Slepton LSP Decays without R Parity

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The model

In the minimally supersymmetrized version of the standard model (SM) the superpotential is given by

$$W = W_{\text{MSSM}} + W_{\not{R}_p}$$

W_{MSSM} defines the minimal supersymmetric standard model (MSSM) in which R parity conservation is imposed.

$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk}\widehat{L}_i\widehat{L}_j\widehat{E}_k + \lambda'_{ijk}\widehat{L}_i\widehat{Q}_j\widehat{D}_k + \frac{1}{2}\lambda''_{ijk}\widehat{U}_i\widehat{D}_j\widehat{D}_k +$$

$$\epsilon_i\widehat{L}_i\widehat{H}_u$$

$\lambda_{ijk} = -\lambda_{jik}, \lambda_{ijk} = -\lambda''_{ikj}$.

$\Rightarrow 9 + 27 + 9 + 3 = 48$ new parameters.

The presence of baryon number violating terms (λ''_{ijk}) together with $\not{L}$ violating terms
$\rightarrow$ too fast proton decay.

Bounds of products of $\not{L} \times \not{B}$ couplings can be found in

H. Dreiner hep-ph/9707435 and G. Bhattacharyya, P. B. Pal, Phys.Lett. B439 (1998) 81

In the following we omit the $\not{B}$ terms for the mentioned phenomenological reasons.

Stau LSP

$\not{R}_p \Rightarrow$ LSP will decay

We study the case where the $\tilde{\tau}_1$ (mainly $\tilde{\tau}_R$) is the LSP.

In MSUGRA and GMSB models the lightest mass eigenstate in the charged slepton sector is usually the $\tilde{\tau}_1$ ($\simeq \tilde{\tau}_R$).

All scalar particles have a common soft SUSY breaking mass parameter at some high scale. RGE's lead to some splitting between the masses of $\tilde{\tau}_1$, $\tilde{\mu}_1$ and $\tilde{e}_1$ at the weak scale.

But since the masses of $\tilde{\mu}_1$ and $\tilde{e}_1$ are not much heavier, we have

$$\boxed{m_{\tilde{\tau}_1} \simeq m_{\tilde{\mu}_1} \simeq m_{\tilde{e}_1}}$$

Therefore also $\tilde{e}_1 \simeq \tilde{e}_R$ and $\tilde{\mu}_1 \simeq \tilde{\mu}_R$ will decay mainly via $\not{R}_p$ vertices.

We consider the decays

$$\tilde{e}_{1i} \to e_j \sum_k \nu_k$$

and

$$\tilde{e}_{1i} \to \bar{u}_j d_k$$

Collider signals if R parity is broken only bilinearly

If R-parity is broken only bilinearly
$\to$ ϵ_i, v_i (6 new parameters).

In order to accommodate neutrino data the models parameter (ϵ_i, v_i) are very constrained.

Collider signals of slepton LSP decays in the framework of bilinear $\not{R}_p$ were studied in M. Hirsch et al. Phys. Rev. D 66, 095006 (2002)

Since neutrino data fixes the model parameters stringently
$\Rightarrow$ sharp predictions can be made

The most relevant one for our concern is

$$B(\tilde{e}_1 \to e \sum \nu_i) \gtrsim 0.99$$

Collider signals if R parity is broken mainly tri-linearly

Leptonic decays:

$$\mathcal{L} = \tilde{e}_{j1}\bar{e}_k[(\sin\theta_{\tilde{e}_j}\lambda_{ijk}+O_L)P_L+(\cos\theta_{\tilde{e}_j}\lambda_{ikj}+O_R)P_R]\nu_i$$

We consider the case where $O_{L,R} \ll \lambda_{ijk}$.

$\tilde{e}_{1j} \simeq \tilde{e}_{Rj} \leftrightarrow |\sin\theta_{\tilde{e}_j}| \ll |\cos\theta_{\tilde{e}_j}|$

$$\Gamma(\tilde{e}_{j1} \to e_k \sum \nu_i) =$$

$$\frac{m_{\tilde{e}_{j1}}}{16\pi}\sum_i[(\sin\theta_{\tilde{e}_j}\lambda_{ijk})^2 + (\cos\theta_{\tilde{e}_j}\lambda_{ikj})^2]$$

Hadronic decays:

$$\Gamma(\tilde{\ell}_1 \to u_j\bar{d}_k) = 3\ \beta\ \frac{m_{\tilde{\ell}}}{16\pi}\ \sin^2\theta_{\tilde{\ell}}\ {\lambda'}^2_{\tilde{\ell}jk}\ ,$$

$\beta = 1$ for $j \neq 3$ and $\beta = (1-(\frac{m_t}{m_{\tilde{\ell}}})^2)^2$ for $j = 3$, respectively. For $\tilde{\ell}_1 \simeq \tilde{\ell}_R$ the width is highly suppressed compared to the leptonic width if $\lambda' \lesssim \lambda$.

Remark: In the pure bilinear case the hadronic decay widths are tiny and indeed unobservable.

Branching ratios: For $\tilde{\ell}_1 \simeq \tilde{\ell}_R$

$$B(\tilde{e}_1 \to (e, \mu, \tau) \sum \nu_i) \simeq \frac{1}{2}\left[1 - \frac{(\lambda^2_{231}, \lambda^2_{131}, \lambda^2_{121})}{\sum_{i<j} \lambda^2_{ij1}}\right]$$

$$B(\tilde{\mu}_1 \to (e, \mu, \tau) \sum \nu_i) \simeq \frac{1}{2}\left[1 - \frac{(\lambda^2_{232}, \lambda^2_{132}, \lambda^2_{122})}{\sum_{i<j} \lambda^2_{ij2}}\right]$$

$$B(\tilde{\tau}_1 \to (e, \mu, \tau) \sum \nu_i) \simeq \frac{1}{2}\left[1 - \frac{(\lambda^2_{233}, \lambda^2_{133}, \lambda^2_{123})}{\sum_{i<j} \lambda^2_{ij3}}\right]$$

This means:

$$B(\tilde{e}_i \to e_j \sum_k \nu_k) < 0.5, \ \forall \ i, j$$

Corrections are $\propto \theta^2_{\tilde{\ell}} \lll 1$. This implies a criterion to decide whether bilinear or trilinear $\not{R}_p$ dominates

Recall: $B(\tilde{e}_1 \to e \sum \nu_i) \gtrsim 0.99$ (bilinear)

But: $B(\tilde{e}_1 \to e \sum \nu_i) \lesssim 0.5$ (trilinear)

Remark: This criterion is independent of any assumptions made about how neutrino data is accommodated by trilinear $\not{R}_p$

Parameter determination

The solutions to the leptonic decay widths with respect to the trilinear couplings λ^2_{ijk} by making an expansion in $\theta_{\tilde{\ell}}$ read

$$\lambda^2_{121} = \frac{1}{2}\, C^{-1}\, \{\Gamma^{\tilde{e}}_{\rm tot}(1 - 2B^{\tilde{e}}_3) +$$

$$\theta^2_{\tilde{e}}(\Gamma^{\tilde{e}}_{\rm tot}(B^{\tilde{e}}_2 - B^{\tilde{e}}_3) - \Gamma^{\tilde{\mu}}_{\rm tot}B^{\tilde{\mu}}_1 + \Gamma^{\tilde{\tau}}_{\rm tot}B^{\tilde{\tau}}_1)\} + \mathcal{O}(\theta^3_{\tilde{e}}) \ ,$$

where $\Gamma^{\tilde{\ell}}_{\rm tot}$ denotes the total leptonic decay width of the appropriate scalar lepton. $C_{\tilde{e}} \simeq C_{\tilde{\mu}} \simeq C_{\tilde{\tau}}$ $(\equiv C)$. $B^{\tilde{\ell}}_{(1,2,3)} \equiv B(\tilde{\ell} \to (e, \mu, \tau) \sum \nu_k)$.

The λ^2's are expressed in terms of measureable quantities. However, one has to know the total decay width (by measuring the decay length)

Since the next to leading term is only of the order $\theta^2_{\tilde{\ell}}$ ratios of λ^2's could be given by ratios of branching ratios. i.e.,

$$\frac{\lambda^2_{121}}{\lambda^2_{131}} \simeq \frac{1 - 2B^{\tilde{e}}_3}{1 - 2B^{\tilde{e}}_2}$$

The solutions for the other λ^2's are quite similar.

Neutrino masses due to R parity violation

The contribution to the neutrino mass matrix at tree-level is induced by the bilinear terms:

$$m_{\text{eff}} = \frac{M_1 g^2 + M_2 g'^2}{4 \ \det(\mathcal{M}_{\chi^0})} \begin{pmatrix} \Lambda_e^2 & \Lambda_e \Lambda_\mu & \Lambda_e \Lambda_\tau \\ \Lambda_e \Lambda_\mu & \Lambda_\mu^2 & \Lambda_\mu \Lambda_\tau \\ \Lambda_e \Lambda_\tau & \Lambda_\mu \Lambda_\tau & \Lambda_\tau^2 \end{pmatrix},$$

$\Lambda_i = \mu v_i + v_d \epsilon_i$. m_{eff} has rg(1) $\rightarrow$ only one neutrino mass $\neq 0$.

As a result m_{eff} is diagonalized by a orthogonal matrix (V_ν) consisting of two angles (one angle can be rotated away).

1-loop contribution: $\tilde{\ell}_1$ decays are dominated by trilinear $\not{R}_p$ couplings, e.g. $\lambda_{ijk}, \lambda'_{ijk}$.

$\Rightarrow$ 1-loop contributions only by trilinear couplings are important.

1-loop contribution:

$$m_{ii'}^{\lambda(\lambda')} = -\frac{1(N_c)}{32\pi^2} \lambda_{ijk}^{(\prime)} \lambda_{i'kj}^{(\prime)} \times$$

$$\left[m_k \sin 2\theta_j \ln\left(\frac{m_{2j}^2}{m_{1j}^2}\right) + m_j \sin 2\theta_k \ln\left(\frac{m_{2k}^2}{m_{1k}^2}\right) \right],$$

m_k (fermion mass), θ_j (sfermion mixing angle), $m^2_{(1,2)j}$ (sfermion masses).

The full neutrino mass matrix: $M_\nu \simeq m_{\text{eff}} + m^\lambda + m^{\lambda'}$.

Two scenarios in which the neutrino data is accommodated (Neutrino Physics $\leftrightarrow$ Collider Physics)

$\lambda_{ijk}, \lambda'_{ijk}$ parameters determine the widths as well as the entries of the neutrino mass matrix.

Neutrino Physics $\leftrightarrow$ Collider Physics

Defining two scenarios how M_ν may be constructed.

Scenario 1:

The atmospheric mass scale is provided by m_{eff}, whereas the solar mass scale is provided by m^λ. Moreover $m^{\lambda'} \ll m^\lambda$. The couplings $\lambda_{ijk}, \forall\ i,j,k$, are roughly of the same order of magnitude.

$\Rightarrow M_\nu \simeq m_{\text{eff}} + m^\lambda$, with

$$m^\lambda \approx \frac{-1}{16\pi^2} m_\tau \sin 2\theta_{\tilde{\tau}} \ln\left(\frac{m^2_{\tilde{\tau}_2}}{m^2_{\tilde{\tau}_1}}\right) \begin{pmatrix} \lambda^2_{133} & \lambda_{133}\lambda_{233} & 0 \\ \lambda_{133}\lambda_{233} & \lambda^2_{233} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Outcome:

$$\tan 2\theta_{12} = \frac{2\sqrt{2}\ \lambda_{133}\lambda_{233}}{\lambda_{233}^2 - 2\ \lambda_{133}^2}\ ,$$

Leading order parameter reconstruction:

$$\lambda_{133}^2 \simeq \frac{1}{2}\, C^{-1}\Gamma_{\rm tot}^{\tilde\tau}(1 - 2B_1^{\tilde\tau})$$

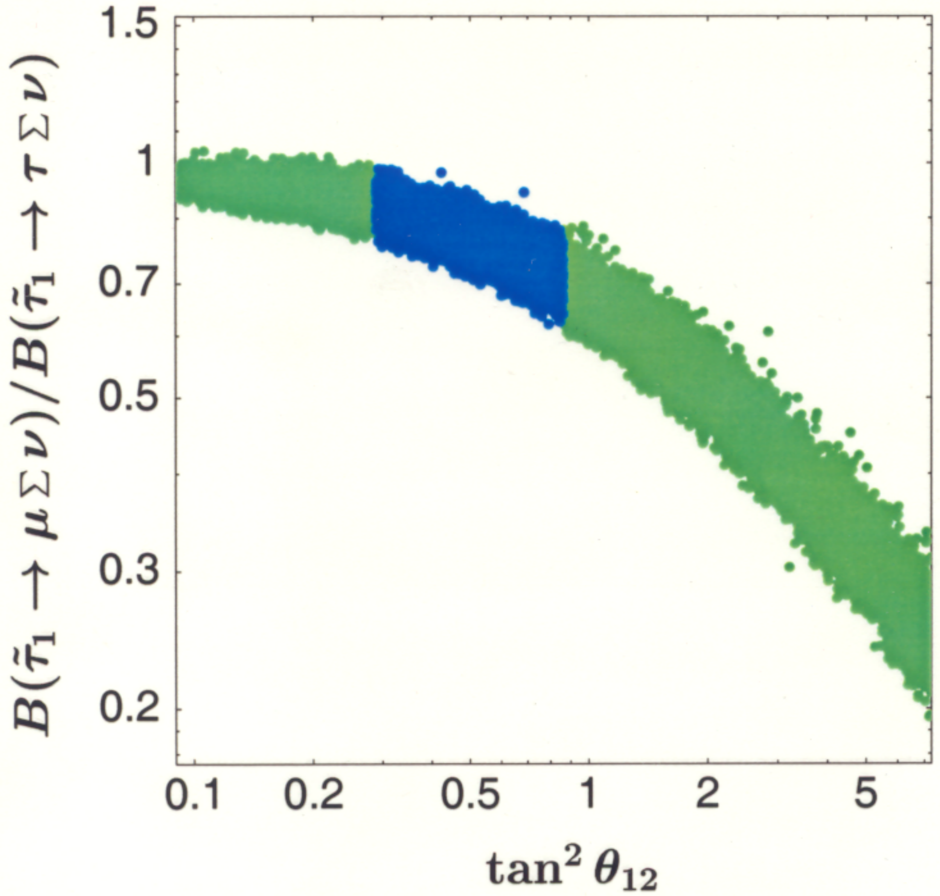
$$\lambda_{233}^2 \simeq \frac{1}{2}\, C^{-1}\Gamma_{\rm tot}^{\tilde\tau}(1 - 2B_2^{\tilde\tau})$$

Correlation between <u>branching ratios</u> and <u>solar mixing angle</u>:

$$\Rightarrow \tan 2\theta_{12}[1 + 2B_1^{\tilde\tau} - 4B_2^{\tilde\tau}] \mp$$

$$2\sqrt{2}\sqrt{(1 - 2B_1^{\tilde\tau})(1 - 2B_2^{\tilde\tau})} \approx 0$$

Correlation between $B(\tilde{\tau}_1 \to e \sum \nu_k)/B(\tilde{\tau}_1 \to \mu \sum \nu_k)$ and θ_{12}.



Constraints from neutrino data:

$$0.3 < \sin^2 \theta_{23} < 0.7$$

$$1.2 \times 10^{-3} \text{ eV}^2 < \Delta m^2_{Atm} < 4.8 \times 10^{-3} \text{ eV}^2$$

$$0.29 < \tan^2 \theta_{12} < 0.86$$

$$5.1 \times 10^{-5} \text{ eV}^2 < \Delta m^2_{\odot} < 1.9 \times 10^{-4} \text{ eV}^2$$

$$\sin^2 \theta_{13} < 0.05$$

Scenario 2:

The atmospheric mass scale is provided by $m^{\lambda'}$, whereas the solar mass scale is provided by m^{λ}. For m_{eff} the relation $m_{\text{eff}} \ll m^{\lambda}$ holds. The couplings λ_{ijk} and $\lambda'_{ijk}, \forall\ i, j, k$, are roughly of the same order of magnitude.

$\Rightarrow M_\nu \simeq m^{\lambda'} + m^{\lambda}$.

m^{λ} is the same as before while $m^{\lambda'}$ is approximately given by

$$m^{\lambda'} \approx -\frac{3}{16\pi^2} m_b \sin 2\theta_{\tilde{b}} \ln\left(\frac{m^2_{\tilde{b}_2}}{m^2_{\tilde{b}_1}}\right) \times$$

$$\begin{pmatrix} \lambda'^2_{133} & \lambda'_{133}\lambda'_{233} & \lambda'_{133}\lambda'_{333} \\ \lambda'_{133}\lambda'_{233} & \lambda'^2_{233} & \lambda'_{233}\lambda'_{333} \\ \lambda'_{133}\lambda'_{333} & \lambda'_{233}\lambda'_{333} & \lambda'^2_{333} \end{pmatrix}$$

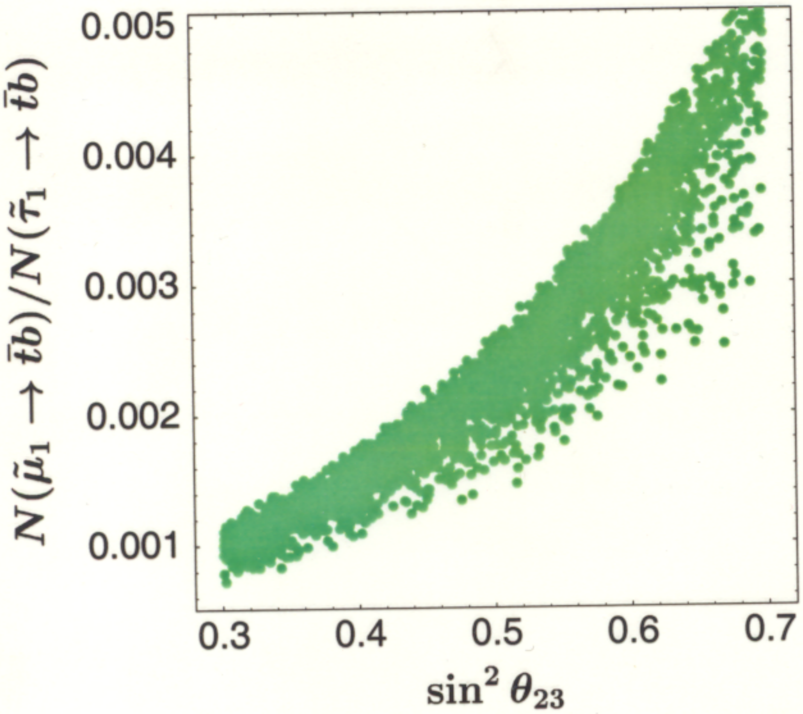
$\tan\theta_{23}$ can be approximately expressed as

$$\tan\theta_{23} \approx -\frac{\lambda'_{233}}{\lambda'_{333}}$$

This ratio squared can be related to the observable

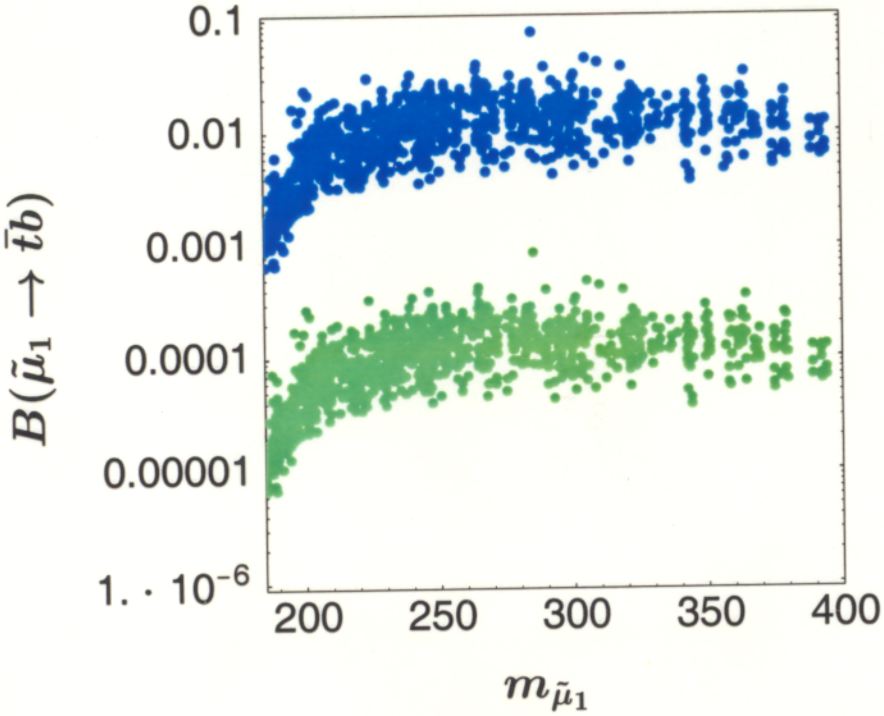
$$\frac{N(\tilde{\mu}_1 \to \bar{t}b)}{N(\tilde{\tau}_1 \to \bar{t}b)} \approx \left(\frac{\sin\theta_{\tilde{\mu}}\ \lambda'_{233}}{\sin\theta_{\tilde{\tau}}\ \lambda'_{333}}\right)^2 \approx \frac{m^2_{\mu}}{m^2_{\tau}}\ \tan^2\theta_{23},$$

where $N(\tilde{\ell}_1 \to \bar{t}b)$ denotes the number of $\tilde{\ell}_1$ which decay into the final state $\bar{t}b$.



Green points: All λ's of the same order of magnitude.

Blue points: $\lambda_{ij2} \sim 10^{-1}\lambda_{ij3}$.



Conclusion

We have studied the R-parity violating decay properties of the LSP being the $\tilde{\tau}_1$ (mainly $\tilde{\tau}_R$, as suggested in a mSUGRA or GMSB model). In such models $\tilde{\mu}_1$ and $\tilde{e}_1$ are not much heavier than $\tilde{\tau}_1$. Therefore, also $\tilde{\mu}_1$ and $\tilde{e}_1$ decay mainly via $\not{R}_p$ vertices.

We have assumed that these decays are dominated by the trilinear couplings e.g. $\lambda_{ijk}, \lambda'_{ijk}$, and the bilinear contribution is suppressed (the reversed situation was studied by M. Hirsch et al. Phys. Rev. D 66, 095006 (2002))

The results:

- $B(\tilde{e}_i \to e_j \sum_k \nu_k) \lesssim 0.5,\ \forall\ i,j$ (this provides a test whether bilinear or trilinear $\not{R}_p$ dominates).

- The absolut values of the 9 λ's may be determined through the 9 leptonic $\not{R}_p$ decays. However, the knowledge of the total decay widths is needed. If this information is not accessible still certain ratios of the λ's may be given. Because of the small mixing angles $\theta_{\tilde{\ell}}$, informations about the λ''s are only obtainable if $\lambda' \gg \lambda$.

- We have demonstrated (in 2 scenarios) that testable connections between neutrino physics and collider physics exist, irrespective of the large number of parameters.