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Search for the Supersymmetric Partner of the Top Quark in Dilepton Events from $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

D. Acosta,[14] T. Affolder,[25] H. Akimoto,[51] M. G. Albrow,[13] D. Ambrose,[37] D. Amidei,[28] K. Anikeev,[27] J. Antos,[1] G. Apollinari,[13] T. Arisawa,[51] A. Artikov,[11] T. Asakawa,[49] W. Ashmanskas,[10] F. Azfar,[35] P. Azzi-Bacchetta,[36] N. Bacchetta,[36] H. Bachacou,[25] W. Badgett,[13] S. Bailey,[18] P. de Barbaro,[41] A. Barbaro-Galtieri,[25] V. E. Barnes,[40] B. A. Barnett,[21] S. Baroiant,[5] M. Barone,[15] G. Bauer,[27] F. Bedeschi,[38] S. Behari,[21] S. Belforte,[48] W. H. Bell,[17] G. Bellettini,[38] J. Bellinger,[52] D. Benjamin,[12] J. Bensinger,[4] A. Beretvas,[13] J. Berryhill,[10] A. Bhatti,[42] M. Binkley,[13] D. Bisello,[36] M. Bishai,[13] R. E. Blair,[2] C. Blocker,[4] K. Bloom,[28] B. Blumenfeld,[21] S. R. Blusk,[41] A. Bocci,[42] A. Bodek,[41] G. Bolla,[40] A. Bolshov,[27] Y. Bonushkin,[6] D. Bortoletto,[40] J. Boudreau,[39] A. Brandl,[31] C. Bromberg,[29] M. Brozovic,[12] E. Brubaker,[25] N. Bruner,[31] J. Budagov,[11] H. S. Budd,[41] K. Burkett,[18] G. Busetto,[36] K. L. Byrum,[2] S. Cabrera,[12] P. Calafiura,[25] M. Campbell,[28] W. Carithers,[25] J. Carlson,[28] D. Carlsmith,[52] W. Caskey,[5] A. Castro,[3] D. Cauz,[48] A. Cerri,[38] L. Cerrito,[20] A. W. Chan,[1] P. S. Chang,[1] P. T. Chang,[1] J. Chapman,[28] C. Chen,[37] Y. C. Chen,[1] M.-T. Cheng,[1] M. Chertok,[5] G. Chiarelli,[38] I. Chirikov-Zorin,[11] G. Chlachidze,[11] F. Chlebana,[13] L. Christofek,[20] M. L. Chu,[1] J. Y. Chung,[33] W.-H. Chung,[52] Y. S. Chung,[41] C. I. Ciobanu,[33] A. G. Clark,[16] M. Coca,[41] A. P. Colijn,[13] A. Connolly,[25] M. Convery,[42] J. Conway,[44] M. Cordelli,[15] J. Cranshaw,[46] R. Culbertson,[13] D. Dagenhart,[4] S. D'Auria,[17] S. De Cecco,[43] F. DeJongh,[13] S. Dell'Agnello,[15] M. Dell'Orso,[38] S. Demers,[41] L. Demortier,[42] M. Deninno,[3] D. De Pedis,[43] P. F. Derwent,[13] T. Devlin,[44] C. Dionisi,[43] J. R. Dittmann,[13] A. Dominguez,[25] S. Donati,[38] M. D'Onofrio,[38] T. Dorigo,[36] N. Eddy,[20] K. Einsweiler,[25] E. Engels, Jr.,[39] R. Erbacher,[13] D. Errede,[20] S. Errede,[20] R. Eusebi,[41] Q. Fan,[41] H.-C. Fang,[25] S. Farrington,[17] R. G. Feild,[53] J. P. Fernandez,[40] C. Ferretti,[28] R. D. Field,[14] I. Fiori,[3] B. Flaugher,[13] L. R. Flores-Castillo,[39] G. W. Foster,[13] M. Franklin,[18] J. Freeman,[13] J. Friedman,[27] Y. Fukui,[23] I. Furic,[27] S. Galeotti,[38] A. Gallas,[32]

M. Gallinaro,[42] T. Gao,[37] M. Garcia-Sciveres,[25] A. F. Garfinkel,[40] P. Gatti,[36] C. Gay,[53] D. W. Gerdes,[28] E. Gerstein,[9] S. Giagu,[43] P. Giannetti,[38] K. Giolo,[40] M. Giordani,[5] P. Giromini,[15] V. Glagolev,[11] D. Glenzinski,[13] M. Gold,[31] N. Goldschmidt,[28] J. Goldstein,[13] G. Gomez,[8] M. Goncharov,[45] I. Gorelov,[31] A. T. Goshaw,[12] Y. Gotra,[39] K. Goulianos,[42] C. Green,[40] A. Gresele,[36] G. Grim,[5] C. Grosso-Pilcher,[10] M. Guenther,[40] G. Guillian,[28] J. Guimaraes da Costa,[18] R. M. Haas,[14] C. Haber,[25] S. R. Hahn,[13] E. Halkiadakis,[41] C. Hall,[18] T. Handa,[19] R. Handler,[52] F. Happacher,[15] K. Hara,[49] A. D. Hardman,[40] R. M. Harris,[13] F. Hartmann,[22] K. Hatakeyama,[42] J. Hauser,[6] J. Heinrich,[37] A. Heiss,[22] M. Hennecke,[22] M. Herndon,[21] C. Hill,[7] A. Hocker,[41] K. D. Hoffman,[10] R. Hollebeek,[37] L. Holloway,[20] S. Hou,[1] B. T. Huffman,[35] R. Hughes,[33] J. Huston,[29] J. Huth,[18] H. Ikeda,[49] C. Issever,[7] J. Incandela,[7] G. Introzzi,[38] M. Iori,[43] A. Ivanov,[41] J. Iwai,[51] Y. Iwata,[19] B. Iyutin,[27] E. James,[28] M. Jones,[37] U. Joshi,[13] H. Kambara,[16] T. Kamon,[45] T. Kaneko,[49] J. Kang,[28] M. Karagoz Unel,[32] K. Karr,[50] S. Kartal,[13] H. Kasha,[53] Y. Kato,[34] T. A. Keaffaber,[40] K. Kelley,[27] M. Kelly,[28] R. D. Kennedy,[13] R. Kephart,[13] D. Khazins,[12] T. Kikuchi,[49] B. Kilminster,[41] B. J. Kim,[24] D. H. Kim,[24] H. S. Kim,[20] M. J. Kim,[9] S. B. Kim,[24] S. H. Kim,[49] T. H. Kim,[27] Y. K. Kim,[25] M. Kirby,[12] M. Kirk,[4] L. Kirsch,[4] S. Klimenko,[14] P. Koehn,[33] K. Kondo,[51] J. Konigsberg,[14] A. Korn,[27] A. Korytov,[14] K. Kotelnikov,[30] E. Kovacs,[2] J. Kroll,[37] M. Kruse,[12] V. Krutelyov,[45] S. E. Kuhlmann,[2] K. Kurino,[19] T. Kuwabara,[49] N. Kuznetsova,[13] A. T. Laasanen,[40] N. Lai,[10] S. Lami,[42] S. Lammel,[13] J. Lancaster,[12] K. Lannon,[20] M. Lancaster,[26] R. Lander,[5] A. Lath,[44] G. Latino,[31] T. LeCompte,[2] Y. Le,[21] J. Lee,[41] S. W. Lee,[45] N. Leonardo,[27] S. Leone,[38] J. D. Lewis,[13] K. Li,[53] C. S. Lin,[13] M. Lindgren,[6] T. M. Liss,[20] J. B. Liu,[41] T. Liu,[13] Y. C. Liu,[1] D. O. Litvintsev,[13] O. Lobban,[46] N. S. Lockyer,[37] A. Loginov,[30] J. Loken,[35] M. Loreti,[36] D. Lucchesi,[36] P. Lukens,[13] S. Lusin,[52] L. Lyons,[35] J. Lys,[25] R. Madrak,[18] K. Maeshima,[13] P. Maksimovic,[21] L. Malferrari,[3] M. Mangano,[38] G. Manca,[35] M. Mariotti,[36] G. Martignon,[36] M. Martin,[21] A. Martin,[53] V. Martin,[32] J. A. J. Matthews,[31] P. Mazzanti,[3] K. S. McFarland,[41] P. McIntyre,[45] M. Menguzzato,[36] A. Menzione,[38] P. Merkel,[13] C. Mesropian,[42] A. Meyer,[13] T. Miao,[13] R. Miller,[29] J. S. Miller,[28] H. Minato,[49] S. Miscetti,[15] M. Mishina,[23] G. Mitselmakher,[14]

Y. Miyazaki,[34] N. Moggi,[3] E. Moore,[31] R. Moore,[28] Y. Morita,[23] T. Moulik,[40] M. Mulhearn,[27] A. Mukherjee,[13] T. Muller,[22] A. Munar,[38] P. Murat,[13] S. Murgia,[29] J. Nachtman,[6] V. Nagaslaev,[46] S. Nahn,[53] H. Nakada,[49] I. Nakano,[19] R. Napora,[21] F. Niell,[28] C. Nelson,[13] T. Nelson,[13] C. Neu,[33] M. S. Neubauer,[27] D. Neuberger,[22] C. Newman-Holmes,[13] C.-Y. P. Ngan,[27] T. Nigmanov,[39] H. Niu,[4] L. Nodulman,[2] A. Nomerotski,[14] S. H. Oh,[12] Y. D. Oh,[24] T. Ohmoto,[19] T. Ohsugi,[19] R. Oishi,[49] T. Okusawa,[34] J. Olsen,[52] W. Orejudos,[25] C. Pagliarone,[38] F. Palmonari,[38] R. Paoletti,[38] V. Papadimitriou,[46] D. Partos,[4] J. Patrick,[13] G. Pauletta,[48] M. Paulini,[9] T. Pauly,[35] C. Paus,[27] D. Pellett,[5] A. Penzo,[48] L. Pescara,[36] T. J. Phillips,[12] G. Piacentino,[38] J. Piedra,[8] K. T. Pitts,[20] A. Pompoš,[40] L. Pondrom,[52] G. Pope,[39] T. Pratt,[35] F. Prokoshin,[11] J. Proudfoot,[2] F. Ptohos,[15] O. Pukhov,[11] G. Punzi,[38] J. Rademacker,[35] A. Rakitine,[27] F. Ratnikov,[44] H. Ray,[28] D. Reher,[25] A. Reichold,[35] P. Renton,[35] M. Rescigno,[43] A. Ribon,[36] W. Riegler,[18] F. Rimondi,[3] L. Ristori,[38] M. Riveline,[47] W. J. Robertson,[12] T. Rodrigo,[8] S. Rolli,[50] L. Rosenson,[27] R. Roser,[13] R. Rossin,[36] C. Rott,[40] A. Roy,[40] A. Ruiz,[8] D. Ryan,[50] A. Safonov,[5] R. St. Denis,[17] W. K. Sakumoto,[41] D. Saltzberg,[6] C. Sanchez,[33] A. Sansoni,[15] L. Santi,[48] S. Sarkar,[43] H. Sato,[49] P. Savard,[47] A. Savoy-Navarro,[13] P. Schlabach,[13] E. E. Schmidt,[13] M. P. Schmidt,[53] M. Schmitt,[32] L. Scodellaro,[36] A. Scott,[6] A. Scribano,[38] A. Sedov,[40] S. Seidel,[31] Y. Seiya,[49] A. Semenov,[11] F. Semeria,[3] T. Shah,[27] M. D. Shapiro,[25] P. F. Shepard,[39] T. Shibayama,[49] M. Shimojima,[49] M. Shochet,[10] A. Sidoti,[36] J. Siegrist,[25] A. Sill,[46] P. Sinervo,[47] P. Singh,[20] A. J. Slaughter,[53] K. Sliwa,[50] F. D. Snider,[13] R. Snihur,[26] A. Solodsky,[42] J. Spalding,[13] T. Speer,[16] M. Spezziga,[46] P. Sphicas,[27] F. Spinella,[38] M. Spiropulu,[10] L. Spiegel,[13] J. Steele,[52] A. Stefanini,[38] J. Strologas,[20] F. Strumia, [16] D. Stuart,[7] A. Sukhanov,[14] K. Sumorok,[27] T. Suzuki,[49] T. Takano,[34] R. Takashima,[19] K. Takikawa,[49] P. Tamburello,[12] M. Tanaka,[49] B. Tannenbaum,[6] M. Tecchio,[28] R. J. Tesarek,[13] P. K. Teng,[1] K. Terashi,[42] S. Tether,[27] J. Thom,[13] A. S. Thompson,[17] E. Thomson,[33] R. Thurman-Keup,[2] P. Tipton,[41] S. Tkaczyk,[13] D. Toback,[45] K. Tollefson,[29] D. Tonelli,[38] M. Tonnesmann,[29] H. Toyoda,[34] W. Trischuk,[47] J. F. de Troconiz,[18] J. Tseng,[27] D. Tsybychev,[14] N. Turini,[38] F. Ukegawa,[49] T. Unverhau,[17] T. Vaiciulis,[41] J. Valls,[44] A. Varganov,[28] E. Vataga,[38] S. Vejcik III,[13]

G. Velev,[13] G. Veramendi,[25] R. Vidal,[13] I. Vila,[8] R. Vilar,[8] I. Volobouev,[25] M. von der Mey,[6] D. Vucinic,[27] R. G. Wagner,[2] R. L. Wagner,[13] W. Wagner,[22] N. B. Wallace,[44] Z. Wan,[44] C. Wang,[12] M. J. Wang,[1] S. M. Wang,[14] B. Ward,[17] S. Waschke,[17] T. Watanabe,[49] D. Waters,[26] T. Watts,[44] M. Weber,[25] H. Wenzel,[22] W. C. Wester III,[13] B. Whitehouse,[50] A. B. Wicklund,[2] E. Wicklund,[13] T. Wilkes,[5] H. H. Williams,[37] P. Wilson,[13] B. L. Winer,[33] D. Winn,[28] S. Wolbers,[13] D. Wolinski,[28] J. Wolinski,[29] S. Wolinski,[28] M. Wolter,[50] S. Worm,[44] X. Wu,[16] F. Würthwein,[27] J. Wyss,[38] U. K. Yang,[10] W. Yao,[25] G. P. Yeh,[13] P. Yeh,[1] K. Yi,[21] J. Yoh,[13] C. Yosef,[29] T. Yoshida,[34] I. Yu,[24] S. Yu,[37] Z. Yu,[53] J. C. Yun,[13] L. Zanello,[43] A. Zanetti,[48] F. Zetti,[25] 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] *University of California at Santa Barbara, Santa Barbara, California 93106*

[8] *Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*

[9] *Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*

[10] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*

[11] *Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

[12] *Duke University, Durham, North Carolina 27708*

[13] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[14] *University of Florida, Gainesville, Florida 32611*

[15] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

[16] *University of Geneva, CH-1211 Geneva 4, Switzerland*

[17] *Glasgow University, Glasgow G12 8QQ, United Kingdom*

[18] *Harvard University, Cambridge, Massachusetts 02138*

[19] *Hiroshima University, Higashi-Hiroshima 724, Japan*

[20] *University of Illinois, Urbana, Illinois 61801*

[21] *The Johns Hopkins University, Baltimore, Maryland 21218*

[22] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*

[23] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan*

[24] *Center for High Energy Physics: Kyungpook National University, Taegu 702-701; Seoul National University, Seoul 151-742; and SungKyunKwan University, Suwon 440-746; Korea*

[25] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[26] *University College London, London WC1E 6BT, United Kingdom*

[27] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

[28] *University of Michigan, Ann Arbor, Michigan 48109*

[29] *Michigan State University, East Lansing, Michigan 48824*

[30] *Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*

[31] *University of New Mexico, Albuquerque, New Mexico 87131*

[32] *Northwestern University, Evanston, Illinois 60208*

[33] *The Ohio State University, Columbus, Ohio 43210*

[34] *Osaka City University, Osaka 588, Japan*

[35] *University of Oxford, Oxford OX1 3RH, United Kingdom*

[36] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

[37] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*

[38] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*

[39] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*

[40] *Purdue University, West Lafayette, Indiana 47907*

[41] *University of Rochester, Rochester, New York 14627*

[42] *Rockefeller University, New York, New York 10021*

[43] *Instituto Nazionale de Fisica Nucleare, Sezione di Roma, University di Roma I, "La Sapienza," I-00185 Roma, Italy*

[44] Rutgers University, Piscataway, New Jersey 08855

[45] Texas A&M University, College Station, Texas 77843

[46] Texas Tech University, Lubbock, Texas 79409

[47] Institute of Particle Physics, University of Toronto, Toronto M5S 1A7, Canada

[48] Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy

[49] University of Tsukuba, Tsukuba, Ibaraki 305, Japan

[50] Tufts University, Medford, Massachusetts 02155

[51] Waseda University, Tokyo 169, Japan

[52] University of Wisconsin, Madison, Wisconsin 53706

[53] Yale University, New Haven, Connecticut 06520

Abstract

We have searched for the supersymmetric partner of the top quark (stop) in 107 pb^{-1}of $p\bar{p}$ collisions at $\sqrt{s}$= 1.8 TeV collected by the Collider Detector at Fermilab (CDF). Within the framework of the Minimal Supersymmetric extension of the Standard Model (MSSM) each of the pair-produced stops is assumed to decay into a lepton, bottom quark and supersymmetric neutrino. Such a scenario would give rise to events with two leptons, two hadronic jets, and a substantial imbalance of transverse energy. No evidence of such a stop signal has been found. We calculate a 95% confidence level (C.L.) upper limit on the stop production cross section, which excludes stop masses in the region ($80 \leq m_{\tilde{t}} \leq 135$ GeV/c^2) in the mass plane of stop versus sneutrino.

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One of the most promising theories beyond the Standard Model (SM) [1] is the Minimal Supersymmetric Standard Model (MSSM) [2]. It predicts that each SM particle has a superpartner (sparticle) with the same quantum numbers, except for spin which differs by one half unit. Experimental results indicate that supersymmetric (SUSY) particles are generally not as light as their SM partners. SUSY, therefore, is broken at or above the electroweak scale, and we treat the sparticle masses as free parameters. Due to the large top quark mass, there may be a large mixing between the superpartners of the left and right helicity states of the top quark [3]. This can lead to substantial mass splitting of the stop mass eigenstates ($\tilde{t}_1$, $\tilde{t}_2$) with the lighter one (denoted $\tilde{t}$ from now on) potentially being the lightest squark.

Stop-antistop pairs ($\tilde{t}\bar{\tilde{t}}$) are strongly produced in the $p\bar{p}$ collisions at the Fermilab Tevatron if kinematically accessible. The production cross section has been calculated using QCD in the next-to-leading order (NLO) approximation [4]. For a given stop mass ($m_{\tilde{t}}$) the cross section depends only weakly on the other parameters of the MSSM. In the mass region of interest to our search ($m_{\tilde{t}}$=80-140 GeV/c^2), the cross section drops from 44 pb to 1 pb.

We assume SUSY R-parity [5] conservation, from which the stability of the lightest supersymmetric particle (LSP) follows. All SUSY particles, including the stop, eventually decay into this LSP. Stop decays into the top quark are kinematically not accessible in our region of interest due to the high top mass ($m_{\tilde{t}} < m_t$). For the stop decay into a bottom quark and an on-shell chargino ($\widetilde{\chi}_1^{\pm}$), only a very small window of opportunity remains at the Tevatron due to the high $\widetilde{\chi}_1^{\pm}$ mass limit from LEP2 [6]. Another possible 2-body stop decay would be the flavor-changing, $\widetilde{t} \to c\tilde{\chi}_1^0$, decay [7]. It would proceed via higher order loop diagrams and is thus highly suppressed. The 3-body decay into a charged supersymmetric lepton, $\tilde{t} \to \; \widetilde{l}\nu b$, is closed for most of the stop region currently within the reach of CDF because of the slepton mass limit of LEP2 [6]. The existing mass limit of the supersymmetric neutrino, $m_{\tilde{\nu}} \geq 45$ GeV/c^2 [8], leaves the decay into sneutrino, $\tilde{t} \to \; l\widetilde{\nu}b$, open. This 3-body decay proceeds via a virtual chargino, and is expected to yield equal e, μ, and τ branching ratios.

Stop pair production with the $\tilde{t} \rightarrow l\tilde{\nu}b$ decay will yield two leptons with opposite electric charge, two hadronic jets from the bottom quarks and considerable transverse energy imbalance ($\not{E}_{T}$) in the detector [9] due to the escaping sneutrinos. CDF has reported earlier on an analysis based on B identification [10]. In this Letter we use dilepton events. Only a few SM processes yield dileptons and can thus potentially mimic our stop signature. The most significant ones are (1) $t\bar{t}$ production with leptons from W and/or bottom decays; (2) heavy flavor, *i.e.* $b\bar{b}$ and $c\bar{c}$ with semileptonic decays; (3) Drell-Yan production with hadronic jets from higher order processes; (4) diboson production, WW, WZ and ZZ; (5) lepton pairs from the decay of vector mesons, such as J/ψ and Υ; (6) events without two genuine prompt leptons, where a hadron is misidentified as a lepton, or decays in flight to a lepton.

The search presented here is based on 107 pb^{-1}of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected by the Collider Detector at Fermilab (CDF) during the 1992 to 1995 running period of the Tevatron. A detailed description of the CDF detector can be found in Ref. [11]. Online triggers selected approximately 6.4 million single lepton events and an additional 3.3 million dilepton events. All of those events have been reconstructed, and 13,295 events were selected as a dilepton sample, by requiring at least one tight electron ($E_T \geq 10$ GeV, $|\eta| \leq 1.0$) or muon ($p_T \geq 10$ GeV/c, $|\eta| \leq 0.6$) candidate, and a second loose electron ($E_T \geq 6$ GeV, $|\eta| \leq 1.0$) or muon ($p_T \geq 6$ GeV/c, $|\eta| \leq 1.0$) candidate. No explicit tau lepton identification was done, but taus can enter the search sample if they decay leptonically. Electrons are identified by energy deposition in the electromagnetic calorimeter with a track of corresponding energy in the central drift chamber (CTC) pointing to it. Muons are identified by track segments in both the CTC and the muon drift chambers that are located behind 4.5 to 10 interaction lengths of absorber. Standard lepton identification cuts are used and described elsewhere [12]. Each lepton is required to be isolated, *i.e.* we require the total p_T of all other tracks within a cone $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$ around the lepton's track not to exceed 4 GeV/c. The jets were reconstructed with a cone algorithm with cone radius $\Delta R = 0.7$ [13]. We require at least one jet in the central region of the calorimeter ($|\eta| \leq 1.0$) with $E_T \geq$ 15 GeV, that is separated by $\Delta R \geq 0.7$ from both leptons in the event. For increased efficiency, we require only one of the two jets to be identified. Sequential B decays, J/ψ, Υ and Z events were removed requiring the invariant dilepton masses $m_{ll'} \geq 6$ GeV/c^2 or $m_{ll} \geq 12$ GeV/c^2 and excluding $76 < m_{ll} < 106$ GeV/c^2 (where prime indicates any mixture of e and μ flavors and no prime indicates same-flavor dileptons). At the preselection level we start with $\not\!\!E_T \geq 15$ GeV. Experimental backgrounds, like electrons from conversions and muons from cosmic rays are removed with additional cuts [14]. 176 events fulfill the above preselection requirements.

To estimate the number of SM and stop events in the sample, events of the various physics processes are generated by ISAJET [15] and simulated for the CDF detector. We have used CTEQ-3 parton distribution functions (PDF) [16]. The stop production cross section was calculated with PROSPINO [17] and the ISAJET cross section was adjusted accordingly. We have generated events over a large range of stop (80-140 GeV/c^2) and sneutrino (45-90 GeV/c^2) masses.

The Drell-Yan and $t\bar{t}$ production cross sections were normalized to CDF measurements [18]. The Monte Carlo (MC) $b\bar{b}$ and $c\bar{c}$ cross sections were verified by inclusive electron-muon samples [19]. The $B^0\bar{B}^0$ oscillation effect was added based on the CDF measured inclusive χ mixing fraction [20]. The diboson production cross sections of the MC were scaled to those of NLO calculations [21].

For low p_T leptons the contribution due to misidentification can be significant and is calculated in two steps [14]. First we measure in various data samples the so-called “fake lepton probabilities” (momentum-dependent, separately for electrons and muons, and dependent on detector region). These “fake lepton probabilities” include hadrons being misidentified as electrons or muons, and also include leptons from in-flight decays of pions and kaons. The data samples used were (i) a minimum-bias trigger sample and (ii) a sample with a 50 GeV jet trigger threshold. We remove events in those samples similarly to the dilepton analysis, and, to be unbiased, we exclude all hadrons associated with a jet required by the online trigger. We measure misidentification probabilities between 0.4% and 7% for both e's and μ's [14], and the results are consistent between the two data samples.

Second, in a single lepton sample we use these "fake lepton probabilities" successively on each other track in the event to simulate dilepton events. We use the "fake lepton probabilities" to simulate both the number of misidentified-lepton events as well as their kinematic properties.

The major background to the preselection sample comes from heavy flavor production, with about a quarter of the events having leptons of the same charge. Another significant background comes from Drell-Yan processes. In those events the $\not\!\!E_{\rm T}$ comes from τ decays or jet and lepton energy mismeasurements due to uninstrumented detector regions. We expect a total background of 155 $\pm$ 55 events, while a stop and sneutrino mass combination of 100 and 75 GeV/c^2 would contribute 24 $\pm$ 9 events. Table I shows the expected contributions in detail for like sign and opposite sign leptons. To verify our background calculation further, we compare kinematic distributions of the data and the expected background. Figure 1 shows a few such distributions. Top and diboson production yield generally more energetic leptons than $b\bar{b}$, $c\bar{c}$ or misidentified leptons. The $\rm p_T$ distributions of the leptons show that both high and low $\rm p_T$ lepton sources agree well with the observed data. The observed $\not\!\!E_{\rm T}$ distribution agrees both at low $\not\!\!E_{\rm T}$, where detector effects dominate, and at high $\not\!\!E_{\rm T}$, where neutrinos from W and Z bosons determine the spectrum. We also note that the parton shower MC describes well the observed jet multiplicity. From the signal to background ratio, it is clear that the preselection sample does not have sufficient sensitivity to answer the question of stop pair production. In contrast to an earlier search [22] we select a kinematic region in which we expect higher S/B where S is the stop signal and B is the background which includes SM processes and misidentified leptons. This decreases the systematic uncertainty associated with low $\rm p_T$ leptons in our analysis.

In less than 5% of stop events the two leptons will have the same electric charge due to the semileptonic decay of one of the b-quarks. However, 20% of the SM background yields like-sign (LS) lepton events. We thus focus our search on events with opposite-sign charge

(OS) leptons. For R_p-conserving supersymmetry we expect large missing energy from the rather heavy sneutrinos. In Fig. 1 we see most of the background events clustering at low missing E_T. A $\not\!\!E_T$ cut of 30 GeV removes 77% of the SM background but keeps about 57% of the stop events. Energy mismeasurement of leptons, or the presence of neutrinos from Drell-Yan τ decays, would cause the leptons (and the dilepton system as well) to be aligned with the $\not\!\!E_T$ direction. This is not typical for the signal, where we expect true $\not\!\!E_T$ from the sneutrinos in the stop decay. We therefore require the azimuthal angles between $\not\!\!E_T$ and the individual leptons and the dilepton system $\Delta\phi_{l_1}^{\not E_T}$, $\Delta\phi_{l_2}^{\not E_T}$, and $\Delta\phi_{l_1 l_2}^{\not E_T}$ to be larger than 30°.

In Drell-Yan plus jets events or when $b\bar{b}$ or $c\bar{c}$ events originate from gluon splitting (initial or final state) events, the two leptons balance the jets in the transverse plane. We veto events where the angle between either lepton and the most energetic central jet, $\Delta\phi_{l_1}^{\rm jet}$ and $\Delta\phi_{l_2}^{\rm jet}$, is larger than 90°.

Events from top pair production pass the above cuts with efficiencies similar to stop pair events and are now the dominant source of SM background. In top events the leptons come from W decay and are very energetic. In the case of stop, we have 3-body decays containing a very heavy sneutrino. The amount of available energy in the decay depends on the stop-sneutrino mass difference, $\Delta m_{\tilde{t}-\tilde{\nu}}$. For small mass difference, the leptons and jets are quite soft and a large fraction of the event energy escapes detection through the sneutrinos, unlike a $t\bar{t}$ event. For best stop sensitivity at small $\Delta m_{\tilde{t}-\tilde{\nu}}$ we require the scalar sum of lepton p_T, $p_T^{l_1} + p_T^{l_2} \leq 75$ GeV/c, and the p_T of the dilepton system, $p_T^{l_1 l_2} \leq 30$ GeV/c. Although a large amount of energy escapes undetected, the sneutrinos tend to be back-to-back, thus reducing the measured $\not\!\!E_T$. We also require the sum of the most energetic central jet E_T and the missing E_T, ${E_T}^{\rm jet} + \not\!\!E_T \leq 160$ GeV.

For large stop-sneutrino mass difference, the leptons are more energetic and we can increase our lepton p_T requirement to 10 GeV/c without much loss in stop efficiency. However, leptons and jets are still significantly softer than in $t\bar{t}$ events. We place the same jet, missing E_T, and lepton requirements as at small $\Delta m_{\tilde{t}-\tilde{\nu}}$, ${E_T}^{\rm jet} + \not\!\!E_T \leq 160$ GeV and $p_T^{l_1} + p_T^{l_2} \leq 75$ GeV/c, but loosen the requirement on the dilepton p_T to $p_T^{l_1 l_2} \leq 55$ GeV/c.

Table II shows the expected number of stop events for the two search regions. We start our search at stop masses of 80 GeV/c^2 to overlap with previous LEP limits. Near the kinematic limit of the stop decay, $m_{\tilde{t}} = m_{\tilde{\nu}} + m_b$, lepton and jet energies become very soft, limiting our stop detection capabilities. At high stop mass our sensitivity is limited by the steeply falling production cross section. In the region of interest to this search the final stop event acceptance varies between 0.3% and 2.3%.

The biggest source of uncertainty on the number of expected stop events arises from the choice of the renormalization and factorization scale, Q^2, which characterizes the amount of energy transferred during the collision. The $\not\!\!E_{\mathrm{T}}$ is reduced (due to the sneutrinos being more back-to-back) when Q is increased, and the jet E_{T} gets softer when Q is decreased. By varying Q by a factor of two up and down, we determine the uncertainty due to the choice of Q^2 to be 32%. Other significant sources of uncertainty are: (1) the choice of PDF (11%) (2) the absolute energy scale of the detector (11%) (3) the amount of gluon radiation (7%) (4) trigger, lepton and isolation efficiency (5%), and (5) the luminosity measurement (4%). The statistical uncertainties of the MC samples are about 8%. Combining the statistical and systematic uncertainties we obtained a total uncertainty of 38% for the signal expectation. Similarly, we evaluated the uncertainty of the background calculation to be 30%.

After establishing the selection cuts by using a "blind" analysis technique, we then apply the cuts to the preselection data. We observe zero events for both the small and the large $\Delta m_{\tilde{t}-\tilde{\nu}}$ sets of cuts, consistent with our background expectation of 1.52±0.47 and 2.07±0.46 events. We used the frequentist method [23] with zero observed events, no background subtraction and a total uncertainty of 38% on the predicted signal to calculate a 95% confidence level upper limit of 4.01 stop events. Consequently, we exclude all stop-sneutrino mass combinations that would yield more than 4.01 events. Figure 2 shows our result compared to LEP2 [6] and DØ [22]. The improvement in the small $\Delta m_{\tilde{t}-\tilde{\nu}}$ region is due to our increased signal to background ratio of 4:1.

In conclusion, we have searched for stop pair production in 107 pb^{-1}of data from $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV collected by CDF. The observed dilepton, jet, and missing

E_T events are consistent with expectations from SM sources. Failing to find a signal of supersymmetry, we establish mass limits at 95% C.L.: we exclude stop masses up to $m_{\tilde{t}} =$ 135 GeV/c^2 (at $m_{\tilde{\nu}}$ of 72-79 GeV/c^2) and sneutrino masses up to 88.4 GeV/c^2 (at $m_{\tilde{t}}$ of 126 GeV/c^2).

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[9] In the CDF coordinate system θ and ϕ are the polar and azimuthal angles, respectively, with respect to the proton beam direction (z axis). The pseudorapidity η is defined as $-\ln\tan(\theta/2)$. The transverse momentum of a particle is denoted as $\mathrm{p_T} = \mathrm{p}\sin\theta$. Similarly for $\mathrm{E_T}$. The missing transverse energy, $\not{\mathrm{E}}_\mathrm{T}$, is defined as $-\sum \mathrm{E_T}^i\,\hat{\mathrm{n}}_i$, where $\hat{n}_i$ is the unit vector in the transverse plane pointing from the interaction point to the energy deposition in calorimeter cell i.

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FIGURES

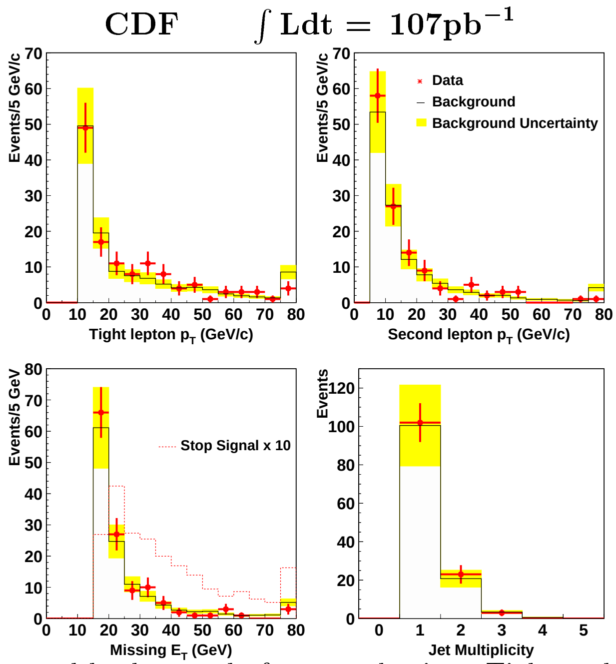

FIG. 1. Data and expected background after preselection. Tight and second lepton transverse energies, missing transverse energy (for comparison we also show the missing $E_{\rm T}$ distribution for a 10 times stop signal of $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 100 (75) GeV/c^2) and jet multiplicity distributions shown for events with opposite charge leptons. The last high bins contain overflows.

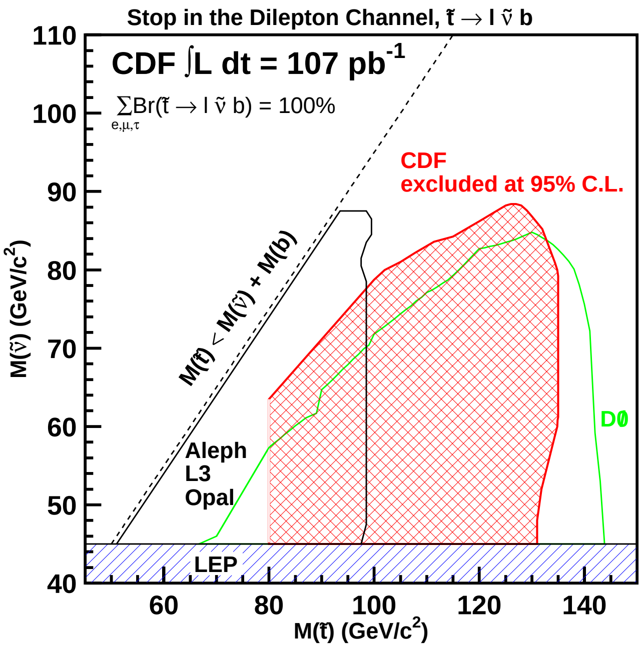

FIG. 2. Stop and sneutrino mass plane showing the CDF 95% C.L. excluded region as hatched area. For the 3-body stop decay, $\tilde{t} \rightarrow \ l\tilde{\nu}b$, a 33.3% branching ratio to each of the three lepton flavors is used.

TABLES

TABLE I. Data, expected backgrounds for the preselection sample, and expected stop signal for $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 100 (75) GeV/c^2. The stop event acceptance is 2.5% at this stage.

Source	OS	LS
Drell-Yan	52.2 ± 13.7	0.4 ± 0.4
$b\bar{b}$, $c\bar{c}$	43.5 ± 32.1	16.4 ± 17.6
$t\bar{t}$	9.5 ± 2.9	0.6 ± 0.2
WW, WZ, ZZ	3.8 ± 0.9	0.4 ± 0.1
Misidentified Leptons	16.3 ± 4.4	12.4 ± 3.4
Total Background	125.2 ± 46.7	30.1 ± 18.4
Data	128	48
Expected $\tilde{t}\bar{\tilde{t}}$	22.6 ± 8.9	1.0 ± 0.4

TABLE II. Data, expected background, and expected stop signals after final cuts. Stop A scenario represents a small $\Delta m_{\tilde{t}-\tilde{\nu}}$ with $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 100 (75) GeV/c^2. Stop B scenario represents a large $\Delta m_{\tilde{t}-\tilde{\nu}}$ with $m_{\tilde{t}}$ ($m_{\tilde{\nu}}$) = 120 (60) GeV/c^2.

Selection	Data	Background	Stop A	Stop B
Preselection	176	155.3 ± 50.2	23.6 ± 8.9	34.5 ± 13.0
OS & $\not{E}_{\mathrm{T}}$	26	28.7 ± 8.6	12.9 ± 4.9	25.1 ± 9.5
$\Delta\phi_{l,ll}^{\not{E}_{\mathrm{T}}}$ & $\Delta\phi_{l}^{\mathrm{jet}}$	4	8.1 ± 2.4	6.7 ± 2.5	14.8 ± 5.6
small $\Delta m_{\tilde{t}-\tilde{\nu}}$	0	1.5 ± 0.5	5.7 ± 2.1	-
large $\Delta m_{\tilde{t}-\tilde{\nu}}$	0	2.1 ± 0.5	-	8.2 ± 3.1
95% C.L. cross section limit:			9.0 pb	2.2 pb