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Top pair production cross-section results at Tevatron

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Abstract. We present the latest measurements of the cross section of the production of the top quark in $t\bar{t}$ pairs from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.
Measurements are performed using up to 9.1 fb^{-1} of data collected by the CDF and DØ experiments at the Tevatron.
The first combination of measurements from the two experiments is presented. From six different measurements, the cross section is measured to be $\sigma\left(p\bar{p} \to t\bar{t}, \sqrt{s} = 1.96\text{ TeV}\right) = 7.65\ \pm 0.42\,\text{pb}$.

1. Introduction

According to the Standard Model, the top quark can be produced in association with a b quark via electroweak interaction, or in a $t\bar{t}$ pair via strong interaction. The rate of the two production mechanisms are predicted to be of the order of 3 and 7 pb, respectively, at $\sqrt{s} = 1.96$ TeV.
In a recent achievement, the computation of the production cross section from strong interaction has been completed at Next-to-Next-to-Leading Order (NNLO), achieving an uncertainty of about 3.5% (evaluated as $7.24^{+0.15}_{-0.24}$ *(scale)*$^{+0.18}_{-0.12}$ *(PDF)* pb using `Top++`[1] with $\sqrt{s} = 1.96$ TeV, MSTW2008nlo68cl PDF set and $m_t = 172.5\ \text{GeV}/c^2$).
The experimental precision required for the falsification of this prediction is a challenge for the experiments at Tevatron, that can be won only by the combination of their results.

The most recent measurements of $t\bar{t}$ cross section ($\sigma_{t\bar{t}}$) from the CDF collaboration are described, together with the first combination of $\sigma_{t\bar{t}}$ measurements from the CDF and DØ experiments. For a detailed description of the detectors, see [2] and [3].

2. Statistical methods for cross section measurements

The simplest way to measure the $t\bar{t}$ production cross section employs the observation of a number of events (N_{obs}) and the estimation of the expected background events (N_{bkgr}) and of the fraction of $t\bar{t}$ events reconstructed by the detector and selected by the analysis (ε). The cross section is then $\sigma = \frac{N_{\text{obs}} - N_{\text{bkgr}}}{\mathcal{BR} \cdot \varepsilon \cdot \mathcal{L}\,\text{d}t}$ (1), where $\mathcal{L}\,\text{d}t$ is the integrated luminosity corresponding to the analysed sample and $\mathcal{BR}$ is the branching fraction of the final state.
If the prediction of the background is dependent on σ, the cross section can be extracted from the maximization of a likelihood $L(\sigma) = \mathcal{P}\left(N_{\text{obs}}, N_{\text{pred}}\right)$ (2), where $\mathcal{P}$ typically describes the Poisson distribution. Methods based on the likelihood also provide an estimation of the statistical uncertainty.
This method can be extended by splitting the sample in independent subsamples and building a joint likelihood as the product $L(\sigma) = \prod_k \mathcal{P}\left(N^{(k)}_{\text{obs}}, N^{(k)}_{\text{pred}}\right)$ (3) of one likelihood from each

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subsample, or *bin* ("binned likelihood").

3. New cross section measurements

The most precise measurements at $\sqrt{s} = 1.96\,\text{TeV}$ to date are based on $\approx 5\,\text{fb}^{-1}$, on events with one reconstructed light lepton ("ℓ", either electron or muon), and they achieve singularly the precision of about 7 to 9%.
The measurements presented here focus on different final states. While their branching fraction is too small for them to compete with the former in precision, they provide independent information on the decay of the top quark.

3.1. Measurement from τ+jets *final state* ($\tau \to$ hadrons)

The measurement of $t\bar{t}$ cross section in final states including τ leptons is particularly interesting in that it could reveal the presence of intermediate particles, such as a charged Higgs boson, whose coupling to fermions is proportional to their mass. The final state is characterized by four jets, two of which from b quarks, a neutrino and a τ lepton.

This measurement [4] is performed on 2.2fb^{-1} of CDF data. The section of the events includes at least four jets, at least one of which is identified as coming from a b quark ("b-tagging"), a minimum imbalance of transverse momentum in the event and a τ lepton. The latter is identified as a narrow hadronic jet associated to either one or three tracks, representing the lepton decay into one or three charged mesons. The tracks are required to be isolated: no additional track and less than 10% of the total jet energy must fall in a cone of radius 30° around the jet axis.

The main source of background is from events with many reconstructed jets ("multijet"), where one of them can mimic the signature of a τ lepton. The second largest source is from events with a W boson and jets ("W+jets"), where W decays into a real τ lepton. To describe the multijet background, events are selected out of the data sample. These events are required to fulfill all the criteria of the analysis, except that the jet candidate as τ must be *non*-isolated. A discriminant based on a Neural Network is built to separate the signal from the multijet background.

The shape of the distribution of the discriminant is used to quantify the contribution of the two dominant backgrounds (Fig. 1). The size of W+jets contamination is determined without the requirement of b-tagging. The contributions from all the processes are fixed to the predicted values, except for the one from the multijet and the W+jets processes. Their size is estimated by the maximization of a Poisson likelihood on the binned discrimnant distribution. The value obtained for the W+jets fraction is used, together with the knowledge of b-tagging efficiency, for the estimation of the W+jets background in the data sample used for the measurement. The estimation of the multijet background does not come from this maximization. Instead, a similar procedure is performed on the samples *with* the b-tagging requirement, after fixing all the contributions from the processes other than multijet to their expectation (including the one from $t\bar{t}$ signal, assumed $\sigma_{t\bar{t}} = 7.4\,\text{pb}$). By this second maximization, the *fraction* of data coming from multijet processes is obtained.

The expected number of $t\bar{t}$ events and of multijet events can be computed for each given $\sigma_{t\bar{t}}$, using the multijet fraction from the previous step. The expectation of the contributions from all the other processes does not depend on $\sigma_{t\bar{t}}$. The cross section is extracted from a signal region defined by the requirement of the discriminant value being above 0.85. This region encompasses 41 candidate events, with an expectation, for $\sigma_{t\bar{t}} = 7.4\,\text{pb}$, of 20.4 background events.

By maximizing a Poisson likelihood Eq. 2, the measured value of cross section is $\sigma_{t\bar{t}} = 8.8 \pm 3.3$ *(stat)* ± 2.2 *(syst+lumi)* pb, compatible with the theoretical prediction. The dominant systematic uncertainty is from the modelling of the multijet background.

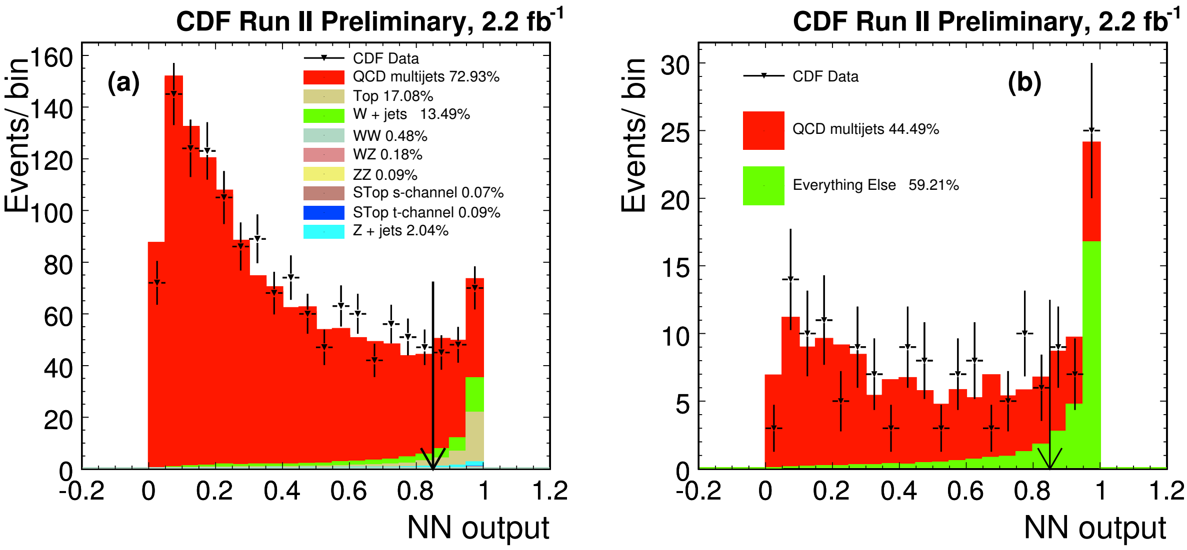

Figure 1. Distribution of the discriminant of $t\bar{t}$ signal vs. multijet background for τ+jets events, *(a)* before and *(b)* after the b-tagging requirement. The arrows mark the lower bound (0.85) of the signal region for the final measurement.

3.2. Measurement from $\tau + \ell$+jets *final state* ($\tau \rightarrow$ hadrons)

CDF has performed a cross section measurement on events with signature including one light lepton (electron or muon) and one τ lepton decaying hadronically [5]. The light lepton can either come from the prompt W decay or from a cascade decay $W \rightarrow \tau\nu_\tau$, $\tau \rightarrow \ell\nu_\ell\nu_\tau$. This final state can give the same insight on additional charged-Higgs-like t decay channels as the one described in Sect. 3.1. The signature is cleaner, because of the presence of the light lepton and large missing energy, but it is suppressed by the lower branching fraction of the additional $W \rightarrow \ell\nu_\ell$ decay. This is the first analysis presented here which uses the complete CDF RunII dataset (9.0 fb^{-1}).

There are two main sources of background for this signature. The first is from Z+jets events, when the Z boson decays into two τ leptons, one decaying into hadrons, the other into leptons. The second background comes from W+jets events, where the light lepton comes from the $W \rightarrow \ell\nu_\ell$ decay and one of the additional jets is misidentified as a τ lepton decaying into hadrons.

After the first kinematic selection, requiring a light lepton and a narrow jet (the τ candidate) with opposite charge, two or more additional jets, and moderate transverse momentum imbalance (10 GeV/c), the signal-over-background ratio (S:B) is estimated to be 2:9. The Z+jets events can be effectively rejected by requiring one jet to be identified as coming from a b quark. After this requirement, S:B becomes 2:1.

To further increase the signal purity, a log-likelihood-ratio discriminant (LLR) is designed to resolve the signal from the W+jets background. The quantities employed in the LLR include the transverse momentum imbalance ($\not{p}_T$), the transverse mass of the system composed by the light lepton and the $\not{p}_T$, and the transverse energy (E_T) of the jet with the third largest E_T.

The selection of events with $LLR \geq 0$ yields to a final sample of 36 candidate events, with an expected S:B ratio of 5:1 and an expected background of 6.9 events. The cross section is measured to be $8.2\ \pm 2.3$ *(stat)* $^{+1.2}_{-1.1}$ *(syst)* ± 0.5 *(lumi)* pb, also compatible with the theoretical prediction. This measurement is affected by large statistical uncertainty. Nevertheless, the

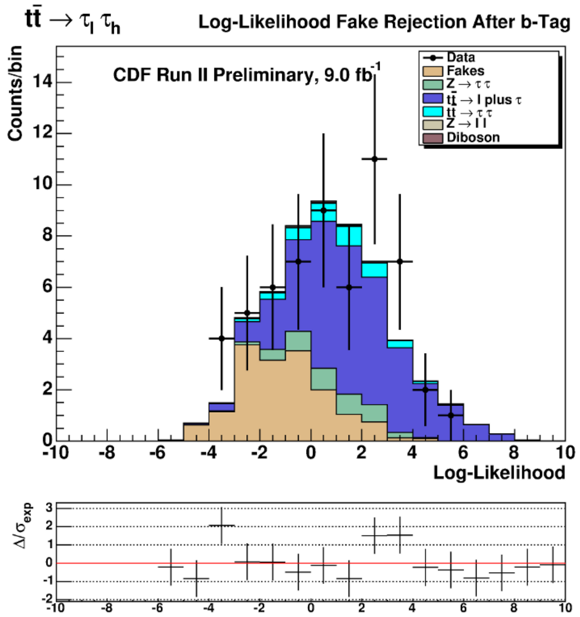

Figure 2. Distribution of the discriminant of $t\bar{t}$ signal vs. W+jets background for $\tau + \ell$+jets events.

aggressive pursue of a pure sample allows the resolution of prompt $t\bar{t} \to b\bar{b}\,\tau\nu_\tau\,\ell\nu_\ell$ and cascade $t\bar{t} \to b\bar{b}\,\tau\nu_\tau\,\tau\nu_\tau \to b\bar{b}\,\tau\nu_\tau\,\ell\nu_\ell\nu_\ell\nu_\tau$ decays, which was described by A. Jung in this same conference.

3.3. Measurement from 2ℓ+jets *final state*

The last single measurement by CDF presented here [6] is also performed on the complete RunII dataset. The final state is defined by the presence of two light leptons and jets. It is characterized by large transverse momentum imbalance, two jets from b quarks and light leptons of opposite charge.

This final state is fairly pure due to the presence of the two light leptons. The most relevant background sources are the production of Z+jets, and W+jets events with one real lepton and one jet misidentified as the other lepton.

The measurement is performed twice, using two different sets of selection criteria. The first one includes the requirement for large $\not{E}_T$, very large H_T (sum of the transverse energy of all the reconstructed objects, $H_T \geq 200$ GeV/c) and at least two jets. In addition, other cuts are aimed to reduce specific backgrounds (e.g. the exclusion of events with the invariant mass of the leptons in the $[76; 106]$ GeV/c^2 range). This selection yields to 625 candidate events for 9.1 fb^{-1} of CDF data, achieving a signal-over-background ratio of 2:1. The measured cross section is $\sigma_{t\bar{t}} = 7.66\ \pm 0.46\,(stat)\ \pm 0.66\,(syst)\ \pm 0.47\,(lumi)$ pb. The main systematic uncertainty comes from the modelling of the background processes.

The second selection adds the requirement for at least one of the jets to be identified as coming from a b quark. This last requirement roughly halves the signal, but annihilates the background and achieves S:B of 14:1. The selection includes 254 events out of 8.8 pb^{-1} of CDF data (the smaller size of the dataset is due to the stricter data quality requirements needed by the b-jet identification algorithm). This yields to a measured cross section of $\sigma_{t\bar{t}} = 7.47\ \pm 0.50\,(stat)\ \pm 0.53\,(syst)\ \pm 0.46\,(lumi)$ pb. The background modelling is not a factor anymore in a measurement on a sample with less than 10% of background contamination. Unfortunately the additional uncertainty from the b-tagging undermines this gain. Nevertheless this measurement turns to be more precise.

4. Combination of measurements

The combination of different results can sensibly increase the precision of a measurement. In the case of two different experiments like CDF and DØ, not only the doubled size of the sample reduces the statistical uncertainty, but also many of the systematic uncertainties are largely independent due to the different detectors and algorithms. The first combination of measurements of top quark properties was for its mass (the latest of which can be found in [7]). The experience and techniques of that combination have been employed now, for the first time, to the measurements of the production rate. A *Best Linear Unbiased Estimator* is used to quantify the cross section.

A detailed knowledge of the uncertainties is required. The uncertainties from each measurement have been split in 10 categories in order for each of them to be defined consistently between the analyses. These uncertainties are considered either completely correlated within each experiment (as for the ones relates to detector modelling) or across the two experiments (as for the integrated luminosity), or completely independent (as for the statistical uncertainty). The uncertainties are assumed to follow a normal distribution. All the measurements from CDF and all the ones from DØ are combined into a CDF and a DØ combination result on the first step, then the two experiment-wide combinations are combined again into the Tevatron combination.

The choice of the measurements has been performed with the goal to achieve the largest independence. There are four measurements contributed by CDF: one from 8.8 fb^{-1} of di-lepton events (see Sect. 3.3); one from 4.6 fb^{-1} of events with one electron or muon, which is a relative measurement of $\sigma(t\bar{t})/\sigma(Z)$; another from the same dataset (4.3 fb^{-1}), with the additional identification of jets from b quarks; and one from 2.9 fb^{-1} of all-jet events. There are two measurements contributed by DØ: one based on 5.3 fb^{-1} of events with one electron or muon, and one based on 5.4 fb^{-1} of events with two leptons chosen between electrons and muons.

The combined result yields to a cross section at $\sqrt{s} = 1.96$ TeV

$$\sigma\,(p\bar{p} \to t\bar{t}) = 7.65\ \pm 0.20\,\textit{(stat)}\ \pm 0.29\,\textit{(syst)}\ \pm 0.22\,\textit{(lumi)}\,\text{pb} = 7.65\ \pm 0.42\,\text{pb}$$

assuming the mass of the top quark to be $172.5\,\text{GeV}/c^2$. This corresponds to a precision of 5.5%, to be compared with the 3.5% of the current state-of-the-art prediction from theory [1].

5. Conclusion

We described here the first two measurements of the production cross section of $t\bar{t}$ using the complete dataset available to CDF. Other analyses will follow in order to cover all the main observable signatures of a $t\bar{t}$ event.

While it is important to have all these separate measurements, the main goal is to achieve the best possible precision in the characterization of the $p\bar{p} \to t\bar{t}$ process at $\sqrt{s} = 1.96$ TeV. The challenge of the precision can be won only by the combination of heterogeneous measurements relying on different datasets, experimental apparatuses and analysis techniques. The combination presented here is even more important as preparation to such final $\sqrt{s} = 1.96$ TeV combination, and as an example for similar efforts that could be undertaken in the future by the collaborations working on LHC as the preferred path to the reduction of systematic uncertainties.

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