ON R-PARITY VIOLATION AT $e^+e^-$ COLLIDERS

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Abstract
I discuss several promising R-parity violating processes at $e^+e^-$ colliders.

1 R-Parity Violation: Pandora’s Box of SUSY

In the Minimal Supersymmetric Standard Model several new interactions are allowed if R-parity is explicitly broken. The superpotential $W = W_R^\sqrt{\,} + W_R^\times$ now reads

$$W_R^\sqrt{\,} = h_{ij}^U \hat{Q}_i \hat{H}_u \hat{u}_j^c + h_{ij}^D \hat{Q}_i \hat{H}_d \hat{d}_j^c + h_{ij}^E \hat{L}_i \hat{H}_d \hat{e}_j^c + \mu \hat{H}_d \hat{H}_u \quad \text{(1)}$$

and

$$W_R^\times = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{e}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}_k^c + \lambda''_{ijk} \hat{u}_i \hat{d}_j \hat{d}_k^c + \kappa_i \hat{L}_i \hat{H}_u \quad \text{(2)}$$

Note that $i, j, k = 1, 2, 3$, $\lambda_{ijk} = -\lambda_{jik}$ because $\hat{L}_i \hat{L}_j = \epsilon_{ab} \hat{L}_i^a \hat{L}_j^b = \hat{L}_i^1 \hat{L}_j^2 - \hat{L}_i^2 \hat{L}_j^1$, and $\lambda''_{ijk} = -\lambda''_{ikj}$ to counter-balance the antisymmetry of the color indices of the superfields $\hat{d}^c$. In general there are thus 39 $L$-number ($\lambda, \lambda', \kappa$) and 9 $B$-number violating ($\lambda''$) couplings.

Since the superfields $\hat{L}_i$ ($i = 1, 2, 3$) and $\hat{H}_d$ carry the same quantum numbers, one can rotate them by an arbitrary $SU(4)$ rotation $U$. This operation in general mixes the Yukawa couplings $h^D$ with $\lambda'$, $h^E$ with $\lambda$, and $\kappa_a$ with $\mu$, respectively. This

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implies that none of these terms in $W$ can be a priori neglected since a rotation $U$ would in general re-generate them.

In particular, following Hall and Suzuki \[1\], one usually rotates away the terms $\kappa_{L_iL_jL_k}$ by suitably choosing the rotation matrix $U$. No other terms can be eliminated without further assumptions. After these terms have been rotated away, only the lepton fields can still mix among themselves.

It should be stressed that by rotating away the $\kappa$-terms one, in general, induces sneutrino \textit{vevs} \[2, 3\]. One can next conveniently rotate the lepton doublet superfields so that only the sneutrino of one generation will acquire a \textit{vev} and the corresponding neutrino will acquire mass at the tree level. The masses of the other two neutrinos will be induced via one-loop diagrams.

A non-zero sneutrino \textit{vev} will also mix leptons with charginos and neutrinos with neutralinos, and thus induce new couplings: $Z^0\nu\chi^0_i$, $Z^0l^\pm\chi_i^\mp$, $W^\pm\nu\chi^0_i$, and $W^\pm l^\mp\chi^0_i$ ($i = 1, 4$ and $j = 1, 2$) \[2, 3\]. While these are strongly suppressed by stringent constraints on lepton universality, they do constitute a separate class of $R$-parity violating terms and a priori cannot be ignored.

The lagrangian terms $\mathcal{L} = \mathcal{L}_\lambda + \mathcal{L}_{\lambda'} + \mathcal{L}_{\lambda''}$ corresponding to $W_{R_X}$ read

$$\mathcal{L}_\lambda = (\lambda_{ijk} - \lambda_{jik})[\bar{\nu}_i\tilde{e}_kP_Le_i + \bar{e}_i\tilde{\nu}_k\nu_j + \bar{\nu}_i\bar{\nu}_k\nu_j] + h.c. \quad (3)$$
$$\mathcal{L}_{\lambda'} = \lambda'_{ijk}[\bar{\nu}_i\tilde{e}_kP_Lu_j - \bar{u}_j\tilde{d}_kP_Le_i + \bar{d}_k\tilde{u}_jP_Le_i - \bar{\nu}_i\tilde{d}_kP_Ld_j - \bar{d}_j\tilde{d}_k\nu_i - \bar{\nu}_i\bar{\nu}_k\nu_j] + h.c. \quad (4)$$

and

$$\mathcal{L}_{\lambda''} = -\frac{1}{2}(\lambda''_{ijk} - \lambda''_{jik})[\bar{d}_k\tilde{u}_jP_Ld_j + \bar{u}_j\tilde{d}_kP_Ld_j] + h.c. \quad (5)$$

Note that $i, j, k = 1, 2, 3$, and the symmetry properties of the Yukawas are now explicitly displayed.

Since $R = (-1)^{3B+2s+L}$, where $B, s, L$ are the baryon, spin, and lepton numbers of a given (s)particle, respectively, $R$-parity is broken if either $L$- or $B$-number is broken (or both). Simultaneous violation of both $L$ and $B$ leads to a fast proton decay. (More precisely, this is true when simultaneously $\lambda' \neq 0$ and $\lambda'' \neq 0$. But one cannot simply set $\lambda'_{ijk}$ to zero since it would be next regenerated by rotating out the $\kappa$-terms.)

Below I discuss several signatures of potential interest at $e^+e^-$ accelerators in the case of explicit $R$-parity breaking. (It occurs that very similar phenomenology actually results also in the case of spontaneous $R$-parity breaking \[4\].) I mainly focus on $L$ violating processes at $e^+e^-$ machines but will also comment on the case $\Delta B \neq 0, \Delta L = 0$. The phenomenology of $R$-parity breaking at hadronic colliders has been discussed, \textit{eg.}, in Refs. \[5, 6\] and at HERA, \textit{eg.}, in Ref. \[8\].

### 2 Unstable LSP

If $R$-parity is broken there is no distinction between particles and sparticles and the concept of the lightest supersymmetric particle (LSP) is ill-defined. (For example,
if $\Delta L \neq 0$ then the sneutrinos and neutral Higgs scalars carry the same quantum numbers. The same is true with the neutrinos and neutralinos.) Nevertheless it is still convenient to use it in the limit $\lambda, \lambda', \lambda'' \ll g$ and $\langle \bar{\nu} \rangle \ll m_Z$, i.e., when $R$-parity is ‘almost’ unbroken. In the present study I will assume that the LSP is the lightest of the four neutralinos, $\chi \equiv \chi_1^0$ (neglecting their small mixing with the neutrinos, induced by the sneutrino vevs). Other choices, like the stop, slepton, chargino, or sneutrino are considered much more exotic and/or constrained by cosmology but have been claimed not to be fully excluded yet [12].

Fig. 1. Indirect decays of $\chi$.

An unstable LSP can decay into ‘ordinary’ matter. There are essentially three regions of interest for the LSP lifetime $\tau_\chi$. If $\tau_\chi \lesssim 10^{-8}$ sec, $\chi$ will decay inside the detector. (For more details, see, eg., Refs. [3, 4,]). Otherwise it escapes detection. For $\tau_\chi \gtrsim 10^{17}$ sec, the neutralino is also stable cosmologically and thus constitutes a good candidate for dark matter in the Universe. In this case $R$-parity would be effectively conserved. In what follows I will discuss the cases of both the LSP decaying inside and stable in the detector even though cosmological arguments suggest much larger $\tau_\chi$.

Fig. 2. Direct $\chi$ decay into $\nu f \bar{f}$. A similar diagram leads to the final state $l f f'$ via the $W$-exchange.

There are two classes of decays the LSP can undergo. In indirect decays $\chi \rightarrow f \bar{f}$ followed by $\bar{f} \rightarrow f' f''$ (Fig. 1), where $f$ stands for any lepton or quark field. The LSP $\chi$ can therefore decay into $\nu_i l_j \bar{l}_k, \nu_i q_j \bar{q}_k$, or $l_i q_j \bar{q}_k$ via $\Delta L \neq 0$ diagrams, or into 3 quarks via a $\Delta B \neq 0$ squark exchange. In direct decays ($\Delta L \neq 0$ only) $\chi$ decays to $\nu f f'$ (Fig. 2) or to $l^\pm f f'$ via either real or virtual $Z$ and $W$ exchange, respectively. Direct LSP decays are possible due to the couplings $Z \chi \nu$ and $W^{\pm} \chi l^\pm$ induced by the sneutrino vev discussed above. (In this case also the (massive) neutrino may in
principle be unstable; the possibility I will put aside here.) Below, for definiteness, I will only consider indirect LSP decays. Of course including direct decays would lead to several additional final states and thus potentially interesting signatures.

I will discuss three classes of processes characteristic for \( R \)-parity violation in \( e^+e^- \) collisions.

1. \( R \)-parity-breaking **single sfermion production** is next followed by its decay via either \( R \times \) or \( R \sqrt{\cdot} \) couplings.

2. A **double sfermion production** involving either \( R \times \) or \( R \sqrt{\cdot} \) couplings, with each sfermion next decaying via \( R \times \) vertices.

3. Sneutrino-\( \nu \)-\( \nu \)-induced processes involving **no sfermion production** but rather double \( \text{ino} \) (both neutrino and neutralino) production and decay. They both in principle occur via \( R \times \) or \( R \sqrt{\cdot} \) vertices.

Some of these processes lead to signatures identical to those resulting from \( R \sqrt{\cdot} \) processes. This adds to the complexity of the situation and shows that in general one cannot fully separate \( R \times \) processes from the \( R \sqrt{\cdot} \) ones.

### 3 Single Sfermion Production

In \( e^+e^- \) accelerators one can only produce a single \( \tilde{\nu}_\mu \) or \( \tilde{\nu}_\tau \) via \( \lambda_{121} \) and \( \lambda_{131} \), respectively. In addition, there is an associated \( \tilde{\nu}_{\mu,\tau}Z \)-production diagram involving a \( t \)-channel \( \text{ino} \)-exchange which is, however, \( g^2 \)-suppressed. Similarly, there is a class of \( t \)-channel processes involving an associate \( W \)-charged-slepton production.

At present experimental constraints on the involved couplings are not very stringent: \( \lambda_{121} \lesssim 0.04 \) and \( \lambda_{131} \lesssim 0.1 \) [9]. They also depend on various assumptions.

The sneutrino \( \tilde{\nu}_i \) (\( i = \mu, \tau \)) can next decay in a variety of ways. The resulting signatures depend on whether or not the LSP(s) produced at some point will escape from the detector. I will discuss both possibilities separately.

1. \( \tilde{\nu}_{\mu,\tau} \rightarrow \nu \chi \). Since the coupling \( \tilde{\nu}_i \chi_i \) \((i = 1, 4)\) is of the order of the weak gauge coupling \( g \) (for gaugino-type \( \chi_i \)), this decay mode may well be dominant.

   If the LSP \( \chi \) escapes detection the final state is completely invisible \((e^+e^- \rightarrow s\text{-nothing})\).

   The LSP \( \chi \) can also decay (indirectly) in the detector into a neutrino and either two (charged) leptons or two quarks via a sfermion exchange (Fig. 1). In this case the final state, either \( l_i \bar{l}_j + p_T \) \((i, j = 1, 2, 3)\) or 2 jets and \( p_T \) will be, however, obscured by the background from \( e^+e^- \rightarrow ZZ \). More study is needed to assess to what extent the different geometry will help in extracting the signal.

2. \( \tilde{\nu}_{\mu,\tau} \rightarrow \nu \chi' \) (where \( \chi' \) denotes one of the heavier neutralinos). In this case \( \chi' \) will cascade-decay into one or more LSPs and several fermions leading to many possible final states.
3. $\tilde{\nu}_{\mu,\tau} \rightarrow l_{\mu,\tau}^\pm \chi^\mp$ with the chargino next decaying to the LSP and either $(l, \nu_l)$ or $(q, \bar{q})$. Even if the LSP escapes detection, the final state signatures: $e^+e^- \rightarrow \mu/\tau + l + \not{p}_T$ or $\rightarrow \mu/\tau + 2$ jets + $\not{p}_T$ should be distinguishable from the background caused by $WW$-pairs.

4. $\tilde{\nu}_{\mu,\tau} \rightarrow l_{\mu,\tau}^\pm W^\mp$. The smuon (stau) next decays into the LSP and a $\mu$ ($\tau$) leading to the same signature as in the previous point. In both cases, if the LSP decays inside the detector, there will be an additional pair of leptons or jets with missing $p_T$.

5. $\tilde{\nu}_{\mu,\tau} \rightarrow \tilde{\nu}_{\mu,\tau} Z$. The singly produced sneutrino may emit off a $Z$ before decaying along one of the several possible patterns. The classes of final states are the same as in point 1, and similarly one needs to worry about the background from $ZZ$.

6. $\tilde{\nu}_{\mu,\tau} \rightarrow \bar{l}_j l_k, d_r d_s$ via $\lambda_{ijk} (j = 2, 3; i \neq j, and k = 1, 2, 3)$, and $\lambda_{rjs} (r, s = 1, 2, 3)$ respectively. A detection of two charged leptons or jets of different flavors would provide a striking signal for $R$-parity violation. (Same-flavor final states will suffer from the background due to neutral gauge boson exchange.) These processes would also allow for a direct reconstruction of the sneutrino mass but, being doubly suppressed relative to $R\sqrt{s}$ decays, are probably less likely to be observed. (On the other hand, experimental bounds \[9\] on $R\times$ operators do not apply now \[10\].)

Several of the above processes have been discussed in Ref. [11]. A numerical example \[11\] for $e^+e^- \rightarrow \tilde{\nu}Z$ at the NLC shows that the process should be clearly visible up to the kinematic limit even for rather small values of $\lambda$.

It is clear that even if a single $\tilde{\nu}_\mu$ or $\tilde{\nu}_\tau$ is produced there will in general be a variety of possibly striking signatures, even if the LSP does not decay in the detector. This is also true in the case of hadronic colliders \[i\].

4 Double Sfermion Production

Pairs of sleptons and squarks can be produced in $e^+e^-$ collisions via $R\sqrt{s}$ neutral gauge boson ($\gamma$ and $Z$) $s$-channel exchange. Pairs of $\tilde{e}^+\tilde{e}^-$ can also be created through a diagram involving a $t$-channel exchange of $\chi^0_i$ ($i = 1, 4$). In addition, there exist $t$-channel $R\times$ processes which are, however, doubly suppressed and thus probably less important.

Each sfermion will next decay via either $R\sqrt{s}$ or $R\times$ vertices into one of several possible final states following the pattern discussed above in the case of $\tilde{\nu}_{\mu,\tau}$. For definiteness, let us focus on a (charged) slepton. It can decay into $l\nu$ (via $\lambda$) or $qq'$ (via $\lambda'$). But it can also decay into $l\chi$ without breaking $R$. Clearly in all these processes the main background will come from $WW$ pairs but should be tractable by cutting on $m_W$. 

5
If $\chi$ next escapes detection, the possible final states are

$$e^+e^- \rightarrow \bar{l}^+\bar{l}^- \rightarrow \bar{l} + \not{p}_T \quad (6)$$

$$\rightarrow l + 2\text{jets} + \not{p}_T. \quad (7)$$

If $\chi$ decays in the detector, many more possibilities arise:

$$e^+e^- \rightarrow \bar{l}^+\bar{l}^- \rightarrow 6l + \not{p}_T, \quad (8)$$

$$\rightarrow (4 \text{ or } 5)l + 2 \text{jets} + \not{p}_T, \quad (9)$$

$$\rightarrow 4l + 4 \text{jets}, \quad (10)$$

$$\rightarrow (2 \text{ or } 3)l + 4 \text{jets} + \not{p}_T, \quad (11)$$

$$\rightarrow 2l + 6 \text{jets} + \not{p}_T. \quad (12)$$

One can see that $R$-parity breaking can show up in a variety of ways. In the case considered above a distinct signal is provided by multiple lepton events and relatively little background. (Further discussion of some of these processes and numerical examples in the case of the NLC can be found in Ref. [11].)

5 Ino Production

Another class of processes involves two inos in the final state. Usually one considers only $R\sqrt{\chi}$-pair-production processes. (See, eg., Ref. [12].) In addition, however, the sneutrino-vev-induced $R\times$ couplings $Z\nu\chi^0$ and $Wl\chi$ allow for $\nu\chi$ in the final state. These processes are presumably suppressed by constraints from lepton universality but in general should not be neglected.

6 Conclusions

$R$-parity breaking can truly be called Pandora’s box of supersymmetry. Once it is allowed it leads to an enormous number of new processes and final states. In this brief review I have attempted to at least systematize major $R$-breaking processes in $e^+e^-$ collisions. Some specific numerical examples were quoted for the NLC but the classification presented here is (with some modifications, like $ZZ$ or $WW$ background) applies also to LEP. Clearly, an extensive study is needed to assess all the possibilities. It is not even easy to clearly distinguish dominant and sub-dominant processes without making ad hoc assumptions regarding the couplings. Moreover, in general one cannot separate $R$-parity violating processes from the conserving ones.

On the other hand, a discovery of $R$-parity breaking could have very profound consequences for our understanding of several fundamental issues. Among them are, for example, hints for specific ways of GUT symmetry breaking and the nature of dark matter in the Universe. The task of searching for $R$-parity violation may not be an easy one but it may well be worth the effort.
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