Measurement of the Differential Cross Section $d\sigma/d(\cos\theta_t)$ for Top-Quark Pair Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report a measurement of the differential cross section $d\sigma/d(\cos\theta_t)$ for top-quark pair production as a function of the top-quark production angle in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV. This measurement is performed using data collected with the CDF II detector at the Tevatron, corresponding to an integrated luminosity of 9.4 fb^{-1}. We employ the Legendre polynomials to characterize the shape of the differential cross section at the parton level. The observed Legendre coefficients are in good agreement with the prediction of the next-to-leading-order standard-model calculation, with the exception of an excess linear-term coefficient $a_1 = 0.40 \pm 0.12$, compared to the standard-model prediction of $a_1 = 0.15^{+0.07}_{-0.03}$.

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The Collider Detector at Fermilab (CDF) and D0 experiments have measured an anomalously large forward-backward asymmetry ($A_{\rm FB}$) in top-quark pair ($t\bar{t}$) hadroproduction. The latest measurements are $A_{\rm FB} = (16.4 \pm 4.5)\%$ from CDF [1] and $A_{\rm FB} = (19.6 \pm 6.5)\%$ from D0 [2]. This asymmetry is the manifestation of a charge asymmetry in $t\bar{t}$ production via the CP-even [3] initial state at the Fermilab Tevatron proton-antiproton ($p\bar{p}$) collider. The standard model (SM) [4] predicts a small forward-backward asymmetry $(8.8 \pm 0.6)\%$ at next-to-leading order (NLO) in the strong coupling constant α_s [5,6]. The tension between the Tevatron measurements and the predictions has stimulated new work on the SM calculation [7–10] and on possible non-SM sources for the asymmetry [11]. The charge asymmetry is also under study at the LHC, but any effects are expected to be much smaller due to the forward-backward symmetric (proton-proton) initial state [12], and the results are so far inconclusive [13,14].

We measure the differential cross section $d\sigma/d(\cos\theta_t)$, where θ_t is the angle between the top-quark momentum and the incoming proton momentum, as measured in the $t\bar{t}$ center-of-mass frame. The inclusive measurements of $A_{\rm FB}$ are equivalent to a two-bin measurement of this differential cross section, with one bin forward ($\cos\theta_t > 0$) and one bin backward ($\cos\theta_t < 0$). The full shape of the differential cross section provides additional information and has the potential to discriminate among various calculations of the SM as well as models of non-SM physics. One of the aims of this study is to identify what aspects of the shape of $d\sigma/d(\cos\theta_t)$ explain the $A_{\rm FB}$.

We characterize the shape of $d\sigma/d(\cos\theta_t)$ by employing the Legendre polynomials [15], which are fundamental to the general theory of scattering of particles in the present spin-averaged case [16]. The orthonormality of these polynomials on the interval $[-1, 1]$ allows a unique decomposition of the cross section into a Legendre polynomial series. We write

$$\frac{d\sigma}{d(\cos\theta_t)} = \sum_{\ell=0}^{\infty} a_\ell P_\ell(\cos\theta_t), \quad (1)$$

where P_ℓ is the Legendre polynomial of degree ℓ, and a_ℓ is the Legendre moment of degree ℓ. Because the experimental sensitivity degrades as ℓ increases, we restrict the sum to $\ell \leq 8$. Since the moment a_0 contains only the total cross section, we scale all the moments so that $a_0 = 1$.

At leading order (LO) in the SM, the differential cross section for $q\bar{q} \to t\bar{t}$ is

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\Omega}(\cos\theta_t, \hat{s}) = \frac{\beta\alpha_s^4}{144\pi\hat{s}}[2 - \beta^2(1 + \cos^2\theta_t)], \quad (2)$$

where β is the velocity of the top quark in units of c [17] and $\hat{s}$ is the Mandelstam variable [18]. After integrating over $\hat{s}$ to obtain $d\sigma/d(\cos\theta_t)$ and comparing to the Legendre polynomials, we expect nonzero values only for a_0 and a_2. The addition of the $gg \to t\bar{t}$ process is expected to add small contributions to all the even-degree Legendre moments. We study the LO SM via a sample of simulated events generated by PYTHIA [19]. At next-to-leading order in the SM, additional contributions to all the Legendre moments appear, including the odd moments. These nonzero odd moments introduce the lowest-order contributions to A_{FB}. The NLO SM theoretical calculation adopted in this Letter includes the full effects of both quantum chromodynamics and the electroweak theory [5].

A wide variety of non-SM proposals has been put forward to explain the large value of A_{FB} observed at the Tevatron. These form two broad classes, depending on whether the new physics is dominated by s- or t-channel exchange. In order to characterize the effect of these models on the differential cross section, we study two representative models. An s-channel model "Octet A" hypothesizes the existence of a heavy ($m_{G'} = 2$ TeV$/c^2$) partner of the gluon with axial-vector couplings to quarks [20]. This produces an enhanced linear-term coefficient a_1 in $d\sigma/d(\cos\theta_t)$ [17]. A t-channel model "Z' 200" contains a new, heavy ($m_{Z'} =$ 200 GeV$/c^2$) vector boson with a flavor changing u-Z'-t coupling [21]. The resulting additional term in the cross section has a leading dependence $\hat{s}/\hat{t} = 1/(1 - \cos\theta_t)$, where $\hat{t}$ is the Mandelstam variable [18]. This behavior produces large Legendre moments at all degrees. These leading behaviors are generic predictions of s- and t-channel models [17]. Both models are studied via samples of simulated events generated at LO by MADGRAPH [22]. The LO and NLO SM calculations, as well as these two benchmark non-SM models, are shown in Figs. 1 and 2.

We study the full sample of top-quark pair candidate events in the decay channel with a single lepton in the final state collected by the CDF experiment during Run II of the Fermilab Tevatron. The CDF II detector 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 [23,24]. The collected data correspond to an integrated luminosity of 9.4 fb^{-1} of $p\bar{p}$ collisions. The general features of the event selection requirements are as follows. We require exactly one well-reconstructed charged-lepton candidate (electron or muon) with $p_T >$ 20 GeV$/c$, an imbalance in the total event transverse momentum (missing transverse energy [25]) $\not\!\!E_T >$ 20 GeV, and four or more calorimeter-energy clusters (jets [26]), three with $E_T > 20$ GeV and the fourth with $E_T > 12$ GeV, in the central part of the detector ($|\eta| <$ 2.0). We further require that at least one of the jets be identified (tagged) as having a displaced vertex resulting from the decay of a bottom-quark meson, which is produced from the dominant top-quark decay $t \to Wb$. Further details on the on-line and off-line event selection requirements are in Ref. [1]. The resulting data set is enriched in $t\bar{t}$ events, but it contains non-$t\bar{t}$ background events as well, dominated by events in which a W boson is produced in association with hadron jets. The rates and differential distributions of all the sources of non-$t\bar{t}$ backgrounds are well understood [1]. We expect to observe 2750 ± 427 $t\bar{t}$ events and 1026 ± 210 non-$t\bar{t}$ background events, and we observe 3864 $t\bar{t}$ candidate events.

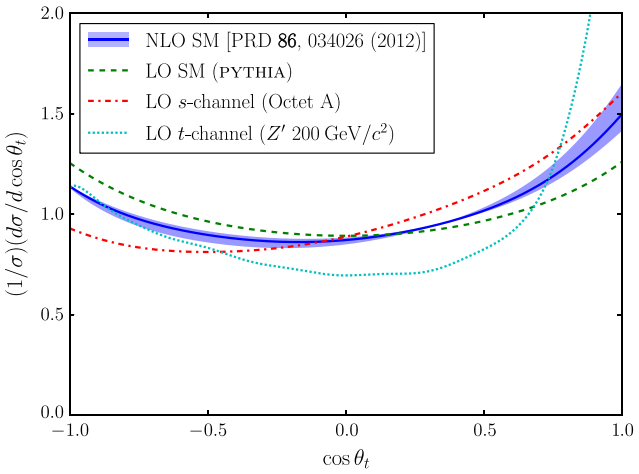

FIG. 1 (color online). The predicted differential cross sections of the LO SM [19], the NLO SM [5], and the benchmark models for s- and t-channel new physics [20,21]. The band around the NLO SM prediction represents the uncertainty due to renormalization-scale choice.

We reconstruct the top quark and the top antiquark from their decay products, using the measured momentum of the lepton and the four jets, as well as the missing transverse energy. We fit each possible jet-to-parton assignment to the $t\bar{t}$ hypothesis. We require that two of the jets be consistent with the decay of a W boson of mass 80.4 GeV$/c^2$ and that

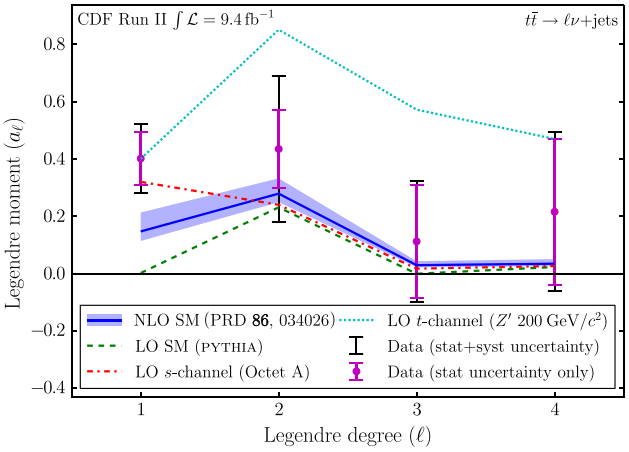

FIG. 2 (color online). Measured Legendre moments a_1–a_4, with theory predictions overlaid.

the lepton and missing transverse energy also be consistent with the decay of a W boson. We further require that each reconstructed W boson, when paired with one of the remaining jets, be consistent with the decay of a top quark of mass 172.5 GeV/c^2 [27]. The jet-to-parton assignment which is most consistent with this $t\bar{t}$ hypothesis is used to calculate the top-quark production angle as measured in the detector $\cos\theta_t^{\rm det}$ for each event.

We exploit the orthonormality of the Legendre polynomials to estimate the Legendre moments without performing a fit. Given a distribution $f(\cos\theta_t)$, the Legendre moments of f are

$$a_\ell = \frac{2\ell+1}{2}\int_{-1}^{1} d(\cos\theta_t) f(\cos\theta_t) P_\ell(\cos\theta_t). \quad (3)$$

The data are described by an empirical distribution [28] $f(\cos\theta_t^{\rm det}) = \sum_i \delta(\cos\theta_t^{\rm det} - \cos\theta_{t,i}^{\rm det})$, where $\delta(x)$ is the Dirac δ function and the index i runs over the events in the data set. Using this distribution in Eq. (3) greatly simplifies the integration due to the Dirac delta functions, so the moments of the observed $\cos\theta_t^{\rm det}$ distribution are

$$a_\ell^{\rm det} = \frac{2\ell+1}{2}\sum_i P_\ell(\cos\theta_{t,i}^{\rm det}). \quad (4)$$

Then, the estimate of the moments is

$$a_\ell = \sum_m K_{\ell m}\left(\sum_i P_m(\cos\theta_{t,i}^{\rm det}) - a_m^{\rm BG}\right), \quad (5)$$

where $a_m^{\rm BG}$ represents the Legendre moments of the distribution of $\cos\theta_t^{\rm det}$ predicted by the background model, and $K_{\ell m}$ is a correction matrix that accounts for the finite resolution of the detector and for the nonuniform detector acceptance and selection efficiency. The matrix K is developed from a sample of fully simulated $t\bar{t}$ Monte Carlo events generated by the POWHEG NLO SM generator [29]. It describes the response of the detector and the effects of the event selection requirements. No smoothing or regularization is applied in this correction procedure, in contrast to the correction procedure of Ref. [1].

The statistical uncertainties on the moments are given by a root-mean-square covariance matrix including correlations. In order to estimate the effect from each of several sources of systematic uncertainty in the model assumptions, we vary the corresponding nuisance parameter that alters either the background prediction or correction matrix, and then perform the full correction procedure again. The resulting parton-level moments estimate is compared to the unvaried moments, and then the covariance matrix describing the uncertainty on the measurement is $\sigma_{m\ell} = \delta_m \delta_\ell$, where $\delta_\ell \equiv a_\ell^{\rm varied} - a_\ell^{\rm nominal}$. We study systematic shifts due to the uncertainty in the jet-energy scale, the rate of the backgrounds, the shape of the backgrounds, the modeling of parton showering, the modeling of color reconnection, the modeling of initial- and final-state radiation, and the parton distribution functions of the proton and antiproton. We sum the resulting covariance matrices and add them to the statistical covariance matrix to obtain a covariance matrix that fully describes the uncertainty of the measurement of the parton-level Legendre moments. The eigenvalues and eigenvectors of the covariance matrix [30] can be used to calculate a χ^2 goodness-of-fit statistic with 8 degrees of freedom in order to perform fits to the data.

TABLE I. Measured Legendre moments a_1–a_8, with NLO SM predictions. The uncertainty on the measured moments is the total uncertainty from statistical and systematic sources. The uncertainty on the prediction reflects reasonable variations in the renormalization scale [5].

ℓ	a_ℓ (obs)	a_ℓ (pred)
1	0.40 ± 0.12	$0.15^{+0.07}_{-0.03}$
2	0.44 ± 0.25	$0.28^{+0.05}_{-0.03}$
3	0.11 ± 0.21	$0.030^{+0.014}_{-0.007}$
4	0.22 ± 0.28	$0.035^{+0.016}_{-0.008}$
5	0.11 ± 0.33	$0.005^{+0.002}_{-0.001}$
6	0.24 ± 0.40	$0.006^{+0.002}_{-0.003}$
7	-0.15 ± 0.48	$-0.003^{+0.001}_{-0.001}$
8	0.16 ± 0.65	$-0.0019^{+0.0003}_{-0.0003}$

The parton-level Legendre moments are shown in Fig. 2 and in Table I. We observe good agreement within the uncertainties with the NLO SM prediction for moments a_2–a_8, but a_1 is in excess of the prediction. That is, a mild excess is observed in the differential cross section in the term linear in $\cos\theta_t$, while all other terms are as predicted by the SM. The LO SM prediction is strongly disfavored by the linear term, with a significance of more than 3 standard deviations. The benchmark t-channel model Z' 200 is disfavored by a_2 and a_3. The benchmark s-channel model Octet A is in good agreement with the data.

We determine the contribution of each Legendre moment to the $A_{\rm FB}$ from the inherent asymmetry of each polynomial (Fig. 3). The observed $A_{\rm FB}$ $(19.9 \pm 5.7)\%$ is completely dominated by the excess linear term $a_1 \cos\theta_t$, which contributes $(20.1 \pm 6.1)\%$. The $A_{\rm FB}$ contributed by the nonlinear asymmetric terms a_3, a_5, and a_7 is negligible $(-0.2 \pm 3.1)\%$ and is consistent with the SM prediction (7.3% from the linear term, -0.3% from the nonlinear terms). The correlation between the measurements of $A_{\rm FB}$ from the linear and nonlinear terms is -29%.

A more traditional picture of the differential cross section (Fig. 4) is obtained by integrating the Legendre series over intervals (bins) in $\cos\theta_t$. This shows the fraction of the total cross section that accrues in each bin. The uncertainties are strongly correlated, and they are dominated by the large uncertainties on the high-degree Legendre moments.

Because the nonlinear moments a_2–a_8 are in good agreement within the uncertainties with the NLO SM prediction, we may obtain a more precise, but model-dependent, estimate of the linear term by explicitly

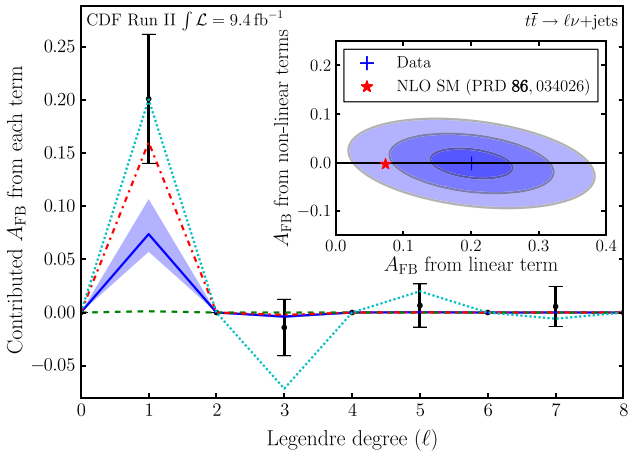

FIG. 3 (color online). Absolute contributions of the Legendre moments to the A_{FB}, with theory predictions overlaid. The lines and symbols are the same as in Fig. 2. The inset shows the 1-, 2-, and 3-standard-deviation uncertainty ellipses.

assuming that the nonlinear moments are as predicted by the NLO SM calculation. Using the covariance matrix and the fitting procedure described in Ref. [30], we fit to the measured moments, taking the NLO SM prediction for the nonlinear moments with their scale uncertainties as a prior assumption, obtaining $a_1 = 0.39 \pm 0.11$ (including statistical and systematic uncertainty). Through the correlations among the measured moments, this reduces the uncertainty on a_1 by about 10% while shifting the central value less than 3%. The resulting curve is also shown in Fig. 4.

In conclusion, we have presented the first measurement of the top-quark pair production differential cross section $d\sigma/d(\cos\theta_t)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV as a function of the production angle of the top quark. In order to probe the origin of the top-quark production asymmetry, we decompose the angular form into Legendre polynomials. We observe that the coefficient of the $\cos\theta_t$ term in the differential cross section $a_1 = 0.40 \pm 0.12$ is in excess of the NLO SM prediction $0.15^{+0.07}_{-0.03}$, while the remainder of the differential cross section is in good agreement within the uncertainties with the NLO SM prediction. The top-quark forward-backward asymmetry is thus completely dominated by the linear term. The result constrains t-channel explanations of the asymmetry and favors asymmetry models with strong s-channel components.

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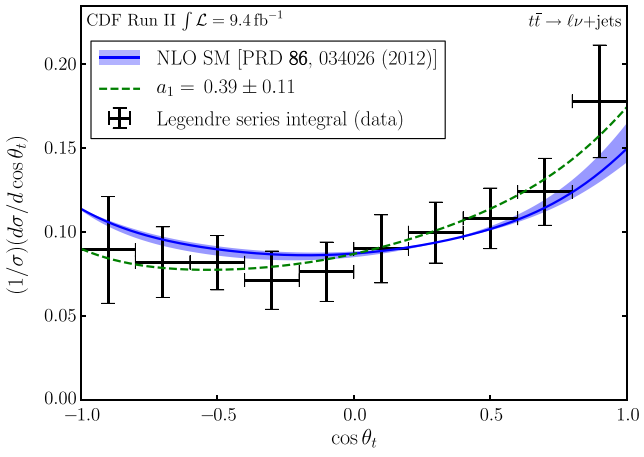

FIG. 4 (color online). Fraction of cross section accruing in 10 bins of $\cos\theta_t$, obtained by integrating the series of Legendre polynomials over the width of each bin.

[a]Deceased.
[b]Visitor from University of British Columbia, Vancouver, BC V6T 1Z1, Canada.
[c]Visitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.
[d]Visitor from University of California, Irvine, Irvine, CA 92697, USA.
[e]Visitor from Institute of Physics, Academy of Sciences of the Czech Republic, Prague 182 21, Czech Republic.
[f]Visitor from CERN, CH-1211 Geneva, Switzerland.
[g]Visitor from Cornell University, Ithaca, NY 14853, USA.
[h]Visitor from University of Cyprus, Nicosia CY-1678, Cyprus.
[i]Visitor from Office of Science, U.S. Department of Energy, Washington, DC 20585, USA.
[j]Visitor from University College Dublin, Dublin 4, Ireland.
[k]Visitor from ETH, 8092 Zürich, Switzerland.
[l]Visitor from University of Fukui, Fukui City, Fukui Prefecture 910-0017, Japan.

[m]Visitor from Universidad Iberoamericana, Lomas de Santa Fe, C.P. 01219, Distrito Federal, México.
[n]Visitor from University of Iowa, Iowa City, IA 52242, USA.
[o]Visitor from Kinki University, Higashi-Osaka City 577-8502, Japan.
[p]Visitor from Kansas State University, Manhattan, KS 66506, USA.
[q]Visitor from Brookhaven National Laboratory, Upton, NY 11973, USA.
[r]Visitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.
[s]Visitor from University of Melbourne, Victoria 3010, Australia.
[t]Visitor from Muons, Inc., Batavia, IL 60510, USA.
[u]Visitor from Nagasaki Institute of Applied Science, Nagasaki 851-0193, Japan.
[v]Visitor from National Research Nuclear University, Moscow 115409, Russia.
[w]Visitor from Northwestern University, Evanston, IL 60208, USA.
[x]Visitor from University of Notre Dame, Notre Dame, IN 46556, USA.
[y]Visitor from Universidad de Oviedo, E-33007 Oviedo, Spain.
[z]Visitor from CNRS-IN2P3, Paris F-75205, France.
[aa]Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.
[bb]Visitor from The University of Jordan, Amman 11942, Jordan.
[cc]Visitor from Universite catholique de Louvain, 1348 Louvain-La-Neuve, Belgium.
[dd]Visitor from University of Zürich, 8006 Zürich, Switzerland.
[ee]Visitor from Massachusetts General Hospital, Boston, MA 02114, USA.
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[gg]Visitor from Hampton University, Hampton, VA 23668, USA.
[hh]Visitor from Los Alamos National Laboratory, Los Alamos, NM 87544, USA.
[ii]Visitor from Università degli Studi di Napoli Federico I, I-80138 Napoli, Italy.

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