CDF note 9144

Measurement of W Boson Helicity Fractions in Top Quark Decay to Lepton+Jets Events using a Matrix Element Analysis Technique with 1.9 fb^{-1} of Data

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We present a measurement of the fraction of longitudinally polarized W bosons from top quark decay (f_0) using $t\bar{t}$ events in the lepton+jets channel. The analysis is based on a matrix element analysis technique where a likelihood function is calculated for each event from the leading order $t\bar{t}$ and W+jets differential cross sections and parameterized parton showering. In the likelihood function the fraction of right-handed polarized W bosons from top decay is kept fixed to the Standard Model predicted value ($f_+ \sim 0$). Using 468 events observed in 1.9 fb^{-1} of data collected at the CDF II detector we find $f_0 = 0.637 \pm 0.084(\text{stat.}) \pm 0.069(\text{syst.})$, for a top-quark mass of 175 GeV/c^2.

Preliminary Results for Winter 2008 Conferences

I. INTRODUCTION

The top quark was discovered in 1995 by the CDF and D0 experiments at the Fermilab Tevatron during the Run I operation. The mass of the top quark m_t is much larger than the masses of all the other quarks and is in the same order of magnitude as the masses of W and Z bosons [1]. Due to the large mass the top quark lifetime in the Standard Model (SM) is expected to be about 0.5×10^{-24} s. As a result, unlike any other quark, the top quark in the SM decays before hadronization [2] and provides us with the unique opportunity to study the properties of a "bare" quark.

Top quark decays to a W boson and a b quark most of the time. In the SM the coupling at the Wtb vertex is purely left-handed and can be used to test the $V - A$ structure of weak interaction. Different helicity states of the W bosons: longitudinal, right-handed and left-handed, are reflected in the angular distribution of the decay products. The differential decay rate for unpolarized top quarks is given by:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = f_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + f_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2, \tag{1}$$

where $\cos\theta^*$ is the angle between the momentum of the charged lepton (or down type quark) in the W rest frame and the momentum of the W boson in the top quark rest frame; f_-, f_0, and f_+ are the fractions for left-handed, longitudinal, and right-haded helicity states, respectively, and $f_- + f_0 + f_+ = 1$. The three terms in the equation above corresponds to three different helicity states. In the SM at the tree level [3], $f_0 = 0.703$, $f_- = 0.297$ and $f_+ = 3.4 \times 10^{-4}$, for $m_t = 175$ GeV/c^2, $M_W = 80.413$ GeV/c^2 [4] and $m_b = 4.7$ GeV/c^2. In the beyond the SM scenarios deviations from the SM expectation are possible due to the presence of anomalous couplings [3].

The helicity of the W boson from top decay has been measured by the CDF and D0 collaborations [5–7]; however all the measurements were limited by small statistics of the sample. We perform a measurement of f_0 using a matrix element technique [7, 8], which provides ~20% better statistical sensitivity compared to existing CDF analyses on the same dataset.

For the current measurement the value f_+ has been fixed to zero in the likelihood. The analysis can be extended to simultaneously measure all three W helicity fractions. With the increasing data sample at the Tevatron the W helicity fractions will be measured with considerable precision.

More details about this analysis can be found from Ref [9].

II. DATA SAMPLE AND EVENT SELECTION

We select events in lepton+jets channel by requiring one isolated high-transverse energy electron (muon) candidate, large missing transverse energy, and four or more high transverse energy jets. At least one of the jets must satisfy tight secondary vertex b-tag selection. Further the scalar sum of all the transverse energy in the event H_T must exceed 200 GeV; this requirement selects over 98% signal events and rejects a significant amount of QCD background events. Details of event selection and background estimation procedures can be found in [10]. The expected sample composition is listed in Table I, where $t\bar{t}$ event yield is estimated using the CDF measured top pair production cross section in the lepton+jets decay channel [10].

The signal acceptance varies based on the W helicity fractions. The average signal acceptance as a function of f_0 is determined from PYTHIA Monte Carlo (MC) [11] events and is parameterized using an analytical function (Figure 1).

III. METHOD

The Matrix Element method was first used by D0 Collaboration during Run I [7, 8]. The likelihood for each event is created based on the leading order matrix elements for signal $t\bar{t}$ and dominant background $W+jets$. The likelihood L for a sample of N events is reconstructed by taking the product of the per event likelihood:

$$L(f_0, C_s) = \prod_{i=1}^{N} C_s P_{t\bar{t}}(\vec{x}_i; f_0) + (1-C_s) P_{W+jets}(\vec{x}_i), \tag{2}$$

where $\vec{x}$ are the measured quantities, $P_{t\bar{t}}(\vec{x}_i; f_0)$ and $P_{W+jets}(\vec{x}_i)$ are the probabilities of $t\bar{t}$ and W+jets production for an event i, respectively, and C_s is the fraction of events consistent with the signal hypothesis.

TABLE I: Number of expected and observed events in 1.9 fb^{-1}.

Expected/Observed Event (1.9 fb^{-1})		
	$\ell + 4jets$	$\ell + > 4jets$
Background		
W+Light (Mistags)	13.77 ± 3.59	2.86 ± 1.09
Non-W (QCD)	13.12 ± 11.49	4.66 ± 4.73
Wbb	13.65 ± 5.69	3.03 ± 1.36
W+Charm	10.81 ± 4.53	2.33 ± 1.05
Electro-weak	8.97 ± 5.26	2.06 ± 1.47
Total Background	60.33 ± 16.40	14.94 ± 5.56
Signal $t\bar{t}$ (8.2 pb)	311.54 ± 43.12	105.80 ± 14.64
Total Expected	371.87 ± 46.13	120.74 ± 15.66
Observed	356	112

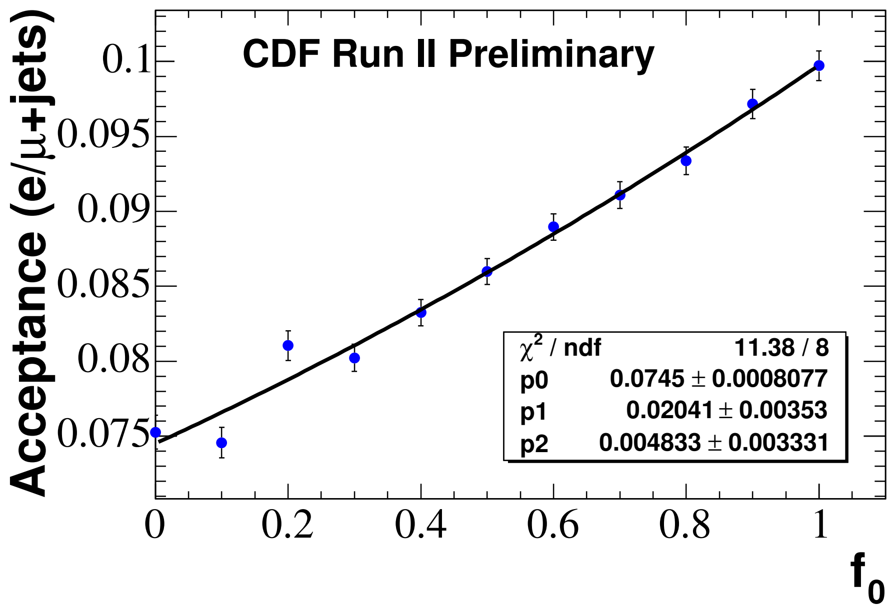

FIG. 1: Average $t\bar{t}$ acceptance as a function of f_0 determined from PYTHIA MC. Acceptance is calculated as the ratio of total number of selected $t\bar{t} \to \ell +$ jets ($\ell = e, \mu$) events over total number of such generated events.

The signal probability for a given set of measured parameters $\vec{x}$ is obtained by integrating over the parton level differential cross-section $d\sigma(\vec{y})/d\vec{y}$. The integral over the parton level parameters $\vec{y}$ is performed using transfer functions $W(\vec{x}, \vec{y})$, which translate the measured parameters to parton level with their corresponding resolution. We also convolute the integral with the parton distribution function (PDF) $f(\tilde{q}_i)$ and include an integral over the transverse components of the momentum of the $t\bar{t}$ system:

$$P(\vec{x}) = \frac{1}{\sigma_{obs}} \int \frac{d\sigma(\vec{y})}{d\vec{y}} \; f(\tilde{q}_1) f(\tilde{q}_2) \; W(\vec{x}, \vec{y}) \; d\tilde{q}_1 d\tilde{q}_2 \; d\tilde{p}^x_{t\bar{t}} d\tilde{p}^y_{t\bar{t}} \; d\vec{y}. \tag{3}$$

We also integrate over the longitudinal momentum of the unmeasured neutrino p^z_ν. In equation 3 σ_{obs} normalizes the signal probability, and corresponds to the average $t\bar{t}$ acceptance as a function of f_0 (Figure 1) for this analysis. Signal probability only uses the leading order matrix-element of the $q\bar{q} \to t\bar{t}$ process from [12], expressed in terms of the helicity fractions. The background probability $P_{W+jets}(x)$ is based on leading order matrix element for $W + 4jets$ events from VECBOS MC [13] routine.

In this analysis the transfer functions for the electron momenta, muon momenta, and jet angles are delta functions. The jet energy response of our detector is parameterized with MC determined jet energy transfer functions $W(\vec{x}, \vec{y})$

assuming the response is independent for each jet.

We evaluate the joint likelihood of equation 2, $L(f_0, C_s)$, at discreet values of f_0 in steps of 0.05 units. At each step we minimize the likelihood with respect to C_s and obtain an optimized curve of $-lnL(f_0)$ which is then fit to a fifth order polynomial whose minimum is used to determine the fitted f_0. The statistical uncertainty is taken from the fitted curve corresponding to changes in the $-lnL(f_0)$ of 0.5 units. Both the central value and statistical uncertainty are corrected as detailed in the next Section.

IV. CALIBRATION AND VALIDATION WITH MONTE CARLO

The MC $t\bar{t}$ events and various background events are used for determining the response and sensitivity of the measurement. A MC $t\bar{t}$ sample with SM helicity fractions is re-weighted based on the generated $\cos\theta^*$ to obtain different f_0 samples. To determine the response curve we look at the output f_0 as a function of the input f_0 value used in the reweighting. The output f_0 is determined using ensembles of signal and background pseudo experiments constructed using the expected sample composition given in Table I. The results are shown in Figure 2; a linear fit to these points, which has a slope less than unity, is used to correct the obtained f_0 value from the $-lnL(\vec{x}; f_0)$ curve. The uncertainties on the fit parameters, including their correlation, are taken into account in the method related systematic uncertainty on f_0 (Section VI).

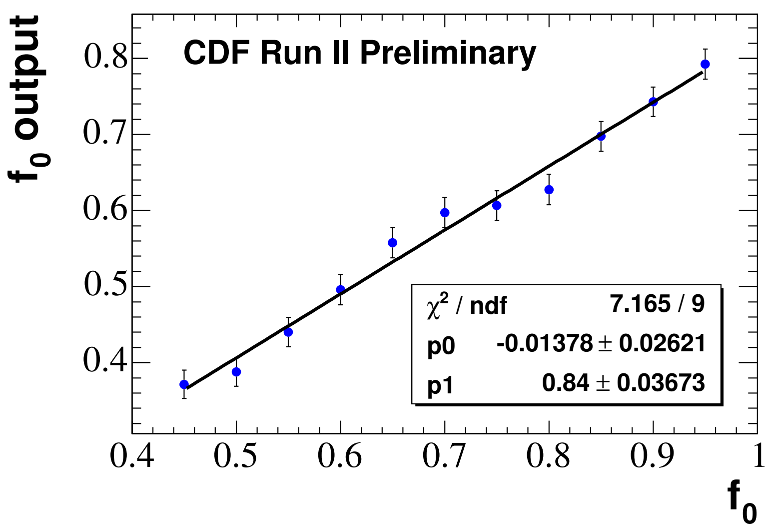

FIG. 2: Plot of output f_0 as a function of f_0 values of the input $t\bar{t}$ MC events for ensembles for $t\bar{t}$ and background events.

That the slope in Figure 2 is less than unity is due to the events which are not completely described by the signal and background matrix elements. For example, the signal probability is based on leading order $t\bar{t}$ matrix element, which does not include effects like initial- and final state radiation or the four-jets not corresponding to the four-quarks from $t\bar{t}$ decay.

We use the pseudo-experiments described above to determine whether or not the width of the $-lnL(\vec{x}; f_0)$ curve provides an accurate estimate of the statistical uncertainty by studying the pull width as a function of f_0. The average pull width is found to be 0.93 independent of f_0. The statistical uncertainty will be scaled by this average pull width.

V. RESULTS

We apply the method to the 468 events selected in 1.9 fb^{-1} of CDF II data. The obtained f_0 from the negative log likelihood (NLL) curve for the data events is corrected by the response curve (Figure 2). The NLL value as a function of corrected f_0 is shown in Figure 3. From the NLL curve, after incorporating all corrections, we determine:

$$f_0 = 0.637 \pm 0.084(\mathrm{stat}).$$

Figure 4 shows the expected statistical uncertainty from pseudo experiments for $t\bar{t}$ MC with input f_0 the same as the measured f_0 value from data.

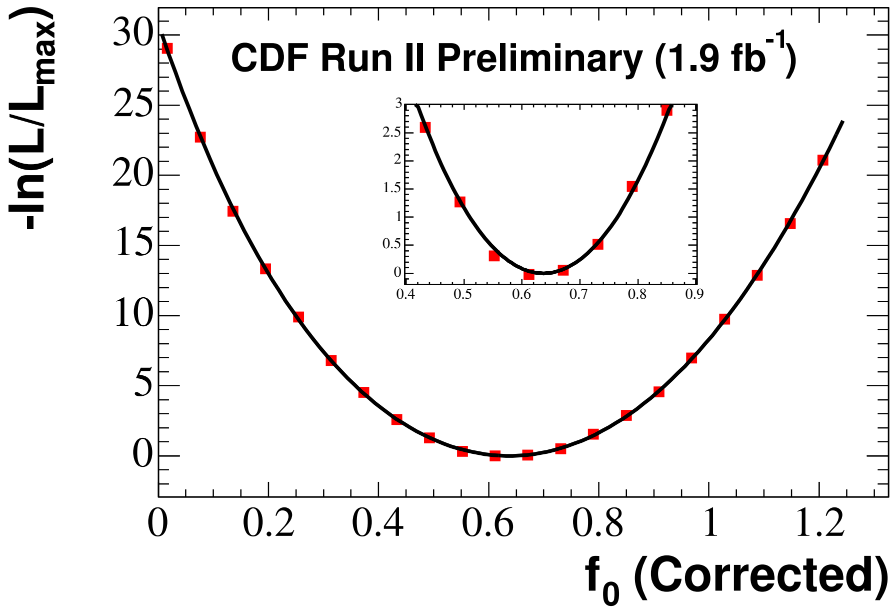

FIG. 3: Negative log likelihood as a function of corrected f_0 from the data events.

As a cross-check we divide the data events based on lepton types. In data we find 267 electron and 201 muon events. The measured values for the electron and muon channels after all corrections are: $f_{0,e} = 0.660 \pm 0.111(\text{stat.})$ and $f_{0,\mu} = 0.609 \pm 0.128(\text{stat.})$, respectively.

VI. SYSTEMATIC UNCERTAINTIES

Various sources of systematic uncertainties affecting the measurement are summarized in Table II. The generator uncertainty, which is the largest source of systematic uncertainty for this measurement, is obtained by comparing the different output f_0 values obtained with two different MC models PYTHIA and HERWIG [15] both generated with the same input f_0. This uncertainty takes into account several modeling differences between the two generators - fragmentation and showering,. $t\bar{t}$ spin-correlations, and the P_T of the $t\bar{t}$system. The uncertainty from variations in the MC modeling of initial and final state radiation is taken into account by comparing the output f_0 in PYTHIA samples generated with variations in the initial state and final state radiation parameters constrained using data control samples. To estimate the uncertainties due to the choice of PDFs we compare the output f_0 for default CTEQ PDF and MRST PDFs with $\Lambda_{QCD} = 228$ MeV and $\Lambda_{QCD} = 300$. Further, we look at the bias in f_0 due to variation in the 20 CTEQ eigenvectors. The Jet Energy Scale (JES) uncertainty is estimated by coherently fluctuating the jet energies up and down by one sigma as defined in Ref [14] and measuring the changes in output f_0. The method related uncertainty includes variations of the acceptance curve parameterization and propogating the uncertainty on the fit parameters of the response curve, including their correlations. To systematic uncertainty related to variations in the background composition is determined by separately varying the expected yield of each component by the uncertainty listed in Table I and measuring the change in the output f_0. The systematic uncertainty related to the b-tag efficiency is evaluated by introducing a jet E_T dependent efficiency that's allowed to vary with one sigma of the range determined from data control samples. Differences in instantaneous luminosity between the data and MC sample used are found to be negligibly affect the measurement. Total systematic uncertainty on f_0 is 0.069.

VII. CONCLUSION

We have measured the fraction of longitudinally polarized W boson from top quark decay (f_0) using a matrix element method in 1.9 fb^{-1} CDF II data. Fixing the fraction of the right-handed polarized W boson from top decay to it's SM value, $f_+ = 0.0$, we find

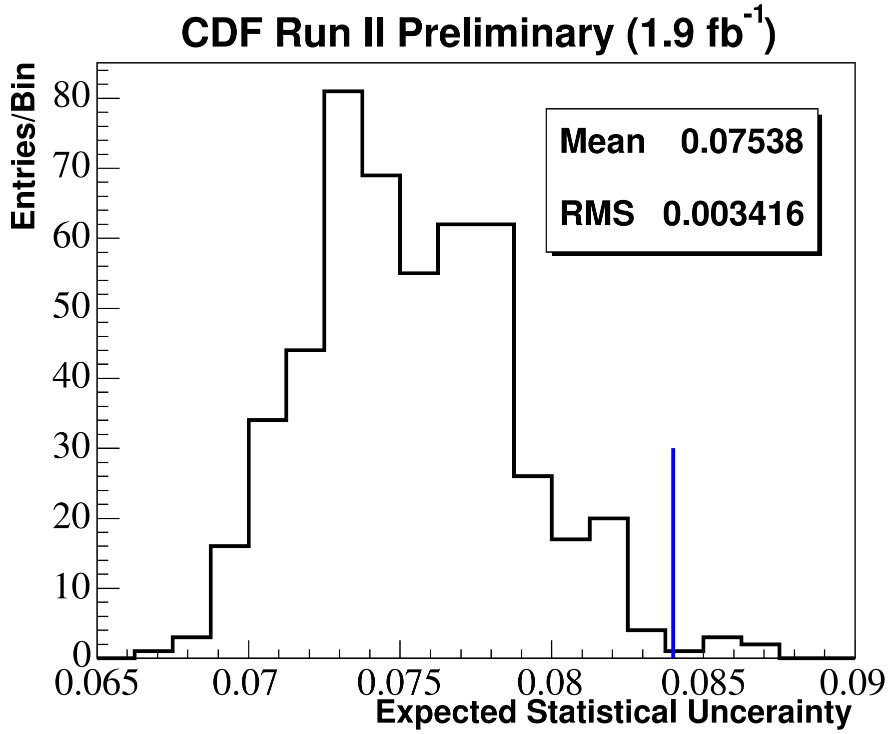

FIG. 4: Distribution of expected statistical uncertainty from pseudo experiments for $t\bar{t}$ MC events with input $f_0 = 0.637$. The blue line indicates the corresponding value from data.

TABLE II: Summary of Systematic Uncertainties.

Source	Uncertainty on f_0
MC Generator	0.050
Initial State Radiation	0.026
Final State Radiation	0.020
PDF	0.023
Jet Energy Scale	0.019
Method	0.012
Background composition	0.009
b-tag Scale Factor	0.002
Total	0.069

$$f_0 = 0.637 \pm 0.084(\text{stat.}) \pm 0.069(\text{syst.})$$

assuming a top-quark mass of 175 GeV/c^2. For a $\pm 2.5\ GeV/\text{c}^2$ variation in the assumed top-quark mass our measured f_0 changes by about ∓ 0.035.

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