Updated Measurement of the Single Top Quark Production Cross Section and |V_{tb}| in the Missing Transverse Energy Plus Jets Topology in pp Collisions at √s = 1.96 TeV

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with a pair of jets, one of which is $b\ell\nu_b$ This sample of events (hereafter the "sample") provides a distinctive signature against backgrounds produced by the strong interaction (QCD multijet or "MJ" background), which contain no leptons and multiple jets.

A complementary approach consists in using final states that contain two or three jets and significant imbalance in the total transverse energy, jets identified as originating from $b$ quarks, and no identified leptons. The sum of the $s$- and $t$-channel single top quark cross sections is measured to be $3.02^{+0.49}_{-0.48}$ pb and a lower limit on $|V_{tb}|$ of 0.84 is obtained at the 95% credibility level

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The CDF II detector is a multipurpose particle detector described in detail elsewhere [12]. It is comprised
of an inner silicon vertex detector, a 96-layer drift chamber spectrometer used for reconstructing charged-particle trajectories (tracks), and a calorimeter that is divided radially into electromagnetic and hadronic compartments, which are constructed of projective towers that cover pseudorapidities of up to $|\eta| < 3.6$ [13]. A system of drift chambers located outside the hadronic calorimeter is used for muon identification.

Jets are formed by clustering calorimeter energy deposits with an opening angle of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. Lepton candidates with large transverse momentum are identified by associating tracks with signatures in the appropriate detectors: energy deposits in the electromagnetic calorimeters for electrons, and muon-detector track segments for muons.

Events are selected in which the calorimeter missing transverse energy $E_T^{\text{cal}}$ satisfies a minimum online selection (trigger) threshold of at least 45 GeV, or 35 GeV if at least two jets are present. In the offline analysis, events are accepted if the reconstructed missing transverse energy $E_T$ is at least 35 GeV. A multivariate algorithm is used to parameterize the trigger efficiency as a function of several kinematic and angular variables of the event [14]. Measured jet energies are corrected to account for irregularities in calorimeter response, energy lost outside the jet cone, and underlying event dynamics [15]. The jet energy scale and resolution, as well as the $E_T$ resolution, are further improved by incorporating corrections based on charged-particle momentum measurements [16].

Each event is required to have at least two leading-$E_T$ jets with transverse energies, $E_T^{j1}$ and $E_T^{j2}$, that satisfy $25 < E_T^{j1} < 200$ GeV and $20 < E_T^{j2} < 120$ GeV, respectively. Additionally, both leading-$E_T$ jets are required to be reconstructed within the silicon detector acceptance, corresponding to pseudorapidity requirements of $|\eta| < 2$ for both jets, with one of them satisfying $|\eta| < 0.9$. Events with three jets are considered if the third-most energetic jet in $E_T$ satisfies $15 < E_T^{j3} < 100$ GeV and $|\eta| < 2.4$. Events with four or more jets are rejected if each jet satisfies the criteria $E_T > 15$ GeV and $|\eta| < 2.4$. To discriminate against MJ background, the angular separation between the two highest-$E_T$ jets must satisfy $\Delta R > 0.8$. Events that satisfy these requirements are labeled “pre-tagged” events.

To suppress light-flavor MJ background, at least one of the leading-$E_T$ jets is required to be $b$-tagged by the HOBIT algorithm [17], which assigns to each jet a value between 0 and 1. Jets with a HOBIT value between 0.72 (0.95) and 0.95 (1) are considered to be loosely (tightly) tagged. As two $b$ quarks are present in the signal final state, events are separated into three categories based on the multiplicity and quality of the $b$-tagged jets: events with only one tightly tagged jet and no other tag (1T), events with two tightly tagged jets (TT), and events with one tightly tagged jet and one loosely tagged jet (TL). Events are further classified according to the total number of jets, leading to six event subsamples. Each subsample is analyzed separately to improve the sensitivity and to help separate the $s$- and $t$-channel produced events, which are enhanced in the double- and single-tagging categories, respectively.

All events that satisfy the above kinematic and $b$-tagging criteria are separated into two samples. Events that contain no identified leptons comprise the preselection sample, which includes events in the signal region, defined below. Events that contain at least one identified electron or muon comprise the electroweak sample, which is used to validate the background modeling derived for this analysis.

Most physics processes are modeled using Monte Carlo simulation programs. The single top quark samples are modeled using the POWHEG generator [18]. Backgrounds from $V+$jets (where $V$ represents a $W$ or $Z$ boson) and $W + c$ processes are modeled using ALPGEN [19], with showering simulated by PYTHIA [20]. Events from diboson ($VV$), $t\bar{t}$ (assuming a top-quark mass of 172.5 GeV/$c^2$), and Higgs bosons produced in association with a $W$ or $Z$ boson ($VH$) are simulated using PYTHIA. Two remaining backgrounds include contributions from events with falsely tagged jets (“electroweak mistags”) and MJ events.

The electroweak mistag samples are modeled by weighting $V+$jets and diboson-simulated events with mistag probabilities derived from dedicated data samples [21, 22]. To model the MJ background, the same data-driven method described in Ref. [23] is used: each pretagged data event is weighted by a tag-rate probability derived from a MJ-dominated data sample.

At this stage of the analysis, simple requirements on kinematic properties of the event are not sufficient to separate the single top quark signal from the background. A series of multivariate discriminants that take advantage of nontrivial variable correlations are therefore employed to optimize the suppression of MJ background and to separate the signal from the remaining backgrounds. For each of the multivariate algorithms described below, a combination of inputs is used corresponding to kinematic, angular, and event-topology quantities whose distributions are different between the background under consideration and the single top quark signal.

The dominant background in the preselection sample is MJ events. To discriminate against this background, the same NN$_{QCD}$ multivariate discriminant that was developed in the $E_T^{bb}$ $s$-channel single top quark search [10] is used. All events that satisfy a minimum NN$_{QCD}$ threshold requirement populate the signal region, in which the dominant backgrounds are from MJ production, $V+$heavy-flavor-jets events, and $t\bar{t}$ events. Events that do not meet the minimal NN$_{QCD}$ threshold are used to validate the background prediction with the data. From this validation, multiplicative correction factors ranging from 0.7 to 0.9 are derived for each of the 1T,
FIG. 1. Predicted and observed NN_{sig}^{s+t} distributions in the signal region, for the (a) 1T two-jet, (b) 1T three-jet, (c) TL two-jet, (d) TL three-jet, (e) TT two-jet, (f) and TT three-jet subsamples.

TL and TT MJ predictions so that the total predicted background normalizations are in agreement with data. These corrections are applied to the MJ predictions in the signal region.

For all events in the signal region, two additional discriminants are developed that further exploit the differences in kinematic properties between the signal and the V+jets background, and the signal and t\bar{t} background processes. The first discriminant NN_{Vjets} is trained using simulated t-channel single top quark events for the signal sample and MJ-modeled events that satisfy the requirement on NN_{QCD}, for the background sample. The second discriminant NN_{t}\bar{t} is trained to separate t-channel single top quark from t\bar{t} production, again using simulated t-channel single top quark events for the signal but simulated t\bar{t} for the background. The values of these two discriminants (both supporting values between 0 and 1) are then combined in quadrature for an overall discriminant called NN_{s+t}^{sig}; this is analogous to the strategy adopted to derive the final discriminant in the $E_T^{bb}$ s-channel single top quark search [10].

The s-channel optimized NN_{sig} discriminant as used in the $E_T^{bb}$ s-channel single top quark search [10] and the NN_{t}\bar{t} discriminant of this analysis are combined to obtain an NN_{sig}^{s+t} final discriminant, used to simultaneously separate both s- and t-channel signal processes from the remaining background. For events with NN_{sig} output values larger than 0.6, NN_{sig}^{s+t} is assigned to the NN_{sig} output. For the remaining events, NN_{sig}^{s+t} is defined as the NN_{sig} output multiplied by 0.6. Figure 1 shows the predicted and observed distributions of the NN_{sig}^{s+t} output variable for each of the six event subsamples used in this analysis.

Several sources of systematic uncertainty are taken into account. Uncertainties on assumed cross section values are included for t\bar{t} (5%-6%), VV (6%), VH (5%), and W+c (23%) processes [24–27]. Other systematic uncertainties arise from the normalization of the V+heavy-flavor (30%) and of the MJ (3%-7%) background contributions. All samples whose normalizations are not constrained according to the data are subject to a luminosity uncertainty of 6% [28]. Furthermore, uncertainties are assigned due to the efficiencies of the lepton antiselection criteria (2%). We also assign a normalization uncertainty of 2% due to variations in the assumed parton distribution functions. To account for differences in the trigger efficiency in data and simulation, a 2% rate uncertainty is assigned.

Possible mismodeling in the b-tagging efficiency is taken into account by applying scale factors to the simulation to correct its b-tagging efficiency to that of data. All scale factors are determined from data control samples and are on the order of unity, with small variations depending on the tag category, and uncertainties ranging from 8% to 16% [17]. Mistag rate uncertainties (20%-30%) are also derived from data and included [17].

Uncertainties in the jet energy scale [15] are included by correlating the uncertainties in the predicted yields
of signals and backgrounds (of the order of 1%-6%) with the corresponding distortions in the predicted kinematic distributions arising from jet energy scale shifts in all samples except the MJ background, which is determined entirely from data. An additional systematic uncertainty is incorporated for the MJ model, accounting for shape variations in the MJ prediction.

To measure the signal cross section, a combined likelihood is formed, which is the product of Poisson probabilities for each bin of the six NN s++ discriminants shown in Fig. 1. To account for systematic uncertainties, a Bayesian technique is used, in which each independent source of systematic uncertainty is assigned a nuisance parameter with a Gaussian prior probability density, truncated when necessary to ensure non-negative event yields. The impact of each nuisance parameter is propagated to the predictions of the signal and background yields in each bin of each histogram in the analysis. A non-negative uniform prior probability distribution is assumed for the single top quark cross section, which is extracted from its posterior probability density after integrating over all nuisance parameters.

Tables I and II show the event yields in the two- and three-jet subsamples, respectively, as determined from applying the measurement procedure to the six discriminants shown in Fig. 1. The observed single top quark production cross section |σs+t| is 3.53±1.25 pb, consistent with the SM prediction of 3.15±0.36 pb [5]. The magnitude of Vtb is extracted from the single top quark cross section posterior probability density by the relation |Vtb|2obs = |Vtb|2SMσs+tobs/σs+tSM, where variables with the subscript “SM” (“obs”) correspond to the theoretical predictions (observed values) [29]. We assume |Vtb|2SM is unity and fix the s- and t-channel relative contributions to their SM prediction. Including the theoretical uncertainty of the signal cross section (5.8% for s-channel, 6.2% for t-channel) [5] and assuming a uniform prior in the interval 0 < |Vtb|2 < 1, a lower bound on |Vtb| of 0.63 is obtained at the 95% credibility level (C.L.). We measure the t-channel cross section by itself to be 1.19±0.93 pb, where the s-channel cross section is constrained to its SM prediction [30]; this result is consistent with the SM prediction of 2.10±0.12 pb [5]. We also compute the two-dimensional posterior for the s- and t-channel cross sections, where the relative contributions of both channels are allowed to vary independently; the result is shown in Fig. 2a.

These results are combined with those of the most recent CDF measurement of single top quark production in the ttbb sample [11], which measured a cross section of 3.04±0.57 pb assuming a top quark mass of 172.5 GeV/c². The combination is achieved by taking the product of the likelihoods of both analyses and simultaneously varying the correlated uncertainties, following the procedure explained above. In the ttbb analysis, candidate events were selected by requiring exactly one re-

| Table I. Numbers of predicted and observed events in the two-jet signal region in the subsamples with exactly one tightly tagged jet (1T), one tightly and one loosely tagged jet (TL), and two tightly tagged jets (TT). The uncertainties in the predicted numbers of events are due to the theoretical cross section uncertainties and to the uncertainties on signal and background modeling. Both the uncertainties and the central values are those determined by the fit to the data with theory constraints. |
|---|---|---|---|
| Category | IT | TL | TT |
| tt | 242.9 ± 24.3 | 84.8 ± 9.3 | 92.4 ± 8.4 |
| VH | 12.6 ± 1.4 | 6.6 ± 0.8 | 7.6 ± 0.8 |
| Diboson | 284.9 ± 25.6 | 51.3 ± 4.6 | 37.2 ± 3.4 |
| V+jets | 6527.7 ± 2048.1 | 694.2 ± 216.3 | 220.2 ± 68.7 |
| MJ | 8328.5 ± 180.6 | 885.2 ± 56.7 | 296.8 ± 31.8 |
| s-ch single top | 86.2 ± 47.7 | 41.8 ± 23.2 | 45.9 ± 25.3 |
| t-ch single top | 160.5 ± 30.8 | 10.8 ± 2.1 | 9.2 ± 1.7 |
| Total prediction | 15643.4 ± 2057.2 | 1774.8 ± 225.0 | 709.3 ± 80.3 |
| Observed | 15312 | 1743 | 686 |

| Table II. Numbers of predicted and observed three-jet events in the 1T, TL, and TT subsamples. |
|---|---|---|---|
| Category | IT | TL | TT |
| tt | 596.3 ± 59.6 | 117.5 ± 12.8 | 109.5 ± 9.9 |
| VH | 6.0 ± 0.7 | 1.9 ± 0.2 | 2.2 ± 0.2 |
| Diboson | 107.7 ± 9.7 | 15.7 ± 1.5 | 8.8 ± 0.8 |
| V+jets | 1609.5 ± 505.1 | 164.5 ± 51.3 | 50.4 ± 15.8 |
| MJ | 1818.2 ± 48.7 | 187.5 ± 14.7 | 55.9 ± 7.7 |
| s-ch single top | 45.7 ± 25.3 | 15.4 ± 8.5 | 16.2 ± 8.9 |
| t-ch single top | 82.2 ± 15.8 | 7.5 ± 1.5 | 6.8 ± 1.3 |
| Total prediction | 4265.7 ± 511.9 | 510.0 ± 55.6 | 249.8 ± 22.1 |
| Observed | 4198 | 490 | 237 |

constructed charged lepton (e or µ) in the final state. Hence, no such events are included in the ETbb analysis described above. The uncertainties associated with the theoretical cross sections of the tt, VV, and VH production processes, and those associated with the luminosity are taken as fully correlated between the two analyses.

The combined measurement results in an electroweak single top quark production cross section of 3.02±0.49 pb, consistent with the SM prediction. From the posterior probability density on |Vtb|2, a 95% C.L. lower limit of |Vtb| > 0.84 is obtained. The t-channel cross section, measured in the same way as for the ETbb analysis, is 1.6±0.34 pb, in agreement with the SM prediction given above. The two-dimensional posterior probability is shown in Fig. 2b, where the relative s- and t-channel contributions are allowed to vary freely.

In summary, an updated measurement of the single top quark production cross section of 3.53±1.25 pb is obtained in events with missing transverse energy and jets using the full CDF data set. This represents a relative improvement of 40% in overall precision with respect to the pre-
FIG. 2. Two-dimensional posterior probability densities of the s- and t-channel cross sections for the (a) $E_T\bar{b}b$ analysis presented here, and (b) the CDF combination of the $E_T\bar{b}b$ and $\ell\nu\bar{b}b$ analysis results. Theory uncertainties are not shown.

vious CDF analysis [9]. In addition, a combination with the $\ell\nu\bar{b}b$ CDF result [11] is performed to obtain a more precise cross section measurement of $3.04^{+0.57}_{-0.53}$ pb. Cross sections for the t-channel-only single top quark production process as well as 95% C.L. lower limits on $|V_{tb}|$ are also obtained for the $E_T\bar{b}b$ analysis and the CDF combination. All results are consistent with the corresponding SM predictions.

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We use a cylindrical coordinate system where \( \theta \) is the polar angle relative to the proton beam direction at the event vertex, \( \phi \) is the azimuthal angle about the beam axis, and pseudorapidity is defined as \( \eta = -\ln \tan(\theta/2) \). We define transverse energy as \( E_T = E \sin \theta \) and transverse momentum as \( p_T = p \sin \theta \) where \( E \) is the energy measured in the calorimeter and \( p \) is the magnitude of the momentum measured by the spectrometer.

References:

1. V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 103, 092001 (2009); T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 103, 092002 (2009).
2. N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
3. Charge-conjugate processes are assumed throughout unless explicitly stated otherwise.
4. N. Kidonakis, Phys. Rev. D 74, 114012 (2006).
5. N. Kidonakis, Phys. Rev. D 81, 054028 (2010); 83, 091503(R) (2011).
6. This value assumes equal contributions from singly produced top and antitop quarks.
7. We assume a branching ratio of 100% for the standard-model \( t \to W^+b \) process.
8. The calorimeter missing transverse energy \( \vec{E}_T \) (cal) is defined by the sum over calorimeter towers, \( \vec{E}_T \) (cal) = \(- \sum \vec{E}_T \) \( \hat{n}_i \), where \( i \) is a calorimeter tower number with \( |\eta| < 3.6 \), and \( \hat{n}_i \) is a unit vector perpendicular to the beam axis and pointing at the \( i \)th calorimeter tower. The reconstructed missing transverse energy, \( \vec{E}_T \) (cal) \( \hat{n}_i \), is derived by subtracting from \( \vec{E}_T \) (cal) components of the event not registered by the calorimeter, such as jet energy adjustments. \( \vec{E}_T \) (cal) is the scalar magnitude of \( \vec{E}_T \) (cal).
9. T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D 81, 072003 (2010).
10. T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 112, 231805 (2014).
11. T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett., to be published, arXiv:1407.4031 [hep-ex].
12. D. Acosta et al. (CDF Collaboration), Phys. Rev. D 71, 032001 (2005); 71, 052003 (2005); A. Abulencia et al., (CDF Collaboration) J. Phys. G 34, 2457 (2007).
13. We use a cylindrical coordinate system where \( \theta \) is the polar angle relative to the proton beam direction at the event vertex, \( \phi \) is the azimuthal angle about the beam axis, and pseudorapidity is defined as \( \eta = -\ln \tan(\theta/2) \). We define transverse energy as \( E_T = E \sin \theta \) and transverse momentum as \( p_T = p \sin \theta \) where \( E \) is the energy measured in the calorimeter and \( p \) is the magnitude of the momentum measured by the spectrometer.