



Top quark pair production

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Abstract

These proceedings discuss D0 measurements of the top pair differential cross section and forward-backward asymmetry. All measurements are consistent with the predictions based on the standard model.

Keywords: top quark, hadronic interactions, differential cross section, forward-backward asymmetry, new phenomena.

1. Differential Cross section of $t\bar{t}$ production

The top quark is the heaviest known elementary particle. Despite being discovered almost 20 years ago [1] its properties are still being extensively studied with an emphasis on a potential contribution from new physics. LHC experiments collected large top quark samples in Run I. Yet Tevatron experiments still provide valuable information about top quark properties especially related to the production of this particle. Top quark pair production at LHC is dominated by gluon fusion with only 15% originating from quark-antiquark annihilation. At the Tevatron these fractions are reversed. For this reason Tevatron still provides a cleaner environment to study the top pair production in quark-antiquark annihilation, where most new physics production mechanisms are expected to contribute [2]. These contributions would affect the overall production rate and distributions over sensitive variables. Narrow resonances, e.g. top color Z' [3], in the s -channel are expected to alter the distribution over the invariant mass of the $t\bar{t}$ system, $m_{t\bar{t}}$. The contribution from resonances broader than the experimental resolution might be difficult to identify. They are expected to modify such distributions as the transverse momentum of the (anti)top quark, p_T^{top} and the absolute value of its rapidity, $|y_{top}|$. Thus, the measurement of the differential cross section in these variables is of a particular interest.

Using the full Tevatron Run II data set, D0 performed

the differential $t\bar{t}$ production cross section measurement in the channel where one W boson from $t\bar{t}$ decays leptonically and the other one hadronically [4]. This channel is frequently referred to as lepton+jets (l +jets). To select these events we require a presence of a lepton (electron or muon) with the transverse momentum higher than 20 GeV, with pseudo rapidity region of 1.1 for electrons and 2.0 for muons. The presence of a neutrino is inferred from the imbalance of the transverse momentum of at least 20 GeV. At least four jets are required to be present with a transverse momentum of 20 GeV or high. One of the jets is required to have a transverse momentum above 40 GeV. Jets are identified within pseudo rapidity region of 2.5. The main background to $t\bar{t}$ signal is production of leptonically decaying W bosons in association with jets (W +jets), which are predominantly result from hadronization of light quarks. Since two of the jets from $t\bar{t}$ decay are associated with b -quarks, their identification significantly suppresses the contribution from W +jets production. We require that at least one jet is identified as originating from b quark, i.e. b -tagging. The multi variant technique used to identify b -jets has an efficiency of 60% with the probability to mistakenly tag a light jet of 1.4%. The total number of events that pass these selection criteria is 2540 with the expected number from signal and background sources of 2484. This number is based on the Standard Model cross sections for background pro-

cesses [5] and a previously measured inclusive cross section of $t\bar{t}$ production measured by D0 in a dedicated analysis [6]. In this sample the signal to background ratio is about 3.5.

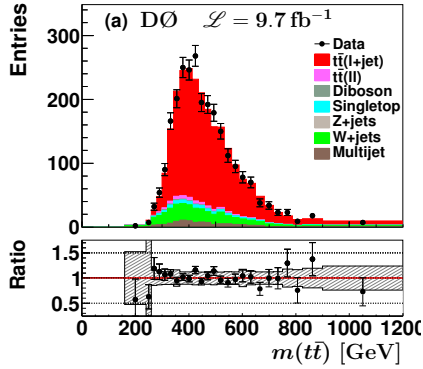


Figure 1: Color online. Distributions in $m_{t\bar{t}}$: reconstructed data compared to prediction (top), ratio of data to prediction(bottom), shaded band shows the systematic uncertainty.

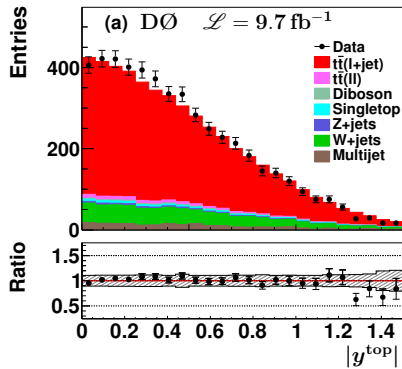


Figure 2: Color online. Distributions in $|y_{top}|$: reconstructed data compared to prediction (top), ratio of data to prediction(bottom), shaded band shows the systematic uncertainty.

Figs. 1, 2 and 3 compare the distributions of the selected events in $m_{t\bar{t}}$, $|y_{top}|$ and p_T^{top} respectively with the expectation based on the standard model. $t\bar{t}$ signal is simulated using MC@NLO event generator [7], while W+jets background is modeled using ALPGEN [8]. The background contribution is then subtracted from data, and the distributions are corrected for the acceptance and detector resolution effects (unfolded). The fully corrected distributions in $m_{t\bar{t}}$, $|y_{top}|$ and p_T^{top} are presented in Figs. 4, 5 and 6 respectively. The observed distributions are compared to the predictions based on approximate NNLO calculation [9] and several new physics scenarios. The distributions are consistent with the Standard Model.

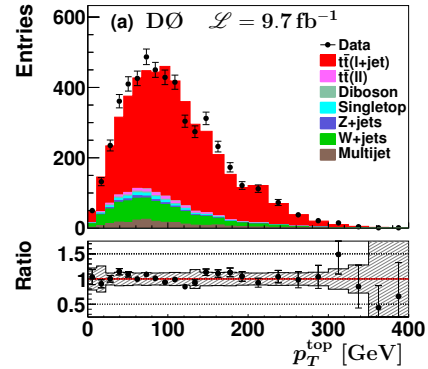


Figure 3: Color online. Distributions in p_T^{top} : reconstructed data compared to prediction (top), ratio of data to prediction(bottom), shaded band shows the systematic uncertainty.

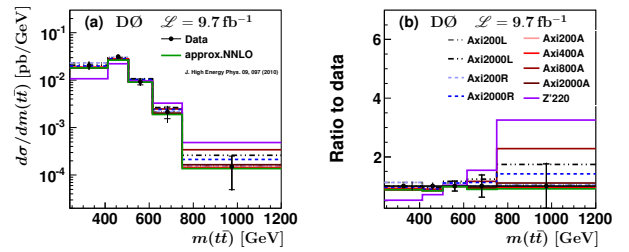


Figure 4: Color online. Unfolded distributions in $m_{t\bar{t}}$: data compared to predictions based on the standard model and several BSM scenarios (left), ratio of predictions based on several models to data (right).

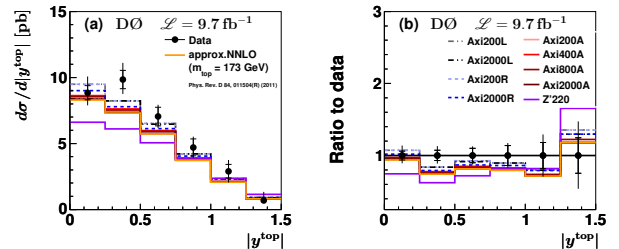


Figure 5: Color online. Unfolded distributions in $|y_{top}|$: data compared to predictions based on the standard model and several BSM scenarios (left), ratio of predictions based on several models to data (right).

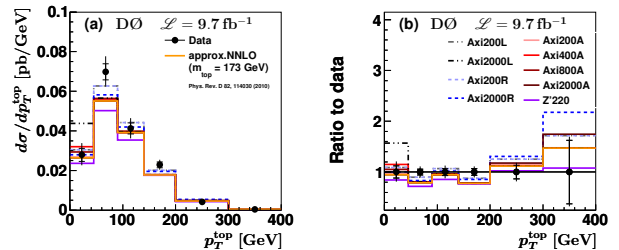


Figure 6: Color online. Unfolded distributions in p_T^{top} : data compared to predictions based on the standard model and several BSM scenarios (left), ratio of predictions based on several models to data (right).

2. Forward-backward asymmetry in $t\bar{t}$ production

Potential mediators of the $t\bar{t}$ production that have axial coupling would affect the forward-backward asymmetry in top pair production [10]. Measurements of this parameter performed by CDF and D0 collaborations based on half statistics for RunII were suggestive of deviations from the standard model prediction [11], [12]. These apparent anomaly prompted in extensive model building [2]. Tevatron, where top pair production is dominated by valence quark-antiquark annihilation, is ideally suited to test these models compared to LHC, where quark-antiquark annihilation constitutes only a small fraction of the overall top quark pair production and the direction of the initial state quark inferred from the overall boost of the system is somewhat ambiguous.

An asymmetry in a certain variable z is defined as:

$$A = \frac{N(z > 0) - N(z < 0)}{N(z > 0) + N(z < 0)}, \quad (1)$$

Fully reconstructed forward-backward asymmetry in $t\bar{t}$ production, A_{FB} , is defined through the difference in rapidity of top (y_t) and antitop ($y_{\bar{t}}$) quarks $z = \Delta y = y_t - y_{\bar{t}}$. In addition, we define a forward-backward asymmetry of leptons from the $t\bar{t}$ decay, A_{FB}^l , by using $z = q_l y_l$, where q_l is the lepton charge and y_l its rapidity.

2.1. Forward-backward asymmetry of leptons from $t\bar{t}$ decay

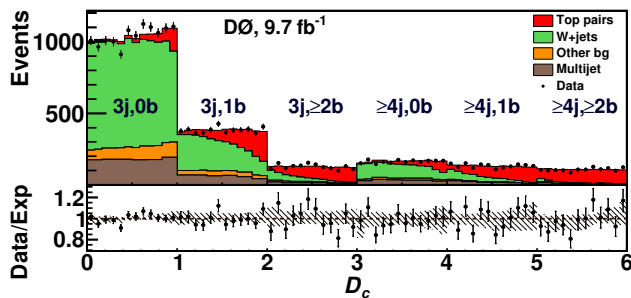


Figure 7: Color online. Distribution in kinematic discriminant D_c : reconstructed data compared to prediction (top), ratio of data to prediction (bottom), shaded band shows the systematic uncertainty.

With the Tevatron operations terminated in 2011 after collecting 10 fb^{-1} per experiment, the emphasis is on maximizing the statistical power of the existing data set. When reconstructing the $t\bar{t}$ signal in l +jets channel it was observed that in about half of the signal events one of the quarks from $t\bar{t}$ decay is associated with a jet that does not pass the selection criteria. This is illustrated in Fig. 7, which presents a kinematic discriminant D_c used

to identify the $t\bar{t}$ signal [13]. The discriminant is constructed using kinematic variables such that $D_c < 3$ for events that contain a lepton and 3 jets, and $D_c > 3$ for events with 4 or more jets. Events with zero b-tags have $D_c < 1$ or $3 < D_c < 4$, 1 b-tag events have $1 < D_c < 2$ or $4 < D_c < 5$ and 2 or more b-tag events have $2 < D_c < 3$ or $5 < D_c < 6$. The working point of the b-tagging algorithm chosen for this analysis has an efficiency of 64% for b-jets coming from $t\bar{t}$ decay and a probability of 7% to b-tag a jet not containing a b -quark. Based on the fit

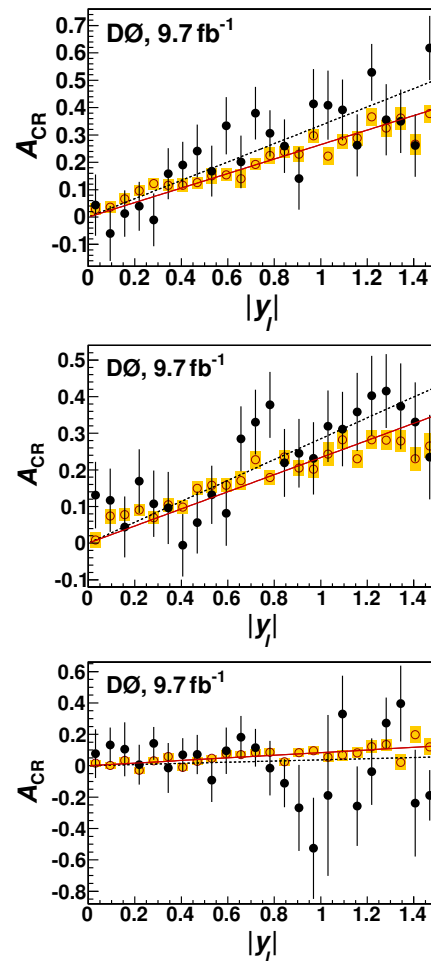


Figure 8: Lepton asymmetry dependence on the absolute values of y_l for events with $p_T^{lep} < 35 \text{ GeV}$ (top), $35 < p_T^{lep} < 60 \text{ GeV}$ (middle) and $p_T^{lep} > 60 \text{ GeV}$ (bottom). Data are presented by black closed circles with dashed black line showing the fit to linear function, Monte Carlo prediction is presented by yellow open squares with solid red line showing the fit to linear function.

to D_c it was found that 2245 $t\bar{t}$ events have exactly 3 jets and at least one b-tag, and 2222 $t\bar{t}$ events have 4 or more jets and at least one b-tag. The signal to background ratio is 0.6 for the former and 3.2 for the later. Thus,

the use of the three jet sample doubles the signal statistics, but it necessitates a thorough understanding of the background properties. In particular, W +jets is a source of leptons that are distributed asymmetrically between forward and backward directions. This asymmetry is a result of the V-A coupling at decay and an imbalance in the momentum of the initial state partons. While the forward-backward asymmetry of leptons from the inclusive production of W bosons is a well measured quantity used to constrain the parton density functions of u and d quarks [14], this is not true for leptons coming from the W bosons produced in association with jets. We used a control sample with a lepton and exactly three jets and zero b-tags to measure the asymmetry of leptons from this background process. This sample is dominated by W +jets events and is not used to measure the asymmetry from $t\bar{t}$ events. The asymmetry of leptons from W +jets is shown as a function of the absolute value of lepton rapidity in Fig. 8. The observed values are compared to the Monte Carlo prediction. The observed difference between the two is larger than the uncertainty on the prediction. For this reason we increased the systematic uncertainty due to the background modeling to account for the entire observed difference.

To measure the asymmetry of leptons from $t\bar{t}$ decay we use events with at least one b-tag. The measured asymmetry after correcting for the acceptance and resolution is $4.7 \pm 2.3(stat)_{-2.0}^{+1.7}(syst)\%$. This result is in agreement with the $MC@NLO$ prediction of 2.0%. The observed dependence of the asymmetry on the transverse momentum of the lepton is presented in Fig. 9. The observation agrees well with the prediction based on $MC@NLO$ generator.

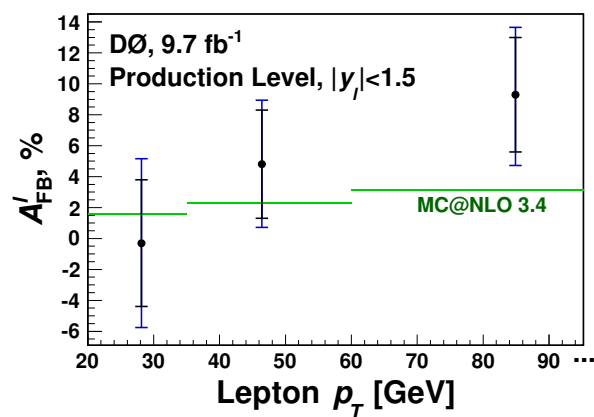


Figure 9: The dependence of the asymmetry of leptons from $t\bar{t}$ decay on the p_T^{lep} . Points present D0 data, inner error bars show the statistical uncertainty, Outer error bars show the total uncertainty. Horizontal lines present the Monte Carlo prediction.

2.2. Fully reconstructed forward-backward asymmetry in $t\bar{t}$ production

While it was straightforward to use the event sample with only three jets for the measurement of the asymmetry of leptons in the $t\bar{t}$ decay, the determination of the asymmetry based on the direction of top and anti top quarks required a development of special algorithm to compensate for the lost jet [15]. This partial reconstruction algorithm assumes that lost jet originates from the fully hadronic top quark decay. This assumption is true in about 80% of the cases. Since the missing jet is usually not reconstructed because of its low energy its effect on the kinematics of the top quark is minimal and the best approach is simply to ignore it entirely. The rapidity of the hadronically decaying top quark is determined from the four vectors of the remaining two jets. For the asymmetry measurement the most important thing is to correctly identify the sign of Δy , which this algorithm does in 75% of the cases, compared to 78% in the events with four or more jets. The resultant distributions in Δy are shown in Fig. 10 for six different channels defined by the jet and b-tag multiplicity. For the A_{FB} measurement only events with at least one b-tag are used [16].

The background-subtracted data distributions in Δy were corrected for the acceptance and detector resolution using the TUnfold algorithm [17], which was modified to allow for simultaneous regularized unfolding in channels with different purity. Finer bins are chosen for small values of Δy , where the migrations over the $\Delta y = 0$ boundary are more probable, and coarser bins are chosen for larger values of Δy , where the statistics is low. To allow for variable bin size the regularization is done based on event density rather than event count. The fully corrected distribution in Δy is shown in Fig. 11.

The corresponding inclusive forward-backward asymmetry in $t\bar{t}$ production is $(10.6 \pm 3.0)\%$, which agrees well with the prediction of 8.8% based on the NLO calculation that accounts for the contribution of the leading logarithms and electroweak corrections [18]. The dependence of the asymmetry on $|\Delta y|$ is presented in Fig. 12. D0 results are compared to this obtained by the CDF collaboration [19] and to predictions based $MC@NLO$.

Based on the full data set of Run II CDF reported strong dependence of the asymmetry on the invariant mass of the top-antitop system. D0 checked for this behavior. To study the dependence of the asymmetry on $m_{t\bar{t}}$ a two dimensional unfolding was performed. The observed asymmetry is consistent with observations by

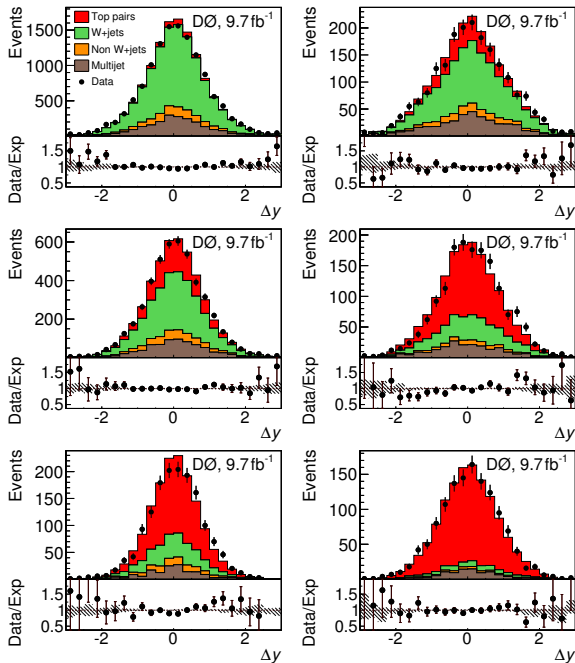


Figure 10: Color online. Distribution in Δy : reconstructed data compared to prediction (top), ratio of data to prediction (bottom), shaded band shows the systematic uncertainty. Left column corresponds to events with exactly three jets, right column - to events with four or more jets. Top row present the events with zero b-tags, middle row - events with exactly one b-tag, bottom row - events with two or more b-tags.

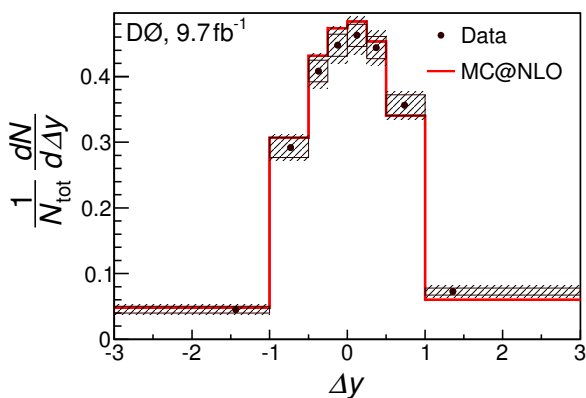


Figure 11: Unfolded distribution over the difference in rapidity of top and antitop. D0 results are compared to the MC@NLO prediction. Shaded band presents the total uncertainty.

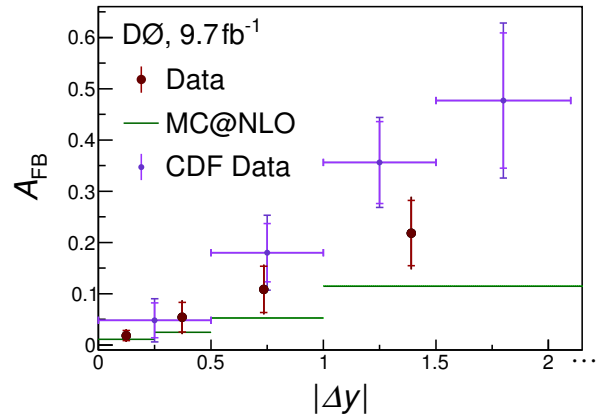


Figure 12: A_{FB} dependence on the absolute value of the difference in rapidity of top and antitop. D0 and CDF results are compared to the MC@NLO prediction. Shaded band presents the total uncertainty.

CDF, but the dependence is not nearly as strong as shown in Fig. 13. The observed asymmetry and the dependences of A_{FB} on $m_{t\bar{t}}$ and $|\Delta y|$ were found to be consistent with the standard model predictions [18].

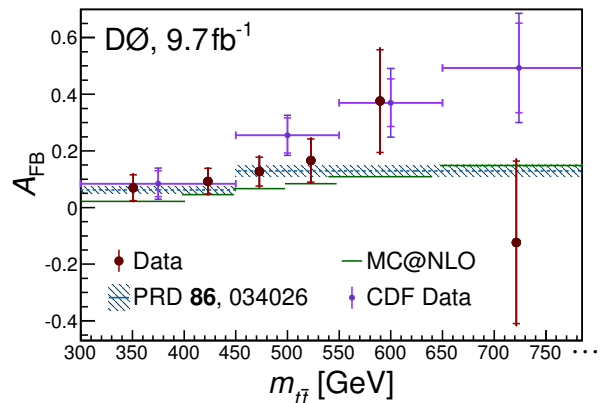


Figure 13: A_{FB} dependence on the invariant mass of the top-antitop system. D0 and CDF results are compared to the MC@NLO prediction (green band).

3. Summary

Using the full statistics of the Tevatron Run II D0 collaboration performed measurements of the top pair production cross section dependence on the invariant mass of the $t\bar{t}$ system, the absolute value of the top quark rapidity and its transverse momentum, and found them to be in agreement with the predictions based on standard model. The forward-backward asymmetry in production of leptons from $t\bar{t}$ decay and the fully reconstructed forward-backward asymmetry and its dependence on

the invariant mass of the $t\bar{t}$ system and the absolute value of the difference in rapidity of top and anti top quarks also agree with the standard model predictions.

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