SEARCHES FOR GAUGE MEDIATED SUSY BREAKING AT LEP

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Searches for neutralinos and sleptons with arbitrary lifetimes, as predicted in the framework of the Gauge Mediated Supersymmetry Breaking (GMSB) model, have been performed by the four LEP collaborations. No evidence for these particles has been found in the data recorded at center–of–mass energies up to $\sqrt{s} = 209$ GeV. Therefore constraints on the production cross–sections and particle masses as well as interpretations in the framework of the GMSB model are presented.

1 Introduction

In supersymmetry (SUSY) for every Standard Model (SM) particle a supersymmetric “partner”, differing in spin by half a unit, is predicted. If SUSY were an exact symmetry, the supersymmetric particles would be degenerate in mass with their Standard Model partners. However, since no SUSY particles have been observed so far, it can be deduced that the SUSY partners must be much heavier than (most of) the Standard Model particles, and therefore SUSY must be a broken symmetry. Several mechanisms for SUSY breaking have been considered. One approach is that SUSY is broken in a “hidden” sector, which couples to the visible sector containing the SM and SUSY particles via gravitational interactions (gravity mediation). Another possibility is that the hidden sector couples only to a “messenger sector”, which in turn couples via the gauge interactions to the visible sector of the SM and SUSY particles. This model is called the Gauge Mediated Supersymmetry Breaking (GMSB) model. In its minimal version six new parameters are introduced in addition to the SM parameters, usually chosen to be the SUSY breaking scale, $\sqrt{F}$, the messenger scale, $M$, the messenger index, $N$, the ratio of the vacuum expectation values of the two Higgs doublets, $\tan \beta$, the sign of the Higgs sector mixing parameter, sign($\mu$), and the mass scale $\Lambda$, which determines the SUSY particle masses at the messenger scale.

In supersymmetric theories the phenomenology depends crucially on the nature of the lightest and next–to–lightest supersymmetric particles, the LSP and the NLSP. The mass of the gravitino $\tilde{G}$, the SUSY partner of the graviton, is determined by the SUSY breaking scale $\sqrt{F}$. In GMSB models the SUSY breaking scale is typically low ($\mathcal{O}(100 \text{ TeV})$), which leads to a light gravitino and makes the gravitino the LSP. Depending on the choice of the other model parameters, the NLSP can either be the lightest neutralino, $\tilde{\chi}^0_1$, which is a mixture of the SUSY partners of the $\gamma$, $Z^0$ and the neutral Higgs bosons, or the lightest SUSY partner of the leptons, a slepton $\tilde{\ell}_R$. In the latter case two scenarios are distinguished: the stau NLSP scenario, in which the lighter stau, $\tilde{\tau}_1$, is lighter than the other sleptons and is the sole NLSP, and the slepton co–NLSP scenario, in which all sleptons are degenerate in mass and act as “co–NLSPs”.

In GMSB models the proper decay length $L$ of the NLSP depends on $\sqrt{F}$:

$$L = \frac{0.01}{\kappa \gamma} \left( \frac{100 \text{ GeV}}{m} \right)^5 \left( \frac{\sqrt{F}}{100 \text{ TeV}} \right)^4 \text{ cm},$$

where $m$ is the mass of the NLSP and $\kappa \gamma$ is the photino component of the neutralino and is equal to one for sleptons. Taking into account the range allowed for $\sqrt{F}$, the NLSP decay length is basically arbitrary and all possible decay lengths between zero and infinity have to be considered.

In the following, R-parity conservation is assumed, implying that SUSY particles are produced only in pairs and that all decay chains terminate with SM particles plus the LSP, which is stable.

The four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, have searched for a great variety of topologies expected from GMSB models. Here a selection of these results, based mainly on the data recorded from 1998–2000 at center-of-mass energies between 189 GeV and 209 GeV, is presented, including the results of a preliminary LEP combination. All presented limits are at 95% confidence level (C.L.).

## 2 The Neutralino as the NLSP

The neutralino can be produced directly in pairs, $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^0$, via the s-channel with $\gamma/Z^0$ exchange, or the t-channel with an exchange of a selectron. Indirect production is also possible, e.g. via pair-production of sleptons, $e^+e^- \rightarrow \tilde{\ell}_R^+\tilde{\ell}_R^- \rightarrow \ell^+\tilde{\chi}_1^- \ell^-\tilde{\chi}_1^0$, or pair-production of charginos, $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^+\tilde{\chi}_1^0 W^-\tilde{\chi}_1^0$. If the neutralino is the NLSP, it decays to a photon and a gravitino, which escapes detection. Therefore the event topology implies photons plus missing energy, possibly with additional detector activity from leptons or jets, depending on the production channel.

### 2.1 Searches for Neutralino Pair-Production

If neutralinos are produced in pairs and decay promptly, two high-momentum acoplanar photons are expected in the detector. The dominating Standard Model background for this topology is neutrino pair-production with two photons from initial state radiation. All four LEP collaborations have searched for this topology, but no excesses were found.

The upper limit on the production cross-section from DELPHI, at 95% C.L. and for $\sqrt{s} = 208$ GeV, is shown on the left side of Figure [1]. Typically, cross-sections above 0.04 pb are excluded. The theoretical cross-section depends on the mass of the exchanged selectron. For $M(\tilde{e}) = 2 \cdot M(\tilde{\chi}_1^0)$ a lower neutralino mass limit of 96 GeV is found at 95% C.L., while for $M(\tilde{e}) = 1.1 \cdot M(\tilde{\chi}_1^0)$ the limit increases to 100 GeV. For the determination of these limits, the right- and left-handed selectrons are assumed to be mass-degenerate and the neutralino is assumed to be pure bino.

On the right side of Figure [1], the excluded region in the selectron–neutralino mass plane from the L3 collaboration is shown for a pure bino neutralino. The region consistent with the GMSB interpretation of the $ee\gamma E_T$ event observed by CDF ($\tilde{e}^+\tilde{e}^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- e^+e^- \rightarrow \gamma\gamma\tilde{G}\tilde{G}e^+e^-$) is completely excluded at 95% C.L.

If the lightest neutralino has a lifetime such that it does not decay promptly but before reaching the electromagnetic calorimeter, the experimental topology is photons that do not point to the primary event vertex. Both ALEPH and DELPHI have searched for such non-pointing photons, requiring at least one photon with a reconstructed impact parameter larger than 40 cm. ALEPH selects two candidates in the data set recorded at $\sqrt{s} = 189–209$ GeV, with 1.0 events expected from Standard Model sources, while DELPHI, using the data collected at $\sqrt{s} = 130–209$ GeV, selects 16 candidates with 14.6 events expected. DELPHI reports 95%
C.L. cross–section limits of the order of 0.4 pb for mean neutralino decay lengths of approximately 2–20 m, taking into account the data collected at \( \sqrt{s} = 192 – 209 \) GeV.

2.2 Searches for Indirect Neutralino Production

If the neutralino is stable or both neutralinos decay outside the detector, direct neutralino pair-production is invisible. The indirect production channels, however, can be used to search for very long–lived neutralinos. Utilising the searches for slepton and chargino pair–production in gravity mediated models, where the neutralino is the NLSP, the ALEPH collaboration reports a lower neutralino mass limit of 54 GeV at 95 % C.L., independent of the neutralino lifetime.

3 The Slepton as the NLSP

If the slepton is the NLSP, it decays to a lepton of the same flavour and a gravitino, leading to final states with leptons and missing energy. Again, different production channels are possible. The most important one is direct slepton pair–production, \( e^+ e^- \rightarrow \tilde{\ell}^+_R \tilde{\ell}^-_R \), which proceeds via the \( s–\)channel and, for sleptons only, also the \( t–\)channel with neutralino exchange. Indirect production is possible at LEP2 via pair–production of neutralinos, \( e^+ e^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow \tilde{\ell}^+_R \ell^-_R \tilde{\ell}^+_R \tilde{\ell}^-_R \tilde{\tau}^+ \tilde{\tau}^- \), and charginos, \( e^+ e^- \rightarrow \tilde{\chi}^+_1 \tilde{\chi}^-_1 \rightarrow \tilde{\ell}^+_R \nu \tilde{\ell}^-_R \bar{\nu} \). Finally, if only the stau is the NLSP, it can be produced indirectly via pair–production of selectrons or smuons: \( e^+ e^- \rightarrow \tilde{\ell}^+_R \ell^-_R \rightarrow \ell^+ \tilde{\tau}^+_1 \ell^- \tilde{\tau}^-_1 \), with \( \tilde{\ell}_R = \tilde{\ell}_R, \tilde{\mu}_R \). Results will be reported only on the first three channels.

3.1 Searches for Slepton Pair–Production

If sleptons are pair–produced and decay promptly, the experimental topology is two high–energetic acoplanar lepton tracks. The same topology is expected in gravity mediated models, where the slepton decays to a lepton and a stable neutralino, if the neutralino is assumed to be very light. Thus the searches for slepton pair–production in the context of the minimal Supergravity model are used. All four LEP collaborations have searched for acoplanar lepton events, but no significant excesses were observed. The LEP–combined upper cross–section limits
at 95% C.L., including the data with $\sqrt{s} = 183 - 209$ GeV, are below 0.05 pb for smuons and below 0.18 pb for staus.

If the sleptons have intermediate lifetimes and decay either before or inside the tracking devices, the topologies of tracks with large impact parameters and tracks with kinks are expected. All four LEP collaborations have searched for these interesting topologies, but observe no excess over the background expectation.

Finally, if the sleptons are stable or both sleptons decay outside the tracking devices, they will distinguish themselves from Standard Model particles by their anomalously high or low specific energy loss, $dE/dx$, due to their large mass. All LEP collaborations have performed searches for this almost background–free topology. No hint for the production of such long–lived sleptons was found.

Combining the searches for sleptons of all lifetimes, cross–section and mass limits in the slepton mass – lifetime plane are obtained. A preliminary LEP combination, including the results of ALEPH, DELPHI and OPAL at center–of–mass energies of $\sqrt{s} = 189 - 209$ GeV, was performed. The resulting cross–section limits at $\sqrt{s} = 206$ GeV, as a function of the lifetime, are shown in Figure 2 for smuons (left) and staus (right). Cross–sections above 0.07 pb, 0.04 pb and 0.09 pb are excluded for selectrons, smuons and staus, respectively. Figure 3 shows the lower limits on the slepton masses, as a function of the slepton lifetime, for smuons (left) and staus (right). The lowest limit is found for small lifetimes, due to irreducible background from leptonic W decays to the acoplanar lepton topology. For $N \leq 5$, slepton mass limits of $M(\tilde{e}_R) > 66.0$ GeV, $M(\tilde{\mu}_R) > 95.2$ GeV and $M(\tilde{\tau}_1) > 86.1$ GeV were obtained, independent on the slepton lifetime. For these limits, the theoretical cross–sections were taken from a scan based on the framework of.

3.2 Searches for Neutralino Pair–Production

If the slepton is the NLSP and is produced via pair–production of neutralinos, the topology is four leptons, of which two might originate from the decays of long–lived sleptons, plus missing energy. ALEPH, DELPHI and OPAL have searched for neutralino pair–production with

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*The L3 collaboration presents results on slepton pair–production only for a subset of the available data ($\sqrt{s} = 200$ GeV).*
promptly decaying sleptons, and ALEPH and OPAL consider in addition the case that the tracks of two of the decay leptons might have large impact parameters or kinks. All three collaborations report good agreement between the number of candidates and the number of events expected from SM sources. By combining this channel with the acoplanar lepton and acoplanar photon searches, ALEPH obtains a lower mass limit for the neutralino of 92 GeV for the case of zero NLSP lifetime.

3.3 Searches for Chargino Pair–Production

DELPHI has searched for chargino pair–production with a slepton NLSP\textsuperscript{10}, taking into account all slepton lifetimes. Since no evidence for the production of charginos has been observed, DELPHI sets chargino mass limits of 100 GeV and 96 GeV at 95 % C.L. in the stau NLSP scenario and the slepton–co NLSP scenario, respectively, independent of the slepton lifetime.

4 Model–Dependent Interpretations

To interpret the experimental results in the framework of the GMSB model, the ALEPH, DELPHI and OPAL collaborations each perform a scan over the GMSB parameters, and exclude points in this GMSB parameter space. On the left side of Figure 3, the regions in the $\Lambda – \tan \beta$ plane excluded by ALEPH\textsuperscript{5} are shown for different values of $N$ and for all NLSP lifetimes. A limit on the parameter $\Lambda$, which determines the SUSY particles masses at the messenger scale, of $\Lambda > 10$ TeV has been found for $N \leq 5$. When the ALEPH results on neutral Higgs boson searches\textsuperscript{14} are taken into account, larger regions in the parameter space can be excluded, as shown in the plot on the right side of Figure 3, and the lower limit on $\Lambda$ increases to 16 TeV for $N \leq 5$. Using the condition $\Lambda \leq \sqrt{F}$ and the relation between the gravitino mass and $\sqrt{F}$, these limits can be translated into lower limits on the gravitino mass of $M(\tilde{G}) > 0.024$ eV and $M(\tilde{G}) > 0.061$ eV, respectively. The DELPHI collaboration reports a limit of $\Lambda > 17.5$ TeV for $N \leq 4$ and the case of a negligible NLSP lifetime\textsuperscript{14}.

5 Conclusions

The four LEP collaborations have performed searches for neutralinos and sleptons with arbitrary lifetimes, as predicted in the framework of the GMSB model. Since no evidence for the produc-
tion of such particles has been observed, cross-section and mass limits have been obtained using the data recorded at center-of-mass energies up to 209 GeV, and the experimental results were used to constrain the GMSB parameter space.

References

1. H.P. Nilles, *Phys. Rept.* **110**, 1984 (1).
2. G.F. Giudice and R. Rattazzi, *Phys. Rept.* **322**, 1999 (419).
3. S. Ambrosanio, G.D. Kribs and S.P. Martin, *Phys. Rev. D* **56**, 1997 (1761).
4. S. Dimopoulos, S. Thomas and J.D. Wells, *Nucl. Phys. B* **488**, 1997 (39).
5. ALEPH Collaboration, “Search for Gauge Mediated SUSY Breaking Topologies in $e^+e^-$ Collisions at Center–of–Mass Energies up to 209 GeV”, hep-ex/0203024, March 2002.
6. DELPHI Collaboration, E. Anashkin et al., “Update at 202–209 GeV of the analysis of photon events with missing energy”, DELPHI 2002–08 CONF 549, March 2002.
7. L3 Collaboration, “Search for Supersymmetry in $e^+e^-$ Collisions at $\sqrt{s} = 202 – 208$ GeV”, L3 Note 2731, March 2002.
8. OPAL Collaboration, “New Particle Searches in $e^+e^-$ Collisions at $\sqrt{s} = 200 – 209$ GeV”, OPAL Physics Note PN470, May 2001.
9. CDF Collaboration, F. Abe et al., *Phys. Rev. D* **59**, 092002 (1999).
10. DELPHI Collaboration, T. Alderweireld et al., “Update of the Search for Supersymmetric Particles in Light Gravitino Scenarios”, DELPHI 2002–011 CONF 552, March 2002.
11. LEP SUSY Working Group, ALEPH, DELPHI, L3 and OPAL experiments, LEPSUSYWG/01–01.1 (2001).
12. OPAL Collaboration, “Searches for Intermediate Lifetime Signatures in GMSB Models with a Slepton NLSP in $e^+e^-$ Collisions at $\sqrt{s} = 189 – 209$ GeV”, OPAL Physics Note PN478, July 2001.
13. LEP SUSY Working Group, ALEPH, DELPHI, L3 and OPAL experiments, LEPSUSYWG/02–09.1 (2002).
14. ALEPH Collaboration, A. Heister et al., *Phys. Lett. B* **526**, 2002 (191).