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Search for Gluinos and Squarks Using Like-Sign Dileptons in $p\bar{p}$ Collisions at $\sqrt{s}$= 1.8 TeV

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We present results of the first search for like-sign dilepton ($e^\pm e^\pm$, $e^\pm\mu^\pm$, $\mu^\pm\mu^\pm$) events associated with multijets and large missing energy using 106 pb^{-1} of data in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected during 1992–1995 by the CDF experiment. Finding no events that pass our selection, we examine pair production of gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) in a constrained framework of the minimal supersymmetric standard model. At $\tan\beta = 2$ and $\mu = -800\ \text{GeV}/c^2$, we set 95% confidence level limits of $M_{\tilde{g}} > 221\ \text{GeV}/c^2$ for $M_{\tilde{g}} \simeq M_{\tilde{q}}$, and $M_{\tilde{g}} > 168\ \text{GeV}/c^2$ for $M_{\tilde{q}} \gg M_{\tilde{g}}$, both with small variation as a function of μ.

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The standard model (SM) of particle physics is enormously successful in explaining a wide variety of phenomena. In spite of this, there are a number of structural defects in the model, such as the quadratic mass divergence of the Higgs boson. Supersymmetry (SUSY) provides a promising solution and in the minimal supersymmetric standard model (MSSM) [1] each SM particle has a SUSY partner which is required to be lighter than or of the order of 1 TeV/c^2 [1]. Conservation of R parity [2] requires SUSY particles to be produced in pairs and the lightest SUSY particle (LSP) to be stable.

At the Fermilab Tevatron, pair production and sequential decays of supersymmetric quarks (squarks, $\tilde{q}$) and supersymmetric gluons (gluinos, $\tilde{g}$) can result in events with final state leptons. The $\tilde{q}$ can decay to the lightest chargino ($\tilde{\chi}_1^\pm$) or the next-to-lightest neutralino ($\tilde{\chi}_2^0$) via $\tilde{q} \to q'\tilde{\chi}_1^\pm$ or $\tilde{q} \to q\tilde{\chi}_2^0$, and the $\tilde{q} \to q\tilde{g}$ decay occurs when kinematically allowed. The decays of the $\tilde{g}$ are $\tilde{g} \to q\bar{q}'\tilde{\chi}_1^\pm$ or $\tilde{g} \to q\bar{q}\tilde{\chi}_2^0$. Each $\tilde{q}$ and $\tilde{g}$ decay can eventually produce isolated leptons and missing transverse energy ($\not{E}_T$) [3] via the decays $\tilde{\chi}_1^\pm \to \ell^\pm\nu_\ell\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ where $\tilde{\chi}_1^0$ is the LSP [4] which exits the detector without interacting. Thus, $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\bar{\tilde{q}}$ production can lead to the like-sign (LS) dilepton signatures of $e^\pm e^\pm$, $e^\pm\mu^\pm$, and $\mu^\pm\mu^\pm$ [5] with two or more jets and appreciable $\not{E}_T$. The fraction of dilepton events which are LS can be as large as 30% in some regions of MSSM parameter space.

The $\ell^\pm\ell^\pm + \geq 2$ jets $+ \not{E}_T$ channel is a clean signature to search for SUSY. It has an advantage over the opposite-sign (OS) dilepton channel as there are only small SM backgrounds. Even without the $\not{E}_T$ requirement the LS analysis is also useful for testing other theories beyond the SM, including R parity violating SUSY [6]. The dilepton decay channels are a natural complement to other direct searches for squarks and gluinos in the $\not{E}_T$ plus multijet channel [7–12].

In this Letter, we present the results of the first search for $\ell^\pm\ell^\pm + \geq 2$ jets $+ \not{E}_T$ events using 106 pb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The data were collected by the Collider Detector at Fermilab (CDF) [13] during the 1992–1995 run of the Tevatron. We briefly describe the detector subsystems relevant to this analysis. The location of the $p\overline{p}$ collision event vertex (z_{vertex}) is measured along the beam direction with a time projection chamber. The p_T of charged particles are measured in the region $|\eta| < 1.1$ by a central tracking chamber (CTC) which is located in a 1.4 T solenoidal magnetic field. The momentum resolution is $\delta p_T/{p_T}^2 \simeq 0.001$ where p_T is measured in GeV/c. Electromagnetic and hadronic calorimeters are segmented in a projective tower geometry surrounding the solenoid and cover the region $|\eta| < 4.2$. A muon detector is located outside the hadron calorimeter and covers the region $|\eta| < 1.0$.

The analysis begins with a sample of 515 699 loosely selected dilepton events [14,15] from which we select an initial dilepton plus dijet sample. To ensure that the trigger is fully efficient, we require each event to have a lepton with $p_T \geq 11\ \text{GeV}/c$ and $|\eta| < 1.0$ for electrons or $|\eta| < 0.6$ for muons. A second electron or muon is required with $p_T \geq 5\ \text{GeV}/c$ and $|\eta| < 1.0$. If there are more than two isolated leptons, we take the two leading-p_T leptons. Each lepton is required to be isolated such that there is no more than 4 GeV of transverse energy (measured by the calorimeter or CTC) in a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the direction of the lepton. To ensure that both leptons originated from the same collision event and are well measured, we require $|z_{\text{vertex}}| \leq 60$ cm and $|z_{\text{lepton}} - z_{\text{vertex}}| \leq 5$ cm for each lepton, where z_{lepton} is measured along the beam line. In addition to the leptons, we require two or more jets with $E_T \geq 15$ GeV and $|\eta| < 2.4$.

Since the OS sample is used as a check of our understanding of the LS backgrounds, we place the same cuts on both samples in parallel, but with additional cuts on the OS events so as to remove events which might give a kinematic bias. To reduce the large J/ψ and Υ component of the background we remove the events with $M_{\ell\ell} < 12\ \text{GeV}/c^2$. A total of 239 OS and 16 LS dilepton events pass the requirement.

The dominant SM backgrounds are from Drell-Yan (γ^*/Z^0), $t\bar{t}$, $b\bar{b}$, $c\bar{c}$, and diboson (W^+W^-, $W^\pm Z^0$, Z^0Z^0) production. Each is estimated using the ISAJET Monte Carlo (MC) event generator [16] and a simulation of the CDF detector. The cross sections for γ^*/Z^0 and $t\bar{t}$

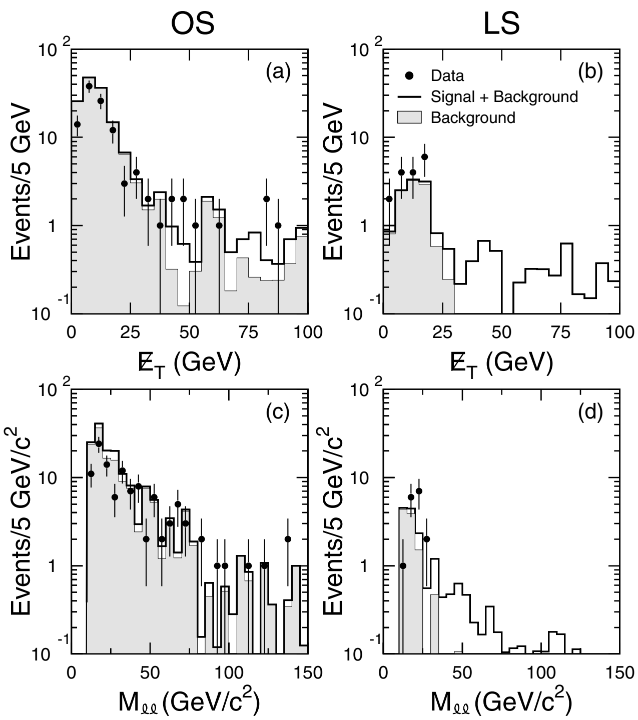

FIG. 1. Distributions for the dilepton + dijet data after the $M_{\ell\ell} > 12$ GeV$/c^2$ and Z^0 veto requirements. (a) and (b) show the $\not\!E_T$ distributions for OS and LS samples, respectively. The data (points) are compared to the standard model background (shaded line) with a SUSY contribution (solid line) for $\tan\beta = 2$, $\mu = -800$ GeV$/c^2$, $M_{\tilde{g}} = 210$ GeV$/c^2$, and $M_{\tilde{q}} = 211$ GeV$/c^2$. (c) and (d) show the $M_{\ell\ell}$ distributions in the OS and LS samples for the same requirements.

production and contributions due to $B^0\bar{B}^0$ mixing events are normalized to CDF measurements [17–19]. We use next-to-leading order (NLO) cross sections for diboson production [20]. The contribution from $W(\rightarrow \ell\nu_\ell) + \geq 3$ jets events where one of the jets is misidentified as a lepton is found to be negligible.

Given the large $\not\!E_T$ signature from SUSY, we require at least 25 GeV of $\not\!E_T$ for all dilepton events. In the OS sample, we also remove all same-flavor OS dilepton events with $76 < M_{\ell^+\ell^-} < 106$ GeV$/c^2$. Figure 1 compares the $\not\!E_T$ and $M_{\ell\ell}$ distributions for the data and the SM backgrounds for the OS and LS samples after the Z^0 veto but before the $\not\!E_T$ requirement. After all cuts, we observe 19 OS (4 ee, 10 $e\mu$, 5 $\mu\mu$) events and no LS events in agreement with the SM expectation of 14.1 ± 1.3 (stat) ± 2.8 (syst) OS events and 0.55 ± 0.25 ± 0.08 LS events. Tables I and II show a comparison of the data reduction and the SM backgrounds. We note that $t\bar{t}$ and $Z^0 \rightarrow \tau^+\tau^-$ are two major SM sources of the $e\mu$ events. The 19 event sample also contains six dilepton (1 ee, 5 $e\mu$) events out of nine $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow (\ell^+\nu b)(\ell^-\bar{\nu}\bar{b})$ event candidates (1 ee, 7 $e\mu$, 1 $\mu\mu$) from the CDF $t\bar{t}$ analysis in the dilepton channel [21]. The remaining three top dilepton event candidates are not in our final sample because our lepton isolation requirement for the second lepton is stricter than the top analysis. There is no evidence for new particle production.

We examine the exclusion region of $M_{\tilde{q}}$ and $M_{\tilde{g}}$ in a constrained framework of the MSSM. We assume five squarks ($\tilde{u}$, $\tilde{d}$, $\tilde{s}$, $\tilde{c}$, $\tilde{b}$) with nearly mass-degenerate left and right helicity states. Production of top squarks is not considered even though the lighter of the two top-squark mass eigenstates can be lighter than the other squarks [22]. We impose common scalar and common gaugino masses at a grand unified theory scale as in the minimal supergravity model [23], and use the renormalization group equations [24] that relate the mass parameters, leading to a general prediction: $M_{\tilde{q}} \gtrsim 0.9 M_{\tilde{g}}$. To avoid a region in MSSM parameter space where there are significant branching ratios of chargino and neutralino decays into Higgs particles, the pseudoscalar Higgs mass is set to 500 GeV$/c^2$ which is above the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses. With these assumptions, the sensitivity of our search can be studied as a function of four parameters: the gluino mass ($M_{\tilde{g}}$), the squark mass ($M_{\tilde{q}}$), the ratio of the vacuum expectation values of the two Higgs fields ($\tan\beta$), and the Higgs mass parameter (μ). Since we choose to decouple our search from the Higgs sector we scan a range of μ that is both consistent with LEP results [9,25] and less than the SUSY mass scale: $100 \lesssim |\mu| \lesssim 1000$ GeV$/c^2$.

The acceptance for SUSY processes is estimated by performing the final data selection on events simulated with ISAJET [16] using CTEQ3L [26] parton distribution functions (PDFs). These events are then passed through the CDF detector simulation. We define the acceptance as the ratio of the number of LS dilepton events that pass our cuts

TABLE I. A comparison of the event reduction for the data, standard model (SM) backgrounds and a model of SUSY production with $\tan\beta = 2$, $\mu = -800$ GeV$/c^2$, $M_{\tilde{g}} = 210$ GeV$/c^2$, and $M_{\tilde{q}} = 211$ GeV$/c^2$.

Selection	Data	SM backgrounds	SUSY
Dilepton dataset	515,699		
Dilepton dijet	350		
$M_{\ell\ell} \geq 12$ GeV$/c^2$	255	279 ± 9 ± 79	27 ± 1 ± 5
$Z^0(\rightarrow \ell^+\ell^-)$ veto	128	158 ± 7 ± 45	27 ± 1 ± 5
$\not\!E_T \geq 25$ GeV	19	14.1 ± 1.3 ± 2.8	24 ± 1 ± 5
Like-sign dilepton	0	0.55 ± 0.25 ± 0.08	5.9 ± 0.6 ± 1.4

TABLE II. The expected backgrounds from standard model contributions to the final data selection after all but the LS requirement in Table I. Opposite-sign and like-sign dilepton events are listed.

Source	Opposite-sign	Like-sign
Drell-Yan	$8.7 \pm 0.9 \pm 2.5$	$0.00\ ^{+0.01}_{-0.00}\ ^{+0.01}_{-0.00}$
$t\bar{t}$	$4.0 \pm 0.3 \pm 1.2$	$0.08 \pm 0.04 \pm 0.02$
$b\bar{b}/c\bar{c}$	$0.9 \pm 0.9 \pm 0.3$	$0.23 \pm 0.23 \pm 0.07$
Diboson	$0.5 \pm 0.1 \pm 0.1$	$0.24 \pm 0.10 \pm 0.04$
Total	$14.1 \pm 1.3 \pm 2.8$	$0.55 \pm 0.25 \pm 0.08$
Data	19	0

to the total number of generated SUSY events which contain at least two leptons. For a nominal SUSY scenario of $M_{\tilde{g}} = 200\ \mathrm{GeV}/c^2$, infinite squark mass (and hence infinite slepton mass), $\tan\beta = 2$ and $\mu = -800\ \mathrm{GeV}/c^2$, the acceptance is 1%, due mostly to the lower p_T values of the leptons. For the case where $M_{\tilde{q}} \simeq M_{\tilde{g}} \simeq 200\ \mathrm{GeV}/c^2$, the slepton ($\tilde{\ell}_R$) mass is lighter. This enhances the leptonic branching ratio due to $\tilde{\chi}_2^0 \to \ell\tilde{\ell}_R$, resulting in an increase of LS dilepton events in $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\bar{\tilde{q}}$ production and a rise of the overall acceptance to 3%. Table I and Fig. 1 compare the data reduction, the expectations from SM processes, and a SUSY scenario.

The total systematic uncertainty on the expected number of LS signal events comes from uncertainties on the theoretical calculation of the production cross section of gluinos and squarks, the event acceptance, and the integrated luminosity. The NLO cross section depends mainly on the choices of the QCD renormalization scale (Q^2) and PDFs [27]. The nominal choice of Q^2 is m^2, where m is $M_{\tilde{q}}$, $M_{\tilde{g}}$, or $\frac{1}{2}\sqrt{M_{\tilde{q}}{}^2 + M_{\tilde{g}}{}^2}$ for $\tilde{q}\tilde{q}/\tilde{q}\bar{\tilde{q}}$, $\tilde{g}\tilde{g}$, or $\tilde{q}\tilde{g}$ production, respectively. The uncertainty due to the choice of Q^2 is determined to be 21% by taking the larger of the variation of the cross section at $Q^2 = (m/2)^2$ and at $Q^2 = (2m)^2$ from the nominal cross section value. Similarly, the variation of the cross section due to the choice of PDFs yields an 8% uncertainty, estimated as the maximum deviation between the nominal choice of CTEQ3M [26] and MRS(G) [28] or GRV94HO [29]. Uncertainty on the signal acceptance is due to uncertainties on the efficiencies of the lepton trigger, identification and isolation efficiencies, as well as on the jet energy scale and the amount of gluon radiation. By varying the measured lepton trigger and identification efficiencies by 1 standard deviation, the acceptance uncertainties are estimated to be 5% and 3%, respectively. Since the lepton isolation efficiency depends on jet multiplicity, the uncertainty is estimated using $Z^0(\to \ell^+\ell^-) + \geq 2$ jet events and is found to be 11%. By varying the jet energy scale by 1 standard deviation, we find a 5% effect on the acceptance. The uncertainty due to the initial and final state gluon radiation (ISR and FSR) is estimated by turning the ISR and/or FSR radiation off, which gives at most 7% variation in the acceptance. Enough MC events are generated so as to keep the statistical uncertainty below 3%. The uncertainty on the luminosity is 4%. The combined uncertainty is calculated by adding all uncertainties in quadrature, and is found to be 28%.

Since no LS events pass our cuts, we calculate the upper limit on the number of SUSY events at the 95% confidence level (C.L.) using a frequentist algorithm [30] with a systematic uncertainty of 28% and no background subtraction. This corresponds to 3.46 events which we use to exclude regions in the $M_{\tilde{q}}$-$M_{\tilde{g}}$ plane. Figure 2 shows the exclusion region for $\tan\beta = 2$ and $\mu = -800\ \mathrm{GeV}/c^2$. We set 95% C.L. limits at $M_{\tilde{g}} > 168\ \mathrm{GeV}/c^2$ for $M_{\tilde{q}} \gg M_{\tilde{g}}$ and $M_{\tilde{g}} > 221\ \mathrm{GeV}/c^2$ for $M_{\tilde{g}} \simeq M_{\tilde{q}}$. These results are better than the previous limits from complementary searches by about $5\ \mathrm{GeV}/c^2$ [10,11].

We examine the dependence of the mass limit as $\tan\beta$ and μ are varied in the region $M_{\tilde{g}} \simeq M_{\tilde{q}}$. For $\mu = -800\ \mathrm{GeV}/c^2$, the variation in the mass limit is smaller than 2% in the range of $\tan\beta$ between 1.7 and 10 if the mixings of the third generation SUSY particles (especially $\tilde{\tau}$) are minimal. In the case of maximal $\tilde{\tau}$ mixing, the mass limit remains the same for $\tan\beta$ up to about 3. For $\tan\beta = 2$, the limit deviates by at most 3.6% from the $221\ \mathrm{GeV}/c^2$ limit in the range $\mu \leq -150\ \mathrm{GeV}/c^2$, while the limits in $\mu \geq 150\ \mathrm{GeV}/c^2$ are systematically 8%–12% lower.

In conclusion, we have searched for new physics using LS dilepton events in association with two or more jets and $\not{E}_T$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Production of both OS and LS dilepton events is consistent with the SM expectations. Within a framework of constrained MSSM

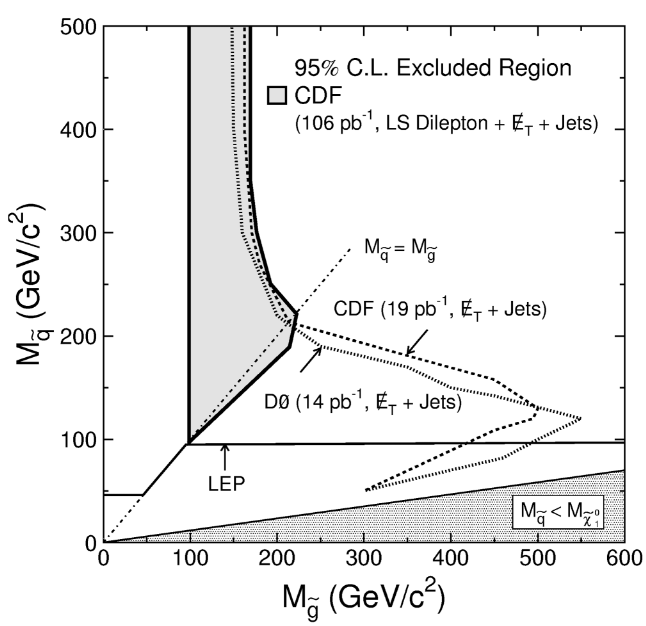

FIG. 2. Limit in the $M_{\tilde{q}}$-$M_{\tilde{g}}$ plane at the 95% confidence level for a constrained MSSM scenario ($M_{\tilde{q}} \gtrsim 0.9M_{\tilde{g}}$) for $\tan\beta = 2$ and $\mu = -800\ \mathrm{GeV}/c^2$. The results of other direct, but complementary, searches are also presented [8–11].

(five degenerate squarks, $M_{\tilde{q}} \gtrsim 0.9 M_{\tilde{g}}$), for small $\tan\beta$ we set mass limits of $M_{\tilde{g}} > 168$ GeV/c^2 for $M_{\tilde{q}} \gg M_{\tilde{g}}$, and $M_{\tilde{g}} > 221$ GeV/c^2 for $M_{\tilde{q}} \simeq M_{\tilde{g}}$, both with small variation as a function of μ.

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