Searches for Gauge-Mediated Supersymmetry Breaking Topologies in e^+e^- collisions at LEP2

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Abstract. In gauge-mediated supersymmetry (SUSY) breaking (GMSB) models the lightest supersymmetric particle (LSP) is the gravitino and the phenomenology is driven by the nature of the next-to-lightest SUSY particle (NLSP) which is either the lightest neutralino, the stau or mass degenerate sleptons. Since the NLSP decay length is effectively unconstrained, searches for all possible lifetime and NLSP topologies predicted by GMSB models in e^+e^- collisions are performed on the data sample collected by OPAL at centre-of-mass energies up to 209 GeV at LEP.
Results independent of the NLSP lifetime are presented for all relevant final states including direct NLSP pair-production and, for the first time, also NLSP production via cascade decays of heavier SUSY particles.
None of the searches shows evidence for SUSY particle production. Cross-section limits are presented at the 95% confidence level both for direct NLSP production and for cascade decays, providing the most general, almost model independent results.
These results are then interpreted in the framework of the minimal GMSB (mGMSB) model, where large areas of the accessible parameter space are excluded. In the mGMSB model, the NLSP masses are constrained to be $m_{\tilde{\chi}_1^0} > 53.5$ GeVc^2, $m_{\tilde{\tau}_1} > 87.4$ GeVc^2 and $m_{\tilde{\ell}} > 91.9$ GeVc^2 in the neutralino, stau and slepton co-NLSP scenarios, respectively.
A complete scan on the parameters of the mGMSB model is performed, constraining the universal SUSY mass scale Λ from the direct SUSY particle searches: $\Lambda > 40, 27, 21, 17, 15$ TeV/c^2 for messenger indices $N = 1, 2, 3, 4, 5$, respectively, for all NLSP lifetimes.

Keywords: GMSB lifetime scenarios, neutralino and sleptons NLSP, large impact parameters, kinked tracks, heavy stable charged particles, GMSB parameters scan
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INTRODUCTION

Supersymmetry[1], one of the proposed solution to the hierarchy problems of the Standard Model (SM), postulates the existence of a bosonic partner for each SM fermionic particle and viceversa. The discovery of these superpartners would be the most direct evidence for SUSY. Since these particles are not observed to have the same mass as their SM partners, SUSY must be a broken symmetry. In the most widely investigated scenarios, it is assumed that SUSY is broken in some *hidden* sector of new particles and is *communicated* to the *visible* sector of SM and SUSY particles by gravity or gauge interactions.

We present a study of gauge-mediated SUSY breaking topologies [4] using the data collected by the OPAL detector at LEP up to the highest center-of-mass energies of 209 GeV.

SEARCHES FOR GMSB TOPOLOGIES

An attractive feature of GMSB models is that the hidden sector can lie at masses as low as 10^4 GeV$/c^2$. In most current GMSB theoretical work [2], it is assumed that this sector is coupled to a messenger sector, which in turn couples to the visible sector through normal SM gauge interactions.

The minimal GMSB model introduces five new parameters and a sign: the SUSY breaking scale ($\sqrt{F}$), the SUSY particle mass scale (Λ), the messenger mass (M), the number of messenger sets (N), the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$) and the sign of the Higgs sector mixing parameter (sign(μ)).

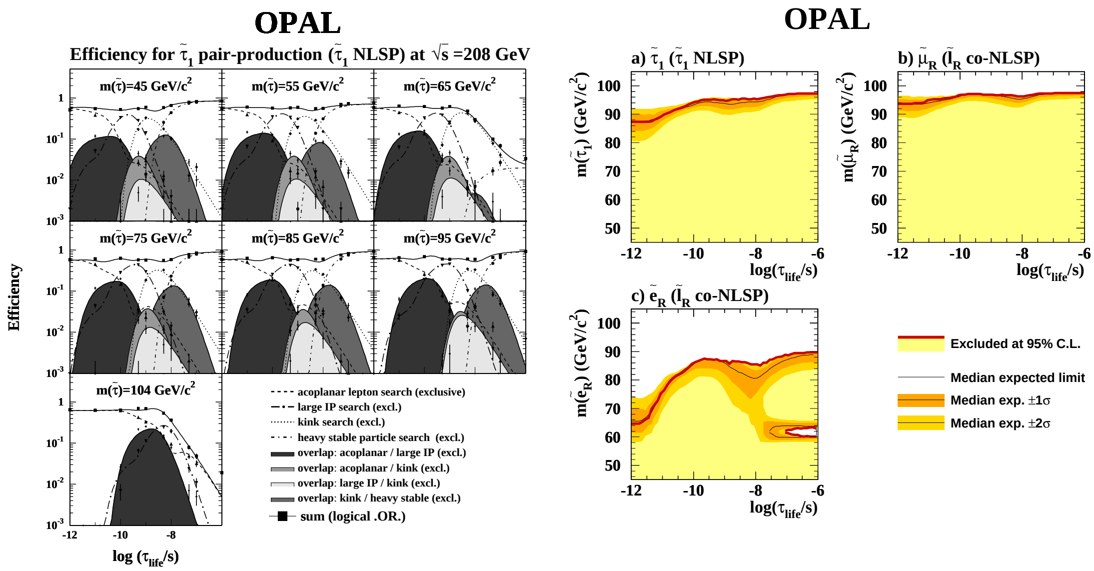
In GMSB models the LSP is a light gravitino ($m_{\tilde{\mathrm{G}}} < 1$ MeV$/c^2$), and the nature of the NLSP, which is either the lightest neutralino ($\tilde{\chi}_1^0$), stau ($\tilde{\tau}_1^{\pm}$) or mass-degenerate sleptons ($\tilde{\mathrm{e}}_R^{\pm}$, $\tilde{\mu}_R^{\pm}$ and $\tilde{\tau}_1^{\pm}$), determines the phenomenology. As the gravitino couples very weakly to heavier SUSY particles, these will decay typically in a cascade to the NLSP which then decays via either $\tilde{\chi}_1^0 \to \gamma\tilde{\mathrm{G}}$ or $\tilde{\ell}^{\pm} \to \ell^{\pm}\tilde{\mathrm{G}}$. We study [4] all relevant final states: both direct NLSP production and its appearance in the decay chain of heavier SUSY particles, like charginos, neutralinos and sleptons.

Since the decay length of the NLSP depends on $\sqrt{F}$ and is effectively unconstrained, the NLSP can decay inside or outside of the detector, so all possible lifetime topologies are searched for. With increasing decay length, the event signatures range from energetic leptons or photons and missing energy due to the undetected gravitino, to tracks with large impact parameters, kinked tracks, or heavy stable charged particles.

In total 14 different selections, each incorporating several signature variations, some based on the analyses described in [3], are implemented to cover all the GMSB topologies: slepton NLSP, neutralino NLSP, direct and cascade production, all lifetimes. In order to obtain lifetime independent results, the results from the various lifetime topologies are combined, with special attention to study the overlaps among the many channels. To achieve a good description of the selection efficiencies over the whole mass and lifetime range at all center-of-mass energies, without generating an excessive number of Monte Carlo samples, an interpolating function is determined. On Fig 1 it is demonstrated how the different selections contribute to the signal detection efficiency as a function of the NLSP lifetime.

None of the searches shows evidence for SUSY particle production. To interpret the results, a detailed scan of the minimal GMSB parameter space is performed with the gravitino mass fixed to 2 eV, corresponding to $\sqrt{F} \approx 100$ TeV, motivated by the requirement that the branching ratio of the next-to-NLSP to the gravitino is small. If that is the case, the cross-sections and branching ratios do not depend on the gravitino mass. One should note that $\sqrt{F}$ can be eliminated from the scan as all limits are computed independent of the NLSP lifetime, and $\sqrt{F}$ has no significant effect on other particle masses.

"Model independent" cross-section limits are derived for each topology as a function of the NLSP lifetime. For direct NLSP decays, this is done by taking the worst limit for a given NLSP mass from the generated GMSB parameter scan points. For cascade channels, the cross-section evolution is assumed to be β/s for spin-1/2 and β^3/s for scalar SUSY particles, respectively, and the highest bound for all intermediate particle masses



(A) **(B)**

FIGURE 1. **(A)** Efficiencies for stau pair-production at $\sqrt{s} = 208$ GeV. The symbols represent the efficiencies for ten simulated lifetimes while the curves show the interpolating efficiency functions of the searches for promptly decaying staus (dashed), large impact parameters (long dash-dotted), kinks (dotted) and stable staus (dash-dotted) together with the overlap efficiencies (filled areas). The total efficiency is shown by full line. **(B)** Observed and expected lower mass limits for pair-produced staus in the stau NLSP (a) and smuons (b), selectrons (c) in the slepton co-NLSP scenario as a function of the particle lifetime using the direct $\tilde{\ell}^+\tilde{\ell}^-$ search. For staus the observed and expected lower limit are identical in the stau NLSP scenario and in the slepton co-NLSP scenario. The mass limits are valid for a messenger index N$\leq$ 5. For the stau NLSP and slepton co-NLSP scenarios, the NLSP mass limits are set by the stau mass limit and by the smuon mass limit, respectively.

is retained. The maximum limit valid for all lifetimes is then quoted as the "lifetime independent" cross-section limit. In the neutralino NLSP scenario this is typically better than 0.04 pb for direct NLSP production, 0.1 pb for selectron and smuon production, 0.2 pb for stau production and 0.3 pb for chargino production. In the stau and slepton co-NLSP scenarios, the limit on direct NLSP production is 0.05 pb for smuons, 0.1 pb for selectrons and staus. For the cascade decays the bounds are typically better than 0.1 pb for neutralino, 0.2 for chargino and in the stau NLSP scenario 0.4 for selectron and smuon production.

The cross-section limits can be turned into constraints on the NLSP mass. For sleptons, the lowest mass limits are found for very short lifetimes, except for selectrons, as shown in Figure 1, where searches using dE/dx measurements lose efficiency for particles with momenta around 65 GeV. The lifetime independent limits are $m_{\tilde{e}_R} > 60.1$ GeV, $m_{\tilde{\mu}_R} > 93.7$ GeV and $m_{\tilde{\tau}_1} > 87.4$ GeV. The limit on the stau mass is the same in the stau and the slepton co-NLSP scenarios. In the slepton co-NLSP scenario, the best limit can be used to derive a universal limit on the slepton masses $m_{\tilde{\ell}} = m_{\tilde{\mu}_R} - m_\tau > 91.9$ GeV, where by definition the mass differences between the different slepton flavors are smaller than the lepton masses. For neutralino NLSP, no lifetime independent NLSP mass limit

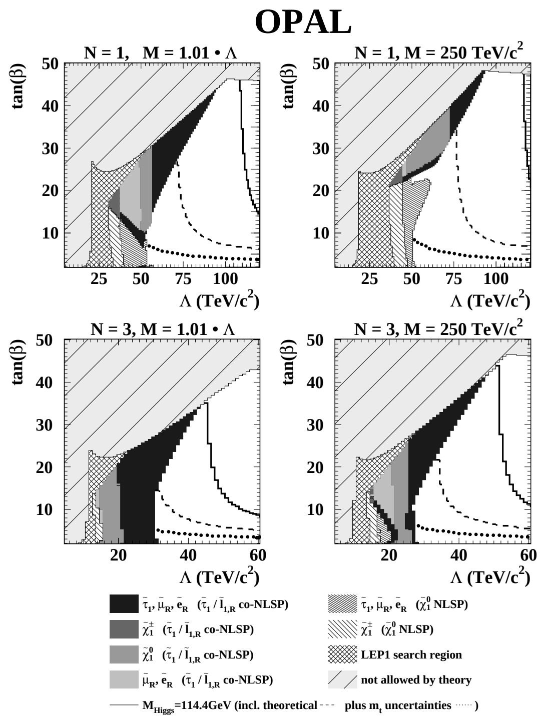


FIGURE 2. Examples of regions in the $\Lambda - \tan\beta$ plane excluded by pair-production searches for different particles, with $\mathrm{sign}(\mu) > 0$ and valid for any NLSP lifetime for four different sets of parameters, $N = 1$ or 3 and $M = 1.01 \cdot \Lambda$ or $250\,\mathrm{TeV}/c^2$.

can be set directly. For short lifetimes ($\tau < 10^{-9}$ s) a mass limit of 96.8 GeV is derived. For the first time limits on the production cross-section for all GMSB search topologies, including cascade, are presented.

The GMSB parameter space is constrained by our results as shown in Figure 2 for $N = 1$, $M = 1.01 \cdot \Lambda$ and sign(μ)>0. The universal SUSY mass scale is $\Lambda > 40, 27, 21, 17, 15$ TeV for messenger indices $N = 1, 2, 3, 4, 5$, respectively, independent of $M, \tan\beta$, sign(μ) and the NLSP lifetime ($\sqrt{F}$). The constraints on Λ imply lower limits on the neutralino mass in the neutralino NLSP scenario: $m_{\tilde{\chi}_1^0} > 53.5$ GeV for N=1 and $m_{\tilde{\chi}_1^0} > 94.0$ GeV for N=5, independent of the lifetime.

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