Search for single top production using multivariate analyses at CDF

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Abstract. This article reports on recent searches for single-top-quark production by the CDF collaboration at the Tevatron using a data set that corresponds to an integrated luminosity of $955\,\mathrm{pb}^{-1}$. Three different analyses techniques are employed, one using likelihood discriminants, one neural networks and one matrix elements. The sensitivity to single-top production at the rate predicted by the standard model ranges from 2.1 to $2.6\,\sigma$. While the first two analyses observe a deficit of single-top like events compared to the expectation, the matrix element method observes an excess corresponding to a background fluctuation of $2.3\,\sigma$. The null results of the likelihood and neural network analyses translate in upper limits on the cross section of 2.6 pb for the t-channel production mode and 3.7 pb for the s-channel mode at the 95% C.L. The matrix element result corresponds to a measurement of $2.7^{+1.5}_{-1.3}$ pb for the combined t- and s-channel single-top cross section.
In addition, CDF has searched for non-standard model production of single-top-quarks via the s-channel exchange of a heavy W' boson. No signal of this process is found resulting in lower mass limits of $760\,\mathrm{GeV}/c^2$ in case the mass of the right-handed neutrino is smaller than the mass of the right-handed W' or $790\,\mathrm{GeV}/c^2$ in the opposite case.

PACS. 14.65.Ha Top quarks – 12.15.Ji Applications of electroweak models to specific processes – 14.70.Fm W bosons – 12.60.Cn Extensions of electroweak gauge sector

1 Introduction

In $p\bar{p}$ collisions at the Tevatron top quarks are mainly produced in pairs via the strong force. However, the standard model also predicts the production of single top-quarks by the weak interaction via the s- or t-channel exchange of an off-shell W boson. While early Run II searches by the CDF and DØ collaborations, based on data sets corresponding to $162\,\mathrm{pb}^{-1}$, $230\,\mathrm{pb}^{-1}$ or $695\,\mathrm{pb}^{-1}$ of integrated luminosity, did not find evidence for single-top production [1,2,3], one of the latest DØ analyses [4] using data with $L_{\mathrm{int}} = 1\,\mathrm{fb}^{-1}$ observes an excess of single-top-like events of $3.4\,\sigma$.

The single-top production cross section is predicted to $\sigma_{\mathrm{s+t}} = 2.9 \pm 0.4\,\mathrm{pb}$ for a top quark mass of 175 GeV/c^2 [5] which is about 40% of the top-antitop pair production cross section. The precise measurement of the production cross section allows the direct extraction of the Cabbibo-Kobayashi-Maskawa matrix element $|V_{tb}|$. Moreover, the search for single top also probes exotic models beyond the Standard Model. New physics, like flavor-changing neutral currents or heavy W' bosons, could alter the observed production rate [6].

The main obstacle in finding single-top is however not the production rate of the signal but the large background rate. After all selection requirements are imposed, the signal to background ratio is approximately 1/16. This challenging, background-dominated dataset is the main motivation for using multivariate techniques.

Furthermore, single-top analyses are an important stepping stone for the Higgs boson search in the WH channel, since the two processes have the same experimental signature. Understanding the background rates and background composition in the W+jets sample using single-top techniques will be a prerequisite for a successful WH analysis.

2 Standard Model Searches

In this article we present three new CDF searches for standard model single-top production and one new search for a W' boson decaying into $t\bar{b}$. All four analyses are based on the same event selection and use the same Run II data set corresponding to an integrated luminosity of $955\,\mathrm{pb}^{-1}$. 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 multi-jet backgrounds, the W originating from the top quark is required to have decayed leptonically. One therefore demands a single, isolated high-energy electron or muon ($E_T(e) > 20$ GeV, or $P_T(\mu) > 20$ GeV$/c$) and

Table 1. Expected number of signal and background events and total number of events observed in 955 pb^{-1} in the CDF single-top dataset.

Process	N events	Process	N events
$W + b\bar{b}$	170.9 ± 50.7	non-W	26.2 ± 15.9
$W + c\bar{c}$	63.5 ± 19.9	$t\bar{t}$	58.4 ± 13.5
Wc	68.6 ± 19.0	Diboson	13.7 ± 1.9
Mistags	136.1 ± 19.7	Z + jets	11.9 ± 4.4
Total background		549.3 ± 95.2	
t-channel	22.4 ± 3.6	s-channel	15.4 ± 2.2
Total prediction		587.1 ± 96.6	
Observed		644	

large missing transverse energy from the undetected neutrino $\not\!\!E_{\mathrm{T}}$>25 GeV. Electrons are measured in the central and in the forward calorimeter, $|\eta| < 2.0$. To further suppress events in which no real W boson is produced, called non-W background, additional cuts are applied. The cuts are based on the assumption that these events do not produce $\not\!\!E_{\mathrm{T}}$ by nature but due to lost or mismeasured jets. Therefore, one would expect small $\not\!\!E_{\mathrm{T}}$ and small values of the angle $\Delta\phi$ between $\not\!\!E_{\mathrm{T}}$ and a jet. We further reject dilepton events from Z decays by requiring the dilepton mass to be outside the range: 76 GeV/c^2 < $M_{\ell\ell}$ < 106 GeV/c^2.

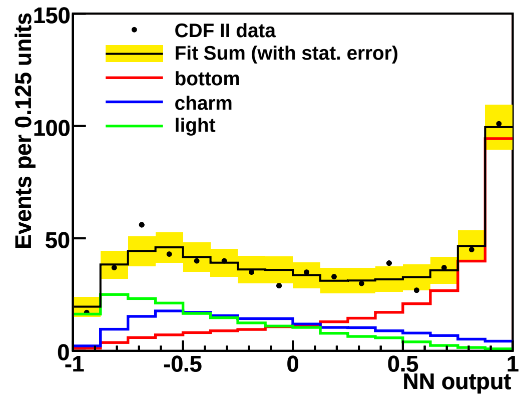
The remaining backgrounds belong to the following categories: $Wb\bar{b}$, $Wc\bar{c}$, Wc, mistags (light quarks misidentified as heavy flavor jets), non-W and diboson WW, WZ, and ZZ. We remove a large fraction of the backgrounds by demanding exactly two jets with $E_T > 15$ GeV and $|\eta| < 2.8$ be present in the event. At least one of these two jets should be tagged as a b quark jet by using displaced vertex information from the silicon vertex detector (SVX). The numbers of expected and observed events are listed in table 1.

2.1 Likelihood Discriminant Analysis

One multi-variate analysis uses likelihood discriminants to combine several variables to a discriminant to separate single-top events from background events. One likelihood discriminant is defined for the t-channel, one for the s-channel search. Seven or six variables are used, respectively. The likelihood functions are constructed by first forming histograms of each variable. The histograms are produced separately for signal and several background processes. The histograms are normalized such that the sum of their bin contents equals 1. For one variable the different processes are combined by computing the ratio of signal and the sum of the background histograms. These ratios are multiplicatively combined to form the likelihood discriminant.

One of the variables used in the analysis is the output of a neural net b tagger. In figure 1a the distribution of this b tag variable is shown for the 644 data events. In case of double-tagged events the leading b jet (highest in E_T) is included in this distribution. The neural net b tagger gives an additional han-

(a)



(b)

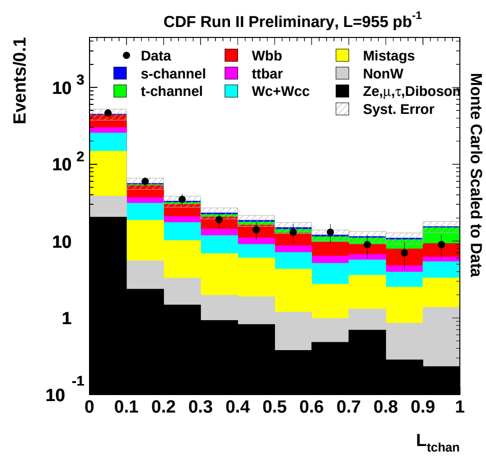


Fig. 1. (a) Output distribution of the neural net b tagger for 644 candidate events in the W+2 jets bin. Overlayed are the fitted components of beauty-like, charm-like and mistag templates The yellow error band indicates the statistical uncertainties of the fitted sum. (b) The distributions of the t-channel likelihood function for CDF data compared to the Monte Carlo distribution normalized to the expected contributions. A logarithmic scale is used.

dle to reduce the large background components where no real b quarks are contained, mistags and charm-backgrounds. Both of them amount to about 50% in the $W + 2$ jets data sample even after imposing the requirement that one jet is identified by the secondary vertex tagger of CDF [7].

The t-channel likelihood function is shown in figure 1b. The best sensitivity (expected p-value 2.5%) is reached by combining the two likelihood discriminants in a two-dimensional fit where t-channel and s-channel are considered as one single-top signal (combined search). The observed data show no indication of a single-top signal and are compatible with a background-only hypothesis (p-value 58.5%). The upper limit on the combined single-top cross section is found to be 2.7 pb at the 95% C.L., while the expected limit is 2.9 pb. The best fit for the cross sections yields $\sigma_t = 0.2^{+0.9}_{-0.2}$ pb and $\sigma_s = 0.1^{+0.7}_{-0.1}$ pb.

2.2 Neural Network Search

In the second analysis a neural network is used to combine 23 kinematic or event shape variables to a powerful discriminant. The output is given between -1 for background-like events and +1 for signal-like events. The five most important input variables are reported by the neural network package. They are: the output of the jet-flavor separator neural network, $M_{l\nu b}$, the dijet mass, η of the untagged jet times the charge of the isolated lepton and the multiplicity of soft jets in the event with 8 GeV ¡ E_T ¡ 15 GeV. Figure 2a shows the observed data for the combined search compared to the expectation in the signal region defined by a neural network output between 0.3 and 1. In the combined search where the ratio of t-channel and s-channel cross sections is fixed to the standard model value a p-value of 54.6% is observed, providing no evidence for single-top production. The corresponding upper limit on the cross section is 2.6 pb at the 95% C.L.. To separate t- and s-channel production two additional networks are trained and a simultaneous fit to both discriminants is performed. The best fit values are $\sigma_t = 0.2^{+1.1}_{-0.2}$ pb for the t-channel and $\sigma_s = 0.7^{+1.5}_{-0.7}$ pb. The corresponding upper limits are 2.6 pb and 3.7 pb, respectively. The observed p-value is 21.9%.

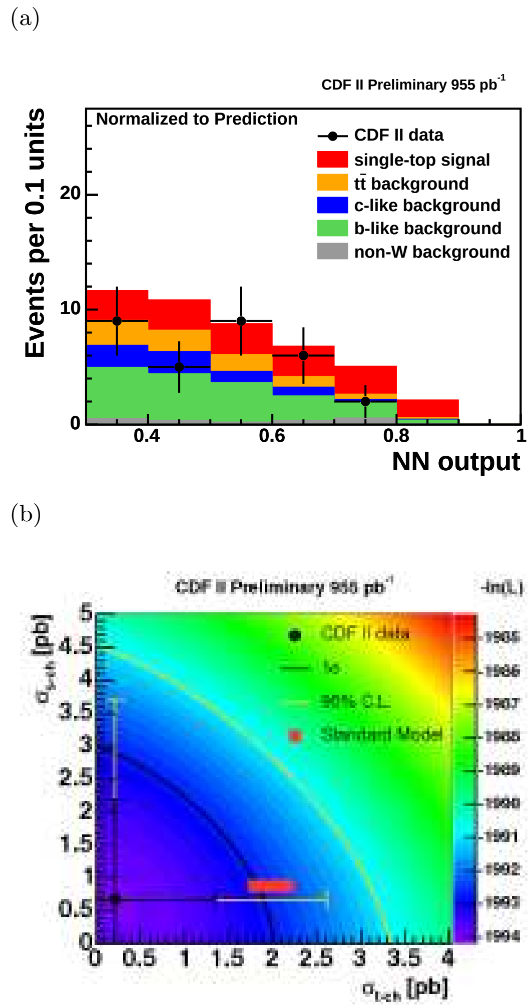


Fig. 2. Single-top search with neural networks at CDF: (a) Data compared to the standard model expectation in the signal region (neural network outputs larger than 0.3). (b) Likelihood contours of the separate neural network search.

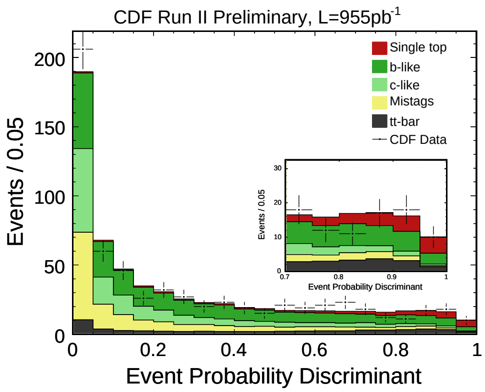
2.3 Matrix Element Analysis

Another way to discriminate signal from background is to compute leading order matrix elements for signal and background processes. The measured four-vectors of the jets and the charged lepton are used as experimental input to compute event-by-event probability densities. Constraints on energy and momentum conservation are applied. The jet energy measurements are corrected to parton level energies using transfer functions. To obtain a relative weight for a certain hypothesis one integrates over jet energies and the momenta of the incoming partons using the parton density functions as integration kernel. The weights for the individual hypotheses are combined event-by-event by forming a ratio signal and signal-plus-background weights. The resulting discriminant is named event probability density (EPD). The measured EPD distribution is shown in figure 3, compared to the fitted event rates for the different processes. A single-top signal corresponding to a 2.3 σ excess is observed. The associated single-top cross section is $2.7^{+1.5}_{-1.3}$ pb.

3 Search for a W' boson

Based on a the same event selection as the standard model searches CDF has also searched for a W' boson in the decay channel, $W' \rightarrow t\bar{b}$ that appear in models with left-right symmetry, extra dimensions, Little Higgs, and topcolor [8]. The signal is modeled using the event generator PYTHIA [9]. The invariant mass of the charged lepton, the reconstructed neutrino and the two leading jets is used as a discriminant. The measured data are shown in comparison to the standard model prediction in figure 3b. No evidence for a resonant W' boson production is found, yielding limits on the production cross section ranging from 2.3 pb at $M(W') = 300$ GeV to 0.4 pb at $M(W') = 950$ GeV. Utilizing theoretical cross section calculations [8], lower limits on the W' mass are set: $M(W') > 760$ GeV if the mass of potential right-handed neutrinos is below $M(W')$ and $M(W') > 790$ GeV otherwise.

(a)



(b)

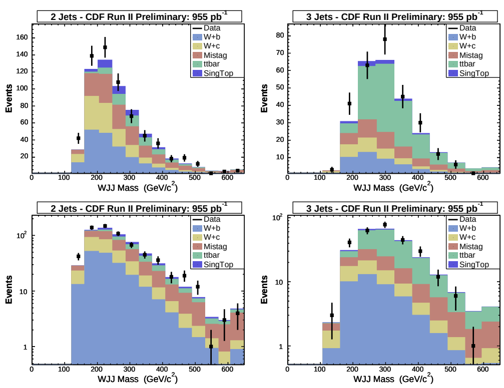


Fig. 3. (a) Event probability density (EPD) based on matrix elements. The inset shows the signal region with EPD > 0.7. (b) $W' \rightarrow t\bar{b}$ search: The invariant mass of the charged lepton, the reconstructed neutrino and the two leading jets.

4 Conclusions

The collaboration has performed searches for standard and non-standard model single-top production using a data set corresponding to an integrated luminosity of $955\,\text{pb}^{-1}$. No evidence for these processes could be established. Two standard model searches based on likelihood discriminants or neural networks find no excess which can be attributed to single-top production, while the matrix element analysis finds an excess of $2.3\,\sigma$ compatible with single-top production. The overall consistency of all there analysis is only 1%, since the analyses feature a correlation between 60% and 70%. At present, there are no hints to other causes than statistical fluctuations. Recent measurements utilizing the matrix element method and likelihood discriminant using 1.5 fb^{-1} show a 3 σ evidence for single top production.

The W' search in the single-top channel establishes new upper limits of $M(W') > 760\,\text{GeV}$ or $M(W') > 790\,\text{GeV}$ depending on the mass of the right-handed neutrino.

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