Search for Charginos and Neutralinos at LEP

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For the LEP collaborations

We report on the searches for charginos and neutralinos at LEP. The results are based on data collected at energies above the Z-peak including a preliminary analysis at $\sqrt{s}$=189 GeV, the highest energy reached at LEP. Assuming R-parity conservation, final states with jets, leptons, jets plus lepton(s), and photon(s), all accompanied by missing energy, are investigated. No evidence for chargino or neutralino production is found and limits are set on their production cross-sections. Exclusion contours in the MSSM parameter space as well as mass limits are derived.

The case of a chargino nearly mass-degenerate with the LSP is studied via tagging of events with an initial state radiation photon. Events with quasi-stable heavy charged particles or with displaced vertices, as expected in extremely degenerate scenarios, are searched for.

I. INTRODUCTION

Increased energies and high luminosities at the LEP e^+e^- collider have substantially extended the possibilities to search for new particles. The first high energy run above Z-peak, $\sqrt{s} = 130 - 136$ GeV, with 12 pb^{-1} luminosity per experiment, was followed by subsequent energy steps through $\sqrt{s} = 161 - 172$ GeV, 183 GeV and 189 GeV with luminosities of 22 pb^{-1}, 55 pb^{-1} and 175 pb^{-1}, respectively. These data have been used to search for new particles predicted in the Standard Model (SM) and theories beyond, among which Supersymmetry (SUSY) is one of the most appealing.

SUSY in its minimal version doubles the number of known particles introducing fermionic (bosonic) partners for ordinary bosons (fermions). In the Minimal Supersymmetric Standard Model (MSSM) [1] with gravity mediated SUSY breaking, sparticle masses and couplings are defined when the following parameters are specified: gaugino masses $M_{1,2,3}$, interrelated with Grand Unification Theory (GUT) assumption M_1:M_2:M_3=α_1:α_2:α_3, the universal scalar mass at GUT scale m_0, the Higgsino mass term μ, the ratio of vacuum expectation values of the two Higgs fields tanβ, and universal trilinear coupling A among scalars. R-parity is assumed to be conserved. This implies pair production of SUSY particles and the existence of the Lightest Supersymmetric Particle (LSP) which appears at the end of each sparticle decay chain. The mixing of the Supersymmetric Higgs and gauge bosons gives two charginos $\tilde{\chi}^{\pm}_{1,2}$ and four neutralinos $\tilde{\chi}^0_{1,2,3,4}$, the lightest of which, $\tilde{\chi}^0_1$, is the most plausible LSP. It is weakly interacting and escapes detection resulting to an energy imbalance in the event.

In e^+e^- collisions chargino pairs $\tilde{\chi}^+_i\tilde{\chi}^-_j$ can be produced through s-channel Z/γ or t-channel sneutrino $\tilde{\nu}$ exchange [2]. Neutralino pairs $\tilde{\chi}^0_i\tilde{\chi}^0_j$ are produced via s-channel Z or t-channel selectron $\tilde{e}_{L,R}$ exchange [3]. The cross-sections of these processes depend, apart from masses, on the Higgsino-gaugino contents of the produced sparticles. When $M_2 >> |\mu|$ the lightest chargino and two lightest neutralinos are mostly Higgsinos and the t-channel contributions are negligible. For $M_2 << |\mu|$ the $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_{1,2}$ are gaugino-like and, if sfermions are light, the t-channel contributions become important. In case of $\tilde{\chi}^+_1\tilde{\chi}^-_1$ production the t-channel interferes destructively with the s-channel leading to a significant decrease of the chargino production cross-section, $\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)$. On the contrary, the t-channel contribution enhances the $\sigma(\tilde{\chi}^0_1\tilde{\chi}^0_2)$. Furthermore, in some regions of the parameter space where the chargino mass is above the pair production threshold, the $\tilde{\chi}^0_1\tilde{\chi}^0_2$ process can be the only visible SUSY signal at LEP. Therefore the $\tilde{\chi}^+_1\tilde{\chi}^-_1$ and $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production processes can be viewed as being complementary. At $\sqrt{s} = 189$ GeV in most of the MSSM parameter space the $\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)$ production cross-section amounts to a few pb for the chargino masses up to almost the kinematic limit. For some sets of MSSM parameters $\sigma(\tilde{\chi}^0_1\tilde{\chi}^0_2)$ can also reach a few pb. In general the $\tilde{\chi}^0_1\tilde{\chi}^0_2$ cross-section is lower than that of the $\tilde{\chi}^+_1\tilde{\chi}^-_1$.

II. FINAL STATES AND SEARCH STRATEGIES

Decays of the lightest chargino, $\tilde{\chi}_1^{\pm}\rightarrow\tilde{\chi}_1^0 f f'$, can proceed through virtual $W^{\pm}$ or $\tilde{l}/\tilde{\nu}$ exchange, enhancing leptonic branching fractions in the latter case. Similarly, decays of the next-to-lightest neutralino, $\tilde{\chi}_2^0\rightarrow\tilde{\chi}_1^0 f\bar{f}$, proceed through the exchange of virtual Z or $\tilde{l}$. The presence of two escaping LSP's in the final states produces an energy imbalance in these events. Depending on the decay mode the expected event topologies are *jets + missing energy*, *leptons + missing energy* or *jets + lepton(s) + missing energy*. When kinematically allowed the cascade decays $\tilde{\chi}_1^{\pm}\rightarrow\tilde{\chi}_2^0 f f'$ or $\tilde{\chi}_2^0\rightarrow\tilde{\chi}_1^{\pm} f\bar{f}$ may occur yielding the final states with *many jets and/or leptons + missing energy*. The higher order radiative decays $\tilde{\chi}_2^0\rightarrow\tilde{\chi}_1^0\gamma$ lead to events with *photon(s)+missing energy* from the $\tilde{\chi}_1^0\tilde{\chi}_2^0$ ($\tilde{\chi}_2^0\tilde{\chi}_2^0$) pair production. They are of importance for MSSM regions with low m_0. Searches for charginos and neutralinos in the various topologies have been carried out by all four LEP experiments [5,7,6,8] at high collision energies including $\sqrt{s}=189$ GeV.

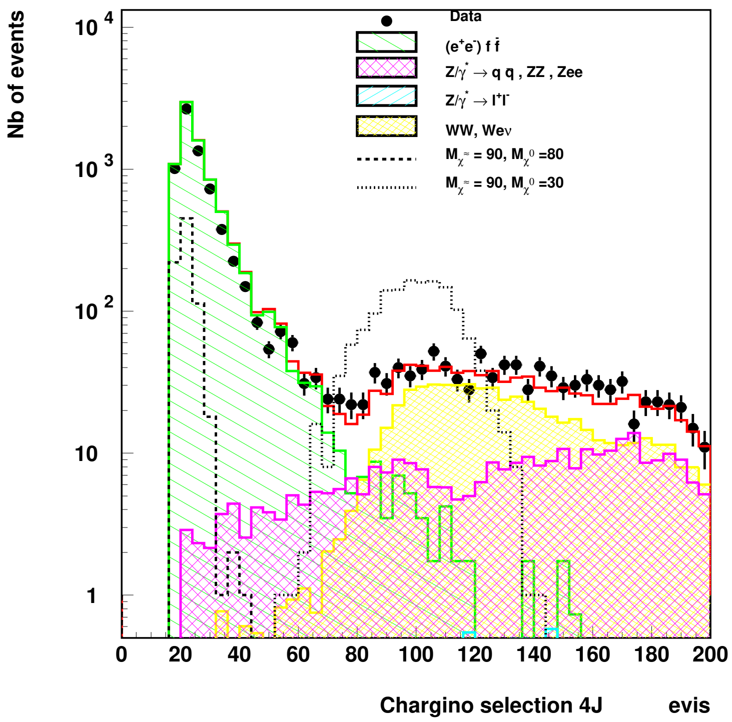

FIG. 1. The visible energy distribution in data (dots) and Monte-Carlo (histogram) events obtained by L3 at $\sqrt{s}$=189 GeV. Contribution from various SM processes are indicated separately. For comparison a distribution is also shown for $\tilde{\chi}_1^+\tilde{\chi}_1^-$events with M($\tilde{\chi}_1^{\pm}$)=90 GeV, M($\tilde{\chi}_1^0$)=80 GeV and M($\tilde{\chi}_1^{\pm}$)=90 GeV, M($\tilde{\chi}_1^0$)=30 GeV (dashed and dotted histograms).

The SM background processes to the *jets + missing energy*, *leptons + missing energy*, or *jets + lepton(s) + missing energy* final states are two fermion production, $f\bar{f}(\gamma)$, four fermion final states, W^+W^-, $W^{\pm}e^{\mp}\nu$, $ZZ^{(*)}$ and Ze^+e^-, and two photon interactions, $e^+e^-q\bar{q}, e^+e^-l^+l^-$. Final states with *photon(s) + missing energy* would be contaminated by the $e^+e^-\gamma(s)$ and $\nu\nu\gamma(s)$ events.

The kinematical configuration of signal events depends strongly on the mass difference between the produced particle (chargino or neutralino) and LSP, ΔM=M($\tilde{\chi}$)–M(LSP). This quantity determines the energy available to the visible decay products. Consequently, the relative composition of the background depends on ΔM and requires dedicated signal selections at different ΔM. When the mass difference is of the order of 3-10 GeV, the signal events, characterised by a low multiplicity and visible energy, are similar to the two-photon interactions. The latter contain e^+/e^- going to forward/backward direction close to the beam pipe. At the same time the cross-section of two-photon interactions, $\sim$ 17 nb, is much higher than that of any SUSY signal expected at LEP. When ΔM is high, $\gtrsim 40-50$ GeV, the dominant backgrounds are $W^{\pm}e^{\mp}\nu$ and W^+W^- production. With increasing collision energy the W^+W^- production exhibits threshold behaviour and the suppression of this background becomes a challenging task. Intermediate ΔM range of ∼ 15 - 40 GeV is the most favourable for the signal-to-background separation with a relatively low contamination from two-fermion processes.

The key kinematical selection variables are visible energy and mass, energy imbalance, acollinearity, acoplanarity, polar angle of missing momentum, fraction of energy deposition in the forward regions of the detector, event thrust, etc.. Figure 1 shows the example of the visible energy distribution for preselected event class with $jets + missing\ energy$ collected by L3 at $\sqrt{s}$=189 GeV. The SM expectation with contributions from different processes are also shown. The data and MC are in a fair agreement. For comparison, the same distribution for the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ signal events with M($\tilde{\chi}_1^\pm$)=90 GeV, M($\tilde{\chi}_1^0$)=80 GeV and M($\tilde{\chi}_1^\pm$)=90 GeV, M($\tilde{\chi}_1^0$)=30 GeV are also shown. After topological preselection of each possible final state the events are subject to further selections where the thresholds on the kinematical variables are adjusted to attain the best signal-to-background separation. The selection techniques are conventional [6,8], or multivariate, which take into account correlation between kinematical variables in the multidimensional space [5,7].

Selection efficiencies range from a few percent (low ΔM) up to 60-70 % (intermediate ΔM). Below ΔM ≃ 3 GeV the detectable energy is very low and the selection efficiencies vanish. These mass-degenerate cases and the dedicated search techniques are discussed separately in section IV.

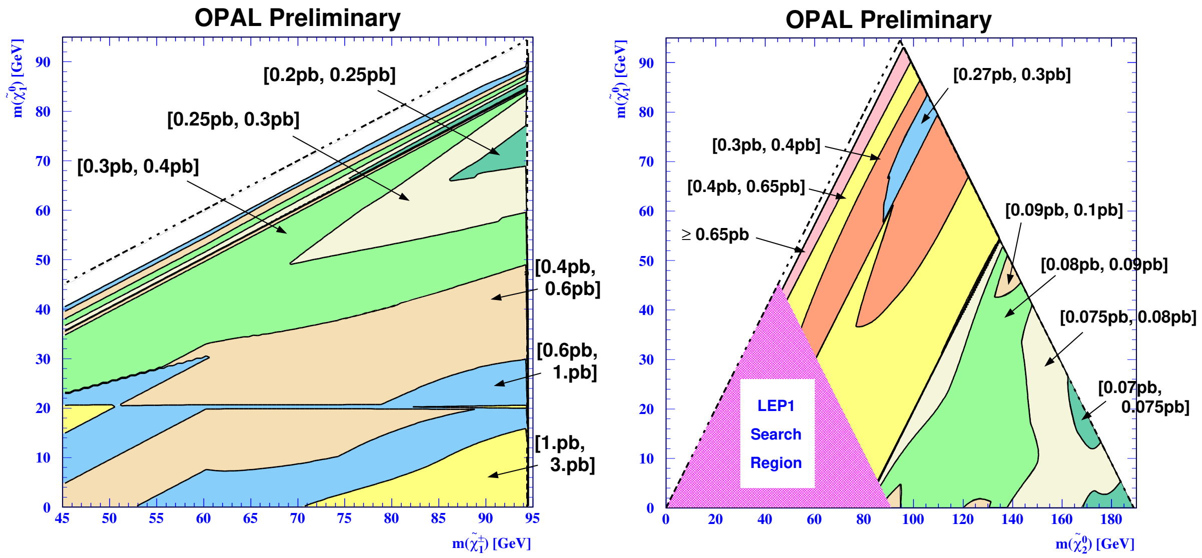

FIG. 2. The regions of different excluded values of $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$ assuming $BR(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^{*\pm} \to \tilde{\chi}_1^0 f f') = 100$ % (the left plot) and $\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)$ assuming $BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^* \to \tilde{\chi}_1^0 f\bar{f}) = 100$ % (the right plot). The exclusions are obtained by OPAL at $\sqrt{s}$= 189 GeV.

III. RESULTS

The numbers of selected events in the different final states, $jets + missing\ energy$, $leptons + missing\ energy$, $jets + lepton(s) + missing\ energy$ and $photons(s) + missing\ energy$ are consistent with the SM predictions. As an example, in the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ ($\tilde{\chi}_1^0\tilde{\chi}_2^0$) searches 7 (1) candidates are selected by ALEPH at $\sqrt{s}$=189 GeV when 5.5 (1.6) are expected. With no indication for chargino or neutralino events, limits are set on their production cross-sections: $\sigma = N/\mathcal{L}\varepsilon$. Here N is 95% C.L. upper limit on the number of events, $\mathcal{L}$ is the integrated luminosity and ε is the selection efficiency. The excluded cross-section is usually mapped in the (M($\tilde{\chi}$), M(LSP)) plane as shown in Fig. 2 for $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0\tilde{\chi}_2^0$ productions. The different contours represent the regions of various excluded cross-section values assuming $BR(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W^{*\pm} \to \tilde{\chi}_1^0 f f') = 100\%$ and $BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^* \to \tilde{\chi}_1^0 f\bar{f})$= 100%. The result is obtained by OPAL at $\sqrt{s}$=189 GeV. High delivered luminosity allows to set an upper limit on the production of the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ ($\tilde{\chi}_1^0\tilde{\chi}_2^0$) pair down to σ=0.2-0.3 pb (0.07-0.08 pb) in the intermediate ΔM regions. As previously mentioned, in the framework of

MSSM the chargino/neutralino pair production cross-section can be as large as a few pb. In general, the $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$ and $\sigma(\tilde{\chi}_1^0\tilde{\chi}_2^0)$ depend on M_2, μ, m_0 and tanβ. The comparison of excluded cross-section to the theoretical calculations allows to exclude the MSSM parameter regions and set limits on the chargino and neutralino masses for corresponding parameters. Different scenarios emerge in terms of mass interrelations, cross-sections and the final state topologies with variation of the MSSM parameters within the following ranges: $0 \leq M_2 \leq 3000$ GeV, 10 GeV $\leq m_0 \leq 500$ GeV, $1 \leq tan\beta \leq 50$, $-$ 500 GeV $\leq \mu \leq 500$ GeV. The chargino-neutralino sector of MSSM is largely insensitive to the parameter A. Figure 3 shows the region of (μ, M_2) parameters excluded from the non-observation of $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0\tilde{\chi}_3^0$ events at $\sqrt{s} = 183$ GeV by OPAL. At each point the relevant final states are exploited and the most discriminating selections are applied using a likelihood ratio method. While the bulk of the excluded region is due to the $\tilde{\chi}_1^+\tilde{\chi}_1^-$ process (dark shaded area), the neutralino pair production extends the domain (light shaded area) to kinematically inaccessible chargino masses. The results are presented for low and high tanβ values (1.5 and 35) and for two distinct cases of high m_0=500 GeV and any m_0. In the 'any m_0' scenario, the obtained limits correspond to the worst possibility which is realized when m_0 is low and sfermions are light. Here the destructive t-channel interference leads to suppressed chargino production. Moreover, when the $\tilde{\chi}_1^{\pm}\rightarrow\tilde{\nu}l$ decays open, selection efficiencies may drop due to the small available phase-space for leptons. Apart from this unfortunate situation the exclusion contours closely resemble the chargino isomass contours at the kinematical boundary of M$(\tilde{\chi}_1^{\pm})$=$\sqrt{s}/2$.

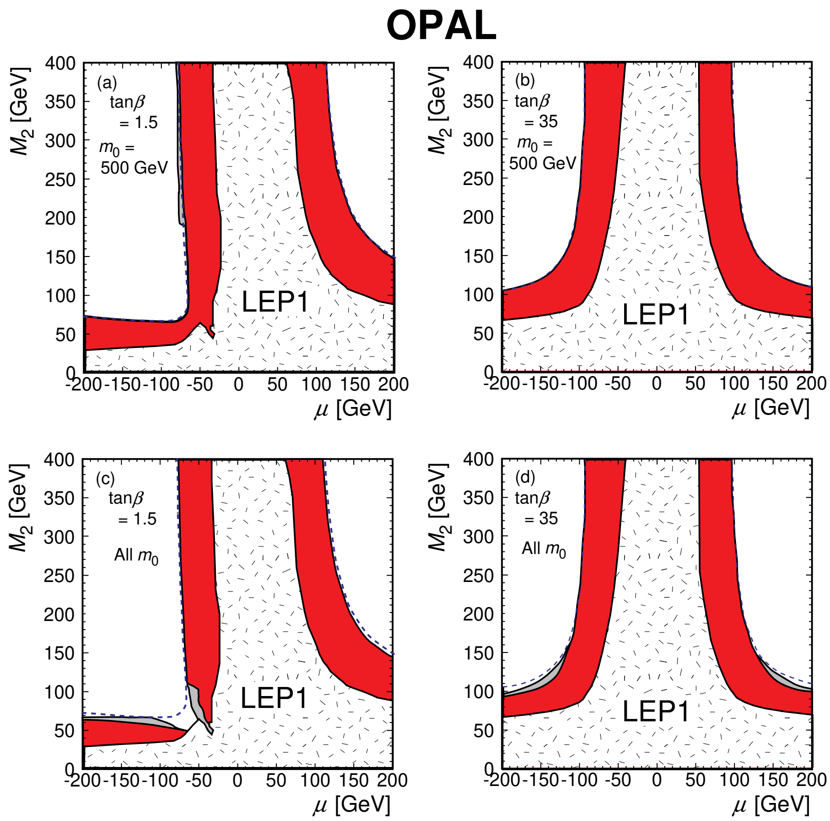

FIG. 3. The regions of MSSM parameter space excluded at 95% C.L. by OPAL at $\sqrt{s}$ = 183 GeV (shaded areas) and at LEP1 (speckled areas). The dark shaded areas are due to chargino pair production. The light shaded regions are excluded from neutralino pair production. The iso-contours of chargino mass at kinematical boundary of M$(\tilde{\chi}_1^{\pm})$=$\sqrt{s}/2$ are also shown by dashed lines. Exclusions are presented for a) tanβ=1.5, m_0=500 GeV, b) tanβ=35, m_0=500 GeV, c) tanβ=1.5, all m_0 and d) tanβ=35, all m_0.

The exclusions of MSSM parameters can be transformed into the limits on masses. Figure 4 a) shows the limit on the mass of lightest chargino $\tilde{\chi}_1^{\pm}$ as a function of tanβ for any m_0. The limit is obtained by L3 at $\sqrt{s}$=189 GeV. The exclusions at high m_0 are derived from chargino and neutralino searches, whereas at low m_0 scalar lepton searches contribute as well. At low tanβ the limit of 71 GeV corresponds to a Higgsino-like scenario and is realized at extremely high values of M_2 ($\sim$2 TeV) where chargino selection efficiencies are low due to low ΔM=M($\tilde{\chi}_1^{\pm}$)–M($\tilde{\chi}_1^0$). At high tanβ the worst limit is observed for gaugino-like chargino, M($\tilde{\chi}_1^{\pm}$)>65.2 GeV. This limit is valid for tanβ <40, M_2 <2 TeV and any m_0.

The limit on the mass of the lightest neutralino $\tilde{\chi}_1^0$ as a function of tanβ for any m_0, obtained by L3 at $\sqrt{s}$ = 189 GeV is shown in Fig. 4 b). At large m_0 the mass limit is set from the chargino and neutralino searches, whereas at low m_0 an indirect limit is obtained from the search of scalar leptons. In the intermediate m_0 region the two-body decays of the chargino $\tilde{\chi}_1^{\pm}\rightarrow\tilde{\nu}l$ and neutralinos $\tilde{\chi}_{2,3,4}^0\rightarrow\tilde{\nu}\nu$ are open and the exclusion is due to the interplay of various searches. The lower limit of 28.2 GeV on LSP mass is obtained for tanβ <40, M_2 <2 TeV and any m_0 and can be regarded as nearly model-independent.

New limits on the heavier neutralinos have also been derived. For the mass difference of $\gtrsim$ 10 GeV, $m_0 \geq$ 500 GeV and tanβ=1.5 (35), the following preliminary limits are obtained by OPAL at $\sqrt{s}$=189 GeV: M($\tilde{\chi}_2^0$) > 66.9 GeV (94.1 GeV) and M($\tilde{\chi}_3^0$)> 105.7 GeV (123.6 GeV).

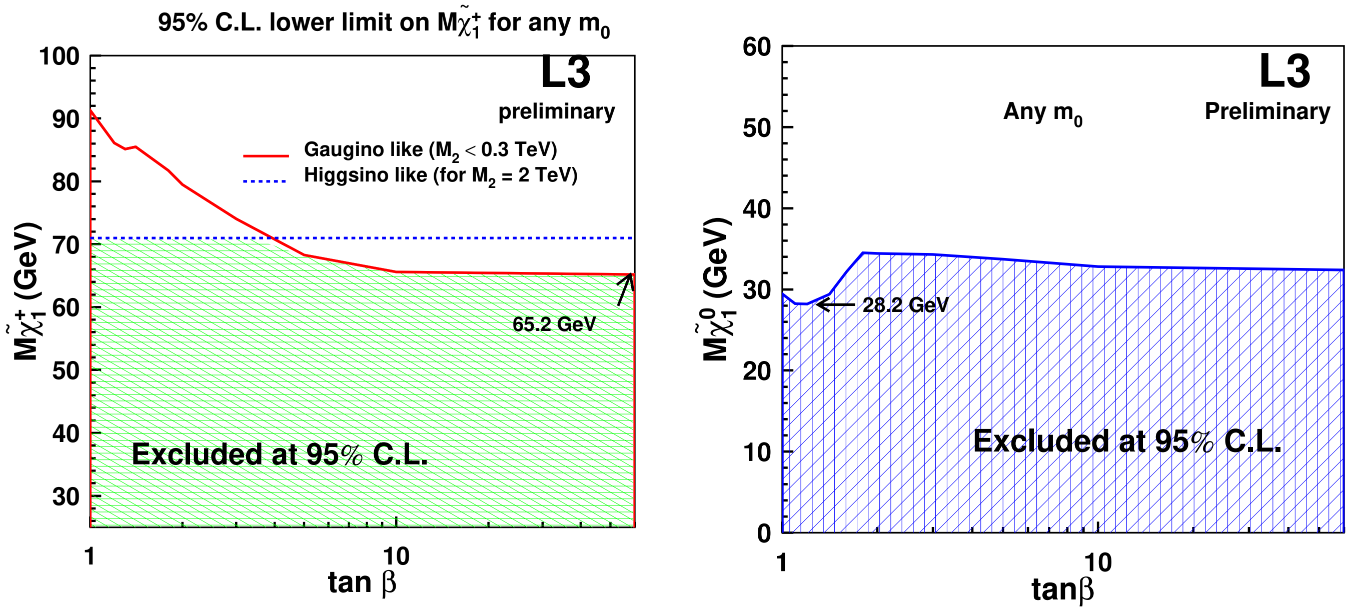

FIG. 4. a) 95% C.L. lower limit on the lightest chargino mass as a function of tanβ for any values of m_0. The two curves correspond to gaugino-like and Higgsino-like scenarios. b) 95% C.L. lower limit on the lightest neutralino mass as a function of tanβ for any values of m_0.

IV. MASS-DEGENERATE CASES

Search for charginos and neutralinos in *jets/leptons/photons+missing energy* final states ('standard searches') is a relevant technique for the ΔM down to $\sim$ 3 GeV. Below this value, however, due to low multiplicity and low detectable energy the signals are washed out by huge two-photon background. For these mass-degenerate cases different search strategies are elaborated. Let us consider the chargino pair production. Within MSSM the mass difference M($\tilde{\chi}_1^{\pm}$)–M(LSP) can be less than a couple of GeV in the following two scenarios: low μ and large $M_{1,2}$ — the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ are both Higgsino-like and nearly mass-degenerate with M($\tilde{\chi}_1^{\pm}$) $\simeq$ M($\tilde{\chi}_1^0$) $\sim \mu$; high μ and low M_2 — the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ are both gaugino-like and mass-degenerate with M($\tilde{\chi}_1^{\pm}$) $\sim$ M($\tilde{\chi}_1^0$) $\sim M_2$. However, in order to get ΔM of the order of hundreds of MeV in the latter case, the ratio $M_1 : M_2$ must be $\geq$ 2 relaxing the GUT relation.

When ΔM=M($\tilde{\chi}_1^{\pm}$)–M($\tilde{\chi}_1^0$) is less than $\sim$1 GeV the chargino lifetime is long enough to produce a displaced decay vertex or even pass whole detector before the decay. When decaying inside the detector such a particle can be identified via secondary vertices or kinks. Quasistable charginos can be discovered by looking for heavy charged particles producing anomalously high ionization in the detector. As an example, DELPHI identifies quasistable particles through ionization in the TPC or by the absence of Čerenkov light in the barrel RICH [9].

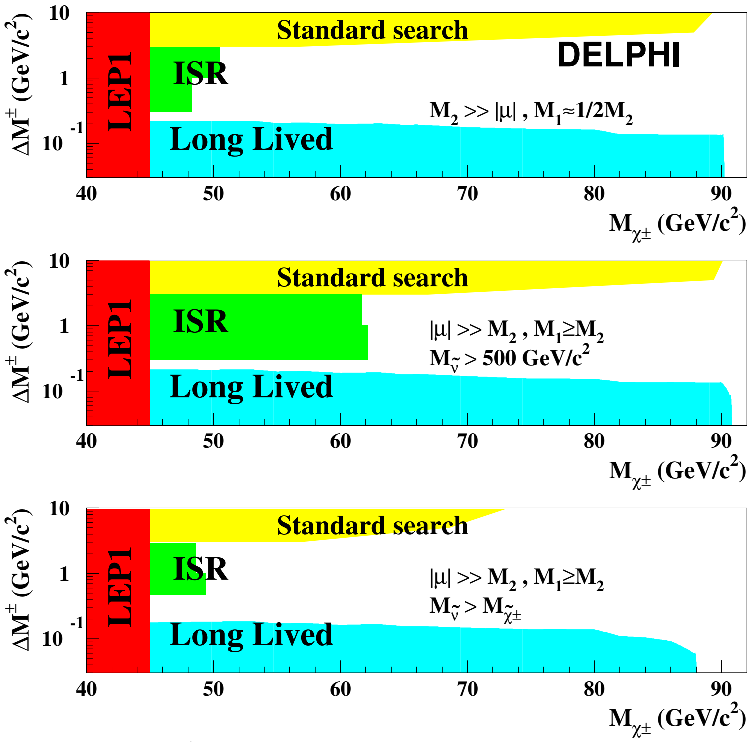

FIG. 5. The 95% C.L. limits on the $\tilde{\chi}_1^{\pm}$ mass as a function of ΔM for three different SUSY scenarios consistent with low ΔM. The excluded regions are obtained from the searches for long-lived charginos or charginos accompanied by ISR photon. The 'standard search' coverages are also shown. The exclusions are obtained by DELPHI at $\sqrt{s} = 183$ GeV.

For the mass differences of the order of 1-3 GeV the lifetime of the chargino becomes small and the secondary vertices can hardly be distinguished from the primary ones. On the other hand, the visible decay products are still too soft carrying only a tiny fraction of the initial energy. Therefore the two-photon interactions remain largely irreducible background. Here one can exploit initial state radiation (ISR) photon to tag the signal events. The two-photon background can be kept under control by requiring the photon transverse energy $E_{\gamma}^{T} > \sqrt{s}\ sin\theta_{min}/(1 + sin\theta_{min})$, where θ_{min} is the lowest polar angle covered by the detector [10]. If an ISR photon from a two-photon event passes this cut, than one of the final state electrons which usually escape in the beam pipe should be deflected above θ_{min}. Thus such events can be recognised as background and rejected. Although only a few percent of signal events irradiates hard ISR photons this technique provides sensitivity in the region of ΔM where other methods fail.

No indication has been observed for heavy long-lived charged particles or events with hard ISR photon plus missing energy and soft tracks. These results are interpreted as an absence of production of a chargino mass-degenerate with LSP. Thus limits have been set on the $\sigma(\tilde{\chi}_1^{+}\tilde{\chi}_1^{-})$ and on the chargino mass. Figure 5 summarises the results of the searches. The limits on the M$(\tilde{\chi}_1^{\pm})$ are given as a function of ΔM. The areas excluded via long-lived particles searches, ISR tag technique as well as 'standard searches' are shown. In the Higgsino-like scenario the long-lived particle searches give similar mass exclusion to the one obtained in the 'standard searches'. The same holds for gaugino-like scenario if M$(\tilde{\nu}) > 500$ GeV. When M$(\tilde{\nu})$ is low the chargino decay width increases due to virtual $\tilde{\nu}$ exchange. More significantly, if M$(\tilde{\nu}) <$ M$(\tilde{\chi}_1^{\pm})$ the exchanged $\tilde{\nu}$ becomes real, the lifetime of $\tilde{\chi}_1^{\pm}$ drops and long-lived searches become inefficient. However, long-lived particle searches still remain very competitive to the 'standard searches' since the discussed scenario is one of the worst possibilities also in non-mass-degenerate cases. The mass coverage of ISR - tag technique is significantly modest due to small fraction of signal events accompanied with hard photon.

V. CONCLUSIONS AND PERSPECTIVES

Searches for charginos and neutralinos have been performed at LEP in the variety of final states. No evidence has been found for these particles and limits have been set on their production cross-sections. In the MSSM with R-parity conservation the model parameters have been constrained and the mass limits for charginos and neutralinos have been derived.

The limit for the LSP mass M($\tilde{\chi}_1^0$) $>$ 28.2 GeV at 95% C.L. is obtained for tan$\beta > 1$ and any m_0. The lightest chargino has been excluded up to the kinematical limit in most of the MSSM parameter space. The absolute limit on the $\tilde{\chi}_1^{\pm}$ mass is set at M($\tilde{\chi}_1^{\pm}$) $>$ 65.2 GeV. This limit is valid for tan$\beta > 1$ and any m_0. The next step in the LEP collision energy of $\sqrt{s}$ = 200 GeV will allow to probe the lightest chargino up to 100 GeV for most of the MSSM parameter space.

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