Measurement of the top quark mass in the dilepton channel

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We present a measurement of the top quark mass in the dilepton channel based on approximately 370 pb^{-1} of data collected by the DØ experiment during Run II of the Fermilab Tevatron collider. We employ two different methods to extract the top quark mass. We show that both methods yield consistent results using ensemble tests of events generated with the DØ Monte Carlo simulation. We combine the results from the two methods to obtain a top quark mass $m_t = 178.1 \pm 8.2$ GeV. The statistical uncertainty is 6.7 GeV and the systematic uncertainty is 4.8 GeV.

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The top quark mass is an important parameter in standard model [1] predictions. For example, loops involving top quarks provide the dominant radiative corrections to the value of the W boson mass. Precise measurements of the W boson and top quark masses provide a constraint on the Higgs boson mass [2].

At the Tevatron, top and antitop quarks are predominantly pair-produced. Top quarks decay to a W boson and a b quark. If the W bosons from the top and the antitop quarks both decay leptonically (to $e\nu$ or $\mu\nu$) the final state consists of two charged leptons, missing transverse momentum ($\not\!\!p_T$) from the undetected neutrinos, and two jets from the fragmentation of the b quarks. We call this the dilepton channel. It has a relatively small branching fraction ($\approx 5\%$) but very low backgrounds. The measurement of the top quark mass in the dilepton channel is statistically limited. It provides an independent measurement of the top quark mass that can be compared with measurements in other $t\bar{t}$ decay channels, and a consistency check on the $t\bar{t}$ hypothesis in the dilepton channel.

The DØ detector is a multipurpose collider detector [3]. The central tracker employs silicon microstrips close to the beam and concentric cylinders covered with scintillating fibers in a 2 T axial magnetic field. The liquid-argon/uranium calorimeter is divided into a central section covering $|\eta| \leq 1.1$ and two endcap calorimeters extending coverage to $|\eta| \leq 4.2$ [4], where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the proton beam direction. The muon spectrometer consists of a layer of tracking detectors and scintillation trigger counters between the calorimeter and 1.8 T toroidal iron magnets, followed by two similar layers outside the toroids.

The event selection was developed for measurements of the cross section for $t\bar{t}$-production in the dilepton channel. The analyses use about 370 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV collected with the DØ detector at the Fermilab Tevatron collider. All jets were corrected using the standard DØ jet energy scale corrections.

We select events with two isolated leptons (e or μ) with transverse momentum $p_T > 15$ GeV and at least two jets with $p_T > 20$ GeV. We distinguish $e\mu$, ee, and $\mu\mu$ events. For $e\mu$ events we require $H_T > 122$ GeV, where H_T is the scalar sum of the larger of the two lepton p_T values and the p_T values of the leading two jets. For ee events we require sphericity [5] $S > 0.15$ and missing transverse momentum $\not\!\!p_T > 35$–40 GeV, depending on the dielectron invariant mass $m(ee)$, and we reject events with $80 < m(ee) < 100$ GeV to reduce the background from $Z \to ee$ decays. For $\mu\mu$ events we require inconsistency with the $Z \to \mu\mu$ hypothesis based on the χ^2 of a kinematic fit, $\Delta\phi(\not\!\!p_T, \mu) < 175°$, and $\not\!\!p_T > 35$ GeV. We tighten the $\not\!\!p_T$ requirement if the leading muon and the $\not\!\!p_T$ are approximately collinear in the transverse direction.

For our mass measurements we use the following samples of events. The "b-tag" sample consists of events that have at least one jet that contains a secondary vertex tag with transverse decay length significance $\Lambda_{xy} > 7$ [6]. This sample has very low backgrounds. The "no-tag" sample consists of events that have no such secondary vertex tags. The 26 events in these two samples consist of 20 $e\mu$ events, 5 ee, and 1 $\mu\mu$ event. The "tight" sample does not use the b-tagging information. It contains all ee and $\mu\mu$ events that are in either the b-tag or the no-tag samples. For $e\mu$ events the tight sample requires more restrictive H_T, $\not\!\!p_T$, and electron selection cuts to reduce backgrounds.

To increase the acceptance for dilepton decays, we also analyze a sample of events that requires only one well-identified lepton (e or μ) with $p_T > 15$ GeV and an isolated track with $p_T > 15$ GeV instead of the second identified lepton. The events must also have at least two jets with $p_T > 20$ GeV, at least one jet with a secondary vertex tag, and $\not\!\!p_T > 15$–35 GeV, depending on lepton flavor and the invariant mass of the lepton+track system. We call this the ℓ+track sample. Events with two well-identified leptons are vetoed from this sample so that there is no overlap between the ℓ+track sample and the other dilepton samples. There are 9 e+track events and 6 μ+track events in this sample. The expected and observed event yields for each of the data samples are listed in Table I.

TABLE I: Expected and observed dilepton event yields for $t\bar{t}$ production with $m_t = 175$ GeV and the backgrounds from WW and Z production based on Monte Carlo, and from misidentified leptons (mis-id) based on collider data.

Sample	$t\bar{t}$	WW	Z	Mis-id	Total	Data
$\ell\ell$ no-tag	7.2	1.1	2.6	2.2	$13.2^{+2.8}_{-2.1}$	12
$\ell\ell$ b-tag	9.9	0.05	0.12	0.09	10.1 ± 0.9	14
$\ell\ell$ tight	15.8	1.1	2.4	0.5	19.8 ± 0.6	21
ℓ+track	11.3	0.02	4.4	0.4	16.2 ± 1.1	15

Monte Carlo samples are generated for nineteen values of the top quark mass between 120 and 230 GeV. The simulation uses ALPGEN [7] with CTEQ5L parton distribution functions [10] as the event generator, PYTHIA [8] for fragmentation and decay, and GEANT [9] for the detector simulation. The energy of Monte Carlo jets is increased by 3.4% in addition to the nominal jet energy scale corrections. This factor was determined by fitting top mass and jet energy scale in lepton+jets events and brings the invariant mass distribution of the two jets from the W boson decay in lepton+jets MC events in agreement with that observed in the data.

We use only the two jets with the highest p_T in this analysis. We assign these two jets to the b and $\bar{b}$ quarks from the decay of the t and $\bar{t}$ quarks. If we assume a value m_t for the top quark mass, we can determine the pairs of t and $\bar{t}$ momenta that are consistent with the observed lepton and jet momenta and $\not\!\!p_T$. We call a pair of top-antitop quark momenta that is consistent with the observed event a solution. For each assignment of ob-

served momenta to the final state particles and for each hypothesized value of m_t, there may be up to four solutions. We assign a weight function $w(m_t)$ to each solution, as described below. We reject two events for which no solution exists for any value of m_t.

We consider each of the two possible assignments of the two jets to the b and $\overline{b}$ quarks. We account for detector resolutions by repeating the weight calculation with input values for the lepton and jet momenta that are drawn from the detector resolution functions for objects with the observed momenta. We refer to this procedure as resolution sampling. For each event we obtain a weight $W(m_t) = 1/N \times \sum_{j=1}^{N} \sum_{i=1}^{n} w(m_t)_{ij}$ by summing over all n solutions and averaging over N resolution samples. This weight characterizes the likelihood that the event is produced in the decay of a $t\overline{t}$ pair as a function of m_t.

The techniques we use are similar to those used by the DØ Collaboration to measure the top quark mass in the dilepton channel using Run I data [11]. The data are analyzed using two different methods that differ in the event samples that they are based on, in the calculation of the event weight, and in the algorithm that compares the weights for the observed events to Monte Carlo predictions to extract the top quark mass.

The matrix-element weighting technique ($\mathcal{M}$WT) follows the ideas proposed by Dalitz and Goldstein [12] and Kondo [13]. The solution weight is

$$w(m_t) = f(x)f(\overline{x})p(E_\ell^*|m_t)p(E_{\overline{\ell}}^*|m_t),$$

where $f(x)$ is the parton distribution function of the proton and x ($\overline{x}$) is the momentum fraction carried by the initial (anti)quark. The quantity $p(E_\ell^*|m_t)$ is the probability that the lepton has energy E_ℓ^* in the top quark rest frame for the hypothesized top quark mass m_t.

For each event we use the value of the hypothesized top quark mass $m_{\rm peak}$ at which $W(m_t)$ reaches its maximum as the estimator for the mass of the top quark. We generate probability density functions of $m_{\rm peak}$ for a range of top quark masses using Monte Carlo simulations. We call these distributions templates. To compute the contribution of backgrounds to the templates, we use $Z \to \tau\tau$ and WW events generated with the full DØ Monte Carlo. Backgrounds arising from detector signals that are misidentified as electrons or muons are estimated from collider data samples.

We compare the distribution of $m_{\rm peak}$ for the observed events to these templates using a binned maximum likelihood fit. The likelihood is calculated as

$$L(m_t) = \prod_{i=1}^{n_{\rm bin}} \left[\frac{n_s s_i(m_t) + n_b b_i}{n_s + n_b} \right]^{n_i},$$

where n_i is the number of data events observed in bin i, $s_i(m_t)$ is the normalized signal template contents for bin i at top quark mass m_t, b_i is the normalized background template contents for bin i. The product runs over all $n_{\rm bin}$ bins. The background template consists of events from all background sources added in the expected relative proportions. The signal-to-background fraction is fixed to n_s/n_b with the numbers of signal and background events (n_s, n_b) taken from Table I.

To calibrate the performance of our method, we generate a large number of simulated experiments for several input top quark mass values. We refer to each of these experiments as an ensemble. Each ensemble consists of as many events of each type as we have in our collider data sample. A given event is taken from the signal and background samples with probabilities that correspond to the fraction of events expected from each sample. We use a quadratic function of m_t to fit the $-\ln L$ points to thirteen mass points centered on the point with the smallest value of $-\ln L$. The distribution of measured top quark mass values from the ensemble fits gives an estimate of the parent distribution of our measurement. The ensemble test results indicate that the measured mass tracks the input mass with an offset of 1.9 ± 0.8 GeV, which we correct for in the final result.

The $\mathcal{M}$WT analysis uses the no-tag and b-tag samples of events. Separating out the very-low-background b-tagged events improves the precision of the result. The analysis is performed with separate templates for ee, $e\mu$, and $\mu\mu$ events and separate signal-to-background fractions for events without a b-tag and ≥ 1 b-tags. The maximum of the joint likelihood for all events, shown in Fig. 1, corresponds to $m_t = 176.2 \pm 9.2$(stat) GeV after the offset correction. Figure 2 shows the distribution of $m_{\rm peak}$ from collider data compared to the sum of Monte Carlo templates with $m_t = 180$ GeV.

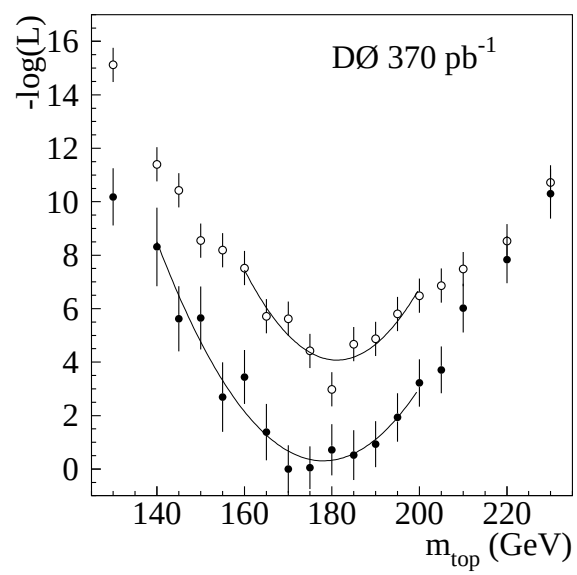

FIG. 1: Joint likelihoods from the $\mathcal{M}$WT analysis (closed circles) and the νWT analysis (open circles). The minima of the likelihood curves do not include the correction for the offset in the response.

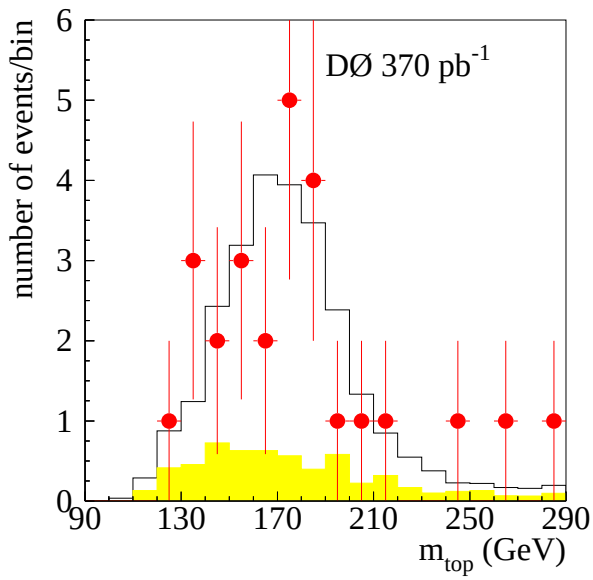

FIG. 2: Distribution of $m_{\rm peak}$ from the $\mathcal{M}$WT analysis (circles) compared to the sum of Monte Carlo templates for the no-tag and b-tag channels and all lepton flavors for $m_t = 180$ GeV (open histogram). The shaded histogram indicates the background contribution.

The neutrino weighting technique (νWT) ignores the measured $\not\!\!p_T$ in reconstructing the event. Instead we assume a representative range of values for the pseudorapidities of the two neutrinos and the solution weight

$$w(m_t) = \frac{1}{N_\eta}\sum_{i=1}^{N_\eta} \exp\left[\frac{-(\not\!\!p_{x_i} - \not\!\!p_x)^2}{2\sigma_x^2}\right] \exp\left[\frac{-(\not\!\!p_{y_i} - \not\!\!p_y)^2}{2\sigma_y^2}\right]$$

characterizes the consistency of the resulting solutions with the observed $\not\!\!p_T$. The sum is over the N_η steps of neutrino rapidity values, $\not\!\!p_{x_i}$ and $\not\!\!p_{y_i}$ are the x and y components of the sum of the neutrino momenta computed for step i, and σ_x and σ_y are the measurement resolutions for $\not\!\!p_x$ and $\not\!\!p_y$. We then normalize the event weight $W(m_t)$ over the range $80 < m_t < 330$ GeV and integrate it over ten bins in m_t. Every event is thus characterized by a 9-component vector $\overrightarrow{W} = (W_1, ..., W_9)$ (the 10th bin is fixed by the first nine and the normalization condition). We compare the vectors from the collider data events to sets of N Monte Carlo events generated with different values of m_t by computing the signal probability

$$f_s(\overrightarrow{W}|m_t) = \frac{1}{N}\sum_{j=1}^{N}\prod_{i=1}^{9} \frac{\exp[-(W_i - W_{ij}^{MC})^2/2h^2]}{\int_0^1 \exp[-(W' - W_{ij}^{MC})^2/2h^2]dW'},$$

where $\overrightarrow{W}_j^{MC}$ is the vector of weights from Monte Carlo event j. The resolution parameter h is optimized using Monte Carlo studies. We compute a similar probability $f_b(\overrightarrow{W})$ for backgrounds and combine them in the likelihood

$$L(m_t, \overline{n}_b, n) = G(n_b - \overline{n}_b, \sigma)P(n_s + n_b, n) \times \prod_{i=1}^{n}\left[\frac{n_s f_s(\overrightarrow{W}_i|m_t) + n_b f_b(\overrightarrow{W}_i)}{n_s + n_b}\right],$$

which we optimize with respect to m_t, the number of signal events n_s, and the number of background events n_b. G is a gaussian constraint on the difference between n_b and the expected number of background events $\overline{n}_b$, and P is a Poisson constraint on $n_s + n_b$ to the number of events n observed in data.

The νWT analysis uses the tight sample and the ℓ+track sample. The analysis is performed with separate templates for ee, $e\mu$, and $\mu\mu$ events in the tight sample and the two lepton flavors in the ℓ+track sample. We fit the $-\ln L$ points for values of m_t within 20 GeV of the point with the smallest value of $-\ln L$ with a quadratic function of m_t. The performance of the νWT algorithm is checked using ensemble tests as described for the $\mathcal{M}$WT algorithm. The average measured values of m_t track the input values with an offset of 1.7 ± 0.2 GeV. For the νWT analysis, the maximum of the joint likelihood of all events (Fig. 1) corresponds to $m_t = 179.5 \pm 7.4$(stat) GeV after the offset correction.

We also use ensemble tests to study the size of systematic uncertainties (see Table II). For example we determine the effect of the uncertainty in the calibration of the jet energy scale of 4.1% by generating ensemble tests with the jet energy scale increased and decreased by one standard deviation. We follow the method for combining correlated measurements from Ref. [14] in combining the results from the $\mathcal{M}$WT and νWT analyses. We determine the statistical correlation between the two measurements using ensemble tests. The correlation factor between the two analyses is 0.35. The systematic uncertainties from each source in Table II are taken to be completely correlated between the two analyses. The results of the combination are also listed in Table II.

TABLE II: Summary of dilepton mass measurements.

	$\mathcal{M}$WT	νWT	Combined
Top quark mass	176.2	179.5	178.1 GeV
Statistical uncertainty	9.2	7.4	6.7 GeV
Systematic uncertainty	3.9	5.6	4.8 GeV
Jet energy scale	3.6	4.8	4.3 GeV
Parton distribution functions	0.9	0.7	0.8 GeV
Gluon radiation	0.8	2.0	1.5 GeV
Background	0.2	1.4	0.9 GeV
Heavy flavor content	—	0.6	0.3 GeV
Monte Carlo statistics	0.8	1.0	0.9 GeV
Jet resolution	—	0.6	0.3 GeV
Muon resolution	—	0.4	0.2 GeV
Total uncertainty	10.0	9.3	8.2 GeV

In conclusion, we measure the top quark mass in the dilepton channel. We obtain $m_t = 178.1 \pm 6.7$(stat) $\pm$

4.8(syst) GeV as our best estimate of the top quark mass. This is in good agreement with the world average $m_t = 172.5 \pm 2.3$ GeV [15], based on Run I and Run II data collected by the CDF and DØ Collaborations.

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