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Studies of single top production at the Tevatron

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Summary. — I present the newest measurements of the production cross sections of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$ in a data sample corresponding to an integrated luminosity of $5.4\,\text{fb}^{-1}$ collected by the D0 detector at the Fermilab Tevatron Collider. The data is also used to extract limits on the CKM matrix element $|V_{tb}|$.

PACS `14.65.Ha` – Top quarks.
PACS `12.15.Ji` – Applications of electroweak models to specific processes.
PACS `13.85.Qk` – Inclusive production with identified leptons, photons, or other nonhadronic particles.
PACS `12.15.Hh` – Determination of Kobayashi-Maskawa matrix element.

1. – Introduction

At the Tevatron, the electroweak production of top quarks proceeds mainly via the decay of a time-like virtual W boson accompanied by a bottom quark in the s channel ($tb = t\bar{b}+\bar{t}b$) [1] or via the exchange of a space-like virtual W boson between a light quark and a bottom quark in the t channel ($tqb = tq\bar{b}+\bar{t}qb$, where q refers to the light quark or antiquark) [2,3]. A third process tW, in which the top quark is produced together with a W boson, has a small cross section at the Tevatron [4] and is therefore not considered in this analysis. Single top quark events can be used to probe the Wtb vertex and to directly measure the magnitude of the Cabibbo-Kobayashi-Maskawa (CKM) [5] quark mixing matrix element $|V_{tb}|$, without assuming unitarity of the CKM matrix and that there are three quark generations. Previous measurements of single top quark production cross section performed by the D0 and CDF collaborations and their combination [6] included events from both the tb and tqb processes, assuming a ratio of cross sections for the two processes based on the standard model (SM). However, several beyond-the-SM theories predict individual tb and tqb cross sections that deviate from the SM [7-12]. It is therefore important to also measure the individual tb and tqb production rates. Using data corresponding to $5.4\,\text{fb}^{-1}$ of integrated luminosity recorded with the D0 detector [13], we present an improved measurement of the production rate of $tb+tqb$. We also present measurements of the production rates of the individual tb and tqb processes performed assuming, respectively, tqb and tb production rates as predicted by the SM. Finally, we present a new direct measurement of $|V_{tb}|$ extracted from the measured $tb+tqb$ cross section. These results have been described in more detail in [14].

2. – Data analysis

As already mentioned, the result presented in this document is based on $5.4\,\text{fb}^{-1}$ of data recorded using the D0 detector between 2002 and 2010. The data were collected with a logical OR of many trigger conditions that results in a fully efficient trigger selection for the single top signal. Events are selected containing exactly one isolated high p_T electron or muon, missing transverse energy, and at least two jets, with at least one jet being identified as originating from the fragmentation of a b quark. The $\not{E}_T$ is required not to be aligned with the direction of the lepton or the leading jet to limit the number of events originating from multijet production entering our candidate samples. The data are divided into six mutually exclusive subsamples to take advantage of the different signal:background ratios and dominant sources of background. The sample is divided based on lepton flavor (e or μ), the jet multiplicity (2, 3 jets or 4 jets), and the number of jets identified as originating from b quarks (1 or 2 b-tags). The efficiency of the event selection, including branching fraction and the b-tagging requirements, is $(2.9 \pm 0.4)\%$ for the s channel and $(2.0 \pm 0.3)\%$ for the t channel.

Single top signal events are modeled using the COMPHEP-based next-to-leading order (NLO) Monte Carlo (MC) event generator SINGLETOP [15]. The SINGLETOP generator is chosen as it preserves the spin information for the decay products of the top quark and resulting W boson. PYTHIA [16] is used to model the hadronization of any generated partons. We assume SM production for the ratio of the tb and tqb cross sections. The $t\bar{t}$, W+jets, and Z+jets backgrounds are simulated using the ALPGEN leading-log MC event generator [17], with PYTHIA used to model hadronization. The $t\bar{t}$ background is normalized to the predicted cross section for a top quark mass of 172.5 GeV [18]. The normalization of the W/Z+jets background is obtained by scaling the ALPGEN cross sections by factors derived from calculations of NLO effects [19]. Additional factors are applied to processes involving heavy flavor jets: $Wb\bar{b}$ and $Wc\bar{c}$ are scaled by 1.47, Wcj by 1.32, $Zb\bar{b}$ by 1.52, and $Zc\bar{c}$ by 1.67. Diboson backgrounds are modeled using PYTHIA and the normalization scaled to match NLO predictions [19]. All MC events are passed through a GEANT-based simulation [20] of the D0 detector. Small additional corrections are applied to all reconstructed objects to improve the agreement between collider data and simulation. In particular, we correct mismodeling of the pseudorapidity of the jets, and the distance between the two leading jets in the W+jets sample.

The multijet background is modeled using collider data containing leptons that are not isolated. In the electron channel, the transverse momentum of the lepton is reweighted to properly match the shape of the background events passing the candidate selection. To increase the statistics in the muon channel, the jet closest to the muon is removed and $\not{E}_T$ recalculated. Cuts on the total transverse energy of the event (H_T) ensure that the multijet background is a small (less than 5%) contribution to the candidate sample. The overall normalization of the multijet and the total W+jets background is obtained by comparing the background expectation to collider data in three sensitive variables: $p_T(\ell)$, $\not{E}_T$, and the W boson transverse mass. This normalization is done after subtracting from the data sample the contributions from the small backgrounds ($t\bar{t}$, Z+jets, and dibosons) separately for each leptonic channel (e or μ), and jet multiplicity bin (2, 3, or 4 jets).

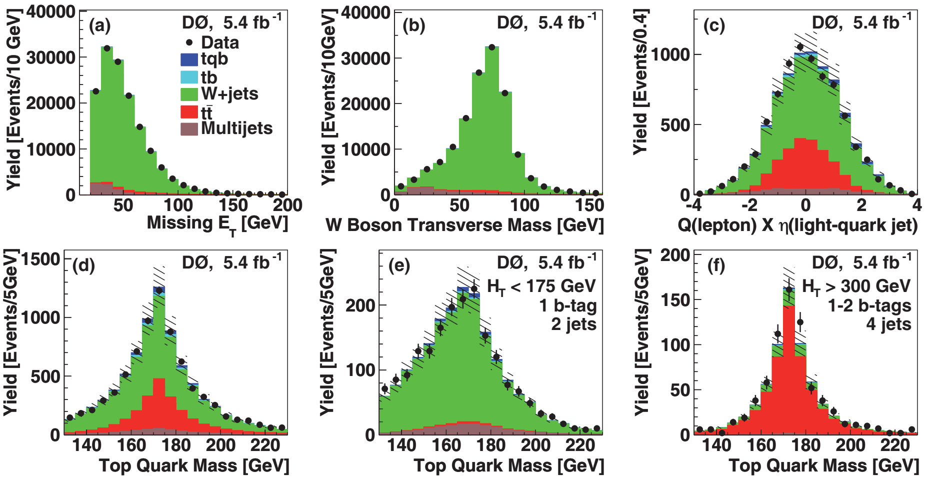

Fig. 1. – Comparisons between the data and the background model before b-tagging for (a) $\not{E}_T$ and (b) W boson transverse mass; after b-tagging for (c) light quark jet pseudorapidity multiplied by lepton charge and (d) reconstructed top quark mass; (e) in a control sample dominated by W+jets, and (f) in a control sample dominated by $t\bar{t}$. The hatched bands show the $\pm 1\sigma$ uncertainty on the background prediction for distributions obtained after b-jet identification.

The normalization is performed before b-tagging, when the expected signal to background ratio is on average S:B=1:280.

The probability for the b-tagging algorithm to identify a jet as originating from a b quark is measured in a sample of data with jets containing muons and compared to the corresponding efficiency measured in a MC sample. From this comparison we derive correction factors that we parametrize as a function of jet flavor, p_T, and η and apply to all the MC samples used in this analysis. After b-tagging, we check the normalization of the $Wb\bar{b}$ and $Wc\bar{c}$ samples in a sample that has no overlap with the one used in the single top quark cross section measurement and find the normalization to be consistent with unity. We assign a 12% uncertainty on the normalization of the $Wb\bar{b}$ and $Wc\bar{c}$ samples to account for variations in the Wcj $(j = u, d, s)$ cross section and the $Wb\bar{b}$ to $Wc\bar{c}$ cross section ratio used in this study. We select 8,471 events and expect 399 ± 33 signal events.

We also define two control samples to check the background model components separately for the two main backgrounds: W+jets and $t\bar{t}$. The W+jets-dominated sample has low H_T, exactly two jets, and only one b-tagged jet. The $t\bar{t}$-dominated sample has high H_T, exactly four jets, and one or two b-tagged jets. We find good agreement for both normalization and shape in most of distributions studied for the cross-check samples and also for the candidate sample before b-tagging, when the signal contribution is negligible.

Systematic uncertainties are considered for all corrections applied to the background model. Most affect only the normalization, but some corrections modify in addition the shapes of the background distributions.

Figure 1 shows comparisons between data and simulation before and after applying b-tagging. In the same figure, the normalization and differential spectra of the two dominant backgrounds are checked using the control samples dominated by W+jets, and by $t\bar{t}$ events. These plots are indicative of the adequate background modeling attained for various sample conditions in the analysis.

TABLE I. – *Expected and observed cross sections in pb for* tb, tqb, *and* $tb + tqb$ *production. All results assume a top quark mass of 172.5 GeV.*

Discriminant	Expected	Observed
	tb production	
BNN	$1.08^{+0.52}_{-0.50}$	$0.72^{+0.44}_{-0.43}$
BDT	$1.07^{+0.47}_{-0.43}$	$0.68^{+0.41}_{-0.39}$
NEAT	$1.06^{+0.54}_{-0.50}$	$0.17^{+0.41}_{-0.17}$
B_{tb}	$1.12^{+0.45}_{-0.43}$	$0.68^{+0.38}_{-0.35}$
	tqb production	
BNN	$2.49^{+0.76}_{-0.67}$	$2.92^{+0.87}_{-0.73}$
BDT	$2.40^{+0.71}_{-0.66}$	$3.03^{+0.78}_{-0.66}$
NEAT	$2.36^{+0.80}_{-0.77}$	$2.75^{+0.87}_{-0.75}$
B_{tqb}	$2.43^{+0.67}_{-0.61}$	$2.86^{+0.69}_{-0.63}$
	$tb + tqb$ production	
BNN	$3.46^{+0.84}_{-0.78}$	$3.11^{+0.77}_{-0.71}$
BDT	$3.41^{+0.82}_{-0.74}$	$3.01^{+0.80}_{-0.75}$
NEAT	$3.33^{+0.94}_{-0.80}$	$3.59^{+0.96}_{-0.80}$
B_{tb+tqb}	$3.49^{+0.77}_{-0.71}$	$3.43^{+0.73}_{-0.74}$

3. – Cross section measurements

Since the expected single top quark contribution is smaller than the uncertainty on the background, we use multivariate analysis (MVA) methods to extract the signal. Three different MVA techniques are used in this analysis: i) Bayesian neural networks (BNN) [21], ii) boosted decision trees (BDT) [22], and iii) neuroevolution of augmented topologies (NEAT) [23]. Each MVA method is trained separately for the two single top quark production channels: i) for the tb discriminants, with tb considered signal and tqb treated as a part of the background, and ii) for tqb discriminants, with tqb considered signal and tb treated as a part of the background. Using ensembles of datasets containing contributions from background and SM signal, we infer that the correlation among the outputs of the individual MVA methods is $\approx 70\%$. An increase in sensitivity can therefore be obtained by combining these methods to form a new discriminant that takes as inputs the three discriminant outputs of BDT, BNN, and NEAT.

The single top quark production cross sections are measured using a Bayesian approach as detailed in [14], and are summarized in table I. All of the results are consistent with SM predictions for a top quark mass of 172.5 GeV. The measured $tb + tqb$ production cross section is the most precise current measurement, with a precision comparable to the world average [6].

Figure 2 shows a comparison of the distributions of four kinematic variables with large discriminating power, for single top quark production in a data sample selected with S:B > 0.24. Variables shown are: leading b-tagged jets p_T, W boson transverse mass, centrality, defined as the ratio of the scalar sum of the p_T of the jets to the scalar sum of the energy of the jets in the event, and reconstructed m_t. The presence of the single top quark signal is needed to ensure a good description of the data.

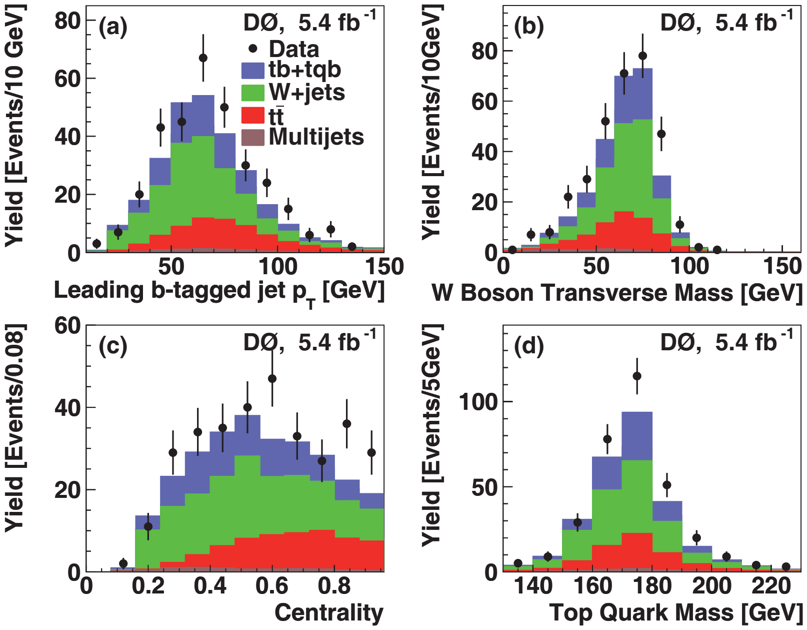

Fig. 2. – Distributions for data in the regions of large value for signal discrimination: (a) leading b-tagged jet p_T, (b) W boson transverse mass, (c) centrality, defined as the ratio of the scalar sum of the p_T of the jets to the scalar sum of the energy of the jets in the event, and (d) reconstructed m_t. The contributions from signal have been normalized to the measured $tb + tqb$ cross section.

4. – $|V_{tb}|$ measurement

The single top quark production cross section is directly proportional to the square of the CKM matrix element $|V_{tb}|^2$, enabling us to measure $|V_{tb}|$ directly without any assumption on the number of quark families or the unitarity of the CKM matrix. We assume only SM sources for single top quark production and that top quarks decay exclusively to Wb. We also assume that the Wtb interaction is CP-conserving and of the $V - A$ type, but maintain the possibility for an anomalous strength of the left-handed Wtb coupling (f_1^L), which could rescale the single top quark cross section [24]. Therefore, we are measuring the strength of the $V - A$ coupling, *i.e.*, $|V_{tb} f_1^L|$, which can be > 1. We form a Bayesian posterior $|V_{tb} f_1^L|^2$ with a flat prior based on the B_{tb+tqb} discriminant. Using the measured $tb + tqb$ cross section, we obtain $|V_{tb} f_1^L| = 1.02^{+0.10}_{-0.11}$. If we restrict the prior to the SM region [0,1] and assume $f_1^L = 1$, we extract a limit of $|V_{tb}| > 0.79$ at the 95% C.L.

5. – Summary

In summary, we have measured the single top quark production cross section using $5.4\,\mathrm{fb}^{-1}$ of data collected by the D0 experiment at the Fermilab Tevatron Collider and used it to derive a direct limit on the CKM matrix element $|V_{tb}| > 0.79$ at the 95% C.L. assuming a flat prior within $0 \leq |V_{tb}|^2 \leq 1$.

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