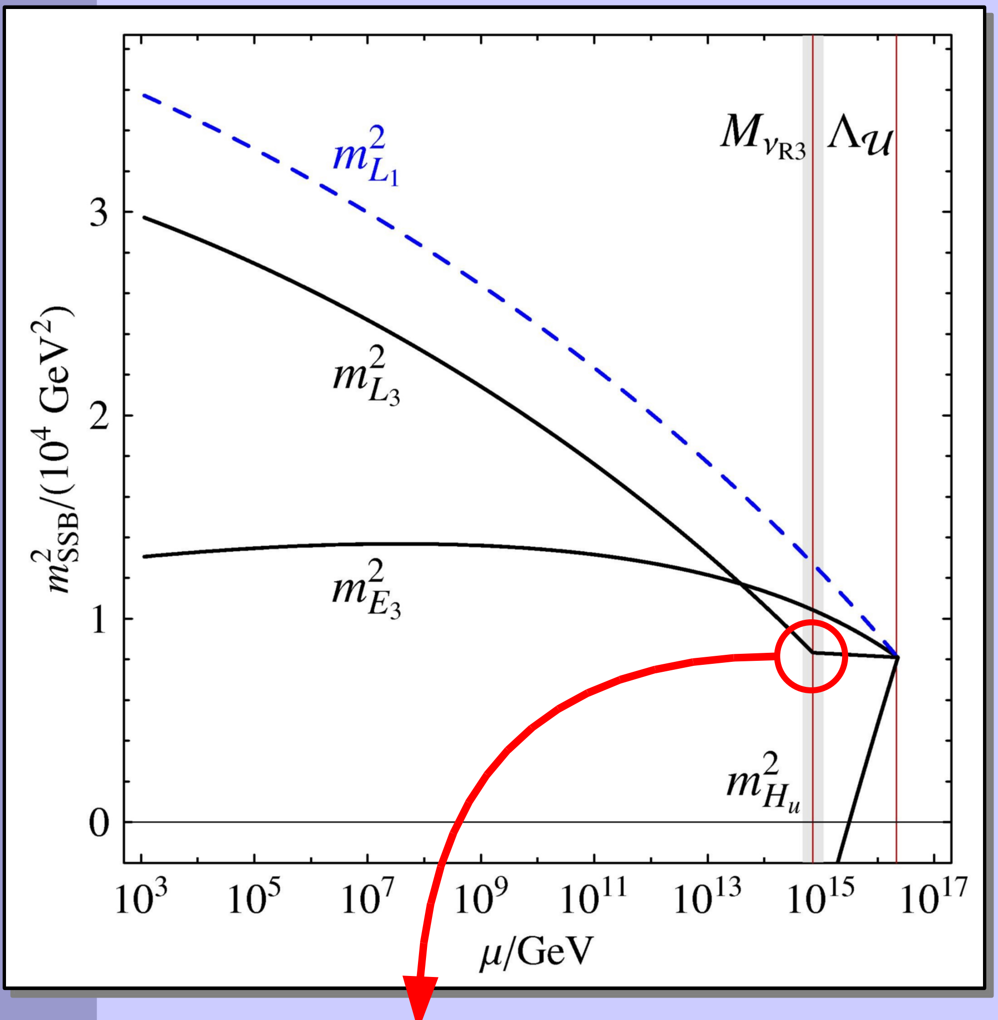
SUSY parameter measurements (combined LHC+ILC sensitivity)

Parameter	Value	Error	Parameter	Value	Error
$m_{\tilde{e}_R}$	140.9 GeV	0.05 GeV	μ	481.1 GeV	4.5 GeV
$m_{\tilde{e}_L}$	190.4 GeV	0.4 GeV	$\tan\beta$	10.0	1.0
$m_{\tilde{\nu}_e}$	173.4 GeV	1.3 GeV	$M_{1/2}$	250.0 GeV	0.4 GeV
$m_{\tilde{\tau}_1}$	104.2 GeV	0.3 GeV	A_0	−640.0 GeV	13 GeV
$m_{\tilde{\tau}_2}$	187.8 GeV	1.1 GeV			
$m_{\tilde{\nu}_\tau}$	154.7 GeV	1.6 GeV			

Aguilar-Saavedra et al., Weiglein et al.

Precision Mass Measurements

Slepton Mass Evolution



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Aguilar-Saavedra et al., Weiglein et al.

Global Fit

Model input parameters

Parameters in SO(10) → SM	Ideal	Error
unification scale $\Lambda_{\mathcal{U}}$	$2.16 \cdot 10^{16}$ GeV	$0.02 \cdot 10^{16}$ GeV
matter scalar mass M_0	90 GeV	0.25 GeV
GUT D-term $\sqrt{-D_{\mathcal{U}}}$	30 GeV	0.9 GeV
heaviest R-neutrino mass $M_{\nu_{R3}}$	$7.2 \cdot 10^{14}$ GeV	$[4.8, 11] \cdot 10^{14}$ GeV
lightest neutrino mass m_{ν_1}	$3.5 \cdot 10^{-3}$ eV	$[1.6, 6.7] \cdot 10^{-3}$ eV

Precision Mass Measurements

Determination of Neutrino Mass Scales

- **Theory: RG evolution**

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

- **Experiment: Slepton mass measurements (ILC sensitivity)**

$$\Delta_{\nu_\tau} = (4.7 \pm 0.5)\cdot 10^3\,\mathrm{GeV}^2$$

Fit

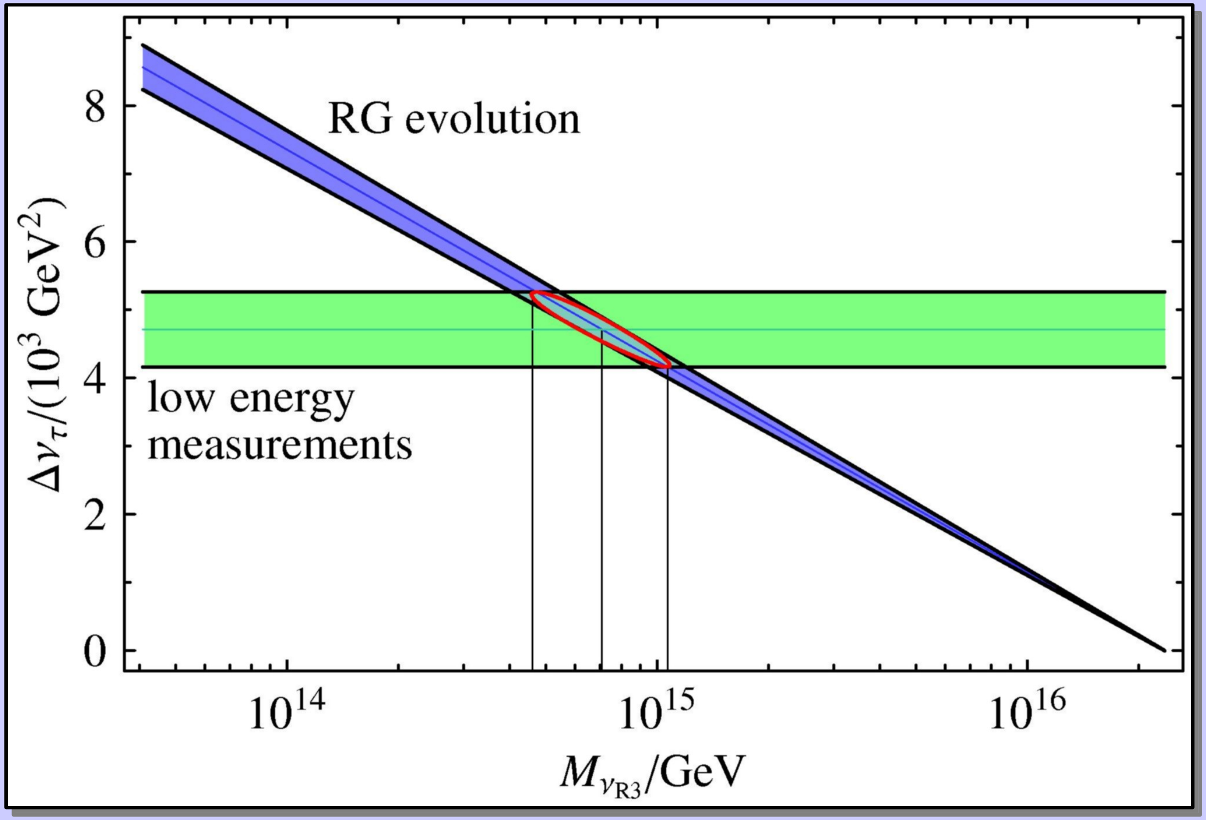
- **Heavy neutrino mass**

$$M_{\nu_{R3}} = \left(7.2^{+4.0}_{-2.5}\right)\cdot 10^{14}\,\mathrm{GeV}$$

Seesaw

- **Light neutrino mass**

$$m_{\nu_1} = \left(3.0^{+3.5}_{-1.5}\right)\cdot 10^{-3}\,\mathrm{eV}$$



Conclusion

- **SUSY Seesaw**
  - Effective Description emerging naturally from SO(10)
  - Connecting Neutrino, EW, SUSY and GUT Scale Physics
  - CP Violation Effects, Leptogenesis, EDMs
  - Charged Lepton Flavor Violation
- **Charged LFV Processes**
- **Reconstruction of Model Parameters**
- **Outlook**

Conclusion

- **SUSY Seesaw**
- **Charged LFV Processes**
  - Low Energy Processes such as $Br(\mu \to e\gamma)$
  - Decays of Second Lightest Neutralino at the LHC
  - Slepton Pair Production at the ILC
  - Correlations among Processes and Neutrino Parameters
- **Reconstruction of Model Parameters**
- **Outlook**

Conclusion

- **SUSY Seesaw**
- **Charged LFV Processes**
- **Reconstruction of Model Parameters**
  - LFV Processes probe Neutrino Yukawa Couplings
  - Synergy between Neutrino and Collider Physics
  - Example: Determination of Heaviest and Lightest Neutrino Mass in SO(10)
- **Outlook**

Conclusion

- **SUSY Seesaw**
- **Charged LFV Processes**
- **Reconstruction of Model Parameters**
- **Outlook**
  - Synergy and Interplay between Neutrino and Collider Physics
  - Systematic Study of Slepton Flavor Structure at LHC "Slepton Oscillations"
  - Application to realistic SO(10) GUT Models