Supersymmetry phenomenology with spontaneous R parity breaking in Z^0 decays

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We study some of the phenomenological implications of spontaneous R parity breaking for the decays of the Z^0. These include new experimental signatures, e.g., the decay $Z^0 \to \chi^\pm \tau^\pm$ which may occur with branching ratio in the range 6×10^{-5} to 10^{-6}, that could be visible at LEP, and sizeable enhancements in the expected rates for *zen events*, with respect to those of the standard supersymmetric model. In addition, the lightest chargino $\chi^\pm$ may dominantly decay as $\chi^\pm \to \tau^\pm$ + majoron.

1. Introduction

R parity is a selection rule that has been taken to be the basis of most discussions of supersymmetric phenomenology [1] including the limits recently extracted from the first 10^4 Z^0 decays observed at LEP on the masses of some of the charged supersymmetric particles [2]. R parity is related to total lepton number according to $R_p = (-1)^{3B+L+2S}$ where S denotes spin, B and L denote baryon and total lepton number, respectively. It follows that all particles of the standard model (including the Higgs scalars) are R-even while their supersymmetric partners are R-odd.

R parity breaking may occur in a spontaneous way, through nonzero vacuum expectation values (VEVs) for scalar neutrinos [3]

$$v_L = \langle \tilde{\nu}_{L\tau} \rangle . \qquad (1)$$

In the absence of any additional R_p breaking this leads to a dynamical *tracer* that consists of the existence of a physical massless Nambu–Goldstone boson – a majoron – denoted by J [4–6]. Thus, in spontaneously broken R parity models, *the lightest supersymmetric particle is the massless majoron.* These models also predict the existence of a related light scalar ρ which receives a mass of order v_L, the scale characterizing spontaneous R parity breaking. This gives rise to a new decay mode for the neutral gauge boson

$$Z^0 \to \rho + J . \qquad (2)$$

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The most restrictive constraint on this model comes from astrophysics. It arises due to the fact that if majorons are produced in a stellar environment, through Compton-like processes of the type $\gamma+e\to e+J$, they freely escape due to their tiny coupling to matter. These new mechanisms of stellar energy loss lead to a severe constraint on the majoron coupling to the electron $g_{ee}\lesssim 2\times 10^{-13}$ [7], from where we deduce the limit on the sneutrino VEV $v_L\lesssim 30$ keV. As a result, the decay in eq. (2) is always possible and increases the invisible width of the Z^0 by $\Gamma^{\rm inv}_{Z^0}\sim 85$ MeV, i.e., the equivalent of one half additional neutrino species. The recent precision measurement of the Z^0 width at LEP [2] is sufficient to exclude this model [8].

However, in many extensions of the minimal SU(2)⊗U(1) supersymmetric model, R parity breaking may be driven by *isosinglet* lepton VEVs so that the majoron is mainly singlet [9]. In this case it is possible to relate the isodoublet breaking of R parity and lepton number to some parameter in the superpotential that can be made arbitrarily small. The LEP constraint on $\Gamma^{\rm inv}_{Z^0}$ is then avoided, since the majoron being an isosinglet does not couple to the Z^0. In addition, the astrophysical bound can be obeyed without the need of fine-tuning, unlike the minimal broken R parity model.

Here we analyse some of the signals of R parity breaking in Z^0 decays. We assume that all supersymmetric scalar particles other than the majoron are too heavy to be pair-produced in Z^0 decay.

2. *R* parity breaking

A simple model to generate the spontaneous violation of R parity and lepton number driven by nonzero VEVs for additional singlets was proposed in ref. [9]. The model is characterized by the basic superpotential terms

$$h_u u^c Q H_u + h_d d^c Q H_d + h_e e^c l H_d + (h_0 H_u H_d - \mu^2)\Phi + \text{h.c.} \tag{3}$$

to which one adds the following terms:

$$h_\nu \nu^c l H_u + h\Phi \nu^c S + \text{h.c.} \tag{4}$$

involving additional isosinglet superfields (ν^c_i, S_i) carrying lepton numbers (−1, 1) respectively. All couplings h_u, h_d, h_e, h_ν, h are arbitrary matrices in generation space, which explicitly break flavour conservation. However, the form of the superpotential is restricted by imposing the exact conservation of *total* lepton number and R parity. The addition of the new singlets to the minimal SU(2)⊗U(1) model [10,11] may lead to many novel weak interaction phenomena [12–15]. Most relevant for us here, the presence in a supersymmetric model of an isosinglet scalar Φ with a linear superpotential coupling allows both electroweak and R parity breaking to proceed at the tree level. R parity is spontaneously broken by the following nonzero VEVs [9]:

$$v_R = \langle \tilde{\nu}_{R\tau} \rangle, \tag{5}$$

$$v_S = \langle \tilde{S}_\tau \rangle, \tag{6}$$

which are generated at the electroweak scale, whereas electroweak breaking and fermion masses arise from

$$\langle H_u \rangle = v_u, \tag{7}$$

$$\langle H_d \rangle = v_d \tag{8}$$

with $v^2 = v_u^2 + v_d^2$ fixed by the W mass.

The majoron is given by the imaginary part of ref. [9]

$$\frac{v_L^2}{V v^2}(v_u H_u - v_d H_d) + \frac{v_L}{V}\tilde{\nu}_\tau - \frac{v_R}{V}\nu^c_\tau + \frac{v_S}{V}\tilde{S}_\tau, \tag{9}$$

where $V=\sqrt{v_R^2+v_S^2}$. Since the majoron is now mainly an SU(2)⊗U(1) singlet, its properties are fundamentally different from those of the majoron of ref. [6] because it does not contribute to the invisible Z^0 decay width. Moreover, one may easily satisfy the astrophysical limit for $v_R = O(1\text{ TeV})$ and $v_L \leqslant O(100\text{ MeV})$. As discussed in ref. [9], this may be achieved in a natural way.

3. Mass matrices

In order to study the phenomenology of the supersymmetric fermion sector we start by displaying the structure of the *chargino* and *neutralino* mass matrices in a class of spontaneously broken R parity models that includes the one considered in ref. [9]. In these models the form taken by the chargino mass matrix is

$$\begin{array}{c} \\ e_i \\ \tilde{H}_d^- \\ -\mathrm{i}\tilde{W}^- \end{array} \begin{array}{c} \begin{array}{ccc} e_j^+ & \tilde{H}_u^+ & -\mathrm{i}\tilde{W}^+ \end{array} \\ \begin{pmatrix} h_{eij}v_d & -h_{\nu ij}v_{Rj} & \sqrt{2}g_2v_{Li} \\ -h_{eij}v_{Li} & \mu & \sqrt{2}g_2v_d \\ 0 & \sqrt{2}g_2v_u & M_2 \end{pmatrix} \end{array}, \tag{10}$$

where $g_{1,2}$ are the SU(2)⊗U(1) gauge couplings divided by $\sqrt{2}$ and $M_{1,2}$ denote the supersymmetry breaking gaugino mass parameters, related by $M_1/M_2 = \frac{5}{3}\tan^2\theta_W$.

Similarly, the effective 7×7 neutralino mass matrix that remains after appropriately diagonalizing out any possible heavy isosinglet leptons that may be present, takes the following form:

$$\begin{array}{c} \\ \nu_i \\ \tilde{H}_u \\ \tilde{H}_d \\ -\mathrm{i}\tilde{W}_3 \\ -\mathrm{i}\tilde{B} \end{array} \begin{array}{c} \begin{array}{ccccc} \nu_i & \tilde{H}_u & \tilde{H}_d & -\mathrm{i}\tilde{W}_3 & -\mathrm{i}\tilde{B} \end{array} \\ \begin{pmatrix} 0 & h_{\nu ij}v_{Rj} & 0 & g_2v_{Li} & -g_1v_{Li} \\ h_{\nu ij}v_{Rj} & 0 & -\mu & -g_2v_u & g_1v_u \\ 0 & -\mu & 0 & g_2v_d & -g_1v_d \\ g_2v_{Li} & -g_2v_u & g_2v_d & M_2 & 0 \\ -g_1v_{Li} & g_1v_u & -g_1v_d & 0 & M_1 \end{pmatrix} \end{array}, \tag{11}$$

In many models, such as the one in ref. [9], the effective higgsino mixing parameter μ may be given as $\mu = h_0\langle\Phi\rangle$, where $\langle\Phi\rangle$ is the VEV of an appropriate singlet scalar.

As a result of R parity breaking, the supersymmetric fermions (partners of gauge and Higgs particles) will now mix with the weak-eigenstate leptons, through eq. (10) and eq. (11). The form of these matrices applies to a wide class of models. They determine the masses of the physical leptons as well as those of the supersymmetric inos. They also specify the structure of the majoron couplings to the leptons and the inos, which will determine their expected decay patterns.

4. Neutrino decays

In the approximation where we neglect v_L, the τ neutrino acquires a mass given by

$$m_{\nu_\tau} \simeq -\frac{\sum_i h_{\nu i\tau}^2 M_0 v_R^2 v_d^2}{h_0\langle\Phi\rangle(2v_uv_dM_0 - h_0\langle\Phi\rangle M_1M_2)} \tag{12}$$

where we have set $M_0 = g_1^2M_2 + g_2^2M_1$ while ν_μ and ν_e remain massless in this approximation. For reasonable values of the parameters, the mass of ν_τ can easily violate the cosmological limit on stable neutrinos [16]. However, there are new modes of invisible neutrino decay $\nu' \to \nu + J$ involving majoron emission [5,17,13]. The corresponding decay lifetimes are much faster than required by cosmology so as to efficiently suppress the contribution of relic ν_τ, as long as

$$C \gtrsim 3\times10^{-16}(m_{\nu_\tau}/\text{keV})^{1/2}, \tag{13}$$

where C is the nondiagonal majoron coupling connecting the τ neutrino to one of the other neutrinos. Eq. (13) is always fulfilled for all values of the supersymmetric parameters. As a result, in all of these models m_{ν_τ} can be as large as allowed by laboratory experiments. This enables the R parity violating effects to be correspondingly enhanced. It is interesting to stress that some of these effects may be substantially even if the τ neutrino is very light.

5. Chargino and neutralino decays

The heavy sector of the charged matrix in eq. (10) leads to two heavy *chargino* (i.e., charged supersymmetric partners of gauge and Higgs bosons). The lightest of these states, denoted $\chi^{\pm}$, has not yet been produced in Z^0 decays at LEP. Assuming that $m_{\tilde{l}} > m_{\chi^\pm}$ the lightest chargino would decay leptonically as

$$\chi^{\pm} \to \chi^0 l^{\pm} \nu_\tau, \tag{14}$$

or semileptonically, i.e., $\chi^{\pm} \to \chi^0 \bar{q}q$, when the virtual W decays hadronically. The existence of a majoron implies that in broken R parity models, charginos *always have two-body decays* of the type

$$\chi^{\pm} \to \tau^{\pm} + J, \tag{15}$$

where J is the majoron.

In spontaneously broken R parity models the lightest neutralino is also unstable, and has *visible*

$$\chi^0 \to \nu_\tau + \bar{f}f \tag{16}$$

as well as *invisible*

$$\chi^0 \to \nu_\tau + J \tag{17}$$

decays. In eq. (16) f denotes any quark or lepton. The relative importance of these decay modes depends on the values of the parameters, especially on the R parity violating parameter $h_\nu v_R$. These decays will lead to *zen events* [18] induced by Z^0 decays to neutralinos, e.g.,

$$Z^0 \to \chi^0 \chi^{0\prime}, \tag{18}$$

where one of the neutralinos decays visibly eq. (16) and the other decays invisibly eq. (17). Note that in spontaneously broken R parity *the missing energy is always carried by ν_τ and the majoron*, not by the "photino", as in eq. (20).

6. Experimental constraints

One may use recent LEP/SLC data on Z^0 decays and $\bar{p}p$ collider limits on $W^{\pm}$, Z^0 and gluino production to constrain the parameters of the minimal supersymmetric extension of the standard model, with conserved R parity [19]. The analysis presented in ref. [19] is, however, *not* directly applicable and needs to be appropriately reinterpreted in models where R parity is spontaneously broken. In addition, one has *other* constraints, characteristic of broken R parity models. These are related to neutrino mass considerations. We now list the most relevant constraints used in our present analysis:

– Lower limits on the lightest chargino mass from LEP [20]. The nonobservation of the decay $Z^0 \to \chi^+ \chi^-$ implies a lower bound on the lightest chargino mass $m_{\chi^\pm} \geqslant 44$ GeV. However, in spontaneously broken R parity models there may be sizeable $SU(2) \otimes U(1)$ electroweak couplings of the τ and ν_τ to the inos. As a result, the chargino may dominantly decay into τ's as in eq. (15). The existence of this decay could affect the experimental analysis from which one derives the lower limit on the lightest chargino mass discussed above, such as that of the L3 Collaboration.

– $p\bar{p}$ collider limits on the R ratio, $\sigma_{W^\pm} B(W^\pm \to e^\pm \nu)/\sigma_{Z^0} B(Z^0 \to e^+e^-)$ [21].

– LEP/SLC limits on the total and invisible Z^0 widths $\Delta\Gamma_{Z^0}^{\text{total}}$ and $\Delta\Gamma_{Z^0}^{\text{inv}}$ [2,22].

– the ARGUS limit on the τ neutrino mass

$$m_{\nu_\tau} < 35 \text{ MeV}. \tag{19}$$

In addition, there are constraints from LEP on the peak cross section versus total Z^0 width, for visible Z^0 decays [23], as well as the CDF lower limit on the gluino mass $m_{\tilde{g}}$ [24] which restricts soft supersymmetry breaking electroweak gaugino mass parameters, in models where these scale like the renormalized gauge coupling strengths.

Given these constraints, the minimal supersymmetric model leads to several signals, including the *zen events* (those in which the Z^0 decays into two neutral particles, one of which is invisible and the other decays visibly). In the minimal supersymmetric model these arise from

$$Z^0 \to \chi^0 + \chi^{0\prime}, \tag{20}$$

where the stable χ^0 escapes detection and $\chi^{0\prime}$ decays visibly as

$$\chi^{0\prime} \to \chi^0 + f\bar{f}. \tag{21}$$

In most of these events, all the visible Z^0 decay products are contained in one hemisphere.

7. Implications for LEP physics

We now study some of the phenomenological implications of the spontaneously broken R parity models. Some of the new signatures of supersymmetry in these models could be experimentally measurable, for values of the model parameters that are consistent with all of the constraints discussed above. For definiteness we fix the values $v_R = 1$ TeV and $v_L = 100$ MeV. The effects of R parity breaking are then controlled by the parameter h_ν which also determines the neutrino mass, eq. (12). We also fix a characteristic value for

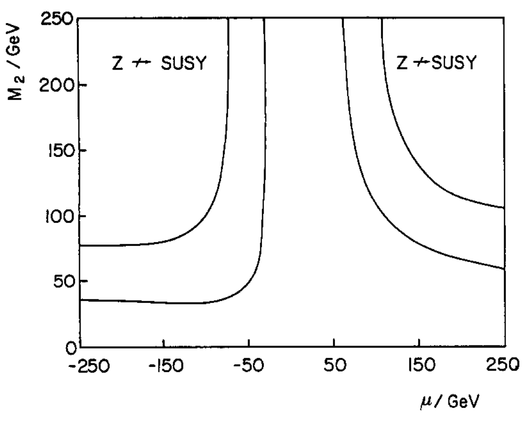

Fig. 1. Presently allowed regions of the supersymmetric parameters accessible to LEP searches in the spontaneously broken R parity model, for the case of a small h_{ν_τ}. We assumed the input values discussed in the text and $\tan\beta = 4$.

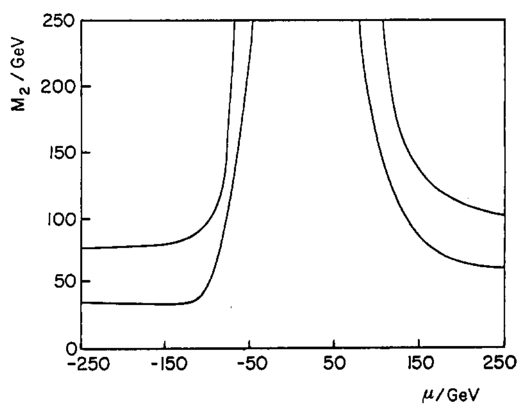

Fig. 2. Smaller region allowed in the case of a large h_{ν_τ}. We assumed the input values discussed in the text and $\tan\beta = 4$.

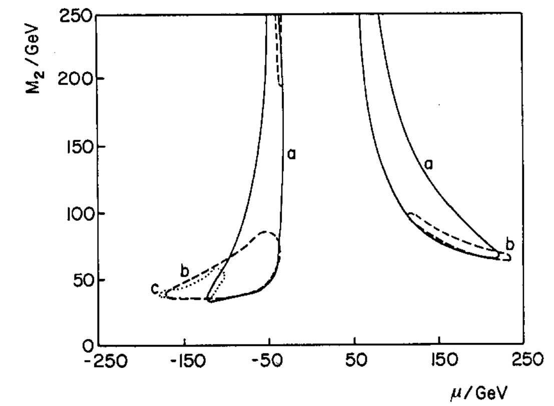

Fig. 3. Presently allowed regions of the supersymmetric parameters leading to BR(zen) $\geqslant 10^{-4}$ for different values of h_{ν_τ}: (a) for $h_{\nu_\tau}=10^{-6}$, (b) for $h_{\nu_\tau}=10^{-4}$ and (c) for $h_{\nu_\tau}=8\times10^{-3}$. We assumed the input values discussed in the text and $\tan\beta=4$.

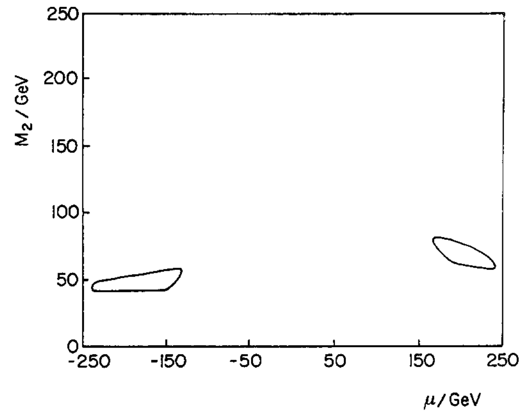

Fig. 4. Present allowed regions of the supersymmetric parameters leading to BR$(\chi\tau)\geqslant 2\times10^{-5}$ for $h_{\nu_\tau}=1.4\times10^{-2}$ and $\tan\beta=6$.

$$\tan\beta=v_u/v_d. \tag{22}$$

We have determined the allowed ranges of the supersymmetric parameters μ and M_2 [#1] consistent with all the above constraints. The size of this region depends on the value of h_ν. We consider two representative values $h_\nu=10^{-6}$ and $h_\nu=8\times10^{-3}$, corresponding to the cases where τ neutrino is light and very massive, respectively. Our results are plotted in figs. 1 and 2.

We have then studied how the rates for the supersymmetric signals more closely related to the question of R_p breaking vary as a function of h_ν. We now summarize our results:

(1) The missing energy signature associated to conventional supersymmetry could be *substantially modified* as a result of R parity breaking. For example, for a wide range of our parameters, in the case of small h_ν, zen events arise mostly from $Z^0\to\chi^0\chi^0$ where the neutralino produced in one hemisphere decays as in eq. (16) and the other as in eq. (17). This should be contrasted with the origin of the zen events in the usual R_p conserving scenario, eqs. (20) and (21). The corresponding rates in our model could be significantly *enhanced* over the minimal supersymmetry predictions, as shown in fig. 3. This happens because for this choice of parameters, although the lightest neutralino decays visibly only about 5% of the times, its pair production in Z^0 decays (that would lead to missing energy in the standard supersymmetric model) is so large that it can lead to a zen event rate BR(zen) $\geqslant 10^{-4}$. We have also studied the corresponding rates for other parameter choices, involving *larger* h_ν. The results are summarized in the various contours shown in fig. 3. We see that BR(zen) $\geqslant 10^{-4}$ may be obtained for a wide range of the supersymmetric parameters.

(2) Supersymmetric particles can be singly-produced in Z^0 decays. There is a new Z^0 decay mode, e.g., $Z^0\to\chi\tau$ that may occur with branching ratio at a level of $B(\tau^\pm\chi^\pm)>2\times10^{-5}$. The corresponding region is plotted in fig. 4 as a function of the supersymmetric parameters. Larger h_ν values could result in larger values for this branching ratio.

(3) The limits on supersymmetric masses are modified with respect to the standard supersymmetric scenario. For example, the lightest chargino may dominantly decay as in eq. (15).

The predictions given above are all consistent with the existing constraints. In addition, we also expect signals of R parity breaking at hadron colliders. Our model may also lead to related lepton flavour violating processes

[#1] It is always possible, if CP is conserved in this sector, to choose $M_2>0$, while μ may have either sign.

such as $\mu\to e+\gamma$ and $\mu\to 3e$. The first occurs at one-loop while in contrast the process $\mu\to 3e$ can arise at tree level due to the existence of flavour changing couplings of the Z^0 to charged leptons. Although potentially large all these processes involve unknown mixing angles which may be very small, thus suppressing their expected rates. There are also flavour-violating processes such as μ and τ decays with majoron emission [6].

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