

Searches for gauge mediated SUSY breaking at LEP

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Abstract

The four LEP collaborations have performed searches for supersymmetric particles in light gravitino scenarios, when neutralinos and sleptons are produced and may present measurable decay lengths. The highest energy data has been analysed including centre-of-mass energies up to 209 GeV. No evidence for such particles is found, but preliminary limits from the combination allow to exclude at 95% confidence level neutralino masses up to $97 \text{ GeV}/c^2$ if neutralinos decay promptly and stau masses up to $86.9 \text{ GeV}/c^2$ for all stau lifetimes. The interpretation of these results in general models is studied to set limits on the parameters of the theory.

1 Introduction

The fact that supersymmetry (SUSY) is a broken symmetry makes searches for the predicted super-partners very rich phenomenologically. If SUSY is broken spontaneously at some very high energy scale, several models exist that predict how this breaking is communicated to the MSSM particles. If gravitational interactions are responsible for the MSSM spectrum, the neutralino is most probably the lightest supersymmetric particle (LSP) and these models are usually referred to as SUGRA [1]. Another possibility is that some new very heavy particles, called messengers, couple radiatively to the MSSM particles via gauge interactions. This model is the subject of the present note and is called gauge mediated supersymmetry breaking or GMSB [2]. The main difference between gravity and gauge mediated SUSY breaking models arises from the higher energy scale of SUSY breaking in the former. This will 1) introduce possible flavour changing neutral currents (FCNC), severely constrained at the electroweak scale; and 2) make the gravitino, the massive spin- $\frac{3}{2}$ partner of the graviton consequence of the super-Higgs mechanism, as heavy as the rest of SUSY particles with a mass of at least some $\mathcal{O}(100) \text{ GeV}/c^2$. In gravity mediated SUSY breaking models the MSSM masses are linked directly with the Planck mass $M_{\text{P}} \sim 10^{19} \text{ GeV}/c^2$, where gravity is assumed to become strong. Alternatively, if a new messenger sector is introduced like in GMSB models with common mass M_{m} as low as $10^4 \text{ GeV}/c^2$ and clearly much lower than M_{P} , then:

1. FCNC effects are naturally suppressed because the SM Yukawa couplings are already present when MSSM mass generation takes place and gauge interactions are flavour blind. Thus squark and slepton mass differences are very small.

2. The gravitino becomes very light: $m_{\tilde{G}} \lesssim \mathcal{O}(1) \text{ keV}/c^2$ [3], and is the LSP. But it will not only couple with gravitational strength to other SUSY particles. Its longitudinal components allow it to interact with the next-to-lightest supersymmetric particle (NLSP) via the SM gauge couplings.

Six new parameters, in addition to those of the SM, are needed to completely specify the MSSM spectrum and phenomenology of minimal GMSB models. These are: \sqrt{F} , the energy scale of SUSY breaking in the hidden sector; M_m , the common mass of the messenger particles; N_5 , the number of SU(5) families of messenger supermultiplets; Λ , the mass scale parameter responsible for the MSSM masses at M_m ; $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets; and $\text{sign}(\mu)$, where μ is the Higgs mixing-mass parameter.

GMSB signatures at colliders crucially depend on the nature of the NLSP. In general, for $N_5 = 1$ the neutralino is the NLSP and decays to $\gamma\tilde{G}$, while for $N_5 \geq 2$ the lightest stau is predominantly the NLSP and decays into $\tau\tilde{G}$. In GMSB models, the selectron and smuon masses are equal and the stau may become lighter due to the possible large mixing in the third family. But depending on the scale of SUSY breaking \sqrt{F} , or equivalently on the gravitino mass $m_{\tilde{G}}$, the NLSP may be long-lived:

$$\lambda_{\text{NLSP}} = c\tau_{\text{NLSP}}\gamma\beta = \frac{0.01}{\kappa_\gamma} \left(\frac{100 \text{ GeV}/c^2}{m_{\text{NLSP}}} \right)^{-5} \left(\frac{m_{\tilde{G}}}{2.4 \text{ eV}/c^2} \right)^2 \sqrt{\frac{E^2}{m_{\text{NLSP}}^2} - 1} \text{ cm}$$

where κ_γ is the photino content of the neutralino or one for a slepton NLSP. Since the gravitino mass can range from $\sim 10^{-2}$ to $10^5 \text{ eV}/c^2$ this implies that the NLSP may decay immediately after production at LEP, somewhere inside the detector or be stable for searches purposes. There are thus many different topologies to be considered as a function of the NLSP type and its possible decay length.

This report is organised as follows: topologies arising from neutralino pair production in the neutralino NLSP scenario are described first. The results from slepton NLSP direct pair-production searches are reported next in Sec. 3. Cascade decays of neutralino to slepton NLSPs and other multilepton final states are described in Sec. 4. In each case, the different searches devised to cover all possible lifetimes of the NLSP will be detailed. Finally, the interpretation of the results and outlook will be presented in Secs. 5 and 6 respectively. All limits are given at 95% confidence level.

2 Photon(s) and \cancel{E} signatures

Signatures consisting of two energetic photons and missing energy may arise in the neutralino NLSP scenario if a pair of neutralinos are pair-produced and decay promptly into $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$. The main background source for this topology is $e^+e^- \rightarrow \nu\bar{\nu}$, from diagrams with s -channel Z exchange or t -channel W exchange and one or two initial state radiation (ISR) photons. By imposing a threshold cut on the energy of the least energetic photon the SM background can be effectively reduced. A preliminary combination of the results from the ALEPH, DELPHI and OPAL collaborations exists with data from 192

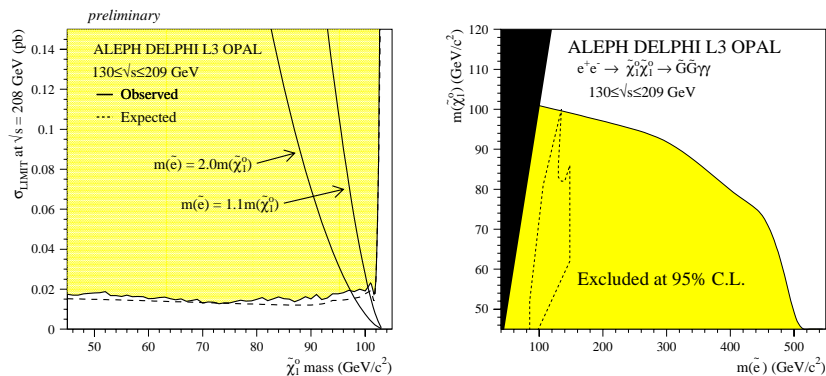


Fig. 1. Left: cross section lower limit versus neutralino mass from the combined two-photon searches. The production cross sections are calculated in two scenarios. Right: excluded area in the selectron-neutralino mass plane assuming a purely bino neutralino. The dashed overlaid area is the region consistent with the GMSB interpretation of the $e\bar{e}\gamma\gamma + \cancel{E}_T$ CDF event [9], now completely excluded.

to 208 GeV and yields no excess with respect to the SM expectation [4]. The individual results can be found in Refs. [5–8]. Figure 1 shows the interpretation of these results assuming a purely bino neutralino and mass degeneracy between \tilde{e}_L and \tilde{e}_R . Neutralino pair-production cross sections above 0.02 pb are excluded at 95% C.L. Since the cross section depends on the mass of the exchanged selectron, the lower limit on the neutralino mass can be conservatively estimated to be 97 GeV/ c^2 if $m_{\tilde{e}} = 2 \cdot m_{\tilde{\chi}_1^0}$, improving for larger $\tilde{\chi}_1^0 - \tilde{e}$ mass differences.

If the gravitino mass lies in the range between a few eV/ c^2 and a few hundred eV/ c^2 , the neutralino NLSP will decay somewhere inside the detector. The probability for only one of the pair-produced neutralinos to decay before the electromagnetic calorimeter is greater than for both of them [2], thus the expected final topology consists in a single non-pointing photon. ALEPH [5] and DELPHI [6] have searched for single photons with a minimum impact parameter of 40 cm and have found 2/1.0 and 5/3.0 candidates/background, respectively in their $\sqrt{s} = 189 - 209$ and $\sqrt{s} = 202 - 209$ data sets. The efficiency for this search reaches a maximum of around 10% for decay lengths of 8 m. This yields an approximate upper limit of 0.4 pb in the production cross section.

3 Two leptons and \cancel{E} signatures

We discuss next the pair-production of sleptons in the slepton NLSP scenario. In general the $\tilde{\tau}_1$ will be the lighter slepton, but a degenerate case is possible in which the three $\tilde{\tau}_1$, \tilde{e}_R and $\tilde{\mu}_R$ act as co-NLSP's. Thus searches for pairs of sleptons decaying into their SM counterpart and a gravitino were developed by all four collaborations taking into account the possible lifetime of the slepton.

3.1 Acoplanar leptons

In the case of zero slepton lifetime two acoplanar leptons and missing energy are expected. This is the same final state as the one arising in SUGRA models if we take a

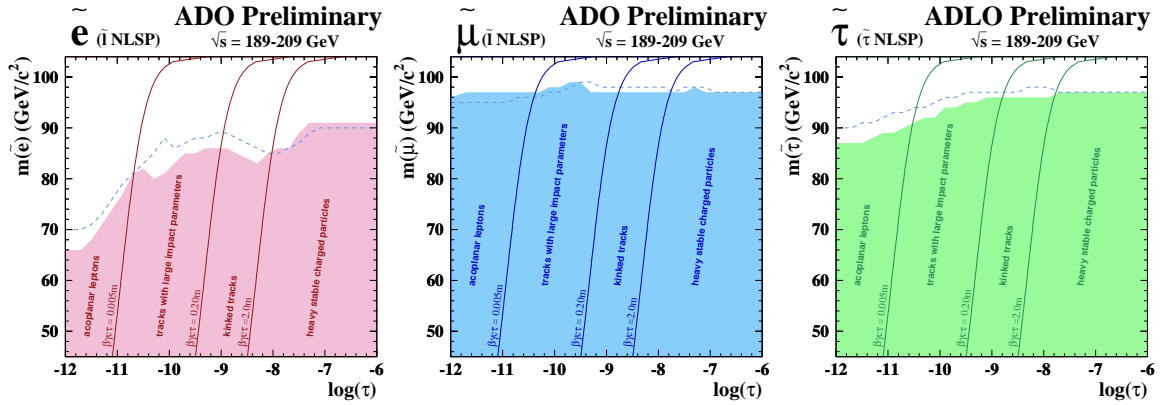


Fig. 2. Combined exclusion on the selectron, smuon and stau masses as a function of lifetime for sleptons co-NLSP's and stau NLSP. The combined preliminary limits are set at: $m_{\tilde{e}} > 65.8$, $m_{\tilde{\mu}} > 96.3$ and $m_{\tilde{\tau}} > 86.9$ GeV/c^2 , valid for any lifetime and $N_5 \leq 5$.

massless neutralino. The existing limits at 95% C.L. on the slepton masses derived from the combination [4] for $m_{\tilde{\chi}_1^0} = 0$ are: $m_{\tilde{e}} > 99.6$, $m_{\tilde{\mu}} > 94.9$ and $m_{\tilde{\tau}} > 85.0$ GeV/c^2 .

3.2 Kinks and large impact parameters

When sleptons decay in the tracking chambers of the detectors they are expected to produce kinks formed by their own track and the emerging lepton. If they do not reach the tracking devices, events will present tracks with large impact parameters. In these searches the most important sources of background are hadronic interactions in the material of the detector from K_s^0 for the large impact parameter topology and K^\pm or π^\pm decays in the kinks search. Both can be reduced by cuts on the opening angle between the two segments and with energy vetos. ALEPH reports 1/1.1 candidates/background, DELPHI 9/7.4 and OPAL 1/1.1 for selectrons and smuons and 7/4.4 for staus in their $\sqrt{s} = 189 - 209$ GeV data.

3.3 Heavy stable charged particles

For large gravitino masses, above a few hundred eV/c^2 , the sleptons decay outside the detector. This topology is characterised by two back-to-back highly ionising tracks which if produced at threshold may completely saturate the chamber electronics by their high dE/dx . Very high efficiencies can be attained in this search and no collaboration has found any discrepancy with the expected background. The combination of results from the four collaborations yields a lower limit on $m_{\tilde{\mu}}$ of 97.5 GeV/c^2 for NLSP lifetimes greater than 10^{-6} s.

4 Multi-lepton and \cancel{E} signatures

If neutralinos are accessible at LEP in the slepton NLSP scenario, they provide a clear advantage over slepton direct production: a higher cross section. Indeed, their production cross section may be even twice that of sleptons, specially for very light selectrons. Searches have been developed by ALEPH [10], DELPHI [11] and OPAL [8] for four leptons (two

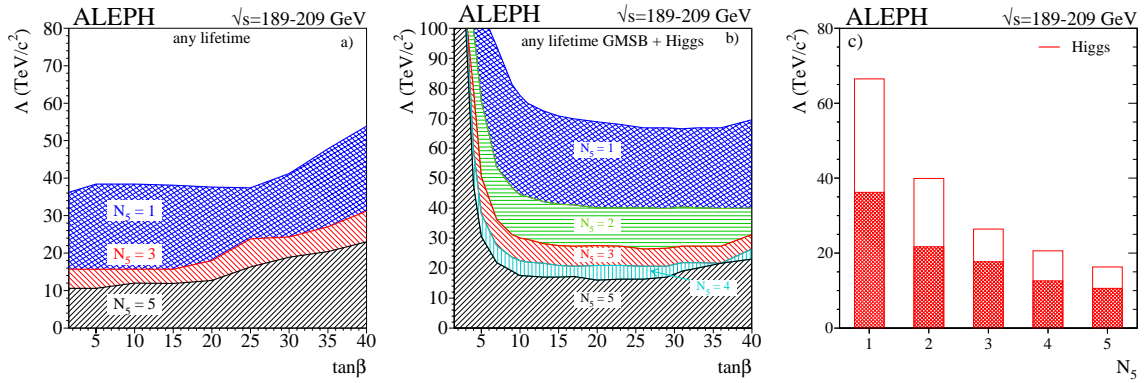


Fig. 3. Excluded values of the mass scale parameter Λ as a function of $\tan\beta$ for different values of N_5 , as set by ALEPH searches for (a) GMSB topologies and (b) neutral Higgs bosons. The minimum allowed value of Λ as a function of N_5 (c) if GMSB only (shaded) or Higgs only (unshaded) searches are included in the exclusion procedure. From Ref. [10].

of them could be soft) and missing energy in the final state. Only ALEPH and OPAL have also explored the possibility of two of the tracks exhibiting large impact parameters or kinks. The results are again negative. In the case of zero lifetime this search helps to exclude an area in parameter space that searches for direct slepton production do not reach. In addition to neutralino production in the slepton NLSP scenario, OPAL and DELPHI have looked for charginos $\tilde{\chi}_1^+ \rightarrow \tilde{\ell}_R^+ \nu$ and OPAL and ALEPH for selectrons or smuons in the stau NLSP case: $l_R^+ \rightarrow l^+ \tilde{\chi}_1^0 \rightarrow l^+ \tau \tilde{\tau}_1$, where $l = e, \mu$. No evidence for any of the above has been found and limits have been set on the mass of charginos ($100 \text{ GeV}/c^2$ for any lifetime by DELPHI) and sleptons ($94 \text{ GeV}/c^2$ for selectrons and zero lifetime by ALEPH) in the $\tilde{\tau}_1$ NLSP scenario.

5 Interpretation in mGMSB

By using the upper limits on the cross sections, the searches results constrain the available parameter space in minimal GMSB models. ALEPH, DELPHI and OPAL have performed scans over the six variables that determine GMSB phenomenology, \sqrt{F} , M_m , Λ , N_5 , $\tan\beta$ and $\text{sign}(\mu)$ to assess the impact of the different searches and set limits on these parameters. An example from ALEPH is shown in Fig. 3, where the $(\Lambda, \tan\beta)$ plane is shown with the excluded areas. This analysis places a lower limit on the mass scale parameter Λ of $10 \text{ TeV}/c^2$ for any lifetime and $N_5 \leq 5$, which is increased to $16 \text{ TeV}/c^2$ if Higgs boson searches are included, as can be seen in Fig. 3. OPAL results (without Higgs limits) are able to exclude $\Lambda > 40, 27, 21, 17, 15 \text{ TeV}/c^2$ for $N_5 = 1, 2, 3, 4, 5$ respectively, taking all NLSP lifetimes into account in a similar scan to the one by ALEPH. DELPHI reports a limit of $\Lambda > 17.5 \text{ TeV}/c^2$ for $N_5 \leq 4$ and negligible NLSP lifetimes.

6 GMSB after LEP

To conclude, the LEP SUSY working group has performed the combination of available results in the most important searches within the GMSB framework. They have been presented here, including some other results that the collaborations have performed to

completely cover most of the GMSB parameter space. No hint for any of these topologies has been found. Neutralino and stau masses have been excluded up to 54 and 87 GeV/ c^2 in the neutralino and stau NLSP scenarios respectively and independently of lifetime. This can be translated into a lower limit on the mass scale parameter $\Lambda > 10 \text{ TeV}/c^2$ for $N_5 \leq 5$. The quest for SUSY is now open to the Tevatron RunII. Chargino masses up to 290 (160) GeV/ c^2 could be discovered by 2004 with 2 fb^{-1} in the $\tilde{\chi}_1^0$ ($\tilde{\tau}_1$) NLSP scenario with short (long) lifetimes, as described in Ref. [12]. ALEPH alone for example has excluded chargino masses of 160 (100) GeV/ c^2 for short (long) NLSP lifetimes.

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