

## Measurement of the helicity of $W$ bosons in top-quark decays

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We measure the branching fraction of the top quark to longitudinally and right-handed polarized  $W$  bosons,  $F_0$  and  $F_+$ , using approximately  $200 \text{ pb}^{-1}$  of  $\bar{p}p$  collisions collected by the CDF II detector. We analyze two quantities sensitive to the  $W$  helicity: the invariant mass of the charged lepton and the bottom-quark jet in the decay  $t \rightarrow Wb \rightarrow \ell \nu b$  (where  $\ell = e$  or  $\mu$ ), and the transverse momentum of the charged lepton. Constrained fits yield  $F_0 = 0.74_{-0.34}^{+0.22}$ , and  $F_+ < 0.27$  at the 95% confidence level. These measurements are consistent with the standard model predictions.

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The top quark is the most massive known elementary fermion, with  $m_t \sim 175 \text{ GeV}/c^2$  [1,2]. At the Fermilab Tevatron proton-antiproton collider, with a center-of-mass energy of  $\sqrt{s} = 1.96 \text{ TeV}$ , most top quarks are pair-produced via the strong interaction [3,4]. However, the decay  $t \rightarrow Wb$  proceeds entirely via the weak interaction. Given the  $V - A$  structure of the weak interaction in the standard model (SM), in the limit of a massless bottom quark the top quark can decay to either a left-handed or

longitudinally polarized  $W^+$  boson [5] and a bottom quark. The fraction  $F_0$  of longitudinally polarized  $W$  bosons is enhanced due to the large coupling of the top quark to the Higgs field responsible for electroweak symmetry breaking. The leading-order SM prediction is [6]

$$F_0 \equiv \frac{\Gamma(t \rightarrow W_0 b)}{\Gamma(t \rightarrow W_0 b) + \Gamma(t \rightarrow W_{\pm} b)} = \frac{m_t^2}{2M_W^2 + m_t^2}, \quad (1)$$

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where  $W_0$  and  $W_{\pm}$  indicate longitudinally and transversely polarized  $W$ 's, respectively, and  $M_W = 80.4 \text{ GeV}/c^2$  is the  $W$  boson mass [7]. For  $m_t = 175 \text{ GeV}/c^2$ ,  $F_0 = 0.70$ . A deviation from this prediction could indicate non-SM physics such as large  $CP$ -violation in top-quark decays [8], as could a value for the right-handed fraction  $F_+$  different from its SM value of  $\sim 10^{-4}$  [9].

We use two observables in  $t\bar{t}$  candidate events to measure the  $W$  helicity. The first is the decay angle  $\theta^*$  of the charged lepton in the  $W$  decay frame, measured with respect to the top-quark direction, and the second is the transverse momentum  $p_T$  of the charged lepton. Leptons from longitudinally polarized  $W$  boson decays have a symmetric angular distribution  $\propto (1 - \cos^2\theta^*)$ , while left-handed  $W$  decays have an asymmetric distribution  $\propto (1 - \cos\theta^*)^2$ . We can approximate  $\cos\theta^*$  by relating it to the invariant mass of the system composed of the  $b$  quark and the charged lepton  $M_{lb}$ :

$$\cos\theta^* = \frac{p_{\ell} \cdot p_b - E_{\ell}E_b}{|\mathbf{p}_{\ell}||\mathbf{p}_b|} \simeq \frac{2M_{lb}^2}{m_t^2 - M_W^2} - 1, \quad (2)$$

a variable that depends only on lab-frame momenta. The second observable, the charged lepton  $p_T$ , exploits the fact that charged leptons from left-handed  $W$  decays are preferentially emitted in the backward direction with respect to the  $W$  direction of motion, leading to a softer  $p_T$  in the lab frame, while the leptons from right-handed  $W$ 's are preferentially emitted forward and thus have a harder  $p_T$  spectrum. Longitudinal  $W$  decays represent an intermediate case. Figure 1 shows the predicted  $\cos\theta^*$  and lepton  $p_T$  distributions for  $m_t = 175 \text{ GeV}/c^2$ , after the event selection and reconstruction described below.

A measurement of  $F_0$  has been previously reported by the CDF Collaboration [10] using  $\approx 100 \text{ pb}^{-1}$  of data from the 1992–1996 Tevatron collider run (Run I). Using the  $p_T$  technique, a value of  $0.91 \pm 0.37(\text{stat}) \pm 0.13(\text{syst})$  was obtained. Using the same data set, CDF has also placed a limit on the right-handed helicity fraction of  $F_+ < 0.18$  at the 95% confidence level (C.L.) with the  $\cos\theta^*$  technique [11]. The D0 Collaboration has used 125  $\text{pb}^{-1}$  of Run I data to obtain  $F_0 = 0.56 \pm 0.31$  [12], and has recently reported  $F_+ = 0.00 \pm 0.13(\text{stat}) \pm 0.07(\text{syst})$  [13]. Here we report measurements of  $F_0$  and  $F_+$  that combine the  $\cos\theta^*$  and  $p_T$  techniques.

The CDF II detector [14] consists of a charged-particle tracking system in a magnetic field of 1.4 T, segmented electromagnetic and hadronic calorimeters, and muon detectors. A silicon microstrip detector provides tracking over the radial range 1.5–28 cm and is used to detect displaced secondary vertices. The fiducial region of the silicon detector covers the pseudorapidity range  $|\eta| < 2$ , while the central tracking system and muon chambers provide coverage for  $|\eta| < 1$  [15]. For electron identification we use the calorimeter region  $|\eta| < 1$ , while for jet identification we use  $|\eta| < 2.5$ . A three-level trigger sys-

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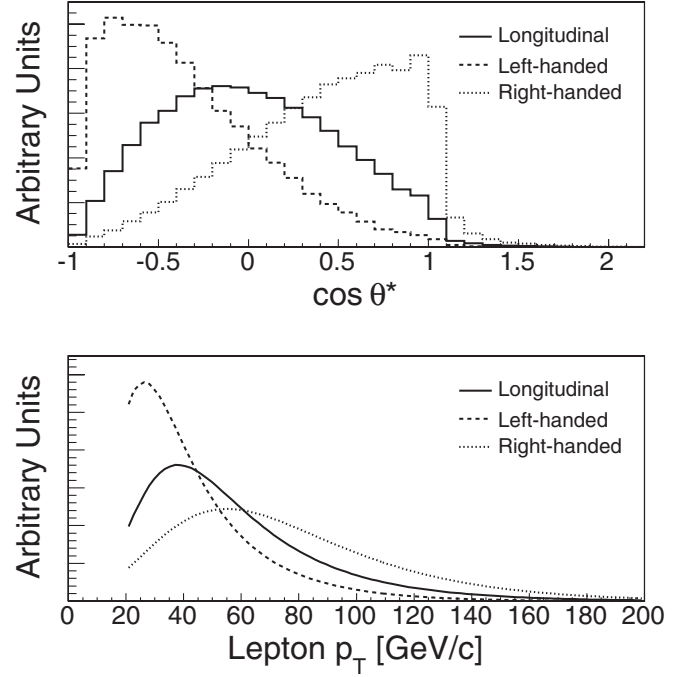


FIG. 1. Distributions of reconstructed  $\cos\theta^*$  (upper plot) and lepton  $p_T$  (lower) for top-quark decays to left-handed, right-handed, and longitudinally polarized  $W$  bosons.

tem selects events with electron (muon) candidates with  $E_T(p_T) > 18 \text{ GeV}$  ( $18 \text{ GeV}/c$ ), which form the data set for this analysis.

In the decay process  $t\bar{t} \rightarrow W^+bW^-\bar{b}$ , events can be classified based on the observed number of isolated charged leptons with large transverse momentum, where a lepton signifies an electron or muon of either charge; typically these leptons come from the decay  $W \rightarrow \ell\nu$ . Transverse momentum for electrons from  $W$  decay is best measured at CDF using the transverse energy  $E_T$  deposited in the calorimeter, while for muons the transverse momentum  $p_T$  is measured by the tracking system. We will use the symbol  $p_T$  to denote the appropriate calorimeter- or tracking-based quantity. The 193  $\text{pb}^{-1}$  “dilepton” sample [16] consists of events with two oppositely charged lepton candidates, each with  $p_T > 20 \text{ GeV}/c$ . Events in this sample are required to have missing transverse energy  $\cancel{E}_T > 25 \text{ GeV}$ , and two or more jets with pseudorapidity  $|\eta| < 2.5$  and transverse energy  $E_T > 15 \text{ GeV}$ . The scalar sum of the transverse energy of the jets, leptons, and  $\cancel{E}_T$ , is required to be greater than 200 GeV. We observe 13 events in this sample, with a predicted total background from  $WW$  pairs,  $Z \rightarrow \bar{\tau}\tau$ , the Drell-Yan process, and hadrons misidentified as leptons (“fakes”) of  $2.7 \pm 0.7$  events. The 162  $\text{pb}^{-1}$  “lepton plus jets” sample [17] consists of events with a single isolated lepton candidate with  $p_T > 20 \text{ GeV}/c$ ,  $\cancel{E}_T > 20 \text{ GeV}$ , and three or more jets with  $|\eta| < 2$  and  $E_T > 15 \text{ GeV}$ . To reduce backgrounds, we require that one or more jets have a displaced secondary-vertex tag, indicating that it

is consistent with the decay of a long-lived  $b$  hadron. Fifty-seven events pass the selection cuts, of which approximately  $2/3$  are  $t\bar{t}$  events. The largest remaining backgrounds come from  $W$  plus jets events containing bottom or charm jets, QCD multijet events, and  $W$  plus light-quark events misidentified as  $b$ 's.

The  $p_T$  analysis [18] uses both samples, while the  $\cos\theta^*$  analysis [19] uses the lepton plus jets sample only. In addition to the selection requirements described above, events selected for the  $\cos\theta^*$  analysis are required to have a fourth jet with  $E_T > 8$  GeV and  $|\eta| < 2$ . Thirty-seven events pass this cut. The presence of four jets allows the event to be kinematically reconstructed as a  $t\bar{t}$  event [1] with the top mass constrained to  $175$  GeV/ $c^2$ , and to associate the appropriate jet to the lepton in Eq. (2). We find that 31 of the 37 events pass a cut on the fit quality, with an estimated background of  $6.9 \pm 0.9$  events.

To create reconstructed  $\cos\theta^*$  templates for  $t\bar{t}$  signal events, we use the MADEVENT [20] Monte Carlo program. Hadronization and fragmentation are carried out using PYTHIA [21]. Events for the  $p_T$  analysis are generated using HERWIG [22]. In both cases, we fix the helicity in the top rest frame of one  $W$  boson, while the other  $W$  takes on values according to the SM prediction. The events are then passed through the CDF simulation and reconstruction algorithms. The lepton from the  $W$  whose helicity was fixed is used to create the templates; we find that the helicity of the other  $W$  has a negligible effect on the  $P_T$  distribution of this lepton. For the lepton plus jets sample, all backgrounds except QCD are modeled with Monte Carlo simulations. We model the QCD background using lepton plus jets events where the primary lepton is nonisolated. For the dilepton sample all but the fake background is modeled with Monte Carlo. We model the latter background using lepton plus jet events containing jets that could be misidentified as a charged lepton.

The data are fit separately to the  $\cos\theta^*$  and  $p_T$  templates using likelihood functions that include a Gaussian constraint on the background, as well as corrections for trigger and event selection cuts that have helicity-dependent biases, such as those on the lepton  $p_T$ . Because the statistical power of the sample is insufficient to fit  $F_+$  and  $F_0$  simultaneously, we constrain  $F_+$  to zero when fitting for  $F_0$ ; when fitting for  $F_+$  we constrain  $F_0$  to 0.70. (If the  $tWb$  interaction vertex is expanded to include a  $V + A$  term,  $F_0$  is unaffected [6].) We require  $\sum F_i = 1$ , resulting in a one-parameter fit. The results of the fits to the various subsamples are shown in Table I. The reconstructed  $\cos\theta^*$  distribution from the data and the best-fit templates are shown in Fig. 2. The observed  $\cos\theta^*$  distribution extends somewhat beyond the physical range  $-1 \leq \cos\theta^* \leq 1$  because the world-average top and  $W$  masses are used in Eq. (2), rather than the true event-by-event reconstructed masses, whose much larger uncertainties would unnecessarily smear the  $\cos\theta^*$  distribution obtained from the  $M_{lb}$  approximation. In

TABLE I. Summary of results for the  $\cos\theta^*$ ,  $p_T$ , and combined measurements of  $F_0$  and  $F_+$ .  $N$  is the number of events or leptons used in the measurement. Where two uncertainties are given the first is statistical and the second is systematic. Uncertainties on the combined measurements are the total statistical and systematic uncertainty. In obtaining the limits, the likelihood function is integrated over the physical region  $[0,1]$  only.

Analysis	$N$	$F_0$	$F_+$
$\cos\theta^*$	31	$0.99^{+0.29}_{-0.35} \pm 0.19$	$0.23 \pm 0.16 \pm 0.08$
$p_T$ (dilepton)	26	$-0.54^{+0.35}_{-0.25} \pm 0.16$	$-0.47 \pm 0.10 \pm 0.09$
$p_T$ (lep + jets)	57	$0.95^{+0.35}_{-0.42} \pm 0.17$	$0.11^{+0.21}_{-0.19} \pm 0.10$
$p_T$ (combined)	83	$0.31^{+0.37}_{-0.23} \pm 0.17$	$-0.18^{+0.14}_{-0.12} \pm 0.12$
Combined	...	$0.74^{+0.22}_{-0.34}$	$0.00^{+0.20}_{-0.19}$
95% C.L. limit	...	$<0.95, >0.18$	$<0.27$

the dilepton sample, the best-fit value of  $F_0$  falls at  $-0.54^{+0.35}_{-0.25}$ , outside the physical range. In this case, the observed distribution of lepton  $p_T$  is softer than any component of signal or background in our model. A measured central value of  $-0.54$  or less is expected 0.5% of the time for a true  $F_0$  of 0.7; however the dilepton result is consistent with the lepton plus jets result at the  $2\sigma$  level when the uncertainties on both measurements are properly taken into account. Moreover a previous analysis of the kinematics of these dilepton data [23] has found them to be consistent with the SM at the 1.0%–4.5% level, and measurements of the  $t\bar{t}$  cross section [16] and top mass [24] in our dilepton samples are also consistent with the SM. We therefore carry out our *a priori* decision to perform a combined  $p_T$  fit to the two samples. The lepton  $p_T$  distribution for the two samples and the results of the fit are shown in Fig. 3.

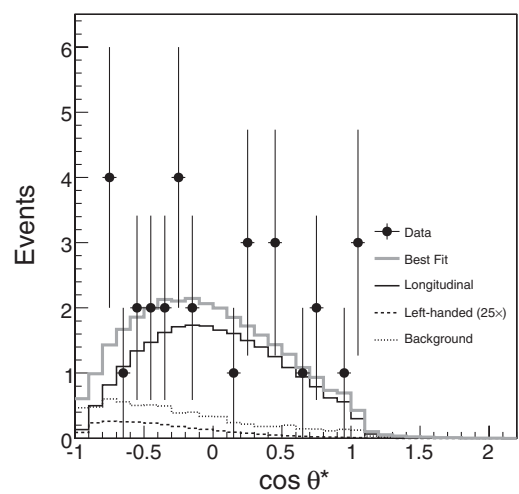


FIG. 2. The reconstructed  $\cos\theta^*$  distribution for the lepton plus jets sample, overlaid with signal and background templates according to their best-fit values. The left-handed template has been scaled up by a factor of 25.



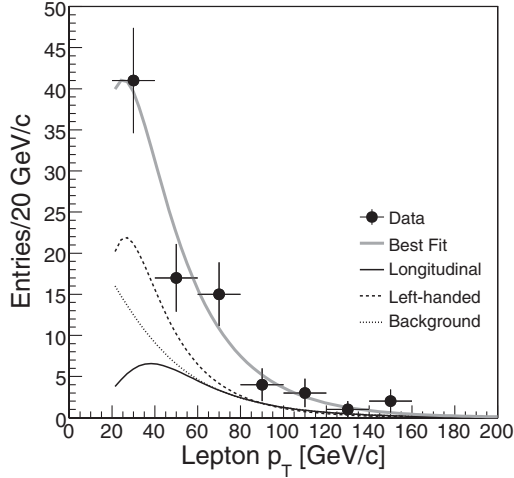


FIG. 3. Distribution of lepton  $p_T$  for the lepton plus jets and dilepton samples, overlaid with the total signal and background templates according to their best-fit values.

The dominant systematic uncertainties in the  $\cos\theta^*$  and  $p_T$  analyses arise from uncertainties in the top-quark mass, the background shape and normalization, the effects of initial- and final-state radiation (ISR/FSR), and the parton distribution functions (PDFs). We determine these uncertainties by performing Monte Carlo experiments in which the systematic parameter in question is varied by  $\pm 1\sigma$  and the resulting simulated data are fit to the default templates. We compare the mean  $F_0$  or  $F_+$  returned by the likelihood fit with the default (unfluctuated) value. The results are summarized in Table II. The sum in quadrature of all sources of systematic uncertainty leads to a final result of  $F_0 = 0.99^{+0.29}_{-0.35}$ (stat.)  $\pm 0.19$ (syst.) for the  $\cos\theta^*$  analysis and  $F_0 = 0.31^{+0.37}_{-0.23}$ (stat.)  $\pm 0.17$ (syst.) for the  $p_T$  analysis.

We combine the results of the  $\cos\theta^*$  and  $p_T$  analyses taking into account both the statistical and systematic correlations between the two techniques. Statistical correlations arise because the two analyses share the subset of the lepton plus jets sample that passes the fit quality cut on the top mass reconstruction. Common sources of systematic uncertainty include the top mass uncertainty and background normalizations. The correlation coefficients of  $\sim 0.6$  are determined via Monte Carlo experiments. The

TABLE II. Summary of systematic uncertainties for the measurements of  $F_0$  and  $F_+$ .

Systematic Source	$p_T$ Method		$\cos\theta^*$ Method	
	$\Delta F_0$	$\Delta F_+$	$\Delta F_0$	$\Delta F_+$
Top Mass	0.11	0.09	0.08	0.04
Bkg. Modeling	0.10	0.06	0.13	0.05
ISR/FSR	0.04	0.03	0.03	0.02
PDF	0.03	0.03	0.04	0.01
MC Statistics	0.01	<0.01	0.01	0.01
Acceptance Correction	0.02	0.01	<0.005	<0.005
Trigger Correction	0.02	0.02	...	...
Jet Energy Scale	...	...	0.09	0.04
MC Modeling	...	...	0.04	0.02
$b$ -tagging	...	...	0.01	<0.005
Total	0.17	0.12	0.19	0.08

combined result is  $F_0 = 0.74^{+0.22}_{-0.34}$  (stat. + syst.). In addition, we find  $F_+ = 0.00^{+0.20}_{-0.19}$  (stat. + syst.) and  $F_+ < 0.27$  at the 95% C.L. These results are consistent with the SM predictions of  $F_0 = 0.70$ ,  $F_+ = 0$ .

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