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Update of the search for charginos nearly mass-degenerate with the lightest neutralino

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Abstract

The data collected by DELPHI in 1998 at the centre-of-mass energy of 189 GeV have been used to update the search for charginos nearly mass-degenerate with the lightest supersymmetric particle, which is assumed to be the lightest neutralino. Mass differences below $\Delta M = 3$ GeV/c^2 are considered. No excess of events with respect to the Standard Model expectation has been observed, and exclusions in the plane of ΔM versus chargino mass are given. The new ΔM independent lower limit on the mass of the chargino is 62.4 GeV/c^2 in the higgsino scenario (which includes the gaugino mass unification scenario), if all sfermions are heavier than the lightest chargino. In the approximation of large sfermion masses the limit is 59.8 GeV/c^2, independently of the field content.

1. Introduction

This paper updates the results of the search for charginos ($\tilde{\chi}_1^{\pm}$) nearly mass-degenerate with the lightest neutralino ($\tilde{\chi}_1^0$) reported in Ref. [1], with the data collected by DELPHI in 1998 at the centre-of-mass energy of 189 GeV.

The experimental techniques used depend on the mass difference ΔM between the chargino and the lightest neutralino (assumed to be the Lightest Supersymmetric Particle, LSP), as described in Ref. [1]. When ΔM is below the mass of the pion, the chargino lifetime is typically long enough to let it pass through the entire detector before decaying. This range of ΔM can be covered by the search for long-lived heavy charged particles. For ΔM of few hundred MeV/c^2 the $\tilde{\chi}_1^{\pm}$ can decay inside the main tracking devices of DELPHI. Therefore, a search for secondary vertices or kinks can be used to explore this region. With increasing mass difference, the mean lifetime falls and it becomes difficult to distinguish the position of the $\tilde{\chi}_1^{\pm}$ decay vertex from the initial interaction point. In this case, the tagging of a high energy Initial State Radiation (ISR) photon can help in exploring the ΔM region between a few hundred MeV/c^2 and 3 GeV/c^2.

Compared to Ref. [1], the search using a tagged ISR photon has been improved with the use of an additional cut and a wider range of mass differences between the chargino and the lightest neutralino explored. Moreover, the selection cuts were optimized for each point in the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$, depending on the kinematics of the signal in that point. This significantly improved the sensitivity in a region of the space of the SUSY parameters that will probably never be covered by the searches at hadron machines [2].

All the new data have been combined with the samples already used in Ref. [1]. In the search which uses ISR, all the old data-sets have been re-analysed according to the new prescriptions.

Three SUSY scenarios were considered, depending on the values of the SU(2) gaugino mass M_2, the U(1) gaugino mass M_1, the Higgs mixing parameter μ, and the mass of the sneutrino $M_{\tilde{\nu}}$:

1. $M_{1,2} \gg |\mu|$ (higgsino-like);
2. $|\mu| \gg M_1 \geq M_2$ and heavy sneutrino (gaugino-like);
3. $|\mu| \gg M_1 \geq M_2$ and light sneutrino (gaugino-like).

Gauginos couple to $\tilde{\nu}$, thus heavy and light sneutrinos define two phenomenologically different gaugino scenarios, with different cross-sections (because of the possible chargino production through $\tilde{\nu}$ exchange in the t-channel), lifetimes and branching ratios. In the following, in the heavy sneutrino scenario $M_{\tilde{\nu}} > 500$ GeV/c^2 is assumed. In all other cases the assumption is $M_{\tilde{\nu}} > M_{\tilde{\chi}_1^+}$.

Also the charged sfermions couple to the gauginos, and if light they can modify the lifetimes and the branching ratios considered. In the following, the heavy charged sfermions approximation will be used for the two gaugino scenarios, while for the higgsino it is enough to consider $M_{\tilde{f}_i} > M_{\tilde{\chi}_1^+}$ for all sfermions.

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A charged gaugino (cases 2 and 3) can get a mass $M_{\tilde{\chi}_1^+} \leq M_{\tilde{\chi}_1^0} + 1$ GeV/c^2 only if the constraint of gaugino mass unification at the GUT scale, implying the electroweak scale relation $M_1 \sim 1/2\ M_2$, is released. Several interesting scenarios without gaugino mass unification or with near mass-degeneracy between the lightest supersymmetric particles have been proposed [3–7], and all of them can be studied by using the techniques reported in the present paper.

2. Data samples and event generators

The DELPHI detector is described in [8]. The integrated luminosity collected by DELPHI at 189 GeV was approximately 158 pb^{-1}, out of which 155.3 pb^{-1} were used in the searches for long-lived particles and 152.9 pb^{-1} in the search for soft particles accompanied by an ISR photon.

SUSYGEN [9] was used to generate all signal samples and to calculate cross-sections. The decay modes of the chargino when $\Delta M < 2$ GeV/c^2 were modelled using the computation of [3], while the widths given by SUSYGEN were used for $\Delta M \geq 2$ GeV/c^2. About 325000 events were generated, in correspondence of six different chargino masses and seven different ΔM's.

The background process $e^+e^- \to q\bar{q}\ (n\gamma)$ was generated with PYTHIA 5.7 [10], while DYMU3 [11] and KORALZ 4.2 [12] were used for $\mu^+\mu^-(\gamma)$ and $\tau^+\tau^-(\gamma)$, respectively. Processes leading to four-fermion final states, $(Z/\gamma)^*(Z\gamma)^*$, W^+W^-, $We\nu$ and Zee, were generated using EXCALIBUR [13] and GRC4F [14].

Two-photon interactions leading to hadronic final states were generated using TWOGAM [15], including the VDM, QCD and QPM components. The generators of [16] were used for the leptonic final states. As in the previous analysis [1], one had to deal with the fact that part of the two-photon background was not simulated, because of phase-space cuts applied during the event generation. For instance, in the simulation at 189 GeV the e^+e^- final state had no ISR; in the hadronic samples, the mass of the two photon system was required to be $M_{\gamma\gamma} > 3$ GeV/c^2, and at the same time there had to be at least one charged particle with $p_T > 1.2$ GeV/c.

All generated signal and background events were passed through a detailed simulation of the DELPHI detector [17] and then processed with the same reconstruction and analysis programs as real data events. The number of simulated events from different background processes was several times the number of real events recorded.

3. Search for long-lived charginos

3.1. Search for heavy stable charged particles

The results of the search for heavy stable charged particles at 189 GeV are described in Ref. [18], where all the details on the techniques used and on the efficiency can be found. The efficiencies for selecting heavy stable particles presented there were then convoluted with the expected distribution of the decay length of the chargino in a given scenario, in order to derive an event selection efficiency for long-lived charginos as a function of their mass and lifetime. One event was selected in the data, while 1.02 ± 0.13 events were expected from Standard Model (SM) processes.

3.2. Search for decay vertices inside the detector

To search for chargino decays inside the sensitive detector volume the same selection as in Ref. [1] was used. No events remained in the data collected at 189 GeV. The number of background events expected from SM processes was 0.87 ± 0.65 (0.63 from Bhabha scattering, 0.12 from $e^+e^- \to \mu^+\mu^-$ and 0.12 from $e^+e^- \to \tau^+\tau^-$).

The efficiencies for the signal have been estimated using simulated samples of charginos with different decay lengths. Fig. 1 shows, as an example, efficiencies as functions of the decay radius for a chargino mass of 70 GeV/c^2. The first plot shows the efficiency for selecting a single chargino. The efficiency first increases with the decay radius since longer chargino tracks are better reconstructed. For even larger radii the efficiency decreases due to the poorer reconstruction of the low momentum decay products. The vertex reconstruction reaches the max-

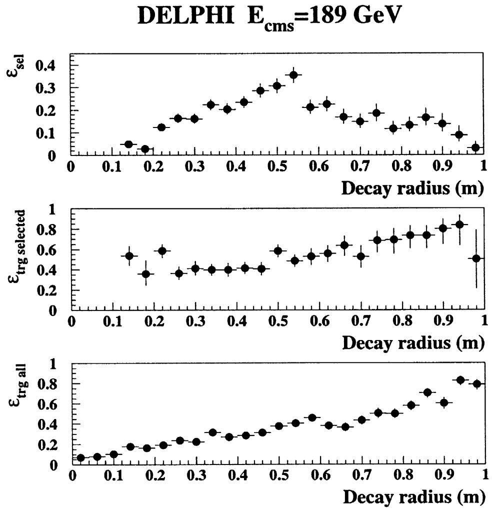

Fig. 1. Top: efficiency for selecting a single 70 GeV/c^2 chargino in the search for displaced decay vertices (kinks), as function of its decay radius in DELPHI. Middle: trigger efficiency for charginos selected with the offline criteria. Below: trigger efficiency for all 70 GeV/c^2 charginos, whether or not they are selected.

imum of the efficiency in the middle of the TPC. The second plot displays the trigger efficiency for the charginos passing the selection criteria. The third plot shows the trigger efficiency for all charginos of that mass, whether or not they were selected. Trigger efficiencies were estimated by using a Monte Carlo simulation of the performances of the relevant trigger components.

3.3. *Results in the search for long-lived charginos*

In the absence of evidence for a signal in any of the searches for long-lived charginos at 189 GeV, the results of the two methods can be combined, as explained in Ref. [1]. Again, these results can be further combined with the outcomes of the search at lower centre-of-mass energies, also described in Ref. [1]. The regions excluded, with a confidence level (CL) of at least 95%, by such a combination of searches for long-lived charginos in the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$ will be shown in Fig. 5. No limit is derived in the gaugino scenario with light $\tilde{\nu}$, since the lifetime limit cancels out when $M_{\tilde{\nu}}$ approaches $M_{\tilde{\chi}_1^+}$.

4. Search for charginos with ISR photons

With respect to the analysis described in Ref. [1] a new variable was taken into account to better discriminate between nearly mass-degenerate charginos and the dominant two-photon background. This variable is the ratio between the missing transverse momentum (P_T^{miss}) and the visible transverse energy (E_T^{vis}) in the event. Another improvement in the analysis at 189 GeV is that for $\Delta M < 1$ GeV/c^2 the requirement of at least two charged tracks consistent with coming from a common primary vertex was removed. This increased the efficiency for events with charginos decaying up to a few cm from the interaction point.

In summary, after a common preselection, which remained unchanged with respect to Ref. [1], the cuts applied to the data and to the simulated signal and background samples, as functions of $M_{\tilde{\chi}_1^+}$ and ΔM, were the following (E_{cms} is the centre-of-mass energy):

- There must be at least two and at most six good charged particles and, in any case, no more than ten tracks in the event. Tracks reconstructed in the tracking devices of DELPHI are taken as good charged particles if they have a momentum above 100 MeV/c, measured with $\delta p/p <$ 100%, and an impact parameter below 4 cm in the azimuthal plane and below 10 cm in the longitudinal plane.
- The transverse energy of the ISR photon was required to be greater than $(E_T^{\gamma})^{\min}$, where $(E_T^{\gamma})^{\min} \simeq 0.03 \cdot E_{\text{cms}}$.
- The mass recoiling against the photon must be above $2M_{\tilde{\chi}_1^+} - \delta M$, where the term δM takes into account the energy resolution in the electromagnetic calorimeters.
- The photon had to be isolated by at least 30° with respect to any other charged or neutral particle in the event.
- The sum of the energies of the particles emitted within 30° to the beam axis (E_{30}) was required to be less than 25% of the total visible energy. If the photon was inside this angular region its energy was included neither in E_{30}, nor in the visible energy.

- If the ISR photon candidate was detected in the very forward DELPHI calorimeter (STIC), it must not be correlated with a signal in the scintillators placed in front of STIC.
- (In the data collected since 1997) if the ISR photon candidate was at an angle between 10° and 25° with respect to the beam direction, the region where the Time Projection Chamber (TPC) cannot be used in the tracking, it must not be correlated with hits in the Silicon Tracker.
- $(E_{vis} - E_{\gamma})/E_{cms}$ must be below a kinematical threshold which depends on ΔM and on $M_{\tilde{\chi}_1^+}$ (and in any case below 6%).
- P_T^{miss}/E_T^{vis} must be above 0.40 if $\Delta M > 300$ MeV$/c^2$, and above 0.75 for smaller ΔM's.
- If $\Delta M > 1$ GeV$/c^2$, at least two charged particles in the event must be consistent with coming from the interaction vertex.

Fig. 2 shows the efficiencies for the signal of nearly mass-degenerate charginos, computed with the fully simulated samples at 189 GeV, for some values of $M_{\tilde{\chi}_1^+}$ and ΔM. The difference between the efficiencies in the higgsino and in the gaugino scenario with heavy $\tilde{\nu}$ are due to the different ISR energy spectrum. The efficiencies for gauginos in case of light sneutrinos get smaller at the lowest ΔM because of the larger fraction of missing energy in the $\tilde{\chi}_1^+ \to l^+ \nu \tilde{\chi}_1^0$ decay. Mass differences below 500 MeV$/c^2$ were not simulated in the light sneutrino scenario.

The overall trigger efficiency for these samples depend on $M_{\tilde{\chi}_1^+}$ and ΔM and it was found to always be above 78%. It was obtained as the logical OR of the single photon trigger efficiency [19] and the trigger efficiency for low momentum tracks. Both trigger efficiencies were measured by using the data

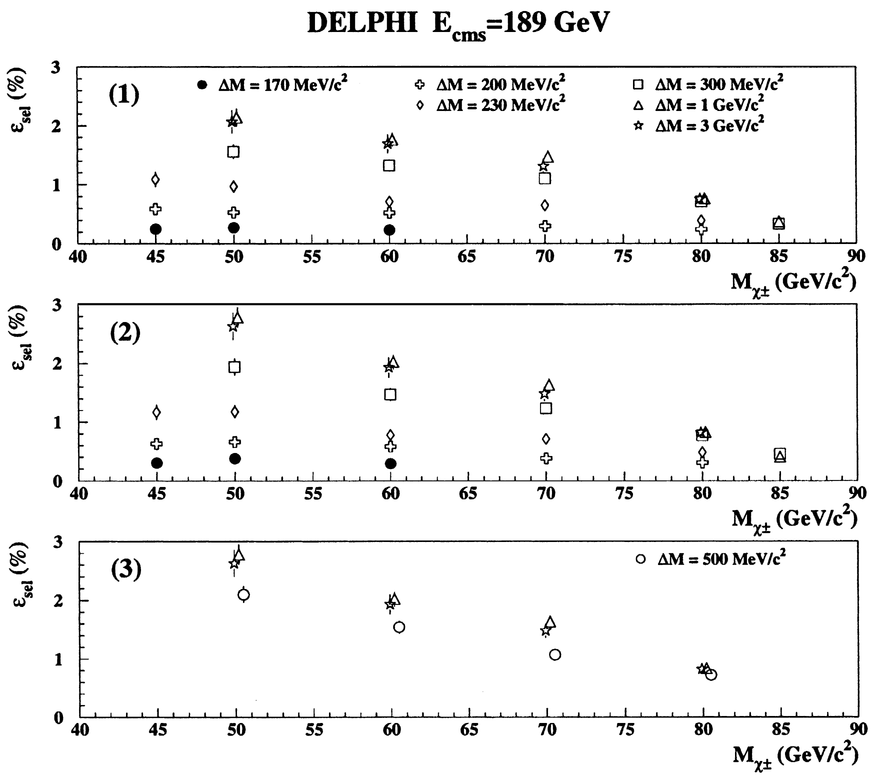

Fig. 2. Selection efficiencies in the search with ISR for charged higgsinos (1), charged gauginos in case of heavy sneutrinos (2) and charged gauginos in case of light sneutrinos (3) at the centre-of-mass energy of 189 GeV, as functions of their mass and of the mass difference with the lightest neutralino.

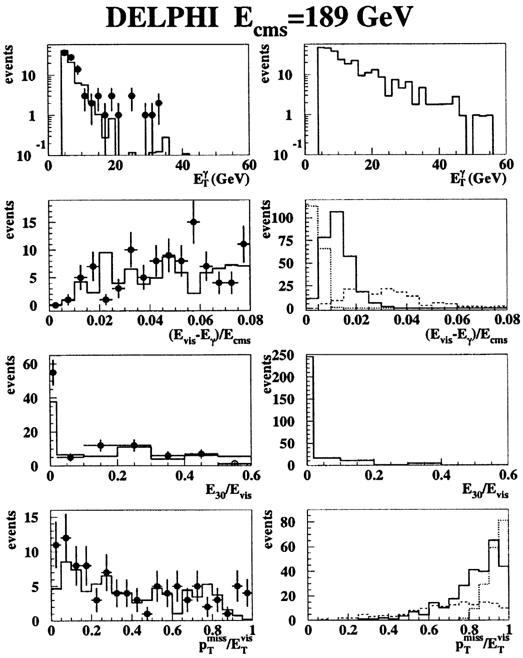

Fig. 3. Some of the variables used in the selection at 189 GeV. In the left plots the data (dots) are compared with the SM expectations. On the right, as an example, the corresponding distributions (with arbitrary normalisation) are shown for the signal with $M_{\tilde{\chi}_1^+} = 60$ GeV/c^2 and $\Delta M = 1$ GeV/c^2. In the plot of the visible energy (second row) and of the ratio P_T^{miss}/E_T^{vis} (last row) three different mass splittings are shown for the signal: dotted, $\Delta M = 0.3$ GeV/c^2; solid line, $\Delta M = 1$ GeV/c^2; dashed, $\Delta M = 3$ GeV/c^2.

collected by DELPHI during the same period of data acquisition.

4.1. Results in the search for charginos with ISR photons

In spite of the limitation due to the cuts applied at the generation on the two-photon samples, described in Section 2, the agreement between the data and the simulation is reasonable after the preselection and the removal of all events where the candidate ISR photon was compatible with being a charged particle in the forward region. A comparison can be seen in Fig. 3, where the distributions of the transverse energy of the photon, of the visible energy besides the ISR photon, of the visible energy within 30° to the beam axis and of the ratio P_T^{miss}/E_T^{vis} are shown for the data (dots), for the sum of the SM backgrounds (left histograms) and for the signal sample with $M_{\tilde{\chi}_1^+} = 60$ GeV/c^2 (histograms on the right).

There is indeed some excess of data over simulated background in signal-like regions in the plots of the transverse energy of the photon and of the ratio P_T^{miss}/E_T^{vis}, although of little statistical significance. Once all the selections cuts were applied, however, only one event at 189 GeV with a photon with $E_T^\gamma > 20$ GeV remained, where 0.36 ± 0.20 were expected.

Table 1 gives the number of events observed and the expected background in the search at 189 GeV and after the re-analysis of all the data collected at the lower centre-of-mass energies. The logical OR of the selections, for all masses and ΔM considered, was used.

The selection cuts are different for different points of the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$. Therefore, also the expected

Table 1
Events remaining in the data and in the sum of the expected SM backgrounds after the OR of the selections applied in the search for nearly mass-degenerate charginos accompanied by high p_T ISR photons. The breakdown of the three most important sources of background is given, together with the total background.

E_{cms}	$\int\mathscr{L}$	Data	$Z^0\gamma \to \tau^+\tau^-$	$\gamma\gamma \to$ hadr.	$\gamma\gamma \to \tau^+\tau^-$	Σ bckg
130/136 GeV	11.7 pb^{-1}	0	–	0.10 ± 0.10	–	0.10 ± 0.10
161 GeV	9.7 pb^{-1}	0	–	0.67 ± 0.32	0.18 ± 0.12	0.85 ± 0.37
172 GeV	9.9 pb^{-1}	1	0.07 ± 0.05	–	0.08 ± 0.08	0.21 ± 0.10
183 GeV	50.0 pb^{-1}	4	0.08 ± 0.06	1.15 ± 0.40	0.34 ± 0.13	1.67 ± 0.74
189 GeV	152.9 pb^{-1}	8	1.09 ± 0.44	3.50 ± 1.25	1.21 ± 0.42	5.85 ± 1.39
Sum of all centre-of-mass energies		13	1.2 ± 0.4	5.4 ± 1.4	1.8 ± 0.5	8.7 ± 1.6

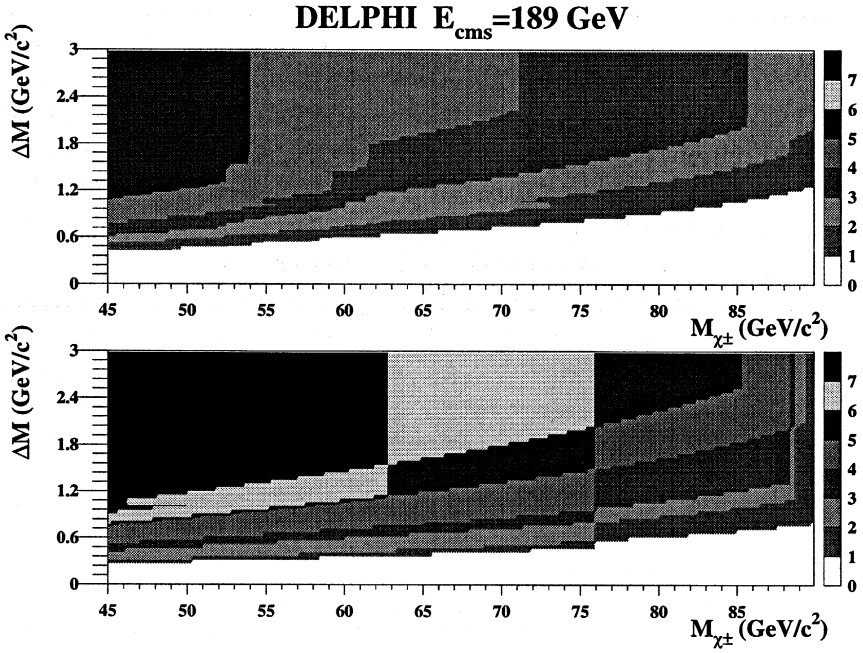

Fig. 4. SM MC (top) and data (bottom) remaining after the final selection in any point of the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$ considered in the search with the ISR photon at 189 GeV.

background content and the number of events remaining in the data are different in any point of that plane. Fig. 4 shows the expected background (top) and data (bottom) content in the different points of the plane, at 189 GeV. Similar figures have been obtained for the other centre-of-mass energies.

After the selection, the data remaining are compatible with coming from background alone and there is no evidence of any significant excess above the SM expectations. Then, the data collected at all LEP2 energies were combined and used to set lower limits on the mass of the chargino in nearly mass-degenerate scenarios.

The procedure for combining results at the different energies was similar to that of Ref. [1]. This procedure takes into account the effect on the limit of the uncertainties on the signal efficiencies and on the background content. The interpolation of the selection and trigger efficiencies between the points of the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$ where a full simulation was produced, was based on SUSYGEN samples produced only at the generator level.

The regions excluded with at least 95% CL by the search with the high p_T ISR photon tag in the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$ after such combination are shown in Fig. 5. Those limits were obtained by subtracting the SM background included in the available simulated samples, possibly incomplete (see par. 2); for that reason the confidence levels obtained are likely to be underestimated (i.e. the limits are conservative). Since $\Delta M = 170$ MeV/c^2 is the smallest ΔM fully simulated for the search with the ISR tag, ISR efficiencies are supposed to vanish completely for all mass differences smaller than 170 MeV/c^2

5. Limit on the mass of nearly degenerate charginos

The results of the searches for long-lived charginos and for soft particles accompanied by a high p_T photon at 189 GeV have been combined with the results of the searches at lower energies to obtain the excluded regions in the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$ shown in Fig. 5. The same figure shows, for comparison, also the region excluded by the independent search in DELPHI for charginos with larger ΔM [20].

By simply superimposing the regions excluded with the search for long-lived charginos and the

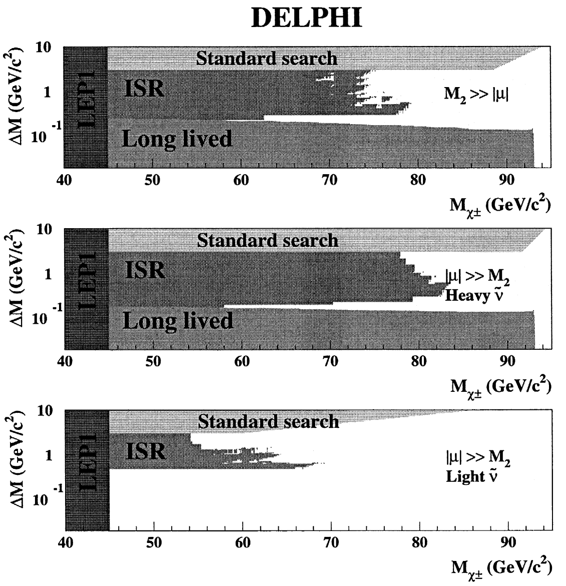

Fig. 5. Regions in the plane $(M_{\tilde{\chi}_1^+}, \Delta M)$ excluded by DELPHI with at least 95% CL using separately the search for high ΔM charginos, the search for soft particles accompanied by ISR and the search for long-lived charginos, in the three scenarios with near mass-degeneracy between the chargino and the lightest neutralino. Better limits in the region of overlap of the different search methods are obtained after combining them in logical OR (see text).

regions excluded with the search with the ISR photon tag, these results permit to exclude $M_{\tilde{\chi}_1^+} < 55.6$ GeV/c^2 for any ΔM, in the higgsino scenario and if $M_{\tilde{\nu}} > M_{\tilde{\chi}_1^+}$. In the gaugino scenario with heavy $\tilde{\nu}$'s one can also exclude $M_{\tilde{\chi}_1^+} < 58.1$ GeV/c^2. The narrow non-excluded bands between the exclusions given separately by the searches for long lived charginos and charginos plus ISR can be covered when combining in logical OR the two search methods. In that case the two limits rise to 62.4 GeV/c^2 and 59.8 GeV/c^2, respectively. Given the efficiencies of the two search methods (see Figs. 1 and 2), the result of the combined search is different from the separate ones only in the narrow band where $\Delta M > 170$ MeV/c^2 and there is a significant number of chargino decays with decay length above 10 cm.

All the exclusion are with a confidence level of at least 95%.

These limits take into account a variation of $\tan\beta$ between 1 and 50, and a variation of M_1, M_2 and μ such that the mass difference between the chargino and the neutralino remains below 3 GeV/c^2 and $M_2 \leq 2M_1 \leq 10M_2$.

The sneutrino is always considered to be heavier than the chargino ($M_{\tilde{\nu}} > 500$ GeV/c^2 in the second scenario). If $M_{\tilde{\nu}} \leq M_{\tilde{\chi}_1^+}$, the limits derived in the searches for long-lived charginos are not valid any more, even in the higgsino scenario (because the two body decay $\tilde{\chi}_1^+ \to \tilde{\nu} l^+$ opens up for the gaugino component, which is always present because of mixing). However, the search exploiting the ISR tag remains sensitive even if $M_{\tilde{\nu}} \leq M_{\tilde{\chi}_1^+}$, with the relevant $\Delta M = M_{\tilde{\chi}_1^+} - M_{\tilde{\nu}}$. The corresponding mass limit is expected to extend to slightly higher $M_{\tilde{\chi}_1^+}$, as compared to what was found for heavier sneutrinos (third plot of Fig. 5), at the smallest ΔM studied with the ISR method. On the contrary, the limit is expected to be somewhat reduced when approaching from below $\Delta M = 3$ GeV/c^2. In both cases, the effect arises because of the larger mean energy of the visible products in the two-body chargino decay, which is expected to increase the detectability at very low ΔM but, at the contrary, tends to lower the selection efficiency when the upper bound on the total visible energy applies.

As far as the masses of the scalar partners of the SM charged fermions are concerned, they were supposed to be large enough in order to not modify in a significant way the lifetimes and branching ratios used to obtain the present results (in the higgsino scenario it is sufficient that $M_{\tilde{f}_i} > M_{\tilde{\chi}_1^+}$).

6. Conclusions

Charginos nearly mass-degenerate with the lightest neutralino were searched for in DELPHI using the data collected at 189 GeV. Two different searches for long-lived charginos were complemented with a search for nearly mass-degenerate charginos that exploits the tag of an ISR photon. An improved selection was used for the search with the ISR photon tag, as compared with the previous analysis. No evidence of a signal was found. The results of the searches at 189 GeV were combined with those obtained at lower centre-of-mass energies, where the old samples were re-analysed according to the new selection criteria, whenever different.

The regions excluded with CL $\geq 95\%$ in the space of SUSY parameters were thus extended in all scenarios in which the chargino and the lightest neutralino acquire similar masses. In particular, if all sfermions are heavy, a lower limit of 59.8 GeV/c^2 on the mass of the chargino can be derived, independently on $\Delta M = M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0}$ and for any field composition of the chargino. If the MSSM gaugino masses unify at the GUT scale, the charginos can only be almost pure higgsinos if nearly mass degenerate with the lightest neutralino. In this case, the CL $\geq 95\%$ ΔM independent lower limit on the mass of the chargino is 62.4 GeV/c^2, and this limit is valid whenever $M_{\tilde{f}_i} > M_{\tilde{\chi}_1^+}$, where $\tilde{f}_i$ represents any scalar partner of the SM fermions.

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