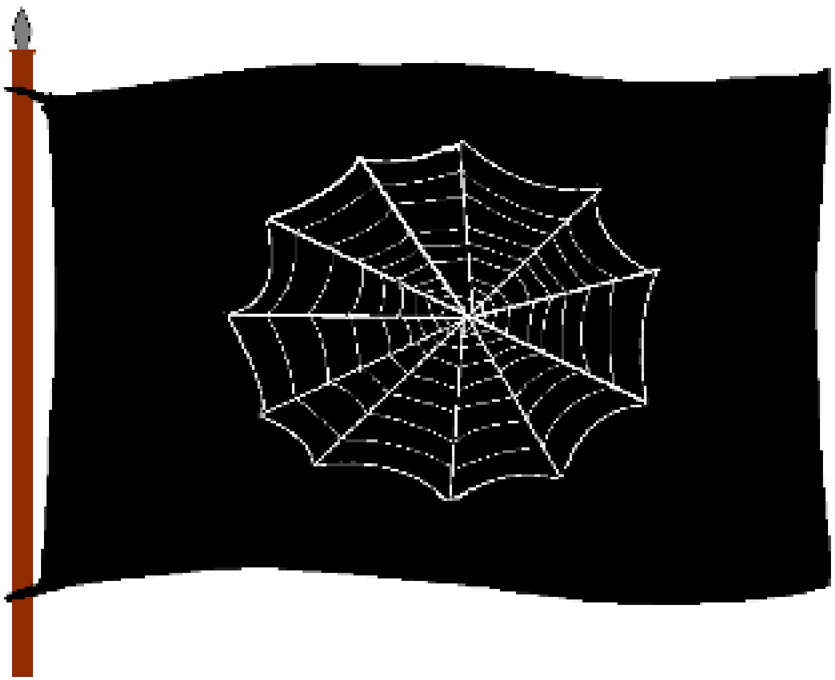
LEPTON FLAVOR VIOLATION IN FUTURE LINEAR COLLIDERS



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+work in progress

- **Neutrino Oscillations.**
- **See Saw Mechanism.**
- **SUSY Flavor and Charged Lepton Flavor Violation.**

- **An Abelian SU(5) model for Yukawa couplings:**
  - **Fitting Neutrino Parameters.**
    - **LFV BR(li->lj+gamma)**

- **Charged Slepton flavor oscillation at Linear colliders,**

  - ***CONCLUSIONS***

Neutrino **Oscillations**

$$\nu_{l\mathrm{L}}(x) = \sum_j U_{lj}\, \nu_{j\mathrm{L}}(x), \quad l = e, \mu, \tau,$$

$$P(\nu_{l(l')} \to \nu_{l'(l)}) \cong P(\bar{\nu}_{l(l')} \to \bar{\nu}_{l'(l)}) \cong \delta_{ll'} - 2|U_{ln}|^2 \left[\delta_{ll'} - |U_{l'n}|^2\right]$$
$$\left(1 - \cos\frac{\Delta m_{n1}^2}{2p} L\right).$$

EW interaction Mixes Lepton Flavor.

There is a matrix: PVMS=U Equivalent to The CKM in the Quark sector.

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Neutrino Masses and the "See-Saw" Mechanism

- Neutrino data: By now convincing for $m_\nu \neq 0$ and physics beyond SM
- What do we know?

Atmospheric problem	Solar problem
$\Delta m^2_{atm} = \left(2.6^{+0.4}_{-0.7}\right) \times 10^{-3}$ eV^2 $\sin^2 2\theta_{atm} > 0.90$	$\Delta m^2_{sol} = \left(8.1^{+0.5}_{-0.5}\right) \times 10^{-5}$ eV^2 $\sin^2 2\theta_{sol} = \left(0.86^{+0.05}_{-0.06}\right)$

$$\mathcal{M} = \begin{pmatrix} 0 & m_\nu^D \\ m_\nu^{D^T} & M_R \end{pmatrix}$$

"See-Saw" explanation for tiny masses.

- The physical masses are:
  1. $m_1 \equiv m_{light} \simeq \frac{\left(m_\nu^D\right)^2}{M_R}$
  2. $m_2 \simeq M_R$
- For $(m_\nu^D)_{33} \approx (200 \text{ GeV})$ $(\lambda_\nu \approx \lambda_t)$ and $M_{N_3} \approx O(10^{14} \text{ GeV})$, $m_{eff} \approx 0.05$ eV

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$0.06 < \sin^2 2\theta_{13} < 0.13$
Reactor data (RENO, Daya Bay).

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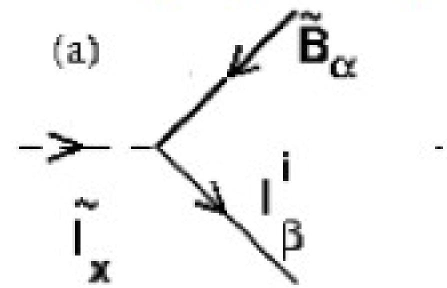
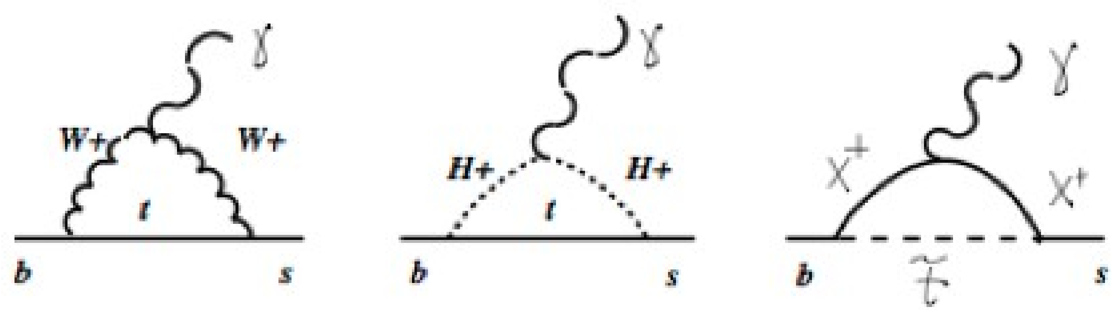
SUSY FLAVOR

R-parity warranties that SUSY particles only appear in pairs:



therefore SM model phenomenology is only modified at *loops level*:



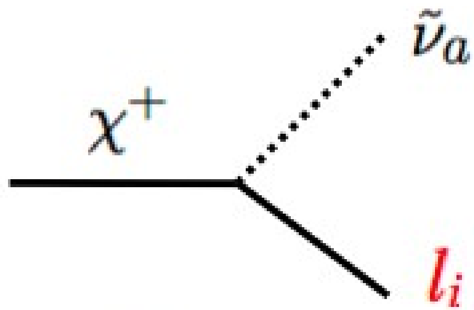
The present average given by the

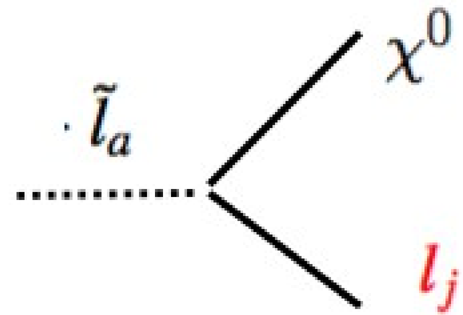
$$BR(b \to s\gamma) = (3{,}55 \pm 0{,}24^{+0{,}09}_{-0{,}10} \pm 0{,}03) \times 10^{-4}$$

The SM prediction: $$BR(b \to s\gamma) = (3.15 \pm 0.30) \times 10^{-4}$$

Charged LFV in SUSY

Lepton pairs in chargino and neutralino decays:





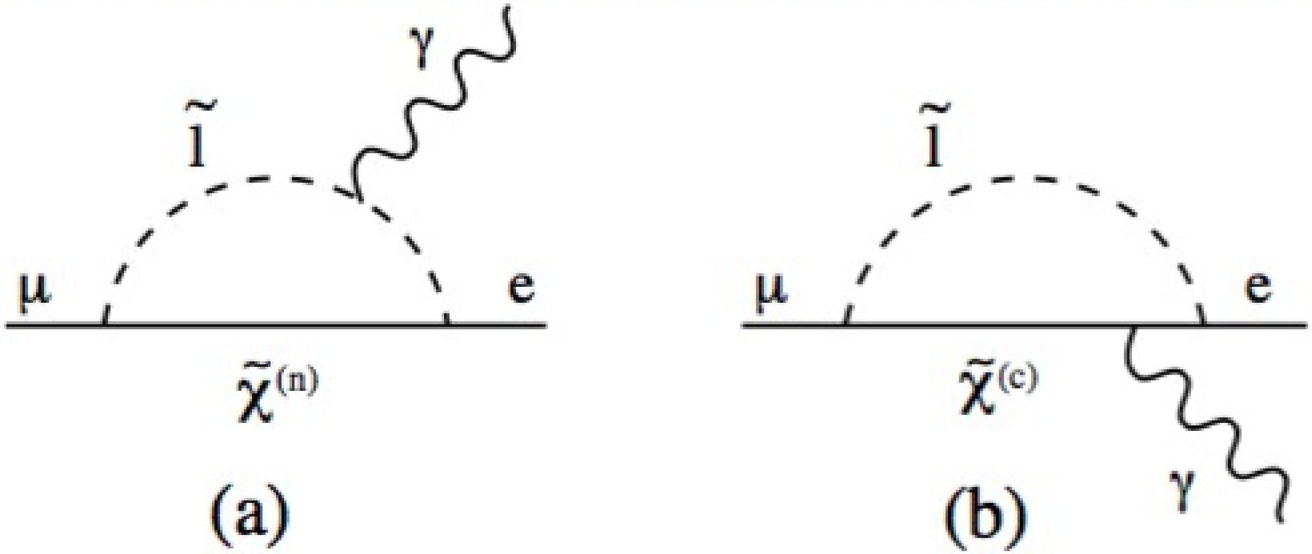
In the basis $\tilde{\ell}_i = (\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R^*, \tilde{\mu}_R^*, \tilde{\tau}_R^*)$, the slepton mass matrix:

$$\mathcal{L}_M = -\frac{1}{2}\tilde{\ell}^\dagger M_{\tilde{\ell}}^2 \tilde{\ell}, \qquad M_{\tilde{\ell}}^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ M_{RL}^2 & M_{RR}^2 \end{pmatrix},$$

$$\begin{aligned} M_{LL}^2 &= \frac{1}{2} m_\ell^\dagger m_\ell + M_L^2 - \frac{1}{2}(2m_W^2 - m_Z^2)\cos 2\beta\, I \\ M_{RR}^2 &= \frac{1}{2} m_\ell^\dagger m_\ell + M_R^2 - (m_Z^2 - m_W^2)\cos 2\beta\, I \\ M_{LR}^2 &= (A^e - \mu \tan\beta)\; m_\ell \\ M_{RL}^2 &= (M_{LR}^2)^\dagger \end{aligned}$$

Charged Lepton Flavor Violation

In SUSY flavor mixing lepton-slepton vertices can induce LFV diagrams:



Lepton-slepton flavor mixing is very constrained by the experimental limits:

$$
\begin{aligned}
BR(\mu \to e\gamma) &< 2.4 \times 10^{-12} \\
BR(\tau \to \mu\gamma) &< 4.4 \times 10^{-8} \\
BR(\tau \to e\gamma) &< 3.3 \times 10^{-8}
\end{aligned}
$$

Soft SUSY Breaking Terms

The soft SUSY breaking masses

$$-\mathcal{L}_{\rm soft} = -\frac{1}{2}\left(M_3\,\lambda_{\tilde g}^a\lambda_{\tilde g}^a + M_2\,\lambda_{\widetilde W}^i\lambda_{\widetilde W}^i + M_1\,\lambda_{\widetilde B}\lambda_{\widetilde B} + \text{h.c.}\right)$$
$$+M_L^2\,\widetilde L^\dagger\widetilde L + M_Q^2\,\widetilde Q^\dagger\widetilde Q + M_U^2\,\widetilde U^*\widetilde U + M_D^2\,\widetilde D^*\widetilde D + M_E^2\,\widetilde E^*\widetilde E +$$
$$m_{H_d}^2\,\widetilde H_d^\dagger\widetilde H_d + m_{H_u}^2\,H_u^\dagger H_u - \left(B\mu\,\widetilde H_d^T H_u + \text{h.c.}\right)$$
$$+\left(y_\ell A_\ell\,H_d^\dagger\widetilde L\widetilde E + y_d A_d\,H_d^\dagger\widetilde Q\widetilde D - y_u A_u\,H_u^T\,\widetilde Q\widetilde U\ + \ \text{h.c.}\right),$$

Inspired from supergravity assume universal soft breaking, $\mathcal{L}_{\rm soft}$:

$$\sum_{f,H} m_0^2\tilde f\tilde f + \sum_\lambda m_{\frac{1}{2}}\lambda\lambda + \sum_f A_0 Y_f\tilde f\tilde F H_f + B\mu H_u H_d$$

m_0, $m_{\frac{1}{2}}$, A_0, $\tan\beta$, sign(μ)

μ and A_0 can be complex, however their phases contraint to be $< 0{,}2$ rad by the bounds on the fermion EDM.

See-saw Neutrinos and SUSY

Even if we start with universal soft terms at GUT, FV entries can be generated:

$$M_{\mathrm{GUT}} : m_{\tilde{\ell},\tilde{\nu}} \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \mathrm{RGEs} \longrightarrow \begin{pmatrix} 1 & \star & \star \\ \star & 1 & \star \\ \star & \star & 1 \end{pmatrix}$$

- RGEs for the charged-lepton mass matrix

$$t\frac{d}{dt}(m^2_{\tilde{\ell}})^j_i = \frac{1}{16\pi^2}\left\{\left(m^2_{\tilde{\ell}}\lambda^\dagger_\ell\lambda_\ell\right)^j_i + \left(m^2_{\tilde{\nu}}\lambda^\dagger_\nu\lambda_\nu\right)^j_i + \cdots\right\}$$

The corrections in the basis where $(\lambda^\dagger_\ell\lambda_\ell)^j_i$ is diagonal, are:

$$\delta m^2_{\tilde{\ell}} \propto \frac{1}{16\pi}\ln\frac{M_{\mathrm{GUT}}}{M_N}\lambda^\dagger_\nu\lambda_\nu m^2_{SUSY}$$

SU(5) RGE effects

The running of the soft terms from a higher scale (M_X) to M_{GUT} introduce non universalities on the soft terms :

- $M_x \to M_{GUT}$

10(Q_L,U_R,E_R), 5(D_R,L)

$$W_{\mathrm{SU}(5)} = \frac{1}{4} f_u^{ij}\, 10_i\, 10_j\, H + \sqrt{2} f_d^{ij}\, 10_i\, \overline{5}_j\, \overline{H} + f_\nu^{ij}\, 1_i\, \overline{5}_j\, H$$

$$f_u^{ij} = f_u^\delta,$$

$$f_d^{ij} = V_{CKM}^* \lambda_d^\delta V_{KM}^\dagger$$

The soft terms:

$$m_{10}\, \widetilde{10} * \widetilde{10} + m_5\, \widetilde{5} * \widetilde{5} + \cdots$$

$$\widetilde{\ell}_R \text{ in } 10's \to m^2_{\widetilde{\ell}_R} = V^\dagger_{\mathrm{CKM}} m^2_{10} V_{\mathrm{CKM}}$$

Hisano et al

- $M_{GUT} \to M_R$

$$W_{\mathrm{MSSM}+\nu_R} = Q^T\, f_u^\delta\, U\, H_2 + Q^T \left(V_{CKM}^\dagger f_d^\delta\right) D\, H_1$$
$$+\; L^T \left(V_{KM}^* f_\ell^\delta\right) E\, H_1 + L^T f_\nu^\delta\, N\, H_2$$

Remember that the $V_{KM} = V_\nu^+ \cdot V_l$ where $V_\nu^+ \cdot f_\nu^+ f_\nu \cdot V_\nu = (f_\nu^\delta)^2$ and $V_l^+ \cdot f_l^+ f_l \cdot V_l = (f_l^\delta)^2$. (Does not involve the RH neutrinos like the V_{NMS}). At scale M_R, the diagonal charged lepton Yukawa implies:

$$L^* \left(m_l^2\right)^{diag} L \to L^* \left[V_{KM}^\dagger \cdot \left(m_l^2\right)^{diag} \cdot V_{KM}\right] L$$

2 SU(5) inspired neutrino mass textures

$$Y_u \propto \begin{pmatrix} \varepsilon^6 & \varepsilon^5 & \varepsilon^3 \\ \varepsilon^5 & \varepsilon^4 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix}, \; Y_\ell \propto Y_d^T \propto \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon \\ \varepsilon^3 & \varepsilon^2 & 1 \\ \varepsilon^3 & \varepsilon^2 & 1 \end{pmatrix}, \; Y_\nu \propto \begin{pmatrix} \varepsilon^{|1\pm n_1|} & \varepsilon^{|1\pm n_2|} & \varepsilon^{|1\pm n_3|} \\ \varepsilon^{|n_1|} & \varepsilon^{|n_2|} & \varepsilon^{|n_3|} \\ \varepsilon^{|n_1|} & \varepsilon^{|n_2|} & \varepsilon^{|n_3|} \end{pmatrix}$$

$$m_N \propto \begin{pmatrix} \varepsilon^{2|n_1|} & \varepsilon^{|n_1+n_2|} & \varepsilon^{|n_1+n_3|} \\ \varepsilon^{|n_1+n_2|} & \varepsilon^{2|n_2|} & \varepsilon^{|n_2+n_3|} \\ \varepsilon^{|n_1+n_3|} & \varepsilon^{|n_2+n_3|} & \varepsilon^{2|n_3|} \end{pmatrix} \quad m_{eff} \approx m_D^{\nu} 1 \frac{1}{M_N} m_D^{\nu\,T},$$

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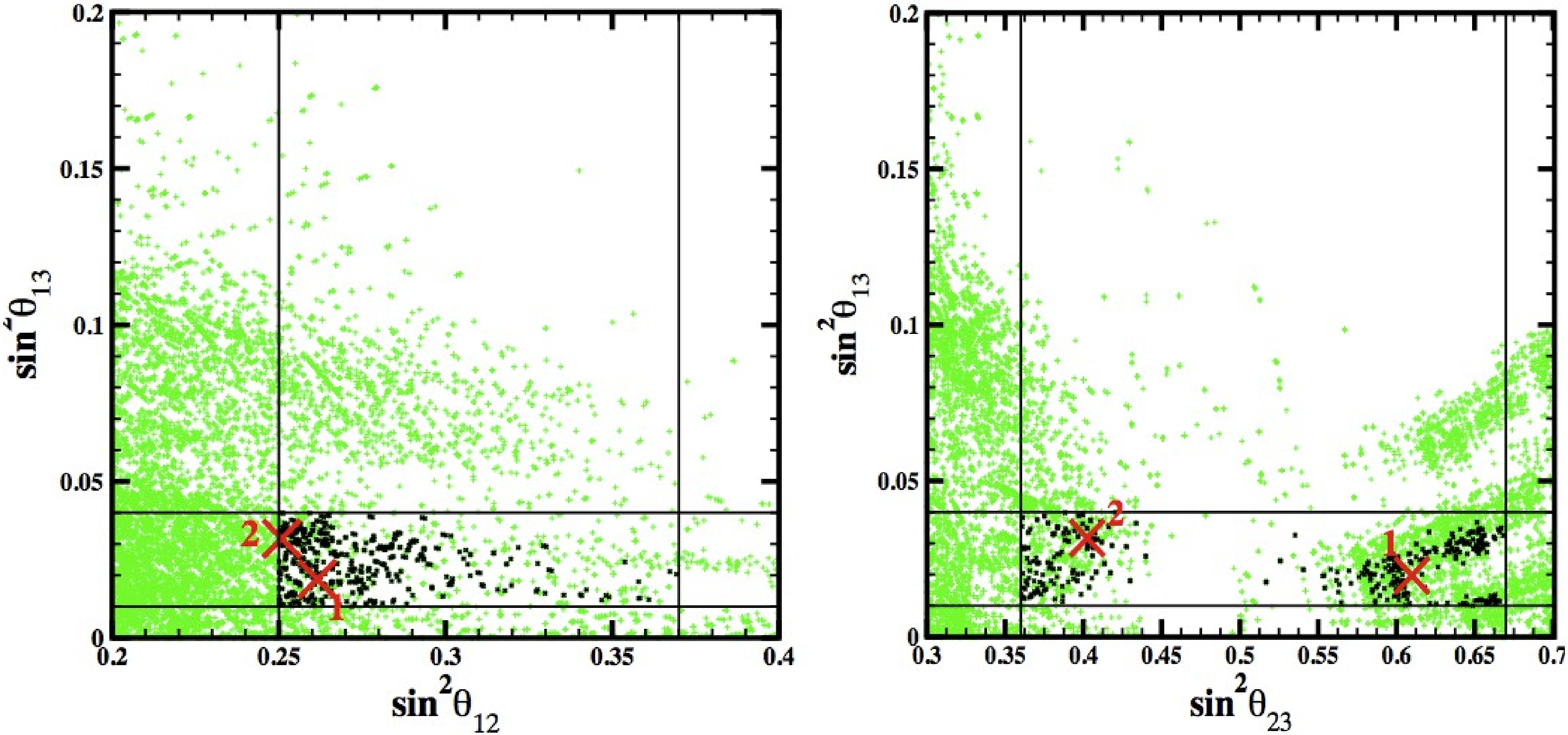
$$m_{eff} \propto \begin{pmatrix} \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix}$$

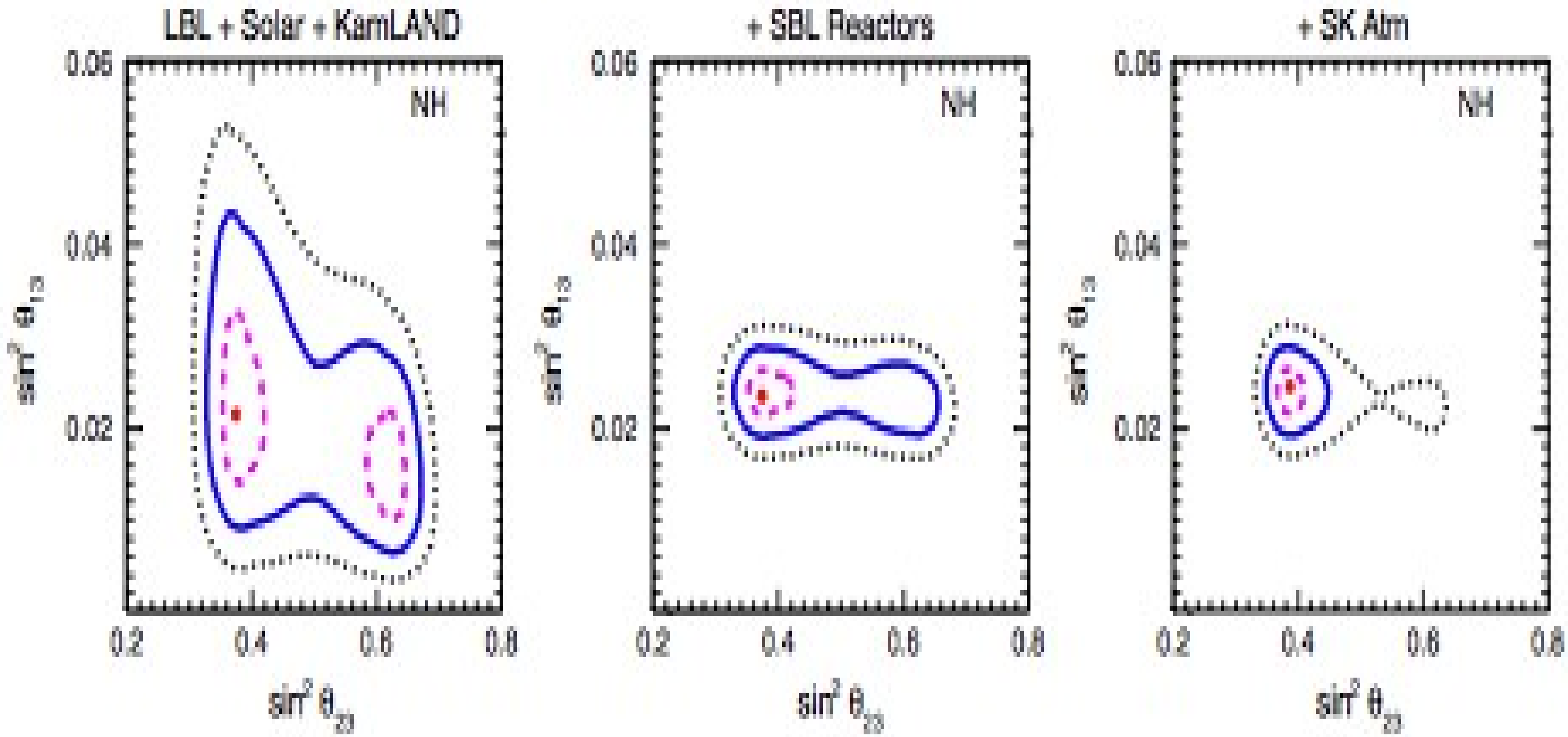
* **Coefficients of O(1) in all entries.**
* **Any choices of n_i leads to the same m_{eff}**

Fitting Of NEUTRINO PARAMETRES



$$0.25 < \sin^2\theta_{12} < 0.37,$$
$$0.36 < \sin^2\theta_{23} < 0.67,$$
$$0.013 < \sin^2\theta_{13} < 0.035,$$

$$\frac{m_{\nu_2}}{m_{\nu_3}} \sim 0.15$$



Data fitting from Flogli et al. **ArXiv:1205.5254, Phys.Rev. D86 (2012) 013012**

Charged-Lepton-Flavour Violation in the CMSSM with heavy right-handed neutrinos

$$
\begin{aligned}
V_\ell{}^T (Y_\ell Y_\ell{}^\dagger) V_\ell^* &= \mathrm{diag}(y_e^2, y_\mu^2, y_\tau^2), \\
V_D{}^T (Y_\nu Y_\nu{}^\dagger) V_D^* &= \mathrm{diag}(y_\nu^2, y_\nu^2, y_\nu^2), \\
U_N{}^T M_N U_N &= \mathrm{diag}(M_1, M_2, M_3), \\
U_\nu{}^T m_{eff} U_\nu &= \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}),
\end{aligned}
$$

$$U_{MNS} \equiv U = V_\ell^\dagger U_\nu,$$

$$V_{LFV} = V_D^\dagger \cdot V_l$$

$$\sin^2\theta_{13} = |U_{e3}|^2, \;\; s_{23}^2 \equiv \sin^2\theta_{23} = \frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2},$$

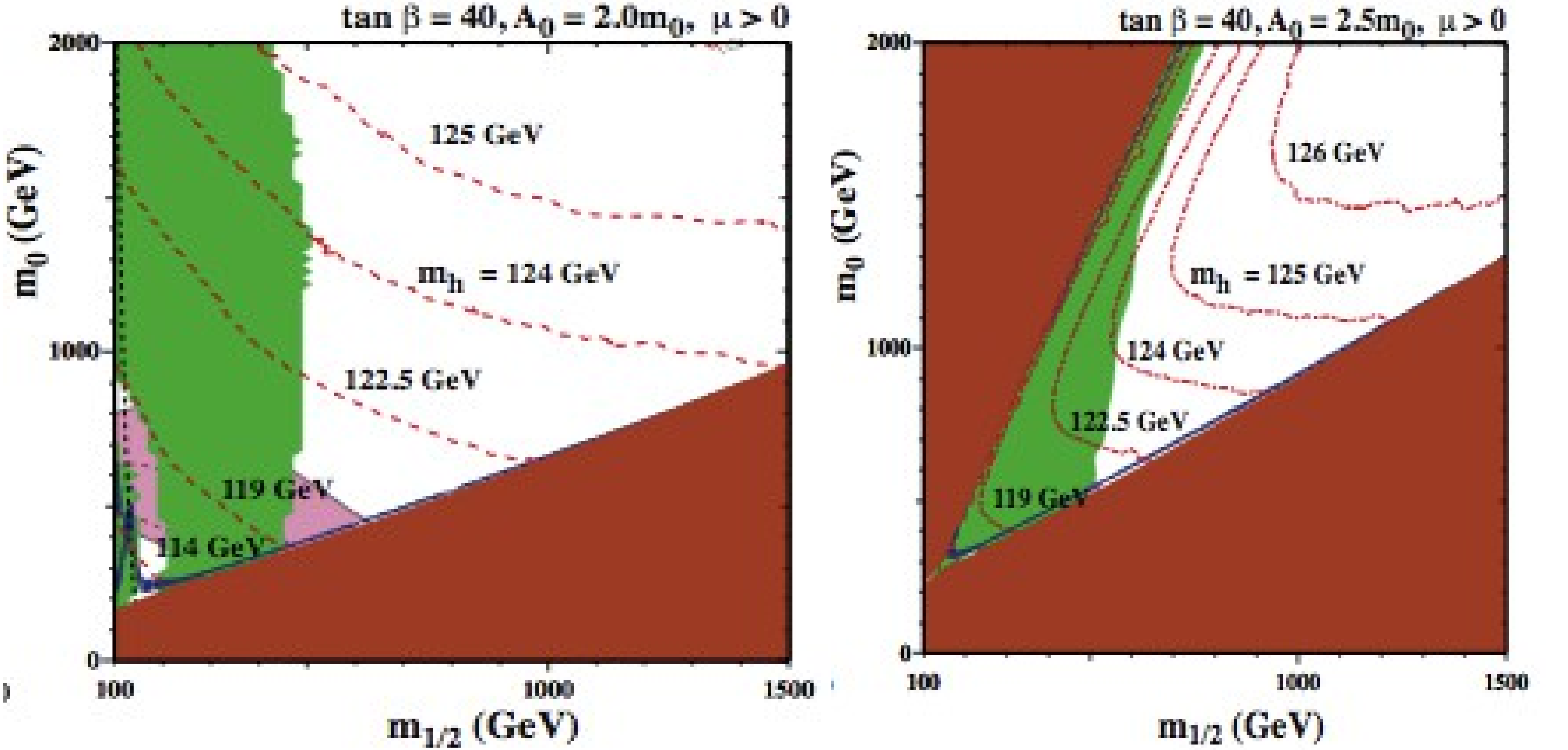
$$c_{23}^2 \equiv \cos^2\theta_{23} = \frac{|U_{\tau 3}|^2}{1-|U_{e3}|^2}.$$

$$\tilde{m}_\ell^2 = \begin{pmatrix} m_{LL}^2 & m_{LR}^2 \\ m_{RL}^2 & m_{RR}^2 \end{pmatrix}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$A_e = V_{l\nu}^T (A_e)^\delta$$

$$m_{LL}^2 = V_{LFV}^\dagger (m_{LL}^2)^\delta V_{LFV}$$



Ellis, Olive

$A)\quad \tan\beta = 40,\quad m_0 = 410\text{GeV},\quad \mathrm{m}_{1/2} = 920\text{GeV},\quad \mathrm{A}_0 = 0.$

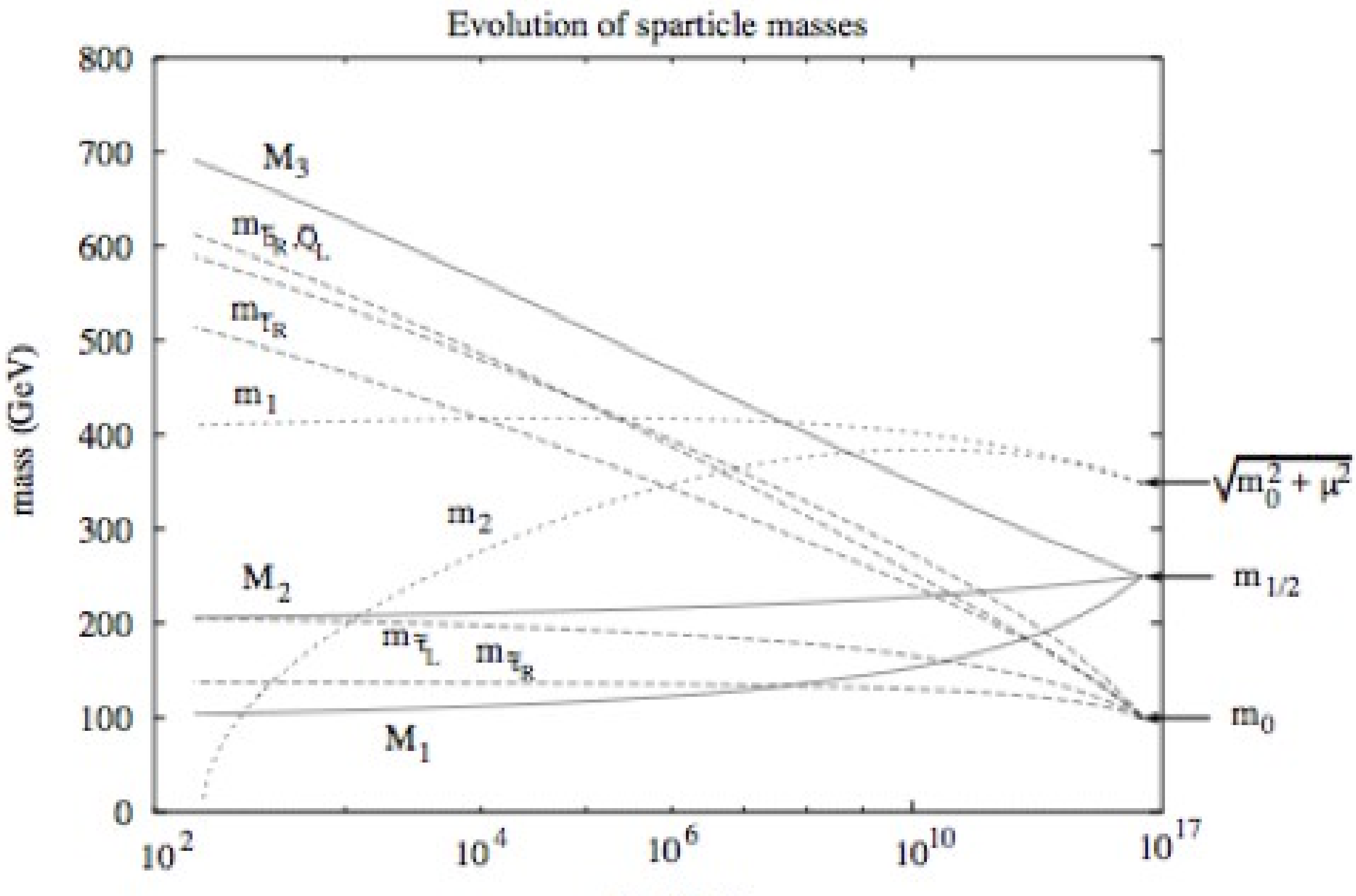
$B)\quad \tan\beta = 41,\quad m_0 = 452\text{GeV},\quad \mathrm{m}_{1/2} = 780\text{GeV},\quad \mathrm{A}_0 = 1100\text{GeV}.$

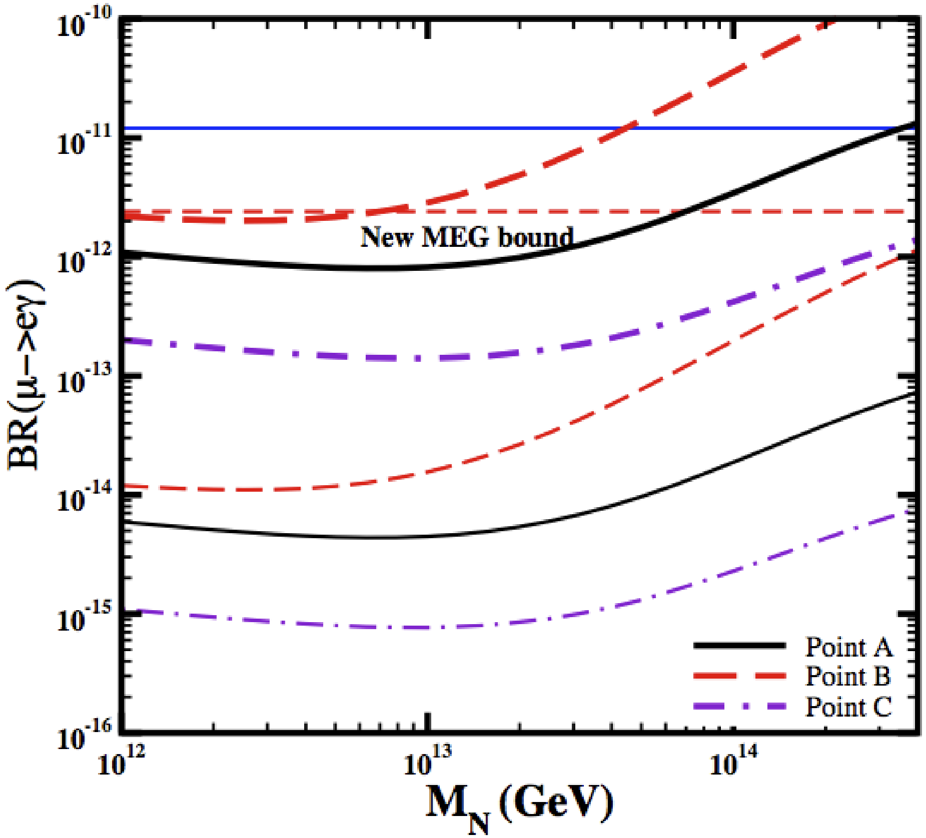
$C)\quad \tan\beta = 45,\quad m_0 = 858\text{GeV},\quad \mathrm{m}_{1/2} = 1780\text{GeV},\quad \mathrm{A}_0 = 0.$

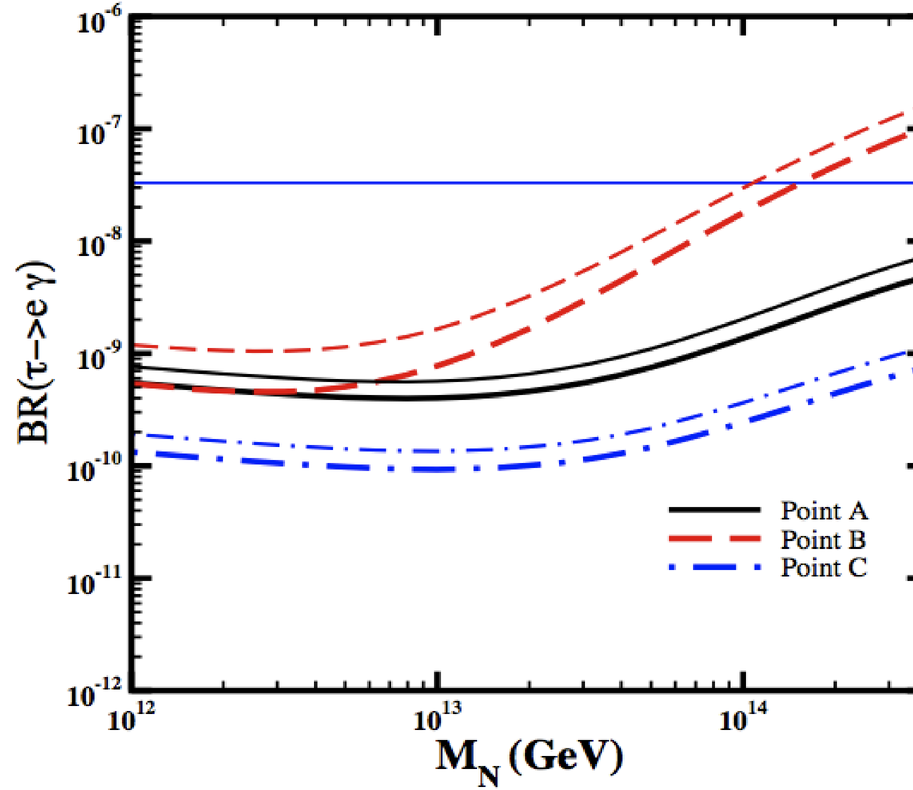
SUSY spectrum

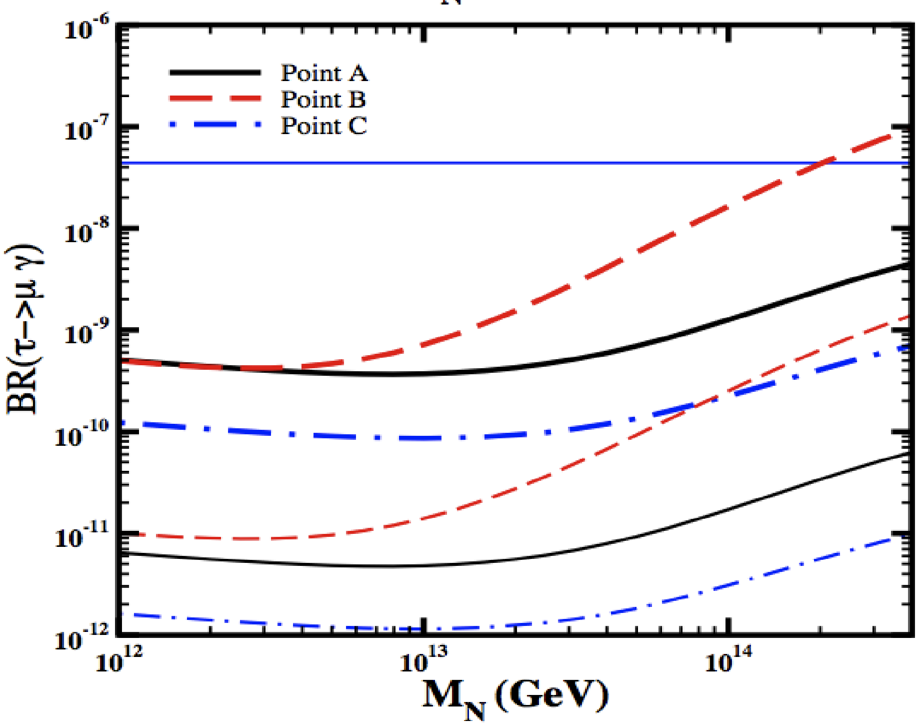
CMSSM, mSUGRA. Parametros de masa universales:

$$m_0,\ M_{1/2},\ A_0,\ \mu_0,\ \alpha_G,\ M_{GUT},\ \tan\beta\ .$$







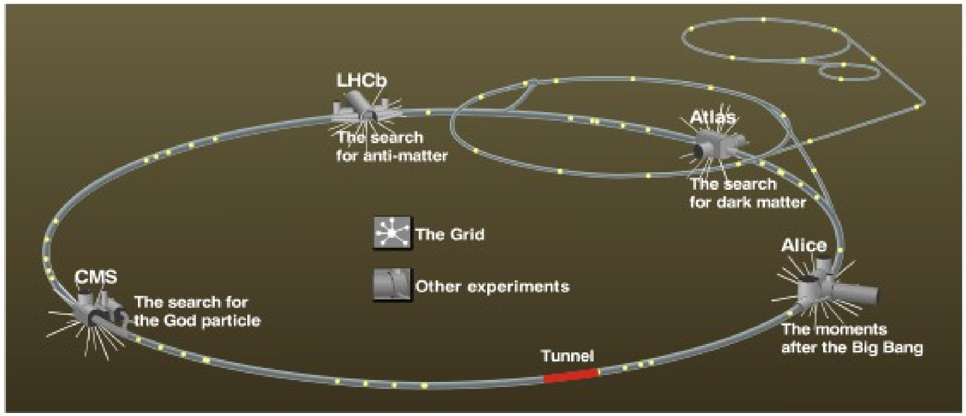


LFV RADIATIVE DECAYS:

Thick (n1=2,n2=1,n3=0)
Mn Hierarchical

Thin (n1=2,n2=0, n3=0)
Mn Two deganerate eigenvalues.

LC vs. LHC searches



LHC hadron collider sleptons appear in gaugino cascade decays:

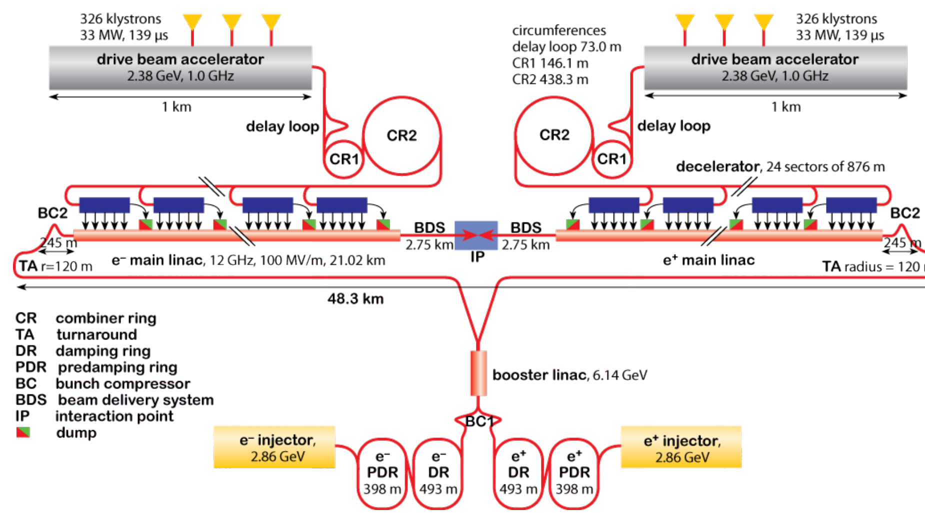
$$\tilde{\chi}_2^0 \to \tilde{l}_i^\pm l_i^\mp$$

$$\tilde{l}_i^\pm \to l_j^\pm \tilde{\chi}_1^0$$

Collider in the post-LHC era for Physics up to the multi-TeV center of mass colliding beam energy range (nominal 3 TeV).

$$e^+e^- \to \tilde{\ell}_i^- \tilde{\ell}_j^+ \to \tau^\pm \mu^\mp \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$e^+e^- \to \tilde{\nu}_i \tilde{\nu}_j^c \to \tau^\pm \mu^\mp \tilde{\chi}_1^+ \tilde{\chi}_1^-$$



$\chi_2 \to \chi + \tau^{\pm} + \mu^{\mp}$ at LHC.

- On-shell slepton production:

$$BR(\chi_2 \to \chi\tau^{\pm}\mu^{\mp}) = \sum_{i=1}^{3} BR(\chi_2 \to \tilde{l}_i\mu)BR(\tilde{l}_i \to \tau\chi) + BR(\chi_2 \to \tilde{l}_i\tau)BR(\tilde{l}_i \to \mu\chi)$$

Bartl et al,
hep-ph/0510074

- the signal in the τ channel to be optimal is definded by the following:

(i) $m_{\chi_2^0} > m_{\tilde{\tau}} > m_{\chi}^0$ (on-shell condition)

(ii) $m_{\tilde{\tau}} >> m_{\chi}^0$ (hadronised τs in the final state)

(iii) Moderate values of m_{χ}^0 (phase space and luminosity considerations).

LFV at LC

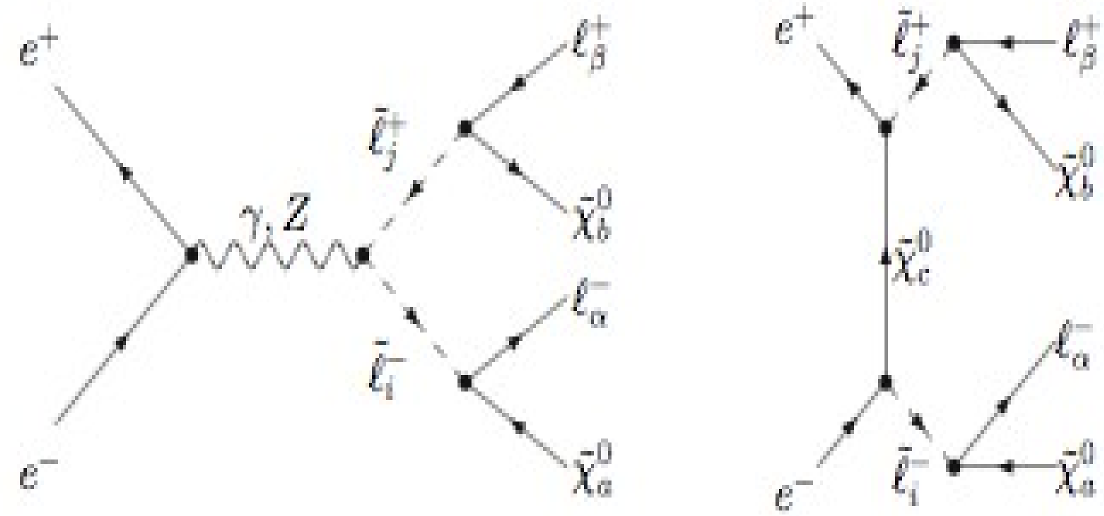
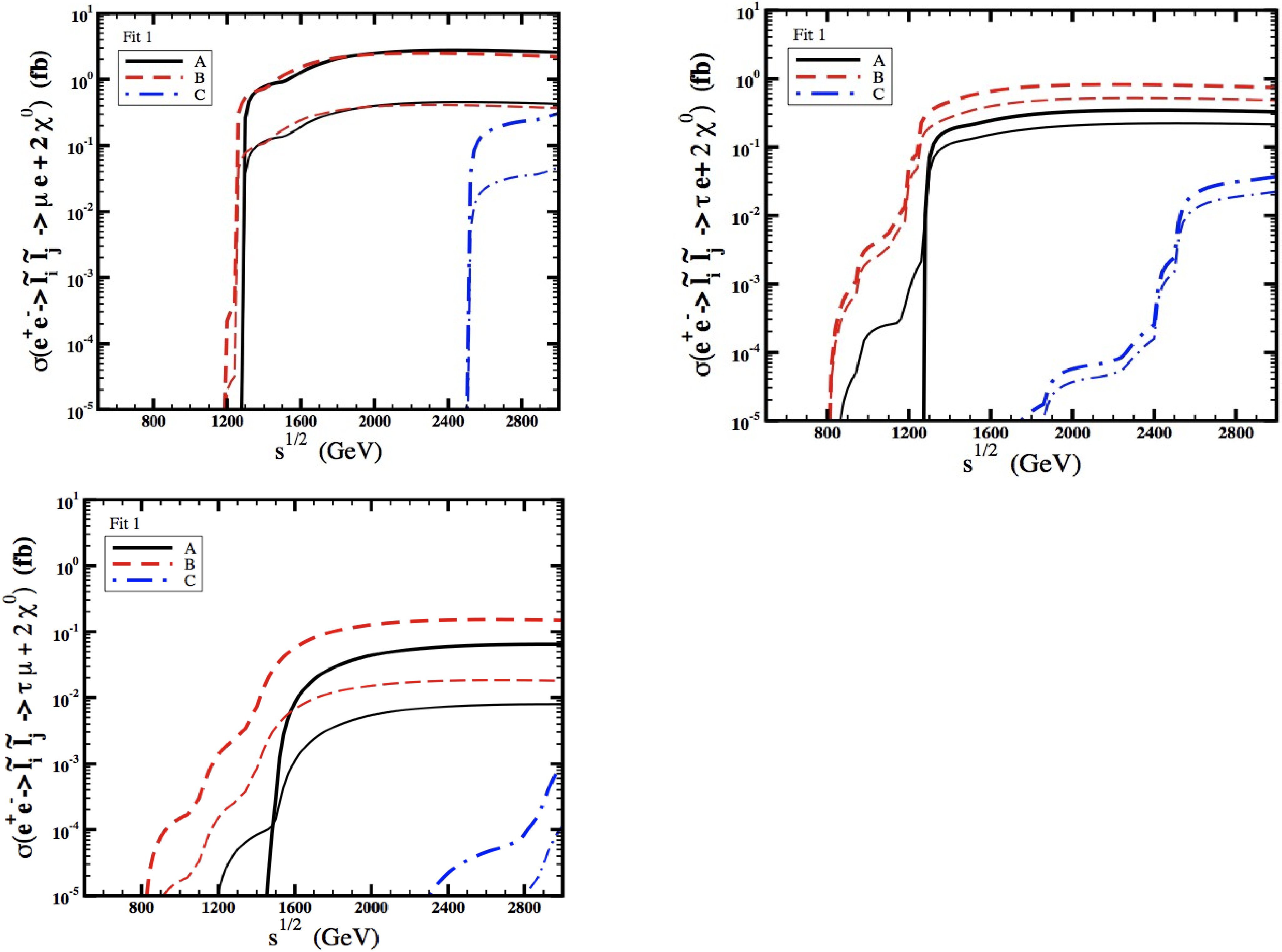


Figure 1: *Feynman diagrams for* $e^+e^- \to \tilde{\ell}_j^+\tilde{\ell}_i^- \to \ell_\beta^+\ell_\alpha^-\tilde{\chi}_b^0\tilde{\chi}_a^0$. *The arrows on scalar lines indicate lepton number flow. Similar diagrams -appropriately modified- exist for charginos.*

Direc production in
Slepton pair decays:

$$e^+e^- \to \tilde{\ell}_i^-\tilde{\ell}_j^+ \to \tau^\pm\mu^\mp\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$e^+e^- \to \tilde{\nu}_i\tilde{\nu}_j^c \to \tau^\pm\mu^\mp\tilde{\chi}_1^+\tilde{\chi}_1^-$$


Fit 1
A
B
C
σ(e+e- -> l̃i l̃j -> μ e + 2 χ0) (fb)
s1/2 (GeV)
σ(e+e- -> l̃i l̃j -> τ e+ 2 χ0) (fb)
σ(e+e- -> l̃i l̃j -> τ μ + 2 χ0) (fb)

Conclusions

- **Abelian SU(5) flavour symmetries provide very interesting possibilities for understanding the hierarchy of fermion masses and mixings. We performed a big scan of fits to the neutrino data, we get a pattern of neutrino predictions and correlations compatible with the global analysis of neutrino data.**

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- LFV identifying the range of parameters where observable signatures are possible. In general, we found that, fittings with similar predictions for the neutrino parameters may lead to very different LFV predictions. However, they can provide information on the heavy Majorana neutrino matrix.

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- Among others, the LHC data, with a neutral Higgs of about 125 GeV implies that observation of slepton flavor violation at a LC will be possible for energies beyond 3 TeV.