Search for Squarks and Gluinos from $\bar{p}p$ Collisions at $\sqrt{s}=1.8$ TeV

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We have analyzed events with jets and large missing transverse energy produced in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV. The observed event rate is consistent with standard model predictions. In a version of the supersymmetry (SUSY) model with a light photino ($m_{\tilde{\gamma}} < 15$ GeV/c^2) and no cascade decays, we exclude at the 90% confidence level the existence of squarks and gluinos with masses less than 126 and 141 GeV/c^2, respectively. The mass limits are lower with other choices of the SUSY parameters. An example is presented.

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In extensions of the standard model with supersymmetry (SUSY) [1] all fermions and bosons have partners with the same fundamental properties except spin and mass. The SUSY partners of quarks and gluons are squarks ($\tilde{q}$) and gluinos ($\tilde{g}$). In the minimal version of SUSY, the gauginos are complex mixtures of the Higgsino, photino, Z-ino, and W-ino. The theory is defined by five free parameters [1] which can be chosen as a SUSY Higgsino mass mixing parameter μ, the ratio of the two Higgs vacuum expectation values $\tan\beta$, and the masses of the charged Higgs boson, squark, and gluino (m_{H^+}, $m_{\tilde{q}}$, and $m_{\tilde{g}}$). These parameters uniquely determine the gaugino masses. There is a conserved SUSY quantum number which implies that SUSY particles are pair produced and that the lightest supersymmetric particle (LSP) cannot decay. In general the squarks and gluinos will decay to quarks and gauginos which subsequently decay to the LSP. The LSP interacts extremely weakly with quarks and electrons and deposits no significant energy in the detector. Thus SUSY particles, if produced, yield events having two or more jets with apparently imbalanced transverse momenta. In the following we assume that there is one very heavy squark and the other five flavors are lighter and nearly mass degenerate.

We describe a search for $\tilde{q}$ and $\tilde{g}$ particles produced in proton-antiproton collisions at a center-of-mass energy $\sqrt{s}=1.8$ TeV. A summary of earlier SUSY particle searches is presented in Ref. [2]. Previous hadron collider searches [3,4] set mass limits by comparing their data with a version of SUSY which assumed that there are six mass-degenerate squarks and that a squark decays directly into an ordinary quark and a light photino, and the photino is assumed to be the LSP. For comparison with these experiments, we have calculated mass limits from our data in the same way. However, when we use the version of SUSY described in the previous paragraph and include the effect of cascade decays [5], we find less stringent mass limits. An example for a specific choice of SUSY parameters is presented below.

Our results are based on 4.3 pb^{-1} of integrated luminosity in the Collider Detector at Fermilab (CDF) [6], which has a fine-grained, projective-tower geometry covering most of the 4π solid angle with electromagnetic and hadron calorimeters. Its principal subsystems are the central scintillator sampling calorimeter ($|\eta| < 1.1$), the end-plug gas sampling calorimeter ($1.1 < |\eta| < 2.4$), and the forward gas sampling calorimeter ($2.4 < |\eta| < 4.2$), where the pseudorapidity $\eta = -\ln\tan(\theta/2)$, and θ is the polar angle. Inside the central calorimeter, a superconducting solenoid generates a 1.41-T magnetic field for tracking chambers surrounding the collision axis. The region $|\eta| < 0.63$ is instrumented with drift chambers for muon detection outside of the hadron calorimeter. Charged tracks with $|\eta| > 0.63$ associated with minimum ionization signals in the calorimeters are also considered muon candidates.

Transverse energy is defined as $E_T = E\sin\theta$. The missing transverse energy $\not\!\!E_T$ is the magnitude of the vector sum of the calorimeter cell E_T vectors directed from the interaction vertex to the cell center. An $\not\!\!E_T$ trigger is used to generate the data sample. This trigger requires $\not\!\!E_T \geq 25$ GeV and $E_T \geq 8$ GeV and $|\eta| \leq 2.4$ for the highest E_T jet. Further details of the trigger can be found in Ref. [7]. The main sources of non-SUSY background in the resulting $\not\!\!E_T$ plus jets data sample arise from cosmic ray interactions, QCD multijet events in which the jet energy has been mismeasured, and events associated with W or Z production and leptonic decay. Off-line cuts are made to reduce these backgrounds.

An off-line analysis eliminates known sources of detector noise, computes tower energies, reconstructs tracks, and applies the CDF jet algorithm which sums the calorimeter E_T within a cone of 0.7 in η-ϕ space [8]. A sample of known cosmic rays is used to define cuts to reject cosmic ray background. Events are selected by requiring $\not\!\!E_T \geq 20$ GeV and ≥ 2 jets, where the jets are in the interval $|\eta| < 3.5$, have $E_T \geq 15$ GeV, and (to reject cosmic rays) deposit between 10% and 90% of their energy in the EM calorimeters. To further reduce cosmic rays, we reject events with a large energy deposition in the central hadron calorimeter out of time with the beam-beam crossing. To remove dijet events with large $\not\!\!E_T$ due to mismeasurement, we reject events with a cluster in the calorimeters with $E_T \geq 5$ GeV opposite in ϕ to the highest E_T jet ($\pm 30°$). This selection yields 1226 events.

A series of more stringent cuts are made in order to get a final sample of events which could contain SUSY particles. The first of these cuts is designed to select events with a well-measured large $\not\!\!E_T$ by requiring $\not\!\!E_T \geq 40$ GeV (281 events survive), and $\not\!\!E_T$ significance $S \geq 2.8$, where $S \equiv \not\!\!E_T/\sqrt{\Sigma E_T}$ (GeV$^{1/2}$) and the sum is over all calorimeter cells (257 events survive). The S cut removes most events with $\not\!\!E_T$ induced by measurement fluctuations. For an event sample with no muons, neutrinos, or other noninteracting particles, we expect the S distribution to reflect the $\not\!\!E_T$ resolution of the detector. Figure 1 shows the observed S distribution for dijet events (jet $E_T > 25$ GeV) to be adequately described by the CDF detector simulation program. This gives confidence that, for events with jets in this E_T range, the simulation correctly models the detector resolution.

We next required the following: (1) No muon candidates of transverse momentum $P_T > 15$ GeV/c. This rejects $W \rightarrow \mu\nu$ and $Z \rightarrow \mu^+\mu^-$ decays (230 events survive). (2) No calorimeter clusters with $E_T > 15$ GeV and $\geq 90\%$ energy deposited in EM calorimeters. This rejects $W \rightarrow e\nu$ decays (196 events survive). (3) No jet cluster within $\pm 30°$ in ϕ from the $\not\!\!E_T$ direction. This rejects mismeasured multijet events (124 events survive). (4) At least one central jet ($|\eta| < 1.0$) with a ratio of summed charged-track momenta to cluster energy ≥ 0.2. This rejects events where timing information from the central hadron calorimeter was unavailable to eliminate cosmic rays (116 events survive). (5) An interaction vertex within ± 60 cm of the detector center on the beam axis and no other beam interaction vertex (100 events survive).

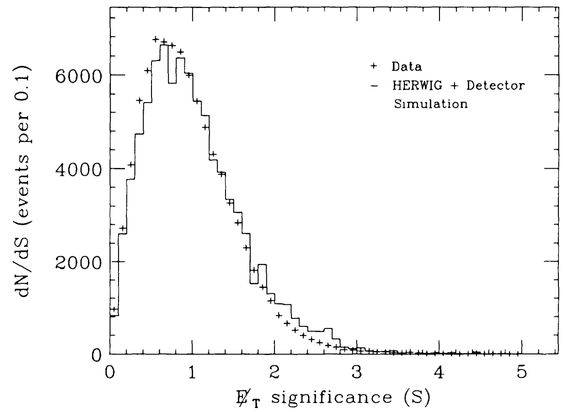

FIG. 1. Missing-E_T significance distribution for a jet sample (jet $E_T > 25$ GeV) compared with the predictions from the HERWIG [9] Monte Carlo and CDF detector simulation.

Remaining events are inspected on a graphics display. We remove one beam-gas collision, one cosmic ray event, and five events with detector malfunctions. The final sample of 93 events has 71 events with two jets, 20 with three jets, and 2 with four jets (jet $E_T > 15$ GeV).

Backgrounds from W and Z production and decay which pass our selection cuts are calculated with a Monte Carlo program [10] and a simulation of our detector. This predicts 23 ± 8 $Z \rightarrow \nu\bar{\nu}$, 41 ± 15 $W \rightarrow \tau\nu$, 18 ± 6 $W \rightarrow \mu\nu$, and 9 ± 3 $W \rightarrow e\nu$ events in our data sample. We also expect events with heavy quark decays (dominated by $b\bar{b}$) and mismeasured jet events. Based on the distribution of angular separations between jet and $\not\!\!E_T$ directions, we estimate 4 ± 4 events from these sources, all with $\not\!\!E_T < 55$ GeV. The total predicted event rate from background (95 ± 19 events) and its associated $\not\!\!E_T$ spectrum agree well with the rate and spectrum for the 93 events in our data (Fig. 2).

We observe two events with $\not\!\!E_T > 150$ GeV. The highest $\not\!\!E_T$ event has $\not\!\!E_T = 185.9$ GeV with three jet clusters: $E_T = 183.9$, 33.8, and 11.3 GeV. The second highest $\not\!\!E_T$ event has $\not\!\!E_T = 167.8$ GeV with four jets: $E_T = 144.7$, 46.6, 19.3, and 16.5 GeV. The third of these jets contains an electron candidate with $E_T = 11.3$ GeV/c. The transverse mass calculated from the electron and $\not\!\!E_T$ vector is 57.2 GeV/c^2. The W or Z plus jets Monte Carlo calculation predicts 0.2 event with $\not\!\!E_T > 150$ GeV will pass our cuts. However, note that this Monte Carlo program only

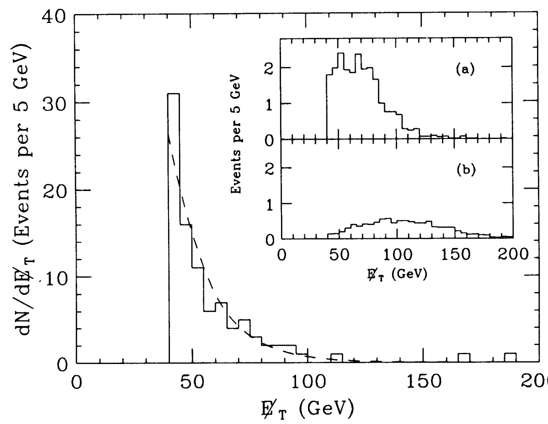

FIG. 2. Missing-E_T distribution (solid line) for the data set described in the text, compared with the estimated background predictions (dashed line) obtained using the Monte Carlo program of Ref. [10] together with the CDF detector simulation plus the estimated QCD background. Insets: Predicted $\not{E}_T$ distributions for squark and gluino production from ISAJET (version 6.22) and the CDF detector simulation for (a) $m_{\tilde{q}}=125$ GeV/c^2 and $m_{\tilde{g}}=5000$ GeV/c^2, and (b) $m_{\tilde{g}}=225$ GeV/c^2 and $m_{\tilde{q}}=225$ GeV/c^2.

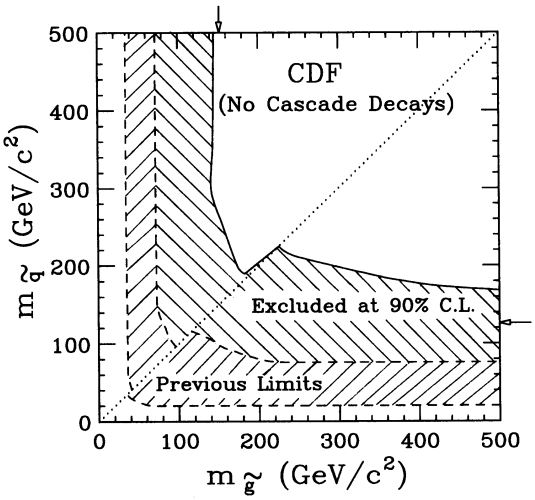

FIG. 3. Squark and gluino mass limits for a version of SUSY with a light photino ($m_{\tilde{\gamma}}<15$ GeV/c^2), six mass-degenerate squarks, and no cascade decays. The region of $m_{\tilde{q}}$ vs $m_{\tilde{g}}$ plane excluded at 90% C.L. is shown. The dashed lines are boundaries of the region excluded by our previous analysis [4]. The solid line indicates the added region excluded by the present analysis. Asymptotic limits are indicated by the arrows. The discontinuity at $m_{\tilde{q}}=m_{\tilde{g}}$ reflects the change in the expected decay chain. Squark masses below 45 GeV/c^2 are excluded by data from LEP [15].

simulates W or Z production with up to three jets. We believe that the two observed events do not constitute a statistically significant deviation from the standard model prediction.

To confirm the predicted backgrounds from W and Z decays, we have used 2700 $W\rightarrow e\nu$ events recorded by CDF and exploited the kinematic similarity [11] to the processes below. For each topology, the result is corrected by the ratio of acceptances between the $W\rightarrow e\nu$ and the $\not{E}_T$ sample.

(1) $Z\rightarrow \nu\bar{\nu}$. We use W events to simulate this process by removing the electron from the W decays, and correcting for electron detection efficiency, W and Z cross sections, and branching ratios $[\sigma B(Z\rightarrow \nu\bar{\nu})/\sigma B(W\rightarrow e\nu)=0.59]$ [12], we expect 33.5 ± 9.1 $Z\rightarrow \nu\bar{\nu}$ decays in our $\not{E}_T$ sample.

(2) $W\rightarrow \tau\nu$ [13]. This contribution is computed by replacing the electrons in $W\rightarrow e\nu$ by simulated $\tau\rightarrow$ hadrons$+\nu$. We expect 31.5 ± 9.8 decays in our $\not{E}_T$ sample.

(3) $W\rightarrow \mu\nu$, where the muon has not been identified in the detector. This contribution is computed by replacing the electrons in $W\rightarrow e\nu$ decays with simulated muons. We expect 17.1 ± 5.3 $W\rightarrow \mu\nu$ events in our $\not{E}_T$ sample.

We also inspected our $\not{E}_T$ sample on a graphic display for $W\rightarrow e\nu$ decays where the electron P_T is below 15 GeV/c or the electron cluster fails the EM fraction cut. There are five such events. After correcting for detector acceptance and kinematic cuts this corresponds to 6.4 ± 2.9 such events in our sample.

The total background, 88 ± 15 events, from W and Z processes estimated using CDF W data is consistent with the Monte Carlo calculation, 91 ± 19 events. In the following, the Monte Carlo predictions for background are used to extract limits on SUSY particle production.

To explore our sensitivity to a SUSY signal, we generate SUSY events using the ISAJET [14] Monte Carlo program (version 6.22) and EHLQ1, EHLQ2 (Eichten-Hinchliffe-Lane-Quigy), DO1, and DO2 (Duke-Owens) structure functions. The lowest rate comes from the EHLQ1 structure function, which is used to provide a conservative production limit for SUSY particles. There are several sources of uncertainty in the predicted rate: $\pm 6.8\%$ in rate from the integrated luminosity, $\pm 10\%$ in rate from the $\pm 5\%$ uncertainty in the energy scale, $\pm 3\%$ in rate from the uncertainty on the $\not{E}_T$ trigger efficiency, and $\pm 15\%$ from various sources in the Monte Carlo calculation—the choice of Q^2, α_s evolution, and the limited number of events generated. The combined acceptance of the simulated detector and analysis programs for generated SUSY events is heavily dependent on the choice of $\tilde{q}$ and $\tilde{g}$ masses. For the mass region we studied, it varies from 3% to 25%.

Our limits on $m_{\tilde{q}}$ and $m_{\tilde{g}}$ are based on a comparison of the observed $\not{E}_T$ distribution with predictions for the standard model background based on the Monte Carlo program of Ref. [10] plus the SUSY contribution based on the ISAJET Monte Carlo samples. For each hypothesized $m_{\tilde{q}}$ and $m_{\tilde{g}}$ we fitted the observed $\not{E}_T$ distribution over the full $\not{E}_T$ range using a binned likelihood method. The resulting upper limit on the rate of SUSY particle production is then compared with the predicted SUSY cross section. Note that if the measured calorimeter energy scale

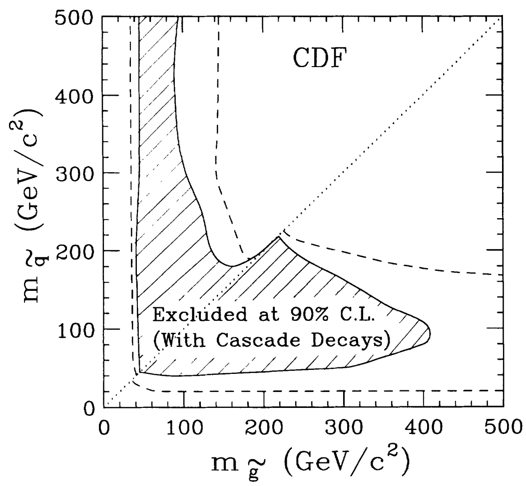

FIG. 4. The shaded region of squark and gluino masses is excluded at 90% C.L. for a version of SUSY with cascade decays, $\mu=-250$ GeV, $\tan\beta=2$, and $m_H=500$ GeV/c^2. For comparison, the dashed line shows the limits corresponding to no cascade decays.

is less than the true scale, the predicted standard model contributions are reduced and the limits are weakened. In extracting our limits to take into account this systematic uncertainty we have reduced the detector energy scale in the Monte Carlo simulation by 5%. The resulting region of the $m_{\tilde{q}}$ vs $m_{\tilde{g}}$ plane excluded at 90% C.L. is shown in Fig. 3. The symmetric and asymptotic points on the limiting boundary are $m_{\tilde{q}}=m_{\tilde{g}}=m=225$ GeV/c^2, $m_{\tilde{q}}=126$ GeV/c^2 (at $m_{\tilde{g}}=5000$ GeV/c^2), and $m_{\tilde{g}}=152$ GeV/c^2 (at $m_{\tilde{q}}=5000$ GeV/c^2). We exclude at the 90% confidence level the existence of squarks and gluinos with masses less than 126 and 141 GeV/c^2, respectively.

Finally we extracted the limits shown in Fig. 4 for cascade decays with a particular choice of SUSY parameters: $\mu=-250$ GeV, $\tan\beta=2$, and $m_H=500$ GeV/c^2 as used in Ref. [5]. The weakened limits are due to cascade decays and nonzero LSP mass. For a gluino mass greater than 410 GeV/c^2, we can place no limit on the squark mass.

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