Searches for GMSB and AMSB at LEP

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We describe the latest results in the search for Gauge Mediated Supersymmetry Breaking (GMSB) and Anomaly Mediated Supersymmetry Breaking (AMSB) topologies at the LEP collider. The four collaborations, ALEPH, DELPHI, L3 and OPAL, have analysed data up to the highest centre–of–mass energy in search of many different signatures characteristic of these models. No significant excess has been observed with respect to the Standard Model predictions on any of them. Some of the searches are combined between the collaborations and limits are extracted on masses, cross sections and parameters in the models.

1. Introduction

Supersymmetry (SUSY) must be a broken symmetry since there is no evidence for supersymmetric particles with masses equal to their Standard Model (SM) partners. Although the mechanism of Supersymmetry breaking is unknown, it is generally assumed that it occurs spontaneously at some very high energy scale and is then transmitted down to the MSSM (Minimal Supersymmetric extension of the Standard Model) at $\mathcal{O}(1\text{ TeV})$ by gravitational interactions. This is normally referred to as Super Gravity (SUGRA) [1]. Including gravity in the mediation of Supersymmetry breaking and thus make it responsible for the electroweak scale is very attractive theoretically and has been the 'standard' phenomenological approach for a long time, but it brings along the unwanted flavour changing neutral currents (FCNC) [2], which are highly constrained by studies of $\mu \rightarrow e\gamma$ or $\bar{K}^0 - K^0$ mass differences. Of course, these effects could be avoided in certain scenarios where approximate universality or approximate alignment between particles and sparticles is guaranteed, but a more natural solution would be that Supersymmetry breaking occurs at some much lower energy scale (as low as 10–100 TeV, as opposed to $M_{\rm Planck}$) [3].

When Supersymmetry breaking occurs at a relatively low energy scale and it is mediated through gauge interactions (flavour blind) one solves all these problems and, furthermore, has a more predictive model with very distinctive phenomenological features [4]. Such models are termed Gauge Mediated Supersymmetry Breaking (GMSB) scenarios and this note describes searches carried out for them at the LEP collider. The first, most important distinguishing property of these models is that the gravitino ($\tilde{\rm G}$), the massive partner of the graviton, is very light. The gravitino mass is given by:

$$m_{\tilde{\rm G}} = \frac{(\sqrt{\rm F}\ )^2}{\sqrt{3}\ M_{Planck}} = 2.4 \left(\frac{\sqrt{F}}{100\ TeV}\right)^2 eV$$

where $\sqrt{\rm F}$ is the energy scale at which SUSY is communicated to the messenger particles and $M_{\rm Planck} = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV. Messenger particles are very heavy pairs of quarks and leptons, its number (N) and their common mass (M) are parameters of the theory. The $\tilde{\rm G}$ is quite heavy in SUGRA and does not play a role in phenomenology, but in GMSB models, because $\sqrt{\rm F} \ll M_{\rm Planck}$, the gravitino is in fact the lightest SUSY particle (LSP). If R parity is conserved, which will be assumed from now on, all of the MSSM particles will decay into states with a gravitino. Thus, the nature of the NLSP (next–to–LSP) becomes crucial in the final state topologies of GMSB models. The NLSP can be either the lightest neutralino $\tilde{\chi}_1^0$, decaying into $\gamma\tilde{\rm G}$, or the lightest stau $\tilde{\tau}_1$, decaying into $\tau\tilde{\rm G}$. The

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$\tilde{\tau}_1$, mass eigenstate of the electroweak $\tilde{\tau}_L$ and $\tilde{\tau}_R$, is in general lighter than the right–sleptons ($\tilde{\ell}_R$, with $\ell = e, \mu$), although there are models for which the three $\tilde{\ell}_R$ act as a co–NLSP. Another fundamental property of the GMSB models and their topologies comes from dependence of the NLSP decay–length on the gravitino mass:

$$c\tau_{NLSP} \approx \frac{0.01}{\kappa_\gamma} \left(\frac{100\ GeV}{m_{NLSP}}\right)^5 \left(\frac{m_{\tilde{G}}}{2.4\ eV}\right)^2 \text{ cm}$$

where κ_γ is the bino component of the χ and $\kappa_\gamma = 1$ for $\tilde{\tau}_1$ NLSP. The allowed range for the gravitino mass is determined by cosmology from above ($m_{\tilde{G}} \lesssim 1$ keV/c^2) [5] and accelerator experiments from below ($m_{\tilde{G}} \gtrsim 10^{-2}$ eV/c^2) [6], hence the NLSP decay–length could be as short as a few microns or as long as a few km. Both the NLSP nature and its lifetime will produce a breadth of topologies to study.

Another, third, possibility also studied at LEP is Anomaly Mediated Supersymmetry Breaking (AMSB) [7], where the transmission of the breaking is done via anomalies in the gravitational lagrangian. The phenomenological consequences of this model will be reviewed in Section 6.

This note reviews the preliminary results from all four collaborations and their combination when available with the latest data from year 2000, including centre–of–mass energies of up to 209 GeV.

2. GMSB topologies with $\tilde{\chi}^0_1$ NLSP

The neutralino is predominantly the NLSP for low values of $\tan\beta$ or when there is only one pair (N=1) of particles mediating the Supersymmetry breaking, or the messenger masses are very high ($M > 10^9$ GeV/c^2). In this scenario, the neutralino decays into a photon and a gravitino and the final topology depends on whether the neutralino has had time to decay in the detector or outside.

2.1. Short $\tilde{\chi}^0_1$ lifetime

For a short–lived neutralino, decaying immediately after its pair–production at LEP (i.e. for a light gravitino) the final topology consists of two acoplanar photons and missing energy. The main SM background comes from neutrino production via W–exchange with photon radiation $e^+e^- \to \nu\bar{\nu}\gamma\gamma$. Different Monte Carlo generators are used by the collaborations to simulate this process (KoralZ, NUNUGPV and KK [8]) and good agreement between data and MC is found on all of them. The invariant mass distribution of the system recoiling against the photon candidates is used as a discriminant variable. Figure 1 shows the combined data from all the LEP experiments and the background expectation [8]. It presents a peak from $Z\gamma\gamma$ production and a tail from W–exchange. Since the signal distribution appears in the lower values of the recoil mass, a cut on this variable eliminates significantly the background. A total of 384 events are observed and 388.7 are expected. As there is no excess

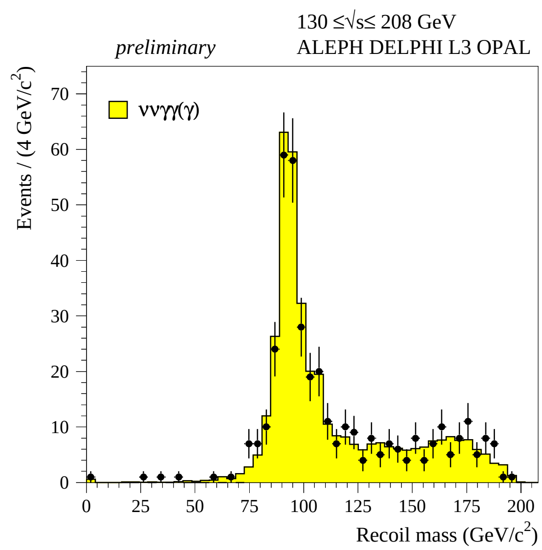

Figure 1. Recoil mass against the photon system in the two acoplanar photon state. The distribution shows good agreement between data (dots) and background expectation.

seen in the data, limits on the neutralino mass are set at 99 GeV/c^2 with 95% confidence level for neutralino lifetimes smaller than 3 ns, assuming $m_{\tilde{e}_R} = 1.1 m_\chi$ [9,10].

2.2. Medium $\tilde{\chi}_1^0$ lifetime

If the neutralino is medium–lived, it would show in a very distinctive topology: a non–pointing photon, where one of the neutralinos has decayed in the tracking devices and the other escapes the detector. In this case the electromagnetic calorimeter resolution is very important in the reconstruction of the shower axis, and hence the displaced vertex determination. To remove events from the process $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$, the impact parameter of the photon is required to be larger than 40 cm. The same MC generators are used to model this background and no significant difference is seen in the combined event counting: 7364 observed versus 7502. Figure 2 shows the distribution of the recoil mass against the photon in this topology [8].

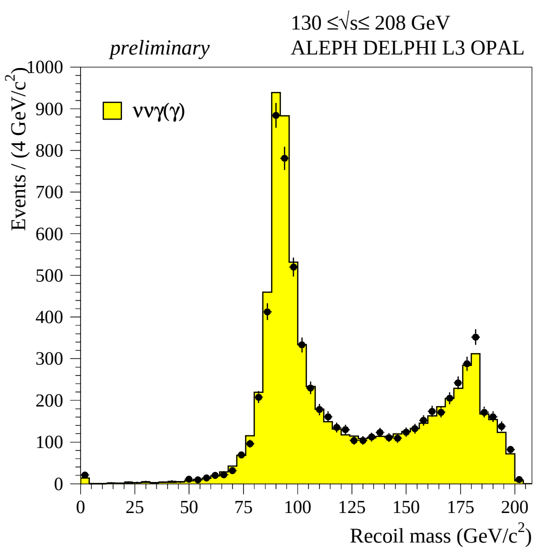

Figure 2. Invariant mass of the system recoiling against the photon in the non–pointing photon search.

2.3. Long $\tilde{\chi}_1^0$ lifetime

For neutralinos with decay–lengths greater than the detector size, indirect searches have to be used to obtain a limit on the neutralino mass. The existing SUGRA searches for charginos and sleptons, in which the neutralino is the LSP, already cover this scenario. See [11] for a description.

3. GMSB topologies with $\tilde{\ell}$ NLSP

In GMSB models the mixing between weak eigenstates is expected to be small since they predict that $|A| \ll |\mu|$. Nevertheless, some mixing in the stau sector is expected if $|\mu|$ and/or $\tan\beta$ are large. If the mixing is small the lightest stau $\tilde{\tau}_1$ will predominantly be $\tilde{\tau}_R$ because $m^2_{\tilde{\tau}_L} > m^2_{\tilde{\tau}_R}$. In this case, all three right–handed sleptons are almost degenerate in mass and can be the NLSP. For moderate or large values of $\tan\beta$, decreasing messenger mass and increasing number of messenger pairs, the mixing in the stau sector will become more important rendering the $\tilde{\tau}_1$ as the only NLSP. Whether the three $\tilde{\ell}_R$ act as co–NLSP or the $\tilde{\tau}_1$ is the NLSP, their decays would proceed via their SM partner and a gravitino. Other possibilities exist of mixed mass hierarchies between the χ, $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_1$, which are not discussed here.

3.1. Short $\tilde{\ell}$ lifetime

If the $\tilde{\ell}$ has a small decay–length [9,12,13], of the order of a few mm, the final state topology will be a pair of acoplanar leptons and missing energy. This process is fully equivalent to the SUGRA case in which a slepton is produced and decays promptly into its SM lepton and a neutralino. Of course, since the gravitino is at least six orders of magnitude lighter than the neutralino, the SUGRA analysis used is restricted to the case of an almost massless neutralino. The existing limits at 95% C.L. on the slepton masses derived from the combination [8] for $m_\chi = 0$ are: $m_{\tilde{e}} > 100.5, m_{\tilde{\mu}} > 95.4$ and $m_{\tilde{\tau}} > 80.0$ GeV/c^2.

3.2. Medium $\tilde{\ell}$ lifetime

When the slepton is allowed to have a lifetime and decays inside the detector [9,12,14] two interesting signatures may appear: *large impact pa-*

rameter tracks, when the decay–length is between 1 and around 40 cm and the pair produced sleptons decay before leaving any trace in the tracking chamber; and *kinked tracks*, for decay–lengths between 10 and 200 cm when the sleptons enter the tracking chamber and decay into two leptons and gravitinos. The major backgrounds of these signals come from cosmics, $\gamma\gamma$ events and hadronic interactions, mainly the decays of K^0_s and $K^\pm$ or $\pi^\pm$.

3.3. Long $\tilde{\ell}$ lifetime

Long–lived sleptons would leave a very distinctive signal in the detectors: two highly ionising back–to–back tracks. Because they are charged and slow they normally saturate the drift chamber's electronics and do not leave any signal on the calorimeters. This distinctive signal has very low SM background and is able to exclude heavy sleptons up to $m_{\tilde{\tau}_R} > 97$ GeV/c^2 at 95% C.L.

3.4. Neutralino production with $\tilde{\ell}$ NLSP

In the $\tilde{\ell}$ NLSP scenario, if the neutralino–pair production is kinematically accessible, the following cascade decay could happen: $\chi \to \ell\tilde{\ell} \to \ell\ell\tilde{\mathrm{G}}$. This process benefits from the larger cross section of neutralinos as opposed to direct slepton production. The topology is then two soft leptons, coming from the first decay, and two harder leptons, those from $\tilde{\ell} \to \ell\tilde{\mathrm{G}}$. This topology has been sought (by ADO) in the case of zero slepton lifetime and (by AO) for medium slepton lifetime. Again, the lack of evidence of excesses above the expectations allows cross section limits to be set on neutralino pair–production as a function of the slepton mass and lifetime.

4. GMSB interpretation

Model dependent interpretations can be made by scanning over the six parameters in a minimal GMSB theory ($\sqrt{\mathrm{F}}$, Λ, N, M, $sign(\mu)$ and $\tan\beta$). These parameters determine uniquely the mass spectrum and the properties of all particles. By combining the direct searches for $\tilde{\ell}$ NLSP and χ NLSP with LEP1 limits and SUGRA searches when applicable, one can restrict a number of models and infer almost–general limits on various parameters, such as Λ, which controls the mass scale of SUSY particles, and the gravitino mass. Figure 4, by ALEPH, shows how the different searches described in the text interplay to exclude different regions in the $(m_{\tilde{\tau}}, m_\chi)$ plane for small gravitino masses ($m_{\tilde{\mathrm{G}}}$ ≤10 eV/c^2). From this scan ALEPH has derived a lower limit of 10.6 TeV/c^2 on Λ for N≤5 which can be translated into a lower bound on the gravitino mass of 0.027 eV/c^2 [6].

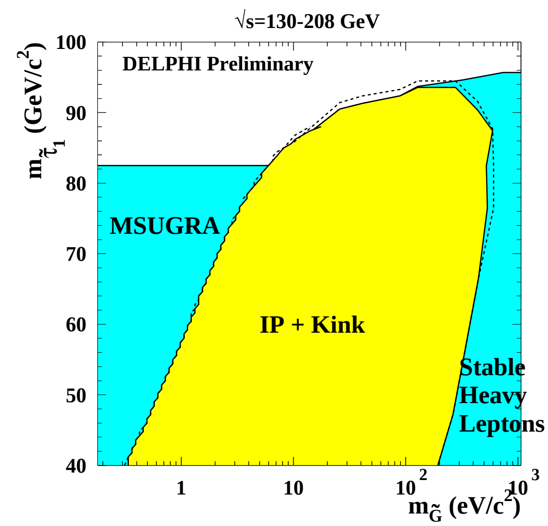

Figure 3. 95% confidence level limits on the lightest stau mass as a function of the gravitino mass for the different searches according to the stau lifetime. The dashed line shows the expected limits for the impact parameter and kink searches. From the DELPHI collaboration [12]. A lifetime independent limit on the lightest stau mass can be set at around 80 GeV/c^2.

5. Sgoldstinos

DELPHI has performed a search for sgoldstinos, the heavy partners of the goldstino [12]. The goldstino is the Nambu–Goldstone particle resulting from the breaking of Supersymmetry (which is a fermionic symmetry). So sgoldstinos are bosons, with even R–parity, which can then be

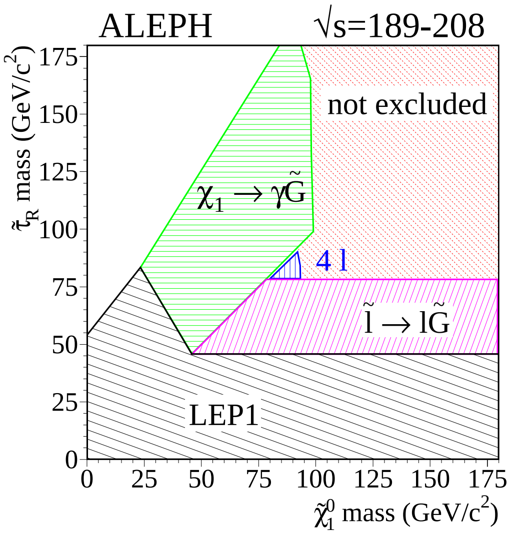

Figure 4. Exclusions at 95% C.L. on the stau–neutralino mass plane by the ALEPH collaboration for short lifetimes ($m_{\tilde{G}} \leq 10$ eV/c^2). The search for two acoplanar photons, in the χ NLSP case, acoplanar sleptons and cascade (4ℓ), in the $\tilde{\ell}$ NLSP case, are all shown to exclude significant areas.

produced along with a monochromatic photon. They would decay into pairs of photons or gluons, depending on the models (for different values of the gaugino masses), and hence searches for final states with three photons and two jets plus a photon have been performed but have not yielded any discovery.

6. Anomaly Mediated Supersymmetry Breaking

If anomalies are responsible for SUSY breaking mediation down to the visible sector, there would be no need for an intermediate 'messenger' sector with its additional particles, and FCNC effects would be naturally suppressed. This type of models is also very predictive, only four parameters are needed: the gravitino mass, the common scalar mass m_0, $\tan\beta$ and $sign(\mu)$. In AMSB, the chargino is expected to be almost degenerate in mass with the neutralino: $M_2 \lesssim M_1 \ll |\mu|$. So that $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_1^0} \sim M_2$ and they are mostly gaugino–like. As in SUGRA, the gravitino would be very heavy (a few TeV/c^2) and is no longer the LSP as it is in GMSB. Given the small difference in mass between the chargino and the neutralino, the pair production of charginos near threshold would give a very soft system and two neutralinos which are stable and escape undetected. This is a very difficult topology to trigger on and suffers a huge background from $\gamma\gamma$ events. The procedure is therefore to require an energetic ISR photon with large transverse energy, which, if coming from a $\gamma\gamma$ process would necessarily include a low–angle beam electron. By rejecting any low–angle electrons and selecting energetic transverse ISR photons, we are then able to suppress the $\gamma\gamma$ background and tag the event as signal. All four

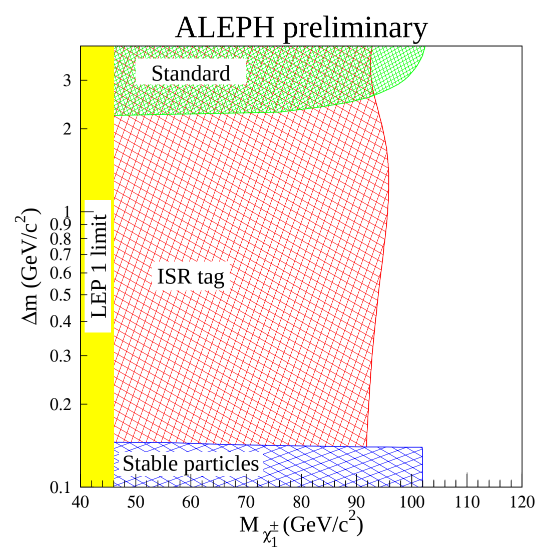

Figure 5. The AMSB topology covers an intermediate case in $\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ by using an ISR photon to tag the event. This plot shows the results from ALEPH for gaugino–like neutralinos and charginos for $\sqrt{s} = 189 - 209$ GeV.

experiments have looked for this signal and their results are summarised on Table 1 [15].

	A	D	L	O
$m_{\tilde{\chi}_1^\pm}$ (GeV/c^2)	91	74	87.6	91

Table 1
Lower 95% C.L. limit on the chargino mass in the gaugino region for heavy sneutrinos (high m_0).

7. Conclusions

No evidence for the production of supersymmetric particles has been observed at LEP2 under the assumption of Gauge or Anomaly Mediated Supersymmetry Breaking models. These models offer distinctive signatures that have been extensively studied by the four LEP collaborations with data up to $\sqrt{s} \sim 209$ GeV. Given the absence of signal, limits are placed on the production cross sections and new particle masses.

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