Search for Squarks and Gluinos in Single-Photon Events with Jets and Large Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV


(DoE Collaboration)
We search for physics beyond the standard model using events with a photon, two or more hadronic jets, and an apparent imbalance in transverse energy, in $p\bar{p}$ collisions at the Fermilab Tevatron at $\sqrt{s} = 1.8$ TeV. Such events are predicted for production of supersymmetric particles. No excess is observed beyond expected background. For the parameter space of the minimal supersymmetric standard model with branching fraction $B(\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0) = 1$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20$ GeV, we obtain a 95% confidence level lower limit of 310 GeV for the masses of squarks and gluinos, where their masses are assumed equal.
We search for physics beyond the standard model (SM) using events with one high transverse energy ($E_T$) photon, two or more jets, and large imbalance in transverse energy ($E_T$). We call these $\gamma E_T + \geq 2$ jets events. This search is motivated by recent suggestions that supersymmetry may result in signatures involving one or more photons together with multiple jets and large $E_T$.

Supersymmetry is a generalization of space-time symmetry. It introduces for every particle in the standard model a supersymmetric partner differing in spin by one half. $R$-parity is defined as +1 for SM particles and −1 for their super-partners, is assumed to be conserved in this analysis, such that supersymmetric particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. In the minimal supersymmetric standard model (MSSM), the gaugino-Higgsino sector (excluding gluinos) is described by four parameters: $M_1$, $M_2$, $\mu$, and $\tan\beta$, where $M_1$ and $M_2$ are the U(1) and SU(2) gaugino mass parameters, $\mu$ is the Higgsino mass parameter, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets. Gaugino-Higgsino mixing gives four neutral mass eigenstates (neutralinos $\tilde{\chi}_i^0$, $i = 1, ..., 4$) and two charged mass eigenstates (charginos $\tilde{\chi}_i^\pm$, $i = 1, 2$). Within the MSSM, the radiative decay of $\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$ dominates in the region $50 \lesssim M_1 \sim M_2 \lesssim 100$ GeV, $1 \lesssim \tan\beta \lesssim 3$ and $-65 \lesssim \mu \lesssim -35$ GeV of parameter space, and has been proposed as an explanation of a candidate event reported by the CDF Collaboration. Assuming that $\tilde{\chi}_1^0$ is the LSP, then the production of $\tilde{\chi}_2^0$, either directly or from decays of other supersymmetric particles, will yield $\gamma E_T + X$ events.

In this Letter, we present a search for physics beyond the SM in the channel $p\bar{p} \rightarrow \gamma E_T + \geq 2$ jets at the Fermilab Tevatron collider. Because of large backgrounds from QCD processes, we do not consider events with less than two jets. We interpret our results in terms of squark ($\tilde{q}$) and gluino ($\tilde{g}$) production in the context of supersymmetric models with a dominant $\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0$ decay.

The data used in this analysis were collected with the DØ detector during the 1992–1996 Tevatron run at a center of mass energy of $\sqrt{s} = 1.8$ TeV, and represent an integrated luminosity of 99.4 $\pm$ 5.4 pb$^{-1}$. A detailed description of the DØ detector can be found in Ref. 1. The trigger requires one electromagnetic (EM) cluster with $E_T > 15$ GeV, one jet with $E_T > 10$ GeV, and $E_T > 14$ GeV ($E_T > 10$ GeV for about 10% of the data taken early in the Tevatron run). Photons are identified via a two-step process: the selection of isolated EM energy clusters, and the rejection of such clusters with any associated charged tracks. The EM clusters are selected from calorimeter energy clusters by requiring: (i) at least 95% of the energy to be deposited in the EM section of the calorimeter; (ii) the transverse and longitudinal shower profiles to be consistent with those expected for an EM shower; and (iii) the energy in an annular isolation cone with radius ($R \equiv \sqrt{\Delta\phi^2 + (\Delta\eta)^2}$) 0.2 to 0.4 around the cluster in $\eta - \phi$ space to be less than 10% of the EM energy in an $R = 0.2$ cone, where $\eta$ and $\phi$ are the pseudorapidity and azimuth, respectively. The EM clusters that have either a reconstructed track or a large number of hits in the tracking chamber along a road joining the cluster and the interaction vertex are vetoed. $E_T$ is determined from the energy deposition in the calorimeter within $|\eta| < 4.5$.

To be selected as $\gamma E_T + \geq 2$ jets candidates, events are first required to have at least one identified photon with $E_T^\gamma > 20$ GeV and pseudorapidity $|\eta^\gamma| < 1.1$ or $1.5 < |\eta^\gamma| < 2.0$, and two or more jets reconstructed with cones of radius $R = 0.5$, having $E_T^j > 20$ GeV and $|\eta^j| < 2.0$. We refer to the events passing these requirements as the $\gamma + \geq 2$ jets sample. The $E_T$ distribution of these events is shown in Fig. 1. We then require $E_T > 25$ GeV. A total of 318 events satisfy all requirements.

![Fig. 1. The $E_T$ distributions of the $\gamma + \geq 2$ jets events. The number of events in the background is normalized to the $\gamma + \geq 2$ jets sample for $E_T < 20$ GeV, the region left of the dot-dashed line. Also shown (dashed and dotted histograms) are the distributions expected from supersymmetry for $m_{\tilde{q}} = m_{\tilde{g}} = 150$ GeV and 300 GeV.](image-url)
the shower profile. These events must also have two or more jets with $E_T^j > 20$ GeV and $|\eta^j| < 2.0$, making them similar to those of the $\gamma + \geq 2$ jets sample, and therefore of similar resolution in $E_T$. The events in this background sample are normalized to the $\gamma + \geq 2$ jets sample for $E_T < 20$ GeV, which provides an estimated background from $E_T$ mismeasurement of $315 \pm 30$ events beyond $E_T = 25$ GeV.

$W + \geq 2$ jets events with $W \rightarrow e\nu$ can mimic $\gamma E_T + \geq 2$ jets events if the electron is misidentified as a photon. This contribution is estimated using a sample of $eE_T + \geq 2$ jets events that pass all our kinematic requirements, with the electron satisfying those defined for the photon. Electrons are selected from identified EM clusters that have matched tracks. The probability that an electron is misidentified as a photon is determined from $Z \rightarrow ee$ events as $0.0045 \pm 0.0008$. Multiplying this probability by the number of $eE_T + \geq 2$ jets events yields a background of $4 \pm 1$ events.

The $W(\rightarrow \nu\nu) +$ jets background is estimated using a data sample of $W(\rightarrow \nu\nu) + \geq 3$ jets events passing all kinematic requirements, with at least one of the jets satisfying those imposed on photons. The probability that a jet is misidentified as a photon is determined by counting the number of photons observed in multijet events. We find this to be $0.0007 \pm 0.0002$. Using this probability and the scale factor $N_{W(\rightarrow \nu\nu) + 3 \text{ jets}}/N_{W(\rightarrow \nu\nu) + 3 \text{ jets}}$ (determined from Monte Carlo), we estimate a background of $1.0 \pm 0.3$ events. The background from $Z(\rightarrow \nu\nu) + \geq 3$ jets is found to be negligible.


table

<table>
<thead>
<tr>
<th>Number of jets</th>
<th>$E_T &gt; 25$ GeV</th>
<th>$E_T &gt; 25$ GeV</th>
<th>$E_T &gt; 50$ GeV</th>
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<tbody>
<tr>
<td></td>
<td>$N_E$</td>
<td>$N_B$</td>
<td>$N_E$</td>
</tr>
<tr>
<td>$n \geq 2$</td>
<td>318</td>
<td>320±1.99</td>
<td>30</td>
</tr>
<tr>
<td>$n \geq 3$</td>
<td>70</td>
<td>70±15</td>
<td>17</td>
</tr>
<tr>
<td>$n \geq 4$</td>
<td>8</td>
<td>10±1.5</td>
<td>6</td>
</tr>
</tbody>
</table>

TABLE I. Number of observed $\gamma E_T + n$ jets events ($N_B$) together with the corresponding number of background events ($N_E$) for $n \geq 2, 3, 4$, for three sets of cutoffs.

The number of observed events and the expected backgrounds are summarized in Table I together with breakdowns into events with three or more and four or more jets. The $H_T$ distribution (defined as the scalar sum of the $E_T$ of all jets with $E_T^j > 20$ GeV and $|\eta^j| < 2.0$) is shown in Fig. 3 for both $\gamma E_T + \geq 2$ jets and background samples. The background distribution is consistent with that observed for $\gamma E_T + \geq 2$ jets. Also given in Table I is the number of observed events and the expected background if the cutoff $H_T > 200$ GeV is applied or if the $E_T$ cutoff is raised to 50 GeV. In all three comparisons, the estimated number of background events agrees with the number of events observed in the data.

To optimize selection criteria for a supersymmetric signal, we simulate squark and gluino pair production, and also production in association with charginos or neutralinos using the SPSHYTA program [6]. The MSSM parameters are set to $M_1 = M_2 = 60$ GeV, $\tan \beta = 2$, and $\mu = -40$ GeV. This set gives $m_{\tilde{\chi}^0_1} = 34$ GeV, $m_{\tilde{\chi}^0_2} = 60$ GeV, and $B(\tilde{\chi}^0_2 \rightarrow \gamma \tilde{\chi}^0_1) = 1$. Sleptons ($\tilde{\ell}$) and stop ($\tilde{t_1}$) are assumed to be heavy. Events with $\tilde{\chi}^0_2$ in the final state are selected and processed through the DO detector-simulation program [8], and the trigger simulator. The same trigger requirements, reconstruction, and selection criteria are then applied as were used with the data. Monte Carlo (MC) events are generated for three squark or gluino mass possibilities: (i) equal mass squark and gluino ($m_{\tilde{q}} = m_{\tilde{g}}$); (ii) heavy squark and light gluino ($m_{\tilde{q}} \gg m_{\tilde{g}}$); and (iii) light squark and heavy gluino ($m_{\tilde{q}} \ll m_{\tilde{g}}$). The $E_T$ and $H_T$ distributions for $m_{\tilde{q}} = m_{\tilde{g}} = 150-300$ GeV events are shown, respectively, in Figs. 1 and 2, where the MC distributions are scaled by the factors shown in parentheses. The distributions expected from supersymmetry differ considerably from those of the background. To increase the sensitivity to supersymmetry, we introduce an $H_T$ cutoff, and maximize the $\epsilon_S/\delta N_B$ ratio by varying the $E_T$ and $H_T$ cutoffs. Here $\epsilon_S$ is the efficiency for signal, and $\delta N_B$ is the uncertainty on the estimated number of background events. To ensure high efficiencies for both low and high squark and gluino masses, the optimization is done for two MC points $m_{\tilde{q}} = m_{\tilde{g}} = 150$ and 300 GeV. The optimum values are $E_T > 35$ GeV and $H_T > 100$ GeV for 150 GeV, and $E_T > 45$ GeV and $H_T > 220$ GeV for 300 GeV. The $\epsilon_S/\delta N_B$ results (a function of squark/gluino mass) for the two sets of optimized cutoffs are equal near 200 GeV. Therefore we apply the cutoffs optimized for the 150 GeV mass point to MC events with squark and

![FIG. 2. The $H_T$ (defined as $\sum_j E_T^j$) distributions of the $\gamma E_T + \geq 2$ jets and background events. The expected distributions from supersymmetry are also shown for comparison.](image-url)
gluino masses below 200 GeV, and apply those optimized for the 300 GeV mass point to masses of 200 GeV or above. The number of events observed for these two sets of cuts is 60 and 5, with 75 ± 17 and 8 ± 6 events expected from background processes. We consequently observe no excess beyond the standard model.

TABLE II. The percentages of events (e0) generated containing χ02 in the final state, and the efficiencies (eS) for their detection using the two sets of optimized cuts of different values of squark/gluino mass. The uncertainties are purely statistical.

<table>
<thead>
<tr>
<th>m̃q̃/m̃g</th>
<th>e0 (%)</th>
<th>eS (%)</th>
<th>m̃q̃(= m̃g̃)</th>
<th>e0 (%)</th>
<th>eS (%)</th>
</tr>
</thead>
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<tr>
<td>150</td>
<td>66.2</td>
<td>15.1±0.8</td>
<td>69.1</td>
<td>11.6±0.9</td>
<td>60.0</td>
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<tr>
<td>200</td>
<td>62.3</td>
<td>7.9±0.6</td>
<td>59.6</td>
<td>5.3±0.6</td>
<td>53.8</td>
</tr>
<tr>
<td>250</td>
<td>59.6</td>
<td>14.8±0.8</td>
<td>49.7</td>
<td>13.6±1.1</td>
<td>55.4</td>
</tr>
<tr>
<td>300</td>
<td>56.1</td>
<td>21.5±1.0</td>
<td>43.1</td>
<td>19.0±1.3</td>
<td>55.4</td>
</tr>
<tr>
<td>350</td>
<td>51.8</td>
<td>22.8±1.1</td>
<td>39.3</td>
<td>23.5±1.5</td>
<td>52.7</td>
</tr>
<tr>
<td>400</td>
<td>46.7</td>
<td>23.5±1.1</td>
<td>33.3</td>
<td>22.7±1.6</td>
<td>54.3</td>
</tr>
</tbody>
</table>

The effect of light sleptons on squark and gluino decays is studied by varying the slepton mass (m̃t = m̃e = m̃μ) from 500 GeV to 80 GeV in the MC. For m̃q̃ = m̃g̃ = 300 GeV MC events, the percentage e0 increases by an additional 25%. sleptons with mass below 80 GeV have already been excluded [10]. The increase in χ02 production increases the mass limit by approximately 10 GeV.

A light stop ̃t1 would also modify squark and gluino decays and would therefore affect χ02 production. If m̃t1 is lowered from 500 GeV to the lower experimental limit of 80 GeV [11], a 15% reduction in χ02 production is predicted. This reduction lowers the limit for equal mass squarks and gluinos by about 6 GeV.

Following the above procedure, we obtain a lower limit for gluino (squark) mass of 240 GeV when squarks together with the leading-order theoretical cross section, calculated using the SPYTHIA program with the CTEQ3L parton distribution functions [8]. The renormalization scale (µRS) is set to the average transverse energy (⟨ET⟩) of the outgoing partons in the calculation. The cross section varies by about ±30% if µRS = 2⟨ET⟩ or µRS = ⟨ET⟩/2 is used. The hatched band represents the range of predictions obtained by varying the supersymmetry parameters with the constraints that B(χ02 → γχ10) = 1 and m̃q̃ - m̃g̃ > 20 GeV, assuming µRS = ⟨ET⟩. The intersection of the limit with the lower edge of the band is at σ × B = 0.38 pb, leading to a lower limit for equal mass squarks and gluinos of 310 GeV at the 95% C.L.
(gluinos) are heavy. Again, these limits vary by approximately 10 GeV if \( \tilde{t}_1 \) and/or sleptons are light.

In summary, we have searched for an excess of \( \gamma E_T \) events with two or more jets in \( pp \) collisions at \( \sqrt{s} = 1.8 \) TeV. Such events are predicted in the minimal supersymmetric standard model. We find that the number of observed \( \gamma E_T + \geq 2 \) jets events agrees well with that expected from background processes. Within the framework of the MSSM, with choices of parameters consistent with \( B(\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0) = 1 \) and \( m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > 20 \) GeV, we obtain a 95\% C.L. lower mass limit of 310 GeV for equal mass squarks and gluinos and of 240 GeV for squarks (gluinos) when gluinos (squarks) are heavy. These limits constrain the models discussed in Ref. [2], but do not exclude all of them.

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