Phenomenology of SUSY-models with spontaneously broken R-parity

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Abstract.

We review the consequences of spontaneously broken R-parity in present and planned lepton-lepton colliders. In the left-right models the R-parity, \( R = (-1)^{3(B-L)+2S} \), is preserved due to the gauge symmetry, but it must be spontaneously broken in order to generate the scalar spectrum to be physically consistent. The spontaneous breaking is generated via a non-vanishing VEV of at least one of the sneutrinos, which necessarily means non-conservation of lepton number \( L \). The R-parity violating couplings are parametrized in terms of mixing angles, whose values depend on model parameters. Combined with the constraints derived from low-energy measurements this yields allowed ranges for various R-parity breaking couplings. The R-parity breaking allows for the processes in which a single chargino or neutralino is produced, subsequently decaying at the interaction point to non-supersymmetric particles.

INTRODUCTION

In minimal supersymmetric model [1] the gauge symmetry and supersymmetry allow three point interactions and bilinear terms that violate either baryon- or lepton number. These interaction terms are restricted by a plethora of as yet unobserved low energy phenomena (see e.g. [2]). If both baryon and lepton number violation are realized, the proton will decay fast [3]. To cure these problems one usually assumes so-called R-parity, defined as \( (-1)^{3(B-L)+2S} \), where \( B \) is a baryon number, \( L \) a lepton number and \( S \) spin of the matter field, to be a conserved global symmetry [4–6].

The assumption of R-parity symmetry is not necessary for the internal consistency of the model. Furthermore, the global symmetries at electroweak scale could be violated by Planck scale effects [7]. A more natural way would be to have the matter parity as a gauge symmetry. The simplest physically consistent model to accomplish this is the supersymmetric left-right model (SLRM) based on a gauge

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1) Talk given in Beyond the Standard Model V in Balholm, Norway. Presented by K. Puolamäki.
group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ [8]. In SLRM the lepton superfields, and similarly as quark fields, are arranged in $SU(2)_{L,R}$ doublets $L$ and $L^c$.

The matter parity is a discrete subgroup of $U(1)_{B-L}$ gauge group. It can be shown that in $U(1)_{em}$ preserving minimum at least one sneutrino has a non-vanishing VEV $\langle \nu_j^c \rangle = \sigma R \neq 0$, which is at least of the order of the breaking scale of the left-right symmetry or supersymmetry [9,10]. Lepton number — and consequently R-parity — is thus spontaneously violated. We have considered the phenomenological consequences of this model in [11]. Here we will review the main results of our study.

**SUPERSYMMETRIC LEFT-RIGHT MODEL**

The minimal Higgs content of the left-right susy model is two $SU(2)_R$ triplets and two $SU(2)_L \times SU(2)_R$ bidoublets:

$$\Delta = \begin{pmatrix} \Delta^0 \\ \Delta^- \\ \Delta^{--} \end{pmatrix} \sim (1, 3, -2), \quad \delta = \begin{pmatrix} \delta^{++} \\ \delta^+ \\ \delta^0 \end{pmatrix} \sim (1, 3, 2),$$

$$\phi = \begin{pmatrix} \phi_1^0 \\ \phi_1^+ \\ \phi_2^0 \end{pmatrix} \sim (2, 2, 0), \quad \varphi = \begin{pmatrix} \varphi_1^0 \\ \varphi_1^+ \\ \varphi_2^0 \end{pmatrix} \sim (2, 2, 0).$$

Two triplet superfields are required in order to cancel $U(1)_{B-L}$ anomalies due to higgsino loops and two Higgs bidoublets are required to obtain a non-trivial CKM quark mixing matrix.

The spontaneous symmetry breaking takes place at two separate scales. At the first stage $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is broken to $SU(2)_L \times U(1)_Y$ by triplet Higgs and sneutrino VEV’s:

$$\langle \Delta^0 \rangle = v_\Delta, \quad \langle \delta^0 \rangle = v_\delta, \quad \langle \nu^c \rangle = \sigma R.$$

This breaking sets the massscale of the right-handed gauge bosons (one could have $m_{W_R} = \mathcal{O}(1...10) \text{ TeV}$). The mass of the charged boson $W_R$ is given by [10]

$$m_{W_R}^2 = g_R^2 \left( v_\Delta^2 + v_\delta^2 + \frac{1}{2} \sigma_R^2 \right).$$

Experimentally $m_{W_R} > 650 \text{ GeV}$ [12]. The standard model symmetry group $SU(2)_L \times U(1)_Y$ is broken to $U(1)_{em}$ by bidoublet VEV’s

$$\langle \Phi^0_1 \rangle = \kappa_1, \quad \langle \varphi^0_2 \rangle = \kappa_2; \quad \tan \beta = \frac{\kappa_2}{\kappa_1}.$$

The connection of this breaking scale to the mass of the ordinary left-handed gauge boson $W_L$ is given by
\[ m^2_{W_L} = \frac{1}{2} g^2_L \left( \kappa_1^2 + \kappa_2^2 \right) = (80 \text{GeV})^2. \]

As a result of the R-parity and lepton number breaking, arising when \( \langle \nu_{\ell} \rangle = \sigma_R \neq 0 \), leptons (\( \nu, l \)) mix with gauginos (\( \lambda \)) and higgsinos (\( \tilde{h} \)). The physical neutralino and chargino states most generally are thus the following kind of superpositions:

\[ \tilde{\chi}_i^0 = a^{(0)}_{ij} \lambda^0_j + b^{(0)}_{ij} \tilde{h}^0_j + c^{(0)}_{ij} \nu_j, \]
\[ \tilde{\chi}_i^\pm = a^{(\pm)}_{ij} \lambda^\pm_j + b^{(\pm)}_{ij} \tilde{h}^\pm_j + c^{(\pm)}_{ij} l^\pm_j. \]

In contrast with lepton number, the baryon number is conserved, since spontaneous baryon number violation would indicate a presence of a non-vanishing VEV of a squark field, which would break the \( SU(3)_C \times U(1)_{em} \) gauge symmetry.

In principle every sneutrino could have a VEV. However, either of the VEV’s for electron and muon sneutrinos \( \langle \nu_{\ell}^c \rangle \) and \( \langle \nu_{\mu}^c \rangle \) should be small or vanish, since otherwise there would be a tree-level amplitude for lepton family number violating decay \( \mu \to 3e \), leading to a branching ratio that contradicts with the experimental bound \( B(\mu \to 3e) < 1.0 \times 10^{-12} \) [13].

In SLRM the physical leptons are chargino mass eigenstates composed of gauginos, higgsinos and leptons. Therefore their couplings to \( Z \)-boson will deviate from their normal form. However, the deviations are not large in general as the components which form the dominant part of the mass eigenstates of charginos and neutralinos corresponding to the SM leptons have all approximately the SM couplings with \( SU(2)_L \) gauge bosons. This is so due to the symmetry breaking structure: the states that diagonalize the Lagrangian after the \( SU(2)_R \times U(1)_{B-L} \) 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 to the composition of the physical states, characterized by \( (m_{W_L} \text{ or } m_{\tau})/m_{W_R} \text{ or } m_{\tau}/m_{\text{susy}} \), where \( m_{\text{susy}} \) is a general susy scale.

We assume that for simplicity only one sneutrino, namely \( \nu_{\tau}^c \), will have a non-vanishing VEV.

**TESTING THE MODEL IN ELECTRON-POSITRON COLLIDERS**

We have considered in [11] two representative models. In the first model the soft gaugino mass terms are about 100 GeV. The lightest supersymmetric particles are almost mass-degenerate neutralino \( (m_{\tilde{\chi}_0^2} \simeq 93 \text{ GeV}) \) and chargino \( (m_{\tilde{\chi}_2^\pm} \simeq 94 \text{ GeV}) \) both almost purely gaugino \( \lambda_L \) states.

In Fig. 1 we have plotted the cross sections for single production of the lightest charginos and neutralinos via reactions \( e^+e^- \to \tilde{\chi}_2^+\tau^- \) and \( e^+e^- \to \tilde{\chi}_0^0\nu_{\tau} \) 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 \( \sqrt{s} \). These processes occur via a gauge boson exchange in s-channel and via a t-channel sneutrino or electron exchange.
One can test the model by studying the production and decays of charginos and neutralinos in electron-positron colliders. LEP 2 is currently running at 160–192 GeV center of mass energies and it will collect about 0.5 $fb^{-1}$ total integrated luminosity by the end of the millennium. The linear collider is planned to operate initially at center of mass energy $\sqrt{s} = 380$ GeV with an annual luminosity of $L_{\text{year}} = 10 fb^{-1}$ and to be gradually upgraded to 1.6 TeV with $L_{\text{year}} = 200 fb^{-1}$ annual luminosity [14].

From these characteristic numbers we can conclude that the single production processes are in Model 1 too suppressed to be visible in LEP 2 or at planned linear colliders. The pair production, when kinematically allowed, would in turn contribute hundreds of reactions.

In Model 1 the neutralino decays at the interaction point to the tau lepton and the ordinary $W$-boson with the decay width of $\Gamma(\tilde{\chi}_0^2 \to \tau + W) \simeq 10$ keV. The chargino can decay either via gauge or Higgs boson, decay widths being $\Gamma(\tilde{\chi}_\pm^2 \to \nu \tau W) \simeq 20$ keV and $\Gamma(\tilde{\chi}_\pm^2 \to \tau^+ H_1^0) \simeq 10$ keV. In the latter case the Higgs boson will further decay, mainly to a pair of bottom quarks.

In Model 2 all soft masses are of the order 1 TeV. An interesting feature of this model is the existence of a relatively light doubly charged Higgs boson $H^{++}$ ($m_{H^{++}} = 334 GeV$). The lightest supersymmetric chargino ($m_{\tilde{\chi}_\pm^2} = 772 GeV$) and neutralino ($m_{\tilde{\chi}_0^2} = 333$ GeV) pair production would be visible in linear collider, whenever kinematically allowed. In this particular model a relatively light extra $Z$-boson, $Z_2$, ($m_{Z_2} \simeq 1 TeV$) also contributes and allows for measureable production cross section for single chargino $\tilde{\chi}_\pm^2$ and $\tilde{\chi}_1^- \sim \tau^-$, as shown in Fig. 2.

The neutralino would decay mainly to a neutrino and the lightest Higgs boson $\Gamma(\tilde{\chi}_0^2 \to \nu H_1^0) \simeq 100$keV. The chargino would decay predominantly to the tau lepton and the doubly charged Higgs boson, which would further decay to same...
FIGURE 2. The production cross section of single or pair produced neutralinos and charginos as a function of center of mass energy in Model 2 with $m_{\tilde{e}_R} = m_{\tilde{\nu}_e} = 1$ TeV.

sign lepton pair. The decay widths for the chargino are $\Gamma(\tilde{\chi}_2^+ \rightarrow \tau^- H^{++}) \simeq 90$ MeV and $\Gamma(\tilde{\chi}_2^+ \rightarrow \tau^+ Z) \simeq 3$ MeV.

SUMMARY

In contrast with the supersymmetric standard model, in extended models, e.g. in the left-right model, R-parity symmetry can be a subgroup of the gauge symmetry, and is spontaneously broken. The spontaneous symmetry breaking mechanism then uniquely determines the R-parity breaking couplings.

As a result of R-parity breaking charginos and neutralinos can in principle be singly produced. We have studied the prospects to measure this production at LEP 2 and linear collider and we have compared it with the pair production.

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