Search for Squarks and Gluinos with the DØ Detector

The DØ Collaboration *
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(July 2, 1997)

Abstract

We report on a search for squarks and gluinos in $p\overline{p}$ collisions at $\sqrt{s}$= 1.8 TeV using the DØ detector at Fermilab. Data corresponding to 79.2 ± 4.2 pb^{-1} were examined for events with large missing transverse energy, three or more jets, and the absence of isolated leptons. No events were observed significantly in excess of Standard Model background predictions, and we place limits on the Minimal Supergravity parameters M_0 and $M_{1/2}$.

---

*Submitted to the *XVIII International Symposium on Lepton Photon Interactions,* July 28 – August 1, 1997, Hamburg, Germany.

B. Abbott,[28] M. Abolins,[25] B.S. Acharya,[43] I. Adam,[12] D.L. Adams,[37] M. Adams,[17] S. Ahn,[14] H. Aihara,[22] G.A. Alves,[10] E. Amidi,[29] N. Amos,[24] E.W. Anderson,[19] R. Astur,[42] M.M. Baarmand,[42] A. Baden,[23] V. Balamurali,[32] J. Balderston,[16] B. Baldin,[14] S. Banerjee,[43] J. Bantly,[5] J.F. Bartlett,[14] K. Bazizi,[39] A. Belyaev,[26] S.B. Beri,[34] I. Bertram,[31] V.A. Bezzubov,[35] P.C. Bhat,[14] V. Bhatnagar,[34] M. Bhattacharjee,[13] N. Biswas,[32] G. Blazey,[30] S. Blessing,[15] P. Bloom,[7] A. Boehnlein,[14] N.I. Bojko,[35] F. Borcherding,[14] C. Boswell,[9] A. Brandt,[14] R. Brock,[25] A. Bross,[14] D. Buchholz,[31] V.S. Burtovoi,[35] J.M. Butler,[3] W. Carvalho,[10] D. Casey,[39] Z. Casilum,[42] H. Castilla-Valdez,[11] D. Chakraborty,[42] S.-M. Chang,[29] S.V. Chekulaev,[35] L.-P. Chen,[22] W. Chen,[42] S. Choi,[41] S. Chopra,[24] B.C. Choudhary,[9] J.H. Christenson,[14] M. Chung,[17] D. Claes,[27] A.R. Clark,[22] W.G. Cobau,[23] J. Cochran,[9] W.E. Cooper,[14] C. Cretsinger,[39] D. Cullen-Vidal,[5] M.A.C. Cummings,[16] D. Cutts,[5] O.I. Dahl,[22] K. Davis,[2] K. De,[44] K. Del Signore,[24] M. Demarteau,[14] D. Denisov,[14] S.P. Denisov,[35] H.T. Diehl,[14] M. Diesburg,[14] G. Di Loreto,[25] P. Draper,[44] Y. Ducros,[40] L.V. Dudko,[26] S.R. Dugad,[43] D. Edmunds,[25] J. Ellison,[9] V.D. Elvira,[42] R. Engelmann,[42] S. Eno,[23] G. Eppley,[37] P. Ermolov,[26] O.V. Eroshin,[35] V.N. Evdokimov,[35] T. Fahland,[8] M. Fatyga,[4] M.K. Fatyga,[39] J. Featherly,[4] S. Feher,[14] D. Fein,[2] T. Ferbel,[39] G. Finocchiaro,[42] H.E. Fisk,[14] Y. Fisyak,[7] E. Flattum,[14] G.E. Forden,[2] M. Fortner,[30] K.C. Frame,[25] S. Fuess,[14] E. Gallas,[44] A.N. Galyaev,[35] P. Gartung,[9] T.L. Geld,[25] R.J. Genik II,[25] K. Genser,[14] C.E. Gerber,[14] B. Gibbard,[4] S. Glenn,[7] B. Gobbi,[31] M. Goforth,[15] A. Goldschmidt,[22] B. Gómez,[1] G. Gómez,[23] P.I. Goncharov,[35] J.L. González Solís,[11] H. Gordon,[4] L.T. Goss,[45] K. Gounder,[9] A. Goussiou,[42] N. Graf,[4] P.D. Grannis,[42] D.R. Green,[14] J. Green,[30] H. Greenlee,[14] G. Grim,[7] S. Grinstein,[6] N. Grossman,[14] P. Grudberg,[22] S. Grünendahl,[39] G. Guglielmo,[33] J.A. Guida,[2] J.M. Guida,[5] A. Gupta,[43] S.N. Gurzhiev,[35] P. Gutierrez,[33] Y.E. Gutnikov,[35] N.J. Hadley,[23] H. Haggerty,[14] S. Hagopian,[15] V. Hagopian,[15] K.S. Hahn,[39] R.E. Hall,[8] P. Hanlet,[29] S. Hansen,[14] J.M. Hauptman,[19] D. Hedin,[30] A.P. Heinson,[9] U. Heintz,[14] R. Hernández-Montoya,[11] T. Heuring,[15] R. Hirosky,[15] J.D. Hobbs,[14] B. Hoeneisen,[1,†] J.S. Hoftun,[5] F. Hsieh,[24] Ting Hu,[42] Tong Hu,[18] T. Huehn,[9] A.S. Ito,[14] E. James,[2] J. Jaques,[32] S.A. Jerger,[25] R. Jesik,[18] J.Z.-Y. Jiang,[42] T. Joffe-Minor,[31] K. Johns,[2] M. Johnson,[14] A. Jonckheere,[14] M. Jones,[16] H. Jöstlein,[14] S.Y. Jun,[31] C.K. Jung,[42] S. Kahn,[4] G. Kalbfleisch,[33] J.S. Kang,[20] R. Kehoe,[32] M.L. Kelly,[32] C.L. Kim,[20] S.K. Kim,[41] A. Klatchko,[15] B. Klima,[14] C. Klopfenstein,[7] V.I. Klyukhin,[35] V.I. Kochetkov,[35] J.M. Kohli,[34] D. Koltick,[36] A.V. Kostritskiy,[35] J. Kotcher,[4] A.V. Kotwal,[12] J. Kourlas,[28] A.V. Kozelov,[35] E.A. Kozlovski,[35] J. Krane,[27] M.R. Krishnaswamy,[43] S. Krzywdzinski,[14] S. Kunori,[23] S. Lami,[42] H. Lan,[14,*] R. Lander,[7] F. Landry,[25] G. Landsberg,[14] B. Lauer,[19] A. Leflat,[26] H. Li,[42] J. Li,[44] Q.Z. Li-Demarteau,[14] J.G.R. Lima,[38] D. Lincoln,[24] S.L. Linn,[15] J. Linnemann,[25] R. Lipton,[14] Q. Liu,[14,*] Y.C. Liu,[31] F. Lobkowicz,[39] S.C. Loken,[22] S. Lökös,[42] L. Lueking,[14] A.L. Lyon,[23] A.K.A. Maciel,[10] R.J. Madaras,[22] R. Madden,[15] L. Magaña-Mendoza,[11] S. Mani,[7] H.S. Mao,[14,*] R. Markeloff,[30] T. Marshall,[18] M.I. Martin,[14] K.M. Mauritz,[19] B. May,[31] A.A. Mayorov,[35] R. McCarthy,[42] J. McDonald,[15] T. McKibben,[17] J. McKinley,[25] T. McMahon,[33] H.L. Melanson,[14] M. Merkin,[26] K.W. Merritt,[14] H. Miettinen,[37] A. Mincer,[28] C.S. Mishra,[14] N. Mokhov,[14] N.K. Mondal,[43] H.E. Montgomery,[14] P. Mooney,[1] H. da Motta,[10] C. Murphy,[17] F. Nang,[2] M. Narain,[14] V.S. Narasimham,[43] A. Narayanan,[2] H.A. Neal,[24] J.P. Negret,[1] P. Nemethy,[28] M. Nicola,[10] D. Norman,[45]

L. Oesch,[24] V. Oguri,[38] E. Oltman,[22] N. Oshima,[14] D. Owen,[25] P. Padley,[37] M. Pang,[19]
A. Para,[14] Y.M. Park,[21] R. Partridge,[5] N. Parua,[43] M. Paterno,[39] J. Perkins,[44] M. Peters,[16]
R. Piegaia,[6] H. Piekarz,[15] Y. Pischalnikov,[36] V.M. Podstavkov,[35] B.G. Pope,[25]
H.B. Prosper,[15] S. Protopopescu,[4] J. Qian,[24] P.Z. Quintas,[14] R. Raja,[14] S. Rajagopalan,[4]
O. Ramirez,[17] L. Rasmussen,[42] S. Reucroft,[29] M. Rijssenbeek,[42] T. Rockwell,[25] N.A. Roe,[22]
P. Rubinov,[31] R. Ruchti,[32] J. Rutherfoord,[2] A. Sánchez-Hernández,[11] A. Santoro,[10]
L. Sawyer,[44] R.D. Schamberger,[42] H. Schellman,[31] J. Sculli,[28] E. Shabalina,[26] C. Shaffer,[15]
H.C. Shankar,[43] R.K. Shivpuri,[13] M. Shupe,[2] H. Singh,[9] J.B. Singh,[34] V. Sirotenko,[30]
W. Smart,[14] R.P. Smith,[14] R. Snihur,[31] G.R. Snow,[27] J. Snow,[33] S. Snyder,[4] J. Solomon,[17]
P.M. Sood,[34] M. Sosebee,[44] N. Sotnikova,[26] M. Souza,[10] A.L. Spadafora,[22]
R.W. Stephens,[44] M.L. Stevenson,[22] D. Stewart,[24] F. Stichelbaut,[42] D.A. Stoianova,[35]
D. Stoker,[8] M. Strauss,[33] K. Streets,[28] M. Strovink,[22] A. Sznajder,[10] P. Tamburello,[23]
J. Tarazi,[8] M. Tartaglia,[14] T.L.T. Thomas,[31] J. Thompson,[23] T.G. Trippe,[22] P.M. Tuts,[12]
N. Varelas,[25] E.W. Varnes,[22] D. Vititoe,[2] A.A. Volkov,[35] A.P. Vorobiev,[35] H.D. Wahl,[15]
G. Wang,[15] J. Warchol,[32] G. Watts,[5] M. Wayne,[32] H. Weerts,[25] A. White,[44] J.T. White,[45]
J.A. Wightman,[19] S. Willis,[30] S.J. Wimpenny,[9] J.V.D. Wirjawan,[45] J. Womersley,[14]
E. Won,[39] D.R. Wood,[29] H. Xu,[5] R. Yamada,[14] P. Yamin,[4] C. Yanagisawa,[42] J. Yang,[28]
T. Yasuda,[29] P. Yepes,[37] C. Yoshikawa,[16] S. Youssef,[15] J. Yu,[14] Y. Yu,[41] Z.H. Zhu,[39]
D. Zieminska,[18] A. Zieminski,[18] E.G. Zverev,[26] and A. Zylberstejn[40]

(DØ Collaboration)

[1]Universidad de los Andes, Bogotá, Colombia
[2]University of Arizona, Tucson, Arizona 85721
[3]Boston University, Boston, Massachusetts 02215
[4]Brookhaven National Laboratory, Upton, New York 11973
[5]Brown University, Providence, Rhode Island 02912
[6]Universidad de Buenos Aires, Buenos Aires, Argentina
[7]University of California, Davis, California 95616
[8]University of California, Irvine, California 92697
[9]University of California, Riverside, California 92521
[10]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[11]CINVESTAV, Mexico City, Mexico
[12]Columbia University, New York, New York 10027
[13]Delhi University, Delhi, India 110007
[14]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[15]Florida State University, Tallahassee, Florida 32306
[16]University of Hawaii, Honolulu, Hawaii 96822
[17]University of Illinois at Chicago, Chicago, Illinois 60607
[18]Indiana University, Bloomington, Indiana 47405
[19]Iowa State University, Ames, Iowa 50011
[20]Korea University, Seoul, Korea
[21]Kyungsung University, Pusan, Korea
[22]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
[23]University of Maryland, College Park, Maryland 20742
[24]University of Michigan, Ann Arbor, Michigan 48109
[25]Michigan State University, East Lansing, Michigan 48824
[26]Moscow State University, Moscow, Russia
[27]University of Nebraska, Lincoln, Nebraska 68588
[28]New York University, New York, New York 10003
[29]Northeastern University, Boston, Massachusetts 02115
[30]Northern Illinois University, DeKalb, Illinois 60115
[31]Northwestern University, Evanston, Illinois 60208
[32]University of Notre Dame, Notre Dame, Indiana 46556
[33]University of Oklahoma, Norman, Oklahoma 73019
[34]University of Panjab, Chandigarh 16-00-14, India
[35]Institute for High Energy Physics, 142-284 Protvino, Russia
[36]Purdue University, West Lafayette, Indiana 47907
[37]Rice University, Houston, Texas 77005
[38]Universidade do Estado do Rio de Janeiro, Brazil
[39]University of Rochester, Rochester, New York 14627
[40]CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, Gif-sur-Yvette, France
[41]Seoul National University, Seoul, Korea
[42]State University of New York, Stony Brook, New York 11794
[43]Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India
[44]University of Texas, Arlington, Texas 76019
[45]Texas A&M University, College Station, Texas 77843

Despite the experimental success of the Standard Model (SM) there is great interest in looking for evidence of its possible extensions. One attractive extension is supersymmetry (SUSY), a spacetime symmetry which relates bosons to fermions and introduces a supersymmetric particle (sparticle) for each SM particle. SUSY provies a natural solution for the fine-tuning problem of the SM and yields a candidate for dark matter. The supersymmetrized SM with arbitrary SUSY-breaking terms leads to a large number of new parameters which make phenomenological analysis of experimental data intractible. Such analyses become more feasible if one assumes that the many SUSY-breaking terms are related, as in a supergravity grand unified theory.

In this paper, we present a search for squarks and gluinos, the SUSY partners of the quarks and gluons, in the framework of Minimal Supergravity [1]. Minimal Supergravity (mSUGRA) is a model which not only unifies the strong, weak, and electromagnetic forces, but also includes gravity at some large energy scale M_X. At M_X, the mass parameters for the gauginos are degenerate and the inclusion of gravity means that all of the SUSY scalars also share a common mass parameter. The only parameters needed to describe the mSUGRA models are then: M_0, the common mass parameter for all scalar sparticles at the M_X scale; $M_{1/2}$, the common mass parameter for all gauginos at the M_X scale; $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets; sign(μ), the sign of the Higgsino mass parameter; and A_0, a common trilinear coupling in the Lagrangian. We note that, at the Tevatron, A_0 only affects top squark mixing. The correspondence of the squark and gluino masses to M_0 and $M_{1/2}$ is shown in Fig. 1. The masses of the squarks corresponding to the light quarks are typically within 1 GeV of each other, while the mass of the bottom squark is within 15 GeV of the other squarks. The masses of the top squarks can be quite different and DØ 's search for those sparticles is described in reference [2].

Assuming the conservation of R parity, squarks and gluinos are produced in pairs and decay, possibly via a complicated chain, to the lightest supersymmetric particle (LSP) plus other particles, which are often quarks and gluons. Since the LSP is stable and weakly interacting, it exits the detector leaving as its signature missing transverse energy $\not\!\!E_T$. We then search for the production of squarks and gluinos by searching for an excess of events with jets and large $\not\!\!E_T$.

The data used in this analysis were obtained with the DØ detector at the Fermilab Tevatron collider operating at a $p\overline{p}$ center-of-mass energy of 1.8 TeV. The integrated luminosity for this analysis is 79.2 ± 4.2 pb^{-1} collected during the 1993-1996 data run. The DØ detector has three major subsystems: central tracking detectors, a nearly hermetic liquid argon calorimeter, and a muon spectrometer. A detailed description of the detector can be found elsewhere [3] . In this analysis, we use the excellent jet resolution and coverage of the DØ calorimeter to look for events with three or more jets and large $\not\!\!E_T$ in the absence of leptons. The major backgrounds to this event signature are top, W or Z bosons produced in association with multiple jets, or poorly measured multijet events. To contribute to the background, one of the leptons in the top, W, or Z decays has to be misidentified or not observed.

We require that each event have at least 3 jets with $E_T > 25$ GeV. All jets with $E_T > 15$ GeV are required to pass standard shape cuts on their longitudinal development, or the event is rejected. Tracks pointing to the leading jet in each event are required to confirm the primary vertex. These cuts distinguish real jets from noisy calorimeter

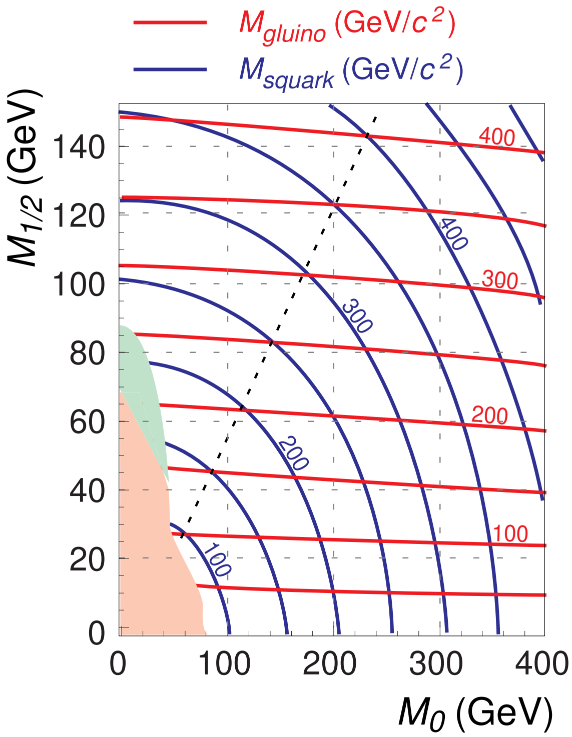

FIG. 1. Mass contours of squarks and gluinos in the $M_0 - M_{1/2}$ plane. The nearly horizontal lines are gluino mass contours and the lines forming radial patterns are the squark mass contours. The dashed line masks where squarks and gluinos have equal mass. The lower hashed region is where MSUGRA does not produce electroweak symmetry breaking. The upper hashed region is where the sneutrino is the LSP. The contours were calculated with $\tan\beta = 2$, $A_0 = 0$ and $\mu < 0$.

electronics channels and also serve to veto both electrons, and events where the vertex as found by the DØ reconstruction was not the hard scattering vertex. The directions of the jet E_T 's are required to be uncorrelated with the direction of the $\not\!\!E_T$. We require H_T in the event to be greater than 100 GeV where H_T is the scalar sum of the E_T of all jets in the event with $E_T > 15$ GeV excluding the highest E_T jet. We require at least one central jet in the event with $E_T > 115$ GeV. We reject events with isolated muons with $E_T > 15$ GeV.

To estimate the W/Z plus jets background in the final candidate sample, we use a Monte Carlo package composed of the VECBOS [4] generator for parton generation and a modified version of ISAJET [5] for subsequent parton generation and hadronization. The events are then passed through a simulation of the DØ detector based on the GEANT [6] program. The cross section uncertainty is taken to be 10% per generated jet. The top quark background is estimated by generating Monte Carlo events using the HERWIG [7] event generator coupled to the standard simulation of the DØ detector based on GEANT. We use 170 GeV for the top quark mass which is in agreement with the DØ measured value of 172.0 ± 7.5 GeV [8] and use the measured DØ top quark pair production cross section [9]. We calculate the background from mismeasured QCD multijet events using two methods, one based on the shape of the distribution of the angles between the $\not\!\!E_T$ and the two leading jets and the other based on an extrapolation of the $\not\!\!E_T$ distribution from low values of $\not\!\!E_T$ into the signal region. The backgrounds from top quark production and from mismeasured QCD multijet production

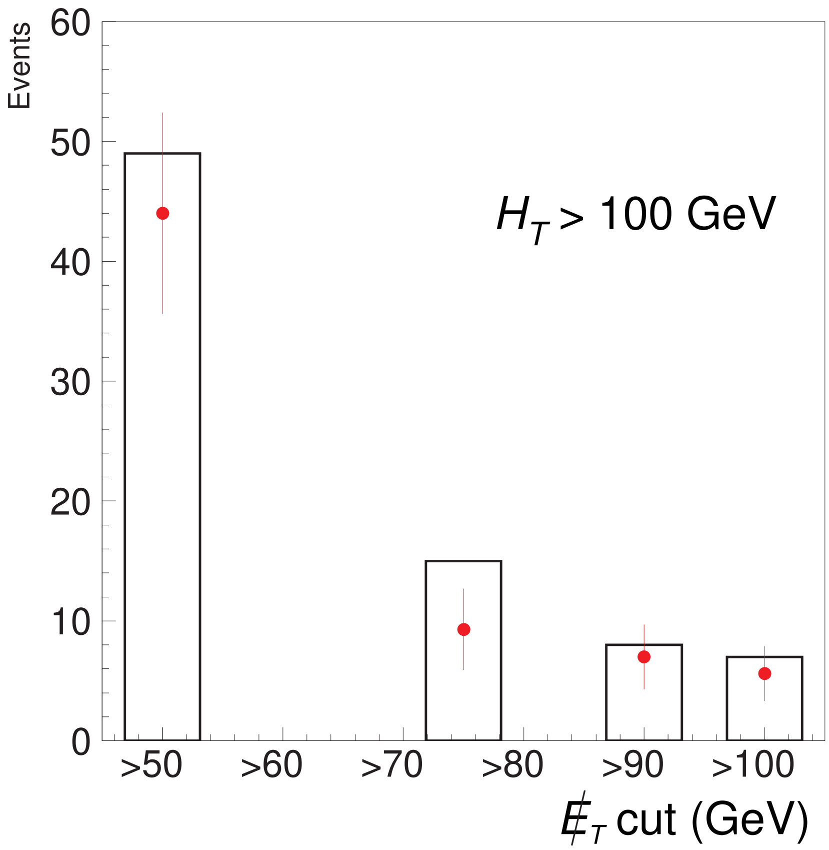

FIG. 2. Number of events as a function of $\not\!\!E_T$ for events with $H_T > 100$ GeV. The points are the calculated background, and the lines are the observed number of events.

are the two largest backgrounds.

In Fig. 2, we show the distribution of observed events and the calculated background as a function of $\not\!\!E_T$ for events with $H_T > 100$ GeV. There is no significant excess of events above background, and, accordingly, we set limits on the mSUGRA parameters M_0 and $M_{1/2}$ [10]. To determine our efficiency for observing squark and gluinos, we use the ISAJET event generator to generate squark and gluino events. We choose $\tan\beta = 2$, $A_0 = 0$, and $\mu < 0$, and allow M_0 and $M_{1/2}$ to vary. These events are then passed through the standard DØ event simulation program. We use squark and gluino NLO cross sections as determined using the PROSPINO [11] program. We optimize the $\not\!\!E_T$ and H_T cuts for each M_0 and $M_{1/2}$ point using the signal efficiencies and theoretical cross sections and our calculated backgrounds. We allow the $\not\!\!E_T$ cut to vary from 50 GeV to 150 GeV, and the H_T cut to vary from 100 GeV to 250 GeV. The resulting limit contour in the M_0 and $M_{1/2}$ plane is shown in Fig. 3. Figure 3 also shows the limit from the DØ dielectron squark and gluino analysis [12]. For small M_0, our limit on $M_{1/2}$ is 102 GeV. We can exclude equal mass squarks and gluinos below 260 GeV.

In conclusion, we report on a search for squarks and gluinos using the DØ detector at Fermilab. Data corresponding to 79.2 ± 4.2 pb^{-1} were examined for events with large missing transverse energy, three or more jets, and the absence of isolated leptons. No events were observed significantly in excess of Standard Model background predictions, and we

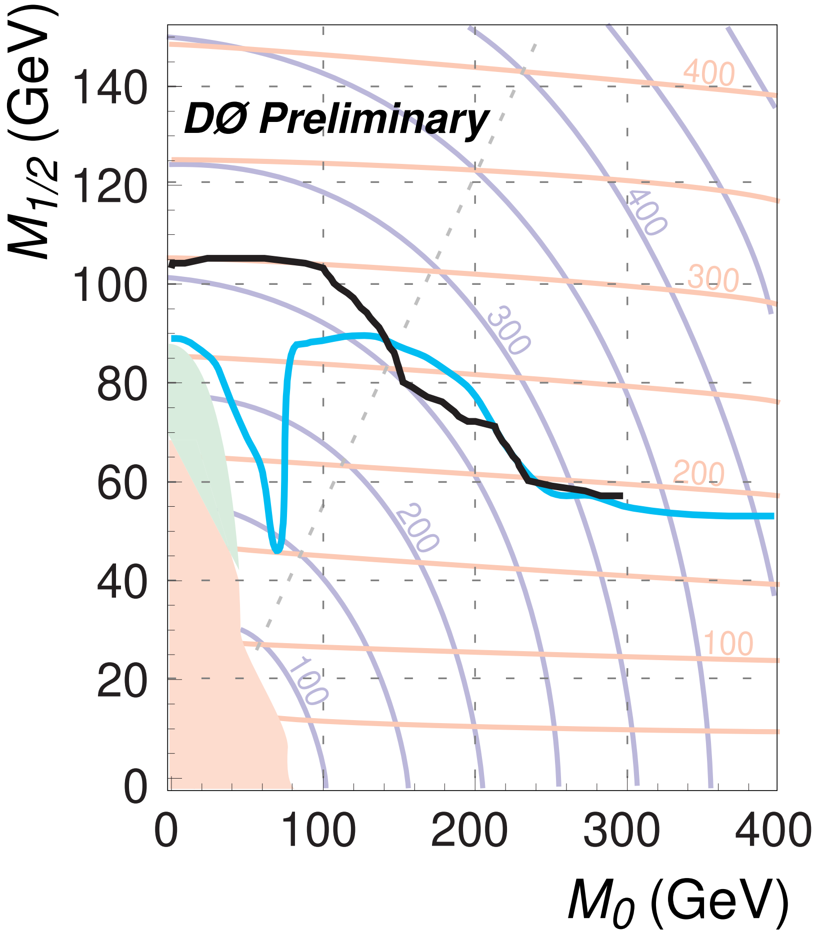

FIG. 3. Exclusion contour in the $M_0 - M_{1/2}$ plane. This analysis rules out M_0 and $M_{1/2}$ points below the solid black line. The dielectron squark and gluino analysis contour is shown in grey. The nearly horizontal lines are gluino mass contours and the lines forming radial patterns are the squark mass contours. The dashed line marks where squarks and gluinos have equal mass. The shaded region is where MSUGRA yields some unphysical condition, such as no electroweak symmetry breaking.

place limits on the Minimal Supergravity parameters M_0 and $M_{1/2}$.

We thank the staffs at Fermilab and collaborating institutions for their contributions to this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à L'Energie Atomique (France), State Committee for Science and Technology and Ministry for Atomic Energy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).

REFERENCES

* Visitor from IHEP, Beijing, China.

† Visitor from Universidad San Francisco de Quito, Quito, Ecuador.

[1] J.L.Lopez, Rep. Prog. Phys. **59**, 819 (1996), A. Chamseddine, R. Arnowitt, and P. Nath, Phys. Rev. Lett. **49**, 970 (1982), R. Barbieri, S. Ferrara, and C. Savoy, Phys. Lett. **B119**, 343 (1982), L.J. Hall, J. Lykken, and S. Weinberg, Phys. Rev. **D27**, 2359 (1983), H. Baer, C. Kao, and X. Tata, Phys. Rev. **D48**, 2978 (1993).

[2] DØ Collaboration, S. Abachi et al., Phys. Rev. Lett. **76**, 2222 (1996).

[3] DØ Collaboration, S. Abachi *et al.*, Nucl. Instrum. Methods **A338**, 185 (1994).

[4] F. Berends *et al.*, Nucl. Phys. **B357**, 32 (1991).

[5] F. Paige and S.D. Protopopescu, Brookhaven National Laboratory report No. 38304, 1986 (unpublished). We use ISAJETversion 7.13a.

[6] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013, 1993 (unpublished).

[7] G. Marchesini *et al.*, Comp. Phys. Comm. **67**, 465 (1992).

[8] DØ Collaboration, S. Abbott *et al.*, hep-ex/9706014, to be published in Phys. Rev. Lett.

[9] DØ Collaboration, B. Abbott *et al.*, hep-ex/9704015, to be published in Phys. Rev. Lett.

[10] Details of the analysis are contained in A.L. Lyon, Ph.D. thesis, University of Maryland, 1997, (unpublished).

[11] W. Beenakker, R. Höpker, and M. Spira, "PROSPINO: A Program for the Production of Supersymmetric Particles in Next to Leading Order QCD", Preprint hep-ph/9611232, 1996 (unpublished).

[12] The DØ Collaboration, Fermilab Conf-96/254-E, 1996 (unpublished).