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Search for Charginos and Neutralinos in e^+e^- collisions at $\sqrt{s} = 192 - 202$ GeV

The L3 collaboration

Abstract

We report the result of a search for charginos and neutralinos, in e^+e^- collisions at centre-of-mass energies between 192 GeV and 202 GeV at LEP. No evidence for such particles is found in a data sample of 233 pb^{-1}. Improved upper limits on the production cross sections of these particles and new lower limits on their masses are set. Under the assumptions of common gaugino and scalar masses at the GUT scale, we set absolute lower limits on the masses of the lightest neutralino of 37.5 GeV and of the lightest chargino of 80.5 GeV.

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1 Introduction

One of the main goals of the LEP experiments is to search for new particles predicted by theories beyond the Standard Model. In this letter we report on searches for unstable charginos and neutralinos. These particles are predicted by supersymmetric theories (SUSY) [1]. In SUSY theories with minimal particle content (MSSM) [2], in addition to the ordinary particles, there is a supersymmetric spectrum of particles with spins which differ by one half with respect to their Standard Model partners.

Charginos ($\tilde{\chi}^{\pm}_{1,2}$), the supersymmetric partners of $\mathrm{W}^{\pm}$ and $\mathrm{H}^{\pm}$, are pair produced via s-channel γ/Z exchange. The production cross section can be reduced by an order of magnitude when the t-channel scalar neutrino ($\tilde{\nu}$) exchange is important. Neutralinos, the supersymmetric partners of Z, γ, and neutral Higgs bosons, are pair produced $\mathrm{e^+e^-} \to \tilde{\chi}^0_i\tilde{\chi}^0_j$ ($i,j = 1,\ldots,4$; ordered by their masses) via s-channel Z exchange and their production cross section can be enhanced by t-channel exchange of a scalar electron ($\tilde{\mathrm{e}}^{\pm}$).

Short-lived supersymmetric particles are expected in R-parity conserving SUSY models. The R-parity is a quantum number which distinguishes ordinary particles from supersymmetric particles. If R-parity is conserved, supersymmetric particles are pair-produced and the lightest supersymmetric particle, assumed to be the lightest neutralino, $\tilde{\chi}^0_1$, is stable. The neutralino is weakly-interacting and escapes detection. In this letter we assume R-parity conservation, which implies that the decay chain of supersymmetric particles always contain, besides standard particles, two invisible neutralinos causing the missing energy signature.

When the masses of the scalar leptons and the charged Higgs bosons ($\mathrm{H}^{\pm}$) are very large, the $\tilde{\chi}^{\pm}_1$ decays via W^*: $\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1\mathrm{W}^* \to \tilde{\chi}^0_1 f\bar{f}'$. If the $\tilde{\ell}^{\pm}$ and $\tilde{\nu}$ masses are comparable to M_{W} the chargino also decays via virtual scalar lepton or scalar neutrino and the leptonic branching fraction is enhanced. Finally for $\tilde{\ell}^{\pm}$ and $\tilde{\nu}$ lighter than the chargino, the decay modes $\tilde{\chi}^{\pm}_1 \to \tilde{\ell}^{\pm}\nu$ or $\tilde{\chi}^{\pm}_1 \to \tilde{\nu}\ell^{\pm}$ become dominant. When the masses of the neutral SUSY Higgs bosons (h^0, A^0) and of the scalar leptons are very large, the heavier neutralinos ($\tilde{\chi}^0_j$, $j \geq 2$) decay via Z^*: $\tilde{\chi}^0_j \to \tilde{\chi}^0_k\mathrm{Z}^* \to \tilde{\chi}^0_k f\bar{f}$ with $k < j$. For a chargino lighter than neutralinos, the latter decay via W^* such as $\tilde{\chi}^0_j \to \tilde{\chi}^{\pm}_1 f\bar{f}'$. If the scalar lepton masses are comparable to the Z mass, the neutralino decays also via a virtual scalar lepton, enhancing the leptonic branching fraction. Finally, for $\tilde{\nu}$ and $\tilde{\ell}^{\pm}$ lighter than neutralinos the two-body decays $\tilde{\chi}^0_j \to \tilde{\ell}^{\pm}\ell^{\mp}$ or $\tilde{\chi}^0_j \to \tilde{\nu}\nu$ ($\mathrm{j} \geq 2$) become dominant. The radiative decays $\tilde{\chi}^0_j \to \tilde{\chi}^0_k\gamma$ are also possible via higher-order diagrams.

The searches presented in this note follow the same analysis procedures as in our previous publications [3,4]. These new results are combined with those obtained previously by L3 at the Z peak [5] and at centre-of-mass energies up to $\sqrt{s} = 189$ GeV [3,4].

2 Data Sample and Simulation

We present the analysis of data collected by the L3 detector [6] in 1999, corresponding to an integrated luminosity of 29.7 pb^{-1}, 83.7 pb^{-1}, 82.8 pb^{-1}, and 37.0 pb^{-1} at respective centre-of-mass energies of 191.6 GeV, 195.5 GeV, 199.5 GeV and 201.7 GeV, denoted hereafter as $\sqrt{s} = 200$ GeV.

Standard Model reactions are simulated with the following Monte Carlo generators: `PYTHIA` [7] for $\mathrm{e^+e^-} \to \mathrm{q\bar{q}}$, $\mathrm{e^+e^-} \to \mathrm{Z\,e^+e^-}$ and $\mathrm{e^+e^-} \to \gamma/\mathrm{Z}\,\gamma/\mathrm{Z}$; `EXCALIBUR` [8] for $\mathrm{e^+e^-} \to \mathrm{W^{\pm}\,e^{\mp}}\nu$; `KORALZ` [9] for $\mathrm{e^+e^-} \to \mu^+\mu^-$ and $\mathrm{e^+e^-} \to \tau^+\tau^-$; `BHWIDE` [10] for $\mathrm{e^+e^-} \to \mathrm{e^+e^-}$; `KORALW` [11] for $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$; two-photon interaction processes have been simulated using `DIAG36` [12]

($e^+e^- \to e^+e^-\ell^+\ell^-$) and PHOJET [13] ($e^+e^- \to e^+e^-$ hadrons), requiring at least 3 GeV for the invariant mass of the two-photon system. The number of simulated events for each background process is equivalent to more than 100 times the statistics of the collected data sample except for two-photon interactions for which it is more than two times the data statistics.

Signal events are generated with the Monte Carlo program SUSYGEN [14], for masses of SUSY particles ($M_{\rm SUSY}$) ranging from 45 GeV up to the kinematic limit and for ΔM values ($\Delta M = M_{\rm SUSY} - M_{\tilde{\chi}^0_1}$) between 3 GeV and $M_{\rm SUSY} - 1$ GeV. The explicit two-body decay branching ratios for charginos $\tilde{\chi}^\pm_1 \to \tilde{\nu}\ell^\pm, \tilde{\ell}^\pm\nu$ or $\tilde{\chi}^0_{2,3,4} \to \tilde{\nu}\nu, \tilde{\ell}\ell$ have been estimated with SUSYGEN.

The detector response is simulated using the GEANT package [15]. It takes into account effects of energy loss, multiple scattering and showering in the detector materials and in the beam pipe. Hadronic interactions are simulated with the GHEISHA program [16]. Time dependent inefficiencies of the different subdetectors are also taken into account in the simulation procedure.

3 Analysis Procedure

Besides the main characteristic of missing transverse momentum, supersymmetric particle signals can be further specified according to the number of leptons or the multiplicity of hadronic jets in the final state. As mentioned in the introduction, chargino pair production gives final states similar to WW production. For neutralinos, we distinguish two classes of detectable processes: $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ and $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2$. For these signals, the final state topologies are given by the Z decay modes. Both for charginos and neutralinos, the event energy is directly related to ΔM ($\Delta M = M_{\rm SUSY} - M_{\tilde{\chi}^0_1}$).

We devise five types of selection criteria oriented to all decays of charginos, as follows: at least two acoplanar leptons (e,μ); hadrons and at least one isolated lepton; at least two acoplanar taus; hadrons and at least one isolated tau; purely hadronic final states with high multiplicity. $\tilde{\chi}^0_2\tilde{\chi}^0_2$ production gives rise to final states very similar to those of chargino pair production, even if with very different branching ratios. Hence, chargino selections based on these five topologies are also effective to select $\tilde{\chi}^0_2\tilde{\chi}^0_2$ events.

The two-acoplanar-jets final state on the other hand deserves a dedicated selection since it accounts for 70% of the decays in $\tilde{\chi}^0_1\tilde{\chi}^0_2$ events, and 28% in $\tilde{\chi}^0_2\tilde{\chi}^0_2$ events.

The signal topologies and the associated background sources depend strongly on ΔM. Therefore the selections are optimised separately for four different ΔM ranges: the very low ΔM range at $3-5$ GeV, the low ΔM range at $10-30$ GeV, the medium ΔM range at $40-70$ GeV and the high ΔM range at $80-94$ GeV. In the low and very low ΔM ranges, the expected topologies for the signal are characterised by a low multiplicity and a low visible energy, and the background is dominated by two-photon interactions. For medium and high ΔM charginos, the signal signatures are very similar to those of W-pair production; in particular for $\Delta M > 80$ GeV on-shell Ws are produced.

The cut values of each selection are *a priori* optimised using Monte Carlo signal and background events. Details of the event selection are given in Ref. [3]. The cut values are reoptimised with respect to our previous publication to take into account the slight differences in luminosity and centre-of-mass energy.

	Low ΔM		Medium ΔM		High ΔM		Combined	
	N_{data}	N_{exp}	N_{data}	N_{exp}	N_{data}	N_{exp}	N_{data}	N_{exp}
$\tilde{\chi}^{\pm}$had	49	62.2	4	4.56	41	40.3	93	106.
$\tilde{\chi}^{\pm}$mix	12	17.4	1	1.33	20	24.6	33	42.3
$\tilde{\chi}^{\pm}$lep	13	5.71	12	12.8	30	27.7	46	38.0
$\tilde{\chi}^{\pm}$	74	77.8	17	18.6	91	92.6	171	177.
$\tilde{\chi}^{0}_{2}$	42	52.1	7	12.5	4	5.04	52	68.2

Table 1: Standard Chargino and Neutralino analyses: number of selected data events and expected backgrounds at $\sqrt{s} = 200$ GeV.

4 Results

All results at $\sqrt{s} = 200$ GeV are summarised in Table 1 for chargino and neutralino selections. The results for the very low and low ΔM selections are shown together. A good agreement between the expected background from Standard Model processes and the selected data is observed.

For intermediate ΔM values different from those chosen for optimisation we choose the combination of selections providing the highest sensitivity [17]. In this combination procedure, we take into account the overlap among the selections within the data and Monte Carlo samples.

Selection efficiencies are very similar to those in our previous publication [3]. Systematic errors on the signal efficiencies are evaluated as in Reference 18, and they are typically 5% relative, dominated by Monte Carlo statistics. Systematic errors on the background prediction are in general 3% except for two-photon processes for which they can be as large as 20%. These errors are taken into account in the calculation of the limits 19.

5 Model independent upper limits on production cross sections

No excess of events is observed and we set upper limits on the chargino and neutralino production cross sections in the framework of the MSSM. Exclusion limits at 95% C.L. are derived taking into account background contributions.

To derive the upper limits on production cross sections and for interpretations in the MSSM we combine the $\sqrt{s} = 200$ GeV data sample with those collected by L3 at lower centre-of-mass energies [3, 17, 18].

The contours of upper limits on the luminosity weighted average production cross section for the process $e^+e^- \to \tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ are shown in Figure 1 assuming $\tilde{\chi}^{\pm}_1 \to W^*\tilde{\chi}^0_1$ for the chargino decay with standard W branching fractions. In most of the kinematically accessible region, cross sections larger than 0.1 pb are excluded.

6 Interpretation in the MSSM

In the MSSM, with Grand Unification assumptions [20], the masses and couplings of the SUSY particles as well as their production cross sections, are entirely described [2] once five parameters

are fixed: $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets, $M \equiv M_2$, the gaugino mass parameter, μ, the higgsino mixing parameter, m_0, the common mass for scalar fermions at the GUT scale, and A, the trilinear coupling in the Higgs sector. The following MSSM parameter space is investigated:

$$\begin{array}{rrlrrl} 0.7 \leq & \tan\beta & \leq 60, & 0 \leq & M_2 & \leq 2000 \text{ GeV}, \\ -2000 \text{ GeV} \leq & \mu & \leq 2000 \text{ GeV}, & 0 \leq & m_0 & \leq 500 \text{ GeV}. \end{array}$$

To derive the absolute limits on the masses of the lightest neutralino and of the lightest chargino, a scan in the MSSM parameter space is performed in steps of 0.2 GeV for M_2, 1.0 GeV for μ and 0.5 GeV for m_0.

Mass eigenstates of scalar quarks and leptons are in general a mixture of the weak eigenstates $\tilde{\mathrm{f}}_R$ and $\tilde{\mathrm{f}}_L$. The mixing between these two states is proportional to the mass of the partner fermion. Hence the mixing can be sizable only for particles of the third generation. The mixing is governed by the parameters A, μ and $\tan\beta$.

All the limits on the cross sections previously shown, combined with the results obtained at lower centre-of-mass energies and with the results of scalar lepton searches obtained at $\sqrt{s} = 200$ GeV [21], can be translated into exclusion regions in the MSSM parameter space. To derive limits in the MSSM, we optimise the global selection for any different point in the parameter space. This is obtained, choosing every time the combination of selections providing the highest sensitivity, given the production cross sections and the decay branching fractions which are calculated with the generator `SUSYGEN`. In general, all limits are evaluated neglecting the mixing in the scalar tau sector.

The effect of the mixing is studied [22] in the mSUGRA framework, and masses and decay branching fractions are recalculated by using the generator `ISAJET` [23]. Mass limits as obtained at $\sqrt{s} = 189$ GeV [3] are checked by scanning on the A parameter between –1000 GeV and 1000 GeV and they are shown to be valid for any mixing.

6.1 Limits on chargino and neutralino masses

In the MSSM, while the cross sections and decay branching fractions of the charginos and neutralinos depend on the masses of the scalar leptons, their masses depend only on M_2, μ and $\tan\beta$. The exclusions in the high m_0 range are derived from chargino and neutralino searches, while for low m_0 the searches for scalar leptons [21], and for photons and missing energy final states [24], also contribute. We also take into account all chargino and neutralino cascade decays:

- $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_2^0\,\mathrm{W}^*$: we observe a slight decrease of the efficiency relative to $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\,\mathrm{W}^*$. The decrease depends on the mass of $\tilde{\chi}_2^0$, which is varied between the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ masses. The lowest efficiency is then used for cascade decays.

- $\tilde{\chi}_{3,4}^0 \to \tilde{\chi}_2^0\,\mathrm{Z}^*$: the efficiency is found to be larger than the efficiency obtained for the $\tilde{\chi}_{3,4}^0 \to \tilde{\chi}_1^0\,\mathrm{Z}^*$ channel, especially in the high ΔM region. The efficiencies obtained in the latter channel are used.

- $\tilde{\chi}_{3,4}^0 \to \tilde{\nu}\nu$: when the $\tilde{\nu}$ becomes detectable through its cascade decays into $\tilde{\chi}_2^0$ or $\tilde{\chi}_1^{\pm}$. This is especially relevant in the mixed region ($\mu \sim -M_2$) for the low $\tan\beta$ values.

Depending on the neutralino-chargino field content, one distinguishes the following cases for the determination of lower limits on the neutralino and chargino masses:

- Higgsino-like $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ ($M_2 \gg |\mu|$): in this case, the production cross sections do not depend on the scalar lepton masses, ΔM is low and decreases with increasing M_2. The chargino mass limit as a function of ΔM, as obtained from the chargino search alone, is shown in Figure 2-a. Consequently, the limit on the mass of the lightest chargino decreases with M_2 as depicted in Figure 2-b and 2-c. For M_2 values larger than a few TeV extremely small ΔM values occur such that a dedicated analysis [4, 25] is necessary to recover the experimental sensitivity.

- Gaugino-like $\tilde{\chi}_1^\pm$ ($|\mu| \gg M_2$): the chargino cross section depends strongly on the scalar neutrino mass. For 50 GeV $\leq M_{\tilde{\nu}} \leq$ 80 GeV the cross section is reduced by one order of magnitude compared to what is expected for $M_{\tilde{\nu}} \geq$ 500 GeV. When the two body decay $\tilde{\chi}_1^\pm \to \ell^\pm \tilde{\nu}$ is dominant, the relevant ΔM becomes $\Delta M = M_{\tilde{\chi}_1^\pm} - M_{\tilde{\nu}}$. If the $\tilde{\nu}$ is mass degenerate with the $\tilde{\chi}_1^\pm$ the acceptance is substantially reduced. However, when this occurs scalar leptons are light and the experimental sensitivity is recovered with these channels.

The absolute mass limit of the lightest chargino is shown in Figure 3 as a function of $\tan\beta$ for all the different chargino field contents. At large $\tan\beta$ values, the lower mass limit of the lightest chargino is obtained when the lightest chargino and the $\tilde{\nu}$ are mass degenerate (gaugino region). At low $\tan\beta$ values the lower mass limit on the lightest chargino is obtained when the lightest chargino and the $\tilde{\chi}_1^0$ (LSP) are mass degenerate (higgsino region) [25]. Finally, for $\tan\beta \leq 60$ and for any m_0 values, the lower mass limit of the lightest chargino is:

$$M_{\tilde{\chi}_1^\pm} \geq 80.5 \text{ GeV}.$$

The scalar tau can be much lighter than the scalar electron and muon. This mass splitting occurs in particular for large $\tan\beta$ and A values. When this happens, chargino and next-to-lightest neutralino decays are affected. Therefore, detection efficiencies are estimated for chargino and next-to-lightest neutralino decays with 100% branching ratio into $\tilde{\tau}_1\nu$ and $\tilde{\tau}_1^\pm\tau^\mp$, respectively. In particular, when the $\tilde{\tau}_1$ and the LSP are mass degenerate the experimental sensitivity is recovered by using the search for chargino pair-production accompanied by ISR [4]. Within the mSUGRA framework the limit on the chargino mass as obtained above (using 189 GeV data) is shown to be valid for any value of the mixing [22].

Indirect limits on the mass of the lightest neutralino are also derived as a function of m_0 and as a function of tanβ. In the low m_0 region ($\leq$ 65 GeV) the mass limit on the LSP comes mainly from the scalar lepton searches. For large m_0 values ($\geq$ 150 GeV), only the chargino and neutralino searches contribute. At low $\tan\beta$ the processes $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_{3,4}^0$ contribute significantly and they are taken into account. The lower mass limit is found at $\tan\beta = 1$ and $m_0 = 500$ GeV. For these values of the parameters, the chargino mass is at the kinematic limit and the mass difference between the chargino and the LSP is maximal.

For intermediate m_0 values (65 GeV $\leq m_0 \leq$ 95 GeV) the production cross section for charginos is minimal and the $\tilde{\nu}$ is light enough to allow the following decay modes: $\tilde{\chi}_{2,3,4}^0 \to \tilde{\nu}\nu$ and $\tilde{\chi}_1^\pm \to \tilde{\nu}\ell^\pm$. This is the region where the exclusion is due to the interplay of many different searches. For low $\tan\beta$ values ($\leq \sqrt{2}$), the minimum is still found at large m_0 values. Better limits are obtained for intermediate m_0 values, where the neutralino production cross sections are large and the two body decays of the $\tilde{\chi}_{3,4}^0$ into $\tilde{\nu}\nu$ are visible through the cascade decays of the $\tilde{\nu}$. For larger $\tan\beta$ values, the minimum is found in the gaugino region (-2000 GeV $< \mu <$ -200 GeV) and for 70 GeV $\leq m_0 \leq$ 80 GeV. In this region of the parameter space, the $\tilde{\nu}$ and

the chargino are mass degenerate, the heavier neutralinos decay invisibly and the experimental sensitivity is entirely due to the scalar lepton searches.

Finally in Figure 4, the mass limit on the lightest neutralino as a function of $\tan\beta$ for any m_0 value is shown. For $\tan\beta \geq 0.7$, the lower mass limit of the lightest neutralino is

$$M_{\tilde{\chi}_1^0} \geq 37.5 \text{ GeV}.$$

The mass limit on the lightest neutralino is not affected by the mixing in the scalar tau sector. The limit, within the mSUGRA framework, holds for any value of the mixing [22].

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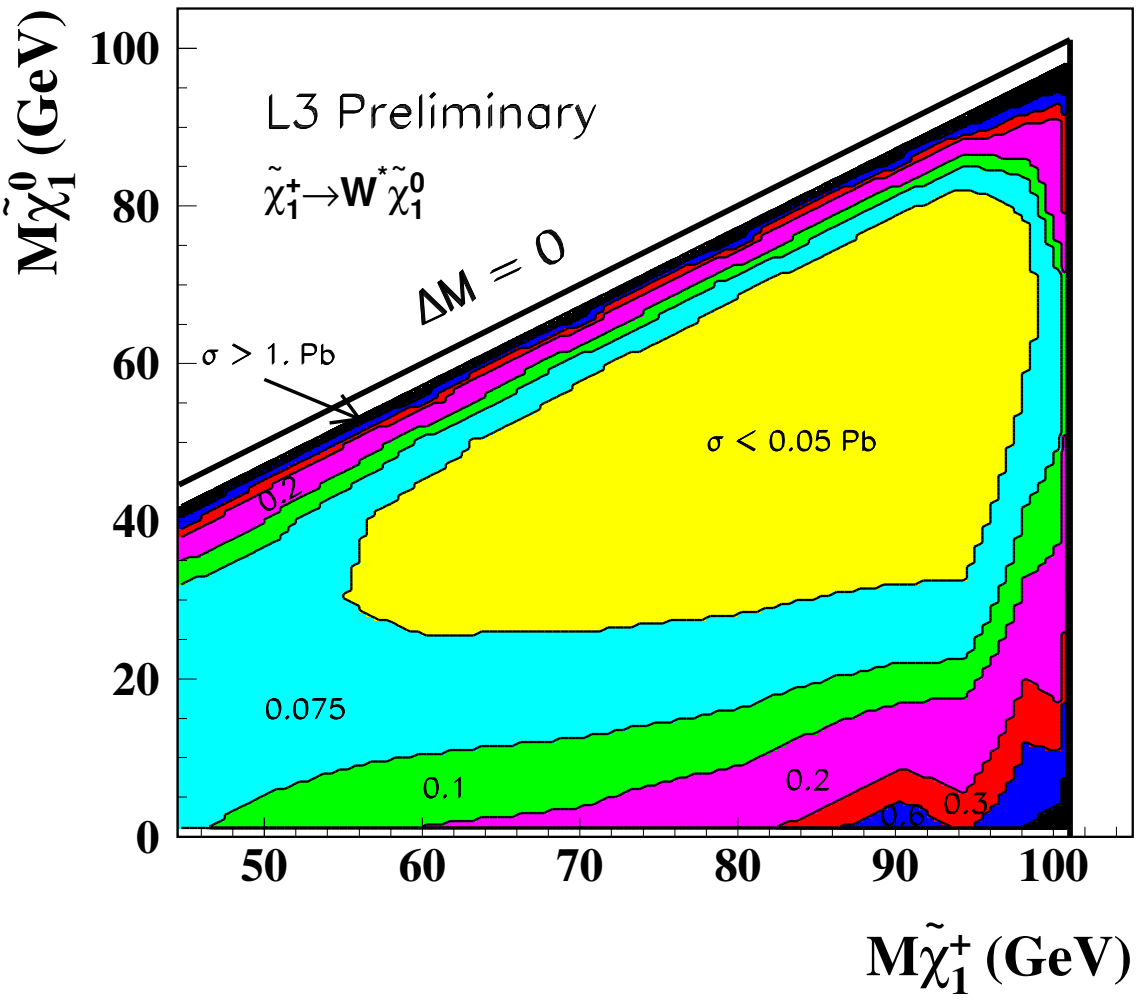

Figure 1: Upper limits on the $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ production cross section up to $\sqrt{s} = 202$ GeV in the $M_{\tilde{\chi}_1^0} - M_{\tilde{\chi}_1^\pm}$ plane. Exclusion limits are obtained assuming standard W branching ratios in the chargino decay.

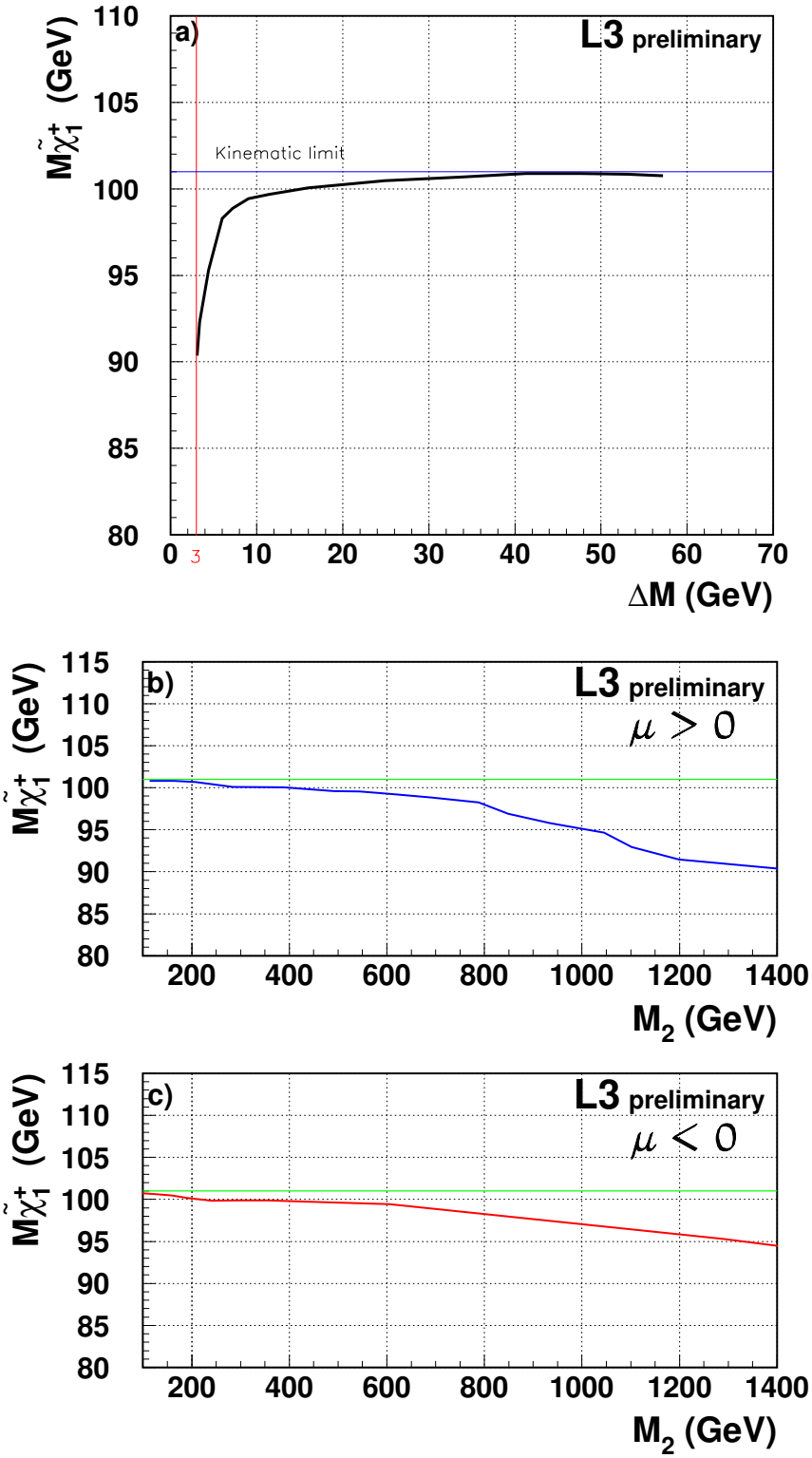

Figure 2: a) Lower limit on $M_{\tilde{\chi}_1^\pm}$ as a function of ΔM for $\tan\beta = 1.41$ and for $m_0 = 500$ GeV. Lower limit on $M_{\tilde{\chi}_1^\pm}$ as a function of M_2 for $\tan\beta = 1.41$ and for $m_0 = 500$ GeV, for b) positive and c) negative μ. These limits are obtained with the chargino search alone.

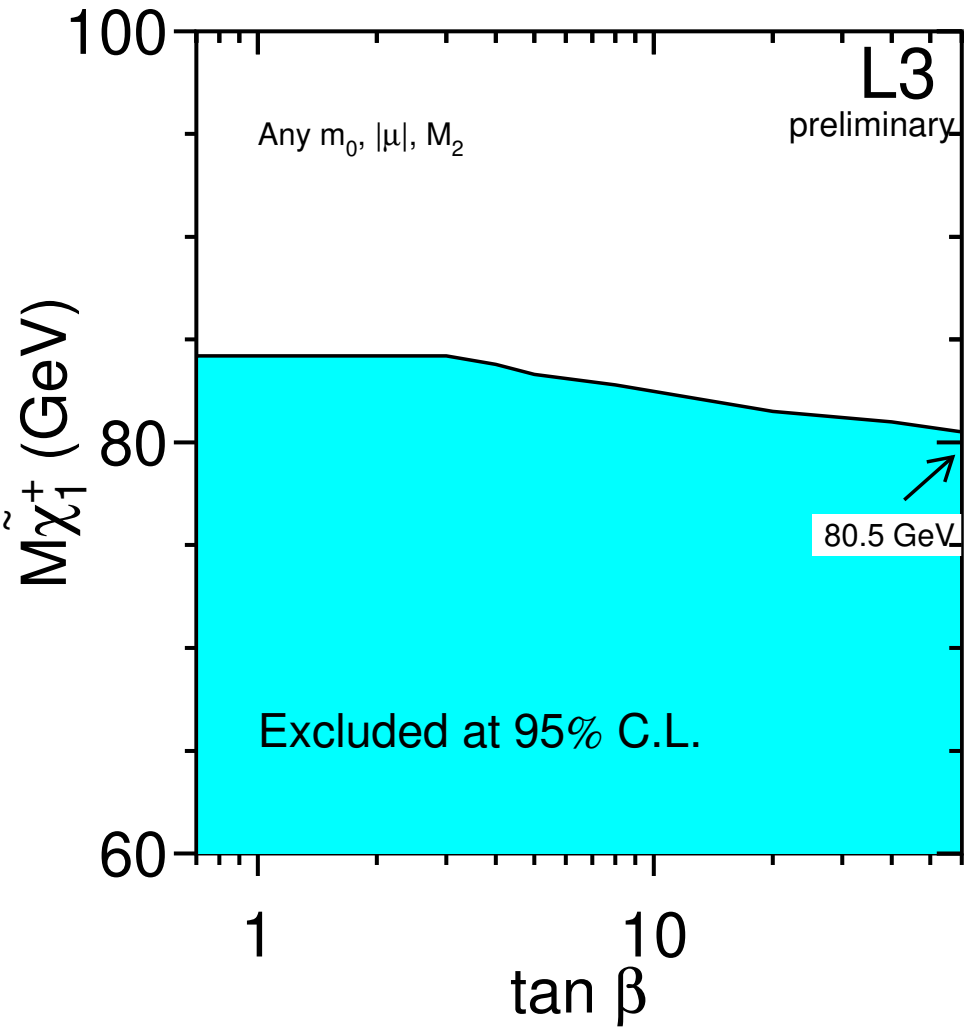

Figure 3: Lower limit on $M_{\tilde{\chi}_1^\pm}$ as a function of $\tan\beta$ valid for any value of m_0, μ and M_2, when combining the chargino, neutralino and scalar lepton searches.

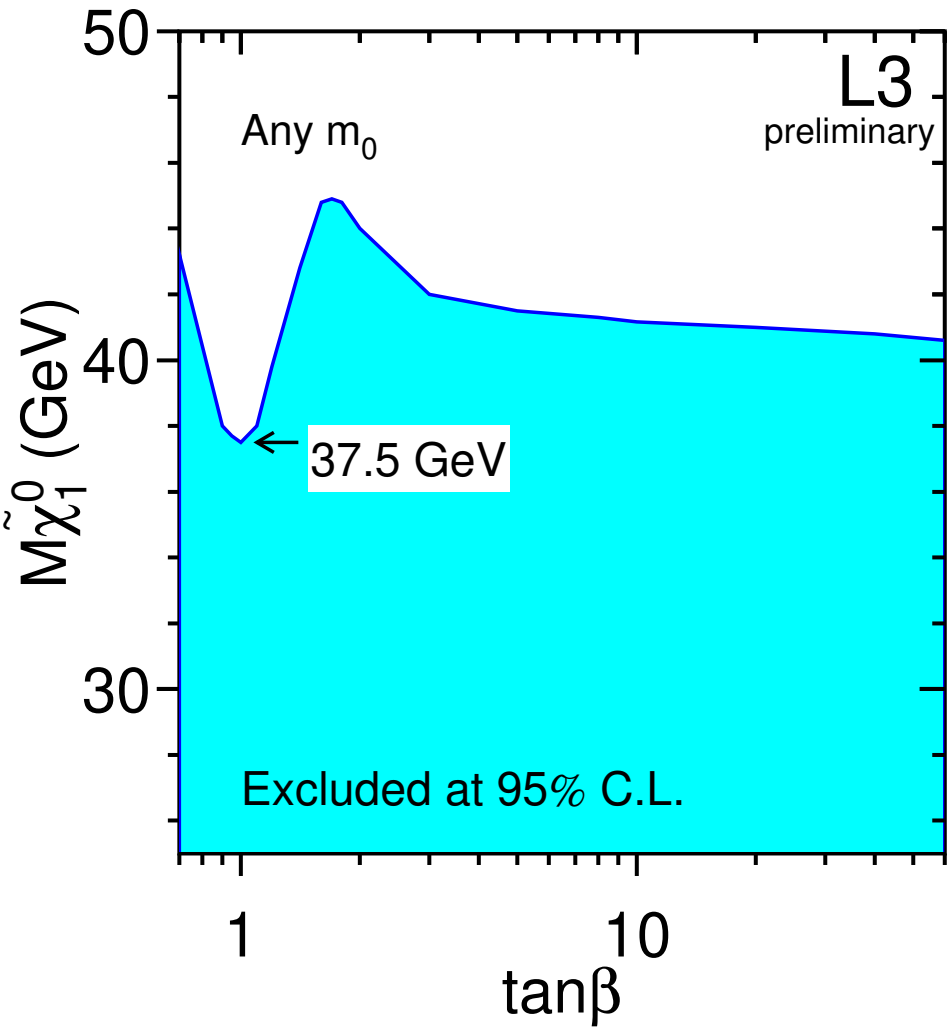

Figure 4: Lower limit on $M_{\tilde{\chi}_1^0}$ as a function of $\tan\beta$ and for any value of m_0, when combining the chargino neutralino and scalar lepton searches.