# Search for Electroweak Production of Single Top Quarks at the Tevatron Collider

The DØ Collaboration *
*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
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## Abstract

We present a search for electroweak production of single top quarks in the electron+jets and muon+jets decay channels. The measurements use $\sim$90 pb$^{-1}$ of data from Run 1 of the Fermilab Tevatron collider collected at 1.8 TeV with the DØ detector between 1992 and 1995. We set an upper limit at the 95% confidence level on the cross section for the $s$-channel process $p\bar{p} \rightarrow tb+X$ of 36 pb. The upper limit for the $t$-channel process $p\bar{p} \rightarrow tqb+X$ is 51 pb.

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## The DØ Collaboration


B. Abbott,[48] M. Abolins,[45] V. Abramov,[21] B.S. Acharya,[15] D.L. Adams,[55] M. Adams,[32] G.A. Alves,[2] N. Amos,[44] E.W. Anderson,[37] M.M. Baarmand,[50] V.V. Babintsev,[21] L. Babukhadia,[50] A. Baden,[41] B. Baldin,[31] S. Banerjee,[15] J. Bantly,[54] E. Barberis,[24] P. Baringer,[38] J.F. Bartlett,[31] U. Bassler,[11] A. Bean,[38] M. Begel,[49] A. Belyaev,[20] S.B. Beri,[13] G. Bernardi,[11] I. Bertram,[22] A. Besson,[9] V.A. Bezzubov,[21] P.C. Bhat,[31] V. Bhatnagar,[13] M. Bhattacharjee,[50] G. Blazey,[33] S. Blessing,[29] A. Boehnlein,[31] N.I. Bojko,[21] E.E. Boos,[20] F. Borcherding,[31] A. Brandt,[55] R. Breedon,[25] G. Briskin,[54] R. Brock,[45] G. Brooijmans,[31] A. Bross,[31] D. Buchholz,[34] M. Buehler,[32] V. Buescher,[49] V.S. Burtovoi,[21] J.M. Butler,[42] F. Canelli,[49] W. Carvalho,[3] D. Casey,[45] Z. Casilum,[50] H. Castilla-Valdez,[17] D. Chakraborty,[50] K.M. Chan,[49] S.V. Chekulaev,[21] D.K. Cho,[49] S. Choi,[28] S. Chopra,[51] B.C. Choudhary,[28] J.H. Christenson,[31] M. Chung,[32] D. Claes,[46] A.R. Clark,[24] J. Cochran,[28] L. Coney,[36] B. Connolly,[29] W.E. Cooper,[31] D. Coppage,[38] M.A.C. Cummings,[33] D. Cutts,[54] O.I. Dahl,[24] G.A. Davis,[49] K. Davis,[23] K. De,[55] K. Del Signore,[44] M. Demarteau,[31] P. Demine,[9] D. Denisov,[31] S.P. Denisov,[21] H.T. Diehl,[31] M. Diesburg,[31] G. Di Loreto,[45] S. Doulas,[43] P. Draper,[55] Y. Ducros,[12] L.V. Dudko,[20] S.R. Dugad,[15] A. Dyshkant,[21] D. Edmunds,[45] J. Ellison,[28] V.D. Elvira,[31] R. Engelmann,[50] S. Eno,[41] G. Eppley,[57] P. Ermolov,[20] O.V. Eroshin,[21] J. Estrada,[49] H. Evans,[47] V.N. Evdokimov,[21] T. Fahland,[27] S. Feher,[31] D. Fein,[23] T. Ferbel,[49] H.E. Fisk,[31] Y. Fisyak,[51] E. Flattum,[31] F. Fleuret,[24] M. Fortner,[33] K.C. Frame,[45] S. Fuess,[31] E. Gallas,[31] A.N. Galyaev,[21] P. Gartung,[28] V. Gavrilov,[19] R.J. Genik II,[22] K. Genser,[31] C.E. Gerber,[31] Y. Gershtein,[54] B. Gibbard,[51] R. Gilmartin,[29] G. Ginther,[49] B. Gómez,[5] G. Gómez,[41] P.I. Goncharov,[21] J.L. González Solís,[17] H. Gordon,[51] L.T. Goss,[56] K. Gounder,[28] A. Goussiou,[50] N. Graf,[51] P.D. Grannis,[50] J.A. Green,[37] H. Greenlee,[31] S. Grinstein,[1] P. Grudberg,[24] S. Grünendahl,[31] A. Gupta,[15] S.N. Gurzhiev,[21] G. Gutierrez,[31] P. Gutierrez,[53] N.J. Hadley,[41] H. Haggerty,[31] S. Hagopian,[29] V. Hagopian,[29] K.S. Hahn,[49] R.E. Hall,[26] P. Hanlet,[43] S. Hansen,[31] J.M. Hauptman,[37] C. Hays,[47] C. Hebert,[38] D. Hedin,[33] A.P. Heinson,[28] U. Heintz,[42] T. Heuring,[29] R. Hirosky,[32] J.D. Hobbs,[50] B. Hoeneisen,[8] J.S. Hoftun,[54] A.S. Ito,[31] S.A. Jerger,[45] R. Jesik,[35] K. Johns,[23] M. Johnson,[31] A. Jonckheere,[31] M. Jones,[30] H. Jöstlein,[31] A. Juste,[31] S. Kahn,[51] E. Kajfasz,[10] D. Karmanov,[20] D. Karmgard,[36] R. Kehoe,[36] S.K. Kim,[16] B. Klima,[31] C. Klopfenstein,[25] B. Knuteson,[24] W. Ko,[25] J.M. Kohli,[13] A.V. Kostritskiy,[21] J. Kotcher,[51] A.V. Kotwal,[47] A.V. Kozelov,[21] E.A. Kozlovsky,[21] J. Krane,[37] M.R. Krishnaswamy,[15] S. Krzywdzinski,[31] M. Kubantsev,[39] S. Kuleshov,[19] Y. Kulik,[50] S. Kunori,[41] V. Kuznetsov,[28] G. Landsberg,[54] A. Leflat,[20] F. Lehner,[31] J. Li,[55] Q.Z. Li,[31] J.G.R. Lima,[3] D. Lincoln,[31] S.L. Linn,[29] J. Linnemann,[45] R. Lipton,[31] A. Lucotte,[50] L. Lueking,[31] C. Lundstedt,[46] A.K.A. Maciel,[33] R.J. Madaras,[24] V. Manankov,[20] S. Mani,[25] H.S. Mao,[4] T. Marshall,[35] M.I. Martin,[31] R.D. Martin,[32] K.M. Mauritz,[37] B. May,[34] A.A. Mayorov,[35] R. McCarthy,[50] J. McDonald,[29] T. McMahon,[52] H.L. Melanson,[31] X.C. Meng,[4] M. Merkin,[20] K.W. Merritt,[31] C. Miao,[54] H. Miettinen,[57] D. Mihalcea,[53] A. Mincer,[48] C.S. Mishra,[31] N. Mokhov,[31] N.K. Mondal,[15] H.E. Montgomery,[31] M. Mostafa,[1] H. da Motta,[2] E. Nagy,[10] F. Nang,[23] M. Narain,[42] V.S. Narasimham,[15] H.A. Neal,[44] J.P. Negret,[5] S. Negroni,[10] D. Norman,[56] L. Oesch,[44] V. Oguri,[3] B. Olivier,[11] N. Oshima,[31] P. Padley,[57] L.J. Pan,[34] A. Para,[31] N. Parashar,[43] R. Partridge,[54] N. Parua,[9] M. Paterno,[49] A. Patwa,[50] B. Pawlik,[18] J. Perkins,[55] M. Peters,[30] R. Piegaia,[1] H. Piekarz,[29] B.G. Pope,[45] E. Popkov,[36] H.B. Prosper,[29] S. Protopopescu,[51] J. Qian,[44] P.Z. Quintas,[31] R. Raja,[31] S. Rajagopalan,[51] E. Ramberg,[31] N.W. Reay,[39] S. Reucroft,[43] J. Rha,[28] M. Rijssenbeek,[50] T. Rockwell,[45] M. Roco,[31] P. Rubinov,[31] R. Ruchti,[36] J. Rutherfoord,[23] A. Santoro,[2] L. Sawyer,[40] R.D. Schamberger,[50] H. Schellman,[34] A. Schwartzman,[1] J. Sculli,[48] N. Sen,[57] E. Shabalina,[20] H.C. Shankar,[15] R.K. Shivpuri,[14] D. Shpakov,[50] M. Shupe,[23] R.A. Sidwell,[39] V. Simak,[7] H. Singh,[28] J.B. Singh,[13] V. Sirotenko,[33] P. Slattery,[49] E. Smith,[53] R.P. Smith,[31] R. Snihur,[34] G.R. Snow,[46] J. Snow,[52] S. Snyder,[51] J. Solomon,[32] V. Sorín,[1] M. Sosebee,[55] N. Sotnikova,[20] K. Soustruznik,[6] M. Souza,[2] N.R. Stanton,[39] G. Steinbrück,[47] R.W. Stephens,[55] M.L. Stevenson,[24] F. Stichelbaut,[51] D. Stoker,[27] V. Stolin,[19] D.A. Stoyanova,[21] M. Strauss,[53] K. Streets,[48] M. Strovink,[24] L. Stutte,[31] A. Sznajder,[3] W. Taylor,[50] S. Tentindo-Repond,[29] J. Thompson,[41] D. Toback,[41] T.G. Trippe,[24] A.S. Turcot,[51] P.M. Tuts,[47] P. van Gemmeren,[31] V. Vaniev,[21] R. Van Kooten,[35] N. Varelas,[32] A.A. Volkov,[21] A.P. Vorobiev,[21] H.D. Wahl,[29] H. Wang,[34] Z.-M. Wang,[50] J. Warchol,[36] G. Watts,[58] M. Wayne,[36] H. Weerts,[45] A. White,[55] J.T. White,[56] D. Whiteson,[24] J.A. Wightman,[37] S. Willis,[33] S.J. Wimpenny,[28] J.V.D. Wirjawan,[56] J. Womersley,[31] D.R. Wood,[43] R. Yamada,[31] P. Yamin,[51] T. Yasuda,[31] K. Yip,[31] S. Youssef,[29] J. Yu,[31] Z. Yu,[34] M. Zanabria,[5] H. Zheng,[36] Z. Zhou,[37] Z.H. Zhu,[49] M. Zielinski,[49] D. Zieminska,[35] A. Zieminski,[35] V. Zutshi,[49] E.G. Zverev,[20] and A. Zylberstejn[12]

[1]Universidad de Buenos Aires, Buenos Aires, Argentina
[2]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[3]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[4]Institute of High Energy Physics, Beijing, People's Republic of China
[5]Universidad de los Andes, Bogotá, Colombia
[6]Charles University, Prague, Czech Republic
[7]Institute of Physics, Academy of Sciences, Prague, Czech Republic
[8]Universidad San Francisco de Quito, Quito, Ecuador
[9]Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France
[10]CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France
[11]LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France
[12]DAPNIA/Service de Physique des Particules, CEA, Saclay, France
[13]Panjab University, Chandigarh, India
[14]Delhi University, Delhi, India
[15]Tata Institute of Fundamental Research, Mumbai, India
[16]Seoul National University, Seoul, Korea
[17]CINVESTAV, Mexico City, Mexico
[18]Institute of Nuclear Physics, Kraków, Poland
[19]Institute for Theoretical and Experimental Physics, Moscow, Russia
[20]Moscow State University, Moscow, Russia
[21]Institute for High Energy Physics, Protvino, Russia
[22]Lancaster University, Lancaster, United Kingdom
[23]University of Arizona, Tucson, Arizona 85721
[24]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
[25]University of California, Davis, California 95616
[26]California State University, Fresno, California 93740
[27]University of California, Irvine, California 92697
[28]University of California, Riverside, California 92521

[29]Florida State University, Tallahassee, Florida 32306
[30]University of Hawaii, Honolulu, Hawaii 96822
[31]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[32]University of Illinois at Chicago, Chicago, Illinois 60607
[33]Northern Illinois University, DeKalb, Illinois 60115
[34]Northwestern University, Evanston, Illinois 60208
[35]Indiana University, Bloomington, Indiana 47405
[36]University of Notre Dame, Notre Dame, Indiana 46556
[37]Iowa State University, Ames, Iowa 50011
[38]University of Kansas, Lawrence, Kansas 66045
[39]Kansas State University, Manhattan, Kansas 66506
[40]Louisiana Tech University, Ruston, Louisiana 71272
[41]University of Maryland, College Park, Maryland 20742
[42]Boston University, Boston, Massachusetts 02215
[43]Northeastern University, Boston, Massachusetts 02115
[44]University of Michigan, Ann Arbor, Michigan 48109
[45]Michigan State University, East Lansing, Michigan 48824
[46]University of Nebraska, Lincoln, Nebraska 68588
[47]Columbia University, New York, New York 10027
[48]New York University, New York, New York 10003
[49]University of Rochester, Rochester, New York 14627
[50]State University of New York, Stony Brook, New York 11794
[51]Brookhaven National Laboratory, Upton, New York 11973
[52]Langston University, Langston, Oklahoma 73050
[53]University of Oklahoma, Norman, Oklahoma 73019
[54]Brown University, Providence, Rhode Island 02912
[55]University of Texas, Arlington, Texas 76019
[56]Texas A&M University, College Station, Texas 77843
[57]Rice University, Houston, Texas 77005
[58]University of Washington, Seattle, Washington 98195

The top quark is the charge $+2/3$ weak-isospin partner of the bottom quark in the third generation of fermions of the standard model (SM). It is extremely massive at $174.3 \pm 5.1$ GeV [1], and with an expected width of $\sim$1.5 GeV [2], it decays before hadronization almost exclusively into a $W$ boson and a $b$ quark. At the Tevatron $p\bar{p}$ collider, most top quarks are pair-produced via the strong interaction from a $gtt$ vertex. This is the mode used in its discovery [3] and subsequent studies of its properties, including measurements of the $t\bar{t}$ production cross section of $5.9 \pm 1.7$ pb by the DØ collaboration [4], and $6.5^{+1.7}_{-1.4}$ pb by CDF [5]. A second production mode is also predicted to exist, where top quarks are created singly from an electroweak $Wtb$ vertex [6]. Observation of the electroweak production of single top quarks will enable the magnitude of the CKM matrix element $V_{tb}$ to be determined [7], since the cross section is proportional to $|V_{tb}|^2$. The measured cross section can also be used to calculate the partial width $\Gamma\,(t \rightarrow Wb)$. Studies of the angular distributions of the decay particles can provide information on anomalous contributions to the $Wtb$ coupling [8–10]. Such studies will become possible with the start of Tevatron Run 2 in 2001. This paper describes a search for single top quarks produced at the Tevatron, using data from the 1992–1995 run at a center-of-mass energy of 1.8 TeV.

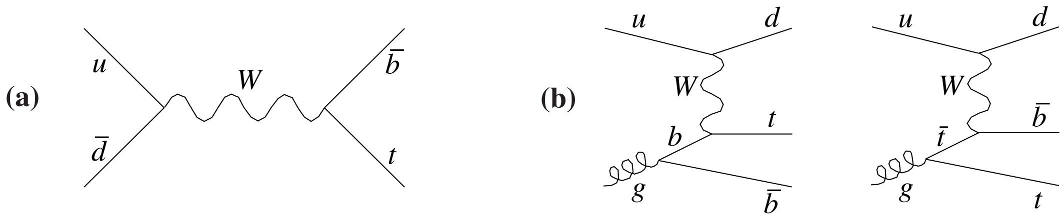


FIG. 1. Leading order Feynman diagrams for single top quark production at the Tevatron, where (a) shows the $s$-channel mode, and (b) the $t$-channel mode.

The SM predicts three modes for the production of single top quarks at a hadron collider. The first is a Drell-Yan $s$-channel process, $q'\bar{q} \rightarrow tb$, illustrated in Fig. 1. For a top quark mass $m_t$ of 175 GeV, it has a next-to-leading-order (NLO) cross section at the Tevatron of $0.73 \pm 0.04$ pb [11]. The decay of the top quark leaves a $W$ boson, and two $b$ quarks which hadronize into two central jets with high transverse momentum $p_T$. The second production mode, sometimes referred to as "$W$-gluon fusion", is a $t$-channel process, $q'g \rightarrow tqb$. The NLO cross section is $1.70 \pm 0.19$ pb [12]. This process produces a $W$ boson, a forward light-quark jet, and two central $b$ jets, one with high $p_T$, and the other with low $p_T$. We have searched for both these modes of top quark production, with decay of the $W$ boson into $e\nu$ or $\mu\nu$. The third mode occurs via both the $s$-channel and $t$-channel, $bg \rightarrow tW$, with a final state containing two $W$ bosons and a single $b$ jet. The leading-order cross section for this process is only $0.13 \pm 0.02$ pb at the Tevatron [8], and with 90 pb$^{-1}$ of data, there is no possibility of separating it from background.

Throughout this paper, we adopt the notation that "$tb$" refers to both $t\bar{b}$ and the charge-conjugate process $\bar{t}b$, and that "$tqb$" refers to both $tq\bar{b}$ and $\bar{t}\bar{q}b$.

The DØ detector [13] consists of three major components: a central tracking system, including a transition radiation detector (TRD), a uranium/liquid-argon calorimeter, and a muon spectrometer. For the measurement in the electron channel, we use $91.9 \pm 4.1$ pb$^{-1}$ of data collected with a trigger that required an electromagnetic (EM) energy cluster in the calorimeter, a jet, and missing transverse momentum $\not\!\!E_T$. For events passing the final selection, the efficiency of the trigger is 90%–93%, depending on the position of the EM cluster in the calorimeter. In the muon channel, we use $88.0 \pm 3.9$ pb$^{-1}$ of data acquired with several triggers, which required either a muon and a jet, or $\not\!\!E_T$. The combined final efficiency of these triggers is 96%–99%. A third data sample, obtained with a trigger requiring three jets, is used for measuring one of the backgrounds. Since the multijet cross section is so large, the trigger was prescaled, and we have 0.8 pb$^{-1}$ of this data. Each of the three samples consists of approximately one million events.

To determine whether an EM energy cluster has been generated by an electron, we require it to be isolated from other activity in the calorimeter, and use a five-variable likelihood function to discriminate electrons from background. This likelihood includes the fraction of cluster energy contained in the EM region of the calorimeter ($>$ 90% for electrons), the cluster shape (it must resemble an electron and not a pion), the presence of a well-matched track between the cluster and a primary $p\bar{p}$ interaction vertex (to discriminate against photons), the $dE/dx$ energy loss along the track (consistent with a single particle and not from a photon conversion into a pair of charged particles), and the TRD response (matching an electron and not a pion). An electron is then required to have transverse energy $E_T > 20$ GeV, and to be within the optimal region of the calorimeters with $|\eta^{\rm det}| < 1.1$ or $1.5 < |\eta^{\rm det}| < 2.5$ [14]. When an electron is isolated, it is more likely to have originated from the decay of a $W$ boson, and not from a $b$ hadron. The efficiency of the combined electron identification requirements is $\sim$60%.

Jets, reconstructed with a cone algorithm of radius $R = 0.5$ [15], are required to fail the electron requirements. We correct the jet energies to account for energy that escapes (e.g., via a muon and its neutrino) in semileptonic decays of particles in the jets [16]. We also correct for energy carried away by particles emitted or scattered outside the jet reconstruction cone. These out-of-cone corrections differ for $b$ jets and for non-$b$ jets [16]. The jet with highest transverse energy is required to have $E_T > 15$ GeV and $|\eta^{\rm det}| < 3.0$. The second jet has to have $E_T > 10$ GeV and $|\eta^{\rm det}| < 4.0$. Other jets in the event are counted if they have $E_T > 5$ GeV and $|\eta^{\rm det}| < 4.0$. We set the $E_T$ thresholds low and the $|\eta^{\rm det}|$ region wide in order to maximize the acceptance for signal, and to be able to calculate inclusive global variables.

We identify a muon by the pattern of hits in the spectrometer drift tubes, a matching track in the calorimeter consistent with a minimum-ionizing particle, a matching central track that passes within 20 cm of the beamline, a hit in the scintillators surrounding the spectrometer within $\pm 12$ ns of the beam-crossing time, and passage through one of the toroids for momentum analysis. Most of these requirements are designed to reject cosmic rays and particles originating from the halo of the beam. Muons must be within the central region of the spectrometer, with $|\eta^{\rm det}| < 1.7$. A muon is called "isolated" if $\Delta R\,(\mu, {\rm jet}) \geq 0.5$ [17] for all jets with $E_T > 5$ GeV. An isolated muon must have $p_T > 20$ GeV, and is attributed to the decay of a $W$ boson. A "tagging" muon has $\Delta R < 0.5$, and $p_T > 4$ GeV, and is attributed to the semileptonic decay of a $b$ hadron in a jet, and as such is used to identify a $b$ jet. The efficiency of the combined muon identification requirements is $\sim$44%.

Since there is a leptonically-decaying $W$ boson in each of the single top quark events we are searching for, we require $\not\!\!E_T > 15$ GeV as evidence of a neutrino.

We use the NLO single top quark cross sections to estimate that about 70 $s$-channel events and 161 $t$-channel events were produced at DØ in Run 1. Of these, about 15 $s$-channel events and 36 $t$-channel events passed the trigger requirements and were recorded for analysis.

The backgrounds to single top quark production include $t\bar{t}$ pairs, $W$+jets (including $WW$ and $WZ$ diboson events), and QCD multijet events. The $W$+jets events form nearly half the final background, and correspond mainly to events with light quark or gluon jets and a false tagging muon. In the electron channel, a significant background from multijet events arises from jets that are misidentified as electrons. In the muon channel, there is a small background from QCD $b\bar{b}$ events, where a muon from a $b$ decay mimics an isolated muon. There is also significant contamination from cosmic rays, but mainly in the early phases of the analysis.

Our analysis starts with a simple baseline selection of events that pass the triggers and have at least one reconstructed electron or isolated muon, and at least two jets with $E_T > 5$ GeV and $|\eta^{\rm det}| < 4.0$. For the results presented in this paper, we also demand at least one tagging muon ($/\mu$), to indicate the possible presence of a $b$ jet. These minimal requirements reduce the $\sim$1 million events in each channel to 116 $e$+jets/$\mu$ events and 110 $\mu$+jets/$\mu$ events. The acceptance for single top quark events for this selection is 0.2–0.3% per channel, which gives a total of $\approx$1 tagged events ($tb$ and $tqb$, with electron and muon $W$ boson decays, combined).

Next, we apply a set of loose criteria to remove mismeasured events, and to reject backgrounds that do not have the same final state characteristics as single top quark events. We reject events that have more than one isolated lepton, or a photon. We remove events that have $\not\!\!E_T$ close to threshold and aligned with or opposite to an electron, muon, or jet. We also reject events with a muon with badly mismeasured $p_T$. We require exactly two, three, or four jets. To remove the remaining contamination from cosmic rays in the isolated muon channel, we reject events where the isolated muon and tagging muon are back-to-back; in particular, we require $\Delta\phi({\rm isol}\mu, {\rm tag}\mu) < 2.4$ rad. These criteria, together with the jet $E_T$ and $|\eta^{\rm det}|$ requirements and the $\not\!\!E_T$ threshold, reject 84% of the baseline QCD multijet "electron" events, 95% of the cosmic ray and misreconstructed isolated "muon" events, 90% of the $b\bar{b}$ "isolated" muon events, 27% of the $W$+jets events in the electron channel, 81% in the muon channel, and 55%–73% of the $t\bar{t}$ background. The signal acceptances are reduced by 14%–51%. There remain 21 $e$+jets/$\mu$ events and 8 $\mu$+jets/$\mu$ events in the data.

We apply the following requirements to obtain the best significance of signal over square-root of background in each channel:

Electron Channel

- $E_T(\text{jet1}) + E_T(\text{jet2}) + E_T(e) + \not{E}_T \ > \ 125$ GeV
- $E_T(\text{jet1}) + 4 \times \not{E}_T \ > \ 155$ GeV
- $E_T(\text{jet3}) + 5 \times E_T(\text{jet4}) \ < \ 47$ GeV

Muon Channel

- $H_T \ > \ 70$ GeV
- $2 \times M_T(\mu, \nu) + \not{E}_T \ > \ 50$ GeV

In the muon channel, $H_T$ is the scalar sum of the $E_T$ of all the jets in the event, and $M_T(\mu, \nu)$ is the transverse mass of the muon and $\not{E}_T$ system [18].

The first variable in each set was chosen by studying reconstructed CompHEP [19] and PYTHIA [20] Monte Carlo (MC) event samples for the $W$+jets backgrounds, the second by studying data samples of QCD backgrounds, and the third variable in the electron channel, from studies of HERWIG [21] $t\bar{t}$ MC events. The distributions were compared with those from CompHEP $s$-channel and $t$-channel single top quark MC samples. The cut points were optimized using the combined samples of untagged and tagged events, with a customized program that tests the impact of different sets of cuts [22].

After applying the loose event selection, the tighter sets of cuts reject an additional 22% of the dominant $W$+jets backgrounds, 60% of the multijet background in the electron channel, 53% of the $b\bar{b}$ background in the muon channel, and 59% of the $t\bar{t}$ background in the electron channel. The signal acceptance is reduced by only 6%–9%. After the final selection, there is no evidence of a significant excess of data over background, and we therefore set an upper limit on each of the cross sections for single top quark production. In order to do this, we must determine the signal acceptance and the numbers of background events in each analysis channel.

We obtain the signal acceptances using Monte Carlo samples of $s$-channel and $t$-channel single top quark events from the CompHEP event generator, with the PYTHIA package used to simulate jet fragmentation, initial-state and final-state radiation, the underlying event, and the leptonic decay of the $W$ boson. The MC events are processed through a detector simulation program based on the GEANT [23] package, and a trigger simulation, and are then reconstructed. We apply all selection cuts directly to the reconstructed MC events, except for several particle identification criteria, which we correct for using efficiencies measured with other DØ data samples. The SM branching fractions of the $W$ boson are assumed. Table I shows the percentage of single top quark signal events remaining after application of the selection requirements and all corrections.

The acceptance for $t\bar{t}$ pairs is calculated in a similar manner to that for signal, and is then converted to a number of events using the integrated luminosity for each channel and the value of the $t\bar{t}$ cross section measured at DØ.

| | | Electron Channel | Muon Channel |
|---|---|---|---|
| Acceptances | Signals | | |
| | $tb$ | $(0.255 \pm 0.022)\%$ | $(0.110 \pm 0.011)\%$ |
| | $tqb$ | $(0.168 \pm 0.015)\%$ | $(0.094 \pm 0.009)\%$ |
| Numbers of Events | Signals | | |
| | $tb$ | $0.18 \pm 0.03$ | $0.08 \pm 0.01$ |
| | $tqb$ | $0.28 \pm 0.05$ | $0.15 \pm 0.03$ |
| | Backgrounds | | |
| | $W$+jets | $5.59 \pm 0.64$ | $1.26 \pm 0.18$ |
| | QCD | $5.92 \pm 0.58$ | $0.30 \pm 0.13$ |
| | $t\bar{t}$ | $1.14 \pm 0.35$ | $1.17 \pm 0.37$ |
| | Total | $12.63 \pm 0.93$ | $2.73 \pm 0.43$ |
| | Data | 12 | 5 |

TABLE I. Signal acceptances as a percentage of the total cross sections, and numbers of remaining events after all selection criteria have been applied.

The QCD multijet background with a jet misidentified as an electron is an instrumentally-generated background, and is measured using multijet data. The events are weighted by the probability that a jet mimics an electron, for each jet that passes the electron $E_T$ and $|\eta^{\rm det}|$ requirements, if the event passes all other selection cuts in that configuration. The probabilities are determined from the same multijet sample, but with $\not\!\!E_T < 15$ GeV, and are found to be $(0.0160 \pm 0.0016)\%$ for $|\eta^{\rm det}| < 1.1$, and $(0.0622 \pm 0.0048)\%$ for $|\eta^{\rm det}| > 1.5$. We normalize the integrated luminosity of the multijet sample so as to match the data sample used for the electron signal search, and apply correction factors for the small difference in trigger efficiencies between the two samples: $1.035 \pm 0.038$ for $|\eta^{\rm det}| < 1.1$, and $0.957 \pm 0.038$ for $|\eta^{\rm det}| > 1.5$.

The QCD $b\bar{b}$ background with a nonisolated muon misidentified as an isolated muon arises when both $b$ quarks decay semileptonically. There are two ways for such events to mimic signal. First, one of the $b$ jets may not be reconstructed, and the muon can therefore appear to be isolated. Second, the muon can be emitted wide of its jet, and be reconstructed as an isolated muon. The background from each source is measured using data collected with the same triggers as used for the muon-signal sample. The events are required to pass all selection cuts, except that the muon, which otherwise passes the isolated muon requirements, is within a jet. Events with truly isolated muons are excluded. Each event is then weighted by the probability that a nonisolated muon is reconstructed as an isolated one. This probability is measured using the same data sample, but with $\not\!\!E_T < 15$ GeV, and found to be $(2.94 \pm 0.53)\%$ for the case of a "lost jet", and $(1.38 \pm 0.25)\%$ for a "wide $\mu$", on average, for muons with $p_T < 32$ GeV. The probabilities are parametrized as a function of the muon $p_T$. We normalize the integrated luminosity of the nonisolated-muon data to that of the isolated-muon data, and calculate a weighted average of the two results to obtain the number of background events.

The final background calculation is for $W$+jets. To estimate this, we apply a set of tag-rate functions to the untagged signal-data candidates that pass the final event selection. The tag-rate functions are measured using the multijet data, and correspond to the relative probability that a jet has a tagging muon, as a function of the jet $E_T$ and $\eta^{\rm det}$, for two run periods when the muon chambers had different operating efficiencies. We then correct the samples for differences in trigger efficiencies between untagged and tagged events, $0.968 \pm 0.035$ for $|\eta^{\rm det}| < 1.1$ and $0.929 \pm 0.035$ for $|\eta^{\rm det}| > 1.5$ in the electron channel, and $1.036 \pm 0.020$ in the muon channel. We also correct the sample in the muon channel by a factor of $0.688 \pm 0.034$ to account for the effect of the cutoff used to minimize cosmic ray backgrounds, a selection cut that cannot be applied directly. Finally, to avoid double counting, we subtract the fraction of events expected from $t\bar{t}$ and QCD backgrounds, and SM single top quark signals. The remaining fraction of $W$+jets in the untagged signal candidates is $0.893 \pm 0.010$ for $|\eta^{\rm det}| < 1.1$ and $0.665 \pm 0.028$ for $|\eta^{\rm det}| > 1.5$ in the electron channel, and $0.911 \pm 0.018$ in the muon channel.

The numbers of events expected for the two signals and three backgrounds are shown in Table I, together with the final numbers of events in the candidate data samples, for the electron and muon channels.

To calculate upper limits on the cross sections for single top quark production in the $s$-channel and $t$-channel modes, we use the numbers of observed events, the signal acceptances and backgrounds, and the integrated luminosities. Correlated-error matrices are used to describe the uncertainties on these quantities. We use a Bayesian approach, with a flat prior for the single top quark cross section and a multivariate Gaussian prior for the other quantities. We calculate the likelihood functions in each channel, and combine them to obtain the following 95% confidence level upper limits:

- $\sigma(p\bar{p} \rightarrow tb + X) < 36$ pb
- $\sigma(p\bar{p} \rightarrow tqb + X) < 51$ pb
- $\sigma(p\bar{p} \rightarrow tb$ or $tqb + X) < 47$ pb

To conclude, we have searched for electroweak production of single top quarks, and find no evidence for such production. We set upper limits on the cross sections for $s$-channel production of $tb$ and $t$-channel production of $tqb$, and on the combined processes. The upper limits are consistent with, but about a factor of 20 or more above the predictions of the standard model.

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[14] The detector pseudorapidity $\eta^{\mathrm{det}}$ is defined as the pseudorapidity of the calorimeter cluster (electron or jet) or central track (muon) with respect to the center of the DØ detector, where $\eta^{\mathrm{det}} = -\ln\tan(\theta^{\mathrm{det}}/2)$, and $\theta^{\mathrm{det}}$ is the polar angle relative to the proton direction. The pseudorapidity $\eta$ and polar angle $\theta$ are defined with respect to the primary interaction point, and not the center of the detector.

[15] The cone radius of a jet is defined as $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, where $\Delta\phi$ and $\Delta\eta$ are the width of the jet in $(\phi, \eta)$ space, and $\phi$ is the azimuthal angle around the beam axis.

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[17] The opening angle between a muon and jet is defined as $\Delta R = \sqrt{(\phi(\mu) - \phi(\mathrm{jet}))^2 + (\eta(\mu) - \eta(\mathrm{jet}))^2}$.

[18] The transverse mass of the muon and neutrino is defined as $M_T(\mu,\nu) = \sqrt{2p_T(\mu)\not{E}_T\left(1 - \cos\left(\phi(\mu) - \phi(\not{E}_T)\right)\right)}$.

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