Probing neutrino properties with charged scalar lepton decays

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(Received 5 August 2002; published 12 November 2002)

Supersymmetry with bilinear *R*-parity violation provides a predictive framework for neutrino masses and mixings in agreement with current neutrino oscillation data. The model leads to striking signals at future colliders through the *R*-parity violating decays of the lightest supersymmetric particle (LSP). Here we study charged scalar lepton decays and demonstrate that if the scalar tau is the LSP (i) it will decay within the detector, despite the smallness of the neutrino masses, (ii) the relative ratio of branching ratios $\mathrm{Br}(\tilde{\tau}_1 \to e \Sigma \nu_i)/\mathrm{Br}(\tilde{\tau}_1 \to \mu \Sigma \nu_i)$ is predicted from the measured solar neutrino angle, and (iii) scalar muon and scalar electron decays will allow us to test the consistency of the model. Thus, bilinear *R*-parity breaking SUSY will be testable at future colliders also in the case where the LSP is not the neutralino.

DOI: 10.1103/PhysRevD.66.095006 PACS number(s): 14.80.Ly, 11.30.Pb, 12.60.Jv, 14.60.Pq

I. INTRODUCTION

Neutrino physics is one of the most rapidly developing areas of particle physics [1]. The solar neutrino data, including the recent measurement of the neutral current rate for solar neutrinos by the SNO Collaboration [2], provide strong evidence for neutrino flavor conversion. If interpreted in terms of neutrino oscillations, the data indicate a large mixing angle between ν_e and $\nu_\mu - \nu_\tau$, with a strong preference towards the large mixing angle (LMA) Mikheyev-Smirnov-Wolfenstein (MSW) solution. At 3σ one has [3]

$$0.25 \leqslant \tan^2\theta_\odot \leqslant 0.83 \tag{1}$$

for 1 degree of freedom (d.o.f.), the best-fit-parameters being

$$\tan^2\theta_\odot = 0.44, \quad \Delta m^2_\odot = 6.6\times 10^{-5}\ \ \mathrm{eV}^2. \tag{2}$$

This nicely confirms earlier hints found in Ref. [4]. The LMA solution will be testable independently by KamLAND [5], and the first results are expected before the end of the year. In addition, current atmospheric neutrino data are most easily explained by $\nu_\mu \leftrightarrow \nu_\tau$ oscillations [6], with the 3σ ranges (1 d.o.f.)

$$0.3 \leqslant \sin^2\theta_{Atm} \leqslant 0.7,$$
$$1.2\times 10^{-3}\ \ \mathrm{eV}^2 \leqslant \Delta m^2_{Atm} \leqslant 4.8\times 10^{-3}\ \ \mathrm{eV}^2. \tag{3}$$

These data leave little doubt that neutrinos are massive particles after all.

Unsurprisingly the discoveries in neutrino oscillation physics have triggered an avalanche of theoretical and phenomenological papers on models of neutrino masses and mixings [7], the majority of which are based on one variation or the other of the seesaw mechanism [8–10]. Here we consider a phenomenologically viable alternative, namely, supersymmetry with bilinear *R*-parity breaking terms [11,12], which, in contrast with the seesaw mechanism, generates neutrino masses at the electroweak scale. Low-scale schemes for neutrino masses have the advantage of being potentially testable in near-future accelerator experiments. In this paper we study the implications of neutrino physics for charged scalar lepton decays.

Supersymmetric models with explicit bilinear breaking of *R* parity (BRPV) [11,12] provide a simple and calculable framework for neutrino masses and mixing angles in agreement with the experimental data [13]. BRPV is a hybrid scheme in which one neutrino mass is generated at tree-level, through the mixing with the neutralinos [14], in an effective "low-scale" variant of the seesaw, while the remaining two masses are generated at 1-loop order. A complete 1-loop calculation of the neutrino-neutralino mass matrix [13] is therefore necessary, before one can confront the model with experimental data from atmospheric and solar neutrino experiments. Especially note that the "solar" angle has no meaning in BRPV at tree-level.

BRPV might be considered either as a minimal three-parameter extension of the minimal supersymmetric standard model (MSSM), valid up to some very high energy scale [such as the grand unified theory (GUT) scale] [15] or as the effective description of a more fundamental theory in which the breaking of *R* parity is spontaneous [14,16]. While spontaneous breaking of *R* parity may be considered theoretically more attractive since, for example, it provides a motivation for the absence of trilinear *R*-parity breaking parameters in the superpotential, for the sake of simplicity in our numerical calculation we will stick to explicit BRPV only.

One should, however, note that the results obtained here are valid also in those classes of models where *R* parity is broken spontaneously including the presence of an additional Goldstone boson, namely the Majoron *J*. This can be seen as follows: The Majoron consists mainly of the imaginary parts of the $SU(2)\otimes U(1)$ singlet scalars, such as the right-handed sneutrinos [16]. The only terms which couple the Majoron directly to sleptons are given by $h^\nu \hat{L}\hat{H}_2\hat{\nu}^c_R$ in the superpotential and the corresponding term in the soft SUSY breaking Lagrangian. These terms can in principle induce decays like $\tilde{\tau}\to\tilde{\mu}J$. However, such a decay requires that one of the charged particles involved contain a large left-handed component whereas the other one contain a large Higgs component. As we will see below, in the cases we will study the sleptons are mainly right-sleptons. In addition, in minimal supergravity (MSUGRA) scenarios the mass differences between the lightest three sleptons is rather small leading to a further suppression of Majoron-emitting charged slepton decays.

If R parity is broken the lightest supersymmetric particle (LSP) will decay. As was shown in [17] (see also [18]), if the LSP is the lightest neutralino, the measured low-energy neutrino properties translate into predictions for the ratios of various branching ratios of the neutralino decay, thus providing a definite test of the model as the origin of neutrino masses and mixings.

However, cosmological and astrophysical constraints on its nature no longer apply if the LSP decays. Thus, within R-parity violating SUSY *a priori any* superparticle could be the LSP. In this paper we study the case where a charged scalar lepton, most probably the scalar tau, is the LSP.[1] We calculate the production and decays of $\tilde{\tau}$, as well as the decays of $\tilde{e}$ and $\tilde{\mu}$, and demonstrate that also for the case of charged sleptons as LSPs neutrino physics leads to definite predictions of various decay properties.

This paper is organized as follows. In Sec. II we will define the model, discuss the charged scalar mass matrix and give some formulas for the two-body decays of charged sleptons, which are the most important decay channels. In Sec. III we will then discuss production and decays of these particles, with special emphasis on possible measurements of R-parity violating parameters. Finally, in Sec. IV we summarize our conclusions.

II. THE MODEL

Since BRPV SUSY has been discussed in the literature several times [11–13,21] we will repeat only the main features of the model here. We will follow the notation of [13].

The simplest bilinear $\not{R}_p$ model (we call it the $\not{R}_p$ MSSM) is characterized by three additional terms in the superpotential

$$W = W_{MSSM} + W_{\not{R}_p} \tag{4}$$

where W_{MSSM} is the ordinary superpotential of the MSSM and

$$W_{\not{R}_p} = \epsilon_i \hat{L}_i \hat{H}_u . \tag{5}$$

These bilinear terms, together with the corresponding terms in the soft SUSY breaking part of the Lagrangian,

$$\mathcal{L}_{soft} = \mathcal{L}^{MSSM}_{soft} + B_i \epsilon_i \tilde{L}_i H_u \tag{6}$$

define the minimal model, which we will adopt throughout this paper. The appearance of the lepton number violating terms in Eq. (6) leads in general to nonzero vacuum expectation values (VEVs) for the scalar neutrinos $\langle \tilde{\nu}_i \rangle$, called v_i in the rest of this paper, in addition to the VEVs v_U and v_D of the MSSM Higgs fields H^0_u and H^0_d. Together with the bilinear parameters, ϵ_i the v_i induce mixing between various particles which in the MSSM are distinguished (only) by lepton number (or R parity). Mixing between the neutrinos and the neutralinos of the MSSM, as mentioned previously, generates a nonzero mass for one specific linear superposition of the three neutrino flavor states of the model at tree-level. For a complete discussion of 1-loop corrections, providing mass for the remaining two neutrino states, see [13].

For the decays of the charged sleptons it is necessary to calculate the mixings between neutrinos and neutralinos, charginos and charged leptons, as well as the charged scalar mixing. Since the various mass matrices can be found in [13], we will discuss only the charged scalar mass matrix in the next section.

A. The charged scalar mass matrix

With R parity broken by the bilinear terms in Eq. (5) the left-handed and right-handed charged sleptons mix with the charged Higgs boson of the MSSM, resulting in an (8×8) mass matrix for charged scalars. As in the MSSM this matrix contains the Goldstone boson, providing the mass of the W boson after electroweak symmetry breaking. One can rotate away the Goldstone mode from this mass matrix, using the following rotation matrix:

$$\hat{R} = \begin{bmatrix} \frac{v_D}{w_3} & -\frac{v_U}{w_3} & \frac{v_1}{w_3} & \frac{v_2}{w_3} & \frac{v_3}{w_3} & 0 & 0 & 0 \\ \frac{v_U}{w_0} & \frac{v_D}{w_0} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{v_1 v_D}{w_0 w_1} & \frac{v_1 v_U}{w_0 w_1} & \frac{w_0}{w_1} & 0 & 0 & 0 & 0 & 0 \\ -\frac{v_2 v_D}{w_1 w_2} & \frac{v_2 v_U}{w_1 w_2} & -\frac{v_2 v_1}{w_1 w_2} & \frac{w_1}{w_2} & 0 & 0 & 0 & 0 \\ -\frac{v_3 v_D}{w_2 w_3} & \frac{v_3 v_U}{w_2 w_3} & -\frac{v_3 v_1}{w_2 w_3} & -\frac{v_2 v_3}{w_2 w_3} & \frac{w_2}{w_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

[1] The case of light top squark decays was considered in Refs. [19,20].

where

$$w_0 = \sqrt{v_D^2 + v_U^2} \tag{8}$$

$$w_1 = \sqrt{v_1^2 + v_D^2 + v_U^2} \tag{9}$$

$$w_2 = \sqrt{v_1^2 + v_2^2 + v_D^2 + v_U^2} \tag{10}$$

$$w_3 = \sqrt{v_1^2 + v_2^2 + v_3^2 + v_D^2 + v_U^2}. \tag{11}$$

This matrix has the property that

$$\hat{R} M_{S^\pm}^2 \hat{R}^T = \begin{bmatrix} 0 & \vec{0}^T \\ \vec{0} & M_{S_7^\pm}^2 \end{bmatrix} \tag{12}$$

where $M_{S_7^\pm}^2$ is a (7×7) matrix and the zeros in the first row and first column correspond to the (massless) Goldstone state in $\xi=0$ gauge.

We divide the remaining $M_{S_7^\pm}^2$ into two parts,

$$M_{S_7^\pm}^2 = (M_{S_7^\pm}^2)^{(0)} + (M_{S_7^\pm}^2)^{(1)} \tag{13}$$

where $(M_{S_7^\pm}^2)^{(0)}$ $[(M_{S_7^\pm}^2)^{(1)}]$ contains only R-parity conserving (R-parity violating) terms. Note that in the following we assume for simplicity that there is no inter-generational mixing among the charged sleptons. This is motivated by existing constraints from flavor changing neutral currents [22] and is consistent with the minimal SUGRA scenario of the MSSM, which we will use in the numerical part of this paper. With this assumption also the branching ratio $\mu \to e\gamma$ is small [23] in the bilinear model in agreement with experimental data. The R-parity conserving part of $M_{S_7^\pm}^2$ is given by

$$(M_{S_7^\pm}^2)^{(0)} = \begin{bmatrix} m_{H^\pm}^2 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & \hat{m}_{L_1}^2 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & \hat{m}_{L_2}^2 & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \hat{m}_{L_3}^2 & \cdot & \cdot & \cdot \\ 0 & \hat{m}_{LR1}^2 & 0 & 0 & \hat{m}_{R_1}^2 & \cdot & \cdot \\ 0 & 0 & \hat{m}_{LR2}^2 & 0 & 0 & \hat{m}_{R_2}^2 & \cdot \\ 0 & 0 & 0 & \hat{m}_{LR3}^2 & 0 & 0 & \hat{m}_{R_3}^2 \end{bmatrix} \tag{14}$$

where the dots indicate that the matrix is symmetric and

$$m_{H^\pm}^2 = m_A^2 + \frac{g^2 v_{R_P}^2}{4} \tag{15}$$

$$\hat{m}_{L_i}^2 = m_{L_i}^2 - (g^2 - g'^2)\frac{v_{R_P}^2}{8} c_{2\beta} + \frac{1}{2}(h_i^E)^2 v_D^2 \tag{16}$$

$$\hat{m}_{R_i}^2 = m_{R_i}^2 - g'^2 \frac{v_{R_P}^2}{4} c_{2\beta} + \frac{1}{2}(h_i^E)^2 v_D^2 \tag{17}$$

$$\hat{m}_{LRi}^2 = + \frac{1}{\sqrt{2}}(h_i^E)(A_i v_D - \mu v_U) \tag{18}$$

with $v_{R_P}^2 = v_U^2 + v_D^2$. m_A^2 is the MSSM pseudoscalar Higgs boson mass parameter $m_A^2 = (\mu B)/(s_\beta c_\beta)$, h_i^E and A_i are the Yukawa couplings and soft breaking trilinear parameters of the charged lepton of generation i, μ is the Higgsino mixing parameter characterizing the superpotential, and $c_{2\beta} = \cos(2\beta)$, where β is defined in the usual way as $\tan\beta = v_U/v_D$. The R-parity violating part of $M_{S_7^\pm}^2$ can be written as

$$(M_{S_7^\pm}^2)^{(1)} = \begin{bmatrix} \Delta m_{H^\pm}^2 & (\vec{X}_{HL})^T & (\vec{X}_{HR})^T \\ \vec{X}_{HL} & M_{LL}^{2(1)} & (M_{LR}^{2(1)})^T \\ \vec{X}_{HR} & M_{LR}^{2(1)} & M_{RR}^{2(1)} \end{bmatrix}. \tag{19}$$

The Higgs mass correction and the Higgs-slepton mixing terms in Eq. (19) are

$$\Delta m_{H^\pm}^2 = \sum \left\{ \left(\frac{v_i}{v_D}\right)^2 \overline{m}_{\tilde{\nu}_i}^2 \frac{c_\beta^4}{s_\beta^2} - \epsilon_i \mu \frac{v_i}{v_D}\frac{c_{2\beta}}{s_\beta^2} + \frac{g^2}{4} v_i^2 c_{2\beta} + \frac{1}{2}(h_i^E v_i)^2 s_\beta^2 \right\} \tag{20}$$

$$(X_{HL})_i = \frac{v_i}{v_D}\overline{m}_{\tilde{\nu}_i}^2 \frac{c_\beta^2}{s_\beta} - \mu \epsilon_i \frac{1}{s_\beta} + \frac{1}{2}[g^2 - (h_i^E)^2] v_D v_i s_\beta \tag{21}$$

$$(X_{HR})_i = -\frac{1}{\sqrt{2}} h_i^E v_i (A_i s_\beta + \mu c_\beta) - \frac{1}{\sqrt{2}} h_i^E \epsilon_i v_D \frac{1}{c_\beta}. \tag{22}$$

$M_{LL}^{2(1)}$ can be written as,

$$M_{LL}^{2(1)} = \begin{bmatrix} \Delta m_{L_1}^2 & (X_{LL})_{12} & (X_{LL})_{13} \\ (X_{LL})_{12} & \Delta m_{L_2}^2 & (X_{LL})_{23} \\ (X_{LL})_{13} & (X_{LL})_{23} & \Delta m_{L_3}^2 \end{bmatrix} \tag{23}$$

with the diagonal terms given by

$$\Delta m_{L_i}^2 = \left(\frac{v_i}{v_D}\right)^2 \overline{m_{\tilde{\nu}_i}^2} c_\beta^2 + \epsilon_i^2 + \frac{1}{2}[g^2 + (h_i^E)^2] v_i^2 c_\beta^2 + \frac{1}{8}(g'^2 - g^2) \sum v_i^2 \tag{24}$$

whereas the off-diagonals are

$$(X_{LL})_{12} = \epsilon_1 \epsilon_2 + \left(\frac{v_1}{v_D}\right)\left(\frac{v_2}{v_D}\right) m_{L_2}^2 c_\beta^2 + v_1 v_2 \left[\frac{1}{4}[g^2 + (h_2^E)^2] - \frac{1}{8}(g^2 - g'^2) c_{2\beta} + \frac{1}{4}(h_2^E)^2 c_{2\beta}\right] \tag{25}$$

$$(X_{LL})_{13} = \epsilon_1 \epsilon_3 + \left(\frac{v_1}{v_D}\right)\left(\frac{v_3}{v_D}\right) m_{L_3}^2 c_\beta^2 + v_1 v_3 \left[\frac{1}{4}[g^2 + (h_3^E)^2] - \frac{1}{8}(g^2 - g'^2) c_{2\beta} + \frac{1}{4}(h_3^E)^2 c_{2\beta}\right] \tag{26}$$

$$(X_{LL})_{23} = \epsilon_2 \epsilon_3 + \left(\frac{v_2}{v_D}\right)\left(\frac{v_3}{v_D}\right) m_{L_3}^2 c_\beta^2 + v_2 v_3 \left[\frac{1}{4}[g^2 + (h_3^E)^2] - \frac{1}{8}(g^2 - g'^2) c_{2\beta} + \frac{1}{4}(h_3^E)^2 c_{2\beta}\right]. \tag{27}$$

Similarly for $M_{RR}^{2(1)}$,

$$\Delta m_{R_i}^2 = \frac{1}{2}(h_i^E)^2 v_i^2 - \frac{1}{4} g'^2 \sum v_i^2 \tag{28}$$

and

$$(X_{RR})_{ij} = \frac{1}{2}(h_i^E)(h_j^E) v_i v_j. \tag{29}$$

Finally, the matrix $M_{LR}^{2(1)}$ has the following peculiar structure:

$$M_{LR}^{2(1)} = \begin{bmatrix} (X_{LR})_{11} & 0 & 0 \\ (X_{LR})_{12} & (X_{LR})_{22} & 0 \\ (X_{LR})_{13} & (X_{LR})_{23} & (X_{LR})_{33} \end{bmatrix} \tag{30}$$

where

$$(X_{LR})_{ii} = -\frac{1}{2\sqrt{2}}(h_i^E)\left(\frac{v_i}{v_D}\right)^2 c_\beta v_D [\mu s_\beta - A_i c_\beta] \tag{31}$$

$$(X_{LR})_{ij} = -\frac{1}{\sqrt{2}}(h_i^E)\left(\frac{v_i}{v_D}\right)\left(\frac{v_j}{v_D}\right) c_\beta v_D [\mu s_\beta - A_i c_\beta]. \tag{32}$$

In the above equations we have used the following abbreviation:

$$\overline{m_{\tilde{\nu}_i}^2} = m_{L_i}^2 + \frac{1}{8}(g^2 + g'^2)(v_D^2 - v_U^2). \tag{33}$$

With the definitions outlined above, once can easily derive approximate expressions for the mixing between the charged Higgs bosons and the charged sleptons induced by the R-parity breaking parameters. These are given by

$$\sin\theta_{HL_i} \simeq \frac{X_{HL,i}}{(m_{H^\pm}^2 - \hat{m}_{L_i}^2)}, \tag{34}$$

$$\sin\theta_{HR_i} \simeq \frac{X_{HR,i}}{(m_{H^\pm}^2 - \hat{m}_{R_i}^2)}. \tag{35}$$

Note that one expects $\sin\theta_{HR_i} \sim h_i^E \sin\theta_{HL_i}$, i.e. the mixing between right-handed sleptons and the Higgs boson should be typically much smaller than the left-handed Higgs-slepton mixing.

Finally, the R-parity conserving mixing between left-handed and right-handed sleptons is approximately given by

$$\sin 2\theta_{\tilde{l}_i} \simeq \frac{2\hat{m}_{LRi}^2}{\hat{m}_{Li}^2 - \hat{m}_{Ri}^2}. \tag{36}$$

B. Formulas for two-body decays

Charged scalar leptons lighter than all other supersymmetric particles will decay through R-parity violating couplings. Possible final states are either $l_j \nu_k$ or $q\overline{q'}$. For right-handed charged sleptons ($\tilde{l}_{Ri}$) the former by far dominates over the hadronic decay mode, since the mixing between $\tilde{l}_{Ri}$ and the charged Higgs boson is small, as explained above.

In the limit $(m_{f_j}, m_{\nu_k}) \ll m_{\tilde{f}_i}$ one has a simple formula for the two-body decays $\tilde{f}_i \to f_j + \nu_k$:

$$\Gamma_{\tilde{f}_i f_j \nu_k} = \frac{m_{\tilde{f}_i}}{16\pi}[(O^{cns}_{L f_j \nu_k \tilde{f}_i})^2 + (O^{cns}_{R f_j \nu_k \tilde{f}_i})^2]. \tag{37}$$

Exact expressions for these couplings can be found, for example, in Ref. [13]. Even though in the results presented in this paper we have always calculated the couplings appearing in Eq. (37) exactly using our numerical code, it is instructive to consider an approximate diagonalization procedure for the various mass matrices. This method is based on the fact that neutrino masses are much smaller than all other particle masses in the theory and therefore one expects that the bilinear R-parity breaking parameters are (somewhat) smaller than the corresponding MSSM parameters. For the charged scalar mass matrix all necessary definitions have been given above; for details for the corresponding procedure for neutralino and chargino mass matrices we refer to [13,21,24].

For the case where $i \neq j$ for $\tilde{l}_{Ri} \to l_j \Sigma \nu_k$ one finds

$$\sum_k [(O^{cns}_{Ll_j\nu_k\tilde{l}_i})^2 + (O^{cns}_{Rl_j\nu_k\tilde{l}_i})^2]$$

$$= \left(-h^E_{l_i} c_{\tilde{l}_i} \frac{\epsilon_j}{\mu} - (g s_{\tilde{l}_i} y_1 + h^E_{l_i} c_{\tilde{l}_i} y_2)\Lambda_j \right)^2 + (h^E_{l_j})^2 (s_\beta \sin\theta_{HR_i} - c^2_\beta s_{\tilde{l}_i} \tilde{v}_i)^2 \tag{38}$$

$$\simeq \left(c_{\tilde{l}_i} h^E_{l_i} \frac{\epsilon_j}{\mu} \right)^2. \tag{39}$$

Here $c_{\tilde{l}_i} \equiv \cos(\theta_{\tilde{l}_i})$ and $s_{\tilde{l}_i} \equiv \sin(\theta_{\tilde{l}_i})$ where $\theta_{\tilde{l}_i}$ is the left-right mixing angle for $\tilde{l}_i$, $\sin\theta_{HR_i}$ characterizes the charged-Higgs-boson–(right-handed)-slepton mixing and $\vec{\Lambda}$ is given by

$$\Lambda_i = \epsilon_i v_D + \mu v_i . \tag{40}$$

The quantities y_1 and y_2 are defined as

$$y_1 = \frac{g}{\sqrt{2}\,\mathrm{Det}M_{\chi^\pm}} \tag{41}$$

$$y_2 = -\frac{g^2 v_U}{2\mu\,\mathrm{Det}M_{\chi^\pm}} \tag{42}$$

with $\mathrm{Det}M_{\chi^\pm}$ being the determinant of the MSSM chargino mass matrix.

While Eq. (38) above keeps all R-parity breaking parameters in the expansion up to second order, Eq. (39) should be valid in the parameter region in which the 1-loop neutrino masses are smaller than the tree-level contribution.

For the case $i=j$ the corresponding formulas are rather cumbersome and therefore of limited utility, except for the case $\tilde{l}=\tilde{e}$. Here, since $h_e \ll 1$ one can simplify the couplings to

$$\sum_k [(O^{cns}_{Le\nu_k\tilde{e}})^2 + (O^{cns}_{Re\nu_k\tilde{e}})^2] \simeq 2g'^2 x_1^2 |\vec{\Lambda}|^2. \tag{43}$$

The parameter $\vec{\Lambda}$ has been defined above and x_1 is given by

$$x_1 = \frac{g' M_2 \mu}{2\,\mathrm{Det}M_{\chi^0}} \tag{44}$$

with $\mathrm{Det}M_{\chi^0}$ being the determinant of the MSSM neutralino mass matrix and M_2 the soft SUSY breaking $SU(2)$ mass parameter.

From Eq. (39) one expects that various ratios of branching ratios should contain rather precise information on ratios of the bilinear R-parity breaking parameters, for example, $\mathrm{Br}(\tilde{\tau}_1 \to e \Sigma \nu_i)/\mathrm{Br}(\tilde{\tau}_1 \to \mu \Sigma \nu_i) \simeq (\epsilon_1/\epsilon_2)^2$. We will discuss this important point in more detail in the next section.

III. SLEPTON PRODUCTION AND DECAYS

In this section we will discuss charged slepton production and decay modes. In order to reduce the number of parameters, the numerical calculations were performed in the MSUGRA version of the MSSM. Unless noted otherwise, we have scanned the parameters in the following ranges: M_2 from [0,1.2] TeV, $|\mu|$ from [0,2.5] TeV, m_0 in the range [0,0.5] TeV, A_0/m_0 and B_0/m_0 $[-3,3]$ and $\tan\beta$ [2.5,10]. All randomly generated points were subsequently tested for consistency with the minimization (tadpole) conditions of the Higgs potential as well as for phenomenological constraints from supersymmetric particle searches. In addition, we selected points in which at least one of the charged sleptons was lighter than the lightest neutralino, and thus the LSP. This latter cut prefers strongly $m_0 \ll M_2$.

R-parity violating parameters were chosen in such a way [13] that the neutrino masses and mixing angles are approximately consistent with the experimental data. A good "fit" to the data would require (a) $\Lambda_\mu \simeq \Lambda_\tau$, in order to account for a nearly maximal $\nu_\mu \to \nu_\tau$ angle in atmospheric oscillations, Eq. (3); (b) $\Lambda_e < \Lambda_\tau$, to fulfill the constraints from ν_e-oscillation searches at reactors [25]; (c) $|\vec{\Lambda}| \simeq [0.05,2]$ GeV^2, for the atmospheric neutrino mass scale, Eq. (3); (d) $\epsilon_1 \simeq \epsilon_2$, to have a large angle in solar oscillations, Eq. (2); and (e) $|\vec{\epsilon}|^2/|\vec{\Lambda}| \simeq [0.1,10]$, for the solar mass scale, Eq. (2).

In order to investigate the dependence of our results on the assumptions about the R-parity violating parameters, we construct three different sets of points. Set1 was calculated to give an approximate "fit" to the neutrino data, as described above. Set2 is similar to Set1, except that ϵ_1/ϵ_2 has been varied in a wider range ([0.1,10]), so as to cover both large and small solar angles.[2] The last set, called Set3 in the following, is again similar to Set1, except that ϵ_2/ϵ_3, which is hardly constrained by neutrino data, is varied in the interval $\epsilon_2/\epsilon_3 \simeq 0.1-2$.

In supersymmetric models in which the scalar leptons have a common soft SUSY breaking mass parameter at some high scale (m_0 in MSUGRA) the renormalization group evolution leads to some splitting between the scalar taus and the $\tilde{e}$ and $\tilde{\mu}$ states at the weak scale. While the lightest mass eigenstate in the charged slepton sector is usually mainly the $\tilde{\tau}_R$, the eigenvalues for $\tilde{e}_R$ and $\tilde{\mu}_R$ are not much heavier,

[2]Although at the moment the small angle solar solution is ruled out by a careful analysis of the solar data [3], it does not cost us much additional effort to keep this option in mind.

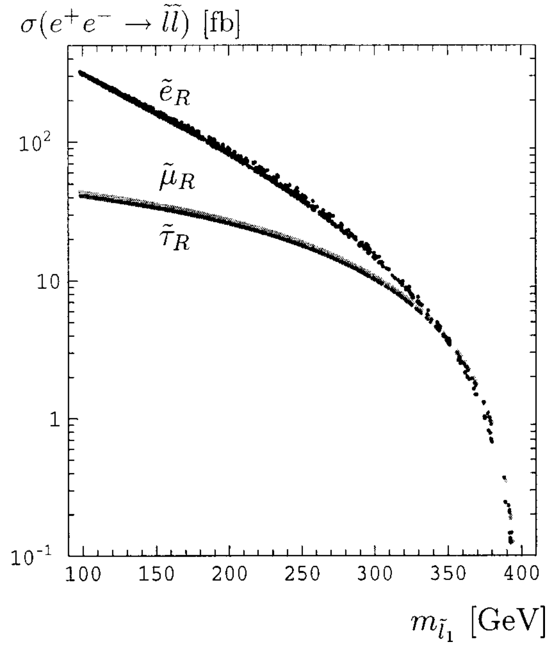


FIG. 1. $e^+e^- \to \tilde{l}\tilde{l}$ production cross section as a function of $m_{\tilde{l}}$ at a linear collider with 0.8 TeV c.m.s. energy. From top to bottom: $\tilde{e}$ (dark), $\tilde{\mu}$ (light shaded) and $\tilde{\tau}$ (dark shaded).

such that also $\tilde{e}_R$ and $\tilde{\mu}_R$ decay mainly via *R*-parity violating two-body decays. In our numerical calculation we therefore not only consider the decays of $\tilde{\tau}_R$, but also those of $\tilde{e}_R$ and $\tilde{\mu}_R$. These decays can provide information on the *R*-parity violating parameters not accessible in $\tilde{\tau}_R$ decays and allow for additional cross checks of the consistency of the model. This is true especially for the case of lepton flavor violating

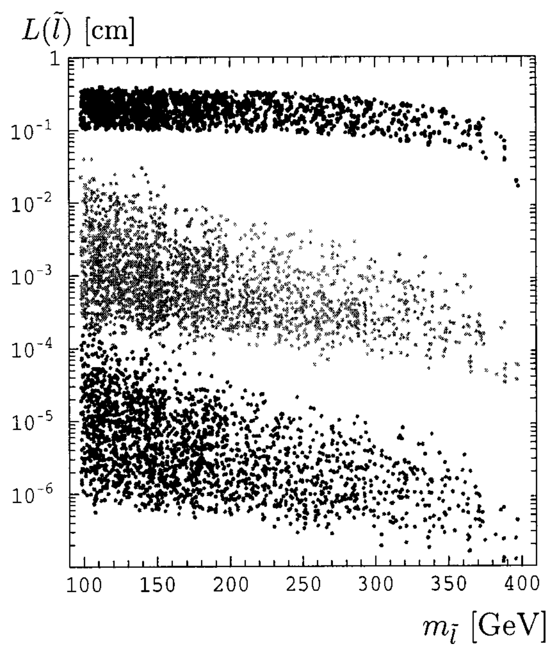


FIG. 2. Charged slepton decay length as a function of $m_{\tilde{l}}$ at a linear collider with 0.8 TeV c.m.s. energy. From top to bottom: $\tilde{e}$ (dark), $\tilde{\mu}$ (light shaded) and $\tilde{\tau}$ (dark shaded).

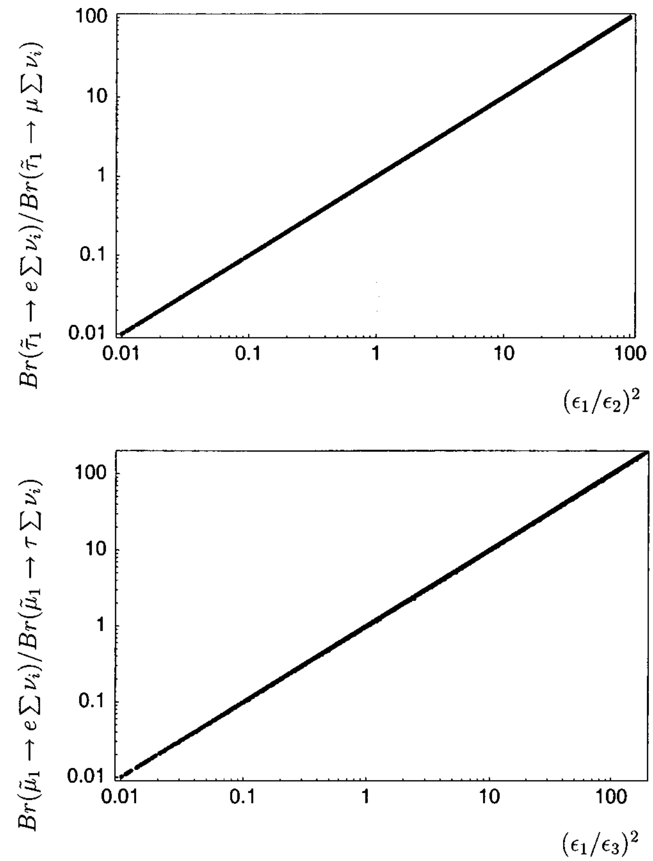


FIG. 3. Ratios of branching ratios for scalar tau decays (top panel) versus $(\epsilon_1/\epsilon_2)^2$, and scalar muon decays (bottom panel) versus $(\epsilon_1/\epsilon_3)^2$ for Set2.

slepton decays since from Eq. (39) one expects them to be directly correlated with the BRPV parameters ϵ_i.

For the calculation of the cross section we have adapted the formulas given in [26] to the bilinear model taking into account correctly all mixing effects in the numerical calculation. In Fig. 1 we show the cross section $\sigma(e^+e^- \to \tilde{l}\tilde{l})$ in fb for $\sqrt{s} = 0.8$ TeV as a function of the charged scalar mass, for $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$, respectively. Assuming an integrated luminosity of 1000 fb^{-1} per year can be achieved at a future

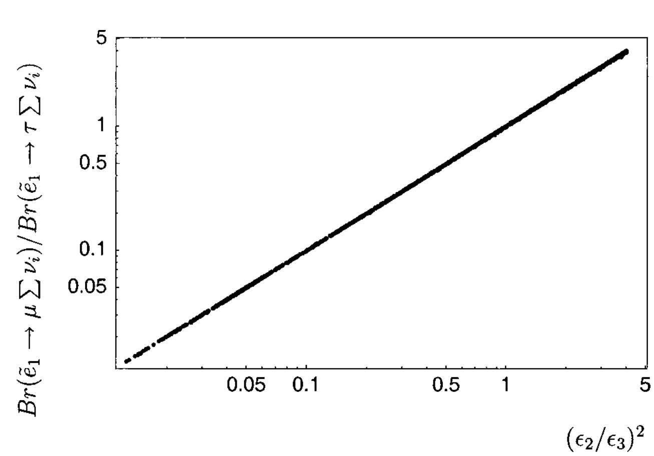
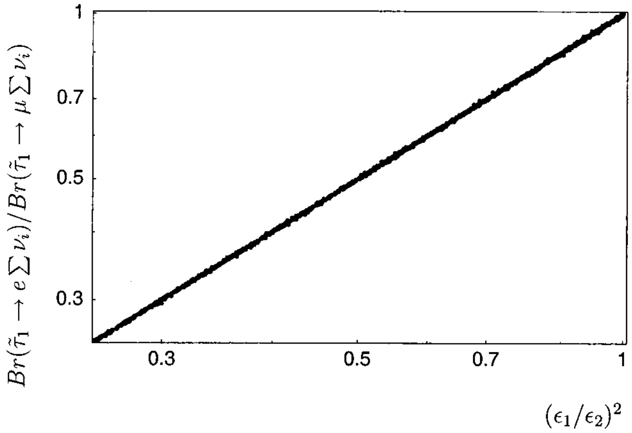


FIG. 4. Ratios of branching ratios for scalar electron decays versus $(\epsilon_2/\epsilon_3)^2$ for Set3.



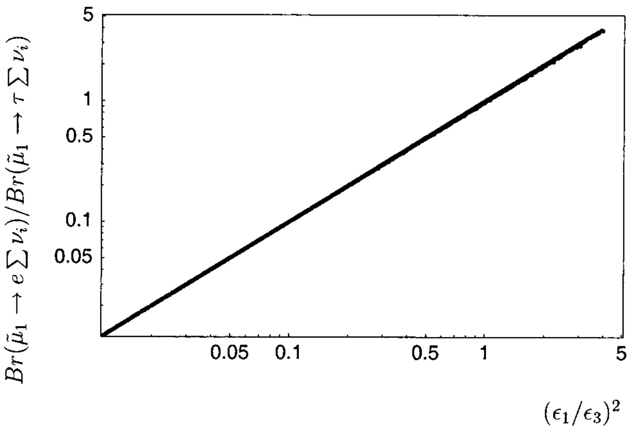
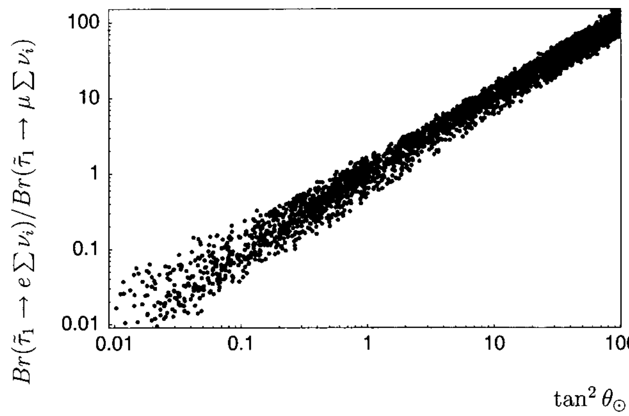


FIG. 5. Ratios of branching ratios for scalar tau (top panel) decays versus $(\epsilon_1/\epsilon_2)^2$ and scalar muon decays (bottom panel) versus $(\epsilon_1/\epsilon_3)^2$ for Set3.



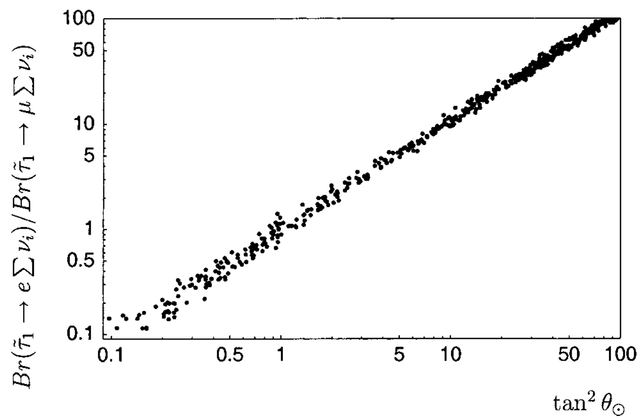


FIG. 6. Ratios of branching ratios for scalar tau decays versus $\tan^2\theta_\odot$ for Set2. The top panel shows all data points, the bottom one refers only to data points with ϵ_2/ϵ_3 restricted to the range [0.9,1.1].

linear collider [27,28] this implies that around 10^4, scalar muons and scalar taus can be directly produced per year. For scalar electrons one expects between 10^4 and 10^5 produced pairs per year. Since the three R-parity violating two-body decay channels of the right-handed sleptons nearly add up to 100%, one can expect that individual branching ratios will be measured to an accuracy of 1% if they occur with similar strength.

At the CERN Large Hadron Collider (LHC) the direct production of right-sleptons is small. As a result, they will be produced mainly in cascade decays. The relative $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_R$ yields will depend on the details of the cascade decays involved. Let us consider for simplicity the case where the cascade decays of the colored particles end up in the lightest neutralino as in the MSSM. Beside the kinematics, the resulting number of $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_R$ arising from these decays depends on the nature of the lightest neutralino. When this is mainly B-ino-like, one expects that it decays dominantly into an equal number of $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_R$'s. As a result the number of right-sleptons is roughly equal to the number of neutralinos. Also in case of a W-ino-like neutralino the amount of $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_R$ will be equal. However, in this case the main lightest neutralino decay mode will be to a W boson and a charged lepton, leaving fewer sleptons to be studied. However, as discussed in [17,18], in this case the neutralino decay modes can be used to probe the large atmospheric neutrino angle. For the case where the lightest neutralino is Higgsino-like it will decay into a W boson and a charged lepton, or into a Z boson and a neutrino, similar to the W-ino case. However for large $\tan\beta$ the decay into $\tilde{\tau}_R$ will again be important, even for Higgsino-like neutralinos.

In Fig. 2 we show the charged scalar leptons decay length ($\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$, from top to bottom) as a function of the scalar lepton masses for Set3. Very similar results hold for the other sets which are therefore not shown. All decay lengths are small compared to typical detector sizes, despite the smallness of the neutrino masses. The three generations of sleptons decay with quite different decay lengths and thus it should be possible to separate the different generations experimentally at a future linear collider. Note that the ratio of the decay lengths $L(\tilde{\tau})/L(\tilde{\mu})$ is approximately given by $(h_\mu/h_\tau)^2$.

As mentioned in the previous section, one expects that ratios of branching ratios of various charged slepton decays contain rather precise information on ratios of the bilinear parameters ϵ_i. That this is indeed the case is shown in Fig. 3 for the data of Set2 and in Fig. 4 and Fig. 5 for the data of Set3.

As can be seen from these figures, the ratio of charged slepton branching ratios is correlated with the ratios of the corresponding BRPV parameters ϵ_i, following very closely the expectation from Eq. (39), nearly insensitive to variation of the other parameters. Recall, that all the points were generated through a rather generous scan over the MSUGRA parameters. Ratios of ϵ_i's should therefore be very precisely measurable. Moreover, since only two of the three ratios of ϵ_i's are independent it is possible to derive the following prediction:

$$\mathrm{Br}\left(\tilde{\tau}_1 \to e \sum \nu_i\right) \Big/ \mathrm{Br}\left(\tilde{\tau}_1 \to \mu \sum \nu_i\right) : \mathrm{Br}\left(\tilde{\mu}_1 \to e \sum \nu_i\right) \Big/ \mathrm{Br}\left(\tilde{\mu}_1 \to \tau \sum \nu_i\right) \simeq \mathrm{Br}\left(\tilde{e}_1 \to \tau \sum \nu_i\right) \Big/ \mathrm{Br}\left(\tilde{e}_1 \to \mu \sum \nu_i\right)$$

which provides an important cross check of the validity of our bilinear R-parity model. Any significant departure from this equality would be a clear sign that the bilinear model is incomplete.

As mentioned in the Introduction, current solar neutrino data prefer a large angle solution (LMA). In the BRPV model the solar angle is mainly determined by the ratio ϵ_1/ϵ_2 [13]. A measured solar angle therefore leads to a prediction for $\mathrm{Br}(\tilde{\tau}_1 \to e \Sigma \nu_i)/\mathrm{Br}(\tilde{\tau}_1 \to \mu \Sigma \nu_i)$, as shown in Fig. 6 for the data of Set2. With the current limits on $\tan^2\theta_\odot$, which are $0.25 < \tan^2\theta_\odot < 0.83$ for the preferred LMA-MSW solution to the solar neutrino problem [3] at 3 σ C.L., one can currently predict that this ratio in the BRPV model must be in the range [0.09,1.8]. Additional input on ϵ_2/ϵ_3, for example $\epsilon_2/\epsilon_3 \simeq 1$ to within 10% would sharpen the predicted value to [0.15,1.1]. Obviously, also a more precise measurement of the solar angle will lead to a tighter prediction in the future. In this context it is worth noting that KamLAND [5] should be able to fix the solar angle to within $\sim 30\%$, if LMA is indeed the correct solution to the solar neutrino problem.

Up to now we have discussed only ratios of R-parity violating parameters, but charged scalar lepton decays allow, in principle, also to gain information on absolute values of

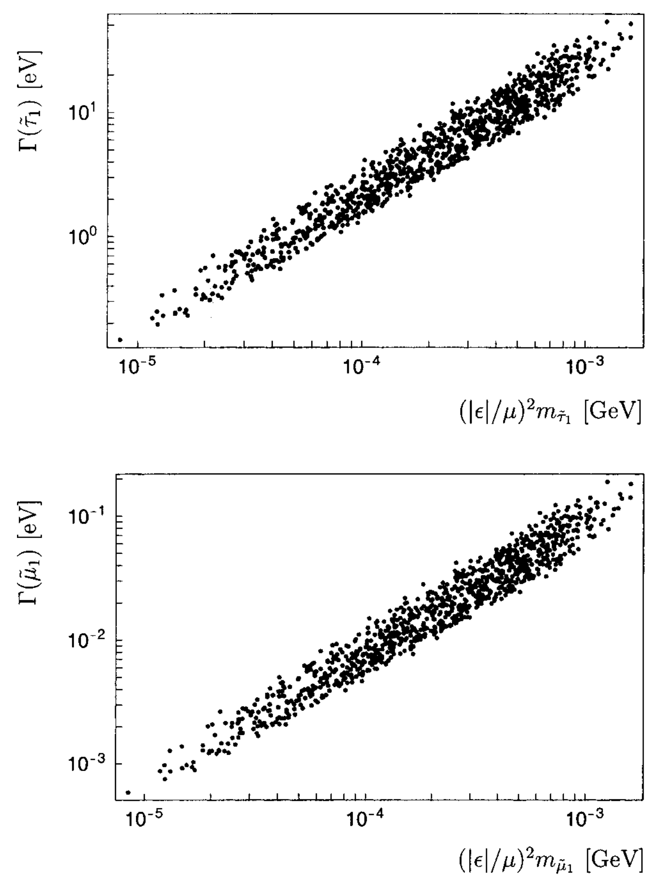


FIG. 7. Total widths in eV for scalar tau decays (top) and scalar muon decays (bottom) for the data of Set1 versus $(|\epsilon|/\mu)^2 m_{\tilde{l}}$. Once μ and $m_{\tilde{l}}$ are measured, the widths provide information on the absolute value of $|\epsilon| \equiv |\vec{\epsilon}|$. Note that Set1 fixes $\epsilon_2/\epsilon_3 \simeq 1$. In general, this ratio must be known with some accuracy, before a value for $|\epsilon|$ can be derived from the widths.

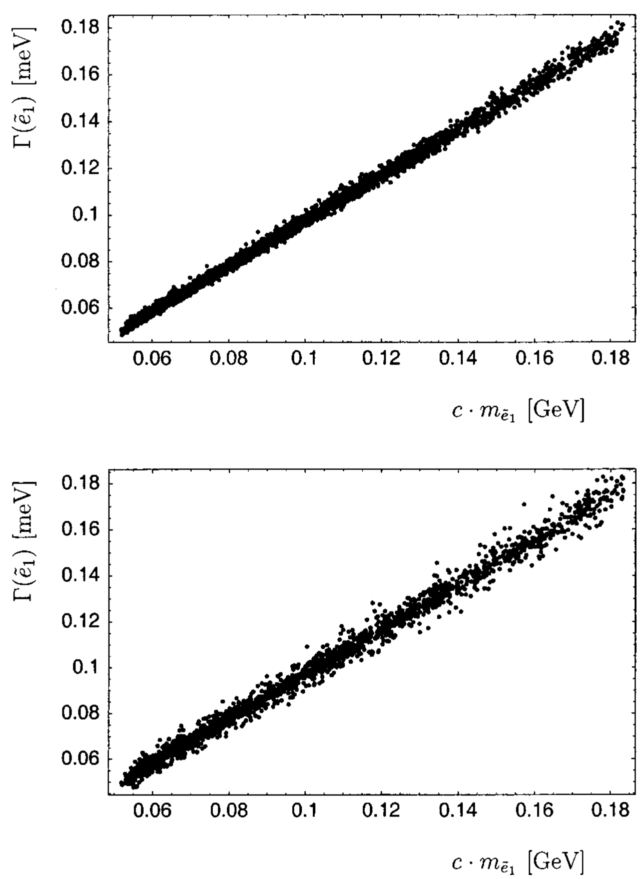


FIG. 8. Charged scalar electron total decay widths in meV, the top panel refers to Set2 while the bottom one is for Set3. The plots are versus $c \cdot m_{\tilde{e}_1}$, where $c = 1/8\pi(g')^2 x_1 |\Lambda|^2$.

these parameters, as relevant, e.g. to fix the scale of neutrino masses determined through the analysis of current solar and atmospheric data [3]. However, such a measurement would require at least some information on MSSM parameters which is at the moment unavailable.

In Fig. 7 we show the total widths in eV for scalar tau decays (top panel) and scalar muon decays (bottom panel) for the data of Set1 displayed versus $(|\epsilon|/\mu)^2 m_{\tilde{l}}$. Once μ and $m_{\tilde{l}}$ have been measured with some accuracy, one can determine the absolute value of $|\epsilon|$ from this measurement, provided ϵ_2/ϵ_3 is known [for example, from the ratio $\mathrm{Br}(\tilde{e}_1 \to \mu \Sigma \nu_i)/\mathrm{Br}(\tilde{e}_1 \to \tau \Sigma \nu_i)$].

In a similar way, the decay width of the scalar electron contains information on $|\vec{\Lambda}|$, as is demonstrated in Fig. 8. *A priori* knowledge on ϵ_2/ϵ_3 leads to a tighter correlation, as can be seen from the comparison of the results for Set2 and Set3.

To deduce the value of $|\vec{\Lambda}|$ from this measurement one needs the parameter combination x_1, as defined in Eq. (44). It contains the MSSM parameters M_1, M_2, μ and $\tan\beta$, which could be determined, for example, if at least some of the neutralino and chargino eigenstates are accessible at the LHC or a possible linear collider.

IV. CONCLUSIONS

Supersymmetric models with bilinear *R*-parity breaking provide a simple, testable framework for neutrino masses and mixings in agreement with current solar, atmospheric and reactor neutrino oscillation data. The model is testable at future colliders if the neutralino is the LSP, as was shown previously, as well as in the alternative case where one of the charged scalar leptons is the LSP, as we have demonstrated here.

The measured neutrino mixing angles fix certain ratios of the bilinear *R*-parity breaking parameters and, therefore, lead to well-defined predictions for the ratio of branching ratios of certain slepton decay modes, which should be easily measurable at a future collider such as a high energy linear collider. Our main result is shown in Fig. 6, where we display $\mathrm{Br}(\tilde{\tau}_1 \to e \Sigma \nu_i)/\mathrm{Br}(\tilde{\tau}_1 \to \mu \Sigma \nu_i)$ versus the solar neutrino angle, $\tan^2\theta_\odot$.

We have also shown how charged scalar lepton decays allow the determination of other parameters of our model, thus providing a definite test that bilinear *R*-parity breaking SUSY is the origin of neutrino masses.

ACKNOWLEDGMENTS

This work was supported by Spanish grants PB98-0693 and by the European Commission RTN network HPRN-CT-2000-00148. M.H. is supported by a Spanish MCyT Ramon y Cajal contract. W.P. is supported by the Erwin Schrödinger Fellowship No. J2095 of the ''Fonds zur Förderung der wissenschaftlichen Forschung'' of Austria FWF and partly by the Swiss ''Nationalfonds.''

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