Fermi National Accelerator Laboratory

Search for Squarks and Gluinos in p$\bar{\text{p}}$ Collisions at the DØ Detector with the Jets and Missing Energy Signature

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Distribution

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The DØ Collaboration[1]
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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 discussed at the end of this paper. 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 $(\tilde{Z}_1)$ 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 down to the stable LSP plus normal quarks

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

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"). We present here a preliminary update of our previous publication on the three jet analysis (2).

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.
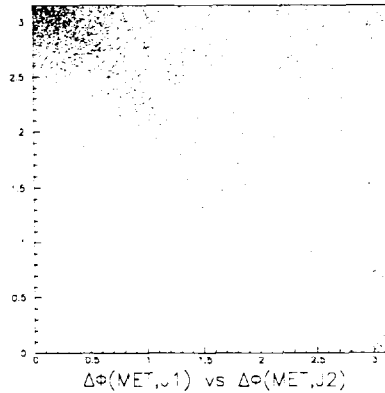
FIG. 1. On this plot the opening angle between the $\not{E}_T$ vector and the leading jet runs up the vertical axis, and the angle between $\not{E}_T$ and the next leading jet runs along the horizontal axis. The events from a low E_T threshold single jet trigger with an offline $\not{E}_T > 15$ GeV cut applied are shown.

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 LSPs. 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
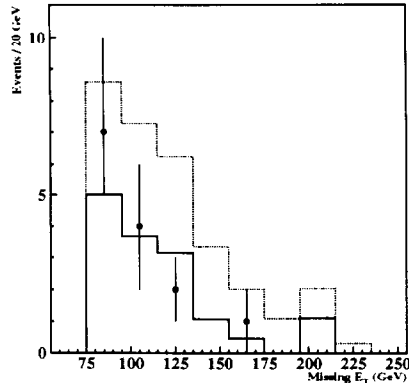
FIG. 2. The $\not{E}_T$ distribution of the final 14 candidates for the three jet search is displayed (solid circles with error bars). Also shown are spectra from vector boson background Monte Carlo (solid line, normalized to the luminosity of the data) as well as from this background combined with signal 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 published three jet analysis has been updated with improved knowledge of the luminosity and jet energy scale as well as a new procedure for treating the associated uncertainties. A total of 14.2 ± 4.4 W/Z events are expected to pass the three jet analysis cuts. For the four jet search, 5.5 ± 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 ± 0.37 events for the three jet analysis with its 75 GeV $\not{E}_T$ requirement. We expect 1.6 ± 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
$W \rightarrow e\nu$	2.7 ± 1.3	1.5 ± 0.7
$W \rightarrow \mu\nu$	4.0 ± 1.7	1.8 ± 0.9
$W \rightarrow \tau\nu$	3.4 ± 1.5	0.9 ± 0.5
$Z \rightarrow \nu\nu$	3.3 ± 1.5	0.9 ± 0.4
$Z \rightarrow$ 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. ISASUSY utilized leading order cross sections for production of supersymmetric particles. 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. Some efficiencies and theoretical cross sections are shown in Table 4.

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. Note that the CDF dilepton analysis is from the 1994-1996 run of the Tevatron and also utilized next to leading order cross sections.

The preliminary updated limit was obtained by combining the three jet and four jet

TABLE 4. Signal production cross sections and efficiencies

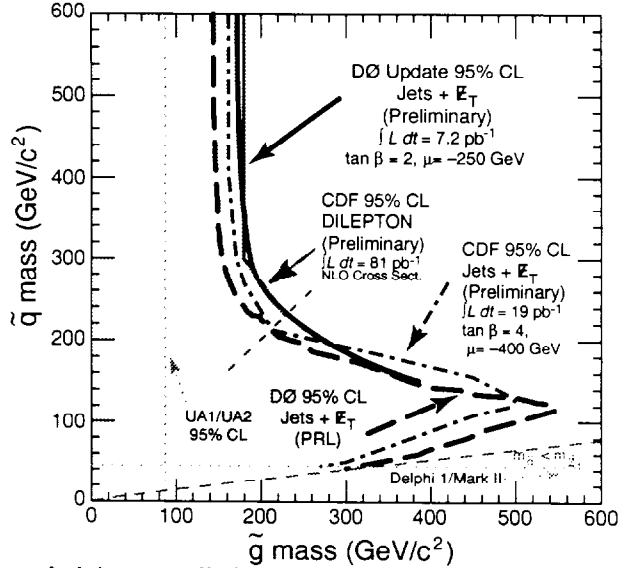| $m_{\tilde{g}}$ (GeV/c^2)	$m_{\tilde{q}}$ (GeV/c^2)	Efficiency	ISASUSY Theoretical Cross section (pb)
175	400	7.5%	9.2
150	300	6.1%	27.5
220	220	7.2%	9.3
300	150	10.5%	35.3
500	150	6.2%	21.2

FIG. 3. The squark and gluino mass limits are presented in this plot. The solid black line marks the *preliminary* DØ 95% confidence level excluded region from the combination of the three jet and four jet analyses. The black dashed 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. Note that the CDF dilepton analysis is from the 1994–1996 run of the Tevatron and utilized next to leading order cross sections.

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/c²), 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/c² for large squark mass and a lower mass limit of $m > 229$ GeV/c² for the case of equal mass squarks and gluinos.

TOP SQUARK SEARCH

The scalar partner of the top quark, the stop, can be lighter than the other squarks. Therefore, a separate analysis has been performed to search for stops, still utilizing the multijet and missing transverse energy signature. This analysis has been previously published (10) and is only briefly described here.

We assume that the stop is lighter than lightest chargino, all of the sleptons and all of the sneutrinos. Therefore, the only decay mode available is to a charm quark and an LSP. Since stops are produced in pairs, the search signature consists of two acolinear jets from the charm quarks and missing transverse energy due to the LSPs. Standard Model backgrounds
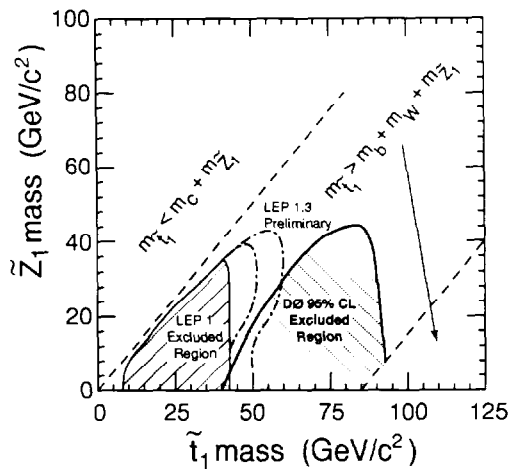
FIG. 4. The stop mass limits are presented in this plot on the stop mass - LSP $(\tilde{Z}_1)$ mass plane. The heavy solid black line marks the DØ 95% confidence level excluded region. The left dashed line indicates the kinematic limit of stop production. The right dashed line indicates where three body decay becomes possible. Such decays are not part of the analysis signature. The limit from LEP 1 and a preliminary limit from LEP 1.3 (dot-dashed curves) are also shown (11) in the figure. The LEP 1.3 limit is dependent on the amount of t_l, t_r mixing in the t_1 mass state. The left dot-dashed curve is for no mixing, and the right curve is for large mixing.

that mimic the signal are vector boson production plus jets and QCD multijet production.

To select signal events and reduce backgrounds, events are required to have $\not{E}_T > 40$ GeV and at least two jets with $E_T > 30$ GeV. Since the two leading jets should be acolinear, the difference in their azimuthal angles is required to be $90° < \Delta\phi(j_1, j_2) < 165°$, where j_1 and j_2 represent the leading and second leading jets respectively. This requirement cuts out some QCD multijet events since they tend to have back-to-back leading jets. To further eliminate the QCD multijet background, we require $10° < \Delta\phi(\not{E}_T, j_1) < 125°$ since QCD multijet events with large $\not{E}_T$ due to mismeasured jets usually have jet directions correlated with the direction of the $\not{E}_T$ vector, as discussed above. In addition, the second, third and fourth jets must not be along the direction of $\not{E}_T$ to within $10°$. To reduce the background due to vector boson production plus jets, events with an electron or muon with $E_T > 10$ GeV are rejected. Finally, events with multiple interactions are also rejected to insure an unambiguous $\not{E}_T$ measurement.

Data corresponding to 13.5 ± 0.7 pb^{-1} were collected using a trigger which required $\not{E}_T > 35$ GeV. The single interaction requirement reduces the collected luminosity to 7.4 ± 0.4 pb^{-1}. This effective luminosity is slightly different than the single interaction luminosity for the squark and gluino analysis because a slightly different data set was utilized in the stop search. Three events are seen in the data that pass all of the analysis criteria.

As in the squark and gluino analysis, VECBOS (5) interfaced with ISAJET (6) was used to estimate the background due to vector boson plus jets production, taking care to include the hadronic decay of taus in the total count of jets in an event. The total number of background events due to vector boson production is predicted to be 3.5 ± 1.2 events.

In order to determine the background due to QCD multijet events, we fit the $\not{E}_T$ spectrum of events collected by a low E_T jet trigger and determine the fraction that pass the analysis selection criteria as a function of $\not{E}_T$. This procedure predicts negligible background due to QCD multijet production. In order to verify this estimate, cuts for the analysis were loosened, allowing more QCD multijet events into the final sample which this method was able to predict successfully.

With three events observed in the data and a prediction of 3.5 events due to the vector boson background, we conclude that there is no excess of events beyond Standard Model processes. With the stop production cross section governed by QCD and since there is only one decay mode, the only SUSY model parameters that need to be specified are the mass of the stop and the LSP mass. Thus, we interpret the lack of an excess as a limit in the $m_{\tilde{t}_1} - m_{\text{LSP}}$ plane. Signal detection efficiencies were determined by using the ISAJET v7.13 (6) event generator along with the DØGEANT (7) detailed detector simulation on a grid of points in the $m_{\tilde{t}_1} - m_{\text{LSP}}$ plane. A Bayesian approach (12) was used to determine the 95% confidence level upper limit contour. Systematic errors are similar to those used in the squark and gluino analysis and are represented as Gaussians. A flat prior probability was used for the signal cross section. The limit contour is displayed in Fig. 4. The gap between the LEP (11) limit and the DØ limit is due to the high trigger threshold used in this analysis.

CONCLUSION

We have performed two searches for squarks and gluinos with the DØ detector. No signal above Standard Model backgrounds was observed. We set a 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.

A search was also performed for scalar top quarks. No excess was observed, and thus we set 95% CL lower mass limits on the stop mass. The largest excluded stop mass is 93 GeV/c^2 corresponding to an 8 GeV/c^2 LSP. The largest excluded stop mass corresponding to the heaviest LSP on the limit contour is an 85 GeV/c^2 stop for a 44 GeV/c^2 LSP. Because the stop and LSP masses are the only parameters needed to specify a SUSY model, this analysis is quite model independent.

The 1994–1996 run of the Fermilab Tevatron has collected an additional ~ 100 pb^{-1} of data, completing Run I of the collider. Both the squark and gluino and the stop analyses are currently being performed with the full Run I data set.

DØ has recently produced results of a search for squarks and gluinos within the a full Supergravity framework utilizing the dielectron plus jets signature. That analysis is described in a companion paper submitted to this conference (13).

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