DISTINCTIVE SIGNALS OF SPONTANEOUS R-PARITY BREAKING AT LEP-II

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ABSTRACT

We consider the signals of pair-produced charginos in an $e^+e^-$ collider, in a scenario where R-parity is spontaneously broken. The possibility of lepton-chargino mixing, together with the presence of a Majoron, opens up the two-body decay channel of a chargino into a tau and a Majoron. We have studied the regions where this is the dominant decay of a chargino, and have shown that over a large region of the parameter space the ensuing signals, namely tau-pairs with missing-$p_T$, may rise well above standard model backgrounds at LEP-II. Such signals can also enable one to distinguish between spontaneous and explicit R-parity breaking.

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Supersymmetric (SUSY) theories which do not conserve R-parity, defined as $R = (-1)^{3B+L+2S}$, have already received considerable attention [1]. All particles in the standard model have $R = 1$ whereas their superpartners have $R = -1$. It also follows from the above definition that the nonconservation of either baryon or lepton number can lead to R-parity violation. While the former is rather seriously restricted by, for example, the absence of proton decay, breakdown of the latter is still phenomenologically viable. Thus an R-parity breaking theory may often be looked upon as a SUSY theory where lepton number is not conserved. Such a scenario implies a wide variety of new phenomena that can be looked for in the up-and-coming experiments.

R-parity can be broken in two ways– explicitly or spontaneously. The former option consists in introducing L(or B?)-violating interactions by hand in the superpotential. Such a model is blessed with the same economy as that of the minimal supersymmetric standard model (MSSM) and its predictions are well-studied [2]. The latter possibility entails the breakdown of R-parity through the vacuum expectation value (VEV) acquired by some scalar fields possessing non-zero lepton numbers. Though such a scenario results in an augmentation of the particle spectrum, it has some theoretical advantages as well. For example, in a situation where the VEV of an SU(2) singlet scalar breaks R-parity, there can be a natural origin of light sterile neutrinos [3] whose existence is being widely conjectured to explain various experimental results.

In this paper, we propose to concentrate on some observable signals of spontaneously broken R-parity. An immediate result of spontaneous breakdown of lepton number in this case is the appearance of a massless Goldstone boson which is called the Majoron [4]. Such a Majoron can be produced in the decay of a chargino, together with a charged lepton like the tau. We give here a detailed prediction of the signals of such decays at the LEP-II experiments.

Two types of models have been proposed in recent approaches to spontaneous R-parity
breaking. Many of their phenomenological implications have also been studied. In the first of these [5]-[7], the additional ingredients over and above those in the MSSM are the two isosinglet neutral superfields $\nu_i^c (i = 1 - 3)$ and $S$ carrying lepton numbers -1 and 2 respectively. The leptonic part of the superpotential here is of the form

$$W = \mu H_1 H_2 + \lambda_l l^c L H_1 + \lambda_\nu \nu^c L H_2 + \lambda_S S \nu^c \nu^c$$ (1)

where $L$ stands for the left chiral lepton-neutrino doublet and $l$, the right chiral charged leptons. $H_1$ and $H_2$ are the Higgs doublets giving masses to the down-and up-type quarks respectively. Here the VEV’s of the scalars $\tilde{\nu}^c$ and $\tilde{S}$ (as well as that of $\tilde{\nu}_L$) can break $L$ spontaneously.

In the other model [8]-[13], three kinds of neutral singlet superfields ($\phi$, $\nu^c$, $S$) are incorporated with lepton numbers (0, -1, 1). The corresponding superpotential is, in the same notation as above,

$$W = h_0 \phi H_1 H_2 + \lambda_l l^c L H_1 + \lambda_\nu \nu^c L H_2 + \lambda_S S \nu^c \phi$$ (2)

Again, lepton number is violated by $< \tilde{\nu}_{R,L}>$ and $\tilde{S}$. This second possibility offers a natural scale to the Higgsino mass parameter $\mu$ through the VEV of $\phi$, although it requires a larger particle spectrum.

Here we shall focus on features which are common to both of the above models, namely:

(i) After spontaneous symmetry breaking, one is left with terms of the form $LH_2$. This gives rise to mixing between charginos and charged leptons (as also between neutralinos and neutrinos). Note that although such terms may apparently be rotated away by redefinition of the $L$ and $H_2$ fields, the mixing inevitably shows up in the scalar potential [14].

(ii) A massless Goldstone boson, named the Majoron ($J$), emerges on the scene. The field
$J$ is composed dominantly of singlet scalars, but carries a doublet component also (because $< \bar{\nu}_L >$ in general contributes to symmetry breaking). However, constraints from $Z-$width measurements \cite{7,9} as well as those from the cooling of red giant stars \cite{15} require its $\bar{\nu}_L$-component to be quite small.

When chargino-lepton mixing takes place, there is a (5 X 5) mass matrix to be diagonalised in that sector. The above features cause the Majoron to have tree-level coupling with a chargino (i.e. one of the two heaviest physical states) and a charged lepton (i.e. one of the three lightest physical states). This can be understood if we remember that in the weak eigenstate basis, the lepton fields do not couple to the Majoron which is dominantly an SU(2) singlet. However, the charginos do couple to it through their Higgsino components. Such a disparity of couplings prevents the Glashow-Illiopoulos-Maiani (GIM) mechanism from being operative when the mass matrix is diagonalised, thereby connecting different mass eigenstates in the Majoron interaction.

The most general parametrisation of such an interaction is

$$\mathcal{L}_{J\chi} = \frac{J}{\sqrt{2}} \chi_i \left[ A_1 \frac{1 - \gamma_5}{2} + A_2 \frac{1 + \gamma_5}{2} \right] l_j$$ \hspace{1cm} (3)

There are strong experimental constraints on lepton flavour violating processes involving the electron or the muon. Also, difficulties related to baryogenesis can be avoided if at least one family has no lepton flavour violation \cite{10}. This makes it natural to assume that R-parity violating effects of the type discussed above are suppressed excepting for the tau family. In the remaining discussion we shall assume that only the tau mixes with the charginos.

Neglecting the $\tau$-mass, the width for $\chi^\pm \rightarrow \tau^\pm J$ is given by

$$\Gamma(\chi \rightarrow \tau J) = \frac{m_\chi A^2}{32\pi}$$ \hspace{1cm} (4)
Where $A^2 = A_1^2 + A_2^2$. The parameter $A$ will henceforth be used as a measure of the lepton number violating interaction strength. The laboratory constraints on the $\tau$-neutrino mass \textit{viz.} $m_{\nu_\tau} < 31 \text{ MeV}$ is perhaps the strongest source of constraint on the parameter $A$. However, the actual limit depends on the actual superpotential as well as on quantities such as the parameter $\mu$ and the right-handed sneutrino VEV. Approximate estimates based on the simplified assumption that all mass parameters are about 100 GeV implies \cite{7} that $A$ can be as high as a few times $10^{-2}$. We shall treat $A$ as a free parameter here.

If the charged sleptons and sneutrinos are heavier than the lighter chargino, then the only decay channels available to the latter are (i) the R-parity violating decay $\chi^\pm \rightarrow \tau^\pm J$, and (ii) the three-body decay $\chi^\pm \rightarrow \chi_0 f f'$ ($\chi_0$ being the lightest neutralino), which is allowed in MSSM itself. In addition, there may be R-parity violating three-body decay modes of the type $\chi^\pm \rightarrow \tau^\pm \nu \bar{\nu}$. These will be suppressed by the R-violating parameter, and can be neglected when one is concerned with the branching ratio for the two-body decay. The relative strengths of (i) and (ii) depend on the quantity $A$ in equation 4, and on the choice of the other SUSY parameters ($\text{gluino mass, } \mu, \tan \beta = <H_2/H_1>$) which fix the masses and couplings governing the R-parity conserving decays. It may be remarked that as far as R-conserving processes are concerned, the relevant interactions and mass relationships have negligibly small effects from R-violating terms. Hence the widths for such decays are equal to those obtained in the MSSM to a high degree of accuracy.

Since the Majoron is massless and sterile, $\chi^\pm \rightarrow \tau^\pm J$ leads to signals of the form $\tau^+ \tau^- + \not{p}_{T}$ in $e^+e^-$ colliders such as the LEP-II where the lighter chargino can be pair-produced. Such signals arise in the standard model from $W-$pairs. However, the decay $W \rightarrow \tau \bar{\nu}_\tau$ has a branching ratio of about 11 per cent, and thus tau-pair production there suffers from a net suppression of two orders of magnitude. There is no such suppression in the region of the parameter space where $\chi^\pm \rightarrow \tau^\pm J$ is dominant. Therefore, in such a region the
τ-pair production rate can considerably exceed what is predicted from W-decays. Given the fact that tau-identification efficiency can easily be as high as 80 per cent at LEP-II, those tau-pairs may prove to be the most important signatures of spontaneous R-breaking if charginos are light enough to be pair-produced.

Chargino pair-production in $e^+e^-$ annihilation proceeds through s-channel diagrams mediated by the photon and the Z, and through a t-channel diagram mediated by the sneutrino $\tilde{\nu}$. The latter is dominant at LEP-II energies so long as $m_{\tilde{g}} \leq 100-120$ GeV. To calculate the branching ratio for $\chi^\pm \to \tau^\pm J$, one needs to obtain also the three-body decay widths. That involves the computation of diagrams with the W, sleptons and squarks in the propagators. We assume all squarks and all sleptons (charged and neutral) to be separately degenerate.

The cross-sections for $e^+e^- \to \chi\chi \to \tau\tau JJ$ have been calculated here at LEP-II energies. For various choices of the SUSY parameters, we have made a full calculation of the different decay widths of the chargino and accordingly fixed the branching ratio for the R-violating two-body decay. The event selection criteria here are $E_\tau \geq 5$ GeV and $\not{p}_T \geq 5$ GeV. Since the energy and $p_T$ available from $\chi^\pm$-decay are roughly equipartitioned between the tau and the Majoron, it is found that the signals under question are practically unaffected by these cuts. For this reason, the spin-averaged cross-sections for the said final states modulo the suggested cuts agree with the spin-correlated ones.

In figures 1-4, we show the $\tau\tau JJ$ cross-sections plotted against the parameter $A$ for different values of the mass of the lighter chargino, using two values each of the gluino mass $(m_{\tilde{g}})$ and $\tan\beta$. These are sample results; for higher $\tan\beta$, the results are in general more optimistic. The squark mass has been fixed at 200 GeV. A slepton mass of 100 GeV is used in figures 2-4; only in figure 1 it is 80 GeV. A comparison between figures 1 and 2 shows the sensitivity of our predictions to the slepton mass. The enhancement due to a lower slepton mass can be attributed to the $t-$channel propagator effect in the production cross-section.
Also, the cross-section gradually flattens out as the parameter $A$ increases beyond about 0.01. This is because then onwards, the two-body decay of the chargino is completely dominant, and the branching ratio remains almost 100% throughout.

The main standard model background i.e. $e^+e^- \rightarrow WW \rightarrow \tau\tau + p_T$ has a cross-section of about 0.18 pb at LEP-II. The other background, namely that from a $Z$-pair, is even more suppressed by the branching ratios for leptonic $Z$-decay. Our results clearly show that over a rather sizable range of the parameter space the chargino decay signals are larger than such backgrounds by up to one order of magnitude in the parameter range shown here. Although the two kinds of event topologies are very similar, it is easy to discern the Majoron signals from a shower of tau-pairs with a large missing $p_T$. The tau’s are separated into two opposite hemispheres so that the narrow, low-multiplicity jets arising from them can be easily distinguished.

Now consider the strengths of similar signals in the MSSM and in a scenario with explicit R-parity breaking. In the MSSM case, a chargino could give rise to a tau together with the lightest supersymmetric particle (LSP) and a tau-antineutrino. The chargino pair-production rates would be the same as in our case here. However, the decay into a tau in the MSSM is controlled by the gauge coupling which treats all the lepton flavours similarly. Thus, for a pair of tau’s to be produced, a minimum branching fraction of 1/3 on each side is unavoidable. Also, there are the $(q\bar{q} + LSP)$ final states which eat further into the available decay rates unless the squarks are very massive. This means that the MSSM signals will be small compared to the case under study here. Similarly, with explicit breakdown of R-parity, $\tau^\pm + p_T$ can occur from three-body decays of chargino and neutralino pairs. Again, all the three lepton flavours are simultaneously produced, in addition to the quark final states, thereby reducing the branching fraction for tau-pairs. For spontaneous R-breaking, on the other hand, the $\tau$-coupling of a chargino and a Majoron is favoured, from considerations
that we have already stated. The tau-signal in the latter case, therefore, may enable one to
distinguish spontaneous R-parity breaking from explicit R-violation.

Similar types of events would also result from pair-produced charged Higgs bosons which
can have the $\tau - \nu_\tau$ decay mode. However, with a centre-of-mass energy of 180 GeV, the pair
production cross-section is approximately 0.1 pb for a charged Higgs pair of mass 80 GeV
\textsuperscript{18}. Even for a theoretically unfavourable charged Higgs of mass 70 GeV it is not more than
0.25 pb. Given the fact that there is a further overall branching fraction supression of 0.25
for going into a tau on each side, this final state cannot rise above the $WW-$background,
and is expected to be drowned by the Majoron channel when the latter is available.

In conclusion, we have scanned the parameter space to demonstrate that the production
of tau-pairs plus missing transverse momentum at LEP-II can be considerably enhanced in
a scenario with spontaneously broken R-parity. This should serve as a distinct experimental
signal for this kind of models, as compared to both the MSSM and an explicitly broken
R-parity, during the operation of LEP-II.

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Figure Captions

Figure 1:
$\sigma(e^+e^- \rightarrow \tau\tau JJ)$ against the parameter $A$, with gluino mass = 250 GeV, $\tan\beta = 10$, squark mass = 200 GeV, sneutrino mass = 80 GeV. The solid, dotted and dashed lines correspond respectively to chargino mass = 60, 70 and 80 GeV. $\sqrt{s} = 180$ GeV.

Figure 2:
Same as in figure 1, but with sneutrino mass = 100 GeV.

Figure 3:
Same as in figure 2, with gluino mass = 300 GeV. The solid, dotted and dashed lines correspond respectively to chargino mass = 70, 80 and 90 GeV. $\sqrt{s} = 200$ GeV.

Figure 4:
Same as in figure 2, with gluino mass = 250 GeV, $\tan\beta = 2$, chargino mass = 90 GeV (solid line), and gluino mass = 300 GeV, $\tan\beta = 2$, chargino mass = 70 GeV (dashed line). $\sqrt{s} = 190$ GeV.
This figure "fig1-1.png" is available in "png" format from:

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