SEARCH FOR SUSY WITH $\mathcal{R}_p$ AT LEP

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Abstract
Searches for supersymmetry at LEP allowing for $\mathcal{R}_p$ are reviewed. The results are compared with the $\mathcal{R}_p$ conserving scenario.

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1 Introduction

The searches for supersymmetry performed at LEP are guided by a minimal supersymmetric extension of the Standard Model (MSSM) $^1$, based on a minimal number of additional degrees of freedom and the addition of soft supersymmetry breaking terms, i.e. those breaking the mass degeneracy inside the supermultiplets preserving the relevant advantages of the theory. Furthermore, in order to insure at tree level lepton ($L$) and baryon ($B$) number conservation - which, contrarily to the Standard Model, in supersymmetry is not guaranteed by gauge invariance - the conservation of the so called $\mathbf{R}_p$ parity is required $^2$, $\mathbf{R}_p$ being defined as $(-1)^{3B+L+2S}$ with $S$ the particle spin.

The so far negative results of these searches have pushed the experimental groups to consider less minimal models. Among these, those obtained allowing some degree of $\mathbf{R}_p$ violation are particularly interesting because they predict significant modifications of the phenomenology of the reactions searched for.

This report summarises the most recent results produced by the LEP collaborations on the subject, focusing on the main ideas. Details can be found in $^3$. ALEPH results are based on $\sim$200 pb$^{-1}$ collected at $\sqrt{s} = 91 - 189$ GeV; L3 results on $\sim$76 pb$^{-1}$ collected at $\sqrt{s} = 161 - 183$ GeV; DELPHI and OPAL results on $\sim$56 pb$^{-1}$ collected at $\sqrt{s} = 183$ GeV.

2 Basic Model and assumptions

The basic model used as guideline contains the minimal set of additional particles: two charginos, $\chi^\pm$, $\chi_2^\pm$, partners of $W^\pm$ and $H^\pm$; four neutralinos, $\chi$, $\chi'$, $\chi''$, $\chi'''$, partners of $\gamma$, $Z$, $h$, $H$, $A$; seven complex scalars per family, squarks ($\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{d}_R$), sleptons ($\tilde{l}_L, \tilde{l}_R$), neutrinos ($\tilde{\nu}$), partners of quarks, charged leptons and neutrinos. The gluinos (the eight partners of gluons) and the gravitino (partner of graviton) are assumed to play no rôle at the energies involved. The masses of the Higgs bosons and of the supersymmetric partners are determined in terms of $\mu$, the Higgs doublet mixing term, tan $\beta$, the Higgs vev ratio, $M_1$ and $M_2 = 3/5 \cot^2 \theta_W M_1$, the soft supersymmetry breaking terms associated with $U(1)_Y$ and $SU(2)_L$, and $M_0$, a common GUT scale mass for the scalar partners of the matter fermions.

The $\mathbf{R}_p$ lagrangian terms can be cast in the form $^4$

$$\frac{\lambda_{ijk}}{2} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{\lambda''_{ijk}}{2} U_i^c D_j^c D_k^c + \mu_i L_i H_u$$

where $i$, $j$, $k$ are generation indices, $L$, $Q$ and $E$, $U$, $D$ are, respectively, the lepton and quark $SU(2)$-doublet and $SU(2)$-singlet superfields, and $H_u$ is the Higgs doublet giving mass to the up-like fermions. Symmetry properties of the $\lambda_{ijk}$’s and $\lambda''_{ijk}$’s reduce the total number of new independent complex parameters to 48. The main phenomenological consequence of the $\mu_i$ terms are contributions to neutrino masses and oscillations $^5$, and are therefore not considered in LEP analyses.

The complexity of the new scenario is reduced by assuming that only one coupling at a time is non-zero. This is a sufficient (although not necessary) condition to cope with the constraints derived from low energy experiments on the $\lambda$ couplings $^6$ or on their products $^7$.

In $e^+e^-$ environments the most straightforward consequence of the $\mathbf{R}_p$ terms is a modification of the final states deriving from pair production of supersymmetric particles. Non vanishing $\mathbf{R}_p$ couplings allow the Lightest Supersymmetric Particle (LSP) to decay into Standard Model (SM) particles. Consequently, usual cosmological arguments demanding a neutral and weakly interacting LSP $^7$ do not apply any longer. The nature of the LSP determines the sensitivity in $\lambda$ of the searches. In LEP analyses it is required that the LSP decays within $\sim 1$ cm from the interaction point. This implies $|\lambda| > 10^{-4}$ if the lightest neutralino is the LSP, or $|\lambda| > 10^{-7}$ if one of the sfermions is the LSP$^4$. Lower $|\lambda|$ values give either a long-lived LSP, behaving as in the $\mathbf{R}_p$ conserving

$\theta_W$Excerpt when the family structure is specified, in the following the symbol “$\lambda$” will denote any of the Yukawa couplings.

$\theta_W$Typical upper limits on $|\lambda|$’s are of the order of a few percent; some products are much more constrained: for example, present lower limits on proton lifetime require $\lambda''_{14k} \lambda''_{31k} < 10^{-22}$.

$\theta_W$Assuming the GUT relation for gaugino masses an LSP chargino exists only for $M_{\tilde{g}}^{±} < M_Z/2$, a mass region ruled out by the Z-lineshape measurement; however, it is noted that the developed searches cover also chargino LSP topologies.
case, or a medium-lived LSP, decaying inside the detector volume and giving topologies not yet addressed\(^a\). In the case of a neutralino LSP, for most of the couplings the decay length constraint can be satisfied only if \(M_\chi \approx 10 \text{ GeV/c}^2\).

The typical experimental situation is summarised in Figure 1 as a function of the relevant parameters: the coupling \(\lambda\) and the mass \(M_f\) of the scalar coupling to the \(R_p\) vertex. The sensitivity of low energy experiments to large \(\lambda\) values decreases almost linearly as \(M_f\) increases. As it will be discussed briefly in Sect. 4, other signatures can be studied at \(e^+e^-\) colliders which can be sensitive to lower values of \(|\lambda|\), for \(M_f\) below the effective centre of mass energy of the experiment. The same is valid for leptoquark searches at \(ep\) colliders\(^9\). Depending on the MSSM parameters, pair production in \(e^+e^-\) can be sensitive to much lower \(|\lambda|\) values. Also indicated is the region possibly covered by \(R_p\) conserving searches.

In the next section the searches for topologies arising from pair production are discussed in some detail. Single production, example of an alternative signature studied at LEP, is discussed in Sect. 4.

### 3 Pair Production

As in the case of \(R_p\) conservation, supersymmetric particles are mostly expected to be pair-produced via \(s\)-channel exchange of \(\gamma, Z\) and, for gaugino and slepton pairs, \(t\)-channel exchange of the relevant slepton or gaugino. \(R_p\) couplings involving electrons allow additional \(t\)-channel contributions which, given the existing limits on the couplings, are expected to be small and neglected. Therefore, total production cross sections follow the usual pattern: typically large for gauginos, allowing in some cases to push the sensitivity very close to the kinematic limit; smaller for sfermions, where the sensitivity is limited by the integrated collected luminosity.

#### 3.1 Decay phenomenology and final state topologies

The decay modes of the supersymmetric particles mediated by \(R_p\) couplings (the so called direct decay modes) are given in Table 1. Depending on the size of the couplings and on the nature of the LSP, indirect decays, i.e. those proceeding in a first stage via the lightest neutralino, can still play a rôle. Direct and indirect decays are treated separately since they can lead to topologies selected with different strategies and performances.

Table 2 gives the possible topologies expected from pair production. It is noted that, despite of the LSP instability, in many cases final state neutrinos can carry away a significant fraction of energy.

#### 3.2 Selections

The complexity of the situation depicted in Table 2 renders necessary to develop many selections, one for every corner of the space of the relevant topological and dynamical quantities.

New signals must be disentangled from the expected...
tions from the Standard Model. The most problematic standard events to reject are the 4-fermion events proceeding via heavy gauge bosons \((W, Z)\), which, in some cases, result in irreducible contamination to be dealt with statistical methods.

Final states mediated by LLE couplings are characterised by a large number of charged leptons and neutrinos. The type of events expected is quite unusual for the SM; consequently they can be tagged efficiently by mainly looking at the number of identified leptons. Hadronic jets from quark hadronization can occur in case of indirect decays. In this case the signal events are tagged by requiring the identified leptons to be isolated from the hadronic system and to carry a large fraction of visible energy.

Direct LQD decays of sleptons or gauginos can lead, respectively, to four jet final states or four jet and two charged leptons final states; in both these cases the equal reconstructed mass constraint can be exploited to enhance the discriminating power. Other decays lead to final states which always contain quarks and, depending on the process and the coupling structure, charged leptons or neutrinos. Selections therefore require hadronic activity, lepton identification and isolation, missing energy. Selection efficiencies are generally lower than in the LLE case.

Direct UDD decays of sleptons or gauginos produce pure hadronic multi-jet events, with no missing energy, suffering huge backgrounds from two-quark and four-quark SM processes. Mass reconstruction and sphericity-like variables are generally exploited for final discrimination. Indirect decay modes can lead either to fully hadronic final states or to mixed topologies with charged leptons and/or missing energy, which can be selected with relatively higher efficiency. Figure 2 shows an example of variable used in these selections.

Table 3 gives an overview of the typical selections developed by the experimental groups and of their performance.

| Table 2: Topologies arising from pair production; here \(l\) stands for any charged lepton, \(q\) for any quark and \(E\) indicates the presence of undetected particles. |
|-----------------|-----------------|-----------------|
| \(\chi^+ \chi^-\) | LLE | LQD | UDD |
| \(6l, 4l+E, 2l+E, 6l+E\). | \(2n+2l, 2nq+E, 2nq+l+E (n=2,3)\). | \(6q, 8q, 10q\). |
| \(5l+2q+E, 4l+4q+E\). | \(8q+2l, 8q+ml+E (m<1)\). | \(8q+1l+E, 6q+2l+E\). |
| \(\chi\chi, \chi\chi'\) | 2ml+\(E\) (\(m=2,3,4\), 4q+4l+E). | 2ml+\(E\) (\(m=2,3,4\)). |
| \(\chi\chi'\) | 2q+2ml+\(E\) (\(m=2,3\)). | 2ml+\(E\) (\(m=2,3,4\)). |
| \(L+J^-\) | 2l+E, 6l+E. | 4q, 4q+2l+E, 4q+ml+E (\(m=2,3\)). |
| \(\tilde{q}\tilde{q}^+\) | 4l, 4l+E. | 4q, 4q+2l+E, 4q+ml+E (\(m=0,1\)). |
| \(\tilde{q}\tilde{q}\) | 2q+4l+E. | 2q+2l, 6q+2l, 2nq+ml+E (\(n=2,3\)). |

| Figure 2: Example of variables used in the selections: reconstructed \(\chi\) and \(\chi^\pm\) masses in DELPHI 10-jet analysis. Data are shown in black dots. The light grey histogram (green in colour) corresponds to the expected background. The dark grey (red in colour) histogram shows the signal \(\chi^+\chi^- \rightarrow 4J\chi\chi\rightarrow 10j\), \(M_W=68\text{ GeV/c}^2\) and \(M_\chi=38\text{ GeV/c}^2\) normalised to 2 pb. |

| Table 3: Typical selections developed by the experiments (denoted with their initial) in searching for pair production of supersymmetric particles. Here \(L\) indicates some degree of charged lepton identifications, \(J\) hadronic activity, and \(E\) missing energy. |
|-----------------|-----------------|-----------------|
| Exp Efficiency | LLE | LQD | UDD |
| Acoplanar Leptons | ADLO | \(~40\%\) | \(~50\%\).\(~70\%\). |
| “4L”, “6L” (\(\omega / o E\)) | ADO | \(~50\%\).\(~70\%\). | \(~30\%\).\(~50\%\). |
| “4L”, “6L” + \(E\) | ADLO | \(~30\%\).\(~50\%\). | \(~35\%\). |
| “L + J” + \(E\) | ADLO | \(~35\%\). | \(~35\%\). |
| LQD | | |
| “4L” (\(\omega / o E\)) | ADO | \(~50\%\). |
| “4L” + \(E\) | ADO | \(~30\%\). |
| “L + J” (\(\omega / o E\)) | ADO | \(~30\%\). |
| “L + J” + \(E\) | ADO | \(~20\%\). |
| UDD | | |
| “6J,8J,10Jf” | AD | \(~15\%\). |
| Multi-\(J\) + \(E\) | A | \(~25\%\). |
| “L + J” (\(\omega / o E\)) | A | \(~50\%\). |
corresponds, in general, to final states with $\tau$ (the production cross section are interpreted in the usual For charginos and neutralinos the derived upper limits on $\lambda$ strain the parameter space. Given the large amount of agreement with the SM expectations.

### 3.3 Results

As expected by the irreducibility of some of the background processes, the developed analyses select candidates. An example is shown in Figure 3. However, the number and dynamics of the selected events is in good agreement with the SM expectations.

The negative results of the searches are used to constrain the parameter space. Given the large amount of $K_p$ couplings, a conservative approach is adopted to reduce the parameter dependence of the limits by scanning the space of the relevant parameters for the most conservative configuration; for $\lambda$ and $\lambda'$ couplings this corresponds, in general, to final states with $\tau$'s.

### Gauginos

For charginos and neutralinos the derived upper limits on the production cross section are interpreted in the usual $(\mu, M_2)$ plane. The ALEPH result for LLE couplings is shown in Figure 4, where the first results from the 189 GeV data have also been included. For large values of $M_0$ the chargino cross section is large enough for the excluded region to come very close to the kinematic limit, while neutralino cross sections are small and can only help when the collected luminosities are large\(^1\). Lowering $M_0$, chargino (neutralino) cross sections move down (up) because of the negative (positive) interference between $t$-channel sneutrino (selectron) and $s$-channel exchanges. The neutralino processes and in particular the visibility of $\chi \chi$ act naturally as a backup for the loss of sensitivity of $\chi^+ \chi^-$.\(^2\)

\(^1\)This is the case, for instance, for LEP 1 results that, as can be seen in Figure 4 begin to be superseded only by the most recent data collected at 189 GeV.

\(^2\)The interplay works particularly well for LLE, since the topologies arising from $\chi \chi$ are exotic and can be selected with high effective efficiency. For LQD, the ALEPH analysis with 161 and 172 GeV data has shown that the most conservative scenario corresponds to dominance of $\chi^+ \chi^- \rightarrow qgqgq$, for which the efficiency was not enough to cover, for low $M_0$, the mixed region $\mu \sim M_2$; assuming similar performances the large luminosity collected at 183 is expected to smooth out the $M_0$ dependence. The full $M_0$ analysis under UDD dominance has not yet been performed, but arguments similar to LQD are expected to hold.

### Charged sleptons

In the case of charged sleptons decaying directly into an acoplanar lepton pair (LLE) or four jets (LQD), the upper limit on the cross section is translated into a lower limit on the mass. For example, in the upper-left part of Figure 5 it can be seen that a $\tilde{\tau}_R$ decaying directly in $\tau^{-}\nu_e$ is excluded by DELPHI if its mass is below 62 GeV/c\(^2\), while from Figure 6 the ALEPH search for four jet excludes $\tilde{\mu}_L$ with masses below 61 GeV/c\(^2\). Indirect decays, dominating mainly when $\chi$ is the LSP, give rise to exotic signatures, like six charged leptons and missing energy (LLE), four quarks and four charged leptons (LQD), or six quarks and two leptons (UDD); these are generally selected with better efficiency; the mass lower limits, expressed usually in the plane ($M_2$, $M_0$), are otherwise than in the case of direct decays. The lower part of Figure 5 gives the DELPHI exclusion region for $\tilde{\mu}$ and $\tilde{\tau}$ decaying indirectly via $\lambda_{133}$ or $\lambda_{122}$. It can be noticed that no unexcluded “corridor” is present near $\Delta M = M_f - M_\chi \sim 0$ as in the equivalent plot for the $R_p$ conserving case. This is a general feature of $K_p$ searches due to the fact that $\chi$ is visible. However, it should be noted that the efficiency is generally lower for small $\Delta M$. Therefore for cross section limited channels the corridor still appear.
Sneutrinos

Direct decays mediated by LLE give the four charged lepton signature selected with high efficiency; the worst case are $\tilde{\nu}_\mu$’s decaying via $\lambda_{233}$ into $\tau\tau$, for which ALEPH gets a lower mass limit of 66 GeV/c². LQD direct decays give the four jet signature whose non evidence translates in a lower mass limit of 61 GeV/c², as shown in Figure 6. Indirect decays lead in this case to less exotic signatures and therefore to worse absolute mass limits. For UDD, improvements on the $Z$-lineshape LEP 1 limit are obtained either for $\tilde{\nu}_e$ in the gaugino region, where constructive $t$-channel interference enhances the cross section, or considering the three sneutrinos mass degenerate.

Squarks

Direct squark decays via UDD lead to four jet final states. As an example, again from Figure 6, ALEPH excludes $\tilde{u}^R$’s of masses below 69 GeV/c². LQD direct decays give final states with two charged leptons and two quarks, which are selected quite efficiently. The OPAL result for $\tilde{t}_1 \to \tau^- d_1$, the most conservative case, is shown in Figure 7; for $\tilde{t}_1$ decoupling from the $Z$ the lower mass limit is 72 GeV/c². Topologies arising from indirect decays are selected with lower efficiencies, and therefore give worse absolute lower mass limits.

It should be noted that hadron colliders are in better position for squark searches, especially for LQD couplings, where the lepton tag can be used to enhance the selection efficiency. First results in this direction have been presented at this conference by D0 and CDF 11.

3.4 Summary of Pair-Production results

The picture that emerges from the study of pair production with $R_p$ shows that, in general, the situation is at least as good as in the $R_p$ conserving case. For gauginos, the $(\mu, M_2)$ analysis for gauginos leads to similar conclusions. The typical sfermion limits are summarised in Table 4; taking into account that the combination of the LEP experiments would bring more or less the same gain as in the $R_p$ conserving case, i.e. 5-10 GeV, the sensitivity reached allowing for $R_p$ is very similar to the one obtained forbidding it.

4 Other Signatures

Dominant $R_p$ couplings whose structure involves the first lepton family can manifest themselves in $e^+e^-$ collisions in alternative ways.

For example, the $e^+ e^- \to e^+ e^-$ cross section is expected to receive a contribution from $s$-channel exchange of $t_j$ if $\lambda_{1j1} \neq 0$; and $t$-channel contributions to the
Figure 8: 95% C.L. cross section upper limits for single resonant sneutrino production via $\lambda_{1j1}$ coupling in ALEPH. The rescaling factor $\sigma_{\text{th}}/\sigma^*$ was calculated explicitly and naturally leads to dips at each centre-of-mass energy except 183 GeV.

5 Conclusions

The LEP collaborations have submitted at this conference the results of several searches for supersymmetry allowing for some degree of $R_p$ violation. Overall, these searches cover, with good efficiency and purity, most of the signatures expected in these scenarios. The resulting sensitivity is, in general, as good as in the $R_p$ conserving case, making the negative results of searches for supersymmetry at LEP not invalidated by $R_p$.

Acknowledgements

I would like to thank the contact persons of the LEP collaborations for their prompt help, in particular I.Fleck and S.Braibant (OPAL), and C.Berat (DELPHI). I am also indebted with my ALEPH colleagues for providing material and helpful comments during the preparation of the talk, in particular to J.Coles, P.Coyle, D.Fouchez and M.Williams. Finally I would like to thank V.Bücher for careful proof-reading of the manuscript.

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