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


(CDF Collaboration)

Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China
Argonne National Laboratory, Argonne, Illinois 60439, USA
University of Athens, 157 71 Athens, Greece
Institut de Fisica d’Altes Energies, ICRA, Universitat Autonoma de Barcelona, E-08193 Bellaterra (Barcelona), Spain
Baylor University, Waco, Texas 76798, USA
Istituto Nazionale di Fisica Nucleare Bologna, Italy
University of Bologna, I-40127 Bologna, Italy
University of California, Davis, Davis, California 95616, USA
University of California, Los Angeles, Los Angeles, California 90024, USA
Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain
Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia
Duke University, Durham, North Carolina 27708, USA
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
University of Florida, Gainesville, Florida 32611, USA
Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy
University of Geneva, CH-1211 Geneva 4, Switzerland
Glasgow University, Glasgow G12 8QQ, United Kingdom
Harvard University, Cambridge, Massachusetts 02138, USA
Division of High Energy Physics, Department of Physics, University of Helsinki, FIN-00014 Helsinki, Finland; Helsinki Institute of Physics, FIN-00014 Helsinki, Finland
University of Illinois, Urbana, Illinois 61801, USA
The Johns Hopkins University, Baltimore, Maryland 21218, USA
Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany
Center for High Energy Physics, Kyungpook National University, Daegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; Sungkyunkwan University, Suwon 440-746, Korea; Korea Institute of Science and Technology Information, Daejeon 305-806, Korea; Chonnam National University, Gwangju 500-757, Korea; Chonbuk National University, Jeonju 561-756, Korea; and Ewha Womans University, Seoul 120-750, Korea
Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
University of Liverpool, Liverpool L69 7ZE, United Kingdom
University College London, London WC1E 6BT, United Kingdom
Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
University of Michigan, Ann Arbor, Michigan 48109, USA
Michigan State University, East Lansing, Michigan 48824, USA
Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
University of New Mexico, Albuquerque, New Mexico 87131, USA
The Ohio State University, Columbus, Ohio 43210, USA
Okayama University, Okayama 700-8530, Japan
Osaka City University, Osaka 558-8585, Japan
University of Oxford, Oxford OX1 3RH, United Kingdom
Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Italy
University of Padova, I-35131 Padova, Italy
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
Istituto Nazionale di Fisica Nucleare Pisa, Italy
University of Pisa, Italy
University of Siena, Italy
Scuola Normale Superiore, I-56127 Pisa, Italy
INFN Pavia, I-27100 Pavia, Italy
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, \(A_{FB}^{\ell}\), to be \(0.072 \pm 0.060\) and the leptonic pair forward–backward asymmetry, \(A_{FB}^{\ell\ell}\), to be \(0.076 \pm 0.082\). The measured values can be compared with the standard model predictions of \(A_{FB}^{\ell} = 0.038 \pm 0.003\) and \(A_{FB}^{\ell\ell} = 0.048 \pm 0.004\), respectively. Additionally, we combine the \(A_{FB}^{\ell}\) result with a previous determination from a final state with a single lepton and hadronic jets and obtain \(A_{FB}^{\ell} = 0.090^{+0.028}_{-0.026}\).

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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 (\(A_{FB}^{t}\)), 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 \(A_{FB}^{t}\) [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 due to interference among diagrams starting at next-to-leading order (NLO), while non-SM particles or interactions could modify \(A_{FB}^{t}\) significantly [5].

A separate set of useful observables relies on the pseudorapidities (\(\eta\)) of the charged leptons that can originate from the cascade decays of the top quarks. These are the asymmetry in the charge-weighted \(\eta\) of the charged lepton (\(\ell\)), where we only consider electrons and muons, the so-called leptonic forward–backward asymmetry (\(A_{FB}^{\ell}\)), and the leptonic pair forward–backward asymmetry (\(A_{FB}^{\ell\ell}\)) 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”), \(A_{FB}^{\ell}\) could deviate from its SM value; equally interesting, the various axigluon couplings to the top quarks could result in the same value of \(A_{FB}^{\ell}\), but with very different values of \(A_{FB}^{\ell}\) and \(A_{FB}^{\ell\ell}\) [7].

In this Letter, we summarize the measurements of the \(A_{FB}^{t}\) and the \(A_{FB}^{\ell\ell}\) 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 \(A_{FB}^{\ell}\) 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 \(A_{FB}^{\ell}\) result from the two final states.
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].

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diboson</td>
<td>31 ± 6</td>
</tr>
<tr>
<td>Z/γ* + jets</td>
<td>50 ± 6</td>
</tr>
<tr>
<td>W + jets</td>
<td>64 ± 17</td>
</tr>
<tr>
<td>t̄t non dilepton</td>
<td>14.6 ± 0.8</td>
</tr>
<tr>
<td>Total background</td>
<td>160 ± 21</td>
</tr>
<tr>
<td>Total SM expectation</td>
<td>568 ± 40</td>
</tr>
<tr>
<td>Observed</td>
<td>569</td>
</tr>
</tbody>
</table>


where $N$ is the number of leptons, $q_\ell$ is the lepton electric
charge, and $\eta_\ell$ is the lepton pseudorapidity. Studies of the
relation between the two charged leptons show negligible
effect on the measurement. An NLO SM calculation with both quantum-chromodynamics effects and electroweak effects predicts $A^\ell_\text{FB} = 0.038 \pm 0.003$ [4]. If the genuine value of $A^\ell_\text{FB}$ would be that measured by the CDF collaboration [1], the predicted value for $A^\ell_\text{FB}$ for top quarks decaying according to the SM would be $0.070 < A^\ell_\text{FB} < 0.076$ [9]. Previous measurements of $A^\ell_\text{FB}$ 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, $A^c_\text{FB}$, can be defined in the dilepton final state analogously to $A^\ell_\text{FB}$ as

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

where $\Delta \eta = \eta_{\ell^-} - \eta_{\ell^+}$. An NLO SM prediction yields $A^c_\text{FB} = 0.048 \pm 0.004$ [4]. The D0 collaboration measured $A^c_\text{FB} = 0.123 \pm 0.056$ [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 $A^\ell_\text{FB} = 0.024$ and $A^c_\text{FB} = 0.030$. 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 $A^\ell_\text{FB}$ value similar to that observed by the CDF collaboration [1], but the polarization of the top quarks results in different values of $A^\ell_\text{FB}$ (−0.063, 0.050, and 0.151, respectively) and $A^c_\text{FB}$ (−0.092, 0.066, and...
listed above as well as SM samples generated with PYTHIA with the various simulated samples, including the models q


The asymmetry in each scenario arises from the shift of the mean of the q\(\eta\) distribution at parton level. The asymmetry in Eq. (3b) is modeled accurately by the simplified functional form

\[
A(q,\eta) = a \cdot \tanh \left( \frac{q \eta}{2} \right),
\]

where \(a\) is the only free parameter related to \(A'_{\mathrm{FB}}\).

Figure 1 shows the differential contribution to the inclusive \(A'_{\mathrm{FB}}\) 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 \(|q\eta| > 2.0\) 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 \(q\eta\) distribution from the POWHEG \(t\bar{t}\) sample to reproduce the parton-level inclusive value of \(A'_{\mathrm{FB}}\). 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 \(A'_{\mathrm{FB}}\) values that are consistent with the parton-level inclusive values. The most significant discrepancy is assigned as the asymmetric-modeling systematic uncertainty, which is ±0.006 and covers any possible bias observed.

FIG. 1 (color online). Differential contribution to \(A'_{\mathrm{FB}}\) for the POWHEG simulation of \(t\bar{t}\) production. The solid curve shows the estimation with Eq. (4) where \(A(q,\eta)\) is obtained with a fit of Eq. (6) on the asymmetric part of the \(q\eta\) spectrum from the sample and \(S(q,\eta)\) 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 \(|q\eta| = 2.0\).
The observed distribution of $q_l \eta_l$ 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). Applying Eq. (5), we find $A_{FB}^l = 0.072 \pm 0.052$(stat).

The dominant source of systematic uncertainty is due to the background uncertainties and is estimated to be ±0.029 using pseudoexperiments [9], which covers both the uncertainties in the background normalizations and the uncertainties in modeling the $A_{FB}^l$ of the backgrounds (including $t\bar{t}$ in nondilepton final state). The next most important source of systematic uncertainty is the ±0.006 asymmetric-modeling contribution discussed above. The jet-energy-scale systematic uncertainty is estimated to be ±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 ±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, ±0.03, is estimated by summing the individual contributions in quadrature. The final result is $a = 0.21 \pm 0.15$(stat) ± 0.08(syst) and $A_{FB}^l = 0.072 \pm 0.052$(stat) ± 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 $A_{FB}^l$. The observed distribution of $\Delta \eta$ is shown in Fig. 3. We measure $a = 0.16 \pm 0.15$(stat) ± 0.08(syst) and $A_{FB}^l = 0.076 \pm 0.072$(stat) ± 0.039(syst), where the dominant systematic uncertainty is from backgrounds and has a value of ±0.037. The asymmetric- and symmetric-modeling systematic uncertainties are estimated to be ±0.012 and ±0.004, respectively. The jet-energy-scale systematic uncertainty is estimated to be ±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 $A_{FB}^l$ with the CDF measurement in the lepton + jets final state reported in Ref. [9], $A_{FB}^l = 0.094 \pm 0.024$(stat) ± 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 $q_{i}E_{\gamma}$ 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 $A_{FB}^{L} = 0.090^{+0.028}_{-0.026}$, 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 using the full CDF Run II data set. The results are $A_{FB}^{L} = 0.072 \pm 0.060$ and $A_{FB}^{L} = 0.076 \pm 0.082$, both consistent with previous determinations and expectations. A combination of the CDF $A_{FB}^{L}$ measurements yields $A_{FB}^{L} = 0.090^{+0.028}_{-0.026}$. This result is about two standard deviations larger than the NLO SM calculation of $A_{FB}^{L} = 0.038 \pm 0.003$ [4] but is consistent with the 0.070–0.076 range expected assuming unpolarized top-quark production and SM top-quark decay, given the measured value of $A_{FB}^{D}$ by the CDF collaboration [9].

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*Deceased.

Visitor from University of British Columbia, Vancouver, BC V6T 1Z1, Canada.
The missing transverse energy $E_T$ is defined to be $-\sum_i E^i \hat{n}_i$ 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.