Search for *R*-Parity Violating Supersymmetry in the Dielectron Channel

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We report on a search for R-parity-violating supersymmetry in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the D0 detector at Fermilab. Events with at least two electrons and four or more jets were studied. We observe two events in 99 ± 4.4 pb^{-1} of data, consistent with the expected background of 1.8 ± 0.4 events. This result is interpreted within the framework of minimal low-energy supergravity supersymmetry models. Squarks with mass below 243 GeV$/c^2$ and gluinos with mass below 227 GeV$/c^2$ are excluded at the 95% C.L. for $A_0 = 0$, $\mu < 0$, $\tan\beta = 2$, and a finite value for any one of the six R-parity-violating couplings λ'_{1jk} ($j = 1$, 2 and $k = 1$, 2, 3).

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The standard model (SM) has survived many precision tests. However, it is thought incomplete, and supersymmetry (SUSY) [1] is considered an attractive extension to the SM because it protects the Higgs mass from large radiative corrections and can provide a dynamical means for breaking electroweak symmetry. SUSY predicts for each particle in the SM a partner with spin differing by half a unit. In its general form, the theory contains over 100 free parameters. For our comparison with data, we have therefore chosen the more tractable framework provided by minimal low-energy supergravity (mSUGRA) [2], which has only five free parameters: a common mass for scalars (m_0), a common mass for all gauginos ($m_{1/2}$), and a common trilinear coupling constant (A_0), all specified at the grand unification scale. The other two parameters are the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$) and the sign of the Higgsino mass parameter μ. The masses and couplings at the weak scale are obtained from these five parameters by solving a set of renormalization group equations.

Most of the searches for supersymmetric particles reported thus far have assumed the conservation of a multiplicative quantum number called R parity [3]. R parity 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 their SUSY partners. In SUSY, R-parity violation can occur quite naturally through the following Yukawa coupling terms in the superpotential:

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

where L and Q are the SU(2)-doublet lepton and quark superfields; E, U, and D are the singlet lepton, up and down type quark superfields, respectively; and i, j, and k are the generation indices. The Yukawa couplings are antisymmetric in the same superfield indices. Thus, there can be up to 45 new Yukawa terms. We have therefore made the following simplifying assumptions for our analysis.

(i) Among the 45 R-parity-violating couplings, only one dominates. This is motivated by the fact that the new couplings are similar to the SM Yukawa couplings, for which the top quark Yukawa term dominates. Moreover, bounds on products of two couplings are generally stringent, because the presence of more than one coupling can induce rare processes such as flavor changing neutral currents at the tree level [4].

(ii) The strength of the R-parity-violating coupling under consideration is $>10^{-3}$, so that the lightest supersymmetric particle (LSP) decays close to the interaction vertex. This is consistent with the existing upper bounds on the strength of the couplings from low-energy experiments [5].

(iii) The strength of the finite R-parity-violating coupling term is significantly smaller than the gauge couplings. Thus, supersymmetric particles are produced in pairs, and R-parity violation manifests itself only in the decay of the LSP.

Of the three kinds of Yukawa coupling terms, the B-violating λ'' are difficult to study at the Fermilab Tevatron as they lead to events with multiple jets that would be overwhelmed by large backgrounds from QCD production of jets. However, the L-violating λ and λ' couplings give rise to multilepton and multijet final states [6], which provide excellent signatures.

This Letter reports on an analysis of the dielectron and four jets channel, interpreted in the mSUGRA framework, with R-parity-violating decays of the LSP. In mSUGRA, the lightest neutralino is almost always the LSP except in a small region of the $(m_0, m_{1/2})$ plane where the sneutrino is the LSP (indicated in Fig. 1). But the mass of the sneutrino in that region is below 39 GeV$/c^2$ and, hence, excluded ($>$43.1 GeV$/c^2$ at 95% C.L.) [7] by the known invisible decay width of the Z boson, assuming that there are three degenerate left handed sneutrino species. We assume that all the R-parity-violating couplings are small except for one of the six λ'_{1jk} ($j = 1$, 2 and $k = 1$, 2, 3), so that each LSP decays into one electron and two quarks which gives rise to final states with two or more electrons and four or more jets that we consider in our analysis.

The D0 detector [8] has three major subsystems: a central tracker, a uranium liquid argon sampling calorimeter, and a muon spectrometer. Electrons are identified as narrow energy clusters that deposit more than 90% of their energy in the electromagnetic sections of the calorimeter. Jets are reconstructed using a cone algorithm [9] with radius 0.5 in pseudorapidity—azimuthal angle (η, ϕ) space. The data used for this analysis were collected during the 1994–1995 Fermilab Tevatron run at a center-of-mass energy of 1.8 TeV, and correspond to an integrated luminosity of 99 ± 4.4 pb^{-1} [10].

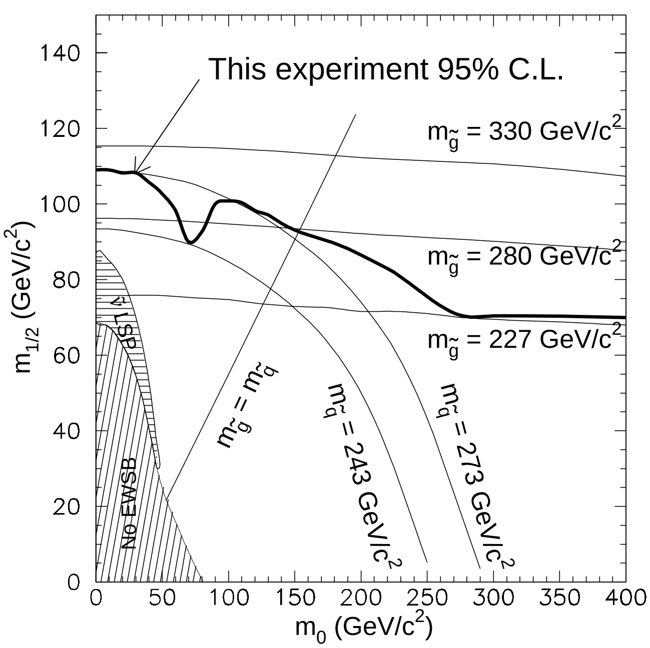

FIG. 1. Exclusion contour in the $(m_0, m_{1/2})$ plane for $A_0 = 0$, $\mu < 0$, $\tan\beta = 2$, and a finite λ'_{1jk} ($j = 1$, 2 and $k = 1$, 2, 3) coupling. The region below the bold line is excluded at the 95% C.L. The slanted hatched region is excluded for theoretical reasons. In the horizontally hatched region, the sneutrino is the LSP, but is excluded by searches at LEP (see the text).

Our initial sample of 163 140 events was collected with triggers requiring at least five calorimeter energy clusters, and $H_T \geq 115$ GeV, where H_T is the scalar sum of the transverse energies (E_T) of all calorimeter clusters. In the off-line analysis, we required at least two electrons, one with $E_T \geq 15$ GeV and the second with $E_T \geq 10$ GeV, and at least four jets with $E_T \geq 15$ GeV. Electrons had to be either within $|\eta| \leq 1.1$ (central calorimeter) or $1.5 \leq |\eta| \leq 2.5$ (forward calorimeters), to be isolated from other energy deposits, and to have shower shape and tracking information consistent with that expected for electrons [11,12]. Jets had to be within $|\eta| \leq 2.5$. The requirement on electrons reduced the original sample to just 38 events, and the subsequent requirements on jets reduced it further to six events. To suppress backgrounds from electron decays of Z bosons, we rejected events whose dielectron invariant mass was in the range of 76–106 GeV/c^2. To ensure high trigger efficiency, events were further required to have $H_T >$ 150 GeV. The cut on Z mass reduced our data sample to two events, but the H_T requirement had no further impact.

The major inherent SM backgrounds are from Drell-Yan production (DY), from the decay of $t\bar{t}$ to electrons, and from the decay of Z bosons to τ pairs that subsequently decay to electrons. Events arising from the misidentification of jets as electrons comprise the major source of instrumental background for this analysis. The huge reduction in our data sample from the requirement of having two isolated electrons reflects the fact that most of the events passing the trigger are due to QCD multijet production, and have no true isolated electrons.

A GEANT [13] based simulation of the D0 detector was used to estimate efficiencies of the kinematic cuts for noninstrumental backgrounds. Measured electron identification efficiencies were then folded in to calculate the net detection efficiency. Using $Z(\rightarrow ee)$ + jets data, we estimated single-electron identification efficiencies to be 0.68 ± 0.07 in the central calorimeter, and 0.60 ± 0.07 in the forward calorimeters. ISAJET [14] was used to generate DY events, with cross section increased by a factor of 1.7 to obtain agreement with the Z + multijet data in the mass region of the Z boson, yielding an expected 0.37 ± 0.14 (stat) ± 0.14 (syst) events. Top quark events were generated using the HERWIG [15] program. The measured cross section for $t\bar{t}$ production (5.9 ± 1.7 pb) [16] was used to estimate this contribution to background to be $0.07 \pm 0.02 \pm 0.02$ events. The production cross section of the Z boson multiplied by its leptonic branching fraction of (221 ± 11) pb [10] was used to estimate the background due to $Z(\rightarrow \tau\tau \rightarrow ee)$ to be $0.07 \pm 0.01 \pm 0.02$ events. The instrumental background was estimated from data in two steps. First, from multijet data, we estimated the probability for misidentifying a jet as an isolated electron. This was $(4.6 \pm 0.4) \times 10^{-4}$ in the central and $(1.4 \pm 0.2) \times 10^{-3}$ in the forward calorimeters. Within statistical accuracy, these probabilities were found to be independent of E_T. We then selected a multijet data sample passing the same kinematic requirements as our data sample, but requiring two additional jets instead of two electrons. The number of background events was estimated to be 1.27 ± 0.24 (with negligible statistical uncertainty) by applying the probability for jet misidentification to these multijet data. The statistical components of uncertainty include fluctuations due to the finite sample size of simulated events and uncertainties in electron identification efficiencies. The systematic components of the uncertainty include those due to jet energy scale and values of cross sections. Our two observed events are consistent with the expected background, both in the number of expected events $1.8 \pm 0.2 \pm 0.3$, and in their kinematic characteristics. In what follows, we interpret this null result in terms of an excluded region in mSUGRA parameter space.

Using ISAJET, we generated signal events at 125 points in the $(m_0, m_{1/2})$ plane, with $A_0 = 0$, $\mu < 0$, and $\tan\beta = 2$. R-parity-violating decays of the LSP are not available in ISAJET. The desired decay modes and branching fractions for the LSP were therefore added separately. The branching fraction of the LSP into a charged lepton or neutrino depends on the gauge composition of the LSP, which in turn depends on the mSUGRA parameters. This was incorporated into ISAJET using the calculation of Ref. [17]. Once we specify a decay mode, ISAJET does a three-body phase-space decay, but does not implement the appropriate matrix element into the differential distribution. The efficiency multiplied by the branching fraction for each signal sample was determined using a method similar to that used for the estimation of the SM background. The expected event yields in the $(m_0, m_{1/2})$ parameter space, corresponding to our integrated luminosity of 99 pb^{-1}, are given in Table I.

For each point in the $(m_0, m_{1/2})$ plane, we obtained a 95% C.L. upper limit on the cross section for signal. This was done using a Bayesian technique, with a flat prior for the signal cross section, and Gaussian priors for the luminosity, efficiency, and expected background. The excluded region in the $(m_0, m_{1/2})$ plane was then obtained by comparing the limits on the measured cross section with the leading-order SUSY prediction given by ISAJET. This is shown in Fig. 1. The slanted hatched area in

TABLE I. Efficiency (ϵ) multiplied by the branching fraction (B) and the expected event yield $\langle N \rangle$, for several points in the $(m_0, m_{1/2})$ parameter space. The uncertainties are the sum in quadrature of the statistical and systematic uncertainties (the statistical uncertainty dominates).

m_0 (GeV/c^2)	$m_{1/2}$ (GeV/c^2)	ϵB(%)	$\langle N \rangle$
0	120	1.59 ± 0.23	3.5 ± 0.5
50	110	1.49 ± 0.22	2.8 ± 0.4
120	110	1.86 ± 0.25	3.3 ± 0.4
190	100	1.56 ± 0.22	3.4 ± 0.4
280	90	0.95 ± 0.15	2.9 ± 0.4
320	90	0.71 ± 0.13	2.2 ± 0.4

Fig. 1 indicates the region in which the model does not produce radiative electroweak symmetry breaking. In the low m_0 region ($m_0 < 150\ \mathrm{GeV}/c^2$), the dominant SUSY process that contributes to the signal is pair production of squarks. Hence, in this region, the exclusion contour follows a squark mass contour ($m_{\tilde{q}} = 273\ \mathrm{GeV}/c^2$). The dip in the contour for $m_0 = 60$–$80\ \mathrm{GeV}/c^2$ can be attributed to the fact that the two electrons can originate either from the decay of LSPs or from other SUSY particles. In about 60% of the cases, both LSPs decay into electrons. However, electrons arising from the decay of LSPs may not always pass the E_T cut. In such cases additional electrons arising from the decay of the second lightest neutralino ($\tilde{\chi}_2^0$) can make the event pass the E_T criterion. But for $m_0 = 60$–$80\ \mathrm{GeV}/c^2$, sneutrinos become lighter than the $\tilde{\chi}_2^0$, and the decay of $\tilde{\chi}_2^0$ to $\tilde{\chi}_1^0$ and neutrinos ($\tilde{\chi}_2^0 \to \nu\tilde{\nu}; \tilde{\nu} \to \tilde{\chi}_1^0\nu$) becomes dominant. This reduces the overall branching fraction to dielectrons, resulting in the observed dip.

As m_0 increases, the sneutrino becomes heavier than $\tilde{\chi}_2^0$, and consequently the branching fraction of $\tilde{\chi}_2^0$ to neutrinos decreases, leading to an increase in the rate for the competing selectron channel, thereby enhancing the branching into the dielectron mode. (That is, when the $\tilde{\chi}_2^0$ decay proceeds through a virtual sneutrino, the decay through a virtual selectron becomes competitive.) The exclusion contour therefore moves up and again follows the 273 GeV/c^2 squark mass curve until the intermediate m_0 region ($150\ \mathrm{GeV}/c^2 < m_0 < 280\ \mathrm{GeV}/c^2$), where processes such as the production of gluinos, $\tilde{\chi}_1^{\pm}$, and $\tilde{\chi}_2^0$, start becoming important. The masses of these particles, as well as their production cross sections, do not change much with the increase of m_0. As a result, the exclusion contour in this region becomes less dependent on m_0.

Finally, in the asymptotic region ($m_0 > 280\ \mathrm{GeV}/c^2$), production of squarks becomes insignificant, and the contour of exclusion becomes totally independent on m_0. In Fig. 1, we have overlaid contours of fixed gluino mass and the average of the masses of the first two generations of squarks. Squarks with mass below 243 GeV/c^2 and gluinos below 227 GeV/c^2 are excluded for $A_0 = 0$, $\mu < 0$, $\tan\beta = 2$, and a finite value ($>10^{-3}$) for any one of the six λ'_{1jk} ($j = 1, 2$ and $k = 1, 2, 3$) couplings. For equal mass squarks and gluinos, the corresponding limit is 277 GeV/c^2.

We note that our results are essentially independent of the choice of A_0, as it affects only third generation sparticle masses. For $\mu > 0$ and higher values of $\tan\beta$, the sensitivity of our search is expected to fall for two reasons: (1) the photino component of the LSP decreases, resulting in the decrease of the branching fraction of the LSP into electrons; and (2) the charginos and neutralinos become light, resulting in events with softer electrons and jets that fail the kinematic requirements. We have estimated the sensitivity of our search for larger values of $\tan\beta$, by extrapolating our $\tan\beta = 2$ results using smeared parton level ISAJET [12] (without full detector simulation). Figure 2 shows the region excluded at 95% C.L. in the $(m_0, m_{1/2})$ plane for $A_0 = 0$, $\mu < 0$, $\tan\beta = 6$, and a value $>10^{-3}$ for any one of the six λ'_{1jk} ($j = 1, 2$ and $k = 1, 2, 3$) couplings. For higher values of $\tan\beta$, the sensitivity of this search deteriorates rapidly and requires a different analysis.

In conclusion, we have searched for events containing at least two electrons and four or more jets. Such events would be characteristic of processes involving the pair production of SUSY particles with the decay of the LSP through a R-parity-violating coupling. Finding no excess of events beyond the prediction of the standard model, we interpret this result within the mSUGRA framework as an excluded region in the $(m_0, m_{1/2})$ plane for fixed values of A_0 and sign of μ and for several values of $\tan\beta$. This is the first result reported from Tevatron on a search for R-parity-violating SUSY involving several λ' couplings in the mSUGRA framework. The Tevatron will continue to provide unique opportunities for searching for R-parity-violating SUSY in a larger range of parameter space with the improved data anticipated from the next run [12].

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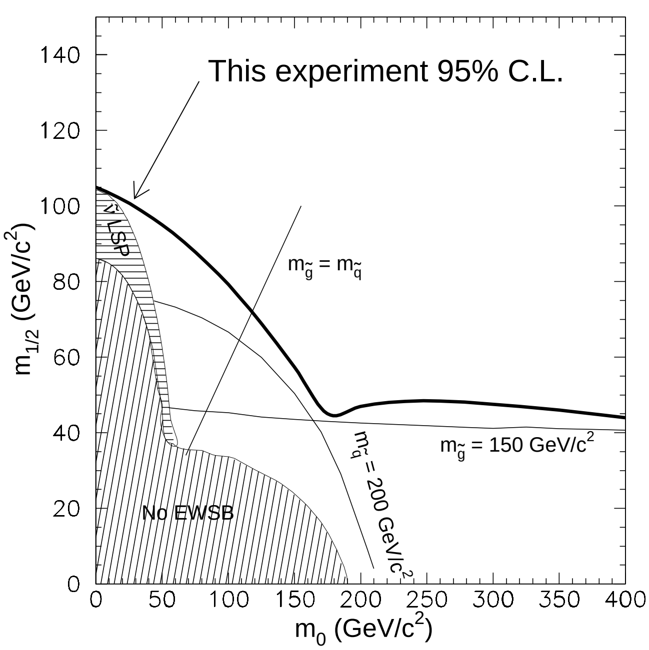

FIG. 2. Exclusion contour in the $(m_0, m_{1/2})$ plane for $A_0 = 0$, $\mu < 0$, $\tan\beta = 6$, and a finite λ'_{1jk} ($j = 1, 2$ and $k = 1, 2, 3$) coupling.

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