New Measurement of the Top Quark Mass in Lepton+Jets $t\bar{t}$ Events at DØ

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We present a new measurement of the mass of the top quark using lepton + jets $t\bar{t}$ events collected by the DØ experiment in Run I of the Fermilab Tevatron Collider. The mass is extracted through a comparison of each event with a leading-order matrix element that depends on the top quark mass.

The result is $M_t = 180.1 \pm 3.6 \text{ (stat)} \pm 3.9 \text{ (sys)} \text{ GeV}/c^2$. Combining this improved measurement with our previous value from dilepton channels yields the new DØ result $M_t = 179.0 \pm 3.5 \text{ (stat)} \pm 3.8 \text{ (sys)} \text{ GeV}/c^2$.

The observation of the top ($t$) quark \cite{1,2} was one of the major confirmations of the validity of the standard
model (SM) of particle interactions. Through radiative corrections of the SM, the mass of the top quark \( M_t \), along with that of the \( W \) boson \( M_W \), constrains the mass of the hypothesized Higgs boson \( M_H \). \( M_W \) is known to a precision of < 0.1%, while the uncertainty on \( M_t \) is at the 3% level. Improvements in both measurements are required to further limit the mass range of the Higgs boson, and to check the self-consistency of the SM. It is therefore important to develop techniques for extracting a more precise value of \( M_t \).

We report a new measurement of the mass of the top quark using \( t\bar{t} \) events containing an isolated lepton and four jets, collected by the DØ experiment in Run I of the Fermilab Tevatron Collider. The data correspond to an integrated luminosity of 125 pb\(^{-1}\), and this analysis is based on the same data sample used to extract \( M_t \) in a previous publication.

As before, we assume that the top quark decays 100% of the time to a \( W^+ \) boson and a \( b \) quark, which for a \( t\bar{t} \) pair implies \( W^+W^-bb \) in the final state. This analysis is based on decay channels containing a lepton (electron or muon from one \( W \to \ell\nu \) decay) and jets (from the evolution of the \( b \) quarks and the quarks from the other \( W \to q\bar{q} \) decay) in the final state. After offline selections on lepton transverse energy \( (E_T^{lep} > 20 \text{ GeV}) \) and pseudorapidities \( (|\eta_\ell| < 1.7 \text{ for muons and }|\eta_\ell| < 2.0 \text{ for electrons}) \), on jet transverse energies \( (E_T > 15 \text{ GeV}) \) and pseudorapidities \( (|\eta| < 2.0) \), and on the top quark was assumed to be identical for the top and antitop quarks in the event. With twelve ways to permute the jets, there were twelve possible fits (six when one of the jets was tagged as a \( b \) jet), and the solution with lowest \( \chi^2 \) was chosen as the best hypothesis, thereby defining the fitted mass \( m_{fit} \) for the event. The same procedure was used to generate templates in variables of interest as a function of input top quark mass. This was based on the HERWIG Monte Carlo (MC) program, which was used to generate events that passed through full detector simulation and event reconstruction. Background events, consisting mainly of multijets (20%) and \( W+jets \) (80%) production, were processed in a similar manner. The background from multijet production was based on studies of multijet events in data, and the background from \( W+jets \) events was based on events generated with VECBOS. A four-variable discriminant \( (D) \) defined the probability that an event represented signal as opposed to background. A probability density was defined as a function of the discriminant \( D \) and \( m_{fit} \), and a comparison of data and MC via a likelihood was used to determine the most likely mass of the top quark. The resulting measurement is \( M_t = 173.3 \pm 5.6 \text{ (stat) } \pm 5.5 \text{ (sys) GeV/c}^2 \).

The new method is similar to that suggested for \( t\bar{t} \) dilepton decay channels, and used in a previous mass analyses of dilepton events. A similar approach has also been suggested for the measurement of the mass of the \( W \) boson at LEP. Given \( N \) events, the top quark mass is estimated by maximizing the likelihood:

\[
L(\alpha) = e^{-N} \int P_m(x, \alpha) dx \prod_{i=1}^{N} P_m(x_i, \alpha)
\]

where \( x_i \) is a set of variables needed to specify the \( i \)th measured event, \( P_m \) is the probability density for observing that event, and \( \alpha \) represents the parameters to be determined (in this case \( \alpha \) is the mass of the top quark). Detector and reconstruction effects are taken into account in two ways. Geometric acceptance, trigger efficiencies, and event selection enter through a multiplicative function \( A(x) \) that is independent of \( \alpha \) and relates the observed probability density \( P_m(x, \alpha) \) to the production probability \( P(x, \alpha) : P_m(x, \alpha) = A(x)P(x, \alpha) \). Energy resolution and merging and splitting of jets are taken into account in a “transfer” function, \( W(y, x) \), discussed below. The production probability density can be written as a convolution of the calculable cross section and \( W(y, x) \):

\[
P(x, \alpha) = \frac{1}{\sigma(\alpha)} \int \sigma(y, \alpha) dq_1 dq_2 f(q_1) f(q_2) W(y, x)
\]

where \( W(y, x) \), our general transfer function, is the normalized probability density that the measured set of variables \( x \) arise from a set of partonic variables \( y \), \( \sigma(y, \alpha) \) is the partonic differential cross section, and \( f(q_i) \) are parton distribution functions for the incoming partons with longitudinal momenta \( q_i \). Dividing by \( \sigma(\alpha) \), the total cross section for the process, ensures that \( P(x, \alpha) \) is properly normalized. The integral in Eq. (1) sums over all possible parton states leading to what is observed in the detector.

For the \( t\bar{t} \) production probability, the measured angles of the jets and of the charged lepton are assumed to be the angles of the partons in the final state. Given the detector resolutions the electron energy is assumed to be exact, and the muon energy is described by its known resolution. Evaluation of Eq. (2) for the \( e+jets \) channel involves two incident parton energies (we take these
partons to be quarks, and ignore the ≈10% contribution from gluon fusion), and six objects in the final state. The integrations over the essentially fifteen sharp variables (three components of electron momentum, eight jet angles, and four equations of energy-momentum conservation), leave five integrals that must be performed to obtain the probability that any event represents $t\bar{t}$ production for some specified value of top quark mass $M_t$:

$$P_{t\bar{t}} = \frac{1}{120|\rho_1|} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \times \sum_{\text{perm.},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f(q_1) f(q_2)}{|q_1||q_2|} \Phi_0 W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$$

For $|\mathcal{M}_{t\bar{t}}|^2$, we use the leading-order matrix element $\frac{1}{|\sin\theta W^2|^2}$, $f(q_1)$ and $f(q_2)$ are CTEQ4M parton distribution functions for the incident quarks $q_1$, $q_2$, $\Phi_0$ is the phase-space factor for the six-object final state, and the sum is over all twelve permutations of the jets (the permutation of the jets from W boson decay was performed by symmetrizing the matrix element), and the up-to-eight possible neutrino solutions. Conservation of transverse momentum is used to calculate the transverse momentum of the neutrino. $W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$ is the part of $W(y, x)$ that refers to the mapping between parton-level energies $E_{\text{part}}$ and energies measured in the detector $E_{\text{jet}}$. Four of the variables chosen for integration ($m_1$, $M_1$, $m_2$ and $M_2$), namely the masses of the $W$ bosons and of the top quarks in the event, are economical in computing time, because the value of $|\mathcal{M}_{t\bar{t}}|^2$ is essentially negligible except at the peaks of the four Breit-Wigner terms in the matrix element. $\rho_1$ is the energy of one of the quarks in the hadronic decay of one of the $W$ bosons. The narrow-width approximation is used to integrate over the top quark masses, and Gaussian adaptive quadrature $\int_1$ is used to perform the three remaining integrals. $W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$ is the product of four functions $F(E_{\text{part}}, E_{\text{jet}})$, one for each jet, with a functional form of the sum of two Gaussians, with parameters having linear dependence on $E_{\text{part}}$. The parameters used for $b$ quarks are different from those for the lighter quarks, and there are therefore twenty jet energy parameters in all. About 15,000 simulated $t\bar{t}$ events (generated with masses between 140 and 200 GeV/$c^2$ in HERWIG, and processed through detector simulation) are used to determine the above twenty parameters. For a final state with a muon, $W_{\text{jets}}$ is expanded to include the muon momentum resolution, and an integration over muon momentum is included in Eq. (3).

The $W+4$ jets matrix element from VECBOS is used in Eq. (2) to calculate the background probability $P_{\text{bkg}}$. The integration is performed over the energy of the four partons leading to jets and the $W$-boson mass. The probability is summed over the twenty-four jet permutations and two neutrino solutions. The integration over parton energies is performed using MC techniques, increasing the number of random points until the integral converges.

(MC studies show that the 20% background from multijet events is represented satisfactorily by that for $W$+jets.)

After adding the probabilities for the non-interfering $t\bar{t}$ and $W$+4 jets channels, the final likelihood as a function of $M_t$ is written as:

$$-\ln L(\alpha) = -\sum_{i=1}^{N} \ln[c_1 P_{t\bar{t}}(x_i, \alpha) + c_2 P_{\text{bkg}}(x_i)] + Nc_1 \int A(x) P_{t\bar{t}}(x, \alpha) dx + Nc_2 \int A(x) P_{\text{bkg}}(x) dx$$

The above integrals are calculated using MC methods, for which the acceptance $A(x)$ is 1.0 or 0.0, depending on whether the event is accepted or rejected by the analysis criteria. The best values of $\alpha$, representing the most likely $M_t$, and the parameters $c_i$ are defined by minimizing $-\ln L(\alpha)$.

Studies of samples of HERWIG MC events used in the previous analysis indicate that the new method should yield almost a factor of two reduction in the statistical uncertainty on the extracted $M_t$. These studies also reveal that there is a systematic shift in $M_t$ that depends on the amount of background in the data sample. For high statistics, the shift is about 2 GeV/$c^2$ when the background approaches 80% of total. To minimize this bias, a selection is introduced based on the probability that an event represents background from $W$+jets. Figure H(a) shows a comparison between the probability for a back-
Figure 2: (a) Negative of the log of the likelihood as a function of the top quark mass. (b) The likelihood normalized to its maximum value in plot (a). The curve is a Gaussian fit to the likelihood plot. The hatched area corresponds to the 68.27% probability interval.

Figure 3: Mass of the top quark as a function of the cutoff in background probability. The number of remaining events is shown above each point. The point with the larger dot is the value used in this analysis.

A discriminant $D = P_{t\bar{t}}/(P_{t\bar{t}} + P_{\text{bkg}})$ was defined to quantify the likelihood for an event to correspond to signal. $D$ was calculated with the signal probability taken at its maximum value. The Gaussian fit in the figure yields $M_t = 179.6 \text{ GeV}/c^2$, with an uncertainty $\delta M_t = 3.6 \text{ GeV}/c^2$. MC studies show that [17]: (i) $\delta M_t$ is compatible with the uncertainties obtained in MC ensemble tests, and (ii) there is a shift of $-0.5 \text{ GeV}/c^2$ in the extracted mass. After applying the 0.5 GeV/$c^2$ correction, our new value of the top quark mass is $M_t = 180.1 \pm 3.6 \text{ (stat) GeV}/c^2$. As Fig. 1(a) indicates, the cutoff chosen in $P_{\text{bkg}}$ does not reduce significantly the number of $t\bar{t}$ events, and therefore $M_t$ should be stable relative to variations in this cutoff. Figure 3 shows that a change in the cutoff in $P_{\text{bkg}}$ by more than an order of magnitude changes the number of events used in the analysis by more than a factor of two, but, as expected, does not have a significant impact on $M_t$.

In conclusion, we have presented a new measurement of the mass of the top quark using a method that compares each individual event with the expected differential cross section for $t\bar{t}$ production and decay. We obtain a sig-
Combining the two uncertainties in quadrature, we obtain an improved systematic uncertainty. The new result is:

\[ M_t = 180.1 \pm 3.6 \text{ (stat)} \pm 3.9 \text{ (sys)} \text{ GeV}/c^2 \]

Combining the two uncertainties in quadrature, we obtain \( M_t = 180.1 \pm 5.3 \text{ GeV}/c^2 \), which has an uncertainty comparable to all the previous measurements of DØ and CDF combined.

Using the procedure described in Ref. [15], the new measurement can be combined with that obtained using the dilepton sample collected at DØ during Run I [11], yielding the new DØ value for the mass of the top quark:

\[ M_t = 179.0 \pm 3.5 \text{ (stat)} \pm 3.8 \text{ (sys)} \text{ GeV}/c^2 \]

This is the most accurate measurement of the top quark mass in any single experiment. The impact of the new DØ top-quark mass measurement on the world average top-quark mass as well as on Higgs and supersymmetry constraints is a subject of a separate recent publication [19].

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