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Citation

As Published
http://dx.doi.org/10.1103/PhysRevLett.113.042001

Publisher
American Physical Society

Version
Final published version

Accessed
Thu Oct 18 15:13:18 EDT 2018

Citable Link
http://hdl.handle.net/1721.1/91201

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Measurement of the Inclusive Leptonic Asymmetry in Top-Quark Pairs that Decay to Two Charged Leptons at CDF

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We measure the inclusive forward–backward asymmetry of the charged-lepton pseudorapidities from top-quark pairs produced in proton–antiproton collisions and decaying to final states that contain two charged leptons (electrons or muons). The data are collected with the Collider Detector at Fermilab and correspond to an integrated luminosity of 9.1 fb\(^{-1}\). We measure the leptonic forward–backward asymmetry, \(A^{\ell}_{FB}\), to be 0.072 ± 0.060 and the leptonic pair forward–backward asymmetry, \(A^{\ell\ell}_{FB}\), to be 0.076 ± 0.082. The measured values can be compared with the standard model predictions of \(A^{\ell}_{FB} = 0.038 ± 0.003\) and \(A^{\ell\ell}_{FB} = 0.048 ± 0.004\), respectively. Additionally, we combine the \(A^{\ell}_{FB}\) result with a previous determination from a final state with a single lepton and hadronic jets and obtain \(A^{\ell}_{FB} = 0.090^{+0.028}_{-0.026}\).

One special property of the production of top quark–antitop quark pairs (\(t\bar{t}\)) in proton–antiproton collisions at the Fermilab Tevatron is the forward–backward asymmetry \((A^{\eta}_{FB})\), which refers to the preference of top quarks to follow the proton direction, forward, and antitop quarks to follow the opposite direction, backward. Recent measurements of \(A^{\eta}_{FB}\) [1–3] show deviations from the prediction calculated assuming the standard model (SM) of particle physics [4]. This has triggered substantial interest in the physics community as the SM predicts only small asymmetry \((\sim 2\%\)) of the charged lepton \(\eta\) that can originate from the cascade decays of the top quarks. These are the asymmetry in the charge-weighted \(\eta\) of the charged lepton \((\ell\)'s, where we only consider electrons and muons), the so-called leptonic forward–backward asymmetry \((A^{\ell}_{FB})\), and the leptonic pair forward–backward asymmetry \((A^{\ell\ell}_{FB})\) for the final state with two charged leptons (dilepton final state), defined with the \(\eta\) difference between the two charged leptons [6]. In a hypothetical scenario where \(t\bar{t}\) pairs could be produced via a gluon with axial couplings (“axigluon”), \(A^{\ell}_{FB}\) could deviate from its SM value; equally interesting, the various axigluon couplings to the top quarks could result in the same value of \(A^{\ell\ell}_{FB}\), but with very different values of \(A^{\ell}_{FB}\) and \(A^{\ell\ell}_{FB}\) [7].

In this Letter, we summarize the measurements of the \(A^{\ell}_{FB}\) and the \(A^{\ell\ell}_{FB}\) in the dilepton final state using the data collected by the CDF II detector during the full Tevatron Run II period, with an integrated luminosity of 9.1 fb\(^{-1}\) [8]. These measurements have the experimental advantage of exploiting the precisely measured angles of the lepton trajectories, which simplifies the analysis by not requiring reconstruction of the four-momenta of the top-quark pairs and reduces systematic uncertainties [9]. The measured asymmetries are reported at parton level in that they are corrected for the detector and selection effects and are inclusive in that they are extrapolated to the full \(\eta\) range. These measurements are complementary to the previous measurement of \(A^{\ell}_{FB}\) in the final state involving one lepton and jets (lepton + jets final state) [9], as they have a different signal topology, independent background estimation techniques, and an extended lepton \(\eta\) coverage to the high \(\eta\) regime that is most sensitive to beyond-SM scenarios. Additionally, we report on the combined \(A^{\ell}_{FB}\) result from the two final states.
The CDF II detector, described in detail in Ref. [10], is a general-purpose particle detector employing a large charged-particle tracking volume inside a solenoidal magnetic field coaxial with the beam direction, surrounded by calorimeters and muon detectors. We use a cylindrical coordinate system with the origin at the center of the detector, $z$ pointing in the direction of the proton beam, $\theta$ and $\phi$ representing the polar and azimuthal angles, respectively, and $\eta = -\ln \tan(\theta/2)$. The transverse momentum $p_T$ is defined as $p \sin(\theta)$, and the transverse energy $E_T$ as $E \sin \theta$.

A sample enriched in $t\bar{t}$ events in the dilepton final state ($t\bar{t} \to \ell^+\ell^-\nu\bar{\nu}b\bar{b}$) is selected by requiring two oppositely charged leptons, two or more narrow clusters of energy deposits in the calorimeters, corresponding to collimated clusters of incident hadrons (jets), and an imbalance in the total event transverse momentum (missing transverse clusters of incident hadrons (jets), and an imbalance in the hadronization; a GEANT-based simulation[15,16] is used to estimate the background and SM events.

Several physical processes mimic the signature of top-quark pairs in the dilepton final state, such as production of a $Z$ boson or a virtual photon with jets ($Z/\gamma^* +$ jets), production of a $W$ boson with jets ($W +$ jets), diboson production ($WW$, $WZ$, $ZZ$, and $W\gamma$), and $t\bar{t}$ production where one of the $W$ bosons from the top-quark pair decays hadronically and one jet from bottom-quark hadronization or $W$-boson hadronic decay is misidentified as a lepton ($t\bar{t}$ nondilepton). The estimation of background and SM $t\bar{t}$ signal is based on the methods of Ref. [12], which exploits both Monte Carlo (MC) simulations and data-based techniques. For the simulations, leading-order event generators are configured to use the CTEQ6.1L set of parton-distribution functions, while NLO event generators use CTEQ6.1M. PYTHIA [14] is used to model the parton hadronization; a GEANT-based simulation[15,16] is used to model the detector response. A $t\bar{t}$ sample to estimate signal and the $t\bar{t}$ nondilepton background is generated with a top-quark mass of 172.5 GeV/$c^2$ using the POWHEG generator [17–20] and is normalized to the theoretical cross section of 7.4 pb [21]. The expected rates of background processes and the signal, together with the observed number of events selected from data, are listed in Table I. Excellent agreement is observed.

Assuming charge-parity symmetry, the $A_{FB}^{\ell\ell}$ can be defined combining leptons of both charges [9] as

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

(1)

where $N$ is the number of leptons, $q_{\ell}$ is the lepton electric charge, and $\eta_{\ell}$ is the lepton pseudorapidity. Studies of the correlation between the two charged leptons show negligible effect on the measurement. An NLO SM calculation with both quantum-chromodynamics effects and electroweak effects predicts $A_{FB}^{\ell\ell} = 0.038 \pm 0.003$ [4]. If the genuine value of $A_{FB}^{\ell\ell}$ would be that measured by the CDF collaboration [1], the predicted value for $A_{FB}^{\ell\ell}$ for top quarks decaying according to the SM would be $0.070 < A_{FB}^{\ell\ell} < 0.076$ [9]. Previous measurements of $A_{FB}^{\ell\ell}$ in the lepton+jets final state by the CDF collaboration and in the lepton+jets and dilepton final states by the D0 collaboration found $0.094^{+0.032}_{-0.029}$ [9] and $0.047 \pm 0.027$ [22,23], respectively. A second observable, $A_{FB}^{\ell\ell}$, can be defined in the dilepton final state analogously to $A_{FB}^{\ell\ell}$ as

$$A_{FB}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)},$$

(2)

where $\Delta\eta = \eta_{\ell^+} - \eta_{\ell^-}$. An NLO SM prediction yields $A_{FB}^{\ell\ell} = 0.048 \pm 0.004$ [4]. The D0 collaboration measured $A_{FB}^{\ell\ell} = 0.123 \pm 0.056$ [22].

We simulate $t\bar{t}$ production and decay in various plausible SM and beyond-SM scenarios to study hypothetical variations in the expected $q_{\ell}\eta_{\ell}$ spectrum. The benchmark SM $t\bar{t}$ sample generated with POWHEG gives parton-level inclusive values of $A_{FB}^{\ell\ell} = 0.024$ and $A_{FB}^{\ell\ell} = 0.030$. These predictions are different from the NLO SM calculation in Ref. [4] since the simulation does not account for the electroweak corrections [24]. We studied a large number of beyond-SM scenarios with axigluons of a wide variety of masses (200–2000 GeV/$c^2$) and different couplings to the quarks using MADGRAPH [25]. Of particular interest are a class of relatively light and wide axigluons (with masses at 200 GeV/$c^2$ and widths at 50 GeV) with left-handed, right-handed, and axial axigluon couplings to the quarks [7]. Each predicts an $A_{FB}^{\ell\ell}$ value similar to that observed by the CDF collaboration [1], but the polarization of the top quarks results in different values of $A_{FB}^{\ell\ell}$ (–0.063, 0.050, and 0.151, respectively) and $A_{FB}^{\ell\ell}$ (–0.092, 0.066, and

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson</td>
<td>31 ± 6</td>
</tr>
<tr>
<td>$Z/\gamma^* +$ jets</td>
<td>50 ± 6</td>
</tr>
<tr>
<td>$W +$ jets</td>
<td>64 ± 17</td>
</tr>
<tr>
<td>$t\bar{t}$ nondilepton</td>
<td>14.6 ± 0.8</td>
</tr>
<tr>
<td>Total background</td>
<td>160 ± 21</td>
</tr>
<tr>
<td>$t\bar{t}$ ($\sigma = 7.4 \text{ pb}$)</td>
<td>408 ± 19</td>
</tr>
<tr>
<td>Total SM expectation</td>
<td>568 ± 40</td>
</tr>
<tr>
<td>Observed</td>
<td>569</td>
</tr>
</tbody>
</table>

TABLE I. Expected number of events in data along with the observed number of events, passing all event selections. The quoted uncertainties in each row are the total uncertainties calculated in the same way as Ref. [12].
with the various simulated samples, including the models listed above as well as SM samples generated with PYTHIA [14] and ALPGEN [26], show that the \( q_\mu \eta_\mu \) distribution of the leptons at parton level approximately follows the sum of two Gaussian distributions with common means and widths and proportions independent of the simulated model [27]. The asymmetry in each scenario arises from the shift of the mean of the \( q_\mu \eta_\mu \) distribution. Using this knowledge, we follow a procedure that is similar to that described in Ref. [9] to account for the detector coverage, detector acceptance, and background effects described above. The \( q_\mu \eta_\mu \) distribution of leptons is decomposed into a symmetric part and an asymmetric part as functions of \( q_\mu \eta_\mu \) in the range \( q_\mu \eta_\mu \geq 0 \),

\[
\mathcal{S}(q_\mu \eta_\mu) = \frac{\mathcal{N}(q_\mu \eta_\mu) + \mathcal{N}(-q_\mu \eta_\mu)}{2} \tag{3a}
\]

and

\[
\mathcal{A}(q_\mu \eta_\mu) = \frac{\mathcal{N}(q_\mu \eta_\mu) - \mathcal{N}(-q_\mu \eta_\mu)}{\mathcal{N}(q_\mu \eta_\mu) + \mathcal{N}(-q_\mu \eta_\mu)}, \tag{3b}
\]

where \( \mathcal{N}(q_\mu \eta_\mu) \) represents the number of events as a function of \( q_\mu \eta_\mu \). The differential contribution to the inclusive \( A_{FB}^\mu \) as a function of \( q_\mu \eta_\mu \) is calculated as

\[
\frac{\mathcal{S}(q_\mu \eta_\mu) \mathcal{A}(q_\mu \eta_\mu)}{\int_0^\infty d(q'_\mu \eta'_\mu) \mathcal{S}(q'_\mu \eta'_\mu)}, \tag{4}
\]

and the inclusive \( A_{FB}^\mu \) defined in Eq. (1) is then written as the integral of Eq. (4),

\[
A_{FB}^\mu = \frac{\int_0^\infty d(q_\mu \eta_\mu) \mathcal{S}(q_\mu \eta_\mu) \mathcal{A}(q_\mu \eta_\mu)}{\int_0^\infty d(q'_\mu \eta'_\mu) \mathcal{S}(q'_\mu \eta'_\mu)}. \tag{5}
\]

The measurement methodology is simplified because the symmetric part of the \( q_\mu \eta_\mu \) distributions at parton level is very similar across models as the mean of the \( q_\mu \eta_\mu \) distribution is always close to zero in all models and small compared to the width, which is almost around unity. We observe that using the distribution from any simulated sample only introduces an uncertainty that is tiny compared to the dominant uncertainties. The methodology also benefits from the fact that the symmetric part of the detector acceptance effect is canceled out in Eq. (3b). Since the detector acceptance, including the effects caused by lepton reconstruction, behaves in a symmetric way in the dilepton final state, no detector acceptance corrections are found to be needed as in Ref. [9]. Additionally, the differential asymmetry described in Eq. (3b) is readily measured and allows for discrimination among models with different values of \( A_{FB}^\mu \). For \( q_\mu \eta_\mu < 2.5 \), the differential asymmetry in Eq. (3b) is modeled accurately by the simplified functional form

\[
\mathcal{A}(q_\mu \eta_\mu) = a \cdot \tanh\left(\frac{q_\mu \eta_\mu}{2}\right), \tag{6}
\]

where \( a \) is the only free parameter related to \( A_{FB}^\mu \).

Figure 1 shows the differential contribution to the inclusive \( A_{FB}^\mu \) expected at parton level from the POWHEG simulation, along with comparisons to predictions from the two-Gaussian model and the functional form of Eq. (6). Both models describe the distribution accurately. The integral gives the total inclusive asymmetry. The fraction of the unmeasured asymmetry where \( |q_\mu \eta_\mu| > 2.0 \) is approximately 11%. The shapes of this distribution for all of the simulated samples are very similar, supporting the methodology.

The strategy is to measure the shape of the asymmetric component of the data after background subtraction and use the symmetric component of the parton-level \( q_\mu \eta_\mu \) distribution from the POWHEG \( t\bar{t} \) sample to reproduce the parton-level inclusive value of \( A_{FB}^\mu \). This method includes the correction for the acceptance of the detected leptons and extrapolation for the undetected ones. It is validated using the SM and beyond-SM physics scenarios. For both the two-Gaussian model and the simplified functional form of Eq. (6), the method returns \( A_{FB}^\mu \) values that are consistent with the parton-level inclusive values. The most significant discrepancy is assigned as the asymmetric-modeling systematic uncertainty, which is \( \pm 0.006 \) and covers any possible bias observed.

![Figure 1](image_url)

**FIG. 1** (color online). Differential contribution to \( A_{FB}^\mu \) for the POWHEG simulation of \( t\bar{t} \) production. The solid curve shows the estimation with Eq. (4) where \( \mathcal{A}(q_\mu \eta_\mu) \) is obtained with a fit of Eq. (6) on the asymmetric part of the \( q_\mu \eta_\mu \) spectrum from the sample and \( \mathcal{S}(q_\mu \eta_\mu) \) is directly from the sample; the dashed curve is from the two-Gaussian model [27]. The vertical dashed line indicates the outer limits of the acceptance regions for charged leptons, which is \( |q_\mu \eta_\mu| = 2.0 \).
Applying Eq. (5), we find the data after background subtraction along with the best fit to the SM expectations from the POWHEG simulation. The inner bars on the data points represent the statistical uncertainties, while the outer bars represent the total uncertainties. The bands indicate the one standard deviation region for statistical and statistical + systematic uncertainties.

**FIG. 3** (color online). The same figures as Fig. 2, but with \( \Delta \eta \) instead of \( q_{\ell} \eta_{\ell} \).

The observed distribution of \( q_{\ell} \eta_{\ell} \) is shown in Fig. 2(a) along with the SM expectations from the \( t \bar{t} \) signal and backgrounds. The shapes are well described by the expectations. Figure 2(b) shows the asymmetric component of the data after background subtraction along with the best fit description, which yields a value of \( a = 0.21 \pm 0.15 \) (stat) from Eq. (6). Applying Eq. (5), we find \( A_{FB} = 0.072 \pm 0.052 \) (stat).

The dominant source of systematic uncertainty is due to the background uncertainties and is estimated to be \( \pm 0.029 \) using pseudoexperiments [9], which covers both the uncertainties in the background normalizations and the uncertainties in modeling the \( A_{FB} \) of the backgrounds (including \( t \bar{t} \) in nondilepton final state). The next most important source of systematic uncertainty is the \( \pm 0.006 \) asymmetric-modeling contribution discussed above. The jet-energy-scale systematic uncertainty is estimated to be \( \pm 0.004 \) by varying the jet energies within their uncertainties. The variations obtained by using the symmetric model from various MC samples are assigned as the symmetric-modeling systematic uncertainty, which is \( \pm 0.001 \). Other sources of uncertainties due to the uncertainties in the parton showering model, the modeling of color reconnection, the amount of initial-state and final-state radiation, and the uncertainty on the parton-distribution functions are found to be negligible. The total systematic uncertainty, \( \pm 0.03 \), is estimated by summing the individual contributions in quadrature. The final result is \( a = 0.21 \pm 0.15 \) (stat) \( \pm 0.08 \) (syst) and \( A_{FB} = 0.072 \pm 0.052 \) (stat) \( \pm 0.030 \) (syst). This result is consistent with the NLO SM expectation, the measurement in the lepton + jets final state by the CDF collaboration [9] and the measurement by the D0 collaboration [22,23].

Identical methodology is used for measuring \( A_{FB} \). The observed distribution of \( \Delta \eta \) is shown in Fig. 3. We measure \( a = 0.16 \pm 0.15 \) (stat) \( \pm 0.08 \) (syst) and \( A_{FB} = 0.076 \pm 0.072 \) (stat) \( \pm 0.039 \) (syst), where the dominant systematic uncertainty is from backgrounds and has a value of \( \pm 0.037 \). The asymmetric- and symmetric-modeling systematic uncertainties are estimated to be \( \pm 0.012 \) and \( \pm 0.004 \), respectively. The jet-energy-scale systematic uncertainty is estimated to be \( \pm 0.003 \). Other systematic uncertainties are negligible. This result is consistent with both the NLO SM calculation [4] and the measurement by the D0 collaboration [22].

In order to obtain a more sensitive measurement, we combine the dilepton measurement of \( A_{FB} \) with the CDF measurement in the lepton + jets final state reported in Ref. [9], \( A_{FB} = 0.094 \pm 0.024 \) (stat) \( \pm 0.017 \) (syst). The combination is based on the asymmetric iterative algorithm of the “best linear unbiased estimates approach” [28,29]. Since the measurements use statistically independent samples, the statistical uncertainties are uncorrelated. The background systematic uncertainties are treated as uncorrelated since they are mainly caused by the
uncertainties in the modeling of the background \( q/\eta \)
distributions, which are largely uncorrelated between the
two measurements. The recoil-modeling systematic uncertainty
in the lepton + jets measurement and the asymmetric-modeling
systematic uncertainty in the dilepton measurement (which includes
the systematic uncertainty of recoil modeling) are treated as fully correlated. The jet-
energy-scale systematic uncertainties are also treated as
fully correlated. The other systematic uncertainties are
negligible in one of the two measurements; thus, only
the non-negligible part is included.

The combined result is \( A_{\text{FB}}^t = 0.090^{+0.028}_{-0.026} \), where 80% of
the measurement weight is due to the lepton + jets result and 20% is due to the dilepton result. The difference in the
weights is mostly due to the larger size of the lepton + jets
final state sample. The correlation factor between the two
measurements is estimated to be 2.6%.

In conclusion, we measure the parton-level inclusive
leptonic forward–backward asymmetry and leptonic pair
asymmetry of top-quark pairs decaying into the dilepton
final state sample. The correlation factor between the two
measurements is estimated to be 2.6%.

We thank the Fermilab staff and the technical staffs of
the participating institutions for their vital contributions. This
work was supported by the U.S. Department of Energy and
National Science Foundation; the Italian Istituto Nazionale
di Fisica Nucleare; the Ministry of Education, Culture,
Sports, Science and Technology of Japan; the Natural
Sciences and Engineering Research Council of Canada;
the National Science Council of the Republic of China; the
Swiss National Science Foundation; the A.P. Sloan
Foundation; the Bundesministerium für Bildung und
Forschung, Germany; the Korean World Class University
Program, the National Research Foundation of Korea; the
Science and Technology Facilities Council and the Royal
Society, United Kingdom; the Russian Foundation for
Basic Research; the Ministerio de Ciencia e Innovación,
and Programa Consolider-Ingenio 2010, Spain; the Slovak
R&D Agency; the Academy of Finland; the Australian
Research Council (ARC); and the EU community Marie
Curie Fellowship Contract No. 302103.

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\(^{1}\) Deceased.

\(^{2}\) Visitor from University of British Columbia, Vancouver, BC V6T 1Z1, Canada.
The missing transverse energy $E_T$ is defined to be $-\Sigma E_i^{j}\hat{n}_i$, where $i$ identifies the calorimeter tower with $|\eta| < 3.6\hat{n}_i$ is a unit vector perpendicular to the beam axis and pointing at the $i$th calorimeter tower.