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R-Parity Violation at LEP2 : Virtual Effects

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Abstract

We investigate the ability of LEP2 to detect possible R-parity violation, especially for the case where direct production cross-sections are too small for all superparticles. We demonstrate that for coupling strengths allowed by present experiments, sfermion-exchange diagrams can contribute significantly to the $e^+e^- \to f\bar{f}$ process. This would be a useful tool in further constraining the parameter space. Similar arguments hold for leptoquarks and dileptons as well.

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Supersymmetry is perhaps the most popular and promising theoretical concept going beyond the Standard Model (SM). The Minimal Supersymmetric Standard Model (MSSM) [1] is obtained from the SM by the naive supersymmetrization of both the particle content and the couplings in the latter. However, the most general Lagrangian consistent with supersymmetry as well as with the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry contains terms that have no analogue within the SM. This comes about as one of the Higgs supermultiplets has the same quantum numbers as the doublet lepton superfields and thus may be replaced by the latter in the Lagrangian. A similar effect may also be spontaneously generated if any of the sneutrino fields develops a vacuum expectation value. Furthermore, trilinear terms involving the singlet quark superfields are also allowed. The additional pieces in the superpotential may thus be parametrized as [2]

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k \ , \qquad (1)$$

where E^c_i, U^c_i, D^c_i are the singlet superfields and L_i and Q_i are the $SU(2)$-doublet lepton and quark superfields. The coefficients λ''_{ijk} are antisymmetric under the interchange of the last two indices, while λ_{ijk} are antisymmetric under the interchange of the first two.

Terms as in eq.(1) obviously have striking phenomenological consequences. For example, the λ_{ijk} and λ'_{ijk} couplings violate lepton number, while the λ''_{ijk} violate baryon number. Simultaneous presence of both may therefore lead to catastrophically high rates for proton decay. In a similar vein, pairs of such couplings may induce tree-level flavour-changing neutral currents. Such considerations led to the introduction of a discrete symmetry known as "R-parity". Expressible in terms of baryon number (B), lepton number (L) and the intrinsic spin (S), $R \equiv (-1)^{3B+L+2S}$ has a value of $+1$ for all SM particles and -1 for all their superpartners. Apart from ruling out each of the terms in eq.(1), an exact R-parity has the additional consequence of rendering the lightest superpartner (LSP) stable.

While this discrete symmetry may be phenomenologically desirable, there is no clear theoretical motivation for it to exist. Even phenomenologically, an exact R-parity is an overkill. The constraints from proton-decay may be evaded by assuming that all of the λ''_{ijk}

vanish identically[1]. Such an assumption is well motivated within certain theoretical scenarios [4] and we shall hold it to be true. The problem of preservation of GUT-scale baryogenesis [5] is thus rendered largely ineffectual. The presence of the other $\not{R}_p$ terms can, however, also affect the baryon asymmetry of the universe. It has been argued [6], though, that such bounds are highly model-dependent and can hence be evaded, for example by conserving one lepton flavour over cosmological time scales.

Couplings as in eq.(1) can also be bounded by using various low-energy data such as lepton- or meson-decays [7, 8], or from analyses of the Z-decay modes at LEP [9]. Many of these constraints are relatively weak though, and the allowed magnitudes for the corresponding couplings may lead to remarkable signals at LEP2 [10, 11, 12]. Most of such studies concentrate on scenarios wherein the LSP and/or other supersymmetric particles are light enough to be produced at LEP2. The breaking of R-parity then leads to certain tell-tale signatures.

In this Letter, we investigate the orthogonal set, namely we assume that *none* of the supersymmetric particles (including the LSP) can be produced with a significant cross-section. The suppression could come from two sources : (*i*) all supersymmetric particles are relatively heavy, or (*ii*) the lighter ones couple very weakly to the relevant SM particles. Any possible effect can then only be virtual. The best testing ground at LEP2 is provided by pair-production of light charged fermions :

$$e^+e^- \to f\bar{f} \ . \qquad (2)$$

For experimental reasons, we confine ourselves to $f = e, \mu, \tau, b, c$, and hence to the couplings $\lambda_{12k,13k,231}$ and $\lambda'_{113,12k}$. The SM contribution to the above process is in the form of γ, Z mediated s-channel diagrams (for $f = e$, additional t-channel ones too). The introduction of the terms in eq.(1) leads to new t-channel (also s-channel for $f = e$) diagrams governed

[1]In fact, only some of these need to be vanishingly small. The constraints on the others are somewhat weaker [3].

by the following Yukawa couplings :

$$
\begin{aligned}
\mathcal{L}_{\lambda,\lambda'} &= \lambda_{ijk}\left[\tilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \tilde{e}_{jL}\overline{e_{kR}}\nu_{iL} + \tilde{e}^*_{kR}\overline{(\nu_{iL})^C}e_{jL} - (i \leftrightarrow j)\right] + \text{h.c} \\
&+ \lambda'_{ijk}\Big[\ \tilde{\nu}_{iL}\overline{d_{kR}}d_{jL} + \tilde{d}_{jL}\overline{d_{kR}}\nu_{iL} + \tilde{d}^*_{kR}\overline{(\nu_{iL})^C}d_{jL} \\
&\qquad - \tilde{e}_{iL}\overline{d_{kR}}u_{jL} - \tilde{u}_{jL}\overline{d_{kR}}e_{iL} - \tilde{d}^*_{kR}\overline{(e_{iL})^C}u_{jL}\Big] + \text{h.c.}
\end{aligned} \tag{3}
$$

For $f = e, \mu, \tau$ we then have sneutrino-mediated diagrams, while for $f = b, c$ we have $\tilde{u}_{jL}$- and $\tilde{d}_{jR}$ exchanges respectively. At this stage it is useful to note that if we close our eyes to the global quantum numbers for the scalars, the squark interaction mimics that of certain scalar leptoquarks while the sneutrinos mimic a dilepton. Thus much of the analysis presented here can trivially be extended to a discussion of leptoquark and dilepton couplings.

Since the $\not{R}_p$interactions have a structure different from the SM one, the angular distribution for the $f\bar{f}$ pair is a sensitive probe for the existence of the former. In fact, this very difference alters the mass-dependence of these bounds from the linear relation derived from low-energy measurements. The sensitivity of the experiment can be gauged by dividing the angular width of the experiment into bins and comparing the observed number of events n_j in each with the SM prediction n_j^{SM}. A quantitative measure is given by a χ^2 test[2]:

$$
\chi^2 = \sum_{j=1}^{\text{bins}} \left(\frac{n_j^{SM} - n_j}{\Delta n_j^{SM}}\right)^2 \quad . \tag{4}
$$

The number of events is obtained by integrating the differential distribution over the angular bin and is given by

$$
n_i = \sigma_i \epsilon L \ . \tag{5}
$$

where ϵ is the detector efficiency and L is the machine luminosity. The error in eq.(4) is obtained by adding the statistical and systematic ones in quadrature :

$$
\Delta n_j^{SM} = \sqrt{(\sqrt{n_j})^2 + (\delta_{\text{syst}} n_j)^2}. \tag{6}
$$

[2]Since the expected number of events is relatively large, we do not envisage a qualitative improvement by adopting an unbinned maximum-likelihood test. However, this should be checked with a full detector simulation.

To be quantitative, we shall use

$$\sqrt{s} = 192\,\mathrm{GeV} \qquad L = 500\ \mathrm{pb}^{-1} \qquad \delta_{\rm syst} = 0.02\ . \tag{7}$$

For experimental convenience, we demand that the outgoing leptons or jets in eq.(2) be at least 20° away from the beam pipe. Within this restricted region we assume uniform detection efficiencies [13]

$$\epsilon_e = \epsilon_\mu = 0.95 \qquad \epsilon_\tau = 0.90 \qquad \epsilon_b = 0.25 \qquad \epsilon_c = 0.05. \tag{8}$$

Dividing the above-mentioned angular region (between 20° and 160°) into 20 equal-sized bins[3], we then perform the χ^2 test as in eq.(4). To avoid spurious contributions to the χ^2 we reject a bin from the analysis if either (i) the difference between the SM expectation and the measured number of events is less than 1 or (ii) the SM expectation is less than 1 event while the measured number is less than 3.

We present our results in the form of 95% C.L. bounds in the two-parameter space of the sfermion mass and the $R\!\!\!/_p$ coupling. The interpretation is straightforward. Any combination of the two parameters *above* the curves (*i.e.* away from the origin) can be ruled out at 95% C.L.[4]. As we are dealing with one-sided bounds, this corresponds to $\chi^2 > 4.61$ in eq.(4) [14].

Figure $(1a)$ shows the bounds for all the relevant λ's as a function of the squark-mass[5]. Since both λ'_{121} and λ'_{121} are probed by the angular distribution of charm jets, the sensitivity is identical. The constraints on λ'_{123} is somewhat stronger as both the c and the b quarks are observable in the final state. A curious point is that inspite of lower detector efficiency, c-jet distributions are more sensitive to the presence of $R\!\!\!/_p$ couplings than the b-jets. This can be traced to the relative size of the interference term. The bounds on λ'_{121} and λ'_{123} are significantly stronger than those available today [7, 8]. Though the direct experimental

[3]We find that the sensitivity of the results to the binning is rather weak for bin cardinality between 15 and 30.

[4]If the value of one of the parameters were known, then a 98.6% C.L. bound on the other would be given by the projection on the corresponding axis.

[5]Where more than one sfermion can contribute, we assume them to have identical mass.

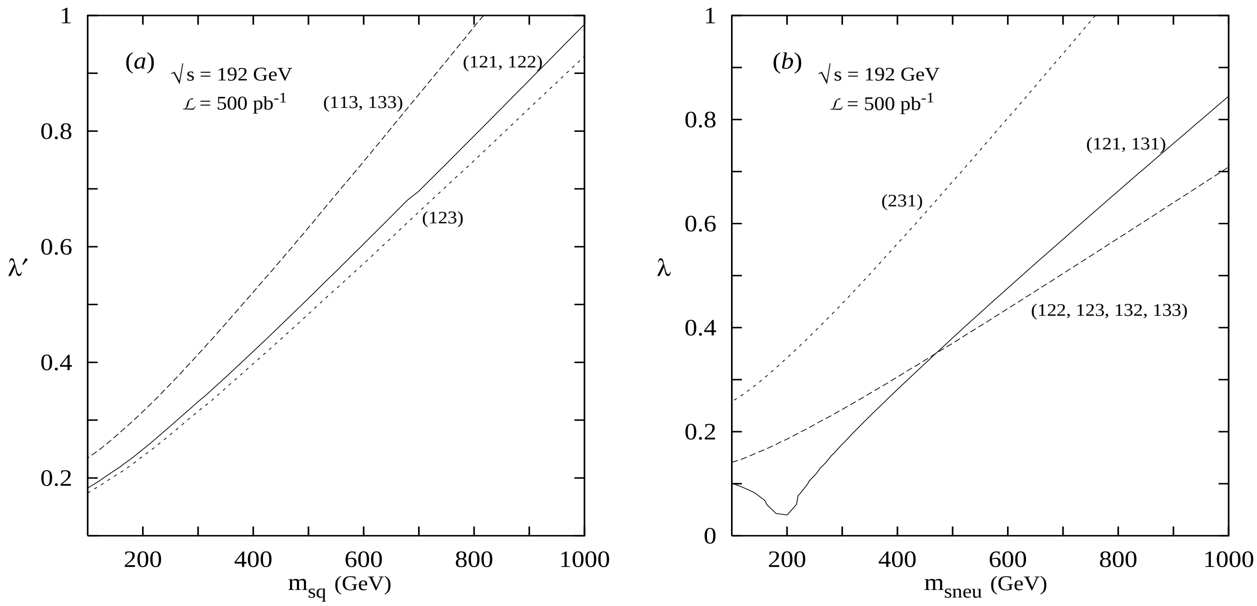

Figure 1: *Contours of detectability in the coupling–sfermion mass plane. The numbers in the parentheses refer to the indices on* λ' (λ)*. The parameter space* above *the curves can be ruled out at 95% C.L. For fixed value of one parameter, the projection onto the other axis defines a 98.6% C.L.*

bounds on λ'_{122} and λ'_{133} as weak, these induce radiative correction to the Majorana mass for the electron neutrino [15, 10, 8] and thus can be restricted severely. On the other hand, λ'_{113} is tightly bound from charged current universality [7].

Figure (1b) shows similar bounds for the λs as a function of the sneutrino mass. While λ_{122} or λ_{132} lead to a t-channel sneutrino ($\tilde{\nu}_{\mu L}$ and $\tilde{\tau}_{\mu L}$ respectively) diagram for $e^+e^- \to \mu^+\mu^-$, λ_{123} or λ_{133} do the same for τ-production. Since the detector efficiencies for μ-pair and τ-pair are quite similar, the corresponding bounds are almost indistuingishable from each other. Though λ_{231} leads to additional diagrams in both the μ– and τ-channels, the sensitivity. This again can be traced back to the size of the interference term (since this coupling sees e_R rather than e_L). The most interesting cases are however those of λ_{121} and λ_{131}. Apart from muonic (tauonic) final states, these couplings contribute to $e^+e^- \to e^+e^-$ as well. The dip in the contour corresponds to a resonance production of a sneutrino which subsequently decays into a e^+e^- pair[6]. As in the λ' case, here too non-observation of a Majorana mass for the ν_e constrains $\lambda_{122,133}$. Of the rest, these new bounds on $\lambda_{131,132}$ would be the strongest yet. The others are at best similar to the present ones. Only in the case of the sneutrinos being considerably lighter than the corresponding charged sleptons, will there be a qualitative improvement.

To conclude, we point out that the present constraints on some of the $R\!\!\!/_p$ couplings are relatively weak. If the supersymmetric particles are light enough to be produced copiously at LEP2, we would shortly be in a position to witness dramatic signals. On the other hand, if they are either too heavy or too weakly coupled to be produced, indirect effects provide us with a means to investigate this sector. We exhibit that quite a few of the lepton-number violating $R\!\!\!/_p$ couplings lead to significant deviations in the $e^+e^- \to f\bar{f}$ angular distributions. For some of the couplings, this effect can be used to impose bounds that are stronger than any available today, while for others it will provide a complementary test. A similar analysis would also be applicable to a large class of leptoquark and dilepton couplings.

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[6]Provided a neutralino or a chargino is lighter than this sneutrino, part of this particular parameter range may also be investigated by looking for decays into these channels [12].

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