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Measurement of the Helicity of W Bosons in Top Quark Decays

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We use the transverse momentum spectrum of leptons in the decay chain $t \to bW$ with $W \to l\nu$ to measure the helicity of the W bosons in the top quark rest frame. Our measurement uses a $t\bar{t}$ sample isolated in 106 ± 4 pb^{-1} of data collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with the CDF detector at the Fermilab Tevatron. Assuming a standard V–A weak decay, we find that the fraction of W's with zero helicity in the top rest frame is $\mathcal{F}_0 = 0.91 \pm 0.37(\mathrm{stat}) \pm 0.13(\mathrm{syst})$, consistent with the standard model prediction of $\mathcal{F}_0 = 0.70$ for a top mass of 175 GeV/c^2.

The weak decays of the top quark should be described by the universal V–A charged-current interactions of the standard model. The theory makes a specific prediction for the polarization state of the W bosons, which can be measured using the lepton momentum spectrum in the decay chain $t \to bW$ with $W \to l\nu$. Because the top, with mass $m_t = 174.3 \pm 5.1$ GeV/c^2 [1], is heavier than the W, the W polarization in top decay is fundamentally different from that of other weak decays. Observation of the predicted lepton momentum spectrum can verify that this is the top quark of the standard model.

In top decays with a pure V–A coupling the amplitude for positive helicity W^+ bosons is suppressed by the chiral factors of order m_b^2/M_W^2, and the W helicity is a superposition of just the zero and negative helicity states [2]. At tree level in the standard model, the relative fraction $\mathcal{F}_0$ of the longitudinal (or zero helicity) W's in the top rest frame is predicted to be [3]:

$$\mathcal{F}_0 = \frac{m_t^2/2M_W^2}{1 + m_t^2/2M_W^2} = (70.1 \pm 1.6)\% \tag{1}$$

This expression is valid when m_t is significantly greater than M_W. The dominance of the zero helicity state may be understood in terms of the large top Yukawa coupling to the longitudinal mode of the W.

We will use $\mathcal{F}_0$ to parametrize the agreement between the predicted and measured lepton momentum spectrum in top decay. Effective Lagrangian treatments can be used to relate the value of $\mathcal{F}_0$ to the strength of non-standard decay couplings [3,4]. Indirect limits on such couplings have been derived from precision b quark measurements [5,6]. The strictest of these uses the measured rate of $b \to s\gamma$ to limit the size of a V+A contribution to top decay to less than a few percent [6,7]. We address the matter of a direct test for a V+A contribution in top decay separately at the end of this paper.

We measure $\mathcal{F}_0$ in $t\bar{t}$ decays where one or both of the W's from top decays leptonically. The V–A coupling at the lepton vertex induces a strong correlation between the W helicity and lepton momentum which survives into the lab frame. Charged leptons from negative helicity W are softer than the charged leptons from longitudinal W bosons. In Figure 1 we show the expected lepton transverse momentum (P_T) in the laboratory frame [8] for the three W helicities. These spectra are generated from a custom version of the HERWIG Monte Carlo program with adjustable W helicity amplitudes [9], followed by a complete simulation of the detector effects. The threshold at 20 GeV/c is a result of our event selection, and will be discussed below.

To measure $\mathcal{F}_0$ we model the lepton P_T in $t \rightarrow bl\nu$ according to the standard model as a superposition of the W boson negative and zero helicity distributions in Figure 1, and then use a maximum likelihood method to find the relative ratio which best fits the data. Our measurement uses a $t\bar{t}$ sample isolated in 106 ± 4 pb^{-1} of data collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with the CDF detector at the Fermilab Tevatron. The detector is described in [10].

Decays of $t\bar{t}$ pairs with a single lepton, called lepton+jet events, are characterized by a single isolated high P_T electron or muon, missing transverse energy ($\not\!\!E_T$) from the neutrino in the $W \rightarrow l\nu$ decay, and four jets, two from the hadronically decaying W boson and two from the b quarks. Our lepton+jet sample is selected by requiring a single electron or muon with $P_T > 20$ GeV/c which is isolated from jet activity, $\not\!\!E_T > 20$ GeV, and at least three jets with measured $E_T > 15$ GeV.

In the manner of previous CDF top analyses, we divide the lepton+jet events into subsamples based on three selections with different top purities. In the SVX tag sample, we require at least one of the jets in the event to be identified as a b jet candidate by reconstructing a secondary vertex from the b quark decay using the silicon vertex tracker (SVX). The SVX tagging algorithm is described in [11]. In the soft lepton tag (SLT) sample, we require that one or more jets be identified as a b jet candidate by identifying an additional lepton in the event, which is presumed to come from a semi-leptonic b decay (see [11]). We also require a fourth jet in the event which has $E_T > 8$ GeV and $\mid \eta \mid< 2.4$. Events that satisfy the requirements of both the SVX and SLT samples are considered to be SVX events, and are removed from the SLT tag sample. In the No-Tag sample, we require a fourth jet in the event with $E_T > 15$ GeV and $\mid \eta \mid< 2.0$. The backgrounds in the SVX sample are described in [12], while those in the No-Tag and SLT tag sample are given in [13].

Events where both W's from top decay into leptons, called dilepton events, are characterized by an electron or muon plus $\not\!\!E_T$ from each of the two $W \rightarrow l\nu$ decays, and two jets from the b quarks. The two leptons must be oppositely charged. The selection requirements and backgrounds we use for the dilepton sample are described in [14]. We make the additional requirement that the two leptons not be of the same flavor. This cut removes a background from Drell-Yan events with large $\not{E}_T$ for which we have no good lepton P_T model. It removes 2 of the 9 events in the standard CDF dilepton analysis (see Ref. [14]), but reduces the background from 2.4 ± 0.5 to 0.76 ± 0.21 events, for an overall gain in purity.

The largest source of background in the lepton+jet sample consists of W bosons produced with associated jets, called W+jets events. We model these, as well as other smaller contributions, using VECBOS [15], a Monte Carlo program that has been shown to be a good representation of these processes [16]. A smaller, but still significant lepton+jet background, $(23 \pm 5)\%$ averaged across the three lepton+jet subsamples, comes from non-W events, i.e. fake leptons and heavy quark production. We use lepton+jet data events, in which the lepton is embedded in jet activity and fails our lepton isolation requirement for the top sample, to model these backgrounds.

The background to the dilepton sample comes from $Z \rightarrow \tau\tau$, WW, WZ, and ZZ production, and fake lepton events where a jet passes our lepton identification cuts. We model these backgrounds using a combination of the PYTHIA and ISAJET Monte Carlo generators [17,18] and CDF data [14].

We summarize in Table I the number of events and the predicted amount of background in each data sample. Note that the dilepton sample contributes 2 entries for each event.

We use an unbinned log-likelihood function to estimate the fraction of top quarks that decay to longitudinal W bosons. Let $\mathcal{P}^S(P_T; \mathcal{F}_0, m_t)$ be the probability density to obtain a lepton with transverse momentum P_T from a top quark of mass m_t and longitudinal fraction $\mathcal{F}_0$. To obtain $\mathcal{P}^S$ we generate two samples of $t\bar{t}$ events at mass m_t, using the HERWIG Monte Carlo generator in concert with a full detector simulation. In one sample top decays only to negative helicity W bosons and in the other top decays only to longitudinal W bosons. We then parameterize the lepton P_T spectrum of each sample as the product of an exponential and a polynomial. We add the resulting functions together, using the factors

$1-\mathcal{F}_0$ and $\mathcal{F}_0$ as weights for the respective components. This yields the probability density $\mathcal{P}^S$ as a smooth function of $\mathcal{F}_0$ and a discrete function of m_t. The probability density $\mathcal{P}^B(P_T)$ of finding a lepton with transverse momentum P_T in the background to our top signal is obtained via a similar parameterization of background model lepton P_T distributions. Both $\mathcal{P}^S$ and $\mathcal{P}^B$ are normalized to a probability of 1 above the lepton P_T threshold of 20 GeV/c.

The negative log-likelihood is the sum of two terms:

$$-\log \mathcal{L} = -\log \mathcal{L}_{shape} - \log \mathcal{L}_{backgr}, \tag{2}$$

where $\mathcal{L}_{shape}(m_t, x_b, \mathcal{F}_0)$ represents the joint probability density for a sample of N leptons with transverse momenta P_{Ti} to be drawn from a population of top candidate events with mass m_t, background fraction x_b, and longitudinal W fraction $\mathcal{F}_0$:

$$\mathcal{L}_{shape} = \prod_{i=1}^{N} [(1-x_b)\mathcal{P}^S(P_{Ti}; \mathcal{F}_0, m_t) + x_b \mathcal{P}^B(P_{Ti})]. \tag{3}$$

We compute the log-likelihood for each of our analysis subsamples separately, and then add them together and minimize them simultaneously. The $\mathcal{L}_{backgr}$ term in Equation 2 is included to allow us to constrain the background fraction x_b to the expected values as shown in Table I. In the lepton+jet subsamples the background estimates are given as a fraction of the size of the sample, so we use a Gaussian probability density $G(x_b, \langle x_b \rangle, \sigma_b)$ with mean $\langle x_b \rangle$ and width σ_b given by the independent background measurements [12,13] to constrain x_b directly. In the dilepton subsample we have an absolute prediction for the number of background events, so we place a Gaussian constraint on n_b, the number of background events in the sample, with the Gaussian mean and width drawn from the background study in [14]. We additionally constrain the sum of the signal and background contributions to the dilepton subsample with a Poisson probability density function $P(N, n_s + n_b)$ in N with mean $n_b + n_s$, where N is the number of events in the dilepton subsample and n_s is the number of signal events in the subsample. In this case N, n_b, and n_s are variable parameters in the log-likelihood minimization, and x_b is derived from the relation $x_b = n_b/N$.

The result must be corrected for an acceptance bias caused by the minimum lepton P_T requirement. Although our Monte Carlo P_T distributions account for detection effects on the shapes of the lepton P_T distributions we must separately correct for the difference in efficiency of the P_T cut for leptons from longitudinal and negative helicity W bosons. The stiffer longitudinal W decays are 30% more likely to be accepted than negative helicity decays. The magnitude of the induced bias depends upon the extracted value of $\mathcal{F}_0$; it adds 0.08 to the measured value when the true value is near 0.50, but vanishes as $\mathcal{F}_0$ approaches 0 or 1. This correction also modifies the statistical uncertainty of the measurement.

We minimize the log-likelihood with respect to $\mathcal{F}_0$ at a top mass of 175 GeV/c^2 and obtain $\mathcal{F}_0 = 0.91 \pm 0.37$, after subtracting 0.02 from the result of the minimization to account for the acceptance bias. The statistical uncertainty corresponds to a half-unit change in the negative log-likelihood with respect to the minimum. In Figure 2 we compare $\mathcal{L}_{shape}$ to the lepton+jet and dilepton data distributions. We summarize the measurement of $\mathcal{F}_0$ in Table I. Included in this table are the results of measurements performed separately in each subsample. Most of the precision comes from the lepton+jet events that pass the SVX tagging criteria because it is a large sample and has a relatively small background. We have verified in Monte Carlo studies that including the less pure No-Tag and SLT events can increase the precision of our result by 10–15%.

The systematic uncertainties associated with this measurement of $\mathcal{F}_0$ are listed in Table II. The largest possible error is due to the uncertainty on the top quark mass, because the lepton P_T spectrum depends upon the mass of the top. The magnitude of the effect is estimated by repeating the analysis on Monte Carlo samples where we vary the top mass. For $\delta M_t = 5.1$ GeV/c^2, $\delta\ \mathcal{F}_0 = 0.07$ [1]

Another significant systematic uncertainty is due to background normalization. The lepton P_T spectrum for non-W processes peaks at low P_T, mimicking the shape from negative helicity W bosons. The effect on our measurement is estimated by varying the amount of non-W contribution in our background shapes within the envelope of normalization errors. We must also account for a 20% uncertainty in the tagging efficiency of the SVX algorithm; this causes a ± 0.05 uncertainty in the measurement of $\mathcal{F}_0$. Other sources of uncertainty include the limits on the generation of Monte Carlo statistics, the acceptance bias introduced by the selection cut on the transverse momentum of the lepton, the shape of the non-W background, the modeling of initial and final state gluon radiation in our Monte Carlo samples, and the parton distribution functions. Adding all of the uncertainties in quadrature, our final result is $\mathcal{F}_0 = 0.91 \pm 0.37(\text{stat}) \pm 0.13(\text{syst})$.

Finally, we return to the question of a V+A component in top decay. Although the indirect limit from $b \to s\gamma$ is already severe, we can still, in principle, use our technique to search directly for a V+A component in the lepton P_T spectrum. As shown in Figure 1, the momentum of leptons from positive helicity W^+ are harder than, and distinguishable from, those with negative or longitudinal helicity. We have accordingly generalized our $\mathcal{L}_{shape}$ to include the positive helicity fraction $\mathcal{F}_+$. Fitting the lepton P_T spectrum for all three components simultaneously, we find no statistical sensitivity with our data set. As an alternative, we hold $\mathcal{F}_0$ constant at its standard model value, and fit for the superposition of positive and negative helicity W's, yielding a positive helicity fraction $\mathcal{F}_+ = 0.11 \pm 0.15$. To find an upper limit on $\mathcal{F}_+$ we exponentiate the log-likelihood and integrate beneath it between $\mathcal{F}_+ = 0.0$ and $\mathcal{F}_+ = 0.30$. We set a 95% confidence level limit such that 95% of the area under the likelihood is to the left of our upper bound. We find $\mathcal{F}_+ < 0.28$. Note that the assumption that $\mathcal{F}_0 = 0.70$ already requires $\mathcal{F}_+ \leq 0.30$.

In summary, we have compared the lepton P_T spectrum in semileptonic decays $t \to bW \to bl\nu$ to the predictions of the standard electroweak model for top quark decay. Assuming a pure V−A coupling, we measure the fraction of longitudinal W bosons in top quark decays to be $0.91 \pm 0.37(\text{stat}) \pm 0.13(\text{syst})$. This measurement is consistent with the prediction of 0.70 for top quarks of mass 174.3 GeV/c^2.

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The transverse momentum of a particle is $P_T = P\sin\theta$. The analogous quantity using calorimeter energies, defined as $E_T = E\sin\theta$, is called transverse energy. The missing transverse energy, $\not\!\!E_T$, is defined as $-\sum E_T^i \hat{n}_i$, where $\hat{n}_i$ are the transverse components of the unit vectors pointing from the interaction point to the energy deposition in the calorimeter (i runs over the calorimeter cells).

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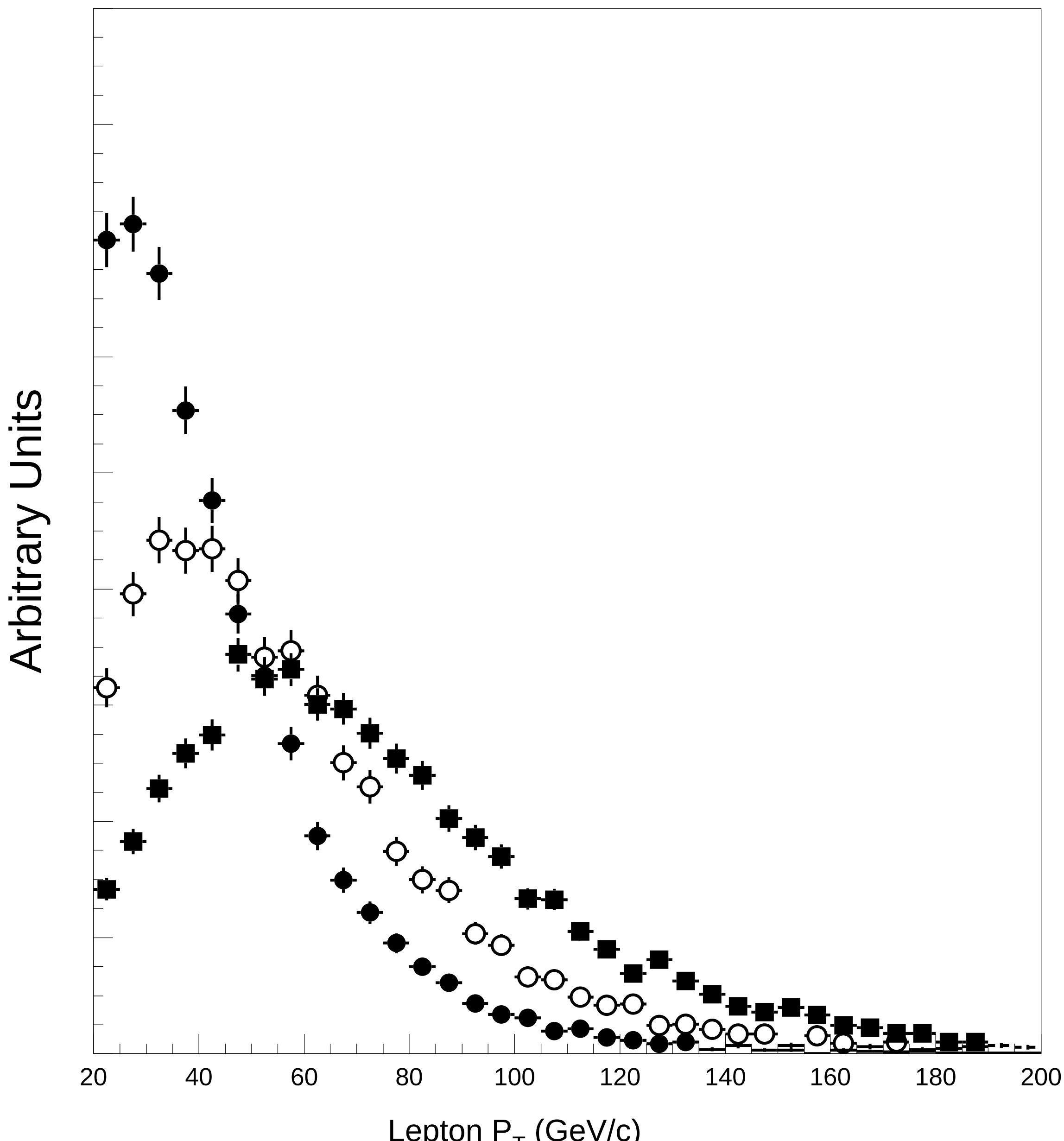

FIG. 1. Lepton P_T distributions for the three W helicities. The solid circles are from negative helicity W^+ and positive helicity W^-, the open circles are from longitudinal W^+ and W^-, and the closed squares are from positive helicity W^+ and negative helicity W^-. All three distributions are normalized to the same area.

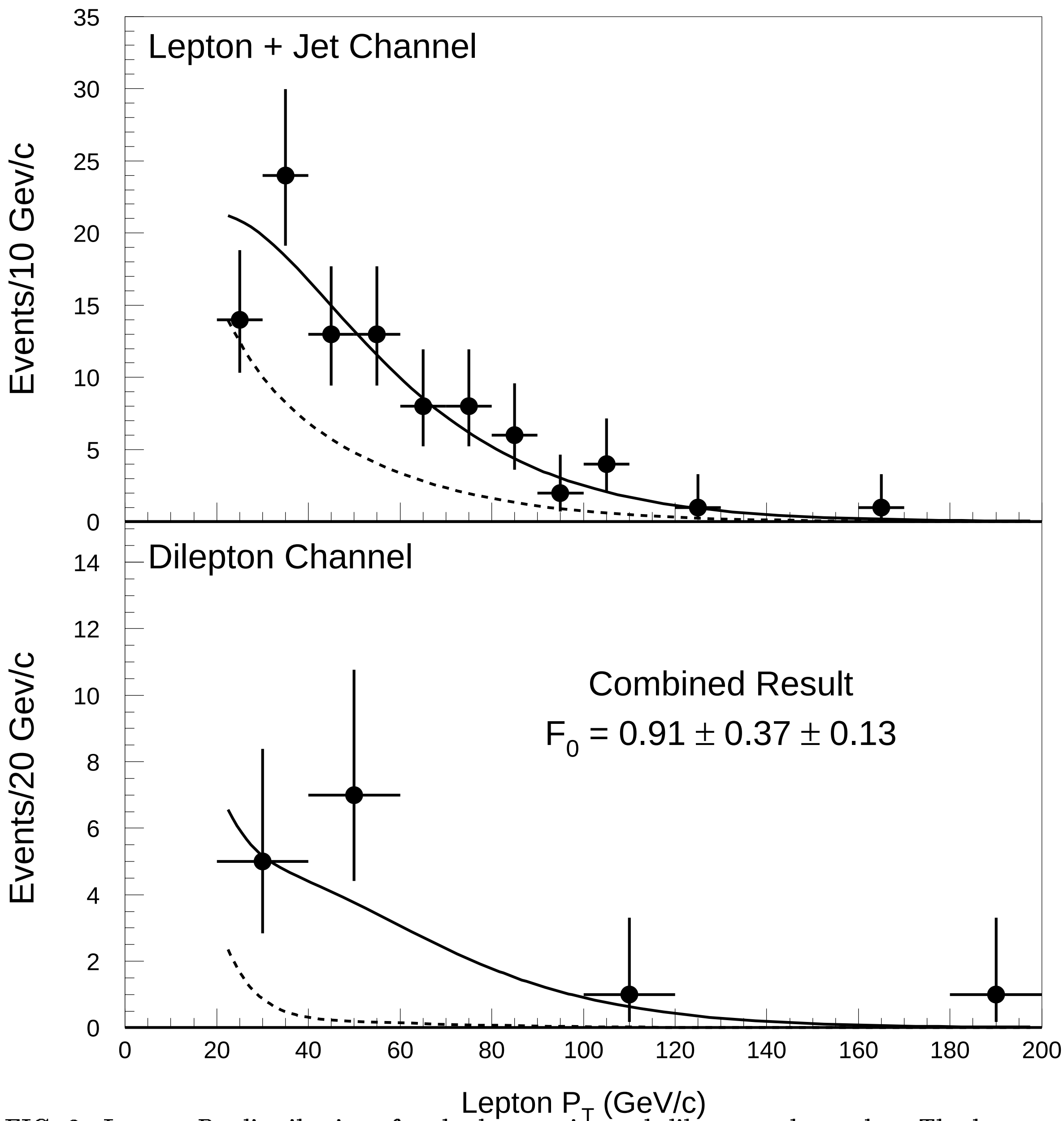

FIG. 2. Lepton P_T distributions for the lepton+jet and dilepton subsamples. The lepton+jet subsamples are added together to simplify presentation. The data (points) are compared with the result of the combined fit (solid line) and with the background component of the fit (dashed line).

TABLE I. Result of measurements for $\mathcal{F}_0$ and description of sample content. The fifth column lists the measurement after a correction for an acceptance bias is applied. Each dilepton event enters twice in the last row.

Sample	Events	Background	$\mathcal{F}_0$	Corrected $\mathcal{F}_0$
SVX tagged	34	9.2 ± 1.2	$0.92^{+0.41}_{-0.41}$	$0.90^{+0.46}_{-0.46}$
SLT tagged	14	6.0 ± 1.2	$-0.07^{+0.91}_{-0.27}$	$-0.07^{+0.87}_{-0.27}$
No tag	46	25.9 ± 6.5	$1.15^{+0.98}_{-0.70}$	$1.15^{+0.98}_{-0.77}$
Dilepton	7	0.76 ± 0.21	$0.60^{+0.57}_{-0.47}$	$0.56^{+0.57}_{-0.45}$
Total Leptons	108	42.6 ± 6.7	$0.93^{+0.32}_{-0.32}$	$0.91^{+0.37}_{-0.37}$

TABLE II. List of systematic uncertainties in the measurement of the helicity of W bosons in top decays.

Source	Uncertainty in $\mathcal{F}_0$
Top Mass Uncertainty	0.07
Non-W Background Normalization	0.06
b-tag efficiency	0.05
Monte Carlo statistics	0.05
Acceptance Uncertainties	0.02
Non W background shape	0.04
Gluon Radiation	0.03
Parton distribution functions	0.02
Total Uncertainty	0.13