The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/100864

Please be advised that this information was generated on 2019-04-01 and may be subject to change.
Search for R-parity Violating Supersymmetry in Dimuon and Four-Jets Channel

B. Pawlik, R.W. Stephens, H.L. Melanson, N.A. Naumann, S. Rajagopalan, Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic
G.R. Snow, Y.A. Yatsunenko, M. Mostafa, Institut des Sciences Nucléaires, IN2P3-CNRS, Université de Grenoble 1, Grenoble, France
H. Zheng, J. Snow, Institute of High Energy Physics, Beijing, People’s Republic of China
N. Parashar, J. Rutherfoord, LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France
J. Rutherfoord, LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France

(DO Collaboration)

1. Universidad de Buenos Aires, Buenos Aires, Argentina
2. LAEFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3. Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4. Institute of High Energy Physics, Beijing, People’s Republic of China
5. Universidad de los Andes, Bogotá, Colombia
6. Charles University, Center for Particle Physics, Prague, Czech Republic
7. Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic
8. Universidad San Francisco de Quito, Quito, Ecuador
9. Institut des Sciences Nucléaires, IN2P3-CNRS, Université de Grenoble 1, Grenoble, France
10. CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France
11. Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS, Orsay, France
12. LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France

2
DAPNIA/Service de Physique des Particules, CEA, Saclay, France
Universität Mainz, Institut für Physik, Mainz, Germany
Panjab University, Chandigarh, India
Delhi University, Delhi, India
Tata Institute of Fundamental Research, Mumbai, India
Seoul National University, Seoul, Korea
CINVESTAV, Mexico City, Mexico
FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
University of Nijmegen/NIKHEF, Nijmegen, The Netherlands
Institute of Nuclear Physics, Kraków, Poland
Joint Institute for Nuclear Research, Dubna, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Moscow State University, Moscow, Russia
Institute for High Energy Physics, Protvino, Russia
Lancaster University, Lancaster, United Kingdom
Imperial College, London, United Kingdom
University of Arizona, Tucson, Arizona 85721
Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
University of California, Davis, California 95616
California State University, Fresno, California 93740
University of California, Irvine, California 92697
University of California, Riverside, California 92521
Florida State University, Tallahassee, Florida 32306
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
University of Illinois at Chicago, Chicago, Illinois 60607
Northern Illinois University, DeKalb, Illinois 60115
Northwestern University, Evanston, Illinois 60208
Indiana University, Bloomington, Indiana 47405
University of Notre Dame, Notre Dame, Indiana 46556
Iowa State University, Ames, Iowa 50011
University of Kansas, Lawrence, Kansas 66045
Kansas State University, Manhattan, Kansas 66506
Louisiana Tech University, Ruston, Louisiana 71272
University of Maryland, College Park, Maryland 20742
Boston University, Boston, Massachusetts 02215
Northeastern University, Boston, Massachusetts 02115
University of Michigan, Ann Arbor, Michigan 48109
Michigan State University, East Lansing, Michigan 48824
University of Nebraska, Lincoln, Nebraska 68588
Columbia University, New York, New York 10027
University of Rochester, Rochester, New York 14627
State University of New York, Stony Brook, New York 11794
Brookhaven National Laboratory, Upton, New York 11973
Langston University, Langston, Oklahoma 73050
University of Oklahoma, Norman, Oklahoma 73019
Abstract

We present results of a search for R-parity-violating decay of the neutralino \( \tilde{\chi}_0^1 \), taken to be the Lightest Supersymmetric Particle. It is assumed that this decay proceeds through one of the lepton-number violating couplings \( \lambda'_{2jk} \) \((j = 1, 2; k = 1, 2, 3)\), and that R-parity is conserved in all other production and decay processes in the event. This scenario provides two muons and four jets in the final state. This search is based on 77.5 ± 3.9 pb\(^{-1}\) of data, collected by the DØ experiment at the Fermilab Tevatron in \( pp \) collisions at \( \sqrt{s} = 1.8 \text{ TeV} \) in 1992–1995. Background expected from standard model processes amounts to 0.18 ± 0.03 ± 0.02 events. In the absence of candidate events, the result is interpreted in terms of limits on squark and gluino masses within the framework of the minimal low-energy supergravity supersymmetry model.

A search for events with multiple leptons and jets is an effective way to look for new physics because such events do not suffer from large standard model (SM) backgrounds. These events can provide evidence of R-parity-violating (RPV) decays of supersymmetric (SUSY) particles \[1,2\]. R-parity is a discrete multiplicative quantum number that distinguishes SM particles from their SUSY partners. It is defined as \( R = (-1)^{3B+L+2S} \), where B, L, and S are the baryon, lepton, and spin quantum numbers, respectively. \( R \) is +1 for SM particles and −1 for the corresponding SUSY particles. Originally, conservation of R-parity was imposed on supersymmetric theories because the combination of lepton-number and baryon-number violating couplings in the Lagrangian could have generated several rare or forbidden processes at unacceptably high rates. One such example is the decay of the proton. However, rapid proton decay as well as other rare decays can be prevented by not allowing simultaneous violations of baryon and lepton numbers. Thus, a small violation of R-parity cannot be excluded.

The Yukawa coupling terms in the superpotential that induce R-parity violation are:

\[ \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} U_i D_j \overline{D}_k, \]

where \( L \) and \( Q \) are the SU(2)-doublet lepton and quark superfields; \( E, U, \) and \( D \) are the singlet lepton, up-type quark, and down-type quark superfields, respectively; and \( i, j, \) and \( k \) are the generation indices. Since \( \lambda \) and \( \lambda'' \) are antisymmetric in the first two and last two indices, respectively, there are in total 45 possible couplings. For experimental searches it is usually assumed that only one of the 45 couplings is non-zero. Since experimental
upper bounds on these couplings from low-energy measurements are quite stringent [4], it is further assumed that R-parity violation manifests itself only in the decay of the lightest supersymmetric particle (LSP). At the same time, these couplings are assumed to be strong enough so that the LSP is unstable and decays within the detector, close to the interaction vertex, which sets the scale for \( \lambda \) at \( \approx 10^{-3} \). A previous study at DØ [1] in the dielectron + jets channel, searched for such a decay for non-vanishing \( \lambda'_{ijk} \) (\( j = 1, 2 \) and \( k = 1, 2, 3 \)) couplings in the framework of the minimal low-energy supergravity supersymmetry model (mSUGRA) [4], with \( \chi_1^0 \) as the LSP. This model contains five parameters: a common mass for scalars \( (m_0) \), a common mass for gauginos \( (m_{1/2}) \), a common trilinear coupling \( (A_0) \), specified at the grand unification scale), the ratio of the vacuum expectation values of the two Higgs doublets (\( \tan \beta \)), and the sign of the Higgsino mass parameter \( (\mu) \). The LSP decay to a charged lepton and two quark jets involving one of the \( \lambda'_{ijk} \) couplings is a viable mode for searching for SUSY at the Tevatron for the following reasons. The LSP can be produced either directly or through cascade decays from squarks or gluinos and can subsequently decay into a lepton and two quarks. The branching fraction of this decay depends on the composition of the LSP, which in turn depends on the mSUGRA parameters described earlier. Studies have shown that at the energy of the Tevatron, the amount of signal in any of the lepton + jets decay channels of the LSP can be substantial for a large range of values of the mSUGRA parameters [4]. Also, such events will not contain any missing energy, thus making it easier to search for a RPV signal. We report a study similar to the previous one [4], for finite \( \lambda'_{222} \) coupling (the study is equally valid for all the \( \lambda'_{2jk} \) couplings with \( j = 1, 2 \) and \( k = 1, 2, 3 \)), based on a signature of two energetic muons and four energetic jets. There are several standard model processes that mimic this signature, e.g., \( \gamma^*/Z \rightarrow \mu\mu \), \( Z \rightarrow \tau\tau \rightarrow \mu\mu \), \( t\bar{t} \rightarrow \mu\mu \), \( WW \rightarrow \mu\mu \), and accompanying jets.

The DØ detector has been described elsewhere [8]. The most important parts for this analysis are the uranium/liquid-argon calorimeter and the muon system. A cone algorithm with a cone radius of 0.5 in the \( \eta-\phi \) space, where \( \eta \) is the pseudorapidity and \( \phi \) is the azimuthal angle, is used for jet identification [8]. Muons are identified as tracks that leave minimum ionizing energy in the calorimeter, and are reconstructed in the muon system. An integrated luminosity of \( 77.5 \pm 3.9 \) pb\(^{-1} \) collected with the DØ detector during the 1992–1995 Tevatron run at \( \sqrt{s} = 1.8 \) TeV is used for this analysis. The data are required to satisfy a trigger demanding one muon \( (p_T > 10 \) GeV/\( c \), \( |\eta| < 1.7 \) \), and one jet \( (E_T > 15 \) GeV, \( |\eta| < 2.5 \)). In the offline analysis, an event is selected only if it has at least two muons within \( |\eta| < 1.7 \) \( (p_T > 15 \) GeV/\( c \) for the first muon, and \( p_T > 10 \) GeV/\( c \) for the second muon), and at least four jets within \( |\eta| < 2.5 \) and with \( E_T > 15 \) GeV. The muons and jets are required to satisfy standard DØ selection criteria [11]. The muons are also required to be isolated from jets by a distance > 0.5 in the \( \eta-\phi \) plane (this rejects muons coming from heavy-flavor decays, pions decaying in flight, and pion-induced punchthroughs). In addition, several other criteria are imposed to minimize background. The aplanarity [11] of the jets in each event is required to be greater than 0.03. The invariant mass of the two muons is required to be greater than 5 GeV/\( c^2 \), which helps to reject low-energy resonances (e.g. \( J/\psi \)) and spurious combinations of muon tracks. \( H_T \), the scalar sum of \( E_T \) of all muons and jets that pass kinematic and fiducial requirements, is required to be greater than 150 GeV.

Of the original 230,688 events passing the trigger requirements, none survive the above selections. The expected backgrounds from the two main SM channels, \( Z(\rightarrow \mu\mu) + \) jets
and \( t\bar{t}(\rightarrow \mu\mu) + \) jets, are shown in Table I, along with their statistical (first) and systematic (second) uncertainties. The contribution to background events from \( Z \) production is estimated from a sample of 21,000 \( Z + \) jets events, generated using \textsc{vecbos} [12]. A total of 254,000 \( t\bar{t} \) events, generated with \textsc{herwig} [13], are used to estimate the contribution from this background. The \( \text{DØ} \) detector is simulated using a \textsc{geant}-based package [14], which provides efficiencies of the selection criteria for signal and background events. We illustrate in Fig. 1, the effect of one of the selection criteria (number of jets in an event) on events at a typical signal point \( (m_0=140 \text{ GeV}/c^2, m_{1/2}=90 \text{ GeV}/c^2, A_0=0, \tan\beta=2, \mu < 0) \) and on events from the background channel \( Z(\rightarrow \mu\mu) + \) jets. The arrow in Fig. 1 indicates the minimum number of jets in accepted events. The instrumental background, which arises from misidentification of jets as muons, is negligible in this analysis. As can be seen from Table I, the expected number of background events is quite small. The statistical error arises from a combination of fluctuations in the Monte Carlo events and uncertainties in the muon and jet identification efficiencies. The systematic error arises due to uncertainty in the jet energy scale and in the values of production cross sections.

Signal events are generated with \textsc{isajet} [15], modified to incorporate RPV decays based on the formalism of Ref. [6]. For each signal sample, the value of efficiency multiplied by the branching fraction of \( p\bar{p} \rightarrow \geq 2 \mu \) and \( \geq 4 \) jets is estimated in the same way as described above for the SM background. Table II shows these values and the event yields expected from an integrated luminosity of 77.5 pb\(^{-1}\) for several points in the \((m_0, m_{1/2})\)

### TABLE I. Summary of major backgrounds. First error is statistical and second error is systematic.

<table>
<thead>
<tr>
<th>Background process</th>
<th>Expected events for 77.5 pb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z(\rightarrow \mu\mu) + ) jets</td>
<td>( 0.140 \pm 0.031 \pm 0.015 )</td>
</tr>
<tr>
<td>( t\bar{t}(\rightarrow \mu\mu) + ) jets</td>
<td>( 0.042 \pm 0.002 \pm 0.013 )</td>
</tr>
<tr>
<td>Total</td>
<td>( 0.182 \pm 0.031 \pm 0.020 )</td>
</tr>
</tbody>
</table>

### TABLE II. Efficiency \((\epsilon)\) multiplied by branching fraction \((B)\), and expected event yield \((\langle N \rangle)\), for several points in the \((m_0, m_{1/2})\) parameter space (for \( \tan\beta=2, A_0=0, \) and \( \mu < 0 \)).

<table>
<thead>
<tr>
<th>( m_0 ) (GeV/c(^2))</th>
<th>( m_{1/2} ) (GeV/c(^2))</th>
<th>( \epsilon B(%) )</th>
<th>( \langle N \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>( 0.60 \pm 0.07 \pm 0.03 )</td>
<td>( 3.0 \pm 0.4 )</td>
</tr>
<tr>
<td>80</td>
<td>90</td>
<td>( 0.74 \pm 0.08 \pm 0.04 )</td>
<td>( 2.7 \pm 0.3 )</td>
</tr>
<tr>
<td>80</td>
<td>110</td>
<td>( 0.34 \pm 0.04 \pm 0.03 )</td>
<td>( 0.6 \pm 0.1 )</td>
</tr>
<tr>
<td>190</td>
<td>90</td>
<td>( 0.78 \pm 0.06 \pm 0.05 )</td>
<td>( 2.1 \pm 0.2 )</td>
</tr>
<tr>
<td>260</td>
<td>70</td>
<td>( 0.42 \pm 0.04 \pm 0.02 )</td>
<td>( 2.7 \pm 0.3 )</td>
</tr>
<tr>
<td>400</td>
<td>90</td>
<td>( 0.31 \pm 0.04 \pm 0.02 )</td>
<td>( 0.8 \pm 0.1 )</td>
</tr>
</tbody>
</table>
parameter space.

Since the expected SM background is compatible with absence of observed events, we proceed to determine the region in mSUGRA space that can be excluded. An upper limit at the 95% confidence level (C.L.) on the cross section for signal is obtained for each point in the \((m_0, m_{1/2})\) plane for fixed values of \(A_0=0\), \(\mu<0\), and \(\tan\beta = 2\) and 6. A technique based on Bayesian statistics \cite{16} is used for this purpose, with a flat prior for the signal cross section and Gaussian priors for luminosity, efficiency, and expected background. The limits on the measured cross section are then compared with the leading-order SUSY prediction given by \textsc{isajet}, to find an excluded region in the \((m_0, m_{1/2})\) plane. Figs. 2 and 3 show the regions of parameter space (below the bold lines) excluded at the 95% C.L. for \(\tan\beta = 2\) and 6, respectively.

The shaded areas in the left-hand corners of the figures indicate the regions where either the model does not produce electroweak symmetry breaking or the lightest neutralino is not the LSP. The area in the \((m_0, m_{1/2})\) plane excluded by experimental searches at LEP \cite{17} already extends beyond the shaded areas. The exclusion contour in Fig. 2 follows essentially a contour of constant squark mass \((m_{\tilde{q}} = 260 \text{ GeV}/c^2)\) for low \(m_0\) values. This is because pair production of squarks is the dominant SUSY process that contributes to the signal in that region. Production of gluinos, \(\tilde{\chi}_2^0\), and \(\tilde{\chi}_1^0\) becomes dominant at larger values of \(m_0\), where the masses and production cross sections of these particles are approximately independent of \(m_0\). The exclusion contour therefore becomes approximately independent of \(m_0\) for \(m_0 > 250 \text{ GeV}/c^2\).

The value of \(A_0\) does not affect the results significantly, since it changes only the third
FIG. 2. Exclusion contour in the \((m_0, m_{1/2})\) plane for \(\tan \beta = 2\), \(\mu < 0\), \(A_0 = 0\), and finite \(\lambda'_{2jk}\) \((j = 1, 2; k = 1, 2, 3)\) coupling. The region below the bold line is excluded at the 95% C.L. The cross hatched region is excluded for theoretical reasons (see text). \(m_{\tilde{q}}\) and \(m_{\tilde{g}}\) denote the squark and gluino masses, respectively.

generation sparticle masses. Both for \(\mu > 0\), and for higher values of \(\tan \beta\) (see Fig. 3 for the exclusion contour at \(\tan \beta = 6\)), the sensitivity of this search diminishes, because of the change in the composition of the LSP, which leads to a decrease of the branching fraction of the LSP into muons [7].

In conclusion, we have searched for RPV decay of the neutralino \(\tilde{\chi}_1^0\) into a muon and two jets in 77.5 pb\(^{-1}\) of data. No candidate events were found. This result is presented as an exclusion contour in the mSUGRA \((m_0, m_{1/2})\) parameter space for \(A_0=0\), \(\tan \beta=2\) and 6, and \(\mu < 0\). In particular, for \(\tan \beta = 2\), squark masses below 240 GeV/c\(^2\) (for all gluino masses) and gluino masses below 224 GeV/c\(^2\) (for all squark masses) can be excluded. For equal masses of squarks and gluinos the mass limit is 265 GeV/c\(^2\).

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L’Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), and the A.P. Sloan Foundation.
FIG. 3. Exclusion contour in the \((m_0, m_{1/2})\) plane for \(\tan \beta = 6\), \(\mu < 0\), \(A_0 = 0\), and finite \(\lambda'_{2jk}\) \((j = 1, 2; k = 1, 2, 3)\) coupling.

REFERENCES

* Visitor from University of Zurich, Zurich, Switzerland.
† Visitor from Institute of Nuclear Physics, Krakow, Poland.