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Search for AMSB with the DELPHI data

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Abstract

The data collected by the DELPHI experiment up to the highest LEP2 energies were used to explore the Anomaly Mediated SUSY Breaking (AMSB) model with a flavour independent m_0 parameter. The searches covered several possible signatures experimentally accessible at LEP, with either the neutralino, the sneutrino or the stau being the Lightest Supersymmetric Particle (LSP). They included: the search for nearly mass degenerate chargino and neutralino (which is always the case in AMSB); the search for Standard Model like or invisible decaying Higgs boson; the search for stable staus; the search for cascade decays resulting in the LSP and a low multiplicity final state containing neutrinos. No evidence of a signal was found and constraints could be put in the space of the parameters of the model.

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1 Introduction

After many years of searches in collider experiments, there is still no evidence for the existence of supersymmetric particles. There are several theoretical motivations to believe that nature must be supersymmetric. The negative results of the searches so far have therefore only set constraints on the spectrum of the SUSY particles and on the parameters of the model. The mechanism of SUSY breaking itself is still unclear. In the gravity mediated scenario (SUGRA) [1], SUSY is broken in a hidden sector and the breaking is transmitted gravitationally to the observable sector. This mechanism is elegant, since it only requires already existing fields and interactions (like gravity). It suffers however from the so called SUSY flavour problem, that is the minimal version of SUGRA (mSUGRA) requires a large amount of fine tuning to avoid unobserved large flavour changing neutral current effects.

To cope with the SUSY flavour problem, different breaking mechanisms have been inspected. In the Gauge Mediated SUSY Breaking scenario (GMSB) [2] the breaking is transmitted via gauge forces. This model predicts a very characteristic mass spectrum, with a light gravitino as the lightest supersymmetric particle (LSP), and typically long lived next to lightest supersymmetric particles (NLSP).

Anomaly Mediated Supersymmetry Breaking (AMSB) [3, 4] is another interesting solution to the flavour problem of mSUGRA. Rescaling anomalies in the supergravity Lagrangian always give rise to soft mass parameters in the observable sector. It follows that anomalies contribute to the SUSY breaking in any case, whatever is the main symmetry breaking mechanism. We shall refer to AMSB as the model in which all other components that mediate the SUSY breaking are suppressed and the anomaly mediation is the dominant mechanism.

The minimal AMSB is very predictive: all the low energy phenomenology can be derived by adding to the Standard Model (SM) just two extra parameters and one sign. Unfortunately, the minimal AMSB model would imply negative squared masses (tachyons) for the sleptons at the electroweak scale. One way of getting rid of tachyons is to suppose additional, non anomaly, contributions to the SUSY breaking which can generate a positive contribution to the soft masses squared. There are a few string motivated solutions that generate such a positive contribution without spoiling the renormalization group (RG) invariance of the soft terms. In most cases, such a contribution is universal for all sfermion masses and, in practice, it is enough to add just one extra parameter to the model. This arises, for instance, when the visible and the hidden sectors lie in separate branes that communicate only through gravitation [3]. There are other solutions [5] that lead to flavour dependent mass terms; such possibilities are less predictive (since the sfermion spectrum depends on more parameters) and they are not going to be investigated further in this paper. However, the characteristic gaugino spectrum of AMSB is the same also for those models and most of the considerations that follow can be applied also to them.

The paper is organized as follows. In section 2 the phenomenology of AMSB relevant for the search at LEP is shortly reviewd. Section 3 lists the data and simulation samples used for the analyses, and the event generators used to simulate the signal. Section 4 describes the results of the searches for the AMSB signatures in DELPHI. In some cases, searches already performed in DELPHI were just reinterpreted in terms of AMSB. Those searches are described in more details in the relevant papers cited in the paragraph of that section. In other cases, that are explained in more length, it was necessary to adapt the original techniques to the requirements specific of the AMSB scenarios. Finally, having had no evidence of excesses above the expectations from standard physics, in section 5 the results of the searches above are combined to put constraints on the parameters of the model and on the spectrum of some SUSY particles.

2 Phenomenology of AMSB

If there is only one common squared mass term for all scalars, all masses and couplings can be derived in terms of just three parameters and one sign:

- the mass of the gravitino, $m_{3/2}$;
- the ratio of the vacuum expectation values of the Higgs fields, $\tan\beta$;
- the common scalar mass parameter m_0;
- the sign of the Higgs term, $sign(\mu)$.

In this context, m_0 can even be considered as a phenomenological term that parameterizes the lack of knowledge of the method with which the sleptons acquire physical masses.

Low energy gaugino masses, scalar masses and trilinear couplings in AMSB are given by:

$$M_\lambda = \frac{\beta_g}{g} m_{3/2} \tag{1}$$

$$M^2_{\tilde{Q}} = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right) {m_{3/2}}^2 + {m_0}^2 \tag{2}$$

$$A_y = -\frac{\beta_y}{y} m_{3/2} \tag{3}$$

where g are the gauge couplings, y the Yukawa couplings and γ and β are RG functions. This soft mass spectrum has distinctive features [4] which differ from the usual SUGRA or GMSB scenarios.

- The gravitino is heavy (this has several advantages for cosmology [4]).
- The ratios of gaugino masses at the electroweak scale are determined by the ratios of the corresponding β functions. Therefore, they assume in a natural way different values with respect to the theories with gaugino mass unification at a Grand Scale:

  $$M_1 : M_2 : M_3 \simeq 2.8 : 1 : -8 \tag{4}$$

  These ratios have been computed by including the largest next to leading corrections [4]. They can still vary a bit as function of the parameters of the model. Typical values of μ allowed by the model imply $M_2 < M_1 < |\mu|$. As a consequence, the chargino and neutralino mass eigenstates are rather well approximated by either pure gaugino or pure higgsino states, with $M_{\tilde{\chi}^0_1} \sim M_{\tilde{\chi}^\pm_1} \sim M_2$, $M_{\tilde{\chi}^0_2} \sim M_1$, $M_{\tilde{\chi}^0_{3,4}} \sim M_{\tilde{\chi}^\pm_2} \sim |\mu|$. Therefore, the lightest chargino and neutralino are always a nearly mass degenerate doublet of gauginos (with nevertheless $M_{\tilde{\chi}^0_1} < M_{\tilde{\chi}^\pm_1}$); the second lightest neutralino is a gaugino of intermediate mass; and the heaviest chargino and neutralinos are heavy and higgsino-like.

- Squark masses are rather insensitive to m_0. AMSB implies squarks and gluinos much heavier than the LSP, and completely out of reach at LEP.
- In the slepton sector, if both the right and the left chiral states receive the same ${m_0}^2$ contribution, the diagonal entries of the mass matrix are accidentally highly degenerate. Nearly mass degenerate and highly mixed same flavour sleptons are a distinctive feature of the minimal AMSB with a flavour independent m_0. The lightest stau is always the lightest charged slepton. The sneutrinos can be lighter than all charged sleptons, and typically the stau sneutrino is the lightest sneutrino.
- The CP-odd neutral Higgs, A, is usually much heavier than the Z, and the lightest CP-even neutral Higgs, h^0 is analogous to the SM one [6]. Also the mass of h^0 is still more tightly bound than in the usual SUSY scenarios, since it should lie below 120 GeV/c^2 [6]. Therefore, the lower limit obtained at LEP for the SM Higgs mass already strongly constrains the AMSB parameter space. Moreover, if such a light Higgs is not to be found at the Tevatron or, further on, at the LHC, the AMSB model itself will be completely ruled out.

In the model considered here, only the slepton mass spectrum and, to some extent, the Higgs depend on the assumptions of a common scalar term m_0. All other features are characteristics of any AMSB scenario, whatever procedure is used to cope with the tachyonic masses of the sleptons.

Since m_0 is a free parameter, according to its value there are three possible candidates for the LSP: the nearly mass degenerate $\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}$, the $\tilde{\nu}$ (for relatively small values of $\tan\beta$ and $m_{3/2}$) or the $\tilde{\tau}$. Scenarios with any of the above as LSP are explored in the following, using the data collected by the DELPHI experiment during the period of LEP running at the Z^0 mass pole (LEP1) and of LEP running at high energy (LEP2, with centre-of-mass energies as high as 208 GeV).

3 Data and simulation samples

The results listed in this paper interpret in terms of AMSB the outcomes of searches performed in the DELPHI experiment [7] at LEP. Some of them were originally prepared for different analyses and used unmodified here. Others, were instead optimized to search specifically for the AMSB phenomenology. If not otherwise specified in the text, the reader should refer to the papers cited for the description of the samples of the data and of the SM background simulation used in the different analyses.

DELPHI collected a grand-total of approximately 116 pb^{-1} while running at the Z^0 pole in the years from 1989 to 1995. Afterwards, globally about 694 pb^{-1} of integrated luminosity were harvested in the LEP2 phase, with centre of mass energies ranging from 130 to 208 GeV.

SUSYGEN [8] was used for signal simulation. As it does not allow for the calculation of the particle spectrum of the AMSB models, the input parameters were set in a way to obtain a spectrum close to the one resulting from the precise calculations in the AMSB framework of [4].

ISAJET [9], since version 7.47, allows the calculation of the particle masses and decay branching modes of the AMSB model of [3, 4] as a function of the four parameters m_0,

$m_{3/2}$, $\tan\beta$ and $sign(\mu)$. To constrain the allowed space of the parameters, the result of the searches were compared with the prediction of mass spectra, cross-sections and decay modes as given by ISAJET 7.63. In the present version of the program only the Leading Order (LO) radiative corrections to the AMSB spectrum are coded.

4 Searches used to investigate the AMSB scenario

Hereafter, the searches able to inspect AMSB scenarios at LEP are reviewed. For completeness, also a few searches not further developed are listed. Indeed, it was verified that the results of those particular searches were not truly fundamental in constraining or testing the AMSB model. In fact, giving the high predictivity of the model, concurring scenarios were always found to be more powerful in testing the same set of SUSY parameters.

4.1 LEP1 limits

The precise measurement of the Z width at LEP1 [10] was used to put severe constraints on all possible non standard contributions. Given the nice agreement between the measured width and the one predicted by the SM theory, non standard contributions are expected to be smaller than 3.2 MeV$/c^2$ at the 95% confidence level (CL) [1]. In particular, this ruled out charginos with mass below 45 GeV$/c^2$ and sneutrinos with mass below 43 GeV$/c^2$, at the same confidence level, independently of their field composition and decay modes [10].

4.2 Search for nearly mass degenerate chargino-neutralino

One of the key features of AMSB is the very small difference between the masses of the lightest chargino and neutralino. Therefore, the results of the search for nearly mass degenerate chargino and neutralino [12] can be used to investigate AMSB.

When the masses of the lightest chargino and neutralino are very close, the visible products of the decay $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 f f'$ carry little momentum. Therefore, they are both difficult to select and trigger on, and they can become almost indistinguishable from the huge background of two-photon events at LEP2. Dedicated techniques were used for this search. If there is a sneutrino lighter than the chargino the decays are different: this case is treated in section 4.3.

For $\Delta M = M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$ below approximately 200 MeV$/c^2$, the phase space available for the decay is limited, and the lifetime can be so long that the chargino produced at the interaction point is seen as a heavy stable charged particle in the detector, or a kink corresponding to the decay can be observed in the reconstructed track. Long-lived charginos are searched for in DELPHI as single tracks with no signal (veto) in the gas or liquid radiator of the Cherenkov counter, and/or with an anomalously high ionization loss in the Time Projection Chamber (TPC). Kinks with both the mother chargino and the daughter charged decay particle reconstructed in the tracking devices were also searched for.

[1] In [11] a method designed to be more model independent gives $\Gamma_Z^{\rm new} < 6.2$ MeV$/c^2$ at 95% CL, using older data. However, this different limit on the allowed non SM Z width would not modify significantly the lower limits derived on the masses of chargino and sneutrino

For ΔM larger than about 200 MeV/c^2 (or even less, if there are light sneutrinos, which increase the leptonic decay width of the chargino), the lifetime tags are no longer effective. It was however observed that the signature of a photon with high transverse momentum radiated from the initial state (ISR), together with the few soft particles from the decay of the chargino, improves both the trigger efficiency of the signal and the rejection of the two-photon background.

Nearly mass-degenerate chargino and neutralino are possible in SUSY only if $M_2 \gg |\mu|$, that is $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ are both almost pure higgsinos (this case does not concern AMSB), or if $M_2 \ll |\mu|$, that is $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ are both almost pure gauginos. To maximize the sensitivity to AMSB scenarios, the analysis of [12] was redone taking further into account additional scenarios with light sneutrinos. The search was done under the following hypotheses: heavy sneutrinos, that is $M_{\tilde{\nu}} \geq 500$ GeV/c^2; 100 GeV/c^2 sneutrinos; sneutrinos with mass between $M_{\tilde{\chi}_1^{\pm}} + 1$ GeV/c^2 and 100 GeV/c^2; sneutrinos lighter than $M_{\tilde{\chi}_1^{\pm}} + 1$ GeV/c^2. In the last case, where all charginos decay promptly, a stricter requirement on the extrapolation to the main event vertex of the charged particle tracks was requested: the event was accepted only if at least two charged particles in it were compatible as coming from the primary e^+e^- interaction vertex.

With respect to the scenario explored in [12], if there is a light sneutrino (either lighter than the chargino or not more than a couple of GeV/c^2 heavier) the leptonic width gets strongly enhanced, and the lifetime shortens. In that case, the efficiencies at the smallest ΔM explored with the ISR tag, turned out to be larger than the ones computed in [12] for the same ΔM. On the other hand, as the lifetime shortens, the searches that explicitly rely on it (stable particles and kinks) lose efficiency.

Since there was no evidence of an excess in the number of events observed above the SM expectations, regions in the plane ($M_{\tilde{\chi}_1^{\pm}}$,ΔM) could be excluded at the 95% CL. Figure 1 shows the regions excluded by the different techniques used in the search for degenerate charginos. Figure 1 (a) is the same plot with the gaugino exclusion as in [12], and includes AMSB scenarios when $M_{\tilde{\nu}} \geq 500$ GeV/c^2. In figure 1 (b) the exclusion was computed for $M_{\tilde{\nu}} = 100$ GeV/c^2, and therefore it gives conservative predictions in case of heavier sneutrinos. Figure 1 (c) was obtained with the minimal chargino cross-section (with respect to $M_{\tilde{\nu}}$) and with the lifetime corresponding to $M_{\tilde{\nu}} = M_{\tilde{\chi}_1^{\pm}} + 1$ GeV/c^2. This exclusion is conservative for all AMSB scenarios with $M_{\tilde{\chi}_1^{\pm}} + 1$ GeV/$c^2 < M_{\tilde{\nu}} <$ 100 GeV/c^2, since as $M_{\tilde{\nu}}$ increases the s-t channels interference weakens and the cross-section gets larger; moreover, also the lifetime increases, thus improving the sensitivity of all searches for long-lived charginos. Finally, figure 1 (d) was computed using the minimal chargino cross-section (again with respect to $M_{\tilde{\nu}}$) and for short lived charginos. It can be used to constrain AMSB scenarios with $M_{\tilde{\nu}} < M_{\tilde{\chi}_1^{\pm}} + 1$ GeV/c^2 (see also section 4.3).

When deriving those excluded regions, the effect of the systematics uncertainties on the signal efficiency and on the expected background content was taken into account according to reference [13].

4.3 Search for $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\nu} l^{\pm}$ decays

If the sneutrino is lighter than the chargino, the chargino decays with practically 100% branching ratio into a sneutrino and a charged lepton. Since the upper limits on the chargino cross-section in the SUGRA scenario were obtained assuming $W^{\pm}$ decays for the chargino [12], they cannot be translated directly into limits in the AMSB scenario. Hence, only the "leptonic" search for charginos described in [12] was used to explore all $\Delta M_{\tilde{\nu}} = M_{\tilde{\chi}_1^{\pm}} - M_{\tilde{\nu}}$ larger than 3 GeV/c^2.

The analysis selected events with low charged multiplicity (i.e. events with no more than five reconstructed charged particles), and without any reconstructed isolated photon[2]. After a preselection obtained with sequential cuts, the final selection was performed using likelihood ratio functions [14] $\mathcal{L}_R(\{x_i\})$ built as follows: for a set of variables $\{x_i\}$ (e.g. multiplicies, visible energy, acoplanarity [3], total transverse momentum, fraction of energy in the forward cone, etc.), the probability distribution functions (pdf) of these variables were estimated by normalized frequency distributions for the signal (with a $\tilde{\chi}_1^0$ LSP) and the background samples. The pdf's of these variables were denoted $f_i^S(x_i)$ for the signal events, and $f_i^B(x_i)$ for the background events that passed the same selection criteria. Six likelihood ratio functions, one per $\Delta M_{\tilde{\nu}}$ region defined as in table 1, were defined as

$$\mathcal{L}_R = \prod_{i=1}^{n} \frac{f_i^S(x_i)}{f_i^B(x_i)} \quad . \tag{5}$$

Events with $\mathcal{L}_R > \mathcal{L}_{R_{CUT}}$ were selected as candidate signal events. The choice of variables and the value of $\mathcal{L}_{R_{CUT}}$ were optimized using samples of simulated events, by minimizing the signal cross-section that was expected to be excluded at 95% CL in the absence of a signal. This procedure was repeated for every investigated centre-of-mass energy. Basically after the final selection, the remaining set of events consisted of low multiplicity events with high acoplanarity and high missing energy.

In the present search, new limits were set using only efficiencies computed on events with fully leptonic decays and selected by the fully leptonic selections.

Table 1 summarizes the number of events observed and expected, and the luminosities used at the different centre-of-mass energies. The data collected during year 2000 with and without the TPC fully operational (see [12]) were treated as different channels in the analyses. No significant excess was observed above the SM expectations.

The efficiencies at the centre-of-mass energy of 208 GeV of the fully leptonic selection are plotted in figure 2 (a) as function of the chargino and sneutrino masses. Since up to five visible charged particles were allowed and no leptonic identification was required, those efficiencies had only very little dependence on the flavour of the charged lepton in the final state. The efficiencies of figure 2 (a) were computed using events simulated with three body $\tilde{\chi}_1^+ \to l^+\nu\tilde{\chi}_1^0$ decays. It was however verified with some samples of fully simulated events with the two body decay $\tilde{\chi}_1^+ \to l^+\tilde{\nu}$ searched for in AMSB, that the efficiencies used in the analysis were never larger than the ones expected for the two body decays. This was expected, since the momentum of the visible charged particles is on average larger in the two body sample than in the three body one. In particular, the efficiencies used are fully compatible with the true ones at large $\Delta M_{\tilde{\nu}}$, and they become up to one and half times smaller when $\Delta M_{\tilde{\nu}}$ approaches 3 GeV/c^2. Therefore, the limits obtained are never overestimated, and possibly conservative at small $\Delta M_{\tilde{\nu}}$.

[2]Events were discarded if there was a photon with more than 5 GeV, and isolated by more than 15 degrees from any other charged or neutral particle. This request was derived from the original "standard" analysis, with the aim of decoupling the selections in the different topologies. In any case, it is not strictly necessary here.

[3]Acoplanarity is defined as the complement to 180^o of the difference in the azimuthal angle of the two charged particles, or of the two forced jets in case of larger multiplicity.

$<E_{cm}>$ (GeV)	191.6	195.6	199.6	201.7	204.9	206.7	208.2	207
$\int\mathcal{L}$ (pb^{-1})	25.8	76.8	84.3	40.5	78.3	78.8	7.2	60.2
	$3 \leq \Delta M_{\tilde{\nu}} < 5$ GeV/c^2							
Data	2	13	17	7	8	11	1	10
MC	$6.0^{+0.7}_{-0.4}$	$17.4^{+1.9}_{-1.2}$	$17.9^{+1.7}_{-1.2}$	$8.7^{+0.8}_{-0.6}$	$9.8^{+1.3}_{-0.8}$	$9.9^{+1.3}_{-0.8}$	$0.9^{+0.1}_{-0.1}$	$18.8^{+1.5}_{-1.1}$
	$5 \leq \Delta M_{\tilde{\nu}} < 10$ GeV/c^2							
Data	2	2	4	5	0	0	0	4
MC	$1.3^{+0.4}_{-0.2}$	$3.8^{+1.1}_{-0.5}$	$4.2^{+1.0}_{-0.4}$	$2.1^{+0.5}_{-0.2}$	$1.0^{+0.7}_{-0.2}$	$1.0^{+0.7}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	$3.6^{+0.8}_{-0.4}$
	$10 \leq \Delta M_{\tilde{\nu}} < 25$ GeV/c^2							
Data	1	5	7	1	5	3	0	3
MC	$1.6^{+0.4}_{-0.1}$	$5.0^{+1.0}_{-0.3}$	$5.1^{+0.9}_{-0.3}$	$2.5^{+0.5}_{-0.2}$	$3.7^{+0.8}_{-0.3}$	$3.7^{+0.8}_{-0.3}$	$0.3^{+0.1}_{-0.1}$	$2.3^{+0.6}_{-0.2}$
	$25 \leq \Delta M_{\tilde{\nu}} < 35$ GeV/c^2							
Data	2	11	5	3	5	8	0	3
MC	$2.8^{+0.4}_{-0.2}$	$9.0^{+1.1}_{-0.4}$	$8.5^{+0.9}_{-0.3}$	$4.1^{+0.5}_{-0.2}$	$5.5^{+0.8}_{-0.3}$	$5.6^{+0.8}_{-0.3}$	$0.5^{+0.1}_{-0.1}$	$5.3^{+0.7}_{-0.2}$
	$35 \leq \Delta M_{\tilde{\nu}} < 50$ GeV/c^2							
Data	6	20	10	4	11	10	2	10
MC	$5.5^{+0.4}_{-0.2}$	$16.0^{+1.1}_{-0.5}$	$15.5^{+0.9}_{-0.4}$	$7.3^{+0.5}_{-0.2}$	$12.8^{+0.8}_{-0.3}$	$12.9^{+0.8}_{-0.3}$	$1.2^{+0.1}_{-0.1}$	$11.7^{+0.7}_{-0.3}$
	50 GeV/$c^2 \leq \Delta M_{\tilde{\nu}}$							
Data	9	32	14	5	22	18	0	16
MC	$8.4^{+0.5}_{-0.2}$	$23.8^{+1.2}_{-0.6}$	$24.0^{+1.1}_{-0.5}$	$11.5^{+0.6}_{-0.3}$	$18.6^{+0.8}_{-0.3}$	$18.7^{+0.8}_{-0.3}$	$1.7^{+0.1}_{-0.1}$	$14.2^{+0.6}_{-0.3}$
	TOTAL (logical .OR. between different $\Delta M_{\tilde{\nu}}$ windows)							
Data	10	52	34	13	37	36	3	31
MC	$15.7^{+0.8}_{-0.5}$	$46.2^{+2.2}_{-1.6}$	$43.9^{+1.9}_{-1.3}$	$21.2^{+0.9}_{-0.7}$	$33.2^{+1.5}_{-1.0}$	$33.4^{+1.5}_{-0.9}$	$3.1^{+0.1}_{-0.1}$	$38.8^{+1.7}_{-1.2}$

Table 1: The number of events observed in data and the expected number of background events in the search for a pair of charginos both decaying into a sneutrino and a charged lepton, at the centre-of-mass energies collected by DELPHI in 1999 and 2000. The last column corresponds to the data collected in year 2000 with the TPC not fully operational (at their mean centre-of-mass energy).

There was no evidence of excess above the SM expectations: figure 2 (b) displays the 95% CL upper limit of the chargino cross-section at the reference centre-of-mass energy of 208 GeV, as function of the masses of the chargino and of the sneutrino. If that exclusion is compared with the theoretical expectation of the same cross-section (in figure 2 (c) the minimal expected $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$ cross-section is shown as function of $M_{\tilde{\chi}_1^\pm}$), a region in the plane ($M_{\tilde{\chi}_1^\pm}$,$M_{\tilde{\nu}}$) can be excluded at the same confidence level. Such excluded region is shown in figure 2 (d).

The exclusion when $0 < \Delta M_{\tilde{\nu}} < 3$ GeV/c^2, as obtained with the results of the search for nearly mass degenerate charginos, can be derived from figure 1 (d), by simply substituting ΔM with $\Delta M_{\tilde{\nu}}$ in the ordinate. The same observation on the conservativeness of the limits obtained when the chargino decays into two bodies also holds for the search at $\Delta M_{\tilde{\nu}} < 3$ GeV/c^2, since the efficiencies are estimated from samples of three body decays. For $M_{\tilde{\chi}_1^\pm} < 55$ GeV/c^2, only a narrow band that corresponds to $0 < \Delta M_{\tilde{\nu}} < 200$ MeV/c^2 cannot be excluded by DELPHI.

If also the stau, or some other charged slepton, has a mass which is intermediate between the mass of the chargino and that of the sneutrino, figure 2 (b) should be interpreted as the 95% CL upper limit of the chargino cross-section times its branching ratio into $l^\pm\tilde{\nu}$.

4.4 Search for $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$

Searches for $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production with $\tilde{\chi}^0_2 \to q\bar{q}\tilde{\chi}^0_1$, $\tilde{\chi}^0_2 \to \mu^+\mu^-\tilde{\chi}^0_1$, $\tilde{\chi}^0_2 \to e^+e^-\tilde{\chi}^0_1$, $\tilde{\chi}^0_2 \to Z\tilde{\chi}^0_1$, and $\tilde{\chi}^0_2 \to \tilde{\tau}\tau$ decays have been presented in [12]. Limits for production cross-section times branching ratio to the corresponding final state ranged typically from 0.05 pb to 0.2 pb, depending primarily on the mass difference $M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1}$.

Since in AMSB $M_1/M_2 \sim 2.8$, and $M_{\tilde{\chi}^0_1} \sim M_{\tilde{\chi}^\pm_1} \sim M_2$ and $M_{\tilde{\chi}^0_2} \sim M_1$, there is relatively little phase space available for the production of $\tilde{\chi}^0_1\tilde{\chi}^0_2$ at LEP energies. Only if $\tilde{\chi}^0_1$ is sufficiently light a $\tilde{\chi}^0_2$ almost three times as heavy can be produced in association, as $M_{\tilde{\chi}^0_1} + M_{\tilde{\chi}^0_2}$ must be below $\sqrt{s}$. In that case, the $\tilde{\chi}^0_2$ decays mainly to $\tilde{\chi}^0_1 Z$ and $\tilde{\chi}^\pm_1 W^\mp$ [9]. For the $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z$ decay, the results of the neutralino searches presented in [12] can be directly used. Since in AMSB scenarios the chargino is nearly mass degenerate with the neutralino, the decay $\tilde{\chi}^0_2 \to \tilde{\chi}^\pm_1 W^\mp$, with $\tilde{\chi}^\pm_1 \to \pi^\pm\tilde{\chi}^0_1$ and $W \to q\bar{q}'$, results in the same final state as $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 q\bar{q}$. Also in this case, limits on $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production with the above final state presented in [12] can be used. On the other hand, when the W decays leptonically, the visible objects in the final states are different from those of the standard search for neutralinos, because of the soft particles from the chargino decay, which can be relevant in a low multiplicity environment. A dedicated search would be needed, not considered in the present paper.

If there are sleptons with a mass between $M_{\tilde{\chi}^0_1}$ and $M_{\tilde{\chi}^0_2}$, cascade decays of $\tilde{\chi}^0_2$ ($\tilde{\chi}^0_2 \to \tilde{l}l$, $\tilde{l} \to \tilde{\chi}^0_1 l$) can take place. In this case there are two mass differences ($\Delta M_{\tilde{\ell}}$) characterizing the process: $M_{\tilde{\chi}^0_2} - M_{\tilde{\ell}}$ and $M_{\tilde{\ell}} - M_{\tilde{\chi}^0_1}$. It was verified that if $\tilde{l} = (\tilde{\mu}, \tilde{e})$ the results of the searches for $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_1$, where $\tilde{\chi}^0_2 \to \mu^+\mu^-\tilde{\chi}^0_1$ or $\tilde{\chi}^0_2 \to e^+e^-\tilde{\chi}^0_1$, can be used, provided that from the $\Delta M_{\tilde{\ell}}$ definitions above the one giving the more conservative result is used in place of $M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1}$.

For $\tilde{\tau}_1$ as the intermediate slepton, the tau cascade search described in [12] was studied in a wider range of $M_{\tilde{\tau}_1} - M_{\tilde{\chi}^0_1}$. The tau cascade search is sensitive to $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production with $\tilde{\chi}^0_2 \to \tilde{\tau}\tau$ and $\tilde{\tau} \to \tilde{\chi}^0_1\tau$, where the second τ produced has very low energy. At the preselection level, well reconstructed low multiplicity events with missing energy, missing mass, and no more than two reconstructed jets were selected. In particular, the total visible energy including badly reconstructed tracks was required to be less than 140 GeV, the number of charged particles was required to be at least two and at most eight, and events with more than four neutral particles were rejected. Two or more of the charged particles also had to satisfy stricter criteria on reconstruction and impact parameters. There was no evidence of excess above the SM expectations after the selection (see [12]). The resulting cross-section limits at the 95% CL are shown in figure 3.

Light sneutrinos lead to an undetectable $\tilde{\chi}^0_2 \to \tilde{\nu}\bar{\nu}$ and $\tilde{\nu} \to \tilde{\chi}^0_1\nu$ decay chain.

4.5 Search for a charged slepton as the LSP

It is rather unlikely that a stau (or another charged slepton) is the LSP in the AMSB. In a scan of the parameter space performed with ISAJET 7.63 [9] no points were obtained with $M_{\tilde{\chi}^0_1} > M_{\tilde{\tau}}$. However, the calculations in [4] still allow some corner in the space of the AMSB parameters with the $\tilde{\tau}_1$ being the LSP. In this case, if R-parity is conserved, the stau must be stable. The DELPHI results of the search for heavy stable charged particles were presented in [15], together with the description of the method used in the analysis.

Staus are expected to be almost maximally mixed in AMSB [4]. Reference [15] showed that the results of the search for heavy stable charged particles in DELPHI can exclude a stable $\tilde{\tau}_1$ with mass below 96 GeV/c^2 at the 95% CL, even at the level of mixing that gives the lowest $\tilde{\tau}_1{}^+\tilde{\tau}_1{}^-$ production cross-section.

4.6 Search for cascades from sleptons

The decay $\tilde{l}^{\pm} \to \tilde{\chi}_1^{\pm}\nu_l$ is practically undetectable, due to the softness of the visible decay products of the chargino. It accounts, however, for two thirds of the total decay width, if the chargino and the neutralino are the only SUSY particles lighter than the charged slepton. The only visible cascades originating from that slepton (in particular a stau, since it is expected to be the lightest) in AMSB are therefore:

- $\tilde{\tau}_1 \to \tilde{\chi}_1^0\tau$, the same channel searched for in MSSM;
- $\tilde{\tau}_1 \to \tilde{\nu}_\tau f f'$, with visible final states that can be similar to the chargino ones.

In the case of the sneutrino production, the decay $\tilde{\nu} \to \tilde{\chi}_1^0\nu$ is clearly invisible. On the other hand, $\tilde{\nu} \to \tilde{\chi}_1^+ l^-$ can be observed, with similar techniques as those used in the usual searches for sleptons.

No dedicated search for those cascades was studied for the present paper. However, limits on cross-section times branching ratio can be derived by interpreting the results of the searches for "standard" charginos and sleptons listed in [12].

4.7 Search for the SUSY Higgs boson

Since in AMSB $M_{\mathrm{A}} \gg M_{\mathrm{Z}}$, the lightest supersymmetric neutral Higgs h^0 has the same couplings as the SM Higgs boson, and the limits obtained on the mass of the Higgs in the SM can be translated into the same lower limits on the mass of the h^0 in AMSB, provided that the decay branching fractions of the Higgs into supersymmetric particles are negligible.

If $M_{\mathrm{A}} \gg M_{\mathrm{Z}}$, h^0 can be produced at LEP only in association with the Z (higgsstrahlung), and with the same cross-section as in the SM. When there are SUSY particles lighter than $M_{\mathrm{h}^0}/2$, also decays of the Higgs into those particles are allowed. This is the case for AMSB, when there are light winos, sneutrinos or charged sleptons. Possible SUSY decays of the h^0 are:

- $\mathrm{h}^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\nu}\tilde{\nu}$, all invisible or practically invisible in AMSB, apart from some possible cascades;
- $\mathrm{h}^0 \to \tilde{l}^+\tilde{l}^-$, the visibility of which depends on the mass difference between the slepton and the LSP.

The DELPHI bound on the SM Higgs mass is $M_H > 114.1$ GeV/c^2 at the 95% CL [16]. DELPHI measured also the limit on the production cross-section of an invisibly decaying Higgs boson [17]. Assuming a 100% branching ratio into invisible particles, DELPHI can exclude Higgs masses below 112.1 GeV/c^2. Reference [17] shows how the limit on the mass of the lightest supersymmetric Higgs boson depends on the branching fraction into invisible states, assuming that all other decay modes are the SM ones. That limit starts from 114.1 GeV/c^2 when BR($\mathrm{h}^0 \to$ inv.) = 0 (that is, the h^0 decays according to the

SM); it reaches a minimum of 112.0 when that branching ratio is between 0.8 and 0.9; and it goes to 112.1 GeV/c^2 when BR($\mathrm{h}^0 \to \mathrm{inv.}) = 1$. The same limits on M_{h^0} apply in AMSB, provided there are no visible SUSY decays with sizeable branching fractions.

5 Constraints on the AMSB spectrum

The negative results of the searches described in this paper were used to constrain the AMSB parameter space. To do that, the experimental exclusions measured were compared with the mass spectra produced by ISAJET 7.63 [9]. A scan over the AMSB parameters was done by varying them in the following ranges: $1 < m_{3/2} < 50$ TeV/c^2; $0 < m_0 < 1000$ GeV/c^2; $1.5 < \tan\beta < 45$; both positive and negative μ. 600,000 SUSY points were generated by choosing at random the parameters within the bounds above. A bigger density of points was allowed in the regions of the space of the parameters near the expected limits or reproducing however some sensitive structure.

With the AMSB model as implemented in that version of ISAJET, only the negative results from the search for nearly mass-degenerate chargino and neutralino, the search for neutral SM-like and invisibly decaying Higgs, and the search for charginos decaying into a sneutrino and a charged lepton were relevant to put the constraints, besides the limit on the non SM Z width from LEP1. The other searches described in this paper were found to be redundant to constrain the model. They have been listed all together to help anyone wanting to test any departure from the implementation of AMSB as coded in ISAJET.

Figure 4 (a) shows the points in the plane $(m_0, m_{3/2})$ generated with ISAJET. The region of the space with no points was not allowed by ISAJET, since there one or more sparticles would result to be tachyonic. This implies a certain degree of correlation between m_0 and $m_{3/2}$, since by cutting away slices at low $m_{3/2}$ the value of the lowest admissible m_0 increases. Figure 4 (b) shows the points that remain after the application of the model independent bounds on the chargino and sneutrino masses obtained at LEP1. Finally, in figure 4 (c) are plotted the points that remain after having applied all the results of the searches described in this paper.

Since the Higgs is preferably light, most of the exclusion in the space of the AMSB parameters arises from the negative results of the searches for the SM and the invisibly decaying Higgs boson. The negative results of the other searches enlarged further the rejection, especially at low $m_{3/2}$ (chargino searches) and low m_0 (searches with sleptons). The effect of the search for the standard and invisible Higgs can be seen in figure 5. Figure 5 (a) shows all the points generated with ISAJET in the plane $(M_{\mathrm{h}^0}, \tan\beta)$. Figure 5 (b) shows all the points remaining after the LEP1 chargino and sneutrino exclusions. Figure 5 (c) shows the points surviving after the negative results of the SM and invisibly decaying Higgs searches in DELPHI. After that stage, still some points with $M_{\mathrm{h}^0} < 114$ GeV/c^2 could not be excluded, because of the presence of light SUSY particles that give rise to unexplored topologies in the Higgs boson decay. However, Figure 5 (d) shows that, after having applied the full set of results presented in this paper to constrain AMSB, no point survived with a mass of the lightest Higgs below the SM limit of 114.1 GeV/c^2.

It is interesting to observe the impact of the searches for AMSB on some sparticle masses. Figure 6 shows the number of points generated by ISAJET and passing the three steps of selection as in figure 4, as a function of the mass of the lightest neutralino and

	$\mu < 0$	$\mu > 0$
m_0	> 191 GeV/c^2	> 158 GeV/c^2
$m_{3/2}$	> 27.2 TeV/c^2	> 23.6 TeV/c^2
$\tan\beta$	> 5.8	> 4.0
$M_{\tilde{\chi}}$	> 75 GeV/c^2	> 68 GeV/c^2
$M_{\tilde{\nu}}$	> 127 GeV/c^2	> 98 GeV/c^2
$M_{\tilde{\ell}}$	> 82 GeV/c^2	> 72 GeV/c^2

Table 2: Bounds on the AMSB parameters and on the sparticle masses, as function of sign(μ), obtained by applying the 95% CL limits derived in the searches for AMSB scenarios. Given the small mass splitting, at the level of few hundred MeV/c^2, $M_{\tilde{\chi}}$ can be viewed both as $M_{\tilde{\chi}_1^0}$ or $M_{\tilde{\chi}_1^\pm}$. $M_{\tilde{\nu}}$ is the mass of the lightest sneutrino, always the tau sneutrino in the model. $M_{\tilde{\ell}}$ refers to the lightest charged slepton, always a stau in the model.

of the lightest sneutrino. Neutralinos lighter than 68 GeV/c^2 and sneutrinos lighter than 98 GeV/c^2 are excluded in AMSB.

Table 2 summarizes the bounds on the AMSB parameters and on the mass of some sparticle obtained by applying the 95% CL exclusions from the searches described in the previos paragraphs to the ISAJET spectra. They are listed separately as function of the sign of μ. Little shifts of those bounds are still possible, in principle, when applying the full next-to-leading order corrections to the model.

According to the bounds listed in table 2, the possible AMSB explanation for a light sneutrino ($M_{\tilde{\nu}}$ less than about 80 GeV/c^2), suggested to cure some of the discrepancies in the fit of the precision electroweak data [18], is ruled out by the results of the searches for AMSB scenarios in DELPHI.

6 Conclusions

The results of the searches performed using the data collected with the DELPHI detector at LEP, and relevant to explore AMSB scenarios, have been presented. An interpretation of the limits obtained in searches motivated by other SUSY breaking scenarios was used, whenever appropriate. In addition, some of the searches were developed specifically to improve the sensitivity to AMSB. There is no evidence for a signal beyond the Standard Model, and limits are set on the sparticle production in the AMSB framework.

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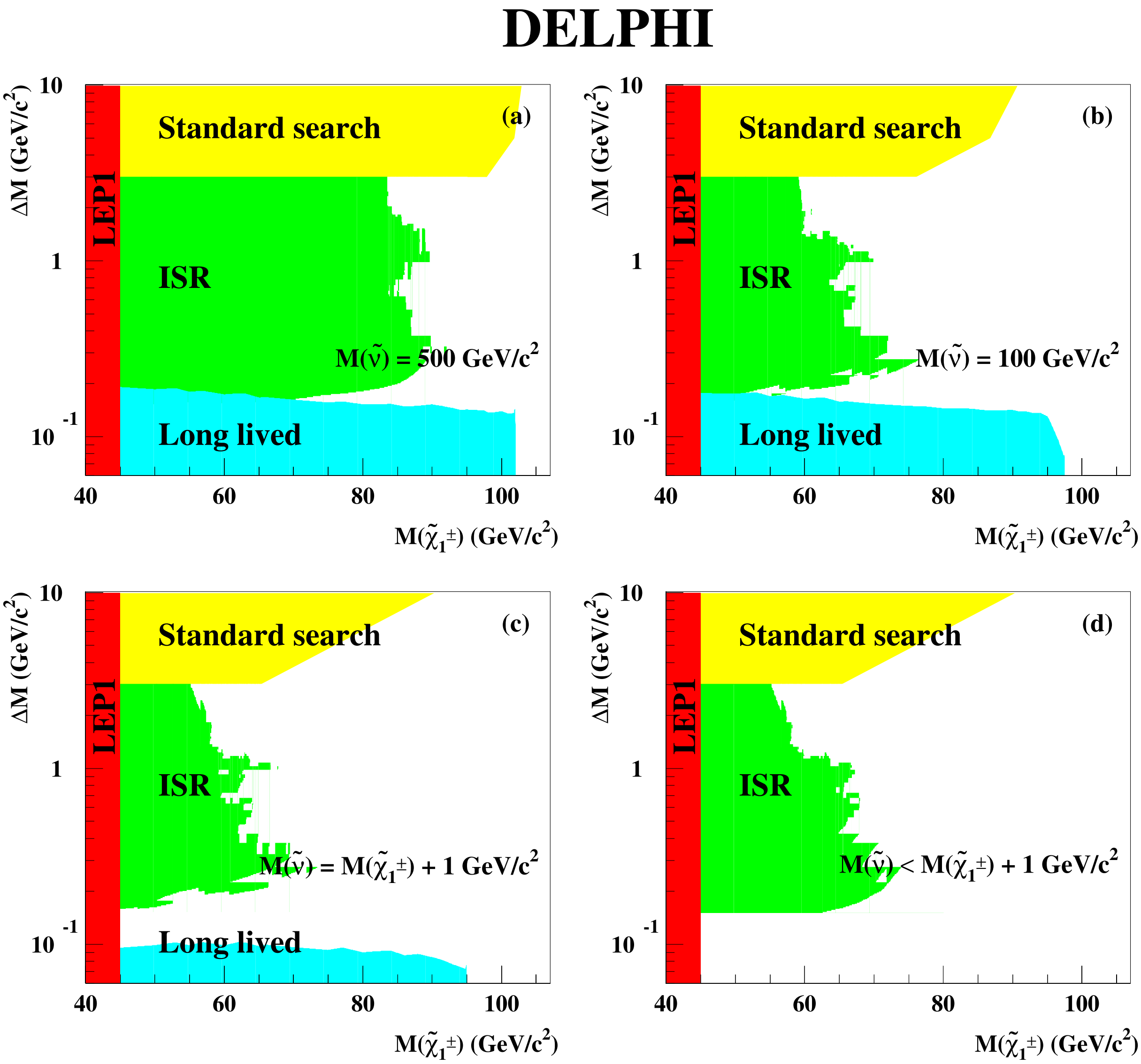

Figure 1: Regions in the plane $(M_{\tilde{\chi}_1^\pm}, \Delta M = M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0})$ excluded by DELPHI at the 95% CL when the chargino is gaugino-like, as in AMSB. The standard search for high ΔM charginos, the search for soft particles accompanied by ISR, and the search for long-lived charginos were used. The scenarios constrained in the four plots are: (a) $M_{\tilde{\nu}} \geq 500$ GeV$/c^2$; (b) $M_{\tilde{\nu}} \geq 100$ GeV$/c^2$; (c) $M_{\tilde{\nu}} \geq M_{\tilde{\chi}_1^\pm} + 1$ GeV$/c^2$ (long-lived charginos); (d) $M_{\tilde{\nu}} < M_{\tilde{\chi}_1^\pm} + 1$ GeV$/c^2$ (short-lived charginos). The exclusions in (a), (b) and (c) holds conservatively also for heavier sneutrinos. Charginos lighter that 45 GeV$/c^2$ were already excluded at LEP1.

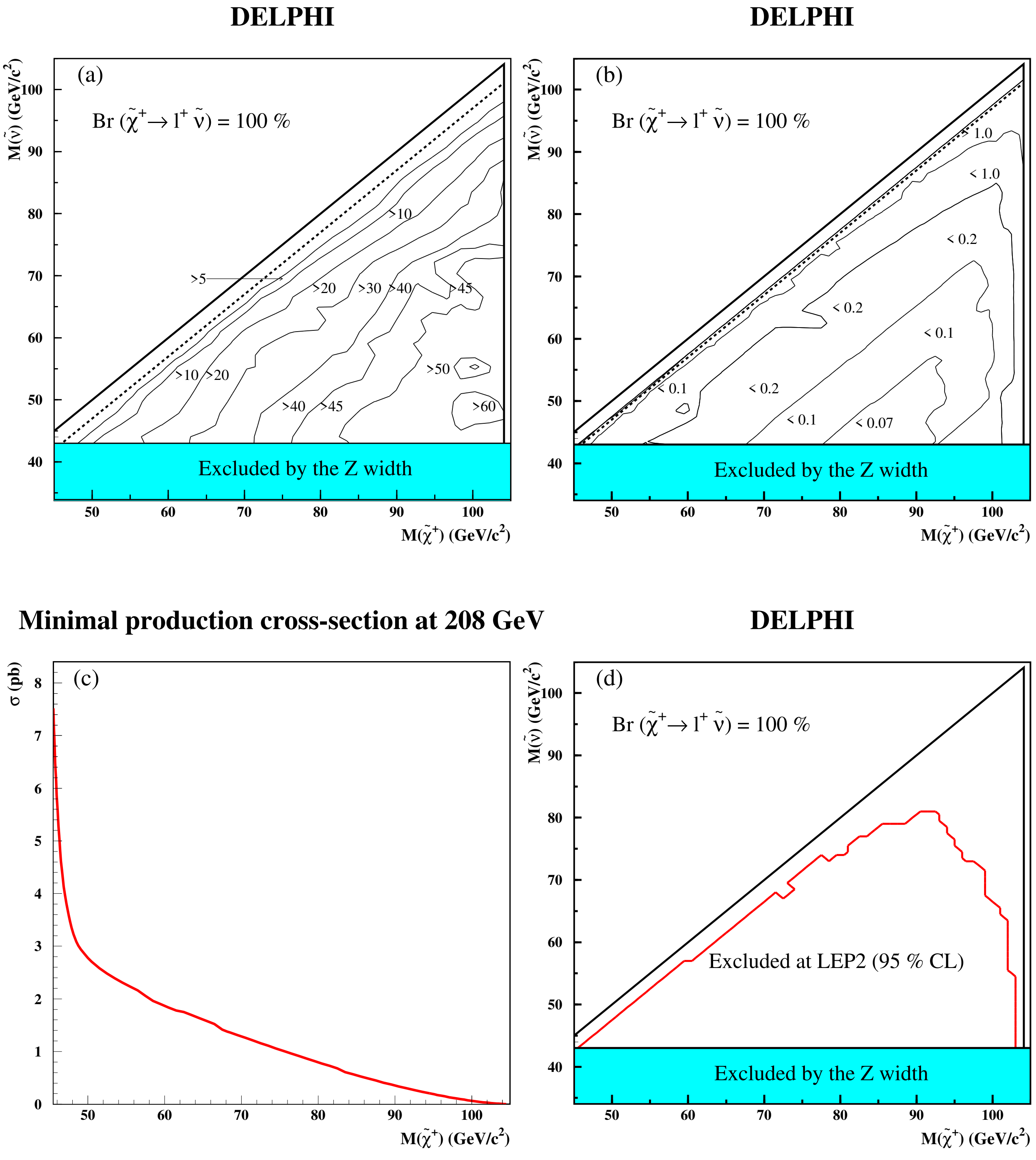

Figure 2: (a) Chargino pair production detection efficiencies (%) for the fully leptonic decay channel at $\sqrt{s}$=208 GeV in the ($M_{\tilde{\chi}_1^\pm}$,$M_{\tilde{\nu}}$) plane; a 100% branching ratio of $\tilde{\chi}_1^\pm \to \tilde{\nu} l^\pm$ is assumed. (b) Equivalent excluded cross-section at the 95% CL (in pb) at 208 GeV. (c) Minimal expected $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ cross-section in AMSB, as function of the mass of the chargino. (d) Region excluded at the 95% CL in the plane ($M_{\tilde{\chi}_1^\pm}$,$M_{\tilde{\nu}}$) by the search described in the text. Sneutrinos lighter than 43 GeV/c^2 were already excluded at LEP1.

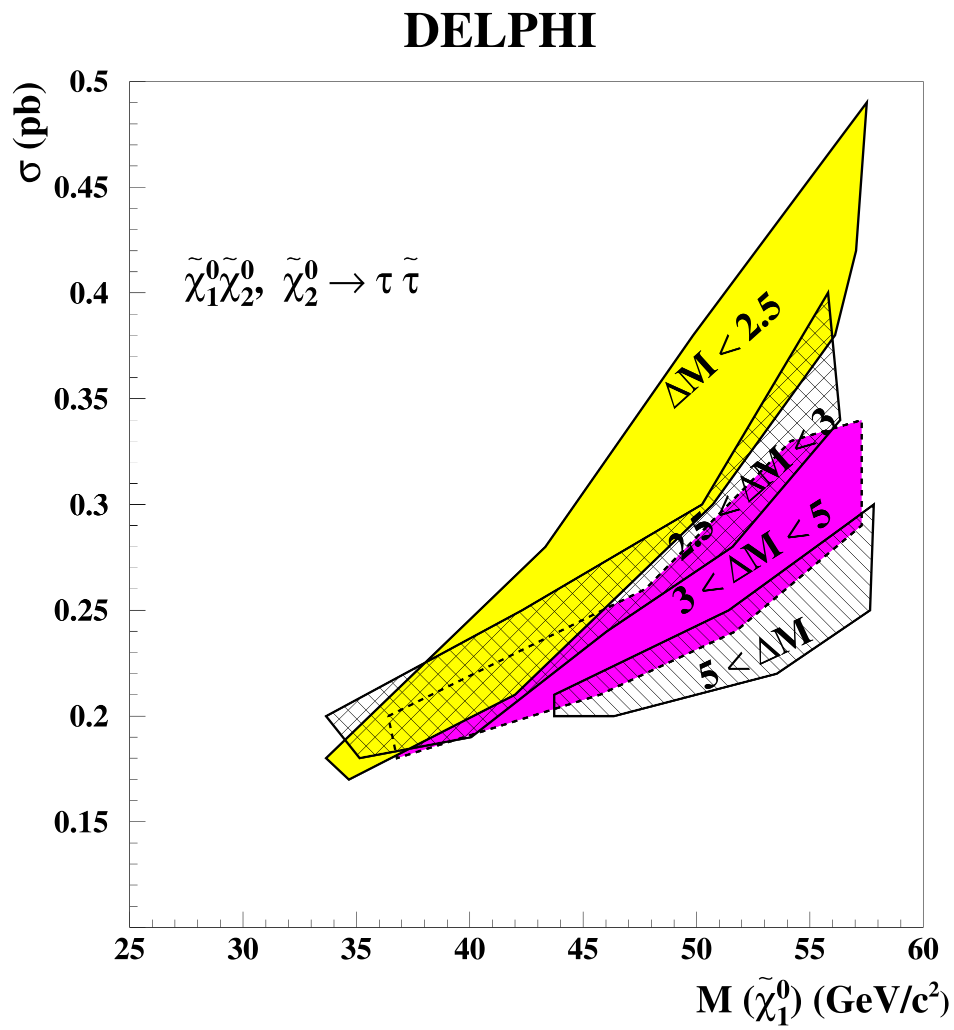

Figure 3: Cross-section limits at the 95% CL for the $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production when $\tilde{\chi}^0_2$ decays entirely to $\tilde{\tau}_1\tau$. The limits are shown for several ranges of ΔM=$M_{\tilde{\tau}_1}$-$M_{\tilde{\chi}^0_1}$ in GeV/c^2. The widths of the bands are due to dependence of the limit on ΔM and to statistical fluctuations of the efficiency due to limited Monte Carlo statistics.

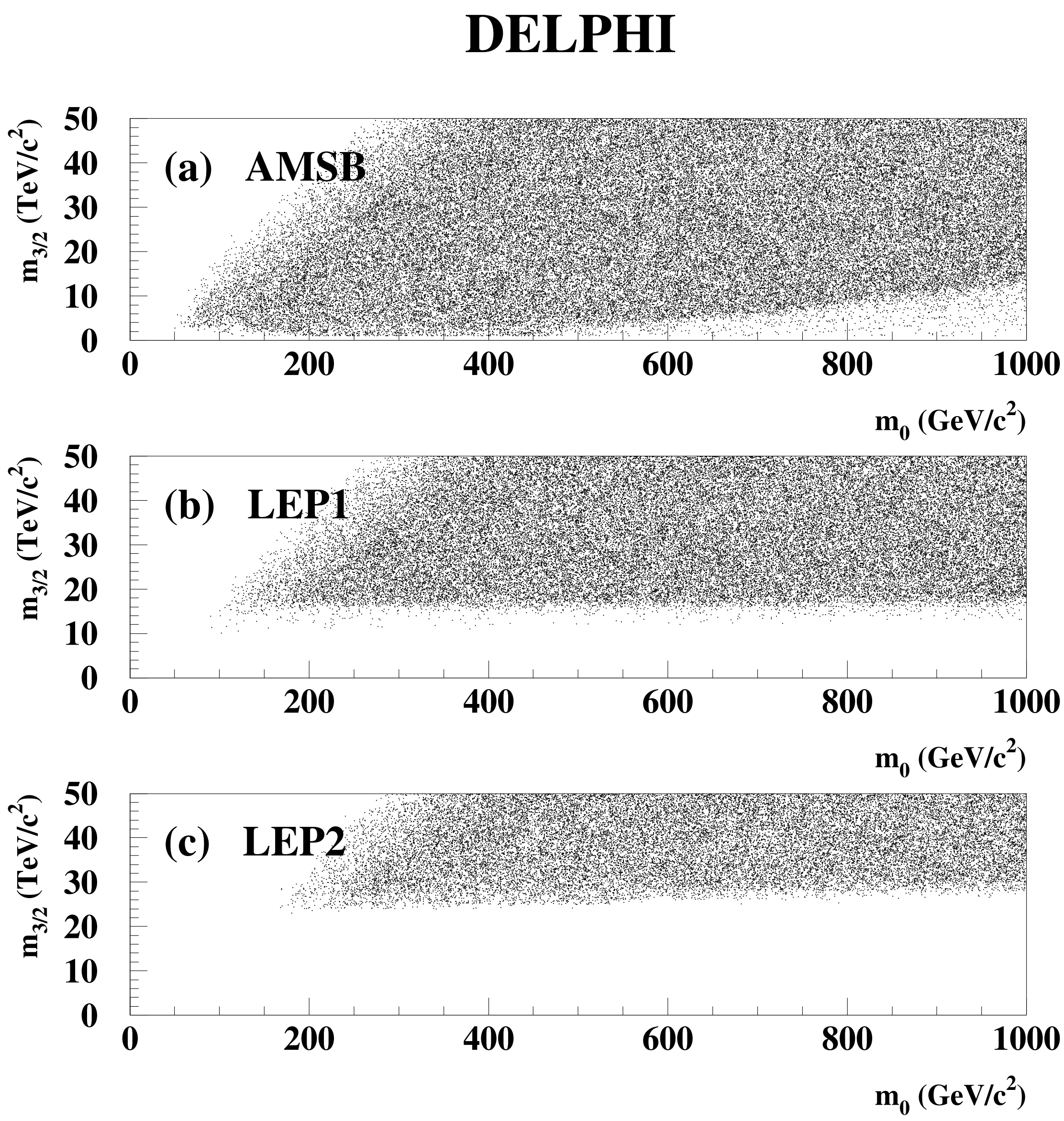

Figure 4: (a) physically allowed m_0 and $m_{3/2}$ parameters in AMSB, as obtained in a scan of the AMSB parameter space with ISAJET, as described in the text. (b) points remaining after having applied the chargino and sneutrino mass bounds of LEP1. (c) set of points from the scan remaining after having considered all the results of the searches described in this work.

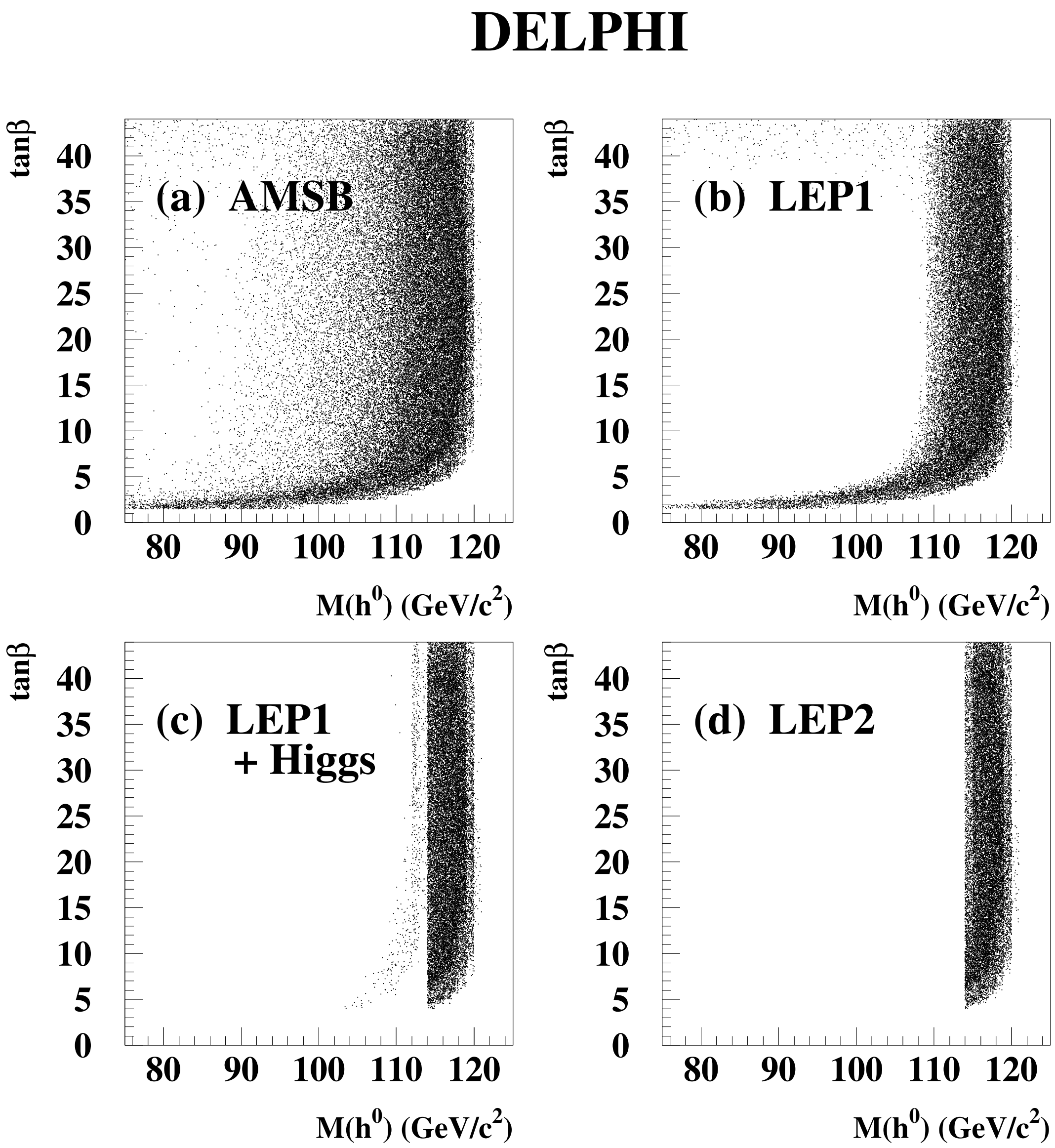

Figure 5: (a) physically allowed M_{h^0} and $\tan\beta$ in AMSB, as obtained in a scan of the AMSB parameter space with ISAJET, as described in the text. (b) points remaining after having applied the chargino and sneutrino mass bounds of LEP1. (c) points remaining after the negative results of the searches for the SM and invisibly decaying Higgs bosons. (d) set of points remaining finally after having considered all the results of the searches described in this work. No points survived for which $M_{\mathrm{h}^0} < 114.1$ GeV/c^2.

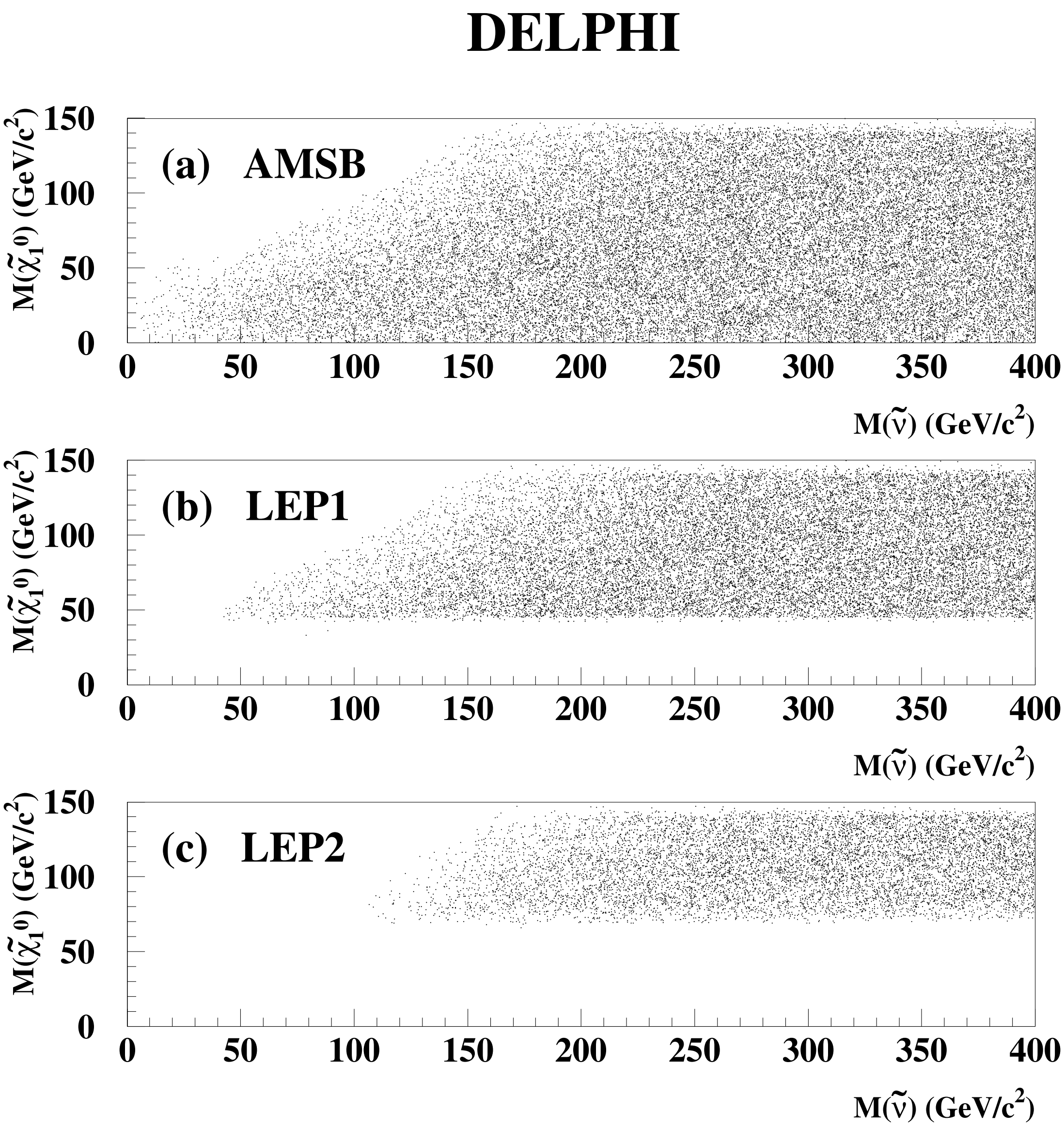

Figure 6: (a) physically allowed $M_{\tilde{\chi}_1^0}$ and $M_{\tilde{\nu}}$ in AMSB, as obtained in a scan of the AMSB parameter space with ISAJET, as described in the text. (b) points remaining after having applied the chargino and sneutrino mass bounds of LEP1. (c) set of points from the scan remaining after having considered all the results of the searches described in this work. No points survived for which $M_{\tilde{\chi}_1^0} < 68$ GeV$/c^2$ or $M_{\tilde{\nu}} < 98$ GeV$/c^2$.