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Signals of spontaneous R parity breaking at LEP and at a linear collider

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Abstract. We study the production of neutralinos and charginos at LEP and at a linear collider in the case of spontaneously broken R-parity. We first investigate the constraints on the single neutralino and chargino production from the LEP 1 experiments, and then we consider the production at LEP 2 and at a linear collider. We concentrate on the supersymmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model, where the spontaneous R-parity breaking is inevitable and is associated with the breaking of the LR-symmetry.

1 Introduction

The lepton and baryon number conservation of the Standard Model (SM) is incorporated in the Minimal Supersymmetric Standard Model (MSSM) by the conservation of R-parity, $R = (-1)^{3(B-L)+2S}$. Under this symmetry the standard model particles are R-even and their superpartners R-odd. The gauge symmetry and supersymmetry do allow an explicit R-parity breaking through three point interactions and bilinear terms. These interactions would, however, violate either lepton or baryon number. If both are realized, the proton will decay fast [1]. Therefore, in MSSM with broken R-parity it is usually assumed that either the couplings that break the lepton number or the couplings that break the baryon number vanish.

In addition to the above mentioned explicit breaking of R-parity, the breaking can be spontaneous. In MSSM the spontaneous breaking could occur through a non-zero VEV of the scalar partner of a neutrino, which would lead – as the lepton number is not part of the gauge symmetry – to the emergence of a physical massless Goldstone boson, a majoron. This would open a new invisible decay mode of the Z-boson ruled out by LEP experiments [2]. Phenomenology of models where R-parity breaking is associated with an isosinglet neutrino instead of a usual isodoublet neutrino and where the majoron has a negligible coupling to the weak Z boson, as well as models with a new $U(1)$ symmetry with an extra Z' absorbing the Goldstone mode, have been studied in [3–5].

In the supersymmetric version (SLRM) [6] of the left-right model [7] with the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, the R-parity is conserved at the level of the Lagrangian [8]. This is because all the terms allowed by the $U(1)_{B-L}$ gauge symmetry are automatically R-even. On the other hand, in the physically consistent minimum one of the neutrinos necessarily has a VEV and R-parity is thus spontaneously broken [9,10]. As the R-parity breaking arises in this model through one or more of the sneutrinos getting a nonzero VEV, only the lepton number is violated and the breaking has no effect on the proton decay. The three point interactions of the MSSM with an explicit R-parity violation are experimentally strictly constrained (see e.g. [11]). In models with spontaneous R-parity violation, like SLRM, these couplings are naturally suppressed since they are proportional to small mixing angles or they are generated by loops.

An important consequence of the spontaneous breaking of the R-parity is that R-odd particles, i.e. supersymmetric particles not present in the Standard Model, can be produced singly and on the other hand they can decay into the Standard Model particles. The single production is possible due to the mixing between the R-odd and R-even particles: neutralinos mix with neutrinos, charginos with charged leptons, and sneutrinos with Higgs bosons. The single production mechanisms provide probes for heavier supersymmetric particles than one can explore when R-parity is conserved in which case the production can only occur in pairs.

The phenomenology of spontaneously broken R-parity models at the Z-peak at LEP has been previously considered in [3,4]. In this paper we shall investigate the production mechanisms of single neutralinos and charginos at LEP and a linear collider in the framework of SLRM.

In Sect. 2 we will investigate the constraints for the mixing of the Standard Model leptons with other constituents of neutralinos and charginos obtained from the negative searches of single neutralino or chargino production in LEP 1 measurements. We will not restrict ourselves to the minimally extended MSSM, as was done e.g. in [3, 4], but use a more general parameterization. In Sect. 3 we will first describe the basic ingredients of the supersymmetric left-right model and then we will investigate in this model the production and detection of neutralinos and charginos at LEP2 and at an e^+e^- linear collider. A summary with conclusions is presented in Sect. 4.

2 Constraints from LEP 1 measurements

In many supersymmetric models the lightest neutral supersymmetric particle is a neutralino and the lightest charged one is a chargino. This kind of model is of great interest from the point of view of spontaneus R-parity breaking as large mixings between neutrinos and the lightest neutralino and between charged leptons and the lightest chargino might naturally occur there. Implications of such mixings, if they exist, could in principle have been seen in LEP 1 experiments, and this can be used to set constraints on various model parameters. In this section we will investigate those constraints.

We will assume that there exists a neutrino which is singlet under the Standard Model gauge group and which couples to one of the lepton families of the Standard Model. The supersymmetric counterpart of the singlet neutrino is assumed to acquire a nonzero VEV, driving the spontaneous breaking of R-parity. The neutralino and chargino states can be schematically written as superpositions of gauginos λ_j, higgsinos $\tilde{h}_j$ and leptons ν_j and l_j as follows:

$$\begin{aligned}\tilde{\chi}_i^0 &= a_{ij}^{(0)}\lambda_j^0 + b_{ij}^{(0)}\tilde{h}_j^0 + c_{ij}^{(0)}\nu_j, \\ \tilde{\chi}_i^\pm &= a_{ij}^{(\pm)}\lambda_j^\pm + b_{ij}^{(\pm)}\tilde{h}_j^\pm + c_{ij}^{(\pm)}l_j^\pm. \end{aligned} \qquad (1)$$

With typical values of the mass parameters in the supersymmetric sector, i.e. of the order of the weak scale, one assumes that the lightest neutralino, $\tilde{\chi}_1^0$, and the lightest chargino, $\tilde{\chi}_1^\pm$, which are identified as the physical neutrino and charged lepton, respectively, have interactions very similar to those of the pure weak eigenstates of neutrino ν and charged lepton $l^\pm$ in the SM.

Let us consider the production of the lightest "supersymmetric" neutralino $\tilde{\chi}_2^0$ and chargino $\tilde{\chi}_2^+$, by assuming that the masses of the other states $(\tilde{\chi}_3^{0(+)}, \tilde{\chi}_4^{0(+)}, ...)$ are beyond the reach of LEP 1. The cross sections of $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ $(\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp)$ at Z^0 peak are suppressed by the mixing of $\tilde{\chi}_2^0$ $(\tilde{\chi}_2^+)$ with the neutrino $\tilde{\chi}_1^0$ (the lepton $\tilde{\chi}_1^+$), but on the other hand heavier neutralinos (charginos) can be produced than in pair production with the same center of mass energy. Of course, if the mass of the neutralino or chargino is larger than $M_Z/2$ it is not possible to pair-produce these particles at Z-pole.

For the neutralino $\tilde{\chi}_2^0$ to be seen, it has to decay inside the detector. If it is the lightest supersymmetric particle, it decays due to the R-parity violating gauge interactions generated by its mixing with the neutrino $\nu \simeq \tilde{\chi}_1^0$. Similarly, the decay of the chargino, if it is the lightest supersymmetric particle, occurs as a result of its mixing with a charged lepton $l^+ \simeq \tilde{\chi}_1^+$. The partial mean length of flight path of the neutralino and chargino in the CM frame of an e^+e^- collison, taking only the decay via a virtual Z boson into account, is given by

$$L = \frac{s - m_{\tilde{\chi}_2}^2}{\eta^2 m_{\tilde{\chi}_2}^6 \sqrt{s}}\, 6.7\times 10^{-4}\ \mathrm{GeV}^5\cdot\mathrm{m}\ , \qquad (2)$$

where $m_{\tilde{\chi}_2}$ is the mass of the neutralino or chargino, $\sqrt{s}$ is the CM energy of the collision, and the masses of neutrinos and charged leptons are neglected. The parameter η is a suppression factor which takes into account the fact that the $\tilde{\chi}_1\tilde{\chi}_2 Z$ coupling is not of the full Standard Model strength. It is a measure of the mixing between R-even leptons and R-odd supersymmetric particles induced by the spontaneous R-parity breaking.

For typical values of the parameters the decay is very fast. The production limit of a $\tilde{\chi}_1^0\tilde{\chi}_2^0$ pair for the luminosity attained at LEP 1 corresponds to the value $\eta = 10^{-3}$ (see Fig. 2). For a neutralino with mass $m_{\tilde{\chi}_2^0} = 45\,\mathrm{GeV}$ this would indicate the decay length of $L = 6$ μm, that is, of the order of the sensitivity of the LEP vertex detectors, for a heavier neutralino the decay length is even shorter. The same is valid for the chargino decays. Hence, whenever the neutralino or chargino coupling is large enough for the single production at LEP, the produced particle also decays immediately in the detector making its detection and identification possible.

In Fig. 1 the R-parity breaking decay modes of the neutralino $\tilde{\chi}_2^0$ (assuming $m_{\tilde{\chi}_2^0} < m_{\tilde{\chi}_2^\pm}$) and of the chargino $\tilde{\chi}_2^\pm$ (assuming $m_{\tilde{\chi}_2^\pm} < m_{\tilde{\chi}_2^0}$) are depicted. It is assumed that the lightest mass eigenstates $\tilde{\chi}_1^{0,\pm}$ are so close to the weak interaction eigenstates ν, $l^\pm$ that their other components can be neglected in the first approximation. In this approximation the three body decays of $\tilde{\chi}_2^{0,\pm}$ through virtual squark exchanges $(m_{\tilde{q}} > m_{\tilde{\chi}_2^{0,\pm}})$ can be ignored. Similarly the decays into physical neutral or charged Higgses due to their slepton components might be possible, but they are suppressed in general by small mixings. Decays involving other components of the Higgs bosons are proportional to the Yukawa type couplings, making the branching ratios of these channels also generally unsignificant (but not always, as we will see in next section in the context of SLRM). The kinematically favoured decay of $\tilde{\chi}_2^\pm$ to $\tilde{\chi}_1^\pm$ is not possible via γ exchange, since the chargino states are orthogonal and γ couples similarly to all components of $\tilde{\chi}_2^\pm$. Thus we are left with the $\tilde{\chi}_2^{0,\pm}$ decay mode via gauge boson Z or W exchange.

The dominant final states resulting from the single production of the neutralino $\tilde{\chi}_2^0$ in e^+e^- collisions at Z^0 pole are thus the following:

$$\begin{aligned} e^+e^- \to \bar{\nu}_l\tilde{\chi}_2^0 &\to \bar{\nu}_l\nu_{l'}l^-l'^+, && (3)\\ &\to \bar{\nu}_l l^- q q', && (4)\\ &\to \bar{\nu}_l\nu_l l'^+ l'^-, && (5)\\ &\to \bar{\nu}_l\nu_l q\bar{q}, && (6)\\ &\to \bar{\nu}_l\nu_l\bar{\nu}_{l'}\nu_{l'}. && (7)\end{aligned}$$

Here ν_l denotes the lightest neutralino $\tilde{\chi}_1^0$. For detection, the most favourable channel is (4) where the visible invariant mass equals the mass of the decaying neutralino. The

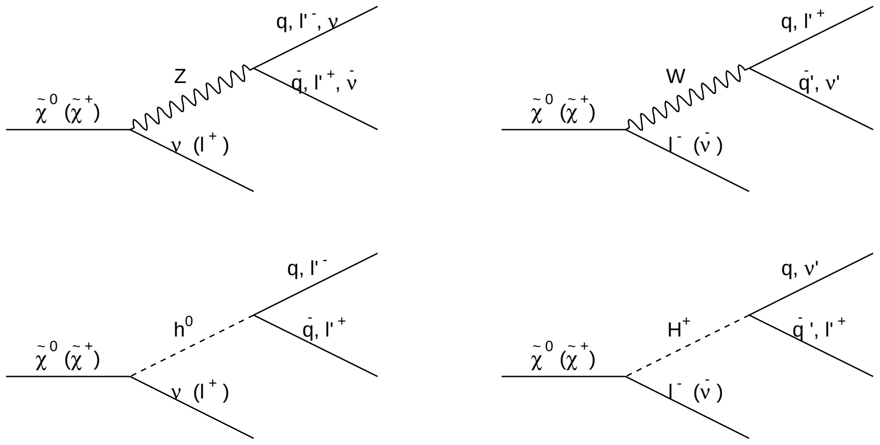

Fig. 1. The R-parity breaking decay modes of neutralinos (charginos). The lightest neutralinos and charginos, $\tilde{\chi}_1^{0,\pm}$, have been denoted by ν, $l^\pm$

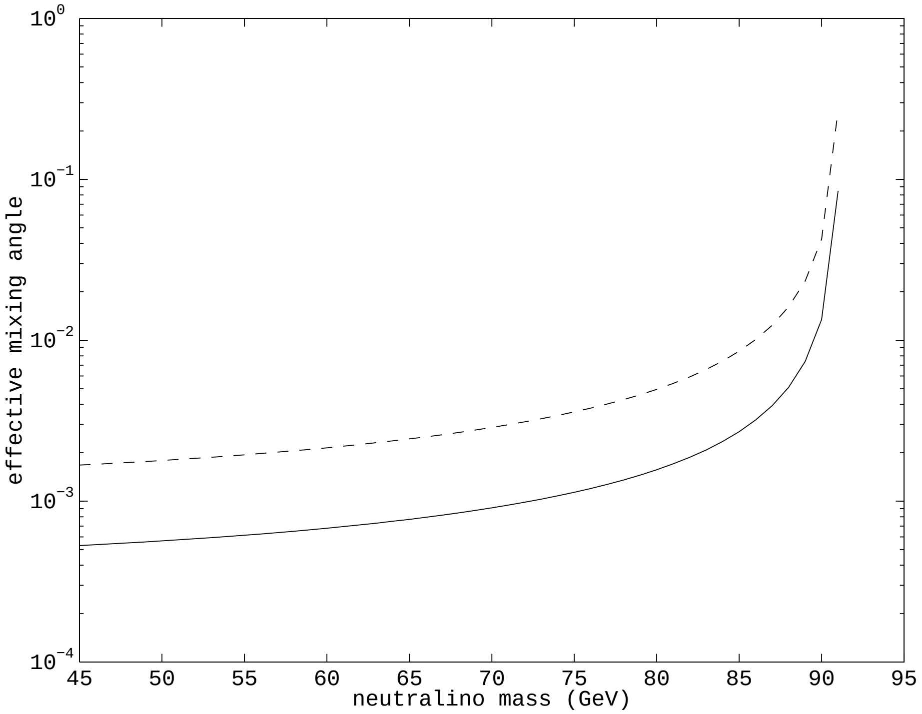

Fig. 2. The mixing between neutralino and neutrino (chargino and lepton) for production of one neutralino (chargino) as a function of the neutralino (chargino) mass (*solid line*). The *dashed line* corresponds to the production of ten neutralinos (charginos)

background from the τ pair production can be effectively eliminated by requiring that the invariant mass of the two jets is larger than the τ mass.

In the case of a single $\tilde{\chi}_2^+$ production the dominant final states are

$$e^+e^- \to \tilde{\chi}_2^+ l^- \to \nu\bar{\nu}l^+l^-, \quad (8)$$

$$\to q\bar{q}'\bar{\nu}l^-, \quad (9)$$

$$\to \nu' l'^+ \bar{\nu} l^-, \quad (10)$$

$$\to l'^+ l'^- l^+ l^-, \quad (11)$$

$$\to q\bar{q} l^+ l^-, \quad (12)$$

where l^- denotes $\tilde{\chi}_1^-$. For the first three reactions, where part of the energy is invisible, there is a Standard Model background from the τ pair production. In the case of the reaction (9) this can be eliminated by a suitable cut in the invariant mass of the hadronic jets. In the case of the (11) and (12) reactions, all the energy is visible, allowing for a direct chargino reconstruction.

An interesting situation arises in the extensions of the MSSM, which include triplet Higgses. Although the doubly charged particles in triplets do not mix with the fermions in (1), they may change the decay pattern of the particles, e.g. decays of the type

$$\tilde{\chi}^+ \to H^{++} l^- \quad (13)$$

become possible. This is exactly the situation we will encounter in the case of the supersymmetric left-right model, which will be discussed in the next section. Furthermore, since H^{++} is typically rather light [10], it is quite possible that (13) is the dominant decay mode. For a large part of the parameter space, H^{++} decays as [12]

$$H^{++} \to l^+ l'^+, \quad (14)$$

Table 1. The upper triangle of the symmetric neutralino mass matrix Y. We use the short-hand notation $V = B - L$

$$\begin{pmatrix}
m_L & 0 & 0 & \frac{g_L\kappa_1}{\sqrt{2}} & 0 & 0 & \frac{-g_L\kappa_2}{\sqrt{2}} & 0 & 0 & 0 & 0 \\
 & m_R & 0 & \frac{-g_R\kappa_1}{\sqrt{2}} & 0 & 0 & \frac{g_R\kappa_2}{\sqrt{2}} & g_R v_\Delta\sqrt{2} & -g_R v_\delta\sqrt{2} & 0 & -\frac{g_R\sigma_R}{\sqrt{2}} \\
 & & m_V & 0 & 0 & 0 & 0 & -g_V v_\Delta\sqrt{2} & g_V v_\delta\sqrt{2} & 0 & \frac{g_V\sigma_R}{\sqrt{2}} \\
 & & & 0 & 0 & 0 & -\mu_1 & 0 & 0 & 0 & 0 \\
 & & & & 0 & -\mu_1 & 0 & 0 & 0 & h^L_\Phi\sigma_R & 0 \\
 & & & & & 0 & 0 & 0 & 0 & 0 & 0 \\
 & & & & & & 0 & 0 & 0 & h^L_\varphi\sigma_R & 0 \\
 & & & & & & & 0 & \mu_2 & 0 & -2h_\Delta\sigma_R \\
 & & & & & & & & 0 & 0 & 0 \\
 & & & & & & & & & 0 & h^L_\varphi\kappa_2 \\
 & & & & & & & & & & -2h_\Delta v_\Delta
\end{pmatrix}$$

providing an excellent detection mode. Being dominant and possibly having an exotic flavour structure, it is even more promising than (11).

The negative search of singly produced neutralinos and charginos at LEP [13] leads to constraints on the mass and couplings of these particles. Considering the R-parity breaking production through the dominant Z-exchange processes only, we present in Fig. 2 the upper limit for the parameter η introduced in (2), describing the R-odd and R-even mixing in $\tilde{\chi}^{0,\pm}$, as a function of neutralino or chargino mass based on the total of 800 pb^{-1} of data gathered by LEP at Z pole [14]. Taking the detection limit of ten events and assuming a 100% detection efficiency, we find an upper limit of $\eta \lesssim 0.01$, valid almost up to the kinematical threshold.

This simple analysis gives us a feeling of the sensitivity of the present collider experiments on the effects of spontaneously broken R-parity. We will now move to the main part of our study. In the next section we will analyse the phenomenology of spontaneously broken R-parity at LEP2 and at a high-energy linear collider. We shall concentrate in our study on the supersymmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model. As was pointed out in the Introduction, in this model R-parity is necessarily broken spontaneously [9,10].

3 R-parity breaking effects at LEP2 and linear collider in SLRM

3.1 The model

The framework of our analysis in the following is the SLRM defined by the superpotential

$$\begin{aligned} W = {} & h^Q_\phi Q^T i\tau_2 \phi Q^c + h^Q_\varphi Q^T i\tau_2 \varphi Q^c \\ & + h^L_\phi L^T i\tau_2 \phi L^c + h^L_\varphi L^T i\tau_2 \varphi L^c + h_\Delta L^{cT} i\tau_2 \Delta L^c \\ & + \mu_1 \mathrm{Tr}(i\tau_2 \phi^T i\tau_2 \varphi) + \mu_2 \mathrm{Tr}(\Delta\delta). \end{aligned} \tag{15}$$

Here Q denotes the left-handed quark superfield doublet, Q^c denotes the conjugate of the right-handed quark superfield doublet and L and L^c are corresponding lepton superfield doublets. The $B-L$ quantum numbers of these doublets are $+1/3$, $-1/3$, -1 and $+1$, respectively. The triplet and the bidoublet Higgs superfields are given by

$$\Delta = \begin{pmatrix} \Delta^-/\sqrt{2} & \Delta^0 \\ \Delta^{--} & -\Delta^-/\sqrt{2} \end{pmatrix}, \quad \delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

$$\sim (\mathbf{1}, \mathbf{3}, -2), \qquad \sim (\mathbf{1}, \mathbf{3}, 2), \tag{16}$$

$$\phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix} \sim (\mathbf{2}, \mathbf{2}, 0), \quad \varphi = \begin{pmatrix} \varphi^0_1 & \varphi^+_1 \\ \varphi^-_2 & \varphi^0_2 \end{pmatrix} \sim (\mathbf{2}, \mathbf{2}, 0).$$

In the level of superfields the R-parity conservation is equivalent to the conservation of the multiplicative "matter parity" [15]

$$(\text{matter parity}) = (-1)^{3(B-L)}. \tag{17}$$

Since $B - L$ is a generator of a gauge symmetry in the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model, the Lagrangian of SLRM conserves R-parity automatically. The spontaneous breaking of the gauged U$(1)_{B-L}$ does not necessarily indicate breaking of R-parity, but it was shown in [9] on general grounds and in [10] explicitly in the model considered here that in order to break the left-right symmetry in a physically consistent way also R-parity must be broken.

The lowest state of the SLRM defined by the superpotential W in (15) corresponds to the following set of vacuum expectation values:

$$\langle \phi^0_1 \rangle = \kappa_1, \ \langle \varphi^0_2 \rangle = \kappa_2, \ \langle \Delta^0 \rangle = v_\Delta, \ \langle \delta^0 \rangle = v_\delta, \ \langle \tilde{\nu}^c \rangle = \sigma_R. \tag{18}$$

We have assumed here for simplicity that only one of the partners of the right-handed neutrinos, $\tilde{\nu}_R$, gets a VEV. The neutrino states of the corresponding family will then mix with neutral higgsinos and the fermionic partners of the neutral gauge bosons, λ^0_L, λ^0_R, and λ^0_{B-L}, to form the physical neutralino states.

The mass Lagrangian of the neutralino sector can be written in the form

$$\mathcal{L} = -\frac{1}{2}\psi^T Y \psi + \text{h.c.}, \tag{19}$$

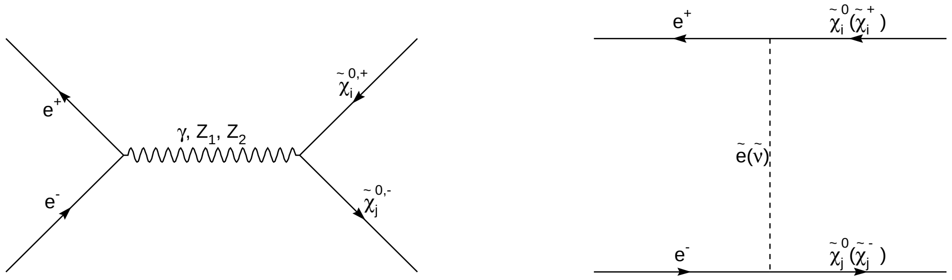

Fig. 3. The Feynman graphs for single and pair production of neutralinos and charginos in SLRM

Table 2. The chargino mass matrix X

$$\begin{pmatrix} m_L & 0 & 0 & g_L\kappa_2 & 0 & 0 \\ 0 & m_R & -g_R\kappa_1 & 0 & g_R v_\delta\sqrt{2} & g_R\sigma_R \\ g_L\kappa_1 & 0 & 0 & \mu_1 & 0 & 0 \\ 0 & -g_R\kappa_2 & \mu_1 & 0 & 0 & 0 \\ 0 & -g_R v_\Delta\sqrt{2} & 0 & 0 & \mu_2 & -h_\Delta\sigma_R\sqrt{2} \\ 0 & 0 & -h^L_\Phi\sigma_R & -h^L_\varphi\sigma_R & 0 & -h^L_\Phi\kappa_1 \end{pmatrix}$$

where $\psi^T = (-i\lambda^0_L, -i\lambda^0_R, -i\lambda^0_{B-L}, \tilde{\Phi}^0_1, \tilde{\Phi}^0_2, \tilde{\varphi}^0_1, \tilde{\varphi}^0_2, \tilde{\Delta}^0, \tilde{\delta}^0, \nu, \nu^c)$ and the symmetric 11×11 matrix Y is given in Table 1.

In addition to the mass terms that follow from (15) and (18), we have introduced in the matrix Y diagonal soft gaugino mass terms m_L, m_R and m_V for λ^0_L, λ^0_R and λ^0_{B-L}, respectively.

The lightest of the neutralinos corresponds to the left-handed neutrino. As usual the masses of the other eigenstates depend on the relative magnitudes of gaugino soft masses, parameters μ_i and the VEVs (18).

The mass Lagrangian of the chargino sector is given by

$$\mathcal{L} = -\frac{1}{2}(\varepsilon^{-T}\eta^{+T}) \begin{pmatrix} 0 & X \\ X^T & 0 \end{pmatrix} \begin{pmatrix} \varepsilon^- \\ \eta^+ \end{pmatrix} + \text{h.c.} \qquad (20)$$

where $\eta^{+T} = (-i\lambda^+_L, -i\lambda^+_R, \tilde{\Phi}^+_1, \tilde{\varphi}^+_1, \tilde{\delta}^+, l^c)$, and $\varepsilon^{-T} = (-i\lambda^-_L, -i\lambda^-_R, \tilde{\Phi}^-_2, \tilde{\varphi}^-_2, \tilde{\Delta}^-, l)$. The 6×6 matrix X is given in Table 2.

In models with R-parity conservation, the lightest neutralino is usually the lightest supersymmetric particle, LSP. In our case where R-parity is spontaneously broken, it may well happen that the lightest chargino $\tilde{\chi}^+_2$ is lighter than $\tilde{\chi}^0_2$.

As a result of the spontaneous R-parity breaking, the neutralinos and charginos corresponding to the SM leptons, being superpositions of gauginos, higgsinos and leptons, have in general couplings different from the couplings of the SM leptons. The precision measurement of those couplings made, e.g., at the Z-boson pole at CERN should be taken into account when constructing realistic models. Apart from the precision collider measurements also some rare processes lead to meaningful constraints. The most stringent bound is obtained from the non-observation of the exotic muon decay $\mu \to 3e$ whose branching ratio obeys $\text{Br}(\mu \to 3e) < 10^{-12}$ [16]. If $\langle\tilde{\nu}_e\rangle$ and $\langle\tilde{\nu}_\mu\rangle$ are both large this constraint is not satisfied in SLRM.

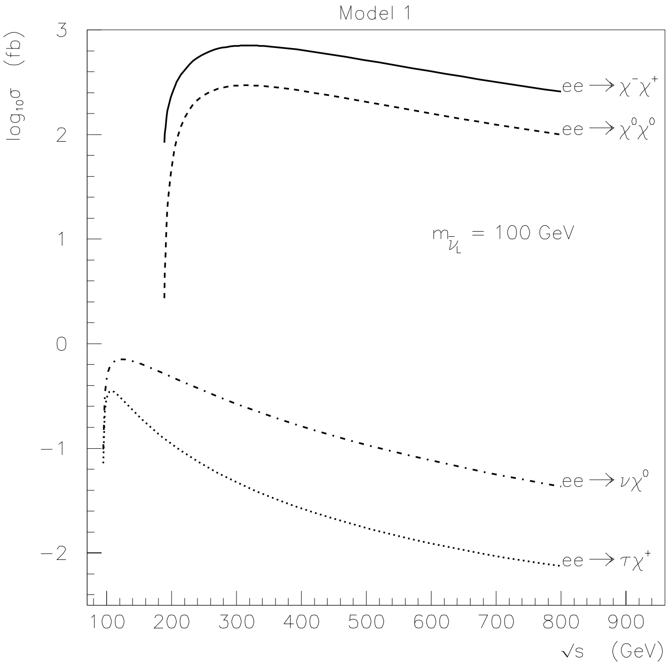

Fig. 4. The production cross section of single or pair produced neutralinos and charginos as a function of center of mass energy in the Model 1 with $m_{\tilde{e}_L} = m_{\tilde{\nu}_{eL}} = 100\,\text{GeV}$

It is interesting to note in this connection that in SLRM the components which usually form the dominant part of the mass eigenstates of charginos and neutralinos corresponding to the SM leptons have automatically approximately the SM couplings with $SU(2)_L$ gauge bosons due to the symmetry breaking structure. This is because the states that diagonalize the Lagrangian after the $SU(2)_R$ breaking have definite $SU(2)_L \times U(1)_Y$ quantum numbers and couplings. The subsequent breakdown to $U(1)_{em}$ cause only small deviations, characterized by (m_{W_L} or $m_\tau)/m_{W_R}$ or m_τ/m_{susy}, where m_{susy} is a general susy scale, to the composition of these states and their couplings.

3.2 Production of neutralinos and charginos at LEP 2 and at a linear collider

Predictions of the SLRM depend on the values of the soft gaugino masses m_L, m_R and m_V which are in principle free parameters. We will consider in the following two representative choices of these parameters. In one case the

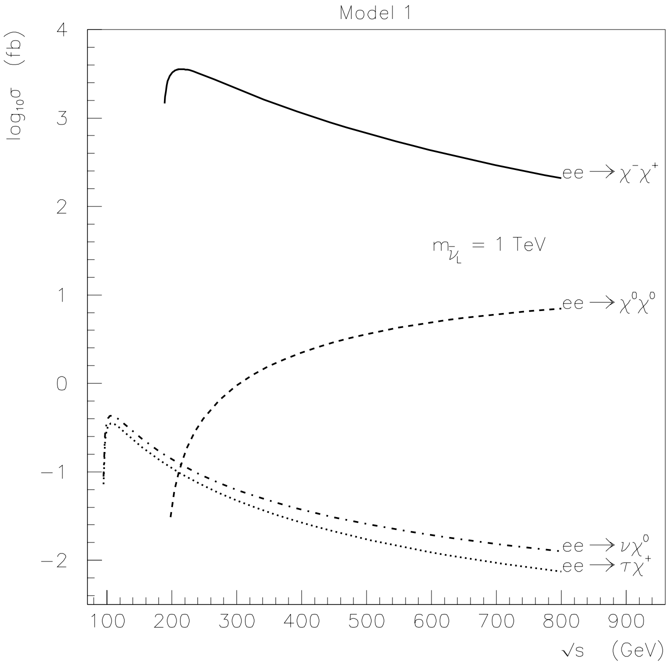

Fig. 5. The production cross section of single or pair produced neutralinos and charginos as a function of center of mass energy in the Model 1 with $m_{\tilde{e}_L} = m_{\tilde{\nu}_{eL}} = 1\,\mathrm{TeV}$

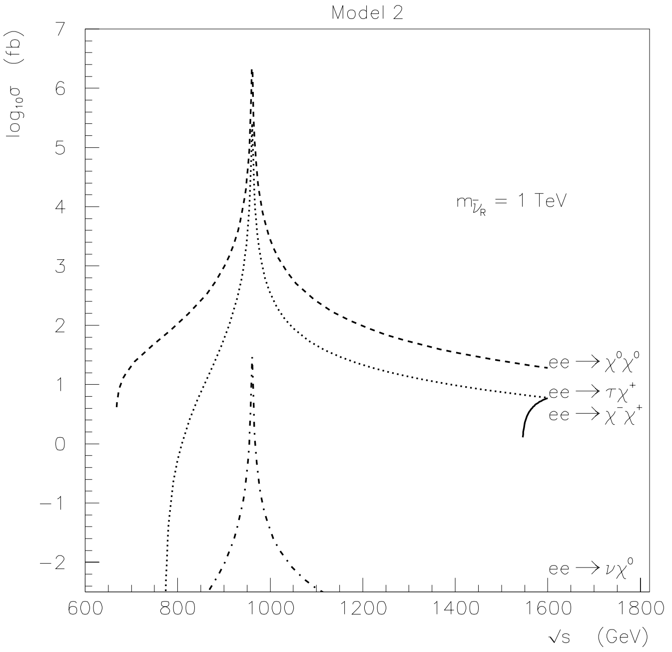

Fig. 6. The production cross section of single or pair produced neutralinos and charginos as a function of center of mass energy in Model 2 with $m_{\tilde{e}_R} = m_{\tilde{\nu}_{eR}} = 1\,\mathrm{TeV}$

soft gaugino masses are all of the order of 100 GeV (Model 1) and in the other one of the order of 1 TeV (Model 2). The masses and compositions of the physical particles relevant for the decays of neutralinos and charginos are listed for both models in Table 3. We have assumed for simplicity that only the tau sneutrino $\tilde{\nu}_\tau$ achieves a non-zero VEV.

Let us consider the two models separately.

Model 1. In Model 1 the lightest supersymmetric chargino $\tilde{\chi}_2^\pm$ and the neutralino $\tilde{\chi}_2^0$ are almost degenerate: their masses are $m_{\tilde{\chi}_2^\pm} \simeq 94\,\mathrm{GeV}$ and $m_{\tilde{\chi}_2^0} \simeq 93\,\mathrm{GeV}$, and they are both almost pure gaugino λ_L states. The possible production amplitudes are depicted in Fig. 3. In Figs. 4 and 5 we have plotted the cross section for the single production via the reactions $e^+e^- \to \tilde{\chi}_2^+\tau^-$ and $e^+e^- \to \tilde{\chi}_2^0\nu_\tau$ and for the pair production via the reactions $e^+e^- \to \tilde{\chi}_2^+\tilde{\chi}_2^-$ and $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0$ as a function of the center of mass energy $\sqrt{s}$. The single production occurs via Z_L exchange in s-channel and via sneutrino or selectron exchange in t-channel. For the chargino pair production there is an additional contribution coming from the s-channel photon exchange.

At LEP 1 the collision energy is not large enough for the production of $\tilde{\chi}_2^\pm$ or $\tilde{\chi}_2^0$, but at LEP 1.5 the single production is possible in principle. From Figs. 4 and 5 one can see, however, that while the single production is kinematically allowed at the LEP 1.5 energies of $\sqrt{s} = 130 - 140\,\mathrm{GeV}$, the cross section is far too small for a signal with the collected data of about 6 pb^{-1}. Even for LEP 2 with $\sqrt{s} = 160 - 192\,\mathrm{GeV}$ and the planned integrated total luminosity of 500 pb^{-1}, the cross section is less than 1 fb and no events would be produced during the whole running time of LEP 2.

Contrary to the single production, the pair production is not suppressed by mixing angles and consequently the cross section of pair production may exceed that of the single sparticle production by several orders of magnitude. As seen from Figs. 4 and 5, the chargino pair production is a particularly promising process. The cross section depends on the mass of the electron sneutrino $\tilde{\nu}_e$, and in Figs. 4 and 5 we have plotted the cross section for two representative values, $m_{\tilde{\nu}_e} = 100\,\mathrm{GeV}$ and $m_{\tilde{\nu}_e} = 1\,\mathrm{TeV}$, respectively. The destructive interference between the s-channel and t-channel contributions reduces the cross section considerably in the case of a light sneutrino, but it is negligible for a heavy sneutrino case. At the center of mass energy of $\sqrt{s} = 192\,\mathrm{GeV}$ the cross section of the pair production process $e^+e^- \to \tilde{\chi}_2^+\tilde{\chi}_2^-$ in the Model 1 assuming $m_{\tilde{\nu}_e} = 1\,\mathrm{TeV}$ is 2.2 pb, resulting in hundreds of signal events.

In Model 1 the neutralino decays mainly to the lightest chargino $\tilde{\chi}_1 \simeq \tau$ and W_1 with the decay width of $\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^+ W_1) \simeq 10$ keV. The chargino can decay either to the W_1 and the lightest neutralino $\simeq \nu_\tau$ for which $\Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^0 W_1) \simeq 20$ keV or to the lightest chargino and Higgs boson for which $\Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^+ H_1^0) \simeq 10$ keV, followed by the decay of Higgs to a pair of bottom quarks. It is evident that the signal for chargino pair production should be detectable at LEP 2 with center of mass energy 192 GeV and integrated luminosity 200 pb^{-1}, as well as at a linear collider with anticipated center of mass energies of 350 to 1600 GeV and luminosities of 10 to 500 fb^{-1} [17], respectively, even if only the channels with all the final state energy visible is used for the detection.

Table 3. Masses and compositions of particles with $m \lesssim m_{\tilde{\chi}_2^{\pm,0}}$ and masses of the heavy gauge bosons in Models 1 and 2. In Model 1, the soft gaugino masses $M_i \simeq 100\,\mathrm{GeV}$ and $\kappa_2/\kappa_1 = 1.9$ and $\sigma_R = 1.7\,\mathrm{TeV}$. In Model 2, the soft gaugino masses $M_i \simeq 1\,\mathrm{TeV}$ and $\kappa_2/\kappa_1 = 50$ and $\sigma_R = 340\,\mathrm{GeV}$. Yukawa coupling $h_\Delta = 0.6$, $v_\Delta/v_\delta \simeq 1.1$ and the soft scalar masses are $\mathcal{O}(1\,\mathrm{TeV})$ in both models

Model 1 particle	mass [GeV]	composition
Z_2	1654	
W_2	1029	
$\tilde{\chi}_1^0 \sim \nu_\tau$	0.02	$(-0.01 i\lambda_L^0 + 0.01 i\lambda_R^0 - 0.05\tilde{\phi}_1^0 - \nu)$
$\tilde{\chi}_2^0$	93	$(0.98 i\lambda_L^0 - 0.11 i\lambda_R^0 - 0.17 i\lambda_{B-L}^0$ $+0.03\tilde{\phi}_1^0 - 0.02\tilde{\varphi}_2^0 - 0.01\nu)$
$\tilde{\chi}_1^+ \sim \tau^+$	1.7	$\begin{pmatrix} 0.79 i\lambda_R^+ - 0.03\tilde{\phi}_1^+ - 0.3\tilde{\delta}^+ + 0.54 l^c \\ 0.01 i\overline{\lambda_L^-} - 0.01 i\overline{\lambda_R^-} - 0.03\overline{\tilde{\phi}_2^-} - 0.05\overline{\tilde{\varphi}_2^-} + 0.01\overline{\tilde{\Delta}^-} - \bar{l} \end{pmatrix}$
$\tilde{\chi}_2^+$	94	$\begin{pmatrix} i\lambda_L^+ + 0.02\tilde{\varphi}_1^+ \\ -i\overline{\lambda_L^-} + 0.04\overline{\tilde{\phi}_2^-} - 0.01\bar{l} \end{pmatrix}$
H_1^0	53	$(-0.03\tilde{\nu}^c - 0.47\phi_1^0 - 0.88\varphi_2^0 - 0.02\Delta^0 - 0.04\delta^0)$

Model 2 particle	mass [GeV]	composition
Z_2	962	
W_2	742	
$\tilde{\chi}_1^0 \sim \nu_\tau$	0.001	$(0.04\tilde{\varphi}_1^0 + \nu)$
$\tilde{\chi}_2^0$	333	$(0.38 i\lambda_R^0 - 0.25 i\lambda_V^0 + 0.22\tilde{\Delta}^0 - 0.82\tilde{\delta}^0 - 0.29\nu^c$
$\tilde{\chi}_1^+ \sim \tau^+$	1.7	$\begin{pmatrix} -0.6 i\lambda_R^+ - 0.68\tilde{\delta}^+ - 0.42 l^c \\ -0.04\overline{\tilde{\varphi}_2^-} - \bar{l} \end{pmatrix}$
$\tilde{\chi}_2^+$	772	$\begin{pmatrix} -0.61 i\lambda_R^+ + 0.73\tilde{\delta}^+ - 0.3 l^c \\ 0.71 i\overline{\lambda_R^-} + 0.71\overline{\tilde{\Delta}^-} \end{pmatrix}$
$\tilde{H}^{++}$	500	$\begin{pmatrix} \tilde{\delta}^{++} \\ \overline{\tilde{\Delta}^{--}} \end{pmatrix}$
H_1^0	108	$(0.02\tilde{\nu}^c + 0.02\phi_1^0 + \varphi_2^0 - 0.01\Delta^0 + 0.01\delta^0)$
H^{++}	334	$(0.91\Delta^{++} + 0.42\delta^{++})$

Model 2. In this model the soft gaugino masses are of the order of 1 TeV. The masses of the lightest supersymmetric chargino and neutralino $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_2^0$ are 772 GeV and 333 GeV, respectively, that is, they are too heavy to be produced at LEP, even singly. At a linear collider with $\sqrt{s}$ up to 1.6 TeV they can be produced both in single or pair production processes. The production cross sections are plotted in Fig. 6. The mass of the heavy neutral weak boson Z_2 in this model is 962 GeV, resulting in a resonance peak in the cross section in the energy range relevant for the future linear collider. The dominant processes are now $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0$ and $e^+e^- \to \tilde{\chi}_2^+\tau$ whose cross sections are at the level of tens of fb's outside the resonance region. In Fig. 6 we have taken the width of the Z_2 resonance to be equal to that of the ordinary Z boson. The single production of the neutralino in this model is negligible, and for the most part of the interesting energy range the pair production of the chargino is kinematically excluded.

The dominant decay channel of the neutralino $\tilde{\chi}_2^0$ in Model 2 is to the lightest neutralino and the lightest Higgs boson, for which the decay width is $\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H_1^0) \simeq 100$ keV. Branching ratios to gauge bosons are in this case more suppressed than in the Model 1, the width being $\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z_1) \simeq \Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^+ W_1) \simeq 30\,\mathrm{keV}$. In Model 2 the special features of SLRM become visible, since the chargino decays predominantly to a doubly charged Higgs boson H^{++}, whose mass is 334 GeV, and a charged lepton followed by the decay of H^{++} to a same sign lepton pair. The width of this channel is $\Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^- H^{++}) \simeq 90$ MeV. These decays lead to a spectacular signature characteristic of SLRM. The kinematically most favoured decay mode of the doubly charged Higgs is $H^{++} \to ll'$. In the case $l = l' = e$ or $l = l' = \mu$ one will have from this decay an unambiguous signature of a same-sign lepton pair with no missing energy. In the case $l = l' = \tau$ the final state would include either two same-sign leptons (e^-e^-, $\mu^-\mu^-$ or $e^-\mu^-$) with missing energy or transverse pions plus missing energy. The decay widths for the other channels are $\Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^+ Z_L) \simeq 3$ MeV, $\Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^0 W_1^+) \simeq 1$ MeV, and $\Gamma(\tilde{\chi}_2^+ \to \tilde{\chi}_1^+ H_1^0) \simeq 0.5$ MeV. If the right-handed slepton is light enough the chargino will decay via R-parity preserving processes into a left-handed slepton and a lepton.

The background for the conventional R-parity violating decay modes, discussed in the case of LEP 1, increases substantially when the center of mass energy is beyond the gauge boson pair production threshold. In the case of separate lepton number violating decays involving doubly charged Higgses there is no Standard Model background for the process.

4 Summary and conclusions

We have studied the production and decay of neutralinos and charginos at LEP 2 and at a linear collider in the case of spontaneously broken R-parity within the framework of supersymmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model. A characteristic of models with R-parity non-conservation is that missing energy is no longer a signature in all of the supersymmetric processes. The signal in SLRM may be similar to the case of MSSM with R-parity breaking (Model 1), but for an interesting part of the parameter space the signals typical for the left-right model, namely the decay via a doubly charged Higgs, is the dominant one (Model 2).

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