Top Production Cross Sections at CDF

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This contribution presents some of the most recent and most precise determinations of the top pair and single top production cross sections from the CDF collaboration. The top pair cross section is measured in events with dilepton and lepton+jets final states using an integrated luminosity of 2.8 fb^{-1}. The combined result is $\sigma(p\bar{p} \to t\bar{t}) = 7.0 \pm 0.6$ pb for a top mass of 175 GeV/c^2, with the total relative uncertainty below 10%. All top pair cross section measurements are consistent with each other and with theoretical predictions. The single top cross section is measured in events with $\not\!\!E_T$ + jets in the final state (with and without an energetic charged lepton) using an integrated luminosity of 3.2 fb^{-1}. Sophisticated multivariate techniques are needed to discriminate the single top signal from the overwhelming backgrounds. For a top mass of 175 GeV/c^2, the combined single top cross section is determined to be $2.3^{+0.6}_{-0.5}$ pb, with a statistical significance of 5 standard deviations.

1 Introduction

The top quark is the heaviest known fundamental particle. Its Yukawa coupling to the Standard Model (SM) Higgs is roughly one, and therefore top might play a special role in electroweak symmetry breaking. Because of its large mass, radiative corrections to other SM observables are dominated by loops involving top. At the Tevatron, top is mainly produced in $t\bar{t}$ pairs via the strong interaction in quark-antiquark annihilation and gluon-gluon fusion. Single top production has a smaller cross section and involves electroweak production of a top quark via the Wtb vertex by a t or s channel exchange of a virtual W boson. Once produced, it decays virtually 100% of the time into a W and a b, $t \to Wb$. The top lifetime is so short that it decays before it has time to hadronize. The final state therefore depends on the disintegration mode of the W bosons and has jets from the hadronization of b quarks.

Measuring the $t\bar{t}$ production cross section in different channels is an important test of perturbative QCD predictions. In addition, the cross section analysis establish a baseline for top quark samples which are used to study other top properties such as the mass, and to estimate top related backgrounds, which are important in many searches for physics beyond the SM. Single top production is interesting because it probes the Wtb electroweak vertex, allowing a direct measurement of the V_{tb} CKM matrix element which is poorly constrained by other measurements. Contributions from processes beyond the SM such as W' or charged Higgs would enhance the single top cross section, so an anomalous cross section would be indicative of physics beyond the SM. In addition, the measurement of the single top cross section is a benchmark to the WH Higgs search, since both processes share final state and dominant backgrounds.

The slides for the presentation corresponding to this contribution can be found in the conference web page [1].

2 Top pair cross section

Since top production has a small cross section [2] and the backgrounds are typically larger, an optimized event selection is required to obtain a data sample with good S/B, and a precise determination of the dominant backgrounds and of the overall signal acceptance is also needed. CDF measures the top cross section in different channels according to the W decay modes. The most precise determinations come from events where at least one W decays to a charged lepton and a neutrino.

Figure 1 (left) shows the signal and background contributions as a function of jet multiplicity for the "dilepton" $t\bar{t}$ sample, where both W bosons decay into electron or muon. The event selection requires two isolated, energetic, oppositely charged electrons or muons with at least one energetic, central jet and with large $\not{E}_T$ from the undetected neutrinos. The one jet bin, where one expects little top contribution, is used as a control region, and the cross section is measured in the bin with ≥ 2 jets, where most of the top signal is expected. The measured cross section is $\sigma_{t\bar{t}} = 6.7 \pm 0.8(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{lumi})$ pb, with a total relative uncertainty 14.6%. The dominant backgrounds are diboson production, Drell-Yan and QCD (direct jet production) events where jets are wrongly identified as leptons. This channel has the advantage of good S/B but suffers from the small branching ration of both W bosons decaying to e or μ, and in fact the statistical uncertainty dominates.

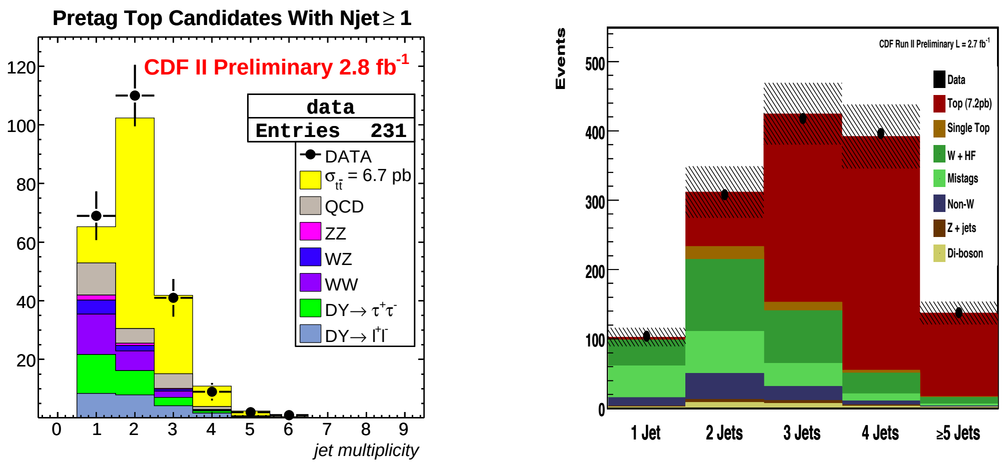

Figure 1: Summary of backgrounds and signal as a function of jet multiplicity for $t\bar{t}$ cross section measurements in the dilepton channel (left) and in the lepton+jets channel with b tagging (right). The low jet multiplicity bins are used as control regions and the cross section is measured in the large jet multiplicity bins, with large $t\bar{t}$ acceptance.

Figure 1 (right) shows the signal and background contributions for the "lepton+jet" $t\bar{t}$ sample, where one W decays into electron or muon and the other to quarks (resulting in more jests in the final state). In order to enhance the top to background ratio, events are required to have at least one b-tagged jet, and the H_T, the scalar sum of all jets, identified leptons and $\not{E}_T$ is required to be large. The one and two jet bins are used as control regions and the cross section is measured in the three, four and ≥ 5 jet bins. The measured cross section is

$\sigma_{t\bar{t}} = 7.1 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.4(\text{lumi})$ pb, with a total relative uncertainty of 11.6%. The dominant sources of background are W bosons produced in association with heavy flavor, W events where a light jet is mistaged as a b-jet, and QCD. The largest uncertainties come from the luminosity normalization, the uncertainty on the b-tagging efficiency ratio between data and Monte Carlo, and the uncertainty on the W + heavy flavor Monte Carlo correction.

In order to reduce the luminosity uncertainty, CDF measures the ratio of top to Z cross sections, $R = \sigma_{t\bar{t}}/\sigma_Z$, which is nearly invariant to the luminosity, only Monte Carlo based backgrounds having any remnant effects. Using the measured Z cross section $\sigma_Z = 253.5 \pm 1.1(\text{stat}) \pm 4.5(\text{syst}) \pm 14.9(\text{lumi})$ pb and the lepton+jets cross section, we determine $1/R = 35.7 \pm 2.0(\text{stat}) \pm 3.25(\text{syst})$. Using $\sigma_Z(\text{theory}) = 251.3 \pm 5.0(\text{scales, PDF})$ pb, we determine $\sigma_{t\bar{t}} = R * \sigma_Z(\text{theory}) = 7.0 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.1(\text{Z} - \text{theory})$ pb, essentially replacing the large luminosity uncertainty by the smaller theoretical uncertainty on σ_Z, with a total relative uncertainty of 10.4%.

The remaining dominant uncertainties come from b tagging corrections. CDF measures the top pair cross section in the lepton+jets final state without requiring b-tagging. In order to deal with the poor resulting signal to background, a tighter event selection is required and a seven-variable neural network (NN) is used to separate the top signal from the large backgrounds. The variables which best discriminate the $t\bar{t}$ signal are H_T, aplanarity, the ratio of total jet longitudinal momenta to total jet E_T, the minimum dijet invariant mass, the maximum jet pseudorapidity, the sum of E_T of the third, fourth and fifth jets, and the minimum dijet separation in $\eta - \phi$. The cross section is extracted by performing a binned likelihood fit to the NN discriminating variable. Figure 2 shows the neural network output used for the fit. The top cross section is measured by taking the ratio over the Z cross section, giving $\sigma_{t\bar{t}} = 6.9 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.1(\text{Z} - \text{theory})$ pb, the single most precise CDF measurement, with a total relative uncertainty of 8.3%.

CDF combines the $t\bar{t}$ cross section measurements from several different channels. All measurements are found to be consistent with each other and with theoretical predictions, as shown in figure 3.

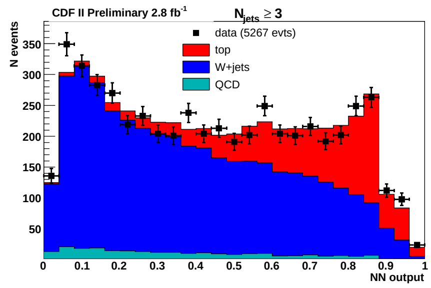

Figure 2: Fit to the NN output variable in the ≥ 3 jet sample.

3 Single top cross section

The single top signature is less striking and less distinguishable than the top pair signature. Its tiny production cross sections, combined with very large backgrounds, make it impossible to extract a single top signal using conventional counting experiments. The NLO production cross sections predicted at the Tevatron are $\sigma_s = 0.88 \pm 0.11$ pb for s-channel production and $\sigma_t = 1.98 \pm 0.25$ pb for the t-channel [3]. Kinematic distributions for single top and dominant backgrounds of two variables with some single-top discriminating power, normalized to unit area and normalized to actual data expectation, are shown in figure 4. No single discriminating variable is powerful enough.

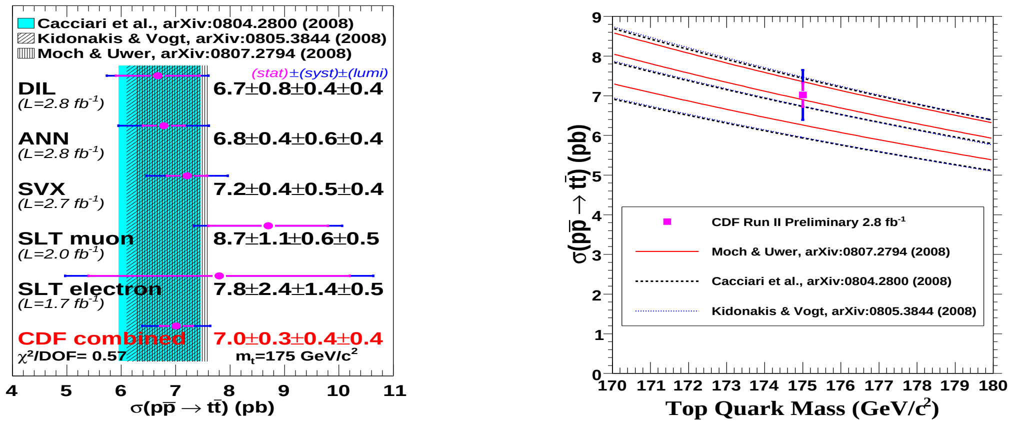

Figure 3: Summary of CDF $t\bar{t}$ cross section measurements (left), where a top mass of 175 GeV/$c^2$is assumed for acceptance calculations, and comparison of $t\bar{t}$ cross section and top mass measurements with theoretical predictions (right).

Instead, multivariate techniques such as matrix element discriminants, neural networks, boosted decision trees and multivariate likelihoods are required.

Two orthogonal event selections are used at CDF. Both require large $\not{E}_T$ and at least two energetic jets of which at least one must be b-tagged. One selection requires a high p_T lepton and the other explicitly vetoes leptons. The high p_T lepton selection has a priori much better S/B. The $\not{E}_T$ + jets selection requires larger $\not{E}_T$, higher energy jets, and uses a specialized neural network to suppress the overwhelming QCD background. This channel recovers events where the e or μ from the W decay falls outside the detector acceptance and $W \to \tau\nu$ events, adding 33% of acceptance to the high p_T lepton selection.

The dominant background processes are W + heavy flavor, mistags, $t\bar{t}$, dibosons, and QCD. Several analysis have been performed using different multivariate techniques. Figure 5 shows the results of the different cross section measurements and the CDF combined result. The discriminants from the neural network, matrix element, likelihood function, and boosted decision tree analyses are used as inputs to a new super-discriminant based on a technique called neuro-evolution which employs genetic algorithms to choose the neural network weights and topology that maximizes a given figure of merit such as the expected p-value. The neuro-evolution package used is Neuro-Evolution of Augmenting Topologies (NEAT) [4]. Figure 6 (left) shows

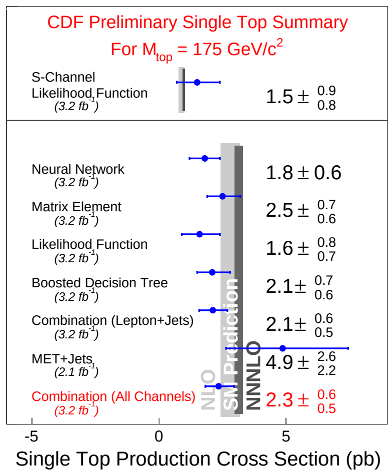

Figure 5: Summary of CDF single top cross section measurements, where a top mass of 175 GeV/$c^2$is assumed for acceptance calculations.

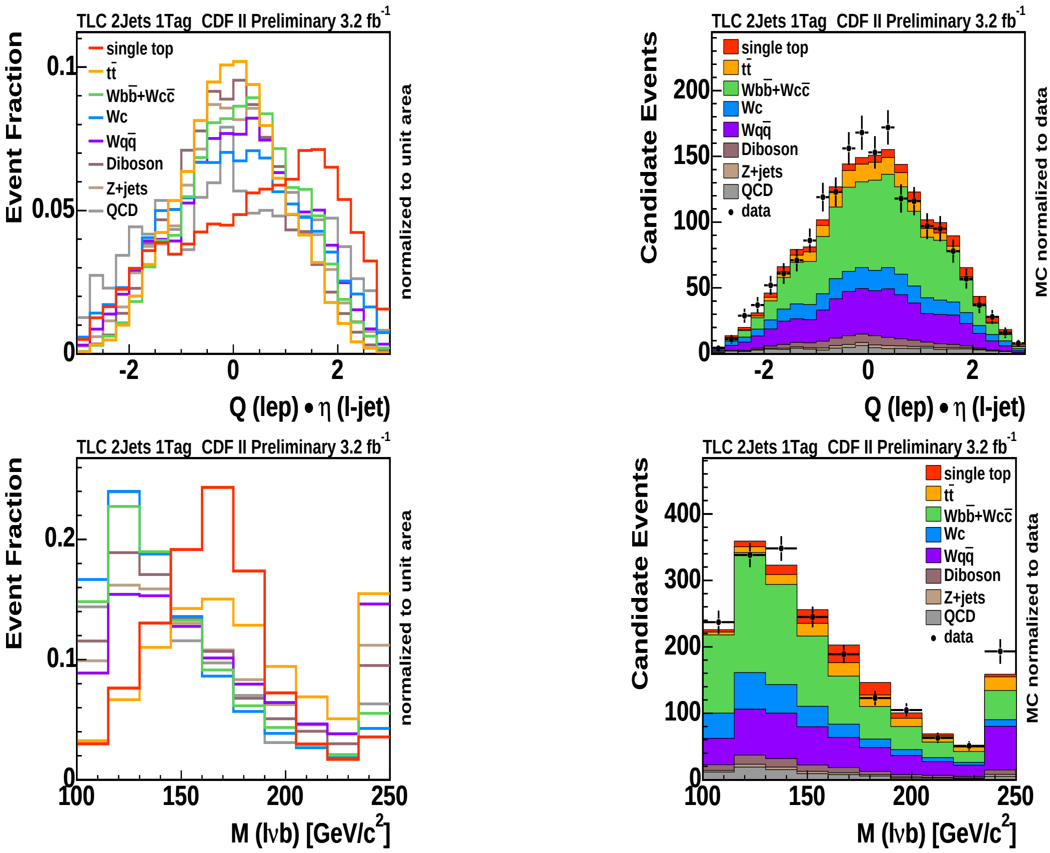

Figure 4: The distribution for single top and for dominant backgrounds of two discriminating kinematic variables. Top: the charge of the charged lepton times the rapidity of the light, non tagged jet. Top left: normalized to unit area. Top right: normalized to data expectation. Bottom: the reconstructed mass of the single top decay products, $M_{l\nu b}$. Bottom left: normalized to unit area. Bottom right: normalized to data expectation.

the super discriminant output used in the fit to measure the combined single-top cross section. When combined with the orthogonal $\not{E}_T$+jets measurement, the single top cross section is determined to be $\sigma_t = 2.3^{+0.6}_{-0.5}$ pb.

The expected p-value of the combined measurement is obtained by running 400 million pseudo-experiments with and without single top signal. Figure 6 (right) shows test statistic distribution for pseudo-experiments drawn from background-only and signal+background hypotheses. The expected p-value is $\sim 10^{-10}$ or $> 5.9\ \sigma$, and the observed p-value is 3.1×10^{-7}. The observed signal significance is therefore 5.0 σ.

Assuming a SM ($V - A$, CP conserving) Wtb vertex, these measurements can be translated into a direct measurement of V_{tb}, yielding $V_{tb} = 0.91 \pm 0.11(\text{stat} + \text{syst}) \pm 0.07(\text{theory})$.

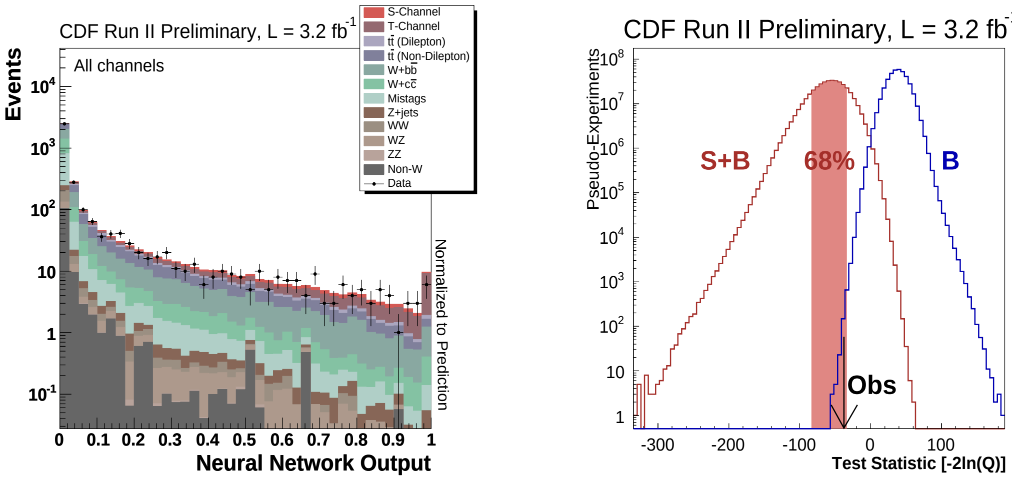

Figure 6: Left: output of the combined NN discriminant used for the final combined cross section fit. Right: test statistic distribution for pseudo-experiments drawn from background-only and signal+background hypotheses. The median of the signal+background distribution determines the expected p-value, and the test statistic value observed in data is indicated by the arrow.

4 Conclusions

The top physics program of the CDF collaboration has entered a phase of precision physics. The top pair production cross section is measured with a total relative uncertainty below 10%, and the top mass is measured to less that 1% uncertainty. The challenging single top production process has been measured with a significance of 5 σ, therefore allowing to claim discovery. This is among the smallest cross sections ever measured at hadron colliders. From the single top cross section, a direct measurement of V_{tb} is derived. All top properties measured so far are in agreement with Standard Model predictions.

References

[1] Slides:
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