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F. Abe,[16] H. Akimoto,[35] A. Akopian,[30] M. G. Albrow,[7] S. R. Amendolia,[26] D. Amidei,[19] J. Antos,[32] S. Aota,[35] G. Apollinari,[30] T. Asakawa,[35] W. Ashmanskas,[17] M. Atac,[7] F. Azfar,[25] P. Azzi-Bacchetta,[24] N. Bacchetta,[24] W. Badgett,[19] S. Bagdasarov,[30] M. W. Bailey,[21] J. Bao,[38] P. de Barbaro,[29] A. Barbaro-Galtieri,[17] V. E. Barnes,[28] B. A. Barnett,[15] M. Barone,[9] E. Barzi,[9] G. Bauer,[18] T. Baumann,[11] F. Bedeschi,[26] S. Behrends,[3] S. Belforte,[26] G. Bellettini,[26] J. Bellinger,[37] D. Benjamin,[34] J. Benlloch,[18] J. Bensinger,[3] D. Benton,[25] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[9] B. Bevensee,[25] A. Bhatti,[30] K. Biery,[7] M. Binkley,[7] D. Bisello,[24] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[29] W. Bokhari,[18] V. Bolognesi,[2] G. Bolla,[28] D. Bortoletto,[28] J. Boudreau,[27] L. Breccia,[2] C. Bromberg,[20] N. Bruner,[21] E. Buckley-Geer,[7] H. S. Budd,[29] K. Burkett,[19] G. Busetto,[24] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[15] C. Campagnari,[7] M. Campbell,[19] A. Caner,[26] W. Carithers,[17] D. Carlsmith,[37] A. Castro,[24] D. Cauz,[26] Y. Cen,[29] F. Cervelli,[26] P. S. Chang,[32] P. T. Chang,[32] H. Y. Chao,[32] J. Chapman,[19] M. -T. Cheng,[32] G. Chiarelli,[26] T. Chikamatsu,[35] C. N. Chiou,[32] L. Christofek,[13] S. Cihangir,[7] A. G. Clark,[10] M. Cobal,[26] E. Cocca,[26] M. Contreras,[5] J. Conway,[31] J. Cooper,[7] M. Cordelli,[9] C. Couyoumtzelis,[10] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] T. Daniels,[18] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[26] M. Dell'Orso,[26] R. Demina,[7] L. Demortier,[30] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[31] J. R. Dittmann,[6] S. Donati,[26] J. Done,[33] T. Dorigo,[24] A. Dunn,[19] N. Eddy,[19] K. Einsweiler,[17] J. E. Elias,[7] R. Ely,[17] E. Engels, Jr.,[27] D. Errede,[13] S. Errede,[13] Q. Fan,[29] G. Feild,[38] C. Ferretti,[26] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[11] M. Frautschi,[34] J. Freeman,[7] J. Friedman,[18] H. Frisch,[5] Y. Fukui,[16] S. Funaki,[35] S. Galeotti,[26] M. Gallinaro,[25] O. Ganel,[34] M. Garcia-Sciveres,[17] A. F. Garfinkel,[28] C. Gay,[11] S. Geer,[7] D. W. Gerdes,[15] P. Giannetti,[26] N. Giokaris,[30] P. Giromini,[9] G. Giusti,[26] L. Gladney,[25] D. Glenzinski,[15] M. Gold,[21] J. Gonzalez,[25] A. Gordon,[11] A. T. Goshaw,[6] Y. Gotra,[24] K. Goulianos,[30] H. Grassmann,[26] L. Groer,[31] C. Grosso-Pilcher,[5] G. Guillian,[19] R. S. Guo,[32] C. Haber,[17] E. Hafen,[18] S. R. Hahn,[7] R. Hamilton,[11] R. Handler,[37] R. M. Hans,[38] F. Happacher,[9] K. Hara,[35] A. D. Hardman,[28] B. Harral,[25] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[31] E. Hayashi,[35] J. Heinrich,[25] B. Hinrichsen,[14] K. D. Hoffman,[28] M. Hohlmann,[5] C. Holck,[25] R. Hollebeek,[25] L. Holloway,[13] A. Hölscher,[14] S. Hong,[19] G. Houk,[25] P. Hu,[27] B. T. Huffman,[27] R. Hughes,[22] J. Huston,[20] J. Huth,[11] J. Hylen,[7] H. Ikeda,[35] M. Incagli,[26] J. Incandela,[7] G. Introzzi,[26] J. Iwai,[35] Y. Iwata,[12] H. Jensen,[7] U. Joshi,[7] R. W. Kadel,[17] E. Kajfasz,[24] H. Kambara,[10] T. Kamon,[33] T. Kaneko,[35] K. Karr,[36] H. Kasha,[38] Y. Kato,[23] T. A. Keaffaber,[28] L. Keeble,[9] K. Kelley,[18] R. D. Kennedy,[7] R. Kephart,[7] P. Kesten,[17] D. Kestenbaum,[11] R. M. Keup,[13] H. Keutelian,[7] F. Keyvan,[4] B. Kharadia,[13] B. J. Kim,[29] D. H. Kim,[7a] H. S. Kim,[14] S. B. Kim,[19] S. H. Kim,[35] Y. K. Kim,[17] L. Kirsch,[3] P. Koehn,[29] K. Kondo,[35] J. Konigsberg,[8] S. Kopp,[5] K. Kordas,[14] A. Korytov,[8] W. Koska,[7] E. Kovacs,[7a] W. Kowald,[6] M. Krasberg,[19] J. Kroll,[7]

M. Kruse,[29] T. Kuwabara,[35] S. E. Kuhlmann,[1] E. Kuns,[31] A. T. Laasanen,[28] S. Lami,[26] S. Lammel,[7] J. I. Lamoureux,[3] T. LeCompte,[1] S. Leone,[26] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[Y]. C. Liu,[32] 13 N. Lockyer,[25] O. Long,[25] C. Loomis,[31] M. Loreti,[24] J. Lu,[33] D. Lucchesi,[26] P. Lukens,[7] S. Lusin,[37] J. Lys,[17] K. Maeshima,[7] A. Maghakian,[30] P. Maksimovic,[18] M. Mangano,[26] J. Mansour,[20] M. Mariotti,[24] J. P. Marriner,[7] A. Martin,[38] J. A. J. Matthews,[21] R. Mattingly,[18] P. McIntyre,[33] P. Melese,[30] A. Menzione,[26] E. Meschi,[26] S. Metzler,[25] C. Miao,[19] T. Miao,[7] G. Michail,[11] R. Miller,[20] H. Minato,[35] S. Miscetti,[9] M. Mishina,[16] H. Mitsushio,[35] T. Miyamoto,[35] S. Miyashita,[35] N. Moggi,[26] Y. Morita,[16] J. Mueller,[27] A. Mukherjee,[7] T. Muller,[4] P. Murat,[26] H. Nakada,[35] I. Nakano,[35] C. Nelson,[7] D. Neuberger,[4] C. Newman-Holmes,[7] C-Y. P. Ngan,[18] M. Ninomiya,[35] L. Nodulman,[1] S. H. Oh,[6] K. E. Ohl,[38] T. Ohmoto,[12] T. Ohsugi,[12] R. Oishi,[35] M. Okabe,[35] T. Okusawa,[23] R. Oliveira,[25] J. Olsen,[37] C. Pagliarone,[26] R. Paoletti,[26] V. Papadimitriou,[34] S. P. Pappas,[38] N. Parashar,[26] S. Park,[7] A. Parri,[9] J. Patrick,[7] G. Pauletta,[26] M. Paulini,[17] A. Perazzo,[26] L. Pescara,[24] M. D. Peters,[17] T. J. Phillips,[6] G. Piacentino,[26] M. Pillai,[29] K. T. Pitts,[7] R. Plunkett,[7] L. Pondrom,[37] J. Proudfoot,[1] F. Ptohos,[11] G. Punzi,[26] K. Ragan,[14] D. Reher,[17] A. Ribon,[24] F. Rimondi,[2] L. Ristori,[26] W. J. Robertson,[6] T. Rodrigo,[26] S. Rolli,[36] J. Romano,[5] L. Rosenson,[18] R. Roser,[13] T. Saab,[14] W. K. Sakumoto,[29] D. Saltzberg,[5] A. Sansoni,[9] L. Santi,[26] H. Sato,[35] P. Schlabach,[7] E. E. Schmidt,[7] M. P. Schmidt,[38] A. Scribano,[26] S. Segler,[7] S. Seidel,[21] Y. Seiya,[35] G. Sganos,[14] M. D. Shapiro,[17] N. M. Shaw,[28] Q. Shen,[28] P. F. Shepard,[27] M. Shimojima,[35] M. Shochet,[5] J. Siegrist,[17] A. Sill,[34] P. Sinervo,[14] P. Singh,[27] J. Skarha,[15] K. Sliwa,[36] F. D. Snider,[15] T. Song,[19] J. Spalding,[7] T. Speer,[10] P. Sphicas,[18] F. Spinella,[26] M. Spiropulu,[11] L. Spiegel,[7] L. Stanco,[24] J. Steele,[37] A. Stefanini,[26] K. Strahl,[14] J. Strait,[7] R. Ströhmer,[7a] D. Stuart,[7] G. Sullivan,[5] K. Sumorok,[18] J. Suzuki,[35] T. Takada,[35] T. Takahashi,[23] T. Takano,[35] K. Takikawa,[35] N. Tamura,[12] B. Tannenbaum,[21] F. Tartarelli,[26] W. Taylor,[14] P. K. Teng,[32] Y. Teramoto,[23] S. Tether,[18] D. Theriot,[7] T. L. Thomas,[21] R. Thun,[19] M. Timko,[36] P. Tipton,[29] A. Titov,[30] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[29] A. Tollestrup,[7] H. Toyoda,[23] W. Trischuk,[14] J. F. de Troconiz,[11] S. Truitt,[19] J. Tseng,[18] N. Turini,[26] T. Uchida,[35] N. Uemura,[35] F. Ukegawa,[25] G. Unal,[25] J. Valls,[7a] S. C. van den Brink,[27] S. Vejcik, III,[19] G. Velev,[26] R. Vidal,[7] R. Vilar,[7a] M. Vondracek,[13] D. Vucinic,[18] R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. B. Wallace,[26] A. M. Walsh,[31] C. Wang,[6] C. H. Wang,[32] J. Wang,[5] M. J. Wang,[32] Q. F. Wang,[30] A. Warburton,[14] T. Watts,[31] R. Webb,[33] C. Wei,[6] C. Wendt,[37] H. Wenzel,[17] W. C. Wester, III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[25] H. H. Williams,[25] P. Wilson,[5] B. L. Winer,[22] D. Winn,[19] D. Wolinski,[19] J. Wolinski,[20] S. Worm,[21] X. Wu,[10] J. Wyss,[24] A. Yagil,[7] W. Yao,[17] K. Yasuoka,[35] Y. Ye,[14] G. P. Yeh,[7] P. Yeh,[32] M. Yin,[6] J. Yoh,[7] C. Yosef,[20] T. Yoshida,[23] D. Yovanovitch,[7] I. Yu,[7] L. Yu,[21] J. C. Yun,[7] A. Zanetti,[26] F. Zetti,[26] L. Zhang,[37] W. Zhang,[25] and S. Zucchelli[2]

(CDF Collaboration)

[1] *Argonne National Laboratory, Argonne, Illinois 60439*

[2] Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy
[3] Brandeis University, Waltham, Massachusetts 02264
[4] University of California at Los Angeles, Los Angeles, California 90024
[5] University of Chicago, Chicago, Illinois 60638
[6] Duke University, Durham, North Carolina 28708
[7] Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[8] University of Florida, Gainesville, FL 33611
[9] Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy
[10] University of Geneva, CH-1211 Geneva 4, Switzerland
[11] Harvard University, Cambridge, Massachusetts 02138
[12] Hiroshima University, Higashi-Hiroshima 724, Japan
[13] University of Illinois, Urbana, Illinois 61801
[14] Institute of Particle Physics, McGill University, Montreal H3A 2T8, and University of Toronto, Toronto M5S 1A7, Canada
[15] The Johns Hopkins University, Baltimore, Maryland 21218
[16] National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 315, Japan
[17] Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720
[18] Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
[19] University of Michigan, Ann Arbor, Michigan 48109
[20] Michigan State University, East Lansing, Michigan 48824
[21] University of New Mexico, Albuquerque, New Mexico 87132
[22] The Ohio State University, Columbus, OH 43320
[23] Osaka City University, Osaka 588, Japan
[24] Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-36132 Padova, Italy
[25] University of Pennsylvania, Philadelphia, Pennsylvania 19104
[26] Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy
[27] University of Pittsburgh, Pittsburgh, Pennsylvania 15270
[28] Purdue University, West Lafayette, Indiana 47907
[29] University of Rochester, Rochester, New York 14628
[30] Rockefeller University, New York, New York 10021
[31] Rutgers University, Piscataway, New Jersey 08854
[32] Academia Sinica, Taipei, Taiwan 11530, Republic of China
[33] Texas A&M University, College Station, Texas 77843
[34] Texas Tech University, Lubbock, Texas 79409
[35] University of Tsukuba, Tsukuba, Ibaraki 315, Japan
[36] Tufts University, Medford, Massachusetts 02155
[37] University of Wisconsin, Madison, Wisconsin 53806
[38] Yale University, New Haven, Connecticut 06511

We report on a search for supersymmetric squark and gluino particles in a data sample of $19\,\mathrm{pb}^{-1}$ of $p\overline{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$ recorded by the Collider Detector at Fermilab. We searched for

events containing jets plus appreciable missing transverse energy ($\not\!\!E_{\rm T}$). This signature is indicative of pair production and subsequent decay of squarks and/or gluinos. After all cuts, there are 18 events with $\not\!\!E_{\rm T} > 60\,{\rm GeV}$ and three jets, and 6 events with $\not\!\!E_{\rm T} > 60\,{\rm GeV}$ and four jets. These numbers of events are consistent with estimates of Standard Model processes plus detector-induced background sources. The analysis yields lower limits on gluino and squark masses, based on the predictions from the Minimal Supersymmetric extension of the Standard Model. At the 95% confidence level, we find gluino and squark mass limits up to $216\,{\rm GeV}/c^2$, assuming equal gluino and squark masses, and gluino mass limits up to $173\,{\rm GeV}/c^2$, independent of squark mass.

Supersymmetry (SUSY) [1] is one of the most appealing theories as a next step towards grand unification. In the Minimal Supersymmetric extension of the Standard Model (MSSM) all fermions of the Standard Model have bosons as supersymmetric partners while all bosons acquire fermions as superpartners. Supersymmetry is especially appealing if its symmetry breaking occurs near the electroweak scale [2]. In such a scenario the superpartner masses must lie below $1\,\mathrm{TeV}/c^2$ and may be produced at the Fermilab Tevatron. We analyzed $19\,\mathrm{pb}^{-1}$ of $p\overline{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$, recorded by the Collider Detector at Fermilab (CDF), in search of gluino and squark production.

Gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) are the SUSY partners of ordinary gluons and quarks. In this analysis we restricted ourselves to search for signals from the first five squarks (assumed to be mass degenerate) and from gluinos. Conservation of SUSY R-parity, a multiplicative quantum number, requires these particles to be produced in pairs and prevents decay of the lightest SUSY particle (LSP). Gluinos and squarks then decay to Standard Model particles plus LSP. The LSP, considered to be neutral, for cosmological reasons [3], and only weakly interacting, would pass through the detector without interaction. In our analysis we assume the lightest neutralino $\tilde{\chi}_1^0$ to be the LSP. Under this assumption, SUSY events should have considerable missing transverse energy, which is defined as the transverse component of the negative vector sum of all energies [4] in an event, and whose magnitude is denoted as $\not\!\!E_{\mathrm{T}}$.

Explicitly, the search was for $\tilde{q}\overline{\tilde{q}}$, $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, and $\tilde{g}\tilde{g}$ production. Direct decays of squarks and gluinos proceed according to $\tilde{q} \rightarrow q\,\mathrm{LSP}$ and $\tilde{g} \rightarrow q\,\overline{q}\,\mathrm{LSP}$, while for sufficiently massive squarks and gluinos, cascade decays proceed through charginos $\tilde{\chi}_n^{\pm}$ (n=1,2) or heavier neutralinos $\tilde{\chi}_n^0$ (n=2,3,4), which in turn decay to quarks, leptons, or neutrinos, and one LSP. Such cascades result in the production of a larger number of jets, reduced but still significant $\not\!\!E_{\mathrm{T}}$, and occasional production of leptons. This analysis and Ref. [5] are sensitive to both direct and cascade decays. Earlier $\not\!\!E_{\mathrm{T}}$ based searches [6] [7] were optimized for direct decays. The dilepton based SUSY search by CDF [8] is sensitive to cascade decays.

A detailed description of the CDF detector can be found elsewhere [9]. The following components are relevant to this analysis: the central tracking chamber, electromagnetic and hadronic calorimeters, and muon drift chambers. The central tracking chamber, inside a 1.4 T superconducting solenoidal magnet, measures the momentum of charged particles with a resolution of $\delta p_{\mathrm{T}}/p_{\mathrm{T}} = 0.001 * p_{\mathrm{T}}$ (p_{T} in GeV/c) [4]. The electromagnetic and hadronic calorimeters cover the pseudorapidity region $|\eta| < 4.2$ and are used to identify jets and electrons. They are also used, within the region $|\eta| < 3.6$, to measure the $\not\!\!E_{\mathrm{T}}$, which can indicate the presence of undetected energetic LSPs or neutrinos. Drift chambers provide muon identification in the region $|\eta| < 1.0$.

Events for this analysis passed a multilevel online trigger system, which selected events with $\not\!\!E_{\mathrm{T}} > 35\,\mathrm{GeV}$ and at least one jet with $E_{\mathrm{T}} > 50\,\mathrm{GeV}$. After offline data reconstruction, events were chosen that had $\not\!\!E_{\mathrm{T}} > 60\,\mathrm{GeV}$ and three or more jets [10] with $E_{\mathrm{T}} > 15\,\mathrm{GeV}$ each, in the region $|\eta| \leq 2.4$. We require the $\not\!\!E_{\mathrm{T}}$-significance $S \equiv \not\!\!E_{\mathrm{T}}/\sqrt{\sum E_{\mathrm{T}}}$, where $\sum E_{\mathrm{T}}$ is the scalar sum of all transverse energy in the calorimeters, to be larger than $2.2\,\mathrm{GeV}^{1/2}$. The $\not\!\!E_{\mathrm{T}}$

was corrected using a jet correction algorithm [11], which takes into account calorimeter non-linearities and reduced calorimeter response at boundaries between modules and calorimeter subsystems. Cosmic ray, accelerator-related, and detector-induced backgrounds were removed, with essentially full signal efficiency, by several requirements: that less than 10 GeV of hadronic E_{T} be deposited outside the beam-beam interaction time window, that the most energetic jet have a ratio of electromagnetic to total energy between 0.075 and 0.925, and that the event have significant momentum in energetic charged particles ($\sum p_{\mathrm{T}} \geq 5\,\mathrm{GeV}/c$ for tracks with $p_{\mathrm{T}} \geq 2\,\mathrm{GeV}/c$).

Mismeasured QCD events that could mimic the SUSY signal contain correlations in the transverse plane between the $\not\!\!E_{\mathrm{T}}$ direction and the jets, since usually only one jet was substantially mismeasured. This background was reduced by removing events that had either (i) the most energetic jet back-to-back within 20° in ϕ of the $\not\!\!E_{\mathrm{T}}$ direction, or (ii) a jet with $E_{\mathrm{T}} > 20\,\mathrm{GeV}$ within 30° in ϕ of the $\not\!\!E_{\mathrm{T}}$ direction. The first cut was more useful for events with a leading two-jet topology (mainly two energetic back-to-back jets), and the second cut for events with a multijet topology.

Events with leptonic W (including W bosons from top quark decays) and Z decays can mimic the SUSY signal. These backgrounds were reduced by rejecting events that contained an identified electron or muon. Electrons and muons with transverse energy above 10 GeV were identified by a combination of calorimeter, tracking, and muon chamber requirements. In addition, we identified muon candidates in η regions not covered by the muon chambers by looking for tracks consistent with being from a minimum ionizing particle with transverse momenta above $15\,\mathrm{GeV}/c$.

After these cuts, 24 events remained in the signal region, of which 18 contained 3 jets, and 6 contained 4 jets.

The expected numbers of events from Standard Model processes in these samples were estimated using a combination of Monte Carlo simulation and normalized data control samples. The VECBOS [12] event generator was used to produce background events from W or Z plus multijet production. There are large uncertainties associated with the W+jets and Z+jets cross-section calculations. Therefore, we normalized both W and Z Monte Carlo simulations to the number of W plus 2 jet events in data in which an electron or muon was identified (as contrasted with the SUSY data selection in which events with identified electrons and muons were rejected). The background from top quark production was estimated using the ISAJET [13] event generator normalized to the top quark pair production cross-section experimentally determined by CDF [14].

The number of events coming from mismeasurement of otherwise balanced QCD multijet events was determined by using a jet sample, selected by the online trigger as having at least one jet with $E_{\mathrm{T}} > 50\,\mathrm{GeV}$. This control sample was required to pass all but three of the SUSY selection cuts: the $\not\!\!E_{\mathrm{T}}$-significance cut, the online trigger $\not\!\!E_{\mathrm{T}}$ cut, and the 3 (or 4) jet requirement. The possible contribution of SUSY events to this sample is small at all $\not\!\!E_{\mathrm{T}}$.

These three cuts were found to be negligibly correlated. The $\not\!\!E_{\rm T}$ distribution of the control sample was fit in the region $\not\!\!E_{\rm T} > 40\,{\rm GeV}$ to the sum of a smooth function (power law or exponential), representing QCD mismeasurement, and small contributions for the estimated W+jets, Z+jets, and $t\bar{t}$ backgrounds. The number of QCD events with $\not\!\!E_{\rm T} > 60\,{\rm GeV}$ was determined from this fit, and the number of expected QCD background events in the SUSY data sample was then derived by including the efficiencies of the three remaining cuts and the relative integrated luminosities of the jet and data samples. The difference between the results found by the fits with the two functional forms was taken as a systematic uncertainty in this background.

Table 1 lists the estimated background contributions to the ≥ 3 and ≥ 4 jet data samples. The estimated backgrounds are slightly larger but statistically consistent with the number of observed events. In the ≥ 3 jet sample we observed 24 events compared to $33^{+12}_{-10}(stat)^{+19}_{-12}(syst)$ estimated background events; in the ≥ 4 jet sample we observed 6 events compared to $8^{+4}_{-3}(stat) \pm 4(syst)$ estimated background events.

Table 1: Expected number of W, Z, $t\bar{t}$, and QCD background events in the signal region. Backgrounds from Z^0 decays to charged leptons were also estimated and found to be negligible.

	≥ 3 jets	≥ 4 jetso
$W^\pm \to e^\pm\nu$	$3.3 \pm 1.0^{+3.2}_{-1.3}$	$0.5 \pm 0.4^{+1.3}_{-0.5}$
$W^\pm \to \mu^\pm\nu$	$1.4 \pm 0.6^{+1.9}_{-0.5}$	$0.5 \pm 0.4 \pm 0.5$
$W^\pm \to \tau^\pm\nu$	$9.2 \pm 1.7^{+6.8}_{-4.0}$	$1.6 \pm 0.7 \pm 1.4$
$Z^0 \to \nu\bar{\nu}$	$5.0 \pm 0.9^{+2.6}_{-2.8}$	$0.4 \pm 0.2^{+0.3}_{-0.4}$
$t\bar{t}$	$4.2 \pm 0.3^{+0.3}_{-0.6}$	$2.2 \pm 0.2^{+0.3}_{-0.4}$
QCD	$10.2^{+11.8}_{-9.5}{}^{+4.6}_{-3.7}$	$3.2^{+4.4}_{-3.2}{}^{+1.4}_{-1.1}$
Total	$33^{+12}_{-10}(stat)^{+19}_{-12}(syst)$	$8^{+4}_{-3}(stat) \pm 4(syst)$

The four major sources of systematic uncertainty included in the background estimate are (i) the uncertainty on the calorimeter energy scale, (ii) the normalization of the W and Z contributions, (iii) the fit and extrapolation of the $\not\!\!E_{\rm T}$ spectrum in the QCD background estimate, and (iv) an uncertainty in the integrated luminosity measurement. For each source, we added the uncertainties of the various W, Z, $t\bar{t}$, and QCD components linearly, except for part of the QCD uncertainty where we take the correlation between W, Z, and $t\bar{t}$ into account. The uncertainties from the various sources were then added in quadrature to yield the total systematic uncertainty.

The $\not\!\!E_{\rm T}$ distributions of the data in the signal region are consistent with the estimated Standard Model and detector backgrounds, as shown in Figures 1a and 1b. In order to place limits on the masses of squarks and gluinos, possible signals due to supersymmetry were generated with the ISAJET Monte Carlo generator [15] and passed through detector simulation programs. In order to reduce the number of SUSY parameters [16], grand unified theories were used to relate gaugino masses to gauge couplings. Minimal supergravity grand unified theories (minimal SUGRA) [17] were used where possible, i.e., in the region where squarks are heavier than gluinos. We generated and analyzed Monte Carlo samples in the $\tilde{q}$-$\tilde{g}$ mass plane with SUSY parameters in the following ranges: gluino masses between 60 and $550\,\mathrm{GeV}/c^2$, squark masses between 40 and $500\,\mathrm{GeV}/c^2$, ratio of the vacuum expectation value of the two Higgs doublets $\tan\beta = 2$, 4, and 8; and higgsino mass parameter $|\mu| < 1600\,\mathrm{GeV}/c^2$. We used MRS(A′) [18] parton distribution functions. Next-to-leading order gluino and squark production cross-sections [19] were used in the region where the squark mass ($m_{\tilde{q}}$) is heavier than gluino mass ($m_{\tilde{g}}$), and leading order calculations were used elsewhere. Figures 1c and 1d show $\not\!\!E_{\mathrm{T}}$ distributions of two representative SUSY Monte Carlo samples close to our mass limits.

Gluino production dominates in the region of large squark masses, whereas squark production dominates in the region of large gluino masses. Gluino decays yield on average one more jet than squark decays. Therefore, for the upper limit determination we used the ≥ 4 jet analysis in the region where squarks are heavier than gluinos and the ≥ 3 jet analysis elsewhere.

A Monte Carlo technique was used to determine the 95% confidence level (C.L.) limits [20]. The numbers of background and signal events were determined by sampling Poisson distributions. The means of the distributions were set at the estimated number of background events and at an assumed mean number of signal events. The mean numbers of background and signal events were varied by their uncertainties, taking correlations between signal and background into account. In the case of asymmetric uncertainties, the larger of the positive or negative uncertainty was used. A trial was discarded if it had more background events than the actual number of observed events. For the trials that were not discarded, the fraction that had a number of background plus signal events greater than the number of observed events gave the confidence level for our limits. The assumed number of signal events was varied until the 95% C.L. limit was achieved. This limit, in the two cases of ≥ 3 jet or ≥ 4 jet samples, was achieved for 29.2 or 11.8 signal events, respectively.

Figure 2 shows the region in the gluino mass versus squark mass plane (with $\tan\beta = 4$ and $\mu = -400\,\mathrm{GeV}/c^2$) excluded at 95% C.L. by this analysis, i.e., the region that would yield more than 29.2 signal events in the ≥ 3 jet sample or more than 11.8 events in the ≥ 4 jet sample from gluino and squark production.

Production cross sections are steeply falling functions of squark and gluino masses and at our 95% C.L. contour are on the order of 10 pb. The total squark and gluino pair detection efficiencies on the contour vary from 2-4% at large squark masses to 10-15% for equal squark and gluino masses. Our mass limits vary by about $10\,\mathrm{GeV}/c^2$ as a function of $\tan\beta$ and μ (for $\mu < -100\,\mathrm{GeV}/c^2$ or $\mu > 200\,\mathrm{GeV}/c^2$) [23]. The best gluino mass limit for all squark masses, i.e. $m_{\tilde{g}} > 173\,\mathrm{GeV}/c^2$, was obtained for $\tan\beta = 2$ and $\mu = -200\,\mathrm{GeV}/c^2$. The best gluino mass limit for equal squark and gluino masses, i.e. $m_{\tilde{g}} > 216\,\mathrm{GeV}/c^2$, was obtained for $\tan\beta = 4$ and $\mu = -400\,\mathrm{GeV}/c^2$. Our mass limits are comparable to our previous results [8]

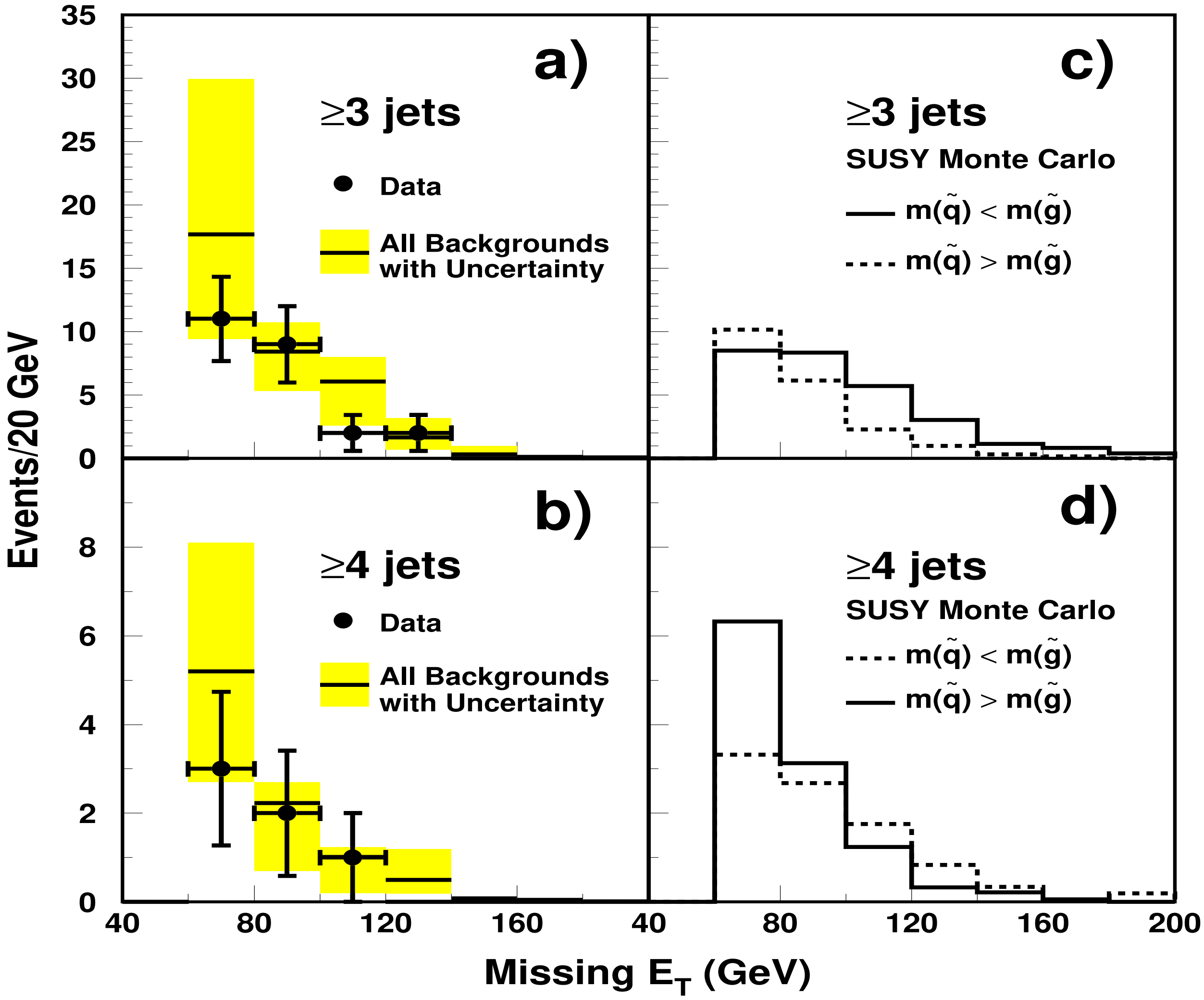

Figure 1: Plots a) and b) show $\not\!\!E_{\rm T}$ distributions of the signal region for data and combined estimated backgrounds with 3 and 4 inclusive jets, respectively. The shaded areas represent the total uncertainty of all the backgrounds. Plots c) and d) show representative signal region $\not\!\!E_{\rm T}$ distributions for SUSY Monte Carlo simulations. The following SUSY parameters are used for the signal Monte Carlo simulation samples: $m_{\tilde{g}} = 170\,{\rm GeV}/c^2$ and $m_{\tilde{q}} = 500\,{\rm GeV}/c^2$ ($m_{\tilde{q}} > m_{\tilde{g}}$), or $m_{\tilde{g}} = 350\,{\rm GeV}/c^2$ and $m_{\tilde{q}} = 180\,{\rm GeV}/c^2$ ($m_{\tilde{q}} < m_{\tilde{g}}$); $\tan\beta = 4$; and $\mu = -400\,{\rm GeV}/c^2$. The total integrated luminosity for all plots is $19\,{\rm pb}^{-1}$.

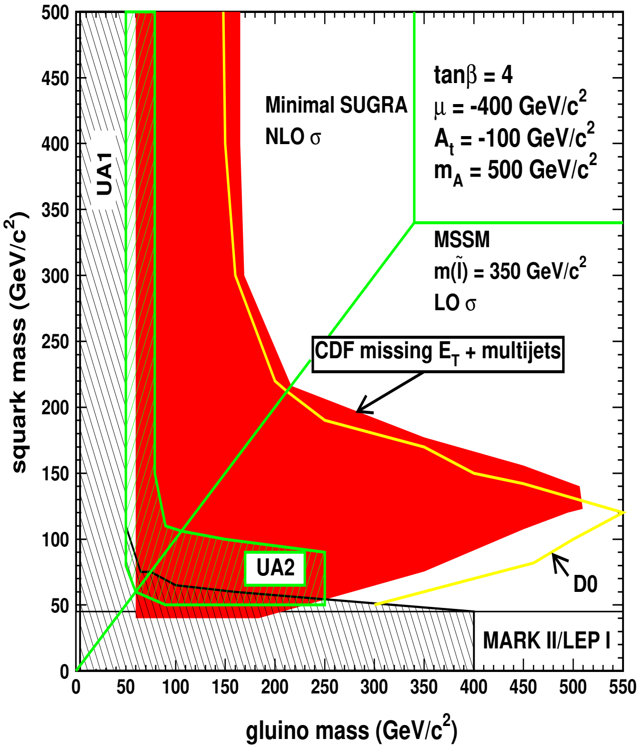

Figure 2: Region in the gluino–squark mass plane ($\tan\beta = 4$, $\mu = -400\,\mathrm{GeV}/c^2$) excluded at 95% C.L. by this $\not\!\!E_{\mathrm{T}}$ based analysis using a total integrated luminosity of $19\,\mathrm{pb}^{-1}$. Next-to-leading order (NLO) cross-section calculations and minimal SUGRA are used above the diagonal, while leading order (LO) cross-section calculations and a fixed value of slepton mass ($m_{\tilde{\ell}}$) of $350\,\mathrm{GeV}/c^2$ are used below the diagonal. Also shown are the UA1, UA2 [7], MARK II [21], LEP I [22], and the D0[5] excluded regions, some of which use slightly different assumptions and SUSY parameters.

using dilepton events with a similar amount of data. These results extend significantly our previous limits in the $\not\!\!E_{\rm T}$ plus multijet channel [6].

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