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Search for Single-Top-Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We search for standard model single-top-quark production in the W-gluon fusion and $W^\star$ channels using 106 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab. We set an upper limit at 95% C.L. on the combined W-gluon fusion and $W^\star$ single-top cross section of 14 pb, roughly six times larger than the standard model prediction. Separate 95% C.L. upper limits in the W-gluon fusion and $W^\star$ channels are also determined and are found to be 13 and 18 pb, respectively.

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The observation of the top quark in $p\bar{p}$ collisions at the Fermilab Tevatron has relied on pair production through the strong interaction, typically $q\bar{q} \to t\bar{t}$. A top quark can also be produced singly, in association with a b quark, through the electroweak interaction [1]. The two dominant "single-top" processes are "Wg"(i.e. W-gluon fusion, $qg \to t\bar{b}q'$) and "$W^\star$" ($q\bar{q}' \to t\bar{b}$). Within the context of the standard model, a measurement of the rate of these processes at a hadron collider allows a determination of the Cabibbo-Kobayashi-Maskawa matrix element V_{tb} [2]. Assuming $|V_{tb}| = 1$, the predicted cross sections for Wg and $W^\star$ are 1.7 pb [3] and 0.7 pb [4] respectively, compared to 5.1 pb for $t\bar{t}$ pair production [5]. The DØ Collaboration has recently published 95% confidence level (C.L.) upper limits of 22 pb on Wg and 17 pb on $W^\star$ production [6]. In this Letter we report on two searches, one for the two single-top processes combined, and the other for each process separately.

The expected final state of a single-top event consists of W-decay products plus two or more jets, including one b-quark jet from the decay of the top quark. In $W^\star$ events, we expect a second b-quark jet from the $W^\star t\bar{b}$ vertex. In Wg events, we expect a jet originating from the recoiling light quark and a second b-quark jet produced through the splitting of the initial-state gluon. This b-quark jet is produced at larger absolute value of pseudorapidity [7] and lower transverse momentum than in $W^\star$ events [1].

Single-top processes are harder to observe than $t\bar{t}$ production because their cross section is smaller and their final state, containing fewer jets, competes with a larger W+multijet background from QCD. A priori we do not expect sensitivity to the standard model cross section in the presently available data. However, a number of new physics processes could enhance the single-top production rate, motivating a search [8, 9].

Our measurement uses 106 ± 4 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab between 1992 and 1995 ("Run I"). The detector is described in detail elsewhere [10]. We restrict our single-top search to events with evidence of a leptonic W-decay: an isolated [11] electron (muon) candidate with E_T (P_T) > 20 GeV (GeV/c) and missing transverse energy [12] $\not\!\!E_T > 20$ GeV from the neutrino. We remove events that were identified in a previous CDF analysis [13] as $t\bar{t}$ dilepton candidates. Events with a second, same-flavor and opposite-charge lepton that forms an invariant mass with the first lepton between 75 and 105 GeV/c^2 are rejected as likely to have come from Z^0 boson decays. Furthermore, to reject those dilepton $t\bar{t}$ or Z^0 candidates where one lepton fails our electron or muon identification, we also remove events that contain a track with $P_T > 15$ GeV/c and charge opposite that of the primary lepton, and such that the total P_T of all tracks in a cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ around this track is less than 2 GeV/c [14]. Jets are formed as clusters of calorimeter towers within cones of fixed radius $\Delta R = 0.4$. Events are required to have one, two, or three jets with $E_T > 15$ GeV and $|\eta| < 2.0$; at least one jet must be identified as likely to contain a b quark ("b-tagged") using displaced-vertex information from the silicon vertex detector (SVX) [14]. If a second jet in the event is also b-tagged, either in the SVX or by the presence of a soft lepton indicative of semileptonic b decay, the event is labeled "double-tag", otherwise it is labeled "single-tag". The above event selection cuts are common to our combined and separate searches for the two single-top processes. Additional cuts are applied within each analysis.

We first describe our search for single-top production in the Wg and $W^\star$ channels combined. The expected signal significance is improved by requiring the invariant mass $M_{\ell\nu b}$ reconstructed from the lepton, neutrino, and highest-E_T b-tagged jet, to lie in a window around the top quark mass, $140 < M_{\ell\nu b} < 210$ GeV/c^2. The neutrino momentum is obtained from the $\not\!\!E_T$ and the constraint that $M_{\ell\nu} = M_W$ [15]. The variable $M_{\ell\nu b}$ discriminates against both non-top and $t\bar{t}$ backgrounds, in the latter case because combinatorial errors in assigning partons to final-state jets broaden the $M_{\ell\nu b}$ distribution compared to single top.

We determine the efficiency of our selection criteria from events generated by the PYTHIA Monte Carlo program [16] and subjected to a CDF detector simulation. The acceptance times branching ratio is (1.7 ± 0.3)% for each of the two single-top processes. The largest contributions to the acceptance uncertainties come from lepton

Process	Combined Search $W+1,2,3$ jets	Separate Search $W+2$ jets Single-tag	Double-tag
Wg	3.0 ± 0.6	1.4 ± 0.3	0.04 ± 0.01
$W^\star$	1.3 ± 0.2	0.55 ± 0.15	0.32 ± 0.06
$t\bar{t}$	8.4 ± 2.7	1.4 ± 0.5	0.7 ± 0.2
non-top	54 ± 12	10 ± 2	1.6 ± 0.4
Total	67 ± 12	14 ± 2	2.7 ± 0.5
Observed	65	15	6

TABLE I: Expected numbers of signal and background events passing all cuts in the W+jets data sample, compared with observations. The uncertainties on the expected numbers of single-top events do not include uncertainties on the theoretical cross section calculations.

triggering and identification (10%), and b-tagging (10%). Combining these acceptances with the cross sections predicted by theory [3, 4] and the size of the CDF Run I dataset, we expect a total signal yield of 4.3 events.

Expectations for signal and background rates are listed in the second column of Table I. We estimate the $t\bar{t}$ background from a HERWIG Monte Carlo calculation [17] followed by a detector simulation. Normalizing to the theoretically-predicted cross section, $\sigma_{t\bar{t}} = 5.1 \pm 0.9$ pb [5], we expect 8.4 ± 2.7 $t\bar{t}$ events to survive our selection criteria, where the uncertainty includes theoretical and acceptance contributions.

The largest component of the non-$t\bar{t}$ background in the SVX-tagged W+jets sample is inclusive W production in association with heavy-flavor jets (e.g. $p\bar{p} \to Wg$, followed by $g \to b\bar{b}$). Additional sources include "mistags," in which a light-quark jet is erroneously identified as heavy flavor, "non-W" (e.g. direct $b\bar{b}$ production), and smaller contributions from WW, WZ, and Z+heavy-flavor [14]. The mistag and non-W rates are estimated from data, the W+heavy-flavor rates from Monte Carlo normalized to data, and the smaller sources such as diboson production from Monte Carlo normalized to theory predictions [14]. The total non-top background expectation is 54 ± 12 events. The uncertainty on our background includes the effect of varying the top mass by its uncertainty of ±5 GeV/c^2.

To measure the combined $Wg + W^\star$ single-top production cross section, we use a kinematic variable whose distribution is very similar for the two single-top processes and is different for background processes: the scalar sum H_T of $\not\!\!E_T$ and the transverse energies of the lepton and all jets in the event. We perform an unbinned maximum-likelihood fit of the H_T distribution from data to a linear superposition of the expected H_T distributions from single-top signal, $t\bar{t}$ and non-top backgrounds. We model the shape of the H_T distribution for all sources of non-top background with VECBOS-generated [18] events containing a W plus two partons that we force to be a $b\bar{b}$ pair. We have checked that VECBOS reproduces the H_T and $M_{\ell\nu b}$ distributions for the b-tagged $W+1$-jet data before the $M_{\ell\nu b}$ cut, a sample in which the non-top backgrounds are expected to dominate. In the search sample, the observed H_T distribution agrees with the spectrum derived from Monte Carlo calculations when the latter are normalized to the a priori predicted numbers of events (Figure 1).

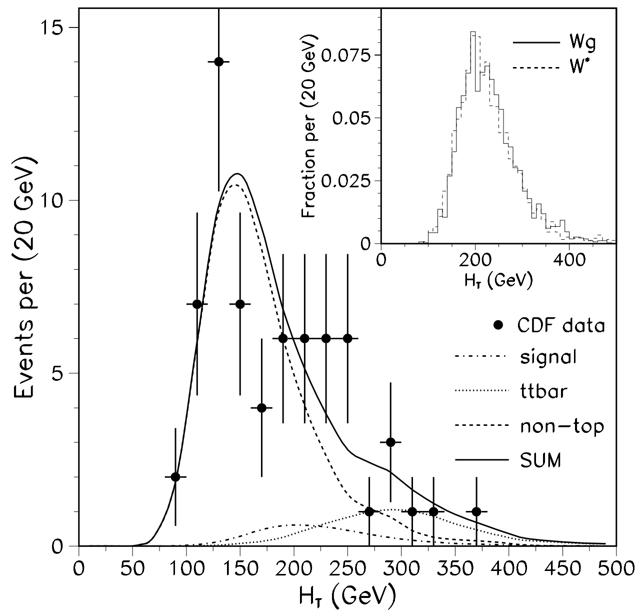

FIG. 1: The H_T distribution for data in the combined search, compared with smoothed Monte Carlo predictions for signal and backgrounds (second column in Table I). H_T is the scalar sum of $\not\!\!E_T$ and the transverse energies of the lepton and all jets in the event. The inset shows that the Monte Carlo modeling of H_T is very similar for both signal processes.

We set an upper limit on the cross section using the likelihood function:

$$\mathcal{L}(\beta_s, \beta_{t\bar{t}}, \beta_{nt}) = G_1(\beta_{t\bar{t}}) \times G_2(\beta_{nt}) \times \mathcal{L}_{\rm shape}(\beta_s, \beta_{t\bar{t}}, \beta_{nt}),$$

where β_s, $\beta_{t\bar{t}}$ and β_{nt} are fit parameters representing, respectively, factors by which the standard model cross section predictions for single-top, $t\bar{t}$ and non-top must be multiplied to fit the data. The functions G_1 and G_2 are Gaussian densities constraining the background factors $\beta_{t\bar{t}}$ and β_{nt} to unity, and $\mathcal{L}_{\rm shape}$ represents the joint probability density for observing the $N_{\rm obs}$ data events at their respective values of H_T:

$$\mathcal{L}_{\rm shape}(\beta_s, \beta_{t\bar{t}}, \beta_{nt}) = \frac{\mu_{\rm fit}^{N_{\rm obs}} e^{-\mu_{\rm fit}}}{N_{\rm obs}!} \times \prod_{i=1}^{N_{\rm obs}} \frac{\beta_s F_s(H_{Ti}) + \beta_{t\bar{t}} F_{t\bar{t}}(H_{Ti}) + \beta_{nt} F_{nt}(H_{Ti})}{\mu_{\rm fit}}.$$

In this expression, $\mu_{\rm fit} \equiv \beta_s \mu_s + \beta_{t\bar{t}} \mu_{t\bar{t}} + \beta_{nt} \mu_{nt}$, where μ_s, $\mu_{t\bar{t}}$ and μ_{nt} are the predicted numbers of events,

	$Wg + W^\star$		Wg		$W^\star$	
Source	δn	ΔS	δn	ΔS	δn	ΔS
Jet E_T scale	0.01	0.25	0.01	0.02	0.01	0.06
Initial-state radiation	0.02	0.15	0.06	0.07	0.06	0.13
Final-state radiation	0.03	0.02	0.07	0.02	0.05	0.01
Parton distributions	0.04	0.02	0.01	0.03	0.01	0.02
Signal generator	0.02	0.25	0.08	0.03	0.07	0.12
Background model	-	0.04	-	0.12	-	0.18
Top mass	0.04	0.01	0.01	0.12	0.00	0.35
Trigger & lepton id.	0.10	-	0.10	-	0.10	-
b-tag efficiency	0.10	-	0.10	-	0.10	-
Luminosity	0.04	-	0.04	-	0.04	-
Total	0.16	0.39	0.19	0.19	0.18	0.44

TABLE II: Systematic uncertainties on the fit result for β_s in the combined search ($Wg + W^\star$), and for β_{Wg} and $\beta_{W^\star}$ in the separate search (see text). The δn columns list fractional uncertainties due to signal normalization effects and the ΔS columns absolute uncertainties due to effects on the shapes of the fitted distributions.

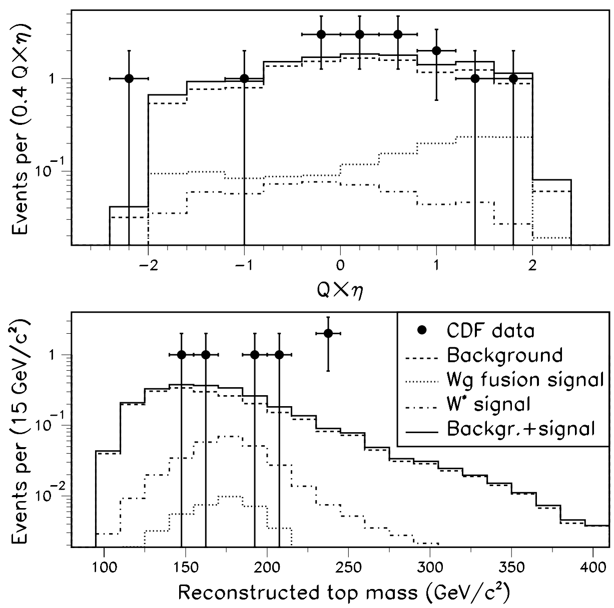

FIG. 2: Top: distribution of the product $Q \times \eta$ of the lepton charge and the untagged jet pseudorapidity for single-tag W+2-jets events. Bottom: distribution of the reconstructed top mass for double-tag events. The data are compared with expectations for signal and backgrounds (third and fourth columns in Table I).

and $F(H_T)$ are smoothed H_T distributions for signal and background, normalized to unity. The maximum of $\mathcal{L}$ is obtained for $\beta_s = 2.0 \pm 1.8$, where the uncertainty is statistical only and includes the effect of correlations with the other fit parameters.

To extract Bayesian upper limits on the single-top production rate, we construct a probability distribution $f(\beta_s)$ by maximizing $\mathcal{L}(\beta_s, \beta_{t\bar{t}}, \beta_{nt})$ with respect to $\beta_{t\bar{t}}$ and β_{nt} for each value of β_s, and multiplying the result with a flat prior distribution for β_s. We then convolute $f(\beta_s)$ with two Gaussian smearing functions. The first one has width $\beta_s \delta n$, where δn is the sum in quadrature of all the normalization uncertainties listed in Table II. The width of the second smearing Gaussian is the sum in quadrature of all the systematic uncertainties relative to the shape of the H_T distribution (ΔS in Table II). Finally, the smeared distribution is integrated to find the 95% C.L. upper limit on single-top production. We find this limit to be $\beta_s^{95} = 5.9$, corresponding to a cross section of 14 pb.

Because of significant differences in the final-state kinematics of the two single-top processes, it is possible to search for them separately. This is interesting, because an exotic single-top production mechanism may contribute to one and not the other, for example a heavy W' decaying to a $t\bar{b}$ quark pair adding to the apparent $W^\star$ rate [9]. For the separated search, we use events in the W+2-jets sample only and consider two non-overlapping subsamples. The first one consists of single-tag events in which the reconstructed top mass lies in the window $145 < M_{\ell\nu b} < 205$ GeV/c^2, and the second consists of double-tag events. The expected compositions, calculated in the same way as for the combined analysis, are shown in the last two columns of Table I: in the single-tag sample, Wg is about 2.5 times larger than $W^\star$; in the double-tag sample, $W^\star$ is about 7.5 times larger than Wg.

The Wg component in the single-tag sample can be measured by considering that the light-quark jet in Wg events is about twice as likely to be in the same hemisphere as the outgoing (anti)proton beam when a (anti)top quark is produced. Thus the product $Q \times \eta$ of the primary lepton charge and the untagged jet pseudorapidity has a strongly asymmetric distribution. In the double-tag sample, the $W^\star$ component can be extracted from the distribution of $M_{\ell\nu b}$. In this case, since both jets are tagged, the b-jet with the largest η ($-\eta$) is used in forming $M_{\ell\nu b}$ for a t ($\bar{t}$) decay, as determined by the sign of the primary lepton in the event, an assignment that is expected to be correct 64% of the time. The $Q \times \eta$ and $M_{\ell\nu b}$ distributions for the data are compared to expectations for signal and background in Figure 2. For the separate Wg and $W^\star$ searches, we use a HERWIG Monte Carlo calculation to model our signals.

A binned maximum-likelihood fit is used to extract the amounts of Wg and $W^\star$ present in the W+2-jets data. The likelihood function has the following form:

$$\mathcal{L}(\beta_{Wg}, \beta_{W^\star}, \beta_{t\bar{t}1}, \beta_{t\bar{t}2}, \beta_{nt1}, \beta_{nt2}) = \\ G_1(\beta_{t\bar{t}1}) \times G_2(\beta_{nt1}) \times \mathcal{L}_1(\beta_{Wg}, \beta_{W^\star}, \beta_{t\bar{t}1}, \beta_{nt1}) \times \\ G_3(\beta_{t\bar{t}2}) \times G_4(\beta_{nt2}) \times \mathcal{L}_2(\beta_{Wg}, \beta_{W^\star}, \beta_{t\bar{t}2}, \beta_{nt2}),$$

where the fit parameters are factors by which the predicted numbers of Wg (β_{Wg}), $W^\star$ ($\beta_{W^\star}$), single-tag $t\bar{t}$ ($\beta_{t\bar{t}1}$), double-tag $t\bar{t}$ ($\beta_{t\bar{t}2}$), single-tag non-top (β_{nt1}) and double-tag non-top (β_{nt2}) events must be multiplied to fit the data. The G_i functions are Gaussian constraints on the normalizations of the various backgrounds, $\mathcal{L}_1$ is a binned Poisson likelihood for the $Q \times \eta$ distribution of single-tag events, and $\mathcal{L}_2$ is a binned Poisson likelihood for the $M_{\ell\nu b}$ distribution of double-tag events.

The result of the maximum-likelihood fit for the single-top content of the data is $-0.6^{+4.8}_{-4.0}$ Wg events and $7.6^{+5.9}_{-4.8}$ $W^\star$ events. The systematic uncertainties are listed in Table II. We extract upper limits on the individual single-top processes in the same way as for the combined search. At the 95% C.L., we find upper limits of 13 and 18 pb on single-top production in the Wg and $W^\star$ channels, respectively. These two limits are correlated since they are derived from the same likelihood function.

In summary, we conclude that electroweak $t\bar{b}$ production is out of reach in the Run I CDF data set. At the 95% C.L., we set an upper limit on the combined $Wg + W^\star$ single-top cross section of 14 pb. Separate 95% C.L. upper limits in the Wg and $W^\star$ channels are 13 and 18 pb, respectively.

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[12] Missing transverse energy $\not\!\!E_T$ is defined as the magnitude of $-\sum_i E^i_T \hat{n}_i$, where $\hat{n}_i$ is a unit vector in the azimuthal plane that points from the beamline to the ith calorimeter tower.

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