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Top-Quark Mass Measurement from Dilepton Events at CDF II

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We report a measurement of the top-quark mass using events collected by the CDF II detector from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron. We calculate a likelihood function for the top-quark mass in events that are consistent with $t\bar{t} \to \bar{b}\ell^- \bar{\nu}_\ell b \ell'^+ \nu'_\ell$ decays. The likelihood is formed as the convolution of the leading-order matrix element and detector resolution functions. The joint likelihood is the product of likelihoods for each of 33 events collected in 340 pb^{-1} of integrated luminosity, yielding a top-quark mass $M_t = 165.2 \pm 6.1(\text{stat}) \pm 3.4(\text{syst})$ GeV$/c^2$. This first application of a matrix-element technique to $t\bar{t} \to b\ell^+ \nu_\ell \bar{b} \ell'^- \bar{\nu}_{\ell'}$ decays gives the most precise single measurement of M_t in dilepton events. Combined with other CDF run II measurements using dilepton events, we measure $M_t = 167.9 \pm 5.2(\text{stat}) \pm 3.7(\text{syst})$ GeV$/c^2$.

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Precision measurements of the top-quark mass M_t place constraints on the masses of particles to which the top-quark contributes radiative corrections, including the unobserved Higgs boson [1] and particles in extensions to the standard model [2]. At the Tevatron, top quarks are primarily produced in pairs. The dilepton channel, consisting of the decays $t\bar{t} \to \bar{b}\ell^- \bar{\nu}_\ell b \ell'^+ \nu'_\ell$, has a small branching fraction but allows measurements which are less reliant on the calibration of the jet energy scale, the dominant systematic uncertainty, than measurements in channels with hadronic W decays. A discrepancy from other channels could indicate contributions from new processes [3].

The reconstruction of the top-quark mass from dilepton events poses a particular challenge as the two neutrinos from W decays are undetected. Previous measurements in this channel [4,5] using run I data have calculated the mass by making several kinematic assumptions and integrating over the remaining unconstrained quantity. To extract maximum information from the small sample of dilepton events, we adapt a technique pioneered for the analysis of $t\bar{t} \to b\ell\nu_\ell \bar{b}q\bar{q}'$ decays [6–10]. This technique uses the leading-order production cross section and a parametrized description of the jet energy resolution. Making minimal kinematic assumptions and integrating over six unconstrained quantities, we obtain per-event likelihoods in top-quark mass which can be directly multiplied to obtain the joint likelihood from which M_t is determined.

This Letter reports a measurement with data collected by the CDF II detector between March 2002 and August 2004, with an integrated luminosity of 340 pb^{-1}, yielding the most precise single measurement of M_t in dilepton events, with statistical uncertainty approximately half that of run I measurements [4,5]. We also report a combination of this measurement with other recent measurements using CDF run II data in the dilepton channel.

The CDF II detector [11,12] is an azimuthally and forward-backward symmetric apparatus designed to study $p\bar{p}$ collisions at the Fermilab Tevatron. It consists of a magnetic spectrometer surrounded by calorimeters and muon chambers. The charged particle tracking system is immersed in a 1.4 T magnetic field parallel to the p and $\bar{p}$ beams. Calorimeters segmented in η and ϕ surround the tracking system and measure the energies of interacting particles. The electromagnetic and hadronic calorimeters are lead-scintillator and iron-scintillator sampling devices. Drift chambers located outside the central hadron calorimeters detect muons.

The data are collected with lepton triggers that require events to have an electron or muon with $p_T > 18$ GeV$/c$. After off-line reconstruction, we select events with (i) two leptons, each with $p_T > 20$ GeV$/c$, (ii) significant missing energy transverse to the beam direction ($\not\!\!E_T$), and (iii) two jets, each with $E_T > 15$ GeV. The selection is defined as "DIL" in Ref. [13] and was used to measure the cross section in the dilepton channel. These requirements yield 33 events in the sample reported in this Letter.

The probability density for $t\bar{t}$ decays is expressed as $P_s(\mathbf{x}|M_t)$, where M_t is the top-quark pole mass and $\mathbf{x}$ contains the measured lepton and jet momenta. We calculate $P_s(\mathbf{x}|M_t)$ using the theoretical description of the $t\bar{t}$ production process expressed with respect to $\mathbf{x}$, $P_s(\mathbf{x}|M_t) = [1/\sigma(M_t)][d\sigma(M_t)/d\mathbf{x}]$, where $\frac{d\sigma}{d\mathbf{x}}$ is the differential cross section and σ is the total cross section.

To evaluate the probability density, we integrate the leading-order matrix element over quantities which are not directly measured by the detector, i.e., neutrino and quark energies. We assume that lepton momenta are perfectly measured, that quark angles are perfectly measured by the corresponding jets, and that the two most energetic jets correspond to the b quarks from top-quark decay. Quark energies, while not directly measured, are estimated from the observed energies of the corresponding jets. We define the transfer function $W(p, j)$ to be the probability of measuring jet energy j given quark energy p. We approximate $W(p, j)$ as a sum of two Gaussians fitted to the predicted distribution of quark-jet energy difference from $t\bar{t}$ events generated with HERWIG [14] and the CDF II detector simulation [15]. The expression for the probability density at a given mass for a specific event can be written as

$$P_s(\mathbf{x}|M_t) = \frac{1}{\sigma(M_t)} \int d\Phi |\mathcal{M}_{t\bar{t}}(q_i, p_i; M_t)|^2 \prod_{\text{jets}} W(p_i, j_i) f_{\text{PDF}}(q_1) f_{\text{PDF}}(q_2), \tag{1}$$

where the integral is over the momenta of the initial and final state particles, q_1 and q_2 are the incoming momenta, p_i are the outgoing momenta, $f_{\text{PDF}}(q_i)$ are the parton distribution functions (PDFs) [16], and $\mathcal{M}_{t\bar{t}}(q_i, p_i; M_t)$ is the $t\bar{t}$ production and decay matrix element as defined in Refs. [17,18] for the process $q\bar{q} \to t\bar{t} \to b\ell^+\nu_\ell \bar{b}\ell'^- \bar{\nu}_{\ell'}$. While up to 15% of $t\bar{t}$ pairs at the Tevatron are produced by gluon-gluon fusion ($gg \to t\bar{t}$), this term can be excluded from the matrix element with negligible effect on the measurement. The term $1/\sigma(M_t)$ in front of the integral ensures that the normalization condition for the probability density $\int d\mathbf{x} P_s(\mathbf{x}|M_t) = 1$ is satisfied. The effect of assumptions and approximations are measured in Monte Carlo experiments of fully realistic events, described below. Where needed, a correction is taken.

We calculate the probability for the dominant background processes $P_{\text{bg}}(\mathbf{x})$ and form the generalized per-event probability density $P(\mathbf{x}|M_t) = P_s(\mathbf{x}|M_t)p_s(M_t) + P_{\text{bg}_1}(\mathbf{x})p_{\text{bg}_1} + P_{\text{bg}_2}(\mathbf{x})p_{\text{bg}_2} \cdots$, where $p_s(M_t)$ and p_{bg_i} are determined from the expected fractions of signal and background events, respectively (see Table I). The P_{bg} are calculated in analogy to Eq. (1), with the background matrix element evaluated numerically using algorithms adapted from the ALPGEN [19] generator. We calculate the probabilities for backgrounds arising from $Z/\gamma^* \to ee, \mu\mu$ plus associated jets $W+ \geq 3$ jets, where one jet is incorrectly identified as a lepton, and WW plus associated jets. Smaller backgrounds, comprising 11% of the expected background, are not modeled. Application of the background probabilities reduces the expected statistical uncertainty by 15%.

The posterior probability density in top-quark mass is the product of a flat Bayesian prior and the joint likelihood,

TABLE I. Expected numbers of signal and background events for a data sample of integrated luminosity of 340 pb^{-1}. Other backgrounds are negligible; all numbers have an additional correlated 6% error from uncertainty in the sample luminosity.

Source	Events
Expected $t\bar{t}$ ($M_t = 178$ GeV/c^2, $\sigma = 6.1$ pb)	15.9 ± 1.4
Expected background	10.5 ± 1.9
Drell-Yan (Z/γ^*)	5.5 ± 1.3
Misidentified lepton	3.5 ± 1.4
Diboson (WW/WZ)	1.6 ± 0.2
Total expected	26.4 ± 2.3
Run II data	33

a product of the individual event likelihoods. The mass measurement (M_t) is the mean of the posterior probability, and the statistical uncertainty (ΔM_t) is the standard deviation. We calibrate the method using Monte Carlo experiments of signal and background events. Signal events are generated with HERWIG for top-quark masses from 155 to 195 GeV/c^2. Misidentified leptons are modeled using events from the data, while all other backgrounds are generated using ALPGEN ($Z/\gamma^* \to ee, \mu\mu$) or PYTHIA [20] ($Z/\gamma^* \to \tau\tau, WW, WZ, ZZ$) Monte Carlo events. The numbers of signal and background events in each Monte Carlo experiment are chosen according to Poisson distributions with mean values given in Table I. The estimates for $t\bar{t}$ yields take into account the mass dependence of the cross section [21] and acceptance. The response of the method for Monte Carlo experiments with both signal and background is shown in Fig. 1. The response is consistent with a linear dependence on top-quark mass but has a slope that is less than unity due to the incomplete modeling of background contributions. Corrections $M_t \to 177.2 + (M_t - 178.0)/0.84$ and $\Delta M_t \to \Delta M_t/0.84$ are derived from this response and applied to both M_t and ΔM_t measured in data.

Examining the width of the pull distributions in these Monte Carlo experiments, we find that the statistical uncertainty is underestimated by a factor of 1.51, independent of top-quark mass. This results from simplifying assumptions described above, made to ensure the computational tractability of the integrals in Eq. (1). The largest effects are from jets which originate from initial or final state radiation rather than b-quark hadronization, imperfect lepton momentum resolution, imperfect jet angle resolution, and unmodeled backgrounds. Correcting by this factor of 1.51, we estimate the mean statistical uncertainty to be 9.4 GeV/c^2 if $M_t = 178$ GeV/c^2 [22] or 7.8 GeV/c^2 if $M_t = 165$ GeV/c^2.

We apply the method described in this Letter to the 33 candidate events observed in the data. Including all corrections described above, we measure $M_t = 165.2 \pm 6.1(\mathrm{stat})$ GeV/c^2. Figure 2 shows the joint probability density, without systematic uncertainty, for the events in our data set.

The measured statistical uncertainty is consistent with the distribution of statistical uncertainties in Monte Carlo experiments where signal events with $M_t = 165$ GeV/c^2 are chosen according to a Poisson distribution with mean $N_{t\bar{t}} = 21.7$ events. This number of events corresponds to the cross section and acceptance at $M_t = 165$ GeV/c^2. Of

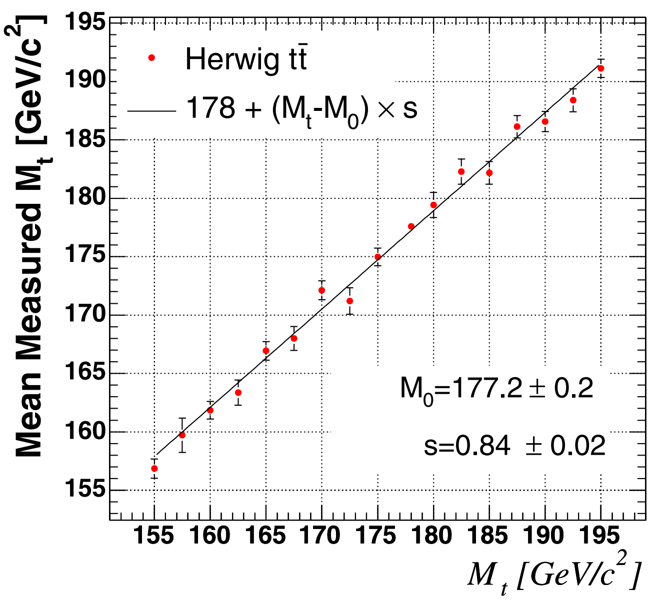

FIG. 1 (color online). Mean measured M_t in Monte Carlo experiments of signal and background events at varying top-quark mass. The solid line is a linear fit to the points.

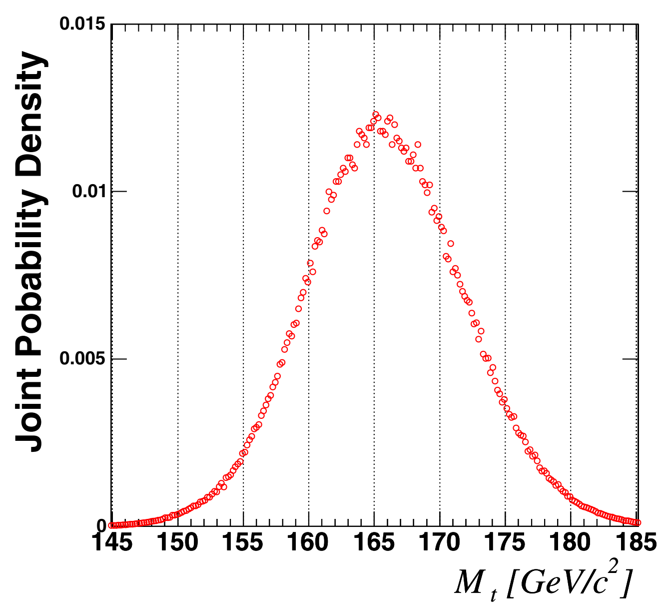

FIG. 2 (color online). Joint posterior probability density as a function of the top-quark mass for the 33 candidate events in data, after all corrections. Systematic uncertainties are not shown.

TABLE II. Summary of systematic uncertainties.

Source	ΔM_t (GeV/c^2)
Jet energy scale	2.6
Limited background statistics	1.2
PDFs	1.0
Generator	0.8
Background modeling	0.8
FSR modeling	0.7
ISR modeling	0.5
Response correction	0.4
Sample composition uncertainty	0.3
Total	3.4

these Monte Carlo experiments, 17% yielded a statistical uncertainty less than 6.1 GeV/c^2.

There are several sources of systematic uncertainty in our measurement which are summarized in Table II. The largest is due to the uncertainty in the jet energy scale [23], which we estimate at 2.6 GeV/c^2 by varying the scale within its uncertainty. An uncertainty of 1.2 GeV/c^2 comes from the limited number of background events available for Monte Carlo experiments. The contribution from uncertainties in the PDFs are estimated by using different PDF sets (CTEQ5L [16] vs MRST72 [24]), different values of $\Lambda_{\rm QCD}$, varying the eigenvectors of the CTEQ6M [16] set, and varying the initial state contributions of gg and $q\bar{q}$; the total corresponding uncertainty added in quadrature is 1.0 GeV/c^2. Dependence on the Monte Carlo generator is estimated as the difference in the extracted top-quark mass from PYTHIA events and HERWIG events; this amounts to 0.8 GeV/c^2. We observe no difference in the extracted top-quark mass in events from a leading-order and a next-to-leading-order generator [25,26]. We estimate the uncertainty coming from modeling of the two largest sources of background, Z/γ^* and events with a misindentified lepton, to be 0.8 GeV/c^2. The uncertainty due to imperfect modeling of initial state (ISR) and final state (FSR) QCD radiation is estimated by varying the amount of ISR and FSR in simulated events [27] and is measured to be 0.7 GeV/c^2 for FSR and 0.5 GeV/c^2 for ISR. The uncertainty in the mass due to uncertainties in the response correction shown in Fig. 1 is 0.4 GeV/c^2. The contribution from uncertainties in background composition is estimated by varying the background estimates from Table I within their uncertainties and amounts to 0.3 GeV/c^2. Adding all of these contributions together in quadrature yields a total systematic uncertainty of 3.4 GeV/c^2.

Applications of other dilepton techniques (referred to as "NWA," "KIN," and "PHI" in Ref. [28]) using the same CDF run II data yield values consistent with this result. The four results are combined using a standard method [29]. We determine statistical correlations between the measurements using Monte Carlo experiments and assume systematic uncertainties to be 100% correlated except the few that are method-specific, which are assumed to be uncorrelated. Table III gives the four dilepton measurements, their statistical correlations, and their weight in the combination. The NWA method uses looser event selection and thus has a smaller statistical correlation. Correlations significantly less than unity suggest that each method extracts unique information.

TABLE III. Measurements of M_t in the dilepton channel with statistical and systematic errors, their statistical correlations, and the weight of each measurement in the combined result.

Method	Result (GeV/c^2)	Correlation matrix				Weight
This Letter	$165.2^{+6.1}_{-6.1} \pm 3.4$	1				0.47
NWA [28]	$170.7^{+6.9}_{-6.5} \pm 4.6$	0.12	1			0.36
KIN [28]	$169.5^{+7.7}_{-7.2} \pm 4.0$	0.40	0.14	1		0.18
PHI [28]	$169.7^{+8.9}_{-9.0} \pm 4.0$	0.43	0.25	0.35	1	0.00

Combining the four CDF run II dilepton measurements, we obtain

$$M_t = 167.9 \pm 5.2(\text{stat}) \pm 3.7(\text{syst})\ \text{GeV}/c^2.$$

This combined result is consistent with the current world average [30] and the single most precise measurement in the lepton + jets channel [31].

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