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

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Abstract

Reconstructable final state kinematics and charge assignment in the reaction $p\bar{p} \rightarrow t\bar{t}$ allows tests of discrete strong interaction symmetries at high energy. We define frame dependent forward-backward asymmetries for the outgoing top quark in both the $p\bar{p}$ and $t\bar{t}$ rest frames, correct for experimental distortions, and derive values at the parton-level. Using 1.9 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded with the CDF II detector at the Fermilab Tevatron, we measure forward-backward top quark production asymmetries in the $p\bar{p}$ and $t\bar{t}$ rest frames of $A_{\mathrm{FB}}^{p\bar{p}} = 0.17 \pm 0.08$ and $A_{\mathrm{FB}}^{t\bar{t}} = 0.24 \pm 0.14$.

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Although QCD is in concordance with measurements at high energy particle colliders, the discrete symmetries of the strong interaction are not well tested at momentum transfers above a few GeV [1]. The utility of the $p\bar{p}$ initial state for the study of strong interaction symmetries was emphasized almost fifty years ago [2], but the information loss in final state parton fragmentation has limited the practicality of these studies at high energies.

We present here two measurements of a forward-backward asymmetry in top quarks produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron. Top quarks are strongly pair produced through single gluon $q\bar{q}$ annihilation (85%) and gluon-gluon fusion (15%) [3, 4]. In events where one top quark undergoes a weak semileptonic decay, the $t\bar{t}$ kinematics are reconstructable and the sign of the lepton charge fixes the charges of all final state partons. These events are a laboratory for symmetry tests in a strong production process at energies above $2M_t \simeq 350$ GeV/c^2.

Taking $N_t(p)$ as the number of top quarks moving in the proton direction we define the integrated forward-backward asymmetry

$$A_{\mathrm{FB}} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}. \tag{1}$$

Unexpected sources of a non-zero A_{FB} in top pair production include Z'-like states with parity violating couplings [5] and theories with chiral color [6, 7]. Asymmetries in these cases can be large (of order 30%) and potentially sensitive to new heavy states above the collision energy.

With the assumption of charge-conjugation invariance, A_{FB} is equivalent a charge asymmetry

$$A_{\mathrm{C}} = \frac{N_t(p) - N_{\bar{t}}(p)}{N_t(p) + N_{\bar{t}}(p)}. \tag{2}$$

In QCD, a small A_{C} arises for $p\bar{p} \to t\bar{t}$ in analogy with the well-known α^3 QED effect in $e^+e^- \to \mu^+\mu^-$ [8]. A positive asymmetry from the interference of the Born and virtual (box) corrections combines with a negative asymmetry from interference of initial and final state radiation amplitudes ($t\bar{t} + g$) [9, 10]. Recent calculations suggest a net positive $A_{\mathrm{C}} = 5.0 \pm 1.5\%$ in the Tevatron $p\bar{p}$ rest frame [11–14], with the theoretical uncertainty driven by the size of corrections at next-to-leading order. The A_{FB} from this charge asymmetry defines the baseline expectation for our measurement.

Since a longitudinal boost changes the top quark direction, A_{FB} is frame dependent. Undetected collinear gluon radiation makes the fundamental $q\bar{q}$ frame experimentally inacessible. We explore the frame dependence of the physics and measurement by defining and evaluating asymmetries in both the $p\bar{p}$ (lab) and $t\bar{t}$ rest frames. The two results are related through the parton distribution functions, with the $p\bar{p}$ frame value reduced by $\approx 30\%$ relative to the $t\bar{t}$ frame [11]. The two measurements use partially different detector information and have partially independent uncertainties. In both cases we correct for acceptance and measurement dilutions in order to calculate the intrinsic parton-level value of the asymmetry.

We use 1.9 fb^{-1} of $p\bar{p}$ collision data recorded by the CDF II detector. The detector is a forward-backward symmetric system of magnetic spectrometer surrounded by projective calorimeters and muon detectors [15]. 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 $\mathrm{Y} = \frac{1}{2}\ln[(E+p_z)/(E-p_z)]$, and the pseudorapidity is $\eta = -\ln[\tan(\theta/2)]$.

We collect a sample of candidate events in the lepton+jets topology $t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (q\bar{q}'b)(\ell^-\bar{\nu}_\ell\bar{b})$ [16] 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 [17] 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 [18]. 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 [19]. We find 484 candidate events.

The expected $t\bar{t}$ signal is studied using the PYTHIA, HERWIG, and MC@NLO event generators [20–23] and a full detector simulation [24]. The top quark mass is set at $M_t = 175$ GeV/c^2. The rates and kinematics of background processes are well modeled with simulation and data control samples [25] which will be discussed later. We expect a total of 87 ± 23 background events, leaving a signal of 397 ± 32 events, consistent with our previous cross-section measurement of 8.2 ± 1.0 pb [26].

In the lepton+jets final state, intermediate state mass constraints 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. [27]. Measured jet energies float within expected resolutions, b-tagged jets are taken as b-quarks, both W

boson masses $M(\ell\nu)$ and $M(q\bar{q}')$ are constrained to 80.1 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. [28, 29] which employs constraints on the W boson masses, the t-$\bar{t}$ mass difference (but not M_t), the total transverse energy, and the b-likelihood of the jets [30]. 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 (15%) non-Gaussian tails.

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, $\cos\alpha_p$. 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 [31]:

$$A_{\mathrm{FB}}^{p\bar{p}} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)} \tag{3}$$

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 of the t and $\bar{t}$ rapidities Y_t and $Y_{\bar{t}}$. At LO this is directly related to the top quark production angle α to the incoming quark line in the $t\bar{t}$ rest frame [28]:

$$\Delta Y = Y_t - Y_{\bar{t}} = 2 \cdot \tanh^{-1}\left(\frac{\cos\alpha}{\sqrt{(1 + \frac{4M_t^2}{\hat{s}-4M_t^2})}}\right). \tag{4}$$

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 [32].

$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta Y > 0) - N(\Delta Y < 0)}{N(\Delta Y > 0) + N(\Delta Y < 0)} \tag{5}$$

To connect this with other hadron collision 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 [33]. 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 asymetries 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 dataset, are discussed later. The calibration of the simulation to the physical detector geometry and acceptance has been checked in studies of electroweak processes [34, 35]. 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.

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

Generator	$A_{\rm FB}^{p\bar{p}}$		$A_{\rm FB}^{t\bar{t}}$	
	Parton-level	Reconstructed	Parton-level	Reconstructed
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

The $A_{\rm FB}$ measured in data must be corrected for background contributions which include asymmetric weak processes. W + jets events with tagged heavy flavor or mistagged light partons are modeled using ALPGEN [36] interfaced to PYTHIA parton showering, along with b-tagging and mistagging rates parameterized from jet data. Small electroweak backgrounds WW, WZ, ZZ are modeled with PYTHIA and single-top with MADEVENT [37]. The non-W 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 re-weighting the lepton acceptance. The background levels and asymmetries expected in the two analyses are shown in Table II and combine to the total asymmetries listed in the last row.

TABLE II: Estimated backgrounds and their effective asymmetries.

Process	Expected Number	$A_{\mathrm{FB}}^{p\bar{p}}$	$A_{\mathrm{FB}}^{t\bar{t}}$
W+heavy flavor	36 ± 10	-0.087 ± 0.005	-0.045 ± 0.003
Mistags	20 ± 5	0.044 ± 0.008	-0.006 ± 0.015
Diboson, $t\bar{b} + c.c$	12 ± 1	-0.022 ± 0.014	-0.015 ± 0.044
QCD (non-W)	18 ± 16	-0.008 ± 0.004	0.006 ± 0.010
Total	87 ± 23	-0.053 ± 0.004	-0.021 ± 0.007

Fig. 1 shows 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. The difference expected from the QCD-induced effect when dividing the sample into exclusive four jets (85% $t\bar{t}$) and five or more jets (53% $t\bar{t} + g$) samples is at the limit of our current precision, but may be visible in $A_{\mathrm{FB}}^{t\bar{t}}$. Subdividing the data by lepton types and lepton charges shows a consistent positive asymmetry across all samples. Our background-corrected $A_{\mathrm{FB}}^{t\bar{t}}$ with ≥ 4 jets is consistent with a similar measurement reporting 0.12 ± 0.08 in Ref. [38].

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

$$P_j = \epsilon_j^{-1} \cdot S_{ji}^{-1} \cdot D_i \tag{6}$$

We simplify each distribution to four bins, with two bins on either side of the cross-over at $\cos\theta = \Delta Y = 0$. The efficiencies and migration matrix S_{ij} are derived by comparing

TABLE III: Predicted (MC@NLO + non-$t\bar{t}$) and measured asymmetries in data, before correction to the parton-level.

	$A_{\mathrm{FB}}^{p\bar{p}}$		$A_{\mathrm{FB}}^{t\bar{t}}$	
	Standard Model	Measured	Standard Model	Measured
Reconstructed Data				
≥ 4 jets	0.001 ± 0.010	0.099 ± 0.045	0.010 ± 0.007	0.087 ± 0.045
Background Subtracted				
≥ 4 jets	0.015 ± 0.016	0.130 ± 0.055	0.017 ± 0.007	0.119 ± 0.064
$= 4$ jets	0.032 ± 0.018	0.120 ± 0.064	0.038 ± 0.008	0.132 ± 0.075
≥ 5 jets	-0.027 ± 0.032	0.160 ± 0.109	-0.033 ± 0.012	0.079 ± 0.123

the parton and reconstructed level quantities using the zero asymmetry PYTHIA $t\bar{t}$ simulations. In the $\cos\theta$ (ΔY) 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} dataset are $\delta A_{\mathrm{FB}}^{p\bar{p}} = 0.09$ and $\delta A_{\mathrm{FB}}^{t\bar{t}} = 0.13$.

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 distribution 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 $A_{\rm FB}^{p\bar{p}} = 0.17 \pm 0.07 \pm 0.04$ and $A_{\rm FB}^{t\bar{t}} = 0.24 \pm 0.13 \pm 0.04$, 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 in the symmetric PYTHIA sample with form $1 + A_{\rm FB} \cos\alpha$ using the measured $A_{\rm FB}$.

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 $A_{\rm FB}^{p\bar{p}} = 0.17 \pm 0.08$ in the $p\bar{p}$ frame and $A_{\rm FB}^{t\bar{t}} = 0.24 \pm 0.14$ in the $t\bar{t}$ frame. QCD predicts a small (~ 0.05) charge asymmetry sensitive to the measurement definition and theoretical uncertainties at higher orders. Speculative sources of $t\bar{t}$ production asymmetries include modifications of QCD and new color singlets with parity violating couplings. Within the large uncertainties, our results show the expected frame dependence and are consistent ($\leq 2\sigma$) with the charge asymmetry expected from QCD.

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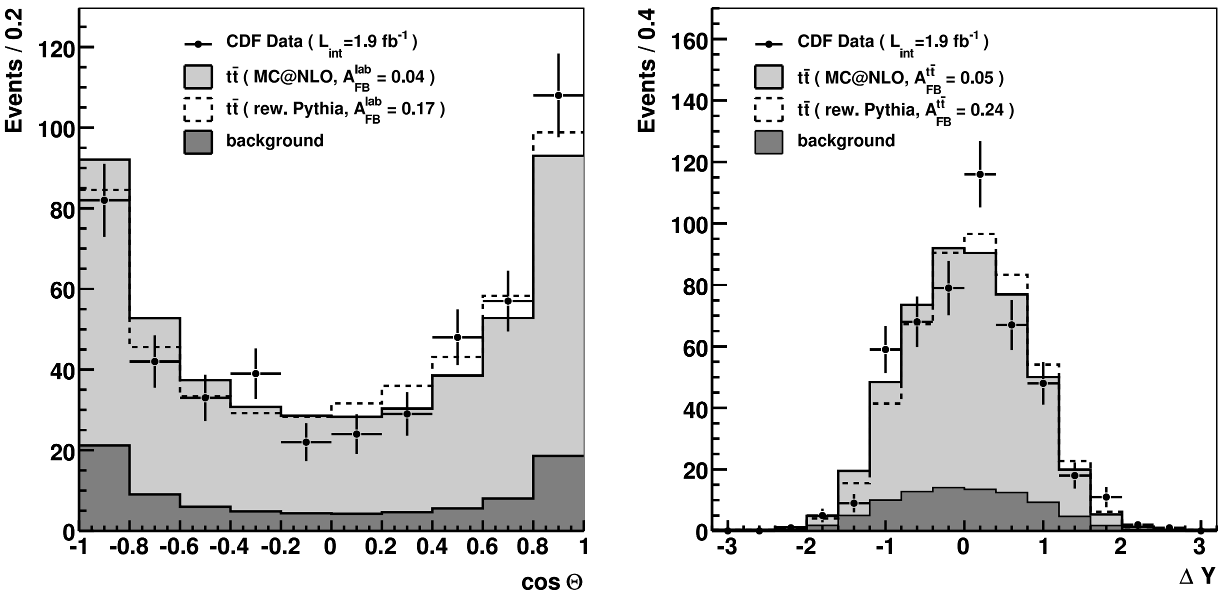

FIG. 1: The two top quark production angle variables, $cos\theta$ for the $p\bar{p}$ frame and ΔY for the $t\bar{t}$ frame. The solid line is the prediction for $t\bar{t}$ with MC@NLO model of the QCD induced charge asymmetry and $\sigma_{t\bar{t}} = 8.2$ pb, plus the expected non-$t\bar{t}$ backgrounds. 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 $A_{\rm FB}$.

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