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Measurements of forward-backward asymmetries in top-quark pair production at the D0 experiment

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Discovered in 1995 by the CDF and D0 collaborations, the top quark is the heaviest elementary particle of the standard model of particle physics. By now, many of its characteristics are known to agree well with the predictions. Nevertheless, discrepancies of about two to three standard deviations are observed in asymmetries of production angular distributions of both top and antitop quarks in $p\bar{p} \rightarrow t\bar{t}$ events. An overview is presented of the recent measurements of this asymmetry that summarizes the latest results from the D0 experiment with up to 5.4 fb^{-1} of integrated luminosity and compares the data with expectations from theory.

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1. Introduction

With a mass of 173.2 ± 0.9 GeV [1], the top quark is the heaviest of the elementary particles. From a theoretical point of view, top quarks are of special interest, as their coupling to the Higgs boson is close to unity, suggesting that the top quark may play a special role in electroweak symmetry breaking [2]. From an experimental point of view, its short lifetime of about 10^{-25} sec [3] is of particular interest as top quarks decay before hadronization and thereby provide an opportunity for studying properties of essentially free quarks.

At the Tevatron $p\bar{p}$ collider, with a center-of-mass energy of 1.96 TeV, 85 % of the $t\bar{t}$ pairs are produced through quark-antiquark annihilation and 15 % originate from gluon-gluon fusion. In next-to-next-to leading order (NNLO) in perturbative quantum chromodynamics (QCD), the $t\bar{t}$ production cross section is predicted to be 7.01 pb [4]. In the standard model (SM), top quarks decay almost exclusively to a W boson and a bottom quark, such that $t\bar{t}$ events can be classified into all-jets, ℓ+jets and dilepton final states, depending on the modes of the decay of the two W bosons.

This article presents measurements of asymmetries in production angular distributions of t and $\bar{t}$ studied by the D0 experiment at the Tevatron collider. The results are based on data of up to 5.4 fb^{-1} of integrated luminosity. In addition to inclusive asymmetries, the $t\bar{t}$ asymmetries have been examined as a function of several variables, that also indicate an enhancement at the Tevatron compared to predictions from the SM.

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

At leading order (LO) in QCD, the angular distributions of t and $\bar{t}$ quarks in $p\bar{p} \to t\bar{t}$ events produced through $q\bar{q}$ annihilation are expected to be forward-backward symmetric in the center-of-mass frame. However, at NLO, interference from contributions symmetric (upper row in Fig. 2) and asymmetric (lower rower in Fig. 2) under exchange of t and $\bar{t}$ lead to a small positive forward-backward asymmetry, which means that the top and antitop quarks are emitted with higher probability in the directions of the incoming quark and antiquark, respectively. Production through gluon-gluon fusion is not expected to lead to a forward-backward asymmetry, as that would violate the Bose-Einstein symmetry of gluon-gluon interactions.

Predictions for the forward-backward asymmetry can be modified by processes beyond the SM [5], through contributions from hypothesized axigluons, Z' or W' bosons or new scalars. Apart from changes in forward-backward asymmetry, these new sources can also lead to polarization of top quarks [6, 7].

As $t\bar{t}$ production at the Tevatron is dominated by the interaction of a valence quark and a valence antiquark, it can be assumed, that the direction of the quark (antiquark) coincides with that of the incoming proton (antiproton). Accordingly, the forward backward asymmetry $A^{t\bar{t}}_{FB}$ can be defined in terms of the rapidity difference of the top and antitop quarks. In particular, $A^{t\bar{t}}_{FB}$

$$A^{t\bar{t}}_{FB} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)}, \tag{2.1}$$

where $\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$ and $y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$, with $N(\Delta y_{t\bar{t}} > 0)$ and $N(\Delta y_{t\bar{t}} < 0)$ the number of events with rapidity difference $\Delta y_{t\bar{t}} > 0$ and $\Delta y_{t\bar{t}} < 0$, respectively.

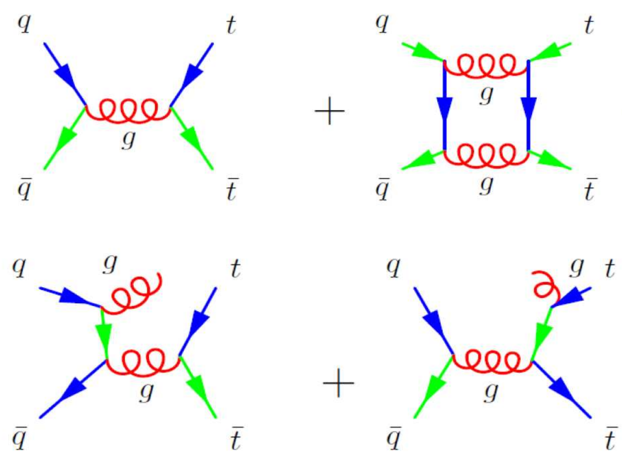

Figure 1: Interference between diagrams result in a net positive angular asymmetry, with the top (antitop) quark emitted preferentially in the direction of the incident quark (antiquark).

Adding contributions from the next-to-next-to leading logarithmic (NLO+NNLL) predict the $t\bar{t}$ forward-backward asymmetry to be $A_{FB}^{t\bar{t}} = 7.2^{+1.1}_{-0.7}$ % [8]. Taking account of electroweak (QED) as well as mixed QCD+QED corrections yields $A_{FB}^{t\bar{t}} = 8.9^{+0.8}_{-0.6}$ % [9].

To measure the forward-backward asymmetry $A_{FB}^{t\bar{t}}$ defined in Eq. 2.1 requires $t\bar{t}$ events to be fully reconstructed. In the ℓ+jets channel, with one undetected neutrino, kinematic constraints can be used to obtain such results. However, the dilepton channel is not as well constrained, and a different approach is preferred. As the electron and muon directions and momenta are well measured, the e and μ leptons can be used to define different forward-backward asymmetries [7], e.g.,

$$A_{FB}^{\ell} = \frac{N(q_\ell y_\ell > 0) - N(q_\ell y_\ell < 0)}{N(q_\ell y_\ell > 0) + N(q_\ell y_\ell < 0)}, \tag{2.2}$$

where q_ℓ is the charge of the lepton. In analogy to $A_{FB}^{t\bar{t}}$ a difference in lepton pseudorapidities, $\Delta\eta_{\ell\bar{\ell}} = \eta_{\bar{\ell}} - \eta_\ell$, can also be considered :

$$A_{FB}^{\ell\bar{\ell}} = \frac{N(\Delta\eta_{\ell\bar{\ell}} > 0) - N(\Delta\eta_{\ell\bar{\ell}} < 0)}{N(\Delta\eta_{\ell\bar{\ell}} > 0) + N(\Delta\eta_{\ell\bar{\ell}} < 0))}. \tag{2.3}$$

In addition, an asymmetry A_{FB}^{CP} can be defined for probing the charge-parity (CP) :

$$A_{FB}^{CP} = \frac{N(\eta_{\bar{\ell}} > 0) - N(\eta_\ell < 0)}{N(\eta_{\bar{\ell}} > 0) + N(\eta_\ell < 0)}. \tag{2.4}$$

To obtain parton-level predictions, the MC@NLO generator [10] is used taking account of QCD and mixed QCD+QED corrections from Ref. [11]. This yields: $A_{FB}^{\ell} = 4.7 \pm 0.1$ %, $A_{FB}^{\ell\bar{\ell}} = 6.2 \pm 0.2$ %, and $A_{FB}^{CP} = -0.3 \pm 0.1$ %.

3. Experimental results

3.1 Measurement of $A_{FB}^{t\bar{t}}$ and A_{FB}^{ℓ} in the ℓ+jets channel

The ℓ+jets channel is characterized by four jets, one isolated, energetic charged lepton ($\ell = e$ or μ), and an imbalance in transverse momentum due to the undetected neutrino [12]. The main irreducible background in this final state comes from W+jets events. Instrumental background arises from events in which a jet is misidentified as a lepton, and from events with heavy quarks that decay into leptons and pass the required isolation. In the ℓ+jets measurement [13], $t\bar{t}$ signal events are modeled using MC@NLO with HERWIG used for parton evolution and hadronization [10, 14], W+jets events are simulated using ALPGEN with PYTHIA [15, 16], and the instrumental background is estimated from data. To increase $t\bar{t}$ signal purity of the data sample, events are selected based on the $t\bar{t}$ event features described above. In addition, at least one jet is required to be identified as arising from a b quark. This yields a total of 1600 selected $t\bar{t}$ candidate events, with an expected signal purity of about 70 %.

Based on mass constraints on the W boson and top quark, $t\bar{t}$ events are reconstructed in a kinematic fit to the $t\bar{t}$ hypothesis taking the detector resolution into account. The most likely solution is retained for the extraction of the forward-backward asymmetry. After subtracting contributions from background, D0 obtains $A^{t\bar{t}}_{FB} = 9.2 \pm 3.7$[1] % at the detector level. The largest systematic effect of 0.5 % reflects uncertainties on jet energy scale and resolution.

The forward-backward asymmetry $A^{t\bar{t}}_{FB}$ depends on several variables, such as $\Delta y_{t\bar{t}}$ and the invariant $t\bar{t}$ mass. In the SM, the later comes about from the fact that the relative fraction of $t\bar{t}$ production from $q\bar{q}$ annihilation increases with increasing $m_{t\bar{t}}$. Contributions from physics beyond the SM can lead to larger effects. At the D0 experiment, no dependence beyond that expected in the SM as a function of $m_{t\bar{t}}$ is observed. With $A^{t\bar{t}}_{FB} = 21.3 \pm 9.7$ %, the measured forward-backward asymmetry for events with $|\Delta y_{t\bar{t}}| > 1.0$ is only slightly larger than predicted in the SM.

Differences in acceptance and detector resolution in different experiments makes it difficult to to compare specific experimental results and calculations in a direct manner. This is accounted for by unfolding the biases and detector resolutions from the observed distributions in data. The D0 experiment uses a regularized unfolding, as this yields a better description of migrations of events across $\Delta y_{t\bar{t}} = 0$. The unfolded asymmetry $A^{t\bar{t}}_{FB} = 19.6 \pm 6.5$ % agrees within 2.4 SD with the predictions from MC@NLO.

Besides $A^{t\bar{t}}_{FB}$, the lepton-based asymmetry A^{ℓ}_{FB} is also measured. Since the lepton resolution is excellent, results are less diluted and no complicated unfolding or $t\bar{t}$ reconstruction is needed. In the ℓ+jets channel, the lepton-based asymmetry is measured to be $A^{\ell}_{FB} = 14.2 \pm 3.8$ % where to avoid large acceptance corrections, only leptons with $|y_\ell| < 1.5$ are included in the measurement. A simple unfolding yields $A^{\ell}_{FB} = 15.2 \pm 4.0$ %. The results agrees with the reweighted predictions from MC@NLO of $A^{\ell}_{FB} = 4.7 \pm 0.1$ % by 2.6 SD. The largest systematic effect on the result is from the modeling of the $t\bar{t}$ transverse momentum.

Cross-checks have been carried out to verify the results in the ℓ+jets channel. No dependence on the polarity of the solenoid or toroid magnets, nor on lepton charge or flavor was observed. In addition, the measured asymmetries of the background enriched in W+jets data agrees well with that predicted from ALPGEN.

3.2 Lepton-based asymmetries in the dilepton channel

The dilepton channel [17] is defined by two jets, two isolated, energetic charged leptons ($\ell =$

[1]Throughout this review, the quoted experimental uncertainties are always combined statistical and systematic uncertainties.

e or μ), and a significant imbalance in transverse momentum from the undetected neutrinos. The main background processes are from Z+jets and diboson events (WW, WZ and ZZ with associated jets), as well as instrumental background with misidentified objects as described above. Applying an event criteria that correspond to the features of the dilepton $t\bar{t}$ topology, selects a total of 490 $t\bar{t}$ candidate events, with an expected signal purity of about 70 %. Again, $t\bar{t}$ events are modeled using MC@NLO + HERWIG, Z+jets events are from ALPGEN + PYTHIA. Background distributions in η_ℓ and $\Delta\eta_{\ell\bar{\ell}}$ are in excellent agreement with data for a background-enriched selection.

Despite the small branching fraction of $t\bar{t}$ to the dilepton final state, the two leptons momenta and directions are well measured and the results offer complementary information, providing the lepton-based asymmetries defined above. After small acceptance corrections using MC@NLO, D0 obtains

$$\begin{aligned} A^{\ell}_{FB} &= 5.8 \pm 5.3\,\%\,, \\ A^{\ell\bar{\ell}}_{FB} &= 5.3 \pm 8.4\,\%\,, \\ A^{CP}_{FB} &= -1.8 \pm 5.3\,\%\,. \end{aligned}$$

All results are in excellent agreement with the predictions from MC@NLO that include QCD and QCD+QED corrections mentioned above. Statistical 5-8 % uncertainties dominate these measurements.

The lepton-based asymmetries from the ℓ+jets and dilepton channels are combined using the BLUE [19] method, yielding $A^{\ell}_{FB} = 11.8 \pm 3.2$ %. This is consistent with 2.2 SD with the predictions from MC@NLO of 4.7 ± 0.1 %. The ℓ+jets channel contributes 64 % to the combination while the dilepton channel 36 %.

Many new or modified models [5], attempting to accommodate the observed asymmetries, have generated results with sizable deviations from the SM. All have to fulfill several constraints from the existing production and properties measurements. Other investigations, involving searches for parity violation in longitudinal top quark polarization still have to be carried out. In the absence of acceptance effects, the distribution of $\cos\theta^-$ and $\cos\theta^+$ should be consistent with the V-A interaction of the SM for unpolarized top quarks [7], where θ^+ (θ^-) is the angle between the direction of the positive (negative) lepton in the t ($\bar{t}$) rest frame and the t ($\bar{t}$) direction in the $t\bar{t}$ rest frame. A longitudinal polarization of the top quark would alter the symmetry of the distributions. Assuming CP invariance, the sum of $\cos\theta^+$ and $\cos\theta^-$ is shown in Fig. 3.2 for the dilepton (left) and ℓ+jets (right) final states. The distribution for $t\bar{t}$ events produced via a leptophobic topcolor Z' boson is added to illustrate the effect of producing top quarks with longitudinal polarization. The agreement between data and the SM prediction in both distributions is good, yielding a Kolmogorov-Smirnov probability of 14 % in the dilepton channel, and 58 % in the ℓ+jets channel. There is no indication of new sources of parity violation leading to a longitudinal polarization in $t\bar{t}$ production at the D0 experiment.

4. Conclusion and outlook

The large positive asymmetries measured by the CDF and D0 collaborations correspond to one of the most interesting results in the top-quark sector today. The current D0 analyses make only use

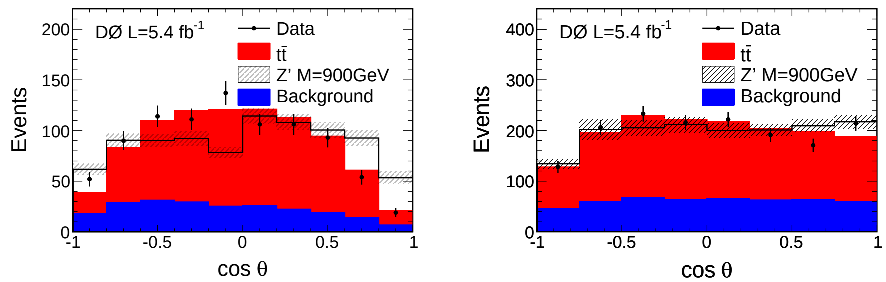

Figure 2: The distribution of $\cos\theta^+$ and $\cos\theta^-$ is shown for the combination of the dilepton channels (left) and the ℓ+jets channels (right). Data are compared to the SM predictions. and the distribution of $t\bar{t}$ pairs produced from a Z' boson is added.

of half of the final Tevatron luminosity and future measurements can therefore put much stronger constraints on the forward-backward asymmetry. In addition, the understanding of modeling of $t\bar{t}$ production and the predictions of theory have improved since the very first results. But nevertheless the latest results from D0 and CDF remain at the order of 2-3 SD relative to the predictions, and final proof of physics beyond the SM may have to wait for results from the LHC experiments.

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