Search for electroweak single top quark production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

D. Acosta,[16] J. Adelman,[12] T. Affolder,[9] T. Akimoto,[54] M.G. Albrow,[15] D. Ambrose,[43] S. Amerio,[42] D. Amidei,[33] A. Anastassov,[50] K. Anikeev,[31] A. Annovi,[44] J. Antos,[1] M. Aoki,[54] G. Apollinari,[15] T. Arisawa,[56] J-F. Arguin,[32] A. Artikov,[13] W. Ashmanskas,[15] A. Attal,[7] F. Azfar,[41] P. Azzi-Bacchetta,[42] N. Bacchetta,[42] H. Bachacou,[28] W. Badgett,[15] A. Barbaro-Galtieri,[28] G.J. Barker,[25] V.E. Barnes,[46] B.A. Barnett,[24] S. Baroiant,[6] M. Barone,[17] G. Bauer,[31] F. Bedeschi,[44] S. Behari,[24] S. Belforte,[53] G. Bellettini,[44] J. Bellinger,[58] E. Ben-Haim,[15] D. Benjamin,[14] A. Beretvas,[15] A. Bhatti,[48] M. Binkley,[15] D. Bisello,[42] M. Bishai,[15] R.E. Blair,[2] C. Blocker,[5] K. Bloom,[33] B. Blumenfeld,[24] A. Bocci,[48] A. Bodek,[47] G. Bolla,[46] A. Bolshov,[31] P.S.L. Booth,[29] D. Bortoletto,[46] J. Boudreau,[45] S. Bourov,[15] C. Bromberg,[34] E. Brubaker,[12] J. Budagov,[13] H.S. Budd,[47] K. Burkett,[15] G. Busetto,[42] P. Bussey,[19] K.L. Byrum,[2] S. Cabrera,[14] M. Campanelli,[18] M. Campbell,[33] A. Canepa,[46] M. Casarsa,[53] D. Carlsmith,[58] S. Carron,[14] R. Carosi,[44] M. Cavalli-Sforza,[3] A. Castro,[4] P. Catastini,[44] D. Cauz,[53] A. Cerri,[28] L. Cerrito,[23] J. Chapman,[33] C. Chen,[43] Y.C. Chen,[1] M. Chertok,[6] G. Chiarelli,[44] G. Chlachidze,[13] F. Chlebana,[15] I. Cho,[27] K. Cho,[27] D. Chokheli,[13] J.P. Chou,[20] M.L. Chu,[1] S. Chuang,[58] J.Y. Chung,[38] W-H. Chung,[58] Y.S. Chung,[47] C.I. Ciobanu,[23] M.A. Ciocci,[44] A.G. Clark,[18] D. Clark,[5] M. Coca,[47] A. Connolly,[28] M. Convery,[48] J. Conway,[6] B. Cooper,[30] M. Cordelli,[17] G. Cortiana,[42] J. Cranshaw,[52] J. Cuevas,[10] R. Culbertson,[15] C. Currat,[28] D. Cyr,[58] D. Dagenhart,[5] S. Da Ronco,[42] S. D'Auria,[19] P. de Barbaro,[47] S. De Cecco,[49] G. De Lentdecker,[47] S. Dell'Agnello,[17] M. Dell'Orso,[44] S. Demers,[47] L. Demortier,[48] M. Deninno,[4] D. De Pedis,[49] P.F. Derwent,[15] C. Dionisi,[49] J.R. Dittmann,[15] P. Doksus,[23] A. Dominguez,[28] S. Donati,[44] M. Donega,[18] J. Donini,[42] M. D'Onofrio,[18] T. Dorigo,[42] V. Drollinger,[36] K. Ebina,[56] N. Eddy,[23] R. Ely,[28] R. Erbacher,[6] M. Erdmann,[25] D. Errede,[23] S. Errede,[23] R. Eusebi,[47] H-C. Fang,[28] S. Farrington,[29] I. Fedorko,[44] W.T. Fedorko,[12] R.G. Feild,[59] M. Feindt,[25] J.P. Fernandez,[46] C. Ferretti,[33] R.D. Field,[16] G. Flanagan,[34] B. Flaugher,[15] L.R. Flores-Castillo,[45] A. Foland,[20] S. Forrester,[6] G.W. Foster,[15] M. Franklin,[20] J.C. Freeman,[28] Y. Fujii,[26] I. Furic,[12] A. Gajjar,[29] A. Gallas,[37] J. Galyardt,[11] M. Gallinaro,[48] M. Garcia-Sciveres,[28] A.F. Garfinkel,[46] C. Gay,[59] H. Gerberich,[14] D.W. Gerdes,[33] E. Gerchtein,[11] S. Giagu,[49] P. Giannetti,[44] A. Gibson,[28] K. Gibson,[11] C. Ginsburg,[58] K. Giolo,[46] M. Giordani,[53] M. Giunta,[44] G. Giurgiu,[11] V. Glagolev,[13] D. Glenzinski,[15] M. Gold,[36] N. Goldschmidt,[33] D. Goldstein,[7] J. Goldstein,[41] G. Gomez,[10] G. Gomez-Ceballos,[31] M. Goncharov,[51] O. González,[46] I. Gorelov,[36] A.T. Goshaw,[14] Y. Gotra,[45] K. Goulianos,[48] A. Gresele,[4] M. Griffiths,[29] C. Grosso-Pilcher,[12] U. Grundler,[23] M. Guenther,[46] J. Guimaraes da Costa,[20] C. Haber,[28] K. Hahn,[43] S.R. Hahn,[15] E. Halkiadakis,[47] A. Hamilton,[32] B-Y. Han,[47] R. Handler,[58] F. Happacher,[17] K. Hara,[54] M. Hare,[55] R.F. Harr,[57] R.M. Harris,[15] F. Hartmann,[25] K. Hatakeyama,[48] J. Hauser,[7] C. Hays,[14] H. Hayward,[29] E. Heider,[55] B. Heinemann,[29] J. Heinrich,[43] M. Hennecke,[25] M. Herndon,[24] C. Hill,[9] D. Hirschbuehl,[25] A. Hocker,[47] K.D. Hoffman,[12] A. Holloway,[20] S. Hou,[1] M.A. Houlden,[29] B.T. Huffman,[41] Y. Huang,[14] R.E. Hughes,[38] J. Huston,[34] K. Ikado,[56] J. Incandela,[9] G. Introzzi,[44] M. Iori,[49] Y. Ishizawa,[54] C. Issever,[9] A. Ivanov,[47] Y. Iwata,[22] B. Iyutin,[31] E. James,[15] D. Jang,[50] J. Jarrell,[36] D. Jeans,[49] H. Jensen,[15] E.J. Jeon,[27] M. Jones,[46] K.K. Joo,[27] S. Jun,[11] T. Junk,[23] T. Kamon,[51] J. Kang,[33] M. Karagoz Unel,[37] P.E. Karchin,[57] S. Kartal,[15] Y. Kato,[40] Y. Kemp,[25] R. Kephart,[15] U. Kerzel,[25] V. Khotilovich,[51] B. Kilminster,[38] D.H. Kim,[27] H.S. Kim,[23] J.E. Kim,[27] M.J. Kim,[11] M.S. Kim,[27] S.B. Kim,[27] S.H. Kim,[54] T.H. Kim,[31] Y.K. Kim,[12] B.T. King,[29] M. Kirby,[14] L. Kirsch,[5] S. Klimenko,[16] B. Knuteson,[31] B.R. Ko,[14] H. Kobayashi,[54] P. Koehn,[38] D.J. Kong,[27] K. Kondo,[56] J. Konigsberg,[16] K. Kordas,[32] A. Korn,[31] A. Korytov,[16] K. Kotelnikov,[35] A.V. Kotwal,[14] A. Kovalev,[43] J. Kraus,[23] I. Kravchenko,[31] A. Kreymer,[15] J. Kroll,[43] M. Kruse,[14] V. Krutelyov,[51] S.E. Kuhlmann,[2] N. Kuznetsova,[15] A.T. Laasanen,[46] S. Lai,[32] S. Lami,[48]

S. Lammel,[15] J. Lancaster,[14] M. Lancaster,[30] R. Lander,[6] K. Lannon,[38] A. Lath,[50] G. Latino,[36] R. Lauhakangas,[21] I. Lazzizzera,[42] Y. Le,[24] C. Lecci,[25] T. LeCompte,[2] J. Lee,[27] J. Lee,[47] S.W. Lee,[51] R. Lefèvre,[3] N. Leonardo,[31] S. Leone,[44] J.D. Lewis,[15] K. Li,[59] C. Lin,[59] C.S. Lin,[15] M. Lindgren,[15] T.M. Liss,[23] D.O. Litvintsev,[15] T. Liu,[15] Y. Liu,[18] N.S. Lockyer,[43] A. Loginov,[35] M. Loreti,[42] P. Loverre,[49] R-S. Lu,[1] D. Lucchesi,[42] P. Lujan,[28] P. Lukens,[15] G. Lungu,[16] L. Lyons,[41] J. Lys,[28] R. Lysak,[1] D. MacQueen,[32] R. Madrak,[20] K. Maeshima,[15] P. Maksimovic,[24] L. Malferrari,[4] G. Manca,[29] R. Marginean,[38] M. Martin,[24] A. Martin,[59] V. Martin,[37] M. Martínez,[3] T. Maruyama,[54] H. Matsunaga,[54] M. Mattson,[57] P. Mazzanti,[4] K.S. McFarland,[47] D. McGivern,[30] P.M. McIntyre,[51] P. McNamara,[50] R. NcNulty,[29] S. Menzemer,[31] A. Menzione,[44] P. Merkel,[15] C. Mesropian,[48] A. Messina,[49] T. Miao,[15] N. Miladinovic,[5] L. Miller,[20] R. Miller,[34] J.S. Miller,[33] R. Miquel,[28] S. Miscetti,[17] G. Mitselmakher,[16] A. Miyamoto,[26] Y. Miyazaki,[40] N. Moggi,[4] B. Mohr,[7] R. Moore,[15] M. Morello,[44] A. Mukherjee,[15] M. Mulhearn,[31] T. Muller,[25] R. Mumford,[24] A. Munar,[43] P. Murat,[15] J. Nachtman,[15] S. Nahn,[59] I. Nakamura,[43] I. Nakano,[39] A. Napier,[55] R. Napora,[24] D. Naumov,[36] V. Necula,[16] F. Niell,[33] J. Nielsen,[28] C. Nelson,[15] T. Nelson,[15] C. Neu,[43] M.S. Neubauer,[8] C. Newman-Holmes,[15] A-S. Nicollerat,[18] T. Nigmanov,[45] L. Nodulman,[2] O. Norniella,[3] K. Oesterberg,[21] T. Ogawa,[56] S.H. Oh,[14] Y.D. Oh,[27] T. Ohsugi,[22] T. Okusawa,[40] R. Oldeman,[49] R. Orava,[21] W. Orejudos,[28] C. Pagliarone,[44] E. Palencia,[10] R. Paoletti,[44] V. Papadimitriou,[15] S. Pashapour,[32] J. Patrick,[15] G. Pauletta,[53] M. Paulini,[11] T. Pauly,[41] C. Paus,[31] D. Pellett,[6] A. Penzo,[53] T.J. Phillips,[14] G. Piacentino,[44] J. Piedra,[10] K.T. Pitts,[23] C. Plager,[7] A. Pompoš,[46] L. Pondrom,[58] G. Pope,[45] O. Poukhov,[13] F. Prakoshyn,[13] T. Pratt,[29] A. Pronko,[16] J. Proudfoot,[2] F. Ptohos,[17] G. Punzi,[44] J. Rademacker,[41] A. Rakitine,[31] S. Rappoccio,[20] F. Ratnikov,[50] H. Ray,[33] A. Reichold,[41] B. Reisert,[15] V. Rekovic,[36] P. Renton,[41] M. Rescigno,[49] F. Rimondi,[4] K. Rinnert,[25] L. Ristori,[44] W.J. Robertson,[14] A. Robson,[41] T. Rodrigo,[10] S. Rolli,[55] L. Rosenson,[31] R. Roser,[15] R. Rossin,[42] C. Rott,[46] J. Russ,[11] V. Rusu,[12] A. Ruiz,[10] D. Ryan,[55] H. Saarikko,[21] S. Sabik,[32] A. Safonov,[6] R. St. Denis,[19] W.K. Sakumoto,[47] G. Salamanna,[49] D. Saltzberg,[7] C. Sanchez,[3] A. Sansoni,[17] L. Santi,[53] S. Sarkar,[49] K. Sato,[54] P. Savard,[32] A. Savoy-Navarro,[15] P. Schlabach,[15] E.E. Schmidt,[15] M.P. Schmidt,[59] M. Schmitt,[37] L. Scodellaro,[42] A. Scribano,[44] F. Scuri,[44] A. Sedov,[46] S. Seidel,[36] Y. Seiya,[40] F. Semeria,[4] L. Sexton-Kennedy,[15] I. Sfiligoi,[17] M.D. Shapiro,[28] T. Shears,[29] P.F. Shepard,[45] D. Sherman,[20] M. Shimojima,[54] M. Shochet,[12] Y. Shon,[58] I. Shreyber,[35] A. Sidoti,[44] J. Siegrist,[28] M. Siket,[1] A. Sill,[52] P. Sinervo,[32] A. Sisakyan,[13] A. Skiba,[25] A.J. Slaughter,[15] K. Sliwa,[55] D. Smirnov,[36] J.R. Smith,[6] F.D. Snider,[15] R. Snihur,[32] A. Soha,[6] S.V. Somalwar,[50] J. Spalding,[15] M. Spezziga,[52] L. Spiegel,[15] F. Spinella,[44] M. Spiropulu,[9] P. Squillacioti,[44] H. Stadie,[25] B. Stelzer,[32] O. Stelzer-Chilton,[32] J. Strologas,[36] D. Stuart,[9] A. Sukhanov,[16] K. Sumorok,[31] H. Sun,[55] T. Suzuki,[54] A. Taffard,[23] R. Tafirout,[32] S.F. Takach,[57] H. Takano,[54] R. Takashima,[22] Y. Takeuchi,[54] K. Takikawa,[54] M. Tanaka,[2] R. Tanaka,[39] N. Tanimoto,[39] S. Tapprogge,[21] M. Tecchio,[33] P.K. Teng,[1] K. Terashi,[48] R.J. Tesarek,[15] S. Tether,[31] J. Thom,[15] A.S. Thompson,[19] E. Thomson,[43] P. Tipton,[47] V. Tiwari,[11] S. Tkaczyk,[15] D. Toback,[51] K. Tollefson,[34] T. Tomura,[54] D. Tonelli,[44] M. Tönnesmann,[34] S. Torre,[44] D. Torretta,[15] S. Tourneur,[15] W. Trischuk,[32] J. Tseng,[41] R. Tsuchiya,[56] S. Tsuno,[39] D. Tsybychev,[16] N. Turini,[44] M. Turner,[29] F. Ukegawa,[54] T. Unverhau,[19] S. Uozumi,[54] D. Usynin,[43] L. Vacavant,[28] A. Vaiciulis,[47] A. Varganov,[33] E. Vataga,[44] S. Vejcik III,[15] G. Velev,[15] V. Veszpremi,[46] G. Veramendi,[23] T. Vickey,[23] R. Vidal,[15] I. Vila,[10] R. Vilar,[10] I. Vollrath,[32] I. Volobouev,[28] M. von der Mey,[7] P. Wagner,[51] R.G. Wagner,[2] R.L. Wagner,[15] W. Wagner,[25] R. Wallny,[7] T. Walter,[25] T. Yamashita,[39] K. Yamamoto,[40] Z. Wan,[50] M.J. Wang,[1] S.M. Wang,[16] A. Warburton,[32] B. Ward,[19] S. Waschke,[19] D. Waters,[30] T. Watts,[50] M. Weber,[28] W.C. Wester III,[15] B. Whitehouse,[55] A.B. Wicklund,[2] E. Wicklund,[15] H.H. Williams,[43] P. Wilson,[15] B.L. Winer,[38] P. Wittich,[43] S. Wolbers,[15] M. Wolter,[55] M. Worcester,[7] S. Worm,[50] T. Wright,[33] X. Wu,[18] F. Würthwein,[8] A. Wyatt,[30] A. Yagil,[15] U.K. Yang,[12] W. Yao,[28] G.P. Yeh,[15]

K. Yi,[24] J. Yoh,[15] P. Yoon,[47] K. Yorita,[56] T. Yoshida,[40] I. Yu,[27] S. Yu,[43] Z. Yu,[59] J.C. Yun,[15] L. Zanello,[49] A. Zanetti,[53] I. Zaw,[20] F. Zetti,[44] J. Zhou,[50] A. Zsenei,[18] and S. Zucchelli,[4]

(CDF Collaboration)

[1] *Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2] *Argonne National Laboratory, Argonne, Illinois 60439*
[3] *Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[4] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[5] *Brandeis University, Waltham, Massachusetts 02254*
[6] *University of California at Davis, Davis, California 95616*
[7] *University of California at Los Angeles, Los Angeles, California 90024*
[8] *University of California at San Diego, La Jolla, California 92093*
[9] *University of California at Santa Barbara, Santa Barbara, California 93106*
[10] *Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[11] *Carnegie Mellon University, Pittsburgh, PA 15213*
[12] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[13] *Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[14] *Duke University, Durham, North Carolina 27708*
[15] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[16] *University of Florida, Gainesville, Florida 32611*
[17] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[18] *University of Geneva, CH-1211 Geneva 4, Switzerland*
[19] *Glasgow University, Glasgow G12 8QQ, United Kingdom*
[20] *Harvard University, Cambridge, Massachusetts 02138*
[21] *The Helsinki Group: Helsinki Institute of Physics; and Division of High Energy Physics, Department of Physical Sciences, University of Helsinki, FIN-00044, Helsinki, Finland*
[22] *Hiroshima University, Higashi-Hiroshima 724, Japan*
[23] *University of Illinois, Urbana, Illinois 61801*
[24] *The Johns Hopkins University, Baltimore, Maryland 21218*
[25] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[26] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan*
[27] *Center for High Energy Physics: Kyungpook National University, Taegu 702-701; Seoul National University, Seoul 151-742; and SungKyunKwan University, Suwon 440-746; Korea*
[28] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[29] *University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[30] *University College London, London WC1E 6BT, United Kingdom*
[31] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[32] *Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8; and University of Toronto, Toronto, Canada M5S 1A7*
[33] *University of Michigan, Ann Arbor, Michigan 48109*
[34] *Michigan State University, East Lansing, Michigan 48824*
[35] *Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
[36] *University of New Mexico, Albuquerque, New Mexico 87131*
[37] *Northwestern University, Evanston, Illinois 60208*
[38] *The Ohio State University, Columbus, Ohio 43210*
[39] *Okayama University, Okayama 700-8530, Japan*
[40] *Osaka City University, Osaka 588, Japan*
[41] *University of Oxford, Oxford OX1 3RH, United Kingdom*

[42] University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
[43] University of Pennsylvania, Philadelphia, Pennsylvania 19104
[44] Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy
[45] University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[46] Purdue University, West Lafayette, Indiana 47907
[47] University of Rochester, Rochester, New York 14627
[48] The Rockefeller University, New York, New York 10021
[49] Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University di Roma "La Sapienza," I-00185 Roma, Italy
[50] Rutgers University, Piscataway, New Jersey 08855
[51] Texas A&M University, College Station, Texas 77843
[52] Texas Tech University, Lubbock, Texas 79409
[53] Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy
[54] University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[55] Tufts University, Medford, Massachusetts 02155
[56] Waseda University, Tokyo 169, Japan
[57] Wayne State University, Detroit, Michigan 48201
[58] University of Wisconsin, Madison, Wisconsin 53706
[59] Yale University, New Haven, Connecticut 06520

(CDF collaboration)

(Dated: October 16, 2004)

We report on a search for Standard Model t-channel and s-channel single top quark production in $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV. We use a data sample corresponding to 162 pb^{-1} recorded by the upgraded Collider Detector at Fermilab. We find no significant evidence for electroweak top quark production and set upper limits at the 95% confidence level on the production cross section, consistent with the Standard Model: 10.1 pb for the t-channel, 13.6 pb for the s-channel and 17.8 pb for the combined cross section of t- and s-channel.

PACS numbers: 14.65.Ha, 12.15.Ji, 13.85.Rm

In $p\bar{p}$ collisions at 1.96 TeV, top quarks are predominantly produced in pairs via strong interaction processes. Within the Standard Model (SM), top quarks are also expected to be produced singly by the electroweak interaction involving a Wtb vertex [1]. At the Tevatron, the two relevant production modes are the t- and the s-channel exchange of a virtual W boson. The measurement of the single top cross section is particularly interesting because the production cross section is proportional to $|V_{tb}|^2$, where V_{tb} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element which relates top and bottom quarks. Assuming three quark generations, the unitarity of the CKM matrix implies that V_{tb} is close to unity [2]. The most recent next-to-leading order calculations, assuming $|V_{tb}| = 1$, predict cross sections of (1.98 ± 0.25) pb for the t-channel and (0.88 ± 0.11) pb for the s-channel mode at $\sqrt{s} = 1.96$ TeV [3]. Using these predictions, a measurement of the single top cross section will allow for a direct determination of $|V_{tb}|$. Single top searches test also exotic models which predict anomalously altered single top production rates [4]. Moreover, single top quark processes result in the same final state as the Standard Model Higgs boson process $WH \to \ell\nu b\bar{b}$ and therefore impact future searches for the Higgs boson at the Tevatron [5]. In this letter we report results of the first search for single top production in Run 2 at the Tevatron. Results of searches for single top production at $\sqrt{s} = 1.8$ TeV (Run 1) can be found in Refs. [6, 7].

The experimental signature of single top events consists of the W decay products plus two or three jets, including one b quark jet from the decay of the top quark. To suppress QCD multijet background we select only $W \to \mu\nu_\mu$ and $W \to e\nu_e$ candidates. In s-channel events we expect a second b quark jet from the Wtb vertex. In t-channel events a second jet originates from the recoiling light quark and a third jet is produced through the splitting of the initial-state gluon into a $b\bar{b}$ pair. Mostly, this third jet escapes detection, since it is produced in the high pseudorapidity (η) regions and at low transverse energy (E_T) [8].

This article describes two analyses: (1) a combined search for the t- plus s-channel single top signal, (2) a separate search, where we measure the rates for the two single top processes individually. The data sample corresponds to an integrated luminosity of $(162 \pm 10)\,\mathrm{pb}^{-1}$ collected with the upgraded Collider Detector at Fer-

TABLE I: Event detection efficiencies in %.

Process	Combined	1-tag	2-tag
t-channel	0.89±0.07	0.86±0.07	0.007±0.002
s-channel	1.06±0.08	0.78±0.06	0.23±0.02

milab (CDF II), which is described elsewhere [9]. The common event preselection of our two analyses resembles closely the one used in the CDF measurement of the $t\bar{t}$ cross section reported in Ref. [10]. We accept events with evidence for a leptonic W decay: (a) missing transverse energy $\not\!\!E_T > 20$ GeV from the neutrino and (b) an isolated central electron with $E_T > 20$ GeV or an isolated central muon candidate with $p_T > 20$ GeV/c. An electron or muon candidate is considered isolated if the non-lepton E_T in an η-ϕ cone of radius 0.4 centered around the lepton is less than 10% of the lepton E_T or p_T. To remove dilepton events from $t\bar{t}$-production and leptonic Z boson decays, we accept events with only one well identified lepton. In addition, we veto events if we find a second, loosely identified lepton candidate that forms an invariant mass with the primary lepton between 76 GeV/$c^2 < M_{\ell\ell} <$ 106 GeV/c^2. The jet reconstruction uses a fixed cone of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$. We count jets with transverse energy $E_T \geq 15$ GeV and $|\eta| \leq 2.8$. We only accept $W + 2$ jets events. At least one of these jets must be identified as likely to originate from a b quark (b-tag) by requiring a displaced secondary vertex within the jet as measured using silicon tracker information. The effective coverage of the b-tagging ranges up to $|\eta| \lesssim 1.4$.

To optimize our sensitivity, we apply a cut on the invariant mass $M_{\ell\nu b}$ of the charged lepton, the neutrino and the b-tagged jet: 140 GeV/$c^2 \leq M_{\ell\nu b} \leq$ 210 GeV/c^2. The transverse momentum of the neutrino is set equal to $\vec{\not\!\!E}_T$; $p_z(\nu)$ is obtained up to a two-fold ambiguity from the constraint $M_{\ell\nu} = M_W$. From the two solutions we pick the one with lower $|p_z(\nu)|$. For the separate search, we subdivide the sample into events with exactly one b-tagged jet or exactly two b-tagged jets. For the 1-tag sample, we require at least one jet to have $E_T \geq 30$ GeV. We determine the total event detection efficiency ϵ_{evt} for the signal from events generated by the matrix element event generator MadEvent [11], followed by parton showering with PYTHIA [12] and a full CDF II detector simulation. MadEvent features the correct spin polarization of the top quark and its decay products. In ϵ_{evt} we include the kinematic and fiducial acceptance, branching ratios, lepton and b-jet identification as well as trigger efficiencies. We combine ϵ_{evt} as given in Table I with the cross sections predicted by theory and thereby obtain the number of expected single top events listed in Table II.

We distinguish between two background components: $t\bar{t}$ and non-top background. We estimate the $t\bar{t}$ background based on events generated with PYTHIA, normalized to the theoretically predicted cross section of $\sigma(t\bar{t}) = 6.7^{+0.7}_{-0.9}$ pb [13]. The primary source (62%) of the non-top background is the W+heavy flavor processes $\bar{q}q' \to Wg$ with $g \to b\bar{b}$ or $g \to c\bar{c}$, and $gq \to Wc$. Additional sources are "mistags" (25%), in which a light-quark jet is erroneously identified as heavy flavor, "non-W"(10%), e.g. direct $b\bar{b}$ production, and diboson (WW, WZ, ZZ) production (3%). The non-W and mistag fractions are estimated using CDF II data. The W+heavy flavor rates are extracted from ALPGEN [14] Monte Carlo (MC) events normalized to data [10]. The diboson rates are estimated from PYTHIA events normalized to theory predictions [15]. The numbers of expected signal and background events are summarized in Table II. Having applied all selection cuts we observe 42 events for the combined search, 33 events in the 1-tag sample and 6 events in the 2-tag sample. Within the uncertainties, the observations are in good agreement with predictions.

TABLE II: Expected number of signal and background events compared with observations.

Process	Combined	1-tag	2-tag
t-channel	2.8 ± 0.5	2.7 ± 0.4	0.02 ± 0.01
s-channel	1.5 ± 0.2	1.1 ± 0.2	0.32 ± 0.05
$t\bar{t}$	3.8 ± 0.9	3.2 ± 0.7	0.60 ± 0.14
non-top	30.0 ± 5.8	23.3 ± 4.6	2.59 ± 0.71
Total Backgr.	33.8 ± 5.9	26.5 ± 4.7	3.19 ± 0.72
Total Expected	38.1 ± 5.9	30.3 ± 4.7	3.53 ± 0.72
Observed	42	33	6

To extract the signal content in data, we use a maximum likelihood technique. We separate t- and s-channel events by using the $Q \cdot \eta$ distribution which exhibits a distinct asymmetry for t-channel events, see Fig. 1a. Q is the charge of the lepton and η is the pseudorapidity of the untagged jet. In Fig. 1b we show the data versus stacked MC templates weighted by the expected number of events in the 1-tag sample. The separate search defines a joint likelihood function for the $Q \cdot \eta$ distribution in the 1-tag sample and the number of events in the 2-tag sample.

$$\mathcal{L}_{sig}(\sigma_1, \ldots, \sigma_4; \delta_1, \ldots, \delta_7) = \frac{e^{-\mu_d} \cdot \mu_d^{n_d}}{n_d!} \cdot \prod_{k=1}^{N_{\rm bin}} \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!} \cdot \prod_{\substack{j=1 \\ j \neq sig}}^{4} G(\sigma_j; \sigma_{\rm SM,j}, \Delta_j) \cdot \prod_{i=1}^{7} G(\delta_i; 0, 1)$$

Four processes are considered and labeled by the index j: t-channel ($j = 1$), s-channel ($j = 2$), $t\bar{t}$ ($j = 3$), and non-top ($j = 4$). The corresponding cross sections are denoted σ_j. The background cross sections are constrained

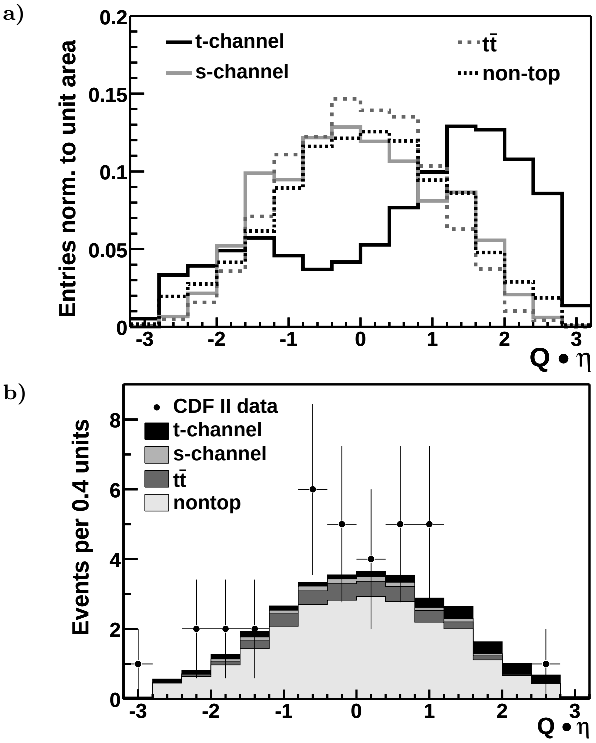

FIG. 1: $Q \cdot \eta$ distributions for a) MC templates normalized to unit area, b) Data in the 1-tag sample (33 events) vs. stacked MC templates normalized to the SM prediction.

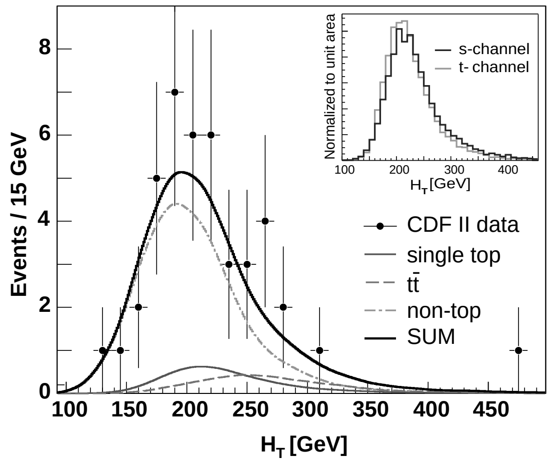

FIG. 2: H_T distribution for data (42 events) in the combined search compared with smoothed MC predictions for signal and background.

to their SM prediction $\sigma_{\mathrm{SM,j}}$ by Gaussian priors of width $\Delta_3 = 23\%\, \sigma_{\mathrm{SM,3}}$ for $t\bar{t}$ and $\Delta_4 = 20\%\, \sigma_{\mathrm{SM,4}}$ for non-top. The index sig denotes the signal process, which is s- or t-channel, respectively. The μ_k are the mean number of events in bin k of the $Q \cdot \eta$ histogram ($N_{bin} \equiv$ number of bins), while μ_d is the mean number of events in the 2-tag sample. n_k and n_d are the event numbers observed in data, respectively. Seven sources of systematic uncertainties are considered in the likelihood function: (1) jet energy scale (JES), (2) initial state radiation (ISR), (3) final state radiation (FSR), (4) parton distribution functions (PDF), (5) the choice of signal MC generator, (6) the top quark mass, (7) trigger, identification and b-tagging efficiencies and the luminosity. The relative strength of a systematic effect due to source i is parameterized by the variable δ_i. Systematic effects change the acceptance and influence the shape of the $Q \cdot \eta$ distribution. When calculating $\mu_{k/d}$ we take the systematic shifts in the acceptance and in the shape of the template histograms, and their full correlation into account. All variables except the signal cross section σ_{sig} are constrained to their expected values by Gaussian functions $G(x; x_0, \Delta_x)$ of mean x_0 and width Δ_x. The largest uncertainties are on the b-tagging efficiency (7%), luminosity (6%), top quark mass (4%) and JES (4%). The effect of uncertainty in the JES is evaluated by applying energy corrections that describe $\pm 1\, \sigma$ variations. Systematic uncertainties due to the modeling of ISR and FSR are obtained from MC samples that describe variations in these effects. To evaluate the uncertainty associated with the choice of a specific parametrization of PDF we investigated several PDF sets and took the maximum deviation (MRST72) from our standard PDF set (CTEQ5L). We estimate the uncertainty associated with the choice of single top MC generator using samples generated with TopReX [16].

To measure the combined t- plus s-channel signal in data, we use a kinematic variable whose distribution is very similar for the two single top processes, but is different for background processes: H_T, which is the scalar sum of $\not\!\!E_T$ and the transverse energies of the lepton and all jets in the event. We use a likelihood function similar to that in the separate search. One difference is that in the combined search the H_T distributions are smoothed. In Fig. 2 we show the H_T distribution observed in data compared to the SM prediction.

We perform Monte Carlo experiments to estimate our *a priori* sensitivity assuming the SM signal cross sections. For each experiment we integrate out all nuisance parameters (*i.e.*, all variables except σ_{sig}) from the full likelihood function and thereby construct the marginalized likelihood $\mathcal{L}^*_{sig}(\sigma_{sig})$. $\mathcal{L}^*_{sig}$ is normalized and interpreted as posterior probability density function $p(\sigma_{sig})$. We calculate the upper limit at the 95% C.L. using a Bayesian method assuming a prior probability density, which is 0 if $\sigma_{sig} < 0$ and 1 if $\sigma_{sig} \geq 0$. The median of the expected upper limits defines our sensitivity and is stated in Table III. We calculate the posterior probability densities for CDF II data and obtain the most probable values (MPV) and highest posterior density (HPD) intervals [2] as given in Table III. Within the statistical uncertainty these results are compatible with SM predictions. We find upper limits of 10.1 pb at the 95% C.L. for the t-

TABLE III: Upper limits at the 95% C.L. and most probable values (MPV) of single top cross sections in pb.

	t-chan.	s-chan.	Combined
expected limit	11.2	12.1	13.6
observed limit	10.1	13.6	17.8
MPV ± HPD	$0.0^{+4.7}_{-0.0}$	$4.6^{+3.8}_{-3.8}$	$7.7^{+5.1}_{-4.9}$

channel cross section and 13.6 pb for the s-channel. For the combined search we find an upper limit of 17.8 pb at the 95% C.L..

In summary, we find no significant evidence for electroweak single top quark production in (162 ± 10) pb^{-1} of integrated luminosity recorded with CDF II. We set the first limits on single top cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in Run 2 at the Tevatron.

We wish to thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Instituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation of Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; in part by the European Community's Human Potential Program under contract HPRN-CT-20002; by the Research Fund of the Istanbul University Project No. 1755/21122001; by the Research Corporation. We acknowledge the help of T. Stelzer and S. Slabospitsky for the generation of MadEvent and TopReX MC samples. We thank S. Mrenna and Z. Sullivan for useful discussions.

[1] T. Stelzer *et al.*, Phys. Rev. D **56**, 5919 (1997); M.C. Smith and S. Willenbrock, Phys. Rev. D **54**, 6696 (1996); S. Mrenna and C.-P. Yuan, Phys. Lett. B **416**, 200 (1998).

[2] K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[3] B.W. Harris *et. al.*, Phys. Rev. D **66**, 054024 (2002); Z. Sullivan, hep-ph/0408049.

[4] T. Tait and C.-P. Yuan, Phys. Rev. D **63**, 014018 (2001) and references therein.

[5] Levan Babukhadia *et al.* (CDF and DØ Higgs Working Group), FERMILAB-PUB-03-320-E.

[6] CDF Collaboration, D. Acosta *et al.*, Phys. Rev. D **65**, 091102 (2002); *ibid.* **69**, 052003 (2004).

[7] DØ Collaboration, V. Abazov *et al.*, Phys. Lett. B **517**, 282 (2001); Phys. Rev. D **63**, 031101 (2000).

[8] The polar angle θ is measured w.r.t. the proton beam direction. The pseudorapidity is defined as $\eta \equiv -\ln\tan(\theta/2)$. $E_T = E\,\sin(\theta)$.

[9] CDF Collaboration, FERMILAB-PUB-96/390-E (1996).

[10] CDF Collaboration, D. Acosta *et al.*, hep-ex/0410041, submitted to Phys. Rev. D.

[11] T. Stelzer and W.F. Long, Phys. Commun. **81**, 337 (1994); F. Maltoni and T. Stelzer, hep-ph/0208156.

[12] T. Sjöstrand *et al.*, Comp. Phys. Commun. **135**, 238 (2001).

[13] R. Bonciani *et al.*, Nucl. Phys. B **529**, 424 (1998); M. Cacciari *et al.*, JHEP 0404:068 (2004).

[14] F. Caravaglios *et al.*, Nucl. Phys. B **539**, 215 (1999); M.L. Mangano *et al.*, Nucl. Phys. B **632**, 343 (2002); M.L. Mangano *et al.*, JHEP 0307:001, (2003).

[15] J.M. Campbell and R.K. Ellis, Phys. Rev. D **60**, 113006 (1999).

[16] S.R. Slabospitsky and L. Sonnenschein, Comput. Phys. Commun. **148**, 87 (2002).