CDF/PUB/ANAL/CDFR/9676
February 2, 2009

Measurement of the $t\bar{t} + jet$ Cross Section

Thomas Schwarz Andrew Ivanov Robin Erbacher
University Of California-Davis

Joey Huston Mohammad Hussein
Michigan State University

Gene Flanagan
Purdue University

Steve Mrenna
Fermi National Laboratory

Abstract

We've performed the first measurement of the cross section of $t\bar{t}$ with an additional hard jet. The measurement is performed in the lepton + jets channel using SecVtx tagged events. Backgrounds are estimated using "Method II". A 2D Likelihood is formed to simultaneously measure $t\bar{t} + j$ and $t\bar{t} + 0j$. The measured results are $\sigma_{t\bar{t}+j} = 1.3 \pm 0.3_{stat} \pm 0.5_{syst} \pm 0.1_{lumi}$ pb and $\sigma_{t\bar{t}+0j} = 5.9 \pm 0.5_{stat} \pm 0.7_{syst} \pm 0.4_{lumi}$ pb. The result is consistent with recent NLO QCD calculations $\sigma_{t\bar{t}+j} \approx 1 - 2$ pb.

Contents

1 Introduction

Top physics plays an important role both at the Tevatron and at the LHC. The top quark is by far the heaviest elementary fermion in the Standard Model and may have a role in electroweak symmetry breaking. There may be deviations from pointlike behavior for the top quark leading to the presence of anomalous couplings, and in particular to anomalous couplings to the gluon. Such anomalous couplings of the gluon may manifest themselves in deviations from the pQCD predictions for jets accompanying the top-antitop pair.

The $t\bar{t}$ + jet cross section has never been explicitly measured at the Tevatron, although a sizeable fraction of $t\bar{t}$ events at the Tevatron are accompanied by an additional jet . The theoretical cross section has been known to leading order in the QCD coupling constant for many years, and has recently been calculated to next-to-leading order (NLO) [1]. The NLO calculation results in a significant decrease in the theoretical uncertainty; that, in conjunction with the large integrated luminosity accumulated by CDF allows for a precision comparison of data to theory to be performed for the first time. Such a comparison is interesting in its own right, but also as a preview of the LHC, where, due to the production of the top quark pairs by low x gluons, essentially every $t\bar{t}$ event contains an additional jet, and $t\bar{t}$ + jet(s) events form a background to many important signatures for possible new physics [2].

The NLO calculation of the $t\bar{t}$ + jet cross section is perhaps the most difficult pQCD calculation performed to date. There is significant complexity due to the fact that: (1) all of the partons are colored, (2) there is an additional mass scale given by the top quark mass, (3) the infrared structure is complex, (4) there are many diagrams, leading to large expressions and (5) the presence of 1-loop pentagon diagrams. This calculation is also an important component for the calculation of the inclusive $t\bar{t}$ cross section to NNLO. If we consider jet production with a threshold of 20 GeV/c, then there are two very different “reasonable scales that can be used in the calculation: the top mass and the tranverse momentum of the jet. At LO, the disparity in these two scales leads to a large disparity in the size of the predicted cross section. This scale uncertainty is greatly reduced at NLO.

The measurement of the $t\bar{t}$ asymmetry in inclusive events in CDF has resulted in a great deal of interest from the theoretical community, due to the larger than expected value observed. Given the possible importance of this result, it is crucial to understand as many aspects of the $t\bar{t}$ production as possible. The asymmetry for inclusive $t\bar{t}$ production appears only at the 1-loop level, and thus a NLO calculation for the inclusive cross section provides only a LO calculation of the asymmetry. On the other hand, an asymmetry (of the opposite sign as that for the inclusive case, and thus nominally a dilution of this asymmetry), is present at LO for $t\bar{t}$ + jet production; thus the NLO calculation for this cross section is truly a NLO calculation for the $t\bar{t}$ + jet asymmetry. It is somewhat surprising that the 1-loop corrections to this process greatly reduce the size of the asymmetry and is worth investigating experimentally.

2 Event Selection

Baseline selection for this analysis is the standard lepton plus jets selection as documented in [5] and [6]. We also apply a slightly tighter $\not\!\!E_T$ cut and an additional H_t cut to reduce background dependence and improve systematics. In particular:

- Tight electron or muon with $E_t > 20$ GeV (CEM, CMUP, CMX)
- At least 3 Tight Jets L5 corrected $E_t > 20$ GeV and $\eta < 2.0$
- $\not\!\!E_T > 25$ GeV
- $H_t > 230$ GeV
- > 1 Tight SecVtx Tagged Jet

3 Defining $t\bar{t}$+j Events

We are interested in measuring the cross section for $t\bar{t}$ + jet(s) production, where the extra jet(s) is produced by radiation off of either the initial state partons or the final state top quarks. It is also possible for gluon radiation to occur from the decay products of the t or $\bar{t}$, but as those emissions are not accounted for in the NLO calculation to which we are comparing (the top quarks are stable), we need to remove those jets from consideration. We wrote a Monte Carlo module which removes all partons that can be directly associated with the decay products of the $t\bar{t}$ system, using the truth information in the Pythia event record. The remaining partons are then clustered using the SpartyJet framework [3]. If a jet passes our transverse momentum threshold (20 GeV to match reference [1]) , then it is counted as an additional jet in the $t\bar{t}$ system. $t\bar{t}$ + jet events, in the lepton + jets final state, may manifest with 3,4,5 or even 6 jets in the final state, depending on the kinematic and acceptance cuts applied, and the presence of additional radiation from the top quark decay products. By implementing the Pythia module described above into the Method 2 framework, we are able to distinguish the number of $t\bar{t}$ + jet events, with the extra jet produced by radiation from the initial or final state, in our lepton + jets sample.

4 Top Acceptance and Tagging Efficiency

Pre-tag acceptance and tagging efficiencies are estimated using a Pythia Monte Carlo. All datasets and Monte Carlo models are listed in the appendix. Detector level effects are corrected by applying lepton scale factors and trigger efficiencies from the Joint Physics Group [7]. The pretag acceptance is simply:

$$A = \frac{N_{selected}}{N_{generated}} \tag{1}$$

The tagging selection efficiency is more complicated. Because Monte Carlo simulations do not model tagging correctly, a tagging scale factor and mistag matrix must be integrated into the tagging efficiency calculation [9]. The tagging scale factor accounts for the fact that Monte Carlo over-estimates the tagging efficiency of jets originating from heavy flavor quarks. The mistag matrix corrects the Monte Carlo for an under-estimate of the number of mis-tagged light flavor jets. Each event is then weighted by a probability of the event being tagged as opposed to using the Monte Carlo to count tags. The probability that an event is tagged is:

$$P_{event}^{tag} = 1 - \prod_{i}^{jets} (1 - p_{tag}^{i}) \tag{2}$$

For jets matched to heavy flavor p_{tag}^{jet} is the tagging scale factor if tagged and zero if not tagged. If the jet is matched to light flavor p_{tag}^{jet} is the mistag probability. The calculation of the tagging efficiency is shown in equation 3.

$$\epsilon = \frac{\sum_{j}^{events} P_{j}^{tag}}{N_{pretag}} \tag{3}$$

The calculation for the tagging efficiency for double tags is performed with the same methodology only the combinatorics is slightly more complicated. Tables 1 and 4 show the top monte carlo acceptance and tagging efficiencies for events with an additional hard jet and without.

Trigger	3 Jets	4 Jets	5 Jets
CEM	1.8%	1.8%	0.3%
CMUP	1.1%	1.1%	0.2%
CMX	0.5%	0.5%	0.1%
Total	3.4%	3.4%	0.6%

Table 1: $t\bar{t}$ Predicted Pre-tag Acceptance for $t\bar{t} + 0j$

Trigger	3 Jets	4 Jets	5 Jets
CEM	1.1%	1.9%	2.0%
CMUP	0.7%	1.2%	1.3%
CMX	0.3%	0.5%	0.5%
Total	2.1%	3.6%	3.8%

Table 2: $t\bar{t}$ Predicted Pre-tag Acceptance for $t\bar{t} + j$

Trigger	3 Jets	4 Jets	5 Jets
CEM	58%	63%	63%
CMUP	57%	62%	62%
CMX	58%	63%	64%
Total	58%	63%	63%

Table 3: $t\bar{t}$ Predicted Tagging Efficiency for $t\bar{t} + 0j$

Trigger	3 Jets	4 Jets	5 Jets
CEM	54%	59%	62%
CMUP	53%	58%	62%
CMX	55%	60%	63%
Total	54%	59%	62%

Table 4: $t\bar{t}$ Predicted Tagging Efficiency for $t\bar{t} + j$

5 Background Estimate

Estimating the background content in tagged lepton plus jets events is infamously referred to as Method II, which is well documented in [5] [6]. We will not go into great detail here, other then a short description along with any relevant quantitative information.

Method II is basically a way to handle inadequacies in the Monte Carlo to model heavy flavor associated with the production of a W boson and tagging of bottom jets. The technique is sequential in that each step depends on the previous. The final result is a complete prediction for the process content in the lepton plus jets data sample. In the following we will go step by step through the procedure.

5.1 Monte Carlo Based Backgrounds

A few of the backgrounds which are considered a small contribution to the overall process content and $t\bar{t}$ (which is an important point as we will discuss later) are calculated based on Monte Carlo efficiencies. Several electroweak processes contribute to the lepton plus jets sample such as WW, WZ, ZZ, and Z $\rightarrow$ *jets* events. They exist in the sample because each process can produce a real lepton and neutrino, as well as a number of jets. The numbers in our sample are estimated using the theoretical cross section, the luminosity of the sample, trigger efficiency, and an overall selection efficiency derived from Monte Carlo simulation of the processes in question. Theoretical cross sections for these processes are shown in Table 5. The calculated number in our sample is given by

Process	Cross Section
$t\bar{t}$+0j	5.5 ± 1.0 pb
$t\bar{t}$+j	1.5 ± 1.0 pb
Single Top - t Channel	1.98 ± 0.08 pb
Single Top - s Channel	0.88 ± 0.05 pb
WW	12.4 ± 0.25 pb
WZ	3.96 ± 0.06 pb
ZZ	1.58 ± 0.02 pb
Z→ *Jets*	787.4 ± 50 pb

Table 5: Theoretical Cross Sections For MC-Based Backgrounds

$$N_{p\bar{p}\to X} = \sigma_{p\bar{p}\to X} \cdot A \cdot \int dt \cdot \mathcal{L} \tag{4}$$

$$N^{tag}_{p\bar{p}\to X} = \sigma_{p\bar{p}\to X} \cdot A \cdot \epsilon \cdot \int dt \cdot \mathcal{L} \tag{5}$$

where $\sigma_{p\bar{p}\to X}$ is the theoretical cross section, $\int dt \cdot \mathcal{L}$ is the total luminosity, A is the pre-tagged selection acceptance derived from Monte Carlo, and ϵ is the tagged selection efficiency. As for top, the acceptance and tagging efficiencies are corrected for trigger efficiencies and tagging. Table 5 shows the cross-section and uncertainties used in the background estimate along with their uncertainties [10].

5.2 Non-W Based Background Estimate

To determine the non-W fraction in both the pretag and tagged sample, we fit the $\not\!\!E_T$ distribution of a non-W template and a MC signal template to data as described in [11]. The non-W template used is the antielectron sample [12].

The pretag non-W fraction is essential to the rest of *method 2*, since it provides the starting point for the heavy flavor fraction and mistag estimate. To perform the fit in the pretag sample, we take the $\not\!\!E_T$ distribution of W+jets MC events as the template for signal. For the non-W template we use the anti-electron sample.

Both templates are fitted to the $\not\!\!E_T$ distribution of isolated pretag data events using a binned likelihood fitter. The results of the fits for this analysis are shown in Figures **??** to **??** in the appendix. Once the fraction is calculated the normalization is simply:

$$N^{pretag}_{QCD} = F_{QCD} \cdot N_{pretag} \tag{6}$$

For the tagged event non-W fraction we again use anti-electrons though weighted by the tagging rate (SF and mistag rate). The tagged qcd fraction is performed only after all other normalizations are obtained from Method II, which are then constrained

Trigger	3 Jets	4 Jets	5 Jets
CEM	33%	21%	17%
CMUP	6%	3%	5%
CMX	7%	3%	5%

Table 6: Fitted pretag QCD fraction

Trigger	3 Jets	4 Jets	5 Jets
CEM	17%	6%	6%
CMUP	4%	0%	1%
CMX	7%	0%	0%

Table 7: Fitted tag QCD fraction

in the fit. Only QCD and W+jets are allowed to float, though W+HF and mistags are fixed within the W+jets shape. Once the fraction is calculated the normalization is simply:

$$N_{QCD}^{tag} = F_{QCD} \cdot N_{tag} \tag{7}$$

A 30% uncertainty is taken on the QCD fraction which is derived from a stress test on the fits and using non-iso and jet electron models in place of anti-electrons. Tables 6 and 7 show the QCD fraction results for the pretag and tag case.

5.3 W + Heavy Flavor

In the pretag data sample, W plus jets is the dumping ground for all events that are not considered QCD, electroweak, or top. The W plus jets normalization is calculated by subtracting the MC-based processes and the QCD from data as shown in equation 8.

$$N_{W\,+\,Jets}^{pretag} = N_{pretag} \cdot (1 - F_{QCD}^{pretag}) - N_{ewk}^{pretag} - N_{top}^{pretag} \tag{8}$$

For the tagged estimate, the W plus jets sample is broken down into two categories: heavy and light flavor. Each of these processes produces a tagged jet very differently and therefore requires different treatment in calculating the normalization.

The contribution of the heavy flavor background to our signal region is calculated by equation 9.

$$N_{W+hf}^{tag} = (N_{pretag}(1 - F_{QCD}) - N_{EW} - N_{singletop} - N_{t\bar{t}}) \cdot f_{HF} \cdot K \cdot \epsilon \tag{9}$$

The number of events predicted in QCD, Electroweak, singletop, and $t\bar{t}$ is subtracted from the pretag sample, leaving an estimate for the number of events with a W-boson. The fraction of these events with jets matched to heavy flavor quarks, f_{HF},

	Jet 1	Jet 2	Jet 3	Jet 4	Jet 5
F_{HF}^{1b}	0.75	1.56	2.57	3.37	3.97
F_{HF}^{2b}	0.00	0.94	1.88	3.01	4.36
F_{HF}^{1c}	5.98	9.57	11.71	12.56	12.66
F_{HF}^{2c}	0.00	1.55	3.43	5.73	8.08

Table 8: Heavy Flavor Fractions For W plus Jets

	Jet 1	Jet 2	Jet 3	Jet 4	Jet 5
ϵ_{1b}	30.8	33.2	35.1	36.4	40.6
ϵ_{2b}	0.00	54.5	56.1	56.7	57.1
ϵ_{1c}	6.9	8.2	9.4	11.0	13.3
ϵ_{2c}	0.00	13.6	14.9	16.8	18.3

Table 9: Tagging Efficiencies For W plus Heavy Flavor Events Where 1 or 2 Jets Are Matched to a Bottom or Charm

is calculated from a detailed Monte Carlo simulation Alpgen [14], which includes all possible processes contributing to the production of a single real W-boson. This fraction is corrected by a scale factor, K, which is a correction to the Monte Carlo heavy flavor fraction. The K-factor is calculated in the 1 jet bin and applied to the rest of the sample. ϵ is the tagging efficiency. f_{HF} and ϵ are calculated for $Wb\bar{b}$, $Wc\bar{c}$, and Wc separately, which define the rates for each of these processes. Only the heavy flavor fraction relies on Monte Carlo, the absolute normalization is derived from the pretag sample in data. The uncorrected heavy flavor fractions and tagging efficiencies for this analysis are shown in Tables 8 and 9. The K-factor is derived by a Neural Network fit to variables sensitive to jets matched to heavy flavor and light flavor. This procedure is described in the next section.

5.4 K-Factor

The calculation of the K-factor is performed by a neural network trained to separate heavy from light flavor jets [13]. This is done in the W+1 jet and W+2 jet bins. We assume the K-factor then applies to the signal region ≥ 3 jets. The calculation for this measurment is documented in cdf note 9403 and 9187 [18] [17]. The K-factor used for this analysis is $KF = 1.5 \pm 0.3_{stat+sys}$.

5.5 Mistags

A secondary vertex is mistakenly reconstructed when poorly reconstructed tracks seem to cross each other near the origin. A secondary vertex that does not originate from heavy flavor quarks is called a mistag.

Trigger	1jet	2jets	3jets	4jets	5jets
CEM	76.9 ± 7.1	118.0 ± 14.1	76.5 ± 9.9	33.9 ± 4.5	11.5 ± 1.5
CMUP	33.8 ± 3.1	51.1 ± 6.1	31.5 ± 4.1	17.1 ± 2.3	4.5 ± 0.6
CMX	22.1 ± 2.0	29.0 ± 3.5	17.8 ± 2.4	7.6 ± 1.0	3.1 ± 0.4
Total	132.7 ± 12.2	198.0 ± 23.7	125.8 ± 16.4	58.6 ± 7.8	19.1 ± 2.5

Table 10: Predicted Number of Raw Mis-tagged Events In Pretag Data

The negative tag rate is found to be well parametrized by five jet variables (jet E_t, number of good SVX tracks, sum of all jet E_t in the event, jet η, jet ϕ) and measured in a very high statistics sample derived from triggers on 50 GeV jets [15]. In any subsequent analysis this parametrization then gives the probability that a jet with given values of the tag parametrization variables will be negatively tagged. The negative tag probability of an event is taken to be the sum of the probabilities of all the jets in the event. Studies in large control samples derived from jet triggers with different energy thresholds (20 GeV, 75 GeV, 100 GeV) show good agreement between the prediction and the actual number of negative tags. Corrections are applied to the mistag matrix for heavy flavor present among the mistags and an asymmetry between the number of negative and positive tags ($\alpha\beta$ corrections).

This technique is applied to estimate the number of events in our sample due to mistags in W + light flavor events. The predicted number of background events from W + light flavor (W+lf) processes is:

$$N_{W+lf}^{tag} = \frac{N_-}{N_{pre}} \cdot (N_{pre} - N_{pre}^{t\bar{t}} - N_{pre}^{QCD} - N_{pre}^{W+hf} - N_{pre}^{EW} - N_{pre}^{singletop}) \qquad (10)$$

Whre N_- is the predicted number of mistags in the event. The predicted amount of $t\bar{t}$, QCD, W+hf, Electroweak, and single top background events is subtracted from the total pretag sample leaving an estimate for the W+lf fraction. The predicted number of mistagged W+lf events is the W+lf fraction multiplied by the predicted amount of mis-tagged events (with $\alpha\beta$ corrections) from the pretag data. The predicted number of raw (without corrections for other process dependence) mis-tagged events extracted from our pretag data is shown in Table 10.

5.6 Full Background Prediction

The following is the background estimate used in our top cross section measurement utilizing 3.0 fb^{-1} of collected data. Inclusive trigger tables for ≥ 1 Tags are shown in Table 11. All tables for each trigger and all the gritty details of the pretag and before MET cut values are shown in the appendix.

Process	1jet	2jets	3jets	4jets	5jets
Pretag Events	4109	4958	2871	1295	376
Wbb	27.7 ± 8.6	85.7 ± 26.4	62.9 ± 19.5	23.7 ± 8.4	5.8 ± 4.6
Wcc	14.1 ± 4.5	36.7 ± 11.5	30.0 ± 9.5	12.4 ± 4.5	3.2 ± 2.5
Wc	17.5 ± 5.5	34.4 ± 10.8	18.9 ± 6.0	6.0 ± 2.2	1.2 ± 1.0
Mistags	65.3 ± 7.2	85.4 ± 12.3	46.7 ± 8.0	14.1 ± 5.1	3.0 ± 4.3
Non-W	27.0 ± 8.6	53.3 ± 16.0	25.7 ± 8.1	6.5 ± 5.7	2.2 ± 2.5
WW	1.7 ± 0.2	8.9 ± 1.1	6.9 ± 0.9	2.9 ± 0.4	0.9 ± 0.1
WZ	0.6 ± 0.1	3.1 ± 0.4	2.2 ± 0.3	0.9 ± 0.1	0.3 ± 0.0
ZZ	0.0 ± 0.0	0.3 ± 0.0	0.4 ± 0.1	0.2 ± 0.0	0.1 ± 0.0
Z+jets	2.4 ± 0.3	6.7 ± 0.8	5.9 ± 0.7	2.3 ± 0.3	0.7 ± 0.1
Single Top (S-Channel)	0.7 ± 0.1	15.7 ± 1.5	9.0 ± 0.9	2.6 ± 0.3	0.6 ± 0.1
Single Top (T-Channel)	0.2 ± 0.0	14.6 ± 1.3	9.0 ± 0.8	2.6 ± 0.2	0.4 ± 0.0
$t\bar{t} + 0j$	6.1 ± 1.1	101.7 ± 18.7	299.6 ± 55.0	319.5 ± 58.6	61.6 ± 11.3
$t\bar{t} + j$	0.3 ± 0.2	6.9 ± 5.3	36.4 ± 28.1	70.6 ± 54.6	79.8 ± 61.7
Total Prediction	163.8 ± 21.5	453.3 ± 56.4	553.8 ± 73.3	464.3 ± 83.3	159.8 ± 63.6
Observed	167	449	550	464	159

Table 11: Background Normalizations for ≥ 1 Tag, ≥ 250 GeV, and $\not\!\!E_T$ 25 GeV

6 Calculating the Cross-section

With the background estimate in hand it we now perform a simultaneous measurement of the tt+0j and tt+j cross section. Because the background estimate is dependent on the top cross-section, extracting the measured value is not so simple. Instead, we construct a poisson likelihood where we take into account the background dependence. To extract the measured values we construct a 2D likelihood from the data and prediction for events with three, four, or five jets.

$$P_i = \frac{\lambda_i^{k_i} \cdot e^{-\lambda_i}}{k_i!} \tag{11}$$

where k is the number of events in data with "i" jets, and λ is the predicted number of events with "i" jets. More specifically:

$$\lambda = A_{0j} \cdot \epsilon_{0j} \cdot \mathcal{L} \cdot \sigma_{t\bar{t}}^{0j} + A_{+j} \cdot \epsilon_{+j} \cdot \mathcal{L} \cdot \sigma_{t\bar{t}}^{+j} + Bkg(\sigma_{t\bar{t}}^{0j}, \sigma_{t\bar{t}}^{+j}) \tag{12}$$

A_x is the acceptance, ϵ is the tagging efficiency, $\mathcal{L}$ is the luminosity, and Bkg is the predicted background. The likelihood is then:

$$L = -ln(P_3 \cdot P_4 \cdot P_5) \tag{13}$$

The likelihood is calculated for several values of the cross-section and the resulting points are fit to a two-dimensional second order polynomial. The minimum of this curve is taken as the measured value. The result for our optimized selection, $H_t \geq 230$

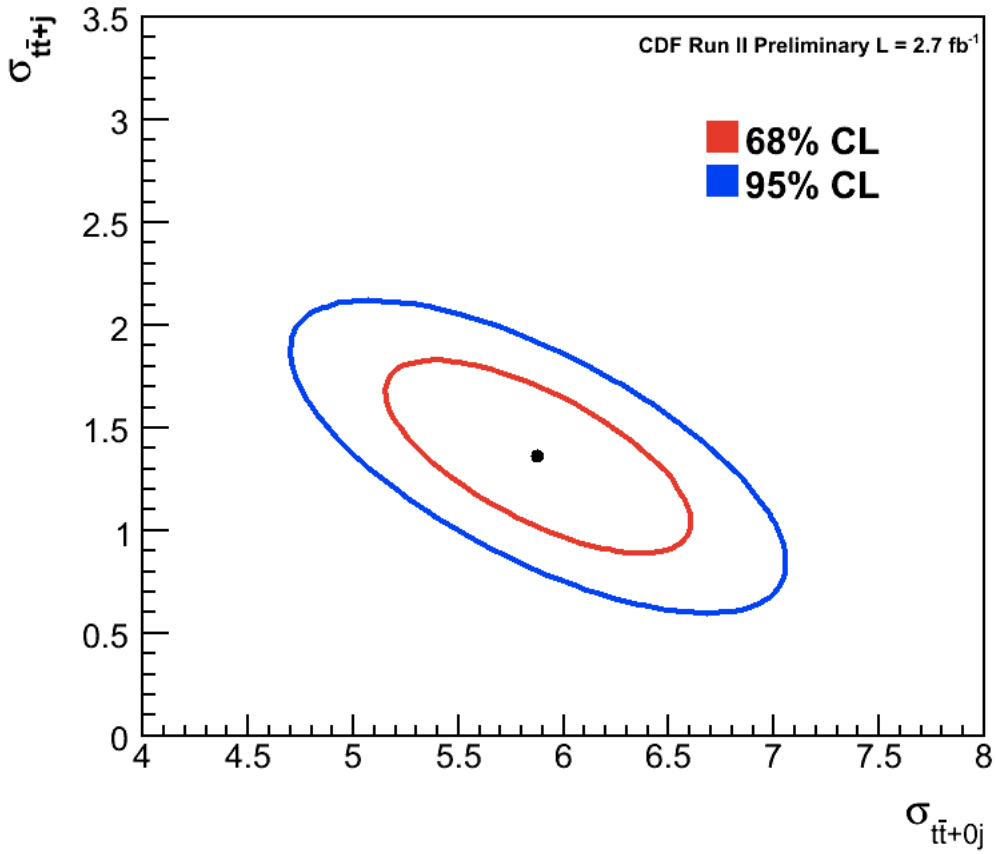

Figure 1: Likelihood Curve For Measured $t\bar{t}+0j$ and $t\bar{t}+j$ Cross-Section

GeV and $\not\!\!E_T \geq 25$ GeV, is shown in Figure 1. The measured values with statistical uncertainty are:

$$\sigma_{t\bar{t}+0j} = 5.9 \pm 0.5_{stat} \;\; pb \tag{14}$$

$$\sigma_{t\bar{t}+j} = 1.3 \pm 0.3_{stat} \;\; pb \tag{15}$$

7 Systematics

Systematic uncertainties in our measure result are calculated by varying a given parameter within it's uncertainty and redoing the entire measurement. Each systematic is described below along with any relevant quantities. The individual evaluated systematic uncertainties are shown in Tables 12 and 13 at the end of the section.

7.1 JES

The energy of jets measured by the calorimeters is subject to multiple systematic uncertainties which are best described by the Jet Energy and Resolution Group [8]. We study the effect on the measurement by varying the JES for our top signal Monte Carlo and background models and then re-performing the measurement. The effect of JES on this measurement is mainly through the acceptance of signal and background. For $t\bar{t}+j$ events, this is by far the largest systematic uncertainty, on the order of statistics. It's not hard to understand why given how drastically it changes the acceptance for events with $+j$.

7.2 ISR/FSR

An interesting aspect of this measurement is that in a way it's a measure of ISR. Because of this, we do not include this effect as a systematic, rather we cross check that our result is invariant to using a Monte Carlo sample where ISR/FSR have been increased. Unfortunately, the FSR effect, which would be a true systematic is present in this cross-check, but we assume the effect is quite small (based on previous x-section measurements).

7.3 Tagging

Because MC does not model SecVtx tagging properly, a scale factor is applied to each tagged jet matched to heavy flavor, and the corresponding event then re-weighted. The scale factor is derived from data and has an uncertainty associate with it which leads to a systematic on the measurement. For "tight" tagged jets matched to bottom quarks the tagging scale factor is 0.95 ± 0.04. The same scale factor is applied to jets matched to charm, though the statistical uncertainty is doubled. The effect on the measured value is calculated by fluctuating the scale factor within it's uncertainty, applying it to each appropriate jet, calculating the new event weights, and repeating the measurement.

7.4 Mistag Matrix

Mistags are so badly modeled in Monte Carlo that we scrap any mis-tagged jet and use a data-based parameterization called the mistag matrix to predict the probability that any given jet is mis-tagged. The uncertainty on any given rate is on the order of 20% (from $\alpha\beta$ corrections) and is taken as a systematic uncertainty on the measurement. The mistag rate on any jet fluctuated by 20% up(down) and the entire measurement is repeated to quantify the effect.

7.5 QCD Fractions

To estimate the uncertainty on the QCD fraction, fits are performed with different binning and different models (non-isolated leptons and jet electrons). The resulting difference in the fits is 30% which is taken as a systematic uncertainty in the measurement.

7.6 K-Factor

The correction to the heavy flavor fractions has an uncertainty derived from the Neural Network fits in the 1 and 2 jet bin as well as the fits to bottom and charm separately. We used $k_{factor} = 1.5 \pm 0.3$ for this measurement.

7.7 MC Generator

Differences in Monte Carlo models for parton showering are studied simply by replacing our $t\bar{t}$ pythia model with the other most popular generator, Herwig, and repeating the measurement. Herwig is separated into $t\bar{t} + 0j$ and $t\bar{t} + j$ events exactly as pythia is and the measurement was repeated.

7.8 Lepton ID

Detector specific corrections are applied to the Monte Carlo to more correctly model the relative trigger efficiencies between CEM, CMUP, and CMX events. The corrections are data-derived from Z events and have a small uncertainty associated with them. There are two types of corrections, trigger ID and trigger efficiencies. Each are fluctuated with their uncertainty, separately, and the resulting errors are added in quadrature.

7.9 PDF

Uncertainty in the parton distribution function are evaluated by a re-weighting scheme at the Monte Carlo Truth level. PDF's are reweighted in our signal Monte Carlo to simulate 46 different PDF parameterizations. The measurement is performed for each different parameterization. A prescription for evaluating the uncertainty derived from the result of this is documented here [16].

7.10 Luminosity

The uncertainty on our calculated luminosity is unfortunately also our largest systematic, which is derived from the CLC accuracy and the uncertainty on the theoretical cross section for inelastic $p\bar{p}$ collisions. The uncertainty on the luminosity is 5.8%. The luminosity used in the measurement is fluctuated within this uncertainty and the measurement redone.

Systematic	$\Delta\sigma$	$\Delta\sigma/\sigma$
JES	0.24	4.0%
BTag SF	0.33	5.6
C Tag SF	0.10	1.5
Mistag Matrix	0.17	2.9
K Factor	0.31	5.1
Luminosity	0.37	6.0
QCD Fraction	0.03	0.4
MC Generator	X	X
CEM SF	0.02	0.4
CMUP SF	0.02	0.4
CMX SF	0.02	0.3
PDF	0.06	1.0
Total	0.65	11.0 %

Table 12: Systematic Uncertainties for $t\bar{t} + 0j$

Systematic	$\Delta\sigma$	$\Delta\sigma/\sigma$
JES	0.46	35.7 %
BTag SF	0.05	3.7
C Tag SF	0.01	0.4
Mistag Matrix	0.01	0.8
K Factor	0.03	2.6
Luminosity	0.08	5.8
QCD Fraction	0.03	1.8
MC Generator	X	X
CEM SF	0.01	0.4
CMUP SF	0.01	0.4
CMX SF	$<$0.01	0.3
PDF	0.01	1.0
Total	0.47	36.5%

Table 13: Systematic Uncertainties for $t\bar{t} + j$

8 Result

The first measured cross section of $t\bar{t}$ in association with a hard jet is:

$$\sigma_{t\bar{t}+j} = 1.3 \pm 0.3_{stat} \pm 0.5_{syst} \pm 0.1_{lumi} \;\; pb \tag{16}$$

which is in agreement with the Stadard Model prediction 1.0 to 2.0 pb from reference [1]. The measured cross section for $t\bar{t}$ without additional radiation is:

$$\sigma_{t\bar{t}+0j} = 5.9 \pm 0.5_{stat} \pm 0.7_{syst} \pm 0.4_{lumi} \;\; pb \tag{17}$$

which when combined with $\sigma_{t\bar{t}+j}$ gives the inclusive cross-section:

$$\sigma_{t\bar{t}} = 7.2 \pm 0.4_{stat} \;\; pb \tag{18}$$

Again, in agreement with the Standard Model prediction at $M_t = 175$ GeV of 6.7pb.

References

[1] S. Dittmaier, P.Uwer, and S.Weinzierl, "Hadronic top-quark pair production in association with a hard jet at next-to-leading order QCD: Phenomenological studies for the Tevatron and the LHC", arXiv:0810.0452 [hep-ph].

[2] J.M.Campbell, J.W.Huston and W.J.Stirling, "Hard interactions of quarks and gluons: A primer for LHC physics", arXiv:hep-ph/0611148.

[3] http://www.pa.msu.edu/~huston/SpartyJet/SpartyJet.html

[4] Franklin, Grinstein, Guimaraes da Costa, Sherman, CDF Note 8767

[5] Adelman et al , CDF Note 9185

[6] Franklin et al, CDF note 8766

[7] http://www-cdf.fnal.gov/internal/physics/joint_physics/

[8] http://www-cdf.fnal.gov/internal/physics/top/jets/corrections.html

[9] http://www-cdf.fnal.gov/internal/physics/top/RunIIBtag/bTag.html

[10] S.Edielman et al., "Review of Particle Physics", Phys. Lett. B 592, 1 (2004).

[11] S. Budd et al., Estimation and modeling of non-W background for single-top searches, CDF note no. 8489.

[12] B. Cooper, A. Messina, Estimation of the Background to W + n Jet Events, CDF note no. 6636.

[13] S. Richter et al, A Neural Network b Tagger for Single-Top Analyses, CDF 7816 T. Chwalek et al., Update of the Neural Network b Tagger for Single-Top Analyses, CDF note no. 8903.

[14] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A. Polosa, "ALPGEN, a generator for hard multiparton processes in hadronic collisions", JHEP 0307:001,2003, hep-ph/0206293.

[15] S.Grinstein and D.Sherman, CDF Note 8910: SecVtx Scale Factors and Mistag Matrix for the 2007 Summer Conferences

[16] http://www-cdf.fnal.gov/internal/physics/joint_physics/instructions/PDFUncertainties/pdf.html

[17] Amidei et al, CDF Note 9187

[18] Ivanov, Schwarz, Erbacher, CDF Note 9403

A Datasets and Monte Carlo Models

Table 14: Datasets

Dataset ID	Trigger	Run Range
bhel0d	CEM	138425-186598
bhmu0d	CMUP, CMX	138425-186598
bhel0h	CEM	190697-203799
bhmu0h	CMUP, CMX	190697-203799
bhel0i	CEM	203819-228596
bhmu0i	CMUP, CMX	203819-228596
bhel0j	CEM	228664-241664
bhmu0j	CMUP, CMX	228664-241664
bhel0k	CEM	241665-261005
bhmu0k	CMUP, CMX	241665-261005
bhel0m	CEM	261119-264071
bhmu0m	CMUP, CMX	261119-264071

Table 15: Background And Signal Models

Process	Dataset ID	Type
$t\bar{t}$	ttop75	Pythia
$t\bar{t}$	otop1s	Herwig
QCD	bhelX	Fake Electrons
Wbb	btopXw,dtopXw	Alpgen
Wcc	ctopXw,etopwX	Alpgen
Wc	stopwX	Alpgen
Wlf	ptopXw, utopXw	Alpgen
WW/WZ/ZZ	itopww, itopwz, itopzz	Pythia
Single Top - S	stop00	MadEvt/Pythia
Single Top - T	stop0m	MadEvt/Pythia
Zbb	ztopbX	Alpgen
Zcc	ztopcX	Alpgen
Zlf	ztoppX	Alpgen