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Combination of CDF and D0 measurements of the *W* boson helicity in top quark decays

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We report the combination of recent measurements of the helicity of the W boson from top quark decay by the CDF and D0 collaborations, based on data samples corresponding to integrated luminosities of 2.7–5.4 fb^{-1} of $p\bar{p}$ collisions collected during Run II of the Fermilab Tevatron collider. Combining measurements that simultaneously determine the fractions of W bosons with longitudinal (f_0) and right-handed (f_+) helicities, we find $f_0 = 0.722 \pm 0.081[\pm 0.062(\text{stat}) \pm 0.052(\text{syst})]$ and $f_+ = -0.033 \pm 0.046[\pm 0.034(\text{stat}) \pm 0.031(\text{syst})]$. Combining measurements where one of the helicity fractions is fixed to the value expected in the standard model, we find $f_0 = 0.682 \pm 0.057[\pm 0.035(\text{stat}) \pm 0.046(\text{syst})]$ for fixed f_+ and $f_+ = -0.015 \pm 0.035[\pm 0.018(\text{stat}) \pm 0.030(\text{syst})]$ for fixed f_0. The results are consistent with standard model expectations.

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I. INTRODUCTION

The study of the properties of the top quark is one of the major topics of the Tevatron proton-antiproton collider program at Fermilab. Using data samples 2 orders of magnitude larger than were available when the top quark was first observed [1], the CDF and D0 collaborations have investigated many properties of the top quark, including the helicity of the W bosons produced in the decays $t \to Wb$. The on-shell W bosons from top quark decays can have three possible helicity states, and we denote the fractions of W^+ bosons produced in these states as f_0 (longitudinal), f_- (left-handed), and f_+ (right-handed). In the standard model (SM), the top quark decays via the V-A weak charged-current interaction, which strongly suppresses right-handed W^+ bosons or left-handed W^- bosons. The SM expectation for the helicity fractions depends upon the masses of the top quark (m_t) and the W boson (M_W). For the world average values $m_t = 173.3 \pm 1.1\ \text{GeV}/c^2$ [2] and $M_W = 80.399 \pm 0.023\ \text{GeV}/c^2$ [3], the expected SM values are $f_0 = 0.688 \pm 0.004$, $f_- = 0.310 \pm 0.004$, and $f_+ = 0.0017 \pm 0.0001$ [4]. A measurement that deviates significantly from these expectations would provide strong evidence of physics beyond the SM, indicating either a departure from the expected V-A structure of the tWb vertex or the presence of a non-SM contribution to the $t\bar{t}$ candidate sample. We report the combination of recent measurements of f_0 and f_+ from data recorded at the Tevatron $p\bar{p}$ collider by the CDF and D0 collaborations. The measurements are combined accounting for statistical and systematic correlations using the method of Refs. [5,6].

II. INPUT MEASUREMENTS

The inputs to the combination are the f_0 and f_+ values extracted from 2.7 fb^{-1} of CDF data in the lepton + jets ($t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu q\bar{q}'b\bar{b}$) channel [7] and 5.1 fb^{-1} of CDF data in the dilepton ($t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu\ell'\nu b\bar{b}$) channel [8] (where ℓ and ℓ' represent an electron or a muon), and from 5.4 fb^{-1} of D0 data for lepton + jets and dilepton events analyzed jointly [9]. All of these measurements use data collected during Run II of the Tevatron. Assuming $f_- + f_0 + f_+ = 1$, two types of measurements are performed: (i) a model-independent approach where f_0 and f_+ are determined simultaneously, and (ii) 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 to as "2D" and "1D," respectively. We label the input measurements as follows:

(i) CDF's measurements of f_0 and f_+ in the lepton + jets channel are labeled as $f_{0,\mathrm{CDF}}^{n\mathrm{D},\ell+j}$ and $f_{+,\mathrm{CDF}}^{n\mathrm{D},\ell+j}$, respectively.
(ii) CDF's measurements of f_0 and f_+ in the dilepton channel are labeled as $f_{0,\mathrm{CDF}}^{n\mathrm{D},\ell\ell}$ and $f_{+,\mathrm{CDF}}^{n\mathrm{D},\ell\ell}$, respectively.
(iii) D0's measurements of f_0 and f_+, which use both the lepton + jets and dilepton channels, are labeled as $f_{0,\mathrm{D0}}^{n\mathrm{D}}$ and $f_{+,\mathrm{D0}}^{n\mathrm{D}}$, respectively.

Here $n = 1$ for 1D measurements and $n = 2$ for 2D measurements.

The $f_{0(+),\mathrm{CDF}}^{n\mathrm{D},\ell+j}$ measurements [7] use the "matrix element" method described in Ref. [10], where the distributions of the momenta of measured jets and leptons as well as the missing transverse energy $\not{E}_T$ are compared to the expectations for leading-order signal and background matrix elements, convoluted with the detector response to jets and leptons. The $t\bar{t}$ matrix elements are computed as a function of the W boson helicity fractions to determine the values of f_0 and f_+ that are most consistent with the data.

The $f_{0(+),\mathrm{CDF}}^{n\mathrm{D},\ell\ell}$ and $f_{0(+),\mathrm{D0}}^{n\mathrm{D}}$ measurements are based on the distribution of the helicity angle $\theta^\star$ for each top quark decay, where $\theta^\star$ is the angle in the W boson rest frame between the direction opposite to the top quark and the direction of the down-type fermion (charged lepton or down-type quark) from the decay of the W boson. The probability distribution in $\cos\theta^\star$ can be written in terms of the helicity fractions as follows:

$$\omega(\cos\theta^\star) \propto 2(1 - \cos^2\theta^\star)f_0 + (1 - \cos\theta^\star)^2 f_- + (1 + \cos\theta^\star)^2 f_+. \quad (1)$$

The momentum of the neutrino required to determine $\theta^\star$ is reconstructed in the lepton + jets channel through a constrained kinematic fit of each event to the $t\bar{t}$ hypothesis, while for the dilepton channel $\theta^\star$ is obtained through an algebraic solution of the kinematics. The distributions in $\cos\theta^\star$ are compared to the expectations from background and $t\bar{t}$ Monte Carlo (MC) simulated events, with different admixtures of helicity fractions, to determine f_0 and f_+.

CDF and D0 treat the top quark mass dependence of the measured helicity fractions differently. CDF assumes a value of $m_t = 175\ \mathrm{GeV}/c^2$ when reporting central values and includes a description of how the values change as a function of m_t. D0 assumes a value of $m_t = 172.5\ \mathrm{GeV}/c^2$ and assigns a systematic uncertainty to cover the m_t dependence of the result. This uncertainty corresponds to a $1.4\ \mathrm{GeV}/c^2$ uncertainty on m_t, accounting for both the difference between D0's assumed m_t and the world average value and the uncertainty on the world average value [2].

TABLE I. Summary of the W boson helicity measurements used in the combination of results. The CDF measurements have been shifted from their published values to reflect a change in the assumed top quark mass from 175 to 172.5 GeV/c^2. The first uncertainty in brackets below is statistical and the second is systematic.

CDF lepton + jets, 2.7 fb^{-1} [7]	
$f_{0,\mathrm{CDF}}^{2\mathrm{D},\ell+j}$	$f_0 = 0.903 \pm 0.123[\pm 0.106 \pm 0.063]$
$f_{+,\mathrm{CDF}}^{2\mathrm{D},\ell+j}$	$f_+ = -0.195 \pm 0.090[\pm 0.067 \pm 0.060]$
$f_{0,\mathrm{CDF}}^{1\mathrm{D},\ell+j}$	$f_0 = 0.674 \pm 0.081[\pm 0.069 \pm 0.042]$
$f_{+,\mathrm{CDF}}^{1\mathrm{D},\ell+j}$	$f_+ = -0.044 \pm 0.053[\pm 0.019 \pm 0.050]$
CDF dilepton, 5.1 fb^{-1}[8]	
$f_{0,\mathrm{CDF}}^{2\mathrm{D},\ell\ell}$	$f_0 = 0.702 \pm 0.186[\pm 0.175 \pm 0.062]$
$f_{+,\mathrm{CDF}}^{2\mathrm{D},\ell\ell}$	$f_+ = -0.085 \pm 0.096[\pm 0.089 \pm 0.035]$
$f_{0,\mathrm{CDF}}^{1\mathrm{D},\ell\ell}$	$f_0 = 0.556 \pm 0.106[\pm 0.088 \pm 0.060]$
$f_{+,\mathrm{CDF}}^{1\mathrm{D},\ell\ell}$	$f_+ = -0.089 \pm 0.052[\pm 0.041 \pm 0.032]$
D0, lepton + jets and dilepton, 5.4 fb^{-1} [9]	
$f_{0,\mathrm{D0}}^{2\mathrm{D}}$	$f_0 = 0.669 \pm 0.102[\pm 0.078 \pm 0.065]$
$f_{+,\mathrm{D0}}^{2\mathrm{D}}$	$f_+ = 0.023 \pm 0.053[\pm 0.041 \pm 0.034]$
$f_{0,\mathrm{D0}}^{1\mathrm{D}}$	$f_0 = 0.708 \pm 0.065[\pm 0.044 \pm 0.048]$
$f_{+,\mathrm{D0}}^{1\mathrm{D}}$	$f_+ = 0.010 \pm 0.037[\pm 0.022 \pm 0.030]$

To facilitate the combination of results, the CDF helicity fractions are shifted to m_t of $172.5\ \mathrm{GeV}/c^2$, and an uncertainty is assigned to account for the $1.4\ \mathrm{GeV}/c^2$ uncertainty on m_t. CDF and D0 also use slightly different M_W values in their measurements ($80.450\ \mathrm{GeV}/c^2$ for CDF and $80.419\ \mathrm{GeV}/c^2$ for D0), but this difference changes the expected helicity fractions only by $\approx 10^{-4}$. The input measurements are summarized in Table I.

III. CATEGORIES OF UNCERTAINTY

The uncertainties on the individual measurements are grouped into categories so that the correlations can be treated properly in the combination. The categories are specified as follows:

(i) *STA* is the statistical uncertainty. In each 2D input measurement, there is a strong anticorrelation between the values of f_0 and f_+. The correlation coefficients are determined from the covariance matrix that is calculated during the simultaneous fit for f_0 and f_+ to be -0.8 in the D0 measurement, -0.6 in CDF's lepton + jets, and -0.9 in CDF's dilepton measurement.
(ii) *JES* is the uncertainty on the jet energy scale. This uncertainty can arise from theoretical uncertainties on the properties of jets, such as the models for

gluon radiation and the fragmentation of b quarks (assessed by comparing the default model [11] to an alternative version [12]), and from uncertainties in the calorimeter response. We assume that the theoretical uncertainties common to CDF and D0 dominate, and therefore take this uncertainty as fully correlated between CDF and D0. Details of the jet energy calibration in CDF and D0 can be found in Refs. [13,14], respectively.

(iii) *SIG* is the uncertainty on the modeling of $t\bar{t}$ production and decay and has several components. The effect of uncertainties on the parton distribution functions (PDFs) is estimated using the 2×20 uncertainty sets provided for the CTEQ6M [15] PDFs. The uncertainty on the modeling of initial- and final-state gluon radiation is assessed by varying the MC parameters for these processes. Uncertainties from modeling hadron showers are estimated by comparing the expectations from PYTHIA [17] and HERWIG [18]. In addition, D0 estimates the potential impact of next-to-leading order (NLO) effects by comparing the leading-order generators (ALPGEN [16], PYTHIA, and HERWIG) with the NLO generator MC@NLO [19], and the uncertainty from color reconnection [20] by comparing PYTHIA models with color reconnection turned on and off. These additional terms increase the $t\bar{t}$ modeling uncertainty by 33% relative to the value that would be determined using only the components considered in the CDF analyses. Signal modeling uncertainties impact the CDF and D0 results in the same manner and therefore are taken as fully correlated among input measurements.

(iv) *BGD* is the uncertainty on the modeling of the background. The procedures used to estimate this uncertainty differ for the separate analyses. In CDF's dilepton measurement, the contribution of each background source is varied within its uncertainty and the resulting effect on the $\cos\theta^\star$ distribution is used to gauge the effect on the measured helicity fractions. In the CDF lepton + jets analysis, the change in the result when the background is assumed to come from only one source (e.g. only $W + b\bar{b}$ production or only multijet production), rather than from the expected mixture of sources, is taken as the uncertainty due to the background shape. The uncertainty on the background yield is evaluated by varying the assumed signal-to-background ratio. In the D0 measurement, the $\cos\theta^\star$ distributions in data and in the background model are compared in a background-dominated sideband region. The background model in the signal region is then reweighted to reflect any differences observed in the background-dominated region, and the resulting changes in the measured helicity fractions are taken as their systematic uncertainties. The correlations among the background model uncertainties in the input measurements are not known, but are presumably large because of the substantial contribution of W/Z + jets events to the background in each measurement. We therefore

TABLE II. Relationship between the individual systematic uncertainties on the input measurements [7–9] and the categories of uncertainty used for the combination.

	Individual measurement uncertainties		
Uncertainty category	CDF lepton + jets	CDF dilepton	D0 lepton + jets and dilepton
JES	Jet energy scale	Jet energy scale	Jet energy scale
			b fragmentation
SIG	Initial state radiation or final state radiation	Generators	$t\bar{t}$ model
	PDF	Initial state radiation or final state radiation	PDF
	Parton shower	PDF	
BGD	Background	Background shape	Background model
			Heavy flavor fraction
MTD	Method-related	Template statistics	Template statistics
			Analysis consistency
MTOP	Top quark mass	Top quark mass	Top quark mass
DET			Jet energy resolution
			Jet identification
			Muon identification
			Muon trigger
MHI		Instantaneous luminosity	

treat this uncertainty as fully correlated between CDF and D0, and also between measurements using dilepton and lepton + jets events.

(v) *MTD* are uncertainties that are specific to a given analysis method. Effects such as the limitations from the statistics of the MC and any offsets observed in self-consistency tests of the analysis are included in this category. These uncertainties are fully anticorrelated for 2D measurements of f_0 and f_+ within a given analysis, but not between different analyses.

(vi) *MTOP* is the uncertainty due to m_t and is fully correlated between all measurements.

(vii) *DET* are uncertainties due to the response of the CDF and D0 detectors. The effects considered include uncertainty in jet energy resolution, lepton identification efficiency, and trigger efficiency. These uncertainties are found to be negligible in the CDF measurements, but are larger in the D0 measurements due to discrepancies observed in muon distributions between data control samples and MC. While the cause of these discrepancies was subsequently understood and resolved, D0 assigns a systematic uncertainty to cover the effect rather than reanalyzing the data.

(viii) *MHI* is the uncertainty due to multiple hadronic ($p\bar{p}$) interactions in a single bunch crossing. This uncertainty pertains only to the CDF dilepton measurement. In D0's measurements the distribution in instantaneous luminosity for the simulated events is reweighted to match that in data, thereby accounting for the impact of multiple interactions. In CDF's lepton + jets measurement this uncertainty is found to be negligible.

The relationships between the uncertainties reported in individual measurements [7–9] and the above categories are given in Table II, and the values of the uncertainties from each input measurement are given in Table III.

IV. COMBINATION PROCEDURE

The results are combined to obtain the best linear unbiased estimators of the correlated observables f_0 and f_+ [5]. The method uses all the measurements and their covariance matrix $\mathbf{M}$, where $\mathbf{M}$ is the sum of the covariance matrices for each category of uncertainty (for the 1D measurements, only the submatrices corresponding to the helicity fraction that is varied are relevant):

$$\mathbf{M} = \mathbf{M}_{\rm STA} + \mathbf{M}_{\rm JES} + \mathbf{M}_{\rm SIG} + \mathbf{M}_{\rm BGD} + \mathbf{M}_{\rm MTD} + \mathbf{M}_{\rm MTOP} + \mathbf{M}_{\rm DET} + \mathbf{M}_{\rm MHI}. \quad (2)$$

The correlation coefficients assumed when populating the covariance matrices for each category of uncertainty are summarized in the above discussion of systematic uncertainties. When there are correlations in systematic uncertainties between measurements of f_0 and f_+, the correlation coefficients are taken to be -1, reflecting the large negative statistical correlations observed between measurements of f_0 and f_+ within a given analysis.

V. RESULTS

The result of the combination of the 2D measurements is

$$f_0 = 0.722 \pm 0.081 \quad [\pm 0.062({\rm stat}) \pm 0.052({\rm syst})],$$
$$f_+ = -0.033 \pm 0.046 \quad [\pm 0.034({\rm stat}) \pm 0.031({\rm syst})]. \quad (3)$$

The contribution from each category of systematic uncertainty is shown in Table IV. The combination has a χ^2 value of 8.86 for 4 degrees of freedom, corresponding to a p-value of 6% for consistency among the input

TABLE III. Values of the uncertainties from each measurement that are used in the combinations.

Measurement	STA	JES	SIG	BGD	MTD	MTOP	DET	MHI
$f_{0,\rm CDF}^{2D,\ell+j}$	0.106	0.004	0.038	0.042	0.024	0.011	0.000	0.000
$f_{0,\rm D0}^{2D}$	0.078	0.011	0.039	0.032	0.022	0.009	0.031	0.000
$f_{0,\rm CDF}^{2D,\ell\ell}$	0.175	0.002	0.050	0.023	0.028	0.005	0.000	0.013
$f_{+,\rm CDF}^{2D,\ell+j}$	0.067	0.012	0.031	0.039	0.024	0.019	0.000	0.000
$f_{+,\rm D0}^{2D}$	0.041	0.009	0.024	0.013	0.012	0.012	0.007	0.000
$f_{+,\rm CDF}^{2D,\ell\ell}$	0.089	0.020	0.022	0.010	0.014	0.005	0.000	0.002
$f_{0,\rm CDF}^{1D,\ell+j}$	0.069	0.018	0.033	0.009	0.010	0.012	0.000	0.000
$f_{0,\rm D0}^{1D}$	0.044	0.016	0.036	0.013	0.021	0.012	0.018	0.000
$f_{0,\rm CDF}^{1D,\ell\ell}$	0.088	0.033	0.044	0.012	0.012	0.013	0.000	0.016
$f_{+,\rm CDF}^{1D,\ell+j}$	0.019	0.017	0.024	0.038	0.005	0.015	0.000	0.000
$f_{+,\rm D0}^{1D}$	0.022	0.012	0.021	0.008	0.008	0.010	0.010	0.000
$f_{+,\rm CDF}^{1D,\ell\ell}$	0.041	0.019	0.022	0.005	0.006	0.007	0.000	0.008

TABLE IV. The contribution from each category of systematic uncertainty in the combined measurements.

Category	2D combination δf_0	2D combination δf_+	1D combination δf_0	1D combination δf_+
JES	0.007	0.012	0.018	0.014
SIG	0.038	0.022	0.036	0.021
BGD	0.028	0.013	0.012	0.009
MTD	0.014	0.008	0.007	0.006
MTOP	0.007	0.010	0.012	0.010
DET	0.016	0.003	0.011	0.007
MHI	0.001	0.0004	0.002	0.002

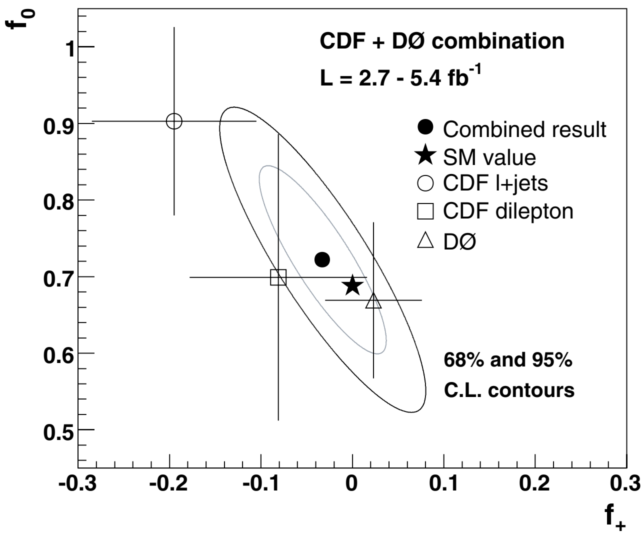

FIG. 1 (color online). Contours of constant χ^2 for the combination of the 2D helicity measurements. The ellipses indicate the 68% and 95% C.L. contours, the dot shows the best-fit value, and the star marks the expectation from the SM. The input measurements to the combination are represented by the open circle, square, and triangle, with error bars indicating the 1σ uncertainties on f_0 and f_+. Each of the input measurements uses a central value of $m_t = 172.5\ \mathrm{GeV}/c^2$.

measurements. The combined values of f_0 and f_+ have a correlation coefficient of -0.86. Contours of constant χ^2 in the f_0 and f_+ plane are shown in Fig. 1. The SM values for the helicity fractions lie within the 68% C.L. contour of probability.

Combining the 1D measurements yields:

$$\begin{aligned} f_0 &= 0.682 \pm 0.057 \\ &\qquad [\pm 0.035(\mathrm{stat}) \pm 0.046(\mathrm{syst})], \\ f_+ &= -0.015 \pm 0.035 \\ &\qquad [\pm 0.018(\mathrm{stat}) \pm 0.030(\mathrm{syst})]. \end{aligned} \tag{4}$$

The contribution of each category of systematic uncertainty is shown in Table IV. The combination for f_0 (f_+) has a χ^2 of 2.12 (4.44) for 2 degrees of freedom, corresponding to a p-value of 35% (11%) for consistency among the input measurements.

VI. SUMMARY

We have combined measurements of the helicity of W bosons arising from top quark decay in $t\bar{t}$ events from the CDF and D0 collaborations, providing the most precise measurements of f_0 and f_+ to date. The results are consistent with expectations from the SM and provide no indication of new physics in the tWb coupling or of the presence of a non-SM source of events in the selected sample.

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