

Precise Measurement of the Top-Quark Mass in the Lepton + Jets Topology at CDF II

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We present a measurement of the mass of the top quark from proton-antiproton collisions recorded at the CDF experiment in Run II of the Fermilab Tevatron. We analyze events from the single lepton plus jets final state ($t\bar{t} \rightarrow W^+ b W^- \bar{b} \rightarrow l\nu b q \bar{q}' \bar{b}$). The top-quark mass is extracted using a direct calculation of the probability density that each event corresponds to the $t\bar{t}$ final state. The probability is a function of both the mass of the top quark and the energy scale of the calorimeter jets, which is constrained *in situ* by the hadronic W boson mass. Using 167 events observed in 955 pb^{-1} of integrated luminosity, we achieve the single most precise measurement of the top-quark mass, $170.8 \pm 2.2(\text{stat.}) \pm 1.4(\text{syst.}) \text{ GeV}/c^2$.

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The top quark is the heaviest known elementary particle. Its large mass plays an important role in loop corrections to several electroweak observables predicted by the standard model. In conjunction with measurements of the W boson mass, a precise measurement of the top-quark mass, m_t ,

constrains the mass of the as yet unobserved Higgs boson [1]. Moreover, by comparing precision electroweak measurements to predictions including the relevant loop corrections, a precise measurement of m_t can help constrain contributions from physics beyond the standard model.

Measuring m_t to the highest achievable precision is therefore one of the main goals of the experiments operating at the Fermilab Tevatron collider.

At the Tevatron, top quarks are mainly produced in pairs. They decay essentially 100% of the time into a W boson and a b quark, with the W decaying into quarks or leptons. The result presented here uses the lepton + jets channel, where one W decays into two quarks and the other decays to an electron or a muon and the corresponding neutrino. In the past, this channel has provided the most precise measurements of m_t , and recent measurements can be found in Ref. [2].

In this Letter we report the single most precise measurement of the top-quark mass from Tevatron proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV, using 955 pb^{-1} of integrated luminosity collected with the CDF II detector from February 2002 to March 2006.

The CDF II detector is a general-purpose particle detector and is described in detail elsewhere [3]. It has a solenoidal charged particle spectrometer, consisting of 7–8 layers of silicon microstrip detectors and a cylindrical drift chamber immersed in a 1.4 T magnetic field, a segmented sampling calorimeter, and a set of charged particle detectors outside the calorimeter used to identify muon candidates. We use a right-handed cylindrical coordinate system with the origin in the center of the detector, where θ and ϕ are the polar and azimuthal angles, respectively, and pseudorapidity is defined as $\eta \equiv -\text{Intan}(\theta/2)$. 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.

Events in the lepton + jets decay channel are selected to have a single, isolated electron or muon candidate with large transverse energy, large imbalance in transverse momentum in the event (missing transverse energy [4], \cancel{E}_T) as expected from the undetectable neutrino, and exactly four jets with large transverse energy. Jets are reconstructed using a cone algorithm with radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. Of these jets, we require at least one to have originated from a b quark by using an algorithm that identifies a long-lived B hadron through the presence of a displaced vertex (b tag) [5]. Backgrounds to the $t\bar{t}$ signal arise from multijet QCD production (non- W), W production in association with jets (W + jets), and electroweak backgrounds (EWK) composed of diboson (WW , WZ , ZZ) and single top production. W + jets background events include jets with real b flavor as well as light flavor jets incorrectly identified as b jets. To remove the non- W backgrounds, where \cancel{E}_T is due to mismeasured jet energies, we require \cancel{E}_T not to be aligned with the highest energy jet by a suitable requirement on $\Delta\phi$ between this jet and \cancel{E}_T . Table I summarizes the selection criteria used in this analysis, and a more detailed description can be found in Ref. [6]. We select 167 events of which we expect about 85% to be $t\bar{t}$ events. Table II shows the expected sample composition determined with

TABLE I. Event selection criteria [6].

Lepton	$E_T > 20$ GeV (electron, muon), $ \eta < 1$
Jets	exactly 4 with $E_T > 15$ GeV, $ \eta < 2.0$
\cancel{E}_T	> 20 GeV, calculated over $ \eta < 3.6$
b tag jets	≥ 1 from a secondary vertex, $ \eta < 1.5$
Non- W veto	$0.5 \leq \Delta\phi \leq 2.5$ when $\cancel{E}_T < 30$ GeV

318 pb^{-1} [6], scaled to 955 pb^{-1} and assuming a $t\bar{t}$ cross section of 8.0 pb. Residual differences due to this scaling are absorbed in the systematic background uncertainty.

We analyze the selected events using a likelihood technique that relies on calculations of probability densities based on matrix elements for the signal ($t\bar{t}$) and dominant background (W + jets) processes [7]. The backgrounds other than W + jets are found to be adequately described by the W + jets probability density. Given a set of observed variables, x , and underlying partonic quantities, y , the signal and background probability densities are constructed by integrating over the appropriate parton-level differential cross section, $d\sigma(y)/dy$, convolved with parton distribution functions (PDFs) and detector resolution effects:

$$P(x) = \sum_{\text{jet perm.}} \int \frac{d\sigma(y)}{dy} f(q_1) f(q_2) dq_1 dq_2 W(x, y) dy. \quad (1)$$

The PDFs [$f(q_1)$ and $f(q_2)$] take into account the flavors of colliding quark and antiquark and are given by CTEQ5L [8]. The detector resolution effects are described by a transfer function $W(x, y)$ relating x to y . The momenta of the leptons and the angles of jets and leptons are taken to be exactly measured, and therefore $W(x, y)$ for these quantities is given by the product of Dirac delta functions. The nontrivial part of $W(x, y)$ maps parton energies to measured jet energies after correction for instrumental detector effects [9]. This mapping is obtained by parametrizing the jet response in fully simulated $t\bar{t}$ events created by the Monte Carlo (MC) generator PYTHIA [10] and including the effects of radiation, hadronization, measurement resolution, and energy omitted from the jet cone by the reconstruction algorithm. The $t\bar{t}$ and W + jets probability densities, $P_{t\bar{t}}$ and $P_{W+\text{jets}}$, include all possible permutations of matching jets with partons as well as all possible longi-

TABLE II. Background composition and expected number of $t\bar{t}$ candidates. All uncertainties are statistical only.

Source	Expected number of events
W + jets	14.5 ± 5.1
non- W	5.2 ± 2.6
EWK	2.2 ± 0.5
Total	22.0 ± 8.2
$t\bar{t}$ ($\sigma = 8.0 \text{ pb}$, $m_t = 170 \text{ GeV}/c^2$)	145.1 ± 16.5
Data	167

tudinal momenta for the neutrino in the W decay. The permutations are reduced to six or two by exploiting b tagging information (single-tag or double-tag, respectively). We use different transfer functions for light quark jets and b jets, depending on the flavor of the parton assigned to the jet. In calculating $d\sigma(y)/dy$, $P_{i\bar{i}}$ uses the leading order matrix element of the $q\bar{q} \rightarrow t\bar{t}$ process [11], and $P_{W+\text{jets}}$ uses the sum of matrix elements of the $W + 4$ jets subroutines encoded in the VECBOS Monte Carlo generator [12].

The final state described by $d\sigma(y)/dy$ contains 6 particles, which introduces 20 integration variables in Eq. (1), including the longitudinal momenta of the incoming quarks. By imposing energy-momentum conservation, in conjunction with the Dirac delta functions in $W(x, y)$, we reduce the dimensionality of the remaining integration to five. The integration in $P_{W+\text{jets}}$ is performed over the energies of the outgoing partons and the invariant mass of the leptonically decaying W using a Monte Carlo technique. In order to reduce the calculation time for $P_{i\bar{i}}$, we integrate over the following variables: the invariant masses of t, \bar{t}, W^+ , and W^- and the energy of one of the quarks from the hadronic W decay. Our method includes two additional integrations over the transverse momentum components of the $t\bar{t}$ system. The integration in $P_{i\bar{i}}$ uses the numerical integration code VEGAS [13].

The largest potential systematic uncertainty in this measurement arises from the energy scale of jets. To decrease this uncertainty, we exploit the fact that the hadronically decaying W provides an *in situ* constraint of the jet energy scale, as the two jets should form an invariant mass consistent with the precisely known mass of the W boson [1]. The jet energy scale and the mass of the top quark are simultaneously determined from a two-dimensional likelihood that includes their correlation. A salient feature of this method is that the uncertainty due to the jet energy scale will be reduced with increasing statistics. Thus $P_{i\bar{i}}$ is evaluated as a function of m_t and an assumed jet energy scale factor $f_{\text{JES}} = E_{\text{jet}}^{\text{obs}}/E_{\text{jet}}$, where $E_{\text{jet}}^{\text{obs}}$ is the observed jet energy and E_{jet} is the true jet energy.

To extract m_t and f_{JES} from the data, we build a likelihood function for N selected events by adding $P_{i\bar{i}}$ and $P_{W+\text{jets}}$ for each event. The combined likelihood is minimized with respect to three variables: m_t , f_{JES} , and C_s , the fraction of events consistent with our $t\bar{t}$ signal hypothesis. The likelihood for N events is given by

$$\begin{aligned} \mathcal{L}(x_1, x_2, \dots, x_N; m_t, f_{\text{JES}}, C_s) &= e^{-N[C_s \langle A_{i\bar{i}}(m_t, f_{\text{JES}}) \rangle + (1 - C_s) \langle A_{W+\text{jets}}(f_{\text{JES}}) \rangle]} \\ &\times \prod_{i=1}^N [C_s P_{i\bar{i}}(x; m_t, f_{\text{JES}}) + (1 - C_s) P_{W+\text{jets}}(x; f_{\text{JES}})], \end{aligned} \quad (2)$$

where the first factor arises from the Poisson extension of

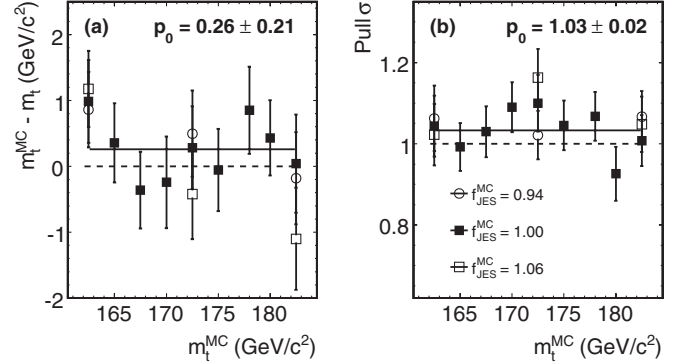


FIG. 1. Results of pseudoexperiment tests. (a) Difference between the measured m_t and the input top-quark mass in the MC event sample (m_t^{MC}), as a function of m_t^{MC} . (b) Gaussian σ of pull distributions (see text), as a function of m_t^{MC} . The plots include results using MC event samples with different values of f_{JES} ($f_{\text{JES}}^{\text{MC}}$). The weighted average p_0 is indicated by the solid horizontal line. The dashed line indicates an example of an unbiased result.

the likelihood and normalizes the combined event probability density, and $\langle A \rangle$ refers to the mean acceptance for $t\bar{t}$ or $W + \text{jets}$ events. We use fully simulated MC $t\bar{t}$ and $W + \text{jets}$ events to determine the functional form of $\langle A \rangle$. $P_{W+\text{jets}}$ is evaluated at the central jet energy scale factor, $f_{\text{JES}} = 1$. The f_{JES} dependence of $P_{W+\text{jets}}$ is determined by varying the input f_{JES} in MC event samples ($f_{\text{JES}}^{\text{MC}}$) and by parametrizing the average likelihood response as a function of f_{JES} . We use the m_t dependence of the theoretical leading order $t\bar{t}$ cross section to normalize $P_{i\bar{i}}$. Because we use a leading order matrix element to calculate $P_{i\bar{i}}$, we find that $t\bar{t}$ events where at least one of the four reconstructed jets cannot be matched to a parton from the $t\bar{t}$ decay within $\Delta R < 0.4$ behave like background events. As a consequence, a pure sample of $t\bar{t}$ events yields C_s of 0.8. The quoted C_s values are corrected for this effect. For each event $P_{i\bar{i}}$ is evaluated in increments of 2 GeV/c^2 in m_t and

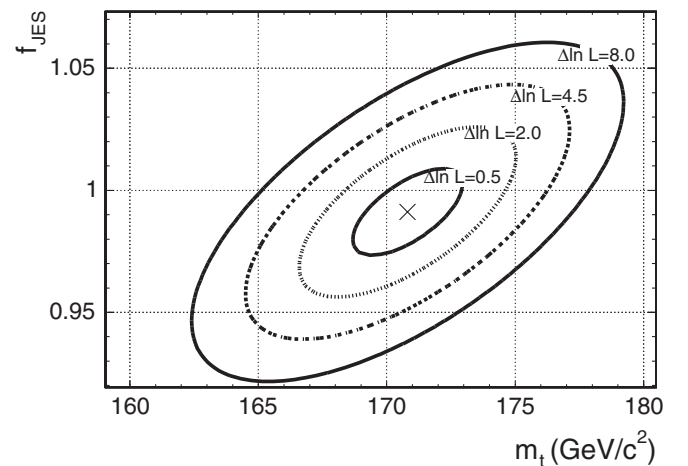


FIG. 2. Contours of likelihood evaluated over the 955 pb^{-1} event sample. Our measurement is indicated by the X .

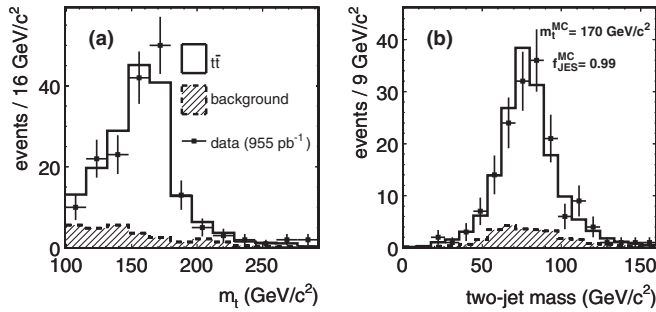


FIG. 3. Comparison of two kinematic variables for data and MC using $f_{\text{JES}}^{\text{MC}} = 0.99$ and $m_t^{\text{MC}} = 170 \text{ GeV}/c^2$. (a) Most probable value of m_t for each event extracted from evaluating $P_{t\bar{t}}$ at $f_{\text{JES}} = 1$. (b) Invariant mass of the pair of jets assigned as W decay products calculated using the most probable permutation at the most probable value of m_t and f_{JES} in each event evaluated from $P_{t\bar{t}}$. The backgrounds contain all contributions shown in Table II.

0.02 in f_{JES} . At each point of this grid we fit the entire sample of N events according to Eq. (2) and the most likely value of C_s is determined using MINUIT [14]. The optimal parameters m_t and f_{JES} are obtained by fitting the likelihood using a two-dimensional Gaussian. The statistical uncertainty on m_t includes the uncertainty on f_{JES} .

The performance of the analysis is tested by extracting m_t from MC pseudoexperiments containing $t\bar{t}$ signal samples with various input top-quark masses (m_t^{MC}) and background samples described in Table II. The signal and electroweak background samples are generated using HERWIG [10]. The W + jets background is generated using ALPGEN [10] with hadronization and fragmentation done by HERWIG. The non- W background is extracted from an independent data sample. All of the MC samples are processed by the CDF detector simulation. We construct pseudoexperiments of signal and background events by fluctuating the number of events around the values shown in Table II. Figure 1(a) shows that the fitted Gaussian mean m_t extracted from 200 pseudoexperiments per point is unbiased with respect to m_t^{MC} up to the statistical uncertainty of $0.21 \text{ GeV}/c^2$, which is taken as a systematic uncertainty. Similar tests are performed for the output of f_{JES} . In this case, we find that a bias of +4% in f_{JES} is present, independent of m_t . We correct for this bias to properly interpret the output of f_{JES} . Figure 1(b) shows the top mass pull width, defined as the Gaussian σ of the top mass residual ($m_t - m_t^{\text{MC}}$) divided by the uncertainty in each pseudoexperiment σ_{m_t} , as a function of m_t^{MC} . The pull width is $3\% \pm 2\%$ larger than 1 on average, and thus, the statistical uncertainty is scaled up by 3%.

Applying this method to data, we measure the top-quark mass to be $m_t = 170.8 \pm 2.2(\text{stat.})$ and the f_{JES} scale to be $f_{\text{JES}} = 0.99 \pm 0.02(\text{stat.})$, in good agreement with the reference scale from the default CDF calibration [9]. Figure 2 shows the fitted two-dimensional likelihood with $\Delta \ln L$

TABLE III. Summary of systematic uncertainties.

Source	Uncertainty (GeV/c^2)
Residual jet energy scale	0.4
b jet energy scale	0.6
Generator	0.2
Initial- and final-state radiation	1.1
PDFs	0.1
Background	0.2
Lepton p_T	0.2
b tag p_T dependence	0.3
Monte Carlo statistics	0.2
Multiple interactions	0.1
Total	1.4

contours. The statistical uncertainty is taken from the maximum and minimum m_t values on the $\Delta \ln L = 0.5$ contour. We find a correlation coefficient of 0.32 between m_t and f_{JES} . The fit yields a signal fraction $C_s = 0.84 \pm 0.10(\text{stat.})$, which corresponds to $140 \pm 17 t\bar{t}$ events and is consistent with the expectation shown in Table II. Monte Carlo tests have shown that the resulting m_t is stable over a wide range of sample purities. Figure 3 shows comparisons of two representative kinematic quantities between data and simulation using $f_{\text{JES}}^{\text{MC}} = 0.99$ and $m_t^{\text{MC}} = 170 \text{ GeV}/c^2$.

The sources of systematic uncertainty are listed in Table III. To first order, f_{JES} is already included in the statistical uncertainty, but we also consider a dependence of f_{JES} on the p_T and η of the jets (residual jet energy scale) using the dependence found in other studies [9]. The other systematic uncertainties listed are explained in detail in Ref. [2]. We also include possible mismodeling of multiple interactions in the simulation at high luminosity. The sum in quadrature of all systematic uncertainties is $1.4 \text{ GeV}/c^2$.

In summary, we present a measurement of the top-quark mass in the lepton + jets channel using 955 pb^{-1} of data collected by the CDF experiment. A matrix element analysis was used with an *in situ* measurement of the jet energy scale. We measure

$$m_t = 170.8 \pm 2.2(\text{stat.}) \pm 1.4(\text{syst.}) \text{ GeV}/c^2, \quad (3)$$

where the statistical uncertainty includes the uncertainty of $1.5 \text{ GeV}/c^2$ due to the jet energy scale. With a total uncertainty of 1.5%, this result is the most precise measurement of the top-quark mass to date and is a 35% improvement over the previous best measurement [2].

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