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Observation of *s*-channel production of single top quarks at the Tevatron

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We report the first observation of single-top-quark production in the s channel through the combination of the CDF and D0 measurements of the cross section 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 measured cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb. The probability of observing a statistical fluctuation of the background to a cross section of the observed size or larger is 1.8×10^{-10}, corresponding to a significance of 6.3 standard deviations for the presence of an s-channel contribution to the production of single-top quarks.

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The top quark, with a mass of $m_t = 173.2 \pm 0.9$ GeV [1], is the most massive and one of the most puzzling elementary particles of the standard model (SM). Detailed studies of top-quark production and decay provide powerful tests of strong and electroweak interactions, as well as sensitivity to physics beyond the standard model (BSM) [2]. At the Tevatron, where protons (p) and antiprotons ($\bar{p}$) collide at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV, top quarks are produced predominantly in pairs ($t\bar{t}$) via the strong interaction [3]. Top quarks are also produced singly in $p\bar{p}$ collisions via the electroweak interaction. The single-top-quark production cross section is expected to be proportional to the square of the magnitude of the quark-mixing Cabibbo-Kobayashi-Maskawa matrix [4] element V_{tb}, and consequently sensitive to potential contributions from a fourth generation of quarks [5, 6], as well as flavor-changing neutral currents [7–10], anomalous top-quark couplings [11–13], heavy W' bosons [14–17], supersymmetric charged Higgs bosons [18, 19], or other new phenomena [20, 21].

At the Tevatron, there are two important processes in which a single top quark is produced in association with other quarks. The dominant channel proceeds through the exchange of a space-like virtual W boson between a light quark and a bottom quark (b quark) in the t channel [22–24]. A second mode occurs through the exchange of a time-like virtual W boson in the s channel, which produces a top quark and a b quark [25]. Figure 1 shows the leading Feynman diagrams for the s- and t-channel production modes. Independent measure-

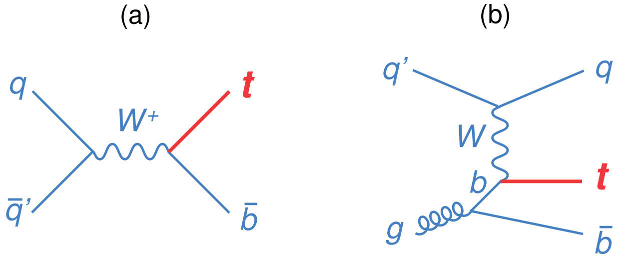

FIG. 1: Dominant Feynman diagrams for (a) s-channel and (b) t-channel single-top-quark production at the Tevatron.

ments of s-channel and t-channel production are important, since BSM contributions could have different effects on the two modes [20].

Single-top-quark production, independent of channel, was reported by the CDF and D0 collaborations in Refs. [26, 27] and [28, 29], respectively. The D0 collaboration subsequently measured with larger data sets the production cross section for the combined s and t channels [30], and obtained $\sigma_{s+t} = 4.11^{+0.59}_{-0.55}$ pb using a data set of 9.7 fb^{-1} in agreement with the SM prediction of 3.15 ± 0.19 pb ($m_t = 172.5$ GeV) [24, 31].

After establishing the $s + t$ process, the cross sections of the individual production modes were measured independently. Several differences in the properties of s- and t-channel events can be used to distinguish them from one another. Events originating from t-channel production typically contain one light-flavor jet in the forward detector region (at large pseudorapidity), which is useful for distinguishing them from events associated with s-channel production and other SM background processes. Moreover, events from the s-channel process are more likely to contain two jets originating from b quarks (b jets) within the central region of the detector where they can be identified. Hence, single-top-like events with two identified b jets are more likely to have originated from s-channel production. Exploiting these differences, the D0 collaboration observed the t-channel process [32], and measured its cross section to be $\sigma_t = 2.90 \pm 0.59$ pb. This compares to the SM prediction of 2.10 ± 0.13 pb ($m_t = 172.5$ GeV) [24]. At the CERN LHC proton-proton collider, t-channel production was also observed by the ATLAS and CMS collaborations [33, 34].

Observing the s-channel process is more difficult, since the expected cross section is smaller than that of the t channel and its kinematic features are less distinct from the background. However, the Tevatron has an advantage over the LHC in this mode, since valence quarks ($q\bar{q}'$ from $p\bar{p}$) generally initiate s-channel single-top-quark production, leading to a larger signal-to-background ratio at the Tevatron than at the LHC. Due to this advantage, the CDF and D0 collaborations have reported evidence for s-channel production independently of each other [30, 35], while the LHC experiments have to date reported only unpublished upper limits on the cross section.

In this Letter, we report a combination of s-channel cross section analyses performed by the CDF [35, 36] and D0 [30] collaborations. The CDF and D0 detectors are central magnetic spectrometers surrounded by electromagnetic and hadronic calorimeters and muon detectors [37–39]. The combined measurement utilizes the full Tevatron Run II data sets corresponding to up to 9.7 fb^{-1} of integrated luminosity per experiment.

The data are selected using a logical OR of many online selection requirements which preserve high signal efficiency for offline analysis. Since the magnitude of the W-top-bottom quark coupling is much larger than the W-top-down and W-top-strange quark couplings [40], each top quark decays almost exclusively to a W boson and a b quark. The selection is split into two distinct final-state topologies, both designed to select single-top-quark events in which the W boson decays leptonically.

One final-state topology (ℓ+jets), analyzed by both collaborations, contains single-top-quark events in which the W boson decays leptonically ($W \to \ell\nu_\ell$). We select events that (i) contain only one isolated lepton ($\ell = e$ or μ) with large transverse momentum p_T, (ii) have large missing transverse energy $\not\!\!E_T$ [39], (iii) have either two jets (CDF analysis) or two or three jets (D0 analysis) with large p_T, and (iv) have one or two b jets. To identify b jets, multivariate techniques are used that discriminate b jets from jets originating from light quarks and gluons [41, 42]. Additional selection criteria are applied to exclude kinematic regions that are difficult to model, and to minimize the quantum chromodynamics (QCD) multijet background where one jet is misreconstructed as a lepton and spurious $\not\!\!E_T$ arises from jet energy mismeasurements.

The other final-state topology, analyzed by the CDF collaboration, involves $\not\!\!E_T$ and jets, but no reconstructed isolated charged leptons ($\not\!\!E_T$+jets). The CDF analysis avoids overlap with the ℓ+jets sample by explicitly vetoing events with identified leptons [36]. Large missing transverse energy is required and events with two or three reconstructed jets are accepted. This additional sample increases the acceptance for s-channel signal events by encompassing those in which the W-boson decay produces a muon or electron that is either not reconstructed or not isolated, or a hadronically decaying tau lepton that is reconstructed as a third jet. After the basic event selection, QCD multijet events dominate the $\not\!\!E_T$+jets event sample. To reduce this multijet background, a neural-network event selection is optimized to preferentially select signal-like events.

Events passing the ℓ+jets and $\not\!\!E_T$+jets selections are further separated into independent analysis channels based on the number of reconstructed jets as well as the number and quality of b-tagged jets. Each of the analyzed channels has a different background composition and signal (s) to background (b) ratio. Analyzing them separately enhances the sensitivity to single-top-quark production [30, 35, 36].

Both collaborations use Monte Carlo (MC) generators to simulate the kinematic properties of signal and background events, except in the case of multijet production, for which the model is derived from data. The CDF analysis models single-top-quark signal events at next-to-leading-order (NLO) accuracy in the strong coupling constant α_s using the POWHEG [43] generator. The D0 analysis uses the SINGLETOP [44] event generator, based on NLO COMPHEP calculations that match the event kinematic features predicted by NLO calculations [45, 46].

Spin information in the decays of the top quark and the W boson is preserved for both POWHEG and SINGLETOP.

Kinematic properties of background events associated with the W+jets and Z+jets processes are simulated using the ALPGEN leading-order MC generator [47], and those of diboson processes (WW, WZ and ZZ) are modeled using PYTHIA [48]. The $t\bar{t}$ process is modeled using PYTHIA in the CDF analysis and by ALPGEN in the D0 analysis. Higgs-boson processes are modeled using simulated events generated with PYTHIA for a Higgs-boson mass of $m_H = 125$ GeV. The D0 analysis models the distributions and their shape uncertainties of the WH production process in the 2-jet, 2-b-tag channel using simulated single-top-quark t-channel events that have been shown to have the same distribution of the discriminant output and to be only a small contamination to the s-channel signal. In all cases PYTHIA is used to model proton remnants and simulate the hadronization of all generated partons. The mass of the top quark in simulated events is set to $m_t = 172.5$ GeV, which is consistent with the current Tevatron average value [1]. All MC events are processed through GEANT-based detector simulations [49] and reconstructed by the same software packages used for the collider data.

Predictions for the normalization of simulated background-process contributions are estimated using both simulation and data. Data are used to normalize the W plus light-flavor and heavy-flavor jet contributions using enriched W+jets data samples that have negligible signal content [27, 30, 36]. All other simulated background samples are normalized to the theoretical cross sections at NLO combined with next-to-next-to-leading log (NNLL) resummation [24] for t-channel single-top-quark production, at next-to-NLO [50] for $t\bar{t}$, at NLO [51] for Z+jets and diboson production, and including all relevant higher-order QCD and electroweak corrections for Higgs-boson production [52]. Differences observed between simulated events and data in lepton and jet reconstruction efficiencies, resolutions, jet-energy scale (JES), and b-tagging efficiencies are adjusted in the simulation to match the data, through correction functions obtained from measurements in independent data samples.

We form multivariate discriminants, optimized for separating the s-channel single-top-quark signal events in each of the analysis samples from the larger background contributions, to extract the cross section measurements [53]. The combined cross section measurement is obtained using a Bayesian statistical analysis of the observed discriminant distributions from each sample, comparing data to the modeled distributions for each of the contributing signal and background processes [54].

A complete list of systematic uncertainties for the ℓ+jets analyses is given in Tab. I. These can arise from uncertainties on differential distributions (Dist) and their normalizations (Norm). The CDF $\not\!\!E_T$+jets analysis has a similar set of systematic uncertainties that are taken as fully correlated with the CDF ℓ+jets analysis except for the uncertainty related to the data-based background. Sources of systematic uncertainty common to measurements of both collaborations are assumed to be 100% correlated, while other uncertainties are assumed to be uncorrelated. The categories of uncertainty correspond generally to those in Ref. [1, 3], and can be summarized as follows:

Detector-specific luminosity uncertainty: The component of the uncertainty on luminosity that comes from the uncertainty on the acceptance and efficiency of the luminosity detector is taken as uncorrelated between the CDF [55] and D0 [56] measurements.

Luminosity from cross section: The portion of the uncertainty in luminosity that comes from uncertainties on the inelastic and diffractive cross sections is fully correlated between the CDF and D0 measurements.

Signal modeling: The systematic uncertainty associated with uncertainties in the modeling of the single-top-quark signal, including uncertainties from the choice of the description of initial- and final-state QCD radiation, and proton and antiproton parton density functions, also covering uncertainties in the applied hadronization models, is taken as fully correlated between the CDF and D0 measurements.

Background from simulation: The systematic uncertainty associated with uncertainties in the modeling of various background contributions is taken as fully correlated between the CDF and D0 measurements. This includes uncertainties in $t\bar{t}$ and diboson process normalizations originating from theoretical calculations.

Background based on data: The systematic uncertainty associated with the modeling of various background sources obtained using data-driven methods is uncorrelated between the CDF and D0 measurements. This includes uncertainties on the normalization of W+jets, $Wb\bar{b}$, and $Wc\bar{c}$ events as well as uncertainties on the modeling of the contributions and discriminant-variable shapes for the W+jets and QCD multijet production processes.

Detector modeling: The systematic uncertainty on efficiencies for identifying reconstructed objects and to cover observed mismodeling of the data from the simulations is uncorrelated between the CDF and D0 measurements.

b-jet tagging: The systematic uncertainty associated with the modeling of b-jet tagging efficiencies and associated mistag rates is uncorrelated between the CDF [41] and D0 [42] measurements.

Jet energy scale (JES): This systematic uncertainty originates from using calibration-data samples to establish the JES. For the CDF analyses, this corresponds to uncertainties associated with the η-dependent JES corrections, which are estimated using dijet events in data. For the D0 analysis, this includes uncertainties in calorimeter response for light jets, uncertainties from η- and p_T-dependent JES corrections, and other small contributions. This uncertainty is assumed to be uncorrelated between the CDF [57] and D0 [58] measurements.

TABLE I: Systematic uncertainties associated with the CDF and the D0 single-top-quark s-channel cross section measurements in ℓ+jets final states. The values shown for each category indicate the range of uncertainties applied to the predicted normalizations for signal and background contributions over the full set of analysis samples from each experiment. The black dots indicate which categories contribute uncertainties on the shape of the final multivariate discriminant output variable. It is also noted if categories are treated as fully correlated between the two experiments.

Systematic uncertainty	CDF		D0		Corre-
	Norm	Dist	Norm	Dist	lated
Lumi from detector	4.5%		4.5%		No
Lumi from cross section	4.0%		4.0%		Yes
Signal modeling	2–10%	●	3–8%		Yes
Background (simulation)	2–12%	●	2–11%	●	Yes
Background (data)	15–40%	●	19–50%	●	No
Detector modeling	2–10%	●	1–5%	●	No
b-jet-tagging	10–30%		5–40%	●	No
JES	0–20%	●	0–40%	●	No

The Bayesian posterior probability density as a function of s-channel signal cross section(σ_s) is given by

$$p(\sigma_s) = \int L(\sigma_s, \{\theta\}|\text{data})\pi(\sigma_s)\Pi(\{\theta\})d\{\theta\}\,, \qquad (1)$$

where L is the joint binned likelihood function for all channels

$$L = \prod_{i=\text{bins, channels}} \frac{(s_i + b_i)^{n_i} e^{-(s_i+b_i)}}{n_i!}\,. \qquad (2)$$

The number of observed events in bin i is n_i. $\{\theta\}$ is the set of nuisance parameters representing the systematic uncertainties, and $\Pi(\{\theta\})$ is the product of the prior probability densities encoding the systematic uncertainties on $\{\theta\}$. The predictions for the number of signal events s_i and background events b_i depend on the values of the nuisance parameters that are integrated over in Eq. (1). The prior density for the signal cross section, $\pi(\sigma_s)$, is taken to be a uniform prior for non-negative cross sections. We quote the measured cross section as the value that maximizes its posterior likelihood, and the uncertainty as the smallest interval that contains 68% of the integrated area of the posterior density.

Figure 2 shows the signal and background expectations and the data as a function of $\log_{10}(s/b)$ of the collected bins, for the combined CDF and D0 analyses. The extracted posterior probability distribution for σ_s is presented in Fig. 3, and Fig. 4 gives a graphical presentation of the individual and combined measurements. All measurements agree within their uncertainties with the SM prediction, $\sigma_s^{SM} = 1.05 \pm 0.06$ pb ($m_t = 172.5$ GeV) [31]. The most probable value for the combined cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb for a top-quark mass of 172.5 GeV. The total expected uncertainty is 20%, and the expected uncertainty without considering systematic uncertainties is 14%. The dependence of the measured value on the assumed value of the top-quark mass is negligible compared to the uncertainty on the measurement [27, 30].

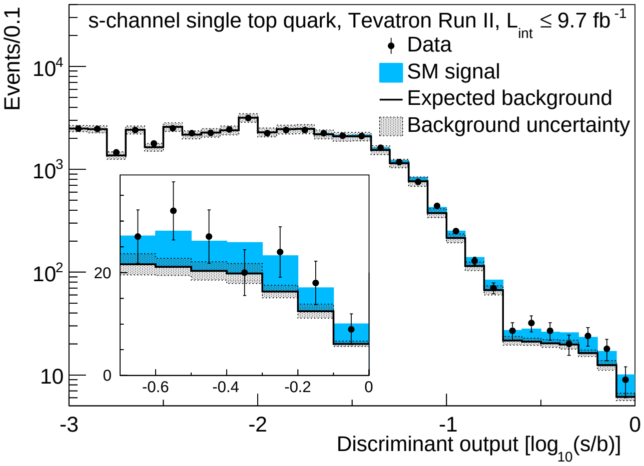

FIG. 2: (Color online) Distribution of the discriminant histograms, summed for bins with similar signal-to-background ratio (s/b). The expected sum of the backgrounds is shown by the unfilled histogram, and the uncertainty of the background is represented by the grey shaded band. The expected s-channel signal contribution is shown by a filled blue histogram.

The statistical significance of this result is quantified through a calculated p-value based on an asymptotic log-likelihood ratio approach (LLR) [59], including systematic uncertainties. The p-value quantifies the probability that the measured value of the cross section or a larger value could result from a background fluctuation in the absence of signal. The distributions of LLR resulting from fits of simulated samples that include background-only, or signal-plus-background, contributions are presented in Fig. 5. The probability to measure an s-channel

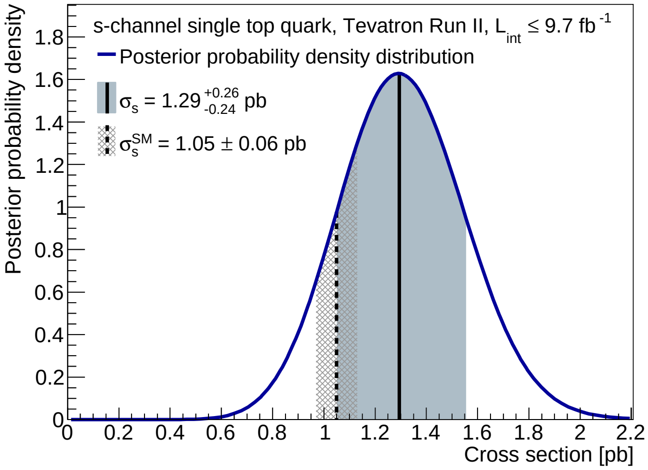

FIG. 3: The posterior probability distribution for the combination of the CDF and D0 analysis channels compared with the NLO+NNLL theoretical prediction [31].

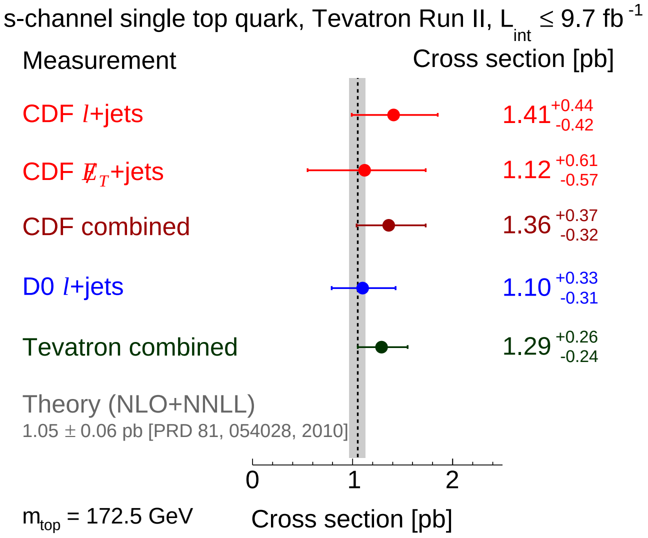

FIG. 4: (Color online) Measured single-top-quark s-channel production cross sections from each of the individual analyses and various combinations of these analyses compared with the NLO+NNLL theoretical prediction [31].

cross section of at least the observed value in the absence of signal is 1.8×10^{-10}, corresponding to a significance of 6.3 standard deviations (s. d.), with a sensitivity expected from the SM of 5.1 s. d.

In summary, we report the first observation of s-channel single-top-quark production with a significance of 6.3 s. d. by combining the CDF and D0 measurements. The combined value of the s-channel single-top-quark production cross section is $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb, in agreement with the SM expectation.

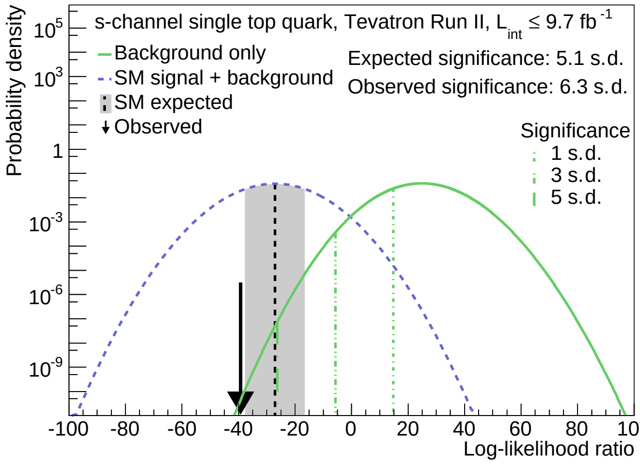

FIG. 5: (Color online) Log-likelihood ratios for the background-only (solid green line) and SM-signal-plus-background (dashed blue) hypotheses from the combined measurement.

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and pointing at the ith calorimeter tower. $\vec{\not{E}}_T$ is corrected for high-energy muons and for mismeasurements of jet energies. We define $\not{E}_T = |\vec{\not{E}}_T|$. The transverse momentum p_T is defined to be $p \sin\theta$.

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