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 squarks ($\tilde{q}$) 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, by investigating the final state of large missing transverse energy and 3 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 $m_{\tilde{g}} \approx m_{\tilde{q}}$, gluino masses below 300 GeV/$c^2$ are excluded.

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baryon and lepton assignments. \( R \)-parity conservation leads to characteristic SUSY signatures with missing transverse energy in the final state due to the stable lightest supersymmetric particle (LSP). We assume in the search described below for the bosonic partners of squarks (squarks) and the fermionic partners of gluons (gluinos) that the LSP is weakly interacting, as is the case for most of the MSSM parameter space.

We consider gluino and squark production within the minimal supergravity model (mSUGRA). In this model the entire SUSY mass spectrum is essentially determined by only five unknown parameters: the common scalar mass at the GUT scale, \( M_0 \); the common gaugino mass at the GUT scale, \( M_{1/2} \); the common trilinear coupling at the GUT scale, \( A_0 \); the sign of the Higgsino mixing parameter, \( \text{sign}(\mu) \); and the ratio of the Higgs vacuum expectation values, \( \tan \beta \). Minimal SUGRA does not make predictions for the part of the \( m_\tilde{g} \)-\( m_\tilde{q} \) mass parameter space where squarks of the first two families are lighter than about 0.8 times the mass of the gluino. Hence for \( m_\tilde{q} < m_\tilde{g} \) we use the constrained MSSM with the set of input parameters being the mass of the gluino, \( m_\tilde{g} \); the \( C\overline{P} \)-odd neutral scalar Higgs mass, \( m_\tilde{H}_0 \); the squark masses, \( m_\tilde{q}_i \); the slepton masses, \( m_\tilde{\ell}_i \); the squark and slepton mixing parameters, \( A_{i(b(c)} \); and \( \mu \) and \( \tan \beta \).

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 \( \tilde{q} \) and/or \( \tilde{g} \). We use the ISAJET Monte Carlo (MC) program with \( \tan \beta = 3 \) to generate datasets of squark and gluino events, and the PROSPINO program 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 in the general MSSM framework; we additionally consider production of the bottom squark \((\tilde{b})\) in the mSUGRA case. The search is based on \( 84 \pm 4 \text{ pb}^{-1} \) of integrated luminosity recorded with the CDF detector during the 1994-95 Tevatron run.

The CDF detector is described in detail elsewhere. The momenta of charged particles are measured in the central tracking chamber (CTC), 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 \( |y| < 4.2 \) 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 $\Delta R \equiv \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7$ in $\eta - \phi$ 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 [1], 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, $E_{\text{miss}} = -\sum_i (E_i \sin \theta_i) \hat{n}_i$, where $E_i$ is the energy of the $i$-th tower, $\hat{n}_i$ 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 on-line trigger which requires $E_{\text{miss}} \equiv |\vec{E}_{\text{miss}}| > 30 \text{ GeV}$.

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 ($F_{em}$) and event charged fraction ($F_{ch}$) to distinguish between real and fake jet events [10]. The preselection requirements and the corresponding missing transverse energy spectra are presented in Figure 1. At least three jets with $E_T \geq 15 \text{ GeV}$, 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. In a QCD multijet event with large missing energy, the highest $E_T$ jet is typically the most accurately measured. When the second or third jet is mismeasured because it lands partially in an uninstrumented region (a ‘gap’), the $E_T$ is pulled close in $\phi$ to the mismeasured jet. A jet is considered non-fiducial 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 $\delta \phi_1 = |\phi_{\text{leading jet}} - \phi_{E_T}|$ versus $\delta \phi_2 = |\phi_{\text{second jet}} - \phi_{E_T}|$ plane. We accept events with $R_1 > 0.75 \text{ rad}$ and $R_2 > 0.5 \text{ rad}$, 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, $N^{\text{iso}}_{\text{trk}}$ [12]. The ‘blind box’ contains events with $E_T \geq 70 \text{ GeV}$, $H_T \geq 150 \text{ GeV}$, and $N^{\text{iso}}_{\text{trk}} = 0$. The large missing transverse energy requirement for the definition of the box is motivated by the requirement that the trigger be fully efficient [13]. The $H_T$ requirement provides good discrimination between signal and background [3]. The $N^{\text{iso}}_{\text{trk}}$ requirement increases the sensitivity of the search for all-hadronic final states by significantly reducing the backgrounds from $W/Z$+jets and top-antitop ($t\bar{t}$) events while retaining the signal cascade decays in which a lepton is produced close to a jet (non-isolated lepton). The analysis path is shown in Table 1. We reduce the background contribution from $W(\to e\nu)$+jets and $t\bar{t}$ production by requiring the two highest energy jets not be purely electromagnetic (jet electromagnetic fraction $f_{em} < 0.9$). 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 estimate the $W$ and $Z$ boson backgrounds by using a leading order perturbative QCD calculation for $W(Z)$+ jets as implemented in the vec-
TABLE I: The data selection path for the $E_T \geq 3$ jets search. After the fourth step, all events that could fall in the ‘blind box’ are removed from the accounting. The events tabulated in the following steps are only in the control bins.

| Requirement | Events |
|-------------|--------|
| Preselection | 286,728 |
| $N_{jet} \geq 3$ ($\Delta R = 0.7$, $E_T \geq 15$ GeV) | 107,509 |
| Fiducial 2nd, 3rd jet | 57,011 |
| $R_1 > 0.75$ rad, $R_2 > 0.5$ rad | 23,381 |
| $E_T \geq 70$ GeV, $H_T \geq 150$ GeV, | |
| $N_{trk}^{iso} = 0$ | |
| $E_T^{(1)} \geq 70$ GeV | 6435 |
| $E_T^{(2)} \geq 30$ GeV | |
| $|\eta| (1$ or $2$ or $3) < 1.1$ | |
| $j_{em(1)}, j_{em(2)} \leq 0.9$ | 6013 |
| $L2$ trigger requirement | 4679 |
| $\delta \sigma_{min}(E_T - j/e) \geq 0.3$ rad | 2737 |

Boson Monte Carlo [1], enhanced with a coherent parton shower evolution of both initial- and final-state partons, hadronization, and a soft underlying event model (vecbos+herwig [4]). Events with large missing transverse energy and $\geq 3$ jets in the final state are expected primarily from $Z(\rightarrow \nu \bar{\nu}) + \geq 3$ jets and $W(\rightarrow \tau \nu) + \geq 2$ jets (the third jet originating from the hadronic $\tau$ decay) processes. The MC predictions for events with $\geq 3$ jets are normalized to the observed $Z(\rightarrow ee) +$ jets data sample via the measured $N_{jet}$ ratio, where $N_{jet}$ is the number of jets. The ratio $\rho \equiv \frac{\sigma(pp\rightarrow W(e^-e^+) + jets)}{\sigma(pp\rightarrow Z(e^-e^+) + jets)}$ is used to normalize the W MC predictions. Assuming lepton universality, the predictions for the number of events with $\geq 2$– and $\geq 3$–jets from $W$ and $Z$ production and decay to all flavors are normalized to the data for $Z(\rightarrow e^+e^-) + \geq 2$ jets. By normalizing the MC predictions to data we avoid large systematic effects due to the renormalization scale, the choice of parton density functions, initial- and final-state radiation, and the jet energy scale. The total uncertainty ($\sim 10\%$) is then dominated by the uncertainty on the luminosity measurement, the uncertainty on the measured ratio $N_{jet}$, and the uncertainty on the predicted ratio $\rho$ as a function of $N_{jet}$.

We estimate the backgrounds from single top, $t\bar{t}$, and diboson events with Monte Carlo predictions normalized using the respective theoretical cross section calculations for these processes. We generate $tt$ events with the PYTHIA MC program [17], normalizing to the fully resummed theoretical cross section $\sigma_{tt} = 5.06^{+0.13}_{-0.36}$ pb for $m_{top} = 175$ GeV/c$^2$ [18]. We assign a total uncertainty of $\pm 18\%$ on the cross-section to take into account the uncertainty on the top quark mass. The top quark can also be produced singly via $W$-gluon fusion and $q\bar{q}$ annihilation with cross sections of $\sigma_{Wq} = 1.7$ pb (±17%), and $\sigma_{W^*\rightarrow t\bar{t}} = 0.73$ pb (±9%) [18]. We use the HERWIG [10] ($W$-gluon fusion) and PYTHIA ($q\bar{q}$ annihilation) programs to generate the single top production processes. We generate boson pair production with the PYTHIA MC and use the calculated cross sections $\sigma_{WW} = 9.5 \pm 0.7$ pb, $\sigma_{WZ} = 2.6 \pm 0.3$ pb and $\sigma_{ZZ} = 1.0 \pm 0.2$ pb [18].

The data samples we use to study and normalize the QCD Monte Carlo predictions consist of events collected by on-line identification of at least one jet with transverse energy above trigger thresholds of 20 and 50 GeV, and with integrated luminosity of 0.094 pb$^{-1}$ and 2.35 pb$^{-1}$, respectively. The corresponding QCD MC samples are generated using the HERWIG program and a CDF detector simulation. The shapes of the $E_T$ and jet multiplicity distributions are in good agreement with the data, as are the jet kinematic distributions. The QCD predictions are absolutely normalized to the data for $N_{jet} \geq 3$. The total uncertainty on the QCD background estimate is $\sim 15\%$, dominated by a $12\%$ uncertainty due to the detector resolution.

There are seven bins around the ‘blind box’ formed by inverting the requirements which define it (i.e. by changing the direction of the inequalities shown in the bin definitions of Table I). We compare the Standard Model background predictions in the bins around the ‘blind box’ with the data. The results are shown in Table II. Of the 35 events from electroweak processes predicted in the ‘blind box’, $\sim 37\%$ are expected from $Z\rightarrow \nu\bar{\nu} + \geq 3$ jets, $\sim 20\%$ from $W\rightarrow \tau\nu + \geq 2$ jets, $\sim 20\%$ from the combined $W\rightarrow e\mu \nu_{e}(\nu_{\mu}) + \geq 3$ jets, and $\sim 20\%$ from $tt$ production and decays. We also compare the kinematic properties between Standard Model predictions and the data around the box and find them to be in agreement.

To probe the SUSY parameter space in a simple and

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TABLE II: Comparison of the Standard Model prediction and the data in the bins neighboring bin 8, the ‘blind box’. After the contents of cons were compared in detail to standard model predictions, we ‘opened the box’. We find 74 events in bin 8.

| Bin Definition | EWK | QCD | All | Data |
|----------------|-----|-----|-----|------|
| $E_T \geq 70, H_T \geq 150, N_{trk}^{iso} > 0$ | 14  | 6.3 | 20±5 | 10  |
| $E_T \geq 70, H_T < 150, N_{trk}^{iso} = 0$ | 2.3 | 6.3 | 8.6±4.5 | 12 |
| $35 < E_T < 70, H_T > 150, N_{trk}^{iso} = 0$ | 1.95 | 135 | 137±28 | 134 |
| $E_T > 70, H_T < 150, N_{trk}^{iso} > 0$ | 1.73 | <0.1 | 1.73±0.3 | 2 |
| $35 < E_T < 70, H_T < 150, N_{trk}^{iso} = 0$ | 5  | 413 | 418±69 | 410 |
| $35 < E_T < 70, H_T < 150, N_{trk}^{iso} > 0$ | 3.3 | 28  | 31±10 | 35 |
| $E_T \geq 70, H_T \geq 150, N_{trk}^{iso} = 0$ | 35 | 41  | 76±13 | □ |
nimize the analyze representative points of each region and opti-
tivity to the signal using MC data. The ratio \( N_{(MSSM, four \tilde{q} m)} \) to SM predicted events. Note that the uncertainty (mostly due to parton density functions, gluon radiation, renormalization scale and jet energy scale) 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±13 Standard Model events, we observe 74 events. In Figure 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 ± 7, 3.7 ± 0.5 and 10.6 ± 0.9 events respectively. Based on the observations, the Standard Model estimates and their uncertainties, and the relative total systematic uncertainty on the signal efficiency, we derive the 95% C.L. upper limit on the number of signal events. The bound is shown on the \( m_{\tilde{q}} - m_{\tilde{g}} \) plane in Figure 3. For the signal points generated with mSUGRA the limit is also interpreted in the \( m_{\tilde{g}}, m_{\chi_0^0} \) plane [13]. Studies of the dependence of the value of \( \tan \beta \) can be found in [21, 27].

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 \( m_{\tilde{g}} \approx m_{\tilde{q}} \), 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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If there are multiple vertices in the event we use the vertex with the largest \( \sum E_T \) defined as

\[
\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4 \text{ is } \sum E_T \leq 2 \text{ GeV/c.}
\]

The measured top cross section (T. Affolder et al., submitted to Phys. Rev. (2001)) is in agreement with the theoretical prediction.

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