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$Z \to$ jets $+ \gamma$ as a Signal for R-Parity Violation*

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Abstract

Supersymmetric models with explicit R-parity violation can induce new rare decay modes of the Z boson into single supersymmetric particles. Here, the rate and signature for one such decay, $Z \to \tilde{\nu}\gamma$, is examined, where it is found that the rate is at least an order of magnitude smaller than that for the process $Z \to H\gamma$, even with larger values of the R-parity violating couplings.

(Talk given at the *Workshop on Photon Radiation from Quarks*, Annecy, France, December 2-3, 1991.)

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Abstract

Supersymmetric models with explicit R-parity violation can induce new rare decay modes of the Z boson into single supersymmetric particles. Here, the rate and signature for one such decay, $Z \to \tilde{\nu}\gamma$ is examined, where it is found that the rate is at least an order of magnitude smaller than that for $Z \to H\gamma$, even with larger values of the R-parity violating couplings.

General supersymmetric extensions of the Standard Model contain dimension 4 and 5 operators which violate baryon (B) and lepton (L) number and lead to unacceptably rapid proton decay. Additional symmetries are then applied to suppress these operators. In the minimal supersymmetric standard model (MSSM) the discrete symmetry matter parity (or R-parity) is applied to prohibit all the dimension 4 B and L violating operators (with the assumption that the dimension 5 operators are suppressed by a large unified mass scale). Each field and its super-partner then possess a conserved multiplicative quantum number which is given by $R=(-1)^{2S+3B+L}$, where S denotes the spin of the particle. In this notation all standard fields have the assignment $R=+1$, while their super-partners have $R=-1$. Conservation of R-parity has two direct consequences; (i) sparticles can only be produced in pairs, and (ii) the lightest supersymmetric particle (LSP) must be stable and experience neither electromagnetic or strong interactions. All supersymmetric collider searches rely on the first condition, and most search techniques also depend heavily on a signature of an excess of missing energy.

However, given the absence of any experimental verification of the MSSM, perhaps we should feel compelled to re-examine the above assumptions and investigate alternative supersymmetric models. (This could appear more attractive than dismissing supersymmetry altogether, or to keep pushing the supersymmetric mass scale to larger values!) One such alternative, supersymmetric models with broken R-parity, has enjoyed a revival[1, 2] in the literature. These models contain the minimal superfield content and break R-parity either spontaneously, by the sneutrino acquiring a vacuum expectation value, or explicitly through terms contained in the superpotential. The most general gauge and supersymmetry invariant superpotential is given by

$$\begin{aligned} W = \ & h_{ij}L^i_L H_2 \bar{E}^j_R + h'_{ij}Q^i_L H_2 \bar{D}^j_R + h''_{ij}Q^i_L H_1 \bar{U}^j_R \\ & +\lambda_{ijk}L^i_L L^j_L \bar{E}^k_R + \lambda'_{ijk}L^i_L Q^j_L \bar{D}^k_R \\ & +\lambda''_{ijk}\bar{U}^i_R \bar{D}^j_R \bar{D}^k_R \,, \end{aligned} \tag{1}$$

where ijk are generation indices, the h's and λ's are *a priori* unknown Yukawa coupling constants, $Q_L, L_L, \bar{U}_R, \bar{D}_R, \bar{E}_R, H_{1,2}$ represent the chiral superfields containing the left-handed quark and lepton doublets, the right-handed u-quark, d-quark, and charged lepton singlets, and the two

Higgs doublets. The first line of the above equation contains the terms which are present in the MSSM, and the second (third) line consists of the explicit lepton (baryon) number violating operators. Instead of forbidding all the terms in the second and third line as in the MSSM, it is sufficient to ensure that the B and L violating terms do not exist simultaneously in order to preserve nucleon stability. It has recently been observed[3] that in models with the minimal superfield content, only two discrete symmetries which forbid rapid nucleon decay are discrete anomaly free. One of these symmetries is the standard R-parity, while the other is a unique Z_3 symmetry which allows the L violating terms in the second line of the superpotential and forbids the B violating ones. This new symmetry is called baryon parity and places R-parity violating models with baryon parity on the same theoretical footing as the MSSM. These new models hence deserve a similar amount of attention to what the MSSM presently enjoys.

The phenomenology of these models is strikingly different than in the MSSM case, as elementary couplings involving an odd number of supersymmetric particles now exist. This results in the possible single production of super-partners and an unstable LSP. For example, the photino may decay into the channels $\tilde{\gamma} \to \ell^+\ell^-\nu$ or $q\bar{q}'\ell^{\pm,0}$ via the L violating operators. If the rates for these R-parity violating interactions occur at large enough levels, the standard search techniques for supersymmetric particles can be invalidated.

The interaction Lagrangians for the $LL\bar{E}$ and $LQ\bar{D}$ operators can be written as

$$\mathcal{L} = \lambda_{ijk}[\tilde{\nu}^i_L \bar{e}^k_R e^j_L + \tilde{e}^j_L \bar{e}^k_R \nu^i_L + (\tilde{e}^K_R)^* (\bar{\nu}^i_L)^c e^j_L - (i \leftrightarrow j)] + h.c. \tag{2}$$

and

$$\begin{aligned}\mathcal{L} = \quad & \lambda'_{ijk}[\tilde{\nu}^i_L \bar{d}^k_R d^j_L + \tilde{d}^j_L \bar{d}^k_R \nu^i_L + (\tilde{d}^k_R)^* (\bar{\nu}^i_L)^c d^j_L \\ & -\tilde{e}^i_L \bar{d}^k_R u^j_L - \tilde{u}^j_L \bar{d}^k_R e^i_L - (\tilde{d}^k_R)^* (\bar{e}^i_L)^c u^j_L] + h.c.\end{aligned} \tag{3}$$

respectfully. Here we will consider the case where one of these operators with a particular generation structure is dominant[1]. This assumption is reasonable, since even in the SM the Yukawa couplings span a wide range, with those for the top-quark being much larger than the rest. Bounds on λ and λ' have been obtained from a large variety of low-energy processes. For couplings involving the first two generations $(i, j, k = 1, 2)$, typical limits are found[1, 4] to lie in the range

$$\lambda_{ijk}, \lambda'_{ijk} \leq (0.05 - 0.50)\frac{m_{\tilde{f}}}{100\text{GeV}} \tag{4}$$

Couplings involving the third generation are much less restricted. The best limits in this case arise[5] from loop induced neutrino masses and neutrino magnetic moment transitions. However, these processes only place constraints on products of the couplings and only for intergenerational couplings, *e.g.*, $\lambda_{233}\lambda_{133}$. Note that a single dominant, generation conserving operator can not give rise to these dangerous processes. Present data thus poses no restrictions on a dominant operator with pure third generation couplings such as λ'_{333}.

The L violating operators allow for a new rare decay of the Z-boson, $Z \to \tilde{\nu}\gamma$, via the Feynman diagram shown in Fig. 1. This is the same type of one-loop triangle diagram that gives rise[7, 8] to $Z \to H\gamma$. Whereas the $Z \to H\gamma$ process also receives a contribution from an internal W-boson loop, only the fermionic loop contributes to $Z \to \tilde{\nu}\gamma$. This is unfortunate as in the $Z \to H\gamma$ process, the W-boson loop is numerically much larger than the fermionic case! The partial width for this new decay mode is directly proportional to the square of the $f\bar{f}\tilde{\nu}$ R-parity violating coupling (generically represented by λ below) and is given by

$$\Gamma(Z \to \tilde{\nu}\gamma) = \frac{\alpha^2\lambda^2 M_Z^3}{192\pi^3 m_f^2}\left(1 - \frac{m_{\tilde{\nu}}^2}{M_Z^2}\right)^3 \left(N_c \frac{Q_f(T_{3L}^f - 2Q_f x_w)}{\sin\theta_w \cos\theta_w}\right)^2 \times \left[|I_1(x,y) - I_2(x,y)|^2 + |I_2(x,y)|^2\right] \tag{5}$$

where m_f, Q_f, and T_{3L}^f are the mass, charge, and third component of weak iso-spin, respectfully, of the internal fermion, N_c is the number of colors of the fermion, $x_w = \sin^2\theta_w$, $x \equiv 4m_f^2/m_{\tilde{\nu}}^2$, $y \equiv 4m_f^2/M_Z^2$, and the integrals $I_{1,2}$ are given in Ref.[8]. This expression includes the contribution from the decay into one generation of sneutrino and anti-sneutrino. In our numerical results we use $M_Z = 91.175$ GeV, $\Gamma(Z \to \mu^+\mu^-) = 0.0838$ GeV, and $x_w = 0.233$ as given by LEP[6].

In the case of the $LQ\bar{D}$ operator the internal fermion is restricted to be a down-type quark (d,s, or b). The integrals $I_{1,2}$ are proportional to m_f^2/M_Z^2 yielding an overall rate which is proportional to $\Gamma \sim M_Z(\lambda')^2 v_f^2(m_f^2/M_Z^2)$, where v_f is the vector coupling constant of the internal fermion to the Z-boson. Clearly, the b-quark gives the dominant contribution in this case. This is fortuitous since, as discussed above, it is the third generation R-parity violating couplings which are the least constrained! The width for $Z \to \tilde{\nu}\gamma$ in this case, relative to that for $Z \to \mu^+\mu^-$, is presented in Fig. 2 as a function of the sneutrino mass for various values of λ' (taking $m_b = 5$ GeV). The corresponding rate for $Z \to H\gamma$ with $m_H = m_{\tilde{\nu}}$ is also displayed in the figure for comparison. Note that the present limit on the sneutrino mass from the invisible width of the Z gives[9] $m_{\tilde{\nu}} > 41.1$ GeV, and that the mass bound from sneutrino pair production with R-parity violating decays, $Z \to \tilde{\nu}\bar{\tilde{\nu}} \to 4jets$, would lie in the range $m_{\tilde{\nu}} > 40 - 45$ GeV. Correspondingly, LEP results place[6] $m_H > 57$ GeV. The rate for $Z \to \tilde{\nu}\gamma$ falls off faster as the sneutrino mass increases, than that for $Z \to H\gamma$. It is clear that the R-parity violating coupling must be quite large in order for this process to be observable and that the high luminosity LEP option would be needed.

For the $LL\bar{E}$ operator, $f = e, \mu$, or τ in Fig. 1 so in this case the τ lepton gives the largest contribution. Here, the $Z \to \tilde{\nu}\gamma$ partial width is now proportional to $\Gamma \sim M_Z\lambda^2 v_\tau^2(m_\tau^2/M_Z^2)$ and gives a rate which is smaller by 2 orders of magnitude (for $\lambda = \lambda'$) than that shown in figure 2. Even for $\lambda = 1$ the rates for $Z \to \tilde{\nu}\gamma$ are clearly unobservable in this case.

If the R-parity violating couplings are large enough for this new Z decay to occur at a visible rate via the $LQ\bar{D}$ operator, then the sneutrino will in turn also decay through these couplings to $\tilde{\nu} \to b\bar{b}$. The partial width for this subsequent decay is

$$\Gamma(\tilde{\nu} \to b\bar{b}) = \frac{3(\lambda'_{333})^2}{16\pi} m_{\tilde{\nu}} \tag{6}$$

where we have again assumed that the dominant λ' is generation conserving. In this case, the topology for this reaction would be exactly the same as for $Z \to H\gamma$ with $H \to b\bar{b}$. If these couplings are not as large, then the sneutrino could also decay via its MSSM mechanism $\tilde{\nu} \to \tilde{\Lambda}\nu$, where $\tilde{\Lambda}$ represents the LSP, with an event signature of a photon plus missing p_T.

Supersymmetric models with R-parity violation have a particularly rich phenomenology, which results in strikingly different signatures than for the MSSM. Here, we have examined one interesting possibility in these models, a new rare decay mode of the Z-boson, $Z \to \tilde{\nu}\gamma$. We have found that if the R-parity violating couplings as are large as is presently allowed by data, the rate for this process is unfortunately small and the event topology would be comparable to that for $Z \rightarrow H\gamma$. We sincerely hope that some positive experimental sign of supersymmetry will soon be discovered!

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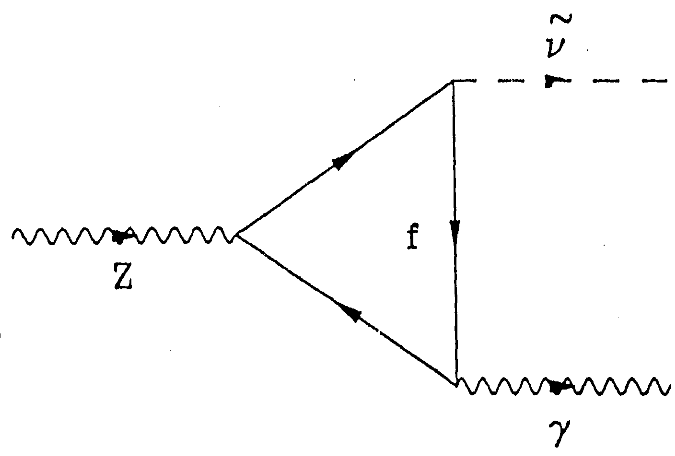

Figure 1: The Feynman diagram responsible for $Z \to \tilde{\nu}\gamma$ in R-parity violating models.

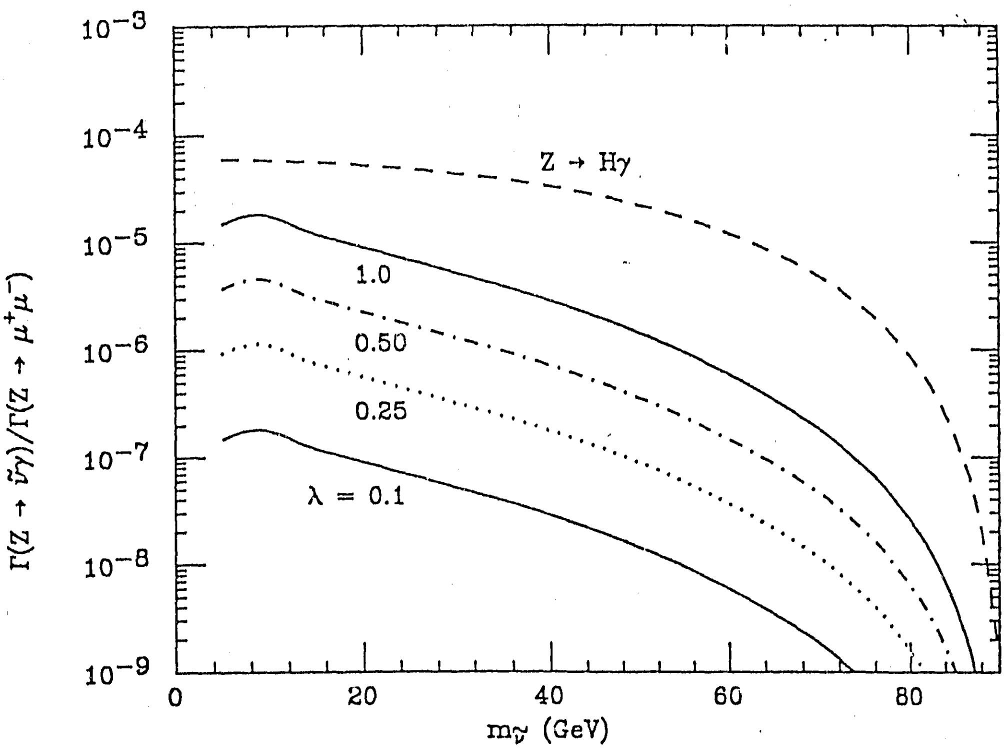

Figure 2: The width for the decay $Z \to \tilde{\nu}\gamma$ relative to $\Gamma(Z \to \mu^+\mu^-)$ as a function of the sneutrino mass for various values of λ' as indicated. The width for $Z \to H\gamma$ with $m_H = m_{\tilde{\nu}}$ (dashed curve) is also shown for comparison.

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