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We present the final combination of CDF and D0 measurements of cross sections for single-top-quark production in proton-antiproton collisions at a center-of-mass energy of 1.96 TeV. The data correspond to total integrated luminosities of up to 9.7 fb^{-1} per experiment. The t-channel cross section is measured to be $\sigma_t = 2.25^{+0.29}_{-0.31}$ pb. We also present the combinations of the two-dimensional measurements of the s- vs t-channel cross section. In addition, we give the combination of the $s+t$ channel cross section measurement resulting in $\sigma_{s+t} = 3.30^{+0.52}_{-0.40}$ pb, without assuming the standard model value for the ratio σ_s/σ_t. The resulting value of the magnitude of the top-to-bottom quark coupling is $|V_{tb}| = 1.02^{+0.06}_{-0.05}$, corresponding to $|V_{tb}| > 0.92$ at the 95% C.L.

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The top quark is the heaviest elementary particle of the standard model (SM). Detailed studies of top-quark production and decay provide stringent tests of strong and electroweak interactions, as well as sensitivity to extensions of the SM [1]. At the Fermilab Tevatron collider, protons (p) and antiprotons ($\bar{p}$) collided at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. Top quarks were produced predominantly in pairs ($t\bar{t}$) via the strong interaction [2]. They were also produced singly via the electroweak interaction. The cross section for single-top-quark production depends on the square of the magnitude of the quark-mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix [3] element V_{tb}, and consequently is sensitive to contributions from a fourth family of quarks [4,5], as well as other new phenomena [6], which would lead to a measured strength of the Wtb coupling $|V_{\mathrm{tb}}|$ different from the SM prediction. Non-SM phenomena could also change the relative fraction of events produced in the various channels that contribute to the total single-top-quark production cross section.

In $p\bar{p}$ scattering, single-top-quark production proceeds in the t-channel via the exchange of a spacelike virtual W boson between a light quark and a bottom quark [7–9]. Single top quarks are also produced in the s channel via the decay of a timelike virtual W boson produced by quark-antiquark annihilation, which produces a top quark and a bottom quark [10], or in association with a W boson

(Wt) [11]. The predicted SM cross section for the t-channel process σ_t is 2.10 ± 0.13 pb [9], while the s-channel cross section σ_s is 1.05 ± 0.06 pb [12], both calculated at next-to-leading-order (NLO) in quantum chromodynamics (QCD), including next-to-next-to-leading logarithmic (NNLL) corrections. A top-quark mass of 172.5 GeV was chosen, which is consistent with the current world average value [13]. The cross section for Wt production σ_{Wt} is negligibly small at the Tevatron and therefore is not considered in the combination described in this Letter. Since the magnitude of the Wtb coupling is much larger than that of Wtd or of Wts [14], each top quark decays almost exclusively to a W boson and a b quark.

Observation of single-top-quark production was reported by the CDF [15–17] and D0 [18,19] Collaborations not differentiating between the s and the t channels (hereinafter $(s+t)$ channel). The CDF Collaboration subsequently measured a single-top-quark production cross section for the sum of the s, t, and Wt channels of $\sigma_{s+t+Wt} = 3.04^{+0.57}_{-0.53}$ pb using data corresponding to 7.5 fb^{-1} of integrated luminosity [20] and for the sum of the s and t channels of $\sigma_{s+t} = 3.02^{+0.49}_{-0.48}$ pb using up to 9.5 fb^{-1} of integrated luminosity [21]. The D0 Collaboration obtained $\sigma_{s+t} = 4.11^{+0.60}_{-0.55}$ pb using data corresponding to 9.7 fb^{-1} of integrated luminosity [22].

The cross sections for individual production modes were also measured separately. The D0 Collaboration observed the t-channel process [23] and measured its cross section to be $\sigma_t = 3.07^{+0.54}_{-0.49}$ pb using data corresponding to 9.7 fb^{-1} of integrated luminosity [22]. The CDF Collaboration measured $\sigma_{t+Wt} = 1.66^{+0.53}_{-0.47}$ pb using data corresponding to 7.5 fb^{-1} of integrated luminosity [20] and $\sigma_t = 1.65^{+0.38}_{-0.36}$ pb using up to 9.5 fb^{-1} [21] of integrated luminosity. The difference between the results for σ_t is about 2 standard deviations (s.d.). Furthermore, both the CDF and D0 Collaborations reported evidence for s-channel production [22,24,25] and combined their results to observe the s-channel process with $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb [26].

At the CERN LHC proton-proton (pp) collider, t-channel production was observed by the ATLAS and CMS Collaborations [27–30]. Furthermore, ATLAS has found evidence for Wt associated production [31], followed recently by an observation at the CMS experiment [32]. All measurements are in agreement with SM predictions [9,12].

In this Letter, we report final combinations of single-top-quark cross section measurements from analyses performed by the CDF [21] and D0 [22] Collaborations using up to 9.7 fb^{-1} of integrated luminosity per experiment. In particular, we present a combined t-channel cross section, a combined two-dimensional measurement of the s- vs t-channel cross sections, and a combination of the $(s+t)$-channel cross sections. The combination is obtained by collecting the inputs from both experiments and reperforming the statistical analysis. This approach allows for a tighter constraint on the systematic uncertainties that are common to both experiments, leading to a higher precision than that achievable from averaging the individual results. Here, we do not include the combination of the s-channel cross-section measurements, which was reported in Ref. [26]. We also measure the magnitude of the CKM matrix element V_{tb} with no assumptions on the number of quark flavors.

The CDF and D0 detectors are large solenoidal magnetic spectrometers surrounded by projective-tower-geometry calorimeters and muon detectors [33,34]. The data were selected using a logical OR of many online selection requirements that preserve high signal efficiency for offline analysis. Both collaborations analyze events with a lepton ($\ell = e$ or μ) plus jets and an imbalance in the total event transverse energy $\not\!\!E_T$, reconstructed as the negative vector sum of all significant transverse energies in the calorimeter cells and the muon transverse momenta subtracting the calorimeter energy deposition due to muons (ℓ + jets). This topology is consistent with single-top-quark decays in which the decay W boson subsequently decays to $\ell\nu$ [20,22]. Events were selected that contain only one isolated lepton ℓ with large transverse momentum p_T, large $\not\!\!E_T$, and two or three clusters of energy in the calorimeters (jets) with large p_T. One or two of these jets were required to be identified as emerging from the hadronization of a b quark (b-tagged jets). Multivariate techniques were used to discriminate b-quark jets from light-quark and gluon jets [35,36]. Additional selection criteria were applied to exclude kinematic regions that were difficult to model and to minimize the background of multiple jets from QCD production (QCD multijet) in which one jet was misreconstructed as a lepton and spurious $\not\!\!E_T$ arose from mismeasurements [20,22].

The other final-state topology, analyzed by the CDF Collaboration, involves $\not\!\!E_T$, jets, and no reconstructed isolated charged leptons ($\not\!\!E_T$ + jets) [21]. In the CDF $\not\!\!E_T$ + jets analysis, overlap with the ℓ + jets sample was avoided by vetoing events with identified leptons. Large $\not\!\!E_T$ was required, and events with either two or three reconstructed jets were accepted. This additional sample increased the acceptance for signal events by including those in which the W-boson decay produced a lepton that is either not reconstructed or not isolated, or a τ lepton that decayed into hadrons and a neutrino, which were reconstructed as a third jet. After the basic event selection, QCD multijet events dominate the $\not\!\!E_T$ + jets event sample. To reduce this background, a selection based on an artificial neural network was optimized to preferentially select signal-like events [21].

Events passing the ℓ + jets and $\not\!\!E_T$ + jets selections were separated into independent channels based on the number of reconstructed jets as well as on the number and quality of b-tagged jets. Each of the channels has a different background composition and signal-to-background ratio, and analyzing them separately enhances the sensitivity to single-top-quark production by approximately 10% [21,22].

Several differences in the properties of s- and t-channel events were used to distinguish them from one another. Events originating from t-channel production typically contain one light-flavor jet at large pseudorapidity magnitude $|\eta|$, which is useful for separating them from events associated with s-channel production and other SM background processes. Events from the s-channel process are more likely to yield two b jets within the central region of the detector.

Both collaborations used Monte Carlo (MC) event generators to simulate kinematic properties of signal and background events, except for multijet production, which was modeled with data using matrix methods [37,38]. Using the POWHEG [39] generator, CDF modeled single-top-quark signal events at NLO accuracy in the strong coupling strength α_s. This is different from D0 where the SINGLETOP [40] event generator was used, based on NLO QCD COMPHEP calculations that match the kinematic features predicted by other NLO calculations [41,42]. Spin information in the decays of the top quark and the W boson is preserved in both POWHEG and SINGLETOP.

Kinematic properties of background events from processes in which a W or Z boson is produced in association with jets ($W+$jets or $Z+$jets) were simulated using the ALPGEN MC generator [43] for the calculation of tree-level matrix elements interfaced to PYTHIA [44] for parton showering and hadronization and using the MLM matrix-element parton-shower matching scheme [45]. Diboson contributions (WW, WZ, and ZZ) were modeled using PYTHIA [44]. The $t\bar{t}$ process was modeled using PYTHIA at CDF and ALPGEN at D0. The mass of the top quark in simulated events was set to $m_t = 172.5$ GeV. Higgs-boson processes were modeled using simulated events generated with PYTHIA for a Higgs boson mass of $m_H = 125$ GeV [46–48]. In all of the above cases, PYTHIA was used to model proton remnants and to simulate the hadronization of all generated partons. The presence of additional $p\bar{p}$ interactions was modeled by overlaying events selected from random beam crossings matching the instantaneous luminosity profile in the data. All MC events were processed through GEANT-based detector simulations [49], and were reconstructed using the same computer programs as used for data.

Data were used to normalize W-boson production associated with both light- and heavy-flavor jet contributions in samples enriched in $W+$jets processes, which have negligible signal content [17,22,25]. All other simulated background samples were normalized to their theoretical cross sections, i.e., $t\bar{t}$ at next-to-next-to-leading order QCD [50], $Z+$jets and diboson production at NLO QCD [51], and Higgs-boson production including all relevant higher-order QCD and electroweak corrections [52]. For the measurement of σ_t, the s-channel single-top-quark production sample was considered as background and normalized to the NLO QCD cross section combined with NNLL resummations [12].

Multivariate discriminants were optimized to separate signal events from large background contributions. To combine the results from the two experiments, we use the s- and t-channel discriminants from the CDF [24] and D0 [22] single-top-quark measurements. We perform a likelihood fit to the binned distribution of the final discriminants. We combine the various channels of the different analyses from each experiment by taking the product of their likelihoods and simultaneously varying the correlated uncertainties and by comparing data to the predictions for each contributing signal and background process. Using a Bayesian statistical analysis [53], we then derive combined Tevatron cross section measurements, taking the prior density for the signal cross sections to be uniform for non-negative cross sections.

For the sources of uncertainties we follow Ref. [26]. We consider the following systematic uncertainties: the integrated luminosity from detector-specific sources and from the inelastic and diffractive cross sections. We also consider systematic uncertainties on the signal modeling, the simulation of background, data-based methods to estimate background, detector modeling, b-jet tagging, and the measurement of the jet-energy scale. Table I of Ref. [26] summarizes the categories that contribute to the uncertainties on the shape of the output of the multivariate discriminants distributions and the range of uncertainties applied to the predicted normalizations for signal and background contributions. Reference [26] gives the sources of systematic uncertainty common to measurements of both collaborations that are assumed to be fully correlated, and lists uncertainties that are assumed to be uncorrelated. The dependence of the results on these correlation assumptions is negligible.

A two-dimensional (2D) posterior-probability density is constructed as a function of σ_s and σ_t in analogy to the one-dimensional (1D) posterior probability described in Ref. [26]. The measured cross section is quoted as the value at the position of the maximum, and the 68% probability contour defines the measurement uncertainty.

Figure 1 shows the distribution of the mean values from the discriminants sorted by the s-channel minus t-channel expected signal contributions divided by the background expectation, $(s-t)/b$. An entry in the histogram corresponds to a collection of bins with similar ratio $(s-t)/b$. The value on the horizontal axis is given by the mean discriminant for those bins. The vertical axis gives the number of events in those bins. We show the data, the SM predictions for the s- and t-channel processes, and the predicted backgrounds separated by source. The distribution for large negative values is dominated by the content of the bins that show a higher t-channel contribution, while large positive values are dominated by the content of the bins with a higher s-channel contribution. The abscissa

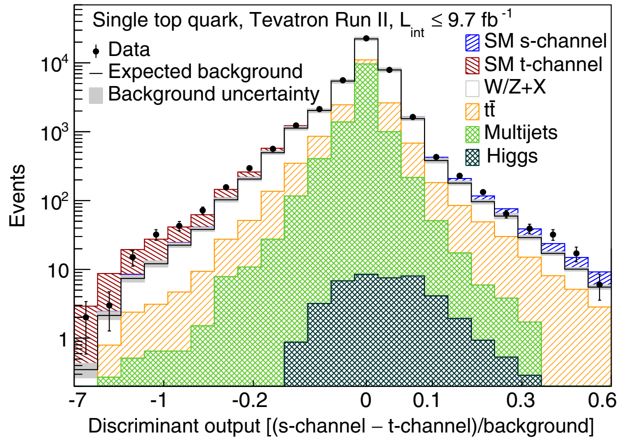

FIG. 1 (color online). Distribution of the mean discriminants for bins with similar ratios of (s-channel − t-channel) signals divided by background yields. The data, predicted SM s- and t-channel yields, and expected background are displayed. The total expected background (black solid line) is shown with its uncertainty (gray shaded band). A nonlinear scale is used on the abscissa to better display the range of the discriminant output values.

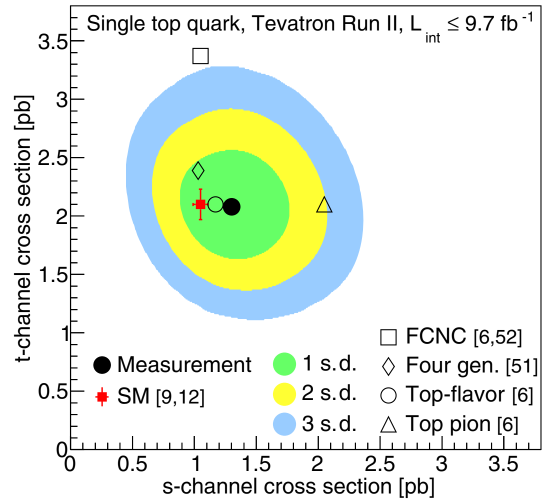

FIG. 2 (color online). Two-dimensional posterior probability as a function of σ_t and σ_s with one s.d. (68% C.L.), two s.d. (95% C.L.), and three s.d. (99.7% C.L.) probability contours for the combination of the CDF and D0 analysis channels compared with the NLO + NNLL theoretical prediction of the SM [9,12]. Several BSM predictions are shown, a model with four quark families with top-to-strange quark coupling $|V_{ts}| = 0.2$ [5], a top-flavor model with new heavy bosons with mass $m_x = 1$ TeV [6], a model of charged top pions with mass $m_{\pi^\pm} = 250$ GeV [6], and a model with flavor-changing neutral currents with a 0.036 coupling κ_u/Λ between up quark, top quark, and gluon [6,54].

extends to larger negative values since we expect more t-channel events than s-channel events and the separation from background is better for t-channel events than for s-channel events. The region corresponding to discriminant values near zero is dominated by the background.

Figure 2 presents the resulting 2D posterior probability distribution as a function of σ_t and σ_s. The value and uncertainty in the individual cross sections are derived through the 1D posterior probability functions obtained by integrating the 2D posterior probability over the other variable. The most probable value of σ_t is $2.25^{+0.29}_{-0.31}$ pb. The measurement of σ_{s+t} is performed without making assumptions on the ratio of σ_s/σ_t by forming a 2D posterior probability density distribution of σ_{s+t} versus σ_t and then integrating over all possible values of σ_t to extract the 1D estimate of σ_{s+t}. The combined cross section is $\sigma_{s+t} = 3.30^{+0.52}_{-0.40}$ pb. The total expected uncertainty on σ_{s+t} is 13%, the expected uncertainty without considering systematic uncertainties is 8%, and the expected systematic uncertainty is 10%. The systematic uncertainty from the limited precision of top-quark mass measurements is negligible [17,22]. Figure 2 also shows the expectation from several beyond the SM (BSM) models. Figure 3 shows the individual [21,22] and combined (this Letter) measurements of the t- and ($s + t$)-channel cross sections including previous measurements of the individual [22,24] and combined [26] s-channel cross sections. All measurements are consistent with SM predictions.

The SM single-top-quark production cross section is directly sensitive to the square of the CKM matrix element V_{tb} [9,12], thus providing a measurement of $|V_{tb}|$ without any assumption on the number of quark families or the unitarity of the CKM matrix [38]. We extract $|V_{tb}|$ assuming that top quarks decay exclusively to Wb final states.

We start with the multivariate discriminants for the s and t channels for each experiment and form a Bayesian

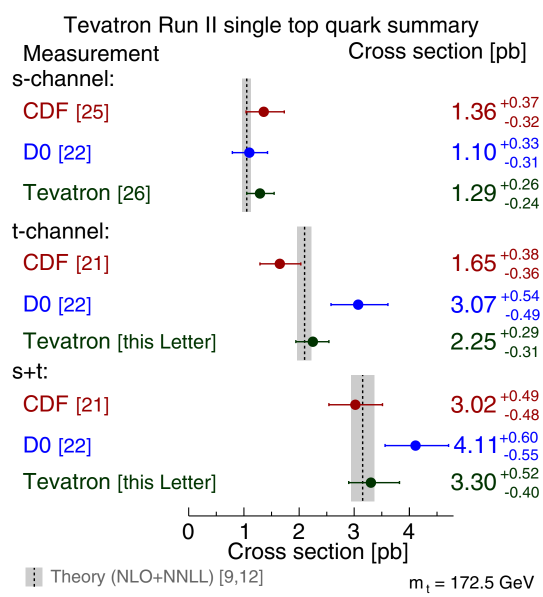

FIG. 3 (color online). Measured single-top-quark production cross sections from the CDF and D0 Collaborations in different production channels and the Tevatron combinations of these analyses compared with the NLO + NNLL theoretical prediction [9,12].

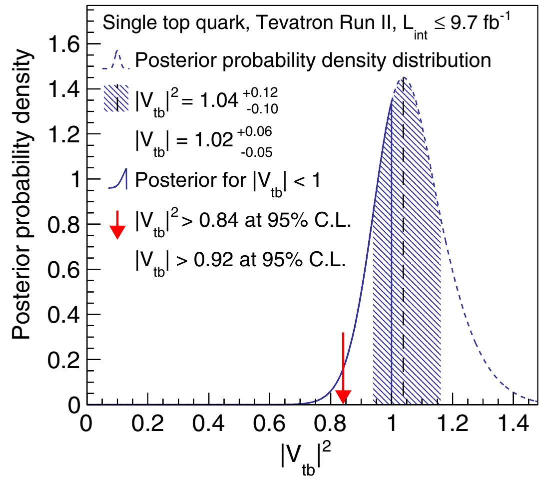

FIG. 4 (color online). Posterior probability distribution as a function of $|V_{tb}|^2$ for the combination of CDF and D0 analysis channels. The arrow indicates the allowed values of $|V_{tb}|^2$ corresponding to the limit of $|V_{tb}| > 0.92$ at the 95% C.L.

posterior probability density for $|V_{tb}|^2$ assuming a uniform-prior probability distribution in the region $[0, \infty]$ corresponding to a uniform prior density of the signal cross section. Additionally, the uncertainties on the SM predictions for the s- and t-channel cross sections [9,12] are considered. The resulting posterior probability distribution for $|V_{tb}|^2$ is presented in Fig. 4. We obtain $|V_{tb}| = 1.02^{+0.06}_{-0.05}$. If we restrict the prior to the SM region [0,1], we extract a limit of $|V_{tb}| > 0.92$ at the 95% C.L.

In summary, using $p\bar{p}$ collision samples corresponding to an integrated luminosity of up to 9.7 fb^{-1} per experiment, we report the final combination of single-top-quark production cross sections from CDF and D0 measurements assuming $m_t = 172.5$ GeV. The cross section for t-channel production is found to be

$$\sigma_t = 2.25^{+0.29}_{-0.31} \text{ pb}. \tag{1}$$

Without assuming the SM value for the relative s- and t-channel contributions, the total single-top-quark production cross section is

$$\sigma_{s+t} = 3.30^{+0.52}_{-0.40} \text{ pb}. \tag{2}$$

Together with the combined s-channel cross section [26], this completes single-top-quark cross-section measurements accessible at the Tevatron. All measurements are consistent with SM predictions [9,12]. Finally, we extract a direct limit on the CKM matrix element of $|V_{tb}| > 0.92$ at the 95% C.L. As a result, there is no indication of sources of new physics beyond the SM in the measured strength of the Wtb coupling.

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