Search for electroweak single-top-quark production in *pp* collisions at s√=1.96 TeV

CDF Collaboration

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Abstract

We report on a search for standard model t-channel and s-channel single-top quark production in pp 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.

Reference

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

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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.

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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 (NLO) 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 article 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). The polar angle θ is measured with respect to the proton beam direction. The pseudorapidity is defined as $\eta \equiv -\ln\tan(\theta/2)$. $E_T = E\sin(\theta)$.[1]

This article describes two analyses: (1) a combined search for the t-channel 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 Fermilab (CDF II), which is described elsewhere [8]. 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. [9]. We accept events with evidence for a leptonic W decay: (a) missing transverse energy $E_T\!\!\!/ > 20$ 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 nonlepton 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 $76\ \mathrm{GeV}/c^2 < M_{\ell\ell} < 106\ \mathrm{GeV}/c^2$. 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: $140\,\mathrm{GeV}/c^2 \leq M_{\ell\nu b} \leq 210\,\mathrm{GeV}/c^2$. The transverse momentum of the neutrino is set equal to the missing transverse energy vector $\vec{E}\!\!\!/_T$; $p_z(\nu)$ 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 $|p_z(\nu)|$. If the $p_z(\nu)$ solution has nonzero imaginary part as a consequence of resolution effects in measuring jet energies, we use only the real part of $p_z(\nu)$. 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 [10], followed by parton showering with PYTHIA [11] and a full CDF II detector simulation. MadEvent features the correct spin polarization of the top quark and its decay products. For t-channel single-top production we generated two samples, one $b + q \to t + q'$ and one $g + q \to t + \bar{b} + q'$ which we merged together to reproduce the p_T spectrum of the $\bar{b}$ as expected from NLO differential cross section calculations. This is an improved model compared to the Pythia modelling used in the Run I analyses. The event detection efficiency ϵ_{evt} includes 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 [3] and thereby obtain the number of expected single-top events listed in Table II.

We distinguish between two background components: $t\bar{t}$ and nontop 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 [12]. The primary source (62%) of the nontop 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.,

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

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
Nontop	30.0 ± 5.8	23.3 ± 4.6	2.59 ± 0.71
Total background	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

[1]The polar angle θ is measured with respect to the proton beam direction. The pseudorapidity is defined as $\eta \equiv -\ln\tan(\theta/2)$. $E_T = E\sin(\theta)$.

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 [13] Monte Carlo (MC) events normalized to data [9]. The diboson rates are estimated from PYTHIA events normalized to theory predictions [14]. 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 six events in the 2-tag sample. Within the uncertainties, the observations are in good agreement with predictions.

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. 1(a). Q is the charge of the lepton and η is the pseudorapidity of the untagged jet. In Fig. 1(b) 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 for the number of events in the 2-tag sample.

$$\mathcal{L}_{\mathrm{sig}}(\sigma_1, \ldots, \sigma_4; \delta_1, \ldots, \delta_7) = \frac{e^{-\mu_d} \cdot \mu_d^{n_d}}{n_d!} \cdot \prod_{k=11}^{N_{\mathrm{bin}}} \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!} \cdot \prod_{\substack{j=1 \\ j \neq \mathrm{sig}}}^{4} G(\sigma_j; \sigma_{\mathrm{SM},j}, \Delta_j) \cdot \prod_{i=1}^{7} G(\delta_i; 0, 1).$$

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

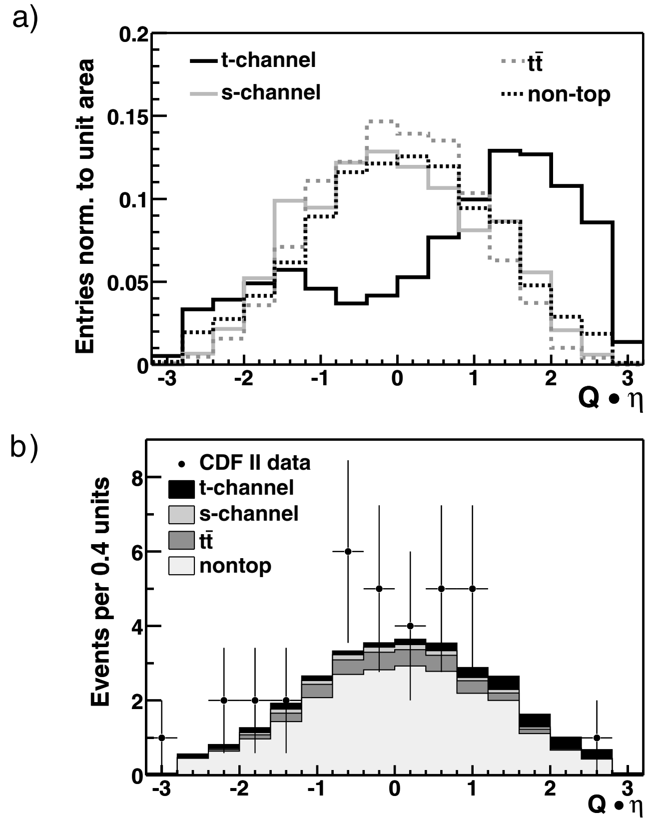

FIG. 1. $Q \cdot \eta$ distributions for a) MC templates normalized to unit area, b) Data in the 1-tag sample (33 events) vs stacked MC templates normalized to the SM prediction.

TABLE III. Fractional changes in ϵ_{evt} of single-top processes in %. ϵ_{trig} is the trigger efficiency, ϵ_{ID} the lepton identification efficiency.

i	Source	t-channel	s-channel	Combined
1	JES	$^{+2.4}_{-6.7}$	$^{+0.4}_{-3.1}$	$^{+0.1}_{-4.3}$
2	ISR	± 1.0	± 0.6	± 1.0
3	FSR	± 2.2	± 5.3	± 2.6
4	PDF	± 4.4	± 2.5	± 3.8
5	Generator	± 5	± 2	± 3
6	Top quark mass	$^{+0.7}_{-6.9}$	-2.3	-4.4
7	ϵ_{trig}, ϵ_{ID}, luminosity	± 9.8	± 9.8	± 9.8

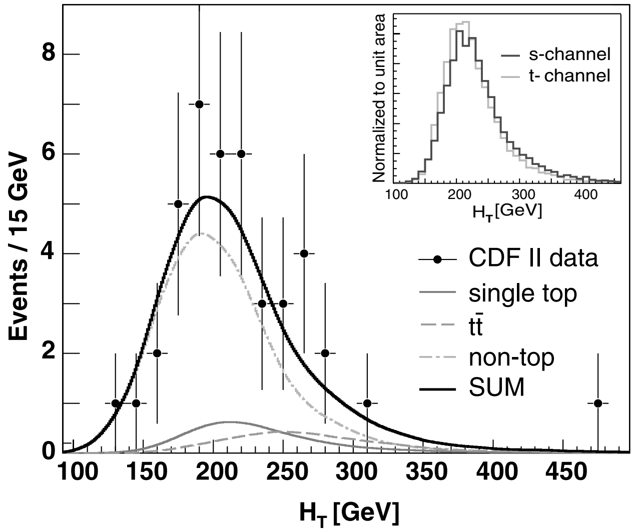

FIG. 2. H_T distribution for data (42 events) in the combined search compared with smoothed MC predictions for signal and background.

(CTEQ5L). We estimate the uncertainty associated with the choice of single-top MC generator using samples generated with TopReX [15]. The values of acceptance uncertainties for the single-top processes are summarized in Table III.

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 $\sigma_{\rm sig}$) from the full likelihood function and thereby construct the marginalized likelihood $\mathcal{L}^*_{\rm sig}(\sigma_{\rm sig})$. $\mathcal{L}^*_{\rm sig}$ is normalized and interpreted as posterior probability density function $p(\sigma_{\rm sig})$. We calculate the upper limit at the 95% C.L. using a Bayesian method assuming a prior probability density, which is 0 if $\sigma_{\rm sig} < 0$ and 1 if $\sigma_{\rm sig} \geq 0$. The median of the expected upper limits defines our sensitivity and is stated in Table IV. 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 IV. 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-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.

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

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

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. If compared with Run one results the upper limits on t-channel and s-channel single-top quark production are considerably improved by 28% (t-channel) or 20% (s-channel), respectively. We have introduced improved Monte Carlo modeling for single-top and a fully Bayesian treatment of systematic uncertainties in the likelihood function which are important steps for future analyses aiming for the observation of single-top quark production.

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[1] T. Stelzer, Z. Sullivan, S. S. Willenbrock, Phys. Rev. D **56**, 5919 (1997); M. C. Smith and S. 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, E. Laenen, L. Phaf, Z. Sullivan, and S. Weinzierl, Phys. Rev. D **66**, 054024 (2002); Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).

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

[5] CDF and D0 Higgs Working Group, Levan Babukhadia *et al.*, Report No. FERMILAB-PUB-03-320-E.

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

[7] D0 Collaboration, V. Abazov *et al.*, Phys. Lett. B **517**, 282 (2001); Phys. Rev. D **63**, 031101 (2000).

[8] CDF Collaboration, Report No. FERMILAB-PUB-96/390-E, 1996.

[9] CDF Collaboration, D. Acosta *et al.*, hep-ex/0410041.

[10] T. Stelzer and W. F. Long, Comput. Phys. Commun. **81**, 337 (1994); F. Maltoni and T. Stelzer, J. High Energy Phys. 02 (2003) 027.

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

[12] R. Bonciani *et al.*, Nucl. Phys. **B529**, 424 (1998); M. Cacciari *et al.*, J. High Energy Phys. 04 (2004) 068.

[13] F. Caravaglios *et al.*, Nucl. Phys. **B539**, 215 (1999); M. L. Mangano *et al.*, Nucl. Phys. **B632**, 343 (2002); M. L. Mangano *et al.*, J. High Energy Phys. 07 (2003) 001.

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

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