Search for R-parity Violation at LEP

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We discuss the present status of the searches for R-parity violation at LEP. The following topics are considered: pair-production of supersymmetric particles via λ, λ' or λ'' couplings, sneutrino single production and spontaneous R-parity breaking. No evidence of signal is found in the total data sample at centre-of-mass energies up to $\sqrt{s} =$ 208 GeV, with an integrated luminosity of 700 pb^{-1}per experiment. Limits are set on the production cross sections, on the MSSM parameters and on the masses of the supersymmetric particles.

1. INTRODUCTION

R-parity is a multiplicative symmetry defined as:

$$\mathrm{R} = (-1)^{3\mathrm{B}+\mathrm{L}+2\mathrm{S}}\,, \qquad (1)$$

where S is the spin, B is the baryonic quantum number and L the leptonic quantum number. R is $+1$ for all ordinary particles, and -1 for their supersymmetric partners. If R-parity is conserved, supersymmetric particles can be produced only in pairs and they decay in cascade to the lightest supersymmetric particle (LSP), which is stable.

R-parity violating terms can be present [1] in the most general superpotential of the Minimal Supersymmetric Standard Model (MSSM) [2], which describes a supersymmetric, renormalizable and gauge invariant theory, with minimal particle content. They are:

$$\lambda_{ijk}\mathrm{L}_i\mathrm{L}_j\overline{\mathrm{E}}_k + \lambda'_{ijk}\mathrm{L}_i\mathrm{Q}_j\overline{\mathrm{D}}_k + \lambda''_{ijk}\overline{\mathrm{U}}_i\overline{\mathrm{D}}_j\overline{\mathrm{D}}_k + \epsilon_i\mathrm{L}_i\mathrm{H}_2\,, \qquad (2)$$

where λ_{ijk}, λ'_{ijk} and λ''_{ijk} are the Yukawa couplings, ϵ_i are dimensional mass parameters and i, j and k the generation indices; L_i and Q_i are the left-handed lepton- and quark-doublet superfields, $\overline{\mathrm{E}}_i$, $\overline{\mathrm{D}}_i$ and $\overline{\mathrm{U}}_i$ are the right-handed singlet superfields for charged leptons, down- and up-type quarks, respectively; H_2 is the Higgs superfield. In order to prevent the simultaneous presence of identical fermionic fields, the following antisymmetry relations are required: $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda''_{ijk} = -\lambda''_{ikj}$, reducing to $9+27+9$ the total number of independent Yukawa couplings. The $\mathrm{L}_i\mathrm{L}_j\overline{\mathrm{E}}_k$ and $\mathrm{L}_i\mathrm{Q}_j\overline{\mathrm{D}}_k$ terms violate the leptonic quantum number L, while the $\overline{\mathrm{U}}_i\overline{\mathrm{D}}_j\overline{\mathrm{D}}_k$ terms violate the baryonic quantum number B. Their simultaneous presence would lead to a fast proton decay[1] [3], which is experimentally excluded. This can be avoided by requiring R-parity conservation, which forbids all terms in Equation 2. However, since the absence of either the B-violating or the L-violating terms is enough to prevent a fast proton decay, there is no need to impose *a priori* R-parity conservation. As a consequence, two new kinds of processes are allowed: single production of supersymmetric particles, or LSP decays into Standard Model particles via scalar lepton or quark exchange. In the latter case, the MSSM production mechanisms are unaltered by the operators in Equation 2.

The LEP experiments have searched for pair-produced neutralinos($\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}^0_m\tilde{\chi}^0_n$, with $m = 1,2$ and $n = 1,..,4$), charginos ($\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1$), scalar leptons ($\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\ell}^+_R\tilde{\ell}^-_R$, $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\nu}\tilde{\nu}$) and scalar quarks ($\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\mathrm{q}}\tilde{\mathrm{q}}$), with subsequent R-parity violating decays, assuming that only one of the coupling constants λ_{ijk}, λ'_{ijk} or λ''_{ijk} is non-negligible. Only $\tilde{\ell}_R$ (supersymmetric partners of the right-handed charged leptons) are considered, since they are expected to be lighter than the corresponding left-handed ones. Supersymmetric particles can decay directly into two or three

[1]With contributions at the tree level from $\lambda'_{11k}\lambda''_{11k}$, and at one-loop level from any product $\lambda_{ijk}\lambda''_{lmn}$ or $\lambda'_{ijk}\lambda''_{lmn}$.

fermions according to the dominant interaction term, as detailed in Table 1. Indirect decays via the LSP can occur as well, as shown in Figure 1. In the present analysis, the dominant coupling is assumed to be greater than 10^{-5} [4], corresponding to decay lengths less than 1 cm.

Pair-production of supersymmetric particles will be discussed in Section 2. Section 3 is dedicated to single sneutrino production. The bilinear term $\epsilon_i \mathrm{L}_i \mathrm{H}_2$ and the spontaneous R-parity violation will be addressed in Section 4.

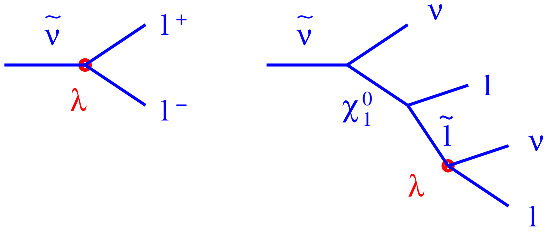

Figure 1. Examples of scalar neutrino direct and indirect decays via λ coupling

2. PAIR PRODUCTION OF SUPERSYMMETRIC PARTICLES

2.1. Data Sample

The results presented here are based on the data collected by the LEP experiments at $\sqrt{s} = 161-208$ GeV, corresponding to an integrated luminosity of about 700 pb^{-1}per experiment. Detailed information can be found in [5] and [6].

Thanks to this luminosity, a sensitivity per experiment to signal cross-section in the range of 0.02-0.05 pb can be reached with selection efficiencies around 30%. For instance the $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production cross section for $M_{\tilde{\chi}_1^0} = 40$ GeV is between 0.02 pb at $\tan\beta = 1$ and $m_0 = 500$ GeV and 1 pb for $m_0 = 0$.

2.2. Signal Topologies and Event Selections

R-parity violating decays of supersymmetric particles give rise to many different final states, depending on the dominant λ, λ' or λ'' couplings and on the ijk indices, as one can find out from Table 1. Decays mediated by λ, λ' or λ'' couplings provide mainly event topologies with leptons, leptons and jets or jets, respectively. Dedicated selections are performed as discussed in [5].

2.3. Model Independent Results

No significant excess of events is observed. Therefore the experiments have set upper limits at the 95% C.L. on the neutralino, chargino, scalar lepton and scalar quark pair-production cross sections assuming direct or indirect R-parity violating decays [5,6]. For example, $\tilde{\chi}_1^0\tilde{\chi}_1^0$ cross section upper limits range from 20 to 180 fb, depending on the neutralino mass value and on the Yukawa coupling considered. The 95% C.L. upper limits on the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ cross section are between 80 and 150 fb depending on the couplings and mass values.

2.4. Limits in the MSSM framework

In the MSSM, the masses, couplings and cross sections of the supersymmetric particles considered here depend on the gaugino mass parameter, M_2, the higgsino mass mixing parameter, μ, the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, and the common mass of the scalar particles at the GUT scale, m_0. The experiments have either performed a scan on the MSSM parameters listed above, or they have calculated mass limits for typical parameter values. The scan has been performed in the ranges: $0 \leq M_2 \leq 1000$ GeV, -500 GeV $\leq \mu \leq 500$ GeV, $0 \leq m_0 \leq 500$ GeV and $0.7 \leq \tan\beta \leq 40$.

Figure 2 shows an example of excluded regions at 95% C.L. by the λ' analysis in the $M_2 - \mu$ plane.

For scalar lepton and scalar quark pair-production, mass limits are derived by direct comparison of the 95% C.L. cross section upper limits with the scalar particle pair-production cross sections, which depend on the scalar particle mass. The 95% C.L. lower limits obtained by the LEP experiments are quoted in Table 2.

Moreover, overall MSSM mass limits are derived from analysis combination. A point in the MSSM parameter space is excluded at 95% C.L. if the total number of expected events is greater

Table 1
R-parity violating decays of the supersymmetric particles. Charged conjugate states are implied. Only supersymmetric partners of the right-handed charged leptons are taken into account. Decays to more than three fermions are not listed. W* indicates virtual W bosons.

Particle	Direct decays			Indirect decays
	λ_{ijk}	λ'_{ijk}	λ''_{ijk}	via $\tilde{\chi}^0_1$
$\tilde{\chi}^0_1$	$\ell^-_i \nu_j \ell^+_k$, $\nu_i \ell^+_j \ell^-_k$	$\ell^-_i \mathrm{u}_j \bar{\mathrm{d}}_k$, $\nu_i\, \mathrm{d}_j \bar{\mathrm{d}}_k$	$\bar{\mathrm{u}}_i \bar{\mathrm{d}}_j \bar{\mathrm{d}}_k$	–
$\tilde{\chi}^+_1$	$\nu_i \nu_j \ell^+_k$, $\ell^+_i \ell^+_j \ell^-_k$	$\nu_i u_j \bar{\mathrm{d}}_k$, $\ell^+_i \bar{\mathrm{d}}_j \mathrm{d}_k$	$\bar{\mathrm{d}}_i \bar{\mathrm{d}}_j \bar{\mathrm{d}}_k$, $\mathrm{u}_i \mathrm{u}_j \mathrm{d}_k$, $\mathrm{u}_i \mathrm{d}_j \mathrm{u}_k$	$\mathrm{W}^* \tilde{\chi}^0_1$
$\tilde{\ell}^-_{kR}$	$\nu_i \ell^-_j$, $\nu_j \ell^-_i$	–	–	$\ell^-_k \tilde{\chi}^0_1$
$\tilde{\nu}_i$, $\tilde{\nu}_j$	$\ell^-_j \ell^+_k$, $\ell^-_i \ell^+_k$	$\mathrm{d}_j \bar{\mathrm{d}}_k$, –	–	$\nu_i \tilde{\chi}^0_1$, $\nu_j \tilde{\chi}^0_1$
$\tilde{\mathrm{u}}_{iR}$	–	–	$\bar{\mathrm{d}}_j \bar{\mathrm{d}}_k$	$\mathrm{u}_i \tilde{\chi}^0_1$
$\tilde{\mathrm{d}}_{jR}, \tilde{\mathrm{d}}_{kR}$	–	$\bar{\nu}_i\, \mathrm{d}_j$, $\ell^-_i \mathrm{u}_j$	$\bar{\mathrm{u}}_i \bar{\mathrm{d}}_k$, $\bar{\mathrm{u}}_i \bar{\mathrm{d}}_j$	$\mathrm{d}_j \tilde{\chi}^0_1, \mathrm{d}_k \tilde{\chi}^0_1$

than the combined upper limit at 95% C.L. on the number of signal events. Neutralino, chargino, scalar lepton and scalar quark analyses are combined since several processes can occur at a given point. Gaugino and scalar mass unification at the GUT scale is assumed. Constraints from the lineshape measurements at the Z pole are also taken into account by some experiments. The overall lower limits at 95% C.L. on the neutralino, chargino and scalar lepton masses are shown in Table 3.

Figure 3 shows the 95% C.L. lower limits on neutralino and scalar lepton masses as a function of $\tan\beta$. The $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ mass limits are shown for $m_0 = 500$ GeV and the $\tilde{\ell}_R$ ones for $m_0 = 0$. These values of m_0 correspond to the absolute minima from the complete scan on M_2, μ, m_0 and $\tan\beta$.

3. SINGLE SNEUTRINO PRODUCTION

The exchange of single scalar neutrinos can produce resonance peaks at LEP energies. The production of $\tilde{\nu}_\mu$ and $\tilde{\nu}_\tau$ can occur in $\mathrm{e}^+\mathrm{e}^-$ collisions via λ_{121} or λ_{131} couplings, respectively. Two kinds of processes are analyzed by the LEP experiments, both allowing to set upper limits on the coupling strength λ as a function of the scalar neutrino mass. The best sensitivity is obtained when the sneutrino is produced on shell for $M_{\tilde{\nu}} = \sqrt{s}$.

Precision electroweak fits are performed on the measurements of leptonic cross sections and asymmetries [7]. As a result, previously unexplored areas in the ($M_{\tilde{\nu}_\mu}$, λ_{121}), ($M_{\tilde{\nu}_\tau}$, λ_{131}), ($M_{\tilde{\nu}_\tau}$, $\sqrt{\lambda_{131}\lambda_{232}}$) and ($M_{\tilde{\nu}_\mu}$, $\sqrt{\lambda_{121}\lambda_{233}}$) planes are excluded.

For λ_{121} or λ_{131} couplings a better sensitivity is obtained in the search for sneutrino decays to neutralino [8]: $\mathrm{e}^+\mathrm{e}^- \to \tilde{\nu} \to \tilde{\chi}^0_1 \nu$, which is plotted in Figure 4. Figure 5 shows the 95% C.L. upper limits on the λ_{131} coupling.

Single sneutrino production has been searched for also in the process $\mathrm{e}\,\gamma \to \tilde{\nu}_j \ell_k$, which allows to access the couplings $1jk$ and 231. This analysis is described in [9].

4. SPONTANEOUS R-PARITY VIOLATION

Spontaneous R-parity violation can be effectively parametrised by three superpotential bilinear terms $\epsilon_i \mathrm{L}_i \mathrm{H}_2$ [10], with $i = 1, 3$. In those models trilinear terms are not present. The bilinear terms, usually assumed to be rotated away by a redefinition of the L_i and Higgs superfileds, cannot be rotated away in the presence of soft supersymmetry breaking, since the rotation would reintroduce R-parity violating trilinear terms. Spontaneous R-parity breaking is assumed to play a

Table 2
Ranges (in GeV) of the 95% C.L. lower limits on the scalar particle masses obtained by the LEP experiments ALEPH (A), DELPHI(D), L3 (L) and OPAL (O). For details see [5,6].

Mass (GeV)	λ_{ijk}		λ'_{ijk}		λ''_{ijk}		Exp.
	Dir.	Ind.	Dir.	Ind.	Dir.	Ind.	
$M_{\tilde{\mathrm{e}}_\mathrm{R}}$	69-89	79-96		93	96	92-96	ADLO
$M_{\tilde{\mu}_R}$	61-75	87-96		90	86	85-86	ADLO
$M_{\tilde{\tau}_R}$	61-75	86-95		76	75	75	ADLO
$M_{\tilde{\nu}_e}$	94-95	98-99		91	99	88-99	ADL
$M_{\tilde{\nu}_{\mu,\tau}}$	65-95	78-89		78	70	65-70	ADL
$M_{\tilde{\mathrm{u}}_R}$					80	79	L
$M_{\tilde{\mathrm{d}}_R}$					56	55	L
$M_{\tilde{t}_1}$		87-91		85	77	72-77	ADL
$M_{\tilde{b}_1}$		90		80	55	48-72	ADL

Table 3
Ranges (in GeV) of the 95% C.L. lower limits on the supersymmetric particle masses obtained from analysis combination by the LEP experiments ALEPH (A), DELPHI(D) and L3 (L). For details see [5,6]. The scalar neutrino mass limit is mainly due to neutralino exclusions, resulting in a 95% C.L. lower limit on the scalar neutrino mass above the kinematic limit.

Mass (GeV)	λ_{ijk}	λ'_{ijk}	λ''_{ijk}	Exp.
$M_{\tilde{\chi}_1^0}$	34-40		38-40	ADL
$M_{\tilde{\chi}_2^0}$	84		80	L
$M_{\tilde{\chi}_1^\pm}$	103	103	103	ADL
$M_{\tilde{\ell}_R}$	83		89	L
$M_{\tilde{\nu}}$	153		149	L

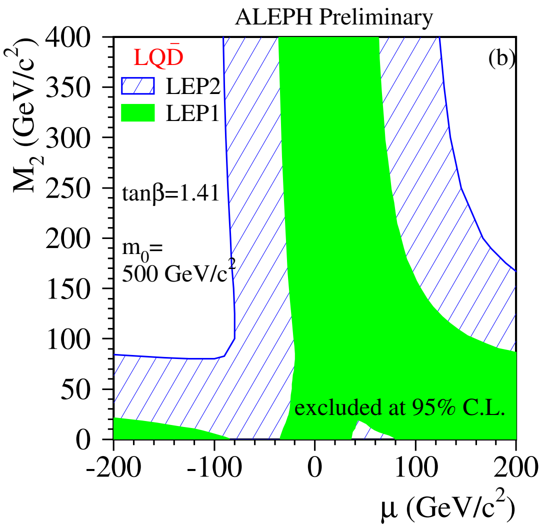

Figure 2. Regions excluded at 95% C.L. by the λ' analysis in the $M_2 - \mu$ plane for $\tan\beta = 1.41$ and $m_0 = 500$ GeV.

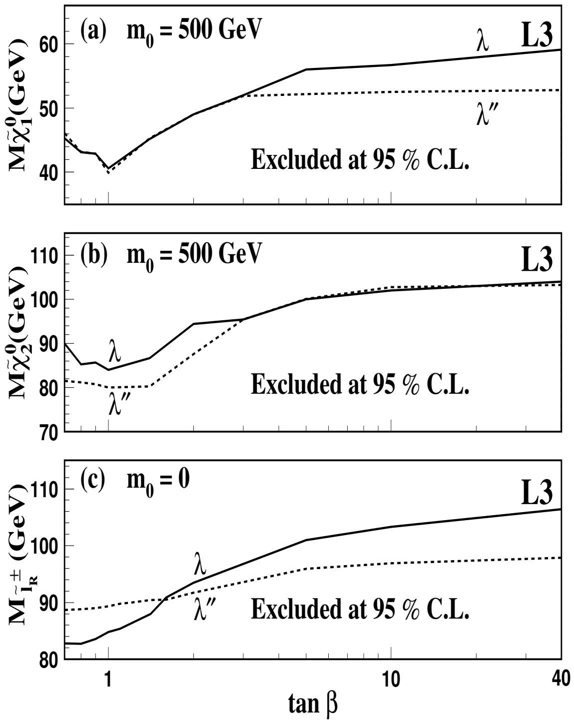

Figure 3. MSSM mass limits from combined analyses for (a) $\tilde{\chi}^0_1$, (b) $\tilde{\chi}^0_2$ and (c) $\tilde{\ell}_R$, as a function of $\tan\beta$, for $0 \le M_2 \le 1000$ GeV and -500 GeV $\le \mu \le 500$ GeV. $m_0 = 500$ GeV in (a) and (b) and $m_0 = 0$ in (c). For those values of m_0 the global minima on the mass limit are obtained. Constraints on $\tan\beta$ from Higgs searches are conservatively not taken into account.

role only in the third generation and it allows new chargino decays: $\tilde{\chi}^{\pm}_1 \to \tau^{\pm} J$, where the Majoron J is a massless Nambu-Goldstone boson.

Two acoplanar taus plus missing energy are searched for in [11]. No evidence of signal is found in the data sample at 183–202 GeV.

5. CONCLUSIONS

Searches for R-parity violation at LEP cover almost every allowed process in the MSSM and reach the same sensitivity as in the R-parity conserving case. Therefore, the supersymmetry limits obtained at LEP are independent of R-parity conservation assumptions.

New limits with about 700 pb^{-1}per experiment are shown in this article.

REFERENCES

1. C.S. Aulakh and R.N. Mohapatra, Phys. Lett. **B 119** (1982) 136; F. Zwirner, Phys. Lett. **B 132** (1983) 103; L.J. Hall and M. Suzuki, Nucl. Phys. **B 231** (1984) 419; R. Barbieri and A. Masiero, Nucl. Phys. **B 267** (1986) 679. For a recent review and a reference to the literature: H. Dreiner, "An introduction to explicit R-parity violation", hep–ph/9707435, in *Perspectives on Supersymmetry*, ed. G.L. Kane, World Scientific, Singapore (1998).
2. A review can be found for example in: H.E. Haber and G.L. Kane, Phys. Rep. **117** (1985) 75.
3. S. Weinberg, Phys. Rev. **D 26** (1982) 287; G. Bhattacharyya and P.B. Pal, Phys. Rev. **D**

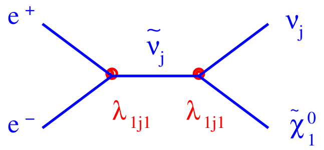

Figure 4. Single sneutrino production via λ_{1j1} coupling. The neutralino decays afterwards via R-parity violation.

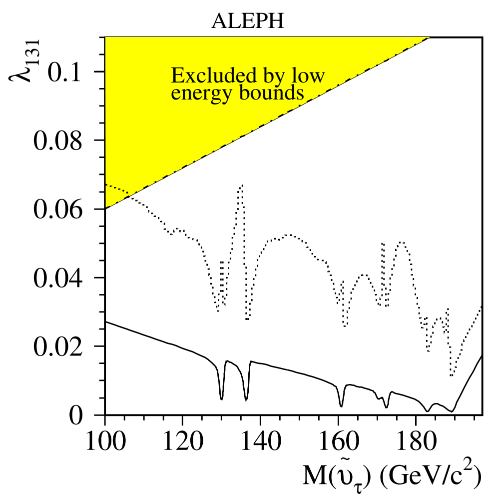

Figure 5. The solid line shows the 95% C.L. upper limits on the λ_{131} coupling as a function of the $M_{\tilde{\nu}_\tau}$ mass for single sneutrino production followed by indirect decays. For comparison the limit obtained for direct decays to e^+e^- is also shown.

59 (1999) 097701.

4. S. Dawson, Nucl. Phys. **B 261** (1985) 297.
5. ALEPH Collab., R. Barate *et al.*, Eur. Phys. J. **C 4** (1998) 433, Eur. Phys. J. **C 7** (1999) 383, Eur. Phys. J. **C 13** (2000) 29, Eur. Phys. J. **C 19** (2001) 415;
DELPHI Collab., P. Abreu *et al.*, Eur. Phys. J. **C 13** (2000) 591, Phys. Lett. **B 487** (2000) 36, Phys. Lett. **B 500** (2001) 22;
L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 459** (1999) 354, Eur. Phys. J. **C 19** (2001) 397, CERN-EP/01-068, accepted by Phys. Lett. **B**;
OPAL Collab., G. Abbiendi *et al.*, Eur. Phys. J. **C 11** (1999) 619, Eur. Phys. J. **C 12** (2000) 1.
6. ALEPH Collab., R. Barate *et al.*, CONF 2001-009, CONF 2001-053, DELPHI Collab., P. Abreu *et al.*, CONF 511, OPAL Collab., G. Abbiendi *et al.*, PN470, notes presented at the *International European Conference on High Energy Physics* July 12-18 2001, Budapest,Hungary.
7. ALEPH Collab., R. Barate *et al.*, Eur. Phys. J. **C 12** (2000) 183; DELPHI Collab., P. Abreu *et al.*, Phys. Lett. **B 485** (2000) 45; L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 489** (2000) 81; OPAL Collab., G. Abbiendi *et al.*, Eur. Phys. J. **C 6** (1999) 1.
8. ALEPH Collab., R. Barate *et al.*, Eur. Phys. J. **C 19** (2001) 415.
9. ALEPH Collab., R. Barate *et al.*, CONF 2001-008, presented at the *International European Conference on High Energy Physics* July 12-18 2001, Budapest,Hungary.
10. J.W.F. Valle *et al.*, Phys. Lett. **B 272** (1991) 436, Phys. Lett. **B 288** (1992) 311, hep-ph/9706315.
11. DELPHI Collab., P. Abreu *et al.*, Phys. Lett. **B 502** (2001) 24, and CONF 512, presented at the *International European Conference on High Energy Physics* July 12-18 2001, Budapest,Hungary.