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Search for Gluinos and Scalar Quarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV Using the Missing Energy plus Multijets Signature

T. Affolder
Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California

Kenneth A. Bloom
University of Nebraska - Lincoln, kbloom2@unl.edu

Collider Detector at Fermilab Collaboration

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T. Affolder,[23] H. Akimoto,[45] A. Akopian,[37] M. G. Albrow,[11] P. Amaral,[8] D. Amidei,[25] K. Anikeev,[24] J. Antos,[1] G. Apollinari,[11] T. Arisawa,[45] A. Artikov,[9] T. Asakawa,[43] W. Ashmanskas,[8] F. Azfar,[30] P. Azzi-Bacchetta,[31] N. Bacchetta,[31] H. Bachacou,[23] S. Bailey,[16] P. de Barbaro,[36] A. Barbaro-Galtieri,[23] V. E. Barnes,[35] B. A. Barnett,[19] S. Baroiant,[5] M. Barone,[13] G. Bauer,[24] F. Bedeschi,[33] S. Belforte,[42] W. H. Bell,[15] G. Bellettini,[33] J. Bellinger,[46] D. Benjamin,[10] J. Bensinger,[4] A. Beretvas,[11] J. P. Berge,[11] J. Berryhill,[8] A. Bhatti,[37] M. Binkley,[11] D. Bisello,[31] M. Bishai,[11] R. E. Blair,[2] C. Blocker,[4] K. Bloom,[25] B. Blumenfeld,[19] S. R. Blusk,[36] A. Bocci,[37] A. Bodek,[36] W. Bokhari,[32] G. Bolla,[35] Y. Bonushkin,[6] D. Bortoletto,[35] J. Boudreau,[34] A. Brandl,[27] S. van den Brink,[19] C. Bromberg,[26] M. Brozovic,[10] E. Brubaker,[23] N. Bruner,[27] E. Buckley-Geer,[11] J. Budagov,[9] H. S. Budd,[36] K. Burkett,[16] G. Busetto,[31] A. Byon-Wagner,[11] K. L. Byrum,[2] S. Cabrera,[10] P. Calafiura,[23] M. Campbell,[25] W. Carithers,[23] J. Carlson,[25] D. Carlsmith,[46] W. Caskey,[5] A. Castro,[3] D. Cauz,[42] A. Cerri,[33] A. W. Chan,[1] P. S. Chang,[1] P. T. Chang,[1] J. Chapman,[25] C. Chen,[32] Y. C. Chen,[1] M.-T. Cheng,[1] M. Chertok,[5] G. Chiarelli,[33] I. Chirikov-Zorin,[9] G. Chlachidze,[9] F. Chlebana,[11] L. Christofek,[18] M. L. Chu,[1] Y. S. Chung,[36] C. I. Ciobanu,[28] A. G. Clark,[14] A. Connolly,[23] J. Conway,[38] M. Cordelli,[13] J. Cranshaw,[40] R. Cropp,[41] R. Culbertson,[11] D. Dagenhart,[44] S. D'Auria,[15] F. DeJongh,[11] S. Dell'Agnello,[13] M. Dell'Orso,[33] L. Demortier,[37] M. Deninno,[3] P. F. Derwent,[11] T. Devlin,[38] J. R. Dittmann,[11] A. Dominguez,[23] S. Donati,[33] J. Done,[39] M. D'Onofrio,[33] T. Dorigo,[16] N. Eddy,[18] K. Einsweiler,[23] J. E. Elias,[11] E. Engels, Jr.,[34] R. Erbacher,[11] D. Errede,[18] S. Errede,[18] Q. Fan,[36] R. G. Feild,[47] J. P. Fernandez,[11] C. Ferretti,[33] R. D. Field,[12] I. Fiori,[3] B. Flaugher,[11] G. W. Foster,[11] M. Franklin,[16] J. Freeman,[11] J. Friedman,[24] H. J. Frisch,[8] Y. Fukui,[22] I. Furic,[24] S. Galeotti,[33] A. Gallas,[16,*] M. Gallinaro,[37] T. Gao,[32] M. Garcia-Sciveres,[23] A. F. Garfinkel,[35] P. Gatti,[31] C. Gay,[47] D. W. Gerdes,[25] P. Giannetti,[33] P. Giromini,[13] V. Glagolev,[9] D. Glenzinski,[11] M. Gold,[27] J. Goldstein,[11] I. Gorelov,[27] A. T. Goshaw,[10] Y. Gotra,[34] K. Goulianos,[37] C. Green,[35] G. Grim,[5] P. Gris,[11] L. Groer,[38] C. Grosso-Pilcher,[8] M. Guenther,[35] G. Guillian,[25] J. Guimaraes da Costa,[16] R. M. Haas,[12] C. Haber,[23] S. R. Hahn,[11] C. Hall,[16] T. Handa,[17] R. Handler,[46] W. Hao,[40] F. Happacher,[13] K. Hara,[43] A. D. Hardman,[35] R. M. Harris,[11] F. Hartmann,[20] K. Hatakeyama,[37] J. Hauser,[6] J. Heinrich,[32] A. Heiss,[20] M. Herndon,[19] C. Hill,[5] K. D. Hoffman,[35] C. Holck,[32] R. 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Liu,[36] Y. C. Liu,[1] D. O. Litvintsev,[11] O. Lobban,[40] N. Lockyer,[32] J. Loken,[30] M. Loreti,[31] D. Lucchesi,[31] P. Lukens,[11] S. Lusin,[46] L. Lyons,[30] J. Lys,[23] R. Madrak,[16] K. Maeshima,[11] P. Maksimovic,[16] L. Malferrari,[3] M. Mangano,[33] M. Mariotti,[31] G. Martignon,[31] A. Martin,[47] J. A. J. Matthews,[2,7] J. Mayer,[41] P. Mazzanti,[3] K. S. McFarland,[36] P. McIntyre,[39] E. McKigney,[32] M. Menguzzato,[31] A. Menzione,[33] C. Mesropian,[37] A. Meyer,[11] T. Miao,[11] R. Miller,[26] J. S. Miller,[25] H. Minato,[43] S. Miscetti,[13] M. Mishina,[22] G. Mitselmakher,[12] N. Moggi,[3] E. Moore,[27] R. Moore,[25] Y. Morita,[22] T. Moulik,[35] M. Mulhearn,[24] A. Mukherjee,[11] T. Muller,[20] A. Munar,[33] P. Murat,[11] S. Murgia,[26] J. Nachtman,[6] V. Nagaslaev,[40] S. Nahn,[47] H. Nakada,[43] I. Nakano,[17] C. Nelson,[11] T. Nelson,[11] C. Neu,[28] D. Neuberger,[20] C. Newman-Holmes,[11] C.-Y. P. Ngan,[24] H. Niu,[4] L. Nodulman,[2] A. Nomerotski,[12] S. H. Oh,[10] Y. D. Oh,[21] T. Ohmoto,[17] T. Ohsugi,[17] R. Oishi,[43] T. Okusawa,[29] J. Olsen,[46] W. Orejudos,[23] C. Pagliarone,[33] F. Palmonari,[33] R. Paoletti,[33] V. Papadimitriou,[40] D. Partos,[4] J. Patrick,[11] G. Pauletta,[42] M. Paulini,[23,†] C. Paus,[24] L. Pescara,[31] T. J. Phillips,[10] G. Piacentino,[33] K. T. Pitts,[18] A. Pompos,[35] L. Pondrom,[46] G. Pope,[34] M. Popovic,[41] F. Prokoshin,[9] J. Proudfoot,[2] F. Ptohos,[13] O. Pukhov,[9] G. Punzi,[33] A. Rakitine,[24] F. Ratnikov,[38] D. Reher,[23] A. Reichold,[30] A. Ribon,[31] W. Riegler,[16] F. Rimondi,[3] L. Ristori,[33] M. Riveline,[41] W. J. Robertson,[10] A. Robinson,[41] T. Rodrigo,[7] S. Rolli,[44] L. Rosenson,[24] R. Roser,[11] R. Rossin,[31] A. Roy,[35] A. Ruiz,[7] A. Safonov,[12] R. St. Denis,[15] W. K. Sakumoto,[36] D. Saltzberg,[6] C. Sanchez,[28] A. Sansoni,[13] L. Santi,[42] H. Sato,[43] P. Savard,[41] P. Schlabach,[11] E. E. Schmidt,[11] M. P. Schmidt,[47] M. Schmitt,[16,†] L. Scodellaro,[31] A. Scott,[6] A. Scribano,[33] S. Segler,[11] S. Seidel,[27] Y. Seiya,[43] A. Semenov,[9] F. Semeria,[3] T. Shah,[24] M. D. Shapiro,[23] P. F. Shepard,[34]

T. Shibayama,[43] M. Shimojima,[43] M. Shochet,[8] A. Sidoti,[31] J. Siegrist,[23] A. Sill,[40] P. Sinervo,[41] P. Singh,[18] A. J. Slaughter,[47] K. Sliwa,[44] C. Smith,[19] F. D. Snider,[11] A. Solodsky,[37] J. Spalding,[11] T. Speer,[14] P. Sphicas,[24] F. Spinella,[33] M. Spiropulu,[16] L. Spiegel,[11] J. Steele,[46] A. Stefanini,[33] J. Strologas,[18] F. Strumia,[14] D. Stuart,[11] K. Sumorok,[24] T. Suzuki,[43] T. Takano,[29] R. Takashima,[17] K. Takikawa,[43] P. Tamburello,[10] M. Tanaka,[43] B. Tannenbaum,[6] M. Tecchio,[25] R. Tesarek,[11] P. K. Teng,[1] K. Terashi,[37] S. Tether,[24] A. S. Thompson,[15] R. Thurman-Keup,[2] P. Tipton,[36] S. Tkaczyk,[11] D. Toback,[39] K. Tollefson,[36] A. Tollestrup,[11] D. Tonelli,[33] H. Toyoda,[29] W. Trischuk,[41] J. F. de Troconiz,[16] J. Tseng,[24] N. Turini,[33] F. Ukegawa,[43] T. Vaiciulis,[36] J. Valls,[38] S. Vejcik III,[11] G. Velev,[11] G. Veramendi,[23] R. Vidal,[11] I. Vila,[7] R. Vilar,[7] I. Volobouev,[23] M. von der Mey,[6] D. Vucinic,[24] R. G. Wagner,[2] R. L. Wagner,[11] N. B. Wallace,[38] Z. Wan,[38] C. Wang,[10] M. J. Wang,[1] B. Ward,[15] S. Waschke,[15] T. Watanabe,[43] D. Waters,[30] T. Watts,[38] R. Webb,[39] H. Wenzel,[20] W. C. Wester III,[11] A. B. Wicklund,[2] E. Wicklund,[11] T. Wilkes,[5] H. H. Williams,[32] P. Wilson,[11] B. L. Winer,[28] D. Winn,[25] S. Wolbers,[11] D. Wolinski,[25] J. Wolinski,[26] S. Wolinski,[25] S. Worm,[27] X. Wu,[14] J. Wyss,[33] W. Yao,[23] A. Yagil,[11] G. P. Yeh,[11] J. Yoh,[11] C. Yosef,[26] T. Yoshida,[29] I. Yu,[21] S. Yu,[32] Z. Yu,[47] A. Zanetti,[42] F. Zetti,[23] and S. Zucchelli[3]

(CDF Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[4]*Brandeis University, Waltham, Massachusetts 02254*
[5]*University of California at Davis, Davis, California 95616*
[6]*University of California at Los Angeles, Los Angeles, California 90024*
[7]*Instituto de Fisica de Cantabria, CSIC–University of Cantabria, 39005 Santander, Spain*
[8]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[9]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[10]*Duke University, Durham, North Carolina 27708*
[11]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[12]*University of Florida, Gainesville, Florida 32611*
[13]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[14]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[15]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[16]*Harvard University, Cambridge, Massachusetts 02138*
[17]*Hiroshima University, Higashi-Hiroshima 724, Japan*
[18]*University of Illinois, Urbana, Illinois 61801*
[19]*The Johns Hopkins University, Baltimore, Maryland 21218*
[20]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[21]*Center for High Energy Physics, Kyungpook National University, Taegu 702-701, Korea and Center for High Energy Physics, Seoul National University, Seoul 151-742, Korea and Center for High Energy Physics, SungKyunKwan University, Suwon 440-746, Korea*
[22]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305 , Japan*
[23]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[24]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[25]*University of Michigan, Ann Arbor, Michigan 48109*
[26]*Michigan State University, East Lansing, Michigan 48824*
[27]*University of New Mexico, Albuquerque, New Mexico 87131*
[28]*The Ohio State University, Columbus, Ohio 43210*
[29]*Osaka City University, Osaka 588, Japan*
[30]*University of Oxford, Oxford OX1 3RH, United Kingdom*
[31]*Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[32]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[33]*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[34]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[35]*Purdue University, West Lafayette, Indiana 47907*
[36]*University of Rochester, Rochester, New York 14627*
[37]*Rockefeller University, New York, New York 10021*
[38]*Rutgers University, Piscataway, New Jersey 08855*
[39]*Texas A&M University, College Station, Texas 77843*
[40]*Texas Tech University, Lubbock, Texas 79409*
[41]*Institute of Particle Physics, University of Toronto, Toronto M5S 1A7, Canada*
[42]*Istituto Nazionale di Fisica Nucleare, University of Trieste/Udine, Italy*

[43] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[44] *Tufts University, Medford, Massachusetts 02155*
[45] *Waseda University, Tokyo 169, Japan*
[46] *University of Wisconsin, Madison, Wisconsin 53706*
[47] *Yale University, New Haven, Connecticut 06520*
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We have performed a search for gluinos ($\tilde{g}$) and scalar quarks ($\tilde{q}$) 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. We investigate the final state of large missing transverse energy and three 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 $m_{\tilde{q}} \approx m_{\tilde{g}}$, gluino masses below 300 GeV$/c^2$ are excluded.

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The standard model (SM) [1] accurately describes physical phenomena down to scales of $\sim 10^{-16}$ cm. There are many extensions of the standard model to smaller length scales, including extra gauge interactions, new matter, new levels of compositeness, and supersymmetry (SUSY). Of these, supersymmetry [2] treats the bosonic and fermionic degrees of freedom equally and provides a robust extension to the standard model. For simplicity, the *minimal* construction (MSSM) is often used to link SUSY with the standard model [3]. The most general MSSM would induce proton decay with a weak-interaction lifetime; to avoid this, baryon and lepton conservation are enforced in the MSSM by postulating a new conserved quantity, R-parity, $R = (-1)^{3(B-L)+2s}$, where for each particle s is the spin, and B and L are the respective baryon and lepton assignments. R-parity conservation leads to characteristic SUSY signatures with $\not\!\!E_T$ in the final state due to the stable lightest supersymmetric particle (LSP). We assume in the search described below for the bosonic partners of quarks (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) [3]. In this model the entire SUSY mass spectrum is essentially determined by only five unknown parameters: the common scalar mass at the grand unified theory (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, $sign(\mu)$; and the ratio of the Higgs vacuum expectation values, $\tan\beta$. Minimal SUGRA does not make predictions for the part of the $m_{\tilde{q}}$-$m_{\tilde{g}}$ mass parameter space where squarks of the first two families are lighter than about 0.8 times the mass of gluino. Hence, for $m_{\tilde{q}} < m_{\tilde{g}}$ we use the constrained MSSM (cMSSM) [3] with the set of input parameters at the electroweak scale being the mass of the gluino, $m_{\tilde{g}}$; the CP-odd neutral scalar Higgs mass, m_A; the squark masses, $m_{\tilde{q}_i}$; the slepton masses, $m_{\tilde{\ell}_i}$; the squark and slepton mixing parameters, $A_{t(b)(\tau)}$; and μ and $\tan\beta$.

We investigate whether the production and decay of gluinos and scalar quarks is observable in the rate of ≥ 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 [4] with $\tan\beta = 3$ to generate datasets of squark and gluino events, and the PROSPINO program [5] 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 [6] 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 ± 4 pb^{-1} of integrated luminosity recorded with the CDF detector during the 1994-1995 Tevatron run.

The CDF detector is described in detail elsewhere [7]. The momenta of charged particles are measured in the central tracking chamber, 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 $|\eta| < 4.2$ [8] 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 θ is the angle formed by the beam line, the event vertex [10], 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, $\vec{\not\!\!E}_T = -\sum_i (E_i \sin\theta_i)\hat{n}_i$, where E_i is the energy of the ith tower, $\hat{n}_i$ is a transverse unit vector pointing to the center of each tower, and θ_i is the polar angle of the tower; the sum extends to $|\eta| < 3.6$. The data sample was selected with an online trigger which requires $\not\!\!E_T \equiv |\vec{\not\!\!E}_T| > 30$ 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 ($F_{\rm ch}$) to distinguish between real and fake jet events [11]. The preselection requirements and the corresponding missing transverse energy spectra are presented in Fig. 1. At least three jets with $E_T \geq 15$ 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. A jet is considered nonfiducial if it is within 0.5 rad in ϕ of the $\not\!\!E_T$ direction and also points in η 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 $\delta\phi_1 = |\phi_{\text{leading jet}} - \phi_{\not E_T}|$ versus $\delta\phi_2 = |\phi_{\text{second jet}} - \phi_{\not E_T}|$ plane. We accept events with $R_1 > 0.75$ rad and $R_2 > 0.5$ rad, where $R_1 = \sqrt{\delta\phi_2^2 + (\pi - \delta\phi_1)^2}$ and $R_2 = \sqrt{\delta\phi_1^2 + (\pi - \delta\phi_2)^2}$.

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: $\not\!\!E_T$, $H_T \equiv E_{T(2)} + E_{T(3)} + \not\!\!E_T$, and isolated track multiplicity, N_{trk}^{iso} [14]. The blind box contains events with $\not\!\!E_T \geq 70$ GeV, $H_T \geq 150$ GeV, and $N_{trk}^{iso} = 0$. The analysis path is shown in Table I. 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 $\not\!\!E_T$ vector not be closer than 0.3 rad in ϕ to any jet in the event.

We expect events with large missing energy and $\geq$3 jets in the final state primarily from QCD multijet production, the processes $Z(\to \nu\bar{\nu})$ + $\geq$3 jets, $W(\to \tau\nu)$ + $\geq$2 jets (the third jet originating from the hadronic τ decay), and $t\bar{t}$ production. To estimate the Z + jets and W + jets backgrounds we use the VECBOS MC [15]. We normalize the MC predictions using the observed $Z(\to ee)$ + jets data sample. For the QCD predictions we use the HERWIG MC program [16] and normalize to the high statistics jet data samples. We estimate the backgrounds from $t\bar{t}$, single top and diboson events with MC predictions [16,17], which we normalize using the respective theoretical cross section calculations for these processes [18].

There are seven control regions around the blind box formed by inverting the requirements which define it (i.e., by changing the direction of the inequalities shown in Table II). We compare the standard model background predictions in the control regions with the data. The results are shown in Table II. Of the 76 events predicted in the blind box, 41 come from QCD and 35 from electroweak processes. Of the latter we estimate $\sim$37% coming from $Z(\to \nu\bar{\nu})$ + $\geq$3 jets, $\sim$20% from $W(\to \tau\nu)$ + $\geq$2 jets, $\sim$20% from the combined $W[\to e(\mu)\nu_e(\nu_\mu)]$ + $\geq$3 jets, and $\sim$20% from $t\bar{t}$ production and decays. We also compare the kinematic properties between standard model

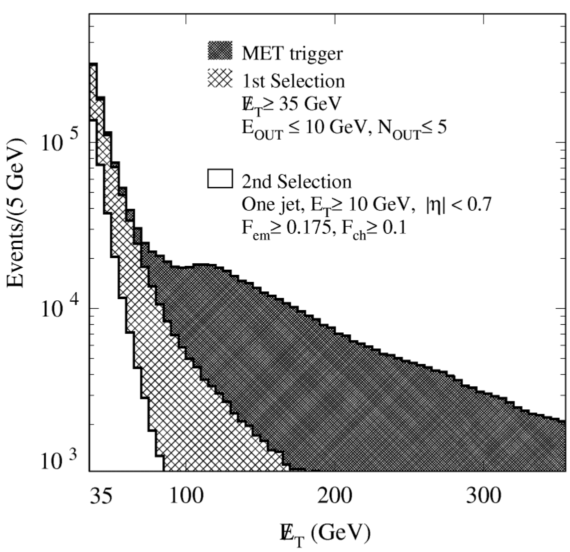

FIG. 1. The $\not\!\!E_T$ spectrum after the online trigger [12] and the two stages of the data preselection. The numbers of events surviving the first and second selections are 892 395 and 286 728, respectively. The variables $E_{\rm OUT}$, $N_{\rm OUT}$ are energy and number of towers out of time [13].

TABLE I. The data selection path for the $\not\!\!E_T$ + $\geq$3 jets search. After the fourth step, all events that could fall in the blind box are removed from the accounting; in the following steps, only the events in the control regions are tabulated.

Requirement	Events
Preselection	286 728
$N_{\rm jet} \geq 3$ ($\Delta R = 0.7, E_T \geq 15$ GeV)	107 509
Fiducial second, third jet	57 011
$R_1 > 0.75$ rad, $R_2 > 0.5$ rad	23 381
$\not\!\!E_T \geq 70$ GeV, $H_T \geq 150$ GeV, $N_{trk}^{iso} = 0$	Blind box (Signal region)
$E_{T(1)} \geq 70$ GeV, $E_{T(2)} \geq 30$ GeV, $\lvert\eta\rvert(1\ or\ 2\ or\ 3) < 1.1$	6435
$f_{em(1)}$, $f_{em(2)} \leq 0.9$	6013
$\delta\phi_{\rm min}(\not\!\!E_T, \text{jet}) \geq 0.3$ rad	2737

TABLE II. Comparison of the standard model prediction and the data in the control regions and the signal candidate region (blind box). After the contents of the control regions were compared in detail to standard model predictions, we "opened the box" and found 74 events ($\not{E}_T$ and H_T in GeV.)

Region definition	EWK	QCD	All	Data
$\not{E}_T \geq 70$, $H_T \geq 150$, $N_{trk}^{iso} > 0$	14	6.3	20 ± 5	10
$\not{E}_T \geq 70$, $H_T < 150$, $N_{trk}^{iso} = 0$	2.3	6.3	8.6 ± 4.5	12
$35 < \not{E}_T < 70$, $H_T > 150$, $N_{trk}^{iso} = 0$	1.95	135	137 ± 28	134
$\not{E}_T > 70$, $H_T < 150$, $N_{trk}^{iso} > 0$	1.7	<0.1	1.7 ± 0.3	2
$35 < \not{E}_T < 70$, $H_T > 150$, $N_{trk}^{iso} > 0$	14	9.4	23 ± 6	24
$35 < \not{E}_T < 70$, $H_T < 150$, $N_{trk}^{iso} = 0$	5	413	418 ± 69	410
$35 < \not{E}_T < 70$, $H_T < 150$, $N_{trk}^{iso} > 0$	3.3	28	31 ± 10	35
Signal candidate region				
$\not{E}_T \geq 70$, $H_T \geq 150$, $N_{trk}^{iso} = 0$	35	41	76 ± 13	74

predictions and the data around the box and find them to be in agreement [13].

To probe the SUSY parameter space in a simple and comprehensive way, we divide the $m_{\tilde{q}}$-$m_{\tilde{g}}$ plane into four general regions: (*A*) $m_{\tilde{q}} > m_{\tilde{g}}$ (mSUGRA, five $\tilde{q}$); (*B*) $m_{\tilde{q}} \sim m_{\tilde{g}}$ (mSUGRA, five $\tilde{q}$); (*C*) $m_{\tilde{q}} < m_{\tilde{g}}$ (cMSSM, four $\tilde{q}$); (*D*) $m_{\tilde{q}} \ll m_{\tilde{g}}$ (cMSSM, four $\tilde{q}$). We analyze representative points of each region and optimize the $\not{E}_T$ and H_T requirements for increased sensitivity to the signal. The ratio $\frac{N_{\rm SUSY}}{\sqrt{N_{\rm SM}}}$ is maximized in region *A* for $\not{E}_T \geq 90$ GeV and $H_T \geq 160$ GeV; in region *B* for $\not{E}_T \geq 110$ and $H_T \geq 230$ GeV; in *C* for $\not{E}_T \geq 110$ and $H_T \geq 170$ GeV; and in *D* for $\not{E}_T \geq 90$ and $H_T \geq 160$ GeV, where $N_{\rm SUSY}$ is the number of signal events and $N_{\rm SM}$ is the number of standard model background events. The signal efficiency 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 Fig. 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

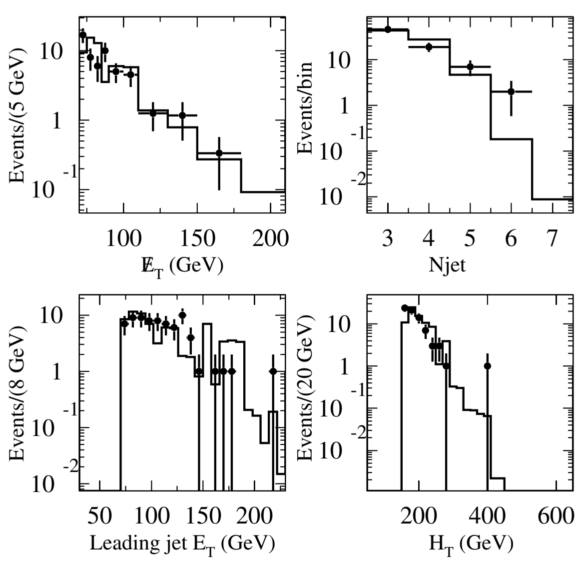

FIG. 2. Comparison in the blind box between data (points) and standard model predictions (histogram) of $\not{E}_T$, $N_{\rm jet}$, leading jet E_T, and H_T distributions. There are 74 events in each of these plots, to be compared with 76 ± 13 SM predicted events. Note that the $\not{E}_T$ distribution is plotted with a variable bin size; the bin contents are normalized as labeled.

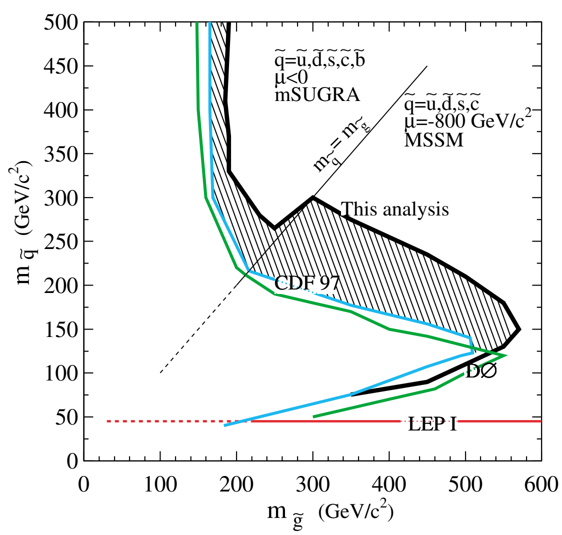

FIG. 3 (color). The 95% C.L. limit curve in the $m_{\tilde{q}}$-$m_{\tilde{g}}$ plane for $\tan\beta = 3$; the hatched area is newly excluded by this analysis. Results from some previous searches are also shown (CDF [22], D0 [23], LEP I [24]); the area at lower masses in the plane has been previously excluded by the UA1 and UA2 experiments [25,26].

signal efficiency, we derive the 95% C.L. [19] upper limit on the number of signal events. The bound is shown on the $m_{\tilde{q}}$-$m_{\tilde{g}}$ plane in Fig. 3. For the signal points generated with mSUGRA, the limit is also interpreted in the M_0-$M_{1/2}$ plane [13]. Studies of the dependence on the value of $\tan\beta$ can be found in [20,21].

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 $m_{\tilde{q}} \approx m_{\tilde{g}}$, 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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*Now at Northwestern University, Evanston, Illinois 60208.
†Now at Carnegie Mellon University, Pittsburgh, Pennsylvania 15213.

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