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# Update of the search for supersymmetric particles in light gravitino scenarios

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## Abstract

The search for sleptons, neutralinos, charginos and sgoldstinos in the context of scenarios where the lightest supersymmetric particle is the gravitino, and the search for heavy stable charged particles in light gravitino scenarios and minimal supersymmetric standard models, is presented. Data collected during 2000 with the DELPHI detector at centre-of-mass energies from around 204 to 208 GeV were analysed and combined with all the data collected from 1995 to 1999 at lower energies. No evidence for the production of these particles was found, therefore preliminary new mass limits for the supersymmetric and the heavy stable charged particles searched for are set.

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# 1 Introduction

In the year 2000 the Large Electron Positron Collider (LEP) at CERN finished its operation achieving record energies of 204 to 208 GeV when the DELPHI detector collected an integrated luminosity of  $223.53 \text{ pb}^{-1}$ . These data were analysed to update the searches for sleptons, neutralinos, charginos and sgoldstinos in the context of gauge mediated supersymmetry breaking (GMSB) models and heavy stable charged particles within the GMSB and gravity mediated supersymmetry breaking scenarios (MSUGRA).

Supersymmetry (SUSY) is usually assumed to be broken in a hidden sector of particles and then communicated to the observable sector (where all the particles and their superpartners lie) via gravitational interactions. An alternative possibility is that this mediation is performed by standard model (SM) gauge interactions, leading to models of gauge mediated supersymmetry breaking. In most current GMSB theoretical work [1, 2, 3], it is assumed that this hidden sector is coupled to a messenger sector, which in turn couples to the visible sector through radiative corrections with gauge-interaction strength. The primary motivation for GMSB is that it naturally accommodates the experimentally observed absence of flavour changing neutral currents due to the fact that gauge interactions are flavour blind. In these models the scale of SUSY breaking ( $\sqrt{F}$ ) can be as low as about  $10^4$  or  $10^5$  GeV<sup>1</sup> in order to have supersymmetric particle (sparticle) masses of the right order of magnitude ( $\sim \text{GeV}/c^2$ ).

The mass of the gravitino ( $\tilde{G}$ ) is related to the scale of SUSY breaking through the expression:

$$m_{\tilde{G}} \simeq 2.5 \times F/(100 \text{ TeV})^2 \text{ eV}, \quad (1)$$

therefore  $m_{\tilde{G}}$  can be as low as few eV/ $c^2$ . Consequently in these models  $\tilde{G}$  is the lightest supersymmetric particle (LSP) and all the other sparticles will decay into final states that include it.

In GMSB models the entire minimal supersymmetric standard model (MSSM) spectrum can be predicted in terms of the following parameters:

$$F, \Lambda, M, n, \tan \beta \text{ and } \text{sign}(\mu). \quad (2)$$

The most important parameter is  $\Lambda$  (the effective SUSY breaking scale) because it sets the overall mass scale of supersymmetric particles.  $M$  is the messenger mass scale. The number of messenger generations,  $n$ , is also very important because it determines which sparticle is the next-to-lightest supersymmetric particle (NLSP). For  $n = 1$  the NLSP is mainly the  $\tilde{\chi}_1^0$ , and for  $n \geq 2$  it is one of the sleptons. The parameter  $\tan \beta$  is the ratio of the Higgs vacuum expectation values, and  $\text{sign}(\mu)$  is the sign of the Higgs sector mixing parameter<sup>2</sup>.

The coupling to the gravitino is very weak, therefore, all the superparticles other than the next-to-lightest supersymmetric particle undergo chain decay down to the NLSP which finally decays to the  $\tilde{G}$ . The mean decay length of the NLSP depends on  $m_{\tilde{G}}$  [4]. Namely, for  $\tilde{l} \rightarrow l \tilde{G}$  decay one has:

$$\hat{L} = 1.76 \times 10^{-3} \sqrt{\left(\frac{E_{\tilde{l}}}{m_{\tilde{l}}}\right)^2 - 1} \left(\frac{m_{\tilde{l}}}{100 \text{ GeV}/c^2}\right)^{-5} \left(\frac{m_{\tilde{G}}}{1 \text{ eV}/c^2}\right)^2 \text{ cm} \quad (3)$$

<sup>1</sup>In gravity mediated SUSY breaking models  $\sqrt{F} \sim 10^{10}$  or  $10^{11}$  GeV.

<sup>2</sup>The magnitude of  $\mu$  is calculable from the other parameters in the model by imposing radiative electroweak symmetry breaking.

where  $m_{\tilde{l}}$  is the slepton mass. Therefore, the gravitino mass determines if the NLSP decays inside or outside the detector, giving rise to very interesting topologies explored in this paper. For example, for  $m_{\tilde{G}} \lesssim 250 \text{ eV}/c^2$  ( $\sqrt{F} \lesssim 1000 \text{ TeV}$ ), the decay of a NLSP with mass greater than for example  $60 \text{ GeV}/c^2$  can take place within the detector. This range of  $\sqrt{F}$  is in fact consistent with astrophysical and cosmological considerations [5, 6]. Figure 1 shows the  $\tilde{\tau}$  mean decay length as a function of the gravitino mass for different  $\tilde{\tau}$  masses.

In this paper the data were analysed within the two possible slepton NLSP scenarios as discussed in the following. Depending on the magnitude of the mixing in the third family between the left and right gauge eigenstates,  $\tilde{\tau}_R$  and  $\tilde{\tau}_L$ , there are two possible scenarios. If the mixing is large<sup>3</sup>,  $\tilde{\tau}_1$  (the lighter mass eigenstate) is the NLSP. However, if the mixing is negligible,  $\tilde{\tau}_1$  is mainly right-handed [7] and almost mass degenerate with the other sleptons. In this case, the  $\tilde{e}_R$  and  $\tilde{\mu}_R$  three body decay ( $\tilde{l} \rightarrow \tilde{\tau}_1 \tau l$  with  $\tilde{\tau}_1 \rightarrow \tau \tilde{G}$ ), is very suppressed, and  $\tilde{e}_R$  and  $\tilde{\mu}_R$  decay directly into  $l\tilde{G}$ . This scenario is called sleptons co-NLSP.

The signature for SUSY particle production within GMSB models at LEP2 depends on the NLSP type and on its mean decay length, or equivalently, on the gravitino mass. The NLSP could be pair produced directly, or other sparticle production could lead to a cascade decay into the NLSP. The NLSP will decay into its non-SUSY partner and a  $\tilde{G}$ . Taking into account all these factors, the following topologies can be expected:

- For  $m_{\tilde{G}}$  below a few  $\text{eV}/c^2$ , the NLSP decays in the vicinity of its production point, before the tracking devices of the detector, and different topologies can be expected. If the sleptons are pair produced the signature in the detector is the same as in the search for sleptons in gravity-mediated supersymmetry breaking scenarios, i.e. two acoplanar<sup>4</sup> leptons and missing energy. However, if neutralino pair production is kinematically allowed, the production cross-section can be larger than for  $\tilde{l}$  even if  $m_{\tilde{\chi}_1^0} > m_{\tilde{l}}$  because of the  $\beta^3$  suppression factor of the scalar production cross-section. In this case the topology is given by four leptons and missing energy since each  $\tilde{\chi}_1^0$  decays into  $\tilde{l}\bar{l}$ , and the sleptons into  $l\tilde{G}$ .
- For  $m_{\tilde{G}}$  between a few  $\text{eV}/c^2$  and a few hundred  $\text{eV}/c^2$  the NLSP has an intermediate mean decay length and it would decay in flight in some part of the detector volume creating well defined secondary vertices or kinks when the  $\tilde{l}$  is reconstructed by the tracking devices, or large impact parameter tracks if it is not.
- For gravitino masses above few hundred  $\text{eV}/c^2$  the NLSP would be sufficiently long-lived to decay outside the detector giving rise to heavy stable charged particles signatures.

In the GMSB parameter space where the  $\tilde{\chi}_1^0$  is the NLSP, the chargino is always much heavier than  $100 \text{ GeV}/c^2$  and cannot be produced. On the contrary, in the parameter space where the  $\tilde{l}$  is the NLSP there are regions where the  $\tilde{\chi}_1^\pm$  is light enough to be produced [8]. In this case the topology for  $m_{\tilde{G}}$  below a few  $\text{eV}/c^2$  is again two acoplanar leptons and missing energy since each  $\tilde{\chi}_1^\pm$  decays into  $\tilde{l}\bar{\nu}$  and each  $\tilde{l}$  into  $l\tilde{G}$ . For  $m_{\tilde{G}}$

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<sup>3</sup>In GMSB models large mixing occurs generally in regions of  $\tan \beta \geq 10$  or  $|\mu| > 500 \text{ GeV}/c^2$ .

<sup>4</sup>Acoplanarity is defined as the complement of the angle between the projections of the two tracks onto the plane perpendicular to the beam

between a few  $\text{eV}/c^2$  and a few hundred  $\text{eV}/c^2$  the topologies are again kinks or large impact parameter tracks and, for gravitino masses above a few hundred  $\text{eV}/c^2$ , heavy stable charged particle signatures are again expected.

The update of the search for heavy stable charged particles is also performed. This kind of particles is predicted not only in GMSB models but also in MSSM with a very small amount of R-parity violation, or with R-parity conservation if the mass difference between the LSP and the NLSP becomes very small. In models with R-parity violation the LSP can be a charged slepton or a squark and decay with a long mean decay length into standard model particles [9]. The typical signature of these events is two massive particles traversing the detector which do not produce Cherenkov radiation in DELPHI's Ring Imaging CHerenkov (RICH) detectors, but high ionization losses in the Time Projection Chamber. Updated lower mass limits on heavy stable charged particles, under the assumption that the LSP is a charged slepton, are presented for both models, GMSB and MSUGRA.

Recently it has been pointed out [10] that an appropriate theory must also contain the supersymmetric partner of the goldstino, called the sgoldstino, which could be massive. In the minimal R-parity conserving model, as considered in [10], the effective theory at the weak scale contains two neutral scalar states:  $S$ , CP-even and  $P$ , CP-odd (from now on the two states will be labelled with the generic symbol  $\phi$  since the discussion applies to both of them). It must be pointed out that sgoldstinos have even R-parity, therefore they are not necessarily produced in pairs and their decay chains do not necessarily contain an LSP. The production of these particles may be relevant at LEP2 energies in light gravitino scenarios. One of the most interesting production channels is the process  $e^+e^- \rightarrow \phi\gamma$  which depends on the  $\phi$  mass ( $m_\phi$ ) and on  $\sqrt{F}$ . The most relevant  $\phi$  decay modes are  $\phi \rightarrow \gamma\gamma$  and  $\phi \rightarrow gg$ . The corresponding branching ratios depend on the gaugino masses  $M_1$ ,  $M_2$  and  $M_3$ , and the total width is  $\Gamma \sim \Gamma(\phi \rightarrow \gamma\gamma) + \Gamma(\phi \rightarrow gg)$ . In this paper two sets for these parameters are considered as suggested in [10]; they are listed in Table 1. The total width for a large interval of the parameter space is narrow (below a few  $\text{GeV}/c^2$ ), except for the region with small  $\sqrt{F}$  where the production cross-section is expected to be very large. The two decay channels considered produce events with very different topologies. The channel  $\phi \rightarrow \gamma\gamma$  gives events with three high energy photons, one of which has monochromatic energy  $E_\gamma = \frac{s-m_\phi^2}{2\sqrt{s}}$  for the large fraction of the parameter space where  $\phi$  has a negligible width. Despite the lower  $\phi$  decay branching ratio (4 and 11% for the two sets of Table 1, respectively), this final state is worth investigating because the main background source is the QED process  $e^+e^- \rightarrow \gamma\gamma(\gamma)$ , which is expected to be small if photons in the forward region are discarded. On the other hand, the channel  $S \rightarrow gg$  gives events with one monochromatic photon (except for the region with small  $\sqrt{F}$ ) and two jets. An irreducible background from  $e^+e^- \rightarrow q\bar{q}\gamma$  events is associated to this topology and therefore the signal must be searched for as an excess of events over the background expectations for every mass hypothesis.

The list of GMSB signatures analysed in this paper is given in Table 2.

A brief description of the DELPHI detector is presented in section 2. The data samples are described in section 3. The different selection criteria, the efficiencies and the number of events selected in data and in the expected Standard Model (SM) background are reported in section 4. Finally, the results are presented in section 5, comprising cross-section limits of the pair produced sparticles, lower mass limits and limits on the GMSB model parameters.

	$M_1$	$M_2$	$M_3$	$BR(\phi \rightarrow \gamma\gamma)$	$BR(\phi \rightarrow gg)$
1)	200	300	400	4%	96%
2)	350	350	350	11%	89%

Table 1: Two choices for the gaugino mass parameters (in  $\text{GeV}/c^2$ ) relevant for the sgoldstino production and decay, and the corresponding branching ratios (BR) of the two channels considered.

Production	Decay mode	$\hat{L}$	Expected topology
$e^+e^- \rightarrow \tilde{l}\tilde{l}$	$\tilde{l} \rightarrow l\tilde{G}$	$\ll \ell_{\text{detector}}$ $\sim \ell_{\text{detector}}$ $\gg \ell_{\text{detector}}$	Acoplanar leptons Kinks and large impact parameters Heavy stable charged particles
$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \rightarrow \tilde{l}\tilde{l} \rightarrow l\tilde{l}\tilde{G}$	$\ll \ell_{\text{detector}}$	Four leptons
$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \rightarrow \tilde{l}^+\nu \rightarrow l^+\tilde{G}\nu$	$\ll \ell_{\text{detector}}$ $\sim \ell_{\text{detector}}$ $\gg \ell_{\text{detector}}$	Acoplanar leptons Kinks and large impact parameters Heavy stable charged particles
$e^+e^- \rightarrow \phi\gamma$	$\phi \rightarrow \gamma\gamma$ $\phi \rightarrow gg$	$\ll \ell_{\text{detector}}$ $\ll \ell_{\text{detector}}$	3 high energy $\gamma$ 1 monochromatic $\gamma$ and 2 jets

Table 2: Final state topologies studied in the different scenarios.

## 2 Detector description

DELPHI was one of the four detectors operating at the LEP collider from 1989 to 2000. It was designed as a general purpose detector for  $e^+e^-$  physics with special emphasis on precise tracking and vertex determination and on powerful particle identification. A detailed description of the DELPHI detector can be found in [11] and the detector performance in [12]. Here only those components relevant for the present analyses are discussed.

Charged particle tracks are reconstructed by a system of tracking chambers inside the 1.2 T solenoidal magnetic field: the Vertex Detector (VD), the Inner Detector (ID), the Time Projection Chamber (TPC) and the Outer Detector (OD) in the barrel region; two planes of drift chambers aligned perpendicular to the beam axis (Forward Chamber A and B) measure tracks in the forward and backward directions.

For the data presented here, the VD consists of three cylindrical layers of silicon detectors, at radii 6.3 cm, 9.0 cm and 11.0 cm, and polar angle acceptance from  $24^\circ$  to  $156^\circ$ . All three layers measure coordinates in the plane transverse to the beam ( $xy$ ), and at least two of the layers also measure  $z$  coordinates along the beam direction. The ID consists of a cylindrical drift chamber with inner radius 12 cm and outer radius 22 cm, surrounded by 5 layers of straw tubes, having a polar acceptance between  $15^\circ$  and  $165^\circ$ . The TPC, the principal tracking device of DELPHI, consists of a 2.7 m long cylinder of 30 cm inner radius and 122 cm outer radius. Each end-plate of the TPC is divided into 6 sectors with 192 sense wires and 16 circular pad rows per sector. The wires are used for  $dE/dx$  measurements and the pad rows are used for 3 dimensional space-point reconstruction. The OD consists of 5 layers of drift cells at radii between 192 cm and 208 cm, covering polar angles between  $43^\circ$  and  $137^\circ$ . The average momentum resolution for charged particles in hadronic final states is in the range  $\Delta p/p^2 \simeq 0.001$  to  $0.01$  ( $\text{GeV}/c$ ) $^{-1}$ .

The electromagnetic calorimeters consist of a High Density Projection Chamber (HPC) covering the polar angle region from  $40^\circ$  to  $140^\circ$  and, a Forward ElectroMagnetic Calorimeter (FEMC) covering the polar angle regions from  $11^\circ$  to  $36^\circ$  and  $144^\circ$  and  $169^\circ$ . The Scintillator Tile Calorimeter (STIC) extends the polar angle coverage down to  $1.66^\circ$  from the beam axis in both directions. The efficiency to detect a photon with an energy above 5 GeV at polar angles between  $20^\circ$  and  $160^\circ$  is of the order of 93%. The Hadron CALorimeter (HCAL) covers 98% of the solid angle. The muons which traverse the HCAL are recorded in a set of Muon Drift Chambers placed in the barrel, forward and backward regions.

The Ring Imaging CHerenkov (RICH) detectors of DELPHI provide charged particle identification in both the barrel (BRICH) and forward (FRICH) regions. They contain two radiators of different refractive indices. The liquid radiator is used for particle identification in the momentum range from 0.7 to 8  $\text{GeV}/c$ . The gas radiator is used for particles with momentum range from 2.5  $\text{GeV}/c$  to 25  $\text{GeV}/c$ .

### 3 Data sample and event generators

The searches reported in this paper are based on data collected with the DELPHI detector during 2000 at centre-of-mass energies from around 204 to 208 GeV. The total integrated luminosity was  $223.53 \text{ pb}^{-1}$ . Table 3 summarises the energies analysed and the integrated luminosities corresponding to each energy during the LEP2 period.

Year	1995	1996	1997	1998	1999	2000
$\sqrt{s}$ (GeV)	130-136	161-172	183	189	192-202	204-208
$\mathcal{L}$ ( $\text{pb}^{-1}$ )	11.9	19.6	54.0	158.0	228.2	223.5

Table 3: Centre-of-mass energies analysed and their corresponding integrated luminosities during the LEP2 period.

To evaluate the signal efficiencies and background contamination, events were generated using different programs, all relying on JETSET 7.4 [13], tuned to LEP1 data [14] for quark fragmentation.

Slepton pair samples at 208 GeV centre-of-mass energy were produced with PYTHIA 5.7[13] with sleptons having mean decay lengths from 0.25 to 200 cm and masses from 60 to 104  $\text{GeV}/c^2$ . Other samples of slepton pairs were produced at 206 and 208 GeV with SUSYGEN [15] for the small impact parameter search with  $m_{\tilde{\tau}}$  from 90  $\text{GeV}/c^2$  to 102  $\text{GeV}/c^2$ , and  $m_{\tilde{\mu}}$  equal to 90  $\text{GeV}/c^2$ . Neutralino pair events and their subsequent decay products were generated with SUSYGEN. Selection efficiencies were computed from samples with neutralino masses from  $72 \text{ GeV}/c^2 \leq m_{\tilde{l}} + 2 \text{ GeV}/c^2 \leq m_{\tilde{\chi}_1^0} \leq \sqrt{s}/2$  at 206 GeV. SUSYGEN was also used to generate the chargino pair production and decay. In order to compute detection efficiencies, samples at 204 GeV and 206 GeV centre-of-mass energies were generated with gravitino masses of 1, 100 and 1000 eV/ $c^2$ ,  $m_{\tilde{l}} + 0.3 \text{ GeV}/c^2 \leq m_{\tilde{\chi}_1^+} \leq \sqrt{s}/2$  and  $80 \text{ GeV}/c^2 \leq m_{\tilde{l}} \leq \sqrt{s} - 2.6 \text{ GeV}/c^2$ . Samples with smaller  $\Delta m = m_{\tilde{\chi}_1^+} - m_{\tilde{\tau}_1}$  were not generated because in that region each chargino decays into a W and a gravitino with an appreciable branching ratio.

In the search for heavy stable charged particles, signal efficiencies were estimated from pair produced heavy smuons generated at energies of 205 GeV, 206.7 GeV and 208 GeV with **SUSYGEN**. The events were passed through the detector simulation as heavy muons. The efficiencies were estimated for masses between  $10 \text{ GeV}/c^2$  and  $100 \text{ GeV}/c^2$ .

For the sgoldstino search, signal efficiencies were estimated from samples obtained as explained in [16].

The background process  $e^+e^- \rightarrow q\bar{q}(n\gamma)$  was generated with **PYTHIA 6.125**, while **KORALZ 4.2** [17] was used for  $\mu^+\mu^-(\gamma)$  and  $\tau^+\tau^-(\gamma)$ . The generator **BHWIDE** [18] was used for  $e^+e^- \rightarrow e^+e^-$  events. Processes leading to four-fermion final states were generated using **EXCALIBUR 1.08** [19] and **GRC4F** [20]. Two-photon interactions leading to hadronic final states were generated using **TWOGAM** [21], including the VDM, QPM and QCD components. The generators of Berends, Daverveldt and Kleiss [22] were used for the leptonic final states.

The cosmic radiation background was studied using the data collected before the beginning of the 2000 LEP run.

The generated signal and background events were passed through the detailed simulation [12] of the DELPHI detector and then processed with the same reconstruction and analysis programs used for real data.

## 4 Data selection

### 4.1 Slepton pair production

This section describes the selection criteria used in the search for the process  $e^+e^- \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow l^+\tilde{G}l^-\tilde{G}$ . Loose preselection cuts were imposed on the events in order to suppress as much as possible the low energy background (beam-gas and beam-wall) and the SM processes. In order to compute general event quantities the reconstructed tracks of charged particles were required to satisfy certain quality criteria: momenta above  $100 \text{ MeV}/c^2$  and impact parameters below 4 cm in the plane transverse to the beam pipe, and below 10 cm in the direction along the beam pipe. Clusters in the calorimeters were interpreted as neutral particles if they were not associated to charged particles and if their energy exceeded 100 MeV. The preselection cuts were the following:

- To eliminate high multiplicity events like  $e^+e^- \rightarrow q\bar{q}(n\gamma)$  or  $WW$ ,  $W\nu_e\nu_e$  and  $ZZ$  when the produced particles had pure hadronic or semileptonic decays, the charged particle multiplicity was required to be between 1 and 6 (the multiplicity of all signal samples was very well contained between these two limits).
- To eliminate two-photon processes, the visible energy in the event was required to be above 10 GeV.
- To eliminate the remaining contribution of two-photon and two-fermion processes, the absolute value of the transverse momentum vector of charged and neutral particles was required to be greater than  $5 \text{ GeV}/c$ .
- The energy measured in the very forward calorimeters (STIC) was required to be below 10 GeV to eliminate the residual contamination of processes mentioned above.

- To eliminate the Bhabha contribution, the total electromagnetic energy was required to be less than the beam energy.

All the events that survive the preselection cuts underwent the search for secondary vertices or kinks. Only the events which were not tagged as kink candidates passed the selection criteria to search for large impact parameter tracks.

#### 4.1.1 Search for secondary vertices or kinks

The analysis exploits a peculiarity of the  $\tilde{l}^\pm \rightarrow l^\pm \tilde{G}$  topology in the case of intermediate gravitino masses (i.e.  $\text{few eV}/c^2 < m_{\tilde{G}} < \text{few hundred eV}/c^2$ ), namely, one or two tracks coming from the interaction point and at least one of them with either a secondary vertex or a kink.

The charged particle tracks (without quality requirements) of the events that survived the preselection cuts were grouped into clusters (in order to group all the tracks coming from a tau decay) according to their first measured point in the xy plane. This clustering procedure was iterative and worked as follows. The pair of tracks with the smallest separation at their respective starting points was considered first. If this separation was smaller than 2 cm, the tracks were grouped to form a cluster whose starting point was defined as the average of their first measured points. The two tracks were then replaced by this cluster which was subsequently treated as a pseudo-track. The process was then repeated until all charged particle tracks or pseudo-tracks were grouped into clusters. This procedure allowed for clusters containing a single track if its momentum was larger than 1.5 GeV/c. Events were rejected if more than 6 tracks were not grouped into clusters or if a cluster could not be obtained. This cut was intended to eliminate the remaining beam related background events<sup>5</sup> that had not been excluded at the preselection level. Once all the tracks were grouped in clusters, the search for kinks was performed in the following way. Slepton candidates were searched for among all the clusters in the event. Among the remaining clusters, the ones corresponding to lepton candidates or decay products of taus were also searched for. The clusters were extrapolated in order to find a crossing point. If the crossing point existed, the event was considered as a kink candidate. Reconstruction of secondary vertices for the case when  $\tilde{\tau} \rightarrow \tau \tilde{G}$  is illustrated in Figure 2, which shows a decay vertex and the variables used in the analysis.

Isolated tracks (clusters with only one particle) were considered as  $\tilde{l}$  candidates if their trajectories were compatible with particles coming from the interaction point according to the following selection criteria:

- the first measured point with respect to the beam spot in the plane transverse to the beam axis ( $R_{sp}^{\tilde{l}}$ ) had to lie in the Vertex Detector (VD);
- the momentum of the particle was greater than 2 GeV/c;
- the polar angle of the track with respect to the beam axis had to satisfy  $|\cos \theta| < 0.8$ , corresponding to the barrel region;
- the impact parameter (with geometrical sign to the primary vertex) of the track along the beam axis and in the plane perpendicular to it was less than 10 and 4 cm, respectively.

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<sup>5</sup>This kind of events was mainly characterized by a high number of low momentum charged particles seen only in the innermost detectors VD and ID.

For every  $\tilde{l}$  candidate, a search was made for a second cluster satisfying the following selection criteria:

- the starting point in the transverse plane ( $R_{sp}^{l_d}$ ) had to be greater than  $R_{sp}^{\tilde{l}}$ . The second cluster starting point was always found in the Inner Detector (ID) or the Time Projection Chamber (TPC);
- the angular separation between the directions defined by the  $\tilde{l}$  candidate and the lepton candidate had to be smaller than  $45^\circ$  in the  $xy$  plane, to consider only the tracks which were in the direction of the slepton.

The  $\tilde{l}$  candidate and the lepton cluster had to define a secondary vertex or kink defined as the crossing point with the  $\tilde{l}$  track. If the lepton cluster included more than one charged particle (which is the case when  $l$  is a  $\tau$  decaying to 3 or 5 prongs), only the one with the highest momentum was used to search for the kink. To find the crossing point between the  $\tilde{l}$  candidate and the cluster with the decay products of the lepton ( $l_d$ ), the track trajectories were represented by a helix in space. Taking into account this parametrization, the point of closest approach between the candidate  $\tilde{l}$  track and the selected track from the candidate  $l_d$  cluster was calculated. The conditions to define a good crossing point between both tracks were the following:

- the minimum distance between the tracks had to be smaller than 1 mm in the  $xy$  plane;
- the crossing point, the end point of the stau track and the starting point of the tau decay products were required to satisfy the following conditions:

$$\begin{aligned} -10 \text{ cm} &< (R_{cross} - R_{end}^{\tilde{l}}) &< 25 \text{ cm} \\ -25 \text{ cm} &< (R_{cross} - R_{sp}^l) &< 10 \text{ cm}, \end{aligned} \quad (4)$$

where  $R_{end}^{\tilde{l}}$ ,  $R_{cross}$  and  $R_{sp}^l$  are the distances from the beam spot of the end point of the slepton track, the crossing point of the tracks and the starting point of the  $l$  decay track in the  $xy$  plane. The cut was optimised to assure that all VD or IDVD only tracks (tracks which only had ID or VD hits) were connected with TPC tracks (tracks reconstructed by the TPC).

The resolution achieved (generated distance minus reconstructed distance) with the algorithm to find secondary vertices in the coordinates  $x$  and  $y$  was 0.14 mm.

Fake decay vertices could be present among the reconstructed secondary vertices, being produced by particles interacting in the detector material or by radiated photons when the particle trajectory was reconstructed as two separated tracks. To eliminate these events, additional conditions were required:

- to reject hadronic interactions, the angle between the direction of any reconstructed hadronic vertex w.r.t. beam spot (secondary vertices reconstructed in region where there is material) and the direction of the slepton candidate must be greater than  $5^\circ$ ;
- to reject segmented tracks, the angle between the tracks used to define a vertex had to be larger than  $6^\circ$ ;

- to reject photon radiation in the case of  $l$  clusters with only one track, there had to be no neutral particle in a  $3^\circ$  cone around the direction defined by the difference between the  $\tilde{l}$  momentum and the momentum of the  $l$  daughter calculated at the crossing point.

If no pair of tracks was found to survive these conditions, the event was rejected. Figure 3 shows the distribution of these three quantities. The distributions compare real data, expected SM background simulation and a simulated signal for  $m_{\tilde{\tau}} = 60$  GeV/c $^2$  with a mean decay length of 50 cm.

Table 4 shows the different SM background contributions and the observed events in data after applying the selection criteria to search for kinks. Efficiencies for different gravitino and stau masses were calculated by applying the above selections to the simulated signal samples. Figure 4 shows the secondary vertex reconstruction efficiency as a function of the stau decay radius. For smuons and selectrons the same dependency is observed. For smuons the efficiency plateau is around 60%, while for selectron it is around 40% due to the preselection cut on total electromagnetic energy.

Observed events	2
Total background	$0.94^{+1.35}_{-0.15}$
$Z^*/\gamma \rightarrow (\tau\tau)(n\gamma)$	$0.16^{+0.09}_{-0.05}$
$Z^*/\gamma \rightarrow (ee)(n\gamma)$	$0.06^{+0.87}_{-0.06}$
4-fermion (except $\gamma\gamma$ )	$0.12^{+0.06}_{-0.01}$
$\gamma\gamma \rightarrow \tau^+\tau^-$	$0.16^{+0.32}_{-0.06}$
$\gamma\gamma \rightarrow e^+e^-$	$0.44^{+0.98}_{-0.11}$

Table 4: The number of observed events at  $\sqrt{s}$  from 204 GeV to 208 GeV together with the total number of expected SM background events and the expected numbers from the individual background sources, for the secondary vertex search.

#### 4.1.2 Large impact parameter search

To investigate the region of low gravitino masses (short decay lengths) the previous search was extended to the case of sleptons decaying between 0.25 cm and around 10 cm, i.e., before the tracking devices. In this case it was only possible to reconstruct the slepton decay products. The impact parameter search was only applied to those events accepted by the same preselection cuts as in the search for secondary vertices, and not selected by the vertex analysis. The events used in this search contained exactly two single track clusters (i.e. two charged particles with momentum larger than 1.5 GeV/c and a distance between starting points greater than 2 cm) which were acollinear and had large impact parameters. The events were accepted as candidates if:

- the first measured point (in the transverse plane and with respect to the beam spot) of at least one of the tracks had to be in the VD;
- both tracks were reconstructed in the TPC to guarantee good track reconstruction quality;

- at least one of the tracks had an impact parameter larger than 0.2 cm in the  $xy$  plane to remove SM events;
- the ratio of the maximum impact parameter over the minimum impact parameter in the  $xy$  plane was smaller than -1.5 or larger than -0.5, to reject cosmic rays since they are characterized by large impact parameters of the same value and opposite sign. The distribution of the maximum impact parameter versus the minimum impact parameter in the  $xy$  plane is shown in figure 5. The cut on the ratio of impact parameters is shown with solid lines;
- the acollinearity between the two tracks was larger than  $10^\circ$  to eliminate back-to-back events with badly reconstructed tracks or interactions which always gave small acollinearities. In addition, to reduce further the cosmic ray muon background, the acollinearity between the two tracks was required to be smaller than  $175^\circ$ , since an off-time cosmic ray muon crossing from one TPC drift sector to another could be reconstructed as two almost parallel tracks.

Figure 6 shows the acollinearity distribution for events with two tracks in the TPC. Simulated signal events with  $m_{\tilde{\tau}} = 60$  GeV/c $^2$  and a mean decay length of 2 cm are compared with cosmic ray muon events, simulated SM background and real data. The data points in this figure contain cosmic events that are not simulated. Table 5 shows the different SM background contributions and the number of events observed in data after applying the selection criteria to search for large impact parameter tracks.

Observed events	2
Total background	$2.40^{+1.45}_{-0.37}$
$Z^*/\gamma \rightarrow (\tau\tau)(n\gamma)$	$0.05^{+0.05}_{-0.01}$
$Z^*/\gamma \rightarrow (ee)(n\gamma)$	$0.12^{+0.91}_{-0.12}$
4-fermion (except $\gamma\gamma$ )	$0.65^{+0.09}_{-0.05}$
$\gamma\gamma \rightarrow \tau^+\tau^-$	$0.09^{+0.31}_{-0.04}$
$\gamma\gamma \rightarrow e^+e^-$	$1.49^{+1.08}_{-0.34}$

Table 5: The number of observed events at  $\sqrt{s}$  from 204 GeV to 208 GeV together with the total number of expected SM background events and the expected numbers from the individual background sources, for the large impact parameter tracks search.

The efficiencies were derived for different slepton masses and decay lengths by applying the same selection criteria to the simulated signal events. In the search for  $\tilde{\tau}_1$  the maximum efficiency was around 32% corresponding to a mean decay length of 2.5 cm. The efficiency decreased sharply for lower decay lengths due to the requirement on minimum impact parameter. For longer decay lengths, the appearance of reconstructed  $\tilde{l}$  in combination with the cut on the maximum number of charged particles in the event caused the efficiency to decrease smoothly. This decrease is compensated by a rising efficiency in the search for secondary vertices. For masses above 60 GeV/c $^2$  no dependence on the  $\tilde{l}$  mass was found far from the kinematic limit.

The same selection was applied to smuons and selectrons. For smuons the efficiency increased to  $\sim 58\%$  for a mean decay length of 2.5 cm and masses over 60 GeV/c $^2$  since

the smuon always has a one-prong decay. For selectrons the efficiency was  $\sim 33\%$  for the same mean decay length and range of masses.

#### 4.1.3 Small impact parameter search

The large impact parameter search can be extended further to mean decay lengths below 0.1 cm. Charged particles were selected if their impact parameter was less than 10 cm in the plane transverse to the beam direction and less than 15 cm in the direction along the beam pipe. The polar angle had to be between  $20^\circ$  and  $160^\circ$ . Their measured momentum was required to be larger than 400 MeV/c with relative error less than 100% and track length larger than 30 cm. Any calorimetric deposit associated to a discarded charged particle was assumed to come from a neutral particle.

The search was restricted to events with 2 to 4 charged particles and missing energy larger than  $0.3\sqrt{s}$ . The  $\gamma\gamma$  events were suppressed by requiring a visible energy greater than  $0.08\sqrt{s}$  and a transverse missing momentum greater than  $0.03\sqrt{s}$ . The polar angle of the missing momentum was required to be between  $30^\circ$  and  $150^\circ$ , and the total energy was required to be less than 10% of the visible energy, and the neutral energy was required to be less than  $0.175\sqrt{s}$ .

The events were then divided into two hemispheres using the thrust axis. The total momentum of charged and neutral particles in each hemisphere was computed and used to define the acoplanarity of the event. Standard  $e^+e^- \rightarrow f\bar{f}(\gamma)$  processes and cosmic rays were reduced by requiring the acoplanarity to be greater than  $10^\circ$ . The charged particle with the largest and good quality momentum ( $\Delta p_i/p_i < 50\%$ ) in each hemisphere was selected as the leading particle. The following quality requirements were only applied to the leading particle: the first measured point of the tracks had to be within 50 cm of the beam spot in the  $xy$  plane, the tracks were required to have at least one segment beyond the ID detector and away from insensitive regions of the electromagnetic calorimeter. In addition, at least one of the tracks was required to be reconstructed with the TPC.

$e^+e^- \rightarrow f\bar{f}(\gamma)$  processes and cosmic rays were further reduced by requiring an angle between the leading particles in the  $xy$  plane of less than 3 radians. Four-fermion and  $q\bar{q}(\gamma)$  events were rejected by requiring  $\sqrt{p_1^2 + p_2^2} > 0.03\sqrt{s}$ , where  $p_1$  and  $p_2$  are the momenta of the leading particles. To reduce Bhabha events the total electromagnetic energy of the leading particles,  $E_1 + E_2$ , had to be less than  $0.35\sqrt{s}$ . By requiring that any leading track with an impact parameter larger than 1 cm in the  $xy$  plane should be reconstructed by the TPC and at least one other detector, the residual cosmic rays were rejected. Finally, photon conversion events with only two tracks were rejected by requiring the angle between tracks at their perigee to be greater than  $5^\circ$ .

The background left after the selection described above consists mainly of events containing  $\tau$  pairs in the final state ( $\gamma^*/Z^* \rightarrow \tau\tau$  and  $WW \rightarrow \tau\nu\tau\nu$ ). To reject these events, the variable  $\sqrt{b_1^2 + b_2^2}$ , where  $b_1$  and  $b_2$  are the impact parameters of the two leading particles, was used. Requiring  $\sqrt{b_1^2 + b_2^2} \geq 600 \mu\text{m}$  eliminated most of the remaining background.

In order to preserve the efficiency in the region of decay length  $\gtrsim 10$  cm, where the  $\tilde{l}$  can be observed as a particle coming from the primary vertex and badly measured due to its limited length, further requirements on the track quality were applied only to the leading track with the larger impact parameter. This particle was required to have a

relative momentum error  $< 30\%$  and the track to be measured at least either in the TPC or in all of the other three track detectors in the barrel (VD, ID and OD).

The efficiency of the search did not show any significant dependence on the  $\tilde{l}$  mass for masses over  $40 \text{ GeV}/c^2$  and far from the kinematic limit, and it could be parameterized as a function of the  $\tilde{l}$  decay length in the laboratory system. The efficiency for  $\tilde{\tau}_1$  detection reaches  $\sim 40\%$  for decay lengths around 2 cm, is still 16% for a decay length of 0.1 cm, and 13% for 20 cm. The efficiency for  $\tilde{\mu}$  detection reaches 45% around 2 cm, 15% at 0.1 cm, and 17% at 20 cm.

In order to increase the efficiency in the search for selectrons, the cut  $(E_1 + E_2) < 0.7\sqrt{s}$  was not applied. The Bhabha events that survived the selection were those where at least one of the electrons underwent a secondary interaction, thus acquiring a large impact parameter. However, it was found that in these cases the measured momentum of the electron was smaller than the electromagnetic energy deposition around the electron track. Therefore, the cut  $(E_1/p_1 + E_2/p_2) < 2.2$  was used for the selectron search. The maximum efficiency reached in the selectron search was  $\sim 35\%$  at  $\sim 2$  cm mean decay length.

The number of events selected in the data was 4 in the  $\tilde{\tau}$  and  $\tilde{\mu}$  search, and 4 in the  $\tilde{e}$  search, while  $3.3 \pm 0.3$  events were expected from the SM background in both searches. Figure 7 shows the  $\sqrt{b_1^2 + b_2^2}$  distribution for data (dots) and simulated backgrounds (histogram) after all other cuts. All of the selected candidates were compatible with SM events.

## 4.2 Neutralino pair production

In this section, the selections used to search for the process  $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\tau}_1\tau\tilde{\tau}_1\tau \rightarrow \tau\tilde{G}\tau\tau\tilde{G}\tau$  within the  $\tilde{\tau}_1$  NLSP scenario, and the process  $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{l}\tilde{l}'\tilde{l}' \rightarrow l\tilde{G}l'\tilde{G}l'$  (with  $\text{BR}(\tilde{\chi}_1^0 \rightarrow \tilde{l}l) = 1/3$  for each leptonic flavour) within the co-NLSP scenario, are presented.

In the following, the preselection of the events, common to both scenarios, is presented. The reconstructed tracks of charged particles were required to have momenta above 100 MeV/c and impact parameters below 4 cm in the transverse plane and below 10 cm in the longitudinal direction. The relative error on the measurement of the momentum had to be smaller than 100%. Clusters in the calorimeters were interpreted as neutral particles if they were not associated to charged particles and if their energy exceeded 100 MeV. All charged and neutral particles that satisfy these criteria were considered good particles and they were used to compute the relevant event quantities. To assure good quality of the data, the ratio of good to total number of particles was required to be above 0.7. Particles that did not pass quality selection but had an associated calorimetric energy of at least 2 GeV had their angles taken from those of the particle, but their momentum was recomputed from the energy of the calorimetric measurement (such particles were not included in the good sample). Events had to have between four and ten good charged particle tracks. In addition, it was required that the thrust be less than 0.99; the transverse momentum,  $p_T$ , had to be bigger than 3 GeV/c, and  $|\cos\theta_{p_{miss}}| < 0.95$  (polar angle of the missing momentum vector). Very forward-going events were eliminated by requiring that the energy in a cone of  $30^\circ$ ,  $E_{30}$ , around the beam-pipe to be less than 70% of the total visible energy,  $E_{vis}$ . With this preselection, the total number of simulated background events and real data events was reduced by a factor of about 6000.

Only events passing these pre-selections were analysed further.

The selection takes advantage of the fact that signal events can be separated into two different kinematic regions of the  $(m_{\tilde{\chi}_1^0}, m_{\tilde{l}})$  space: when the mass difference  $\Delta m = m_{\tilde{\chi}_1^0} - m_{\tilde{l}}$  is bigger than about  $10 \text{ GeV}/c^2$ , all four sleptons carry similar momenta. When the difference becomes smaller, the two leptons coming from the decay of the  $\tilde{l}$  tend to be the most energetic, increasingly so as the  $\tilde{\chi}_1^0$  mass increases. The Durham algorithm [23] was used to divide the event into four jets by allowing  $y_{cut}$  to vary as a free variable. Numbering the jets from 1 to 4 with  $E_1 > E_2 > E_3 > E_4$ , a variable  $r$  was defined as:

$$r = \frac{E_3 + E_4}{E_1 + E_2} . \quad (5)$$

The distribution of  $r$  shifts towards lower values with increasing neutralino masses.

At the preselection level the two main differences between the  $\tilde{\tau}_1$  NLSP and  $\tilde{l}_R$  co-NLSP scenarios come from the fact that the mean number of neutrinos carrying away undetected energy and momentum and the number of charged tracks per event is considerably bigger for the former scenario.

In the  $\tilde{\tau}_1$  NLSP scenario, the simulated background samples were then divided into two samples above and below  $r = 0.1$  and different requirements were imposed in the two cases. No significant dependence on this variable was observed in the  $\tilde{l}_R$  co-NLSP scenario. Two sets of cuts were applied in order to reduce the  $\gamma\gamma$  and  $ff(\gamma)$  backgrounds and a third set of cuts to select events according to their topology:

- Cuts against  $\gamma\gamma$  backgrounds: the transverse energy,  $E_T$ , should be bigger than  $11 \text{ GeV}$  for  $r > 0.1$  ( $E_T > 12 \text{ GeV}$  for  $r \leq 0.1$ ) for the  $\tilde{\tau}_1$  NLSP scenario; and bigger than  $4 \text{ GeV}$  for the  $\tilde{l}_R$  co-NLSP scenario. The energy in a cone of  $30^\circ$  around the beam axis was further restricted to be less than  $60\%$  of the total visible energy to avoid a possible bias from the Monte Carlo samples. The missing mass should be smaller than  $0.88\sqrt{s}$  ( $0.9\sqrt{s}$ ). For the  $\tilde{l}_R$  co-NLSP scenario the optimised value of the cut was  $0.88\sqrt{s}$ . The momentum of the charged particle with largest momentum should be bigger than  $4 \text{ GeV}/c$  ( $3 \text{ GeV}/c$ ). For the  $\tilde{l}_R$  co-NLSP scenario the threshold value was set to  $8 \text{ GeV}/c$ .
- Cuts against  $ff(\gamma)$  backgrounds: the number of good tracks should be smaller than  $7$  ( $9$ ) for above and below  $r = 0.1$  respectively. The maximum thrust was further reduced from  $0.99$  to  $0.975$ . Dividing each event into two jets with the Durham algorithm, its acoplanarity should be bigger than  $8^\circ$ . The missing mass of the events should be bigger than  $0.3\sqrt{s}$ . Regarding the  $\tilde{l}_R$  co-NLSP scenario, the number of good tracks had to be smaller than  $7$ ; the maximum thrust was  $0.95$ ; and the event acoplanarity had to be bigger than  $8^\circ$ . The missing mass had to be bigger than  $0.2\sqrt{s}$ .
- Cuts based on topology: signal events tend naturally to cluster into a 4-jet topology. All jets should be at least  $17^\circ$  and  $18^\circ$  away from the beam direction, for the  $\tilde{\tau}_1$  NLSP and for the  $\tilde{l}_R$  co-NLSP scenarios respectively. When reduced by the jet algorithm into a 2-jet configuration, the charged particles belonging to each of these jets should be in a cone broader than  $20^\circ$  and  $25^\circ$  for the  $\tilde{\tau}_1$  NLSP and  $\tilde{l}_R$  co-NLSP scenarios respectively. Finally, the axes of each of the four jets should be separated from the

others at least by  $8^\circ$  ( $4^\circ$ ) for above and below  $r = 0.1$  respectively, for the  $\tilde{\tau}_1$  NLSP scenario and  $9^\circ$  for the  $\tilde{l}_R$  co-NLSP scenario.

After these cuts, an efficiency between 26 and 44% was obtained for the signal events in the  $\tilde{\tau}_1$  NLSP scenario, and between 35 and 46% in the  $\tilde{l}$  co-NLSP scenario. The number of events remaining in data and simulated samples after the selection procedure were 8 and  $7.1 \pm 0.6$  respectively in the  $\tilde{\tau}_1$  NLSP scenario, and 7 and  $6.6 \pm 0.6$  respectively in the  $\tilde{l}$  co-NLSP scenario.

### 4.3 Chargino pair production

The search for chargino pair production,  $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{l}^+\nu\tilde{l}^-\bar{\nu} \rightarrow l^+\nu\tilde{G}l^-\bar{\nu}\tilde{G}$ , makes use without modification of four different analyses depending on the gravitino mass or, equivalently, on the mean decay length of the slepton. When the slepton decays at the vertex, the combination of two analyses can be exploited, the search for charginos and the search for acoplanar leptons in gravity mediated supersymmetry breaking scenarios. Details of these analyses can be found in [24, 25]. For intermediate mean decay lengths of the slepton the topology is large impact parameter tracks or kinks, therefore, these two analyses, explained in sections 4.1.1 and 4.1.2, can be used. Finally, if the slepton decays outside the tracking devices the signature corresponds to stable heavy leptons and this analysis is explained in section 4.4.

The selections developed for these searches were thus applied to simulated data samples with different gravitino masses, and the results are presented in terms of 95% confidence level (CL) excluded regions in the  $(m_{\tilde{l}}, m_{\tilde{\chi}_1^+})$  plane in section 5.3.

### 4.4 Heavy stable charged particles search

The analysis described in [26, 27] has been applied to the data taken during the year 2000. The data set has been subdivided into 3 energy bins, corresponding to energies below 206 GeV ( $85 \text{ pb}^{-1}$ ), between 206 GeV and 207 GeV ( $124 \text{ pb}^{-1}$ ), and above 207 GeV ( $11.4 \text{ pb}^{-1}$ ). A careful run selection ensured that the RICH detectors were fully operational because the method used to identify heavy stable particles relies on the lack of Cherenkov radiation in DELPHI's RICH detectors. A total background of  $0.25 \pm 0.04$  events was estimated from data itself by counting the number of tracks passing the individual selection criteria. Only events with two or three charged particles were considered. Events were selected, if they contained at least one charged particle with:

- (I) momentum above  $5 \text{ GeV}/c$ , high ionization loss in the TPC and if no photons in the gas radiator of the RICH were associated to the particle (gas veto) or,
- (II) momentum above  $15 \text{ GeV}/c$ , ionization loss at least 0.3 below the expectation for a proton and surviving the gas veto or,
- (III) momentum above  $15 \text{ GeV}/c$ , surviving the gas and the liquid RICH veto.

An event was also selected if both event hemispheres contained particles characterized by a high ionization loss or a gas veto, or both particles having a low ionization loss. Special care has been taken about the  $dE/dx$  in sector 6 (S6) of the Time Projection Chamber which was not operational during the second half of data taking in 2000, reducing the efficiency of the search by several percent as the  $dE/dx$  search windows could not be applied to tracks pointing to S6. To recover some sensitivity for tracks pointing to this

sector, only the double veto search window was applied, requiring hits in the Vertex Detector, Inner Detector and Outer Detector to ensure a good propagation of the tracks through the RICH.

No candidate events were selected in data. Figure 8 shows the data and the three main search windows. The expectation for a  $95 \text{ GeV}/c^2$  mass signal is also shown. For particle masses below  $60 \text{ GeV}/c^2$  the signal efficiencies are of the order of 30% and rise with increasing mass to about 76-78%. Then the efficiency drops when approaching the kinematic limit due to saturation effects, and it is assumed to be zero at the kinematic limit.

## 4.5 Sgoldstino search

This section describes the search for  $e^+e^- \rightarrow \phi\gamma$  events, with the sgoldstino going to two gammas or two gluons. The two channels considered here give rise to two different topologies. On the one hand, if the sgoldstino decays into two photons, the final topology of the event is three high energy photons, one of them monochromatic. On the other hand, if the sgoldstino decays into two gluons, in the final state one monochromatic photon and two jets can be expected.

### 4.5.1 $\phi \rightarrow \gamma\gamma$ channel

The selection criteria were the same as those reported in [16]. Events were selected as  $\gamma\gamma\gamma$  candidates if they had at least two electromagnetic energy clusters with  $0.219 < E/\sqrt{s} < 0.713$ ; at least another one with  $E > 5 \text{ GeV}$  and no more than two additional clusters, the second (if present) with  $E < 5 \text{ GeV}$ . The two most energetic electromagnetic clusters had to be in the HPC region,  $42^\circ < \theta < 89^\circ$ , or in the FEMC region,  $25^\circ < \theta < 32.4^\circ$ . Finally, the third cluster had to be in the region  $42^\circ < \theta$  or  $20^\circ < \theta < 35^\circ$ . The event should not have hits in two of the three Vertex Detector layers compatible within  $\pm 2^\circ$  in the azimuthal angle  $\phi$  with the extrapolated trajectory of a particle from the beam crossing point to an electromagnetic cluster in the calorimeters.

Further, two hemispheres were defined by a plane orthogonal to the direction of the most energetic cluster. One hemisphere was required to have no charged particles detected in the barrel region of the tracking devices other than the VD with a momentum greater than  $1 \text{ GeV}/c$  extrapolating to within 5 cm of the mean beam crossing point. The requirement was strengthened to suppress the larger  $e^+e^-$  background further, by demanding that both hemispheres have no such particle detected by the TPC with  $\theta < 35^\circ$ .

The events obtained after this selection have a three-body final state kinematics if there is no significant initial state radiation lost along the beam pipe. Defining  $\Delta = |\delta_{12}| + |\delta_{13}| + |\delta_{23}|$ , where  $\delta_{ij}$  is the angle between the particles  $i$  and  $j$ ,  $\Delta$  should be  $360^\circ$ . Only the events with  $\Delta > 358^\circ$  were accepted. The energies of the particles can then be determined with very good precision on the basis of the measured photon directions.

In  $\phi\gamma$  events the  $\phi$  decay products are expected to be isotropically distributed in the  $\phi$  centre-of-mass system. This fact implies that the distribution of  $\cos\alpha$ , where  $\alpha$  is the angle between the  $\phi$  direction (opposite to the prompt photon) and the direction of one of the two  $\phi$  decay products, in the  $\phi$  centre-of-mass system, should be flat. On the other hand, in the QED background,  $|\cos\alpha|$  peaks at 1 and therefore only the combinations giving  $|\cos\alpha| < 0.9$  were accepted.

The number of selected events giving up to three combinations and the expected background are 22 and  $20.3^{+1.5}_{-1.9}$ , respectively. The error on the background is due to a correction applied in order to take into account the missing higher orders (additional radiation) in the simulation. All the events, including those from [16] are listed in Table 6. No significant background in addition to  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  events was found.

No significant variation in the acceptance for a  $\phi\gamma$  signal and in the selection efficiency inside the acceptance region were observed in the 2000 data with respect to the lower energies in previous years: acceptance =  $(51 \pm 2)\%$  and efficiency =  $(76.6 \pm 2.5)\%$ .

The energy resolution remained also unchanged and it was better than 0.5% over the whole photon energy range.

The photon recoil mass spectrum obtained for the events collected during the 2000 run including those reported in [16] is shown in Figure 9-a. The data are superimposed on the expected QED background distributions.

#### 4.5.2 $\phi \rightarrow gg$ channel

This channel is expected to give a final state with one photon and two jets. An event was selected as a  $\gamma gg$  candidate if it had an electromagnetic energy cluster identified as photon with  $E > 5$  GeV and  $\theta > 20^\circ$ . The event must not have electromagnetic clusters below  $\theta = 5^\circ$ . The total multiplicity had to be greater than 10, and the charged multiplicity greater than 5. The total transverse momentum had to satisfy  $\sum_{i=1}^n \sqrt{(p_x^2 + p_y^2)_i} > 0.12\sqrt{s}$  where  $n$  is the total multiplicity. Sum of the absolute values of all particle momenta along the thrust axis had to be greater than  $0.20\sqrt{s}$ . An electromagnetic cluster with  $E < 0.45\sqrt{s}$  or a total particle multiplicity greater than 16 when the cluster energy is greater than  $0.45\sqrt{s}$  had to be present. The polar angle of the missing momentum had to satisfy  $|\cos(\theta_{p\_mis})| < 0.995$ . The visible energy had to be greater than  $0.60\sqrt{s}$ . The jets had to be incompatible with the  $b\bar{b}$  hypothesis by requiring the combined btag of the events to be less than zero[28]. Finally, the aforementioned  $|\cos\alpha|$  and  $\Delta$  had to be satisfied to be less than 0.9 and greater than  $350^\circ$ , respectively.

The events were reconstructed forcing all particles but the photon into a 2-jet topology using the Durham [23] algorithm. Events were removed if  $y_{cut} > 0.02$ . The events were also rejected if the angle between the photon and the nearest jet was less than  $10^\circ$ . In the case of more than one photon candidate in the event, the most energetic one was considered as the one produced in  $e^+e^- \rightarrow \phi\gamma$ .

Similar to the  $\gamma\gamma\gamma$  selection, the events obtained after this selection are three-body final state events in absence of additional lost radiation. Therefore kinematic constraints were applied here as well. In this case, however, the jet direction was determined with a poorer precision than that obtained for photons so the cut in  $\Delta$  was less stringent and the resolution for the reconstructed photon energy was poorer: a two-Gaussian fit gave  $\sigma_1 = 1.2$  GeV (55% of the area) and  $\sigma_2 = 4.1$  GeV.

The number of selected events and the expected background were 766 and  $775 \pm 5$ , respectively (Table 6).

Like for the  $\gamma\gamma\gamma$  selection, no significant variation in the acceptance for a  $\phi\gamma$  signal and in the selection efficiency inside the acceptance region was observed in the 2000 data compared to the values at lower energies. The acceptance was  $(76 \pm 2)\%$  and the efficiency ranged from 20 to 55% depending on the photon energy. The energy resolution was also unchanged.

channel	$\sqrt{s}$ (GeV)	events	background
$\phi \rightarrow \gamma\gamma$	189	11	$19 \pm 2$
$\phi \rightarrow \gamma\gamma$	192 to 202	19	$24^{+2}_{-3}$
$\phi \rightarrow \gamma\gamma$	204 to 208	22	$20 \pm 2$
$\phi \rightarrow g g$	189	771	$782 \pm 24$
$\phi \rightarrow g g$	192 to 202	963	$917 \pm 9$
$\phi \rightarrow g g$	204 to 208	766	$775 \pm 5$

Table 6: Selected events for the two decay channels compared to the total expected background. The background for the  $\phi \rightarrow \gamma\gamma$  channel is dominated by the QED process  $e^+e^- \rightarrow \gamma\gamma(\gamma)$  and, for the  $\phi \rightarrow g g$  channel by the process  $e^+e^- \rightarrow q\bar{q}\gamma$ . The errors include systematic effects (see text).

The photon recoil mass spectrum obtained for the events collected during the 2000 run and including those reported in [16] are shown in Figure 9-b. The data are superimposed on the expected background distribution.

## 5 Results and interpretation

Since there was no evidence for a signal above the expected background, the number of candidates in data and the expected number of background events were used to set limits at the 95% confidence level (CL) on the pair production cross-section and masses of the sparticles searched for. The model described in reference [29] was used to derive limits within the GMSB scenarios. This model assumes radiatively broken electroweak symmetry and null trilinear couplings at the messenger scale. The corresponding parameter space was scanned as follows:  $1 \leq n \leq 4$ ,  $5 \text{ TeV} \leq \Lambda \leq 90 \text{ TeV}$ ,  $1.1 \leq M/\Lambda \leq 10^9$ ,  $1.1 \leq \tan\beta \leq 50$ , and  $\text{sign}(\mu) = \pm 1$ , where  $n$  is the number of messenger generations in the model,  $\Lambda$  is the ratio between the vacuum expectation values of the auxiliary component and the scalar component of the superfield and  $M$  is the messenger mass scale. The parameter  $\tan\beta$  is the ratio of the Higgs vacuum expectation values, and  $\text{sign}(\mu)$  is the sign of the Higgs sector mixing parameter. The limits presented here are at  $\sqrt{s} = 208 \text{ GeV}$  after combining these results with those of the searches at lower centre-of-mass energies using the likelihood ratio method [30].

### 5.1 Slepton pair production

The results of the search for slepton pair production are presented in the  $(m_{\tilde{G}}, m_{\tilde{l}})$  plane in Figure 10-a combining the impact parameter, the kink and the stable heavy lepton analyses, and using all DELPHI data from 130 GeV to 208 GeV centre-of-mass energies [27, 31, 32, 33].

The  $\tilde{\tau}_1$  pair production cross-section depends on the mixing in the stau sector. Therefore, in order to put limits on the  $\tilde{\tau}_1$  mass, the mixing angle had to be fixed. The results presented here correspond to a mixing angle in the stau sector which gives the minimum  $\tilde{\tau}_1$  pair production cross-section. Within the  $\tilde{\tau}_1$  NLSP scenario, the impact parameter and kink analyses extended the limit  $m_{\tilde{\tau}_1} > 82.5 \text{ GeV}/c^2$  for  $m_{\tilde{G}} \lesssim 6 \text{ eV}/c^2$ , set by

MSUGRA searches [37], up to  $m_{\tilde{G}} = 400$  eV/c<sup>2</sup>, reaching the maximum excluded value of  $m_{\tilde{\tau}_1} = 93.6$  GeV/c<sup>2</sup> for  $m_{\tilde{G}} = 130$  eV/c<sup>2</sup>. For  $m_{\tilde{G}} > 130$  eV/c<sup>2</sup> the best lower mass limit was set by the stable heavy lepton search.

Within the sleptons co-NLSP scenario, the cross-section limits were used to derive lower limits for  $\tilde{l}_R$  (Figure 10-b) masses at 95% CL. Assuming mass degeneracy between the sleptons, these searches extended the limit  $m_{\tilde{l}_R} > 88$  GeV/c<sup>2</sup> set by MSUGRA searches (this limit is an update of the limit given in [37]) for very short NLSP lifetimes up to  $m_{\tilde{G}} = 800$  eV/c<sup>2</sup>. For the MSUGRA case no lepton combination exists, therefore the best limit from the  $\tilde{\mu}_R$  has been used. The maximum excluded value of  $m_{\tilde{l}_R} = 96.5$  GeV/c<sup>2</sup> was achieved for  $m_{\tilde{G}} = 150$  eV/c<sup>2</sup>. For  $m_{\tilde{G}} > 150$  eV/c<sup>2</sup> the best lower mass limit was set by the stable heavy lepton search.  $\tilde{l}_R$  masses below 40 GeV/c<sup>2</sup> were excluded by LEP1 data [34]. In the case of  $\tilde{l}_R$  degeneracy, this limit improved to 43 GeV/c<sup>2</sup>.

## 5.2 Neutralino pair production

Limits for neutralino pair production cross-section were derived in the  $\tilde{\tau}_1$  NLSP and sleptons co-NLSP scenarios for each  $(m_{\tilde{\chi}_1^0}, m_{\tilde{l}})$  combination. For the  $\tilde{\tau}_1$  NLSP case the combination took into account the results from the LEP runs from 1996 (for  $\sqrt{s} \geq 161$  GeV) to 2000 [27, 31, 32]. The limits for the production cross-section allowed some sectors of the  $(m_{\tilde{\chi}_1^0}, m_{\tilde{l}})$  space to be excluded. In order to exclude as much as possible of the mass plane, the results from two other analyses were taken into account. The first is the search for slepton pair production in the context of MSUGRA models. In the case where the MSUGRA  $\tilde{\chi}_1^0$  is massless, the kinematics correspond to the case of  $\tilde{l}$  decaying into a lepton and a gravitino. The second is the search for lightest neutralino pair production in the region of the mass space where  $\tilde{\chi}_1^0$  is the NLSP [35] (the region above the diagonal line in Figure 11, i.e.  $m_{\tilde{\tau}_1} > m_{\tilde{\chi}_1^0}$ ). Within this zone, the neutralino decays into a gravitino and a photon.

As an illustration, Figure 11 presents the 95% CL excluded areas for  $m_{\tilde{G}} < 1$  eV/c<sup>2</sup> in the  $m_{\tilde{\chi}_1^0}$  vs  $m_{\tilde{\tau}_1}$  plane for the  $\tilde{\tau}_1$  NLSP scenario and for different values of the number of messenger generations ( $n$ ). The negative-slope dashed area is excluded by the analysis searching for neutralino pair production followed by the decay  $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ . The point-hatched area is excluded by the direct search for slepton pair production within MSUGRA scenarios.

## 5.3 Chargino pair production

Limits on the production cross-section for chargino pairs were derived for each  $(m_{\tilde{G}}, m_{\tilde{l}}, m_{\tilde{\chi}_1^+})$  combination. Figure 12-a shows, as an example, the 95% CL upper limit on the chargino pair production cross-section at  $\sqrt{s} = 208$  GeV as a function of  $m_{\tilde{\chi}_1^+}$  and  $m_{\tilde{l}_R}$  after combining the results of the searches for large impact parameter and kink at lower energies using the likelihood ratio method [30], for  $m_{\tilde{G}} = 100$  eV/c<sup>2</sup>. The limits on the chargino pair production cross-section were used to exclude areas within the  $(m_{\tilde{\chi}_1^+}, m_{\tilde{l}})$  plane for different domains of the gravitino mass, combining results from all the centre-of-mass energies from 183 GeV to 208 GeV [27, 31, 36]. Figure 12-b shows the regions excluded at 95% CL in the  $(m_{\tilde{\chi}_1^+}, m_{\tilde{\tau}_1})$  plane (middle figure), for the  $\tilde{\tau}_1$  NLSP

scenario, and in the  $(m_{\tilde{\chi}_1^+}, m_{\tilde{l}_R})$  plane (bottom figure), for the  $\tilde{l}_R$  co-NLSP scenario. The positive-slope area is excluded for all gravitino masses. The negative-slope area is only excluded for  $m_{\tilde{G}} > 100 \text{ eV}/c^2$ . The areas below  $m_{\tilde{\tau}_1} = 82.5 \text{ GeV}/c^2$  in the  $\tilde{\tau}_1$  NLSP scenario, and below  $m_{\tilde{l}_R} = 88 \text{ GeV}/c^2$  (this limit is an update of the limit given in [37]) in the  $\tilde{l}_R$  co-NLSP scenario, are excluded by the direct search for slepton pair production in MSUGRA models [37]. The area of  $\Delta m \leq 0.3 \text{ GeV}/c^2$  is not excluded because in this region the charginos do not decay mainly to  $\tilde{\tau}_1$  and  $\nu_\tau$ , but to W and  $\tilde{G}$ . Thus, if  $\Delta m \geq 0.3 \text{ GeV}/c^2$ , the chargino mass limits are  $100 \text{ GeV}/c^2$  for  $m_{\tilde{G}} = 1 \text{ eV}/c^2$  and  $102 \text{ GeV}/c^2$  for  $m_{\tilde{G}} = 100 \text{ eV}/c^2$  and  $1000 \text{ eV}/c^2$  in the  $\tilde{\tau}_1$  NLSP scenario. In the sleptons co-NLSP scenario the limits are  $96 \text{ GeV}/c^2$  for  $m_{\tilde{G}} = 1 \text{ eV}/c^2$ , and  $102 \text{ GeV}/c^2$  for  $m_{\tilde{G}} = 100 \text{ eV}/c^2$  and  $1000 \text{ eV}/c^2$ . The limit at  $m_{\tilde{G}} = 1 \text{ eV}/c^2$  is also valid for smaller masses of the gravitino because they lead to the same final state topologies. The same argument is true for  $m_{\tilde{G}} > 1 \text{ keV}/c^2$ . The chargino mass limit decreases with decreasing  $m_{\tilde{\tau}_1}$  because in scenarios with gravitino LSP small stau masses correspond to small sneutrino masses (both are proportional to  $\Lambda$ ) and hence to smaller production cross-sections due to the destructive interference between the  $s$ - and  $t$ -channels.

It should be noticed that within the parameter space studied here, the lightest chargino is at least 40% heavier than the lightest neutralino. Thus, for small gravitino masses the search for neutralinos implies a lower limit on the lightest chargino of  $130 \text{ GeV}/c^2$ . Neutralinos are not directly searched for in heavier gravitino mass regions and therefore for this range of gravitino masses the limit of  $102 \text{ GeV}/c^2$  for the chargino mass remains valid.

## 5.4 Heavy stable charged particle pair production

The results presented in section 4.4 were combined with previous DELPHI results in this channel [27, 26, 38], and cross-section limits were derived within MSSM models as indicated in Figure 13. From the intersection points with the predicted cross-sections for smuon or staus in the MSSM, left(right) handed smuons and staus can be excluded up to masses of  $98.0(97.5) \text{ GeV}/c^2$  at 95%CL. No limits are given on selectrons here because the cross-section can be highly suppressed by an additional t-channel sneutrino exchange contribution.

## 5.5 Sgoldstino production

No excess of events nor clear evidence of an anomalous production of events with monochromatic photons is observed in either of the two channels. Therefore a limit on the cross-section of the new physics reaction contributing to the two topologies was set.

Since the expected  $\phi$  branching ratio and total width depend on the mass parameters as explained in [10], the 95% CL cross-section limit was computed as a function of  $m_\phi$  and  $\sqrt{F}$  for the two sets of parameters listed in Table 1, and is shown in Figure 14. By comparing the experimental limits with the expected production cross-section, it is possible to determine a 95% CL excluded region on the parameter space as shown in Figure 15. As explained in [10], to keep the particle interpretation the total width  $\Gamma$  must be much smaller than  $m_\phi$  and therefore the region with  $\Gamma > 0.5m_\phi$  was not considered.

## 5.6 Limits on the GMSB parameter space

Finally, all these results can be combined to produce exclusion plots within the  $(\tan \beta, \Lambda)$  space. The corresponding parameter space was scanned as follows:  $1 \leq n \leq 4$ ,  $5 \text{ TeV} \leq \Lambda \leq 90 \text{ TeV}$ ,  $1.1 \leq M/\Lambda \leq 10^9$ ,  $1.1 \leq \tan \beta \leq 50$ , and  $\text{sign}(\mu) = \pm 1$ . As an example, Figure 16 shows the zones excluded for  $n = 1$  to 4 for  $m_{\tilde{G}} \leq 1 \text{ eV}/c^2$ , which corresponds to the NLSP decaying at the main vertex. The shaded areas are excluded. The areas below the dashed lines contain points of the GMSB parameter space with  $\tilde{\chi}_1^0$  NLSP. The areas to the right (above for  $n = 1$ ) of the dashed-dotted lines contain points of the GMSB parameter space where sleptons are the NLSP. It can be seen that the region of slepton NLSP increases with  $n$ . The contrary occurs to the region of neutralino NLSP. A lower limit is set for the variable  $\Lambda$  at 17.5 TeV.

## 6 Summary

Lightest neutralino, slepton and chargino pair production were searched for in the context of light gravitino models. Two possibilities were explored: the  $\tilde{\tau}_1$  NLSP and the sleptons co-NLSP scenarios. No evidence for signal production was found. Hence, the DELPHI collaboration sets lower limits at 95% CL for the mass of the  $\tilde{\chi}_1^0$  at 89  $\text{GeV}/c^2$  if  $m_{\tilde{G}} < 1 \text{ eV}/c^2$ , and lower mass limits for the sleptons in all the gravitino mass range. The limit on the chargino mass is 100  $\text{GeV}/c^2$  for all  $m_{\tilde{G}}$  in the  $\tilde{\tau}_1$  NLSP scenario and 96  $\text{GeV}/c^2$  in the sleptons co-NLSP scenario. All these results were combined to set limits on the GMSB parameter space. Combining all the data up to 208 GeV, a lower limit is set for the variable  $\Lambda$  at 17.5 TeV.

Mass limits for heavy stable charged particles were also derived within the MSSM. For these particles the DELPHI collaboration sets lower mass limits at 95% CL for the left (right) handed sleptons at 98.0 (97.5)  $\text{GeV}/c^2$ .

Finally, cross-section and mass limits were derived for sgoldstinos at 95% CL since no evidence of an anomalous production of events with monochromatic photons was observed in either of the two channels.

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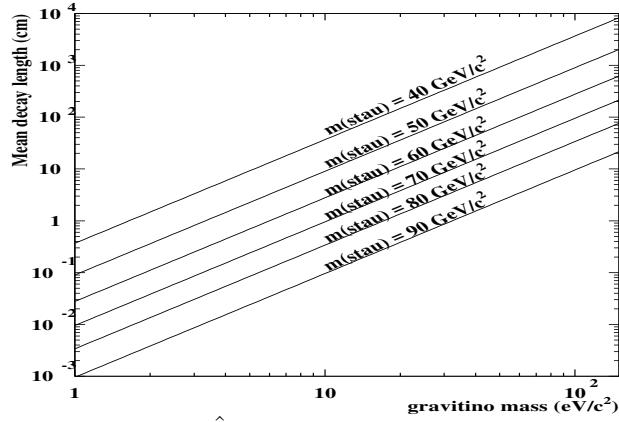


Figure 1:  $\tilde{\tau}$  mean decay length ( $\hat{L} = c\tau\gamma\beta$ ) as a function of the gravitino mass for different  $\tilde{\tau}$  mass values.

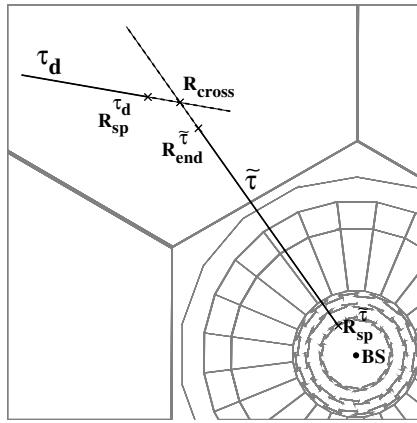


Figure 2: Sketch illustrating the reconstruction of a secondary vertex in the plane perpendicular to the beam direction. All the radii are measured with respect to the beam spot (BS).

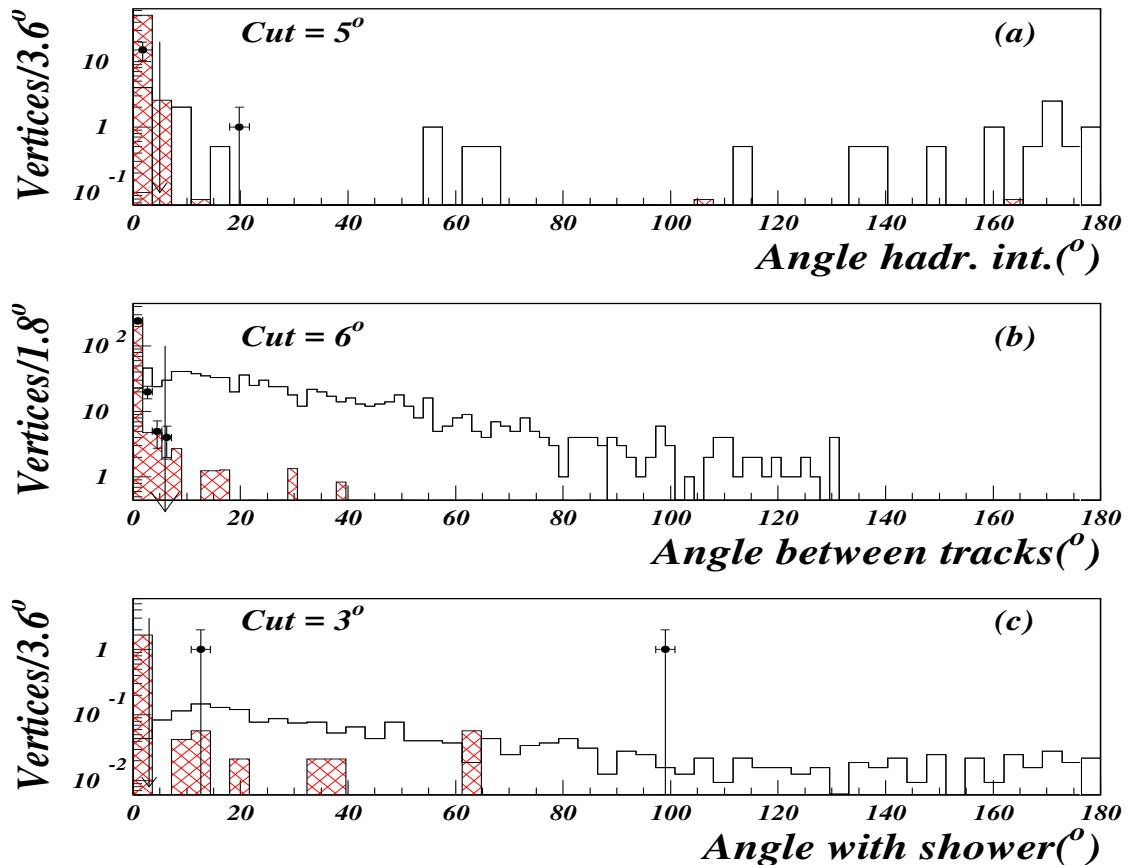


Figure 3: (a) Angle between the directions defined by the hadronic vertex and the reconstructed vertex w.r.t. beam spot, (b) angle between the tracks of the kink, and (c) angle between the electromagnetic shower and the missing momentum. Dots are real data, cross-hatched histogram is the SM background and blank histogram is the simulated signal ( $m_{\tilde{\tau}_1} = 60 \text{ GeV}/c^2$ ,  $\hat{L} = 50 \text{ cm}$  and  $\sqrt{s} = 208 \text{ GeV}$ ).

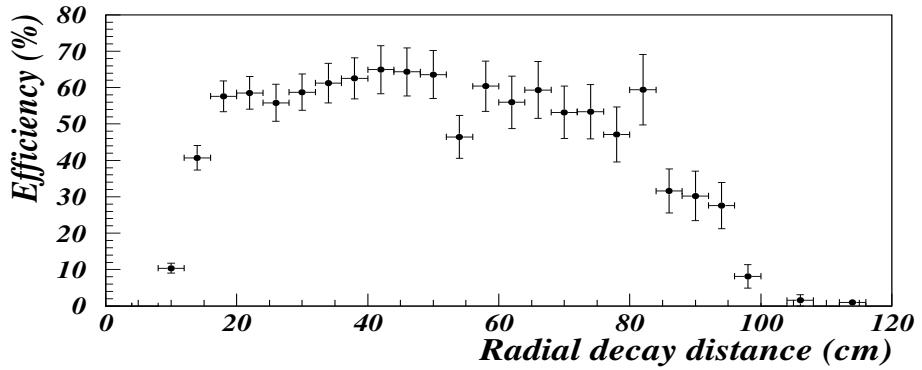


Figure 4: Efficiency as a function of the decay radius for a sample of staus with  $\hat{L} = 50$  cm and  $\sqrt{s} = 208$  GeV.

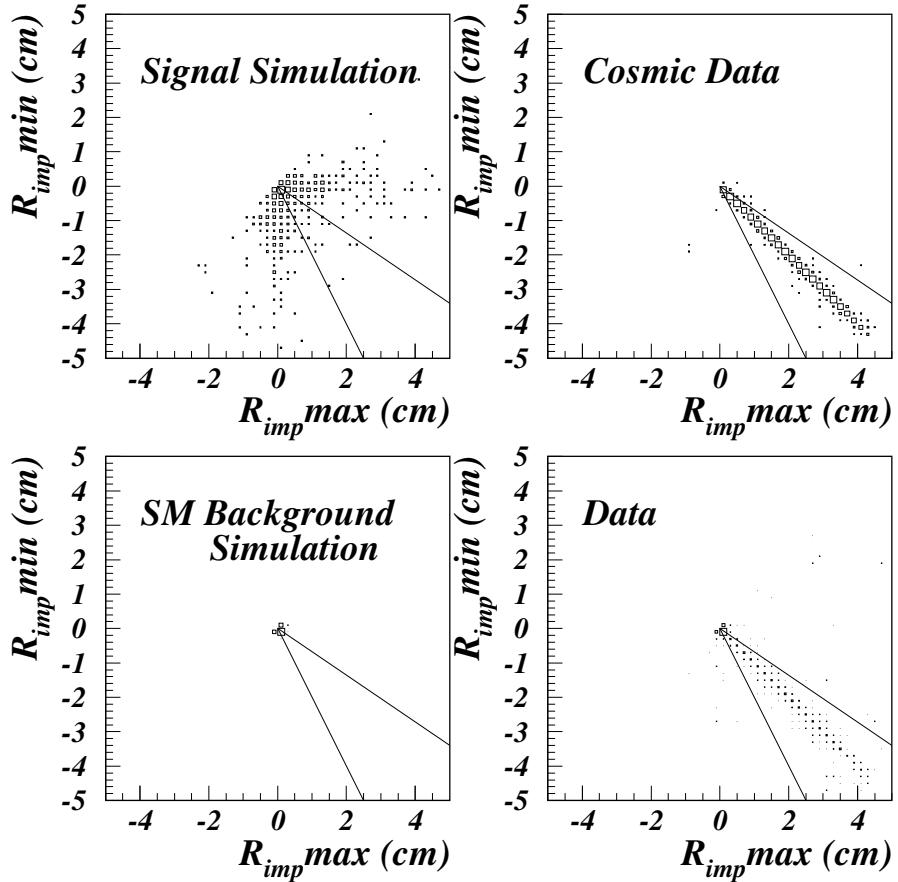


Figure 5: Distribution of the maximum impact parameter versus the minimum impact parameter in the  $R\phi$  plane. The cut on the ratio of impact parameters is shown with solid lines.

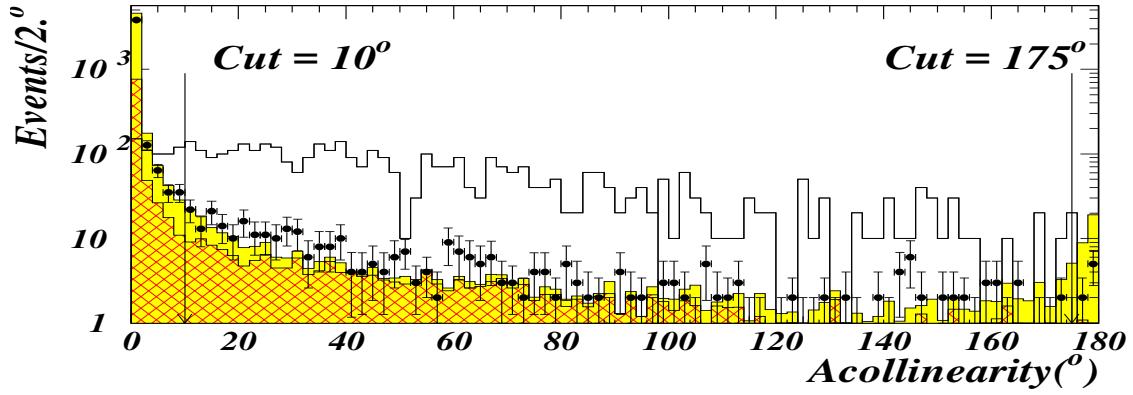


Figure 6: Acollinearity distribution for real data (dots), expected SM background (cross-hatched histogram) and a simulated signal at  $\sqrt{s} = 208$  GeV of  $m_{\tilde{\tau}} = 60$  GeV/c $^2$  with a  $\hat{L} = 2$  cm. The contribution from cosmic ray events is shown in dark grey. The cuts on this variable are shown with arrows.

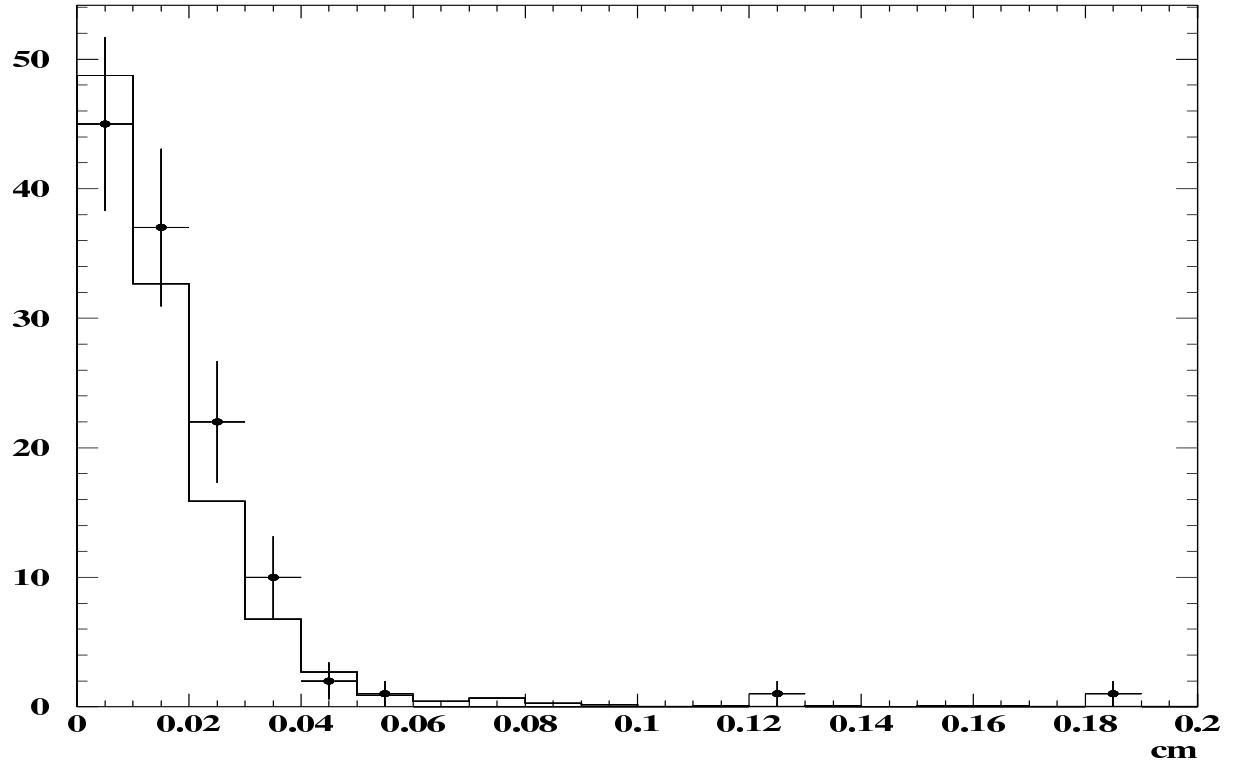


Figure 7:  $\sqrt{b_1^2 + b_2^2}$  distribution for data (dots) and simulated backgrounds (histogram) after all other cuts applied by the small impact parameter search.

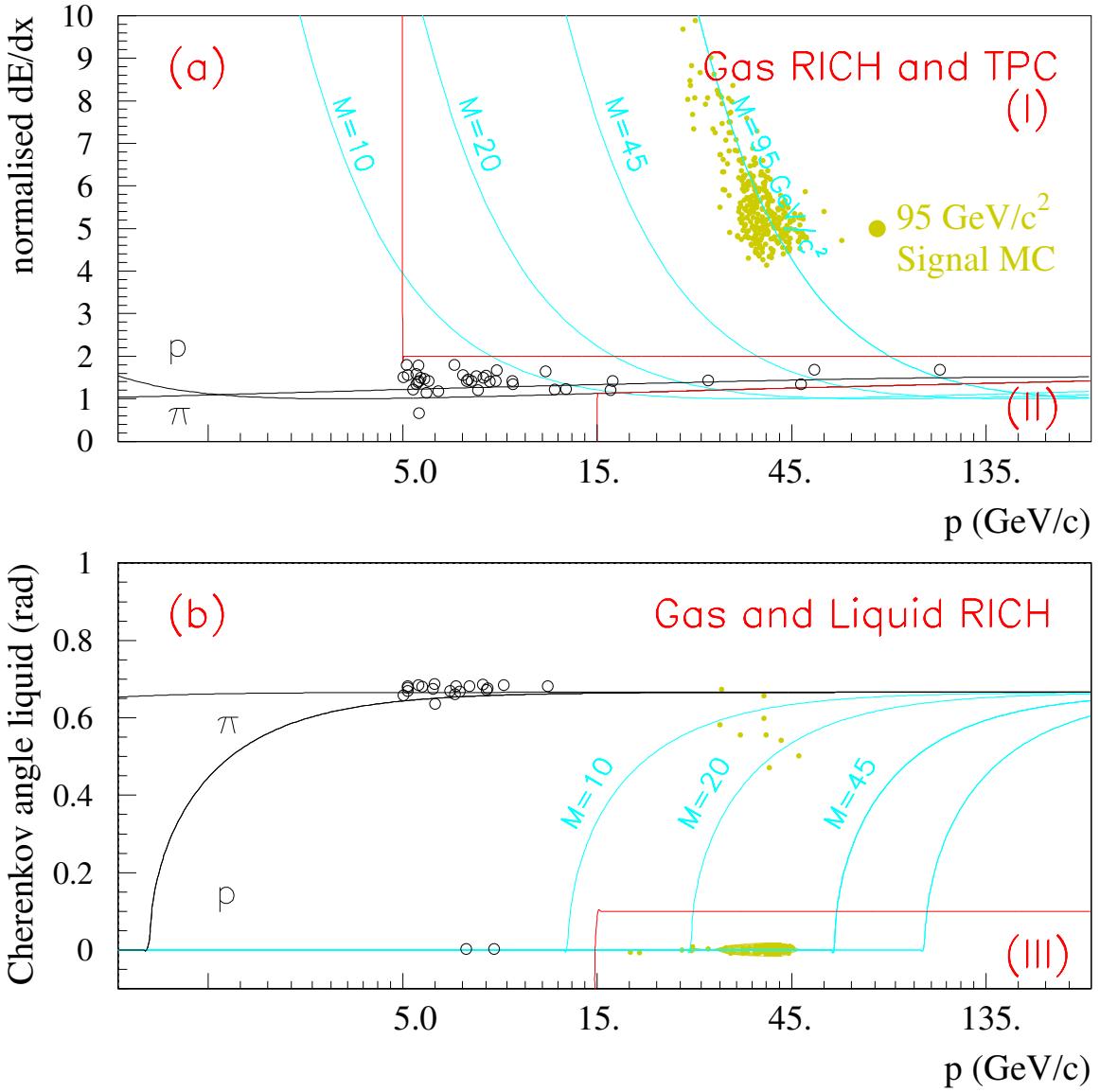
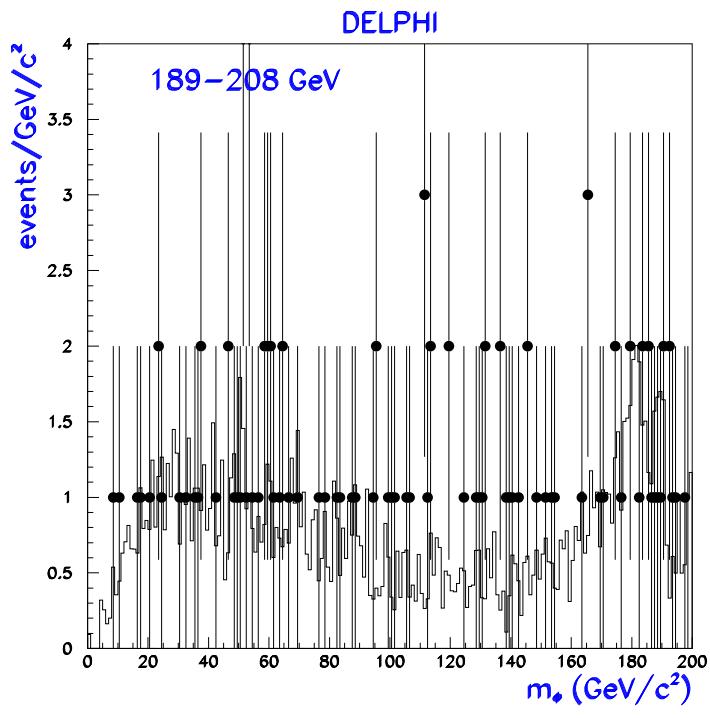
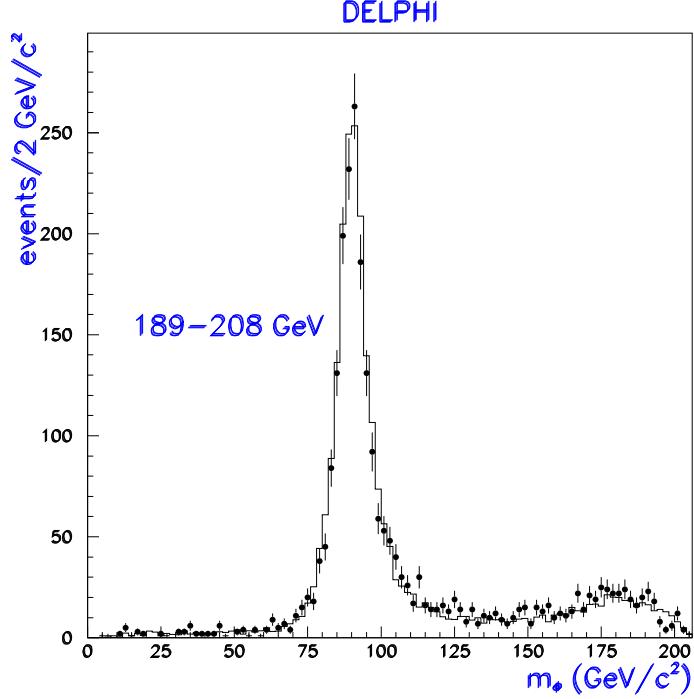


Figure 8: (a) Normalised energy loss as a function of the momentum after the gas veto for the 208 GeV data. (b) Measured Cherenkov angle in the liquid radiator as a function of the momentum after the gas veto: if four photons or less were observed in the liquid radiator, the Cherenkov angle was set equal to zero. The areas labeled (I), (II) and (III) indicate the selection criteria explained in the text. Open circles are data. The small filled circles indicate the expectation for a 95 GeV/c<sup>2</sup> mass signal with charge  $\pm e$ , resulting in a large  $dE/dx$  (upper plot) and no photons (except for a few accidental rings) in the liquid Cherenkov counter (lower plot). The solid lines with a mass signal value indicate the expectation for heavy stable sleptons.



a)



b)

Figure 9: a) Photon recoil mass spectrum for  $\gamma\gamma\gamma$  candidates (points) and the expected background (histogram). The average number of entries per event in the data is 2.3. The bin size takes into account the experimental mass resolution and the expected signal width. b) Photon recoil mass spectrum for  $\gamma\gamma\gamma\gamma$  candidates (points) and the expected background (histogram).

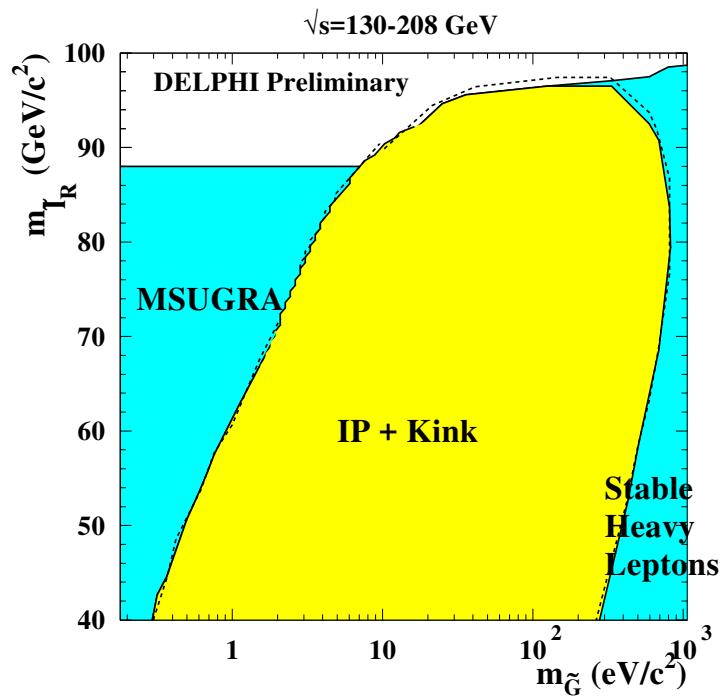
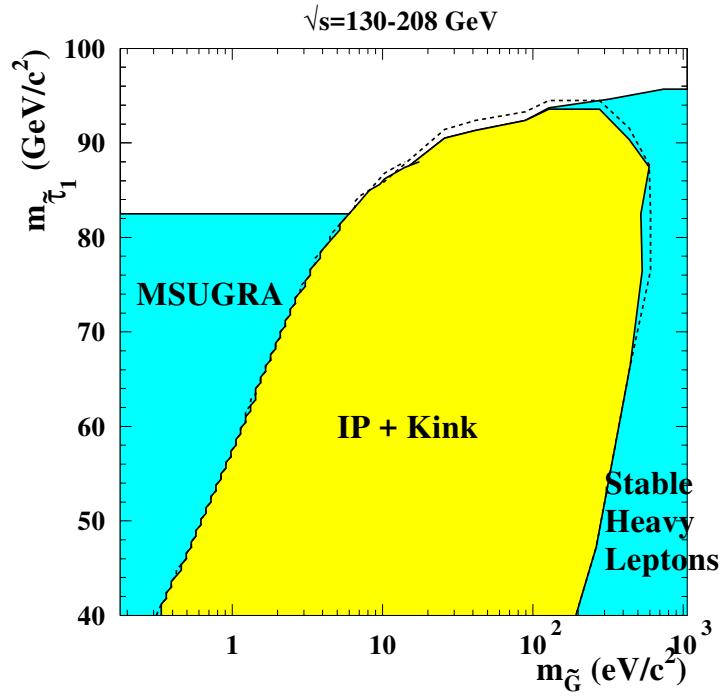


Figure 10: Exclusion regions in the  $(m_{\tilde{G}}, m_{\tilde{\tau}_1})$  (a) and  $(m_{\tilde{G}}, m_{\tilde{l}_R})$  (b) planes at 95% CL for the present analyses combined with the Stable Heavy Lepton search and the search for  $\tilde{l}$  in gravity mediated models (MSUGRA), using all DELPHI data from 130 GeV to 208 GeV centre-of-mass energies. The dashed line shows the expected limits for the impact parameter and kink searches.

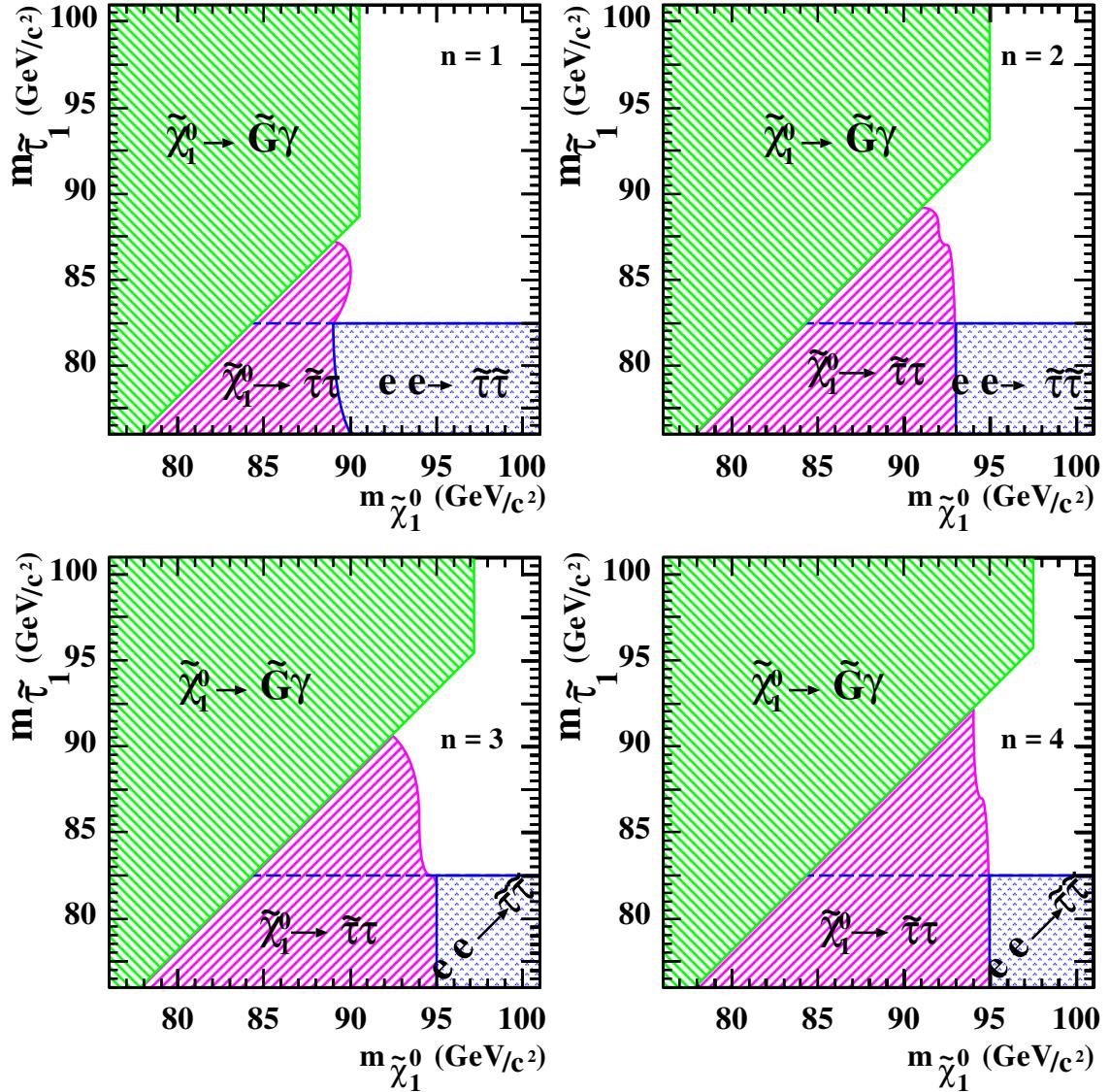


Figure 11: Exclusion regions in the  $(m_{\tilde{\chi}_1^0}, m_{\tilde{\tau}_1})$  plane at 95% CL for the neutralino analysis combined with the search for neutralino pair production followed by the decay  $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$  (negative-slope dashed area), and the direct search for  $\tilde{\tau}_1$  pair production within MSUGRA scenarios (point-hatched area), using all DELPHI data from 161 GeV to 208 GeV centre-of-mass energies.

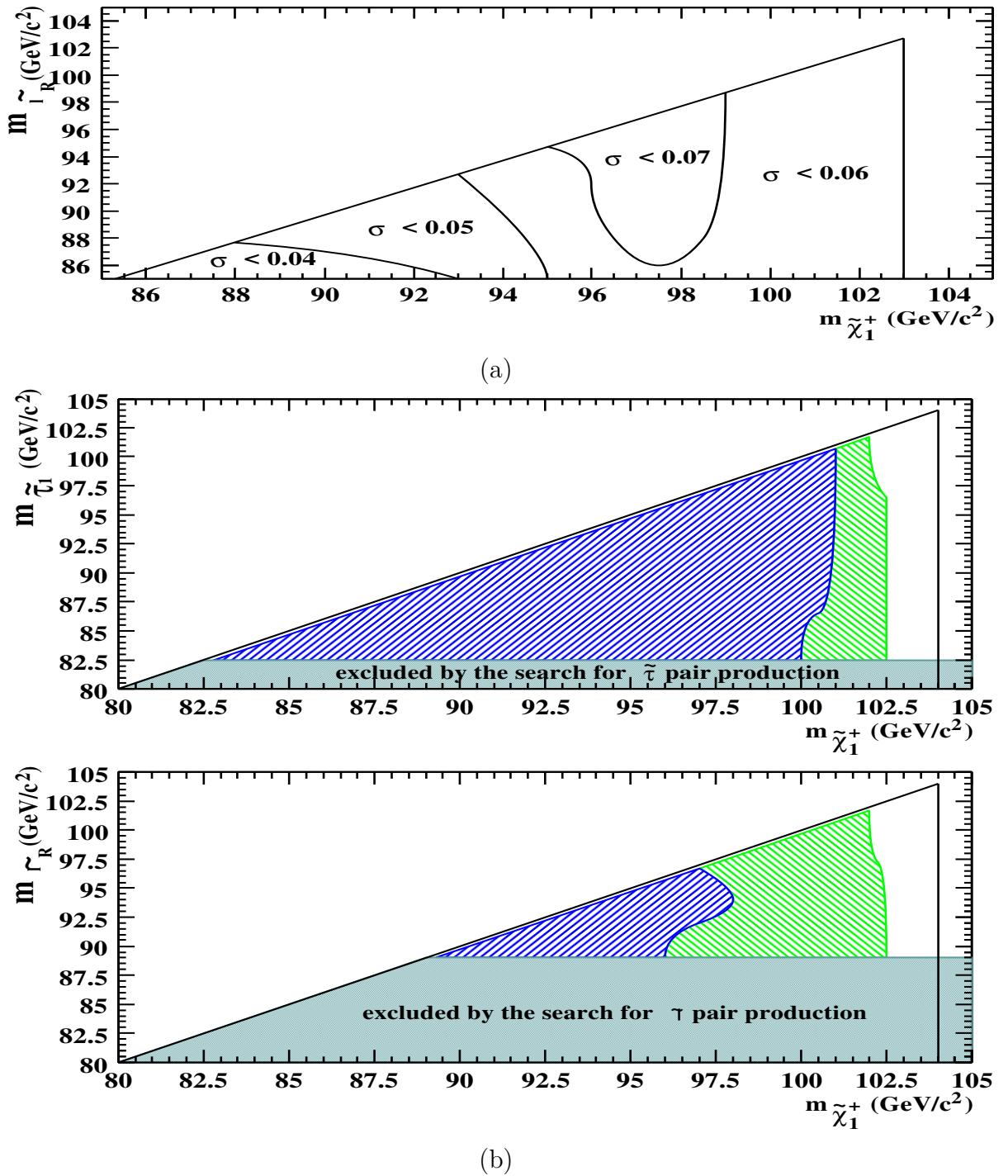


Figure 12: (a) Limits in picobarn on the lightest chargino pair production cross-section at 95% CL. Limits are shown as a function of  $m_{\tilde{l}}$  and  $m_{\tilde{\chi}_1^+}$  for  $m_{\tilde{G}} = 100$  eV/c $^2$ . (b) Areas excluded at 95% CL in the  $(m_{\tilde{\chi}_1^+}, m_{\tilde{\tau}_1})$  plane (middle figure) and  $(m_{\tilde{\chi}_1^+}, m_{\tilde{l}_R})$  plane (bottom figure). The positive-slope hatched area is excluded for all gravitino masses. The negative-slope hatched area is only excluded for  $m_{\tilde{G}} > 100$  eV/c $^2$ . The cross-hatched area is excluded by the search for stau pair production in gravity mediated supersymmetry breaking models. Both plots have been obtained using all DELPHI data from 183 GeV to 208 GeV centre-of-mass energies.

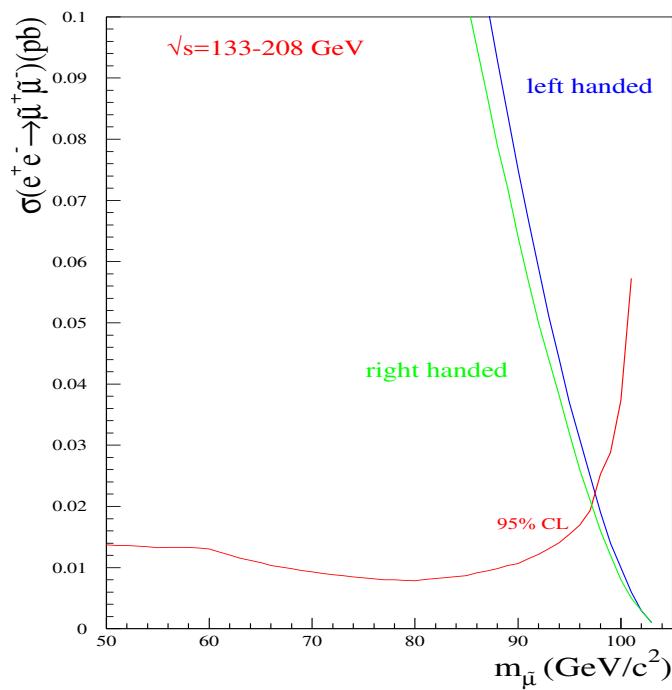


Figure 13: Predicted production cross-section for left and right handed stable smuons (staus) as a function of the particle mass. The cross-section limit indicated in the figure has been derived using all DELPHI data between 130 and 208 GeV.

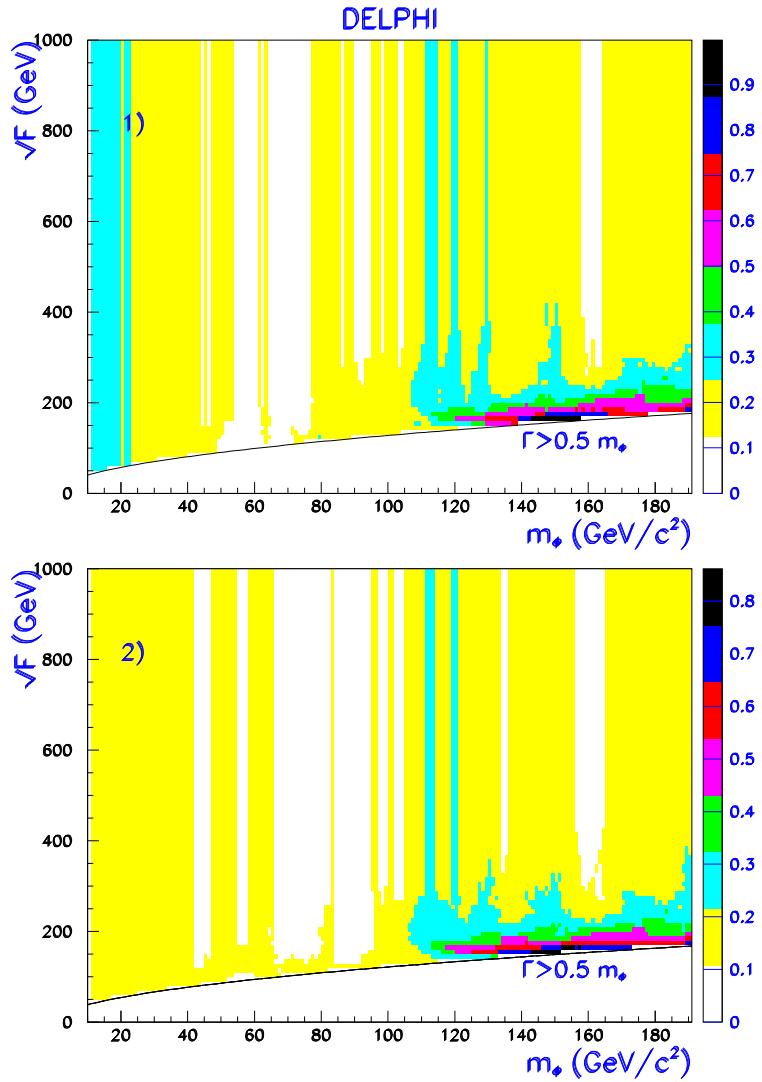


Figure 14: Cross section upper limit (pb scale on the right) at the 95% CL as a function of  $m_\phi$  and  $\sqrt{F}$  for the two sets of parameters of Table 1 and using all DELPHI data between 189 and 208 GeV.

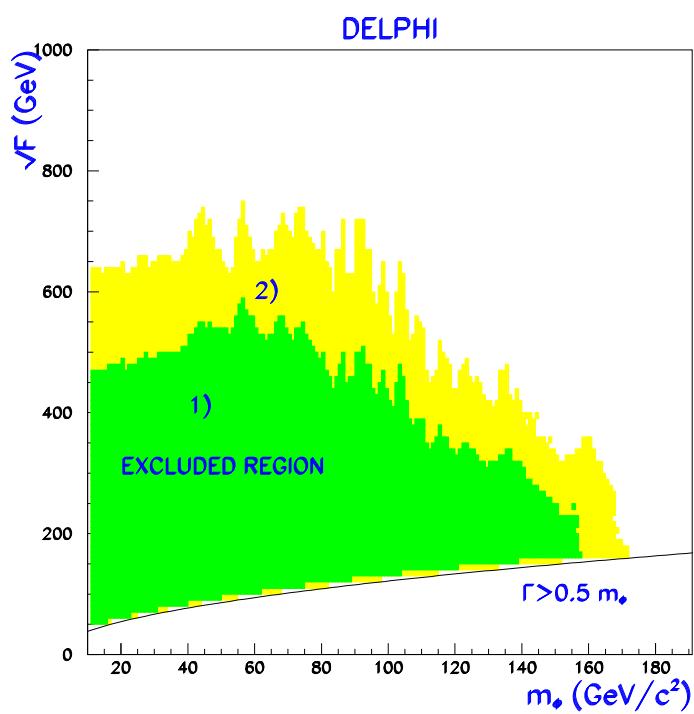


Figure 15: Exclusion region at the 95% CL in the  $(m_\phi, \sqrt{F})$  plane for the two sets of parameters of Table 1 and using all DELPHI data between 189 and 208 GeV.

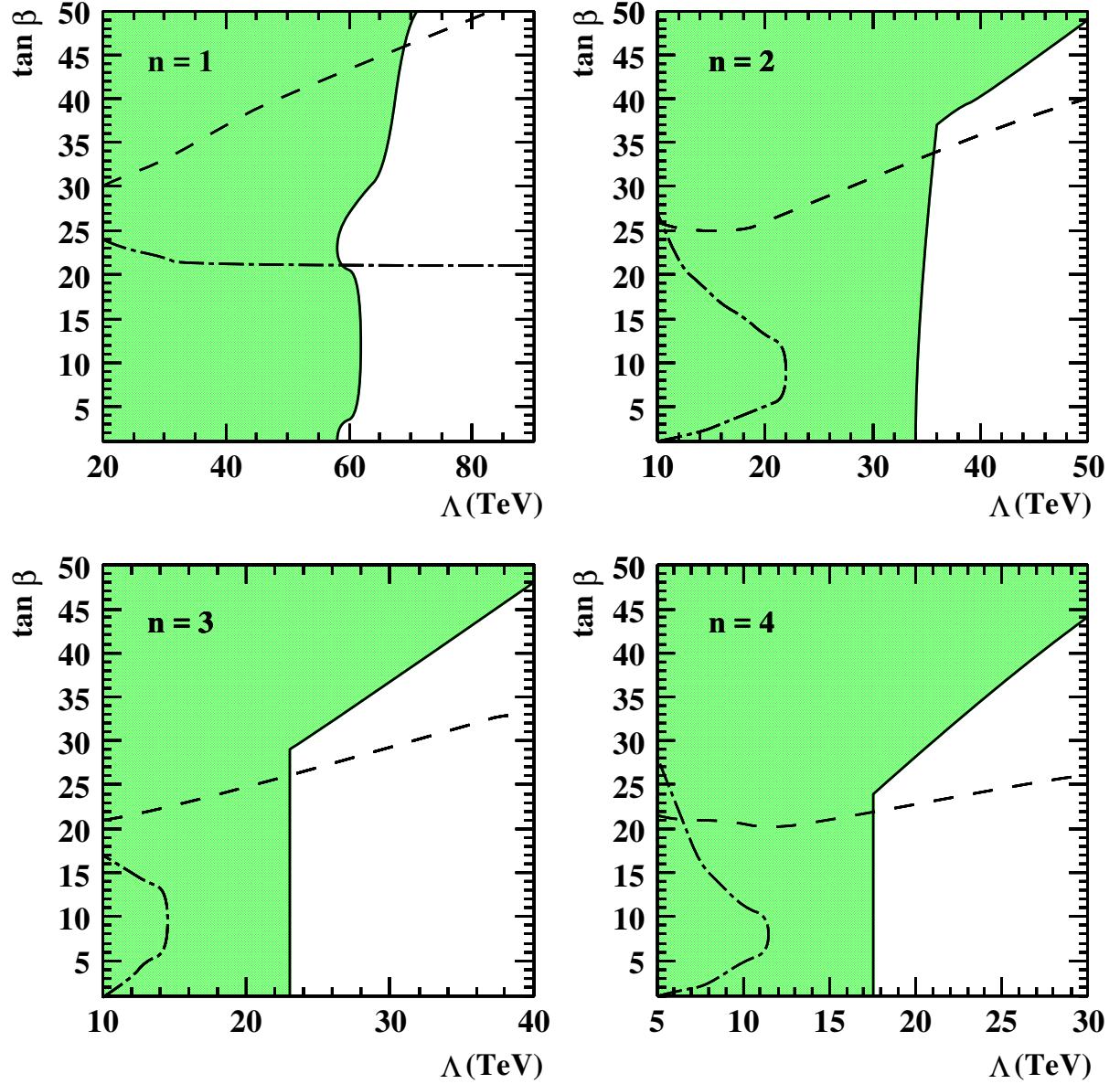


Figure 16: Shaded areas in the  $(\tan \beta, \Lambda)$  plane are excluded at 95% CL. The areas below the dashed lines contain points of the GMSB parameter space with  $\tilde{\chi}_1^0$  NLSP. The areas to the right (above for  $n = 1$ ) of the dashed-dotted lines contain points of the GMSB parameter space where sleptons are the NLSP.