CDF/ANAL/TOP/PUB/8272

Measurement of the $t\bar{t}$ Production Cross Section in SecVtx- and Neural Network-Tagged Lepton+Jets Events

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: May 19, 2006)

We present a measurement of the $p\bar{p} \to t\bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV in the lepton + jets channel using data corresponding to 695 pb^{-1} of integrated luminosity. We require at least one secondary vertex (SecVtx) tag passing a neural network b-tagger and at least three tight jets. In this manner, we measure a cross section of $8.5 \pm 0.6(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})\ \mathrm{pb}^{-1}$.

I. INTRODUCTION

At the Tevatron, protons and antiprotons collide at a center-of-mass energy of 1.96 TeV. The $t\bar{t}$ pair production cross section at such energies is a basic measurement offering insight into top quark physics in the context of QCD. Theoretical calculations predict a $t\bar{t}$ production cross section of $6.7^{+0.9}_{-0.7}\,\mathrm{pb}^{-1}$ [1] for a top quark mass of 175 GeV/c^2. A significant deviation from the predicted value would be an indication of new physics in either the top quark production or decay.

This measurement follows a previous investigation [2] measuring $t\bar{t}$ production using data in the lepton + jets channel with b-tagging via the Secondary Vertex Tagging algorithm (SecVtx). In this analysis, a neural network b-tagger vets the events after application of SecVtx to reduce background, yielding a consistent measurement.

II. DATA SAMPLE & EVENT SELECTION

This measurement uses current high-E_T lepton data samples comprising an integrated luminosity of $695\,\mathrm{pb}^{-1}$, collected between March 2002 and September 2005. The data are collected with the inclusive high-E_T electron and muon triggers, which select leptons above 18 GeV in the central part of the CDF detector. The CDF detector is described in Ref. [3].

Events are required to have an isolated electron ($E_T > 20$ GeV) or muon ($p_T > 20$ GeV) and $\not\!\!E_T > 20$ GeV. Jets reconstructed with a cone of central angle 0.4 are counted only if $E_T > 15\,\mathrm{GeV}$ and $|\eta| < 2$. We further require at least one jet have a secondary vertex tag, with a significant positive decay length, which passes the neural network b-tagger.

A. Secondary Vertex Tagging Algorithm

The SecVtx algorithm relies on the displacement of the secondary vertex relative to the primary event vertex to identify B hadron decays [4]. The primary event vertex is reconstructed for every event with a typical precision of 10-20 μm for $t\bar{t}$ events. Secondary vertex tagging operates on a per-jet basis, where only tracks within the jet cone are considered for b-tagging. Displaced tracks in the jet are selected based on the significance of their impact parameters (d_0) with respect to the primary vertex and are used as input to the algorithm. The algorithm uses a two-pass approach to find secondary vertices: a first pass with loose impact parameter requirements, and a second pass with tighter requirements.

Once a secondary vertex is found, the two-dimensional decay length of the secondary vertex L_{2D} is calculated as the projection onto the jet axis, in the plane transverse to the beam only, of the vector pointing from the primary vertex to the secondary vertex. The sign of L_{2D} is given by the ϕ difference between the jet axis and the secondary vertex vector (positive for $< 90^\circ$, negative for $> 90^\circ$). The secondary vertices corresponding to the decay of b and c hadrons are expected to have large positive L_{2D} while the secondary vertices from a random set of mis-measured tracks are expected to peak around $L_{2D} = 0$. A jet is said to be positively tagged if the significance $L_{2D}/\sigma_{L_{2D}} > 7.5$, and negatively tagged if $L_{2D}/\sigma_{L_{2D}} < -7.5$. Positively tagged jets have a high purity of of heavy flavor jets and are identified as such, while negatively tagged jets are mostly light jets; we use negative tags to estimate the rate of positive mistags.

B. Neural Network b-Tagging Algorithm

The neural network b-tagger relies on eight parameters from the SecVtx tag, and eight general kinematic parameters. The tagger consists of two neural networks: one trained to distinguish bottom jets from light flavor jets, the other, bottom from charm. They are both trained with $t\bar{t}$ Monte Carlo samples. Both were developed using the back-propagation algorithm with one output node, one hidden layer of ten or twelve nodes (for the b-l network and b-c network respectively), using the JETNET package [5]. The output plots for these neural networks are shown in Figures 1 and 2. The tagger subjects a jet to one threshold cut in each of the networks, which the user selects. In this case, the cuts are set so that 90% of SecVtx-tagged b jets are retained, while 65% of light jets and 51% of charm jets are rejected.

The neural network b-tagger is validated through a series of checks with data and Monte Carlo. Inclusive electron samples, which provide very pure bottom jet data, are used to compare b efficiency in the data and Monte Carlo. The Monte Carlo b's survive slightly more often, yielding a data:Monte Carlo scale factor of 0.970 $\pm$ 0.02. Hence, the neural network b-tagger contributes a systematic uncertainty of 2% in addition to that of SecVtx. Similarly, the rejection of light jets is studied from inclusive jet samples. Positive and negative SecVtx-tagged light jets from data and Monte Carlo are confirmed to have consistent rejection rates.

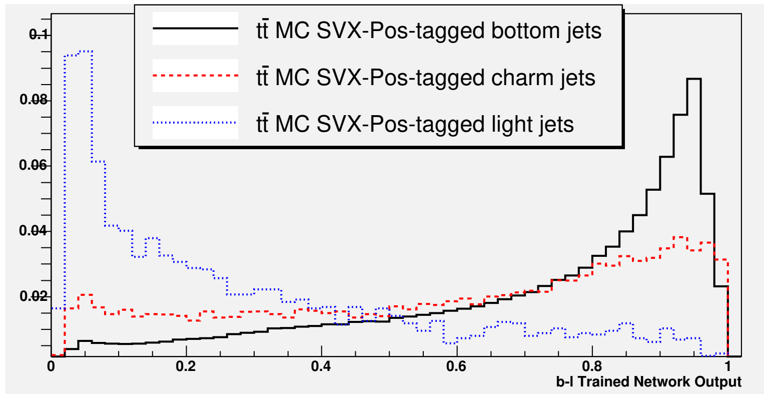

FIG. 1: Output distributions for bottom, charm and light jets from $t\bar{t}$ Monte Carlo samples. The neural network was trained to separate bottom and light jets.

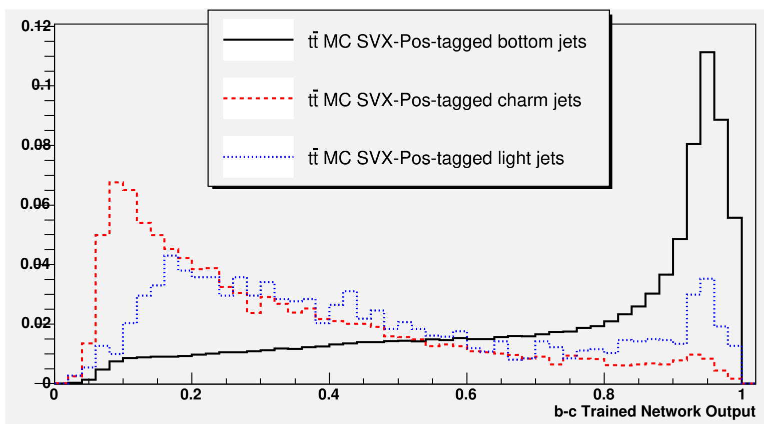

FIG. 2: Output distributions for bottom, charm and light jets from $t\bar{t}$ Monte Carlo samples. The neural network was trained to separate bottom and charm jets.

C. Total $t\bar{t}$ Acceptance

The acceptance is defined as the fraction of produced $t\bar{t}$ events that are actually observed. The total acceptance is calculated from of data and Monte Carlo, as a product the efficiencies of various quality cuts, including the neural network b-tagger. The geometric multiplied by kinematic acceptance of the basic lepton+jets event selection is measured using the Pythia Monte Carlo program [6]. The efficiency for identifying the isolated, high-p_T lepton is scaled to the value measured in the data using the unbiased leg in Z-boson decays. The geometric multiplied by kinematic acceptance, as a function of the number of identified jets above 15 GeV, is shown in Table I. The acceptance differs by lepton type: CEM (central electrons), CMUP (muons with pseudo-rapidity range $|\eta| < 0.6$), and CMX (muons with pseudo-rapidity range $0.6 < |\eta| < 1.1$. The efficiency to tag at least one jet in a $t\bar{t}$ event is 59.7% averaged over all lepton types.

To measure the efficiency for tagging heavy flavor hadrons with SecVtx, we use a control sample of di-jet events in which one of the jets contains a low-p_T electron. This sample is rich in semileptonic decays of bottom and charm hadrons. We measure the efficiency independently in data and simulation, and we find that the ratio of efficiencies (the SecVtx b-tagging efficiency scale factor) is $\epsilon_{\rm data}/\epsilon_{\rm MC} = 0.898 \pm 0.075$. This scale factor is applied to the tagging efficiency determined from the Pythia simulated events. On top of this scale factor and efficiency are those of the neural net b-tagging described in Section II B (90% acceptance factor and 0.97 $\pm$ 0.02 data:Monte Carlo scale factor).

	CEM	CMUP	CMX
Average Tag Eff (%)	59.7±0.0862±3.69		
Average NN Tag Eff (%)	52.9±0.0864±3.46		
Acc. with tag (%)	2.25±0.007±0.186	1.2±0.00481±0.10	0.553±0.00319±0.046511
Acc. no tag (%)	$7.596^{+0.260}_{-0.254}$		
Total Acc. (%)	4±0.00908±0.329		
Luminosity	695±40.3	695±40.3	681±39.5
Denominator	15.6±0.0486±1.58	8.33±0.0334±0.848	3.77±0.0218±0.385
Total Denominator	27.7±0.0629±2.79		

TABLE I: Summary table of $t\bar{t}$ acceptance.

III. BACKGROUNDS

The dominant background for this analysis is production of W boson plus multi-jet events. Unfortunately, theoretical predictions of the W+jets cross section suffer from large uncertainties; we thus rely partially on the data for an absolute normalization. These events enter the signal sample when one of the jets is a heavy flavor jet, or when a light quark jet is mistagged as a heavy flavor jet. Mistags are estimated by parameterizing the rate of negative tags in a control sample as a function of relevant jet and event variables (number of tracks in the jet, jet E_T, η and ϕ of the jet, and sum of the E_T for all jets in the event with $E_T > 10$ GeV and $|\eta| < 2.4$). To first order negative tags are representative of positive mistags since mistags are mostly due to symmetric resolution effects; however, the presence of heavy flavor negative tags, long-lived particles, and nuclear interactions with the detector material contribute asymmetrically to the mistags. We find that the negative tag rates must be corrected by a scaling factor 1.37 ± 0.15 in order to match the positive mistag rate. The positive mistags pass the neural network b-tagger at a $65 \pm 5\%$ rate, the negative, $67 \pm 3\%$; these predicted tagging rates are then applied to the pretag sample. In order to evaluate the background due to W+ heavy flavor, we use ALPGEN+HERWIG Monte Carlo models to estimate the fraction of the inclusive W+jets events which are $Wb\bar{b}$, $Wc\bar{c}$, or Wc, and multiply that fraction by the number of observed W events in the pretag data sample after correcting for QCD and other backgrounds [7, 8]. By using the Monte Carlo only for the fraction of W events with heavy flavor, uncertainties in the MC due to Q^2 scale and NLO contributions are greatly reduced.

The other substantial background in this analysis comes from events without W bosons. These events are typically QCD multi-jet events where one jet has faked a high-p_T lepton, and miss-measured energies produce apparent missing E_T. SecVtx-tagged b-jet associated with this pass the neural net b-tagger 74±2% of the time. We measure this “non-W” QCD background by extrapolating the number of SecVtx-tagged events with an isolated lepton and low missing E_T, passing the neural networks, into the signal region of large missing E_T.

Other small backgrounds from a variety of sources are estimated using events generated with Monte Carlo programs and normalized to the Standard Model cross sections. The predictions for all backgrounds as a function of jet multiplicity are summarized in Table III.

IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis come from Monte Carlo modeling of the geometrical and kinematic acceptance, knowledge of the secondary vertex and neural network tagging efficiencies, the effect on the acceptance of the uncertainty on the jet energy scale, uncertainties on the background predictions, and the uncertainty on the luminosity.

Monte Carlo modeling of geometrical and kinematic acceptance include effects of PDFs, ISR and FSR, and jet energy scale. These are estimated by comparing different choices for PDFs and varying ISR, FSR and the jet energy scale in the Monte Carlo. Finally, the modeling of the lepton ID efficiency in events with multiple jets is an additional source of systematic uncertainty on the acceptance. We use a data to Monte Carlo scale factor taken from inclusive Z data and Monte Carlo, which is dominated by events with no jets. A 2% systematic uncertainty on this scale factor is estimated by convoluting the scale factor measured as a function of ΔR between the lepton and the nearest jet with the ΔR distribution of leptons in $\geq$3 jet $t\bar{t}$ events. The effect of the systematic uncertainties on the cross section measurement are summarized in Table II.

Source	Uncertainty (%)
SecVtx b-tagging	6.5
luminosity	6.0
jet energy scale	3.0
Monte Carlo generator	2.5
lepton identification	2.0
neural network b-tagging	2.0
initial/final state radiation	1.3
parton distribution functions	0.5
Total	11.0

TABLE II: Summary of systematic uncertainties.

V. RESULTS

Table III shows a summary of the background and top estimates for each jet bin and the number of observed, tagged events. These estimates include the statistical and systematic uncertainties on the background predictions. We have also corrected for the non-negligible $t\bar{t}$ contribution to the pretag W+jets sample. Figure 3 shows the signal and background abundances per jet multiplicity after application of neural network b-tagging.

Njets	1 jet	2 jets	3 jets	$\geq$ 4 jets
Pretag	68183	10647	1713	468
Mistag	100.1±20.6	41.7±8.6	12.3±2.5	3.0±0.6
$Wb\bar{b}$	179.2±55.4	100.4±29.7	22.1±5.8	4.1±1.1
$Wc\bar{c}$	37.3±10.7	28.2±8.5	5.6±1.7	1.12±0.35
Wc	137.4±34.6	26.6±6.8	2.7±0.7	0.4±0.1
Single Top	13.0±1.3	20.7±2.1	4.5±0.5	0.79±0.09
Diboson	7.3±1.2	11.9±1.9	3.0±0.5	0.81±0.15
Non-W(QCD)	59.6±10.0	29.5±5.1	8.8±1.7	3.96±0.85
Total Bkg	533.9±79.2	259.2±41.0	58.9±8.2	14.2±1.9
Top	6.6±0.9	48.1±6.7	105.2±14.7	130.2±18.2
Top + Bkg	540.5 ± 79.2	307.3 ± 41.5	164.1 ± 16.8	144.4 ± 18.3
Data	623	332	166	145

TABLE III: Number of tagged events, top and the background summary, after Neural network cuts.

We calculate the $t\bar{t}$ production cross section, $\sigma_{t\bar{t}}$, as:

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{\epsilon_{t\bar{t}} \times \int \mathcal{L} dt} \quad (1)$$

where N_{obs} is the number of events with $\geq$ 3 tight jets that are tagged with at least 1 b-tag, N_{bkg} is the corrected background and $\epsilon_{t\bar{t}}$ is the total acceptance (geometrical times kinematic times tagging efficiency), taken from Tables I and III. For $t\bar{t}$ events in the tagged sample of W+3 or more jets, we find a cross section of $8.5 \pm 0.6 \pm 1.0\,\mathrm{pb}^{-1}$, where the first uncertainty is statistical and the second is systematic. This result assumes a top quark mass of $175\,\mathrm{GeV}/c^2$. Compare this to the complimentary measurement without the neural network, which is consistent at $8.2 \pm 0.6 \pm 1.0$ pb^{-1} [2].

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und

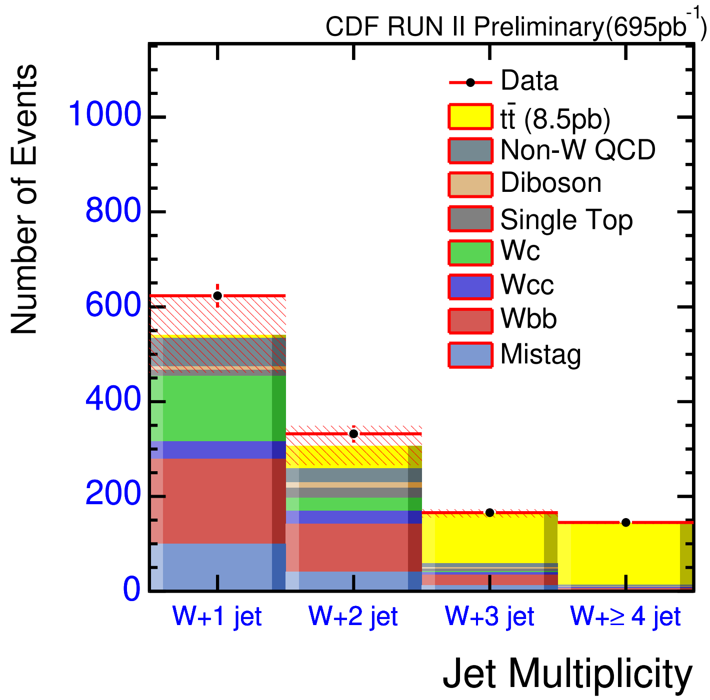

FIG. 3: Observed tagged events as a function of jet multiplicity, The colored histogram represents the background contributions to each bin. (The pretag sample has been corrected for $t\bar{t}$ contribution.)

Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

---

[1] M. Cacciari, et al., JHEP **404**, 68 (2004).
[2] CDF Collaboration, Public Note 8110 (2006).
[3] F. Abe, et al., Nucl. Instrum. Methods Phys. Res. A **271**, 387 (1988); D. Amidei, et al., Nucl. Instum. Methods Phys. Res. A **350**, 73 (1994); F. Abe, et al., Phys. Rev. D **52**, 4784 (1995); P. Azzi, et al., Nucl. Instrum. Methods Phys. Res. A **360**, 137 (1995); The CDFII Detector Technical Design Report, Fermilab-Pub-96/390-E
[4] D. Acosta et al. (CDF Collaboration), Phys. Rev. **D71**, 052003 (2005).
[5] C. Peterson et al., Comput. Phys. Commun. **81**, 185 (1994).
[6] T. Sjostrand et al., Comput. Phys. Commun. **135**, 238 (2001).
[7] G. Corcella et al., JHEP **01**, 10 (2001).
[8] M.L. Mangano et al., JHEP **0307**, 001 (2003).