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Search for gluinos and squarks at the Fermilab Tevatron collider

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We report on a search for supersymmetric squark and gluino particles in a data sample of 19 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}=1.8$ TeV recorded by the Collider Detector at Fermilab. We searched for events containing jets plus appreciable missing transverse energy ($\not{E}_T$). This signature is indicative of pair production and subsequent decay of squarks and/or gluinos. After all cuts, there are 18 events with $\not{E}_T > 60$ GeV and three jets, and 6 events with $\not{E}_T > 60$ GeV and four jets. These numbers of events are consistent with estimates of standard model processes plus detector-induced background sources. The analysis yields lower limits on gluino and squark masses, based on the predictions from the mnimal supersymmetric extension of the standard model. At the 95% confidence level, we find gluino and squark mass limits up to 216 GeV/c^2, assuming equal gluino and squark masses, and gluino mass limits up to 173 GeV/c^2, independent of squark mass.
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Supersymmetry (SUSY) [1] is one of the most appealing theories as a next step towards grand unification. In the minimal supersymmetric extension of the standard model (MSSM) all fermions of the standard model have bosons as supersymmetric partners while all bosons acquire fermions as superpartners. Supersymmetry is especially appealing if its symmetry breaking occurs near the electroweak scale [2]. In such a scenario the superpartner masses must lie below 1 TeV/c^2 and may be produced at the Fermilab Tevatron. We analyzed 19 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s}=1.8$ TeV, re-

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corded by the Collider Detector at Fermilab (CDF), in search of gluino and squark production.

Gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) are the SUSY partners of ordinary gluons and quarks. In this analysis we restricted ourselves to search for signals from the first five squarks (assumed to be mass degenerate) and from gluinos. Conservation of SUSY R parity, a multiplicative quantum number, requires these particles to be produced in pairs and prevents decay of the lightest SUSY particle (LSP). Gluinos and squarks then decay to standard model particles plus LSP. The LSP, considered to be neutral, for cosmological reasons [3], and only weakly interacting, would pass through the detector without interaction. In our analysis we assume the lightest neutralino $\tilde{\chi}_1^0$ to be the LSP. Under this assumption, SUSY events should have considerable missing transverse energy, which is defined as the transverse component of the negative vector sum of all energies [4] in an event, and whose magnitude is denoted as $\not{E}_T$.

Explicitly, the search was for $\tilde{q}\tilde{\bar{q}}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{g}$, and $\tilde{g}\tilde{g}$ production. Direct decays of squarks and gluinos proceed according to $\tilde{q} \rightarrow q$ LSP and $\tilde{g} \rightarrow q\bar{q}$ LSP, while for sufficiently massive squarks and gluinos, cascade decays proceed through charginos $\tilde{\chi}_n^{\pm}$ (n=1,2) or heavier neutralinos $\tilde{\chi}_n^0$ (n=2,3,4), which in turn decay to quarks, leptons, or neutrinos, and one LSP. Such cascades result in the production of a larger number of jets, reduced but still significant $\not{E}_T$, and occasional production of leptons. This analysis and Ref. [5] are sensitive to both direct and cascade decays. Earlier $\not{E}_T$ based searches [6,7] were optimized for direct decays. The dilepton based SUSY search by CDF [8] is sensitive to cascade decays.

A detailed description of the CDF detector can be found elsewhere [9]. The following components are relevant to this analysis: the central tracking chamber, electromagnetic and hadronic calorimeters, and muon drift chambers. The central tracking chamber, inside a 1.4 T superconducting solenoidal magnet, measures the momentum of charged particles with a resolution of $\delta p_T/p_T = 0.001\ p_T$ (p_T in GeV/c) [4]. The electromagnetic and hadronic calorimeters cover the pseudorapidity region $|\eta|<4.2$ and are used to identify jets and electrons. They are also used, within the region $|\eta|<3.6$, to measure the $\not{E}_T$, which can indicate the presence of undetected energetic LSPs or neutrinos. Drift chambers provide muon identification in the region $|\eta|<1.0$.

Events for this analysis passed a multilevel online trigger system, which selected events with $\not{E}_T>35$ GeV and at least one jet with $E_T>50$ GeV. After offline data reconstruction, events were chosen that had $\not{E}_T>60$ GeV and three or more jets [10] with $E_T>15$ GeV each, in the region $|\eta|\leqslant 2.4$. We require the $\not{E}_T$-significance $S \equiv \not{E}_T/\sqrt{\Sigma E_T}$, where ΣE_T is the scalar sum of all transverse energy in the calorimeters, to be larger than 2.2 GeV$^{1/2}$. The $\not{E}_T$ was corrected using a jet correction algorithm [11], which takes into account calorimeter nonlinearities and reduced calorimeter response at boundaries between modules and calorimeter subsystems. Cosmic ray, accelerator-related, and detector-induced backgrounds were removed, with essentially full signal efficiency, by several requirements: that less than 10 GeV of hadronic E_T be deposited outside the beam-beam interaction time window, that the most energetic jet have a ratio of electromagnetic to total energy between 0.075 and 0.925, and that the event have significant momentum in energetic charged particles ($\Sigma p_T \geqslant 5$ GeV/c for tracks with $p_T \geqslant 2$ GeV/c).

Mismeasured QCD events that could mimic the SUSY signal contain correlations in the transverse plane between the $\not{E}_T$ direction and the jets, since usually only one jet was substantially mismeasured. This background was reduced by removing events that had either (i) the most energetic jet back-to-back within 20° in ϕ of the $\not{E}_T$ direction, or (ii) a jet with $E_T>20$ GeV within 30° in ϕ of the $\not{E}_T$ direction. The first cut was more useful for events with a leading two-jet topology (mainly two energetic back-to-back jets), and the second cut for events with a multijet topology.

Events with leptonic W (including W bosons from top quark decays) and Z decays can mimic the SUSY signal. These backgrounds were reduced by rejecting events that contained an identified electron or muon. Electrons and muons with transverse energy above 10 GeV were identified by a combination of calorimeter, tracking, and muon chamber requirements. In addition, we identified muon candidates in η regions not covered by the muon chambers by looking for tracks consistent with being from a minimum ionizing particle with transverse momenta above 15 GeV/c.

After these cuts, 24 events remained in the signal region, of which 18 contained 3 jets, and 6 contained 4 jets.

The expected numbers of events from standard model processes in these samples were estimated using a combination of Monte Carlo simulation and normalized data control samples. The VECBOS [12] event generator was used to produce background events from W or Z plus multijet production. There are large uncertainties associated with the W+jets and Z+jets cross-section calculations. Therefore, we normalized both W and Z Monte Carlo simulations to the number of W plus 2 jet events in data in which an electron or muon was identified (as contrasted with the SUSY data selection in which events with identified electrons and muons were rejected). The background from top quark production was estimated using the ISAJET [13] event generator normalized to the top quark pair production cross-section experimentally determined by CDF [14].

The number of events coming from mismeasurement of otherwise balanced QCD multijet events was determined by using a jet sample, selected by the online trigger as having at least one jet with $E_T>50$ GeV. This control sample was required to pass all but three of the SUSY selection cuts: the $\not{E}_T$-significance cut, the online trigger $\not{E}_T$ cut, and the 3 (or 4) jet requirement. The possible contribution of SUSY events to this sample is small at all $\not{E}_T$. These three cuts were found to be negligibly correlated. The $\not{E}_T$ distribution of the control sample was fit in the region $\not{E}_T>40$ GeV to the sum of a smooth function (power law or exponential), representing QCD mismeasurement, and small contributions for the estimated W+jets, Z+jets, and $t\bar{t}$ backgrounds. The number of QCD events with $\not{E}_T>60$ GeV was determined from this fit, and the number of expected QCD background events in the SUSY data sample was then derived by including the efficiencies of the three remaining cuts and the relative integrated luminosities of the jet and data samples. The differ-

TABLE I. Expected number of W, Z,$t\overline{t}$, and QCD background events in the signal region. Backgrounds from Z^0 decays to charged leptons were also estimated and found to be negligible.

	$\geqslant$3 jets	$\geqslant$4 jets
$W^{\pm}\rightarrow e^{\pm}\nu$	$3.3\pm1.0^{+3.2}_{-1.3}$	$0.5\pm0.4^{+1.3}_{-0.5}$
$W^{\pm}\rightarrow \mu^{\pm}\nu$	$1.4\pm0.6^{+1.9}_{-0.5}$	$0.5\pm0.4\pm0.5$
$W^{\pm}\rightarrow \tau^{\pm}\nu$	$9.2\pm1.7^{+6.8}_{-4.0}$	$1.6\pm0.7\pm1.4$
$Z^0\rightarrow \nu\overline{\nu}$	$5.0\pm0.9^{+2.6}_{-2.8}$	$0.4\pm0.2^{+0.3}_{-0.4}$
$t\overline{t}$	$4.2\pm0.3^{+0.3}_{-0.6}$	$2.2\pm0.2^{+0.3}_{-0.4}$
QCD	$10.2^{+11.8+4.6}_{-9.5-3.7}$	$3.2^{+4.4+1.4}_{-3.2-1.1}$
Total	$33^{+12}_{-10}(\mathrm{stat})^{+19}_{-12}(\mathrm{syst})$	$8^{+4}_{-3}(\mathrm{stat})\pm4(\mathrm{syst})$

ence between the results found by the fits with the two functional forms was taken as a systematic uncertainty in this background.

Table I lists the estimated background contributions to the $\geqslant$3 and $\geqslant$4 jet data samples. The estimated backgrounds are slightly larger but statistically consistent with the number of observed events. In the $\geqslant$3 jet sample we observed 24 events compared to $33^{+12}_{-10}(\mathrm{stat})^{+19}_{-12}(\mathrm{syst})$ estimated background events; in the $\geqslant$4 jet sample we observed 6 events compared to $8^{+4}_{-3}(\mathrm{stat})\pm4(\mathrm{syst})$ estimated background events.

The four major sources of systematic uncertainty included in the background estimate are (i) the uncertainty on the calorimeter energy scale, (ii) the normalization of the W and Z contributions, (iii) the fit and extrapolation of the $\not{E}_T$ spectrum in the QCD background estimate, and (iv) an uncertainty in the integrated luminosity measurement. For each source, we added the uncertainties of the various W, Z, $t\overline{t}$, and QCD components linearly, except for part of the QCD uncertainty where we take the correlation between W, Z, and $t\overline{t}$ into account. The uncertainties from the various sources were then added in quadrature to yield the total systematic uncertainty.

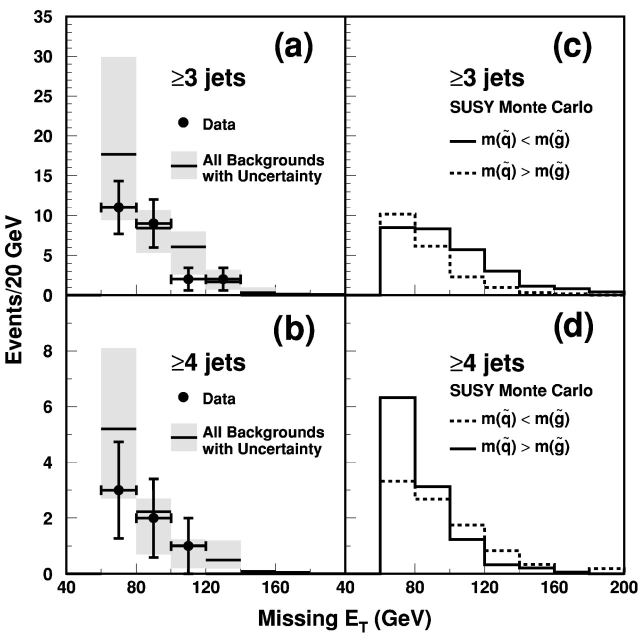

FIG. 1. Plots (a) and (b) show $\not{E}_T$ distributions of the signal region for data and combined estimated backgrounds with 3 and 4 inclusive jets, respectively. The shaded areas represent the total uncertainty of all the backgrounds. Plots (c) and (d) show representative signal region $\not{E}_T$ distributions for SUSY Monte Carlo simulations. The following SUSY parameters are used for the signal Monte Carlo simulation samples: $m_{\tilde{g}}=170$ GeV/c^2 and $m_{\tilde{q}}=500$ GeV/c^2 ($m_{\tilde{q}}>m_{\tilde{g}}$), or $m_{\tilde{g}}=350$ GeV/c^2 and $m_{\tilde{q}}=180$ GeV/c^2 ($m_{\tilde{q}}<m_{\tilde{g}}$); $\tan\beta=4$; and $\mu=-400$ GeV/c^2. The total integrated luminosity for all plots is 19 pb^{-1}.

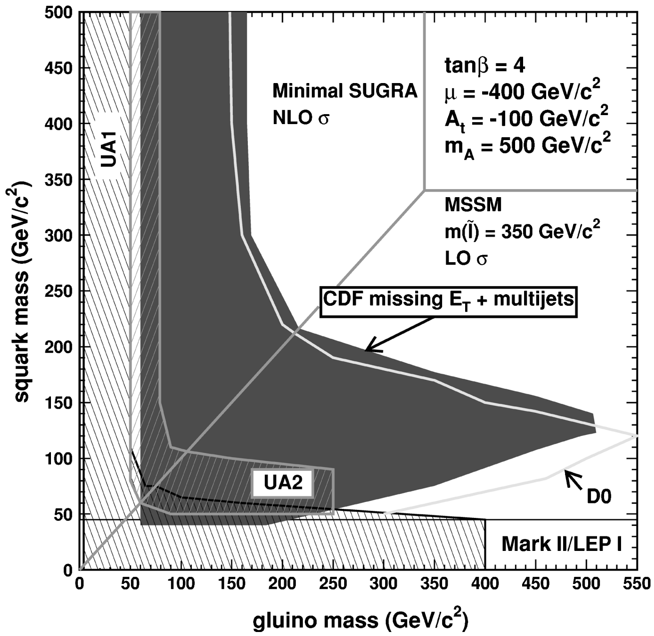

FIG. 2. Region in the gluino–squark mass plane ($\tan\beta=4$, $\mu=-400$ GeV/c^2) excluded at 95% C.L. by this $\not{E}_T$ based analysis using a total integrated luminosity of 19 pb^{-1}. Next-to-leading order (NLO) cross-section calculations and minimal SUGRA are used above the diagonal, while leading order (LO) cross-section calculations and a fixed value of slepton mass ($m_{\tilde{l}}$) of 350 GeV/c^2 are used below the diagonal. Also shown are the UA1, UA2 [7], Mark II [21], CERN e^+e^- collider LEP I [22], and the D0 [5] excluded regions, some of which use slightly different assumptions and SUSY parameters.

The $\not{E}_T$ distributions of the data in the signal region are consistent with the estimated standard model and detector backgrounds, as shown in Figs. 1(a) and 1(b). In order to place limits on the masses of squarks and gluinos, possible signals due to supersymmetry were generated with the ISAJET Monte Carlo generator [15] and passed through detector simulation programs. In order to reduce the number of SUSY parameters [16], grand unified theories were used to relate gaugino masses to gauge couplings. Minimal supergravity grand unified theories [minimal supergravity (SUGRA)] [17] were used where possible, i.e., in the region where squarks are heavier than gluinos. We generated and analyzed Monte Carlo samples in the $\tilde{q}$-$\tilde{g}$ mass plane with SUSY parameters in the following ranges: gluino masses between 60 and 550 GeV/c^2, squark masses between 40 and 500 GeV/c^2, ratio of the vacuum expectation value of the two Higgs doublets $\tan\beta=2$, 4, and 8; and higgsino mass parameter $|\mu|<1600$ GeV/c^2. We used Martin-Roberts-Stirling set A′ [MRS(A′)] [18] parton distribution functions. Next-to-leading order gluino and squark production cross-sections [19] were used in the region where the squark mass ($m_{\tilde{q}}$) is heavier than gluino mass ($m_{\tilde{g}}$), and leading order calculations were used elsewhere. Figures 1(c) and 1(d) show $\not{E}_T$ distributions of two representative SUSY Monte Carlo samples close to our mass limits.

Gluino production dominates in the region of large squark masses, whereas squark production dominates in the region of large gluino masses. Gluino decays yield on average one more jet than squark decays. Therefore, for the upper limit determination we used the $\geqslant$4 jet analysis in the region where squarks are heavier than gluinos and the $\geqslant$3 jet analysis elsewhere.

A Monte Carlo technique was used to determine the 95% confidence level (C.L.) limits [20]. The numbers of background and signal events were determined by sampling Poisson distributions. The means of the distributions were set at the estimated number of background events and at an assumed mean number of signal events. The mean numbers of background and signal events were varied by their uncertainties, taking correlations between signal and background into account. In the case of asymmetric uncertainties, the larger of the positive or negative uncertainty was used. A trial was discarded if it had more background events than the actual number of observed events. For the trials that were not discarded, the fraction that had a number of background plus signal events greater than the number of observed events gave the confidence level for our limits. The assumed number of signal events was varied until the 95% C.L. limit was achieved. This limit, in the two cases of $\geqslant$3 jet or $\geqslant$4 jet samples, was achieved for 29.2 or 11.8 signal events, respectively.

Figure 2 shows the region in the gluino mass versus squark mass plane (with $\tan\beta = 4$ and $\mu = -400$ GeV/c^2) excluded at 95% C.L. by this analysis, i.e., the region that would yield more than 29.2 signal events in the $\geqslant$3 jet sample or more than 11.8 events in the $\geqslant$4 jet sample from gluino and squark production.

Production cross sections are steeply falling functions of squark and gluino masses and at our 95% C.L. contour are on the order of 10 pb. The total squark and gluino pair detection efficiencies on the contour vary from 2–4% at large squark masses to 10–15% for equal squark and gluino masses. Our mass limits vary by about 10 GeV/c^2 as a function of $\tan\beta$ and μ (for $\mu < -100$ GeV/c^2 or $\mu > 200$ GeV/c^2) [23]. The best gluino mass limit for all squark masses, i.e., $m_{\tilde{g}} > 173$ GeV/c^2, was obtained for $\tan\beta = 2$ and $\mu = -200$ GeV/c^2. The best gluino mass limit for equal squark and gluino masses, i.e., $m_{\tilde{g}} > 216$ GeV/c^2, was obtained for $\tan\beta = 4$ and $\mu = -400$ GeV/c^2. Our mass limits are comparable to our previous results [8] using dilepton events with a similar amount of data. These results extend significantly our previous limits in the $\not{E}_T$ plus multijet channel [6].

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