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We present the first model-independent measurement of the helicity of $W$ bosons produced in top quark decays, based on a 1 fb$^{-1}$ sample of candidate $t\bar{t}$ events in the dilepton and lepton plus jets channels collected by the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider. We reconstruct the angle $\theta^*$ between the momenta of the down-type fermion and the top quark in the $W$ boson rest frame for each top quark decay. A fit of the resulting $\cos \theta^*$ distribution finds that the fraction of longitudinal $W$ bosons $f_0 = 0.425 \pm 0.106$ (stat.) $\pm 0.102$ (syst.) and the fraction of right-handed $W$ bosons $f_+ = 0.119 \pm 0.090$ (stat.) $\pm 0.053$ (syst.), which is consistent at the 30% C.L. with the standard model.

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The top quark is by far the heaviest of the known fermions and is the only one that has a Yukawa coupling to the Higgs boson of order unity in the standard model (SM). In the SM, the top quark decays via the $V - A$ charged-current interaction, almost always to a $W$ boson and a $b$ quark. We search for evidence of new physics in the $t \rightarrow Wb$ decay by measuring the helicity of the $W$ boson. A different Lorentz structure of the $t \rightarrow Wb$ interaction would alter the fractions of $W$
bosons produced in each polarization state from the SM val-
ues of $0.697\pm0.012$ \cite{1} and $3.6 \times 10^{-4}$ \cite{2} for the longitudinal
fraction $f_0$ and right-handed fraction $f_+$, respectively, at the
world average top quark mass $m_t$ of $172.5 \pm 2.3$ GeV \cite{3}.

In this Letter, we report a simultaneous measurement of $f_0$
and $f_+$ (the negative helicity fraction $f_-$ is then fixed by the
requirement that $f_+ + f_0 + f_+ = 1$). This is the first model-
dependent $W$ boson helicity measurement. A measurement
of the $W$ boson helicity fractions that differs significantly
from the SM values would be an unambiguous indication of
the $tbW$ vertex at random to calculate

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For hadronic

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and the dilepton channel. The dependence of the distribution of

$$\cos \theta^*$$

with respect to the top quark
direction. The the distribution of the cos $\theta^*$ on the

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boson helicity fractions,

$$\omega(c) \propto 2(1 - c^2)f_0 + (1 - c)^2 f_- + (1 + c)^2 f_+, \quad (1)$$

where $c = \cos \theta^*$, forms the basis for our measurement. We
proceed by selecting a data sample enriched in $tt$ events, re-
constructing the four vectors of the top quarks and their
decay products, and then calculating $\cos \theta^*$. The down-type
fermions in leptonic $W$ boson decays are the charged leptons.
For hadronic $W$ boson decays, we choose a $W$ boson daughter
jet at random to calculate $\cos \theta^*$. Since this introduces a sign
ambiguity into the calculation, we consider only $|\cos \theta^*|$ for
hadronic $W$ boson decays. The $|\cos \theta^*|$ variable does not dis-

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bosons. These distributions in $\cos \theta^*$ are compared with tem-
plates for different $W$ boson helicity models, accounting for
background and reconstruction effects, using a binned maxi-
mum likelihood method.

This measurement uses a data sample recorded with the D0
experiment \cite{13} that corresponds to an integrated luminosity
of about 1 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Events
were selected by the trigger system based on the presence of
energetic leptons or jets. The data sample consists of $tt$ can-
didate events from the lepton plus jets ($\ell$+jets) decay channel

$$tt \rightarrow W^+W^-bb \rightarrow \ell\nu qq'bb$$

and the dilepton channel

$$tt \rightarrow W^+W^-bb \rightarrow \ell\ell'\nu'\nu'bb,$$  

where $\ell$ and $\ell'$ are electrons or

muons. The $\ell+$jets final state is characterized by one charged
lepton, at least four jets, and large missing transverse energy ($E_T$). The dilepton final state is characterized by two charged
leptons, at least two jets, and large $E_T$. In both final states, at
least two of the jets are $b$ jets.

The $\ell+$jets event selection \cite{14} requires an isolated lepton
with transverse momentum $p_T > 20$ GeV, no other lepton
with $p_T > 15$ GeV in the event, $E_T > 20$ GeV, and at
least four jets. In the dilepton channel, events are required
to have two leptons with opposite charge and $p_T > 15$ GeV
and two or more jets. Electrons are required to have pseudo-

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and $W$ bosons, but adds

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bosons. The $W$ boson helicity configurations by reweighting the generated

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distributions.

Backgrounds in the $\ell+$jets channel arise mainly from
$W$+jets production and multijet production. In the dilepton
channel, backgrounds arise from processes such as $WW$+jets or
$Z$+jets. The MC samples used to model background

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and PYTHIA \cite{18} for gluon radiation and subsequent hadroniza-
tion. We generate samples corresponding to each of the three
$W$ boson helicity configurations by reweighting the generated

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distribution from the data sample to obtain the multijet

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background events from data, using the technique de-
scribed in Ref. \cite{14}. We calculate $N_{mj}$ for each bin in the

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distribution from the data sample to obtain the multijet

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templates.

To increase the signal purity, a multivariate likelihood dis-

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values in the range 0 to 1 is calculated using input variables which exploit differences in kinematics

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and jet flavor. The kinematic variables considered are: $H_T$
(scalar sum of the jet $p_T$ values), centrality $C$ (the ratio of $H_T$
to the sum of the jet energies), $k_T^{min}$ (the distance in $\eta - \phi$
space between the closest pair of jets multiplied by the $E_T$
of the lowest-$E_T$ jet in the pair and divided by the $E_T$ of
the $W$ boson), the sum of all jet and charged lepton energies $b$, the
minimum dijet mass of the jet pairs $m_{jj}^{min}$, aplanarity $A$, sphericity $S$ \cite{20}, $E_T$, and the dilepton invariant mass $m_\ell\ell$. In
the dimuon channel, the $\chi^2$ of a kinematic fit to the $Z \rightarrow \mu\mu$
hypothesis $\chi^2_{NN}$ [21] is used instead of $E_T$.

Since jets in background events arise mostly from light quarks or gluons while two of the jets in $t\bar{t}$ events arise from $b$ quarks, we form a neural network discriminant between $b$ and light jets [22] with output value $NN_b$ that tends towards one for $b$ jets and towards zero for light jets. In the $\ell+ jets$ channels we use the average of the two largest $NN_b$ values to form a continuous variable $\langle NN_b \rangle$ whose value tends to be large for $t\bar{t}$ events and small for backgrounds, while in the dilepton channels the $NN_b$ values for the two leading jets $(NN_{b_1}, NN_{b_2})$ are taken as separate variables.

The discriminant is built separately for each of the five final states considered, using the method described in Refs. [14, 23]. We consider all possible combinations of the above variables for use in the discriminant, and all possible requirements on the $D$ value, and choose the variables and $D$ criterion that give the best expected precision for the $W$ boson helicity. The variables chosen and the requirement placed on $D$ for each channel are given in Table I. An example of the distributions of signal, background and data events in $D$ is shown in Fig. 1.

We perform a binned Poisson maximum likelihood fit to compare the observed distribution of events in $D$ to the sum of the distributions expected from $t\bar{t}$ and background events. In the $\ell+ jets$ channels, $N_{mi}$ is constrained to the expected value within the known uncertainty, while in the dilepton channels the ratio of the various background sources is fixed to the expectation from the cross sections times efficiency of the kinematic selection. The likelihood is then maximized with respect to the numbers of $t\bar{t}$ and background events, which are multiplied by the efficiency for the $D$ selection to determine the composition of the sample used for measuring the $W$ boson helicity fractions. Table II lists the composition of each sample as well as the number of observed events in the data.

The top quark and $W$ boson four-momenta in the selected $\ell+ jets$ events are reconstructed using a kinematic fit which is subject to the following constraints: two jets must form the invariant mass of the $W$ boson [24], the lepton and the $E_T$ together with the neutrino $p_T\gamma$ component must form the invariant mass of the $W$ boson, and the masses of the two reconstructed top quarks must be 172.5 GeV. The four highest-$p_T$ jets in each event are used in the fit, and among the twelve possible jet combinations, the solution with the maximal probability, considering both the $\chi^2$ from the kinematic fit and the $NN_b$ values of the four jets, is chosen. The $\cos \theta^*$ distributions for leptonic and hadronic $W$ boson decays obtained in the $\ell+ jets$ data after the full selection are shown in Fig. 2(a) and (b).

Since the two neutrinos in the dilepton final state are not detected, the system is kinematically underconstrained. However, if $m_t$ is assumed, the kinematics can be solved algebraically with a four-fold ambiguity in addition to the two-fold ambiguity in pairing jets with leptons. For each of the two leading jets, we calculate the value of $\cos \theta^*$ resulting from each solution with each of the two leptons associated with the jet. To explore the phase space consistent with the measured jet and lepton energies, we fluctuate them according to their resolution many times, and repeat the above procedure for each fluctuation. The average of these values is taken as $\cos \theta^*$ for that jet. The $\cos \theta^*$ distribution obtained in dilepton data is shown in Fig. 2(c).

To extract $f_0$ and $f_+$, we compute the binned Poisson likelihood $L(f_0, f_+)$ for the data to be consistent with the sum of signal and background templates at any given value for these fractions. The background normalization is constrained to be consistent within uncertainties with the expected value by a Gaussian term in the likelihood. The fit also accounts for the differences in selection efficiency for $t\bar{t}$ events with different $W$ helicity configurations [25].

Systematic uncertainties are evaluated in ensemble tests by varying the parameters that can affect the measurement. Ensembles are formed by drawing events from a model with the parameter under study varied. These are compared to the standard $\cos \theta^*$ templates in a maximum likelihood fit. The average shift in the resulting $f_0$ and $f_+$ values are taken as the systematic uncertainty and are shown in Table II. The total systematic uncertainty is then taken into account in the likelihood by convoluting the likelihood with a Gaussian with a width that corresponds to the total systematic uncertainty. The mass of the top quark is varied by $\pm 2.3$ GeV, and the jet reconstruction efficiency, energy calibration, and $b$ fragmentation parameters by $\pm 1\sigma$ around their nominal values. The $t\bar{t}$ model uncertainty is studied by comparing $t\bar{t}$ events generated by PYTHIA to the standard ALPGEN samples, considering samples with a different model for the underlying event and ones in which only a single primary vertex is reconstructed. Effects of mis-modeling the background distribution in $\cos \theta^*$ are assessed by comparing data to the background model for events with low $D$ values. The uncertainty due to template statistics is evaluated by fluctuating the templates according to their statistical uncertainties and repeating the fit to the data for each fluctuation. Uncertainties due to jet resolution, jet flavor composition in the background, the modeling of the $NN_b$ variable, and parton distribution functions are all found to be less than 0.01 for both $f_0$ and $f_+$.  

![Distribution of $D$ for data (points with error bars), background (shaded histogram), and signal plus background (open histogram) in the $\ell+ jets$ channel.](image)

**FIG. 1:** Distribution of $D$ for data (points with error bars), background (shaded histogram), and signal plus background (open histogram) in the $\ell+ jets$ channel.
TABLE I: Summary of the multivariate selection and number of selected events for each of the $t\bar{t}$ final states used in this analysis. The uncertainties are statistical only, except for the background estimates in the $ee$ and $\mu\mu$ channels, in which systematic uncertainties arising from imperfections in the MC model of the data are included.

<table>
<thead>
<tr>
<th>Variables used in discriminant $D$</th>
<th>$e+$jets</th>
<th>$\mu+$jets</th>
<th>$e\mu$</th>
<th>$ee$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C, S, A, HT$, $m_{jjmin}$</td>
<td>$C, S, HT$, $m_{jjmin}$</td>
<td>$C, S, h, m_{jjmin}$</td>
<td>$A, S, k_{Tmin}$, $NN_b$</td>
<td>$A, S, h, m_{jjmin}$</td>
<td>$A, S, h, m_{jjmin}$</td>
</tr>
<tr>
<td>Signal purity before $D$ selection</td>
<td>$0.38 \pm 0.04$</td>
<td>$0.44 \pm 0.04$</td>
<td>$0.67 \pm 0.11$</td>
<td>$0.014 \pm 0.004$</td>
<td>$0.024 \pm 0.006$</td>
</tr>
<tr>
<td>Requirement on $D$</td>
<td>$&gt; 0.80$</td>
<td>$&gt; 0.40$</td>
<td>$&gt; 0.08$</td>
<td>$&gt; 0.986$</td>
<td>$&gt; 0.990$</td>
</tr>
<tr>
<td>Background after $D$ selection</td>
<td>$21.1 \pm 4.5$</td>
<td>$33.0 \pm 5.2$</td>
<td>$9.9 \pm 2.5$</td>
<td>$2.2 \pm 0.9$</td>
<td>$4.8 \pm 3.4$</td>
</tr>
<tr>
<td>Data events after $D$ selection</td>
<td>121</td>
<td>167</td>
<td>45</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

The measured values of $f_0$ and $f_+$ are:

$$f_0 = 0.425 \pm 0.166 \text{ (stat.)} \pm 0.102 \text{ (syst.)}$$

$$f_+ = 0.119 \pm 0.090 \text{ (stat.)} \pm 0.053 \text{ (syst.)},$$

with a correlation coefficient of $-0.83$. The inclusion of the $|\cos \theta^*|$ measurement from hadronic $W$ boson decays improves the uncertainties on $f_0$ and $f_+$ by about 20% relative to those obtained using only the leptonic decays. The 68%, and 95% C.L. contours from the fit, including systematic uncertainties, are shown in Fig. 3. The data indicate fewer longitudinal and more right-handed $W$ bosons than the SM predicts, but the difference is not significant as there is a 30% chance of observing a larger discrepancy given the statistical and systematic uncertainties in the measurement.

If we fix $f_+$ to the SM value, we find

$$f_0 = 0.619 \pm 0.090 \text{ (stat.)} \pm 0.052 \text{ (syst.)},$$

and if $f_0$ is fixed to the SM value we find

$$f_+ = -0.002 \pm 0.047 \text{ (stat.)} \pm 0.047 \text{ (syst.)}.$$
Eqs. [3] and [4] are directly comparable to previous measurements [9]-[12].

In summary, we have measured the helicity fractions of W bosons in $t\bar{t}$ decays in the $\ell+$jets and dilepton channels with a model-independent fit and find $f_0 = 0.425 \pm 0.166$ (stat.) $\pm 0.102$ (syst.) and $f_+ = 0.119 \pm 0.090$ (stat.) $\pm 0.053$ (syst.). This is the first such measurement reported and is consistent at the 30% level with the SM values of $f_0 = 0.697$ and $f_+ = 3.6 \times 10^{-4}$. We have also measured $f_0$ and $f_+$ in a model-dependent fit and find that they are consistent with the SM values.

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[15] Rapidity $y$ and pseudorapidity $\eta$ are defined as functions of the polar angle $\theta$ with respect to the proton beam and the parameter $\beta$ as $y(\theta, \beta) \equiv \frac{1}{\beta} \ln[(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]$ and $\eta(\theta) \equiv y(\theta, 1)$, where $\beta$ is the ratio of a particle’s momentum to its energy.