SINGLE-TOP-QUARK PHYSICS AT THE TEVATRON*

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In this document we present the status of the searches for the electroweak production of top quarks (single-top-quarks) at the CDF and DØ experiments at the Tevatron.

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1. Introduction

According to the Standard Model, in $p\bar{p}$ collisions at the Tevatron top quarks can be created in pairs via the strong force, or singly via the electroweak interaction. The latter production mode is referred to as "single-top-quark" production and takes place mainly through the $t-$ or s-channel exchange of a W boson. Studying single-top production at hadron colliders [1] is important for a number of reasons. First, it provides a window into measuring the Cabibbo–Kobayashi–Maskawa (CKM) matrix element $|V_{tb}|^2$, which in turn is closely tied to the number of quark generations. Second, measuring the spin polarization of single-top quarks can be used to test the $V{-}A$ structure of the top weak charged current interaction. Third, the estimation of the single-top backgrounds is crucial for several searches for other signals (*e.g.* Higgs boson). Fourth and last, the presence of various new SM and non-SM phenomena may be inferred by observing deviations from the predicted rate of the single-top signal.

The theoretical single-top production cross section is $\sigma_{s+t} = 2.9\,\mathrm{pb}$ for a top mass of $175\,\mathrm{GeV}/c^2$ [2]. The main obstacle in observing the single-top process is however not its small rate, but the large associated backgrounds. After all selection requirements are imposed, the signal to background ratio

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is close to 1/15. This challenging, background-dominated dataset is the main motivation for using multivariate techniques in the CDF and DØ analyses presented here[1].

2. CDF single-top searches

The CDF Collaboration has recently reported single-top results from analyzing the 1 fb^{-1} dataset. The event selection exploits the kinematic features of the signal final state, which contains a top quark, a bottom quark, and possibly additional light quark jets. To reduce multijet backgrounds, the W originating from the top quark is required to have decayed leptonically. This is achieved by demanding a high-energy electron or muon ($E_{\mathrm{T}}(e) > 20$ GeV, or $P_{\mathrm{T}}(\mu) > 20$ GeV/c) and large missing energy from the undetected neutrino $\not\!\!E_{\mathrm{T}} > 25$ GeV. The backgrounds surviving these selections are $t\bar{t}$, W+heavy flavor ($Wb\bar{b}$, $Wc\bar{c}$, Wc), and diboson WW, WZ, and ZZ. In addition, there is instrumental background from: "mis-tagged" events in which light flavor quarks are misidentified as heavy flavor jets, and "non-W" multijet events in which a jet is erroneously identified as a lepton. A large fraction of the $t\bar{t}$ and the non-top backgrounds is further removed by demanding exactly two jets with $E_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $|\eta| < 2.8$ be present in the event. At least one of the two tight jets should be tagged as a b-quark jet by using displaced vertex information from the silicon vertex detector.

TABLE I

Expected numbers of events, along with the observed event yields at CDF.

Process	$W+2$ jets prediction
t-channel	22.4 ± 3.6
s-channel	15.4 ± 2.2
$t\bar{t}$	58.4 ± 13.5
$Wb\bar{b}$	170.9 ± 50.7
$Wc\bar{c}$	63.5 ± 19.9
Wc	68.6 ± 19.0
$W+$ light flavor (mis-tags)	136.1 ± 19.7
Z+jets	11.9 ± 4.4
Diboson (WW, WZ, ZZ)	13.7 ± 1.9
non-W	26.2 ± 15.9
Total predicted	587.1 ± 96.6
Observed	644

[1] The results presented here are current as of June 2007; for the latest results from the CDF and DØ Collaborations we point the reader to Ref. [3].

The expected and observed event yields corresponding to the 1 fb^{-1} dataset are given in Table I.

An Artificial Neural Network (ANN) was developed to increase the b-quark purity of the sample selected by the standard $b-$tagging algorithm. This extended ANN tagger exploits mainly the long lifetime of b-hadrons, the high b-quark mass, and the high decay multiplicity. Fig. 1 shows good shape agreement between the ANN output distributions for the W+2 jet data and a sum of the individual background components normalized to data.

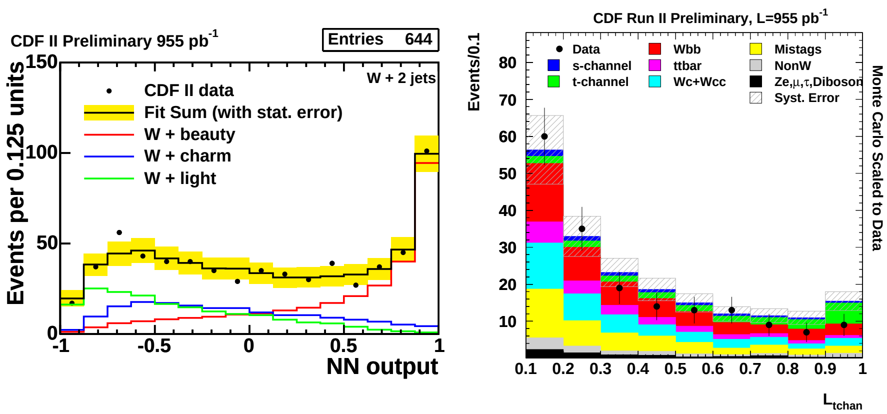

Fig. 1. Left: The ANN extended tagger output distributions for the CDF W+2 jets events (points) compared to the Monte Carlo expectations. Right: Likelihood function discriminant $\mathcal{L}_{\rm t-chan}$ for the CDF data (points) compared to the expected distribution for 1 fb^{-1}.

2.1. CDF multivariate likelihood function analysis

In this analysis, the event variables $(x_1, x_2, \ldots, x_{n_{\rm var}})$ are combined to construct the probability that a given candidate event originates from signal or background processes. The formula below is used to build likelihood function discriminants for s-channel and t-channel single-top:

$$\mathcal{L}(\{x_i\}) = \frac{\prod\limits_{i=1}^{n_{\rm var}} p_i^{\rm sig}}{\prod\limits_{i=1}^{n_{\rm var}} p_i^{\rm sig} + \prod\limits_{i=1}^{n_{\rm var}} p_i^{bkg}}\,, \qquad p_i^{\rm sig} = \frac{N_i^{\rm sig}}{N_i^{\rm sig} + N_i^{bkg}}\,. \tag{1}$$

The t-channel likelihood function is shown in Fig. 1. The data are more consistent with the background-only hypothesis, with a p-value [4] of 58.5% and the best fit for the s-channel and t-channel signal cross sections of $\sigma_t = 0.2^{+0.9}_{-0.2}$ pb and $\sigma_s = 0.1^{+0.7}_{-0.1}$ pb, respectively[2].

[2] The Standard Model predictions are $\sigma_t^{\rm SM} = 2.0$ pb, and $\sigma_s^{\rm SM} = 0.9$ pb, respectively.

2.2. CDF artificial neural networks analysis

For this analysis three ANN's are developed, two of which are trained to identify the individual s-channel and the t-channel single-top processes, while the third one is trained to identify the combined $s+t$ signal events. The three networks use the same input set of 23 event variables which are combined to form the three output discriminants $\mathcal{O}_t$, $\mathcal{O}_s$, and $\mathcal{O}_{s+t}$. The left plot of Fig. 2 shows the signal region of the $\mathcal{O}_{s+t}$ discriminant, in which a lack of candidate events is apparent. The fit to the data points yields a null result with a p-value of 54.6%, while the individual fits return: $\sigma_t = 0.2^{+1.1}_{-0.2}$ pb and $\sigma_s = 0.7^{+1.5}_{-0.7}$ pb, respectively.

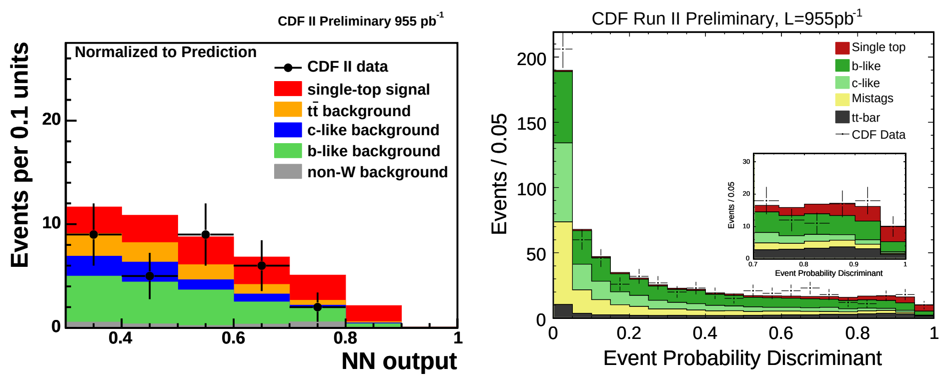

Fig. 2. Left: Data compared to Standard Model expectation in the signal region of the combined network output in the ANN search at CDF. Right: Event Probability Discriminant (EPD) distributions in the CDF matrix element analysis.

2.3. CDF matrix element analysis

In this technique, for every data and Monte Carlo event, the probabilities that the event originated from the signal or the different background processes are calculated [5]. The input to this analysis are the four-vectors of the measured jets and the charged lepton. The probability density results from the integration over the parton-level differential cross section which includes the matrix element from MadEvent [6], the parton distribution functions $f(x_i)$, and the detector resolutions parameterized by transfer functions $W(x,y)$. Assuming the lepton momenta and jet angles to be well-measured, the integration is performed over the quark energies and over the longitudinal component of the neutrino's momentum. With these probabilities in hand, we define:

$$\mathrm{EPD} = \frac{b\,P_{\mathrm{single-top}}}{b\,P_{\mathrm{single-top}} + b\,P_{Wbb} + (1-b)\,P_{Wcc} + (1-b)\,P_{Wcj}}\,, \tag{2}$$

where b is the ANN extended tagger output mapped to the (0,1) interval. The EPD distribution is shown in Fig. 2, and the corresponding p-value is 1% (2.3σ) providing a first hint of signal present in the CDF dataset. The best fit cross section is $\sigma_{s+t} = 2.7^{+1.5}_{-1.3}$ pb.

A calculation of the compatibility among the three CDF analyses yields a compatibility level of 1%. Extensive checks have revealed no source responsible for this low value, other than statistical fluctuations. This will be verified with the larger dataset of 2 fb^{-1} already accumulated by CDF.

3. DØ single-top searches

The event selection at DØ resembles that of CDF presented in the previous section, but additionally includes the 3 and 4 jet channels. The expected and observed contributions are given in Table II.

TABLE II

Expected numbers of events, along with the observed event yields in the DØ single-top analyses.

Source	2 jets	3 jets	4 jets
s-channel	16 ± 3	8 ± 2	2 ± 1
t-channel	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 (light flavor)	119 ± 25	43 ± 9	12 ± 2
Multijets (non-W)	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

3.1. DØ boosted decision tree (DT) analysis

This analysis incorporates the information from 49 event variables. Of these, the ones providing the most discrimination power are the invariant mass of all jets $M_{\rm jets}$, the invariant mass of the reconstructed W boson and the highest-$p_{\rm jT}$ b-tagged jet M_{Wb_1}, the angle between the highest-$p_{\rm jT}$ b-tagged jet and the charged lepton in the rest frame of the reconstructed top quark $\cos\theta(\ell b_1)_{\rm jtop}$, and the lepton charge times the pseudorapidity of the untagged jet $Q_\ell \times \eta_j$. Both separate and combined s- and t-channel searches are performed in each of the 12 channels (two lepton types, three jet bins, and two b-tag bins). Fig. 3 shows the high-discriminant region for the sum of all 12 combined search DT's. The measured cross section is $\sigma_{s+t} = 4.9 \pm 1.4\,\text{pb}$, and the corresponding significance is 3.4σ, which establishes the first evidence for the single-top process. This result is also used to set limits on the value of $|V_{tb}|$: $0.68 < |V_{tb}| \leq 1$ at 95% confidence level, assuming a pure $V{-}A$ and CP conserving Wtb interaction, and that $|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$. For a more in-depth discussion of this result we point the reader to the most recent DØ publication [1].

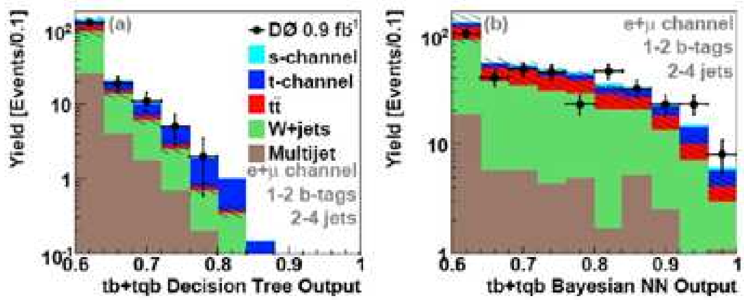

Fig. 3. Expected and observed output distributions for the DØ DT analysis (left) and the BNN analysis (right).

3.2. DØ bayesian neural network (BNN) analysis

In the BNN analysis, a neural network is trained for each of the 12 search channels, with each network using between 18 and 25 input variables. The BNN output approximates the discriminant:

$$D(x) = \frac{f(x|S)}{f(x|S) + f(x|B)}\,, \tag{3}$$

where $f(x|S)$ and $f(x|B)$ are the probability densities for signal and background, and x denotes the variables that characterize the event. The observed BNN output distribution summed over the 12 channels is shown in Fig. 3. The observed p-value of 0.08% for this analysis corresponds to a 3.1σ excess, while the measured cross section is $\sigma_{s+t} = 4.4^{+1.6}_{-1.4}$ pb.

3.3. DØ matrix element analysis

The matrix element technique used in the DØ single-top analysis uses the same general principles as described in the previous section, in addition including the W+3 jets channel. The $W + 4$ jets channel is not included. For any event in these channels, a t-channel and a s-channel discriminant are calculated. The bidimensional space defined by these two discriminants serves to extract the signal cross section of $\sigma_{s+t} = 4.8^{+1.6}_{-1.4}$ pb, assuming the Standard Model cross section ratio $\sigma_s/\sigma_t = 0.44$. The p-value of 0.08% corresponds to a 3.2σ excess.

In conclusion, all three DØ analyses establish evidence for the single-top process. The results are combined using the Best Linear Unbiased Estimate (BLUE) method [7]. The correlations between pairs of analyses range between 59% (ME-BNN), and 66% (DT-BNN). The measured cross section is $\sigma_{s+t} = 4.7 \pm 1.3$ pb with a significance of 3.6 standard deviations (Fig. 4).

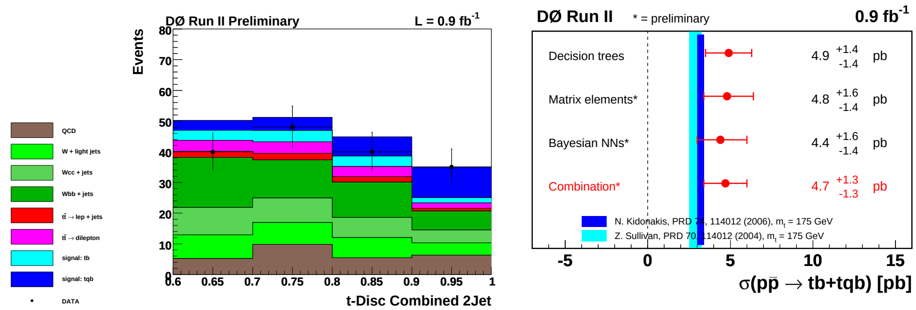

Fig. 4. Left: Expected and observed output distributions for the DØ ME analysis. Right: Summary of the measured cross section results at DØ, showing also the result from the BLUE combination technique.

4. Beyond the standard model single-top production

In addition to the Standard Model analyses, the CDF and DØ Collaborations have performed searches for single-top-quarks produced in exotic processes.

Recently, CDF has used the 1 fb^{-1} dataset to search for heavy W' bosons decaying to $t\bar{b}$ pairs using the standard single-top event selection and analyzing the invariant mass spectrum of the reconstructed W' boson $M(\ell\nu jj)$. No significant evidence for a signal is observed and W' bosons with SM-like couplings to fermions [8] are excluded at the 95% confidence level (C.L.): $M(W') > 760$ (790) GeV$/c^2$ in case the right neutrino mass is smaller (larger) than $M(W')$. These results extend the $W' \to t\bar{b}$ constraints previously set at the Tevatron [9].

The DØ Collaboration has published [10] results from a 230 pb^{-1} search for anomalous production of single-top-quarks via flavor-changing neutral current couplings of a gluon to the top quark and a charm or an up quark. No significant deviation from the Standard Model predictions is observed, and upper limits at 95% C.L. are set on the anomalous coupling parameters κ^c_g/Λ and κ^u_g/Λ, where Λ is the scale of new physics and the κ's are the strengths of the tcg and tug couplings: $\kappa^c_g/\Lambda < 0.15$ TeV^{-1} and $\kappa^u_g/\Lambda < 0.037$ TeV^{-1}.

5. Conclusions

We presented results from analyzing the 0.9–1 fb^{-1} Tevatron datasets accumulated by the CDF and the DØ experiments. The expected sensitivities range from 2.0σ–2.6σ, and 1.9σ–2.2σ for the three CDF and the three DØ analyses, respectively. The CDF matrix element analysis measures a 2.3σ signal excess over the background-only hypothesis, while the other two CDF analyses observe zero excess. All three DØ analyses establish evidence for single-top production, with the BLUE combination measuring a 3.6 standard deviations excess. The next goals of the Tevatron single-top program are the observation of the combined and individual single-top production channels, which will lead to greatly increased precision in the $|V_{tb}|$ determination. The searches for exotic phenomena producing single-top-quarks are in a mature stage and will continue to play an important role in testing the Standard Model boundaries at the Tevatron.

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