First Observation of Electroweak Single Top Quark Production

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We report the first observation of single top quark production using 3.2 fb^{-1} of $p\bar{p}$ collision data with $\sqrt{s} = 1.96$ TeV collected by the Collider Detector at Fermilab. The significance of the observed data is 5.0 standard deviations, and the expected sensitivity is in excess of 5.9 standard deviations. We measure a cross section of $2.3^{+0.6}_{-0.5}(\mathrm{stat+syst})$ pb, extract the CKM matrix element value $|V_{tb}| = 0.91^{+0.11}_{-0.11}(\mathrm{stat+syst}) \pm 0.07(\mathrm{theory})$, and set the limit $|V_{tb}| > 0.71$ at the 95% C.L.

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The establishment of the presence of the electroweak production of single top quarks in $p\bar{p}$ collisions is an important goal of the Tevatron program. The reasons for studying single top quarks are compelling: the production cross section is directly proportional to the square of the CKM matrix [1] element $|V_{tb}|$, and thus a measurement of the rate constrains fourth-generation models, models with flavor-changing neutral currents, and other new phenomena [2]. Furthermore, because single top quark production is a well-understood process in the standard model (SM), it provides a solid anchor to test the analysis techniques that are also used to search for Higgs boson production and other more speculative phenomena.

In the SM, top quarks are expected to be produced singly through t-channel or s-channel exchange of a virtual W boson as shown in Fig. 1. This electroweak production of single top quarks is a difficult process to measure because the expected production cross section ($\sigma_{st} \sim 2.9$ pb [3, 4]) is much smaller than those of competing background processes. Also, the presence of only one top quark in the event provides fewer features to use in separating the signal from background, compared with measurements of top pair production ($t\bar{t}$), which was first observed in 1995 [5]. To overcome these challenges, a variety of multivariate techniques for separating single top events from the backgrounds have been developed. Using different combinations of techniques, both the CDF and D0 collaborations have published evidence for single top quark production at significance levels of 3.7 and 3.6 standard deviations, respectively [6, 7]. This Letter reports a significant update to the previous measurement including a larger data sample and new analysis techniques and achieves a signal significance of 5.0 standard deviations, thus conclusively observing electroweak production of single top quarks.

The likelihood function (LF), matrix element (ME), and neural network (NN) analyses [6] are updated with an additional 1 fb^{-1} of integrated luminosity; their methods remain unchanged. In addition, three new analyses are added: a boosted decision tree (BDT), a likelihood function optimized for s-channel single top production (LFS), and a neural-network-based analysis of events with missing transverse energy $\not{E}_T$ [8] and jets (MJ). The BDT and LFS analyses use events that overlap with the LF, ME, and NN analyses, while the MJ analysis uses an orthogonal event selection that adds about 30% to the signal acceptance. This paper will concentrate on the three new analyses and their combination with the analyses of Ref. [6] using 3.2 fb^{-1} of integrated luminosity collected with the CDF II detector [9].

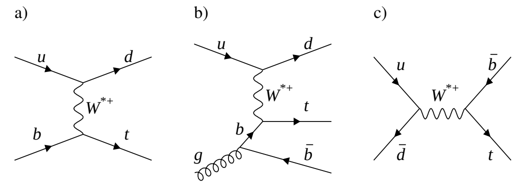

FIG. 1: Representative Feynman diagrams of single top quark production. Figures (a) and (b) are t-channel processes, and Fig. (c) is the s-channel process.

For these analyses, we assume that single top quarks are produced in the s- and t-channel modes with the SM ratio, and that the branching ratio of the top quark to Wb is 100%. We seek events in which the W boson decays leptonically in order to improve the signal-to-background ratio s/b. We simulate single top events using a tree-level matrix-element generator [10].

For the LF, ME, NN, BDT, and LFS analyses we select $\ell + \not{E}_T +$ jet events as described in Ref. [6], where ℓ is an explicitly reconstructed electron or muon from the W boson decay and at least one jet is identified as containing a B hadron. The background has contributions from events in which a W boson is produced in association with one or more heavy flavor jets ($W+HF$), events with mistakenly b-tagged light-flavor jets (mistags), multijet events (QCD), $t\bar{t}$ and diboson processes, as well as Z+jet events. The expected event yields in Table I are estimated as in Ref. [6] where the signal, $t\bar{t}$, and diboson categories are Monte Carlo predictions scaled to the total integrated luminosity while the remaining categories use predictions derived from control samples taken from the full event sample.

The MJ analysis is designed to select events with $\not{E}_T$ and jets and to veto events selected by the $\ell + \not{E}_T$+jet analyses. It accepts events in which the W boson decays into τ leptons and those in which the electron or muon fails the lepton identification criteria. We use data corresponding to 2.1 fb^{-1} of integrated luminosity for the MJ analysis and select events that have $\not{E}_T > 50$ GeV and two jets within $|\eta| < 2.0$, at least one of which has $|\eta| < 0.9$. The jet energy measurements include information from both the calorimeter and the charged-particle

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spectrometer. Events must have one jet with transverse energy E_T greater than 35 GeV, and a second jet with E_T greater than 25 GeV. The angular separation between the two jets, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, is required to exceed 1.0. We reject events with four or more jets with $E_T > 15$ GeV in $|\eta| < 2.4$ in order to reduce the multijet (QCD) and $t\bar{t}$ backgrounds. We identify b jets with the same algorithm as Ref. [6] supplemented with a jet probability algorithm [11].

The main background in the MJ analysis is QCD events in which mismeasured jet energies produce large $\vec{\not\!\!E}_T$ aligned in the same direction as jets. To reduce this background, we use the transverse momentum imbalance ($\vec{\not\!p}_T$) as measured in the spectrometer. This variable is more correlated to the neutrino energy and its direction than $\vec{\not\!\!E}_T$ in this class of events. The absolute amount of $\not\!\!E_T$ and $\not\!p_T$, the angle between them, the azimuthal angles between $\vec{\not\!\!E}_T$ or $\vec{\not\!p}_T$ and the jet directions, and several other less powerful variables are used as inputs to a neural network (NNQCD). The NNQCD output is required to pass a threshold, removing 77% of the QCD background while keeping 91% of the signal acceptance.

The backgrounds in the MJ analysis due to QCD events and events with light flavor jets produced in association with W and Z bosons are estimated using data in a control region composed of events in which the $\vec{\not\!\!E}_T$ is aligned with one of the jets. The observed and expected event counts for the MJ analysis are given in the $\not\!\!E_T$+jets column of Table I.

TABLE I: Background composition and predicted number of single top events in 3.2 fb^{-1} of CDF Run II data for the ℓ+$\not\!\!E_T$+jets samples (LF, ME, NN, and BDT analyses), and 2.1 fb^{-1} of data for the $\not\!\!E_T$+jets sample (MJ analysis).

Process	ℓ + $\not\!\!E_T$ + jets	$\not\!\!E_T$ + jets
s-channel signal	77.3 ± 11.2	29.6 ± 3.7
t-channel signal	113.8 ± 16.9	34.5 ± 6.1
$W + HF$	1551.0 ± 472.3	304.4 ± 115.5
$t\bar{t}$	686.1 ± 99.4	184.5 ± 30.2
Z+jets	52.1 ± 8.0	128.6 ± 53.7
Diboson	118.4 ± 12.2	42.1 ± 6.7
QCD+mistags	777.9 ± 103.7	679.4 ± 27.9
Total prediction	3376.5 ± 504.9	1404 ± 172
Observed	3315	1411

After event selection, the samples are dominated by background. We use multivariate techniques to further discriminate the signal. The LF, ME, and NN discriminants are described in Ref. [6]. The BDT discriminant uses a decision tree method that applies binary cuts iteratively to classify events [12]. The discrimination is further improved using a boosting algorithm [13, 14]. The BDT discriminant uses over 20 input variables. Some of the most sensitive are the neural-network jet-flavor separator [15], the invariant mass of the $\ell\nu b$ system $M_{\ell\nu b}$, the total scalar sum of transverse energy in the event $H_{\rm T}$, $Q \times \eta$ [16], the dijet mass M_{jj}, and the transverse mass of the W boson.

The LFS discriminant uses projective likelihood functions [17] to combine the separation power of several variables and is optimized to be sensitive to the s-channel process (Fig. 1(c)). The subset of the ℓ+$\not\!\!E_T$+jets sample with two b-tagged jets is used and consists of 609 events. The dominant backgrounds are $Wb\bar{b}$ and $t\bar{t}$ production. A kinematic fitter is used to find the most likely resolution of two ambiguities: the z-component of the neutrino momentum and the b jet that most likely came from the top quark decay. In addition to the outputs of the kinematic fitter, other important inputs to the likelihood are the invariant mass of the two b-tagged jets M_{bb}, the transverse momentum of the $b\bar{b}$ system, the leading jet transverse momentum, $M_{\ell\nu b}$, $H_{\rm T}$, and $\not\!\!E_T$.

The MJ discriminant uses a neural network to combine information from several input variables. The most important variables are the invariant mass of the $\vec{\not\!\!E}_T$ and the second leading jet, the scalar sum of the jet energies, the $\not\!\!E_T$, and the azimuthal angle between the $\vec{\not\!\!E}_T$ and the jets.

We combine the LF, ME, NN, BDT, and LFS channels using a super-discriminant (SD) technique similar to that which was applied in Ref. [6]. The SD method uses a neural network trained with neuro-evolution [18] to separate the signal from the background taking as inputs the discriminant outputs of the five analyses for each event. With the super-discriminant analysis we improve the sensitivity (defined below) by 13% over the best individual analysis. We perform a simultaneous fit over the two exclusive channels, MJ and SD, to obtain the final combined results.

Before investigating the sample of selected events, we checked the modeling of the distributions of each input variable and the discriminant outputs in data control samples depleted of signal. These are the lepton + b-tagged four-jet sample, which is enriched in $t\bar{t}$ events, and the two- and three-jet samples in which there is no b-tagged jet. The latter have high statistics and are enriched in W+jets and QCD events with kinematics similar to the b-tagged signal samples. For the MJ analysis, two control samples are used: in the first sample, the $\vec{\not\!\!E}_T$ is required to be aligned along one of the jets, and in the second, the events are required to fail the NNQCD requirement. The data distributions in the control samples are described well by our models.

Figure 2 shows the distributions of the discriminants of the five analyses that are combined by the super-discriminant. We use the distributions of the SD and MJ discriminants shown in Fig. 3 to extract the measured cross section and the signal significance. We measure cross sections using a Bayesian binned likelihood

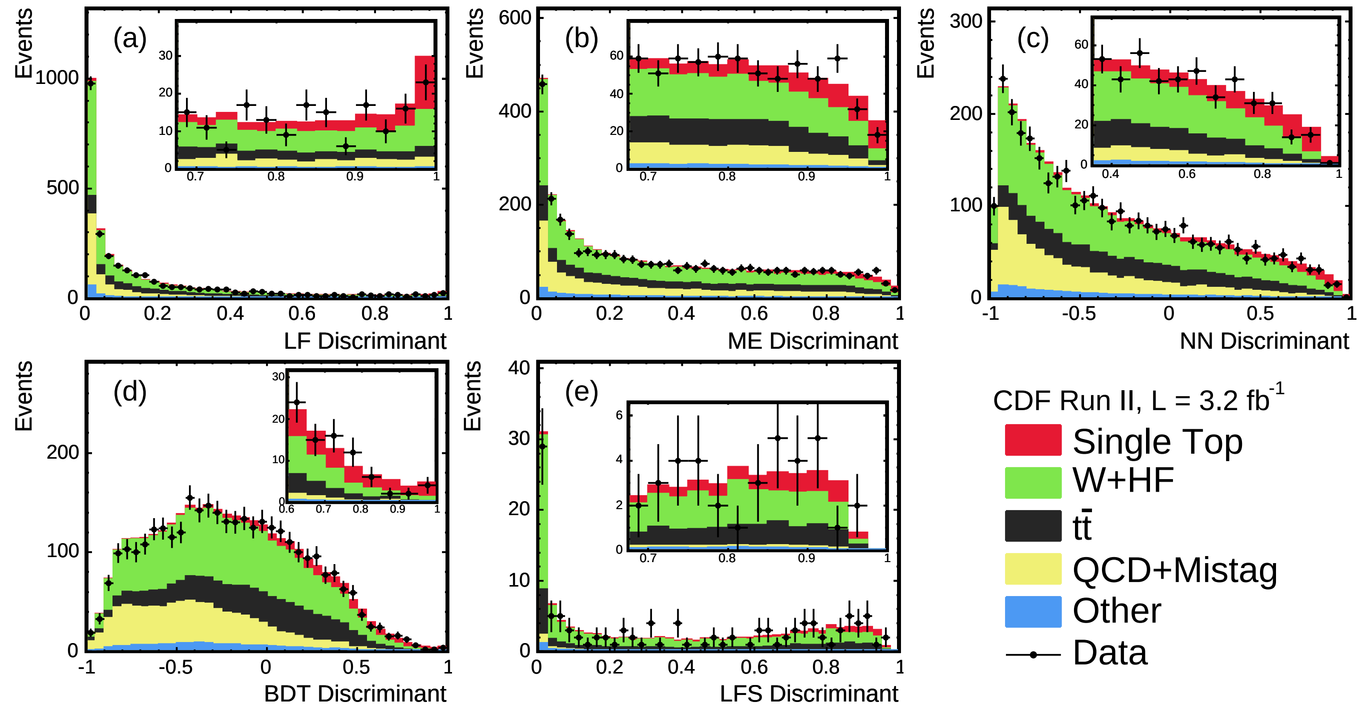

FIG. 2: Discriminant distributions for the $\ell + \not\!\!E_T$+jets analyses. The data are indicated with points, and the predictions are shown separately for each contribution with stacked histograms. The signal expectations shown are the SM predictions. The insets show the distributions of the candidate events in the signal regions.

technique [19] assuming a flat prior in the cross section and marginalizing the systematic uncertainties. We quote the measured cross section as the value that maximizes the posterior likelihood, and use the shortest interval containing 68% of the integral of the posterior to set the uncertainties. We calculate the significance as a p-value [19], which is the probability, assuming single top quark production is absent, that $-2\ln Q = -2\ln(p(\text{data}|s+b)/p(\text{data}|b))$ is less than that observed in the data. Figure 3(c) shows the distributions of $-2\ln Q$ in pseudoexperiments that assume SM single top ($S+B$) and also those that assume single top production is absent (B), along with the value observed in data. We then convert the p-value into a number of standard deviations using the integral of one side of a Gaussian function.

All sources of systematic uncertainty are included and correlations between normalization and discriminant shape changes are considered. Uncertainties in the jet energy scale, b-tagging efficiencies, lepton identification and trigger efficiencies, the amount of initial and final state radiation, PDFs, factorization and renormalization scale, and background modeling have been explored and incorporated in all individual analyses and the combination.

Table II lists the cross sections and significances for each of the component analyses and the combination. We interpret the excess of signal-like events over the expected background as observation of single top production with a p-value of 3.10×10^{-7}, corresponding to a signal significance of 5.0 standard deviations. The sensitivity is defined to be the median expected significance and is in excess of 5.9 standard deviations. The most probable value of the combined s-channel and t-channel cross sections is $2.3^{+0.6}_{-0.5}$ pb assuming a top quark mass of 175 GeV/c^2. The dependence on the top quark mass is $+0.02$ pb/(GeV/c^2). From the cross

TABLE II: Results summary for the five correlated $\ell + \not\!\!E_T$+jets analyses combined by the SD analysis, the SD and the MJ analysis, and the total combination. The LFS analysis measures only the s-channel production cross section, while the other analyses measure the sum of the s- and t-channel cross sections.

Analysis	Cross Section (pb)	Significance (Std. Dev.)	Sensitivity (Std. Dev.)
LF	$1.6^{+0.8}_{-0.7}$	2.4	4.0
ME	$2.5^{+0.7}_{-0.6}$	4.3	4.9
NN	$1.8^{+0.6}_{-0.6}$	3.5	5.2
BDT	$2.1^{+0.7}_{-0.6}$	3.5	5.2
LFS	$1.5^{+0.9}_{-0.8}$	2.0	1.1
SD	$2.1^{+0.6}_{-0.5}$	4.8	>5.9
MJ	$4.9^{+2.5}_{-2.2}$	2.1	1.4
Combined	$2.3^{+0.6}_{-0.5}$	5.0	>5.9

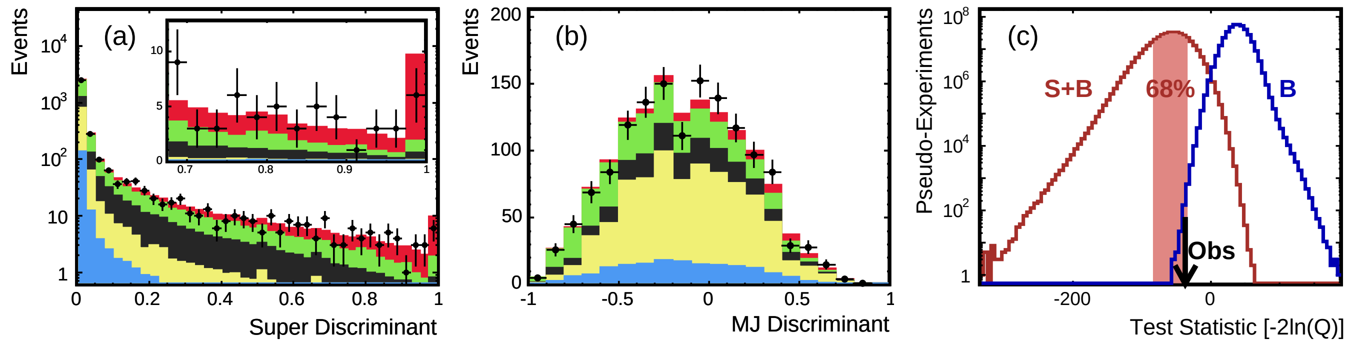

FIG. 3: Discriminant distributions for the (a) SD, and (b) MJ analyses (see Fig. 2 for their caption and legend). Figure (c) shows the distribution of the likelihood ratio test statistic $-2\ln Q$.

section measurement at $m_t = 175$ GeV/c^2, we obtain $|V_{tb}| = 0.91^{+0.11}_{-0.11}(\text{stat}+\text{syst}) \pm 0.07(\text{theory[3]})$ and limit $|V_{tb}| > 0.71$ at the 95% C.L. assuming a flat prior in $|V_{tb}|^2$ from 0 to 1. This is the most precise direct measurement of $|V_{tb}|$ to date.

In summary, we combine six multivariate analysis techniques to precisely measure the electroweak single top production cross section and the CKM matrix element $|V_{tb}|$. We observe single top quark production for the first time with a significance of 5.0 standard deviations.

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