W boson polarization measurement in the $t\bar{t}$ dilepton channel using the CDF II Detector

CDF Collaboration ; et al ; Canelli, F ; Kilminster, B

Abstract: We present a measurement of W boson polarization in top-quark decays in $t\bar{t}$ events with decays to dilepton final states using 5.1fb−1 of integrated luminosity in $p\bar{p}$ collisions collected by the CDF II detector at the Tevatron. A simultaneous measurement of the fractions of longitudinal (f0) and right-handed (f+) W bosons yields the results f0=0.71+0.18−0.17(stat)±0.06(syst) and f+=−0.07±0.09(stat)±0.03(syst). Combining this measurement with our previous result based on single lepton final states, we obtain f0=0.84±0.09(stat)±0.05(syst) and f+=−0.16±0.05(stat)±0.04(syst). The results are consistent with standard model expectation.

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We present a measurement of the W-boson polarization in top-quark decays in $t\bar{t}$ events with decays to dilepton final states using data corresponding to 5.1 fb^{-1} of integrated luminosity in $p\bar{p}$ collisions collected by the CDF II detector at the Tevatron. Assuming a top-quark mass of 172.5 GeV/c^2, a simultaneous measurement of the fractions of longitudinal (f_0) and right-handed (f_+) W-bosons yields the results $f_0 = 0.70^{+0.18}_{-0.17}(\text{stat}) \pm 0.06(\text{syst})$ and $f_+ = -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$. Combining this measurement with our previous measurement based on single-lepton final states, we obtain $f_0 = 0.84 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$ and $f_+ = -0.16 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$. The results are consistent with the standard model expectation.

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Since the top quark discovery by the CDF and D0 experiments in 1995, many of its properties have been measured. Due to its very short lifetime [1, 2], the top quark does not hadronize and therefore its properties are transferred directly to its decay products. The standard model (SM) makes specific predictions for the W-boson polarization in top-quark decays. Precise measurement of the W-boson polarization provides a test of the SM and could reveal new physics beyond the SM [3].

In the SM, the top quark decays to a W-boson and b quark with almost 100% probability [4]. The W-boson is a massive vector particle with three polariza-

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tion states: right-handed (+1), longitudinal (0), and left-handed (–1). The differential decay rate of the top quark is given by:

$$\frac{d\Gamma}{d\cos\theta^*} \propto (1-\cos\theta^*)^2 f_- + 2(1-\cos^2\theta^*) f_0 + (1+\cos\theta^*)^2 f_+ \quad (1)$$

where θ^* is the angle between the direction of the charged lepton (or down-type quark from the decay of the W-boson) and the opposite direction of the top quark in the W-boson rest frame. The polarization fractions satisfy the normalization condition $f_- + f_0 + f_+ = 1$. The right-handed W-boson production in the context of the SM is strongly suppressed due to the $V-A$ structure of the charged-current weak interaction. In the SM at the tree level [3], the fraction of right-handed W-bosons is very close to zero ($f_+ = 3.7\times10^{-4}$) while $f_0 = 0.698$ and $f_- = 0.301$ for a top-quark mass (m_{top}) of 173.3 GeV/c^2 [5], a W-boson mass (m_W) of 80.4 GeV/c^2 [4], and a b-quark mass (m_b) of 4.78 GeV/c^2 [4]. In the $m_b \to 0$ limit, $f_+ = 0$ and $f_0 = m_{\rm top}^2/\left(2m_W^2 + m_{\rm top}^2\right)$. Polarization fractions that deviate from the SM values are predicted in theories with anomalous tWb couplings [3].

An earlier measurement of the polarization fractions of the W-boson in top-quark decays by the CDF collaboration focused on the single-lepton channel [6]. Results have also been reported by the D0 and ATLAS collaborations, where the measurements in the single-lepton and dilepton channels are combined [7, 8] In this Letter we report the CDF measurement in the dilepton channel ($t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$) where $\ell = e, \mu$ and leptonically decaying τ leptons are also included into the signal. We perform two types of measurements: a model-independent approach where f_0 and f_+ are determined simultaneously; and a model-dependent approach where f_0 (f_+) is fixed to its SM value, and f_+ (f_0) is measured. The model-independent and model-dependent approaches are referred as "2D" and "1D", respectively, throughout this article. We also combine this result with our previous measurement [6] in the single-lepton channel.

This analysis is based on data corresponding to an integrated luminosity of 5.1 fb^{-1} collected with the CDF II detector [9] between March 2002 and June 2009 at the Fermilab Tevatron with a center of mass energy $\sqrt{s}$ = 1.96 TeV. The CDF II detector is described in detail elsewhere [9]. The components essential to this analysis are the tracking system consisting of a silicon microstrip tracker and a central drift chamber immersed in a 1.4 T solenoidal magnetic field, electromagnetic and hadronic calorimeters arranged in a projective geometry outside the magnet coil, and drift chambers and scintillation counters for muon detection outside the calorimeters.

The analysis uses the same event selection criteria that were used for the measurement of the $t\bar{t}$ cross-section in the dilepton channel [10]. A brief description of the event selection is as follows: the data were collected with an online inclusive event-selection system (trigger) that requires a lepton (electron or muon) with transverse energy $E_T > 18$ GeV. From the inclusive lepton data, we select events with oppositely-charged leptons of $E_T > 20$ GeV. We define leptons to satisfy very restrictive identification and isolation criteria as "tight" while "loose" leptons satisfy less restrictive identification criteria and has no isolation requirement. We require at least one tight lepton in each dilepton candidate. The pseudorapidity η [11] coverage is $|\eta| < 2.0$ for electrons and $|\eta| < 1.0$ for muons. We require missing transverse energy $\not\!\!E_T > 25$ GeV [13] unless the $\not\!\!E_T$ direction is along (within 20° in ϕ) either a lepton or a jet, in which case we require $\not\!\!E_T > 50$ GeV. Additionally we require at least two jets [14] reconstructed with $E_T > 15$ GeV and $|\eta| < 2.5$. Jet energies are corrected for the effects of calorimeter response, multiple interactions, and the hadronic calorimeter energy scale [15]. Background contributions are further reduced through kinematic cuts on the dilepton invariant mass, total energy in the transverse plane and $\not\!\!E_T$ significance [10]. In this measurement, we split the inclusive data sample into two non-overlapping subsamples ("b-tag" and "non-tag") where for the "b-tag" subsample we require at least one jet in the event to be consistent with having originated from a b quark by using an algorithm that identifies a long-lived b hadron through the presence of a displaced vertex [16]. The two subsamples have different signal-to-background ratios and background compositions; therefore, we can improve the overall measurement uncertainties by analyzing each subsample separately.

The dominant background contribution is from "fake" events where a jet is misidentified as a lepton. The main source of "fake" events is $W(\to \ell\nu)$ + jets events. An additional background is the Drell-Yan production of electrons or muons ($q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$, where $\ell = e, \mu$) with spurious $\not\!\!E_T$. Both of the above background contributions are estimated using data-based methods [10]. The remaining background contributions are from the Drell-Yan production of τ leptons and diboson (WW,WZ,ZZ) production which are estimated using Monte-Carlo (MC) simulation. The detailed description of the background estimation can be found in [10]. The numbers of expected and observed events passing dilepton selection are given in Table I. Statistical and systematic uncertainties are combined for the numbers of events. The correlations among signal and backgrounds systematic uncertainties are considered for the total numbers of events. There is a good agreement between data and expectations from $t\bar{t}$ production and background contributions (this holds also for "b-tag" and "non-tag" subsamples individually).

We use the $\cos\theta^*$ of the leptons defined above to determine the W-boson polarization fractions. In order to reconstruct $\cos\theta^*$, the full event kinematics of $t\bar{t}$ decay chain must be reconstructed. The dilepton channel presents an under-constrained system due to the two un-

TABLE I: Expected and observed numbers of signal and background events after the dilepton selection assuming $\sigma_{t\bar{t}} = 6.7$ pb ($m_{top} = 175$ GeV/c^2).

Source	Events		
Diboson	17.5	±	4.6
$Z/\gamma^* \to \tau\tau$	12.3	±	2.2
$Z/\gamma^* \to ee + \mu\mu$	22.4	±	3.2
Fakes	53.7	±	14.7
Total background	105.8	±	17.2
$t\bar{t}$ ($\sigma = 6.7$ pb)	222.4	±	10.6
Total SM expectation	328.2	±	27.6
Observed		343	

detected neutrinos. We use a simple modification of the kinematic method previously developed for the measurement of the top-quark mass, denoted as the KIN method in [17]. We solve the kinematic equations by Newton's method for nonlinear systems of equations using the top-quark mass constraint with $m_{top} = 175$ GeV/c^2. In principle each event provides two measurements of $\cos\theta^*$. However, some events do not have kinematic solutions under our assumptions, and these events are discarded.

In order to perform a fit to the $\cos\theta^*$ distribution we create templates using $t\bar{t}$ MC simulated samples for exclusive left-handed, longitudinal and right-handed W-bosons using a customized HERWIG [18, 19] MC generator. We create the templates separately for "b-tag" and "non-tag" subsamples which turn out to be similar. Figure 1 shows the templates for the inclusive sample for both the signal and background.

Due to various selection and reconstruction effects (e.g., we consider the two highest E_T jets as jets coming from b-quark hadronization while there is a possibility that one of these two jets comes from initial (ISR) or final (FSR) state gluon radiation) the templates vary significantly from the theoretical distributions in Eq. (1). The effect of the lepton E_T and the isolation cut is seen as a softening of the theoretical peaks near $\cos\theta^* = -1$. Furthermore, the KIN reconstruction method requires the lepton-jet-$\not\!\!E_T$ mass to be close to the mass of the top quark so that the reconstruction is inefficient for high lepton-jet pair masses ($\cos\theta^* \simeq +1$). This gives a polarization-dependent reconstruction efficiency of about 95%, 92%, and 87%, respectively, for left-handed, longitudinal, and right-handed W-bosons. For the background events, the reconstruction efficiency is only 71%. There are also differences in the acceptance of dilepton events. The difference can be as large as about 30%, as observed between events with two left-handed W bosons and those with two longitudinal W bosons, where the latter has a relatively larger acceptance than the former. This is mainly due to the dependence of the acceptance on the lepton p_T and isolation (leptons from left-handed W-bosons tend to be less isolated and have smaller p_T).

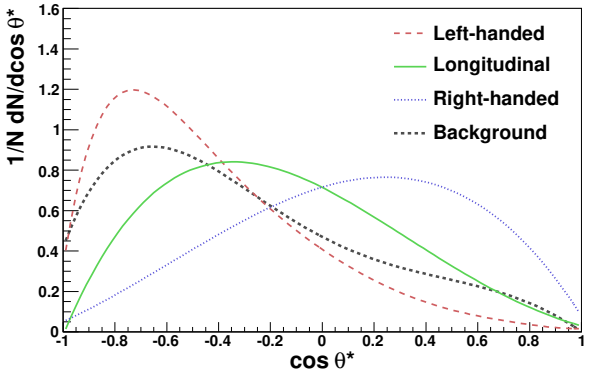

FIG. 1: The signal templates for left-handed, longitudinal and right-handed W-bosons together with the background template for the inclusive dilepton selection.

We combine the signal and background templates taking into account the above W polarization dependent efficiencies. We use an unbinned likelihood method which determines the f_0 and f_+ polarization fractions that best correspond to the observed $\cos\theta^*$ distribution. A Gaussian constraint on the number of background events and a Poisson constraint on the total number of observed events in data are included in the likelihood formula. We multiply the likelihoods for "b-tag" and "non-tag" subsamples to arrive at the final likelihood. The method has been extensively tested in simulated samples across the full range of physically possible values of f_0 and f_+ parameters. From these tests, we obtain small corrections to the measured values of f_0 and f_+.

The determination of W-boson polarization fractions by our method is sensitive to different sources of theoretical and experimental uncertainties, such as the MC simulated templates, the jet reconstruction algorithms, and jet corrections. We have generated ensembles of simulated experiments in order to estimate these systematic uncertainties. One of the largest sources of systematic uncertainty comes from the jet energy scale (JES). We have studied this uncertainty by changing the corrections by $\pm 1\sigma$ of the JES uncertainty [15]. Another large systematic uncertainty is modeling of the signal which we estimate as variations in the ISR and FSR, using different parton distribution functions (PDF) and different MC generators (see [10] for details). We estimate the systematic uncertainty due to the background template shape by changing each individual background within its rate uncertainty thus changing the overall shape. We then combine all these shifts (in quadrature) to obtain an overall background shape uncertainty. The uncertainty in the total number of expected background events is taken into account in the fitting procedure where the amount of background is allowed to float. The method-specific

systematic uncertainties are due to limited statistics of the signal and background templates and are evaluated by fluctuating the templates bin-by-bin. An additional (small) uncertainty is due to the instantaneous luminosity which determines the mean number of interactions per bunch crossing. The systematic uncertainties are summarized in Table II, with the total systematic uncertainty of the measurement being the sum in quadrature of all the partial systematic uncertainties from the various sources.

TABLE II: Summary of systematic uncertainties.

Source	Δf_0^{1D}	Δf_+^{1D}	Δf_0^{2D}	Δf_+^{2D}
Jet energy scale	0.033	0.019	0.002	0.020
Generators	0.035	0.019	0.016	0.011
ISR/FSR	0.024	0.010	0.040	0.017
PDF	0.010	0.003	0.025	0.009
Background shape	0.012	0.005	0.023	0.010
Template statistics				
Signal	0.010	0.005	0.024	0.012
Background	0.007	0.004	0.015	0.007
Instant. luminosity	0.016	0.008	0.013	0.002
Total	0.059	0.031	0.063	0.034

We assume a fixed top-quark mass of $m_{top} = 175$ GeV/c^2 in our dilepton measurement. However, as already noted, within the SM the fraction of W-bosons with a given polarization directly depends on the top-quark and W-boson masses. We do not include this effect in the systematic uncertainties for the result in the dilepton channel. Rather, we provide the m_{top}-dependence of the reconstructed fractions. We estimate that there is a linear shift in reconstructed f_0 of $\pm(0.004 \pm 0.007)$ and $\pm(0.012 \pm 0.004)$ and in reconstructed f_+ of $\pm(0.005 \pm 0.004)$ and $\pm(0.006 \pm 0.002)$ per ± 1 GeV/c^2 change in the top-quark mass for 2D and 1D measurements, respectively. In order to be close to the world average top-quark mass [5], we use the top-quark mass dependence (presented above) to correct the result to a top-quark mass of 172.5 GeV/c^2.

There are 304 events (118 in "b-tag" and 186 in "non-tag" subsamples) passing dilepton selection and kinematic reconstruction, consistent with the SM expectation of 284.3 ± 22.7 events. The comparison of $\cos\theta^*$ distribution between data and the expectations for SM $t\bar{t}$ signal and background can be seen in Fig. 2. There is a good agreement between data and the SM expectation ($\chi^2 = 6.5$ for 9 degrees of freedom, corresponding to a p-value of 69%).

We perform a model-independent simultaneous determination of both f_0 and f_+ fractions: $f_0 = 0.70^{+0.18}_{-0.17}(\text{stat})$ and $f_+ = -0.09 \pm 0.09(\text{stat})$. There is a strong negative correlation of -0.88 between the statistical uncertainties of f_0 and f_+. We also measure each polarization fraction when the other is fixed to its SM value. We measure $f_0 = 0.56 \pm 0.09(\text{stat})$ when f_+ is so fixed and measure $f_+ = -0.09 \pm 0.04(\text{stat})$ when f_0 is so fixed. We also find $f_+ < 0.07$ at 95% C.L. when f_0 is so fixed following a Bayesian procedure assuming a constant a priori probability for f_+ across the physically possible range.

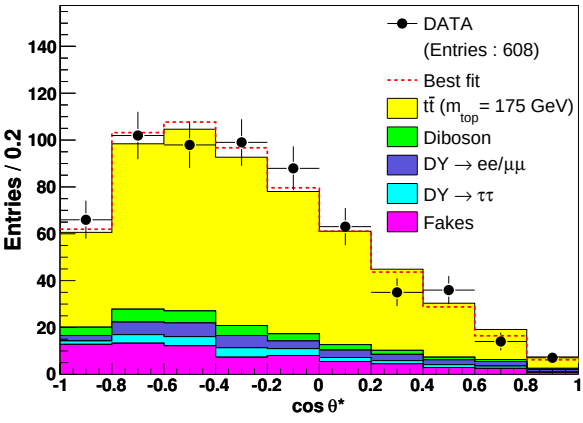

FIG. 2: The $\cos\theta^*$ distributions for data, the expected SM $t\bar{t}$ signal and background, and the best fit value. Each event has two entries in the histogram.

The CDF measurement performed in the single-lepton channel obtained the following result [6], assuming a top-quark mass of 172.5 GeV/c^2: $f_0 = 0.90 \pm 0.11(\text{stat}) \pm 0.06(\text{syst})$ and $f_+ = -0.19 \pm 0.07(\text{stat}) \pm 0.06(\text{syst})$ with the correlation of –0.59 between f_0 and f_+. This is consistent with the result presented in this Letter. We combine both results using the analytic best linear unbiased estimator method [20, 21]. We include the systematic uncertainties corresponding to a ± 1.1 GeV/c^2 uncertainty on m_{top} [5]. The results of the dilepton and single-lepton channels are statistically independent. There is a strong negative correlation of the statistical uncertainty between the f_0 and f_+ observables for both channels as mentioned above. The systematic uncertainties are theoretically dominated and are assumed to be 100% correlated between the measurements, with the exception of the method-specific systematic uncertainties (signal and background template statistics) which are treated as uncorrelated. The luminosity-related systematic uncertainty applies only to the dilepton measurement. For a given measurement, we assume that the f_0 and f_+ uncertainties are 100% anti-correlated for each systematic uncertainty category. Table III presents the full correlation matrix between the measurements and their weights in the combination. The combined result for the simultaneous measurement is $f_0 = 0.84 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$ and $f_+ = -0.16 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$. The combination has a χ^2 value of 0.99 for two degrees of freedom, corresponding to a p-value of 61% for consistency be-

TABLE III: The correlation coefficients among the measurements and their weights in the f_0 and f_+ combined result. The results from single-lepton channel are labeled as 'LJ', the dilepton results as 'DIL'.

Measurement	Correlation matrix				Weight	Weight
	LJf_0	DILf_0	LJf_+	DILf_+	for f_0 (%)	for f_+ (%)
LJf_0	1				80.6	−21.8
DILf_0	0.13	1			19.4	21.8
LJf_+	−0.72	−0.15	1		18.9	24.0
DILf_+	−0.12	−0.88	0.16	1	−18.9	76.0

tween the input measurements. The combined values of f_0 and f_+ have a correlation coefficient –0.81. We also combine the measurements of one polarization fraction when the other one is fixed to its SM expected value. In this case, we arrive at $f_0 = 0.64 \pm 0.06(\text{stat}) \pm 0.05(\text{syst})$ (f_+ is fixed) and $f_+ = -0.07 \pm 0.02(\text{stat}) \pm 0.04(\text{syst})$ (f_0 is fixed). The combination for f_0 (f_+) has a χ^2 of 1.04 (0.61) for one degree of freedom, corresponding to a p-value of 31% (44%) for consistency between the input measurements.

To summarize, we have performed a measurement of W-boson polarization fractions in top-quark dilepton decays. Our method is the first model-independent measurement of the W polarization in the dilepton channel from CDF. We have also combined our dilepton measurement with our previous measurement in the single-lepton channel. Our results are consistent with the SM expectations and do not require the introduction of new physics. They agree with the results obtained by the D0 and ATLAS collaborations [7, 8] which are of comparable precision.

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[11] CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. Pseudorapidity is $\eta \equiv -\ln\tan(\theta/2)$, where θ is the polar angle relative to the proton beam direction and ϕ is the azimuthal angle while $p_T = |p|\sin\theta$, $E_T = E\sin\theta$.
[12] For the muons, transverse momentum p_T rather than transverse energy E_T is considered in the text.
[13] The missing transverse energy ($\vec{\not\!\!E}_T$) is defined by $\vec{\not\!\!E}_T = -\sum_i E_T^i \hat{n}_i$, where i denotes calorimeter tower number with $|\eta| < 2.5$, and $\hat{n}_i$ is a unit vector perpendicular to the beam axis and pointing at the ith calorimeter tower. We also define $\not\!\!E_T = |\vec{\not\!\!E}_T|$.
[14] A jet is defined as a fixed-cone cluster in the calorimeter with a cone size of 0.4 in azimuth-pseudorapidity (η) space.
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