PROCEEDINGS OF SCIENCE

# Measurements of the $t\bar{t}$ forward-backward asymmetry at CDF

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At next-to-leading order in QCD, the $t\bar{t}$ forward-backward asymmetry in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions receives non-zero contributions from interference between leading-order and next-to-leading order exclusive $t\bar{t}$ production, and interference between the leading-order diagrams of $t\bar{t}$ production with a radiated gluon. CDF measurements of the asymmetry differ from the predictions at the $\approx 2\sigma$ level, with maximum deviations at high $t\bar{t}$ invariant mass. The measurements are performed in the $t\bar{t}$ semileptonic decay using the full CDF data set, and in the $t\bar{t}$ fully leptonic decay using data corresponding to 5.1 fb$^{-1}$ of integrated luminosity.

*36th International Conference on High Energy Physics,*
*July 4-11, 2012*
*Melbourne, Australia*

PoS(ICHEP2012)194

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## 1. Introduction

Historically, measurements of forward-backward production asymmetries of quarks and leptons have been used to study the details of electroweak mixing, with large asymmetries expected because of the coupling of the weak force exclusively to left-handed fermions. In QCD, tree-level production of a quark pair has no asymmetry, since the gluon has a pure vector coupling to fermions. However, higher-order effects create a small asymmetry which can be measured as a test of the QCD prediction and a probe for new particles with axial couplings to quarks.

The pair-production of top quarks in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions at the Tevatron proceeds predominantly through valence-quark annihilation ($\approx 85\%$ of the production rate [1]). The forward-backward asymmetry is defined as

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, \tag{1.1}$$

where $\Delta y = y_t - y_{\bar{t}}$ and $y$ represents rapidity.

A positive asymmetry is predicted due to the interference of the $s$-channel annihilation diagram and the box diagram with two internal timelike gluons (Fig. 1). Heuristically, the asymmetry arises from a preference to maintain color flow, giving a relatively small change in momentum between the incoming valence quark and the outgoing top quark. This leads to a large rapidity difference ($\Delta y$) and a high invariant mass of the top-antiquark pair.

Additionally, a negative asymmetry is predicted from the interference between the radiation of a gluon in the initial and final states. In this case the radiation produces a sizeable change in momentum giving a smaller rapidity difference and invariant mass of the top-antiquark pair. Another feature of the negative asymmetry is that it has an additional jet and sizeable $p_T$ of the $t\bar{t}$ system. Figure 1 shows the predicted $p_T$ dependence of the asymmetry in $t\bar{t}$ and $t\bar{t}+\text{jet}$ production.

A final contribution to the forward-backward asymmetry in the Standard Model arises from production diagrams containing an electroweak gauge boson. Such diagrams increase the expected asymmetry by 26%. Table 1 [2] shows the predicted asymmetry from the QCD NLO generators POWHEG, MC@NLO, and MCFM, including a +26% correction to account for electroweak diagrams missing from the generators.

CDF has updated its measurement of the $t\bar{t}$ forward-backward asymmetry using the full Run II data set in $t\bar{t}$ decays to a charged lepton, neutrino and jets [2]. The measurement includes the $p_T t\bar{t}$ dependence of the asymmetry. Additionally, CDF has measured the asymmetry in $t\bar{t}$ decays to two charged leptons, neutrinos, and jets. Both measurements give a larger positive asymmetry than the prediction, particularly at high $m_{t\bar{t}}$.

## 2. Asymmetry measurements in semileptonic decays

The semileptonic final state has many useful features for the $t\bar{t}$ asymmetry measurement. It has relatively high statistics (2653 events in data corresponding to 9.4 fb$^{-1}$ of luminosity) and low background fraction ($\approx 20\%$). It contains a single charged lepton, which can be used to identify the top-quark and anti-top quark decays. And it has sufficient kinematic information that a fit can determine the rapidity of the top and antitop quarks (using the known $W$ boson mass). The

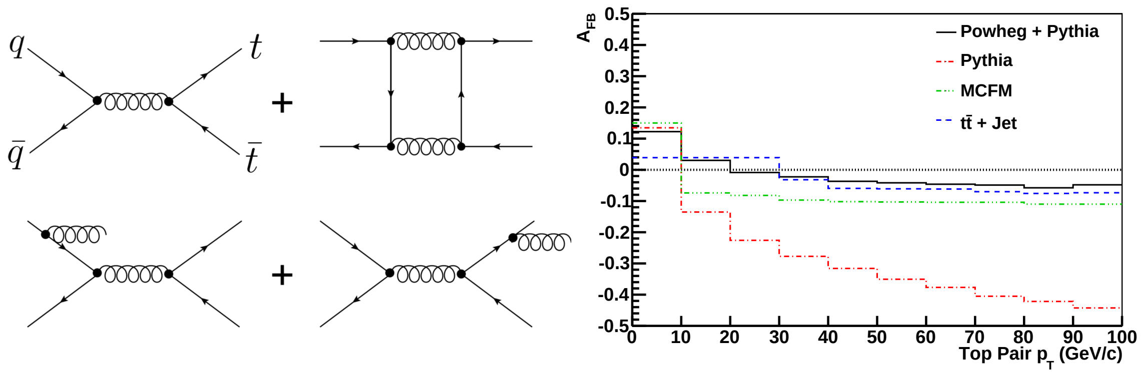

**Figure 1:** Left: The QCD NLO diagrams contributing to the forward-backward asymmetry of $t\bar{t}$ (top) and $t\bar{t}$ + jet (bottom) production. Right: The predicted dependence of the asymmetry on $p_T(t\bar{t})$.

| Region | MCFM | POWHEG | MC@NLO |
|---|---|---|---|
| Inclusive | 0.073 | 0.066 | 0.067 |
| $\lvert\Delta y\rvert < 1$ | 0.049 | 0.043 | 0.047 |
| $\lvert\Delta y\rvert > 1$ | 0.150 | 0.139 | 0.130 |
| $m_{t\bar{t}} < 450$ GeV | 0.050 | 0.047 | 0.054 |
| $m_{t\bar{t}} > 450$ GeV | 0.110 | 0.100 | 0.089 |

**Table 1:** The predicted forward-backward asymmetries [2] by the NLO QCD generators MCFM, POWHEG, and MC@NLO, with a +26% correction to account for missing electroweak contributions. Shown are the inclusive asymmetry and the asymmetry in two $|\Delta y|$ and $m_{t\bar{t}}$ regions. The low $\Delta y$ and $m_{t\bar{t}}$ regions receive a significant negative contribution from initial and final state gluon radiation; the high $|\Delta y|$ and $m_{t\bar{t}}$ regions are dominated by the positive contribution from interfering diagrams without such radiation.

measurement has been updated from the previous measurement based on 5.3 fb$^{-1}$ of integrated luminosity [3]; in addition to the gain in luminosity, the new measurement benefits from extended muon coverage. Combined, the luminosity and extended coverage give more than a factor of two increase in statistics.

To model the data, Monte Carlo $t\bar{t}$ samples are generated using the POWHEG generator interfaced with PYTHIA for the parton-shower model and passed through CDFSIM for detector simulation. Figure 2 shows that the Monte Carlo describes the $m_{t\bar{t}}$ and $p_T(t\bar{t})$ distributions well.

Detector effects are unfolded to extract an inclusive $A_{FB}$ at the parton level, as well as differential cross sections. Figure 3 shows as a function of $|\Delta y|$ and $A_{FB}$ as a function of $m_{t\bar{t}}$. The measured inclusive $A_{FB}$ ($0.164 \pm 0.045$) is $2\sigma$ larger than the POWHEG prediction ($0.066 \pm 0.020$), where the prediction includes a correction for electroweak contributions. The mass dependence of the asymmetry is parameterized as a first-order polynomial; the measured slope ($15.2 \pm 5.0 \times 10^{-4}$) is $2.3\sigma$ larger than the predictiion ($3.4 \pm 1.2 \times 10^{-4}$). The difference is largest at highest invariant mass, a region where the Standard Model asymmetry is dominated by exclusive $t\bar{t}$ production.

In addition, CDF has measured the asymmetry as a function of $p_T(t\bar{t})$ at the detector level (Fig. 4. The distribution shows a deviation from the POWHEG prediction with maximum signif-

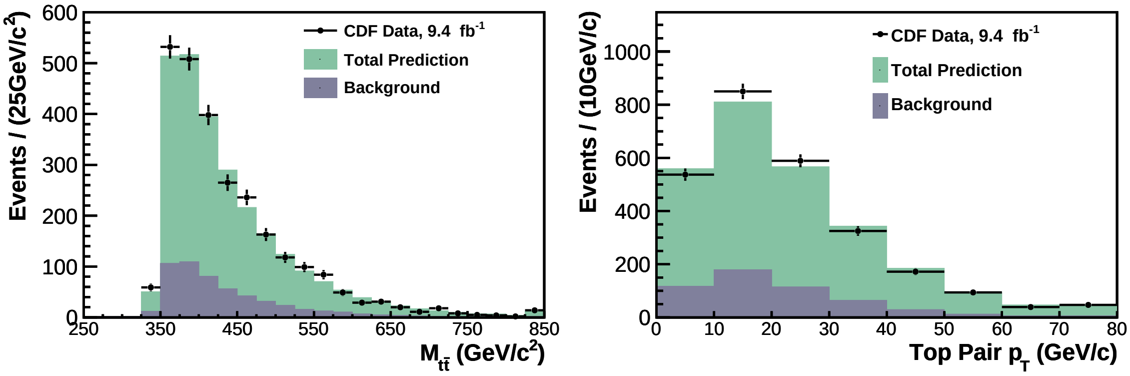

**Figure 2:** The distributions of $m_{t\bar{t}}$ (left) and $p_T(t\bar{t})$ (right) predicted by POWHEG $t\bar{t}$ Monte Carlo and expected background (histograms), compared to data (points).

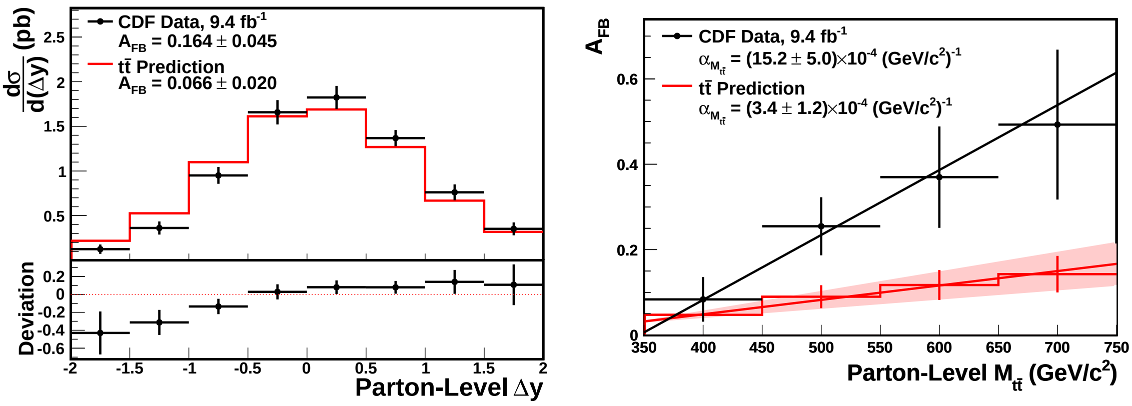

**Figure 3:** Left: The differential cross section of $t\bar{t}$ events as a function of $\Delta y$, after unfolding detector effects. Shown are the data (points) and POWHEG prediction (histogram), as well as the ratio of data to the prediction. The data show a systematic excess relative to prediction at positive $|\Delta y|$. Right: The measured (points) and predicted (histogram) asymmetries as a function of the invariant mass of the top-antitop quarks, after unfolding detector effects.

icance at low $p_T(t\bar{t})$, the region dominated by exclusive $t\bar{t}$ interfering diagrams. However, the measured distribution is also consistent with a deviation constant in $p_T(t\bar{t})$, as shown in the figure.

Uncertainties on the asymmetry measurement are dominantly statistical (0.039 on the total asymmetry). The largest systematic uncertainties are on the background shape (0.014) and normalization (0.013). The asymmetry of the background is studied using a data sample with no jets identified as originating from a $b$ quark ($b$-jets), and found to be well modelled. Additional cross-checks show no evidence of additional systematic effects: the asymmetry is stable as a function of time of data-taking and is consistent between data containing electrons or muons, positive or negative leptons, and one or two identified $b$-jets.

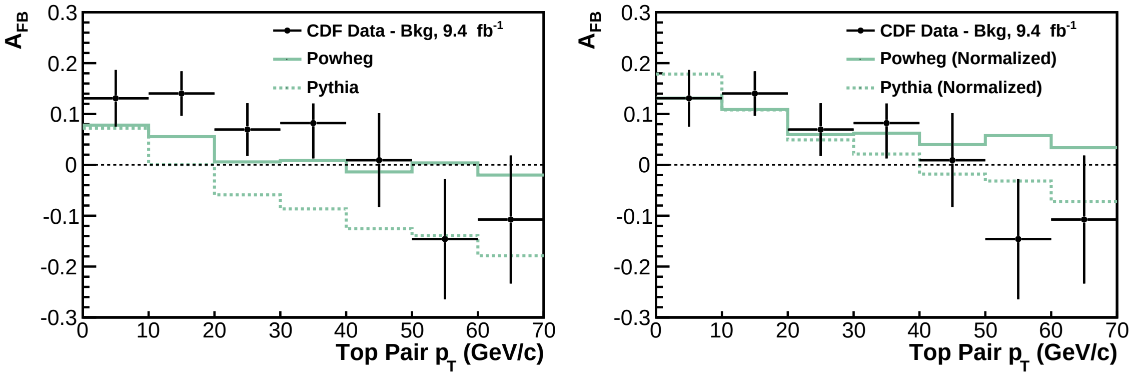

**Figure 4:** Left: The measured asymmetry as a function of $p_T(t\bar{t})$ (points) compared to POWHEG (solid line) and PYTHIA (dashed line). Right: The same measurement compared to POWHEG and PYTHIA, where the predictions include a $p_T(t\bar{t})$-independent correction such that the inclusive asymmetry matches that of the data.

## 3. Asymmetry measurements in fully leptonic decays

The forward-backward asymmetry measurement in the final state with two charged leptons has reduced sensitivity due to the lower branching ratio and the two unmeasured final-state neutrinos carrying kinematic information. The neutrino kinematics are estimated by constraining the invariant masses of the $W$-boson and top-quark decay products to the known particle masses, and minimizing a likelihood based on the expected mass and the transverse and longitudinal momenta of the $t\bar{t}$ system.

Using 334 events in data corresponding to 5.1 fb$^{-1}$ of integrated luminosity, CDF measures a forward-backward asymmetry of $0.42 \pm 0.16$, where the uncertainty is dominantly statistical. The result is consistent with the measurement in semileptonic decays at the $1.5\sigma$ level, and consistent with the Standard Model prediction at the $2.2\sigma$ level.

Since there are a factor of eight fewer events in data with fully leptonic decays than in the semileptonic decays, differential measurements of the asymmetry are less precise. Nonetheless, a split of the measurement in two regions of $m_{t\bar{t}}$ has been made, below and above $m_{t\bar{t}} = 450$ GeV (Fig. 5). In both regions the asymmetry is measured to be larger than the prediction: $A_{FB} = 0.104 \pm 0.066$ (stat) for $m_{t\bar{t}} < 450$ GeV, where the prediction is $0.003 \pm 0.031$; and $A_{FB} = 0.212 \pm 0.096$ (stat) for $m_{t\bar{t}} > 450$ GeV, where the prediction is $-0.040 \pm 0.055$. The asymmetry is larger at high mass, with a more statistically significant deviation from the prediction, though the asymmetries in the two regions are consistent.

## 4. Summary

CDF has updated the measurement of the forward-backward asymmetry of $t\bar{t}$ production in the semileptonic final state using the complete data set. The measured asymmetry is $> 2\sigma$ larger than the prediction, with the discrepancy increasing with increasing $m_{t\bar{t}}$. The asymmetry shows no signficant $p_T(t\bar{t})$ dependence. The uncertainty on the measurements is dominantly statistical and

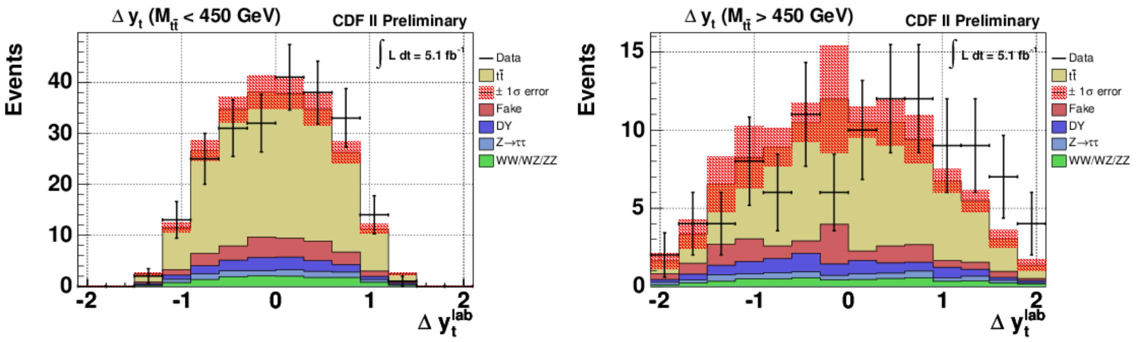

**Figure 5:** Left: The measured $\Delta y$ (points) for $m_{t\bar{t}} < 450$ GeV compared to the Monte Carlo prediction (histogram) for data with fully leptonic $t\bar{t}$ decays. Right: Comparison of measured and predicted $\Delta y$ for $m_{t\bar{t}} < 450$ GeV.

a number of cross-checks show no evidence of a systematic bias. In the fully leptonic final state CDF measures an asymmetry consistent with that of the semileptonic measurement and $> 2\sigma$ larger than the prediction. Taken together these results suggest that calculations based on NLO QCD and LO electroweak production of $t\bar{t}$ do not adequately described the forward-backward production asymmetry in $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions.

## References

[1] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D (R) **79**, 031101 (2009).

[2] T. Aaltonen *et al.* (CDF Collaboration), arXiv:1211:1003v2 (2012).

[3] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **83**, 112003 (2011).