Search for Gluinos and Scalar Quarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV Using the Missing Energy plus Multijets Signature


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We have performed a search for gluinos ($\tilde{g}$) and scalar quarks ($\tilde{q}$) in a data sample of 84 pb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, recorded by the Collider Detector at Fermilab. We investigate the final state of large missing transverse energy and three or more jets, a characteristic signature in R-parity-conserving supersymmetric models. The analysis has been performed "blind," in that the inspection of the signal region is made only after the predictions from standard model backgrounds have been calculated. Comparing the data with predictions of constrained supersymmetric models, we exclude gluino masses below 195 GeV/c$^2$ (95% C.L.), independent of the squark mass. For the case $m_{\tilde{q}} = m_{\tilde{g}}$, gluino masses below 300 GeV/c$^2$ are excluded.

The standard model (SM) [1] accurately describes physical phenomena down to scales of $\sim 10^{-16}$ cm. There are many extensions of the standard model to smaller length scales, including extra gauge interactions, new matter, new levels of compositeness, and supersymmetry (SUSY). Of these, supersymmetry [2] treats the bosonic and fermionic degrees of freedom equally and provides a robust extension to the standard model. For simplicity, the minimal construction (MSSM) is often used to link SUSY with the standard model [3]. The most general MSSM would induce proton decay with a weak-interaction lifetime; to avoid this, baryon and lepton conservation are required in the MSSM by postulating a new conserved lifetime; the most general MSSM construction (MSSM) is often used to link SUSY to the standard model [3]. Of these, supersymmetry [2] treats the bosonic and fermionic degrees of freedom equally and provides a robust extension to the standard model. For simplicity, the minimal construction (MSSM) is often used to link SUSY with the standard model [3]. The most general MSSM would induce proton decay with a weak-interaction lifetime; to avoid this, baryon and lepton conservation are required in the MSSM by postulating a new conserved lifetime; the most general MSSM construction (MSSM) is often used to link SUSY to the standard model [3]. Of these, supersymmetry [2] treats the bosonic and fermionic degrees of freedom equally and provides a robust extension to the standard model. For simplicity, the minimal construction (MSSM) is often used to link SUSY with the standard model [3].

We investigate whether the production and decay of gluinos and scalar quarks is observable in the rate of $\geq 3$ jet events with large missing transverse energy at the Collider Detector at Fermilab (CDF). The large missing energy would originate from the two LSPs in the final states of the squark and gluino decays. The three or more hadronic jets would result from the hadronic decays of the $\tilde{g}$ and/or $\tilde{q}$. We use the ISAJET Monte Carlo (MC) program [4] with $\tan\beta = 3$ to generate datasets of squark and gluino events, and the PROSPINO program [5] to calculate the production cross sections. To be conservative, only the first two generations of squarks ($\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}$) are assumed to be produced [6] in the general MSSM framework; we additionally consider production of the bottom squark ($\tilde{b}$) in the mSUGRA case. The search is based on 84 $\pm 4$ pb$^{-1}$ of integrated luminosity recorded with the CDF detector during the 1994-1995 Tevatron run.

The CDF detector is described in detail elsewhere [7]. The momenta of charged particles are measured in the central tracking chamber, which is positioned inside a 1.4 T superconducting solenoidal magnet. Outside the magnet, electromagnetic and hadronic calorimeters arranged in a projective tower geometry cover the pseudorapidity region $|\eta| < 4.2$ [8] and are used to identify jets. Jets are defined as localized energy depositions in the calorimeters and are reconstructed using an iterative clustering algorithm with a fixed cone of radius $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7$ in $\eta$ and $\phi$ space [9]. Jets are ordered in transverse energy, $E_T = E \sin\theta$, where $E$ is the scalar sum of energy deposited in the calorimeter towers within the cone, and $\theta$ is the angle formed by the beam line, the event vertex [10], and the cone center.

The missing transverse energy is defined as the negative vector sum of the transverse energy in the electromagnetic and hadronic calorimeters, $\vec{E}_T = - \sum_i (E_i \sin \theta_i) \hat{\eta}_i$, where $E_i$ is the energy of the $i$th tower, $\eta_i$ is a transverse unit vector pointing to the center of each tower, and $\theta_i$ is the polar angle of the tower; the sum extends to $|\eta| < 3.6$. The data sample was selected with an online trigger which requires $E_T \equiv |\vec{E}_T| > 30$ GeV.
We use a two-stage preselection to reject accelerator- and detector-related backgrounds, beam halo, and cosmic ray events. The first stage is based on timing and energy information in the calorimeter towers to reject events out-of-time with a $p\bar{p}$ collision. The second stage uses the event electromagnetic fraction ($F_{\text{em}}$) and event charged fraction ($F_{\text{ch}}$) to distinguish between real and fake jet events [11]. The preselection requirements and the corresponding missing transverse energy spectra are presented in Fig. 1. At least three jets with $E_T \geq 15$ GeV, at least one of them within $|\eta| < 1.1$, are then required in events that pass the preselection. A total of 107,509 events, predominantly from QCD multijet production, survive the three-jet requirement.

The observed missing energy in QCD jet production is largely a result of jet mismeasurements and detector resolution. A jet is considered nonfiducial if it is within 0.5 rad in $\phi$ of the $E_T$ direction and also points in $\eta$ to a detector gap. The second and third highest $E_T$ jets in an event are required to be fiducial. We eliminate the residual QCD component by using the correlation in the event are required to be fiducial. We eliminate the residual QCD component by using the correlation in the $T_1, \ldots, T_n$ versus $\phi_{\text{leading jet}} - \phi_{T_1}$ plane. We accept events with $R_1 > 0.75$ rad and $R_2 > 0.5$ rad, where $R_1 = \sqrt{\delta \phi_1^2 + (\pi - \delta \phi_1)^2}$ and $R_2 = \sqrt{\delta \phi_2^2 + (\pi - \delta \phi_2)^2}$.

To avoid potential a posteriori biases when searching for new physics in the tails of the missing transverse energy distribution, once we define the signal candidate data sample we make it inaccessible. This analysis approach is often referred to as a “blind analysis” and the signal candidate data sample as a “blind box.” The blind box data are inspected only after the entire search path has been defined by estimating the total standard model backgrounds and optimizing the sensitivity to the supersymmetric signal. We use three variables to define the signal candidate region: $E_T, H_T \equiv E_{T(2)} + E_{T(3)} + E_T$, and isolated track multiplicity, $N_{\text{iso}}^{\text{trk}}$ [14]. The blind box contains events with $E_T \geq 70$ GeV, $H_T \geq 150$ GeV, and $N_{\text{iso}}^{\text{trk}} = 0$. The analysis path is shown in Table I. We reduce the background contribution from $W(\rightarrow e\nu) +$ jets and $t\bar{t}$ production by requiring the two highest energy jets not be purely electromagnetic (jet electromagnetic fraction $f_{\text{em}} < 0.9$). We further reduce the contribution from QCD backgrounds (mismeasured jets) by requiring the $E_T$ vector not be closer than 0.3 rad in $\phi$ to any jet in the event.

We expect events with large missing energy and $\geq 3$ jets in the final state primarily from QCD multijet production, the processes $Z(\rightarrow \nu\bar{\nu}) + \geq 3$ jets, $W(\rightarrow \tau\nu) + \geq 2$ jets (the third jet originating from the hadronic $\tau$ decay), and $t\bar{t}$ production. To estimate the $Z +$ jets and $W +$ jets backgrounds we use the VECBOS MC [15]. We normalize the MC predictions using the observed $Z(\rightarrow ee) +$ jets data sample. For the QCD predictions we use the HERWIG MC program [16] and normalize to the high statistics jet data samples. We estimate the backgrounds from $t\bar{t}$, single top and diboson events using MC predictions [16,17], which we normalize using the respective theoretical cross section calculations for these processes [18].

There are seven control regions around the blind box formed by inverting the requirements which define it (i.e., by changing the direction of the inequalities shown in Table II). We compare the standard model background predictions in the control regions with the data. The results are shown in Table II. Of the 76 events predicted in the blind box, 41 come from QCD and 35 from electroweak processes. Of the latter we estimate $\sim 37\%$ coming from $Z(\rightarrow \nu\bar{\nu}) + \geq 3$ jets, $\sim 20\%$ from $W(\rightarrow \tau\nu) + \geq 2$ jets, $\sim 20\%$ from the combined $W(\rightarrow e\mu(r_{\mu})) + \geq 3$ jets, and $\sim 20\%$ from $t\bar{t}$ production and decays. We also compare the kinematic properties between standard model

![FIG. 1. The $E_T$ spectrum after the online trigger [12] and the two stages of the data preselection. The numbers of events surviving the first and second selections are 892,395 and 286,728, respectively. The variables $E_{\text{out}}, N_{\text{out}}$ are energy and number of towers out of time [13].](image)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Events</th>
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<td>Preselection</td>
<td>286,728</td>
</tr>
<tr>
<td>$N_{\text{jet}} \geq 3$ ($\Delta R = 0.7, E_T \geq 15$ GeV)</td>
<td>107,509</td>
</tr>
<tr>
<td>Fiducial second, third jet</td>
<td>57,011</td>
</tr>
<tr>
<td>$R_1 &gt; 0.75$ rad, $R_2 &gt; 0.5$ rad</td>
<td>23,381</td>
</tr>
<tr>
<td>$E_T \geq 70$ GeV, $H_T \geq 150$ GeV, $N_{\text{iso}}^{\text{trk}} = 0$</td>
<td>Blind box (Signal region)</td>
</tr>
<tr>
<td>$E_{T(1)} \geq 70$ GeV</td>
<td>6435</td>
</tr>
<tr>
<td>$E_{T(2)} \geq 30$ GeV</td>
<td>6013</td>
</tr>
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<td>$</td>
<td>\eta</td>
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predictions and the data around the box and find them to be in agreement [13].

To probe the SUSY parameter space in a simple and comprehensive way, we divide the $m_{\tilde{q}}$-$m_{\tilde{g}}$ plane into four general regions: (A) $m_{\tilde{q}} > m_{\tilde{g}}$ (mSUGRA, five $\tilde{q}$); (B) $m_{\tilde{q}} \sim m_{\tilde{g}}$ (mSUGRA, five $\tilde{q}$); (C) $m_{\tilde{q}} < m_{\tilde{g}}$ (cMSSM, four $\tilde{q}$); (D) $m_{\tilde{q}} \ll m_{\tilde{g}}$ (cMSSM, four $\tilde{q}$). We analyze representative points of each region and optimize the $E_T$ and $H_T$ requirements for increased sensitivity to the signal. The ratio $N_{SUSY}^\text{Data}$ is maximized in region A for $E_T \geq 90$ GeV and $H_T \geq 160$ GeV; in region B for $E_T \geq 110$ and $H_T \geq 230$ GeV; in C for $E_T \geq 110$ and $H_T \geq 170$ GeV; and in D for $E_T \geq 90$ and $H_T \geq 160$ GeV, where $N_{SUSY}$ is the number of signal events and $N_{SM}$ is the number of standard model background events. The signal efficiency ranges between 1% and 14% for the different points in the parameter space, and its total relative systematic uncertainty (mostly due to parton density functions, gluon radiation, renormalization scale, and jet energy scale) ranges between 10% and 15%.

In the blind box, where we expect $76 \pm 13$ standard model events, we observe 74 events. In Fig. 2 the predicted standard model kinematic distributions are compared with the distributions we observe in the data. For the $A/D$, $B$, and $C$ region requirements, we observe 31, 5, and 14 events where we expect $33 \pm 7$, $3.7 \pm 0.5$, and $10.6 \pm 0.9$ events, respectively. Based on the observations, the standard model estimates and their uncertainties, and the relative total systematic uncertainty on the

<table>
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<th>Region definition</th>
<th>$E_T \geq 70$, $H_T \geq 150$, $N_{iso}^{10} &gt; 0$</th>
<th>$E_T \geq 70$, $H_T &lt; 150$, $N_{iso}^{10} = 0$</th>
<th>$35 &lt; E_T &lt; 70$, $H_T &gt; 150$, $N_{iso}^{10} &gt; 0$</th>
<th>$E_T &gt; 70$, $H_T &lt; 150$, $N_{iso}^{10} &gt; 0$</th>
<th>$35 &lt; E_T &lt; 70$, $H_T &lt; 150$, $N_{iso}^{10} = 0$</th>
<th>$35 &lt; E_T &lt; 70$, $H_T &lt; 150$, $N_{iso}^{10} &gt; 0$</th>
<th>$35 &lt; E_T &lt; 70$, $H_T &lt; 150$, $N_{iso}^{10} &gt; 0$</th>
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<tbody>
<tr>
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<td>$E_T \geq 70$, $H_T &lt; 150$, $N_{iso}^{10} = 0$</td>
<td>$35 &lt; E_T &lt; 70$, $H_T &gt; 150$, $N_{iso}^{10} &gt; 0$</td>
<td>$E_T &gt; 70$, $H_T &lt; 150$, $N_{iso}^{10} &gt; 0$</td>
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<td>QCD</td>
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<td>14</td>
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<td>5</td>
<td>10</td>
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<tr>
<td>2.3</td>
<td>6.3</td>
<td>8.6</td>
<td>4.5</td>
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<td>1.95</td>
<td>135</td>
<td>137</td>
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<td>1.7</td>
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<td>3.3</td>
<td>28</td>
<td>31</td>
<td>10</td>
<td>35</td>
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signal efficiency, we derive the 95% C.L. [19] upper limit on the number of signal events. The bound is shown on the \(m_\tilde{q}-m_\tilde{g}\) plane in Fig. 3. For the signal points generated with mSUGRA, the limit is also interpreted in the \(M_0-M_{1/2}\) plane [13]. Studies of the dependence on the value of \(\tan\beta\) can be found in [20,21].

In conclusion, a search for gluinos and squarks in events with large missing energy plus multijets excludes at 95% C.L. gluino masses below 300 GeV/c\(^2\) for the case \(m_\tilde{q} = m_\tilde{g}\), and below 195 GeV/c\(^2\), independent of the squark mass, in constrained supersymmetric models. This is a significant extension of previous bounds.

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[6] The third generation of squarks can contain states that are lighter than the (assumed degenerate) first and second generation squarks. Alternative search signatures involving \(b\) and \(c\) quark tagging are used for scalar bottom and scalar top searches, as in CDF Collaboration, T. Affolder et al., Phys. Rev. Lett. 85, 5704 (2000).
[8] In the CDF coordinate system, \(\phi\) and \(\theta\) are the azimuthal and polar angles with respect to the proton beam direction. The pseudorapidity \(\eta\) is defined as \(-\ln(\tan(\theta/2))\).
[10] If there are multiple vertices in the event we use the vertex with the largest \(\sum P_T\) of associated tracks.
[11] \(F_{\text{em}} = (\sum_{j=1}^{N_{\text{jet}}} E_T^j \times f_{\text{em}(j)}/(\sum_{j=1}^{N_{\text{jet}}} E_T^j))\), where \(N_{\text{jet}}\) is the number of jets of cone 0.7 with \(E_T > 10\) GeV and \(f_{\text{em}(j)}\) is the electromagnetic fraction of the \(j\)th jet. \(F_{\text{em}} = \langle [\sum_{\text{tracks}} P_T]\rangle/E_T\rangle\), where \(\sum_{\text{tracks}} P_T\rangle\) is the sum of the \(P_T\) of all the tracks \(i\) matched with a central jet \(j\).
[12] The shoulder in the online \(E_T\) distribution is due to the contribution of a trigger that requires a jet above 100 GeV.
[14] \(N_{\text{trk}}^{\text{miss}}\) is the number of high momentum isolated tracks in the event. Tracks qualify as such if they have transverse momentum \(P_T \approx 10\) GeV/c, impact parameter \(d_0 \approx 0.5\) cm, vertex difference \(x_{\text{track}} - x_{\text{event}} < 5\) cm and the total transverse momentum \(\sum P_T\) of all tracks (with impact parameter \(d_0 \leq 1\) cm) around them in a cone of \(\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4\) is the \(\sum P_T \leq 2\) GeV/c.