

A Precision Top Quark Mass Measurement Using the Lepton + Jets Channel at CDF II

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We report measurements of the top quark mass with the CDF II detector at Tevatron. Two complementary techniques are used to measure a top quark mass using pair-produced top quark events in a 318 pb^{-1} data sample. One method uses an event-based likelihood technique that incorporates the full matrix element for the production and decay process, which results in a top quark mass measurement of $173.8^{+2.7}_{-2.5} \text{ (stat.)} \pm 3.3 \text{ (syst.) GeV}/c^2$. The other technique determines the best estimate of the reconstructed top quark mass from each event, and then estimates the top quark mass from a fit to the distribution of reconstructed top quark masses. The measured invariant mass of the hadronically decaying W boson is also used to constraint the jet energy scale. This latter technique results in the most precise measurement of top quark mass of $173.5^{+3.7}_{-3.6} \text{ (stat.)} \pm 1.5 \text{ (other syst.) GeV}/c^2$.

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The top quark is the heaviest known elementary particle, with a mass that is approximately 35 times that of the next-heaviest fermion. Because of this anomalously large mass, top quark studies may provide insight into our understanding of mass in general, and test theories that explain the large mass hierarchy among quarks and leptons, and the interactions that give rise to such disparate properties. Within the context of the Standard Model of particle physics, as the heaviest fermion in the theory, the top quark mass is correlated with the mass of the W intermediate vector boson and the Higgs boson, the latter object being the key to our understanding of the origin of mass. A precision measurement of the top quark and W boson masses tests the consistency of the Standard Model, and in particular the Higgs mechanism for spontaneous symmetry breaking in the theory. A precision measurement of the top quark mass is therefore one of the key goals of the experiments being performed at the Fermilab Tevatron Collider using 2 TeV proton-antiproton collisions.

This Letter reports two measurements of the top quark mass in the lepton + jets decay channel using the Collider Detector at Fermilab (CDF) with 318 pb^{-1} of collision data collected in run II, between March 2002 and August 2004. We focus on the lepton + jets decay channel, which results from the pair production of a top quark and anti-top quark and the subsequent fully hadronic decay of one heavy quark and the semi-leptonic decay of the other. This is the largest decay channel with good signal-to-noise, and previous work has shown that the most accurate mass measurements are possible in this decay mode. In general, $t\bar{t}$ events decaying in the lepton

+ jets channel contain an electron or muon, and a neutrino, both from the leptonic W decay; two light-quark jets from the hadronic W decay; and two additional jets arising from b quarks. We select events consistent with this decay topology, and then analyze them in two complementary ways.

The first technique uses an event-by-event likelihood analysis employing the full matrix element for the production and decay to extract a likelihood distribution as a function of the true top quark mass, M_{top} , for each event. The likelihood distributions are combined to determine the best estimate of M_{top} . This technique, known as the “dynamical likelihood method” or DLM, was developed by the CDF collaboration [1] and is similar to the method used by the $D\bar{0}$ collaboration to make the single most precise measurement of the top quark mass [2]. A second technique, developed by the CDF collaboration in run I [3], reconstructs a top quark mass, m_t^{reco} , in each event and uses the distribution of m_t^{reco} compared with template distributions derived from model calculations with differing top quark masses to estimate M_{top} . We have improved this technique, known as the “template method,” by using the fact that the W boson daughters should form a dijet final state that is consistent with known W boson mass. This gives an independent constraint on the dominant systematic uncertainty in this measurement, the jet energy scale, that allows us to improve the overall accuracy of the measurement.

The data used in this analysis consist of 318 pb^{-1} of events recorded by CDF. The detector is a general-purpose charged and neutral particle detector located at one of the three interaction points along the Tevatron

Collider, and is described in detail elsewhere [4]. Transverse quantities such as p_T are measured in the plane perpendicular to the beamline, and the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the beamline. The detector consists of a solenoidal charged particle spectrometer, consisting of a seven-layer silicon microstrip detector array and a cylindrical drift chamber immersed in a 1.4 T magnetic field. A segmented sampling calorimeter with scintillator tile readout measures energy flow up to $|\eta| = 3.6$ and provides electron and photon identification. A set of charged particle detectors outside the calorimeter are used to identify muon candidates. Due to the high intrinsic data rate of collisions, the experiment employs an on-line, three-level trigger system that only selects approximately one collision in 100,000 to record for subsequent analysis, using various criteria. Events for this analysis were identified by the presence of a charged electron or muon candidate with $p_T > 20$ GeV/c, with a trigger efficiency in excess of 90%.

The resulting event sample was subsequently reduced by requiring in the event the presence of three or more energetic jets with $E_T > 15$ GeV, and by requiring that the missing transverse energy in the event exceed 20 GeV, corresponding to a high-energy neutrino candidate. To reduce backgrounds further, we required either that one of the jets be identified as a bottom quark through the presence of a displaced vertex in the middle of the jet that arises from the decay of the long-lived bottom quark (b tag), or that four jets with $E_T > 21$ GeV be present. In the former case, we also required that there be at least a fourth jet in the event with $E_T > 8$ GeV. In all cases, the jets were required to have pseudorapidity $|\eta| < 2.0$. This selection resulted in ?? events that, based on our background estimates, is significantly enriched in $t\bar{t}$ events.

The two analysis methods employ subsets of these data. The DLM technique uses the subset consisting of four and only four jets with $E_T > 15$ GeV with at least one of the four jets having a b tag. This results in 63 events. The template technique subdivides the data into four subsamples that have different m_t^{reco} distributions and background levels. Ordered by the resulting statistical power, the four subsamples are 1) events with at least four jets with $E_T > 15$ GeV and one b -tagged jet (1-tag Tight sample with 57 events), 2) events with two b -tagged jets (2-tag sample with 16 events), 3) events with a fourth jet with $8 \text{ GeV} < E_T < 15 \text{ GeV}$ and one b -tagged jet (1-tag Loose sample with 25 events), and 4) events with four jets with $E_T > 21$ GeV and no b -tagged jets (0-tag sample with 40 events). Note 13.1 ± 2.2 events in DLM sample, dominated by mistags. There are 1.9 ± 0.5 , 10.4 ± 1.7 and 14.3 ± 2.5 events background in the three template samples with a b tag, in this case the backgrounds being evenly split between mistags, $Wb\bar{b}$, and $Wc\bar{c}$.

The DLM method, described in detail in [5], defines a

TABLE I: The expected background composition and number of identified events for the $t\bar{t}$ -enriched sample used by the template analysis, the subset of those events with ≥ 1 b tag, and the subset of the tagged events used by the DLM analysis.

	Full sample	≥ 1 b tag	DLM sample
	Expected Background		
Source			
W + jets	N/A	19.6 ± 2.4	9.4 ± 1.7
Non- W (QCD)	N/A	4.7 ± 0.7	2.9 ± 1.3
Other	N/A	2.3 ± 0.2	0.8 ± 0.1
Total	N/A	26.6 ± 3.0	13.1 ± 2.2
	Identified $t\bar{t}$ Candidates		
Data	165	121	63

likelihood for each event based on the differential cross section for the event as a function of M_{top} , taking into account detector resolution and combinatorial factors by introducing “transfer functions” that reflect these experimental effects. The actual parton kinematics of the $t\bar{t}$ final state are statistically reconstructed by (a) generating a random value for the virtual mass squared of the W boson in the leptonic channel, s_W , according to the Breit-Wigner form; (b) identifying the momentum of the e or μ with the measured value, and the neutrino transverse momentum with the measured transverse energy flow; and (c) generating random values for the momenta of jets according to the transfer function (TF) probabilities. The transfer function $w(\mathbf{x}, \mathbf{y})$ correlates the partonic and observed variable sets, denoted by \mathbf{x} and \mathbf{y} respectively, which we obtain using simulated $t\bar{t}$ events. We determine The z component of the neutrino momentum, with a two-fold ambiguity, by solving the equation $s_W = (\ell + \nu)^2$. Thus, for a given set of \mathbf{x} and s_W , we unambiguously determine the parton kinematics, and the event likelihood as a function of M_{top} is given by

$$\mathcal{L}(M_{\text{top}}) = N \sum_{I_t} \sum_{I_s} \frac{d\sigma_{t\bar{t}}}{d\Phi}(M_{\text{top}}; \mathbf{x}, s_W), \quad (.1)$$

where the normalization factor, N , is constant for a given event, independent of M_{top} , and the indices, I_t and I_s , run over the parton-jet assignments and the two neutrino solutions, respectively. This process is repeated in each event by generating new random values for s_W and \mathbf{x} until the likelihood converges.

A joint likelihood is formed by multiplying the event likelihoods together. We take into account the presence of background events by modelling the effect of the background as a shift on the top quark mass and making an appropriate correction. This introduces a systematic uncertainty that is constrained by our understanding of the modelling of top quark production and decay. An additional mapping function is employed to convert the top quark mass determined through this procedure to the true top quark mass, again using our model of top quark production and decay to constrain the uncertain-

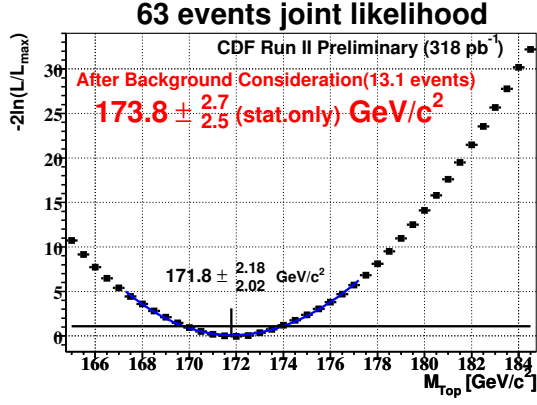


FIG. 1: The joint likelihood curve as a function top quark mass for the 63 events used in the DLM analysis. The likelihood is constructed assuming a pure $t\bar{t}$ sample; a correction for the presence of background events yields the final result of $173.8^{+2.7}_{-2.5}$ (stat.) GeV/c^2 .

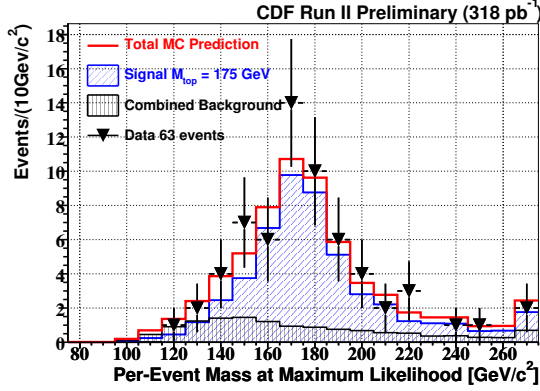


FIG. 2: For each event, the value of the top quark mass at the maximum of the DLM likelihood curve is plotted. Data events are compared to an expected distribution comprising simulated $t\bar{t}$ ($M_{\text{top}} = 175 \text{ GeV}/c^2$) and background events.

ties on this transformation. The joint likelihood function for the 63 events is plotted versus the true top quark mass in Fig. 1, from which we infer the maximum likelihood estimate $M_{\text{top}} = 173.8^{+2.7}_{-2.5}$ (stat.) GeV/c^2 , where the uncertainties are only statistical. Figure 2 shows the distribution of the top quark mass value at the point of maximum likelihood in each event, comparing the 63 data events to the expectation from simulated events.

The template method is described in detail in [6]. This analysis takes each event in the sample and applies a kinematic fit using a χ^2 minimization to determine m_t^{reco} for each event, assuming that the final state arises from the decay of a particle-antiparticle pair into a pair of W bosons and b quarks. We only use the four leading jets in the mass reconstruction. In the χ^2 fit, both sets of W decay daughters are constrained to have the invariant mass of the W boson, and both Wb states are constrained to have the same mass. The jet, lepton, and neutrino en-

ergies are permitted to vary within their respective measurement uncertainties. The ambiguity arising from the different ways of assigning the four jets to the four quarks, taking into account the b -tagging information, is treated by selecting the assignment with the lowest χ^2 . We construct a histogram of m_t^{reco} for each subsample. At the same time, we analyze the events in a slightly different way, removing the W boson mass constraints, identifying for each event all combinations of parton-jet assignments that are consistent with the b -tagging information and determining a set of dijet invariant masses arising from the W boson decay. We create for each subsample a second histogram, which, given the precisely known W boson mass, is sensitive to a jet energy scale correction factor, JES.

We use these eight histograms to measure simultaneously the true top quark mass and JES, which is the source of the dominant uncertainty on the top quark mass measurement. An unbinned likelihood fit is performed to parameterized signal templates taken from simulated events generated using different values of M_{top} and background templates derived from simulations of the relevant background processes. We include in the fit a constraint on JES from the jet energy calibrations done using both in situ data and calibration information [7], and we constrain the background rates in the 2-tag, 1-tag Tight, and 1-tag Loose samples to the estimated background rates. The background rate in the 0-tag sample is determined in the fit using the difference in predicted signal and background mass distributions.

The four reconstructed top quark mass distributions, and the results of the fit are shown in Fig. 3, where we also note the contributions from background sources. We show in Fig. 4 the distributions of the dijet invariant mass for the four subsamples, as well as the result of the fits. In all cases, we see excellent agreement between the observed data distributions and the predictions.

We obtain $M_{\text{top}} = 173.5^{+3.7}_{-3.6}$ (stat.) GeV/c^2 , where the uncertainty is only statistical and incorporates the uncertainties on the JES measurement. Figure 5 shows the likelihood in the M_{top} -JES plane for the combined measurement. The jet energy scale factor is defined as the difference between the observed and nominal jet energy scale, normalized by the calibration uncertainty of JES. If we do not constrain JES to the nominal value of zero, we obtain $\text{JES} = -0.25 \pm 1.22 \sigma$, which indicates our nominal jet energy calibrations are in good agreement with the energy scale information provided by the W boson mass peak in the $t\bar{t}$ decay.

The results from the two techniques have various sources of systematic uncertainty. The dominant systematic uncertainty for both methods arises from our understanding of the CDF jet energy scale. In the DLM technique, the jet energy scale is estimated as the shift in M_{top} arising from a 1σ change in the jet energy scale, where σ is determined by various calibrations and stud-

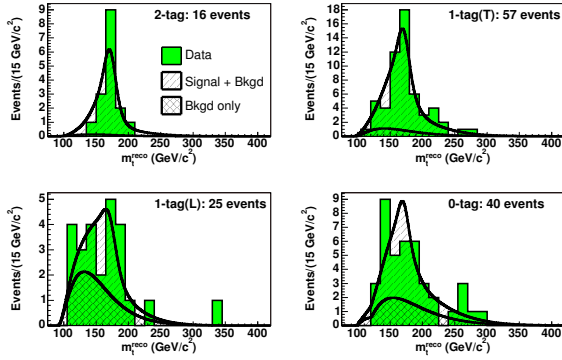


FIG. 3: The reconstructed top quark mass distribution for each subsample is shown overlaid with the expected distribution using the top quark mass, jet energy scale, signal normalization, and background normalization from the combined fit.

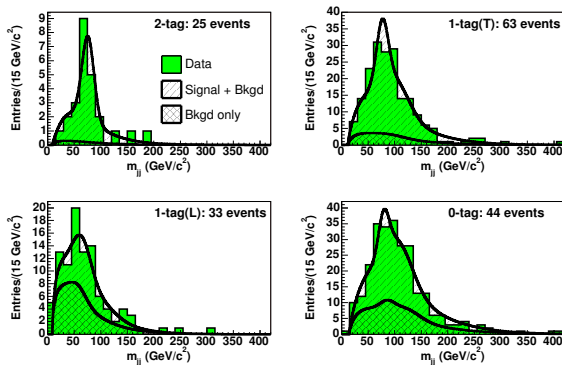


FIG. 4: The reconstructed dijet mass distribution for each subsample is shown overlaid with the expected distribution using the top quark mass, jet energy scale, signal normalization, and background normalization from the combined fit.

ies of control samples. In the template measurement, σ is used as a constraint on the jet energy scale, JES, in the simultaneous measurement of M_{top} and JES to the m_t^{reco} and dijet invariant mass histograms, so that the uncertainty due to jet energy scale is improved with respect to DLM, and is ultimately reported as part of the uncertainty from the likelihood fit. We estimate the contribution of the jet energy scale uncertainty to the uncertainty from the likelihood fit as $2.5 \text{ GeV}/c^2$.

There are a number of sources of additional systematic uncertainty that affect both analyses by introducing uncertainties in the kinematical properties of the events: initial state and final state radiation (ISR/FSR) uncertainties affect the extra jet activity in $t\bar{t}$ events and modify the jet kinematics; uncertainties arising from the parton distribution functions (PDFs); the modeling of b -jet fragmentation, decays, and color connections; modeling of the background processes; and uncertainties arising

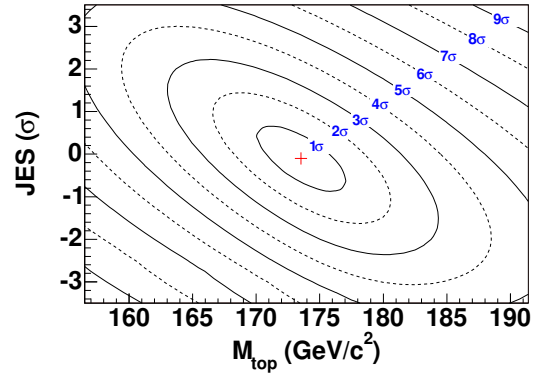


FIG. 5: The contours of the likelihood in the M_{top} -JES plane for the combined fit to all four subsamples. At each point in the plane, the likelihood is maximized with respect to the other free parameters. The crosshair shows the best fit point, and contours are given at intervals of 1σ , where the $k \sigma$ curve is defined by $\Delta \ln L = 0.5k^2$.

TABLE II: The systematic uncertainties for the two analyses are summarized.

Systematic	DLM	Template
	$\Delta M_{\text{top}} \text{ (GeV}/c^2\text{)}$	$\Delta M_{\text{top}} \text{ (GeV}/c^2\text{)}$
Jet Energy Scale	3.0	$[\sim 2.5]^a$
ISR/FSR	0.6	0.7
PDFs	0.5	0.3
Modeling	0.9	1.0
Method	0.6	0.6
Total	3.3	1.5^a

^aThe JES systematic is included in the uncertainty reported by the likelihood fit.

from modelling of the entire event, estimated by comparing the results when we replace the HERWIG Monte Carlo calculations with the PYTHIA generator. Table II summarizes all these uncertainties.

The DLM technique has additional uncertainties that arise from the use of transfer functions and from the procedure that corrects the measured mass for the presence of background. Together with the common sources noted above, the systematic uncertainty on the DLM mass measurement is $3.3 \text{ GeV}/c^2$, which gives a top quark mass measurement of $M_{\text{top}} = 173.8^{+2.7}_{-2.5} \text{ (stat.)} \pm 3.3 \text{ (syst.) GeV}/c^2$.

The template analysis has additional uncertainties arising from the statistical precision of the templates themselves and approximations made in modeling the jet energy scale as a single parameter affecting all jets coherently. The systematic uncertainties for the template technique, combined in quadrature, are $1.5 \text{ GeV}/c^2$. This gives a final top quark mass measurement, using the template technique, of $M_{\text{top}} = 173.5^{+3.7}_{-3.6} \text{ (stat. + JES)} \pm 1.5 \text{ (other syst.) GeV}/c^2$.

In summary, we have made two new measurements of the top quark mass. An analysis using the DLM technique results in $M_{\text{top}} = 173.8^{+2.7}_{-2.5}$ (stat.) ± 3.3 (syst.) GeV/c^2 ; the analysis using the template technique results in $M_{\text{top}} = 173.5^{+3.7}_{-3.6}$ (stat. + JES) ± 1.5 (other syst.) GeV/c^2 . There is a large statistical correlation between these measurements, so that we only choose to quote as a result the single most accurate measurement, the mass obtained using the template method. This provides the most precise single constraint on this important physical parameter, exceeding the accuracy of the current world average for the top quark mass.

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 - [6] ?? (CDF), Phys. Rev. **D??**, ?? (200?), placeholder for run II TMT+JES top mass measurement.
 - [7] ?? (CDF), NIM ??, ?? (200?), placeholder for run II JES NIM.