

# 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, using pair-produced top quark events in a  $318 \text{ pb}^{-1}$  data sample observed in the lepton+jets final state. 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 reconstructed top quark mass from each event, and then extracts 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 used to constraint the jet energy scale, JES. The latter technique results in the most precise measurement of top quark mass of  $173.5^{+3.7}_{-3.6} \text{ (stat. + JES)} \pm 1.5 \text{ (other syst.) GeV}/c^2$ .

PACS numbers: Valid PACS appear here

The top quark is the heaviest known elementary particle, with a mass that is 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 [1], 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. Precision measurements of the top quark and  $W$  boson masses test the consistency of the Standard Model, and in particular the Higgs mechanism for spontaneous symmetry breaking in the theory. Improved 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  $318 \text{ pb}^{-1}$  of collision data collected during run II, between March 2002 and August 2004. We focus on the lepton + jets decay channel, which results from  $t\bar{t}$  pair production 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 observed 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 using two complementary techniques.

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,  $M_{\text{top}}$ , for each event. This technique, known as the “dynamical likelihood method” or DLM, was developed by the CDF collaboration [2] 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 [3]. A second technique, developed by the CDF collaboration in run I [4], reconstructs a top quark mass,  $m_t^{\text{reco}}$ , in each event and uses the distribution of  $m_t^{\text{reco}}$  compared with template distributions derived from model calculations with differing top quark masses to estimate  $M_{\text{top}}$ . 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 the 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 were 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 [5]. Transverse quantities such as  $p_T$  are measured in the plane perpendicular to the beamline, and the pseudorapidity  $\eta$  is defined as  $\eta = -\ln[\tan(\theta/2)]$ , where  $\theta$  is the polar angle with respect to the beamline. The detector comprises a solenoidal charged parti-

cle spectrometer, consisting of a seven-layer silicon microstrip detector array and a cylindrical drift chamber immersed in a 1.4 T magnetic field, and a segmented sampling calorimeter with scintillator tile readout measuring energy flow up to  $|\eta| = 3.6$  and providing 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/ $c$ .

The resulting event sample was subsequently reduced by requiring in each event the presence of three or more 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 primarily  $t\bar{t}$  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. We have estimated the various sources of background contamination in this sample, summarized in Table I, and find that they total  $9.2 \pm 1.8$  events. The template technique subdivides the data into four subsamples that have different  $m_t^{\text{reco}}$  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). The estimated background rates in the samples with a  $b$ -tag are summarized in Table I.

The DLM method, described in detail in [6], defines a likelihood for each event based on the differential cross section for the event as a function of  $M_{\text{top}}$ , 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  $W$

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  $\geq 1$   $b$  tag, and the subset of the tagged events used in the DLM analysis.

	Full sample	$\geq 1$ $b$ tag	DLM sample
	Expected Background		
Source			
$W$ + jets	N/A	$19.6 \pm 2.4$	$5.3 \pm 1.1$
Non- $W$ (QCD)	N/A	$4.7 \pm 0.7$	$3.1 \pm 1.0$
Other	N/A	$2.3 \pm 0.2$	$0.8 \pm 0.1$
Total	N/A	$26.6 \pm 3.0$	$9.2 \pm 1.8$
	Identified $t\bar{t}$ Candidates		
Data	165	121	63

boson in the leptonic channel,  $s_W$ , according to the Breit-Wigner form; (b) identifying the momentum of the  $e$  or  $\mu$  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 using energy conservation. 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  $M_{\text{top}}$  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  $M_{\text{top}}$ , and the indices,  $I_t$  and  $I_s$ , run over the parton-jet assignments and the two neutrino solutions, respectively. A numerical integration is performed by repeating this process for each event by generating a large set of random values for  $s_W$  and  $\mathbf{x}$ .

A joint likelihood is formed by multiplying the event likelihoods together. We take into account the presence of background events by modelling their effect as a shift on the top quark mass. An additional mapping function is employed to convert the top quark mass determined through this procedure to the true top quark mass, using our model of top quark production and decay to constrain the uncertainties 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 [7]. We perform a  $\chi^2$  minimization to fit the parton momentum

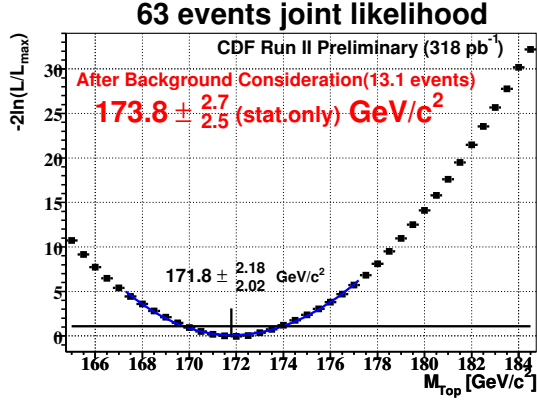


FIG. 1: The joint likelihood as a function top quark mass for the 63 events used in the DLM analysis. The likelihood minimum has to be corrected for the presence of background events, yielding the final result of  $173.8^{+2.7}_{-2.5}$  (stat.)  $\text{GeV}/c^2$ .

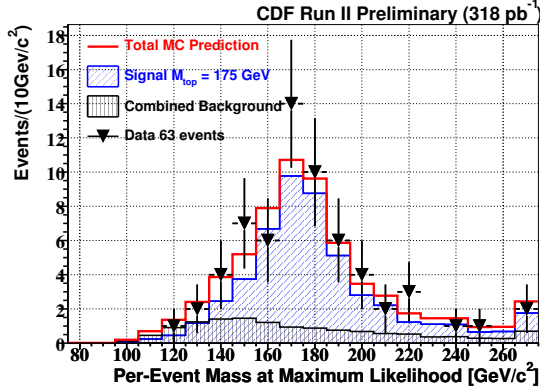


FIG. 2: For each event, the value of the top quark mass at the maximum of the DLM likelihood curve is plotted. Data events are compared to an expected distribution comprising simulated  $t\bar{t}$  ( $M_{\text{top}} = 175 \text{ GeV}/c^2$ ) and background events.

from the  $t\bar{t}$  daughters to determine  $m_t^{\text{reco}}$  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  $\chi^2$  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 ambiguity arising from the different ways of assigning the four jets to the four quarks, taking into account the  $b$ -tagging information, is resolved by selecting the assignment with the lowest  $\chi^2$ . We construct a histogram of  $m_t^{\text{reco}}$  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, refitting the events and determining a set of dijet invariant masses arising from the  $W$  boson decay. We use these masses to create a second histogram for each subsam-

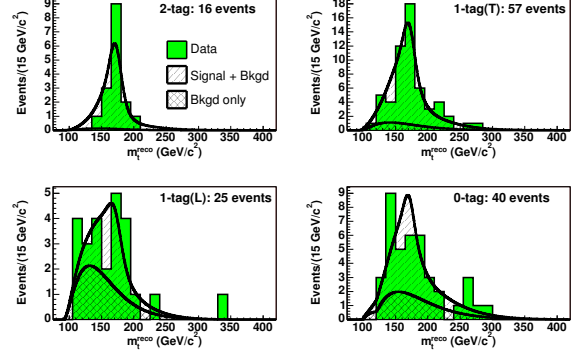


FIG. 3: The reconstructed top quark mass distribution for each subsample is shown overlaid with the expected distribution using the top quark mass, jet energy scale, signal normalization, and background normalization from the combined fit.

ple, 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. An unbinned likelihood fit is performed to parameterized signal templates taken from simulated events generated using different values of  $M_{\text{top}}$ , JES 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 *in situ* data and instrument calibration [8], 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.)  $\text{GeV}/c^2$ , where the uncertainty is only statistical but incorporates the uncertainties on the JES measurement. Figure 5 shows the likelihood in the  $M_{\text{top}}$ -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 JES calibration uncertainty. 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

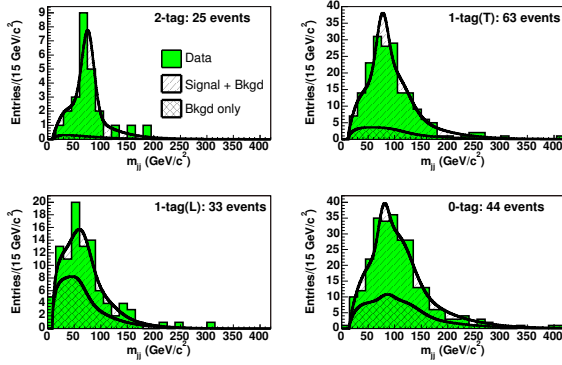


FIG. 4: The reconstructed dijet mass distribution for each subsample is shown overlaid with the expected distribution using the top quark mass, jet energy scale, signal normalization, and background normalization from the combined fit.

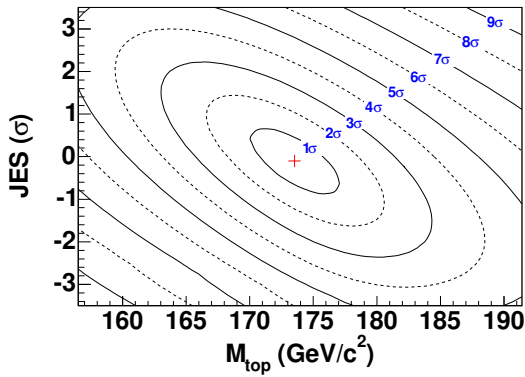


FIG. 5: The contours of the likelihood in the  $M_{\text{top}}$ -JES plane for the combined fit to all four subsamples. At each point in the plane, the likelihood is maximized with respect to the other free parameters. The crosshair shows the best fit point, and contours are given at intervals of  $1\sigma$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

sources of systematic uncertainty. The dominant systematic uncertainty for both methods arises from our understanding of JES. In the DLM technique, the jet energy scale is estimated as the shift in  $M_{\text{top}}$  arising from a  $1\sigma$  change in JES. In the template measurement,  $\sigma$  is used as a constraint on the jet energy scale, JES, in the simultaneous measurement of  $M_{\text{top}}$  and JES to the  $m_t^{\text{reco}}$  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: initial state and final state radiation (ISR/FSR) uncertainties affect the ex-

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	$1.5^a$

<sup>a</sup>The JES systematic is included in the uncertainty reported by the likelihood fit.

tra 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 from modelling of the entire event, estimated by comparing the results when we replace the HERWIG Monte Carlo calculations [9] with the PYTHIA generator [10]. Table II summarizes 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  $M_{\text{top}} = 173.8^{+2.7}_{-2.5} \text{ (stat.)} \pm 3.3 \text{ (syst.) GeV}/c^2$ ; the analysis using the template technique results in  $M_{\text{top}} = 173.5^{+3.7}_{-3.6} \text{ (stat. + JES)} \pm 1.5 \text{ (other syst.) GeV}/c^2$ . 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 [11].

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