DØnote 4839-CONF

Search for Right-handed W Bosons in Dilepton Top Quark Pair Candidates

The DØ Collaboration
URL: http://www-d0.fnal.gov

(Dated: July 6, 2005)

We present a search for right-handed helicity state W bosons in top quark events using $t\bar{t}$ decays in the dilepton final states. A non-zero fraction of right-handed W bosons, f^+, would be evidence for a V+A charged weak current contribution to top quark decays. Using a sample of 15 $e\mu$, 5 ee, and 2 $\mu\mu$ $t\bar{t}$ candidate events collected by the DØ experiment in 370 pb^{-1} of $p\bar{p}$ collisions at the Fermilab Tevatron in Run II, we find $f^+ = 0.13 \pm 0.20$(stat.) $\pm\, 0.06$(syst.). Combining this channel with the lepton plus jets channel gives $f^+ = 0.04 \pm 0.11$(stat.) $\pm\, 0.06$(syst.).

INTRODUCTION

The measurement of the helicity of W bosons in top quark decays is a test of the standard model (SM), in which the top quark decays via the V-A charged weak current interaction. At the Born level and assuming the b quark mass to be zero, this parity violating interaction limits the decays of top quarks into W bosons with longitudinal and left-handed helicity states with fractions f^0 and f^-, respectively. The value of f^0 is a function of the top quark mass (m_t), W boson mass (M_W) and b quark mass (m_b) [1]:

$$f^0 \approx \frac{m_t^2}{m_t^2 + 2M_W^2 + m_b^2}. \tag{1}$$

With the present measured values of the top quark and W boson masses (178.0 ± 4.3 GeV and 80.425 ± 0.038, respectively), the SM prediction gives $f^0 \approx$ 0.70 and $f^- \approx$ 0.30. Higher order corrections to these fractions are expected to be 1-2% [1]. The positive helicity fraction f^+ is suppressed by a factor of $(m_b/m_t)^2$ in the SM, and is predicted at NLO to be 3.6×10^{-4} [1], far too small to be detected at DØ. An early theoretical treatment of top quark decays is given in [2]. In this measurement we search for a non-zero value of f^+ that would be evidence for a V+A admixture in $t \to Wb$ decay.

In Run I of the Tevatron, the CDF collaboration measured $f^+ = 0.11 \pm 0.15$ and $f^0 = 0.91 \pm 0.37 \pm 0.13$ [3], and later updated this result using a new analysis techique to $f^+ < 0.18$ at 95% C.L. [4]. The DØ collaboration obtained $f^0 = 0.56 \pm 0.31$ [5, 6].

The DØ collaboration has measured f^+ using lepton plus jets events in Run II, finding $f^+ = 0.00 \pm 0.13$(stat.) $\pm\, 0.07$(syst.), which corresponds to $f^+ < 0.25$ at 95% C.L. [7].

In addition to direct measurements, data on $b \to s\gamma$ decays have been used to set a limit on W_R and W_L boson mixing in a context of assumptions regarding the penguin contributions [8, 9].

Our analysis consists of selecting events in the dilepton channel, where both W bosons decay to charged lepton and neutrino pairs. We select events with electrons and muons in the final state, so the $\tau\nu$ channel contributes only when the τ decays leptonically.

The presence of two unmeasured neutrinos in the dilepton channels renders the $t\bar{t}$ system underconstrained, which means that one cannot reconstruct the W boson rest frames without making additional assumptions. However, we can still measure f^+ by noting that charged leptons from right-handed W bosons will tend to be emitted along the W boson boost direction, and thus have larger p_T in the laboratory frame. Therefore we use the lepton p_T as our measurement variable. We have two measurements of this quantity for each event.

We estimate the expected distribution of lepton p_T for background and for signal with different f^+ values using Monte Carlo events subjected to the same kinematic selection as used for the signal sample. These expected distributions are referred to as "templates".

We use these templates in a binned likelihood fit to find the V+A fraction f^+ given by the data. The resulting log likelihood curves are interpreted using a Bayesian approach. We also use these templates in fits to ensembles of Monte Carlo events in order to test the veracity, robustness, and validity of our procedure and to estimate systematic uncertainties.

EVENT SELECTION

Data and Monte Carlo Samples

The data used for this analysis were collected by the DØ detector [10], and correspond to an integrated luminosity of 368 pb^{-1} in the $e\mu$ channel, 384 pb^{-1} in the ee channel, and 363 pb^{-1} in the $\mu\mu$ channel.

ALPGEN [11] is the primary Monte Carlo generator used for both signal and background processes. The MC events are passed through a detailed GEANT3 [12] simulation of the detector, and reconstructed with the same algorithm used for detector data. The resolutions and efficiencies of objects are then degraded to match those observed in data control samples.

Kinematic selection

Top quark pair events are expected to have two energetic leptons, two energetic jets, and significant missing transverse energy ($\not\!\!E_T$). The object identification criteria for leptons and jets are similar to those described in Ref. [13]. However, to improve the expected signal significance in the $e\mu$ channel for this analysis, we require a multivariate electron likelihood based on shower shape and E/p to be > 0.25.

The kinematic selection criteria are designed to favor $t\bar{t}$ events over backgrounds. Jets in background events have a softer p_T spectrum because they arise from gluon radiation. In addition, some background sources contain no neutrinos and hence tend to have smaller $\not\!\!E_T$. The selection criteria for all of the dilepton channels are summarized in Table I.

TABLE I: Kinematic selection criteria. $\phi(\mu_1)$ is the azimuthal angle of the leading muon. The contour cut on $\not\!\!E_T$ in the $\mu\mu$ channel requires the $\not\!\!E_T$ to be larger if the $\not\!\!E_T$ vector is nearly colinear with that muon. H_T in the $e\mu$ channel is defined as the sum of the p_T's of the two leading jets and the leading lepton. The Z χ^2 in the $\mu\mu$ channel is the result of a kinematic fit of the two leading leptons to the Z boson mass. Sphericity is defined as $3(\epsilon_1 + \epsilon_2)/2$, where ϵ_1 and ϵ_2 are the two leading eigenvalues of the normalized momentum tensor.

	Selection criteria		
	$e\mu$	ee	$\mu\mu$
Leptons	1 electron, $p_T > 15$ GeV ≥ 1 muon, $p_T > 15$ GeV e, μ have opp. charge	2 electrons, $p_T > 15$ GeV Electrons have opp. charge	2 muons, $p_T > 15$ GeV Muons have opp. charge 0 electrons
Jets	≥ 2 jets, $p_T > 15$ GeV		
$\not\!\!E_T$	> 25 GeV	> 35 GeV > 40 GeV if $80 < M_{ee} < 100$ GeV	$\not\!\!E_T$,$\phi(\mu_1)$ contour cut
Other requirements	$H_T > 140$ GeV	Sphericity > 0.15	Z $\chi^2 > 2$

TABLE II: Expected background and $t\bar{t}$ yields, and the number of events observed in the three dilepton channels. The expected $t\bar{t}$ yield assumes a production cross-section of 7 pb.

Source	$e\mu$	ee	$\mu\mu$
$Z/\gamma^* \to \ell^+\ell^-$	N/A	0.46 ± 0.15	0.95 ± 0.14
$Z/\gamma^* \to \tau\tau$	0.73 ± 0.16	0.30 ± 0.12	0.07 ± 0.02
WW/WZ	0.74 ± 0.27	0.20 ± 0.07	0.20 ± 0.08
Fake lepton	0.32 ± 0.29	0.09 ± 0.03	0.13 ± 0.05
Total bkg	1.8 ± 0.4	1.0 ± 0.3	1.3 ± 0.4
Expected $t\bar{t}$	9.8 ± 1.3	3.5 ± 0.4	2.5 ± 0.3
Observed	15	5	2

Yield and Background Estimates

After applying all of the selection criteria described above, we observe 15 events in the $e\mu$ channel, 5 events in the ee channel, and 2 events in the $\mu\mu$ channel. The expected backgrounds for each channel are listed in Table II. When fitting the lepton p_T distribution to extract f^+, the background level will be constrained to be consistent with these expected backgrounds, as described below.

Normalized plots of the lepton p_T distributions for Monte Carlo signal events that pass the selection are shown in Fig. 1. Both leptons from each selected event are included in the plots, and the range and binning is the same as that used in the maximum likelihood fit to extract f^+. To ensure that all leptons contribute to the maximum likelihood fit, leptons with p_T greater than 200 GeV are included in the uppermost bin of each plot.

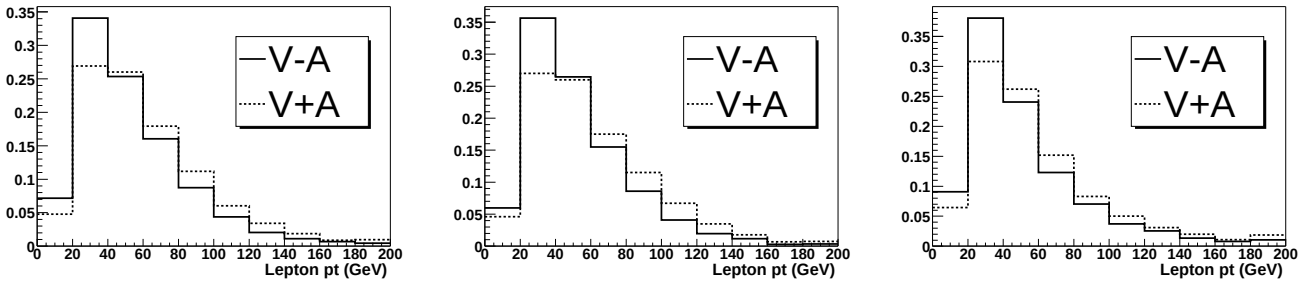

FIG. 1: Lepton p_T distribution for 175 GeV $t\bar{t}$ MC events that pass the $e\mu$ (left), ee (center) and $\mu\mu$ (right) event selection criteria. In each figure, the solid (dashed) histogram is for events with a $V-A$ ($V+A$) tWb coupling. All histograms are normalized to unit area.

MAXIMUM LIKELIHOOD FIT

We perform a binned maximum likelihood fit to extract the value of f^+ favored by the data. As input to the fit we have the distributions of lepton p_T in: the selected data events, ALPGEN $t\bar{t}$ Monte Carlo with $f^+ = 0.00$ and 0.30, and ALPGEN MC models of the backgrounds from sources such as Z/γ^* and WW pair production.

To form models for intermediate values of f^+, we note that all f^+ values arise from linear combinations of the V and A couplings, with $f^+ = 0.00$ representing pure V−A and $f^+ = 0.30$ representing pure V+A. Therefore the templates should vary linearly across the range of f^+; this has in fact been explicitly demonstrated in parton-level studies [7]. We exploit this fact by performing a linear interpolation of the signal templates, to arrive at an expected lepton p_T distribution for any given f^+ value. We choose to evaluate the likelihood in increments of 0.05 in f^+ value when performing the maximum likelihood fit.

For each f^+ value, we compute the likelihood of the data to be consistent with the sum of signal and background templates. The likelihood is computed by multiplying the Poisson probabilities of each template bin being consistent with the data. We also have a prior expectation for the normalization of the background, which is expressed with a Gaussian term in the likelihood. We define the likelihood as:

$$L(f^+) = \prod_{i=1}^{N_{\rm bkg}} e^{(n_{b,i}-\overline{n_{b,i}})^2/2\sigma_{b,i}^2} \times \prod_{j=1}^{N_{\rm bins}} P(d_j; n_j). \tag{2}$$

In the Gaussian term, $N_{\rm bkg}$ is the number of background sources, $\overline{n_{b,i}}$ is the nominal number of events for the ith background, $\sigma_{b,i}$ is the uncertainty on $\overline{n_{b,i}}$, and $n_{b,i}$ is the fitted number of events for the ith background. In the Poisson term, n_j is the total number of events expected in the jth bin ($n_j = n_{s,j} + \sum_{i=1}^{N_{\rm bkg}} n_{b,ij}$, where n_s is the fitted number of signal events), and d_j is the number of data events in the jth bin.

We minimize the $-\ln L$ for each set of signal and background templates and data distribution (the d_j) with respect to n_s and the $n_{b,i}$. We denote the resulting value of L as L_m. The result is a distribution of $-\ln L_m$ points versus f^+. We fit these points to a parabola to estimate the likelihood as a function of f^+. Note that the linear variation in the templates guarantees the distribution of the $-\ln L_m$ points will be parabolic to a good approximation.

The $-\ln L_m$ points are calculated as described above for each channel separately, then summed to arrive at a combined result. A parabola is fit to the summed points to determine the overall likelihood as a function

of f^+.

Bayesian Interpretation of Results

We use a Bayesian technique to determine a confidence level (C.L.) interval for the true value of f^+. We choose to use a prior probability that is flat in the physically-allowed range $0 < f^+ < 0.30$ and zero elsewhere. With this choice, finding a Bayesian confidence interval is equivalent to integrating the likelihood curve. If the parabola that is fit to the $-\ln L_m$ points has its minimum in the allowed range, we take the value of that minimum (i.e. the maximum of L) as the most likely value $x_{\rm ML}$. We then find the points $x_{\rm min}$ and $x_{\rm max}$ such that:

$$\frac{\int_{x_{\rm min}}^{x_{\rm ML}} L(x)dx}{\int_0^{0.30} L(x)dx} = \frac{\int_{x_{\rm ML}}^{x_{\rm max}} L(x)dx}{\int_0^{0.30} L(x)dx} = C.L./2. \tag{3}$$

If $x_{\rm ML}$ lies outside the allowed range (or close enough to the boundary that the $x_{\rm max}$ or $x_{\rm min}$ cannot be found by both equations above), a single-sided range is reported:

$$\frac{\int_{0.0}^{x_{\rm max}} L(x)dx}{\int_0^{0.30} L(x)dx} = C.L. \tag{4}$$

or:

$$\frac{\int_{x_{\rm min}}^{0.30} L(x)dx}{\int_0^{0.30} L(x)dx} = C.L. \tag{5}$$

If $x_{\rm ML}$ is less than or close to 0.0, then $x_{\rm min}$ is set to 0 and $x_{\rm max}$ is calculated. If $x_{\rm ML}$ is greater than or close to 0.30, then $x_{\rm max}$ is set to 0.30 and $x_{\rm min}$ is calculated.

RESULTS FROM ENSEMBLE TESTS

We test the performance of the maximum likelihood fit by means of Monte Carlo ensemble tests. For these tests, we assume a true value of f^+ and form a mock data set by selecting lepton p_T values from the appropriate Monte Carlo samples. For f^+ values intermediate between 0.00 and 0.30, we distribute the lepton p_Ts according to the model formed by interpolating the 0.00 and 0.30 samples. Each data set so formed has the same number of $e\mu$, ee, and $\mu\mu$ events as we observe in the real data sample. On average, the mock data sets have the number of background events reported in Table II, but for each data set the number of signal and background events is varied around the expected value according to the binomial distribution. Also once the number of background events in a particular mock data set is determined, the number of events from each background source is allowed to fluctuate binomially as well.

TABLE III: Results of Monte Carlo ensemble tests on mock data samples that simulate the final data sample. For each assumed value of f^+, the table shows the average fit f^+ and error, the average of the Bayesian estimator for f^+, the average width of the 68% C.L. region, and the fraction of ensembles for which that region contains the true value.

True f^+	Avg. fit f^+	Avg. fit error	Avg. Bayesian result	Avg. size of 68% C.L. range	Fraction within 68% C.L. range
0.00	-0.03	0.24	0.07	0.16	0.69
0.05	0.01	0.24	0.09	0.17	0.69
0.10	0.09	0.24	0.13	0.17	0.64
0.15	0.15	0.23	0.16	0.17	0.76
0.20	0.19	0.23	0.17	0.17	0.65
0.25	0.24	0.23	0.20	0.16	0.68
0.30	0.29	0.22	0.22	0.16	0.67

The mock data set is then fit according to the same procedure used for fitting the real data. By repeating the process one thousand times we can investigate the statistical properties of the maximum likelihood fit. These properties are summarized in Table III. We observe that the average of the fit value of f^+ increases as the true f^+ increases, and the fraction of ensembles for which the true value of f^+ lies within the 68% confidence interval is near 68%. Note that the change in the average Bayesian result is much less than the change in true f^+. This is an unavoidable consequence of having the result defined over a finite range of values with the Bayesian analysis requiring that values of $f^+ < 0$ are set to 0 and values of $f^+ > 0.3$ are set to 0.3.

STATISTICAL AND SYSTEMATIC UNCERTAINTIES

Statistical uncertainties in the data are handled in the likelihood fit using Poisson statistics.

Sources of systematic uncertainties arise from finite Monte Carlo statistics and uncertainties in the top quark mass, jet energy calibration and Monte Carlo models of signal and background. Variations in these parameters can change the measurement in two ways: by altering the estimate of the background in the final sample (i.e. if the final selection efficiency changes) and by modifying the shape of the lepton p_T templates.

To estimate the uncertainty arising from finite Monte Carlo statistics we repeat the fit to the data events 1000 times, each time fluctuating the templates according to a multinomial distribution. The fluctuation is done by creating a new histogram, then populating it with random numbers distributed according to the original histogram until it has the same number of entries as the original histogram. This is done for all templates (both signal and Monte Carlo). The fluctuated signal histograms are then interpolated, just as is done for the baseline likelihood fit. The RMS of the variation in the fitted f^+ value is taken as our systematic uncertainty, and its value is 0.046.

The procedure used to extract the value of f^+ was demonstrated to behave reasonably well in MC ensemble tests. However, in some cases even with high statistics, the average fit f^+ value differed from the input value by 0.01. We assign 0.01 as the uncertainty on our knowledge of the self-consistency of the analysis.

We estimate the contribution of the other uncertainties by running ensemble tests using the standard templates, but with the mock data drawn from samples with the top quark mass, the jet energy calibration, the lepton p_T resolution, the $t\bar{t}$ model, the background model, or the trigger efficiency varied within its uncertainty. The signal and background content of the ensembles is fixed to the values we expect using our

TABLE IV: Summary of the systematic uncertainties on f^+.

Source	Uncertainty
Monte Carlo statistics	0.046
Analysis self-consistency	0.010
Top quark mass	0.008
Jet energy calibration	0.013
$t\bar{t}$ model	0.03
Fake lepton model	0.013
Lepton p_T resolution	0.010
Trigger	0.008
Total	0.061

TABLE V: Bayesian results for f^+ for various confidence levels. These results include statistical uncertainties only.

Result for f^+	C.L.
$0.04 < f^+ < 0.23$	68%
$0.00 < f^+ < 0.27$	90%
$0.00 < f^+ < 0.28$	95%

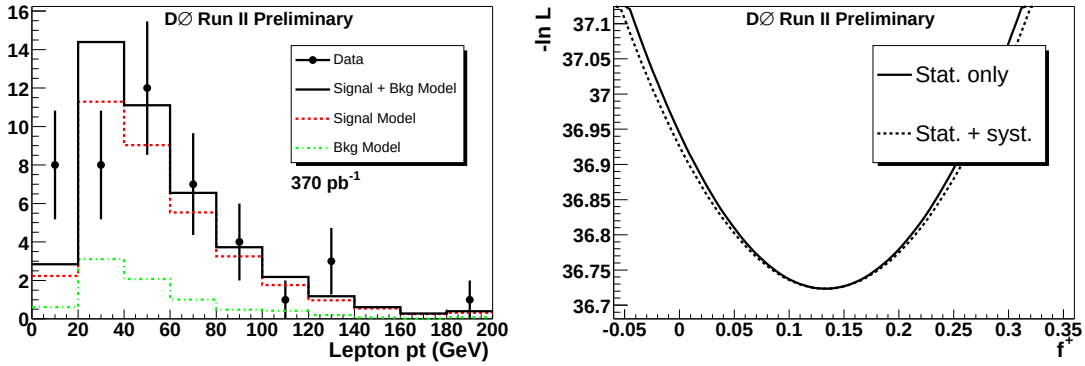

FIG. 2: (Left) Comparison of the sum of $e\mu$, ee, and $\mu\mu$ data (points with errors bars) to the sum of the best-fit templates of signal and background (solid histogram). The signal and background contributions are shown separately as the dashed and dotted histograms. (Right) Results of the combined $e\mu$, ee, and $\mu\mu$ maximum likelihood fits including the statistical uncertainty only (solid line) and including both statistical and systematic uncertainties (dashed line).

nominal final selection efficiencies, but the background constraint input to the maximum likelihood fit is varied to reflect the shifted final selection efficiency of the sample with the appropriate parameter varied.

The results are summarized in Table IV.

RESULTS FROM DATA

The result of applying our maximum likelihood fit to the lepton p_T distribution observed in the data is $f^+ = 0.13 \pm 0.20$, as shown in Fig. 2. The Bayesian confidence intervals for different confidence levels are given in Table V. These results include the statistical uncertainty only.

We also compare the data distribution to the "best fit model", which means that the background models are the nominal models as described above, and the signal model is the nominal model with f^+ value closest to the minimum of the $-\ln L$ curve . The signal and background normalizations are the values returned by

TABLE VI: Bayesian result for f^+ for various confidence levels. This result includes both statistical and systematic uncertainties.

Result for f^+	C.L.
$0.04 < f^+ < 0.23$	68%
$0.00 < f^+ < 0.27$	90%
$0.00 < f^+ < 0.28$	95%

the maximum likelihood fit at that f^+ value. In Fig. 2, the data is shown as the points with error bars, the best fit signal template as the dashed histogram, the best fit background template as the dotted histogram, and the sum as the solid histogram. The best fit templates are normalized according to the fitted signal and background levels at the best fit f^+ point for each sample. The systematic uncertainties in the last section are included in the fit by convoluting a Gaussian function with a width given by the total systematic uncertainty with the Gaussian resulting from the maximum likelihood fit. The results including systematic uncertainties for different confidence levels are given in Table VI. The maximum likelihood distribution including the statistical uncertainty and including both statistical and systematic uncertainties is shown in Fig. 2.

COMBINATION WITH THE LEPTON PLUS JETS CHANNEL

The statistical combination of the results from this analysis and the measurement in the lepton plus jets channel reported in Ref. [7] is done by summing the $-\ln L_m$ curves from each analysis. The result of the combination is:

$$f^+_{\rm comb} = 0.04 \pm 0.11. \tag{6}$$

Systematic Uncertainty

Systematic uncertainties are combined using error propagation on the value of $f^+_{\rm comb}$, with the correlations between the two analyses taken into account. In most cases where the sources of systematic uncertainty are common to the analyses, the errors are assumed to be completely correlated between the channels. The exception is template statistics, which are uncorrelated.

Summing all sources in quadrature yields a total combined systematic uncertainty of 0.06. Thus, the result of combining the two analyses is:

$$f^+_{\rm comb} = 0.04 \pm 0.11({\rm stat.}) \pm 0.06({\rm syst.}) \tag{7}$$

In both channels, the result from the $-\ln L_m$ curve is converted into a Bayesian confidence interval where the prior probability is taken to be flat within the physically-allowed range of 0.0 to 0.3, and zero elsewhere. Doing the same for the combined result yields:

$$f^+_{\rm comb} < 0.14 \text{ @68\% C.L.}$$
$$f^+_{\rm comb} < 0.22 \text{ @90\% C.L.}$$
$$f^+_{\rm comb} < 0.25 \text{ @95\% C.L.}$$

CONCLUSIONS

We have measured the fraction of right-handed W bosons (f^+) in top decays using the dilepton decay channels, and find:

$$f^+ = 0.13 \pm 0.20(\text{stat.}) \pm 0.06(\text{syst.}).$$

Using a Bayesian interpretation for confidence intervals and including both statistical and systematic uncertainties we find:

$$0.04 < f^+ < 0.23 \text{ (68\% C.L.)}$$

$$0.00 < f^+ < 0.27 \text{ (90\% C.L.)}$$

$$0.00 < f^+ < 0.28 \text{ (95\% C.L.)}$$

When combined with the result previously obtained in the lepton plus jets channel, the result becomes:

$$f^+ = 0.04 \pm 0.11(\text{stat.}) \pm 0.06(\text{syst.}).$$

with Bayesian limits of:

$$0.00 < f^+ < 0.14 \text{ (68\% C.L.)}$$

$$0.00 < f^+ < 0.22 \text{ (90\% C.L.)}$$

$$0.00 < f^+ < 0.25 \text{ (95\% C.L.)}$$

This measurement is in agreement with the standard model prediction of $f^+ = 0.0$, and its precision is equal to that of the best previous measurement. Nonetheless, more data will be required to rule out models with a $V + A$ component in the tWb vertex.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L'Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES, CNPq and FAPERJ (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), Natural Sciences and Engineering Research Council and WestGrid Project

(Canada), BMBF (Germany), A.P. Sloan Foundation, Civilian Research and Development Foundation, Research Corporation, Texas Advanced Research Program, and the Alexander von Humboldt Foundation.

[1] H.S. Do, S. Groote, J.G. Korner, and M.C. Mauser, Phys. Rev. D **67**, 091501 (2003).
[2] R.H. Dalitz and G.R. Goldstein, Phys. Rev. D **45**, 1531 (1992).
[3] CDF Collaboration, T. Affolder *et al.*, Phys. Rev. Lett. **84**, 216 (2000).
[4] CDF Collaboration, D. Acosta *et al.*, FERMILAB-PUB-04-353-E (2004).
[5] DØ Collaboration, V.M. Abazov *et al.*, Phys. Lett B **617**, 1 (2004).
[6] M.F. Canelli, *Helicity of the W Boson in Single-Lepton $t\bar{t}$ Events*, Ph.D. Thesis, University of Rochester, (2003).
[7] DØ Collaboration, V.M. Abazov *et al.*, *Measurement of the W Boson Helicity in Top Quark Decays*, to be published in Phys. Rev. D Rap. Comm., hep-ex/0505031.
[8] K. Fujikawa and A. Yamada, Phys. Rev. D **49**, 5890 (1994).
[9] P. Cho and M. Misiak, Phys. Rev. D **49**, 5894 (1994).
[10] DØ Collaboration, V.M. Abazov *et al.*, *The Upgraded DØ Detector*, (to be published).
[11] M.L. Mangano, JHEP 0307:001, 2003, hep-ph/0206293.
[12] S. Agostinelli *et al.*, NIM A 506 (2003), 250-303
[13] DØ Collaboration, V.M. Abazov *et al.*, *Measurement of the $t\bar{t}$ Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV in Dilepton Final States with 370 pb^{-1}*, hep-ex/0505082.