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# Search for SUSY with $R$–parity violating LL$\bar{\text{E}}$ couplings at $\sqrt{s} = 189$ GeV

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**Abstract**

Searches for pair production of supersymmetric particles under the assumption that $R$–parity is not conserved are presented, based on data recorded by the DELPHI detector in 1998 from $e^+e^-$ collisions at a centre-of-mass energy of 189 GeV. Only one $R$–parity violating LL$\bar{\text{E}}$ term (i.e. one $\lambda$ coupling), which couples scalar leptons to leptons, is considered to be dominant at a time. Moreover, it is assumed that the strength of the $R$–parity violating couplings is such that the lifetimes can be neglected. The search for pair production of neutralinos, charginos and sleptons has been performed for both direct $R$–parity violating decays and indirect cascade decays. The results are in agreement with Standard Model expectations, and are used to update the constraints on the MSSM parameter values and the mass limits previously derived at $\sqrt{s} = 183$ GeV. The present 95% C.L. limits on supersymmetric particle masses are:

- $m_{\tilde{\chi}^0} >$ 30 GeV/$c^2$ and $m_{\tilde{\chi}^\pm} > 94$ GeV/$c^2$;
- $m_{\tilde{\nu}} > 76.5$ GeV/$c^2$ (direct and indirect decays);
- $m_{\tilde{\ell}_R} > 83$ GeV/$c^2$ (indirect decay only).


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# 1 Introduction

## 1.1 Motivations

The $R$–parity symmetry plays an essential role in the construction of supersymmetric theories of interactions, such as the Minimal Supersymmetric extension of the Standard Model (MSSM) [1]. The conservation of $R$–parity is closely related to the conservation of lepton ($L$) and baryon ($B$) numbers and the multiplicative quantum number associated to the $R$–parity symmetry is defined by $R_p = (-1)^{3B+L+2S}$ for a particle with spin $S$ [2]. Standard particles have even $R$–parity, and the corresponding superpartners have odd $R$–parity. The conservation of $R$–parity guarantees that the new spin–0 sfermions cannot be directly exchanged between standard fermions. It implies that the new sparticles ($R_p = -1$) can only be pair-produced, and that the decay of a sparticle should lead to another one, or an odd number of them. Then, it ensures the stability of the Lightest Supersymmetric Particle (LSP). The MSSM is designed to conserve $R$–parity: it is phenomenologically justified by proton decay constraints, and by the hope that a neutral LSP will provide a good dark matter candidate.

One of the major consequences of the $R$–parity violation is obviously that the LSP is no longer stable since it is allowed to decay to standard fermions. This fact modifies the signatures of the supersymmetric particle production compared to the expected signatures in case of $R$–parity conservation. In any case, whether it turns out to be absolutely conserved or not, $R$–parity plays an essential role in the study of the phenomenological implications of supersymmetric theories.

In complementarity with the searches for supersymmetric particles in the hypothesis of $R$–parity conservation, direct searches for $R$–parity violation ($\not{R}_p$) signatures in sparticle production have been performed by the LEP2 experiments [3,4]. No evidence for supersymmetric particle production has been observed so far, independently of the hypothesis on $R$–parity. In 1998, the LEP centre-of-mass energy reached 189 GeV, and an integrated luminosity of 158 pb$^{-1}$ was collected by the DELPHI experiment. The results of the searches for pair production of supersymmetric particles under the hypothesis of $R$–parity violating couplings between sleptons and leptons, performed with the data collected by DELPHI in 1997 at a centre-of-mass energy of 183 GeV [3], are updated by the analyses of the data recorded in 1998 presented in this paper.

## 1.2 *R*–parity violation in the MSSM

The $\not{R}_p$ superpotential [5] contains three trilinear terms, two violating $L$ conservation, and one violating $B$ conservation. We consider here only the $\lambda_{ijk}\mathrm{L}_i\mathrm{L}_j\bar{\mathrm{E}}_k$ term ($i, j, k$ are generation indices, L ($\bar{\mathrm{E}}$) denote the lepton doublet (singlet) superfields) which couples the sleptons to the leptons; since $\lambda_{ijk} = -\lambda_{jik}$, there are nine independent $\lambda_{ijk}$ couplings. Upper limits on the $\lambda_{ijk}$ couplings can be derived from indirect searches of $R$–parity violating effects [6]–[8], assuming that only one $\lambda_{ijk}$ is dominant at a time. For example, charged current universality allows a limit on $\lambda_{122}$ to be derived: $\lambda_{122} < 0.049 \times \frac{\mathrm{m}_{\tilde{e}_R}}{100\ \mathrm{GeV/c^2}}$ and the upper limits on the neutrino mass are used to derive a limit on $\lambda_{133}$: $\lambda_{133} < 0.006 \times \sqrt{\frac{\mathrm{m}_{\tilde{\tau}_R}}{100\ \mathrm{GeV/c^2}}}$ [9]. Taking into account recent data on neutrino masses and mixings, smaller values of the upper limits on several $\lambda_{ijk}$ have been derived, all being over 0.0007 (for $\mathrm{m}_{\tilde{\ell}} = 100$ GeV/$c^2$) [10]. In the analyses described here, only one $\lambda_{ijk}$ was assumed to be dominant and its upper bound has been taken into account.

The relevant MSSM parameters for these $\not\!\!R_p$ searches are: $\mathrm{M}_1$, $\mathrm{M}_2$, the U(1) and SU(2) gaugino mass at the electroweak scale, $\mathrm{m}_0$, the scalar common mass at the GUT scale, $\mu$, the mixing mass term of the Higgs doublets at the electroweak scale and tan$\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. The unification of the gaugino masses at the GUT scale, which implies $\mathrm{M}_1 = \frac{5}{3}\tan^2\theta_W \mathrm{M}_2 \simeq \frac{1}{2}\mathrm{M}_2$ at the electroweak scale, is assumed in the study of production and/or decay processes involving neutralinos and charginos.

We assume that the running of the $\not\!\!R_p$ couplings from the GUT scale to the electroweak does not have a significant effect on the evolution of the gaugino and fermion masses. This is an assumption that will be reconsidered once detailed theoretical calculations on this subject become available.

### 1.3 *R*–parity violating decays

This paper presents the searches for pair produced gauginos and sfermions. In case of pair production $R_p$ is conserved at the production vertex; the cross-sections do not depend on the $\not\!\!R_p$ couplings. The $R$–parity violation affects only the decay of sparticles.

Two types of supersymmetric particle decays are considered. First, the *direct decay*, corresponding to the sfermion $\not\!\!R_p$ direct decay into two standard fermions, or to the neutralino (chargino) decay into a fermion and a virtual sfermion which then decays into two standard fermions. Second, the *indirect decay* corresponding to the supersymmetric particle cascade decay through $R$–parity conserving vertices to on-shell supersymmetric particles down to a lighter supersymmetric particle decaying via one $\mathrm{LL\bar{E}}$ coupling.

The direct decay of a neutralino or a chargino via a dominant $\lambda_{ijk}$ coupling leads to purely leptonic decay products, with or without neutrinos ($\ell\ell'\nu$, $\ell\ell'\ell''$, $\ell\nu\nu$). The indirect decay of a heavier neutralino or a chargino adds jets and/or leptons to the leptons produced in the LSP decay.

The sneutrino direct decay gives two charged leptons: via $\lambda_{ijk}$ only the $\tilde{\nu}_i$ and $\tilde{\nu}_j$ are allowed to decay directly to $\ell_j^{\pm}\ell_k^{\mp}$ and $\ell_i^{\pm}\ell_k^{\mp}$ respectively. The charged slepton direct decay gives one neutrino and one charged lepton (the lepton flavour may be different from the slepton one): the supersymmetric partner of the right-handed lepton $\tilde{\ell}_{kR}$ decays directly into $\nu_{iL}\ell_{jL}$ or $\ell_{iL}\nu_{jL}$, and the supersymmetric partner of the left-handed lepton $\tilde{\ell}_{i(j)L}$ decays into $\bar{\nu}_{j(i)L}\ell_{kR}$.

The indirect decay of a sneutrino (resp. charged slepton) into the lightest neutralino and a neutrino (resp. charged lepton) leads to a purely leptonic final state: two charged leptons and two neutrinos (resp. three charged leptons and a neutrino). The indirect decay of a slepton into a chargino and its isospin partner was not considered, and the direct decay of charged slepton is not studied here.

When the charged leptons are $\tau$, additional neutrinos are generated in the $\tau$ decay, producing more missing energy in the decay and leading to a smaller number of charged leptons in the final state.

## 2 Data samples

The total integrated luminosity collected by the DELPHI detector [11] during 1998 at centre-of-mass energies around 189 GeV was 158 pb$^{-1}$. An integrated luminosity of 153 pb$^{-1}$ has been analysed, corresponding to high quality data, with the tracking detectors and the electromagnetic calorimeters in good working condition.

To evaluate background contaminations, different contributions coming from the Standard Model processes were considered. The Standard Model events were produced by the following generators:

- $\gamma\gamma$ events: BDK [12] for $\gamma\gamma \to \ell^+\ell^-$ processes, and TWOGAM [13] for $\gamma\gamma \to$ hadron processes; biased samples containing events with a minimal transverse energy of 4 GeV were used;
- two-fermion processes: BABAMC [14] and BHWIDE [15] for Bhabha scattering, KORALZ [16] for $\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-(\gamma)$ and for $\mathrm{e}^+\mathrm{e}^- \to \tau^+\tau^-(\gamma)$ and PYTHIA [17] for $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q}\bar{\mathrm{q}}(\gamma)$ events;
- four-fermion processes: EXCALIBUR [18] for all types of four fermion processes: non resonant ($\mathrm{f}\bar{\mathrm{f}}\mathrm{f}'\bar{\mathrm{f}}'$), single resonant ($\mathrm{Z}\mathrm{f}\bar{\mathrm{f}}$, $\mathrm{W}\mathrm{f}\bar{\mathrm{f}}'$) and doubly resonant (ZZ, WW) (PYTHIA was used also for cross-checks).

Signal events were generated with the SUSYGEN 2.20 program [19] followed by the full DELPHI simulation and reconstruction program (DELSIM). A faster simulation (SGV[1]) was used to check that the efficiencies were stable at points without full simulation compared to their values at the nearest points determined with the full simulation. The $R$–parity violating couplings were set close to their experimental upper limit derived from the indirect $\not{R}_p$ searches (see section 1.2).

The $\tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1$ pair production was considered at several points in the MSSM parameter space, in order to scan neutralino masses from 15 to 80 GeV/$c^2$ and chargino masses from 45 to 95 GeV/$c^2$. Moreover, for a given mass, several samples with different components and production processes were simulated. The pair production of heavier neutralinos and charginos has been taken into account since one can profit from the threefold increase in luminosity compared to the 1997 data.

For the study of slepton pair production, samples with sneutrino direct decay and samples with sneutrino or charged slepton indirect decay were generated for tan$\beta$ fixed at 1.5. A $\tilde{\nu}$ ($\tilde{\ell}$) mass range from 50 to 90 GeV/$c^2$ was covered; in the case of indirect decay, several ranges of mass difference between sleptons and neutralinos were considered.

# 3 Analysis descriptions

## 3.1 Analysis strategy and validity

Any of the possible $\not{R}_p$ signals produced via one of the $\lambda_{ijk}\mathrm{L}_i\mathrm{L}_j\bar{\mathrm{E}}_k$ couplings can be explored by the analyses described in this paper. In the analyses performed considering a dominant $\lambda_{133}$ coupling, the efficiencies and the rejection power are low, due to the presence of several taus in the final state. The highest efficiencies and background reduction are obtained if $\lambda_{122}$ is the dominant coupling. For final states produced by other $\lambda_{ijk}$, the detection efficiencies lay between these two limiting cases. Analyses are then performed considering both the $\lambda_{122}$ and the $\lambda_{133}$ couplings. The weakest limits were derived considering the results of the analyses performed assuming a dominant $\lambda_{133}$ coupling. The studied final states are summarized in Table 1.

It was supposed that the Lightest Supersymmetric Particle (LSP) decays within a few centimeters of the production vertex. Since the mean LSP decay length depends on $\mathrm{m}_\chi^{-5}$ (if the LSP is a gaugino), and on $\lambda_{ijk}^{-2}$, this assumption has two consequences on the analyses described here. First, they were not sensitive to light $\tilde{\chi}$ ($\mathrm{M}_{\tilde{\chi}_{LSP}} \leq 10$ GeV/$c^2$).

[1] *Simulation à Grande Vitesse* http://home.cern.ch~berggren/sgv.html

| processes | final states with $\lambda_{122}$ | final states with $\lambda_{133}$ |
|---|---|---|
| $\tilde{\chi}^0_i\tilde{\chi}^0_j$, $\tilde{\chi}^+_k\tilde{\chi}^-_l$ (direct and indirect decays) | e$\mu$e$\mu$, e$\mu\mu\mu$, $\mu\mu\mu\mu$ + $E_{miss}$ (+$n\ell$) (+$m$ qq') | e$\tau$e$\tau$, e$\tau\tau\tau$, $\tau\tau\tau\tau$ + $E_{miss}$ (+$n\ell$) (+$m$ qq') |
| $\tilde{\nu}_e\bar{\tilde{\nu}}_e$ (direct decay) | $\mu\mu\mu\mu$ | $\tau\tau\tau\tau$ |
| $\tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau$ (direct decay) | ee$\mu\mu$ | ee$\tau\tau$ |
| $\tilde{\nu}\bar{\tilde{\nu}}$ (indirect decay) | e$\mu$e$\mu$, e$\mu\mu\mu$, $\mu\mu\mu\mu$ + $E_{miss}$ | e$\tau$e$\tau$, e$\tau\tau\tau$, $\tau\tau\tau\tau$ + $E_{miss}$ |
| $\tilde{\ell}^+_R\tilde{\ell}^-_R$ (indirect decay) | e$\mu$e$\mu$, e$\mu\mu\mu$, $\mu\mu\mu\mu$ + $E_{miss}$ + $\ell^+\ell^-$ | e$\tau$e$\tau$, e$\tau\tau\tau$, $\tau\tau\tau\tau$ + $E_{miss}$ + $\ell^+\ell^-$ |

Table 1: Pair production final states with $\lambda_{122}$ or $\lambda_{133}$.

Second, analyses looking for neutralino decay products had a lower limit in the sensitivity of the $\lambda$ coupling of the order of $10^{-4}$; below this value, in some area in the MSSM space, the lightest neutralino has a non-negligible lifetime, and the corresponding event topology was not selected by the analyses. Inside the validity domain defined by the upper bound from indirect searches of $\not{R}_p$ effects and the lower bound due to the LSP flight, the coupling value has no influence on the efficiency of the analyses.

## 3.2 General analysis description

The applied selections were based on the criteria presented in [3], using mainly topological criteria, missing quantities, lepton identification and kinematic properties, and jet characteristics. Compared to the previous analyses, the electron identification has been improved at high energies and in the forward regions of the detector.

As already mentioned, indirect decays of gaugino pairs can add two or more jets to the leptons and missing energy final state, from the hadronic decay of W* and Z*. Moreover, in the case of the $\lambda_{133}$ coupling, thin jets are produced in $\tau$ decay. The jets were reconstructed with the `DURHAM` [20] algorithm. In order to cover the different topologies, the jet number was not fixed, and the jet charged multiplicity could be low (for instance thin jets with one charged particle), or could be zero in case of neutral jets. In the following, the transition value of the $y_{cut}$ in the `DURHAM` algorithm at which the event changes from a $n$-jet to a $(n-1)$-jet configuration is noted $y_{(n-1)n}$.

After a brief description of the $\lambda_{122}$ analyses, the selection procedures when $\lambda_{133}$ is the dominant coupling constant are detailed in the following sections.

## 3.3 Analyses applied in case of $\lambda_{122}$ coupling

As already mentioned, these analyses were based on the selection procedure described in [3]; they are not deeply detailed here.

### 3.3.1 Gaugino and slepton indirect decay searches

One analysis was designed to select leptonic channels with missing energy, with or without jets, in order to study gaugino decays and slepton indirect decays. Events with charged multiplicity greater than three and at least two charged particles with a polar angle between 40° and 140° were selected. The missing transverse momentum, $\not{p}_t$, had to be greater than 5 GeV/$c$ and the polar angle of the missing momentum to be between 20° and 160°. The missing energy had to be at least $0.2\sqrt{s}$. This set of criteria reduced mainly the background coming from Bhabha scattering and two-photon processes. Then, requirements based on the lepton characteristics were applied:

- at least two identified muons were required;
- the energy of the most energetic identified lepton had to be greater than $0.1\sqrt{s}$;
- an isolation criterion was imposed for the identified leptons (no other charged particle in a half cone of seven degrees around the lepton);
- at least two of the identified leptons had to be leading particles in the jets.

One event remained in the data, compared to 1.1±0.3 expected from Standard Model processes contributing to the background (0.6, 0.3 and 0.2 from four-fermion, $\mu^+\mu^-(\gamma)$ and $\gamma\gamma \rightarrow \mu^+\mu^-$ processes respectively). The selection efficiencies were in the range 35–60% for gaugino decays, in the range 50–60% for sneutrino indirect decays, and in the range 20–50% for charged slepton indirect decays.

### 3.3.2 Sneutrino direct decay search

A different selection was used to search for final states with no missing energy and at least two muons, resulting from sneutrino direct decays via $\lambda_{122}$. The thrust value had to be less than 0.95 and the polar angle of the thrust axis had to be between 25°and 155°. The total energy from charged particles had to be greater than $0.33\sqrt{s}$, the missing transverse momentum had to be greater than 2 GeV/$c$ and the missing energy to be less than $0.55\sqrt{s}$. The charged multiplicity had to be four or six with the total event charge equal to 0. At least two muons were required and no other charged particle in a half cone of 20° around each lepton was demanded. One event remained in the data after these criteria with 2.7±0.4 expected from standard background processes, mainly from the $\ell^+\ell^-\ell'^+\ell'^-$ final states (1.4±0.2), and from the $\gamma\gamma \rightarrow \mu^+\mu^-$ process (1.2±0.4). The efficiencies were from 62% to 51% in the explored sneutrino mass range of 60–90 GeV/$c^2$.

## 3.4 Analyses applied in case of $\lambda_{133}$ coupling

### 3.4.1 Preselection criteria for $\lambda_{133}$ analyses

In the search for pair production of gauginos and sleptons in case of a dominant $\lambda_{133}$ coupling, the following criteria were required:

- at least one identified lepton;
- more than three charged particles and at least two of them with a polar angle between 40° and 140°;
- the total energy and the energy from charged particles greater than $0.18\sqrt{s}$ and $0.16\sqrt{s}$ respectively;
- the missing $p_t$ greater than 5 GeV/$c$;
- the polar angle of the missing momentum between 27° and 153°.

This was efficient in suppressing the background coming from Bhabha scattering and two-photon processes and in removing a large part of the $f\bar{f}\gamma$ contribution. After this preselection stage, 2114 events were selected compared with 1984±11 expected from the background sources (see Figure 1). There was an excess of data mostly concentrated in the low charged multiplicity events where $\gamma\gamma$ events contributed to the Standard Model background. A good agreement between data and the expected background was obtained when the contribution of $\gamma\gamma$ events was further reduced (see below).

### 3.4.2 Neutralino and chargino search

| **Selection criteria** | | | Data | MC |
|---|---|---|---|---|
| | $4 \leq N_{charged} \leq 6$ | $N_{charged} \geq 7$ | | |
| acollinearity | | $> 7°$ | 1342 | 1301±8 |
| $E^{30°}_{cone}$ | $\leq 0.5\ E_{total}$ | $\leq 0.4\ E_{total}$ | 1146 | 1121±7 |
| $N_{lepton}$ in the barrel | $\geq 1$ | $\geq 1$ | 929 | 915±6 |
| $E^{l}_{max}$ | [2 GeV, 70 GeV] | [5 GeV, 60 GeV] | 652 | 665±5 |
| isolation | $\Theta^{min}_{\ell-\text{charged particle}} \geq 20°$ if $N_{charged} = 4$<br>$\Theta^{min}_{\ell-\text{charged particle}} \geq 6°$ if $N_{charged} = 5, 6$ | $\Theta^{max}_{\ell-\text{charged particle}} \geq 6°$<br>$\Theta^{max-1}_{\ell-\text{charged particle}} \geq 10°$ if $N_{lepton} \geq 2$ | | |
| $N_{neutral} \leq$ | 10 | 15 | | |
| $N_{electron}$ | | $\geq 1$ | 131 | 147±3 |
| $E_{miss}$ | $>0.3\sqrt{s}$ | $> 0.3\sqrt{s}$ | 96 | 101±2 |
| $\log_{10}(y_{23})$<br>$\log_{10}(y_{34})$<br>$\log_{10}(y_{45})$ | $\geq -2.7$<br>$\geq -4$ | $\geq -1.8$<br>$\geq -2.3$<br>$\geq -3$ | 16 | 14.7±0.7 |
| 4 jets<br>$E^{j}_{min} \times \theta^{j1,j2}_{min}$ | $\geq 1$ GeV.rad | $\geq 5$ GeV.rad | 15 | 13.9±0.6 |
| | 4 charged jets if 4j or 5j | at least 1 jet with 1 or 2 charged particle(s)<br>4 charged jets if 4j<br>4 or 5 charged jets if 5j | 11 | 10.5±0.5 |

Table 2: Selection criteria used in the search for neutralino and chargino decay via $\lambda_{133}$. $n$j means $n$-jet topology, and a charged jet means a jet with at least one charged particle. The number of remaining data and Standard Model background events are reported; the quoted errors are statistical.

Compared to the selection applied to 1997 data [3], it has been necessary to modify some criteria and to distinguish between low and high multiplicity cases in order to reach a higher purity. For events with a charged particle multiplicity from four to six (which corresponds to neutralino or chargino direct decay), the following criteria were applied:

- the energy in a cone of 30° around the beam axis was restricted to be less than 50% of the total visible energy;
- the energy of the most energetic lepton had to be between 2 and 70 GeV;
- there should be no other charged particle in a 10° (6°) half cone around any identified lepton for a charged particle multiplicity equal to four (five or six);
- the number of neutral particles had to be less than or equal to 10.

For events with a charged particle multiplicity greater than six (corresponding to neutralino and chargino indirect decays), the criteria were:

- the acollinearity [2] had to be greater than 7°;
- the energy in a cone of 30° around the beam axis was restricted to be less than 40% of the total visible energy;

[2] the acollinearity is computed between the two vectors corresponding to the sum of the particle momenta in each event hemisphere.

- the energy of the most energetic lepton had to be between 5 and 60 GeV;
- if there was only one identified lepton, no other charged particle in a 6° half cone around it was allowed; and if there were more, there should not be any other charged particle in a 10° half cone around at least two of them;
- at least one well identified electron;
- the number of neutral particles had to be less than or equal to 15.

In both cases the missing energy had to be at least 30% of the available energy, and the polar angle of at least one lepton had to be between 40° and 140°. These criteria removed $\mathrm{f\bar{f}}\gamma$ and hadronic ZZ and $\mathrm{W^+W^-}$ events.

The selection based on the jet characteristics and topologies was then applied. First, constraints have been imposed to $\mathrm{y}_{(n-1)n}$ values to reduce, in particular the $\mathrm{f\bar{f}}\gamma$ contribution. In events with more than six charged particles, at least one jet with low charged particle multiplicity was required. In four- or five-jet configurations, a minimum of four charged jets was required. In case of a four-jet topology, a cut was applied on the value of $\mathrm{E}^j_{\mathrm{min}} \times \theta^{j_a j_b}_{\mathrm{min}}$ where $\mathrm{E}^j_{\mathrm{min}}$ is the energy of the least energetic jet, and $\theta^{j_a j_b}_{\mathrm{min}}$ is the minimum angle between any pair of jets. These requirements significantly reduced the background from $\mathrm{f\bar{f}}\gamma$ and $\mathrm{W^+W^-}$ production. The number of remaining real data and background events during the selection are reported in Table 2, and the contributions of the relevant Standard Model processes are detailed in Table 3. The main contribution comes from the $\mathrm{W^+W^-}$ production, with a semi-leptonic decay of the W pair, due to the specific design of the analysis to be efficient for channels with leptons (mainly taus) and jets in final states.

| case | Data | total MC | $\mathrm{q\bar{q}}(\gamma)$ | $\tau^+\tau^-(\gamma)$ | $\mathrm{Ze^+e^-}$ | $\mathrm{We}\nu_{\mathrm{e}}$ | $\mathrm{W^+W^-}$ | ZZ |
|---|---|---|---|---|---|---|---|---|
| Low | 2 | 1.8±0.2 | 0. | 0.12±0.12 | 0.42±0.14 | 0. | 0.77±0.14 | 0.41±0.08 |
| High | 9 | 8.7±0.5 | 0.14±0.09 | 0. | 0.06±0.06 | 0.05±0.02 | 8.27±0.44 | 0.21±0.07 |

Table 3: Standard Model background contributions to the neutralino and chargino pair production analysis ($\lambda_{133}$). The results in the row labelled "Low" ("High") are obtained with the selection applied to the low (high) multiplicity events. The quoted errors are statistical.

Using the events produced with `DELSIM`, selection efficiencies have been studied on $\tilde{\chi}^0_1\tilde{\chi}^0_1$ and $\tilde{\chi}^+_1\tilde{\chi}^-_1$ signals. In order to benefit from the high luminosity, all $\mathrm{e^+e^-} \to \tilde{\chi}^0_i\tilde{\chi}^0_j$, $\mathrm{e^+e^-} \to \tilde{\chi}^+_k\tilde{\chi}^-_l$ processes which contribute significantly have been simulated, at each MSSM point of this study. `SUSYGEN` followed by `SGV` was used for the scan. Then a global event selection efficiency was determined for each point, since the performed analyses were sensitive to many different topologies. The global selection efficiencies obtained with `SGV` simulated events have been cross-checked at several points with `DELSIM` simulated events. The efficiencies laid between 18% and 40%.

### 3.4.3 Sneutrino and charged slepton searches

Considering the $\lambda_{133}$ coupling, searches for sneutrino pair production and subsequent direct ($\tilde{\nu}\to \ell^+\ell^-$) or indirect ($\tilde{\nu}\to \tilde{\chi}^0_1\nu$) decay and searches for charged slepton pair production decaying indirectly ($\tilde{\ell}\to \tilde{\chi}^0_1\ell$) have been performed. In these different searches, a large amount of energy is missing in the final states, due to neutrinos (from $\tau$ and/or $\tilde{\chi}^0_1$ decays), except in the case of $\tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau$ direct decay search ($\mathrm{ee}\tau\tau$ final state). Two different analyses were then performed, one applied to the channels with a large amount of missing energy, and the other one dedicated to the ee$\tau\tau$ channel, with less missing energy.

**• Analysis for channels with high value of missing energy**

The selection procedure was close to the one applied to low charged particle multiplicity events in the search for neutralino and chargino pair production. The same event characteristics were used. A large amount of missing energy was required, but only events with four to eight charged particles were selected. The criteria are listed in Table 4; the number of observed events and expected ones from the Standard Model background during the selection procedure is also given. At the end, one event remains in the data compared to 2.1±0.3 from the SM processes. The relevant contributions are listed in Table 5. The four-fermion contributions have been checked also with EXCALIBUR, and apart from the WW-like processes, the two other important background sources were the ee$\tau\tau$ and ee$\mu\mu$ final states.

| **Selection criteria** | Data | MC |
|---|---|---|
| $N_{charged} \leq 8$<br>$E_{miss} > 30\% \sqrt{s}$ | 120 | 106.6±3.4 |
| $2 \leq E^{\ell}_{max} \leq 70$ GeV | 88 | 89.2±2.9 |
| $\Theta^{min}_{\ell-\text{charged particle}} \geq 20°$ if $N_{charged} = 4$<br>$\Theta^{min}_{\ell-\text{charged particle}} \geq 6°$ if $N_{charged} > 4$ | 62 | 61.5±2.4 |
| $N_{neutral} \leq 10$ | 55 | 52.3±2.2 |
| at least 1 lepton in the barrel | 25 | 22.4±1.3 |
| $\log_{10}(y_{23}) \geq -2.7$<br>$\log_{10}(y_{34}) \geq -4$ | 5 | 4.4±0.4 |
| in 4-jet events:<br>$\theta^{j1,j2}_{min} \geq 20°$<br>at least 1 jet with 1 or 2 charged particles | 1 | 2.1±0.3 |

Table 4: Selection criteria used in the search for slepton pair production with $\not{R}_p$ decay via $\lambda_{133}$. The number of remaining data and Standard Model background events are reported; the quoted errors are statistical.

| Data | total MC | $\tau^+\tau^-(\gamma)$ | $Ze^+e^-$ | $W^+W^-$ | ZZ |
|---|---|---|---|---|---|
| 1 | 2.13±0.27 | 0.12±0.12 | 0.54±0.16 | 1.13±0.16 | 0.34±0.08 |

Table 5: Standard Model background contribution to the slepton pair production analysis ($\lambda_{133}$); the quoted errors are statistical.

For the 4$\tau$ channel produced in $\tilde{\nu}_e\bar{\tilde{\nu}}_e$ decay, the efficiencies were between 27% and 31%. The sneutrino indirect decay efficiencies ranged from 17% ($m_{\tilde{\nu}}$ = 50 GeV/$c^2$, $m_{\tilde{\chi}^0}$ = 23 GeV/$c^2$) to 36% ($m_{\tilde{\nu}}$ = 80 GeV/$c^2$, $m_{\tilde{\chi}^0}$ = 60 GeV/$c^2$). The charged slepton indirect decay efficiencies wrre higher, due to the presence of two additional charged leptons in the final state, and laid between 33% and 40%.

**• Analysis for channels with low value of missing energy**

In order to obtain higher efficiencies for the ee$\tau\tau$ channel, the selection criteria were modified. In particular, the missing energy cut was reduced to 8% of the available energy.

The number of charged particles was restricted to be between four and six. Moreover, the lower limit on the energy of the most energetic lepton was increased to 20 GeV, and the isolation angle had to be greater than 10°. Additional criteria were used: the acollinearity had to be greater than 2°, and the presence of at least one identified electron was required. After the event selection 3 events remained, while 2.3±0.3 events were expected from SM processes. The main sources of background were the $ee\tau\tau$ (57%) and the $ee\mu\mu$ (29%) four-fermion processes. The efficiencies were between 38% and 46%.

# 4 Interpretation of the results

The results of the searches presented in this paper, summarised in Table 6, were in agreement with the Standard Model expectation. They were used to extend the previously excluded part of the MSSM parameter space and to update limits obtained with the analysis of the 1997 data collected in DELPHI. In all the pair production processes

| Coupling | Process | Efficiency range in % | Selected events Data | MC |
|---|---|---|---|---|
| $\lambda_{122}$ | $\tilde{\chi}^0_i\tilde{\chi}^0_j$, $\tilde{\chi}^+_k\tilde{\chi}^-_l$ direct and indirect decays | 35–60 | 1 | 1.1±0.3 |
| | $\tilde{\nu}\bar{\tilde{\nu}}$ indirect decay | 50–60 | | |
| | $\tilde{\ell}^+\tilde{\ell}^-$ indirect decay | 20–50 | | |
| | $\tilde{\nu}_\mu\bar{\tilde{\nu}}_\mu$ direct decay | 51–62 | 1 | 2.7±0.4 |
| $\lambda_{133}$ | $\tilde{\chi}^0_i\tilde{\chi}^0_j$ direct decay | 18–40 | 2 | 1.8±0.2 |
| | $\tilde{\chi}^+_k\tilde{\chi}^-_l$ indirect decay | 18–40 | 9 | 8.7±0.5 |
| | $\tilde{\nu}_e\bar{\tilde{\nu}}_e$ direct decay | 27–31 | 1 | 2.1±0.3 |
| | $\tilde{\nu}\bar{\tilde{\nu}}$ indirect decay | 17–36 | | |
| | $\tilde{\ell}^+\tilde{\ell}^-$ indirect decay | 33–40 | | |
| | $\tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau$ direct decay | 38–46 | 3 | 2.3±0.3 |

Table 6: LL$\bar{\mathrm{E}}$ analyses: efficiency ranges in the different cases studied, and data and Monte Carlo events remaining after the applied selection.

studied, the weakest limits were derived from the results of the $\lambda_{133}$ analyses, and are hence valid for any choice of dominant $\lambda_{ijk}$ coupling, provided that the coupling is strong enough for the LSP to decay within a few centimetres.

In the searches for neutralino and chargino pair production, the number of expected events at each point of the explored MSSM parameter space was obtained by:

$$N_{exp} = \mathcal{L}\times\epsilon_g\times\ \{\textstyle\sum_{i,j=1}^{4}\sigma(e^+e^- \rightarrow \tilde{\chi}^0_i\tilde{\chi}^0_j) + \sum_{k,l=1}^{2}\sigma(e^+e^- \rightarrow \tilde{\chi}^+_k\tilde{\chi}^-_l)\}$$

where $\mathcal{L}$ is the integrated luminosity, and $\epsilon_g$ is the global efficiency determined as explained in section 3.4.2. This number has been compared to the number of signal events, $N_{95}$, expected at a confidence level of 95% in presence of background [21]. All points which satisfied $N_{exp} > N_{95}$ were excluded at 95% C.L. The excluded area in $\mu$, $M_2$ planes obtained with the present searches are shown in Fig. 2, for $m_0 = 90$ GeV/$c^2$ (the t–channel contribution to the gaugino cross-sections has an important effect), $m_0 = 300$ GeV/$c^2$ (the t-channel contribution vanishes) and tan$\beta$ =1.5, 30. The smaller excluded area in the $\mu$, $M_2$ planes for a given tan$\beta$ is obtained for high $m_0$ values.

For each tan$\beta$, the highest value of neutralino mass which can be excluded has been determined in the $\mu$, $M_2$ plane (–200 GeV/$c^2 \le \mu \le$ 200 GeV/$c^2$, 5 < $M_2 \le$ 400 GeV/$c^2$) for several $m_0$ values varying up to 500 GeV/$c^2$. The smaller excluded area in the $\mu$, $M_2$ plane is obtained for $m_0$ = 500 GeV/$c^2$. The most conservative mass limit was obtained for high $m_0$ values, for which it reaches a plateau. The corresponding limit on neutralino mass as a function of tan$\beta$ is plotted in Fig. 3. From these studies, a neutralino lighter than 30 GeV/$c^2$ was excluded at 95% C.L. for 1 $\le$tan$\beta \le$ 30. The same procedure was applied to determine the most conservative lower limit on the chargino masses. The result is less dependent on tan$\beta$, almost reaching the kinematic limit for any value of tan$\beta$: a chargino lighter than 94 GeV/$c^2$ was excluded at 95% C.L. Finally, using the same method, a lower limit of 50 GeV/$c^2$ for the $\tilde{\chi}^0_2$ mass has been derived at 95% C.L.

The results obtained from the sneutrino pair production studies were used to derive limit on the sneutrino mass. In the case of the sneutrino direct decay, the results improved the upper limit on the sneutrino pair production cross-section. Taking into account the results of the two analyses and the efficiencies obtained when varying the sneutrino mass, the cross-section limits for 2e2$\tau$ and 4$\tau$ channels were derived and are reported in Fig. 4. The $\tilde{\nu}_e\bar{\tilde{\nu}}_e$ cross-section depends not only on the $\tilde{\nu}_e$ mass but also on other MSSM parameters (due to the possible $t-$channel $\tilde{\chi}^+_1$ exchange contribution) and it is plotted for a specific MSSM point: $M_2$ = 100 GeV/$c^2$ and $\mu$ = –200 GeV/$c^2$. The upper limit on the cross-section leads to a lower limit on the sneutrino mass of 78 GeV/$c^2$.

In the case of the $\tilde{\nu}$ indirect decay into $\nu\tilde{\chi}^0_1$ with the $\not{R}_p$ decay of the neutralino via $\lambda_{133}$, the efficiencies depend on the sneutrino and neutralino masses. The search results allowed an area in the $m_{\tilde{\chi}^0}$ versus $m_{\tilde{\nu}}$ plane to be excluded, as shown on Fig. 5. The same procedure has been followed for the charged slepton indirect decays. The indirect decay of a $\tilde{\tau}$ pair gives two taus and two neutralinos, and the final state selection was less efficient than for the $\tilde{e}$ or $\tilde{\mu}$ pair; the results obtained for the $\tilde{\tau}_R$ pair production gave the most conservative limits on the slepton mass for any flavour, assuming that $\tilde{\ell}_R$ decays exclusively to $\ell\tilde{\chi}^0_1$. The area excluded in the $m_{\tilde{\chi}^0}$ versus $m_{\tilde{\ell}_R}$ plane is plotted in Fig. 6. The region where $m_{\tilde{\ell}_R}$ - $m_{\tilde{\chi}^0}$ is less than 2–3 GeV/$c^2$ was not covered by the present analysis, since then the direct decay becomes the dominant mode, leading to two leptons and missing energy. Taking into account the limit on the neutralino mass at 30 GeV/$c^2$, sneutrinos with mass lower than 76.5 GeV/$c^2$ and supersymmetric partners of the right-handed lepton, decaying indirectly, with mass lower than 83 GeV/$c^2$ were excluded at 95% C.L.

# 5 Summary

Searches for $R$–parity violating effects in $e^+e^-$ collisions at $\sqrt{s}$ = 189 GeV have been performed with the DELPHI detector. The pair productions of neutralinos, charginos and sleptons have been studied under the assumption that the LL$\bar{\text{E}}$ term is responsible for the supersymmetric particle decays into standard particles. It was assumed that one $\lambda_{ijk}$ coupling is dominant at a time and that the $\lambda_{ijk}$ coupling is strong enough for the LSP to decay within a few centimetres. No evidence for $R$–parity violation has been observed, allowing to update the limits previously obtained at $\sqrt{s}$ =183 GeV. The present 95% C.L. limits on supersymmetric particle masses are:

- $m_{\tilde{\chi}^0} >$ 30 GeV/$c^2$ and $m_{\tilde{\chi}^\pm} >$ 94 GeV/$c^2$;
- $m_{\tilde{\nu}} >$ 76.5 GeV/$c^2$ (direct and indirect decays);
- $m_{\tilde{\ell}_R} >$ 83 GeV/$c^2$ (indirect decay only).

These limits are valid for tan$\beta \geq 1$ and $m_0 < 500$ GeV/$c^2$ and for all the generation indices $i$,$j$,$k$ of the $\lambda_{ijk}$ coupling, and for any coupling value from $10^{-4}$ up to the existing limits.

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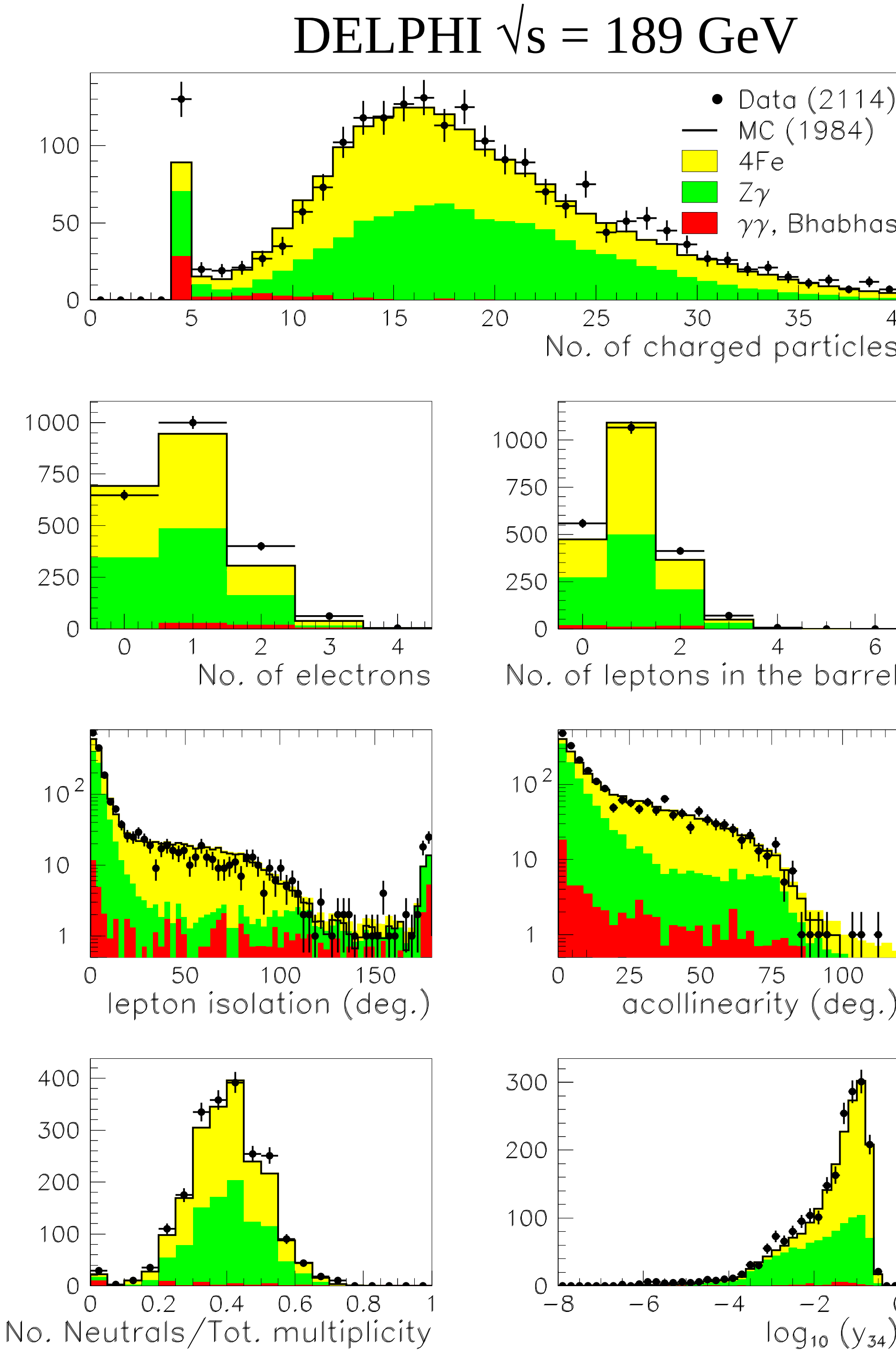


Figure 1: Distributions, after the preselection applied for the $\lambda_{133}$ analyses, of the number of charged particles, the number of well identified electrons in the event, the number of identified leptons with a polar angle between 40° and 140°, the lepton isolation angle, the acollinearity, the ratio of the number of neutral particles to the total event multiplicity, and the $\log_{10}(y_{34})$. The black dots show the real data distributions, and the shaded histograms the expected background from Standard Model processes.

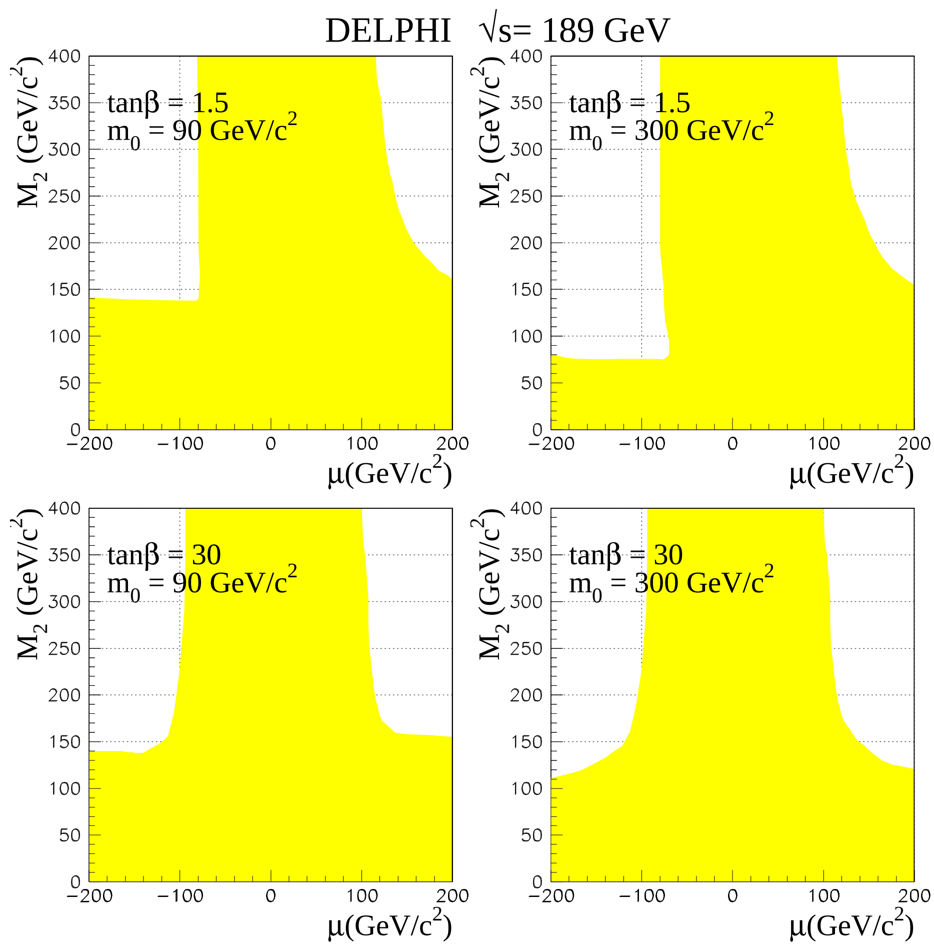


Figure 2: Decays through the $\lambda$ $R$–parity violating operator: excluded regions at 95% C.L. in the $\mu$, $M_2$ parameter space by the neutralino and chargino searches in DELPHI at 189 GeV for two values of tan$\beta$ and two values of $m_0$.

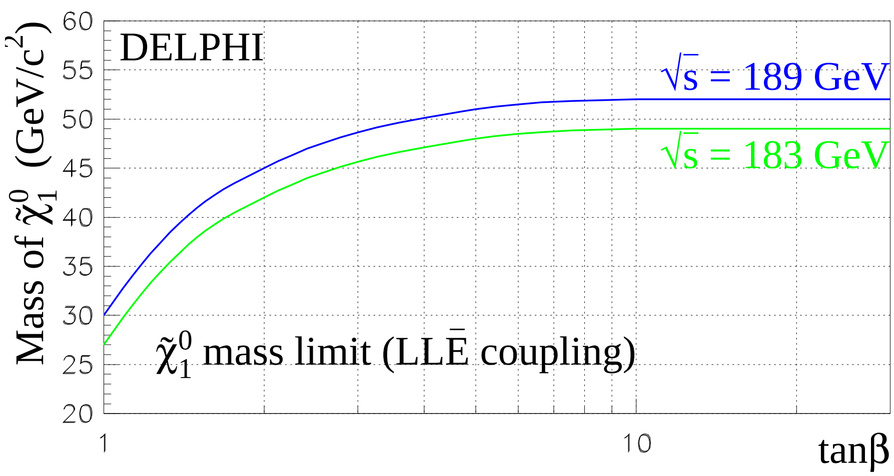


Figure 3: The excluded lightest neutralino mass as a function of tan$\beta$ at 95% confidence level. This limit is valid for all generation indices $i$,$j$,$k$ of the $\lambda_{ijk}$ coupling and all values of $m_0$

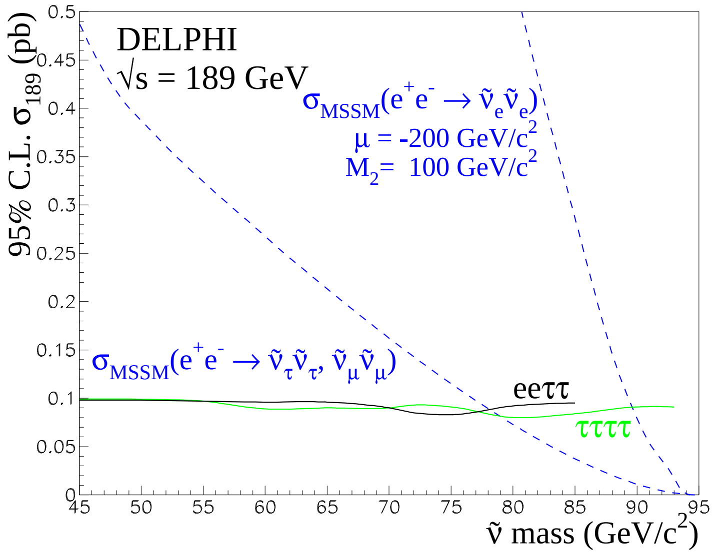


Figure 4: Sneutrino direct decay with $\lambda_{133}$ coupling: limit on the $\tilde{\nu}\tilde{\bar{\nu}}$ production cross-section as a function of the mass for two different final states. The MSSM cross-sections are reported in order to derive a limit on the sneutrino mass in the case of direct $\not{R}_p$ decay. The dashed lower curve corresponds to both $\tilde{\nu}_\mu\tilde{\bar{\nu}}_\mu$ and $\tilde{\nu}_\tau\tilde{\bar{\nu}}_\tau$ cross-sections which depend only on the $\tilde{\nu}$ mass. The dashed upper curve is the $\tilde{\nu}_e\tilde{\bar{\nu}}_e$ cross-section obtained for $\mu = -200$ GeV/$c^2$ and $M_2 = 100$ GeV/$c^2$, the corresponding chargino mass lies between 90 and 120 GeV/$c^2$.

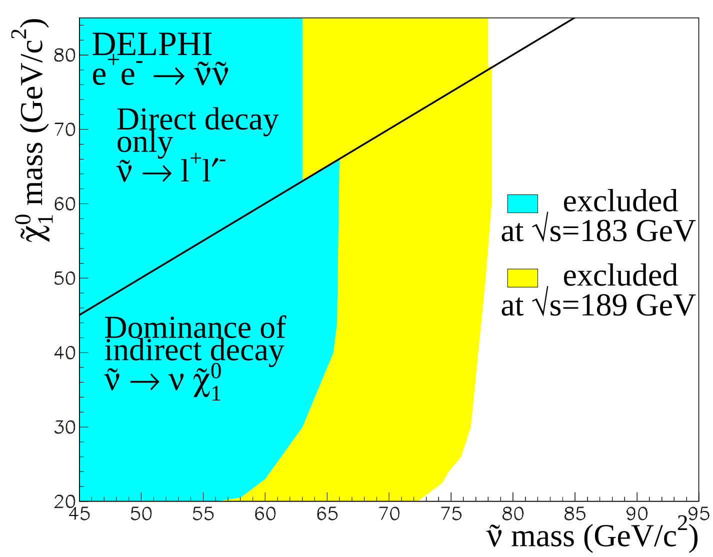


Figure 5: Excluded region at 95% C.L. in $m_{\tilde{\chi}^0}$, $m_{\tilde{\nu}}$ parameter space by $\tilde{\nu}$ pair production for direct and indirect decays. The dark grey area shows the part excluded by the searches at 183 GeV, the light grey area the one excluded by the present analysis.

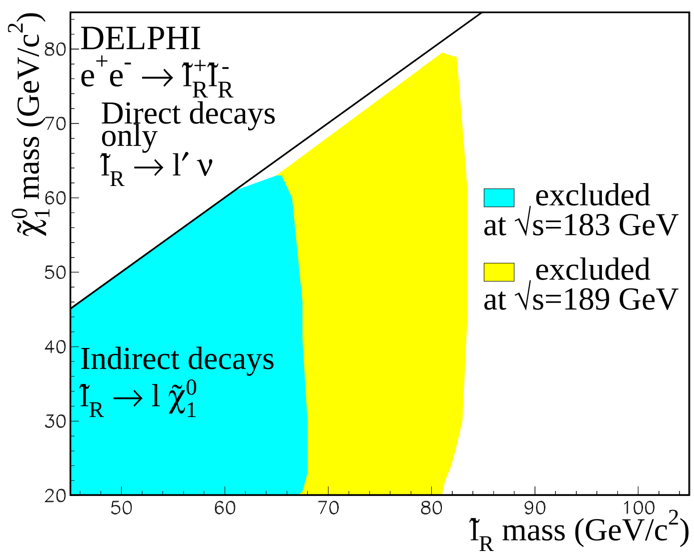


Figure 6: Charged slepton indirect decay: excluded region at 95% C.L. in $m_{\tilde{\chi}^0}$, $m_{\tilde{\ell}_R}$ parameter space by $\tilde{\ell}_R$ pair production. The dark grey area shows the part excluded by the searches at 183 GeV, the light grey area the one excluded by the present searches at 189 GeV.