Precise measurement of the top quark mass in the dilepton channel at D0

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We measure the top quark mass ($m_t$) in $p\bar{p}$ collisions at a center of mass energy $\sqrt{s} = 1.96$ TeV using dilepton $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell^+\nu_\ell b\ell^-\bar{\nu}_b$ events, where $\ell$ denotes an electron, a muon, or a tau lepton that decays leptonically. The data correspond to an integrated luminosity of 5.4 fb$^{-1}$ collected with the D0 detector at the Fermilab Tevatron Collider. We obtain $m_t = 174.0 \pm 1.8$(stat) $\pm 2.4$(syst) GeV, which is in agreement with the current world average $m_t = 173.3 \pm 1.1$ GeV. This is currently the most precise measurement of $m_t$ in the dilepton channel.

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The measurement of the properties of the top quark has been a major goal of the Fermilab Tevatron Collider experiments since its discovery in 1995 [1, 2]. As the heaviest known elementary particle, the top quark may play a special role in the mechanism of electroweak symmetry breaking. A precise measurement of its mass ($m_t$) is of particular importance, since, combined with the measurement of the $W$ boson mass, it provides an indirect constraint on the mass of the Higgs boson in the standard model (SM), and can also constrain possible extensions of the SM.

We present a new measurement of the top quark mass in the dilepton channel ($ee, e\mu, \mu\mu$) in $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell^+\nu_\ell b\ell^-\bar{\nu}_b$ events, where $\ell$ denotes an electron, a muon or a tau decaying leptonically, using the matrix element (ME) method. The first measurement of $m_t$ based on this method was performed in the lepton+jets channel by the D0 experiment [3]. The CDF collaboration has applied the ME approach to determine $m_t$ in the dilepton and all-hadronic final states [4, 5], obtaining a mass precision of 4.0 GeV for dilepton events [4]. The measurement of $m_t$ in the dilepton channel has also been carried out using other techniques [6–10], reaching a precision of 4.8 GeV.

We report a measurement based on data collected by the D0 detector, corresponding to 5.4 fb$^{-1}$ of integrated luminosity from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

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The D0 detector has a central tracking system, consisting of a silicon microstrip tracker and a central fiber tracker, both located within a 1.9 T superconducting solenoidal magnet [11], with design providing tracking and vertexing at pseudorapidities $|\eta| < 3$ [12]. The liquid-argon and uranium calorimeter has a central section (CC) covering pseudorapidities $|\eta|$ up to $\approx 1.1$ and two end calorimeters (EC) that extend coverage to $|\eta| \approx 4.2$, with all three housed in separate cryostats [13]. A muon system outside the calorimeters covers $|\eta| < 2$ and consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids [14].

Despite the small branching fraction of this final state and the presence of two neutrinos in each event, the measurement of $m_t$ in the dilepton channel is interesting because the lower background and the smaller jet multiplicity relative to the lepton+jets channel result in a reduced sensitivity to the ambiguity from combining jets in the reconstruction of $m_t$. The dilepton measurement therefore complements the results from other final states. Moreover, significant differences in measured values of $m_t$ in different $t\bar{t}$ decay channels can be indicative of the presence of physics beyond the SM [15].

As the SM predicts top quarks to decay almost 100% of the time into a $W$ boson and a $b$ quark, $t\bar{t}$ events are classified according to the decays of the $W$ boson. In the dilepton channel, both $W$ bosons decay leptonically, $W^+ \to \ell^+\nu_{\ell}$ [16] with $\ell = e, \mu$ or $\tau$. We analyze the events characterized by two leptons $ee$, $e\mu$, or $\mu\mu$, with a large transverse momenta ($p_T$), large imbalance in transverse momentum from the undetected neutrinos ($\not{p}_T$), and two high-$p_T$ jets from the $b$ quarks. The $W^+ \to \tau^+\nu_\tau$ decays contribute through secondary $\tau^+ \to \ell^+\nu_{\ell}\bar{\nu}_\tau$ transitions.

For the $ee$ and $\mu\mu$ analysis, we consider events selected by a set of single-lepton triggers. For the $e\mu$ channel, we use a mixture of single and multilepton triggers and lepton+jet triggers. Dilepton $t\bar{t}$ events are required to have at least two oppositely charged, isolated leptons with $p_T > 15$ GeV, and either $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$ for electrons and $|\eta| < 2$ for muons. If more than one lepton-pair combination is found in an event, only the pair with the largest sum in scalar $p_T$ is used. Events must have at least two jets with $p_T > 20$ GeV and $|\eta| < 2.5$, well separated from the selected electrons. No explicit $b$ jet identification is required in this analysis.

The main sources of background in the dilepton channel are Drell-Yan and $Z$ boson production ($Z/\gamma^* \to \ell^+\ell^-$), diboson production ($WW, WZ, ZZ$), and instrumental background that originates from limited detector resolution and lepton misidentification. In the $ee$ channel, the discrimination between the $t\bar{t}$ signal and background improves by requiring a large significance of the measured $\not{p}_T$, which is defined through a likelihood discriminant constructed from the ratio of $\not{p}_T$ to its uncertainty [17]. In the $\mu\mu$ channel, we require, in addition, $\not{p}_T > 40$ GeV. In the $e\mu$ channel, the requirement $H_T > 115$ GeV, where $H_T$ is the scalar sum of the transverse momenta of the leading lepton and the two leading jets, rejects most of the contribution from $\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau$. The above selections minimize the expected statistical uncertainty on $m_t$. In total, we select 479 candidate events with 73, 266, and 140 events, respectively, in the $ee$, $e\mu$, and $\mu\mu$ channels, of which about 13 $\pm$ 5, 48 $\pm$ 15, and 56 $\pm$ 15 events, respectively, are expected to arise from background.

The matrix element method is based on the probability for a given event to resemble signal, which depends on the value of $m_t$, or background, which is usually independent of $m_t$. Assuming that the different physics processes leading to the same final state do not interfere, the event probability can be written as the sum of probabilities from all possible contributions. In practice, because the ME method requires significant computing time, only the dominant background is taken into account, and the total event probability is given by

$$P_{\text{evt}} = f_{t\bar{t}}P_{t\bar{t}}(x; m_t) + (1 - f_{t\bar{t}})P_{Z+2 \text{ jets}}(x),$$

where $f_{t\bar{t}}$ is the fraction of $t\bar{t}$ events, $P_{t\bar{t}}$ and $P_{Z+2 \text{ jets}}$ are the signal and background probability densities, respectively, $m_t$ is the signal and background multiplicity densities, respectively, $m_t$ is the assumed top quark mass, and $x$ reflects the observed kinematic variables, i.e., the four-momenta of the measured jets and leptons. In the $ee$, $e\mu$, and $e\mu$ channels, $Z + 2$ jets events with $Z \to \ell^+\ell^-$, $Z \to \mu^+\mu^-$ and $Z \to \tau^+\tau^- \to e^+\nu_\ell\mu^-\bar{\nu}_\mu$ are expected to be the dominant source of background. There is no bias expected from neglecting other background probabilities, as the analysis is calibrated using all significant sources of background, which provides a way to correct for the limitations of the model, as described below.

The leading-order (LO) matrix element for $q\bar{q} \to t\bar{t}$ is written as the sum of probabilities for each final state $y$ of the six produced partons, the signal probability is given by

$$P_{t\bar{t}}(x; m_t) = \frac{1}{\sigma_{\text{obs}}(m_t)} \sum_{i=1}^{8} \int dq_1 dq_2 f_{\text{PDF}}(q_1) f_{\text{PDF}}(q_2) \left(\frac{(2\pi)^4 |M(y)|^2}{q_1q_2s} d\Phi_0 \right) W(x, y) W(p_T^T),$$

where $q_1, q_2$ denote the momentum fractions of the incident quarks in the proton and antiproton, $f_{\text{PDF}}$ are the parton distribution functions (PDF) for finding a parton of a given flavor and longitudinal momentum fraction in the proton or antiproton (in this analysis we use the CTEQ6L1 PDF [18]), $s$ is the square of the energy in the $q\bar{q}$ rest frame, $M(y)$ is the leading-order matrix element [19] and $d\Phi_0$ is an element of the 6-body phase space.
space. Detector resolution is taken into account through a transfer function \( W(x, y) \) that describes the probability of the partonic final state \( y \) to be measured as \( x \) in the detector. The finite transverse momentum of the \( t\bar{t} \) system is accounted for through an integration over its probability distribution, which is derived from parton-level simulated events using the ALPGEN event generator [20], employing PYTHIA [21] for parton shower development and hadronization. As the angular resolution of the jets and leptons, as well as the electron energy resolution, are sufficiently well determined, there is no need to introduce resolution functions for these variables. Consequently, taking into account energy and momentum conservation, the integration in Eq. (2) can be reduced to an integration over the energies associated with the \( b \) quarks, the lepton-neutrino invariant masses, the differences between neutrino transverse momenta, the transverse momentum of the \( t\bar{t} \) system, and the radii of curvature \( (p_T^{-1}) \) of muons. The sum in Eq. (2) runs over both possible jet-parton assignments and over up to two real solutions for each neutrino energy [22]. The normalization factor \( \sigma_{\text{obs}} \) in Eq. (2) corresponds to the product of the LO cross section and the mean efficiency of the final kinematic selections.

A transfer function \( W(x, y) \) is used for each jet and each muon in the final state. The jet energy resolution is parametrized as the sum of two Gaussians, with parameters depending linearly on parton energies, while the resolution in muon track curvature is described by a single Gaussian. All parameters in \( W(x, y) \) are determined from simulated Monte Carlo (MC) \( t\bar{t} \) events, tuned to match the resolutions observed in data.

To take account of all individual background processes and to provide a correct statistical sampling of possible spin, flavor, and color configurations, the background probability \( P_{\gamma+2 \text{jets}} \) is calculated using VECBOS [23]. Since \( Z \rightarrow \tau^+\tau^- \) decay is not modeled in VECBOS, an additional transfer function in the \( e\mu \) channel is used to describe the energy of the final state lepton relative to the initial \( \tau \) lepton, and is derived from parton-level information [22]. The direction of the final state lepton is assumed to be close to that of the original \( \tau \) lepton, since only in such cases the lepton from the \( \tau \) decay is sufficiently energetic to pass the jet \( p_T \) selection. For the \( (Z \rightarrow \tau^+\tau^- \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu) \) + 2 jets probability, the energy fractions for final state leptons are sampled according to this \( \tau \) transfer function. Just as for the case of the signal probabilities, the jet and charged-lepton directions are assumed to be well-measured, and each kinematic solution is weighted according to the \( p_T \) of the \( Z + 2 \) jets system. The integration of the probability for \( Z + 2 \) jets is performed over the energies of the two partons that lead to the jets. Both possible assignments of jets to quarks are considered in this analysis.

To calculate the signal and background probability densities, a MC-based integration of Eq. (2) is performed and \( m_t \) is changed in steps of 2.5 GeV over a range of 30 GeV. For each mass hypothesis, a likelihood function \( L_{\text{tot}}(m_t, f_{\text{fit}}) \) is defined by the product of individual event probabilities \( P_{\text{evt}} \), and the signal fraction \( f_{\text{fit}} \) is determined by minimizing \(-\ln L_{\text{tot}}\). Finally, the most likely value of \( m_t \) and its uncertainty are extracted from a fit of \( L_{\text{tot}}(m_t) \) to a Gaussian form near its maximum using the value of \( f_{\text{fit}} \) found in the previous step.

To check for any bias caused by approximations of the method, such as the use of the LO matrix element for \( P_{\text{fit}} \), or from neglecting backgrounds other than \( Z + 2 \) jets, the measurement is calibrated using MC events generated with ALPGEN + PYTHIA. All events are processed through a full GEANT3 [24] detector simulation, followed by the same reconstruction and analysis chain as used for data. Effects from additional \( pp \) interactions are simulated by overlaying data from random \( pp \) crossings over the MC events.

Five \( t\bar{t} \) MC samples are generated with input top quark masses of \( m_t = 165, 170, 172.5, 175, \) and 180 GeV. Probabilities for the \( t\bar{t} \) signal and for \( Z/\gamma^* \rightarrow \ell^+\ell^- \), diboson and instrumental backgrounds, are used to form randomly drawn pseudo-experiments. The total number of events in each pseudo-experiment is fixed to the number of events in data for the combined dilepton channels. The signal and background fractions are fluctuated according to multinomial statistics around the fractions determined from the measured \( t\bar{t} \) cross section in the separate channels [25].

The mean values of \( m_t \) measured in 1,000 pseudo-experiments as a function of the input \( m_t \) are shown in Fig. 1(a). The deviation from the ideal response, where the extracted mass corresponds to the input mass, is caused by the presence of background. For the case of background-free pseudo-experiments, no difference is observed. The width of the distribution of the pulls ("pull width"), defined as the mean deviation of \( m_t \) in single pseudo-experiments from the mean for all 1,000 values at a given input \( m_t \), in units of the measured uncertainty per pseudo-experiment, is shown in Fig. 1(b). The statistical uncertainty measured in data is corrected for the deviation of the pull width from unity. The calibrated value of \( m_t \) from the fit to the data is shown in Fig. 2(a). Figure 2(b) compares the measured uncertainty for \( m_t \) with the distribution of expected uncertainties in pseudo-experiments at \( m_t = 175 \) GeV.

Systematic uncertainties on the measurement of \( m_t \) can be divided into three categories. The first involves uncertainties from modeling of the detector, such as the uncertainty on the energy scale of light-quark jets, the uncertainty in the relative calorimeter response to \( b \) and light-quark jets, as well as in the energy resolution for jets, muons, and electrons. The second category is related to the modeling of \( t\bar{t} \) production. This includes possible differences in the amount of initial and final state radiation, effects from next-to-leading order con-
tions and different hadronization models, color re-
connection, and modeling of $b$-quark fragmentation as
well as uncertainties from choice of PDF. The third
category comprises effects from calibration, such as the un-
certainties in the calibration function shown in Fig. 1(a),
and from variations in signal and background contribu-
tions in the pseudo-experiments. Contributions to the
total systematic uncertainty in the measurement of $m_t$
are summarized in Table I.

The dominant systematic uncertainty in the dilepton
channel is from the difference in detector response be-
tween light and $b$-quark jets that is estimated by propa-
gating the difference in response of single pions in data
and MC to the jet energy scale of jets arising from $b$
quarks. The next important uncertainty arises from un-
certainties in the global jet energy scale of light quarks
(JES). This jet energy scale is calibrated using $\gamma$/jets
data events [26]. It has a total uncertainty of
typically 2% per jet, which translates into an uncertainty
on $m_t$ of 1.5 GeV. The main systematic uncertainty from
modeling $t\bar{t}$ production is from higher-order effects and
hadronization. This uncertainty is evaluated by using
$t\bar{t}$ events generated with MC@NLO [27] and evolved in
HERWIG [28]. The next leading uncertainty on modeling
$t\bar{t}$ arises from the modeling of $b$ quark fragmentation. It
is derived by comparing the extracted $m_t$ for the default
measurement with the result using a re-weighting of the
default MC samples to a Bowler scheme tuned to LEP
or SLD data. [29]. The largest difference is quoted as the
uncertainty.

In summary, we have presented a measurement of
the mass of the top quark in the $t\bar{t} \to W^+bW^\mp \bar{b} \to
\ell^+\ell^-b\bar{b}\nu\bar{\nu}$ channel using the matrix element method.
Based on an integrated luminosity of 5.4 fb$^{-1}$ collected
by the D0 collaboration, the top quark mass is found to be

$$m_t = 174.0 \pm 1.8\text{(stat)} \pm 2.4\text{(syst)} \text{ GeV.} \quad (3)$$

This measurement is in good agreement with the cur-
rent world average $m_t = 173.3 \pm 1.1$ GeV [30]. Its total
uncertainty of 3.1 GeV corresponds to a 1.8 % accuracy,
and represents the most precise measurement of $m_t$ from
dilepton $t\bar{t}$ final states.

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![FIG. 1](image1.png)

FIG. 1: (a) Mean values of $m_t$ and (b) pull width from sets
of 1,000 pseudo-experiments as a function of input $m_t$ for the
combined dilepton channels. The dashed lines represent the
ideal response in (a), where the extracted mass is identical to
the input mass, and in (b), where the statistical uncertainty
requires no correction.

![FIG. 2](image2.png)

FIG. 2: Combined for all channels: (a) Calibrated and nor-
malized likelihood for data as a function of $m_t$ with best es-
timate as well as 68% confidence level region marked by the
shaded area and in (b) the expected distribution of uncertain-
ties with the measured uncertainty indicated by the arrow.
As the top quark mass is measured to be $m_t = 174.0$ GeV,
the expected distribution in (b) is shown for the closest input
mass $m_t = 175$ GeV used in the pseudo-experiment.

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TABLE I: Summary of systematic uncertainties on the measurement of $m_t$ in dilepton events.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detector modeling:</strong></td>
<td></td>
</tr>
<tr>
<td>$b$/light jet response</td>
<td>±1.6</td>
</tr>
<tr>
<td>JES</td>
<td>±1.5</td>
</tr>
<tr>
<td>Jet resolution</td>
<td>±0.3</td>
</tr>
<tr>
<td>Muon resolution</td>
<td>±0.2</td>
</tr>
<tr>
<td>Electron $p_T$ scale</td>
<td>±0.4</td>
</tr>
<tr>
<td>Muon $p_T$ scale</td>
<td>±0.2</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>±0.2</td>
</tr>
<tr>
<td><strong>Signal modeling:</strong></td>
<td></td>
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<tr>
<td>Higher order and hadronization</td>
<td>±0.7</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>±0.1</td>
</tr>
<tr>
<td>$b$-quark modeling</td>
<td>±0.4</td>
</tr>
<tr>
<td>PDF uncertainty</td>
<td>±0.1</td>
</tr>
<tr>
<td><strong>Method:</strong></td>
<td></td>
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<tr>
<td>MC calibration</td>
<td>±0.1</td>
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<tr>
<td>Signal fraction</td>
<td>±0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>±2.4</td>
</tr>
</tbody>
</table>

655, 7 (2009).


[12] The pseudorapidity $\eta$ is defined relative to the center of the detector as $\eta = -\ln[tan(\theta/2)]$ where $\theta$ is the polar angle with respect to the proton beam direction.


[16] Throughout this Letter, charge conjugated processes are included implicitly.


[29] The ALEPH Collaboration, the DELPHI Collaboration, the L3 Collaboration, the OPAL Collaboration, the SLD Collaboration, the LEP Electroweak Working Group, the SLD electroweak, heavy-flavor groups, arXiv:hep-ex/0509008.