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Measurement of the Inclusive Forward-Backward Asymmetry and its Rapidity Dependence $\mathbf{A_{fb}(\Delta y)}$ in $\mathbf{t\bar{t}}$ Production in 5.3 fb^{-1} of Tevatron Data

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Abstract

We measure the forward-backward asymmetry of pair produced top quarks in 1.96 TeV $p\bar{p}$ collisions using 1260 fully reconstructed semi-leptonic b-tagged ttbar events in 5.3 fb^{-1} of data collected at CDF. We study the top rapidity in both the laboratory and $t\bar{t}$ rest frames. We find the parton-level forward-backward asymmetry to be

$$A^{\mathrm{lab}} = 0.150 \pm 0.050 \pm 0.024$$
$$A^{t\bar{t}} = 0.158 \pm 0.072 \pm 0.017$$

where the first error is statistical and the second is systematic. These results should be compared with the small asymmetries expected in in QCD at NLO, 0.038 ± 0.006 in the lab frame and 0.058 ± 0.009 in the $t\bar{t}$ frame.

Additionally, we introduce a simple measurement of the parton level rapidity dependent asymmetry in two regions of the $t\bar{t}$ rapidity difference:

$$A(|\Delta y_t| < 1.0) = 0.026 \pm 0.104 \pm 0.055$$
$$A(|\Delta y_t| \geq 1.0) = 0.611 \pm 0.210 \pm 0.141$$

to be compared with the MCFM predictions of 0.039 ± 0.006 and 0.123 ± 0.018 for these Δy_t regions respectively.

1 Introduction

We report on a new study of the forward-backward charge asymmetry in $\mathrm{t\bar{t}}$ production at $\sqrt{s} = 1.96$ TeV, using 5.3fb^{-1} recorded with the CDF II Detector at the Fermilab Tevatron.

In QCD at LO, top production is symmetric. In NLO the soft Coulomb field of an incoming light quark repels the t quark to larger rapidity while attracting the $\bar{t}$ quark to smaller rapidities, creating a positive asymmetry at large η, as defined by the quark direction [1]. We have studied the effect using Version 5.7 of MCFM, a parton-level NLO Monte Carlo [2], with CTEQ6.1 (NLO) PDFs and $M_t = 172.5\mathrm{GeV}/c^2$. The MCFM predictions for the asymmetries in the two frames are $A_{\mathrm{lab}} = 0.038 \pm 0.006$ and $A_{\mathrm{t\bar{t}}} = 0.058 \pm 0.009$. Previous inclusive measurements at CDF and D0 have found large positive asymmetries that were nevertheless consistent with predictions within large uncertainites [3, 4, 5].

The cross section terms responsible for the QCD asymmetry are proportional to the β of the top/anti-top quarks in the center-of-mass, so the asymmetry increases with the rapidity separation of the two quarks. In MCFM, we find strong variation of the asymmetry with respect to $\Delta y = Y_t - Y_{\bar{t}}$, rising roughly linearly from A = 0.05 at $|\Delta y| = 0.5$ to A = 0.23 at $|\Delta y| = 2.5$.

We study lepton+jets events in which the $\mathrm{t\bar{t}}$ four-vectors are completely reconstructable using only mass constraints on the two top quarks and two W bosons in each event. The asymmetries are measured in the distributions of the top quark rapidity in lab frame and in the frame invariant $\mathrm{t\bar{t}}$ rapidity difference. Backgrounds are subtracted, and acceptance and smearing effects (as parameterized by Pythia after radiation) are deconvolved to yield distributions that can be compared to predictions for both the inclusive and the rapidity dependent asymmetry.

The $\mathrm{A_{fb}}$ is also a charge asymmetry, so that if CP is good, the asymmetries of top and anti-top will be equal and opposite. Previous results combine the top and anti-top events in a classic "$Q \cdot Y$" fashion to maximize statistical precision. The current dataset is large enough to test the consistency of the asymmetries in the separate charge species, as measured with the unambiguous lepton charge.

2 The Inclusive Forward-Backward Asymmetry

2.1 Sample and Reconstruction

This analysis uses $t\bar{t}$ events in the lepton plus jets channel where one top decays semi-leptonically ($t \rightarrow l\nu b$) and the other hadronically ($t \rightarrow q\bar{q}b$). Selection begins by requiring a single high transverse momentum electron or muon in the central portion of the detector ($|p_t| > 20$ GeV/c and $|\eta| < 1.1$). In addition, we require a large amount of missing transverse energy as evidence of the presence of a neutrino ($\not{E}_T \geq 20$ GeV). Each event must have four or more tight jets ($|E_t| > 20$ GeV/c and $|\eta| < 2.0$) and at least one jet must have at least two tracks that form a secondary vertex consistent with a b quark decay. The "b-jet" identification in the central region ($|\eta| < 1.0$) reduces the W plus light flavor background processes which dominate the event sample, and aids in the assignment of jets to partons in the $\mathrm{t\bar{t}}$ reconstruction. The backgrounds to this selection are estimated using data and Monte Carlo simulation based samples. The background analysis has been shown to provide accurate measures of both the normalizations and shapes of the non-$\mathrm{t\bar{t}}$ processes in the sample. The size of the backgrounds is estimated to be 283.3 ± 91.2 events and the signal to background ratio in the sample is $977/283 = 3.5$. Further details on the samples selection and backgrounds can be found in Reference [6].

The parton assignment and event reconstuction are performed using simple χ^2 based fit of the event kinematics to the $\mathrm{t\bar{t}}$ hypothesis. This is the same reconstruction used in the precision top mass measurements [7]. The reconstructed data is compared to a prediction made using the Pythia model of $\mathrm{t\bar{t}}$ ($M_t = 172.5\mathrm{GeV}/c^2$) at $\sigma = 7.1$ pb and our standard background model shapes and normalizations, all run through the full CDf detector simulation. Pythia has no charge asymmetries and represents a null signal. Validation comparisons of the data to the model for a compendium of interesting variables can be found from the link on our public page (`http://www-cdf.fnal.gov/physics/new/top/2010/tprop/Afb/`).

2.2 Rapidity Variables

The charge asymmetry appears as a difference between the distributions of t and $\bar{t}$ production angles or rapidities. In lepton plus jet events, the t and $\bar{\mathrm{t}}$ have distict signatures: one is a "leptonic" decay and a one is a "hadronic" decay. The t or $\bar{\mathrm{t}}$ assignments are different according to the lepton charge q_l:

The centrality of the b-tag and lepton ID create the possibility of acceptance biases. For example, in an event with a b-tagged leptonic decay, all of the leptonic measureables are centrally confined. This limits the rapidity range of the leptonic top, while meanwhile for the hadronic top system all its jets scan extend to $|\eta| \leq 2.0$. In order to

$\mathbf{q_l}$	$\mathbf{t_{lep}}$	$\mathbf{t_{had}}$
$+$	t	$\bar{t}$
$-$	$\bar{t}$	t

Table 1: The leptonic and hadronic systems in events with positive and negative leptons

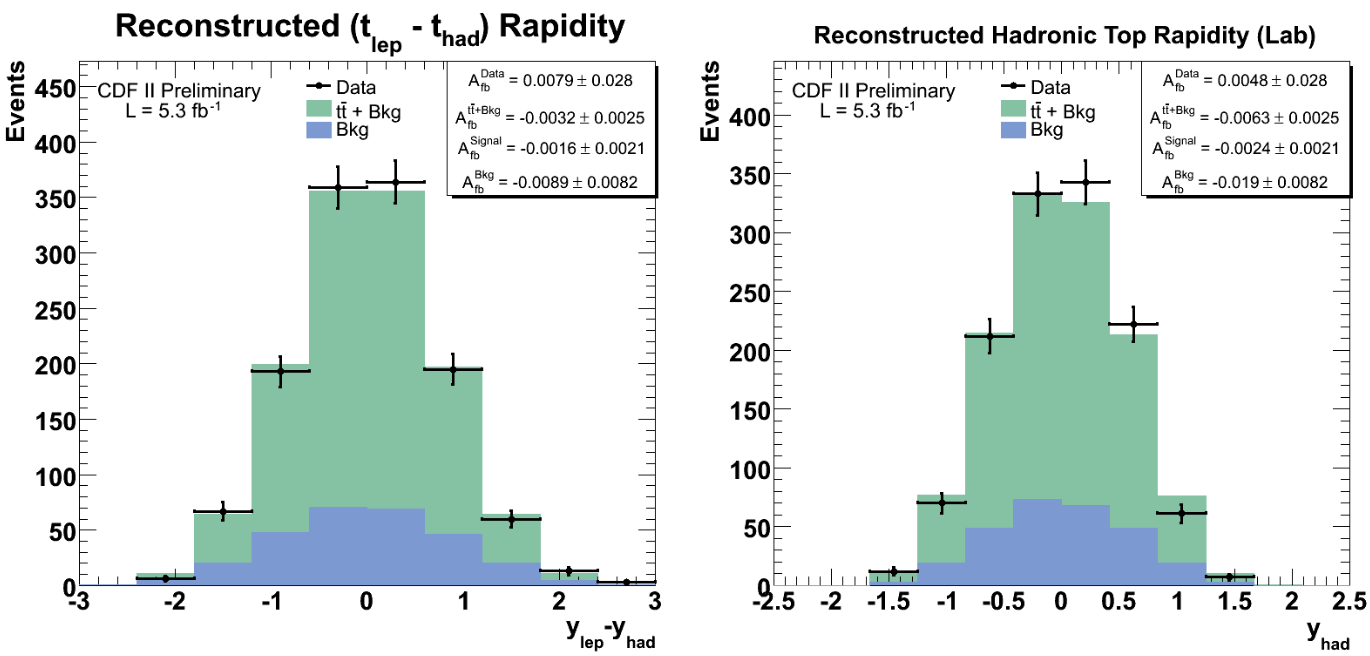

Figure 1: Rapidity distributions in data compared to the Pythia+ background prediction. Left: $\Delta y = y_{lep} - y_{had}$ Right: y_{had}

control effects of this kind, our treatment of top rapidity variables keeps the leptonic vs. hadronic distinction primary, with the conversion to t and $\bar{t}$ following according to Table 1.

The most direct measurement of the "top direction" is the lab rapidity of the hadronic top system, y_{had}. In events with a negative lepton, y_{had} is the lab rapidity of the t quark, $y_t^{\rm lab}$. In events with a positive lepton, y_{had} is the rapidity of the $\bar{\rm t}$ quark, $y_{\bar{\rm t}}^{\rm lab}$. If CP is good, $y_{\bar{\rm t}}^{\rm lab} = -y_t^{\rm lab}$, and we can combine both samples by weighting with the lepton charge. Keeping in mind that half the sample is hadronic $y_{\bar{\rm t}}^{\rm lab}$ going the other way, we therefore consider $-qy_{had}$ equivalent to $y_t^{\rm lab}$, the rapidity of the top quark in the lab frame. $y_t^{\rm lab}$ has good directional precision and η acceptance, at the cost of including an unknown boost from the q$\bar{\rm q}$ frame to the lab frame. The resulting bin-to-bin smearing in y_t^{lab} can be corrected for on average, and this is a major component in the unfold to the parton-level asymmetry.

An alternative, frame independent, variable is the rapidity difference of the leptonic and hadronic systems $\Delta y = y_{lep} - y_{had}$. After multiplication by the lepton charge q_l, this variable measures the frame independent difference between the top and antitop rapidities:

$$\begin{aligned} q\Delta y &= q(y_{lep} - y_{had}) && (1) \\ &= y_t^{\mathrm{lab}} - y_{\bar{t}}^{\mathrm{lab}} && (2) \\ &= \Delta y_t && (3) \end{aligned}$$

The rapidity difference $q\Delta y = \Delta y_t$ uses all of the information in the event, at the cost of adding complications from the $\not{E}_{\mathrm{T}}$ and unknown longitudinal motion of the leptonic side. It has the significant advantage of compensating for the $\mathrm{t\bar{t}}$ system motion. It can be shown that the top quark rapidity in the $\mathrm{t\bar{t}}$ rest frame is given simply by $y_t^{\mathrm{rest}} = \frac{1}{2}\Delta y_t$.

Since the transformation from angles to rapidities preserves sign, an asymmetry in $q\Delta y$ is identical to an asymmetry in the top quark production angle in the $\mathrm{t\bar{t}}$ rest frame.

Our analysis appeals to $-qy_{had} = y_t^{\mathrm{lab}}$ as the simplest most experimentally straightforward test of the existence of an asymmetry. The frame invariant variable $q\Delta y = \Delta y_t$ is most readily connected with mechanism of the asymmetry and will be used to study its rapidity dependence.

The inclusive distributions of the y_{had} and Δy variables are shown in Figure 1. The asymmetries in the data, the signal model, the background model, and the combined signal+background prediction are shown in the legend on the top right. The distributions in Figure 1 contain the full sample of both lepton signs and should be symmetric. For both variables the data agrees very well with prediction, and, in particular, the asymmetries in are consistent with zero.

2.3 Charge Dependent Forward-Backward Asymmetry

The asymmetry becomes apparent when the sample is partitioned by charge. We define the charge asummetry in Δy:

$$A^{\pm} = \frac{N^{\pm}(\Delta y > 0) - N^{\pm}(\Delta y < 0)}{N^{\pm}(\Delta y > 0) + N^{\pm}(\Delta y < 0)} \quad (4)$$

Note that this is before the sign weighting, $\Delta y = y_{lep} - y_{had}$. The top row of Figure 2 shows the Δy distributions for events with negative leptons (left) and positive (right). We find $A^{+} = +0.067 \pm 0.040$ and $A^{-} = -0.048 \pm 0.039$, equal and opposite with modest significance. We also define the charge asymmetry in hadronic top system:

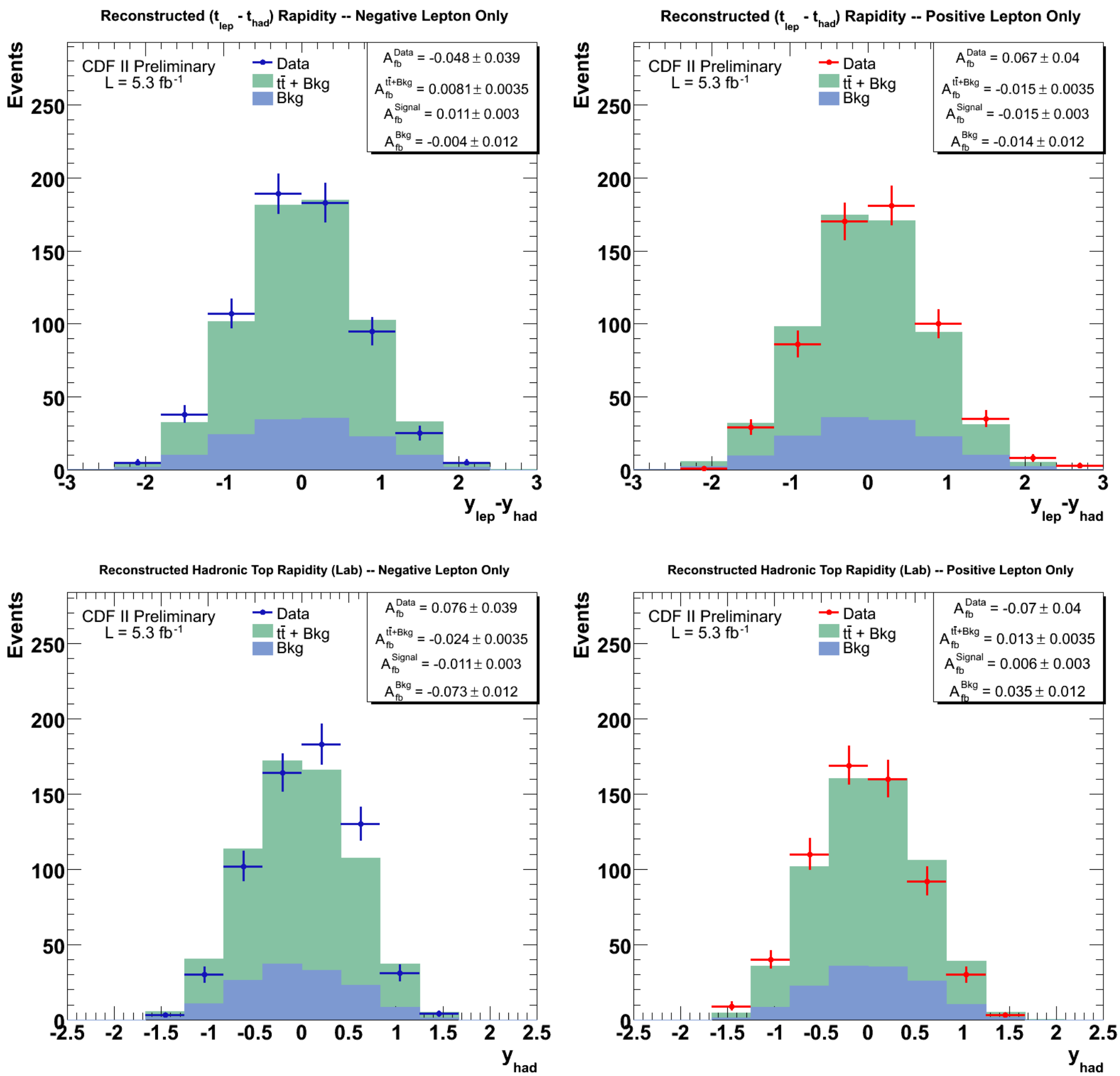

Figure 2: Top: Δy distribution for events with negative leptons (left) and positive leptons (right). Bottom: y_{had} distribution for events with negative leptons (left) and positive leptons (right).

$$A^{\pm}_{lab} = \frac{N^{\pm}(y_{had} > 0) - N^{\pm}(y_{had} < 0)}{N^{\pm}(y_{had} > 0) + N^{\pm}(y_{had} < 0)} \tag{5}$$

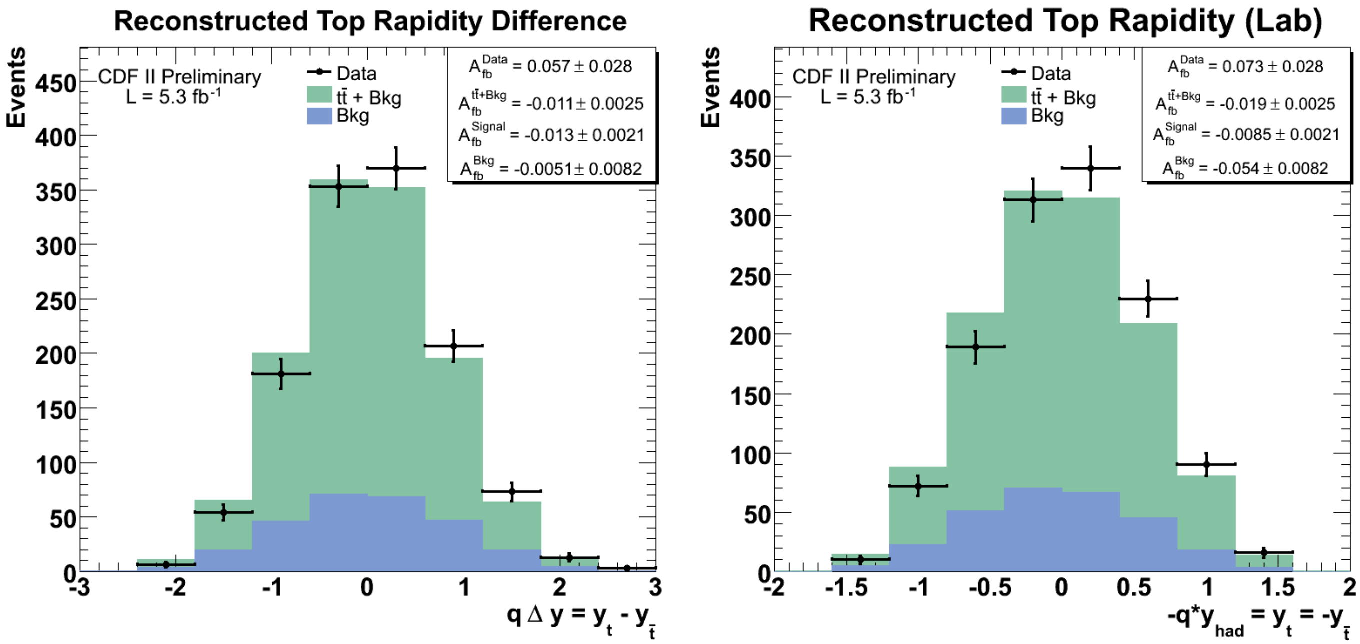

Figure 3: $q\Delta y$ and qy_{had} distributions in data vs prediction.

The bottom row of Figure 2 shows the y_{had} distributions for events with positive leptons (left) and negative leptons (right). Using Table 1, this figure suggests a preference for the t quarks to move in the proton (forward) direction and the $\bar{\mathrm{t}}$ quarks to move in the $\bar{p}$ direction. The measured asymmetries are $A^{+}_{lab} = -0.070 \pm 0.040$ and $A^{-}_{lab} = +0.076 \pm 0.039$, equal and opposite with moderate statistical significance.

We measure the total CP conserving asymmetry by combining the separate charge samples after weighting the distributions by lepton charge q, so that in the sense of Table 1, and assuming the CP consistent inversion $y_t = -y_{\bar{\mathrm{t}}}$, $-qy_{had} = y_t$ and $q\Delta y = y_t - y_{\bar{\mathrm{t}}}$

We define the frame independent asymmetry

$$A = \frac{N(q\Delta y > 0) - N(q\Delta y < 0)}{N(q\Delta y > 0) + N(q\Delta y < 0)} \quad (6)$$

$$= \frac{N((y_t - y_{\bar{\mathrm{t}}}) > 0) - N((y_t - y_{\bar{\mathrm{t}}}) < 0)}{N((y_t - y_{\bar{\mathrm{t}}}) > 0) + N((y_t - y_{\bar{\mathrm{t}}}) < 0)} \quad (7)$$

$$(8)$$

and the lab frame asymmetry

$$A_{lab} = \frac{N(qy_{had} > 0) - N(y_{had} < 0)}{N(qy_{had} > 0) + N(qy_{had} < 0)} \quad (9)$$

$$= \frac{N(y_t > 0) - N(y_t < 0)}{N(y_t > 0) + N(y_t < 0)} \quad (10)$$

$$(11)$$

The distributions of these variables are shown in Figure 3. The frame independent asymmetry is $A = 0.057 \pm 0.028$, and the inclusive asymmetry in the lab frame is $A_{lab} = 0.073 \pm 0.028$.

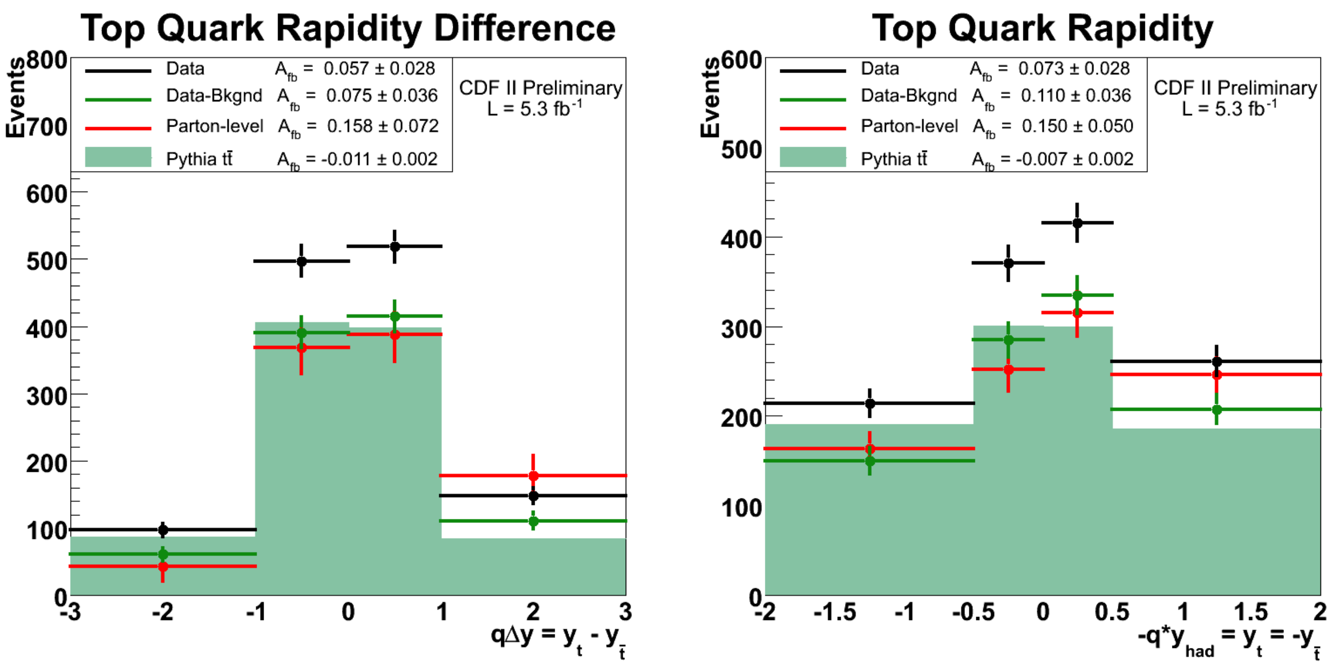

Figure 4: Four-bin reresentation of $q\Delta y = y_t^{\text{rest}}$ and $-qy_{had} = y_t^{lab}$ with background subtraction and unfold.

2.4 Correction to the Parton-Level

In to compare our results to theoretical predictions we must correct our detector level measurements for backgrounds, for detector acceptance losses and the finite rapidity resolution of the reocnstruction. The background correction is the straightforward subtraction of our standard background model.

For calculation of the rapidity distributions and asymmetries at the parton level, we employ a simple linear unfold in the four rapidity bins based on acceptance and smearing effects as measured with the Pythia ttop25 simulation. The binning is optimized to minimize the uncertainty in the correction, with the intermediate bin-edge put at $|\Delta y_t| = 1.0$ or $|y_t^{\rm lab}| = 0.5$. More detail on the procedure for correction to the parton level can be found in Reference [5].

Figure 4 shows the Δy_t and y_t distributions in the 4-bin representation used in References [5, 8]. The black marker shows the data and the green marker is the data after background subtraction. The green histogram is the Pythia $t\bar{t}$ model. The background subtracted data is near the background-free prediction, but continues to show the asymmetries.

The red marker shows the rapidity distributions after correcting for acceptance and bin migration. The corrected inclusive asymmetries, which represent the physics at the parton level in the assumption of Pythia acceptance and reconstruction, are $A = 0.158 \pm 0.072$ and $A_{lab} = 0.150 \pm 0.050$.

Uncertainties enter the measurement through our model assumptions, notably with respect the backgrounds, our generator models for additional jets, parton distribution functions, and color reconnection, and the energy scale of the calorimeter. These additional systematic uncertainties are propagated into the result by repeating the analysis with reasonable variations in the model assumptions, leading to the systematic uncertainities shown in Table 3.

The correction of course is dependent on the input physics model and the corrections for a real asymmetry may differ from the predictions of the symmetric Pythia. We have studied this using a Madgraph model of a simple axigluon whose couplings and mass are tuned to give a good representation of the data. When the correction response is derived from this model, we find the maximal excursion in the corrected inclusive asymmetries varies by roughly ~ 0.02.

In one final study of systematic effects we separate the sample according to whether the events contain one or two b-tags. The two asymmetries in these two samples at the data level are shown in Table 4. The $q\Delta y$ results are consistent across the tagging variation. The qy_{had} variable shows an absence of asymmetry in double tags and a larger asymmetry in single tags. These numbers are compatible within the large systematic uncertainty.

The asymmetries in the raw data, in the backgrounds (a la M24U), in the background subtracted data, and fully corrected to the parton level are summarized in Table 5, along with the expected NLO QCD asymmetry predicted by MCFM. The lab frame asymmetry is 3σ from null, and more than 2σ from the MCFM prediction.

Systematic Uncertainty	qy_{had}	$q\Delta y_t$	$A_{fb}(\lvert q\Delta y\rvert < 1.0)$	$A_{fb}(\lvert q\Delta y\rvert > 1.0)$
Background size	0.012	0.006	0.003	0.030
Background shape	0.011	0.004	0.003	0.015
Total Uncertainty	0.016	0.007	0.004	0.033

Table 2: Systematic Uncertainties for Data-Background A_{fb}
CDF II Preliminary, L = 5.3 fb^{-1}

Systematic Uncertainty	qy_{had}	$q\Delta y_t$	$A_{fb}(\lvert q\Delta y\rvert < 1.0)$	$A_{fb}(\lvert q\Delta y\rvert > 1.0)$
Background size	0.015	0.011	0.002	0.086
Background shape	0.014	0.007	0.005	0.107
ISR/FSR	0.010	0.001	0.004	0.004
JES	0.003	0.007	0.002	0.003
PDF	0.005	0.005	0.054	0.013
Color Reconnection	0.001	0.004	0.007	0.007
MC Generator	0.005	0.005	0.004	0.033
Total Uncertainty	0.016	0.007	0.004	0.033

Table 3: Systematic Uncertainties for Corrected Data A_{fb}
CDF II Preliminary, L = 5.3 fb^{-1}

	$q\Delta y$	qy_{had}
inclusive	0.057 ± 0.028	0.073 ± 0.028
single tags	0.058 ± 0.032	0.095 ± 0.032
double tags	0.053 ± 0.060	-0.004 ± 0.060

Table 4: Asymmetries in all b-tagged events, single b-tags, and double b-tags.
CDF II Preliminary, L = 5.3 fb^{-1}

	$q\Delta y$	qY_{had}
data	0.057 ± 0.028	0.073 ± 0.028
data-bkgd	$0.075 \pm 0.036 \pm 0.007$	$0.110 \pm 0.036 \pm 0.016$
corrected	$0.158 \pm 0.072 \pm 0.017$	$0.150 \pm 0.050 \pm 0.024$
mcfm	0.058 ± 0.009	0.038 ± 0.038

Table 5: Summary of inclusive asymmetries.
CDF II Preliminary, L = 5.3 fb^{-1}

3 Rapidity Dependence of the Asymmetry $A(\Delta y_t)$

In the NLO QCD effect we expect a linear dependence of the asymmetry on Δy_t. The MCFM prediction rises roughly linearly from A = 0.05 at $|\Delta y| = 0.5$ to A = 0.23 at $|\Delta y| = 2.5$. In our binned data, we would calculate this as

$$A(\Delta y_t) = \frac{N(\Delta y_t) - N(-\Delta y_t)}{N(\Delta y_t) + N(-\Delta y_t)} \tag{12}$$

The differential asymmetry observed in the data, and in the background subtracted data is shown on the left in Figure 5. The asymmetry is an increasing function of Δy_t.

A two-bin parton-level measurement of this function is available if we use the full binning of the corrected Δy_t distribution in Figure 4. We calculate the asymmetry separately for the low rapidity difference inner bin pair $|\Delta y| < 1.0$ and the high rapidity difference outer bin pair $|\Delta y| > 1.0$. In Table 6 and Figure 5 right, we show the asymmetry in the two bins for the raw, background subtracted data, and fully corrected distributions. The small data level asymmetry in the central bin leads to a small parton level value with large error. In the high Δy_t region the background corrected data has asymmetry is $A = 0.291 \pm 0.090$, and after the acceptance and migration corrections the parton level asymmetry is $A = 0.611 \pm 0.210$ compared to the MCFM prediction of 0.123 ± 0.014. Additional systematic uncertainties in this result are evaluated in the same manner as in the inclusive measurement. A summary of our inclusive and rapidity dependent measurement of the $t\bar{t}$ production asymmetry in Δy_t is given in Table 6.

Note that this $A(\Delta y_t)$ decomposition uses the same information as the inclusive result, and the system of asymmetries is internally consistent by definition. The 3σ inclusive asymmetry is apparently concentrated at high Δy_t. MCFM predicts a linear growth in $A(\Delta y_t)$. Measured across our two large bins, we see an increase but the apparent slope, within the limits of our large error, is much larger.

	all $q\Delta y$	$\lvert q\Delta y\rvert < 1.0$	$\lvert q\Delta y\rvert \geq 1.0$
data	0.057 ± 0.028	0.021 ± 0.031	0.208 ± 0.062
data-bkgd	$0.075 \pm 0.036 \pm 0.007$	$0.029 \pm 0.040 \pm 0.004$	$0.291 \pm 0.090 \pm 0.033$
corrected	$0.158 \pm 0.072 \pm 0.017$	$0.611 \pm 0.210 \pm 0.141$	$0.611 \pm 0.210 \pm 0.141$
mcfm	0.058 ± 0.007	0.039 ± 0.005	0.123 ± 0.014

Table 6: Asymmetries inclusively, and at central and high rapidity difference
CDF II Preliminary, L = 5.3 fb^{-1}

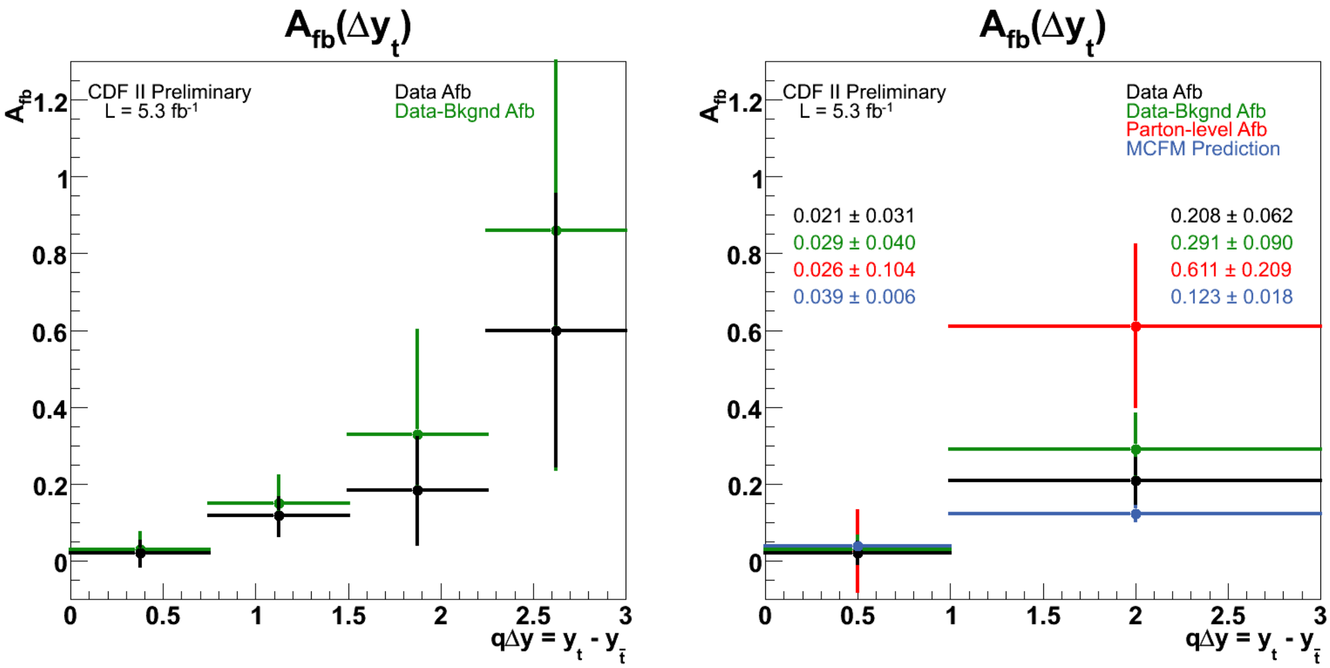

Figure 5: Left: Differential Asymmetry vs. Δy_t in data, using 4 bins.
Right: "Two-bin" rapidity dependence inclusing correction to parton level

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