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

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Abstract

An update of the searches for supersymmetric particles under the assumption that R-parity is not conserved is presented, based on data recorded by the DELPHI detector in 1998 in e^+e^- collisions at centre-of-mass energy of 189 GeV. Only one R-parity violating LL$\bar{\text{E}}$ coupling, which couples scalar leptons to leptons, is considered to be dominant at a time. The results are in agreement with Standard Model expectation. They are used to constrain MSSM parameter values and to derive limits on the mass of supersymmetric particles.

Note for Moriond

1 Introduction

In 1998, the LEP centre-of-mass energy reached 189 GeV, and an integrated luminosity of 158 pb^{-1} has been collected by the DELPHI experiment. The data have been analysed to search for pair production of neutralinos, charginos and sneutrinos in the hypothesis of R-parity violation ($\not{R}_p$) [1]. One major consequence of the non conservation of the R-parity is the allowed decay of the Lightest Supersymmetric Particle (LSP) in standard fermions. Though it exists three terms in the $\not{R}_p$ superpotential [2], we consider here only the $\lambda_{ijk}L_iL_j\bar{E}_k$ term, which couples the sleptons to the leptons. It is assumed that only one λ_{ijk} is dominant at a time, and that its value is such that the Lightest Supersymmetric Particle (LSP) decays within a few centimeters close to the production vertex. This has two consequences on the analyses described here: first, they are not sensitive to light $\tilde{\chi}$ ($M_{\chi_{LSP}}$ $\leq$10 GeV/c^2); second, they are valid only for λ coupling values from 10^{-4}–10^{-5} up to the upper limits derived from Standard Model processes [3, 4, 5, 6].

This paper presents an update of the results described in [7] concerning the search for signatures of $\tilde{\chi}^0_i$, $\tilde{\chi}^{\pm}$ and $\tilde{\nu}$ pair production at 189 GeV. The Minimal Supersymmetric Standard Model (MSSM) scheme [8] with the assumption that the gaugino masses are unified at the Grand Unified Theories (GUTs) scale is assumed. The relevant parameters for these searches are then: M_1, M_2, the U(1) and SU(2) gaugino mass at the electroweak scale (where $M_1 = \frac{5}{3}tan^2\theta_W M_2$), m_0, the scalar common mass at the GUT scale, μ, the mixing mass term of the Higgs doublets at the electroweak scale and tanβ, the ratio of the vacuum expectation values of the two Higgs doublets.

The direct and indirect decay of a neutralino or a chargino pair via a dominant λ_{ijk} coupling lead to either purely leptonic final states, with or without missing energy ($4l + \text{E}_{\text{miss}}$, $6l$, $6l + \text{E}_{\text{miss}}$), or to leptons + jets + missing energy final states (Fig. 1). The direct decay of a sneutrino pair gives four charged leptons (Fig. 2-a): via λ_{ijk} only the $\tilde{\nu}_i$ and $\tilde{\nu}_j$ are allowed to directly decay in $l^{\pm}_j l^{\mp}_k$ and $l^{\pm}_i l^{\mp}_k$ respectively. The indirect decay of a sneutrino pair into a neutralino-neutrino pair (Fig. 2-b) leads to a purely leptonic final state ($4l + \text{E}_{\text{miss}}$), as in $\tilde{\chi}^0_1\tilde{\chi}^0_1$ $\not{R}_p$ decay, with additional missing energy due to the neutrinos produced in the R_p conserved decay. When the charged leptons are τ (for example in λ_{133} case), a certain amount of missing energy is present in the final states due to the neutrino(s) from the τ decay.

2 Data samples

The data corresponding to an integrated luminosity of 158 pb^{-1} collected during 1998 by the DELPHI detector [9] at center of mass energies around 189 GeV have been analysed.

To evaluate background contaminations, the different contributions coming from the Standard Model processes : $\text{e}^+\text{e}^- \to \text{f}\bar{\text{f}}\gamma$, $\gamma\gamma$, e^+e^-, $\text{We}\nu_\text{e}$, Ze^+e^-, W^+W^-, ZZ were considered. The $\text{e}^+\text{e}^- \to \text{e}^+\text{e}^-$ events were produced by the generator of Ref. [10]. To have a sufficiently large equivalent luminosity, the samples generated at 184 GeV were also used. The two-photon interactions leading to leptonic final states were generated with the BDK program [11]. The $\gamma\gamma$ QPM component leading to hadronic final states was generated with the BDK program, while the VDM and QCD components were generated with TWOGAM [12]. In case of two-photon interactions, biased samples (total transverse energy greater than 4 GeV) generated at 184 GeV were used. The event samples produced by PYTHIA were used to study $q\bar{q}(\gamma)$, while those produced by KORALZ [15] allowed the study of $\tau^+\tau^-(\gamma)$ and $\mu^+\mu^-(\gamma)$ final states. For the four-fermion final states, PYTHIA and EXCALIBUR [14] generators were used and cross-checked.

Signal events were generated with the SUSYGEN [16] program. Neutralino and chargino pair productions were considered at several points in the MSSM parameter space. Compared to what has been done for 1997 data collected at centre-of-mass energy of 183 GeV, the three times larger integrated luminosity demands to take into account more neutralino and chargino pair production processes whose contribution was negligible in 1997.

To study sneutrino pair production, samples with sneutrino direct decay and samples with sneutrino indirect decay were generated. A $\tilde{\nu}$ mass range from 50 to 90 GeV/c^2 was covered; in the case of indirect decay, several ranges of mass difference between sneutrinos and neutralinos were considered.

The signal events were generated for both λ_{122} and λ_{133} couplings, set to their experimental upper limits of 0.04 and 0.003 respectively. They were processed either with the DELPHI detector simulation program DELSIM, or with the fast simulation SGV [17]. Studies have been performed to compare the signal efficiencies obtained with these two programs. It has been checked that the difference between them was less than 5%.

3 Analysis description

The applied selections were based on the criteria presented in [7], using mainly missing quantities, lepton identification and kinematical properties, and jet characteristics. Thin jets are produced in the τ decays; jets may be produced in the hadronic decay of the W and the Z coming from the indirect decay of charginos and heavier neutralinos. The jets were reconstructed with the DURHAM [18] algorithm. In order to cover the different topologies, the jet number was not fixed, and the jet charged multiplicity could be low (thin jets with one charged particle for instance), 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 m-jet configuration is noted Y_{mn}.

3.1 Neutralino and chargino searches

Concerning the neutralino and chargino searches with a dominant λ_{122} coupling, the selection procedure has not been modified compared to the analysis performed at 183 GeV, except an additional criteria in the preselection procedure, which required at least two charged particles with an azimuthal angle between 40° and 140°. A fairly good agreement between the number of observed and expected events was obtained (see Table 1). Two events remained in the data, compared to 1.0 expected from standard background processes (0.1 and 0.9 from $f\bar{f}\gamma$ and four-fermion processes respectively). The selection efficiencies were in the range 25–60%.

In the search for neutralino and chargino pair production in case of a dominant λ_{133} coupling, the same preselection requirements described in [7], plus an additional condition requiring at least two charged particles detected in the barrel (azimuthal angle between 40° and 140°) were used. This was efficient to suppress the background coming from Bhabha scattering and two-photon processes, and to remove a large part of the $f\bar{f}\gamma$ contribution.

Selection criteria for λ_{122}	Data	Monte Carlo
Preselection - bhabhas and $\gamma\gamma$ rejection : No. of charged particles $\geq$ 4 No. of charged particles in barrel $\geq$ 2 No. of charged / No. of neutrals $\geq$ 0.5 60 GeV $\leq$ E_{tot} $\leq$ 190 GeV Missing p_t $\geq$ 5 GeV/c 20^o $\leq$ Θ_{miss} $\leq$ 160^o	6988	6769 ± 17
Number of standard or tight μ $\geq$ 2	95	85 $\pm$ 3
Selection on lepton characteristics: (remove $Z\gamma$ and four-fermion final states) E(most energetic lepton) $\geq$ 10 % $\sqrt{s}$ Angle between lepton and next charged $\geq$ 6.5^o	42	43 ± 2
Final selection to remove remaining four-fermions: Number of jets with a lepton as leading particle $\geq$ 2 20^o $\leq$ angle between jets $\leq$ 160^o Missing energy $\geq$ 20 % $\sqrt{s}$	2	1.0 ± 0.3

Table 1: Selection criteria used in the search for neutralino and chargino decay via λ_{122}. The number of data and Monte Carlo selected events are reported.

The number of remaining real and simulated data events after the preselection are reported in Table 2.

Preselection criteria for λ_{133}	Data	Monte Carlo
$N_{charged} \geq 4$, $N_{lepton} \geq 1$ $E_{tot} \geq 18\%\sqrt{s}$, $E_{charged} \geq 16\% \sqrt{s}$ at least 2 charged particles with $40^\circ \leq \Theta \leq 140^\circ$ missing $p_t > 5$ GeV/c, $27^o \leq \Theta_{miss} \leq 153^o$	3976	3934 $\pm$13
$E_{miss} > 30\%\sqrt{s}$	1474	1434 $\pm$9

Table 2: Preselection criteria used in the λ_{133} searches. The number of remaining data and simulated events after the preselection are reported.

Compared to the analysis applied to 1997 data, it has been necessary to modify the selection criteria to be efficient for both low and high multiplicity cases. 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 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 4 (5, 6).

For events with a charged particle multiplicity greater than six, the previous criteria became:

- the energy of the most energetic lepton had to be between 5 and 60 GeV;

- if there is only one identified lepton, there should be no other charged particle in a 6° half cone around it, if there are more than one identified lepton there should be no other charged particle in a 10° half cone around at least two of them;
- at least one electron (loose identification) is required.

In any case, the azimuthal 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

Selection criteria for λ_{133}			Data	MC	eff. for $\tilde{\chi}_1^+\tilde{\chi}_1^-$	eff. for $\tilde{\chi}_1^0\tilde{\chi}_1^0$
	$4 \leq \mathrm{N_{charged}} \leq 6$	$\mathrm{N_{charged}} \geq 7$				
$\mathrm{E^l_{max}}$	[2 GeV, 70 GeV]	[5 GeV, 60 GeV]	1022	1014 ±8	72%	52%
acolin	-	$> 7^o$	821	806 ±6	71%	51%
$\mathrm{E^{30^o}_{cone}}$	$\leq 50\%\ \mathrm{E_{total}}$	$\leq 40\%\ \mathrm{E_{total}}$	711	694 ±5	69%	50%
isolation	$\Theta^{\mathrm{min}}_{\mathrm{lepton-track}} \geq 20^o$ if $\mathrm{N_{charged}}=4$; $\Theta^{\mathrm{min}}_{\mathrm{lepton-track}} \geq 6^o$ if $\mathrm{N_{charged}} = 5, 6$	$\Theta^{\mathrm{max}}_{\mathrm{lepton-track}} \geq 6^o$; $\Theta^{\mathrm{max-1}}_{\mathrm{lepton-track}} \geq 10^o$ if $\mathrm{N_{lepton}} \geq 2$	345	369 ±4	59%	45%
$\log_{10}(\mathrm{Y_{23}})$ $\log_{10}(\mathrm{Y_{34}})$ $\log_{10}(\mathrm{Y_{45}})$	≥ -2.7 ≥ -4	≥ -1.8 ≥ -2.3 ≥ -3	51	60±2	55%	38%
4 jets $\mathrm{E^j_{min}} \times \theta^{j1,j2}_{\mathrm{min}}$	≥ 1 GeV.rad	≥ 5 GeV.rad	46	54±2	53%	33%
	4 charged jets if 4j or 5j	at least 1 jet with 1 or 2 charged particle(s) 4 charged jets if 4j 4 or 5 charged jets if 5j	35	34±1	45%	30%
$\mathrm{N_{neutral}} \leq$	10	15	24	26±0.9	44%	30%
$\mathrm{N_{lepton}}$ in the barrel $\mathrm{N_{electron}}$	≥ 1	≥ 1 ≥ 1	11	12.6±0.6	38%	29%

Table 3: Selection criteria used in the search for neutralino and chargino decay via λ_{133}. nj means n-jet topology, and a charged jet means a jet with at least one charged particle. The number of data and Monte Carlo selected events are reported, as well as the efficiencies obtained for $\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ simulated signals generated for $\mathrm{m}_{\tilde{\chi}^0} = 34$ GeV/c^2 and $\mathrm{m}_{\tilde{\chi}^\pm} = 91$ GeV/c^2 respectively.)

on the jet characteristics and topologies was then applied. First, constrains have been imposed to Y_{nm} 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 demanded. In four- or five-jet configuration, a minimum number of charged jets was required. In case of a four-jet topology, a cut was applied on the value of $\mathrm{E^j_{min}} \times \theta^{j_a j_b}_{\mathrm{min}}$ where $\mathrm{E^j_{min}}$ is the energy of the less 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 $\mathrm{f\bar{f}}\gamma$, $\mathrm{W^+W^-}$

production. An upper cut was finally imposed on the number of neutral particles: it has to be less than 11 when the number of charged particles is lower than 7, and less than 16 when the number of charged particles is greater or equal to 7. The number of remaining real and simulated data events after the selection are reported in Table 3.

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, processes which contribute significantly have been simulated altogether for each MSSM studied point, using SUSYGEN coupled to SGV. Then a global event selection efficiency has been determined for each point, since the performed analyses were sensitive to many different topologies. The global selection efficiencies were in the range 14%–40%.

3.2 Sneutrino searches

Searches for sneutrino pair production with either direct decay ($\tilde{\nu}\rightarrow l^+l^-$) or indirect decay ($\tilde{\nu}\rightarrow \tilde{\chi}^0_1\nu$) via λ_{133} have been performed. The selection procedure was close to the one applied to low charged particle multiplicity events in the search for neutralino and chargino pair production; only events with four to eight charged particles were selected. The criteria are summarized in Table 4; the number of observed events and expected ones from the standard background are reported.

Selection criteria for λ_{133}	Data	MC	efficiency direct decay	efficiency indirect decay
$2 \leq {E_{max}}^l \leq 70$ GeV	1367	1353 ±8	53%	53%
$\Theta^{min}_{lepton-track} \geq 20^o$ if $N_{charged}=4$ $\Theta^{min}_{lepton-track} \geq 6^o$ if $N_{charged}>4$	554	573± 5	47%	48%
$N_{charged} \leq 8$ $N_{neutral} \leq 10$	63	63.3±2.6	45%	47%
at least 1 lepton in the barrel	23	26.8 ±1.6	39%	41%
$\log_{10}(Y_{23}) \geq -2.7$	9	9.5±0.9	37%	40%
$\log_{10}(Y_{34}) \geq -4$	3	4.0±0.5	33%	36%
case of 4 jets : $\theta^{j1,j2}_{min} \geq 20^o$	1	2.1±0.3	33%	35%
at least 1 jet with 1 or 2 charged particles	1	1.9±0.3	32%	35%

Table 4: Selection criteria used in the search for sneutrino direct and indirect decay via λ_{133}. The number of data and Monte Carlo selected events are reported, as well as the efficiencies obtained on simulated signals generated for $m_{\tilde{\nu}} = 60$ GeV/c^2 (direct decay) and $m_{\tilde{\nu}} = 60$ GeV/c^2, $m_{\tilde{\chi}^0} = 40$ GeV/c^2 (indirect decay).

Although the direct decay of a sneutrino pair leads to four charged leptons, a large amount of missing energy was required since the four leptons are mainly taus. The analysis was less efficient for the 2e2τ channel produced in $\tilde{\nu}_\tau\tilde{\nu}_\tau$ decay (between 23 and 28 %) than for the 4τ channel produced in $\tilde{\nu}_e\tilde{\nu}_e$ decay (between 29 to 34%). The indirect decay efficiencies ranged from 18% ($m_{\tilde{\nu}} = 50$ GeV/c^2, $m_{\tilde{\chi}^0} = 23$ GeV/c^2) to 38% ($m_{\tilde{\nu}} = 80$ GeV/c^2, $m_{\tilde{\chi}^0} = 60$ GeV/c^2).

4 Results

The results of the searches presented in this note are in agreement with the Standard Model expectation. They are 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 the searches for neutralino and chargino pair production, the number of expected events in each point of the explored MSSM parameter space, was obtained by:

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

where $\mathcal{L}$ is the integrated luminosity, and ϵ_g is the global efficiency determined as explained in section 3.1. This number has been compared to the number of signal events, N_{95}, expected at a confidence level of 95% in presence of background, determined following the Feldman and Cousins prescription [19]. All points which satisfied $N_{exp} > N_{95}$ were excluded at 95% C.L. Compared to the results of the 1997 data analysis, the excluded area in μ, M_2 planes obtained with the present searches are extended as shown in Fig. 3, for m_0 = 90, 300 GeV/c^2 and tanβ =1.5, 30. The analysis performed considering the λ_{133} coupling as the dominant one provided the most conservative constrains on the MSSM parameter values.

For each tanβ, the highest value of neutralino mass which can be excluded has been determined in μ, M_2 planes for several m_0 values varying up to 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 tanβ is plotted on Fig. 4. From these studies, a neutralino lighter than 30 GeV/c^2 was excluded at 95% C.L. The same procedure has been applied to determine the most conservative lower limit on the chargino mass. The result is less dependent on tanβ, allowing to almost reach the kinematical limit for any value of tanβ: a chargino lighter than 93 GeV/c^2 was excluded 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 efficiencies obtained when varying the sneutrino mass, the cross-section limits for 2e2τ and 4τ channels were derived and reported on Fig. 5. The MSSM cross-sections are also plotted; since the $\tilde{\nu}_\mathrm{e}\tilde{\bar{\nu}}_\mathrm{e}$ cross-section depends not only on the $\tilde{\nu}_\mathrm{e}$ mass but also on the MSSM parameters (due to the eventual $t-$channel $\tilde{\chi}_1^+$ exchange contribution) it is plotted for M_2 = 100 GeV/c^2 and μ = -200 GeV/c^2. The upper limit on the cross-section in case of the sneutrino direct decay led to a lower limit on the sneutrino mass of 77 GeV/c^2. In the case of the indirect decay, the efficiencies depend on the sneutrino and neutralino masses, and the area excluded by the λ_{133} searches in the $\mathrm{m}_{\tilde{\chi}^0}$ versus $\mathrm{m}_{\tilde{\nu}}$ plane is plotted on Fig. 6. Taking into account the limit on the neutralino mass at 30 GeV/c^2, sneutrinos with mass lower than 78 GeV/c^2 were excluded at 95% C.L. when considering their indirect decay.

5 Summary

Searches for $\not{R}_p$ effects in e$^+$e$^-$ collisions at $\sqrt{s}$ = 189 GeV have been performed with the DELPHI detector. The pair production of neutralinos, charginos and sneutrinos have been studied under the assumption that the LL$\bar{\mathrm{E}}$ term is responsible for the supersymmetric particle decays into standard particles. No evidence for R-parity violation has been observed, allowing to update the limits previously obtained at $\sqrt{s}$ =183 GeV; the present limits are:

- $m_{\tilde{\chi}^0}$ >30 GeV/c^2 and $m_{\tilde{\chi}^\pm}$ >93 GeV/c^2;
- $m_{\tilde{\nu}}$ >77 GeV/c^2.

The lower mass limits have increased by 3 GeV/c^2 for neutralinos/charginos, and by 15 GeV/c^2 for sneutrinos.

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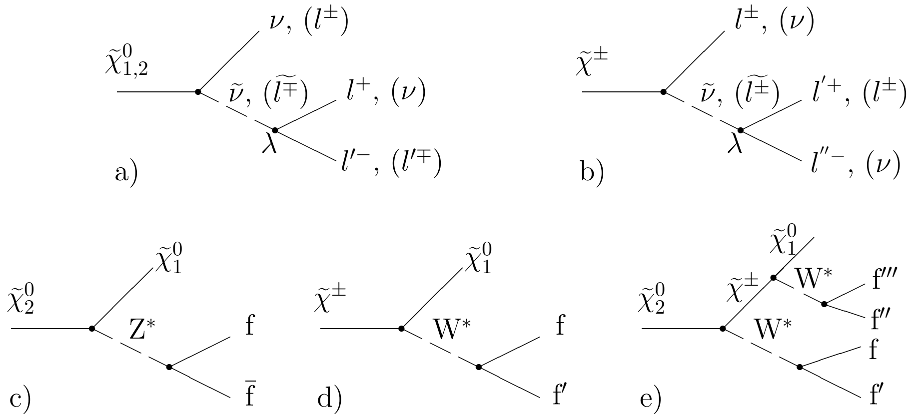

Figure 1: Neutralino and chargino decay diagrams. a: $\widetilde{\chi}^0$ direct decay; b: $\widetilde{\chi}^\pm$ direct decay; in these diagrams the λ indicates the R-parity violating vertex; c, e: $\widetilde{\chi}^0_2$ indirect decay; d: $\widetilde{\chi}^\pm$ indirect decay; the subsequent neutralino $\not{R}_p$ decay is shown in a.

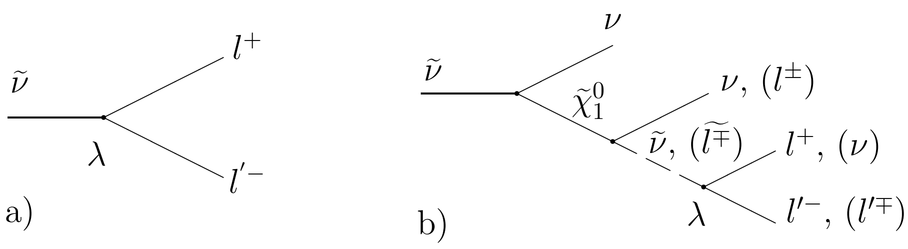

Figure 2: Sneutrino decay diagrams. a: $\tilde{\nu}$ direct decay; b: $\tilde{\nu}$ indirect decay via a $\widetilde{\chi}^0$.

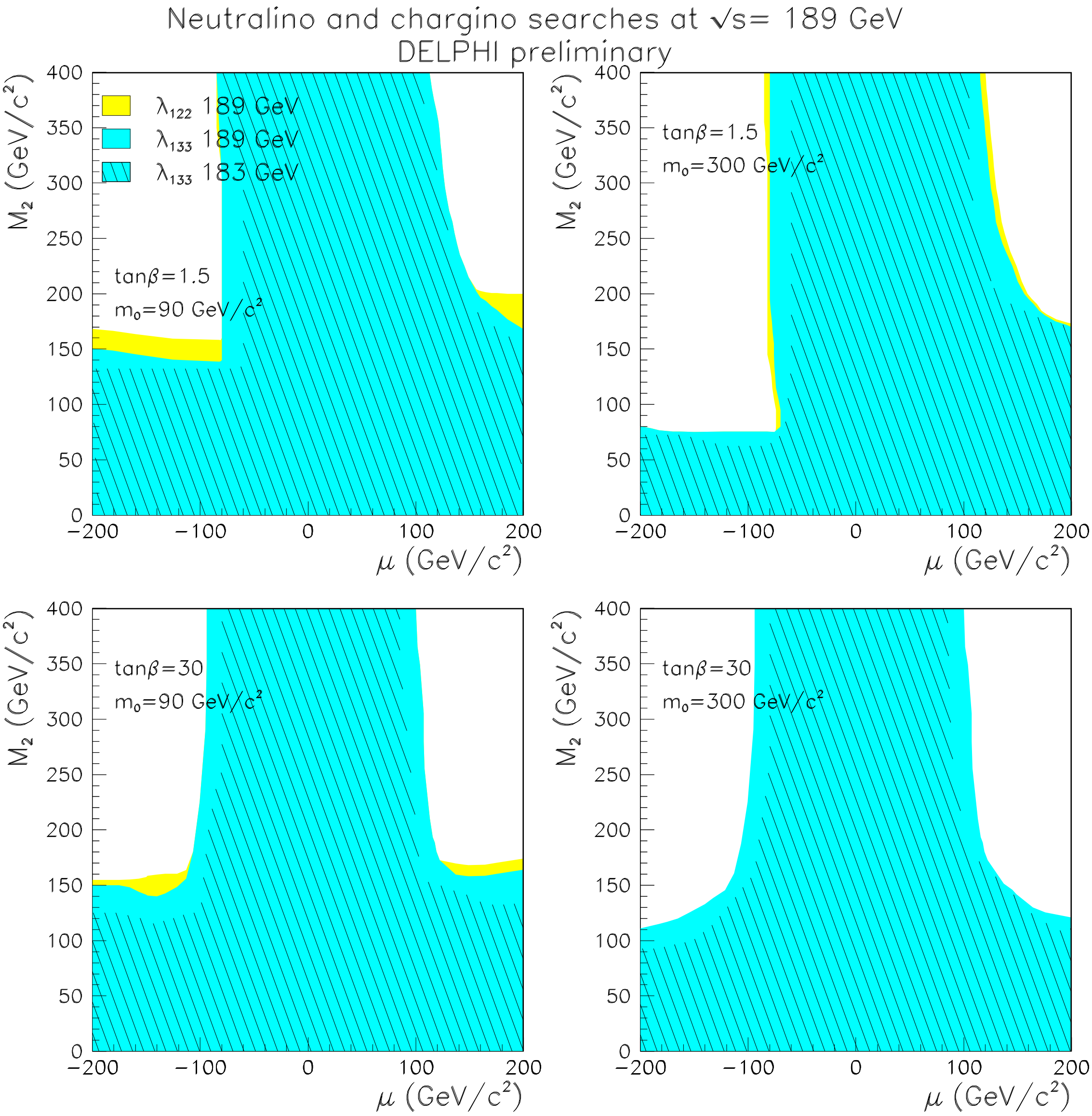

Figure 3: Neutralino and chargino searches in DELPHI data at 189 GeV with a dominant λ coupling: regions in μ, M_2 parameter space excluded at 95 % C.L. for two values of tanβ and two values of m_0. The exclusion area obtained from the λ_{133} search is shown in dark grey and the corresponding area for the λ_{122} search (visible at the edge of the λ_{133} excluded zone) is shown in light grey. The second exclusion area includes the first one. The hatches show the area excluded by the searches at 183 GeV.

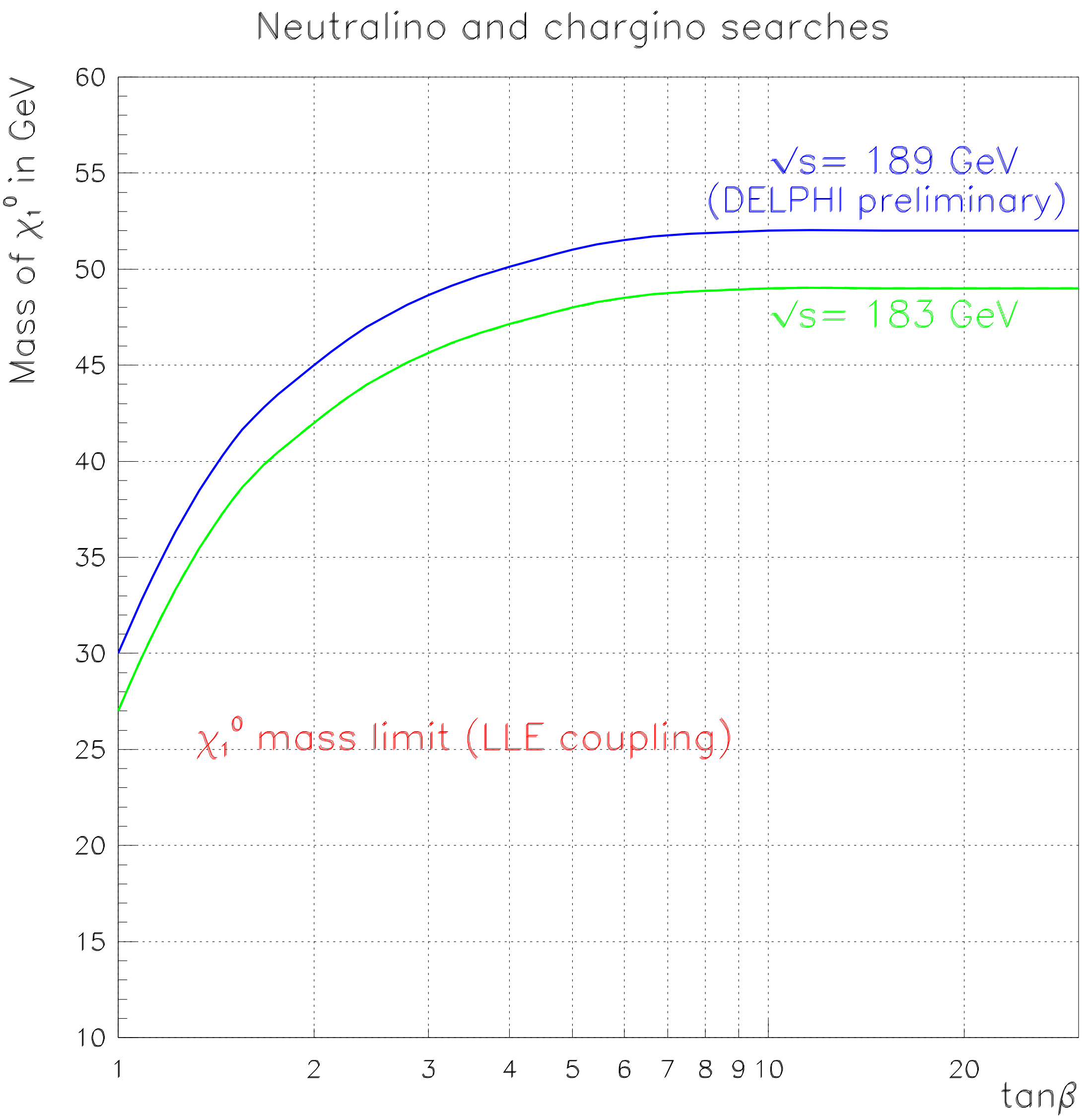

Figure 4: The lightest neutralino mass as a function of tanβ at 95 % confidence level. This limit is independent of the choice of m_0 in the explored range and of the generation indices i,j,k of the λ_{ijk} coupling.

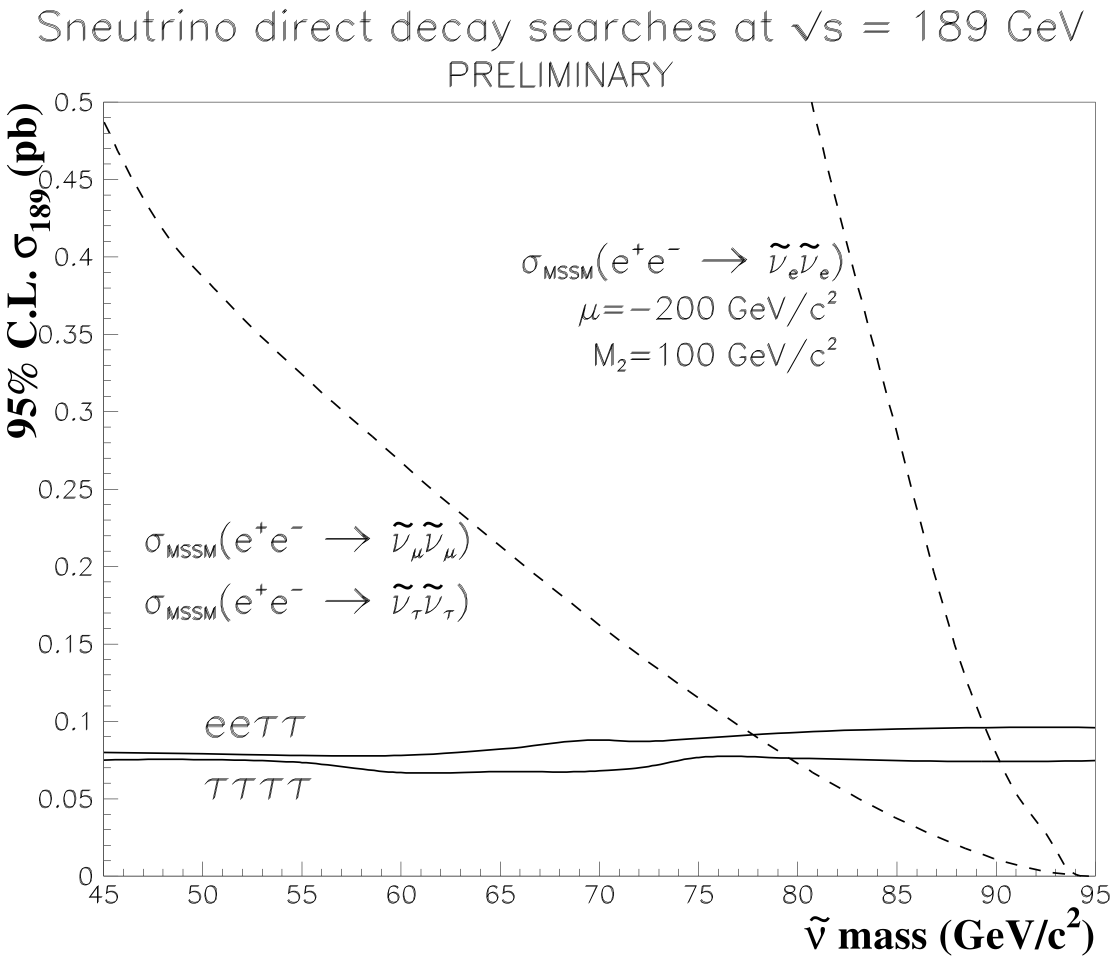

Figure 5: Sneutrino direct decay with λ_{133} coupling: limit on the $\tilde{\nu}\tilde{\bar{\nu}}$ production cross-section as a function of the mass for different final states. The MSSM cross-sections are reported in order to derive a limit on the sneutrino mass in the case of direct $\not{R}_p$ decay. The dashed upper curve on the plot is the $\tilde{\nu}_{\rm e}\tilde{\bar{\nu}}_{\rm e}$ 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.

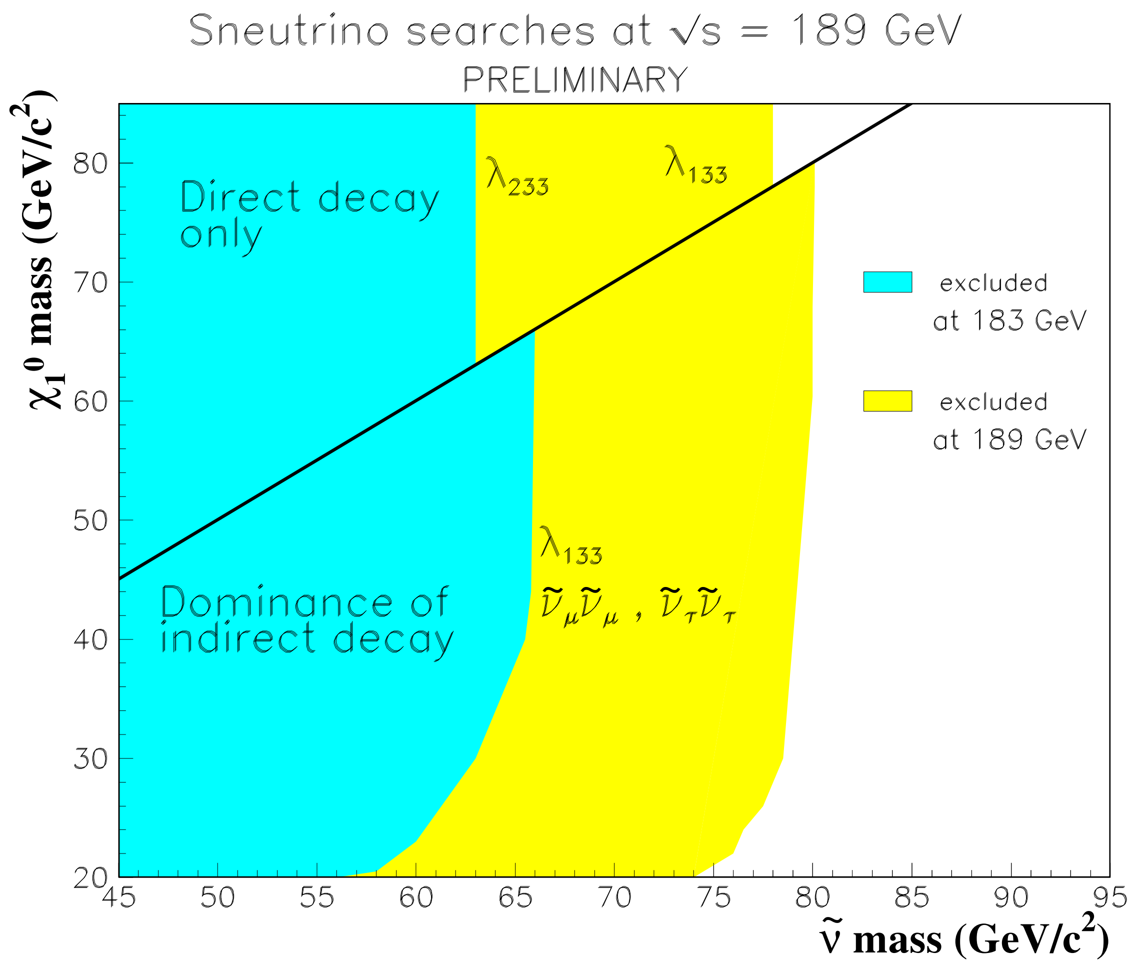

Figure 6: Sneutrino search with λ_{133} coupling: exclusion domain in $m_{\tilde{\chi}^0}$ versus $m_{\tilde{\nu}}$ for $\tilde{\nu}$ pair production cross-section; the diagonal line separates the plot into two regions: in the upper part, only the direct decay is allowed; in the lower part, the indirect decay is dominant, so the exclusion limit also depends on the neutralino mass. 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.