Neutrino properties and the decay of the lightest supersymmetric particle

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Abstract

Supersymmetry with broken R-parity can explain the neutrino mass squared differences and mixing angles observed in neutrino oscillation experiments. In the minimal model, where R-parity is broken only by bilinear terms, certain decay properties of the lightest supersymmetric particle (LSP) are correlated with neutrino mixing angles. Here we consider charginos, squarks, gluinos and sneutrinos being the LSP and calculate their decay properties in bilinear R-parity breaking supersymmetry. Together with the decays of charged scalars and neutralinos calculated previously this completes the proof that bilinear R-parity breaking as the source of neutrino masses will be testable at future colliders. Moreover, we argue that in case of GMSB, the decays of the NLSP can be used to test the model.

1 Introduction

In supersymmetric models with R-parity violation (RpV) [1, 2, 3] the lightest supersymmetric particle (LSP) is unstable and decays. Thus astrophysical constraints on its nature [4] no longer apply and a priori *any* SUSY particle could be the LSP. On the other hand, most studies of LSP phenomenology at accelerators in RpV models up to now have concentrated on a) the lightest neutralino [5, 6] or b) a charged scalar (most probably the right scalar tau) [7, 8] being the LSP. The purpose of the present work is to study the phenomenology of the remaining LSP candidates (charginos, gluinos, scalar quarks and scalar neutrinos) at future colliders for the case where R-parity is broken by bilinear terms only.

Arguably at present the main motivation to study RpV SUSY models is the astonishing *experimental* progress in neutrino physics in the past few years. Super-K observations of atmospheric neutrinos [9], solar neutrino measurements by the SNO collaboration [10] and the reactor anti-neutrino experiment KamLAND [11] have finally established non-zero neutrino masses and mixings beyond any reasonable doubt. Bilinear RpV (BRpV) SUSY models necessarily produce Majorana neutrino masses and indeed in [12] it was shown that BRpV SUSY can explain current neutrino data, once 1-loop corrections are carefully taken into account.

Can one test BRpV SUSY being the origin of neutrino masses and mixings? Conventional wisdoms says, if SUSY is to solve the gauge hierarchy problem, superpartners should be found at the next generation of colliders. In general, the only predictable difference between R-parity conserving and R-parity violating SUSY then would be a decaying LSP. Given the relatively small number of free parameters in BRpV SUSY, however, one can go further and from measured data on neutrino properties *predict* several decay properties of the LSP. This was shown for the case of the neutralino being LSP in [5] and for charged scalar LSPs in [7]. In both cases, interesting relations between certain decay patterns and low-energy neutrino data have been found. The most important are: (i) The ratio $BR(\chi_1^0 \to \mu q\bar{q}')/BR(\chi_1^0 \to \tau q\bar{q}') \simeq \tan^2\theta_{Atm}$ and (ii) $BR(\tilde{\tau}_1 \to e\nu)/BR(\tilde{\tau}_1 \to \mu\nu) \simeq \tan^2\theta_{sol}$.

The minimal supersymmetric extension of the standard model (MSSM) [13] contains more than a hundred free parameters, most of which are soft SUSY breaking masses and phases. Supplementing the MSSM with universal mSugra boundary conditions [13] reduces this number to just four free parameters plus an undetermined sign (in addition to the standard model parameters). These are given at the grand unification (GUT) scale as: m_0, the common scalar mass, $m_{1/2}$, the gaugino mass, and A_0, the common trilinear parameter. In addition one usually chooses $\tan\beta = v_u/v_d$ and the sign of the Higgs mixing term $|\mu|$ as free parameters. Parameters at the electro-weak scale can then be calculated from RGE running, reducing considerably the available parameter space.

In such a constrained version of the MSSM (CMSSM) one finds essentially only two LSP candidates, namely, the lightest neutralino and the right sleptons, in particular the right scalar tau if $\tan\beta$ is large. Arguably it is this theoretical prejudice why also in RpV models other possibilities so far have attracted little attention.

Models which depart from strict mSugra in one way or another, however, can be found in the literature. Just to mention a few representative examples, there are string inspired

models where supersymmetry breaking is triggered not only by the dilaton fields but also by moduli fields [14]. In $SO(10)$ or $E(6)$ models, where all neutral gauge bosons, except those forming Z and γ, have masses of the order of m_{GUT} one expects additional D-term contributions to the sfermion mass parameters at m_{GUT} [15]. This is equivalent to assuming non-universal values of m_0 for left-sleptons, right-sleptons, left-squarks and right squarks, giving rise e.g. to sneutrino LSPs. In gauge mediated supersymmetry breaking (GMSB) models [16] exists the possibility, that the gluino is the LSP [17]. In AMSB models [18] one can find parameter regions where the chargino is the LSP (nearly mass degenerate with the lightest neutralino).

To be as general as possible, however, in this work we will not resort to any specific model of SUSY breaking. Instead we will simply point out in which way one has to depart from mSugra to obtain the corresponding LSP and then proceed to calculate its decay properties. To summarize our main result it can be said that independent of which SUSY particle is the LSP there is at least one ratio of decay branching ratios which is fixed by either the solar or the atmospheric neutrino angle, i.e. independent of the LSP nature, BRpV SUSY as the origin of neutrino masses is testable at future colliders.

This paper is organized as follows. In the next section we will recapitulate the main features of the bilinear R-parity violating model. Then we will turn to the numerical calculations. Decays of squarks, gluinos, charginos and scalar neutrinos will be discussed in detail. Before concluding with a short summary, we will argue that also in case of GMSB [18], BRpV SUSY remains testable due to the decay patterns of the NLSP.

2 The Model

Bilinear R-parity breaking supersymmetry has been discussed extensively in the literature [1, 12]. We will therefore summarize only the main features of the model here, with emphasis on neutrino physics. The Lagrangian of the model is obtained by adding bilinear terms breaking lepton number to the MSSM superpotential:

$$W_{\mathrm{BRpV}} = W_{\mathrm{MSSM}} - \varepsilon_{ab}\epsilon_i \widehat{L}_i^a \widehat{H}_u^b \,, \tag{1}$$

and consistently the corresponding terms to the soft SUSY breaking potential:

$$V_{\mathrm{soft}} = V_{\mathrm{soft,MSSM}} - \varepsilon_{ab}B_i\epsilon_i \widetilde{L}_i^a H_u^b \,. \tag{2}$$

The latter induce vacuum expectation values v_i for the sneutrinos which are in turn responsible for mixing between standard model particles with supersymmetric particles: Higgs bosons with sleptons, charged leptons with charginos and, most importantly for the following considerations, neutrinos with neutralinos.

The mixing of neutrinos with neutralinos gives rise to one massive neutrino at tree level. The other two neutrinos obtain masses due to loop effects [12]. Assuming that the heaviest neutrino obtains its mass at tree level, the main features relevant for our current purpose are the following. The mass of the heaviest neutrino is given by:

$$m_{\nu_3} = \frac{(gM_1 + g'M_2)|\vec{\Lambda}|^2}{4\mathrm{Det}(\tilde{\chi}^0)} \tag{3}$$

$$\Lambda_i = \epsilon_i v_d + \mu v_i \,. \tag{4}$$

The atmospheric neutrino mixing angle is given by

$$\tan\theta_{\mathrm{Atm}} = \left|\frac{\Lambda_2}{\Lambda_3}\right| \tag{5}$$

and the so-called CHOOZ angle by

$$U_{e3}^2 \simeq \frac{\Lambda_1^2}{\Lambda_2^2 + \Lambda_3^2}. \tag{6}$$

The scale of the loop-induced solar mass is given by

$$m_{\nu_2} \propto \frac{|\vec{\epsilon}|^2}{16\pi^2\mu^2}m_b \tag{7}$$

and the solar mixing angle by

$$\tan\theta_{\mathrm{sol}} \simeq \left|\frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2}\right| \tag{8}$$

$$\tilde{\epsilon}_i = V_{ij}^{\nu,\mathrm{tree}}\epsilon_j \tag{9}$$

where $V^{\nu,\mathrm{tree}}$ is the tree level neutrino mixing matrix [12]. In the region where the condition $(\epsilon_2\Lambda_2)/(\epsilon_3\Lambda_3) < 0$ is fulfilled one finds that $\tilde{\epsilon}_1/\tilde{\epsilon}_2 \simeq \epsilon_1/\epsilon_2$. For a more thorough discussion see ref. [12].

In this model the neutrino spectrum is hierarchical and hence the neutrino mass scales coincide with the (square roots of) the mass squared differences measured in oscillation experiments. This implies that the R-parity violating parameters are significantly smaller than the R-parity conserving parameters: $|\epsilon_i| \ll |\mu|$ and $|v_i| \ll v_d$. This feature allows for the possibility that all R-parity violating couplings can be expanded in terms of the ratios

$$\frac{\epsilon_i}{\mu}, \quad \frac{\Lambda_i}{\sqrt{\mathrm{Det}(\tilde{\chi}^0)}} \quad \text{or} \quad \frac{\Lambda_i}{\mathrm{Det}(\tilde{\chi}^+)}. \tag{10}$$

Several examples of this kind can be found in [5, 7, 12, 19]. We have used this possibility for a systematic expansion of the R-parity violating couplings to obtain a semi-analytical understanding of the results presented in the following section. For completeness we want to note that in our model also gauginos and gauge bosons have R-parity violating couplings implying that one can clearly distinguish BRpV from a model where only trilinear R-parity violating couplings are present.

3   Numerical results

In this section we present various collider observables and their correlations with neutrino observables for the following LSP candidates: charginos, sneutrinos, squarks and gluino. The numerical results are obtained in the following way except if stated otherwise: (i) We create a random sample over the SUSY parameter space, using five free parameters: m_0,

$m_{1/2}$, A_0, $tan\beta$ and μ. Motivated by mSugra, we calculate the gaugino masses approximately from $m_{1/2}$, for the sfermion mass parameters we use m_0 directly at the electroweak scale. We have checked explicitly for several LSP sets that the latter simplification has no impact on our results. We then violate one of the following mSugra conditions at a time. Each condition is necessary but not sufficient to obtain the corresponding LSP, i.e. after calculating the SUSY spectrum we post-select points which have the desired candidate LSP. Chargino LSPs are obtained by the condition $m_2 \simeq (5/3) \tan^2 \theta_W m_1$, sneutrino LSPs by $m_{L_i}^2 \ll m_0^2$, squark LSPs by $m_Q^2, m_D^2, m_U^2 \ll m_0^2$ and gluino LSPs by $m_3 \ll m_2, m_1$. (ii) The R-parity violating parameters are added such, that Δ_{Atm}^2 and Δ_{sol}^2 are consistent with the experimental data.

We want to stress that the correlations between low-energy and high-energy observables shown in the following are predictions after a generous sampling over the SUSY parameter space. Much tighter correlations could be obtained, once information on at least a part of the SUSY spectrum is put in, see e.g. ref. [5] for the case of neutralinos. In particular information on $\tilde\chi_j^0$, $\tilde\chi_k^+$, $\tilde\tau_i$, $\tilde b_i$ and H^+ would be important in this respect.

3.1 Charginos

For chargino LSPs possible final states are

$$\tilde\chi_1^+ \quad\rightarrow\quad \sum_{q=d,s;q'=u,c} \bar q q' \nu_i; \bar b t \nu_i \tag{11}$$

$$\tilde\chi_1^+ \quad\rightarrow\quad l_i^+ \sum_{q=u,d,s} q\bar q; l_i^+ \bar c c; l_i^+ \bar b b; l_i^+ \bar t t; \tag{12}$$

$$\tilde\chi_1^+ \quad\rightarrow\quad l_i^+ l_j^+ l_k^- \tag{13}$$

$$\tilde\chi_1^+ \quad\rightarrow\quad l_i^+ \nu_r \nu_s \tag{14}$$

where $l_i = e, \mu, \tau$ and we sum over the three neutrino flavours as well as the lighter quark states u, d and s which cannot be separated experimentally. Note, that we calculate here the 3-body decays even if an intermediate real 2-body final state is possible by including the finite width of the intermediate states. These intermediate states contain in general a gauge boson, whose R-parity violating couplings to charginos are typically an order of magnitude smaller compared to the R-parity violating couplings of the virtual sfermions.

Numerically one finds that the final state $\bar q q' \sum_j \nu_j$ has usually the largest branching ratio (up to 65 %). Typical branching ratios for other final states not containing a top quark are in the range of several per mille to a few per–cent. Final states with top quarks are found to be always very small or kinematically closed, because $m_{\tilde\chi_1^+}$ does not exceed 300 GeV in our numerical data sets. Moreover, the intermediate states are always off-shell in this case contrary to final states involving light quarks.

As a first example how neutrino physics allows to predict observables for collider physics we plot in Fig. 1 $\Gamma/m_{\tilde\chi^+}^5$ [meV/(100 GeV)^5] as a function of the heaviest neutrino mass m_{ν_3} [eV]. We scale out a fifth power of the chargino mass to account approximately for the phase space of the decay. [1]

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[1]Although this was not discussed in [5] a similar correlation holds for the case of the lightest neutralino being the LSP.
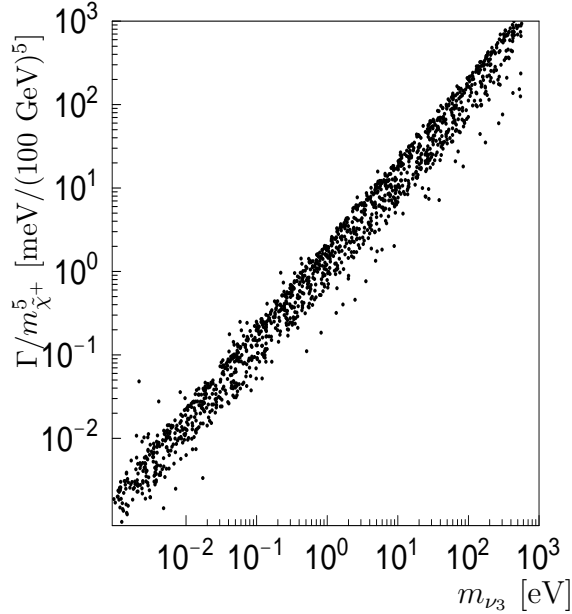
Figure 1: Chargino decay width divided by $m_{\tilde{\chi}^+}^5$ as a function of the heaviest neutrino mass

Fig. 1 shows an obvious correlation between chargino decay width and neutrino mass. However, there is a sizable spread in the prediction. Thus such a measurement could probably never compete with neutrino oscillation experiments in terms of accuracy. Nevertheless, from the current data on atmospheric neutrinos one can roughly predict,

$$\frac{\Gamma}{m_{\tilde{\chi}^+}^5} = (0.02 - 1.2) \quad [\frac{meV}{(100 GeV)^5}] \tag{15}$$

Eq.(15) can be considered as a consistency check for the completeness and uniqueness of the bilinear model as the main source of the (atmospheric) neutrino mass. Significantly smaller or larger widths would be a clear signal that BRpV cannot explain the neutrino data. Note that the width of the band gets reduced sizeably once some information on the SUSY spectrum is available.

As discussed previously [5], ratios of different branching ratios of the LSP decays can trace information on ratios of RpV parameters. In case of the lightest chargino being the LSP we have found that various ratios are sensitive to ratios of Λ_i/Λ_j. Two examples are shown in Fig. 2. In this figure we show $BR(\tilde{\chi}^+ \to e\bar{c}c)/BR(\tilde{\chi}^+ \to \mu\bar{c}c)$ (to the left) and $BR(\tilde{\chi}^+ \to \mu\bar{c}c)/BR(\tilde{\chi}^+ \to \tau\bar{c}c)$ (to the right) as function of Λ_1/Λ_2 and Λ_2/Λ_3, respectively. Obviously measurements of these branching ratios would determine the corresponding ratio of Λ's to high accuracy. Somewhat worse results are obtained if one has to sum over the quarks of the first two generations.

Since Λ_2/Λ_3 determines the atmospheric angle in BRpV, one expects the ratios discussed above to be correlated with $\tan^2\theta_{Atm}$. That this is indeed the case is shown in Fig. 3, where we plot $BR(\tilde{\chi}^+ \to \mu\bar{q}q)/BR(\tilde{\chi}^+ \to \tau\bar{q}q)$ as a function of $\tan^2\theta_{\text{Atm}}$ summing over all quarks of the first two generations. For the currently preferred value of
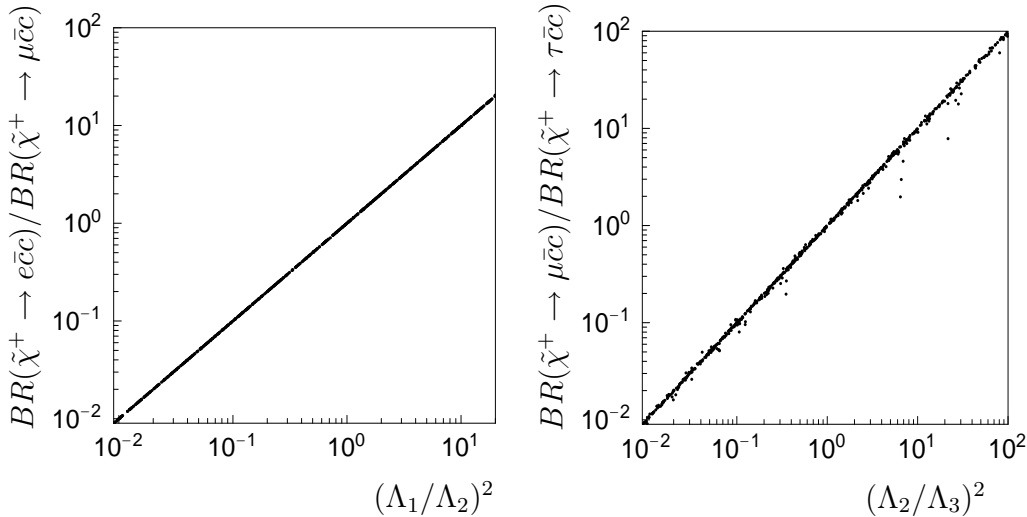
Figure 2: Ratio of branching ratios for chargino decay. To the left, $BR(\tilde{\chi}^+ \to e\bar{c}c)/BR(\tilde{\chi}^+ \to \mu\bar{c}c)$ as a function of $(\Lambda_1/\Lambda_2)^2$. To the right, $BR(\tilde{\chi}^+ \to \mu\bar{c}c)/BR(\tilde{\chi}^+ \to \tau\bar{c}c)$ as a function of $(\Lambda_2/\Lambda_3)^2$.

Table 1: Ratio of branching ratios for chargino LSP decays as required by the consistency of the model. These ratios all trace the ratio Λ_2/Λ_3. The experimentally allowed range for the atmospheric neutrino angle, $0.3 \leq \sin^2(\theta_{Atm}) \leq 0.7$ (at $3\,\sigma$ c.l.), has been used to obtain the quoted ranges. Ratios have been sorted with respect to increasing uncertainties.

Ratio	lower bound	upper bound
$\mathrm{Br}(\mu\bar{c}c)$ / $\mathrm{Br}(\tau\bar{c}c)$	0.45	1.4
$\mathrm{Br}(\mu\bar{q}q)$ / $\mathrm{Br}(\tau\bar{q}q)$	0.45	1.4
$\mathrm{Br}(\mu 2e)$ / $\mathrm{Br}(\tau 2e)$	0.45	1.4
$\mathrm{Br}(\mu\bar{b}b)$ / $\mathrm{Br}(\tau\bar{b}b)$	0.46	2.1
$\mathrm{Br}(3\mu)$ / $\mathrm{Br}(\tau 2\mu)$	0.28	1.8
$\mathrm{Br}(3\mu)$ / $\mathrm{Br}(3\tau)$	0.096	1.4

$\tan^2\theta_{Atm} = 1$ one expect approximately equal branching ratios for these final states, nearly independent of any other parameter.

Due to the fact that the chargino has many possible final states, one can devise various cross checks of the bilinear model. We have found that the following ratios are sensitive to Λ_1/Λ_2 only to a good approximation: $BR(\tilde{\chi}^+ \to e\bar{q}q)/BR(\tilde{\chi}^+ \to \mu\bar{q}q)$, $BR(\tilde{\chi}^+ \to 3e)/BR(\tilde{\chi}^+ \to \mu 2e)$ and $BR(\tilde{\chi}^+ \to 3e)/BR(\tilde{\chi}^+ \to 3\mu)$.

Similarly there are a number of ratios which trace very well the ratio Λ_2/Λ_3. Since the latter quantity is related to the atmospheric angle, using the currently available experimental data on $\tan^2(\theta_{Atm})$, one can *predict* various ratios of branching ratios. Ranges allowed by current data are listed in Table 1.
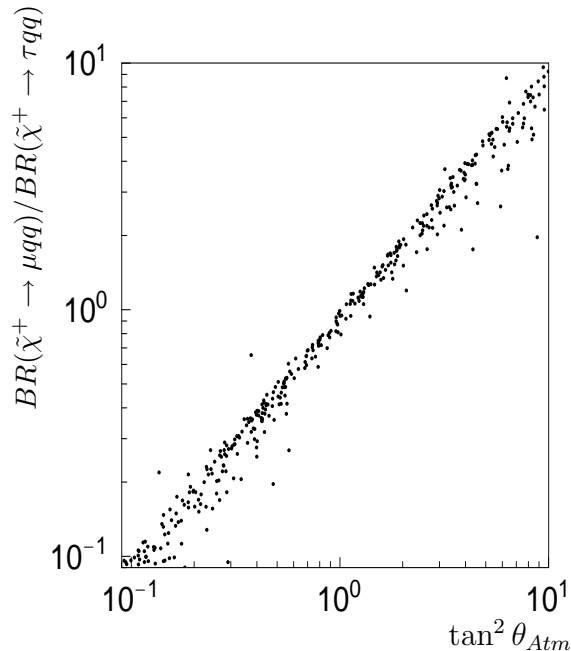
Figure 3: Ratio of chargino decay branching ratios $BR(\tilde{\chi}^+ \to \mu qq)/BR(\tilde{\chi}^+ \to \tau qq)$ versus $\tan^2 \theta_{Atm}$. For the currently preferred value of $\tan^2 \theta_{Atm} = 1$ one expect approximately equal branching ratios for these final states.

3.2 Sneutrinos

In the case that sneutrinos are the LSPs they will decay according to

$$\tilde{\nu}_i \rightarrow q\bar{q} \tag{16}$$
$$\tilde{\nu}_i \rightarrow l_j^+ l_k^- \tag{17}$$
$$\tilde{\nu}_i \rightarrow \nu_j \nu_k \tag{18}$$

Scanning over the parameter space one finds the following general features: (i) The main decay mode is for all sneutrinos $\tilde{\nu}_i \to b\bar{b}$. (ii) The branching ratios for decays into charged leptons are $O(10^{-2})$. (iii) The invisible decay mode into two neutrinos is $O(10^{-3})$ and below. Moreover, it turns out that the decay lengths of all sneutrinos have the same order of magnitude because (a) the largest couplings are of the form $\epsilon_i Y_b$ and (b) the largeness of the solar mixing angle requires $\epsilon_1 \simeq \epsilon_2$ and one expects that also ϵ_3 is of similar size. This implies that one has to sum over all sneutrinos if one considers the direct production at an e^+e^- collider. Therefore we consider the following quantity:

$$\sigma * BR(l_i^\pm l_j^\mp) \equiv \sum_{r,s=1}^{3} \sigma(e^+e^- \to \tilde{\nu}_s \tilde{\nu}_r \to b\bar{b}l_i^\pm l_j^\mp) \tag{19}$$

In Fig. 4a – d we show the ratio of these observables as a function of $(\epsilon_1/\epsilon_2)^2$ and $\tan^2 \theta_{sol}$. The correlations of the collider observables with neutrino physics are obvious. The range for the observables under study is $\sigma * BR(e\mu) = O(10^{-2})$–$O(1)$ fb, $\sigma * BR(\mu\mu) = O(0.1)$ fb, $\sigma * BR(\mu\tau) = O(0.1)$–$O(10)$ fb at a 800 GeV e^+e^- linear collider and unpolarized beams.

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Larger cross sections are obtained for polarized beams with left–handed electrons and right–handed positrons. We want to stress again, that the spread in the correlations is mainly due to the unknown SUSY spectrum. It gets considerably reduced once information on the SUSY spectrum is plugged in.

In principal one could tag the flavour of the sneutrino in cascade decays, e.g. in the decay $\tilde{\chi}_1^+ \to l^+ \tilde{\nu}$ and then study the subsequent decay of the sneutrino into leptons. Due to the fact that all involved decays are two-body decays, one can distinguish the lepton stemming from the chargino from the ones stemming from the sneutrino by measuring the lepton energy except in the case where $m_{\tilde{\chi}_1^+} \simeq 3m_{\tilde{\nu}}/2$. In Fig. 4e and f we show correlations between the branching ratio of the muon sneutrino and $(\epsilon_1/\epsilon_2)^2$ and $\tan^2 \theta_{\rm sol}$ assuming that such a flavour tag can indeed be performed. As can be seen, current results for the solar mixing angle predict that $\mathrm{BR}(\tilde{\nu}_\mu \to e^\pm \mu^\mp) / \mathrm{BR}(\tilde{\nu}_\mu \to \mu^\pm \tau^\mp)$ is in the range $0.4 - 2$ independent of the remaining SUSY parameters.

In scenarios, where sneutrinos are the LSPs, the left charged sleptons are not much heavier. The difference between the masses of the charged left sleptons and sneutrinos is roughly given by: $m_{\tilde{l},L}^2 - m_{\tilde{\nu}}^2 \simeq -\cos 2\beta m_W^2 > 0$. Depending on the mass difference the left sleptons decay in these scenarios either via three body decays, which conserve R-parity, into [20, 21]

$$\tilde{l}_L \quad \to \quad \tilde{\nu}\,\bar{q}q' \tag{20}$$
$$\tilde{l}_L \quad \to \quad \tilde{\nu}\,\nu l \tag{21}$$

or via R-parity violating couplings into

$$\tilde{l}_L \quad \to \quad \bar{q}q' \tag{22}$$
$$\tilde{l}_L \quad \to \quad \nu l\,. \tag{23}$$

The latter decay modes give in principal rise to additional observables correlated with neutrino physics. However, we have found that for mass differences larger than $\simeq 5$ GeV the three body decays clearly dominate. Therefore this additional information is only aviable if either $\tan \beta$ is small and/or if all particles have masses above $\gtrsim 400$ GeV.

3.3 Squarks

Here we discuss the decays of the squarks of the first two generations as well as the decays of the lighter sbottom. The decays of the lighter stops have been discussed in detail in ref. [19] and are similar to the results for the sbottoms discussed below.

In the case that squarks are the lightest SUSY particle, they will decay according to

$$\tilde{q} \quad \to \quad q\,\nu \tag{24}$$
$$\tilde{q} \quad \to \quad q'\,l \tag{25}$$

In case that the mass difference between the squarks of the first two generation is larger than approx. 5 GeV, the heavier ones will dominantly decay according to

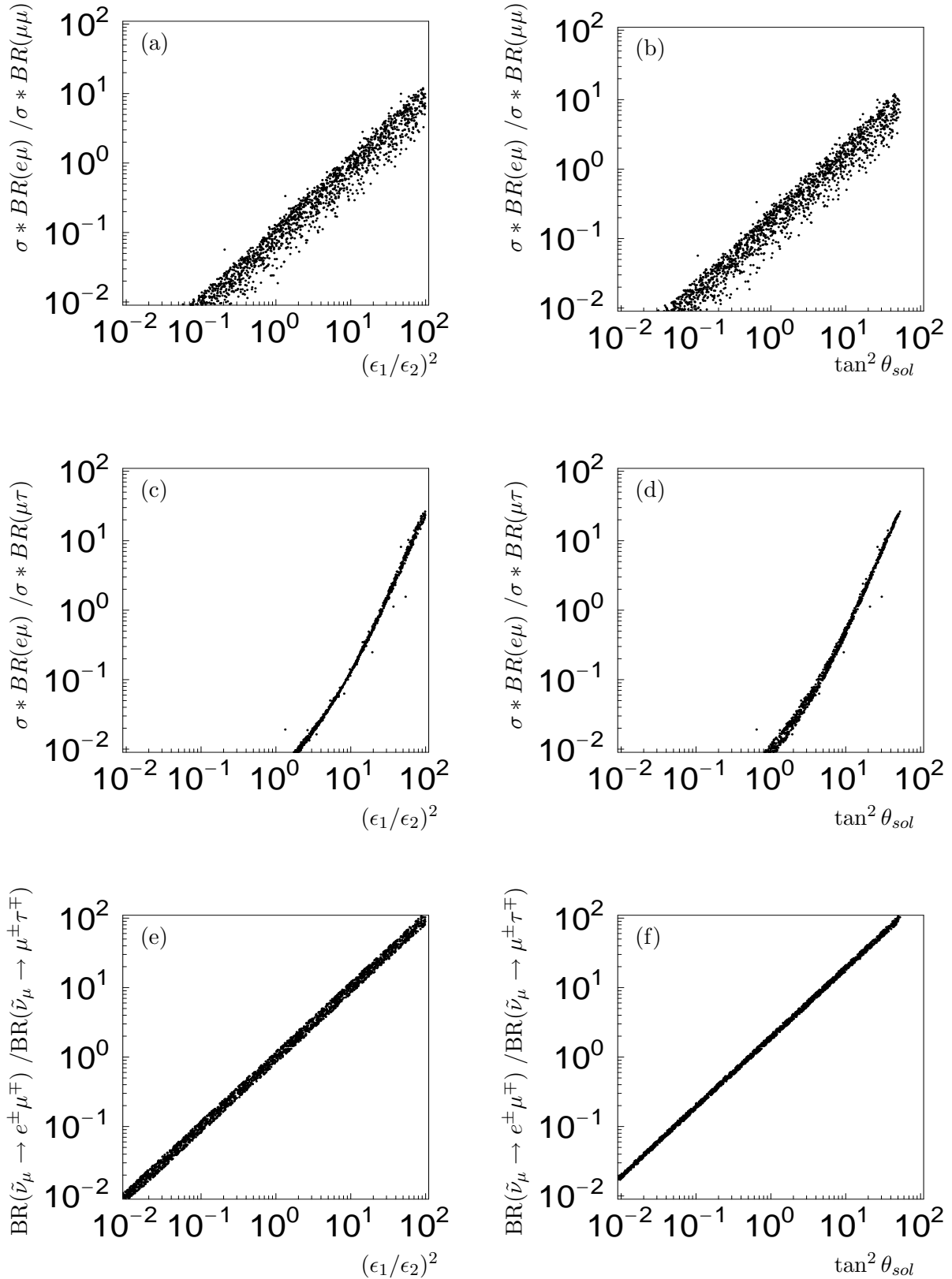$$\tilde{q} \quad \to \quad \tilde{q}'\,q\,\bar{q}' \tag{26}$$

Figure 4: Various sneutrino observables as a function of $(\epsilon_1/\epsilon_2)^2$ (left column) and $\tan^2 \theta_{sol}$ (right column). $\sigma * BR(l_i l_j)$ is defined as $\sum_{r,s=1}^{3} \sigma(e^+ e^- \to \tilde{\nu}_s \tilde{\nu}_r \to b\bar{b} l_i^{\pm} l_j^{\mp})$. For discussion see text.

mediated mainly via gluino exchange. Here we have used the formulas given in [21]. This decay mode dominates the decays of $\tilde{d}_L$, because $m_{\tilde{d}_L} > m_{\tilde{u}_L} + 5$ GeV for $m_{\tilde{Q}} < 500$ GeV and $\tan\beta \geq 3$ due to the D-terms in the mass matrix.

The important decay modes related to neutrino physics are those induced by the effective $\hat{L}_i\hat{Q}\hat{D}_R^c$ coupling which is proportional to $\epsilon_i h_d$. In the numerical results below we assume that the first two generations of squarks are mass degenerate. This assumption is motivated by the experimental constraints from meson physics, in particular for the K^0-$\bar{K}^0$ mixing [22]. However, we do not assume left and right squarks have the same mass.

Typical examples are shown in Fig. 5, where we consider three different scenarios: (i) In Fig. 5a and b we show the case where $\tilde{u}_L$ and $\tilde{c}_L$ are the LSPs. One sees that the corresponding relations between $\tan^2\theta_{sol}$ (or $(\epsilon_1/\epsilon_2)^2$) and ratios of branching ratios into charged leptons are extremely pronounced. Note that the decays into leptons clearly dominate, with a total branching ratio of $0.6 - 0.9$ summed over all charged leptons. (ii) In Fig. 5c and d we show how the results are changed if one sums over the left and right squarks of the first two generations. As discussed above, $\tilde{d}_L$ and $\tilde{s}_L$ are not included in this sum because their R-parity violating decay modes are negligible. The correlations are somewhat worse compared to the previous case because $\tilde{u}_R$ ($\tilde{c}_R$) decay into leptons only via their mixing with the corresponding left partner and the corresponding branching ratios are of order 10^{-3}–10^{-2}. The branching ratios of $\tilde{d}_R$ and $\tilde{s}_R$ into leptons is approximately in the range 0.05 - 0.5. (iii) In Fig. 5e and f we show the correlations if $\tilde{b}_1$ is the LSP. One sees that the ratio of branching ratios into top quarks is nicely related to the ratios of the ϵ_i squared. In the case that this decay is suppressed the decays into a lepton and a c–quark give similar, although somewhat worse, results. In this case the branching ratio is of order 10^{-2}.

Finally, we want to note that these correlations are hardly affected by QCD corrections because they nearly drop out by taking the ratio of branching ratios. We have checked this explicitly by adopting the formulas given in [23] to the bilinear model.

3.4 Gluinos

In the case that the gluino is the LSP, it decays according to

$$\tilde{g} \rightarrow \nu_i q\bar{q} \tag{27}$$
$$\tilde{g} \rightarrow l^\pm qq' \tag{28}$$
$$\tilde{g} \rightarrow \nu_i g \tag{29}$$

These decays proceed via virtual squarks. For this reason one expects also correlations between ratios of branching ratios into $l_i q\bar{q}'$ and ratios of ϵ_i and, thus, the solar mixing angle. We have adopted the formulas given in [24] for the calculation. The general features of a gluino LSP are: (i) The decay into the final state $\nu_i b\bar{b}$ dominates, where we sum over all neutrinos. This can be seen in Fig. 6. (ii) The sum of the branching ratios of the decays into $l^\pm bt$ ($l = e, \mu, \tau$) final states is of order 10^{-2}–10^{-1} if summed over all charged leptons. Note that at the LHC O(10^5) gluino pairs can be produced per year if $m_{\tilde{g}} = 500$ GeV. (iii) All other decay modes are at most of order 10^{-2}.
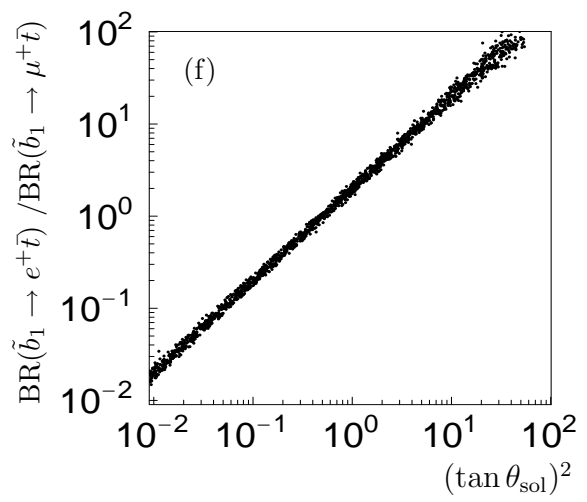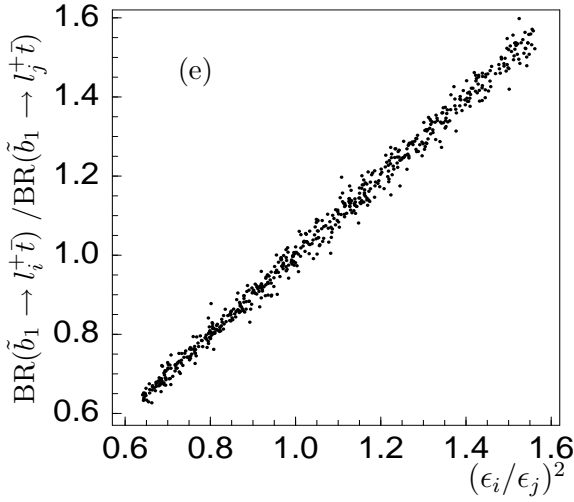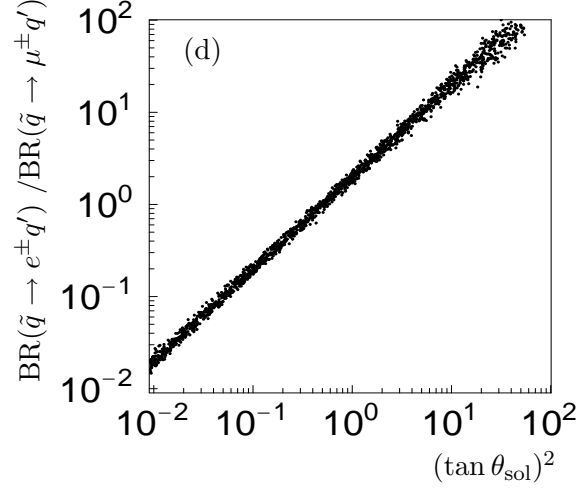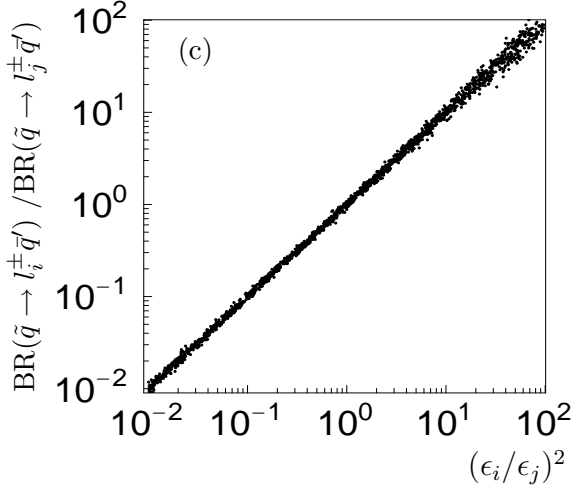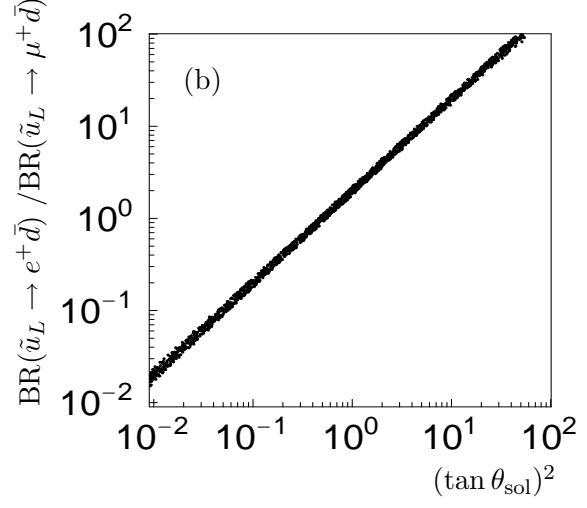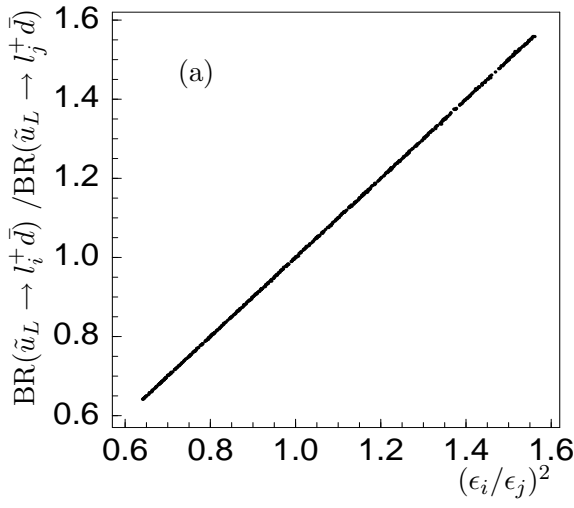
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Figure 5: Ratios of branching ratios for squark decays as function of $(\epsilon_i/\epsilon_j)^2$ (left column) and $\tan^2\theta_{sol}$ (right column).
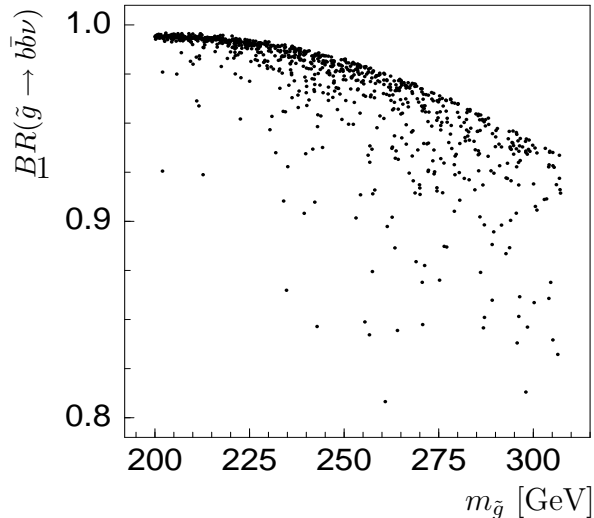
Figure 6: $BR(\tilde{g} \to b\bar{b}\nu)$ as a function of $m_{\tilde{g}}$

The important decay modes for testing correlations between gluino branching ratios and neutrino angles are the final states $l^{\pm}bt$ ($l = e, \mu, \tau$). The sum of these decay modes is normally of the order of a few per–cent. In these decays the same class of couplings induced by the effective vertex $\hat{L}_i\hat{T}_L\hat{B}_R^c$ being proportional to $h_b\epsilon_i$ are probed as in the decays of the lighter stop [19] and in the decays of the lighter sbottom. As can be seen in Figs. 7a and b, there is a clear relation between the ratios of the final states into $l_i tb$ and the corresponding ratio of ϵ_i. In case of the ratio BR($\tilde{g} \to etb$) / BR($\tilde{g} \to \mu tb$) this implies a clear correlation with the solar mixing angle as can be seen in Fig. 7b.

3.5 Gravitino

In gauge mediated SUSY breaking [16] the gravitino $\tilde{G}$ is the LSP. Depending on the scale of SUSY breaking, its mass is typically of the order eV up to several MeV. If R-parity is broken, the gravitino decays, but it is long lived from the point of view of collider physics, because the width is proportional to an R-parity violating coupling squared and the ratio $(m_{\tilde{G}}/m_{SUSY})^4$. This implies that the gravitino will escape the detector before decaying.

However, one can consider the decays of the next-to-lightest SUSY particle (NLSP). For a gravitino with a mass of 1 eV one finds a partial width for NLSP decays into gravitino of O(10^{-3}) eV and significantly smaller values for larger gravitino masses. Partial widths of the lightest neutralino (or chargino) into R-parity violating final state are of the same order of magnitude. This implies that branching ratios for R-parity violating final states of the neutralino are at least of O(10^{-2}). For slepton NLSPs typical partial widths into R-parity violating states are of O(1) eV in case of staus and thus clearly exceed the decay into a gravitino. Very similar arguments apply to all the other NLSP candidates discussed in the previous sections. Therefore, we conclude that in GMSB models with bilinear R-parity violating terms, the decays of the NLSP can be used to establish the correlations with neutrino physics we have discussed.
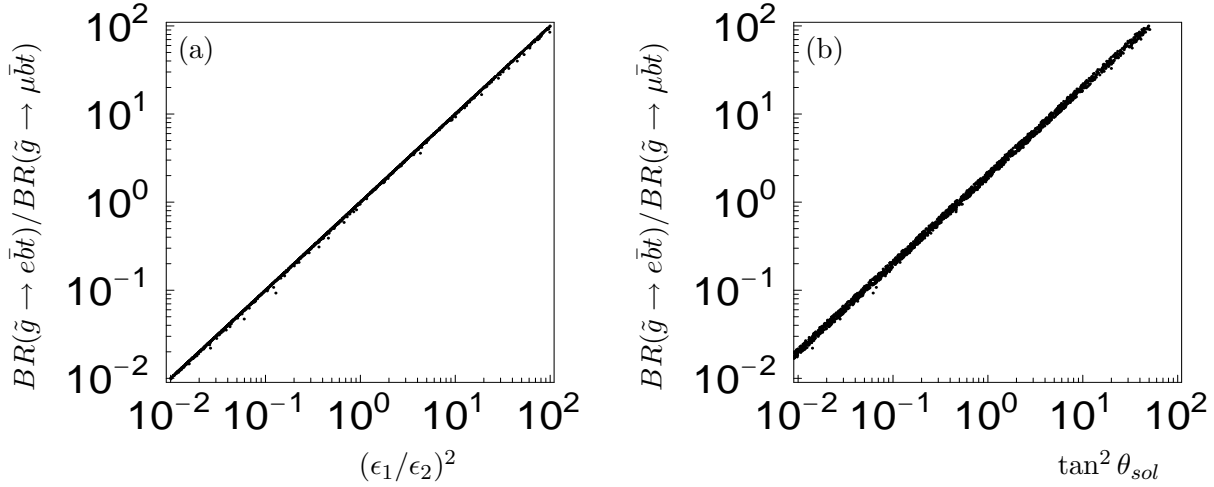
Figure 7: a) Ratio $BR(\tilde{g} \to e\bar{b}t)/BR(\tilde{g} \to \mu\bar{b}t)$ as a function of $(\epsilon_1/\epsilon_2)^2$; b) Ratio $BR(\tilde{g} \to e\bar{b}t)/BR(\tilde{g} \to \mu\bar{b}t)$ as a function of $(\tan\theta_{sol})^2$.

4 Summary

We have calculated the decay patterns of various possible LSPs within bilinear R-parity violating supersymmetry. The main conclusion of the present work is that whichever SUSY particle is the LSP, measurements of branching ratios at future accelerators will provide a definite test of bilinear R-parity breaking as the model of neutrino mass. In case of GMSB, where the gravitino is the LSP, we find that correlations with neutrino physics exist for the decays of the NLSP.

One can state the above more carefully. Observation of a decaying LSP would provide proof that R-parity is violated. Measuring ratios of branching ratios then presents the ultimate cross-check of the completeness and uniqueness of the bilinear model. The most robust predictions of BRpV are shown in this paper, but many ratios of branching ratios are tightly constrained by neutrino physics. In fact, for several different LSP candidates many different decay channels have sizable branching ratios which should follow the specific patterns discussed in the previous sections. Thus this simplest model of R-parity violation can be over constrained by the measurements we have discussed and - in this sense - easily ruled out.

Acknowledgments

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