Fermi National Accelerator Laboratory

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Search for Squarks and Gluinos in $p\bar{p}$ Collisions at the D0 Detector

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A search for squarks and gluinos has been performed using the DØ detector at the $\sqrt{s} = 1.8$ TeV Tevatron $p\bar{p}$ collider. Data from the 1992-1993 collider run corresponding to an integrated luminosity of 13.5 pb^{-1} were examined via the missing E_T plus jets signature with two separate analyses. No events above Standard Model backgrounds were observed.

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INTRODUCTION

This paper describes a search for the SUSY partners of quarks and gluons, named squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) respectively, performed at the DØ detector in two separate analyses. The large number of SUSY parameters needed to interpret such a search were reduced to five by utilizing a Supergravity–GUT inspired Minimal Supersymmetric Standard Model (MSSM) framework (1). With this model, the low energy SUSY parameters are as follows: masses of the squarks and gluinos, mass of the charged Higgs (m_{H^+}), the Higgs mass mixing parameter (μ), and the ratio of vacuum expectation values of the two Higgs doublets ($\tan\beta$). For this search, we assume that all squarks except the scalar top are mass degenerate. Because the stop is expected to be lighter than the other squarks, it is searched for with a separate analysis not discussed here. The degeneracy of the remaining squarks is motivated by the assumption that all squarks share a common mass at the SUSY breaking scale. With the five parameters and the top quark mass, the masses of SUSY particles, as well as all couplings and branching ratios, are calculable. We assume R–parity, a multiplicative quantum number (+1 for SM particles and -1 for SUSY particles), is conserved. Consequently, SUSY particles must be produced in pairs, and there exists a lightest SUSY particle (LSP) which is stable. From cosmological considerations, the LSP is taken to be the lightest neutralino which escapes detection, producing large amounts of missing energy in the detector. Finally, we assume that squarks and gluinos cascade decay through lighter charginos and neutralinos

TABLE 1. The final selection cuts for the three jet and four jet analyses.

Three Jet Analysis	
Cut	# of events passing
Trigger selection and initial filtering	9625
Single interaction	3730
$\not{E}_T > 75$ GeV	107
3 jets $E_T > 25$ GeV and jet quality	32
Reject jet–$\not{E}_T$ azimuthal correlation	22
No e with $E_T > 20$ GeV and no μ with $p_T > 15$ GeV	17
Reject 1 event with $\not{E}_T$ due to cosmic ray, and 2 with $\not{E}_T$ due to incorrect vertex	**14**

Four Jet Analysis	
Cut	# of event passing
Trigger selection and initial filtering	9163
Single interaction	3347
4 jets $E_T > 20$ GeV and jet quality Reject jet–$\not{E}_T$ azimuthal correlation	223
$\not{E}_T > 65$ GeV	**5**

down to the stable LSP plus normal quarks and leptons. The two analyses involved searching for squarks and gluinos via their hadronic decays with the jets and missing transverse energy ($\not{E}_T$) signature. One analysis required large $\not{E}_T$ and three or more jets (the "three jet analysis"), while the other required four or more jets with a softer $\not{E}_T$ cut (the "four jet analysis"). The three jet analysis is complete and will be published shortly in Physical Review Letters (2). The four jet analysis is preliminary.

THE DETECTOR AND DATA SET

DØ is a large general purpose detector consisting of a central tracking system with no magnetic field, a nearly hermetic liquid argon calorimeter, and a toroidal muon spectrometer. Further details of the detector may be found elsewhere (3). Data used in this analysis were collected during the 1992-1993 run of the Fermilab Tevatron $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collider and corresponds to a total integrated luminosity of 13.5 ± 0.7 pb^{-1}. Events were collected using a missing E_T trigger whose threshold ranged over the course of the run from 20 GeV to 40 GeV of $\not{E}_T$. In both analyses, we required that each event contain only one reconstructed vertex, since events with multiple interactions can introduce uncertainties in jet E_T and $\not{E}_T$ measurements. The uncertainties arise because angles assigned to calorimeter clusters may be incorrect. This single interaction requirement reduced the effective luminosity to 7.2 ± 0.4 pb^{-1}. The uncertainty includes the probability of misidentifying a multiple interaction as a single interaction.

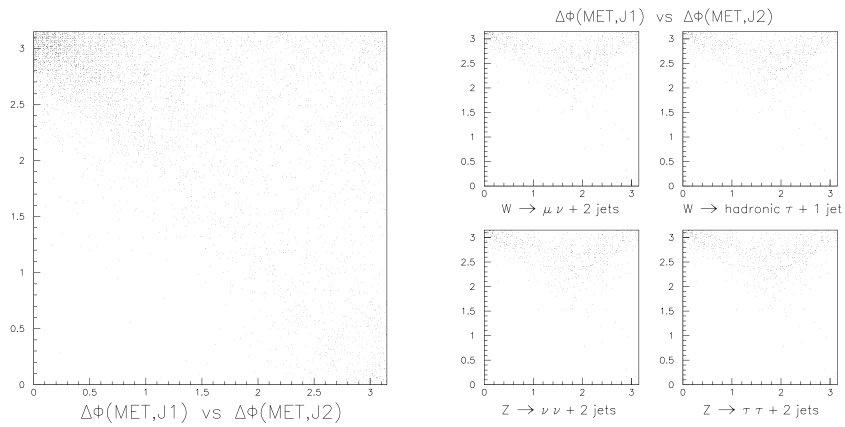

FIG. 1. On each plot the opening angle between the $\not\!\!E_T$ vector and the leading jet runs up the vertical axis, and the angle between $\not\!\!E_T$ and the next leading jet runs along the horizontal axis. On the left is shown events from a low E_T threshold single jet trigger with an offline $\not\!\!E_T > 15$ GeV cut applied. Monte Carlo of some vector boson backgrounds are displayed at right.

EVENT SELECTION AND OFFLINE CUTS

Table 1 describes the offline cuts used for each analysis. The signature for hadronic decays of squarks and gluinos is events with high jet multiplicity from the cascade decays and large missing transverse energy from the LSP's. To select events with this signature, the three jet analysis required at least three jets with E_T above 25 GeV and 75 GeV of missing transverse energy in the event. The four jet analysis required at least four jets above 20 GeV and $\not\!\!E_T$ greater than 65 GeV.

Both searches utilized angular correlation cuts to reject QCD events with badly measured jets that produced large false $\not\!\!E_T$. A jet whose energy has been overestimated tends to be opposite the produced $\not\!\!E_T$, while an underestimated jet will usually be along the false $\not\!\!E_T$ direction. Figure 1 shows clumping of events due to these phenomena which is not characteristic of the SUSY signal or any of the backgrounds with true $\not\!\!E_T$. The dense region is observed, however, in low E_T jet data (after applying a small $\not\!\!E_T$ cut) used to determine detector induced backgrounds. To remove events with this false $\not\!\!E_T$, events with $\not\!\!E_T$ along or opposite (within 0.1 radians) to any of the three leading jets were rejected. Furthermore, to remove more of the dense region of events seen in Fig. 1, we required $(\sqrt{\delta\phi_1 - \pi)^2 + (\delta\phi_2)^2} < 0.5)$ where $\delta\phi_i$ is the azimuthal angle between jet i and the $\not\!\!E_T$ vector. This cut addresses the case where a fluctuation of the second leading jet masks the correlation between the leading jet and the missing transverse energy.

Since only hadronic cascade decays were desired, events with leptons were also rejected (this cut was not needed for the four jet analysis). After final detector clean up cuts were applied, mainly to reject events with noisy calorimeter cells, a total of 17 events pass these cuts for the three jet analysis and 5 events pass for the four jet search. The events passing the three jet analysis cuts were scanned for anomalies. One event consisted of a large calorimeter energy deposit due to a cosmic ray muon, and two events had their vertices reconstructed far from the true origin of the jets. The latter two events were the result of a rare failure of the vertex algorithm. When they were reconstructed with vertices forced to be placed at the jets origin, they both failed the 75 GeV $\not\!\!E_T$ cut. All three of these events were rejected, leaving 14 events for the three jet analysis. The $\not\!\!E_T$ spectrum for these 14

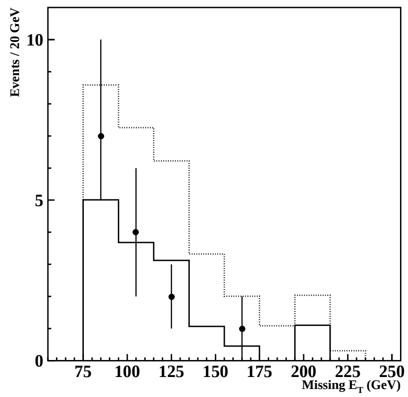

FIG. 2. The $\not\!\!E_T$ distribution of the final 14 candidates for the three jet search is displayed (solid circles with error bars). Also shown are spectra from vector boson background Monte Carlo (solid line, normalized to the luminosity of the data) as well as from this background combined with signal Monte Carlo for $m_{\tilde{g}} = m_{\tilde{q}} = 200$ GeV/c^2 (dotted line, normalized to the luminosity of the data).

events is shown in Fig. 2. Also shown are the background estimation (solid line) and a signal sample ($m_{\tilde{g}} = m_{\tilde{q}} = 200$ GeV/c^2) combined with the background (dotted line). Both the background and combined background and signal estimates are shown normalized to the luminosity of the data.

BACKGROUNDS

The backgrounds are from vector bosons and Standard Model multijet production. W/Z plus jets backgrounds were estimated with the VECBOS (5) Monte Carlo generator utilizing ISAJET (6) to hadronize final partons and supply the underlying event. We produced events specifying the number of jets associated with the W or Z and used ISAJET to handle the decay of tau leptons, taking care to include hadronic decays in the background estimation. The detector response was simulated using the DØGEANT (7) detector simulation program. All events were then reconstructed, and the previously discussed offline cuts were applied. The soon to be published three jet analysis has been updated with improved knowledge of the luminosity and jet energy scale systematic errors as well as a new procedure for treating these uncertainties. A total of 14.2 $\pm$ 4.4 W/Z events are expected to pass the three jet analysis cuts. For the four jet search, 5.5 $\pm$ 2.2 events are predicted. A breakdown of these backgrounds is shown in Table 2.

The contribution from Standard Model multijet production was estimated using data from low jet E_T triggers. In order to obtain good statistics, we fitted the $\not\!\!E_T$ spectrum of events passing the jet-$\not\!\!E_T$ correlation cut and then determined the fraction of events passing the selection requirements as a function of $\not\!\!E_T$. We predict 0.42 $\pm$ 0.37 events for the three jet analysis with its 75 GeV $\not\!\!E_T$ requirement. We expect 1.6 $\pm$ 0.9 events for the four jet search, but this background was not subtracted for a more conservative limit.

The number of events seen in the squark–gluino data sample are consistent with these Standard Model backgrounds and thus no signal was observed.

TABLE 2. Vector boson background estimates.

Channel	Expected # of Events	
	Three Jet Analysis	Four Jet Analysis
$W \to e\nu$	2.7 ± 1.3	1.5 ± 0.7
$W \to \mu\nu$	4.0 ± 1.7	1.8 ± 0.9
$W \to \tau\nu$	3.4 ± 1.5	0.9 ± 0.5
$Z \to \nu\nu$	3.3 ± 1.5	0.9 ± 0.4
$Z \to$ other ℓ	0.9 ± 0.4	0.1 ± 0.1
TOTAL W/Z	14.2 ± 4.4	5.2 ± 2.2

TABLE 3. Parameters and assumptions used for signal Monte Carlo generation.

$$m_{\tilde{\ell}} = m_{\tilde{q}}$$
$$m_{H+} = 500 \text{ GeV/c}^2$$
$$\tan\beta = 2$$
$$\mu = -250 \text{ GeV/c}^2$$
$$m_{top} = 140 \text{ GeV/c}^2$$

MASS LIMIT

We can interpret the lack of excess events as a limit on the masses of $\tilde{g}$ and $\tilde{q}$. Events were generated on a grid of $\tilde{g}$,$\tilde{q}$ mass pairs using the ISASUSY (8) generator and then sent though DØGEANT and the standard reconstruction program. Other MSSM parameters needed to produce the signal Monte Carlo are specified in Table 3. The results of the search are not very sensitive to the choice of charged Higgs mass nor the top quark mass. Signal efficiencies were determined at each mass point by applying the analysis cuts and then interpolating between the points. For example, the efficiency at the point $(m_{\tilde{g}}, m_{\tilde{q}}) = (200$ GeV/c^2, 200 GeV/c^2) for the three jet analysis is 19 $\pm$ 2%, and the expected combined cross section for producing squarks and gluinos at that mass is approximately 10 pb. With these signal efficiencies and background estimates, we determine the 95% confidence limit contour in the $m_{\tilde{g}}$–$m_{\tilde{q}}$ mass plane shown in Fig. 3. Limits from other previous publications (9) are also displayed.

The preliminary updated limit was obtained by combining the three jet and four jet analyses in the following manner. The mass limit for a particular region in the $m_{\tilde{g}}, m_{\tilde{q}}$ plane is calculated from the 95% confidence level cross section limit given by the more sensitive of the two analyses for that region. Sensitivity for an analysis is determined independently from the data by calculating the ratio of the number of Monte Carlo signal events passing the analysis cuts (obtained from a sample appropriate for the region in question) to the square root of the analysis' estimated background. The analysis with the higher ratio is the most sensitive. In the area around the limit, the three jet analysis is more sensitive for small squark mass (below approximately 220 GeV/c^2), while the four jet analysis is the most sensitive for larger squark mass. This procedure yields a preliminary 95% CL lower mass limit of $m_{\tilde{g}} > 173$ GeV/c^2 for large squark mass and a lower mass limit of $m > 229$ GeV/c^2 for the case of equal mass squarks and gluinos.

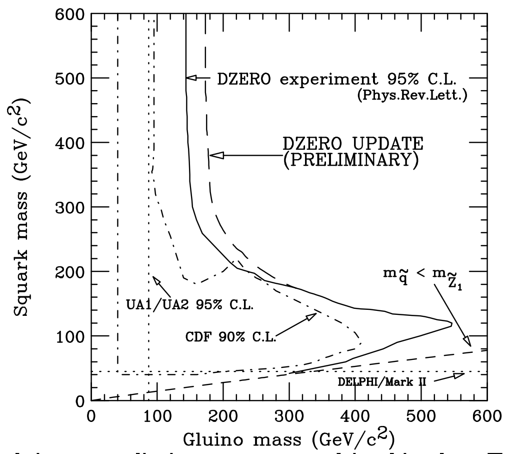

FIG. 3. The squark and gluino mass limits are presented in this plot. The long dashed line marks the *preliminary* DØ 95% confidence level excluded region from the combination of the three jet and four jet analyses. The solid line indicates the DØ three jet search PRL (2) result. The region below the dashed line labeled $m_{\tilde{q}} < m_{\tilde{Z}_1}$ is excluded since there the squark becomes lighter than the LSP. Other published limits from CDF, UA1, UA2, and DELPHI (9) are displayed as well.

CONCLUSION

We have performed two searches for squarks and gluinos with the DØ detector. No signal above Standard Model backgrounds was observed. We set preliminary 95% CL lower mass limit on the gluino mass for very heavy squarks of $m_{\tilde{g}} > 173$ GeV/c^2. If squarks and gluinos have equal mass, the 95% CL lower mass limit is $m > 229$ GeV/c^2.

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