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Search for *R*-Parity Violating Supersymmetry Using Like-Sign Dielectrons in $p\bar{p}$ Collisions at √s = 1.8 TeV

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We present a search for like-sign dielectron plus multijet events using 107 pb^{-1} of data in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected in 1992–1995 by the CDF experiment. Finding no events that pass our selection, we set $\sigma \times \mathrm{BR}$ limits on two supersymmetric processes that can produce this experimental signature: gluino-gluino or squark-antisquark production with R-parity violating decays of the charm squark or lightest neutralino via a nonzero λ'_{121} coupling. We compare our results to the next-to-leading order calculations for gluino and squark production cross sections and set lower limits on $M(\tilde{g})$, $M(\tilde{t}_1)$, and $M(\tilde{q})$.

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The minimal supersymmetric standard model (MSSM) [1] is an extension of the standard model (SM) that adds a supersymmetric (SUSY) partner for each SM particle and is constructed to conserve baryon number (B) and

lepton number (L). The requirement of R-parity (R_p) [2] conservation is imposed on the couplings: for a particle of spin S, the multiplicative quantum number $R_p \equiv (-1)^{3B+L+2S}$ distinguishes SM particles ($R_p = +1$) from SUSY particles ($R_p = -1$). If R_p is conserved, SUSY particles can be produced only in pairs and the lightest supersymmetric particle (LSP) is stable. The assumption of R_p conservation thus leads to experimental signatures with appreciable missing transverse energy ($\not{E}_T$), provided that the LSP is electrically neutral and colorless [3]. R_p conservation, however, is not required by SUSY theories in general and viable R_p violating ($\not{R}_p$) models can be built by adding explicitly B *or* L violating couplings to the SUSY Lagrangian [4]. Since the LSP can be unstable in this case, the standard $\not{E}_T$ signature is diluted.

The results at high Q^2 from the DESY ep Collider (HERA) [5] have sparked interest in $\not{R}_p$ SUSY, since the excess of events observed at high Q^2 could be explained by the production and decay of a single squark: $e^+ + d \rightarrow \tilde{q} \rightarrow e^+ + d$, where R_p is violated at both vertices [6–9]. In this scenario, $\tilde{c}_L$ (the SUSY partner of the left-handed charm quark) with mass $M(\tilde{c}_L) \simeq 200\ \mathrm{GeV}/c^2$ is the preferred squark flavor because its associated $\not{R}_p$ Yukawa coupling λ'_{121} is less constrained by experiment than the other couplings [10]. Another possibility to explain the excess is the production and decay of a first-generation leptoquark; D0 and CDF have ruled out this explanation [11].

In this Letter, we examine two $\not{R}_p$ processes in an MSSM framework that involve the same λ'_{121} coupling: (1) $p\overline{p} \rightarrow \tilde{g}\tilde{g} \rightarrow (c\tilde{c}_L)(c\tilde{c}_L) \rightarrow c(e^{\pm}d)c(e^{\pm}d)$ "charm squark analysis"; and (2) $p\overline{p} \rightarrow \tilde{q}\overline{\tilde{q}} \rightarrow (q\tilde{\chi}_1^0)(\overline{q}\tilde{\chi}_1^0) \rightarrow q(dce^{\pm})\overline{q}(dce^{\pm})$ "neutralino analysis." For process (1) we assume $M(\tilde{q}) > M(\tilde{g}) > M(\tilde{c}_L) = 200\ \mathrm{GeV}/c^2$, where $M(\tilde{q})$ denotes the degenerate mass for all up-type (except for $\tilde{c}_L$) and all right-handed down-type squarks. The masses of the left-handed down-type squarks are calculated using the relations given in Ref. [6]. These assumptions are motivated by the HERA results. Process (2) is a complementary search also based on $\lambda'_{121} \neq 0$. It is favored if the size of the $\not{R}_p$ coupling is small compared to the SM gauge couplings. We separately consider $\tilde{q}\overline{\tilde{q}}$ production (five degenerate squark flavors) and $\tilde{t}_1\overline{\tilde{t}}_1$ production, and make the mass assumptions: $M(\tilde{\chi}_1^{\pm}), M(\tilde{\chi}_2^0) > M(\tilde{q}) > M(\tilde{\chi}_1^0)$, where $\tilde{q}$ refers here to either the degenerate squark or $\tilde{t}_1$, and $M(\tilde{\chi}_1^{\pm}) \approx 2M(\tilde{\chi}_1^0)$. The first relation suppresses $\tilde{q} \rightarrow \tilde{\chi}_1^{\pm} + X$ and the second approximation is generally true for most combinations of SUSY parameters, particularly when assumptions leading to gaugino mass unification are made. For the case of $\tilde{t}_1\overline{\tilde{t}}_1$ production, we further assume $M(\tilde{\chi}_1^{\pm}) > M(\tilde{t}_1) - M(b)$ to ensure that $B(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = 100\%$ for the relevant case: $M(\tilde{t}_1) < M(t)$. For these two searches, we make the conservative and simplifying assumption that there is only one nonzero $\not{R}_p$ coupling. Given the Majorana nature of the gluino and neutralino, reactions (1) and (2) each yield like-sign (LS) and opposite-sign (OS) dielectrons with equal probability. Since LS dilepton events have the benefit of small SM backgrounds, we search for events with LS dielectrons and two or more jets.

We present results of a search for $p\overline{p} \rightarrow e^{\pm}e^{\pm} + \geq 2$ jet events using 107 pb^{-1} of data from $p\overline{p}$ collisions at a center of mass energy of $\sqrt{s} = 1.8$ TeV. The data were collected by the Collider Detector at Fermilab (CDF) [12] during the 1992–1993 and 1994–1995 runs of the Fermilab Tevatron. At CDF the location of the $p\overline{p}$ collision event vertex (z_{vertex}) is measured along the beam direction with a time projection chamber. The transverse momenta (p_T) of charged particles are measured in the pseudorapidity region $|\eta| < 1.1$ with a drift chamber, which is located in a 1.4 T solenoidal magnetic field. Here $p_T \equiv p\sin\theta$ and $\eta \equiv -\ln\tan(\theta/2)$, where θ is the polar angle with respect to the proton beam direction. The electromagnetic (EM) and hadronic calorimeters are segmented in a projective tower geometry surrounding the solenoid and cover the central ($|\eta| < 1.1$) and plug ($1.1 < |\eta| < 2.4$) regions. A gas proportional chamber located at shower maximum in the central EM calorimeter provides shower position and profile measurements in both the z and $r - \phi$ directions.

Dielectron plus multijet candidates are selected from events that pass the central electron triggers with $E_T(e) >$ 9.2 GeV in the 1992–1993 run, while for the 1994–1995 run there are two such triggers, with thresholds of 8 and 16 GeV. The 8 GeV trigger imposes additional requirements on the development of the EM shower. In our analysis, we require two electrons with $E_T > 15$ GeV. Each electron candidate must exhibit a lateral shower profile consistent with that which is expected for electrons, be well matched to a track [13] with $p_T \geq E_T/2$, and pass a sliding cut on the ratio of energy in the hadronic calorimeter to the energy in the EM calorimeter (hadronic energy fraction) [14]. At least one electron candidate must also pass more stringent identification requirements on its shower profile and hadronic energy fraction [15]. Each electron must pass an isolation cut in which the total calorimeter E_T in an $\eta - \phi$ cone of radius $R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the electron, excluding the electron E_T, is less than 4 GeV. This helps to remove the background from $b\overline{b}$ and $c\overline{c}$ production ($b\overline{b}/c\overline{c}$) while retaining much of the sensitivity to the SUSY signal. The $\eta - \phi$ distance $\Delta R_{ee} \equiv \sqrt{(\Delta\phi_{ee})^2 + (\Delta\eta_{ee})^2}$ between the two electrons must be greater than 0.4 to avoid shower overlap in the calorimeter. The event $|z_{\mathrm{vertex}}|$ must be less than 60 cm to restrict the analysis to the region of the detector that retains the projective nature of the calorimeter towers, and both electrons must be consistent with originating from the same vertex. Jets are identified in the calorimeter using a fixed cone clustering algorithm [16] with cone size $R = 0.7$. We require at least two jets with $E_T > 15$ GeV and $|\eta_j| < 2.4$, separated by $\Delta R_{jj} > 0.7$, and $\Delta R_{ej} > 0.7$. Finally, there must be no significant $\not{E}_T$ in the event: $\not{E}_T/\sqrt{\sum E_T} < 5\ \mathrm{GeV}^{1/2}$, where $\sum E_T$ is the scalar sum of transverse energy in the calorimeter for

the two electrons and two leading jets. These selection requirements are effective in removing the $b\bar{b}/c\bar{c}$ and $t\bar{t}$ backgrounds while retaining the signal. No LS candidate events survive this selection, while 165 OS events are retained.

We calculate the event acceptance using Monte Carlo samples generated with ISAJET 7.20 [17], CTEQ3L parton distribution functions [18], and passed through the CDF detector simulation program. For the charm squark analysis, we examine four values of the gluino mass: 210, 250, 300, and 400 GeV$/c^2$ while the charm squark mass, $M(\tilde{c}_L)$, is fixed at 200 GeV$/c^2$. For the neutralino analysis, we create Monte Carlo samples with $M(\tilde{q})$ in the range 100–350 GeV$/c^2$. For each $M(\tilde{q})$, we generate samples for two extremes of the neutralino mass: $M(\tilde{\chi}_1^0) = M(\tilde{q})/2$, which corresponds to $M(\tilde{\chi}_1^{\pm}) \simeq M(\tilde{q})$, and $M(\tilde{\chi}_1^0) = M(\tilde{q}) - M(q)$, the kinematic limit for the decay.

The dominant SM backgrounds for this search are $t\bar{t}$ and $b\bar{b}/c\bar{c}$ production, where both can give rise to LS ee events. We use ISAJET 7.20 [17] Monte Carlo samples to estimate the sizes of these backgrounds. For $t\bar{t}$ production and decay, we analyze 25 K events (corresponding to $\int \mathcal{L}\, dt = 3.3$ fb^{-1}) with $M(t) = 175$ GeV$/c^2$ and $\sigma_{t\bar{t}} = 7.6$ pb [19] and find zero accepted LS ee events. Top dilepton events typically have appreciable $\not{E}_T$ and are rejected by the $\not{E}_T$ significance cut. We study Monte Carlo samples of $b\bar{b}/c\bar{c}$ events for two different processes: direct production and final state gluon splitting, and expect a contribution of 0.3 ± 0.3 LS events from this source in 107 pb^{-1}. The isolation cut on the electrons is efficient in removing this background as semileptonic b quark decays yield poorly isolated leptons. The total expected background is therefore consistent with zero events, so we forego background subtraction in setting limits. The remaining 165 OS events are consistent with the expected contribution of 153.0 ± 14.5 events from SM backgrounds. Drell-Yan production of dielectron pairs accounts for 150.1 ± 14.1 of these events, where we analyze Drell-Yan samples generated with $p_T(Z^0/\gamma^*) > 5$ GeV$/c$ [20] and normalize this production to CDF data [21] before applying the two jet requirement. There is also good agreement in the $\sum E_T$ distributions for the remaining OS events and for the expected OS background (Fig. 1).

The sources of systematic uncertainty on the kinematic acceptances for these analyses include initial and final state gluon radiation (4% for the charm squark analysis, 4%–14% for the neutralino analysis), uncertainty on the integrated luminosity (7%), electron identification (3%), structure functions (3%), Monte Carlo statistics (1%–5%), jet energy scale (1%), and uncertainty on the trigger efficiency (1%). The total systematic uncertainty on the kinematic acceptance is 10% for the charm squark analysis, while for the neutralino analysis it ranges from 10% to 16%.

We set limits on the cross section times branching ratio for the two processes under study. In each case we exclude $\sigma \times \mathrm{BR} \geq N_{95\%}/(A\epsilon_{\mathrm{trig}} \int \mathcal{L}\, dt)$, where $N_{95\%}$ is the Poisson 95% confidence level (C.L.) upper limit for observing zero events combined with a Gaussian distribution for the systematic uncertainty and BR is the branching ratio. For both analyses, $N_{95\%} = 3.1$ events. The acceptance, A, is the product of the kinematic and geometric acceptance and the efficiency of identifying two electrons and two jets, and ϵ_{trig} is the trigger efficiency for dielectrons. The integrated luminosity is $\int \mathcal{L}\, dt = 107 \pm 7$ pb^{-1}.

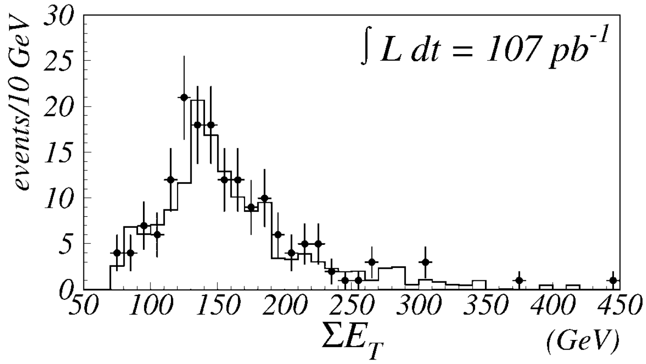

FIG. 1. Scalar sum of transverse energy for the two electrons and two leading jets for the remaining 165 OS events after all selection (points) and expected background from SM processes (histogram). These events are dominated by Drell-Yan e^+e^- pairs plus two or more jets.

For the charm squark analysis, A is a very weak function of $M(\tilde{g})$ and ranges from 16.0% to 16.6%. For dielectrons with $E_T(e) > 15$ GeV, $\epsilon_{\mathrm{trig}} = 98.4\% \pm 1.3\%$. We exclude $\sigma \times \mathrm{BR} \geq 0.18$ pb independently of $M(\tilde{g})$. Figure 2 shows the results for the charm squark analysis in the gluino-squark mass plane. Exclusion contours at the 95% C.L. are shown for two values of the branching ratio

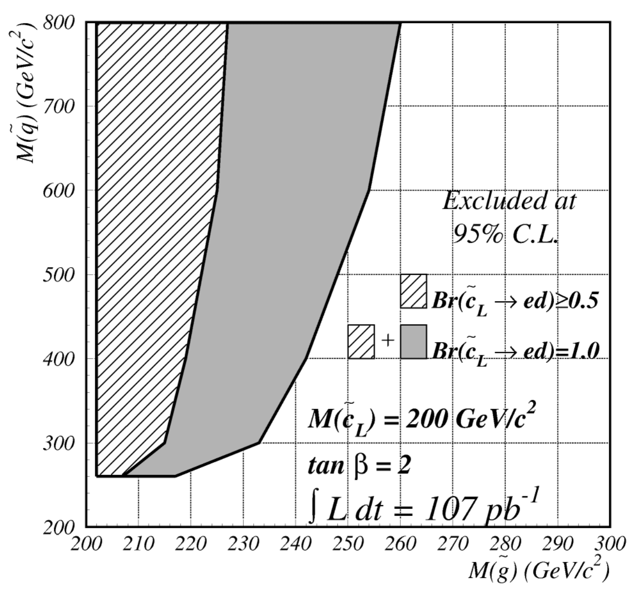

FIG. 2. Exclusion region in the $\tilde{g}$-$\tilde{q}$ mass plane for the charm squark analysis. The branching ratio to LS ee is calculated using the scenario in Ref. [7], which requires $M(\tilde{g}) > M(\tilde{c}_L)$.

$B(\tilde{c}_L \to ed)$, where we compare our results to the next-to-leading order (NLO) $\tilde{g}\tilde{g}$ production cross section [22] multiplied by the branching ratio to LS ee from Ref. [7]. Our sensitivity vanishes for $M(\tilde{q}) \lesssim 260\ \mathrm{GeV}/c^2$. In this region $\tilde{b}_L$ is lighter than 200 GeV/c^2 (and thus lighter than $\tilde{c}_L$) due to the large top quark mass [7], so the decay of $\tilde{g} \to \overline{b}\tilde{b}_L$ dominates and $\tilde{g} \to \overline{c}\tilde{c}_L$ is suppressed. Since our analysis assumes a nonzero $R\!\!\!/_p$ coupling only for $\tilde{c}_L$, the signal of LS electrons with no $E\!\!\!/_T$ disappears in this region of parameter space.

For the neutralino analysis, A is determined for each squark and neutralino mass pair and ranges from 3.7% to 15.2%. In this case, $\epsilon_{\mathrm{trig}} = 96.5\% \pm 1.9\%$, which is slightly lower than for the charm squark analysis because the E_T spectrum of the second electron in the neutralino analysis is softer. We calculate the upper limit on the cross section times branching ratio to LS ee for each squark and neutralino mass combination, and obtain $\sigma \times$ BR limits which range as a function of the squark mass from 0.81 to 0.26 pb for a light neutralino, and from 0.35 to 0.20 pb for a heavy neutralino. Figure 3 shows the results for the neutralino analysis for the case of $\tilde{t}_1\bar{\tilde{t}}_1$ production. Plotted are our 95% C.L. upper limits along with the NLO cross section [23] multiplied by the branching ratio to LS ee. The branching ratio $B(\tilde{t}_1 \to c\tilde{\chi}_1^0)$ is taken to be 1.0 [24]. We also assume $B(\tilde{\chi}_1^0 \to q\overline{q}'e) = B(\tilde{\chi}_1^0 \to q\overline{q}'\nu) = 1/2$, although the actual branching ratios are a function of the SUSY parameters [25]. Since each neutralino decays to

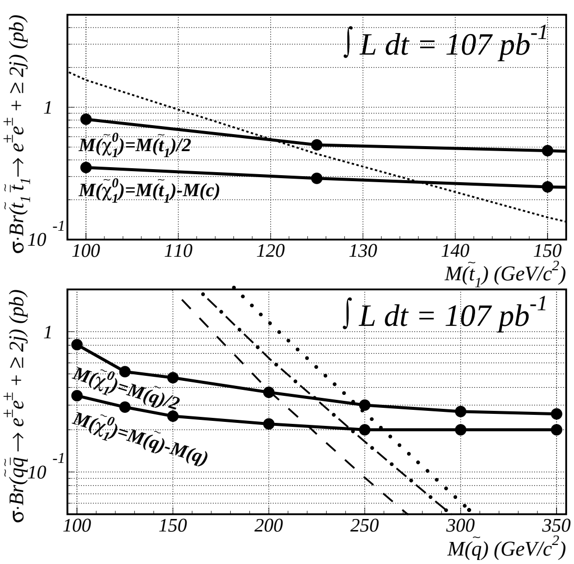

FIG. 3. Top: upper limits on the cross section times branching ratio for $\tilde{t}\bar{\tilde{t}}_1$ production decaying to electrons and jets via neutralinos (solid lines). The dashed curve is the theoretical prediction for $\sigma \times$ BR. Bottom: upper limits on the cross section times branching ratio for the production of five degenerate squark flavors decaying to electrons and jets via neutralinos (solid lines). Also shown is the theoretical prediction for $\sigma \times$ BR for three values of the gluino mass: 200 GeV/c^2 (dotted line), 500 GeV/c^2 (dot-dashed line), and 1 TeV/c^2 (dashed line).

e^+ or e^- with equal probability, the branching ratio to LS ee is 1/8. The limit is shown for two extremes of the neutralino mass, and excludes $M(\tilde{t}_1)$ below 120 (135) GeV/c^2 for a light (heavy) neutralino. Similarly, the results for the case of five degenerate $\tilde{q}\bar{\tilde{q}}$ production are displayed in Fig. 3. In this case, the NLO cross section [26] includes a gluino mass dependent t-channel contribution, and we assume the branching ratio $B(\tilde{q} \to q\tilde{\chi}_1^0) = 1.0$. Thus, we set gluino and neutralino mass-dependent lower limits on the degenerate squark mass in the range from 200 to 260 GeV/c^2. The neutralino analysis presented here assumes that the only nonzero $R\!\!\!/_p$ coupling is λ'_{121}. Since our analysis does not distinguish the quark flavors in jet reconstruction, however, the results are equally valid for any λ'_{1jk} coupling, for which j is 1 or 2 and k is 1, 2, or 3.

We note that our limit for the neutralino decay analysis with five degenerate squark flavors assumes the branching ratio $B(\tilde{q} \to q\tilde{\chi}_1^0) = 1.0$, whereas the branching ratio $B(\tilde{c}_L \to ed)$ must be appreciable to explain the HERA results. However, even allowing for $B(\tilde{q} \to q\tilde{\chi}_1^0) < 1$, our analysis is sensitive to the interesting region of 200 GeV, depending on $M(\tilde{g})$: for example, we can exclude the $R\!\!\!/_p$ scenario with $B(\tilde{q} \to q\tilde{\chi}_1^0) > 0.43$ for $M(\tilde{g}) = 200$ GeV. For heavier gluino mass, the exclusion becomes weaker.

In conclusion, we find no evidence for LS dielectron plus multijet events in 1.8 TeV $p\overline{p}$ collisions and set $\sigma \times$ BR limits on two $R\!\!\!/_p$ SUSY processes that could lead to this signature. In the charm squark analysis we exclude the scenario of $M(\tilde{c}_L) = 200\ \mathrm{GeV}/c^2$ as a function of $M(\tilde{g})$ and $M(\tilde{q})$. In the neutralino analysis we set mass limits of $M(\tilde{t}_1) > 135\ \mathrm{GeV}/c^2$ for a heavy neutralino $[M(\tilde{\chi}_1^0) = M(\tilde{t}_1) - M(c)]$ and, for the degenerate squark, $M(\tilde{q}) > 260\ \mathrm{GeV}/c^2$ for a heavy neutralino $[M(\tilde{\chi}_1^0) = M(\tilde{q}) - M(q)]$ and a light gluino $[M(\tilde{g}) = 200\ \mathrm{GeV}/c^2]$.

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