Search for Spontaneous $R$-parity violation
at $\sqrt{s} = 183$ GeV and 189 GeV

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Abstract
Searches for $R$-parity spontaneously violating signals at $\sqrt{s} = 183$ GeV and $\sqrt{s} = 189$ GeV have been performed in 1997 and 1998 DELPHI data, under the assumption of $R$-parity breaking in the third lepton family. The expected topology for the decay of a pair of charginos into two acoplanar taus plus missing energy was investigated and no evidence of signal was found. The results were used to derive a limit on the chargino mass and to constrain domains of the MSSM parameter space.
1 Introduction

R-parity is a discrete symmetry assigned as \( R_p = (-1)^{3B+L+2S} \), where \( B \) is the baryon number, \( L \) is the lepton number and \( S \) is the particle spin. In the Minimal Supersymmetric Standard Model (MSSM) the R-parity symmetry is assumed to be conserved \([2]\). Under this assumption the supersymmetric particles must be produced in pairs, every SUSY particle decays into another SUSY particle and the lightest of them is absolutely stable. These features underly most of the experimental searches for new supersymmetric states.

One alternative supersymmetric scenario is to consider the R-parity as an exact Lagrangian symmetry, broken spontaneously through the Higgs mechanism \([3]\). This may take place via non zero vacuum expectation values (VEVs) for scalar neutrinos, such as

\[
v_R = \langle \tilde{\nu}_R \rangle ; \quad v_L = \langle \tilde{\nu}_L \rangle .
\]

In this case there are two main scenarios depending on whether the lepton number is a gauge symmetry or not \([4, 5, 6, 7, 8]\). In the absence of an additional gauge symmetry, it leads to the existence of a physical massless Nambu-Goldstone boson, called Majoron \((J)\) \([5]\). In this context the Majoron remains massless and therefore stable, if there is no explicit R-parity violating terms.

1.1 Spontaneous R-Parity violation

In the present work we considered the simplest version of the R-parity spontaneous violation model described in Ref. \([5, 6]\). In this model the Lagrangian is specified by the superpotential

\[
W = h_u QH_u U + h_d QH_d D + h_e LH_d E \\
+ (h_0 H_u H_d - e^2) \phi + h_u L H_u \nu^c + h_0 S \nu^c \\
+ h.c.
\]

that conserves the total lepton number and R-parity. The couplings \( h_u, h_d, h_e, h_0, h \) are described by arbitrary matrices in the generation space which explicitly break flavour conservation. The additional chiral superfields \( \nu^c, S \) \([11]\) and \( \phi \) \([12]\) are singlets under \( SU(2) \otimes U(1) \) and carry a conserved lepton number assigned as -1, 1 and 0, respectively. These superfields may induce the spontaneous violation of R-parity leading to a Majoron, that is R-odd, given by the imaginary part of

\[
\frac{v_R^2}{V} (v_u H_u - v_d H_d) + \frac{v_L}{V} \tilde{\nu}_\tau - \frac{v_R}{V} \tilde{\nu}_\tau + \frac{v_S}{V} S_\tau
\]

where the isosinglet VEVs \( v_R = \langle \tilde{\nu}_R \rangle \) and \( v_S = \langle S_\tau \rangle \), with \( V = \sqrt{v_R^2 + v_S^2} \), characterize the R-parity breaking and the isodoublet VEVs \( v_u = \langle H_u \rangle, v_d = \langle H_d \rangle \) and \( v_L = \langle \tilde{\nu}_L \rangle \) induce the electroweak breaking and generate the fermion masses. For theoretical reasons the R-parity breaking was introduced only in the third family, since the largest Yukawa couplings are those of the third generation. In that case the R-parity breaking is effectively parameterized by a bilinear superpotential term given by:

\[
\epsilon_i \equiv h_{\nu_3} v_{R3} .
\]

This effective parameter leads to the R-parity violating gauge couplings and contributes to the mixing between the charged (neutral) leptons and the charginos (neutralinos), as can be seen from the fermions mass matrices in Ref. \([9]\).
By construction, neutrinos are massless at the Lagrangian level but get mass from the mixing with neutralinos [7, 9]. As a result, all \( R \)-parity violating observables are directly correlated to the \( \tau \) neutrino mass as following:

\[
m_{\nu_{\tau}} \sim \frac{\xi e^2}{m_{\tilde{\chi}}} ,
\]

where \( \xi \) is an effective parameter given as a function of \( M_2, \mu \) and \( \tan \beta \) [10].

1.2 Chargino Decay Modes

At LEPII the chargino can be pair produced via \( e^+e^- \) annihilations into \( \gamma, Z, \tilde{\nu} \). In the present analysis we assumed that all sfermions are sufficiently heavy \( (M_{\tilde{g}} \geq 300 \text{GeV}/c^2) \) not to influence the chargino production, as well as its decays. Therefore, only the \( \gamma \) and \( Z \) s-channels contribute to the chargino cross section. In the spontaneous \( R \)-parity violation model, considering that the \( R \)-parity breaking occurs in the third generation, the lightest chargino (\( \tilde{\chi}^\pm \)) can undergo a two-body decay mode

\[
\tilde{\chi}^\pm \rightarrow \tau^\pm J
\]

in addition to the “conventional” chargino channels

\[
\begin{align*}
\tilde{\chi}^\pm & \rightarrow \nu_i W^* \rightarrow \nu_i q\bar{q}', \nu_i l_1^\pm \nu_i , \\
\tilde{\chi}^\pm & \rightarrow \tilde{\chi}^0 W^* \rightarrow \tilde{\chi}^0 q\bar{q}' , \tilde{\chi}^0 l_1^\pm \nu_i
\end{align*}
\]

The two-body decay mode is \( R \)-parity conserving as in equation (8), while in equation (7) the chargino decays through an \( R \)-parity violating vertex. The decay modes branching ratios depend strongly on the effective violation parameter \( (\epsilon) \), as can be observed in figure 1. One should notice that in a large range of \( \epsilon \) the new two-body decay mode is the dominant channel and, since it is \( R \)-parity conserving, it can be quite sizeable.

1.3 Parameters Values

All the results discussed in the following sections were achieved by considering the new two body chargino decay as the dominant decay mode. As it was mentioned before we considered that all sfermions are sufficiently heavy \( (M_{\tilde{g}} \geq 300 \text{GeV}/c^2) \) not to influence the chargino production, as well as its decays. We assumed typical values for SUSY parameters \( \mu \equiv h_0\langle \Phi \rangle \) and \( M_2 \),

\[
\begin{align*}
-200 \text{GeV}/c^2 & \leq \mu \leq 200 \text{GeV}/c^2 \\
40 \text{GeV}/c^2 & \leq M_2 \leq 400 \text{GeV}/c^2 ,
\end{align*}
\]

which accounts for the chargino production within the kinematical reach of LEP. The GUT relation \( M_1/M_2 = 5/3 \tan^2 \theta_W \) is assumed and we have also required that \( \tan \beta \) lies in the range

\[
2 \leq \tan \beta = \frac{v_u}{v_d} \leq 40 .
\]
2 Detector Description

The following is a summary of the properties of the DELPHI detector [1] relevant to this analysis. Charged particle tracks were reconstructed in the 1.2 T solenoidal magnetic field by a system of cylindrical tracking chambers. These were the Microvertex Detector (VD), the Inner Detector (ID), the Time Projection Chamber (TPC), and the Outer Detector (OD). In addition, two planes of drift chambers aligned perpendicular to the beam axis (Forward Chambers A and B) tracked particles in the forward and backward directions, covering polar angles $11^\circ < \theta < 33^\circ$ and $147^\circ < \theta < 169^\circ$ with respect to the beam ($z$) direction.

The VD consisted of three cylindrical layers of silicon detectors, at radii 6.3 cm, 9.0 cm and 11.0 cm. All three layers measured coordinates in the plane transverse to the beam. The closest (6.3 cm) and the outer (11.0 cm) layers contained double-sided detectors to measure also $z$ coordinates. The polar angle coverage of the VD was from $25^\circ$ to $155^\circ$ for the closest and from $44^\circ$ to $136^\circ$ for the outer layer. The ID was a cylindrical drift chamber (inner radius 12 cm and outer radius 22 cm) covering polar angles between $15^\circ$ and $165^\circ$. The TPC, the principal tracking device of DELPHI, was a cylinder of 30 cm inner radius, 122 cm outer radius and had a length of 2.7 m. Each end-plate was divided into 6 sectors, with 192 sense wires used for the dE/dx measurement and 16 circular pad rows used for 3 dimensional space-point reconstruction. The OD consisted 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 the charged particles in hadronic final states was in the range $\Delta p/p^2 \simeq 0.001$ to 0.01 (GeV/c)$^{-1}$, depending on which detectors were used in the track fit [1].

The electromagnetic calorimeters were the High density Projection Chamber (HPC) covering the barrel region of $40^\circ < \theta < 140^\circ$, the Forward ElectroMagnetic Calorimeter (FEMC) covering $11^\circ < \theta < 36^\circ$ and $144^\circ < \theta < 169^\circ$, and the STIC, a Scintillator Ttile Calorimeter which extended coverage down to 1.66 from the beam axis in either direction. The $40^\circ$ taggers were a series of single layer scintillator-lead counters used to veto electromagnetic particles that would otherwise have been missed in the region between the HPC and FEMC. The efficiency to register a photon with energy above 5 GeV measured with the LEP1 data was above 99%. The hadron calorimeter (HCAL) covered 98% of the solid angle. Muons with momenta above 2 GeV penetrated the HCAL and were recorded in a set of muon drift chambers.

3 Data Samples

The data collected by the DELPHI detector during 1997 at $\sqrt{s} \simeq 183$ GeV and 1998 at $\sqrt{s} \simeq 189$ GeV, corresponding to an integrated luminosity of 53 pb$^{-1}$ and 158 pb$^{-1}$ respectively, were analysed.

To evaluate background contaminations, different contributions from the Standard Model processes were considered. The background processes $WW$, $W\nu\bar{\nu}$, $ZZ$, $Ze^+e^-$ and $Z/\gamma \rightarrow q\bar{q}(\gamma)$ were generated using PYTHIA [13], while the events $Z/\gamma \rightarrow \tau^+\tau^-(\gamma)$, $\mu^+\mu^-(\gamma)$ were produced by KORALZ [14] and DYMU3 [15] respectively. A cross-check was performed using the four-fermion final states generated with EXCAL-
Ibur [16]. The generator BABAMC was used for the Bhabha scattering. Two-photon inter-
actions leading to leptonic and hadronic final states were produced by the BDK [17] and
TWOGAM [18] programs, respectively. All the background events were passed through a
detailed detector response simulation (DELSIM [19]) and reconstructed as the real data.

To calculate masses, cross sections and branching ratios of the chargino production and
its corresponding decays we used the program RP-generator II described in reference [6, 20]. The chargino pair production was considered for different values of the R-parity
violation parameter ($\epsilon$) and in several points of the MSSM parameter space ($\tan \beta, \mu, M_2$).
For the signal, a faster simulation program SGV\(^1\) was used to check the points that were
not generated by the full DELPHI simulation program (DELSIM). The SGV program
does not simulate the DELPHI taggers. To correct for this effect, ten chargino mass
points, with 1000 events each, were simulated by DELSIM and the selection efficiency\(^2\)
of the programs were compared. This procedure was done for the 183 GeV analysis and the
correction factors for the SGV efficiency if the taggers are considered, showed in figure 2,
were also used for the 189 GeV simulation.

4 Chargino Searches

With the $R$-parity spontaneous breaking, the chargino can decay through an $R$-parity
conserving vertex into $\tau^\pm J$ events that have the topology of two acoplanar taus plus
missing energy due to the undetectable Majoron. To select events with this signature
it was demanded that there were exactly two clusters of well reconstructed charged and
neutral particles with invariant mass below 5.5 GeV/c\(^2\) and less than 7 charged tracks in
the event. In order to avoid events with many forward going tracks, it was required no
energy deposition in a 30° cone around the beam axis. Finally, no signal in any of the
90° or 40° taggers was required. A good agreement between data and simulated events
is observed after this preselection. Figure 3 shows this agreement for some variables
distributions at 183 GeV and 189 GeV.

4.1 Event Selection at 183 GeV

The events were selected requiring an acoplanarity between 4° and 175°. To reject the
radiative return to the Z background, no events with isolated photons with more than
5 GeV were accepted. The $\gamma\gamma$ and $\mu^+\mu^- (\gamma)$ backgrounds were reduced by requiring that
the events had at least one track with momentum between 5 GeV/c and 60 GeV/c. To
reduce the $\tau^+\tau^- (\gamma)$ background the square of transverse momentum with respect to the
thrust axis divided by the thrust had to be above 0.75 (GeV/c)\(^2\).
To further reduce the $\gamma\gamma$ background, events with momentum of their most ener-
getic charged particle ($P_{\text{max}}$) below 10 GeV/c had to have transverse momentum above
10.5 GeV/c. For events with $P_{\text{max}} > 10$ GeV/c, the main remaining contamination comes
from $Z/\gamma \rightarrow \tau^+\tau^-$ and WW. For those, if the acoplanarity is below 165°, the polar angle
of the missing momentum should be between 30° and 150°. On the other hand, if the
acoplanarity is above 165°, it was required that the momentum of the most energetic

\(^1\)http://delphiwww.cern.ch/~berggren/sgv.html

\(^2\)The efficiency of the chargino selection is defined as the number of events satisfying the cuts divided
by the total number of generated charginos events.
lepton was below 23.5 GeV/c and the polar angle of the missing momentum had to be between 34.5° and 145.5°.

4.2 Event Selection at 189 GeV

Since LEP delivered a higher luminosity for this energy, tighter cuts should be applied in this case. The required acoplanarity had to be between 4° and 170° and no events with isolated photon were accepted. The momentum of each of the two particle clusters had to be above 5 GeV/c and below 55 GeV/c and the square of transverse momentum with respect to the thrust axis divided by the thrust had to be above $1.0 \text{(GeV/c)}^2$. All the events had to have the polar angle of the missing momentum between 35° and 145°.

The events from radiative return to the Z and WW processes were mainly rejected by requiring a total transverse momentum greater than 9 GeV/c and that the momentum of the most energetic lepton was below 23 GeV/c.

If one cluster had a momentum above 10 GeV/c and an acoplanarity below 165° it was also demanded that the value of $\sqrt{s}$ did not fall in the region between 90 GeV and 94 GeV. For an acoplanarity greater than 165° we required that the polar angle of the missing momentum should be between 40° and 140° and that the visible mass was lower than 70 GeV/c². This last cut is very efficient to remove the WW background.

5 Results

As a result of the described selection procedure, 6 candidates of $\tilde{\chi}^\pm \rightarrow \tau^\pm + J$ were found at 183 GeV and 9 candidates at 189 GeV. The number of events selected in the data and the expected number of background events are summarised in table 1. Figure 4 shows the selection efficiency as a function of the chargino mass for 183 GeV data analysis.

The combined results obtained for 183 GeV and 189 GeV were used to calculate the maximum number of signal events in the presence of a background with 95% of confidence level, given by the standard formula in [21], the minimal excluded cross section and the chargino mass limit, showed in figure 5. We also constrained the domains of the MSSM parameter space for $\tan \beta = 2$ and $\tan \beta = 40$ (figure 6).

6 Conclusion

Searches for R-parity spontaneously violating signals were performed in a data sample of about 211 pb⁻¹ collected by the DELPHI detector during 1997 and 1998 at centre-of-mass energy of 183 GeV and 189 GeV. No evidence for R-parity spontaneously breaking has been observed, assuming a sneutrino mass above 300 GeV/c². A limit on the chargino production cross section of 0.23 pb is obtained. For this analysis the lower limit on the chargino mass is 94.4 GeV/c², at 95% confidence level.

7 Acknowledgements

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References

DELPHI coll, P.breu et al., Nucl. Instr. and Meth. 3 78 (1996) 57.


Table 1: Chargino candidates with the total number of background expected and the contributions from major background sources at centre-of-mass energy of 183 GeV and 189 GeV.

<table>
<thead>
<tr>
<th>Centre-of-mass Energy</th>
<th>183 GeV</th>
<th>189 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Total background</td>
<td>$6.28 \pm 0.40$</td>
<td>$9.55 \pm 0.44$</td>
</tr>
<tr>
<td>$Z/\gamma \to ee, \mu\mu, \tau\tau, q\bar{q}$</td>
<td>$0.86 \pm 0.23$</td>
<td>$0.57 \pm 0.12$</td>
</tr>
<tr>
<td>4-fermion events except WW</td>
<td>$0.60 \pm 0.05$</td>
<td>$1.20 \pm 0.16$</td>
</tr>
<tr>
<td>$\gamma\gamma \to ee, \mu\mu, \tau\tau$</td>
<td>$0.28 \pm 0.13$</td>
<td>$0.21 \pm 0.21$</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>$4.38 \pm 0.28$</td>
<td>$7.57 \pm 0.33$</td>
</tr>
</tbody>
</table>

Figure 1: Chargino decay branching ratios as a function of the effective violation parameter $\epsilon$ at 189 GeV for $\tan \beta = 2$, $\mu = 100$ and $M_2 = 400$. 


Figure 2: Efficiency correction factors for SGV simulated signals. The left picture shows the selection efficiency ratio between the DELSIM simulated events and the SGV simulated events, if the taggers are not considered in the DELSIM simulated events. The right picture shows the ratio between the selection efficiency for the DELSIM simulated events if we consider the tagger cut and DELSIM simulated events if we don’t consider the tagger cut.
Acoplanarity

\[ \frac{N}{10^6} \]

DELPHI at √s=183GeV

Energy of the most energetic isolated photon [GeV]

\[ \frac{N}{10^6} \]

DELPHI at √s=183GeV

Square of transverse momentum/thrust [GeV/c]^2

\[ \frac{N}{10^6} \]

DELPHI at √s=189GeV

Missing Transverse Momentum Polar Angle [°]

\[ \frac{N}{10^6} \]

DELPHI at √s=189GeV

Square of transverse momentum/thrust [GeV/c]^2

Figure 3: (a) Distribution of acoplanarity, (b) energy of the most energetic isolated photon, (c) angle between the missing momentum and the beam-axis and (d) square of transverse momentum with respect to the thrust axis. The upper plots were generated at 183 GeV and the bottom ones at 189 GeV. The points with error bars show the real data and the histograms show the simulated backgrounds.
Figure 4: Selection efficiency as a function of the chargino mass for $\tan \beta = 2$ and 183 GeV of centre-of-mass energy.
Figure 5: Expected $e^+e^- \rightarrow \tilde{\chi}^+\tilde{\chi}^-$ cross section at 189 GeV (dots) as a function of chargino mass, assuming a heavy sneutrino ($M_{\tilde{\nu}} \geq 300$ GeV/$c^2$). The indicated values are the minimal cross section in the excluded mass region and the chargino mass limit.
Figure 6: The left plots show the excluded regions in \((\mu, M_2)\) plane at 95% confidence level for \(\tan \beta = 2\) (top) and \(\tan \beta = 40\) (bottom), assuming \(M_\phi \geq 300\,\text{GeV}/c^2\). The central region of those ones is excluded by the LEP1 data\[22\]. The right plots show the branching ratio levels in the \((\mu, M_2)\) plane for the same \(\tan \beta\) values.