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Forward-Backward Asymmetry in Top-Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present measurements of the forward-backward charge asymmetry in top pair production using 1.9 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded with the Collider Detector at Fermilab II. Correcting for acceptance and measurement dilutions we obtain parton-level asymmetries of $A_{\mathrm{FB}}^{p\bar{p}} = 0.17 \pm 0.08$ in the $p\bar{p}$ frame and $A_{\mathrm{FB}}^{t\bar{t}} = 0.24 \pm 0.14$ in the $t\bar{t}$ frame. The values are consistent with the standard model expectation and disfavor exotic production mechanisms with significant negative values.

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The top quark, discovered in 1995 by both Tevatron experiments [1], is the only known fermion with a mass of the order of the electroweak breaking scale. This suggests that it may play a special role in new physics. A detailed investigation of the production mechanism of top quarks will give insights into whether top quarks are produced via new physics processes.

In this Letter we present two analyses studying the forward-backward charge asymmetry of top quark pairs in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron. In standard model QCD a charge asymmetry A_C arises in next-to-leading order $t\bar{t}X$ production. Because the strong interaction is invariant under charge conjugation A_C is equivalent to a forward-backward asymmetry A_{FB}. Recent calculations predict a slightly positive total $A_{FB} = 5.0 \pm 1.5\%$ in the Tevatron $p\bar{p}$ rest frame [2,3], with the theoretical uncertainty driven by the size of corrections at higher orders. This small total A_{FB} combines a positive asymmetry from the interference of the Born and virtual (box) corrections ($t\bar{t}$) with a negative asymmetry from interference of initial and final state radiation amplitudes ($t\bar{t} + g$) [4].

While the total A_{FB} value expected by the standard model is hardly measurable at the presently achievable precision, we are sensitive to large A_{FB} values (of order $\pm 30\%$) predicted in some models with new physics, e.g. Z'-like states with parity violating couplings [5] and theories with chiral color [2,6]. In contrast to searches for heavy resonances in the spectrum of the mass of the top pair [7], a measurement of A_{FB} is sensitive to both narrow and broad resonances. In addition, the presence of a massive gluon may be visible in the asymmetry even above the collision energy due to interference with the standard model gluon.

Since a longitudinal boost changes the top quark direction, A_{FB} is frame dependent. Undetected collinear gluon radiation makes the fundamental initial parton frame experimentally inaccessible. However, the $t\bar{t}$ and the $p\bar{p}$ frame are experimentally accessible and according to [2] the A_{FB} values in the $p\bar{p}$ frame are predicted to be reduced by $\approx 30\%$ relative to the $t\bar{t}$ frame.

We present here the first measurement of the top-quark production A_{FB}, fully corrected to the parton level, in both the $p\bar{p}$ and $t\bar{t}$ frames. Correction to the intrinsic parton value allows direct comparison to theoretical prediction, and measurements in two frames probe the consistency and the frame dependence of the effect. A recent study [8] measures a quantity which is related to the $t\bar{t}$ frame asymmetry but is uncorrected for acceptance and resolution effects. The result $(12 \pm 8 \pm 1)\%$ is larger than expected, within errors, but difficult to interpret.

We use 1.9 fb^{-1} of $p\bar{p}$ collision data recorded by the Collider Detector at Fermilab II (CDF). The detector is a forward-backward symmetric system consisting of a magnetic spectrometer surrounded by projective calorimeters and muon detectors [9]. Charged track reconstruction in a 1.4 T axial field uses a large open cell drift chamber and silicon microstrip detectors for displaced secondary vertex detection. We use coordinates where ϕ is the azimuthal angle and θ is the polar angle with respect to the proton beam z axis. Transverse energy is $E_T = E\sin\theta$, the rapidity is $Y = \frac{1}{2}\ln[(E + p_z)/(E - p_z)]$, and the pseudorapidity is $\eta = -\ln[\tan(\theta/2)]$.

We collect a sample of candidate events in the lepton + jets topology $t\bar{t} \rightarrow (W^+ b)(W^- \bar{b}) \rightarrow (q\bar{q}' b)(\ell^- \bar{\nu}_\ell \bar{b})$ [10], where one W-boson decays leptonically and the other hadronically, by triggering on a central ($|\eta| \leq 1.0$) electron with $E_T > 18$ GeV or central muon with transverse momentum $p_T > 18$ GeV/c. After offline reconstruction we select events with an isolated electron with $E_T \geq 20$ GeV or muon with $p_T \geq 20$ GeV/c, missing transverse energy $\not{E}_T \geq 20$ GeV [11] consistent with a neutrino from W decay, and at least four hadronic jets with $|\eta| \leq 2.0$ and $E_T \geq 20$ GeV. Jets are clustered in fixed cones of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$ and jet energies are corrected to parton-level values [12]. At least one jet must be b tagged, i.e., contain a reconstructed secondary vertex consistent with the decay of a bottom hadron in the jet [13]. We find 484 candidate events.

The expected $t\bar{t}$ signal is studied using the PYTHIA, HERWIG, and MC@NLO event generators [14] and a full detector simulation [15]. The top quark mass is set equal to $M_t = 175$ GeV/c^2. The rates and kinematics of background processes are well modeled with simulation and data control samples [16] which will be discussed later. We expect a total of 87 ± 23 background events, leaving a $t\bar{t}$ signal of 397 ± 32 events, consistent with our previous cross-section measurement of 8.2 ± 1.0 pb [17].

Mass constraints on the W bosons from top quark decay fix the jet parton assignment and allow complete reconstruction of the $t\bar{t}$ kinematics. For the $p\bar{p}$ frame analysis we use the algorithm employed in the top quark mass measurement of Ref. [18]. Measured jet energies float within expected resolutions, b-tagged jets are taken as fragmented b quarks, both W boson masses $M(\ell\nu)$ and $M(q\bar{q}')$ are constrained to 80.4 GeV/c^2, and the top quark mass is constrained to 175 GeV/c^2. For the $t\bar{t}$ frame analysis we use the technique described in Refs. [19] which employs constraints on the W boson masses, the reconstructed t-$\bar{t}$ mass difference (but not M_t), the total transverse energy, and the b likelihood of the jets [20]. In simulated $t\bar{t}$ samples the two procedures resolve the top direction with similar accuracy. The resolution on the direction of the hadronically decaying top quark t_h, expressed in terms of rapidity, is $\sigma_Y(t_h) \simeq 0.29$. The leptonically decaying top quark system t_l, which includes the indirectly measured neutrino, has $\sigma_Y(t_\ell) \simeq 0.46$ and significant non-Gaussian tails (15%).

We measure the direction of the top quark in the $p\bar{p}$ center-of-mass frame using the cosine of the polar angle between the hadronic top quark and the proton beam,

TABLE I. Measured asymmetries in large simulated $t\bar{t}$ samples.

Generator	Parton-level $A_{\mathrm{FB}}^{p\bar{p}}$	Reconstructed $A_{\mathrm{FB}}^{p\bar{p}}$	Parton-level $A_{\mathrm{FB}}^{t\bar{t}}$	Reconstructed $A_{\mathrm{FB}}^{t\bar{t}}$
PYTHIA	0.000 ± 0.003	-0.007 ± 0.006	0.000 ± 0.001	-0.005 ± 0.003
HERWIG	0.000 ± 0.006	-0.013 ± 0.012	-0.003 ± 0.002	-0.003 ± 0.006
MC@NLO	0.038 ± 0.002	0.015 ± 0.016	0.049 ± 0.002	0.017 ± 0.007

$\cos\alpha_p$. The sign of the t_h electric charge is opposite that of Q_ℓ, the leptonic charge observed in the t_l decay. Assuming CP invariance, we find one top quark angle $\cos\theta = -Q_\ell \cdot \cos\alpha_p$ in each event and calculate the asymmetry in the $p\bar{p}$ center-of-mass frame [21]

$$A_{\mathrm{FB}}^{p\bar{p}} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}. \tag{1}$$

This technique has the simplicity of relying only on the hadronic top quark reconstruction, but has the drawback of measuring asymmetries which are diluted by 30% compared to the $t\bar{t}$ frame.

The $t\bar{t}$ rest frame measurement exploits the Lorentz invariant difference between the t and $\bar{t}$ rapidities Y_t and $Y_{\bar{t}}$. We use the reconstructed rapidity of t_ℓ and t_h in each event, assume CP invariance, and determine $\Delta Y = Y_t - Y_{\bar{t}} = Q_\ell \cdot (Y_{t_\ell} - Y_{t_h})$ from which we calculate the asymmetry in the approximate (LO) $t\bar{t}$ rest frame [22]

$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta Y > 0) - N(\Delta Y < 0)}{N(\Delta Y > 0) + N(\Delta Y < 0)}. \tag{2}$$

To connect this with other asymmetry measurements, we note that in the case of ideal resolution $A_{\mathrm{FB}}^{t\bar{t}}$ reproduces the asymmetry measured in the equivalent Collins-Soper frame [23]. While it is sensitive to the larger $t\bar{t}$ frame asymmetry, ΔY combines the uncertainties of both quark reconstructions, including the neutrino-related complications of the t_ℓ quark system.

The expected measurement performance is evaluated using simulated samples. In Table I we compare asymmetries found after selection and reconstruction to parton-level asymmetries calculated using perfect acceptance and resolution. The uncertainties reflect the simulation statistics. With the parton-shower generators PYTHIA and HERWIG we see no intrinsic charge asymmetry at the parton level, as expected, and verify that any forward-backward bias from selection and reconstruction is small. With the MC@NLO generator, which includes the small QCD-induced charge asymmetry, we find parton-level values consistent with theoretical expectation in magnitude and the level of frame dependence. With large statistics the measured values are sensitive to the small asymmetry, but diluted by acceptance and reconstruction effects. Dilution corrections, as well as the expected sensitivity in our finite data set, are discussed later. The calibration of the simulation to the physical detector geometry and acceptance has been checked in studies of electroweak processes [24]. For example, the leptonic charge asymmetry in $W^\pm \to l^\pm \nu$ agrees with our simulated physics and detector model within the statistical uncertainty of ≈ 0.004.

The A_{FB} measured in data must be corrected for background contributions which include asymmetric weak processes. W + jets events with tagged heavy flavor (W + hf) or mistagged light partons (W + lf) are modeled using ALPGEN [25] interfaced to PYTHIA parton showering, along with b tagging and mistagging rates parametrized from jet data. Small electroweak backgrounds (EW), WW, WZ, ZZ and single-top, are modeled with PYTHIA and with MADEVENT [26], respectively. The non-W (QCD) electron background is studied using data events with five jets where one jet models a misreconstructed electron; the same sample is used for non-W muons after reweighting the lepton acceptance. The background levels and asymmetries expected in the two analyses are shown in Table II. The combined results are listed in the last row.

Figure 1 shows the measured distributions of $\cos\theta$ and ΔY in the 484 b-tagged $t\bar{t}$ candidates, along with predictions based on simulated $t\bar{t}$ events from the MC@NLO generator in combination with our non-$t\bar{t}$ background models. The measured asymmetries are displayed in Table III. The background-corrected values, derived by subtracting the composite model shape bin-by-bin, show a positive asymmetry which is larger than but consistent with the MC@NLO predictions within uncertainties. Our background-corrected $A_{\mathrm{FB}}^{t\bar{t}}$, although measured in a slightly different visible phase space, is very consistent with the measurement from the D0 Collaboration [8]. Subdividing the data by lepton types and lepton charges shows a consistent positive asymmetry across all samples.

To study the two contributions $t\bar{t}$ and $t\bar{t} + g$ with different expected sign in A_{FB}, we split our data sample into events without any additional hard jet ($N_{\mathrm{jets}} = 4$, 85% $t\bar{t}$) and events with at least one additional hard jet ($N_{\mathrm{jets}} \geq 5$, 53% $t\bar{t} + g$). Our background-corrected $A_{\mathrm{FB}}^{p\bar{p}}$ and $A_{\mathrm{FB}}^{t\bar{t}}$ val-

TABLE II. Backgrounds, estimated number of events N_{exp}, and their effective asymmetries.

Process	N_{exp}	$A_{\mathrm{FB}}^{p\bar{p}}$	$A_{\mathrm{FB}}^{t\bar{t}}$
W + hf	37 ± 10	-0.087 ± 0.005	-0.045 ± 0.003
W + lf	20 ± 5	0.044 ± 0.008	-0.006 ± 0.015
EW	12 ± 1	-0.022 ± 0.014	-0.015 ± 0.044
QCD	18 ± 16	-0.008 ± 0.004	0.006 ± 0.010
Total	87 ± 23	-0.053 ± 0.004	-0.021 ± 0.007

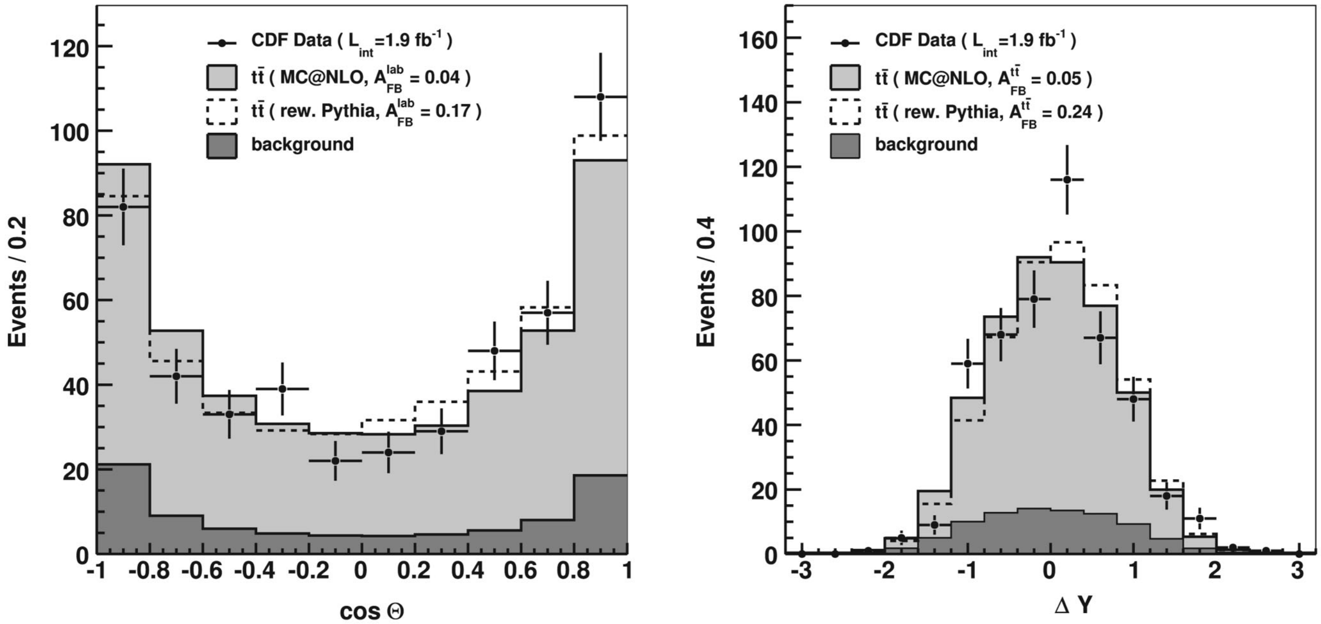

FIG. 1. The two top-quark production angle variables, cosθ for the $p\bar{p}$ frame and ΔY for the $t\bar{t}$ frame. The solid line is the prediction for $t\bar{t}$ with MC@NLO model of the QCD-induced charge asymmetry and $\sigma_{t\bar{t}} = 8.2$ pb, plus the expected non-$t\bar{t}$ backgrounds. The dashed curve shows the prediction when $t\bar{t}$ is reweighted according to the form $1 + A_{\rm FB}\cos\alpha$ using measured values of $A_{\rm FB}$.

ues for this study are presented in Table III. The $N_{\rm jets}$ dependence is not as strong as seen in [8], but the limited statistics does not allow a firm conclusion.

The distributions in Fig. 1 are distorted from their true parton-level shapes by acceptance bias and reconstruction errors. We use a matrix inversion technique to derive the parton-level distributions and $t\bar{t}$ asymmetries. If an event in bin j at parton level is collected with efficiency ϵ_j and migrates to bin i at the measurement level with probability S_{ij}, the bin-by-bin parton-level distributions P_j can be found from the background-corrected data distributions D_i by the inverse transformation

$$P_j = \epsilon_j^{-1} S_{ji}^{-1} D_i. \qquad (3)$$

We simplify each distribution to four bins, with two bins on either side of the crossover at cos$\theta = \Delta Y = 0$. The efficiencies and migration matrix S_{ij} are derived by comparing the parton and reconstructed level quantities using the zero asymmetry PYTHIA $t\bar{t}$ simulations. In the cos$\theta(\Delta Y)$ analysis roughly 13% (25%) of events change signs, but the matrix is symmetric within uncertainties. The symmetry of the matrix, which follows from the forward-backward symmetry of the detector, ensures that the inversion is insensitive to small errors in the modeling of the migration parameters.

The expected performance of the complete calculation is evaluated with simulated samples. Sensitivity to the asymmetry model is studied using PYTHIA samples that have been reweighted in the top-quark production angle for a range of possible asymmetry functions and magnitudes varying between 0.0 and 0.30. Sensitivity to the QCD-induced asymmetry is studied with MC@NLO. The effect of extra jets is studied with exclusive $t\bar{t} + 0$ parton and $t\bar{t} +$ 1 parton samples made with the ALPGEN generator. Each sample was reconstructed, measured, and propagated back to the parton level with the procedures described above. For all conditions the procedure returns mean values within 0.02 of the true value. The predicted statistical precisions in our 1.9 fb^{-1} data set are $\delta A_{\rm FB}^{p\bar{p}} = 0.09$ and $\delta A_{\rm FB}^{t\bar{t}} = 0.13$.

Additional sources of uncertainty are evaluated using simulated samples with reasonable variations on the assumptions for background shape and normalization, signal shapes, the top quark mass, the parton distribu-

TABLE III. Predicted (MC@NLO + non-$t\bar{t}$) and measured asymmetries without further corrections.

	$N_{\rm jets}$	Predicted $A_{\rm FB}^{p\bar{p}}$	Measured $A_{\rm FB}^{p\bar{p}}$	Predicted $A_{\rm FB}^{t\bar{t}}$	Measured $A_{\rm FB}^{t\bar{t}}$
Recontructed data	≥ 4	0.001 ± 0.010	0.099 ± 0.045	0.010 ± 0.007	0.087 ± 0.045
Background subtracted	≥ 4	0.015 ± 0.016	0.130 ± 0.055	0.017 ± 0.007	0.119 ± 0.064
	$= 4$	0.032 ± 0.018	0.120 ± 0.064	0.038 ± 0.008	0.132 ± 0.075
	≥ 5	-0.027 ± 0.032	0.160 ± 0.109	-0.033 ± 0.012	0.079 ± 0.123

tion functions, the amount of initial and final state gluon radiation, and the calorimeter energy scale. The largest uncertainty in the $A_{\mathrm{FB}}^{p\bar{p}}$ analysis is the background normalization and the largest in the $A_{\mathrm{FB}}^{t\bar{t}}$ analysis is the ΔY shape modeling, being roughly $\delta A_{\mathrm{FB}} \simeq 0.02$ in each. The total systematic uncertainty is $\delta A_{\mathrm{FB}} = 0.04$ for both techniques.

Applying our algorithm to the inclusive background-subtracted distributions in Fig. 1, we find parton-level asymmetries of $A_{\mathrm{FB}}^{p\bar{p}} = 0.17 \pm 0.07 \pm 0.04$ and $A_{\mathrm{FB}}^{t\bar{t}} = 0.24 \pm 0.13 \pm 0.04$, where the uncertainties are statistical and systematic, respectively. In Fig. 1, the dashed lines show that the data are in good agreement with models derived by reweighting the generated top-quark production angle α in the symmetric PYTHIA sample with form $1 + A_{\mathrm{FB}} \cos\alpha$ using the measured A_{FB}.

In conclusion, we have measured a forward-backward and (equivalent) charge asymmetry in a strong process at high energy using reconstructed $t\bar{t}$ events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We find forward-backward parton-level asymmetries of $A_{\mathrm{FB}}^{p\bar{p}} = 0.17 \pm 0.08$ in the $p\bar{p}$ frame and $A_{\mathrm{FB}}^{t\bar{t}} = 0.24 \pm 0.14$ in the $t\bar{t}$ frame. Our results show the expected frame dependence, are consistent ($\leq 2\sigma$) with the small (~ 0.05) charge asymmetry expected from QCD, and they disfavor exotic sources of top-quark production with significant negative A_{FB} values [2].

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