

## Studies of single top quark production at the Tevatron

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In this paper we present several measurements of single top quark production from the CDF and D0 experiments at the Tevatron. The various analyses utilize integrated luminosity ranging from 2.1 to 4.8 fb<sup>-1</sup>. The results include the observation of single top production with a combined cross section of  $2.76_{-0.47}^{+0.58}$  pb for a top quark mass of 170 GeV/c<sup>2</sup>, as well as measurements of top quark polarization and first evidence for *t*-channel production.

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## 1. Introduction

Within the Standard Model (SM), top quarks can be produced either as  $t\bar{t}$  pairs through the strong interaction, or singly in association with  $b$  quarks through the electroweak interaction. Studies of single top production rates and properties could enhance understanding of SM processes, in particular yielding a direct measurement of the CKM parameter  $|V_{tb}|$ . These measurements are also sensitive to the effects of several new physics scenarios. In proton-antiproton collisions at the Tevatron, the cross section for single top production is expected to be nearly half the cross section for  $t\bar{t}$  [1, 2]. However, even though strong production of top was discovered in 1995 [3], it took 12 more years to find evidence for the electroweak counterpart [4] due to much more challenging backgrounds.

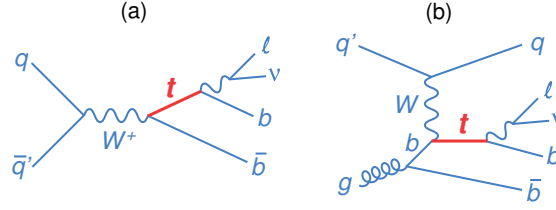
In Tevatron collisions with  $\sqrt{s} = 1.96$  TeV,  $s$ - and  $t$ -channel single top production modes dominate, with expected cross sections of  $\sigma_s = 1.12 \pm 0.05$  pb and  $\sigma_t = 2.34 \pm 0.13$  pb (at  $m_t = 170$  GeV/ $c^2$ ). Figure 1 shows diagrams of these two processes, where the  $W$  boson from the  $t$  decay subsequently decays to a charged lepton and neutrino offering the cleanest signature for experimental observation of single top. In this paper, several results from the CDF and D0 experiments examining these lepton+jets events in 2.1 to 4.8 fb<sup>-1</sup> of integrated luminosity are presented.

## 2. Observation

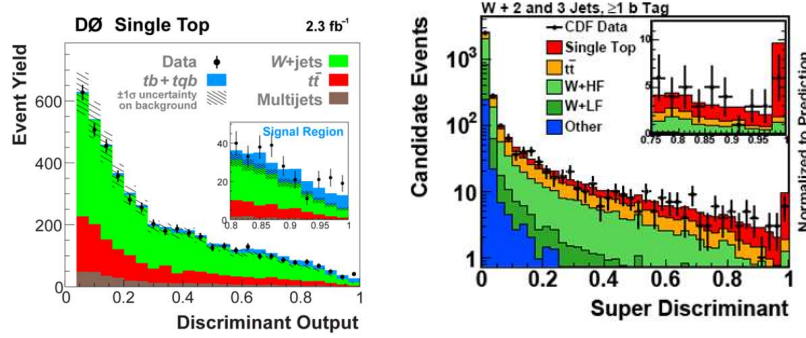
The main background obscuring single top signal is  $W$ +jets events (including light and heavy flavor jets) which have a similar topology and cross section some four orders of magnitude greater. Other major backgrounds are  $t\bar{t}$  and multijet production, with smaller contributions from dibosons and  $Z$ +jets. Monte Carlo simulations are used to model the signal and all backgrounds except multijets, which is obtained from data samples.  $W$ +jets and multijets are normalized to the data, while all other backgrounds are normalized to SM NNLO cross section calculations.

Events selected from the data must include an isolated, high transverse momentum electron or muon, missing transverse energy ( $\cancel{E}_T$ ) from the escaped neutrino, and associated  $b$  jet all from the top decay.  $s$ -channel events have a second  $b$  jet from the  $b$  produced with the top, and  $t$ -channel events have an additional light quark jet and can have a second  $b$  jet. Therefore, selected events must have 2 or 3 (or 4 for D0) jets, 1 or 2 of which must be identified as  $b$  jets ( $b$ -tagged). After selection, signal to background is only on the order of 1:20, so multivariate techniques are employed to further isolate the signal.

Both experiments perform multiple multivariate analyses (MVAs) in order to maximize the discriminating power of many separate variables. CDF and D0 each perform boosted decision tree, neural net, and matrix element analyses, and CDF employs a likelihood function and  $s$ -channel only likelihood function. CDF also performs a neural net analysis on an orthogonal  $\cancel{E}_T$ +jets sample to recover events with taus from the  $W$  decay [5]. For each MVA, the data is separated into several individual analysis channels based on number of jets, number of  $b$ -tags, and for D0 the lepton type. The cross section is determined using a likelihood formed as a product over all channels. Finally, an overall cross section measurement for each experiment is made by combining the separate MVAs. D0 does this with a bayesian neural net, CDF with a neural net for lepton+jets followed by a simultaneous fit of lepton+jets and  $\cancel{E}_T$ +jets.



**Figure 1:** Feynman diagrams for (a)  $s$ -channel and (b)  $t$ -channel single top quark production, with subsequent top decay to  $b$  quark, charged lepton and neutrino.



**Figure 2:** Discriminants combining all lepton+jets multivariate analyses for D0 (left) and CDF (right).

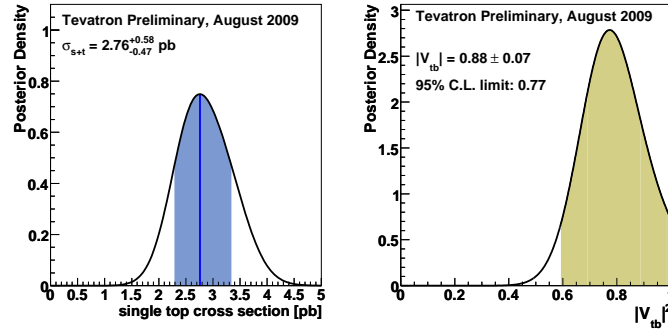
	Luminosity	Cross Section	Exp Sig	Obs Sig	$ V_{tb} $ Meas	$ V_{tb} $ Lower Lim
D0	$2.3 \text{ fb}^{-1}$	$3.94 \pm 0.88 \text{ pb}$	$4.5\sigma$	$5.0\sigma$	$1.07 \pm 0.12$	0.78
CDF	$2.1\text{-}3.2 \text{ fb}^{-1}$	$2.3^{+0.6}_{-0.5} \text{ pb}$	$5.9\sigma$	$5.0\sigma$	$0.91 \pm 0.13$	0.71

**Table 1:** Single top production cross section and  $|V_{tb}|$  results for CDF and D0.

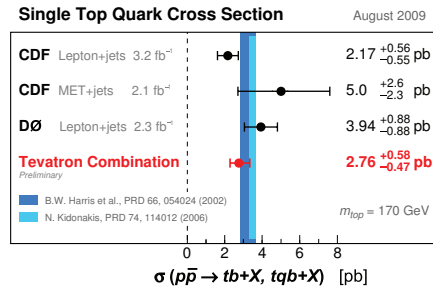
The combined lepton+jets discriminants are shown in Figure 2, which illustrates the signal separation key to the single top production observations by both experiments published on the same day[6]. The combined  $s$ -channel and  $t$ -channel cross section measurements and extracted values and lower limits on  $|V_{tb}|$  (assuming  $0 \leq |V_{tb}|^2 \leq 1$ ) are detailed in Table 1. The CDF and D0 results were then combined with a Bayesian analysis using all nine CDF and D0 MVA discriminants as inputs, and the posterior probability densities for the cross section and  $|V_{tb}|$  can be seen in Figure 3[7]. The Tevatron measurement of  $\sigma_{s+t} = 2.76^{+0.58}_{-0.47} \text{ pb}$  is consistent with the SM, and the two experiments' values are compatible with each other at the level of  $1.6\sigma$  (Figure 4).

### 3. Other Measurements

Several other studies of single top quarks have been completed since the joint discovery was made. Within the SM, single top quarks are produced purely through  $V - A$  interactions, and thus should have 100% left-handed polarization. However, non-SM production can introduce



**Figure 3:** Posterior probability distributions of the Tevatron combination for the single top production cross section for  $m_t = 170 \text{ GeV}/c^2$  (left), and  $|V_{tb}|$  assuming a theory cross section of 3.46 pb (right).



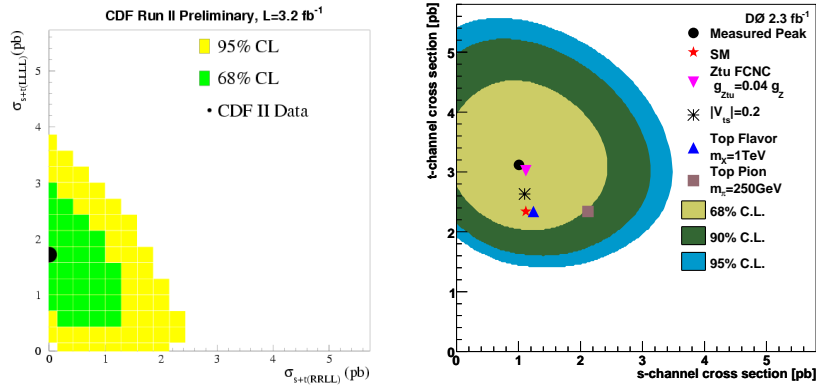
**Figure 4:** Combination of CDF and DØ single top cross section measurements, with theoretical predictions.

right-handed  $V + A$  couplings, so a polarization measurement different than pure left would be an indication of new physics. CDF performed a 2D analysis with separate discriminants for left-handed production and decay (LLLL), and right-handed production with left-handed decay (RRLL) (Figure 5, left). With measured cross sections of  $\sigma_{LLLL} = 1.72$  and  $\sigma_{RRLL} = 0$ , and polarization  $\sigma_R - \sigma_L / \sigma_R + \sigma_L = -1^{+1.5}_{-0}$ , no evidence for right-handed couplings was found.

The  $t$ -channel production rate is particularly sensitive to flavor changing neutral currents and anomalous couplings, thus DØ retained the MVAs to treat  $s$ -channel single top as part of the background and  $t$ -channel single top as the signal. In this analysis, the individual  $s$ - and  $t$ -channel cross sections are measured simultaneously, without constraining  $\sigma_t / \sigma_s$  to the SM value[8]. The plot of  $\sigma_t$  vs.  $\sigma_s$  in Figure 5, right shows a ratio consistent with the SM, and a measured value of  $\sigma_t = 3.1 \pm 0.9$ , representing the first evidence for  $t$ -channel single top production with an observed significance of  $4.8\sigma$ . DØ has also published a single top cross section measurement using boosted decision trees to analyze tau+jets events, with a result of  $\sigma_{s+t} = 3.4^{+2.0}_{-1.8}$  pb[9], and a bayesian neural net search which found no evidence for flavor changing neutral currents in single top production[10].

#### 4. Summary

Several studies of single top quarks have been completed at the Tevatron, all employing a



**Figure 5:** 2D fit of SM left-handed (LLLL) vs. anomalous right-handed (RRL) production cross sections (left), and posterior probability of  $t$ -channel and  $s$ -channel production cross sections (right).

variety of multivariate analysis techniques to extract the signal from an extremely challenging background environment. After the CDF and D0 discovery of single top quark production, the experiments' analyses have been combined to yield Tevatron measurements of  $\sigma_{s+t} = 2.76^{+0.58}_{-0.47}$  pb and  $|V_{tb}| > 0.77$ . Among other results are the CDF measurement of left-handed top quark polarization, and D0's first evidence for  $t$ -channel production. More single top results with greater precision will be forthcoming as the Tevatron data sets will more than double by 2011.

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