Fermi National Accelerator Laboratory

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D0

Search for Squarks and Gluinos in Events Containing Jets and a Large Imbalance in Transverse Energy

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Abstract

Using data corresponding to an integrated luminosity of 79 pb^{-1}, DØ has searched for events containing multiple jets and large missing transverse energy in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron collider. Observing no significant excess beyond what is expected from the standard model, we set limits on the masses of squarks and gluinos and on the model parameters m_0 and $m_{1/2}$, in the framework of the minimal low-energy supergravity models of supersymmetry. For $\tan\beta = 2$ and $A_0 = 0$, with $\mu < 0$, we exclude all models with $m_{\widetilde{q}} < 250$ GeV/c^2. For models with equal squark and gluino masses, we exclude $m < 260$ GeV/c^2.

Supersymmetry (SUSY) [1] is a symmetry that relates fermions and bosons, and can solve the hierarchy problem of the Higgs sector of the standard-model (SM) [2]. Minimal SUSY extensions of the SM (MSSM) require partners (sparticles) for all standard model particles: a scalar partner for each quark and lepton (called squarks and sleptons), and a spin-half partner for each of the gauge bosons and Higgs scalars, which form the gluinos and the mixed states called charginos and neutralinos. Such models also require the presence of two Higgs doublets, and thus four Higgs particles. Each particle in a SUSY model has an internal quantum number called R-parity. If R is conserved, as is assumed in this analysis, then sparticle states must be produced in pairs, and each sparticle that decays must contain an odd number of sparticles in its decay products. Consequently, in this scenario, the lightest SUSY particle (LSP) must be stable, and can thereby provide a candidate for dark matter.

The most general supersymmetric extension of the SM has over 100 undetermined parameters. Consequently, models have been developed that contain additional symmetries and constraints. Some of these involve Grand Unified Theories that include a supersymmetry (SUSY-GUTs). In this work, we consider the class of models containing gravity-mediated SUSY breaking, called supergravity (SUGRA) models [3]. In minimal low-energy supergravity (MLES), the scalar (squark and slepton) masses are unified to a single value m_0 at the GUT energy scale, and the gaugino masses are unified to a single value $m_{1/2}$. Three other parameters describe the Higgs sector of the model: $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets; A_0, a universal trilinear coupling constant; and the sign of μ, a mixing parameter in the Higgsino mass matrix. Models in which the lightest neutralino ($\widetilde{\chi}_1^0$) is the LSP, the LSP interacts only weakly. It therefore cannot be observed directly, providing an excellent experimental SUSY signature: large missing transverse energy ($\not\!\!E_T$). In such models, squarks ($\widetilde{q}$) and gluinos ($\widetilde{g}$) can decay through a cascade of charginos and neutralinos to final states consisting of quarks, leptons, and the LSP. In this Letter we describe a search for squarks and gluinos in the jets and $\not\!\!E_T$ channel.

The data, corresponding to an integrated luminosity of 79.2 ± 4.2 pb^{-1}, were collected with the DØ detector [4] at the Fermilab Tevatron $p\overline{p}$ collider operating at a center-of-mass energy of 1.8 TeV during 1993–95. DØ has three major components: a central tracking system, central and forward uranium/liquid-argon calorimeters with towers in pseudorapidity and azimuth of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, and a toroidal muon spectrometer. Jets are reconstructed using a cone algorithm [5] with a cone radius of 0.5 in $\eta - \phi$ space. The electromagnetic (EM) energy scale is set using the $Z \to ee$ signal. The jet energy scale is determined from energy balance in events containing a hadronic jet and a photon candidate. $\not\!\!E_T$ is calculated from the vector sum of energy deposited in all calorimeter cells.

Events were collected using a trigger that required $\not\!\!E_T > 40$ GeV, and at least one calorimeter trigger tower (of size $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$) with transverse energy $E_T > 5$ GeV. Offline filtering required $\not\!\!E_T > 40$ GeV and at least two jets with $E_T > 8$ GeV.

Backgrounds arise from several sources, among which are $t\bar{t}$ production and the production of W and Z bosons in association with jets. Purely instrumental sources of background include QCD multijet production in which jets are mismeasured, resulting in apparent $\not\!\!E_T$.

To remove events with false large $\not\!\!E_T$, due to detector noise and losses from the accelerator, we required events to have a summed scalar E_T (S_T) $0.0 < S_T < 1.8$ TeV. This requirement has little effect on the efficiency for hard-scattering events with additional overlapping soft $p\overline{p}$ interactions, because these contribute little E_T (typical $< S_T >$ for a squark-glunio event is 400 GeV). The position of the primary interaction vertex is required to be within 60 cm of the detector center. The initial data sample contains 71,023 events. To reject events with large $\not\!\!E_T$ caused by poorly measured jets, we required all jets with $E_T > 15$ GeV meet quality criteria based on cluster shape [6], and that the three jets with highest E_T be within $|\eta| < 1.1$, or within $1.4 < |\eta| < 3.5$. The shape requirements included rejecting events in which any jet deposited more than 90% of its energy in the EM portion of the calorimeter; this significantly reduced the $W \to e\nu$ background.

To select events consistent with being hadronic decays of squarks and gluinos, we required at least three jets with $E_T > 25$ GeV, and $\not\!\!E_T > 75$ GeV. Our trigger was fully efficient under these conditions. We also required the leading jet to have $E_T > 115$ GeV, leaving 544 events. To suppress QCD multijet background we required the azimuthal difference between the $\not\!\!E_T$ and a jet of $E_T > 25$ GeV be $\delta\phi > 0.1$, or $< (\pi - 0.1)$ radians. To reject events where a fluctuation of the second leading jet masks a fluctuation of the leading jet, we also required $(\delta\phi_1 - \pi)^2 + \delta{\phi_2}^2 \geq (0.5)^2$, where 1(2) denotes the leading (second-leading) jet in E_T. To reduce the background from W and Z boson production in association with jets, we required $H_T > 100$ GeV, where H_T is defined as the scalar sum of the transverse energies of all but the leading jet. To remove the remaining $W \to \mu\nu$ + jets events, we rejected events containing isolated muons with $p_T > 15$ GeV/c. A total of 49 events satisfied all the above requirements.

The average Tevatron luminosity was $\approx 9 \times 10^{30}$ cm^{-2} s^{-1}, and peaked at about 2×10^{31} cm^{-2} s^{-1}. For the average value, there is a 75% probability of having an additional $p\bar{p}$ interaction accompanying the hard scattering. These additional events contribute many charged tracks, which can occasionally cause the soft collision to be chosen as the primary interaction vertex, and cause a gross mismeasurement of the $\not\!\!E_T$. To remove events with large $\not\!\!E_T$ caused by the misreconstruction of the interaction point, we required the charged tracks associated with the central jet of highest E_T be consistent with emanating from the primary interaction vertex [6]. The 15 events passing this criterion formed our penultimate event sample.

The final selection criteria for each $(m_0, m_{1/2})$ point were determined by choosing H_T and $\not\!\!E_T$ thresholds that maximized the $S/\delta B$ ratio, where S is the expected number of SUSY events and δB is the combined systematic and statistical error on the background predicted from the SM. Table I shows the thresholds used, the number of events expected from SM sources, and the number of events observed in the data.

The largest noninstrumental background arises from the production of $t\bar{t}$ pairs in which one t quark decays into jets and the other decays into $b\ell\nu$, where $\ell = e$, μ, or τ, and the lepton is not detected. We generated $t\bar{t} \to b\ell\nu$ + jets events using the HERWIG Monte Carlo [7]. These were subjected to a detailed detector simulation based on GEANT [8] and reconstructed with the same reconstruction program used for data. We assumed the $t\bar{t}$ production cross section of 5.9 ± 1.6 pb [9], which yielded a prediction of $3.1 \pm 0.2(\mathrm{stat})^{+1.4}_{-1.3}(\mathrm{syst})$ background events.

Comparable backgrounds come from the production of W and Z bosons. Substantial $\not\!\!E_T$ can arise in events with a W boson decaying to leptons where the charged lepton is not identified, and in events with $Z \to \nu\nu$ or $Z \to \tau\tau$ decays. To estimate these backgrounds, we generated Monte Carlo samples for W boson events with VECBOS [10] (quark hadronization simulated using ISAJET [11]), Z bosons with PYTHIA [12], and WW and WZ events with

TABLE I. Optimized $\not\!\!E_T$ and H_T thresholds for several regions of MLES parameter space. The optimal thresholds were chosen for the specified m_0 and $m_{1/2}$ values that correspond to the listed gluino and squark masses. The next-to-leading order cross sections and the total efficiency for signal events, with their combined statistical and systematic uncertainties, the total number of events expected from backgrounds, with their statistical and systematic uncertainties, the number of observed events, the probability for observing $N_{\rm obs}$ events or greater given the background prediction, and the 95% confidence level upper limit on the cross section are given in the remaining columns. Note that the entries in this table are strongly correlated.

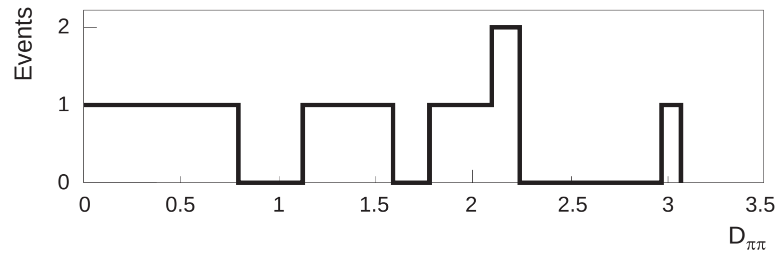
$\not\!\!E_{T\,\rm thresh}$ (GeV)	$H_{T_{\rm thresh}}$ (GeV)	$(m_0,\, m_{1/2})$ (GeV/c^2)	$(m_{\tilde g},\, m_{\tilde q})$ (GeV/c^2)	$\sigma_{\rm sig}$ (pb)	ϵ (%)	$N_{\rm bck-pred}$	$N_{\rm obs}$	$P_{\rm over}$ (%)	σ_{95} (pb)
50	100	– (Relaxed $\not\!\!E_T$ threshold) –				$43.0 \pm 0.8\,^{+\,8.5}_{-\,8.2}$	49	29.5	—
75	100	(150, 80)	(243, 249)	4.4	$5.8 \pm 0.5^{+1.7}_{-1.4}$	$8.3 \pm 0.8\,^{+\,3.4}_{-\,3.2}$	15	9.2	4.4
75	120	(300, 50)	(172, 318)	15.7	$1.5 \pm 0.3^{+0.3}_{-0.2}$	$5.5 \pm 0.5\,^{+\,2.7}_{-\,2.6}$	12	6.2	14.8
75	140	(200, 80)	(246, 278)	2.4	$5.8 \pm 0.4^{+1.0}_{-1.6}$	$3.6 \pm 0.2 \pm 2.1$	11	2.0	5.1
75	150	(250, 60)	(198, 286)	7.1	$3.1 \pm 0.3^{+0.4}_{-0.9}$	$3.0 \pm 0.1 \pm 1.9$	8	6.1	8.1
75	160	(300, 70)	(228, 339)	2.0	$4.2 \pm 0.4^{+0.7}_{-0.8}$	$2.6 \pm 0.1\,^{+\,1.8}_{-\,1.7}$	6	12.9	3.3
90	100	(100, 100)	(290, 266)	1.8	$7.7 \pm 0.5^{+1.4}_{-1.5}$	$6.0 \pm 0.7\,^{+\,2.7}_{-\,2.5}$	8	31.8	1.7
100	100	(0, 100)	(288, 250)	2.8	$4.9 \pm 0.4^{+1.0}_{-1.1}$	$4.6 \pm 0.7\,^{+\,2.2}_{-\,2.0}$	7	25.4	2.7
100	150	(200, 110)	(322, 330)	0.3	$9.2 \pm 0.5^{+0.6}_{-1.3}$	$1.3 \pm 0.1 \pm 1.2$	3	24.4	0.9

ISAJET. The detector response was modeled as for the $t\bar{t}$ sample. From all vector boson production sources, we predict $2.8 \pm 0.8^{+0.7}_{-0.5}$ events, 85% of which are from $W \to \ell\nu$ and $Z \to \nu\nu$ decays.

A major source of background is from events with three or more jets, where one (or more) is mismeasured, yielding apparent $\not\!\!E_T$. To determine this background, we used events from 56 pb^{-1} of data collected with a trigger requiring at least one jet with $E_T > 85$ GeV. The trigger was fully efficient for events containing a jet with $E_T > 115$ GeV. Events with $\not\!\!E_T < 50$ GeV were used to determine the instrumental background to events with larger $\not\!\!E_T$ using two different estimations. The primary method relied on a Bayesian shape analysis [13]. We define the quantity $D_{\pi\pi} = \sqrt{(\delta\phi_1 - \pi)^2 + (\delta\phi_2 - \pi)^2}$, which has a distribution that is strongly peaked at large $D_{\pi\pi}$ for events with apparent $\not\!\!E_T$ due to mismeasured jets. For $t\bar{t}$ and signal the distribution is less peaked, as shown in Fig. 1. For the multijet events described previously, the shape of this distribution is found to be nearly independent of the $\not\!\!E_T$ threshold. To determine the multijet contribution, we performed a three-component ($t\bar{t}$, multijet, and signal) fit to the shape of the $D_{\pi\pi}$ distribution in the data. The backgrounds quoted in Table I include the multijet contribution, as determined in this fit. As a check, we fit the $\not\!\!E_T$ spectrum of our event sample between 25 and 50 GeV to an exponential in $\not\!\!E_T$; extrapolation to higher $\not\!\!E_T$ yielded a prediction in agreement with the fit to $D_{\pi\pi}$, as shown in Table II.

To check these background calculations, we relaxed the $\not\!\!E_T$ threshold to 50 GeV, and obtained predictions of $7.6 \pm 0.8^{+2.9}_{-2.1}$ events from $t\bar{t}$ and W and Z boson production, and 35.4 ± 7.9 events from QCD multijet, for a total of $43.0 \pm 0.8^{+8.5}_{-8.2}$ events from background, as shown in Table I. We observed 49 events in the data.

We note that for all the entries in Table I the number of observed events is greater



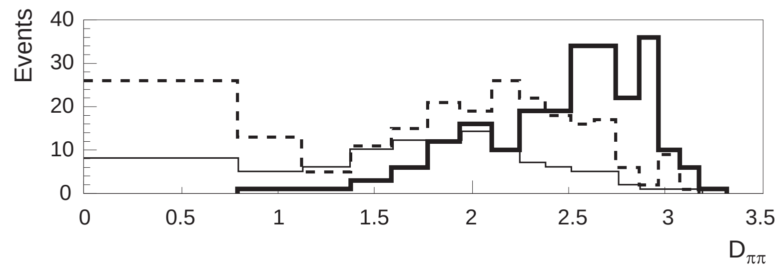


FIG. 1. Sample $D_{\pi\pi}$ distributions used in the Bayesian shape fitter. Note that the bins do not have uniform widths. The top plot shows data passing the analysis requirements with $\not\!\!E_T >$ 75 GeV and $H_T > 150$ GeV (eight candidate events are accepted). The lower plot shows the $D_{\pi\pi}$ distributions for QCD multijet (thick line), $t\bar{t}$ (dashed line), and an MLES sample with $m_0 = 250$ GeV/c^2 and $m_{1/2} = 60$ GeV/c^2(thin line) for events passing the same requirements. The normalizations for the QCD multijet, $t\bar{t}$ and MLES plots are 55.9, 7000, and 350 pb^{-1}, respectively.

TABLE II. Comparison of the number of background events expected from QCD multijet sources, as obtained from fits to $D_{\pi\pi}$ and from extrapolations from lower $\not\!\!E_T$ (see text). *The uncertainties in the extrapolation do not include the systematic uncertainty due to the dependence on the choice of functional form.*

$\not\!\!E_{T\,\mathrm{thresh}}$ (GeV)	$H_{T\,\mathrm{thresh}}$ (GeV)	Bayesian Fit to $D_{\pi\pi}$	Extrapolation
75	100	2.5 ± 2.6	2.8 ± 0.9
75	150	0.8 ± 1.6	1.7 ± 0.3
100	100	0.7 ± 1.6	0.6 ± 0.1

than the number predicted from background. The results are highly correlated, since most rows are subsets of previous rows. The probability for obtaining at least the number of events observed for any of the listed cutoffs is more than 2%, and we therefore interpret our result as a constraint on the m_0 and $m_{1/2}$ parameters of MLES. Simulating squark and gluino production and decay with ISAJET, followed by the same detector response and event reconstruction as in our previous simulations, we generated samples at several values of m_0 and $m_{1/2}$, all with the MLES parameters $\tan\beta = 2$, $A_0 = 0$, and $\mu < 0$. Using the next-to-leading order squark and gluino production cross sections from PROSPINO [14], and a Bayesian technique with a flat prior for the signal, we determined 95% confidence level limits on the parameters.

Figure 2 shows the region excluded by this analysis. Excluded are all MLES models with $m_{\tilde{q}} < 250$ GeV/c^2. For small m_0, we exclude $m_{\tilde{g}} < 300$ GeV/c^2, and for $m_{\tilde{q}} = m_{\tilde{g}}$, we exclude masses less than 260 GeV/c^2. In Fig. 3, we show the exclusion contour in the $(m_{\tilde{g}}, m_{\tilde{q}})$ plane and compare our results to those from other experiments. We extend significantly the limits on squarks and gluinos, especially in the region where $m_{\tilde{g}} > m_{\tilde{q}}$. Within MLES models, for negative μ and $\tan\beta = 2$, the CERN LEP limits on charginos $m_{\widetilde{\chi}_1^{\pm}} < 86$ to 45 GeV/c^2 [21] translate roughly to a limit on $m_{1/2}$ of 45 GeV/c^2 for small m_0, and 86 GeV/c^2 for large m_0. Our limit on $m_{1/2}$ ranges between 100 GeV/c^2 for small m_0, and 60 GeV/c^2 for large m_0. There are no self-consistent MLES models below the solid diagonal line.

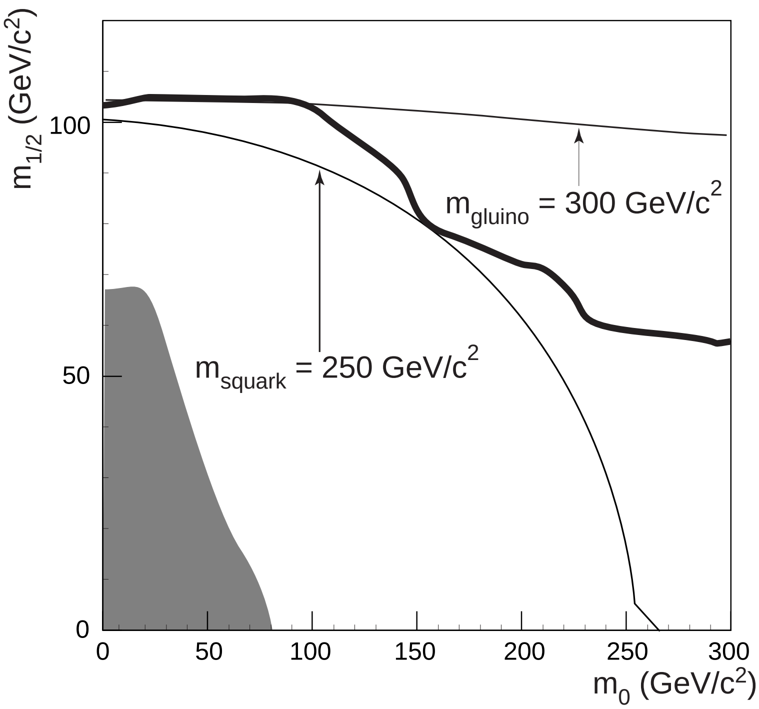


FIG. 2. The exclusion contour obtained in this analysis (heavy line), the region below which is excluded at the 95% confidence level. The thin lines are contours of constant squark or gluino mass in the $m_0 - m_{1/2}$ plane, as indicated. In the shaded region MLES does not contain electroweak symmetry breaking, and is excluded apriori.

In summary, we have searched for events with large $\not\!\!E_T$ and multiple jets, and observe no statistically significant excess of events beyond expectations from SM processes. This null result is interpreted in the context of MLES as an excluded region in the $(m_0, m_{1/2})$ plane.

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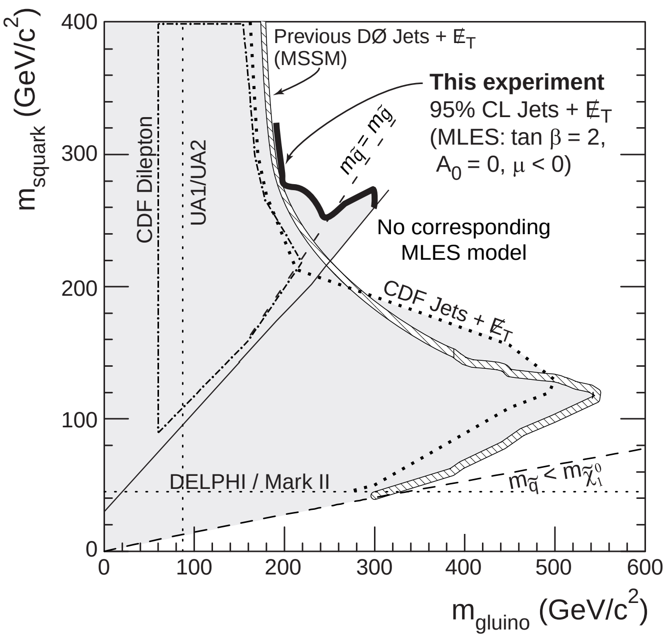

FIG. 3. The limit from this analysis in the $(m_{\tilde{g}}, m_{\tilde{q}})$ mass plane ("This experiment"). The figure also shows curves of previous limits from jets and $\not{E}_T$ from DØ [15,16] (hatched) using 7.2 pb^{-1} of data and MSSM parameters $\tan\beta = 2$ and $\mu = -250$ GeV/c^2, the jets and $\not{E}_T$ limit from CDF [17] based on 19 pb^{-1} of data with $\tan\beta = 4$ and $\mu = -400$ GeV/c^2 (thick dots), the dilepton CDF limit [18] from 19 pb^{-1} of data with MLES parameters $\tan\beta = 4$ and $\mu < 0$ (dashed-dotted), and limits using only direct decays from UA1/UA2 [19] (dotted) and DELPHI/Mark II [20] (dotted). More recent model dependent CERN LEP limits are given in the text. All limits are at the 95% confidence level. The region below the diagonal dashed line is excluded because there the squark is the LSP.

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