Measurement of W-Boson Polarization in Top-Quark Decay in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report measurements of the polarization of W bosons from top-quark decays using 2.7 fb^{-1} of $p\bar{p}$ collisions collected by the CDF II detector. Assuming a top-quark mass of 175 GeV$/c^2$, three measurements are performed. A simultaneous measurement of the fraction of longitudinal (f_0) and right-handed (f_+) W bosons yields the model-independent results $f_0 = 0.88 \pm 0.11(\text{stat}) \pm 0.06(\text{syst})$ and $f_+ = -0.15 \pm 0.07(\text{stat}) \pm 0.06(\text{syst})$ with a correlation coefficient of -0.59. A measurement of f_0 [f_+] constraining f_+ [f_0] to its standard model value of 0.0 [0.7] yields $f_0 = 0.70 \pm 0.07(\text{stat}) \pm 0.04(\text{syst})$ [$f_+ = -0.01 \pm 0.02(\text{stat}) \pm 0.05(\text{syst})$]. All these results are consistent with standard model expectations. We achieve the single most precise measurements of f_0 for both the model-independent and model-dependent determinations.

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The top quark is the most massive fundamental particle observed by experiment [1]. Because of its large mass, in the standard model (SM) the top quark decays before forming a bound state via the charged current weak interaction into a W^+ boson and a b quark [2], with a branching fraction above 99% [3]. This provides a unique opportunity to study the properties of a ''bare'' quark. In particular, the V-A structure of the weak interaction can be tested by reconstructing the polarization of the W^+ boson from top-quark decay. In the SM at tree level [4], the W^+ boson is expected to have longitudinal polarization $f_0 = 0.703$, left-handed polarization $f_- = 0.297$, and right-handed polarization $f_+ = 3.6 \times 10^{-4}$ for a top-quark mass $m_t = 175\ \text{GeV}/c^2$, a W-boson mass $M_W = 80.413\ \text{GeV}/c^2$ [5], and a b-quark mass $m_b = 4.79\ \text{GeV}/c^2$ [3]. In the limit of $m_b \to 0$, $f_0 = m_t^2/(2m_W^2 + m_t^2)$ and $f_+ = 0$. The higher-order QCD and electroweak radiative corrections modify these predictions at the 1%–2% (relative) level [6]. In beyond-the-SM scenarios, significant deviations from the SM expectation are possible due to the presence of anomalous couplings [4] in the tWb vertex. Measurements of W-boson polarization and single top-quark production together set constraints on the anomalous coupling vector and tensor form factors [7].

In this Letter, we measure the polarization of the W boson from top-quark decay. We assume the $t\bar{t}$ production mechanism is in agreement with the SM, and we study a data sample enriched in $t\bar{t} \to W^+ b W^- \bar{b} \to \ell \nu b q \bar{q}' \bar{b}$ events where one of the W bosons decays hadronically and the other leptonically (lepton plus jets). We apply a likelihood technique based on the theoretical matrix elements for both the dominant signal process, $q\bar{q} \to t\bar{t}$, and the main background process, inclusive production of $W +$ jets. This technique was first developed for the measurements of top-quark mass and f_0, constraining f_+ to its SM value [8], and utilizes the kinematic and topological information from the event through integrations over poorly known parton-level quantities. We express the matrix element in terms of the W-boson polarization fractions and the cosine of the angle θ^* between the momentum of the charged lepton or down-type quark in the W-boson rest frame and the momentum of the W boson in the top-quark rest frame. Therefore we extract information on the W-boson polarization from both the leptonic and hadronic W-boson decays. Previous CDF measurements [9,10] used only information from the leptonic decay. While the information from the hadronic W-boson decay carries a sign ambiguity in $\cos\theta^*$ since we are unable to identify the down-type quark jet its inclusion still improves the sensitivity to the f_0 polarization fraction. The analysis described in this Letter improves the statistical sensitivity on f_0 by 20% relative to the best previous CDF measurement [9] for the same event sample. The latest D0 measurement also utilizes information from both the leptonic and hadronic W-boson decays [11].

We report measurements of the W-boson polarization for three different hypotheses of top-quark decay: (i) model-independent with simultaneous measurement of f_0 and f_+; (ii) anomalous tensor couplings with measurement of f_0 for fixed $f_+ = 0$; and (iii) anomalous right-handed couplings with measurement of f_+ for fixed $f_0 = 0.70$.

The polarization fractions are determined using an unbinned likelihood function L maximized with respect to f_0, f_+, and the fraction of events consistent with the $t\bar{t}$ signal hypothesis, C_s,

$$L(f_0, f_+, C_s) = \prod_{i=1}^{N} \left[C_s \frac{P_s(x; f_0, f_+)}{\langle A_s(x; f_0, f_+) \rangle} + (1 - C_s) \times \frac{P_b(x)}{\langle A_b(x) \rangle} \right].$$

Here, N is the number of observed events, x is a set of observed variables, and $\langle A_s \rangle$ and $\langle A_b \rangle$ refer to the average acceptances for $t\bar{t}$ and $W +$ jets background events, respectively. The dependence of the $t\bar{t}$ signal acceptance on the polarization fractions is accounted for in $\langle A_s \rangle$. The signal probability P_s and background probability P_b densities are constructed as in [12] by integrating over the appropriate parton-level differential cross section convolved with the proton parton distribution functions (PDFs). The parton four momenta are estimated from the single lepton and the four highest transverse energy E_T [13] jets in the event, and transfer functions derived from Monte Carlo (MC) are used to unfold the detector resolution effects. There is an ambiguity in the jet-parton assignments and all permutations are used for each event.

The signal differential cross section uses the leading-order matrix element of the $q\bar{q} \to t\bar{t}$ process [14], expressed in terms of $\cos\theta^*$ and the polarization fractions:

$$|M|^2 = \frac{g_s^4}{9} F_\ell \bar{F}_h (2 - \beta^2 \sin^2\theta_{qt}),$$

where g_s is the strong coupling constant, θ_{qt} describes the angle between the incoming parton and the top quark in the rest frame of the incoming partons, and β is the velocity of the top quarks in the same rest frame. The factors F_ℓ and $\bar{F}_h$ correspond to the top quarks with a leptonic and a hadronic W-boson decay, such that

$$F_\ell = \frac{2\pi g_W^4 m_{\bar{\ell}\nu}^2}{3 m_t \Gamma_t} (2E_b^{*2} + 3E_b^* m_{\bar{\ell}\nu} + m_b^2) \left[\frac{3}{8}(1 + \cos\theta^*)^2 f_+ + \frac{3}{4}(1 - \cos^2\theta^*) f_0 + \frac{3}{8}(1 - \cos\theta^*)^2 (1 - f_0 - f_+) \right].$$

Here g_W is the weak coupling constant, $m_{\bar{\ell}\nu}$ is the invariant mass of the lepton and neutrino, Γ_t is the width of the top quark, m_t and m_b are the masses of the top quark and b quark, respectively, and $E_b^* = \frac{m_t^2 - m_b^2 - m_{\bar{\ell}\nu}^2}{2m_{\bar{\ell}\nu}}$. The hadronic factor $\bar{F}_h$ is similar, with the exception that we do not distinguish between up-type and down-type quarks from W-boson decay and use the average $\bar{F}_h$ related to the two permutations. The background differential cross section uses the sum of matrix elements for $W +$ jets from the VECBOS [15] MC generator.

The measurement is based on a data set with an integrated luminosity of 2.7 fb^{-1} acquired by the collider detector at Fermilab (CDF II) [16] from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The data used are collected using high-transverse momentum (p_T) [13] central (pseudorapidity [13] $|\eta| < 1.1$) electron and muon triggers, a high-p_T forward ($1.2 < |\eta| < 2.0$) electron trigger, and a trigger that requires large missing transverse energy $\not{E}_T$ [13] with either an energetic electromagnetic cluster or two separated jets ($\not{E}_T +$ jets) [17]. The $\not{E}_T +$ jets trigger is used to select additional events with high-p_T muons, which are not selected by the lepton triggers.

Candidate events for the lepton plus jets final state are selected to have a single, isolated electron or muon candidate with $E_T > 20$ GeV, large $\not{E}_T$ in the event ($\not{E}_T >$ 20 GeV) as expected from the undetectable neutrino, and at least four jets with $E_T > 20$ GeV. Jets are reconstructed using a cone algorithm with radius $\Delta R = 0.4$ in $\eta - \phi$ space, and their energies are corrected for nonuniformities in the calorimeter response as a function of jet η, multiple $p\bar{p}$ interactions, and the hadronic jet energy scale of the calorimeter [18]. Of these jets, we require at least one to have originated from a b quark by using an algorithm that identifies a long-lived b hadron through the presence of a displaced vertex (b tag) [19]. Backgrounds to the $t\bar{t}$ signal arise from multijet QCD production (QCD), W-boson production in association with jets ($W +$ jets), and electroweak backgrounds (EWK) composed of diboson (WW, WZ, ZZ) and single top-quark production. The $W +$ jets background includes b-flavor jets as well as light flavor jets incorrectly identified as b jets.

A detailed description of the background estimation can be found in Ref. [20]. Table I shows the expected sample composition assuming a $t\bar{t}$ cross section of 6.7 pb. There are overlapping events between those collected by the high-p_T lepton triggers and the $\not{E}_T +$ jets trigger which are included in the central e/μ and forward e categories, and are eliminated from the $\not{E}_T +$ jets category.

TABLE I. Number of expected and observed events in 2.7 fb^{-1} assuming a $t\bar{t}$ cross section of 6.7 pb.

Process	Central	Forward	$\not{E}_T$ + jets
	e, μ	e	μ
$t\bar{t}$	478 ± 66	58 ± 8	134 ± 19
W + jets	94 ± 23	18 ± 11	25 ± 6
EWK	17 ± 10	3 ± 1	5 ± 3
QCD	28 ± 22	46 ± 37	1 ± 1
Total expected	616 ± 74	125 ± 40	165 ± 20
Observed	650	136	178

The HERWIG [21] MC generator is used to model the $t\bar{t}$ signal events with $m_t = 175\ \text{GeV}/c^2$. For estimation of various systematic uncertainties and background modeling MC samples are created using the PYTHIA [22] generator, and ALPGEN [23] or MADEVENT [24] with PYTHIA or HERWIG supplying the parton shower and fragmentation. The QCD background is modeled using data control samples. The signal and background modeling has been extensively checked. Figure 1 compares the observed data and the MC-predicted distributions of different kinematic variables. We have validated the background model by studying a high-statistics control sample of $W +$ jets candidates extracted by vetoing events containing b-tagged jets.

We calibrate the results of the likelihood fit using the simulated $t\bar{t}$ and background samples, and the sample composition of Table I. For the simultaneous measurement of f_0 and f_+, we find our estimate $f_{0,m}$ is related to the true value of f_0 by $f_{0,m} = (0.88 \pm 0.02)f_0 + (-0.12 \pm 0.01)$ and our estimate of $f_{+,m}$ is related to the true value of f_+ and f_0 by $f_{+,m} = (1.26 \pm 0.01)f_+ + (0.17 \pm 0.02)f_0 + (0.06 \pm 0.01)$. We use these calibration functions and the measured polarization fractions to extract the true polarization fractions. For our measurement of f_0 with $f_+ = 0$, we find our estimate $f_{0,m} = (1.15 \pm 0.04)f_0 + (-0.09 \pm 0.02)$, and for our measurement of f_+ with $f_0 = 0.7$, we

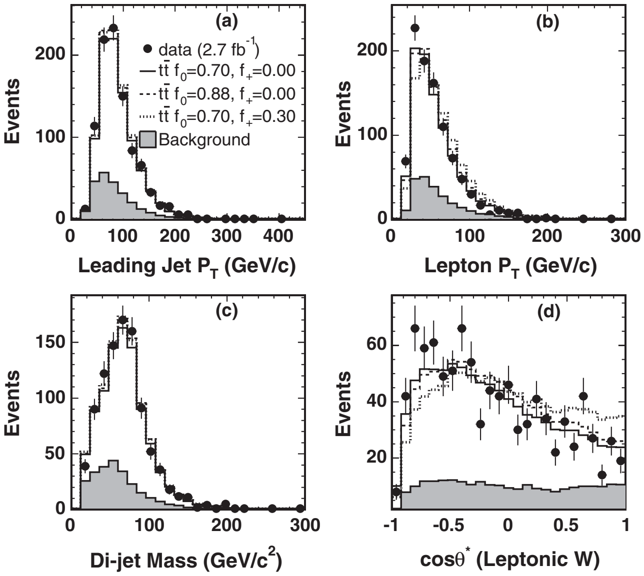

FIG. 1. Comparison of four kinematic variables for data and simulation for different W polarization fractions: solid, dashed and dotted histograms correspond to (f_0, f_+) values of (0.7, 0.0), (0.88,0.0), and (0.7, 0.3), respectively. Plotted are (a) leading jet p_T, (b) lepton p_T; and for the reconstruction chosen as most likely by the per-event likelihood (c) the invariant mass of the pair of light quark jets from the hadronically decaying W boson and (d) the $\cos\theta^*$ of the leptonically decaying W boson.

TABLE II. Summary of systematic uncertainties.

Source	Δf_0	Δf_+	Δf_0 simultaneous	Δf_+ simultaneous
ISR or FSR	0.020	0.018	0.020	0.021
PDF	0.024	0.013	0.009	0.016
JES	0.018	0.017	0.004	0.012
Parton shower	0.012	0.008	0.031	0.017
Background	0.009	0.038	0.042	0.039
Method-related	0.010	0.005	0.024	0.024
Total	0.041	0.048	0.062	0.057

find our estimate $f_{+,m} = (1.17 \pm 0.05) f_+ + (0.01 \pm 0.01)$. The uncertainties on the coefficients of the calibration functions are included in the method-related systematic uncertainties, which cover possible biases due to the calibration procedure. The differences between our measured values and the true values arise because the signal and background probabilities used in the likelihood do not accurately model the effects of extra jets arising from initial and final state radiation (ISR/FSR) nor the full set of contributing background processes. Even though likelihood can be calculated only for the physical values of f_0 and f_+, after calibration the corrected measured values can be slightly outside their physical ranges.

The robustness of the fitting procedure over all physical values of (f_0, f_+) has been tested with simulated experiments, using the number of observed data events and the sample composition of Table I. In all cases, the method is unbiased. Near the physical boundaries, we find that the statistical uncertainty is underestimated by as much as a factor of 1.5. We apply a correction to the statistical uncertainty in these regions. Assuming the SM, the expected statistical uncertainties after all corrections for the simultaneous measurement are ± 0.116 and ± 0.074 for f_0 and f_+, respectively.

Various sources of systematic uncertainty affecting the measurement are summarized in Table II. The leading sources of systematic uncertainty arise from MC modeling of initial and final state radiation (ISR and FSR), choice of PDFs, choice of parton shower model, uncertainties on the measured jet energy, and the background shape and normalization. The method-related uncertainty includes propagating the uncertainty on the fit parameters of the calibration functions, including their correlations. All systematic uncertainties are determined by performing simulated experiments in which the systematic parameter in question is varied, the default method and calibrations are applied, and the shifts in the mean measured polarization fractions are used to quantify the uncertainty. All shifts are evaluated at the SM helicity fraction.

For the simultaneous measurement of f_0 and f_+, we exclude the events from the forward electron trigger as this significantly reduces the systematic uncertainty from the background model. With 828 events and after all corrections, we measure

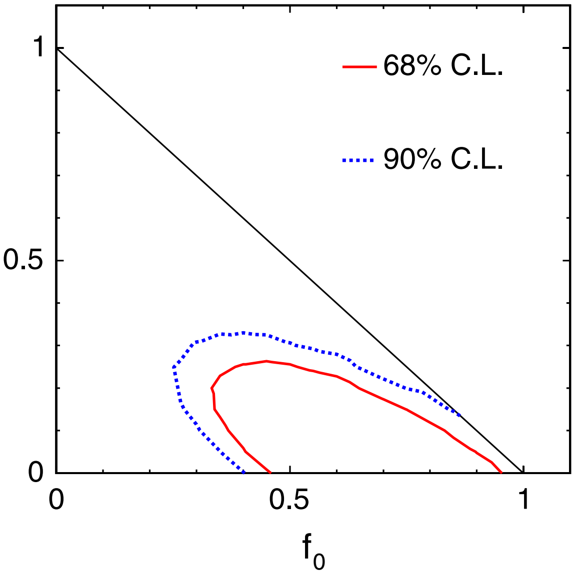

FIG. 2 (color online). Contours in the (f_0, f_+) plane indicating 68% and 90% C.L. intervals determined using the Feldman-Cousins method. Note that the coverage is correct although the center of the contours is not at the measured value obtained after calibration.

$$f_0 = 0.879 \pm 0.106(\text{stat}) \pm 0.062(\text{syst}),$$
$$f_+ = -0.151 \pm 0.067(\text{stat}) \pm 0.057(\text{syst}).$$

The statistical correlation between f_0 and f_+ is $\rho = -0.59$. We estimate a shift of $\mp(0.010 \pm 0.005)$ in f_0 and $\pm(0.017 \pm 0.003)$ in f_+ per ± 1 GeV/c^2 shift in the top-quark mass from the central value of 175 GeV/c^2. As the central value is unphysical we have elected to ensure coverage by applying the Feldman-Cousins method [25] to obtain the confidence level (C.L.) intervals shown in Fig. 2.

Fixing $f_+ = 0$ and with 964 events, we measure after all corrections $f_0 = 0.701 \pm 0.069(\text{stat}) \pm 0.041(\text{syst})$. Fixing $f_0 = 0.70$, we measure after all corrections $f_+ = -0.010 \pm 0.019(\text{stat}) \pm 0.049(\text{syst})$ and find $f_+ < 0.12$ at 95% C.L. We estimate a shift of $\pm(0.011 \pm 0.003)$ in f_0 and $\pm(0.013 \pm 0.002)$ in f_+ per ± 1 GeV/c^2 shift in the top-quark mass from the central value of 175 GeV/c^2.

In summary, we have measured the polarization of the W boson in top-quark decays using a matrix-element method in 2.7 fb^{-1} of CDF II data. Our results are consistent with the SM. This result improves the combined statistical and systematic precision on both the model-independent and model-dependent determinations of the longitudinal polarization f_0 by a factor of 1.3 compared to the best previous measurement [9] for a 1.4 times increase in luminosity, and are the most precise measurements to date.

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[1] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **74**, 2626 (1995); S. Abachi *et al.* (D0 Collaboration), Phys. Rev. Lett. **74**, 2632 (1995).

[2] Charge-conjugate modes are included implicitly throughout this Letter.

[3] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008) and 2009 partial update for the 2010 edition.

[4] J. Aguilar-Saavedra *et al.*, Eur. Phys. J. C **50**, 519 (2007).

[5] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, 151801 (2007).

[6] M. Fischer *et al.*, Phys. Rev. D **63**, 031501(R) (2001); H. S. Do *et al.*, Phys. Rev. D **67**, 091501(R) (2003).

[7] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **102**, 092002 (2009).

[8] V. M. Abazov *et al.* (D0 Collaboration), Nature (London) **429**, 638 (2004); V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **617**, 1 (2005).

[9] T. Aaltonen *et al.* (CDF Collaboration), Phys. Lett. B **674**, 160 (2009).

[10] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, 072001 (2007); A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **75**, 052001 (2007); A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **73**, 111103 (2006); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 031101 (2005).

[11] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **100**, 062004 (2008).

[12] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, 182002 (2007).

[13] We use a cylindrical coordinate system where the z axis is along the proton beam direction and θ is the polar angle. Pseudorapidity is $\eta = -\ln\tan(\theta/2)$, while transverse momentum is $p_T = |p|\sin\theta$, and transverse energy is $E_T = E\sin\theta$. Missing transverse energy, $\not\!\!E_T$, is defined as the magnitude of $-\sum_i E_T^i \hat{n}_i$, where $\hat{n}_i$ is the unit vector in the

azimuthal plane that points from the beam line to the *i*th calorimeter tower.

[14] G. Mahlon and S. Parke, Phys. Lett. B **411**, 173 (1997); G. Mahlon and S. Parke, Phys. Rev. D **53**, 4886 (1996).

[15] F. A. Berends, W. T. Giele, and H. Kuijf, Nucl. Phys. B **321**, 39 (1989).

[16] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 031101(R) (2005).

[17] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **74**, 072006 (2006); T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **100**, 211801 (2008).

[18] A. Bhatti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **566**, 375 (2006).

[19] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).

[20] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **97**, 082004 (2006).

[21] G. Corcella *et al.*, J. High Energy Phys. 01 (2001) 010.

[22] T. Sjostrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).

[23] M. Mangano *et al.*, J. High Energy Phys. 07 (2003) 001.

[24] J. Alwall *et al.*, J. High Energy Phys. 09 (2007) 028.

[25] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).