

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

The CDF Collaboration
URL <http://www-cdf.fnal.gov>
(Dated: July 21, 2005)

We report measurements of the top quark mass with the CDF II detector at the Fermilab Tevatron using pair-produced top quark events in a 318 pb^{-1} data sample observed in the lepton+jets final state. One method uses an event-based likelihood technique that results in a top quark mass, M_{top} , of $173.2^{+2.6}_{-2.4} \text{ (stat.)} \pm 3.2 \text{ (syst.) GeV}/c^2$. The second method determines the reconstructed top quark mass from each event, using the measured invariant mass of the hadronically decaying W boson to constrain the jet energy scale, JES, to obtain the more precise value for M_{top} 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 35 times that of the next-heaviest fermion. Because of this anomalously large mass, top quark studies provide insight into our understanding of mass in general, and test theories that explain the large mass hierarchy among quarks and leptons. Within the context of the Standard Model of particle physics, the top quark mass is correlated with the masses of the W intermediate vector boson and the Higgs boson, the latter object being the key to our understanding of the origin of mass [1]. Precision measurements of the top quark and W boson masses test the consistency of the Standard Model, and in particular the Higgs mechanism. Improved measurement of the top quark mass is therefore a key goal of the experiments at the Fermilab Tevatron Collider using 1.96 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 during run II between February 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-background, and previous work has shown that accurate mass measurements are possible in this decay mode. Events 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 methods.

The first method uses an event-by-event likelihood analysis employing the full matrix element for the production and decay to extract a joint likelihood as a function of the true top quark mass, M_{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 that used by the DØ collaboration to make the previous most precise measurement of the top quark mass [3]. A second method, developed by the CDF collaboration [4], 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 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 final state consistent with the known W boson mass. This gives an independent constraint on the dominant systematic uncertainty in this measurement, the jet energy scale JES.

The CDF detector is a general-purpose charged and neutral particle detector located at one of the two interaction points along the Tevatron Collider, and is described in detail elsewhere [5]. The detector comprises 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 measuring energy flow up to $|\eta| = 3.6$, and a set of charged particle detectors outside the calorimeter used to identify muon candidates. Events for this analysis were selected by the presence of a charged electron or muon candidate with $p_T > 20 \text{ GeV}/c$ and $|\eta| < 1$.

The event sample was reduced by requiring in each event the presence of four or more jets, and 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 $E_T > 21 \text{ GeV}$ be present. In the former case, we also required that there be at least a fourth jet in the event with $E_T > 8 \text{ GeV}$. In all cases, the jets were required to have pseudorapidity $|\eta| < 2.0$. This selection resulted in 165 events that, based on our

TABLE I: The background composition and number of identified events for the subsets of events with ≥ 1 b tag, and the subset of the tagged events used in the DLM analysis.

	≥ 1 b tag	DLM sample
Source	Expected Background	
W + jets	19.6 ± 2.4	5.3 ± 1.1
QCD	4.7 ± 0.7	3.1 ± 1.0
Other	2.3 ± 0.2	0.8 ± 0.1
Total	26.6 ± 3.0	9.2 ± 1.8
	Identified $t\bar{t}$ Candidates	
Data	121	63

background estimates, are primarily $t\bar{t}$ events.

The two analysis methods employ subsets of these data. The DLM uses the subset consisting of only four jets with $E_T > 15$ GeV with at least one of the 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 ± 1.8 events. The template technique subdivides the data into four subsamples with different expected top mass distributions and background levels. Ordered by 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 $E_T > 21 \text{ GeV}$ 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. We used the HERWIG event generator and a detailed detector simulation to model the signature of signal $t\bar{t}$ events [10].

The DLM, 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_{top} , taking into account detector resolution by introducing “transfer functions” that incorporate these effects. The 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 final state quarks according to the transfer function probabilities. The transfer function $w(\mathbf{x}, \mathbf{y})$ correlates the quark and observed jet transverse energies, 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

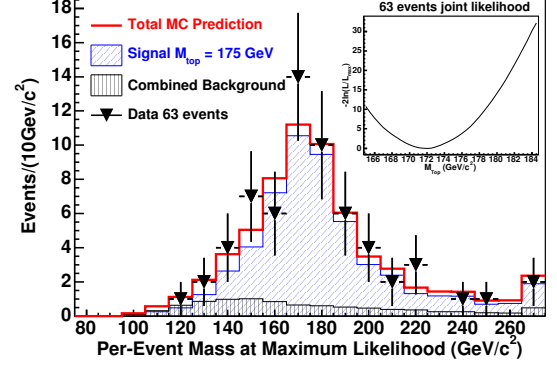


FIG. 1: The value of the top quark mass at the maximum of the DLM likelihood is plotted for each event. Data events (points) are compared to an expected distribution (histogram) comprising simulated $t\bar{t}$ ($M_{\text{top}} = 175 \text{ GeV}/c^2$) and background events. The inset shows the joint likelihood for the 63 events.

event likelihood as a function of M_{top} is given by

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

where the normalization factor, N , is constant for a given event, independent of M_{top} , Φ are phase space variables and the indices, I_j and I_ν , run over the parton-jet assignments and the two neutrino solutions, respectively. A numerical integration is performed by repeating this process for each event several thousand times.

A joint likelihood is formed by multiplying the event likelihoods together. We take into account the presence of background events by modeling their effect as a small shift in the top quark mass. Figure 1 shows the distribution of the top quark mass value at the point of maximum likelihood in each event compared with the expectation from simulated events. An inset shows the joint likelihood as a function of M_{top} , from which we infer $M_{\text{top}} = 173.2^{+2.6}_{-2.4} \text{ (stat.) GeV}/c^2$, where the uncertainties are only statistical.

The template method is described in detail in [7]. We perform a χ^2 minimization to fit the parton momentum from the $t\bar{t}$ daughters and determine m_t^{reco} for each event, assuming that the final state arises from the decay of a particle-antiparticle pair into W bosons and b quarks. We use only 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 ambiguity arising from the different ways of assigning the jets to the four quarks, taking into account the b -tagging information, is resolved 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

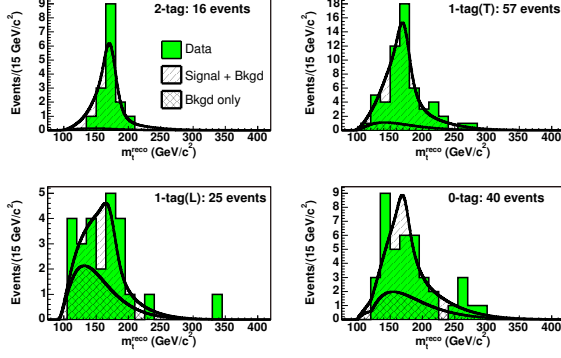


FIG. 2: The m_t^{reco} distribution for each subsample is shown overlaid with the expected distribution using the top quark mass, jet energy scale, signal normalization, and background normalization from the combined fit.

each event all pairs of parton-jet assignments that would be consistent with the W boson final state. We use the invariant masses of these pairs to create a second histogram for each subsample, which, given the precisely known W boson mass [8], is sensitive to a JES defined as the difference between the observed and nominal jet energy scale, normalized by its calibration uncertainty, σ_c .

We use these eight histograms to measure simultaneously M_{top} and JES. An unbinned likelihood fit is performed to parameterized signal templates taken from simulated $t\bar{t}$ events generated using different values of M_{top} and JES, and background templates derived from studies 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 [9], 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 differences in predicted signal and background mass distributions.

The four reconstructed top quark mass distributions, and the results of the fit are shown in Fig. 2, where we also note the contributions from background sources. We show in Fig. 3 the distributions of the dijet invariant mass for the four subsamples, as well as the result of the fits. In all cases, we see agreement between the observed data distributions and the fitted curves.

We obtain $M_{\text{top}} = 173.5^{+3.7}_{-3.6}$ (stat.) GeV/c^2 , where the uncertainty is only statistical but incorporates the uncertainties on the JES measurement. Figure 4 shows the likelihood in the M_{top} -JES plane for the combined measurement. If we do not constrain JES to the nominal value of zero, we obtain $\text{JES} = -0.25 \pm 1.22 \sigma_c$, which indicates our nominal jet energy calibrations are in good agreement with information provided by the W boson mass peak in the $t\bar{t}$ decay.

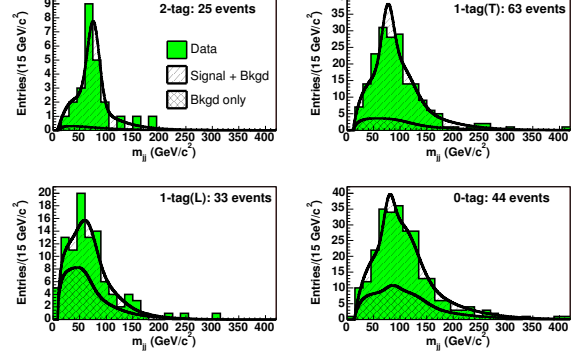


FIG. 3: The reconstructed dijet mass distribution for each subsample is shown overlaid with the expected distribution using the top quark mass, jet energy scale, signal normalization, and background normalization from the combined fit.

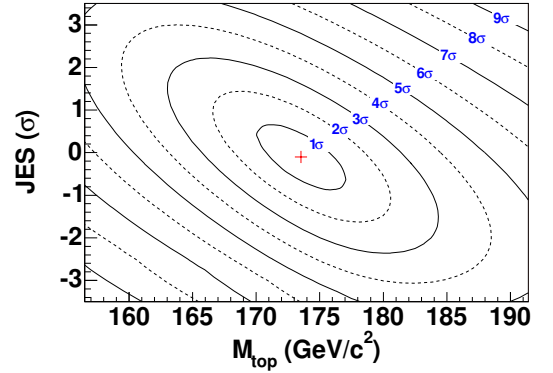


FIG. 4: The contours of the likelihood in the M_{top} -JES plane for the combined fit to all four subsamples. At each point in the plane, the likelihood is maximized with respect to the other free parameters. The crosshair shows the best fit point, and contours are given at intervals of 1σ , where the $k \sigma$ curve is defined by $\Delta \ln L = 0.5k^2$.

The results from the two methods have various sources of systematic uncertainty, the largest arising from our understanding of JES. In the DLM method, the jet energy scale is estimated as the shift in M_{top} arising from a $1 \sigma_c$ change in JES. In the template measurement, σ_c is used as a constraint on the jet energy scale, JES, so that the uncertainty due to the jet energy scale is improved with respect to DLM, and is reported as part of the uncertainty from the likelihood fit. We estimate the contribution of the jet energy scale uncertainty 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 uncertainties (ISR/FSR); uncertainties arising from the parton distribution functions (PDFs); uncertainties arising from b -jet fragmen-

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

Systematic	DLM $\Delta M_{\text{top}} \text{ (GeV}/c^2\text{)}$	Template $\Delta M_{\text{top}} \text{ (GeV}/c^2\text{)}$
Jet Energy Scale	3.0	$[\sim 2.5]^a$
ISR/FSR	0.6	0.7
PDFs	0.5	0.3
Modelling	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.

tation, decays, and color connections, modeling of the background processes, and uncertainties arising from the event generators we employ (Modelling). Table II summarizes these uncertainties.

The DLM method 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 $3.3 \text{ GeV}/c^2$. The template method has additional uncertainties arising from the statistical precision of the templates themselves and approximations made in treating JES as a single parameter affecting all jets coherently. These uncertainties, combined in quadrature, are $1.5 \text{ GeV}/c^2$.

In summary, we have made two new measurements of the top quark mass. An analysis using the DLM method results in $M_{\text{top}} = 173.2^{+2.6}_{-2.4} \text{ (stat.)} \pm 3.2 \text{ (syst.) GeV}/c^2$; 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 quote as a result only 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 previous world average for the top quark mass [8].

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of En-

ergy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

-
- [1] J. Erler and P. Langacker, Phys. Lett. **B592**, 1 (2004), hep-ph/0407097.
 - [2] K. Kondo, J. Phys. Soc. Jap. **57**, 4126 (1988).
 - [3] V. M. Abazov et al. (D0), Nature **429**, 638 (2004), hep-ex/0406031.
 - [4] F. Abe et al. (CDF), Phys. Rev. **D50**, 2966 (1994).
 - [5] D. Acosta et al. (CDF), Phys. Rev. **D71**, 032001 (2005), hep-ex/0412071. We employ a cylindrical coordinate system where θ is the polar angle with respect to the proton beam, ϕ is the azimuthal angle, and pseudorapidity is $\eta = -\ln \tan(\theta/2)$. Transverse energy and momentum are $E_T = E \sin \theta$ and $p_T = p \sin \theta$, respectively, where E and p are energy and momentum.
 - [6] ?? (CDF), Phys. Rev. **D??**, ?? (200?), placeholder for run II DLM top mass measurement.
 - [7] ?? (CDF), Phys. Rev. **D??**, ?? (200?), placeholder for run II TMT+JES top mass measurement.
 - [8] S. Eidelman et al. (Particle Data Group), Phys. Lett. **B592**, 1 (2004).
 - [9] ?? (CDF), NIM ??, ?? (200?), placeholder for run II JES NIM.
 - [10] G. Corcella, I. G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M. H. Seymour, and B. R. Webber, JHEP **01**, 010 (2001), [hep-ph/0011363]; hep-ph/0210213.
 - [11] T. Sjostrand, L. Lonnblad, and S. Mrenna, TP 01-21, LU (2001), hep-ph/0108264.