Limits on the Masses of Supersymmetric Particles from 1.8-TeV $p\bar{p}$ Collisions

F. Abe,[16] D. Amidei,[3] G. Apollinari,[11] G. Ascoli,[7] M. Atac,[4] P. Auchincloss,[14] A. R. Baden,[6] A. Barbaro-Galtieri,[9] V. E. Barnes,[12] F. Bedeschi,[11] S. Behrends,[12] S. Belforte,[11] G. Bellettini,[11] J. Bellinger,[17] J. Bensinger,[2] A. Beretvas,[14] P. Berge,[4] S. Bertolucci,[5] S. Bhadra,[7] M. Binkley,[4] R. Blair,[1] C. Blocker,[2] J. Bofill,[4] A. W. Booth,[4] G. Brandenburg,[6] D. Brown,[6] A. Byon,[12] K. L. Byrum,[17] M. Campbell,[3] R. Carey,[6] W. Carithers,[9] D. Carlsmith,[17] J. T. Carroll,[4] R. Cashmore,[4] F. Cervelli,[11] K. Chadwick,[4,12] T. Chapin,[13] G. Chiarelli,[11] W. Chinowsky,[9] S. Cihangir,[15] D. Cline,[17] D. Connor,[10] M. Contreras,[2] J. Cooper,[4] M. Cordelli,[5] M. Curatolo,[5] C. Day,[4] R. DelFabbro,[11] M. Dell'Orso,[11] L. DeMortier,[2] T. Devlin,[14] D. DiBitonto,[15] R. Diebold,[1] F. Dittus,[4] A. DiVirgilio,[11] J. E. Elias,[4] R. Ely,[9] S. Errede,[7] B. Esposito,[5] B. Flaugher,[14] E. Focardi,[11] G. W. Foster,[4] M. Franklin,[6,7] J. Freeman,[4] H. Frisch,[3] Y. Fukui,[8] A. F. Garfinkel,[12] P. Giannetti,[11] N. Giokaris,[13] P. Giromini,[5] L. Gladney,[10] M. Gold,[9] K. Goulianos,[13] C. Grosso-Pilcher,[3] C. Haber,[9] S. R. Hahn,[10] R. Handler,[17] R. M. Harris,[9] J. Hauser,[3] T. Hessing,[15] R. Hollebeek,[10] P. Hu,[14] B. Hubbard,[9] P. Hurst,[7] J. Huth,[4] H. Jensen,[4] R. P. Johnson,[4] U. Joshi,[14] R. W. Kadel,[4] T. Kamon,[15] S. Kanda,[16] D. A. Kardelis,[7] I. Karliner,[7] E. Kearns,[6] R. Kephart,[4] P. Kesten,[2] H. Keutelian,[7] S. Kim,[16] L. Kirsch,[2] K. Kondo,[16] U. Kruse,[7] S. E. Kuhlmann,[12] A. T. Laasanen,[12] W. Li,[1] T. Liss,[3] N. Lockyer,[10] F. Marchetto,[15] R. Markeloff,[17] L. A. Markosky,[17] P. McIntyre,[15] A. Menzione,[11] T. Meyer,[15] S. Mikamo,[5] M. Miller,[10] T. Mimashi,[16] S. Miscetti,[5] M. Mishina,[8] S. Miyashita,[16] N. Mondal,[17] S. Mori,[16] Y. Morita,[16] A. Mukherjee,[4] C. Newman-Holmes,[4] L. Nodulman,[1] R. Paoletti,[11] A. Para,[4] J. Patrick,[4] T. J. Phillips,[6] H. Piekarz,[2] R. Plunkett,[13] L. Pondrom,[17] J. Proudfoot,[1] G. Punzi,[11] D. Quarrie,[4] K. Ragan,[10] G. Redlinger,[3] J. Rhoades,[17] F. Rimondi,[4] L. Ristori,[11] T. Rohaly,[10] A. Roodman,[3] A. Sansoni,[5] R. Sard,[7] V. Scarpine,[7] P. Schlabach,[7] E. E. Schmidt,[4] P. Schoessow,[1] M. H. Schub,[12] R. Schwitters,[6] A. Scribano,[11] S. Segler,[4] M. Sekiguchi,[16] P. Sestini,[11] M. Shapiro,[6] M. Sheaff,[17] M. Shibata,[16] M. Shochet,[3] J. Siegrist,[9] P. Sinervo,[10] J. Skarha,[17] D. A. Smith,[7] F. D. Snider,[3] R. St.Denis,[6] A. Stefanini,[11] Y. Takaiwa,[16] K. Takikawa,[16] D. Theriot,[4] A. Tollestrup,[4] G. Tonelli,[11] Y. Tsay,[3] F. Ukegawa,[16] D. Underwood,[1] R. Vidal,[4] R. G. Wagner,[1] R. L. Wagner,[4] J. Walsh,[10] T. Watts,[14] R. Webb,[15] T. Westhusing,[7] S. White,[13] A. Wicklund,[1] H. H. Williams,[4] T. Yamanouchi,[4] A. Yamashita,[16] K. Yasuoka,[16] G. P. Yeh,[4] J. Yoh,[4] and F. Zetti[11]

[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Brandeis University, Waltham, Massachusetts 02254*
[3]*University of Chicago, Chicago, Illinois 60637*
[4]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[5]*Laboratori Nazionali di Frascati, Istituto Nationale di Fisica Nucleare, Frascati, Italy*
[6]*Harvard University, Cambridge, Massachusetts 02138*
[7]*University of Illinois, Urbana, Illinois 61801*
[8]*National Laboratory for High Energy Physics (KEK), Tsukuba-gun, Ibaraki-ken 305, Japan*
[9]*Lawrence Berkeley Laboratory, Berkeley, California 94720*
[10]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[11]*Istituto Nationale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, Pisa, Italy*
[12]*Purdue University, West Lafayette, Indiana 47907*
[13]*Rockefeller University, New York, New York 10021*
[14]*Rutgers University, Piscataway, New Jersey 08854*
[15]*Texas A&M University, College Station, Texas 77843*
[16]*University of Tsukuba, Ibaraki 305, Japan*
[17]*University of Wisconsin, Madison, Wisconsin 53706*

(Received 19 January 1989)

An analysis of $p\bar{p}$ collision events at $\sqrt{s}=1.8$ TeV with jets and large missing transverse energy finds no event with missing transverse energy >40 GeV. This result yields a 90%-C.L. limit on the cross section for one-jet-event production of <0.1 nb for events with the jet in the pseudorapidity range $|\eta|<1.0$ and with jet $E_T>52$ GeV. Limits on the masses of squarks and gluinos in a minimal supersymmetry model are also set. At the 90% C.L., $m_{\tilde{q}}>74$ GeV and $m_{\tilde{g}}>73$ GeV.

PACS numbers: 14.80.Ly, 13.85.Qk, 13.85.Rm

One signature for new physics is the appearance in high-energy hadron collisions of events with large missing transverse momentum signaling the possible presence of noninteracting particles. We have searched for such events in 25.3 nb^{-1} of 1.8-TeV center-of-mass energy $p\bar{p}$ data taken with the Collider Detector at Fermilab (CDF) at the Tevatron Collider. The absence of such events is discussed in terms of a simple supersymmetry model.

Supersymmetry (SUSY) is a proposed symmetry that links fermions and bosons.[1] In this theory, fundamental fermions and bosons have supersymmetric partners with properties differing only by spin (and mass). In particular, the quark, gluon, and photon have SUSY partners the squark ($\tilde{q}$), gluino ($\tilde{g}$), and photino ($\tilde{\gamma}$). The model of SUSY used here assumes that the six squark masses are degenerate, and the $\tilde{\gamma}$ is the lightest SUSY particle, taken to be massless. There are two free parameters, $m_{\tilde{q}}$ and $m_{\tilde{g}}$. We assume there is a rigorous conservation of a SUSY quantum number. This implies that SUSY particles are always pair produced, and that the lightest SUSY particle is stable. The $\tilde{\gamma}$ does not deposit energy in the detector. Decay modes for the case of $m_{\tilde{q}} > m_{\tilde{g}}$ are $\tilde{q} \to \tilde{g}q$ and $\tilde{g} \to q\bar{q}\tilde{\gamma}$. For $m_{\tilde{g}} > m_{\tilde{q}}$, $\tilde{g} \to \tilde{q}g$ and $\tilde{q} \to q\tilde{\gamma}$. (More complex decay modes, as those suggested by Ref. 2, are not addressed in this paper.) We note that the final states are always composed of normal quarks and gluons, and photinos, so the SUSY events manifest themselves as events with jets and imbalanced transverse momentum. Therefore our analysis searched for this signature.

The CDF[3] is a fine-grained projective-tower-geometry calorimeter covering much of 4π solid angle. Electromagnetic (EM) calorimeters (lead radiator) are followed by hadron (iron absorber) calorimeters. There are three principal parts of the calorimeter: the "central" scintillator sampling calorimeter with $|\eta| < 1.1$; the "plug" gas sampling calorimeter with $1.1 < |\eta| < 2.4$; and the "forward" gas sampling calorimeter with $2.4 < |\eta| < 4.2$, where η is pseudorapidity, $\eta = -\ln[\tan(\theta/2)]$, with θ the polar angle. Inside of the central calorimeter, a superconducting solenoid provides a 15-kG magnetic field for tracking chambers interior to it.

The data set for this analysis was 4×10^5 events triggered by either two triggers: an "electron" trigger and a "jet" trigger. The electron trigger required E_T[4] deposition in an EM-calorimeter trigger tower ($\delta\eta = 0.2$, $\delta\phi = 15°$) greater than a luminosity-dependent threshold that ranged from 7 to 15 GeV during the course of the experiment. The jet trigger required the sum of calorimeter-trigger-tower energies to be greater than a threshold that varied from 20 to 45 GeV. Also required in both triggers was a coincidence in forward-backward scintillation counters which signaled a $p\bar{p}$ interaction.

The data were filtered by the following requirements:

(1) Missing E_T, $\not\!E_T$, is the vector sum of the transverse projections of energy depositions in all calorimeter cells. The magnitude of the $\not\!E_T$ was required to be greater than 30 GeV.

(2) Calorimeter energies were first clustered with a nearest-neighbor algorithm, and clusters separated by $R = [(\delta\eta^2) + (\delta\phi^2)]^{0.5} \leq 0.7$ were combined. The highest E_T cluster was required to have $|\eta| < 1.0$, and to have $E_T \gtrsim 15$ GeV.

(3) The significance of the $\not\!E_T$ of an event was characterized by the quantity $S = \not\!E_T/\sqrt{E_T^t}$, where E_T^t is E_T summed over the central and plug calorimeters, with $\not\!E_T$ and E_T^t measured in GeV. The S distribution for a set of jet events with a central jet of $E_T \gtrsim 15$ GeV is shown in Fig. 1. To reject $\not\!E_T$ events due to calorimetry measurement fluctuations, we required $S > 2.8$.

(4) An important source of background events with large $\not\!E_T$ was two-jet events where the energy of one of the jets was mismeasured. These events typically were of a back-to-back topology, with the two jets separated by $\Delta\phi \approx 180°$. Any event with a cluster of $E_T \gtrsim 5$ GeV within $\pm 30°$ in ϕ from the back-to-back direction of the highest E_T cluster was removed from the sample.

(5) Events contaminated by cosmic-ray showers were removed if more than 3 GeV E_T deposited in the central hadron calorimeter was out of time with the event. This cut had greater than a 97% acceptance for jet events with jet $E_T \gtrsim 15$ GeV.

(6) Cosmic-ray showers in the EM calorimeter lacked timing information. They were removed by requiring that the ratio of the sum of charged track transverse momenta (measured in the central tracking chamber) divided by the total cluster E_T must be greater than 0.2 for the highest E_T cluster. This cut was 90% efficient for jets with $E_T \gtrsim 15$ GeV.

(7) At this point, many of the remaining events were of the process $W \to e\nu$.[5] To eliminate these events, we required that, for the highest E_T cluster, at least 10% of its E_T was deposited in the hadron calorimeter. This re-

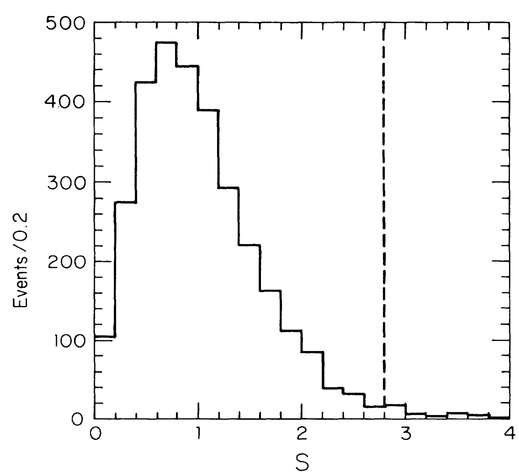

FIG. 1. S (as defined in text) for events containing jets with $E_T \gtrsim 15$ GeV. The dotted line shows our cut.

quirement was 95% efficient for jets with $E_T \geq 15$ GeV.

Two of the 4 events surviving these cuts were mismeasured two-jet events, where a high-momentum charged track opposite the highest E_T cluster did not deposit energy in the calorimeter. One of these events had a high-momentum muon candidate opposite the leading jet. The other event had a high-momentum track hitting a crack region of the calorimeter. Adding the track momenta into the $\not{E}_T$ calculation caused the events to fall below the 30-GeV threshold and be removed from the sample. The 2 surviving events had $\not{E}_T$ values of 35.2 and 36.1 GeV.

We have estimated the expected number of events with large $\not{E}_T$ produced by conventional mechanisms using the ISAJET event generator[6] and a detailed simulation of the CDF and hardware trigger. For $\mathcal{L}=25.3$ nb^{-1}, our set of filtering cuts, and $\not{E}_T > 30$ GeV (>40 GeV), we expect 0.9 (0.2) event due to the process $W \rightarrow \tau\nu$; 0.4 (0.2) event due to high-E_T Z's decaying into ν's; and 0.2 (0.0) event from heavy-quark decays. We based our limits on no event observed with $\not{E}_T > 40$ GeV.

We can express this result as a limit on the production cross section for events with a single jet of $E_T \geq 52$ GeV where the jet is produced in $|\eta| < 1.0$ (Because of the effects of detector response and clustering, a 40-GeV observed cluster corresponds on average to a jet of $E_T = 52$ Ge.[7]) For this type of event, the topological cuts will be automatically satisfied. Cuts that would reduce acceptance are cuts (5), (6), and (7) with a combined acceptance of 85% for jets of this E_T. Observing no such event in $\mathcal{L}=25.3$ nb^{-1} implies that the production cross section for this type of event is less than 0.1 nb, at 90% C.L., independent of the production mechanism.

To determine limits on masses of SUSY particles, sets of events with different combinations of $(m_{\tilde{q}}, m_{\tilde{g}})$ in the mass range 20–300 GeV were generated via the ISAJET Monte Carlo program. $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$, and $\tilde{q}\tilde{g}$ pairs were produced using the calculations of Ref. 8. The squarks and gluinos decayed via two- or three-body phase space with the decay modes as described above. Finally, the quarks and gluons form jets through parton evolution and the Field-Feynman fragmentation prescription.

These generated events were then passed through a detailed simulation of the CDF which included the effects of cracks, dead areas, calorimeter thickness, and nonlinearity. All events satisfying the required trigger were passed through our set of cuts. Table I shows results for some of the different mass combinations considered.

The shaded region in Fig. 2 is the region we exclude with this analysis. The upper boundary is the contour below which we expected (with 90% probability) to detect at least 1 event with $\not{E}_T > 40$ GeV passing our cuts. This 90%-C.L. limit includes the effects of systematic error. The arrows in the figure are the asymptotic limits, where the $\tilde{g}$ or $\tilde{q}$ mass is very large. The asymptotic mass limits are $m_{\tilde{g}} > 73$ GeV and $m_{\tilde{q}} > 74$ GeV. The discontinuity along the line $m_{\tilde{q}} = m_{\tilde{g}}$ is due to different acceptances of the different decay modes allowed for the SUSY particles. Effects due to finite mass widths of the SUSY particles were ignored in this analysis.

Sources of systematic uncertainty in the predicted number of events were luminosity (15% uncertainty), and uncertainty in our understanding of the CDF jet response due to calorimeter response to low-energy particles, calibration systematic errors, uncertainties in jet fragmentation, and the detector simulation of cracks and energy leakage (10% uncertainty in the jet energy scale[7] corresponding to a 30% uncertainty in the expected number of events). The uncertainty in the predicted cross section due to choice of structure functions was addressed by a study of four sets of structure functions.[9] We conservatively chose the set with the smallest predicted cross section (Eichten-Hinchliffe-Lane-Quigg set I), and did not assign additional systematic error from this source.

The individual errors taken in quadrature yielded a to-

TABLE I. Expected number of events passing cuts for combinations of $(m_{\tilde{g}}, m_{\tilde{q}})$.

$(m_{\tilde{q}}, m_{\tilde{g}})$ (GeV)	σ (nb)	Acceptance (%)	No. of events predicted
(200,80)	2.0	5.0	2.5
(80,200)	1.0	15	3.9
(140,80)	2.3	6.5	3.8
(90,140)	0.9	19	4.3
(80,90)	3.9	15	14.1
(80,30)	283	0.2	14.3
(30,80)	87	0.6	13.5

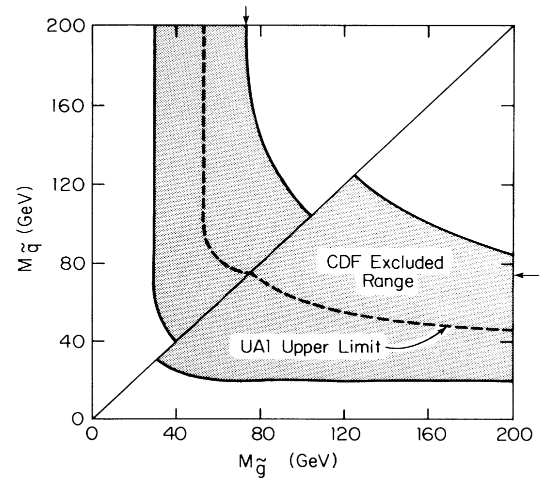

FIG. 2. The 90%-C.L. excluded region in the $(m_{\tilde{g}}, m_{\tilde{q}})$ plane.

tal systematic error of $\pm 35\%$ in the expected number of events for a given $(m_{\tilde{q}},m_{\tilde{g}})$ combination. Our 90%-C.L. limit in Fig. 2 included the probabilities of Poisson fluctuations in the observed number of events, and Gaussian fluctuations in the expected number of events due to our systematic error.

At small $m_{\tilde{q}}$ or $m_{\tilde{g}}$ where the predicted acceptance was very low, we were no longer confident of the reliability of the event simulation. Therefore we chose to set our lower-limit curve where our acceptance dropped to 0.1%. This sensitivity boundary (the lower solid line in Fig. 2) overlapped well with previously quoted results.[10]

Varying $m_{\tilde{\gamma}}$ from 0 to 30 GeV had no effect on the expected number of events in the high-mass region. The event topology is significantly altered if $m_{\tilde{\gamma}} \approx m_{\tilde{q}}$ or $m_{\tilde{\gamma}} \approx m_{\tilde{g}}$, and our results are not sensitive to these cases. Our analysis assumed that all six quarks had the same mass. If only two squarks are degenerate in mass (the other four are very heavy), our squark limit decreases by approximately 20 GeV.

In conclusion, by searching for events with $\not{E}_T > 40$ GeV, we found the production cross section for one-jet events with jet $E_T > 52$ GeV in the pseudorapidity range $|\eta| < 1.0$ to be less than 0.1 nb. We also set limits on the masses of SUSY particles in a minimal SUSY model: At 90% C.L., $m_{\tilde{g}} > 73$ GeV, independent of $m_{\tilde{q}}$; similarly, $m_{\tilde{q}} > 74$ GeV, independent of $m_{\tilde{g}}$.

We would like to thank the Fermilab Accelerator Division and the CDF technical staff for their efforts in the construction and operation of the Tevatron, the Antiproton Source, and this experiment. In addition we would like to thank M. Barnett, E. Eichten, T. Han, and F. Paige for many valuable discussions. This work was supported by the Department of Energy, the National Science Foundation, Istituto Nazionale de Fisica Nucleare, the Ministry of Science, Culture, and Education of Japan, and the A. P. Sloan Foundation.

[1]Recent reviews of supersymmetry include H. P. Nilles, Phys. Rep. **110**, 1 (1984); H. E. Haber and G. L. Kane, Phys. Rep. **117**, 75 (1985).

[2]H. Baer, J. Ellis, G. B. Gelmini, D. V. Nanopoulos, and X. Tata, Phys. Lett. **161B**, 175 (1985).

[3]F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).

[4]E_T is the energy deposited in a calorimeter tower weighted by the sine of the polar production angle.

[5]F. Abe *et al.*, Phys. Rev. Lett. **62**, 1005 (1989).

[6]F. Paige and S. Protopopesceau, BNL Report No. BNL 38034, 1986 (unpublished). We used ISAJET version 6.1.

[7]F. Abe *et al.*, Phys. Rev. Lett. **62**, 613 (1989).

[8]S. Dawson, E. Eichten, and C. Quigg, Phys. Rev. D **31**, 1581 (1985).

[9]We studied cross sections predicted for sets of structure functions of E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984); D. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).

[10]C. Albajar *et al.*, Phys. Lett. B **198**, 261 (1987).