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Measurement of the Top Quark Mass in $p\bar{p}$ Collisions using Events with Two Leptons

We present a measurement of the top-quark mass ($m_t$) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using $t\bar{t}$ events with two leptons ($ee$, $e\mu$, or $\mu\mu$) and accompanying jets in 4.3 fb$^{-1}$ of data collected with the D0 detector at the Fermilab Tevatron collider. We analyze the kinematically underconstrained dilepton events by integrating over their neutrino rapidity distributions. We reduce the dominant systematic uncertainties from the calibration of jet energy using a correction obtained from $t\bar{t}$ events with a final state of a single lepton plus jets. We also correct jets in simulated events to replicate the quark flavor dependence of the jet response in data. We measure $m_t = 173.7\pm2.8$ (stat) $\pm 1.5$ (syst) GeV and combining with our analysis in 1 fb$^{-1}$ of preceding data we measure $m_t = 174.0\pm2.4$ (stat) $\pm 1.4$ (syst) GeV. Taking into account statistical and systematic correlations, a combination with the D0 matrix element result from both data sets yields $m_t = 173.9\pm1.9$ (stat) $\pm 1.6$ (syst) GeV.

PACS numbers: 12.15.Ff, 14.65.Ha

The masses of fundamental fermions in the standard model (SM) are generated through their interaction with a hypothesized scalar Higgs field with a strength given by a Yukawa coupling specific to each fermion species. The Yukawa coupling of the top quark corresponds to unity within uncertainties, and this value is constrained by a measurement of the top-quark mass ($m_t$). In direct searches at the LHC for the standard model Higgs boson, both the CMS and ATLAS experiments observe local excesses above the background expectations for a Higgs boson mass ($m_H$) of approximately 125 GeV/c$^2$ [1, 2], decaying to diboson final states. Combined results in searches from the CDF and D0 experiments at the Tevatron show evidence for events above background expectation in $b\bar{b}$ final states [3]. It is therefore important to sharpen the measurement of $m_t$, as its precise value, along with the mass of the $W$ boson ($m_W$), constrain the standard model prediction for $m_H$ through well defined radiative corrections.

In $p\bar{p}$ collisions, top quarks ($t$) are primarily produced in $t\bar{t}$ pairs, with each top quark decaying with $BR(t \rightarrow Wb) \sim 100\%$. These events yield final states with either 0, 1, or 2 leptons from decays of the two $W$ bosons. We consider the dilepton channels ($2\ell$) that contain either electrons or muons of large transverse momentum ($p_T$) and at least two jets. We analyzed such events previously [4, 5] using the neutrino-weighting ($\nu$WT) approach [6]. While the $2\ell$ channels have low background, the small decay branching ratio into leptons means that

\begin{itemize}
  \item[*] with visitors from \(^{4}\)Augustana College, Sioux Falls, SD, USA,
  \(^{5}\)The University of Liverpool, Liverpool, UK, \(^{6}\)UPITA-IPN, Mexico City, Mexico, \(^{7}\)DESY, Hamburg, Germany, \(^{8}\)SLAC, Menlo Park, CA, USA, \(^{9}\)University College London, London, UK, \(^{10}\)Centro de Investigacion en Computacion - IPN, Mexico City, Mexico, \(^{11}\)ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico, and \(^{12}\)Universitat Bern, Bern, Switzerland.
  \item[\^{\dagger}] Deceased.
m_{t}\) measurements from these events remained statistically limited unlike in channels with one lepton and four or more jets (...\ell+\text{jets}). This situation has changed recently (e.g., Ref. [7]). Now, dominant systematic uncertainties from jet energy calibration, which have been larger [4] in the dilepton channel compared to \ell+\text{jets}, are limiting precision of the \m_{t} measurement. In \ell+\text{jets} events, two quarks originate from \(W\) boson decay and yield a dijet mass signature that permits a precise calibration of jet energies for the measurement of \m_{t} in \ttbar events [8]. While this calibration has greatly improved measurements in the \ell+\text{jets} channels, it has not been carried over to the calibration in other analyses. This is primarily due to differences in event topologies that can affect the details of the jet energy scale.

We present a new measurement of \m_{t} using the D0 detector with 4.3 fb\(^{-1}\) of pp collider data in the ee, \(e\mu\), and \(\mu\mu\) final states. We improve the jet energy calibration for the accompanying jets using the energy scale from \ell+\text{jets} events [10]. Our approach differs from that of Ref. [11] in that we do not use the \ell+\text{jets} scale as a constraint in a combined fit of \ell+\text{jets} and dilepton events. Instead, we use this constraint as a calibration, and estimate the uncertainties of transferring that calibration to the dilepton event topology. This procedure demonstrates how the calibration obtained using the dijet constraint from \m_{W} can be applied to different final states, and has wide applicability beyond the measurement of \m_{t} in 2\ell events.

We also employ flavor-dependent corrections to jet energies for the first time in a dilepton analysis that substantially reduce the uncertainties on jet energy resulting from jet flavor. The presented \m_{t} measurement is performed using the same data as Ref. [7], and is correlated with it as discussed below.

The D0 detector [12] is a multipurpose detector operated at the Fermilab Tevatron pp collider. The inner detector consists of coaxial cylinders and disks of silicon microstrips for track and vertex reconstruction. Eight layers of scintillating fibers arranged in doublets surround the silicon microstrip tracker and extend tracking measurements to forward pseudorapidities, \(\eta\) [13]. A 1.9 T solenoid produces a magnetic field for the tracking detectors. Uranium-liquid argon calorimeters surround the tracking volume and perform both electromagnetic and hadronic shower energy measurements. Thin scintillation intercryostat detectors sample showers in the region between the central and end calorimeters. Three layers of proportional drift tubes and scintillation counters reside outside the calorimetry, with 1.8 T toroids that provide muon identification and independent measurement of muon momenta.

We simulate \ttbar events using Monte Carlo (MC) samples for 140 GeV < \m_{t} < 200 GeV using the ALPGEN generator [14] and PYTHIA [15] for parton fragmentation. Backgrounds originate from \(Z/\gamma^{*}\rightarrow 2\ell+\text{jets}\) and \(WW/WWZ/ZZ\rightarrow 2\ell+\text{jets}\) production. For the former, we use ALPGEN combined with PYTHIA, while diboson backgrounds are simulated entirely with PYTHIA. We pass all MC events through a full detector simulation based on GEANT [16]. Backgrounds from instrumental effects that result in misidentified leptons are modeled using data.

We use single and two-lepton triggers to select events for this analysis. Data and simulated events are reconstructed to provide the momenta of tracks, jets, and lepton candidates. Charged and simulated events are reconstructed to provide the momenta of tracks, jets, and lepton candidates. Charged lepton masses are required to be isolated from other calorimeter energy deposits, and to have an associated track in the inner detector. Calorimeter and tracking information are combined to identify electrons. Track parameters in the muon and inner detector system are used to identify muons. We reconstruct jets with an iterative, midpoint cone algorithm with radius \(R_{\text{cone}}=0.5\) [17]. Jets are calibrated with the standard D0 jet energy correction which is derived from data [18]. The method corrects the measured jet energy to the value obtained by applying the reconstruction cone algorithm to particles from jet fragmentation before they interact with the detector. We establish the efficacy of the method in the MC, where we compare the measured jet and the jet reconstructed from fragmentation particles. The jets in data and MC are calibrated independently so that their relative response is close to unity. This corrects for detector response, energy deposited outside of the jet cone, electronics noise, and pileup. The largest correction compensates for the detector response, and is extracted using \(\gamma+\text{jets}\) in data and MC. We also correct jets for the \(p_{T}\) of any embedded muon and that of the associated neutrino. We initially apply this standard calibration [18] because it provides detailed \(p_{T}\) and \(\eta\) dependent corrections. It also provides distinct corrections to jets and the imbalance in event transverse momentum (\(E_{T}\)) because several components (e.g., noise and out-of-cone effects) result from the jet reconstruction algorithm rather than any undetected energy. In the \(p_{T}\) range of jets found in \ttbar events, the uncertainty of the standard D0 jet energy calibration averages 2\%, and is dominated by systematics. Because the flavor dependence of jet energy calibration can yield one of the largest systematic uncertainties on our measurement [4], we have improved our analysis by accounting for this dependence. We use responses of single particles from data and MC to determine the energy scale for different jet flavors. We correct MC jets by the ratio of data response to MC response according to their flavor to ensure that the MC reflects the flavor dependence in data, as in Ref. [10]. We calculate \(E_{T}\) as the negative of the vector sum of all transverse components of calorimeter cell energies and muon track momenta, corrected for the response to electrons and jets.

Events are selected to have two leptons (ee, \(e\mu\), \(\mu\mu\)) and two or more jets. The leptons must have \(p_{T} > 15\) GeV and the jets must have \(p_{T} > 20\) GeV. Electrons and jets are required to satisfy \(|\eta| < 2.5\), while muons must have \(|\eta| < 2\). We further require \(E_{T} > 40\) GeV in the \(\mu\mu\) channel. The \(e\mu\) events must satisfy \(H_{T} > 120\) GeV, where \(H_{T}\) is defined to be the sum of the \(p_{T}\)s of jets and the leading lepton. In \(\mu\mu\) and ee events, we also require \(E_{T}\) to be significantly larger than typical values.
found in the distribution from $Z$ boson events. These 
and all other selections are detailed in Ref. [19]. We 
observe 50, 198, and 84 events with expected background 
yields of 10.4, 28.1, and 31.0 events in the $ee$, $e\mu$, and $\mu\mu$ 
channels, respectively.

In $\ell+\text{jets}$ events, one W boson decays to two quarks 
that fragment to jets. The invariant mass of this jet pair 
can be used to improve the calibration for all jets in these 
events. Complications arise because the four jets in the 
$\ell+\text{jets}$ events can be incorrectly assigned to the initial 
four quarks. Energy from different partons is also mixed 
in the same jet due to a high jet multiplicity. Observed jet 
energies are also affected by color flow effects, which are 
different for the $b$-quark jets and for jets from the decay 
of color singlet W bosons. These attributes are specific 
to a particular event topology such as $\ell+\text{jets}$. Neverthe-
less, a scale factor based on the dijet invariant mass that 
is correlated with $m_W$ can be extracted. The most 
recent analysis of this kind by D0 used 2.6 fb$^{-1}$ of data and 
obtained a calibration factor of $1.013 \pm 0.008$ (stat) [10]. 
The uncertainty of 0.8% is smaller than that of the stan-
dard jet energy correction and will decrease with addi-
tional data. There are additional systematic effects on 
this energy scale that one must account for when ap-
plying it to $b$-quark jets in the $\ell+\text{jets}$ analysis. These 
also affect our analysis, and we similarly evaluate the 
flavor dependence and residual energy scale systematic 
uncertainties directly on the measured $m_t$ to avoid dou-
ble counting. These are quoted in Table II and discussed 
below. Beyond this, we have the possible difference be-
tween $b$-quark jets in dilepton events and $b$-quark jets in 
$\ell+\text{jets}$ events and the effect of using a calibration based 
on a subset of the total data, each of which we discuss 
now in detail.

The event topology is different in $2\ell$ and $\ell+\text{jets}$ events. 
This has prevented significant progress in reducing the 
large standard jet energy scale uncertainties in dilepton 
analyses. To overcome this challenge and carry over the 
$\ell+\text{jets}$ calibration, we must account for the possibility 
that the energy scale of the $b$-quark jets in the two 
channels can differ. We calculate the energy scale, $R^{2\ell}$, for 
$b$-quark jets in the dilepton sample using responses for 
single particles that fall within the reconstructed jet cone. 
This is done by scaling single particle responses in MC 
to reproduce the energy response of jets in data [9], giving 
$R^{2\ell}_{\text{data}}$, and using particle responses from MC, giving 
$R^{2\ell}_{\text{MC}}$. We calculate the ratio of these two responses in the 
dilepton channel and the analogous ratio for $b$-quark jets 
in the $\ell+\text{jets}$ sample. The corresponding double ratio 

\[ R^{2\ell}_{\text{data}}(p_T) = \frac{R^{2\ell}_{\text{data}}(p_T^b)}{R^{2\ell}_{\text{MC}}(p_T^b)}, \]

varies between 1.001 and 1.003 depending on $b$-quark jet 
$p_T$, $p_T^b$. The multiplicity of particles in $b$-quark jets in 
$\ell+\text{jets}$ events at the MC generator level is, after application 
of the offline jet algorithm, a few percent higher than in the dilepton sample, which is a sufficiently large 
difference to account for the observed value of $R^{2\ell}_{\text{data}}$. We 
therefore take 0.3%, the maximum excursion of $R^{2\ell}_{\text{data}}$ from 
unity, as a systematic uncertainty on carrying over the 
$\ell+\text{jets}$ scale to the jets in our dilepton sample. The $\ell+\text{jets}$ 
cale is applied as a direct correction to the standard cal-
ibration.

The jet energy scale calibration obtained in Ref. [10] is 
based on a subset of the data, and we must therefore es-
imate the effect of using the calibration on a larger data 
set. The instantaneous luminosity of the dilepton sample 
is higher on average. We reweight the distribution of 
the number of primary vertices in the $\ell+\text{jets}$ sample to 
match the distribution in the 4.3 fb$^{-1}$ $\ell+\text{jets}$ data and 
recalculate the $\ell+\text{jets}$ energy scale. This produces a neg-
ligible effect. To account for a possible shift in the energy 
scale of the liquid argon calorimeter, we apply a correc-
tion derived from 4.3 fb$^{-1}$ rather than 2.6 fb$^{-1}$, and this 
yields a 0.7% shift in jet energy scale. From these stud-
ies, we obtain a total uncertainty on the $\ell+\text{jets}$ energy 
scale as applied to our analysis as the sum in quadrature 
of the statistical uncertainty (0.8%), $R^{2\ell}_{\text{data}}$ (0.3%), and 
the calorimeter calibration (0.7%). This yields a 1.1% uncer-
tainty for applying the $\ell+\text{jets}$ energy scale.

The consequence of two neutrinos in dilepton events is 
an underconstrained kinematics. We employ the $\nu$WT 
technique to extract $m_t$ [6] due to its weak sensitivity to 
the modeling details of $t\bar{t}$ events. We integrate over the 
$\eta$ distributions predicted for both neutrinos, solve the 
event kinematics, and calculate $E_T$ from the neutrino 
momentum solutions. The expected neutrino $\eta$ distribu-
tion in the dilepton channel is symmetric around $\eta=0$ 
and found to be well-described by a Gaussian distribu-
tion. The width of the distribution decreases gradually 
with increasing $m_t$ (i.e., as the neutrinos become more 
central). Hence, we model the neutrino $\eta$ distributions 
with a Gaussian probability distribution using a width 
parametrized as a linear function of $m_t$. Several more 
sophisticated parametrizations were tested, but provided 
negligible improvement in expected precision in pseudo-
experiments. By comparing the calculated $E_T$ to 
the measured $E_T$ for each event, we calculate a weight for a 
given choice of $m_t$. For each neutrino rapidity sampling, 
we sum the weights calculated from all combinations of 
neutrino momentum solutions and jet assignments. We 
therefore arrive at a distribution of relative weight for a 
range of $m_t$ for each event. We found in Ref. [4] that 
most of the statistical sensitivity to $m_t$ is obtained from 
the first two moments of this weight distribution, the 
mean ($\mu_w$) and RMS ($\sigma_w$). A coarse granularity of our 
sampling of the $\eta$ distribution causes these moments to 
be unstable. To reduce this variation, we have increased 
the sampling for this integration by an order of magni-
tude relative to our previous analysis [4]. This improves 
the expected statistical uncertainty on $m_t$ by 4%. Re-
quiring the integral of this distribution to be nonzero 
excludes events with a measured $E_T$ that is incompatible 
with coming from neutrinos from $t\bar{t}$ decay. This intro-
duces a small inefficiency for the $t\bar{t}$ signal and reduces
the background contamination in the final sample. Our final kinematically reconstructed data sample consists of 49, 190, and 80 events in the ee, eµ, and µµ channels, respectively.

Probability distributions for µw and σw are constructed for background in each channel. Each background component is normalized to its expected event yield. We generate distributions of \( t\bar{t} \) signal probability as a function of µw, σw, and \( m_t \). We use a binning that provides the minimum expected statistical uncertainty, as checked in pseudoexperiments. We perform a binned maximum likelihood fit to the probability distributions, fixing the total signal and background yields expected in our data. The signal is normalized to the cross section calculated for \( t\bar{t} \) production [20], evaluated at \( m_t = 172.5 \) GeV. For all measurements, we obtain a likelihood (L) vs \( m_t \). We fit a parabola to the dependence of \(-\ln L\) vs \( m_t \), and the fitted mass, \( m_t^{\text{fit}} \), is defined as the lowest point of the parabola. Point-to-point fluctuations mean that the initial placement of the window may result in a nonconvergent fit. We therefore iterate the fit around the current fit minimum. This results in a significant improvement in fitting efficiency, particularly in the dimuon channel. The final \(-\ln L\) vs \( m_t \) for data is shown in Fig. 1. The statistical uncertainty for each measurement is taken as the half-width of the parabola at 0.5 units in \(-\ln L\) above the minimum at \( m_t^{\text{fit}} \).

The above procedure is followed for the extraction of \( m_t \) from data and is used to calibrate the result as follows. We construct pseudoexperiments from signal and background MC samples according to their expected yields and allow fluctuations in each such that the total equals the number of observed events. We perform 1000 pseudoexperiments for each channel, and measure \( m_t^{\text{fit}} \) in each. A linear fit of \( m_t^{\text{fit}} \) vs the input \( m_t \) provides a calibration for our method. We also calculate the pull width of the average estimated statistical uncertainty vs the rms of \( m_t^{\text{fit}} \) values. The resulting slopes, offsets, and pull widths are given in Table I. The \( m_t^{\text{fit}} \) and estimated statistical uncertainty are corrected with these parameters. We obtain a calibrated mass measurement for the 4.3 fb\(^{-1}\) sample in the ee, eµ, and µµ channels.

The largest systematic uncertainties are associated with the jet calibration. We change the \( \ell+\)jets energy scale factor by \( \pm 1.1\% \), and perform our analysis to obtain a systematic uncertainty on \( m_t \) of 0.9 GeV. The result of the \( \ell+\)jets analysis is a single scale factor averaged over all jet \( p_T \)s that are utilized in the dijet mass, i.e. dominated by light quark jets from W boson decay. As in Ref. [10], we estimate an uncertainty due to the difference in \( p_T \) distributions of b-quark jets, in our case in dilepton events, vs the calibrating jets from the \( W \rightarrow jj \) sample. To estimate an uncertainty from this difference, we treat the \( p_T \) and \( \eta \) dependence of the uncertainty in the standard jet energy scale as a possible dependence of the residual energy scale following the calibration to \( \ell+\)jets. We calculate the average of the energy scale uncertainty for jets in the \( W \rightarrow jj \) sample. For each jet in the dilepton sample, we apply a shift corresponding to the difference between its uncertainty in energy scale and the \( W \rightarrow jj \) sample’s average uncertainty in energy scale. Propagating this difference through the mass analysis yields a 0.3 GeV uncertainty on \( m_t \).

The flavor-dependent jet energy corrections described earlier provide MC-based mass templates that accurately reflect the data. As in [10], we propagate the uncertainty in these corrections and obtain a systematic uncertainty on \( m_t \) of 0.5 GeV. The uncertainties due to flavor dependence and residual scale together with the uncertainty originating from the carry over of the jet energy scale from the \( \ell+\)jets sample account for the difference between b-quark jets in dilepton events and jets from \( W \rightarrow jj \) in \( \ell+\)jets events.

We evaluate the effect of our uncertainty in modeling initial state radiation (ISR) and final state radiation (FSR) by comparing two Pythia samples having identical values of generated \( m_t \) but different input parameters taken from a CDF study [21] corresponding to an increased or decreased amount of ISR/FSR. Color reconnection uncertainties are estimated by comparing the analysis with Pythia Tune Apro and Pythia Tune ACP using [22]. Higher order QCD evolution is estimated by comparing Alpgen configured with Pythia to MC@NLO with Herwig [23] and this accounts for the uncertainty due to underlying event as well. To estimate sensitivity to uncertainties in the parton distribu-

### Table I. Parameters used to calibrate \( m_t^{\text{fit}} \) in the analysis of ee, eµ, and µµ channels and their combination.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Slope</th>
<th>Offset [GeV]</th>
<th>Pull width</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>0.976 ± 0.014</td>
<td>0.03 ± 0.16</td>
<td>1.01 ± 0.01</td>
</tr>
<tr>
<td>eµ</td>
<td>0.973 ± 0.012</td>
<td>0.43 ± 0.14</td>
<td>1.03 ± 0.01</td>
</tr>
<tr>
<td>µµ</td>
<td>1.038 ± 0.022</td>
<td>0.49 ± 0.23</td>
<td>1.06 ± 0.03</td>
</tr>
</tbody>
</table>

![FIG. 1. -ln L as a function of \( m_t \) for the combined ee, eµ, and µµ channels. A parabolic fit is shown near the minimum value in \( m_t \).](image-url)
TABLE II. Estimated systematic uncertainties on \( m_t \) at the 95% confidence level, obtained by combining the four dilepton channels. The uncertainties are expressed in terms of the difference between the upper and lower limits of the 1.0 fb\(^{-1}\) measurement, which gives \( m_t = 173.9 \pm 13.9 \pm 16 \) GeV after accounting for all systematic effects. The statistical uncertainties are calculated from the 100 new measurements of the signal fraction by shifting the jet energy resolution in MC events to account for the uncertainty in the method that arises from the uncertainties in the fitted resolution functions. We use CTEQ6M, and employ the method described in Ref. [2].

<table>
<thead>
<tr>
<th>Method</th>
<th>Signal fraction</th>
<th>Jet resolution</th>
<th>Jet identification</th>
<th>Electron energy scale</th>
<th>Electron energy resolution</th>
<th>Muon energy scale</th>
<th>Muon energy resolution</th>
<th>Flavor dependence</th>
<th>QCD scale</th>
<th>Residual scale</th>
<th>PDF uncertainty</th>
<th>Overall scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
<td>0.9</td>
</tr>
</tbody>
</table>

We modify the jet energy resolution in MC events to account for the uncertainty in the method that arises from the uncertainties in the fitted resolution functions. We use CTEQ6M, and employ the method described in Ref. [2].

We estimate the uncertainty due to the statistics employed in our templates of the signal and background, and vary their bin contents within their Gaussian uncertainties. With these templates, we evaluate the effect of systematic uncertainties on the extraction of the signal fraction by shifting the jet energy resolution by one standard deviation. We construct 1000 new templates, for both signal and background, and vary their bin contents within their Gaussian uncertainties. With these templates, we evaluate the effect of systematic uncertainties on the extraction of the signal fraction by shifting the jet energy resolution by one standard deviation. We construct 1000 new templates, for both signal and background, and vary their bin contents within their Gaussian uncertainties.
[13] The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$ where $\theta$ is the polar angle relative to the beam axis, defined relative to the center of the detector.