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# Search for $R$ -parity Violating Supersymmetry in the Dielectron Channel

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## Abstract

We report on a search for  $R$ -parity violating supersymmetry in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV using the DØ detector at Fermilab. Events with at least two electrons and four or more jets were studied. We observe 2 events in  $99 \pm 4.4$  pb<sup>-1</sup> of data, consistent with the expected background of  $1.8 \pm 0.4$  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  $227 \text{ GeV}/c^2$  are excluded at the 95% confidence level (C. L.) for  $A_0 = 0$ ,  $\mu < 0$ ,  $\tan \beta = 2$  and a finite value for  $R$ -parity violating Yukawa coupling  $\lambda'_{1jk}$  ( $j = 1, 2$  and  $k = 1, 2, 3$ ). For equal squark and gluino masses, the corresponding mass limit is  $277 \text{ GeV}/c^2$ .

The standard model (SM) of particle physics has survived many precision tests. However, it is thought incomplete, and supersymmetry [1] is considered to be 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. Supersymmetric extensions of the SM predict partners for all SM particles, with spins differing by half a unit. The simplest extension, the minimal supersymmetric standard model (MSSM), has over one hundred free parameters. We have therefore chosen the more constrained minimal low-energy supergravity (mSUGRA) [2] framework for our comparison with data. mSUGRA has only five free parameters specified at the unification scale: a common mass for scalar fermion partners ( $m_0$ ), a common mass for all gauginos ( $m_{1/2}$ ), the ratio of the vacuum expectation values of the two Higgs doublets ( $\tan \beta$ ), a common trilinear coupling constant ( $A_0$ ), and the sign of the Higgsino mass parameter ( $\mu$ ). 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 supersymmetric partners. In supersymmetry,  $R$ -parity violation can occur quite naturally through the following Yukawa coupling terms in the superpotential:

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

where  $L$  and  $Q$  are the  $SU(2)$ -doublet lepton and quark superfields;  $E$ ,  $U$ , and  $D$  are the singlet lepton, up 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.

- Among the 45  $R$ -parity violating coupling terms, only one dominates. This assumption is motivated by the fact that the new couplings are similar to the SM Yukawa couplings, where the top quark Yukawa term dominates. Moreover, when more than two couplings are finite, they often induce rare processes, like flavor changing neutral currents at the tree level, therefore bounds on the products of two couplings are generally very stringent [4].
- The  $R$ -parity violating coupling under consideration is strong enough so that the lightest supersymmetric particle (LSP) decays within the detector. If the strength of the coupling is  $> 10^{-3}$ , the LSP decays close to the interaction vertex. This requirement is consistent with the existing upper bounds on the strength of the couplings obtained from low energy experiments [5].

- 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  $\lambda''$  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  $\lambda$  and  $\lambda'$  type couplings give rise to multilepton and associated multijet final states [6], which provide excellent signatures at the Tevatron.

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 the mSUGRA framework, 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  $39 \text{ GeV}/c^2$  and, hence, excluded ( $> 43.1 \text{ GeV}/c^2$  at 95% C. L.) [7] by the measurement of the invisible decay width of the  $Z$  boson, assuming that there are three degenerate left handed sneutrino species. We assume that all of the  $R$ -parity violating couplings are small except  $\lambda'_{1jk}$  ( $j = 1, 2$  and  $k = 1, 2, 3$ ), so that each LSP that decays into one electron and two quarks, gives rise to final states with two or more electrons and four or more jets, that we consider in our analysis.

The DØ detector [8] has three major subsystems: a central tracker, a hermetic 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  $(\eta, \phi)$  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  $99 \pm 4.4 \text{ pb}^{-1}$  [10].

After studying the effect of different cuts on signal (Monte Carlo) and on background (data as well as Monte Carlo based), we have chosen the following set of trigger and kinematic requirements to reduce background while keeping a high efficiency for signal. Events for this analysis were collected with triggers requiring at least five calorimeter energy clusters, each with a radius of 0.3 in  $(\eta, \phi)$  space,  $E_T > 10 \text{ GeV}$ , confined to  $|\eta| \leq 2.5$ , and having  $H_T \geq 115 \text{ GeV}$ , where  $H_T$  is defined as the scalar sum of the transverse energies of all calorimeter energy clusters within  $|\eta| \leq 2.0$ . In the offline analysis, events were further required to have at least two electrons, one with  $E_T \geq 15 \text{ GeV}$  and the second with  $E_T \geq 10 \text{ GeV}$ , and at least four jets with  $E_T \geq 15 \text{ GeV}$ . Electrons were required 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. Jets were required to be within  $|\eta| \leq 2.5$ . To suppress backgrounds from electron decays of  $Z$  bosons, we rejected events whose dielectron invariant mass was in the range of 76–106  $\text{GeV}/c^2$ . To ensure high trigger efficiency, events were further required to have  $H_T > 150 \text{ GeV}$ . Two events survived all requirements. Table I shows the cumulative effect of the cuts on the data. The huge reduction in the number of events caused by the requirement of 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.

The major inherent SM backgrounds are from Drell-Yan production (DY), from the

TABLE I. Cumulative effect of the analysis cuts on the data sample.

Cut	No. of events
Passed trigger requirement	163140
At least 2 electrons	38
At least 4 jets	6
Invariant mass cut ( $ m_{ee} - m_Z  > 15 \text{ GeV}/c^2$ )	2
$H_T$ cut ( $H_T > 150$ )	2

decay of  $t\bar{t}$  to electrons, and from the decay of  $Z$  bosons to pairs of taus that subsequently decay to electrons. Events arising from the misidentification of jets as electrons comprise the major source of instrumental background for this analysis.

A GEANT [11] based simulation of the DØ detector was used to estimate the efficiencies of the kinematic cuts for non-instrumental backgrounds. Measured electron identification efficiencies were then folded in to calculate the net detection efficiency. Using  $Z(\rightarrow ee) + \text{jets}$  data, we estimated electron identification efficiencies to be  $0.68 \pm 0.07$  in the central calorimeter and  $0.60 \pm 0.07$  in the forward calorimeters. ISAJET [12] was used to generate DY events. The DY cross section given by ISAJET was normalized by comparing Monte Carlo events with  $Z + \text{multijet}$  data in the  $Z$  boson mass region. Top quark events were generated using the HERWIG [13] program. The DØ measured cross section for top quark pair production ( $5.9 \pm 1.7 \text{ pb}$ ) [14] was used to estimate the number of background events due to top quark pair production. The DØ measurement of the production cross section of the  $Z$  boson multiplied by its leptonic branching fraction of  $(221 \pm 11) \text{ pb}$  [10] was used to estimate the background due to  $Z(\rightarrow \tau\tau \rightarrow ee)$ . The instrumental background was estimated from data in two steps. First, from multijet data, we estimated, the probability of misidentification of a jet as an isolated electron in various fiducial regions of the detector. The probability for a jet to mimic an electron was estimated to be  $(4.56 \pm 0.37) \times 10^{-4}$  in the central calorimeter and  $(1.38 \pm 0.22) \times 10^{-3}$  in the forward calorimeters. These probabilities were found to be independent of the jet  $E_T$ . 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 by applying the probability for jet misidentification to these multijet data.

Table II summarizes the background contributions with their statistical and systematic uncertainties. The statistical component of the uncertainty includes the uncertainty due to the finite sample size of simulated events and the uncertainties in the electron identification efficiencies. The systematic component of the uncertainty includes uncertainties due to jet energy scale and values of cross sections.

The expected background is  $1.8 \pm 0.2 \pm 0.3$  events, consistent with the number of events observed in the data. 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  $\tan \beta = 2$ . (These are the values used by most of the current SUSY searches at the DØ and CDF experiments.)  $R$ -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

TABLE II. Summary of backgrounds. The first uncertainty is statistical and the second is systematic. The statistical uncertainty is negligible for instrumental background.

Background Processes	Expected events in 99 pb <sup>-1</sup>
DY $\rightarrow ee$	0.37 $\pm$ 0.14 $\pm$ 0.14
Z $\rightarrow \tau\tau \rightarrow ee$	0.07 $\pm$ 0.01 $\pm$ 0.02
$t\bar{t} \rightarrow ll \rightarrow ee$	0.07 $\pm$ 0.02 $\pm$ 0.02
Instrumental	1.27 $\pm$ 0.24
Total	1.8 $\pm$ 0.2 $\pm$ 0.3

TABLE III. Efficiency ( $\epsilon$ ) 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/ $c^2$ )	$\epsilon B(\%)$	$\langle N \rangle$
0	120	1.59 $\pm$ 0.23	3.5 $\pm$ 0.5
50	110	1.49 $\pm$ 0.22	2.8 $\pm$ 0.4
120	110	1.86 $\pm$ 0.25	3.3 $\pm$ 0.4
190	100	1.56 $\pm$ 0.22	3.4 $\pm$ 0.4
280	90	0.95 $\pm$ 0.15	2.9 $\pm$ 0.4
320	90	0.71 $\pm$ 0.13	2.2 $\pm$ 0.4

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 in Ref. [15]. 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 an integrated luminosity of 99 pb<sup>-1</sup>, are given in Table III.

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 Fig. 1 indicates the region in which the model does not produce radiative electroweak symmetry breaking. To understand the characteristics of the exclusion contour, it is convenient to divide the  $(m_0, m_{1/2})$  plane into three regions: the low  $m_0$  region ( $m_0 < 150$  GeV/ $c^2$ ), the intermediate  $m_0$  region ( $150$  GeV/ $c^2 < m_0 < 280$  GeV/ $c^2$ ), and the asymptotic region ( $m_0 > 280$  GeV/ $c^2$ ).

In the low  $m_0$  region, the dominant SUSY process that contributes to the signal is pair production of squarks. As we move toward higher  $m_0$  values, the corresponding squark mass also increases, thereby reducing the squark pair production cross section. Hence, in this region, the exclusion contour is expected to follow a squark mass contour. This is



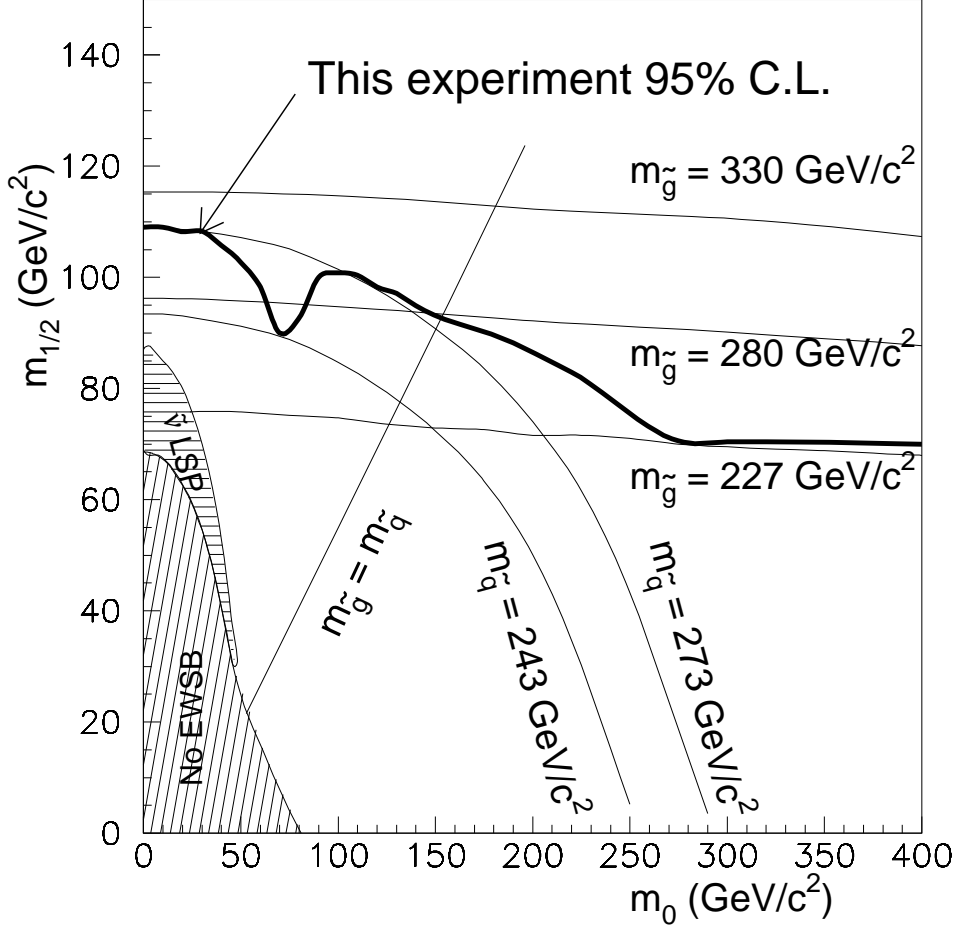


FIG. 1. Exclusion contour in the  $(m_0, m_{1/2})$  plane for  $A_0 = 0$ ,  $\mu < 0$ ,  $\tan \beta = 2$  and a finite  $\lambda'_{1jk}$  ( $j = 1, 2$  and  $k = 1, 2, 3$ ) coupling. The region below the bold line is excluded at the 95% C.L. The slanted hatched region is excluded for theoretical reasons.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

demonstrated in Fig. 1, where the exclusion contour closely follows the curve for which the mass of the squark is  $273 \text{ GeV}/c^2$ . The dip in the contour for  $m_0 = 60 - 80 \text{ GeV}/c^2$  can be attributed to the fact that the two electrons can originate either from the decay of LSPs or from any other SUSY particles. In about 60% of the cases, both LSPs decay into electrons. Moreover, electrons arising from the decay of LSPs do not always pass the  $E_T$  cut. In such cases, however, 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  $m_0 = 60 - 80 \text{ GeV}/c^2$ , sneutrinos become lighter than the  $\tilde{\chi}_2^0$ , and the decay of  $\tilde{\chi}_2^0$  to  $\tilde{\chi}_1^0$  and neutrinos ( $\tilde{\chi}_2^0 \rightarrow \nu\tilde{\nu}$ ;  $\tilde{\nu} \rightarrow \tilde{\chi}_1^0\nu$ ) 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  $\text{GeV}/c^2$  squark mass curve until about  $m_0 = 150 \text{ GeV}/c^2$ .

In the intermediate  $m_0$  region, 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 deviates from the constant squark mass contour, becoming flatter in  $m_0$ .

Finally, in the asymptotic region, production of squarks becomes insignificant, and the contour of exclusion becomes completely flat. 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  $\text{GeV}/c^2$  and gluinos below 227  $\text{GeV}/c^2$  are excluded for  $A_0 = 0$ ,  $\mu < 0$ ,  $\tan \beta = 2$ , and a finite value ( $> 10^{-3}$ ) of  $\lambda'_{1jk}$  ( $j=1, 2$  and  $k=1, 2, 3$ ) coupling. For equal mass squarks and gluinos, the corresponding limit is 277  $\text{GeV}/c^2$ .

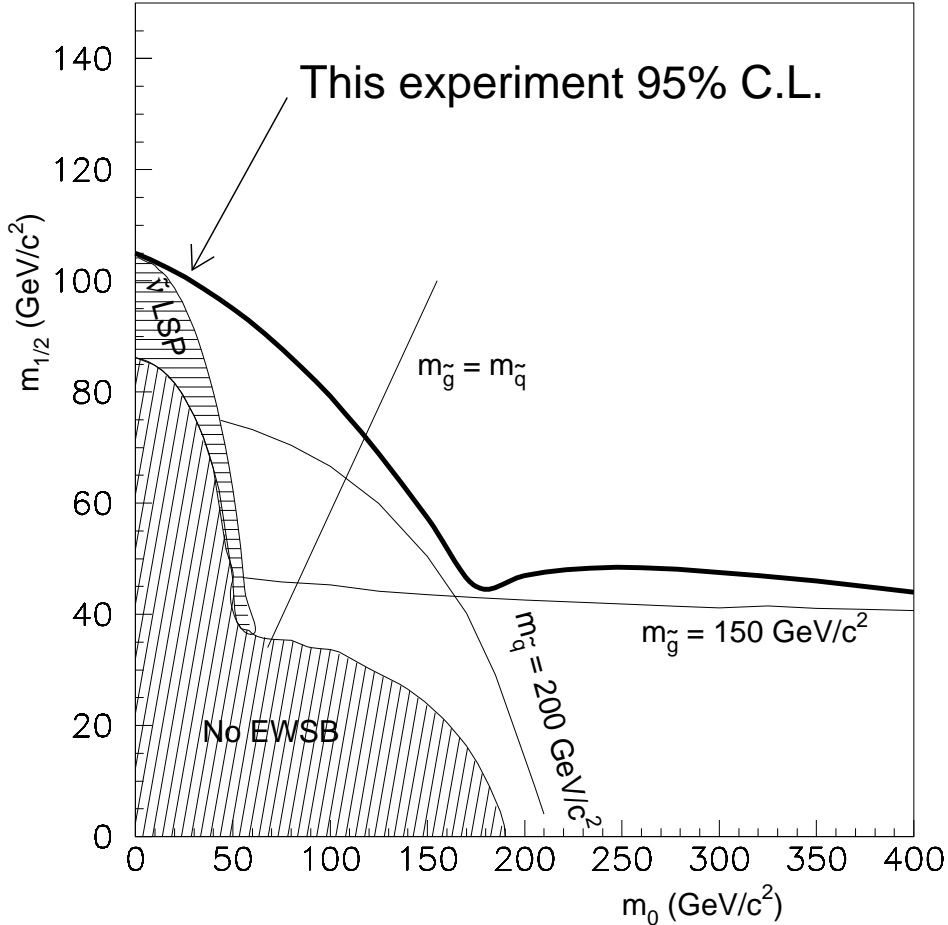


FIG. 2. Exclusion contour in the  $(m_0, m_{1/2})$  plane for  $A_0 = 0$ ,  $\mu < 0$ ,  $\tan \beta = 6$ , and a finite  $\lambda'_{1jk}$  ( $j=1, 2$  and  $k=1, 2, 3$ ) coupling.

We note that our results are mostly independent of the choice  $A_0$ , 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 due to two reasons: 1) the photino component of the LSP decreases, resulting in the decrease of the branching fraction of the LSP into electrons; 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 [16] (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 finite value ( $> 10^{-3}$ ) of  $\lambda'_{1jk}$  ( $j=1, 2$  and  $k=1, 2, 3$ ) coupling.

For even higher values of  $\tan \beta$  the sensitivity of this search with the present set of requirements becomes very poor. For these choices of parameters, it may be necessary to reduce the requirement on the number of electrons, and impose a requirement on  $\cancel{E}_T$ , to gain better sensitivity.

In conclusion, we have searched for events containing at least two electrons and four or more jets. Finding no excess of events beyond the prediction of the standard model, we interpret the result within the mSUGRA framework as an excluded region in the  $(m_0, m_{1/2})$  plane for fixed values of  $A_0$  and  $\mu$  and for several values of  $\tan \beta$  in a model with  $R$ -parity violating decay of the LSP.

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