Studies of Top Quark Production at D0

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Abstract. I present recent results on top quark production in $p\overline{p}$ collisions at a center of mass energy of 1.96 TeV. The studies were performed by the D0 collaboration using approximately 5 fb^{-1} of data taken during Run II at the Fermilab Tevatron accelerator.

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INTRODUCTION

The top quark is the heaviest known elementary particle and completes the quark sector of the three-generation structure of the standard model (SM). It differs from the other quarks not only by its much larger mass, but also by its lifetime which is too short to build hadronic bound states.

The SM predicts that top quarks are created via two independent production mechanisms at hadron colliders. The primary mode, in which a $t\bar{t}$ pair is produced from a gtt vertex via the strong interaction, was used by the D0 and CDF collaborations to establish the existence of the top quark in 1995 [1, 2]. The second production mode of top quarks at hadron colliders is the electroweak production of a single top quark from a Wtb vertex. The predicted cross section for single top quark production is about half that of $t\bar{t}$ pairs [3, 4] but the signal-to-background ratio is much worse; observation of single top quark production has therefore until recently been impeded by its low rate and difficult background environment compared to the top pair production [5, 6].

In the following sections I will present results for the measurement of the $t\bar{t}$ pair and the single top quark production cross section using respectively 5.3 fb^{-1} and 5.4 fb^{-1} of data taken by the D0 experiment.

TOP QUARK PAIR PRODUCTION CROSS SECTION

Within the SM, the top quark decays almost exclusively into a W boson and a b quark, resulting in two W bosons and two b jets in each $t\bar{t}$ pair event. The W boson itself decays into one lepton and its associated neutrino, or hadronically. We have classified the $t\bar{t}$ pair decay channels as follows: the dilepton channels where both W bosons decay leptonically into an electron or a muon, the lepton + jets channels where one of the W bosons decays leptonically and the other hadronically, and the all-jets channel where both W bosons decay hadronically. Production cross sections have been measured in all decay channels. The lepton + jets channels have less statistics than the all-jets channel, but the background level is significantly smaller, making it the channel of choice for the measurement of top quark properties. The dilepton channel has negligible contribution from backgrounds but also has the smallest branching ratio for top quark pair decays. All channels contain two b-jets in the final state. D0 has implemented a neural network (NN) b-tagging algorithm [9] to identify jets that originate from the hadronization of long-lived b hadrons ("b-tagged jet"), which can aid in the identification of top quark events.

The total top quark pair production cross section for a hard scattering process initiated by a $p\overline{p}$ collision at $\sqrt{s}$ is a function of the top quark mass m_t [3]. Deviations of the measured cross section from the theoretical prediction could indicate effects beyond QCD perturbation theory. Explanations might include substantial non-perturbative effects, new production mechanisms, or additional top quark decay modes beyond the SM. Recent new results became available for the lepton + jets [7] and dilepton [8] final state. In the lepton + jets channel, we select events containing one high p_T isolated electron or muon, missing transverse energy and at least two jets, and use three different techniques to separate the top events from the backgrounds. The first one relies on specific kinematic features of the $t\bar{t}$ events, the second one uses b-tagging to identify the bottom quarks present in the top quark decay, and the third one combines both techniques and determines the $t\bar{t}$ production cross section simultaneously with the ratio of the production rates of W+heavy flavor jets and W+light flavor jets. This technique reduces the impact of the systematic uncertainties related to the background estimation. In the dilepton channel, we select events with two leptons $(ee, e\mu, \mu\mu)$ and at least one jet in the $e\mu$ channel, and at least two jets in the ee and $\mu\mu$ channels. The cross section is measured simultaneously fitting the b-tagging NN output distributions in the four channels.

A summary of the measured cross sections can be found in Table 1. In all cases, we account for systematic uncertainties by assigning a parameter to each independent systematic variation, and then allow these nuisance parameters [10] to vary within uncertainties during the maximization of the likelihood function procedure used to extract the cross sections. By combining the lepton + jets and dilepton channels we obtain $\sigma_{t\bar{t}} = 7.56^{+0.63}_{-0.56}$ (stat + syst) pb, in agreement with the SM expectations for a top quark mass $m_t = 172.5$ GeV. This measurement has a relative precision of 8%, comparable to the latest theoretical calculations.

SINGLE TOP QUARK PRODUCTION CROSS SECTION

At the Tevatron, single top quarks are produced through W boson exchange, and accompanied by a b quark in the s channel [11], or by both a b and a light quark in the t-channel [12, 13]. A third process, usually called "associated production," in which the top quark is produced together with a W boson, has negligible cross section at the Tevatron [4]. Prior publications measured the production cross section for the sum of the s and t channel while assuming the relative rate between the two processes as predicted by the SM. Several new physics models predict relative rates that depart from the SM predicion, making it of interest to measure the individual cross sections using a methodology that is independent of theoretical assumptions about their relative rates.

We select events containing exactly one isolated high p_T electron or muon, missing transverse energy, and at least two jets, with at least one b-tagged jet. The main background contributions arise from W bosons produced in association with jets (W+jets), $t\bar{t}$, and multijet production in which a jet mimics an isolated lepton. The signal-to-background (S:B) ratio is approximately 1:33 (1:50) for the sample with one (two) b-tagged jets. Because the uncertainty on the background is larger than the expected signal, we need to improve the discrimination between signal and background employing multivariate analysis (MVA) techniques as described in [14]. We use three methods: boosted decision trees (BDT) [15] and Bayesian neural networks (BNN) [16]. In addition, we use a third method, neuroevolution of augmented topologies (NEAT) [17]. Even though the three MVA techniques use the same data sample, they are only $\approx 70\%$ correlated with each other. We therefore combine these methods using an additional BNN algorithm (BNNComb) that takes as input the individual output discriminants of the BDT, BNN, and NEAT methods, and produces a single combined output discriminant. Each method is optimized to maximize the sensitivity to the t channel by treating the s channel as a background component.

We construct a two-dimensional (2D) posterior probability density [18] as a function of the cross sections for the t- and s-channel processes. The BNNComb output discriminants for the signals, backgrounds, and data are used to form a binned likelihood as a product over all analysis channels and all bins. No constraint is imposed on the relative rates of s- and t-channel production. We assume a Poisson distribution for the observed number of events and uniform prior probabilities with positive values for the two signal cross sections. We integrate over the systematic uncertainties which are described by Gaussian priors. The t-channel cross section is then extracted from a one-dimensional posterior probability density obtained from this 2D posterior by integrating over the s-channel axis, thus not making any assumptions about the value of the s-channel cross section. Figure 1 shows the 2D posterior probability density for the combined discriminant together with predictions from the SM [4] and various beyond-the-SM scenarios.

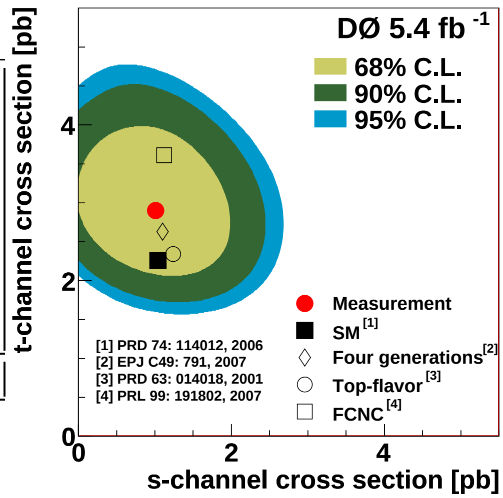
The measured cross sections [19] of $\sigma(p\bar{p} \to tqb + X) = 2.90 \pm 0.59$ pb and $\sigma(p\bar{p} \to tb + X) = 0.98 \pm 0.63$ pb are in good agreement with the SM expectation for a top quark mass of 172.5 GeV [4]. The cross section for t-channel single top quark production is the most precise measurement of an individual single top quark production channel to date with an uncertainty of 20%. The probability of the background to fluctuate to the measured t-channel cross section [20] is 1.6×10^{-8}, corresponding to a significance larger than 5 standard deviations (SD).

CONCLUSIONS

Using 5.4 fb^{-1} of $p\overline{p}$ collisions data taken at a center of mass energy of 1.96 TeV, the D0 collaboration has performed precise measurements of the strong and electroweak production processes of top quarks. These type of measurements not only test the validity of the parton distribution functions of the proton and antiproton, but also the strength of the Wtb couplings and higher-order corrections from quantum chromodynamics. These high-precision comparisons are important to check the self-consistency of the SM.

TABLE 1. (left): Summary of the measured $t\bar{t}$ production cross sections. The combined result has a relative precision of 8%, comparable to the latest theoretical calculations. (right): Posterior probability density for t- vs s-channel single top quark production in contours of equal probability density. The measured cross section and various theoretical predictions are also shown.

Lepton + jets (kinematic)	$7.68 \pm 0.31^{+0.64}_{-0.56}$ pb
Lepton + jets (b-tagging)	$8.13 \pm 0.25^{+0.99}_{-0.86}$ pb
Lepton + jets (combined)	$7.78^{+0.77}_{-0.64}$ pb
Dilepton	$7.36^{+0.90}_{-0.79}$ pb
All Combined	$7.56^{+0.63}_{-0.56}$ pb



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