Evidence for Single Top Quark Production at D0

Liang Li

Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA

E-mail: `liangli@fnal.gov`

Abstract. We present evidence for the production of single top quarks at the Fermilab Tevatron $p\bar{p}$ collider. Using a 0.9 fb^{-1} dataset collected with D0 detector, the analysis is performed in the electron+jets and muon+jets decay modes, taking special care in modeling the large backgrounds, applying a new powerful b-quark tagging algorithm and using three multivariate techniques to extract the small signal. The combined measured production cross section is $\sigma(p\bar{p} \to tb + X,\ tqb + X) = 4.7 \pm 1.3$ pb. The probability to measure a cross section at this value or higher in the absence of signal is 0.014%, corresponding to a 3.6 standard deviation significance. We use the cross section measurement to directly determine the CKM matrix element that describes the Wtb coupling and find $0.68 < |V_{tb}| \leq 1$ at 95% C.L. within the standard model.

1. Introduction

Top quarks were first observed produced in $t\bar{t}$ pairs via the strong interaction at the Tevatron collider in 1995. In the standard model (SM), top quarks are also expected to be produced via the exchange of a W boson in s- or t-channel. The final state in these channels thus consists of one "single" top quark together with a b quark in the s-channel (tb) and an additional light quark in the t-channel (tqb). Single top quarks can also be produced in association with a W boson (tW), but the cross section for this process at the Tevatron is very small and will be ignored here. The next-to-leading order prediction for the s-channel single top quark cross section is $\sigma(p\bar{p} \to tb + X) = 0.88 \pm 0.11$ pb, and for the t-channel process, the prediction is $\sigma(p\bar{p} \to tqb + X) = 1.98 \pm 0.25$ pb [1].

Both the CDF and D0 collaborations have performed searches for this process in the past [2, 3]. The analysis presented here, described in more detail in Ref. [4], draws many techniques and experience from the previous D0 analyses, where it was made clear that multivariate techniques are necessary to be sensitive to the SM production cross section with limited data statistics.

Observation of single top quark production allows one to study the Vtb coupling and directly measure the CKM element V_{tb} without the standard model (SM) assumption of three families.

2. Event selection, Backgrounds and Data Samples

The data used in this search was collected from 2002 to 2005 with triggers that required an electron or a muon and at least one jet. Events are required to have exactly one isolated electron (muon) with $p_T > 15$ GeV (18 GeV) within $|\eta| < 1.1$ (2.0), and $\not{E}_T > 15$ GeV. Events are also required to contain two, three or four jets, using a cone algorithm with radius $\mathcal{R} = \sqrt{(\Delta y)^2 + (\Delta\phi)^2} = 0.5$ (where y is rapidity and ϕ is azimuthal angle) to cluster energy deposits in the calorimeter. The leading jet has $p_T > 25$ GeV and $|\eta| < 2.5$, the second leading jet has $p_T > 20$ GeV and $|\eta| < 3.4$, and subsequent jets have $p_T > 15$ GeV and $|\eta| < 3.4$. To enhance the signal content of the selection, at least one jet in the event is required to be identified as a b-quark jet (b-tagging).

There are three main backgrounds to single top: W bosons produced in association with jets; top quark pairs decaying into the lepton+jets and dilepton final states, when a jet or a lepton is not reconstructed; and multijet production, where a jet is misreconstructed as an electron, or a heavy-flavor quark decays to a muon that passes the isolation criteria. The $t\bar{t}$ background is normalized to the integrated luminosity times the predicted $t\bar{t}$ cross section of $6.8^{+0.6}_{-0.5}$ pb [5]. The W+jets background, together with the multijet background, is normalized to the data in each channel (defined by lepton flavor and jet multiplicity) before b-tagging.

To increase the search sensitivity, we divide these events into twelve independent analysis channels based on the lepton flavor (e or μ), jet multiplicity (2, 3, or 4), and number of identified b jets (1 or 2). We do this because the signal acceptance and signal-to-background ratio differ significantly from channel to channel. Event yields are given in Tab. 1 (*left*), shown separated only by jet multiplicity for simplicity. The acceptances for single top quark signal as percentages of the total production cross sections are $(3.2 \pm 0.4)\%$ for tb and $(2.1 \pm 0.3)\%$ for tqb.

Table 1: The numbers of expected and observed events in 0.9 fb^{-1} for e and μ, 1 b tag and 2 b tag channels combined (*left*). The sizes of systematic uncertainties (*right*).

Source	2 jets	3 jets	4 jets
tb	16±3	8±2	2±1
tqb	20±4	12±3	4±1
$t\bar{t} \to \ell\ell$	39±9	32±7	11±3
$t\bar{t} \to \ell$+jets	20±5	103±25	143±33
$Wb\bar{b}$	261±55	120±24	35±7
$Wc\bar{c}$	151±31	85±17	23±5
Wjj	119±25	43±9	12±2
Multijets	95±19	77±15	29±6
Total bkgd	686±41	460±39	253±38
Data	697	455	246

Source	Size
Top pair normalization	18%
W+jet & multijet normalization	18-28%
Integrated luminosity	6%
Trigger modeling	3-6%
Lepton ID corrections	2-7%
Other small components	Few%
Jet energy calibration	1-20%
b-tagged jet modeling	2-16%

3. Systematic uncertainties

The dominant contributions to the uncertainties on the backgrounds come from: normalization of the $t\bar{t}$ background (18% of the $t\bar{t}$ component), which includes a term to account for the top quark mass uncertainty; normalization of the W+jets and multijet backgrounds to data (18–28%), which includes the uncertainty on the heavy-flavor fraction of the model; the jet energy scale corrections (1–20%); and the b-tagging probabilities (2–16%). The uncertainties and their sizes are shown in Tab.1 (*right*). The uncertainties from the jet energy scale corrections and the b-tagging probabilities affect both the shape and normalization of the simulated distributions.

Having selected the data samples, we check that the background model reproduces the data in a multitude of variables (e.g., transverse momenta, pseudorapidities, azimuthal angles, masses) for each analysis channel and find agreement within uncertainties.

4. Multivariate Methods and Results

It can be seen from Tab. 1 that the single top signal is smaller than the background uncertainty, a counting experiment will not have sucient sensitivity to verify their presence. We proceed instead to calculate multivariate discriminants that separate the signal from background and thus enhance the probability to observe single top quarks.

Three separate multivariate techniques have been employed in D0 to extract the signal from the data: Boosted Decision Trees [6], Matrix Elements discriminants [7] and Bayesian Neural Networks [8]. The output distributions in the most sensitive channel, shown in Fig. 1 for the three methods, also demonstrate good overall agreement between data and background.

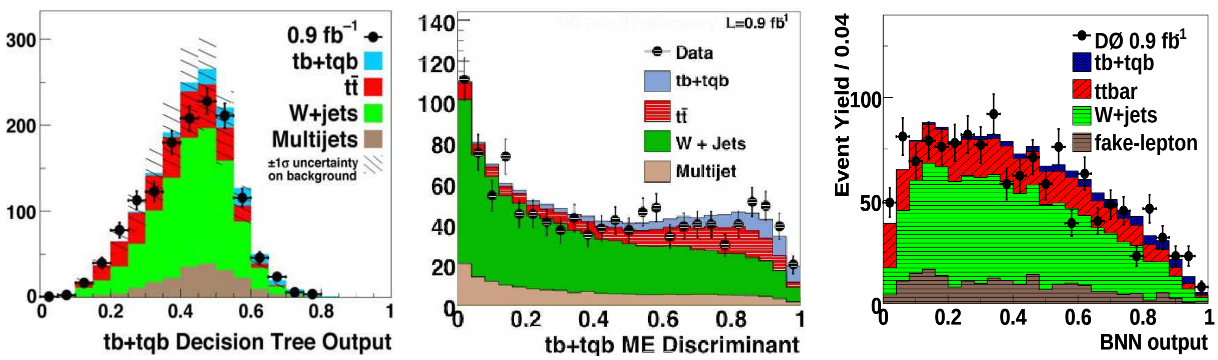


Figure 1: Output distributions of full discriminant (all channels combined) for the Decision Tree(left), for the Matrix Element (center), and for the Bayesian Neural Net (right) analysis.

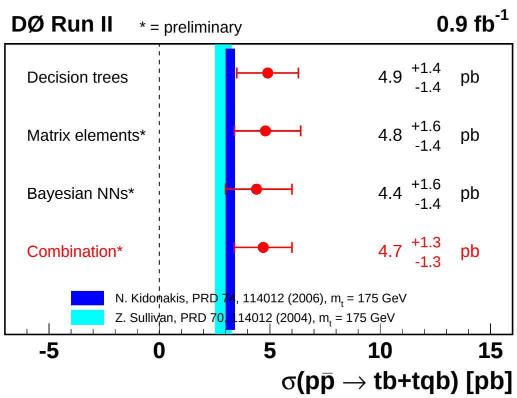
In order to extract the maximum information from the discriminant outputs, instead of cutting on the outputs and counting events, the full distributions are fed into a Bayesian statistical analysis to measure the single top quark production cross section. The expected and observed cross section results are summarized in Fig. 2. The uncertainties include statistical and systematic components combined. The data statistics contribute 1.2 pb to the total 1.4 pb uncertainty on the tb+tqb cross section for the DT analysis. The significance is measured re-running the analysis on 70,000 pseudo-datasets generated with all the uncertainties on the background model taken into account, but including only background sources. Thus we obtain the probability for the background-only hypothesis to fluctuate up to give the measured (or SM) value of the tb+tqb cross section or greater.

The three analyses are highly correlated since they all use the same signal and background models and data, with almost the same systematic uncertainties. The correlation between the three methods has been measured in fake pseudo data-sets (which include the systematic uncertainties on our background model), with the SM single top cross section. The Best Linear Unbiased Estimate method (BLUE) [9] has been applied to the three measurements to give a combined measured cross section of $\sigma(p\bar{p} \rightarrow tb + X,\ tqb + X) = 4.7 \pm 1.3$ pb. The probability to measure this value of the cross section or higher in the absence of signal is 0.014%, corresponding to a 3.6 standard deviation significance.

We use the decision tree measurement of the tb+tqb cross section to derive a first direct measurement of the strength of the $V - A$ coupling $|V_{tb} f_1^L|$ in the Wtb vertex, where f_1^L is an arbitrary left-handed form factor [10]. We measure $|V_{tb} f_1^L| = 1.3 \pm 0.2$. This measurement assumes $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$ and a pure $V - A$ and CP-conserving Wtb interaction. Assuming in addition that $f_1^L = 1$, we obtain $0.68 < |V_{tb}| \leq 1$ at 95% C.L.. These measurements make no assumptions about the number of quark families or CKM matrix unitarity.

5. Summary

We have performed a search for single top quark production using 0.9 fb^{-1} of data collected by the D0 experiment at the Tevatron collider. We find an excess of events over the background



	$\sigma(tb + tqb)$ [pb]		Significance	
	Expected	Observed	Expected	Observed
DT	$2.7^{+1.5}_{-1.4}$	4.9 ± 1.4	2.1σ	3.4σ
ME	$2.8^{+1.6}_{-1.4}$	$4.8^{+1.6}_{-1.4}$	2.1σ	3.2σ
BNN	$2.7^{+1.4}_{-1.4}$	$4.4^{+1.6}_{-1.4}$	2.2σ	3.1σ

Figure 2: The observed combination result for three measurements ($left$); The expected and observed cross sections and significance for three measurements ($right$).

prediction in the high discriminant output region from three analyses and interpret it as evidence for single top quark production. The excess has a combined significance of 3.6 standard deviations and the combined measurement of the single top quark cross section is: $\sigma(p\bar{p} \to tb + X,\ tqb + X) = 4.7 \pm 1.3$ pb.

Acknowledgements

I thank the organizers of the HEP2007 conference in Manchester for holding such a nice conference and thank colleagues and insitutions from D0 Collaboration and Fermilab for making the result possible. I acknowledge support from the DOE (USA).

References

[1] Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).
[2] Cfr. article by B. Stelzer in these proceedings; D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 012005 (2005).
[3] V.M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **622**, 265 (2005); V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **75**, 092007 (2007)
[4] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **98**, 181802 (2007)
[5] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).
[6] Additional information can be found here: `http://www-d0.fnal.gov/Run2Physics/top/public/fall06/singletop/`
[7] D0 Conference Note 5392.
[8] D0 Conference Note 5397.
[9] L. Lyons, D. Gibaut, and P. Clifford, Nucl. Instrum. Methods **A 270**, 110 (1988); R. J. Barlow, *Statistics: A Guide To The Use Of Statistical Methods In The Physical Sciences*, The Manchester Physics Series, John Wiley and Sons, New York (1989); G. Cowan, *Statistical Data Analysis*, Oxford (1998).
[10] G.L. Kane, G.A. Ladinsky, and C.-P. Yuan, Phys. Rev. D **45**, 124 (1992); A.S. Belyaev, private communication.