Search for R-Parity Violating Supersymmetry in Two-Muon and Four-Jet Topologies

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We present results of a search for R-parity-violating decay of the neutralino $\tilde{\chi}_1^0$, taken as the lightest supersymmetric particle, to a muon and two jets. The decay proceeds through a lepton-number violating coupling λ'_{2jk} ($j = 1, 2$; $k = 1, 2, 3$), with R-parity conservation in all other production and decay processes. In the absence of candidate events from $77.5 \pm 3.9\ \text{pb}^{-1}$ of data collected by the D0 experiment at the Fermilab Tevatron in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, and with an expected background of $0.18 \pm 0.03 \pm 0.02$ events, we set limits on squark and gluino masses within the framework of the minimal low-energy supergravity-supersymmetry model.

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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. Such 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

$$\lambda_{ijk}L_iL_j\overline{E}_k + \lambda'_{ijk}L_iQ_j\overline{D}_k + \lambda''_{ijk}\overline{U}_i\overline{D}_j\overline{D}_k,$$

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 λ and λ'' 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 nonzero. Since measurements at low-energy provide upper bounds on most of these couplings, and are especially stringent for the couplings involving the first and second generation [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 (within $\sim$1 cm) the interaction vertex, which sets the scale for λ' at $\approx 10^{-3} - 10^{-2}$. A previous study at D0 [4] in the two-electron + four-jet channel, searched for such a decay for nonvanishing λ'_{1jk} and $k = 1, 2, 3$) couplings in the framework of the minimal low-energy supergravity supersymmetry model (mSUGRA) [5], with the neutralino, $\tilde{\chi}_1^0$ 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), all 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 (μ). For the following reasons, LSP decay to a charged lepton and two quark jets involving just one of the λ'_{ijk} couplings is a viable mode for searching for SUSY at the Tevatron. 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 for this decay depends on the composition of the LSP, which in turn depends on the mSUGRA parameters. Studies have shown that, at the energy of the Tevatron, the signal in lepton + jets decay channels of the LSP can be substantial for a large range of values of these parameters [6,7], and such events do not contain missing energy, thereby making it easier to search for a signal from RPV.

The CDF, LEP, and HERA experiments have searched for SUSY particles assuming R-parity violation in the minimal supersymmetric SM (MSSM [8]) and mSUGRA scenarios. CDF reported limits for masses of charm squark and the lightest neutralino, for λ'_{121}

coupling, in like-sign two-electron + multijet events. They excluded charm squarks with mass near 200 GeV/c^2, and gluinos with masses below 260 GeV/c^2 for heavy squarks [9]. Searches at LEP were performed for several λ_{ijk}, λ'_{ijk}, and λ''_{ijk} couplings and the best limits from on the lightest neutralino and chargino masses were set at $\sim$30 GeV/c^2 and $\sim$100 GeV/c^2, respectively. The best limits on slepton and stop/sbottom squark masses were $\sim$65 GeV/c^2 and $\sim$75 GeV/c^2, respectively [10]. The H1 experiment at HERA has searched for R-parity violating SUSY within the unconstrained MSSM, the constrained MSSM, and the mSUGRA model. A search, performed assuming a non-zero λ'_{1j1} coupling, excluded squarks with masses <260 GeV/c^2 at 95% confidence [11].

We report a study similar to our previous one [4], but involving muons, for finite λ'_{222} coupling (the study is equally valid for all the λ'_{2jk} couplings with $j = 1, 2$ and $k = 1, 2, 3$). The specific signature is of two or more energetic muons and four or more energetic jets. Several SM processes can mimic this signature, e.g., $\gamma^*/Z \to \mu\mu$, $Z \to \tau\tau \to \mu\mu$, $t\bar{t} \to \mu\mu$, $WW \to \mu\mu$, and accompanying jets.

The D0 detector has been described elsewhere [12]. The most important parts for this analysis involve the uranium/liquid-argon calorimeter and the muon system. A cone algorithm with a radius of 0.5 in η-ϕ space, where η is the pseudorapidity and ϕ is the azimuthal angle, is used for jet identification [13]. Muons are defined as tracks that leave minimum ionizing energy in the calorimeter, and are reconstructed in the muon system. An integrated luminosity of 77.5 ± 3.9 pb^{-1} collected with the D0 detector during the 1992–1996 Tevatron run at $\sqrt{s} = 1.8$ TeV is used in 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 $E_T > 15$ GeV. The muons and jets are required to satisfy standard D0 selection criteria [14,15]. The muons are also required to be isolated from jets by a distance > 0.5 in the η-ϕ plane (this rejects muons from heavy-flavor decays, pions decaying in flight, and pion-induced punch-throughs). In addition, several other criteria are imposed to minimize background. The aplanarity [15] of the jets in each event is required to be greater than 0.03, 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, and 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/ψ). The poor momentum resolution of the muon system prevents the use of tighter criteria on the invariant mass of the two muons, which could have reduced the background from Z events.

TABLE I. Summary of major backgrounds. The first error is statistical and the second error is systematic.

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

Of the original 230 688 events passing the trigger requirements, none survive the above selections. The expected backgrounds from the two main SM channels, $Z(\to \mu\mu)$ + jets and $t\bar{t}(\to \mu\mu)$ + jets, are shown in Table I, along with their statistical (first) and systematic (second) uncertainties. The contribution to background from Z production is estimated from a sample of 21 000 Z + jets events, generated using VECBOS [16]. A total of 254 000 $t\bar{t}$ events, generated with HERWIG [17], are used to estimate the contribution from this background. The contribution from intermediary γ^* processes is negligible because the produced dimuons have small invariant masses and the decay muons do not survive the p_T requirement. The D0 detector is simulated using a GEANT-based package [18], which provides efficiencies of the selection criteria for signal and background events. In Fig. 1, we illustrate the effect of the selection on the number of jets in an event for a typical signal point ($m_0 = 140$ GeV/c^2, $m_{1/2} = 90$ GeV/c^2, $A_0 = 0$, $\tan\beta = 2$, $\mu < 0$) and for the background channel $Z(\to \mu\mu)$ + jets. The arrow in Fig. 1 indicates the minimum number of

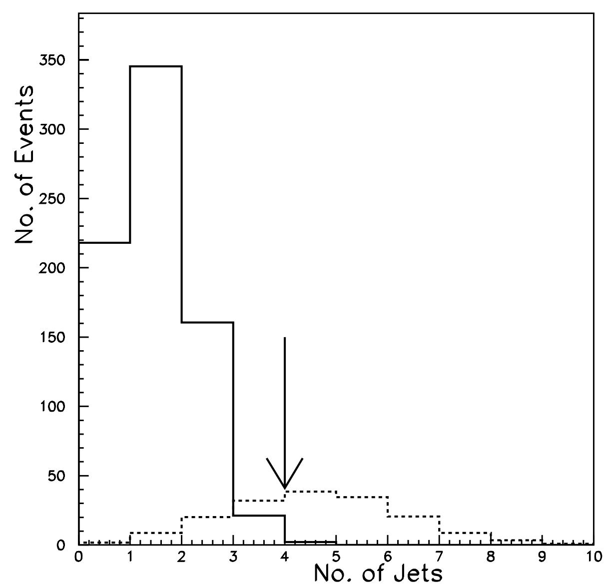

FIG. 1. Distribution in the number of jets per MC event at a typical signal point ($m_0 = 140$ GeV/c^2, $m_{1/2} = 90$ GeV/c^2) (dashed line) and for background from, $Z(\to \mu\mu)$ + jets (solid line), both normalized to 77.5 pb^{-1} integrated luminosity. The vertical arrow indicates the position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

jets required for accepted candidate events. No offline selections or trigger conditions other than the above jet requirement were applied to the Monte Carlo (MC) events in this figure. In order to check the modeling of the background, the selection criteria were relaxed one at a time and it was checked that the total number of events remaining in the background match the number in the data. These studies indicate that the modeling of background is indeed correct.

The instrumental background, which can come 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. Uncertainties in the jet energy scale and in the measured background cross sections contribute almost equally to the total systematic error. A smaller contribution comes from the uncertainty in luminosity. The error due to uncertainty in jet energy scale is estimated by varying the threshold in jet E_T by one standard deviation, and taking the resulting change in the number of accepted events as the systematic error.

Signal is studied at several points of the mSUGRA parameter space, with m_0 and $m_{1/2}$ ranging from 0 to 400 GeV$/c^2$ and 60 to 120 GeV$/c^2$, respectively. The other parameters are kept fixed at $A_0 = 0$, $\mu < 0$, and $\tan\beta = 2$ and 6. These events are generated with ISAJET [19], modified to incorporate R-parity violating decays based on the formalism of Ref. [6]. For each signal sample, the value of efficiency multiplied by the branching fraction of $p\overline{p} \rightarrow \geq$ two muons and $\geq$ four jets is estimated in the same way as for the SM background. Table II shows the branching fractions (B) (for $\tilde{\chi}_1^0 \rightarrow$ muon + jets), the product of efficiency and B, and the event yields expected for an integrated luminosity of 77.5 pb^{-1} for several points in the (m_0, $m_{1/2}$) parameter space.

Since the background expected from the SM is compatible with the absence of signal, we proceed to determine the region in mSUGRA space that can be excluded in this analysis. An upper limit on the cross section for

TABLE II. Branching fraction (B), efficiency (ϵ) multiplied by 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 (GeV$/c^2$)	$m_{1/2}$ (GeV$/c^2$)	B	$\epsilon B(\%)$	$\langle N \rangle$
0	100	0.75	$0.60 \pm 0.07^{+0.05}_{-0.03}$	3.0 ± 0.4
80	90	0.77	$0.74 \pm 0.08^{+0.06}_{-0.04}$	2.7 ± 0.3
80	110	0.72	$0.34 \pm 0.04^{+0.03}_{-0.03}$	0.6 ± 0.1
190	90	0.75	$0.78 \pm 0.06^{+0.05}_{-0.03}$	2.1 ± 0.2
260	70	0.78	$0.42 \pm 0.04^{+0.03}_{-0.02}$	2.7 ± 0.3
400	90	0.69	$0.31 \pm 0.04^{+0.02}_{-0.02}$	0.8 ± 0.1

signal at the 95% confidence level (C.L.) 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 is used for this purpose, with a flat prior for the cross section for signal and Gaussian priors for luminosity, efficiency, and expected background. Details on our method are given in Ref. [20]. 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. Figures 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 replaced by the sneutrino as the LSP. However, the sneutrino mass in this region is 39 GeV$/c^2$, which is already excluded by searches at LEP [21]. At small values of m_0, the exclusion contour in Fig. 2 follows essentially a contour of constant squark mass ($m_{\tilde{q}} \sim$ 260 GeV$/c^2$). 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 for these particles are approximately independent of m_0. The exclusion contour therefore becomes approximately independent of m_0 for $m_0 > 250$ GeV$/c^2$. The loss of sensitivity in the mass range $m_0 = 60$ to 80 GeV$/c^2$ occurs because, in this region, the sneutrino becomes lighter than the $\tilde{\chi}_2^0$. As a

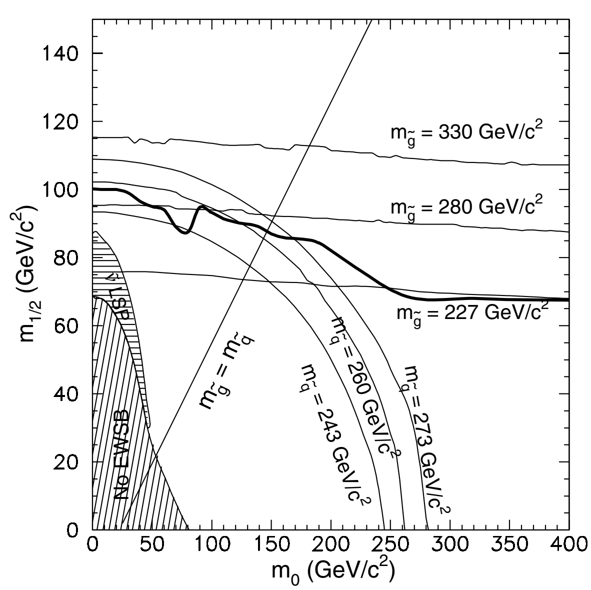

FIG. 2. Exclusion contour in the (m_0, $m_{1/2}$) plane for $\tan\beta = 2$, $\mu < 0$, $A_0 = 0$, and finite λ'_{2jk} ($j = 1, 2$; $k = 1, 2, 3$) coupling. The region below the bold line is excluded at the 95% C.L. The crosshatched region is excluded for theoretical reasons (see text). $m_{\tilde{q}}$ and $m_{\tilde{g}}$ denote squark and gluino masses, respectively.

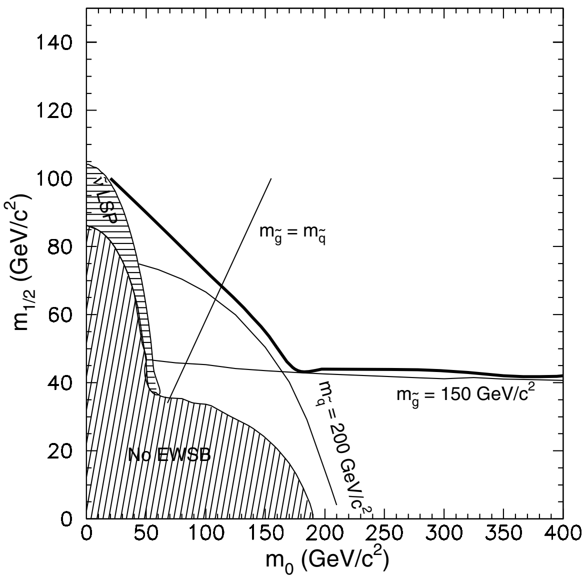

FIG. 3. Exclusion contour in the $(m_0, m_{1/2})$ plane for $\tan\beta = 6$, $\mu < 0$, $A_0 = 0$, and finite λ'_{2jk} ($j = 1, 2$; $k = 1, 2, 3$) coupling.

result, $\tilde{\chi}_2^0$ decays predominantly to $\tilde{\chi}_1^0$ and a neutrino (via the sneutrino) instead of decaying to muons. This reduces the number of high p_T muons in an event, and therefore the number of accepted events decreases.

The value of A_0 does not affect the results significantly, because its main impact is on the third-generation sparticle masses. Both for $\mu > 0$, and for higher values of $\tan\beta$ (see Fig. 3 for the exclusion contour for $\tan\beta = 6$), 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]. The errors on muon identification efficiencies at D0 are much larger than those on electrons. This results in larger errors on the quantity ϵB (in Table II), which reduces the sensitivity of the search.

In conclusion, we have performed the first search for R-parity violating 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. These limits are comparable to those achieved previously in complementary channels.

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