SEARCHES FOR GAUGE MEDIATED SUPERSYMMETRY BREAKING SIGNATURES AT LEP2

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Searches for neutralinos and sleptons predicted by Gauge Mediated Supersymmetry Breaking models have been performed by the LEP collaborations at center-of-mass energies of up to $\sqrt{s} = 209$ GeV. No significant excesses have been observed, so model independent limits on the production cross-sections and mass limits within the context of GMSB are presented.

1 Introduction

In supersymmetry (SUSY), an extension of the Standard Model (SM) designed mainly to solve the finetuning problem, every Standard Model particle has a supersymmetric 'partner' whose spin differs by half a unit.

If SUSY were an exact symmetry, the SUSY particles would have the same masses as their SM partners. From the fact that no SUSY particles have been observed yet it can be followed that the SUSY partners must be much heavier than the Standard Model particles and therefore SUSY must be a broken symmetry. Several breaking mechanisms have been considered. One possibility is that SUSY is broken via the usual gauge interactions in a 'hidden' sector, which couples to the visible sector of the SM and SUSY particles via a 'messenger sector' ^{1,2}. This model is called Gauge Mediated Supersymmetry Breaking (GMSB). In its minimal version there are five new parameters in addition to the SM parameters, usually chosen to be the effective SUSY breaking scale, Λ , which sets the mass scale of the SUSY particles, the messenger scale, M , the messenger index, N , the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, and the sign of the Higgs sector mixing parameter, $\text{sign}(\mu)$. The scale of dynamical SUSY breaking, $\sqrt{F}$, depends on Λ and M and is typically of the order of 100 TeV.

In supersymmetric theories the phenomenology depends crucially on the nature of the lightest and next-to-lightest supersymmetric particles, the LSP and the NLSP. In GMSB the SUSY partner of the graviton, the gravitino $\tilde{G}$, is light due to the low SUSY breaking scale, and is the LSP. Depending on the choice of parameters of the model the NLSP can either be the lightest neutralino, $\tilde{\chi}_1^0$, which is a mixture of the SUSY partners of the γ , Z^0 and the neutral Higgs bosons, or the lightest SUSY partner of the leptons, a (right-

handed) slepton, $\tilde{l}_R$.

One speciality of GMSB concerns the decay length $c\tau$ of the NLSP, which depends, apart from kinematical factors, only on $\sqrt{F}$:

$$c\tau = \frac{0.01}{\kappa_\gamma} \left(\frac{100\text{GeV}}{m} \right)^5 \left(\frac{\sqrt{F}}{100\text{TeV}} \right)^4 \left(\frac{E^2}{m^2} - 1 \right)^{1/2} \text{ cm} \quad (1)$$

where κ_γ is a parameter of order unity depending on the photino component of the neutralino and m and E are the mass and energy of the NLSP. Taking into account the range allowed for $\sqrt{F}$ the NLSP decay length is basically unconstrained and therefore all possible decay lengths between zero and infinity have to be considered.

In the following it is assumed that R-parity is conserved, which implies that SUSY particles can be produced only in pairs and all decay chains have to terminate with the LSP, which is stable, plus SM particles.

The four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, have searched for a variety of topologies expected from GMSB models. In this report a selection of these results^{3,4,6,7,8}, based mainly on the data recorded from 1998–1999 with center-of-mass energies between 189 GeV and 202 GeV, is presented. Some preliminary results from the data recorded in the year 2000 with center-of-mass energies of up to 209 GeV are also shown^{5,9,10}. All presented limits are at 95% confidence level (C.L.).

2 The Neutralino NLSP Scenario

In GMSB, the main production channel for the $\tilde{\chi}_1^0$ in e^+e^- collisions is direct pair production in s-channel processes mediated by γ^*/Z^0 or in the t-channel via exchange of a selectron. Indirect production via slepton pair production followed by decays $\tilde{l}_R \rightarrow l\tilde{\chi}_1^0$, is also possible. In non-minimal versions of GMSB, chargino pair production followed by decays $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$, and production of $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ with $\tilde{\chi}_2^0 \rightarrow Z^0 \tilde{\chi}_1^0$, have to be considered as well.

If the $\tilde{\chi}_1^0$ is the NLSP, all final states will contain photons and missing energy, since the $\tilde{\chi}_1^0$ decays as $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, and the gravitino, due to its weakly interacting nature, escapes detection.

2.1 Searches for Promptly Decaying Neutralinos

If the neutralinos are produced in pairs and decay promptly, the topology is two high momentum photons and significant missing energy and transverse momentum. The SM background in this channel is dominated by neutrino pair events with at least two radiated photons. All four LEP collabora-

Figure 1. (a) Recoil mass distribution and (b) LEP combined cross-section limits at 95% C.L. for $\tilde{\chi}_1^0$ pair production. The theoretical expectations for two different $\tilde{e}_R$ masses are also shown.

tions have searched for this signature and the results have been combined⁹. The distribution of the mass recoiling against the photonic system (Figure 1(a)) shows good agreement between data and the expectation from the neutrino background. As no excess over the SM expectation has been observed, cross-section limits at 95% C.L. have been derived (Figure 1(b)). The lower neutralino mass limit depends on the $\tilde{e}_R$ mass and is about 93 GeV for $m(\tilde{e}_R) = 2m(\tilde{\chi}_1^0)$, using the combined data from all four LEP experiments at $\sqrt{s} = 183 - 202$ GeV.

Promptly decaying neutralinos from indirect production, with a signature of photons, missing energy and leptons and/or jets from the decays of the $\tilde{l}_R$ and the $W^\pm$ and Z^0 bosons, have been searched for by the OPAL collaboration, but no excess over the estimated background has been found.

2.2 Searches for Long-lived Neutralinos

If the $\tilde{\chi}_1^0$ has a lifetime such that it decays in the detector, the signature consists of photons which do not point to the primary interaction point, and missing energy. To detect such non-pointing photons the direction of the photon must be reconstructed from the shower profile in the electromagnetic calorimeter. The ALEPH and DELPHI collaborations have searched for this signature but see no excess over the background expectation.

As stable neutralinos are invisible, only indirect searches are possible for decay lengths exceeding the detector dimensions. A relationship between the particle masses can be exploited to extract indirect limits on the $\tilde{\chi}_1^0$ mass from the results for MSSM sleptons and charginos.

3 The Slepton NLSP Scenario

In GMSB, sleptons can be produced in e^+e^- collisions either directly in pairs via s-channel processes (and via t-channel with $\tilde{\chi}_1^0$ exchange for the $\tilde{e}_R$) or indirectly via $\tilde{\chi}_1^0$ pair production followed by the decay $\tilde{\chi}_1^0 \rightarrow \tilde{l}_R l$. If the $\tilde{\tau}_R$ is significantly lighter than the other sleptons, which means that only the $\tilde{\tau}_R$ forms the NLSP, production might take place also via $\tilde{l}_R$ pair production followed by decays $\tilde{l}_R \rightarrow l \tilde{\tau}_R \tau$, where $\tilde{l}_R = \tilde{e}_R$ or $\tilde{\mu}_R$. This is called the stau NLSP scenario in contrast to the slepton co-NLSP scenario in which all sleptons are mass-degenerate.

If the sleptons form the NLSP, all final states will contain leptons and missing energy, since the $\tilde{l}_R$ decays as $\tilde{l}_R \rightarrow l \tilde{G}$.

3.1 Searches for Promptly Decaying Sleptons

If the sleptons are produced in pairs and decay promptly the topology is an acoplanar high-momentum lepton pair. This signature is completely identical to the topology expected in the 'Constrained Minimal Supersymmetric Standard Model' for a massless LSP (which is the $\tilde{\chi}_1^0$ in this model). All LEP collaborations have searched for this topology and no excess of candidates over the estimated background has been observed¹⁰. The LEP-combined mass limits using the data recorded at $\sqrt{s} = 183 - 208$ GeV are 100.5 GeV for the $\tilde{e}_R$, 95.4 GeV for the $\tilde{\mu}_R$, and 80.0 GeV for the $\tilde{\tau}_R$.

Promptly decaying sleptons from $\tilde{\chi}_1^0$ production have also been searched for by the ALEPH, DELPHI and OPAL collaborations, but good agreement between the data and the estimated SM background has been found. The same is true for promptly decaying staus from $\tilde{e}_R$ or $\tilde{\mu}_R$ pair production, searched for by the OPAL collaboration.

3.2 Searches for Long-lived Sleptons

Sleptons with a lifetime such that the decay happens in the tracking devices of the detector lead to topologies of tracks with large impact parameters or tracks with kinks, depending on the decay length. Long-lived sleptons have been searched for by the ALEPH, DELPHI and OPAL collaborations, but

Figure 2. Excluded regions in the m_{NLSP} vs. $m_{\tilde{G}}$ plane ($m_{\tilde{G}}$ corresponds to the NLSP lifetime) obtained for (a) staus and (b) mass-degenerate sleptons by DELPHI using data at $\sqrt{s} = 130 - 202$ GeV by combining the results for long-lived sleptons (hatched) with results for promptly decaying and stable sleptons.

no excess over the expectation from SM events has been found. The limits on the slepton masses at 95% C.L. obtained by DELPHI using the data at $\sqrt{s} = 130 - 202$ GeV are shown as hatched regions in Figure 2 for the stau NLSP scenario (a) and the slepton co-NLSP scenario (b).

3.3 Searches for Stable Sleptons

If the sleptons are stable, they, owing to their large masses, can be identified by their anomalous, high or low ionization energy loss (dE/dx) in the tracking chamber (Figure 3, left). Searches for this almost background-free signature have been performed by all LEP collaborations and good agreement between the data and the expectations from the SM background have been found. Therefore cross-section limits have been computed, e.g. by OPAL (Figure 3, right), and mass limits of 98 GeV for smuons and staus have been achieved using 220 pb^{-1} of data recorded in 2000 with the OPAL detector.

3.4 Lifetime Independent Slepton Mass Limits

The results for promptly decaying, long-lived and stable sleptons have been combined and lifetime independent lower limits of $m_{\tilde{l}_R} > 80$ GeV in the slepton co-NLSP scenario (DELPHI, $\sqrt{s} = 130 - 202$ GeV) and $m_{\tilde{\tau}} > 67$ GeV in the stau NLSP scenario (ALEPH, $\sqrt{s} = 189$ GeV) have been obtained.

Figure 3. Left, top: dE/dx of SM particles measured in the OPAL jet chamber. The two hatched regions are the search regions. Left, bottom: Expanded view of the search regions with simulated dE/dx of heavy particles for different masses and $\sqrt{s}$. Right: Cross-section limits, and theoretical expectations for stable smuons and staus, from OPAL.

4 Interpretations

By combining the results for sleptons and neutralinos in the different search channels with corresponding results from LEP1 and indirect constraints on stable neutralinos general NLSP mass limits have been calculated (Figure 4). The lowest limit is obtained for long lifetimes if staus and neutralinos are almost mass-degenerate, as can be seen from Figure 4(b). A general NLSP mass limit independent of the nature of the NLSP of 45 GeV has been reported by the ALEPH collaboration using data recorded at $\sqrt{s} = 189$ GeV.

Scans over the GMSB parameter space have been performed by the LEP collaborations resulting in limits on the parameter Λ which sets the overall mass scale for the SUSY sector. For $N \leq 5$, a lower bound on Λ of 9 TeV has been found by ALEPH using the data at $\sqrt{s} = 189$ GeV, from which a lower limit on the gravitino mass of 0.02 eV has been derived.

5 Conclusions

Searches for neutralinos and sleptons in topologies predicted by GMSB have been performed by the four LEP collaborations at center-of-mass energies

Figure 4. Excluded regions in the $m_{\tilde{\tau}}$ vs. $m_{\tilde{\chi}_1^0}$ plane for (a) short and (b) long lifetimes from ALEPH at $\sqrt{s} = 189$ GeV. The white regions are theoretically inaccessible.

of up to 209 GeV. Since no evidence for the production of these particles has been observed, limits are placed on the production cross-sections and the particle masses in the framework of the GMSB model.

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