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J.-B. de Vivie

Laboratoire de l'Accélérateur Linéaire
IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex

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Jean Baptiste de Vivie

E-mail: devivie@lal.in2p3.fr

Laboratoire de l'Accélérateur Linéaire
IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex

Abstract

HIGGS and SUSY searches performed by the ALEPH Experiment at LEP are interpreted in the framework of two constrained R-parity conserving models: Minimal Supergravity and minimal Gauge Mediated Supersymmetry Breaking.

1 Introduction

Searches for supersymmetric and Higgs particles have been performed using the data collected with the ALEPH detector at LEP, at centre-of-mass energies up to 189 GeV. All have given negative results. This can be interpreted as constraints on the parameter space of a given model. The results are here presented in the framework of two different R-parity conserving constrained models: Minimal Supergravity (MSUGRA) [1] and Gauge Mediated Supersymmetry Breaking (GMSB) [2] models. Scans of their parameter space are carried out [3, 4] in order to set a lower limit on the mass of the lightest neutralino in MSUGRA and on the universal SUSY mass scale in GMSB. The detailed interpretation of searches in such constrained frameworks is of particular relevance to understand the interplay of the various experimental constraints. Moreover, it allows a direct comparison with TEVATRON limits.

2 Interpretation in the Minimal Supergravity model

2.1 Model parameters and constraints

The MSUGRA model allows to reduce the parameter space of the Minimal Supersymmetric Standard Model (MSSM) down to four parameters and one sign. In this framework, several constraints are assumed at the Grand Unification (GUT) scale: all scalar soft masses (including those pertaining to the Higgs sector) are equal to m_0 , all gaugino masses are equal to $m_{1/2}$, and the trilinear couplings are unified in a single parameter A_0 . These three parameters are used as inputs to the renormalization group equations, to determine the low energy parameters. The bilinear coupling between the two Higgs fields is traded for the ratio of their vacuum expectation values $\tan\beta$. Finally, μ is determined up to a sign ambiguity by requiring that Electroweak Symmetry Breaking be dynamically triggered by radiative corrections due to the large top Yukawa coupling.

From a given $(m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu))$ set, all couplings and masses of SUSY particles are computed. Several constraints are applied to define the allowed parameter sets. First, theoretical constraints are imposed to determine whether a set is physically acceptable: no particle should be tachyonic, a proper Electroweak Symmetry Breaking is required and the top Yukawa coupling should not develop a Landau pole up to the GUT scale. The top quark mass is set to $175 \text{ GeV}/c^2$. Experimental constraints are then applied. LEP1 limits on non-standard contributions to the total or invisible Z width are used. Nonetheless, the main rôle is played by direct searches for new particles at LEP2. Low $m_{1/2}$ values are excluded by chargino searches and further constrained by slepton searches at low m_0 . Higgs boson searches allow for a wide exclusion in the low $\tan\beta$ regime. Finally searches for heavy stable charged particles are also used to deal with quasi-stable staus.

2.2 Results in the $(m_0, m_{1/2})$ plane

The results of the scan are first presented for $A_0 = 0$. Exclusion domains in the $(m_0, m_{1/2})$ plane for $\tan\beta = 3$ (top) and 10 (bottom) are shown in Fig. 1. Chargino searches lead to a lower limit on $m_{1/2}$ approximately independent of m_0 , except for low m_0 , where the experimental sensitivity is reduced. In this region, slepton searches can be used. For $\tan\beta = 3$ and negative μ where stop mixing is small, Higgs searches exclude a large fraction of the parameter space.

The impacts of the further mSUGRA constraints are studied with a special attention payed to the *corridor* region, corresponding to small sneutrino masses. In this region, the chargino production cross section is reduced due to the negative interference between s and t-channel processes and two body decays of charginos to lepton-sneutrino dominate, leading to almost invisible final states when $0 < m_{\chi^\pm} - m_{\tilde{\nu}} < 3 \text{ GeV}/c^2$. An example of such a region is shown in Fig. 2(a), for $\tan\beta = 4.2$ and $\mu < 0$. The combination of the Z width and the chargino constraints yields a lower limit on $m_{1/2}$ of $63 \text{ GeV}/c^2$; adding slepton searches increases this limit to $94 \text{ GeV}/c^2$. Finally Higgs searches allow to set a lower limit on $m_{1/2}$ of $107 \text{ GeV}/c^2$, corresponding to a χ mass of $45.4 \text{ GeV}/c^2$.

2.3 Mass limit for the lightest neutralino

The mass limit for the lightest neutralino is presented in Fig. 2(b), as a function of $\tan\beta$. For positive μ , it is approximately independent of $\tan\beta$. For negative μ , a structure is observed. At small $\tan\beta$, Higgs searches are used to cover the corridor region. As $\tan\beta$ increases, Higgs searches become less efficient and slepton searches become constraining. However, they cannot completely cover the corridor for intermediate $\tan\beta$, and therefore a gap appears in the m_χ limit. Altogether, for $A_0 = 0$, the lower limit on m_χ is $41.5 \text{ GeV}/c^2$. However, as can be seen in Fig. 2(b), the impact of non zero A_0 value cannot be neglected. Scanning over A_0 leads to the final mass lower limit for the lightest neutralino within mSUGRA, for $\tan\beta \leq 10$:

$$m_\chi > 35.8 \text{ GeV}/c^2$$

This result improves by $\sim 3 \text{ GeV}/c^2$ on the one obtained in the less constrained minimal model (MSSM) considered in Ref. [3]. The limitation to relatively low $\tan\beta$ values comes from the fact that the combined analyses are optimized for the case of negligible stau mixing. In the MSSM interpretation, the latter condition is met by fine-tuning the trilinear coupling A_τ . However, in mSUGRA such an adjustment is not any longer possible; the regions in the parameter space where the stau is the NLSP and nearly degenerate with the lightest neutralino are less covered by direct selectron searches. For these parameter sets, charginos predominantly decay into $\tilde{\tau}\nu_\tau$ with very soft tracks from subsequent stau decays which are difficult to detect. In such cases, the lower limit on $m_{1/2}$ is set by the Z width measurement leading to a degradation of the

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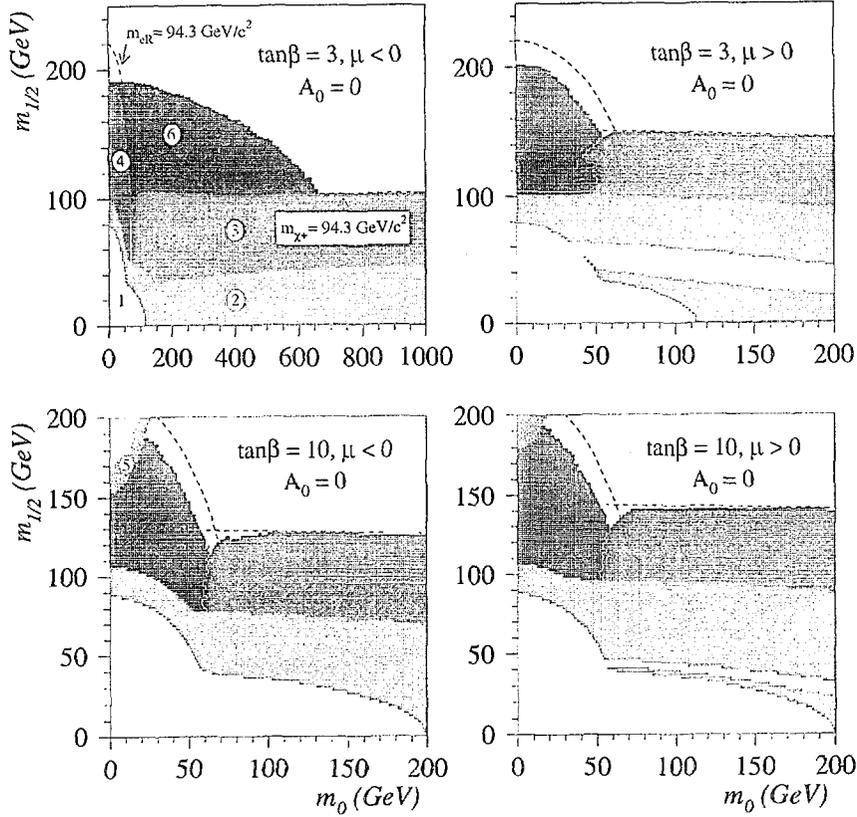


Figure 1: Regions of the $(m_0, m_{1/2})$ plane excluded for $A_0 = 0$ and $\tan \beta = 3$ (upper plots) and $\tan \beta = 10$ (lower plots). Region 1 is theoretically forbidden. The other regions are excluded by LEP1 constraints (2), chargino (3), slepton (4), heavy stable charged particle (5) and Higgs (6) searches. The thin dashed lines represent the kinematic limit for direct chargino and selectron searches.

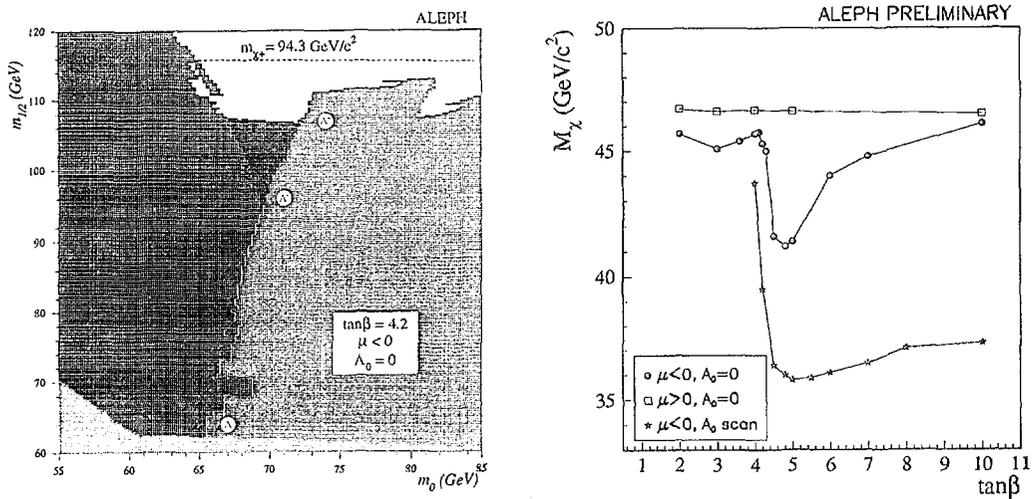


Figure 2: Zoom of the corridor region for $\tan \beta = 4.2$ and $\mu < 0$ (a). Mass limit for the lightest neutralino as a function of $\tan \beta$ (b).

absolute lower limit on the LSP mass. To recover sensitivity in these cases, specific neutralino analyses should be included.

3 New topologies in Gauge Mediated Supersymmetry Breaking models

3.1 Model parameters

The other generic class of models studied by the LEP collaborations are the GMSB models. In this framework, Supersymmetry breaking is mediated to the observable sector by a number of messenger pairs charged under the Standard Model (SM) gauge groups. In minimal models, five parameters and one sign are needed to determine masses and couplings: F , the SUSY breaking scale which fixes the coupling of superparticles to the gravitino, $\tan\beta$, $\text{sign}(\mu)$, N , the effective number of messenger pairs, Λ , the universal mass scale of SUSY particles and M_{mess} , the mean messenger mass, used as starting point for the RGEs. In these models, the soft masses are computed from N , Λ and M_{mess} , as well as the trilinear couplings which however are expected to be small.

3.2 Relevant topologies

In GMSB, the Lightest Supersymmetric Particle (LSP) is the gravitino, which can be considered as massless and not interacting from an experimental point of view. The experimental topologies depend on the nature of the Next to Lightest Supersymmetric Particle (NLSP) and its lifetime, determined by the gravitino mass: $\tau \propto m_G^2 \propto (F/M_{pl})^2$. The lightest neutralino and the sleptons are in general the only superparticles relevant for LEP2 searches, in addition to the gravitino.

The lightest neutralino NLSP case

In this case the relevant process is the pair-production of neutralinos, decaying into a photon and a gravitino. For short neutralino lifetimes, the experimental topology consists of two acoplanar photons and missing energy. No excess of candidates has been observed in the data.

In the minimal model, and for very short lifetimes, this search excludes χ masses smaller than $90 \text{ GeV}/c^2$. Since the pair production of bino neutralinos can only occur via a t-channel selectron exchange, this limit depends slightly on the selectron mass as shown in Fig. 3. This search allows to almost completely rule out the GMSB interpretation of the CDF event in the selectron pair-production scenario.

For moderate lifetimes, the previous search is complemented by a search for a single photon with large ‘‘impact parameter’’ (non pointing photon), which takes advantage of the high granularity of the ALEPH electromagnetic calorimeter. For very long lifetimes, neutralinos decay outside the detector, giving rise to an invisible final state.

The slepton NLSP case

Depending on $\tan\beta$, two distinct *scenarii* can be considered: the slepton co-NLSP scenario at low $\tan\beta$, where all right handed sleptons are mass-degenerate, and the stau NLSP scenario, at large $\tan\beta$ where the stau becomes lighter due to a large mixing. Again, topologies depend on lifetime. For very short lifetimes, the standard MSSM slepton searches for very high Δm (the mass difference between the slepton and the LSP) can be used. The topology consists of a pair of acoplanar leptons and missing energy. For intermediate lifetimes, sleptons can fly and decay in the tracking volume and therefore give rise to detectable kinks. If they decay inside the beam pipe, the associated track has a large impact parameter. Finally, for long lifetimes, sleptons decay outside the detector. The final state therefore consists of a pair of heavy stable charged particles, with two main characteristics: the kinematics of the pair-production and the

high specific ionization in the Time Projection Chamber. The number of candidate events observed in the data and their properties are compatible with the SM expectation. The negative results of these searches are translated into a lower limit for the mass of the slepton NLSP, independent of its lifetime: in the co-NLSP scenario, $m_{\tilde{l}_R} > 85 \text{ GeV}/c^2$ and for the stau NLSP, $m_{\tilde{\tau}_R} > 68 \text{ GeV}/c^2$.

To extend the sensitivity of the search in the case of short lifetimes, a search for sleptons produced in cascade decays of neutralinos has been performed. The process of interest is $e^+e^- \rightarrow \chi\chi \rightarrow \tilde{l}\tilde{l}\tilde{l}\tilde{l} \rightarrow \ell^+\ell^-\tilde{G}\ell^+\ell^-\tilde{G}$. Here advantage is taken of the multi lepton topology. Two leptons may be soft (from the neutralino decays) and two are hard (from the slepton decays). Due to the majorana nature of the neutralino, the charge (and flavour) of the two hard leptons are uncorrelated, leading to spectacular final states, *e.g.* with two energetic equally charged muons. Moreover, the neutralino production (via t-channel selectron exchange) cross section is large, since the neutralino is mainly bino and the right handed selectron is light. For $m_\chi < 87 \text{ GeV}/c^2$ and $m_\chi - m_{\tilde{\tau}} > m_\tau$, this search is used to improve the stau mass limit to $84 \text{ GeV}/c^2$.

4 Scan of the GMSB parameter space

4.1 Ranges for the parameters and constraints

In the absence of any excess with respect to the SM, all these searches are used to put constraints on the parameter space. The five parameters presented in 3.1 are varied in order to cover a large fraction of the parameter space, relevant for LEP2 studies and compatible with the main motivations for GMSB models: five values of N are probed (from 1 to 5), \sqrt{F} is varied from 10 to $10^4 \text{ TeV}/c^2$, M_{mess} from 10 to $10^9 \text{ TeV}/c^2$, Λ from $1 \text{ TeV}/c^2$ to $\min(\sqrt{F}, M_{mess})$ and $\tan\beta$ is required to be above 1.3. Several constraints are applied on each parameter set. Direct searches for acoplanar taus and heavy stable charged particles performed at LEP1 and constraints from the Z width are used to exclude very low NLSP masses. Standard SUSY searches for charginos and sleptons at LEP2 are also used to cover long neutralino lifetimes. Finally all searches presented above contribute to exclude a large fraction of the parameter space.

4.2 Interplay between the various searches and mass limit for the NLSP

An example of the complementarity of the standard MSSM and GMSB searches is shown in Fig 4, where N , M_{mess} and $\tan\beta$ have been chosen in order for the lightest neutralino to be the NLSP. For long lifetimes, the neutralino escapes the detector and therefore only indirect limits can be set, as in the usual MSSM. For short lifetimes, the acoplanar photons complemented by the non pointing photon searches determine the limit. Finally in this case, the lower limit on m_χ is $45 \text{ GeV}/c^2$.

The mass limit for the NLSP is obtained by varying all the parameters in the considered range. The results of this scan, presented as excluded regions in the $(m_\chi, m_{\tilde{\tau}})$ plane, are illustrated in Fig. 5. It can be emphasized that all searches contribute, in particular that the multi lepton topology significantly extends the exclusion domain for sleptons nearly degenerate with the lightest neutralino. Altogether, the mass limit is $45 \text{ GeV}/c^2$ for the neutralino NLSP, and $67 \text{ GeV}/c^2$ for the stau NLSP.

4.3 Lower limit on Λ

In GMSB models, the parameter which sets the overall scale for SUSY masses is Λ . The lower limit on Λ as a function of $\tan\beta$ obtained in this study is shown in Fig. 6. It is essentially derived from the mass limit for the NLSP. Within the considered parameter ranges, the absolute lower

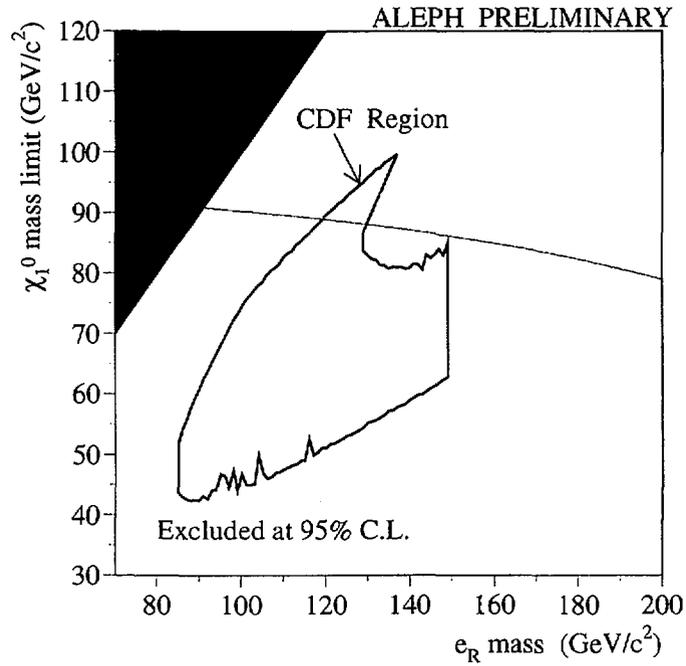


Figure 3: Excluded region in the $(m_{\tilde{e}_R}, m_{\chi^0_1})$ plane for a bino neutralino.

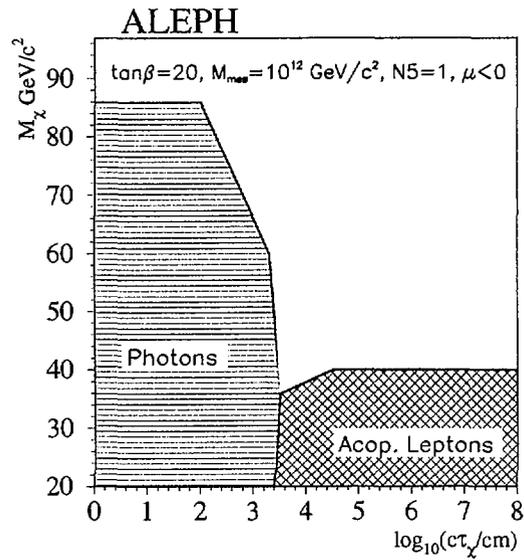


Figure 4: Mass limit for the lightest neutralino as a function of its lifetime.

limit on Λ is $9 \text{ TeV}/c^2$, found at low $\tan\beta$ for a quasi stable χ NLSP. This can be translated into an indirect mass lower limit for the gravitino: $m_{\tilde{G}} > 2 \cdot 10^{-2} \text{ eV}/c^2$.

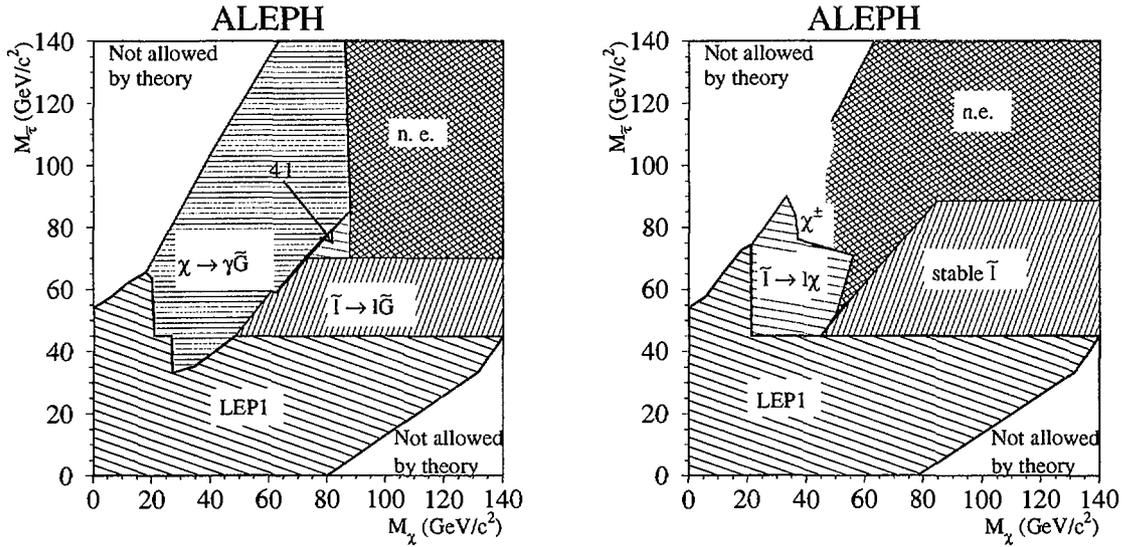


Figure 5: Excluded regions in the $(m_\chi, m_{\tilde{\tau}})$ plane for short (left) and long (right) NLSP lifetimes. The *n.e.* region is not excluded and the *not allowed by theory* regions correspond to regions unaccessible within the parameter ranges considered.

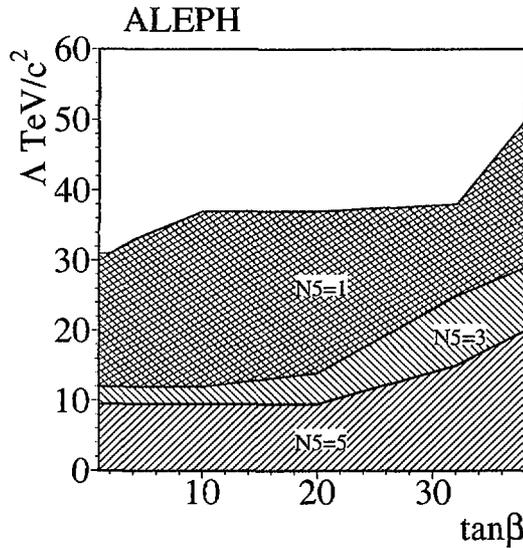


Figure 6: Lower limit on Λ as a function of $\tan\beta$ for three different values of the effective number of messenger pairs.

5 Conclusion

The search for Supersymmetry is one of the paramount physics goal of LEP2. A detailed interpretation of searches has been performed by the ALEPH Collaboration in the constrained framework of mSUGRA. For $\tan\beta \leq 10$, this results in a lower limit on the mass of the lightest neutralino: $m_\chi > 35.8 \text{ GeV}/c^2$. Nevertheless, there are regions in the parameter space at

large $\tan\beta$ where the constraints are weak and this limit is degraded. New specific topologies pertaining to GMSB models have been extensively searched for. In the absence of any hints for a signal, limits are set on masses and model parameters. In particular, the overall mass scale of SUSY particles has to be larger than $9 \text{ TeV}/c^2$, almost independently of all the other GMSB parameters.

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