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# Search for R-parity Violating Supersymmetry in Dimuon and Four-Jets Channel

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## Abstract

We present results of a search for R-parity-violating decay of the neutralino  $\tilde{\chi}_1^0$ , 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  $77.5 \pm 3.9 \text{ pb}^{-1}$  of data, collected by the DØ experiment at the Fermilab Tevatron in  $p\bar{p}$  collisions at  $\sqrt{s}=1.8 \text{ TeV}$  in 1992–1995. Background expected from standard model processes amounts to  $0.18 \pm 0.03 \pm 0.02$  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:

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k,$$

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 [3], 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 [4] in the dielectron + jets channel, searched for such a decay for non-vanishing  $\lambda'_{1jk}$  ( $j = 1, 2$  and  $k = 1, 2, 3$ ) couplings in the framework of the minimal low-energy supergravity supersymmetry model (mSUGRA) [5], with  $\tilde{\chi}_1^0$  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 [6,7]. 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 [9]. Muons are identified as tracks that leave minimum ionizing energy in the calorimeter, and are reconstructed in the muon system. An integrated luminosity of  $77.5 \pm 3.9 \text{ pb}^{-1}$  collected with the DØ detector during the 1992–1995 Tevatron run at  $\sqrt{s} = 1.8 \text{ TeV}$  is used for this analysis. The data are required to satisfy a trigger demanding one muon ( $p_T > 10 \text{ GeV}/c$ ,  $|\eta| < 1.7$ ), and one jet ( $E_T > 15 \text{ GeV}$ ,  $|\eta| < 2.5$ ). In the offline analysis, an event is selected only if it has at least two muons within  $|\eta| < 1.7$  ( $p_T > 15 \text{ GeV}/c$  for the first muon, and  $p_T > 10 \text{ GeV}/c$  for the second muon), and at least four jets within  $|\eta| < 2.5$  and with  $E_T > 15 \text{ GeV}$ . The muons and jets are required to satisfy standard DØ selection criteria [10,11]. 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  $5 \text{ GeV}/c^2$ , 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  $150 \text{ GeV}$ .

Of the original 230,688 events passing the trigger requirements, none survive the above selections. The expected backgrounds from the two main SM channels,  $Z(\rightarrow \mu\mu) + \text{jets}$

and  $t\bar{t}(\rightarrow \mu\mu) + \text{jets}$ , 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  $Z + \text{jets}$  events, generated using VECBOS [12]. A total of 254,000  $t\bar{t}$  events, generated with HERWIG [13], are used to estimate the contribution from this background. The DØ detector is simulated using a 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  $Z(\rightarrow \mu\mu) + \text{jets}$ . The arrow in Fig. 1 indicates the minimum number of jets in accepted events. The instrumental background, which arises

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

Background process	Expected events for $77.5 \text{ pb}^{-1}$
$Z(\rightarrow \mu\mu) + \text{jets}$	$0.140 \pm 0.031 \pm 0.015$
$t\bar{t}(\rightarrow \mu\mu) + \text{jets}$	$0.042 \pm 0.002 \pm 0.013$
Total	$0.182 \pm 0.031 \pm 0.020$

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 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  $p\bar{p} \rightarrow \geq \text{two muons and } \geq \text{four jets}$  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  $77.5 \text{ pb}^{-1}$  for several points in the  $(m_0, m_{1/2})$

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  $\mu < 0$ ).

$m_0 \text{ (GeV}/c^2)$	$m_{1/2} \text{ (GeV}/c^2)$	$\epsilon B(\%)$	$\langle N \rangle$
0	100	$0.60 \pm 0.07_{-0.03}^{+0.05}$	$3.0 \pm 0.4$
80	90	$0.74 \pm 0.08_{-0.04}^{+0.06}$	$2.7 \pm 0.3$
80	110	$0.34 \pm 0.04_{-0.03}^{+0.03}$	$0.6 \pm 0.1$
190	90	$0.78 \pm 0.06_{-0.03}^{+0.05}$	$2.1 \pm 0.2$
260	70	$0.42 \pm 0.04_{-0.02}^{+0.03}$	$2.7 \pm 0.3$
400	90	$0.31 \pm 0.04_{-0.02}^{+0.02}$	$0.8 \pm 0.1$

parameter space.

Since the expected SM background is compatible with absence of observed events, we

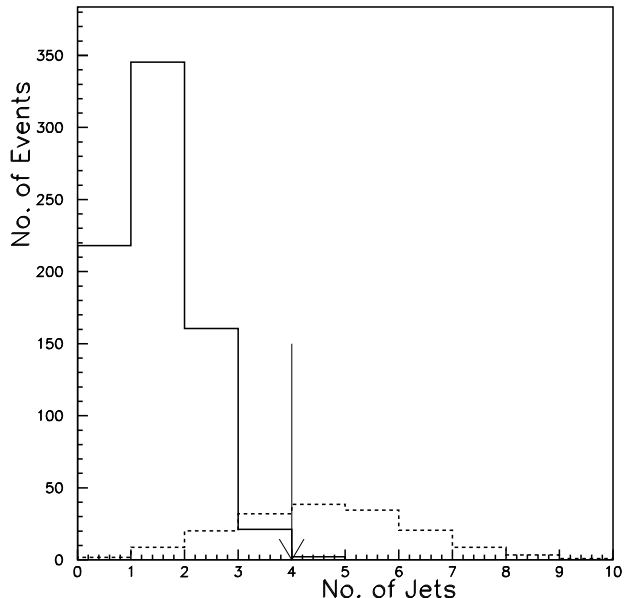


FIG. 1. Distribution of the number of jets per event at a typical signal point ( $m_0=140 \text{ GeV}/c^2$ ,  $m_{1/2}=90 \text{ GeV}/c^2$ ) (dashed line) and background sample,  $Z(\rightarrow \mu\mu) + \text{jets}$  (solid line) for  $77.5 \text{ pb}^{-1}$  integrated luminosity. The vertical arrow indicates the position of the applied cut.

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 [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 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 [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



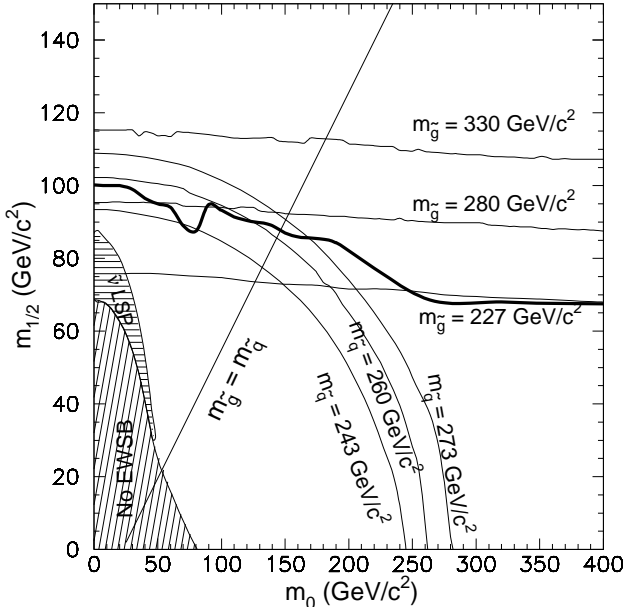


FIG. 2. Exclusion contour in the  $(m_0, m_{1/2})$  plane for  $\tan\beta = 2$ ,  $\mu < 0$ ,  $A_0 = 0$ , and finite  $\lambda'_{2jk}$  ( $j = 1, 2$ ;  $k = 1, 2, 3$ ) coupling. The region below the bold line is excluded at the 95% C.L. The cross hatched region is excluded for theoretical reasons (see 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  $77.5 \text{ pb}^{-1}$  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  $240 \text{ GeV}/c^2$  (for all gluino masses) and gluino masses below  $224 \text{ GeV}/c^2$  (for all squark masses) can be excluded. For equal masses of squarks and gluinos the mass limit is  $265 \text{ GeV}/c^2$ .

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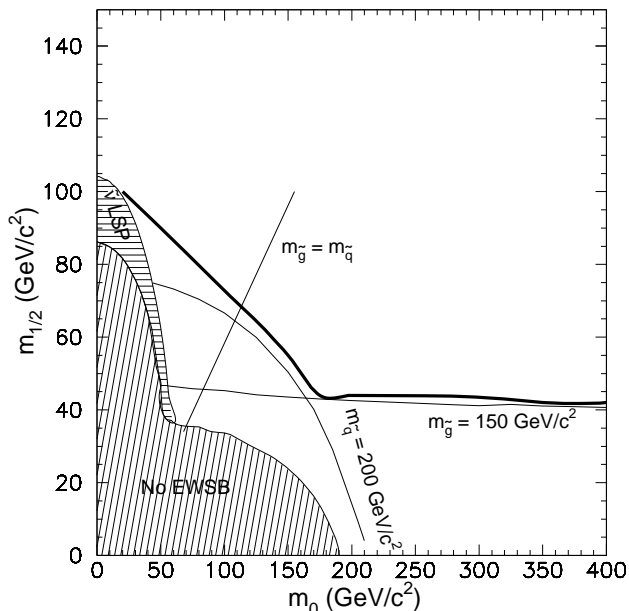


FIG. 3. Exclusion contour in the  $(m_0, m_{1/2})$  plane for  $\tan\beta = 6$ ,  $\mu < 0$ ,  $A_0 = 0$ , and finite  $\lambda'_{2jk}$  ( $j = 1, 2; k = 1, 2, 3$ ) coupling.

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