# Optimal Use of Information to Measure Top Quark Properties

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We present a method developed at DØ for extracting information from data through a direct calculation of a probability for each event. This probability, which is a function of any parameter of interest, is calculated by convoluting the differential cross section with the resolution and acceptance of the detector. The method is used to remeasure the mass of the top quark and to extract the fraction of longitudinal polarized $W$ bosons in the lepton + jets $t\bar{t}$ sample, previously collected by the DØ experiment during Run I of the Fermilab Tevatron. The new method yields a top mass of $M_{top}(preliminary)$=180.1±3.6 (stat) ± 4.0 (syst) GeV/c$^2$, which corresponds to a significant reduction in the uncertainty on $M_{top}$. Assuming Standard Model coupling in the $tbW$ vertex, we also extract the fraction of longitudinal $W$ decays as $F_0(preliminary)$=0.56±0.31 (stat) ± 0.04 (syst).

## 1. INTRODUCTION

In proton-antiproton collisions top quarks are produced primarely in pairs, either via $q\bar{q}$ or gg fusion. At the Tevatron, the main contribution to the $t\bar{t}$ yield is from $q\bar{q}$ annihilation. This is purely the result of the fact that the parton distribution functions (PDFs) favor this channel at Run I $\sqrt{s}$=1.8 TeV and Run II $\sqrt{s}$=1.96 TeV. In fact, about 90% of the top quarks are produced through the quark interaction.

The top quark is detected indirectly via its decay products. It decays via the weak interaction, and according to the Standard Model (SM) is almost always expected to decay to a $b$ quark and a $W$ boson. This is followed by $W$ decay into two quarks or a lepton and a neutrino. The final state of the $t\bar{t}$ system has different topological classifications that depend on the decay of the $W$ boson. The results presented here use the lepton+jets channel, which corresponds to one $W$ decaying leptonically (into a electron or a muon), and the other $W$ hadronically. This channel has a branching fraction of about 30%.

Although its value is not predicted, $M_{top}$ is a fundamental parameter in the Standard Model. The best value of the top quark mass found from combining all channels at the Tevatron is [1]

$$M_{top} = 174.4 \pm 5.1 \text{ GeV/c}^2 \quad (1)$$

The top-quark mass, along with the mass of the $W$ boson, provides through radiative corrections the best indication for the value of the mass of the Higgs boson [2]. The measurement of $M_W$ will improve significantly in the future, with an uncertainty of about 25 GeV/c$^2$ being a goal for Run II of the Tevatron. To be able to make maximum use of this precision measurement to constrain the mass of the Higgs, the top mass should be measured with an uncertainty of less than 3 GeV/c$^2$. This will yield a prediction for the Higgs mass with an uncertainty of 40%. It is therefore important to develop techniques for extracting the mass of the top quark that will optimize the use of Run II data.

The observation of the top quark at the Tevatron [3] has provided a new laboratory for examining the more subtle implications of the SM. The fact that the top quark is so massive has led to speculations that its interactions might be especially sensitive to the impact of symmetry breaking and any new physics that is expected to appear at the TeV energy scale. And, in fact, several pioneering studies of the decays of the top quark have already appeared int the literature [4, 5]. Although these have been severely limited by the low statistics of the data sample of Run I, they have nevertheless indicated that it is feasible to extract such information from the complex $t\bar{t}$ final states.

The standard top quark decays via V–A charged-current weak interaction. Hence, for massless $b$ quarks [6], a top quark can decay to a left-handed $W$ (negative helicity $W_-$) or a longitudinal $W$ (zero helicity $W_0$). In the SM, top quarks decay to longitudinal $W$ bosons with a branching ratio [7]:

$$F_0 = \frac{M_{top}^2}{M_{top}^2 + 2M_W^2} \approx 0.7 \quad (2)$$

where we take $M_{top} = 174.3$ GeV/c$^2$ and $M_W = 80.4$ GeV/c$^2$ [1].

We report a preliminary new measurement of the mass of the top quark and the longitudinal component of the helicity of the $W$ boson in DØ data from Run I. The analysis is based on a new method of extracting parameters from hadron-collider data [8].

## 2. THE GENERAL METHOD

This method is similar to that suggested for $t\bar{t}$ dilepton decay channels, and used in previous mass analyses of dilepton events [9]. A similar approach was also suggested for the measurement of the mass of the $W$ boson at LEP [10]. It compares each individual event with the differential cross section for $t\bar{t}$ production and decay. The luminosity used in this analysis corresponds to 125 events/pb, and the data was accumulated by the DØ experiment during Run I of the Tevatron. This analysis is based on the same sample that was used to extract the mass of the top quark in a previous publication [11]. A set of selections was introduced to improve acceptance for lepton+jets from $t\bar{t}$ relative to background. The standard requirements were: $E_T^{lepton} > 20$ GeV, $|\eta_e| < 2$, $|\eta_\mu| < 1.7$, $E_T^{jets} > 15$ GeV, $|\eta_{jets}| < 2$, $\not{E}_T > 20$ GeV, $|E_T^{lepton}| + |\not{E}_T| > 60$ GeV; $|\eta_{(lepton+\not{E}_T)}| < 2$. A total of 91 events remained after these selections. In our analysis we will use events that contain exactly four jets.

Given $N$ events, a parameter $\alpha$ is estimated by maximizing the likelihood,

$$L(\alpha) = e^{-N \int P(x,\alpha)\mathrm{d}x} \prod_{i=1}^{N} P_m(x_i, \alpha) \quad (3)$$

where $x$ is the set of variables needed to specify the measured event, $P_m(x, \alpha)$ is the probability of measuring that event, and $\alpha$ represents the parameters to be determined. The probability density can be written as a convolution of the calculable differential cross section and measurement resolution:

$$P(x, \alpha) = \frac{1}{\sigma} \int \mathrm{d}^n\sigma(y, \alpha)\mathrm{d}q_1\mathrm{d}q_2 f(q_1)f(q_2)W(x, y) \quad (4)$$

$W(y, x)$, our general transfer function, is the normalized probability that the measured set of variables $x$ come from a set of partonic variables $y$, $d^n\sigma(y, \alpha)$ is the partonic differential cross section, and $f(q)$ are the parton distribution functions. Dividing by the total cross section $\sigma$ for the process ensures $P_m(x, \alpha)$ is properly normalized. The integral in Eq. 4 sums over all possible parton states leading to what is observed in the detector.

The $t\bar{t}$ production probability is calculated as:

$$P_{t\bar{t}}(x; \alpha) = \frac{1}{12\sigma_{t\bar{t}}} \int \mathrm{d}\rho_1 \mathrm{d}m_1^2 \mathrm{d}M_1^2 \mathrm{d}m_2^2 \mathrm{d}M_2^2 \times \sum_{\text{perm.},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{jet}(E_y, E_x) \quad (5)$$

where $|\mathcal{M}_{t\bar{t}}|^2$ is the leading order matrix element [12], $f(q_1)$ and $f(q_2)$ are the CTEQ4M parton distribution functions for the incident quarks [13], $\Phi_6$ is the phase-space factor for the 6-object final state, and the sum is over all 12 permutations of the jets (the permutation of the jets from $W$ decay was performed by symmetrizing the matrix element), and all possible longitudinal momenta of the neutrino solutions. The integration variables used in the calculation are the top masses ($m_{1,2}$), the $W$ masses ($M_{1,2}$), and the energy of one of the quarks in the hadronic decay of the $W$ bosons ($\rho_1$). Observed electron momenta are assumed to correspond to those of produced electrons. The angles of the jets are also assumed to reflect the angles of the partons in the final state, and we ignore any transverse momentum for the incident partons. $W_{jet}(E_y, E_x)$ corresponds to a function that parameterizes the mapping between parton-level energies $E_y$ and energies measured in the detector $E_x$. A large Monte Carlo sample of $t\bar{t}$ events (generated with top masses between 140−200 GeV/c$^2$ in HERWIG [14], and processed through the DØ detector-simulation package) is used to determine $W_{jet}(E_y, E_x)$. For a final state with a muon, $W_{jet}$ is expanded to include the known muon momentum resolution, and an integration over muon momentum is added to Eq. 5. Effects such as geometrical acceptance, trigger efficiencies, event selection, etc, are taken into account through a multiplicative function $A(x)$ that is independent of $\alpha$. This function relates the production probability $P(x; \alpha)$ to the measured probability $P_m(x; \alpha)$: $P_m(x; \alpha) = A(x)P(x; \alpha)$. All processes that can contribute to the observed final state must be included in the probability. Therefore the final probability is written as $c_1P(x; \alpha) + c_2P_{\text{bkg}}(x)$. The VECBOS [15] $W$+jets matrix element is used to calculate the background probability, which is integrated over the four quark energies and the $W$-boson mass, and later summed over the 24 jet permutations and neutrino solutions.

Since the method involves a comparison of data with a leading-order matrix element for the production and decay process, as mentioned above the sample is restricted to only four-jet events, thereby reducing the sample to 71 events. In order to increase the purity of signal, a selection is made on the probability that any event corresponds to background. This selection is required to minimize a bias introduced by the presence of background, and its imposition leaves a sample of only 22 events. Figure 1a) shows a comparison between the probability for a background interpretation of events calculated for a sample of Monte Carlo events (solid histogram) and for the 71 $t\bar{t}$ candidates (data points). The left-hatched (right-hatched) histogram shows the contribution from $t\bar{t}$ ($W$+4 jets) MC events. The ratio of $t\bar{t}$ to $W + 4$ jets events in the MC is normalized to the ratio $S/B = 12/10$ observed in the data to the left of the vertical line. The selected value of the cuttoff $P_{\text{bgd}} < 10^{-11}$ was based on MC studies carried out before applying the method to data, and, for a top mass of 175 GeV/$c^2$, it retains 70% of the signal while rejecting 70% of the background.

A discriminant $D = P_{t\bar{t}}/(P_{t\bar{t}} + P_{\text{bkg}})$ was defined to compare the probability that an event corresponds to signal or background [11]. Since the signal probability depends on $M_{top}$, $D$ was calculated with the signal probability taken at its most likely value. Figure 1b) shows a comparison of the discriminant calculated for data (points with error bars) and for MC (solid his-

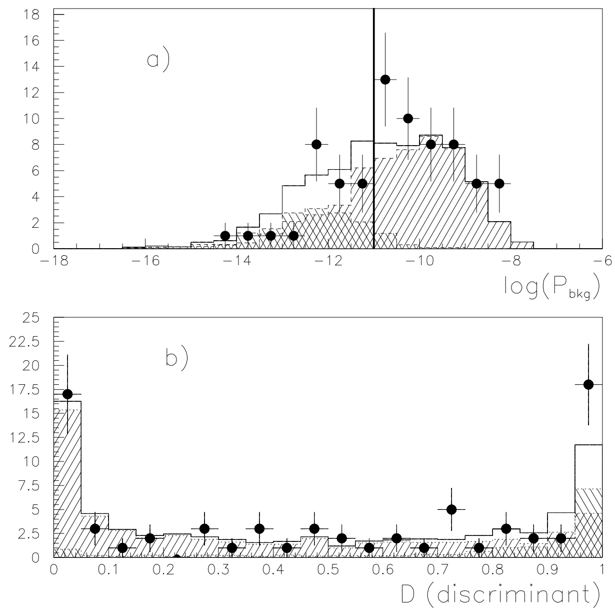


Figure 1: a) Distribution for probability of events being background, and b) discriminant $P_{t\bar{t}}/(P_{t\bar{t}} + P_{\rm bkg})$, calculated for the 71 $t\bar{t}$ candidates (data points). The data is compared with the results expected from MC-simulated samples (solid histogram). Only events with $P_{\rm bkg} < 10^{-11}$ are considered in the final analysis.

togram) events, with the MC normalized as in Figure 1a). The discriminant was not used to reject background, because (unlike the background probability) its value depends directly on $M_{top}$, and is shown simply to illustrate the level of discrimination of signal from background.

The probabilities are inserted into the likelihood function of Eq. 3, and the best estimate of $M_{top}$ and $F_0$ is obtained by maximizing this likelihood function. (-ln$L$ was minimized with respect to the parameters $c_1$, $c_2$, and $M_{top}$ or $F_0$.)

Figure 2a) shows the value of -ln$L$ as a function of $M_{top}$ for the 22 events that pass all the selection criteria, 12 of which are signal and 10 background. Figure 2b) shows the likelihood normalized to its maximum value. The Gaussian fit in the figure yields $M_{top}$=179.6 GeV/c$^2$, and an uncertainty $\delta M_{top}$=3.6 GeV/c$^2$. Monte Carlo studies show that there is a shift to 0.5 GeV/c$^2$ in the extracted mass. Applying this shift, yields the new preliminary result:

$$M_{top}(preliminary) = 180.1 \pm 3.6(\text{stat}) \pm 4.0(\text{sys})\ \text{GeV/c}^2 \quad (6)$$

The main systematic uncertainties are due to the jet-energy scale (3.6 GeV/c$^2$), model for $t\bar{t}$ (1.5 GeV/c$^2$), model for background (1.0 GeV/c$^2$), noise and multiple interactions (1.3 GeV/c$^2$), parton distribution functions (0.2 GeV/c$^2$), and acceptance corrections (0.5 GeV/c$^2$).

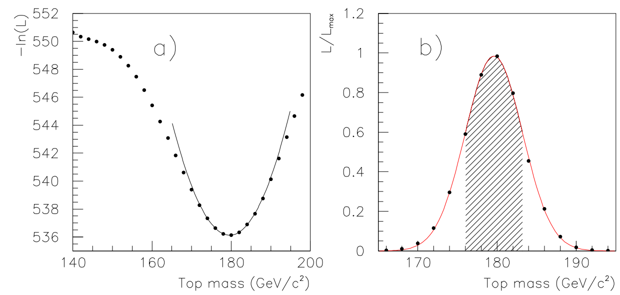


Figure 2: a) Negative of the log of the likelihood as a function of the mass of the top quark for the 22 $t\bar{t}$ candidates in our final sample. b) Likelihood normalized to the maximum value. The curves are Gaussian fits to the likelihood plot b). The hatched area corresponds to the 68.27% probability interval.

Figure 3a) shows the log of the likelihood as a function of $F_0$ for the 22 data events and Fig. 3b) shows the likelihood normalized to its maximum value. The shaded region corresponds to the most narrow 68.27% probability interval about the most probable value, and reflects the statistical error convoluted with the uncertainty on the top mass. The uncertainty on the top mass was included through an integration of the probability over the top mass, assuming a uniform prior. This likelihood also has a response correction to $F_0$, which was obtained from Monte Carlo studies. This probability is fitted to a $5^{th}$ order polynomial as a function of $F_0$. We use the most probable output value and the smallest 68.27% interval within the physical region to define our extracted value of $F_0$:

$$F_0(preliminary) = 0.56 \pm 0.31(\text{stat}) \quad (7)$$

The other systematic uncertainties were calculated by varying their impact in the Monte Carlo or data, and added in quadrature. The systematic uncertainties are due to the jet-energy scale (0.014), model for $t\bar{t}$ (0.020), background (0.010), multiple interactions (0.009), parton distribution functions (0.007), $t\bar{t}$ spin correlations (0.008), and acceptance corrections (0.021). The final preliminary result is

$$F_0(preliminary) = 0.56 \pm 0.31(\text{stat}) \pm 0.04(\text{syst}) \quad (8)$$

consistent with expectations of the SM.

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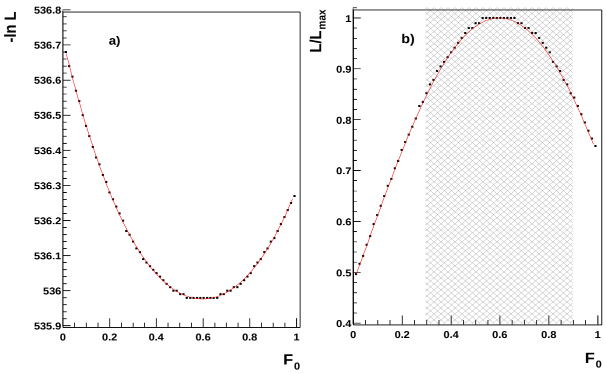


Figure 3: a) -ln L as a function of $F_0$ from the Run I data sample. b) Likelihood normalized to the maximum value. The curves are polynomial of 5th order fits to the likelihood plot b). The hatched area corresponds to the 68.27% probability interval.

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