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

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Abstract

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

The observation of the top (t) quark [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) [3] , constrains the mass of the hypothesized Higgs boson [4]. M_W is known to a precision of $< 0.1\%$, while the uncertainty on M_t is at the 3% level [3]. 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 [5] 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 [6].

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 $W^+W^-b\bar{b}$ in the final state. This analysis is based on decay channels containing a lepton (electron or muon from one $W \to l\nu_l$ 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 [6]. After offline selections on lepton transverse energy ($E_T^{lep} > 20$ GeV) and pseudorapidities ($|\eta_\mu| < 1.7$ for muons and $|\eta_e| < 2.0$ for electrons), on jet transverse energies ($E_T > 15$ GeV) and pseudorapidities ($|\eta| < 2.0$), imbalance in transverse energy ($\not\!\!E_T > 20$ GeV), and on W boson decay products ($E_T^{lep}+\not\!\!E_T > 60$ GeV) and pseudorapidity ($|\eta_W| < 2.0$), and after applying several less-important criteria [6], the original event sample consists of 91 events with one isolated lepton and four or more jets. (Unlike the previous analysis, we do not distinguish between events that have or lack a muon associated with one of the jets, signifying the possible presence of a b-quark jet in the final state.) The new analysis involves a comparison of these 91 events with a leading-order matrix element for $t\bar{t}$ production and decay. To minimize the effect of higher-order corrections, we restrict the study to events containing exactly four jets, which reduces the sample to 71 events.

In the previous analysis, the four jets with highest E_T were assumed to represent the four quarks in the event. These, along with the lepton and the unobserved neutrino were fitted to the kinematic hypothesis $p\bar{p} \to t\bar{t} \to WWb\bar{b}$, subject to the constraints of overall momentum-energy conservation, the known mass of the W boson, and the fact that the unknown mass of 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 χ^2 was chosen as the best hypothesis, thereby defining the fitted mass $m_{\rm fit}$ 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 [7], which was used to generate events that were passed through full detector simulation and event reconstruction [8]. 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 [6], and the background from W+jets events was based on events generated with VECBOS [9]. 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 $m_{\rm fit}$, 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 $M_t = 173.3 \pm 5.6$ (stat) $\pm\, 5.5$ (sys) GeV/c^2.

The new method is similar to that suggested for $t\bar{t}$ dilepton decay channels [10], and used in a previous mass analyses of dilepton events [11]. A similar approach has also been suggested for the measurement of the mass of the W boson at LEP [12]. Given N events, the top quark mass is estimated by maximizing the likelihood:

$$L(\alpha) = e^{-N\int P_m(x,\alpha){\rm d}x} \prod_{i=1}^{N} P_m(x_i, \alpha) \tag{1}$$

where x_i is a set of variables needed to specify the ith measured event, P_m is the probability density for observing that event, and α represents the parameters to be determined (in this case α 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 α, 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 $W(y, x)$:

$$P(x, \alpha) = \frac{1}{\sigma(\alpha)} \int {\rm d}\sigma(y, \alpha){\rm d}q_1{\rm d}q_2 f(q_1)f(q_2)W(y, x) \tag{2}$$

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, $\mathrm{d}\sigma(y, \alpha)$ 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.(2) 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 [13]. 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:

$$P_{t\bar{t}} = \frac{1}{12\sigma_{t\bar{t}}} \int \mathrm{d}\rho_1 \mathrm{d}m_1^2 \mathrm{d}M_1^2 \mathrm{d}m_2^2 \mathrm{d}M_2^2 \times \sum_{\mathrm{perm},\nu} |\mathcal{M}_{t\bar{t}}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{\mathrm{jets}}(E_{\mathrm{part}}, E_{\mathrm{jet}})$$

For $|\mathcal{M}_{t\bar{t}}|^2$, we use the leading-order matrix element [14], $f(q_1)$ and $f(q_2)$ are CTEQ4M parton distribution functions for the incident quarks [15], Φ_6 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. $W_{\mathrm{jets}}(E_{\mathrm{part}}, E_{\mathrm{jet}})$ is the part of $W(y, x)$ that refers to the mapping between parton-level energies E_{part} and energies measured in the detector E_{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. ρ_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 [16] is used to perform the three remaining integrals. $W_{\rm jets}(E_{\rm part}, E_{\rm jet})$ is the product of four functions $F(E^i_{\rm part}, E^i_{\rm jet})$, one for each jet, with a functional form of the sum of two Gaussians, with parameters having linear dependence on $E^i_{\rm part}$. 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, $W_{\rm jets}$ 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 $P_{\rm bkg}$. 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 probabilitites for the non-interfering $t\bar{t}$ and W+4 jets channels, the final likelihood as a function of M_t is written as:

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

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 α, 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 1(a) shows a comparison between the probability for a background interpretation

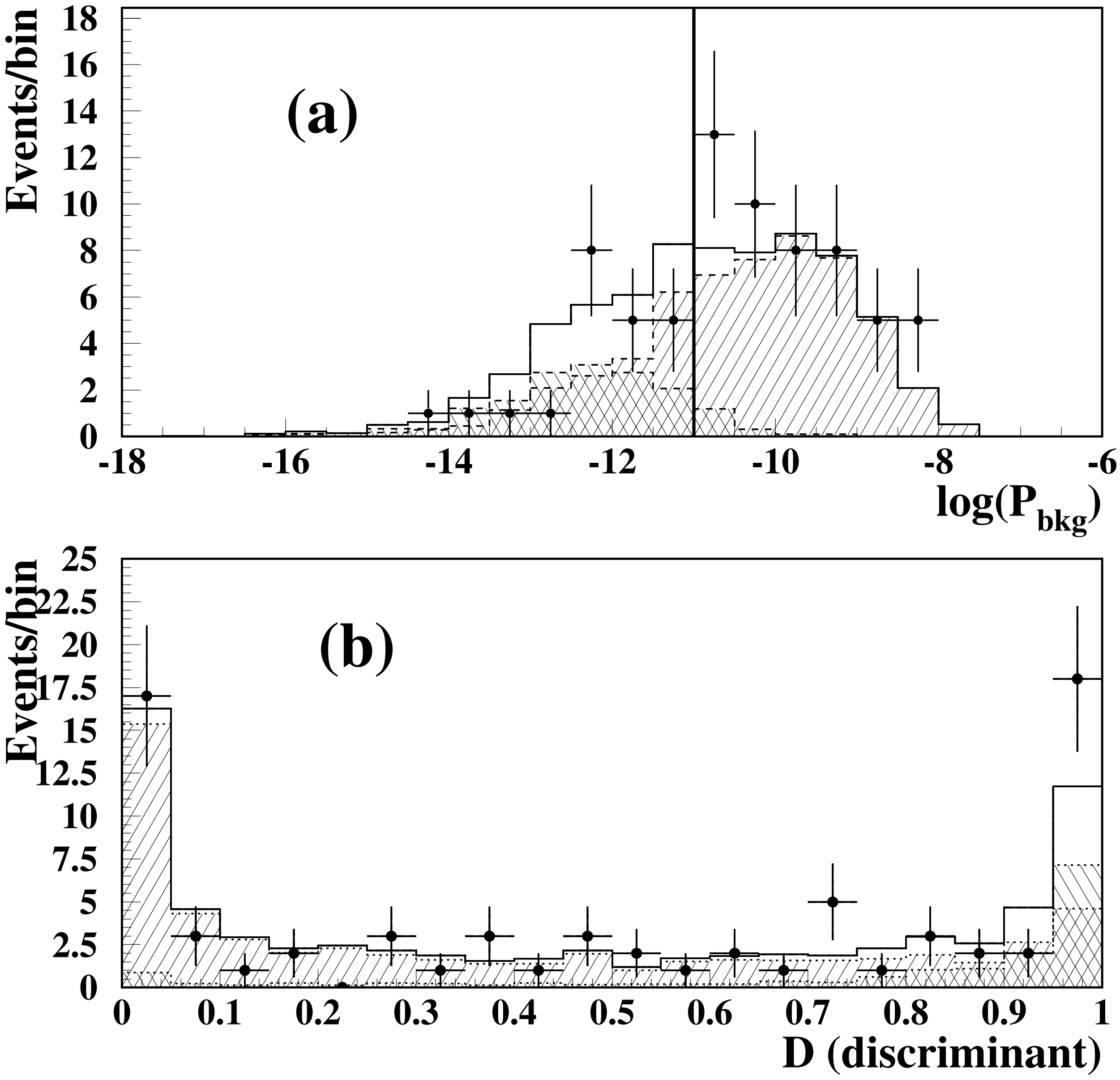

Figure 1: (a) Distribution in probability of events being background, and (b) discriminant $P_{t\bar{t}}/(P_{t\bar{t}} + P_{\mathrm{bkg}})$, calculated for the 71 $t\bar{t}$ candidates (data points). The data are compared with results expected for the sum (open histogram) from MC-simulated sources of $t\bar{t}$ (left-hatched) and W+jets (right-hatched) events. Only events with $P_{\mathrm{bkg}} < 10^{-11}$ (indicated by the vertical line) are considered in the final analysis.

of a large sample of mixed MC events (upper-most histogram) and the 71 $t\bar{t}$ candidates (data points). The total number of MC events is normalized to the 71 4-jet $t\bar{t}$ candidates. The left-hatched (right-hatched) histogram shows the contribution from $t\bar{t}$ ($W + 4$ jets) MC

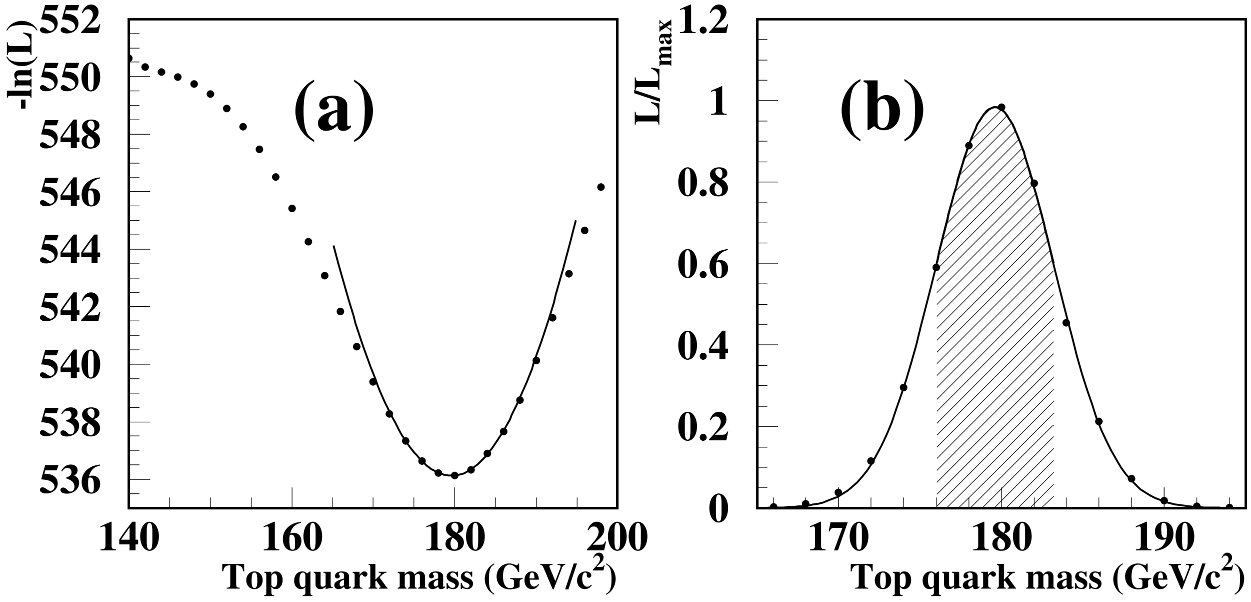

Figure 2: (a) Negative of the log of the likelihood as a function of the top quark mass. (b) The likelihood normalized to its maximum value in plot (a). The curve is a Gaussian fit to the likelihood plot. The hatched area corresponds to the 68.27% probability interval.

events to the total. Only the 22 events to the left of the vertical line are chosen for the final analysis ($P_{\rm bkg} < 10^{-11}$). The ratio of $t\bar{t}$ to $W + 4$ jets events in the MC is normalized to the 12/10 ratio found for the data to the left of the vertical line, as described below. (The selected value of $P_{\rm bkg} < 10^{-11}$ is based on MC studies carried out before applying the method to data, and, for a top quark mass of 175 GeV/c^2, it retains 71% of the signal and 30% of the background.)

A discriminant $D = P_{t\bar{t}}/(P_{t\bar{t}} + P_{\rm bkg})$ was defined to quantify the likelihood for an event to correspond to signal [6]. Since the signal probability depends on M_t, D was calculated with the signal probability taken at its most likely value. Figure 1(b) shows a comparison of the discriminant calculated for data (points with error bars) and for MC events (open histogram), with the MC normalized as in Fig. 1(a). Since the discriminant depends directly on M_t, it was not used to reject background and is shown simply to illustrate the level of discrimination of signal from background.

Figure 2(a) shows the value of $-\ln L(\alpha)$ as a function of M_t for the 22 events that passed all selection criteria. $-\ln L(\alpha)$ was minimized with respect to the parameters c_i at each mass point. Figure 2(b) shows the likelihood normalized to its maximum value. The Gaussian fit

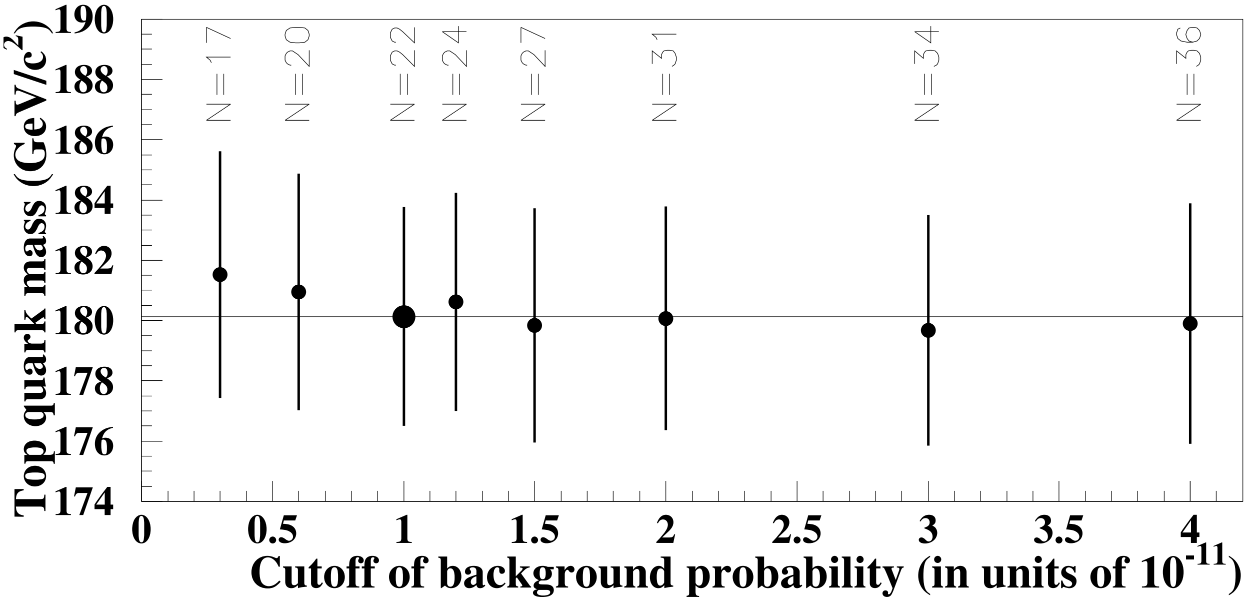

Figure 3: Mass of the top quark as a function of the cutoff in background probability. The number of remaining events is shown above each point. The point with the larger dot is the value used in this analysis.

in the figure yields $M_t = 179.6$ GeV/c^2, with an uncertainty $\delta M_t = 3.6$ GeV/c^2. MC studies show that [17]: (*i*) δM_t is compatible with the uncertainties obtained in MC ensemble tests, and (*ii*) there is a shift of -0.5 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 $M_t = 180.1 \pm 3.6$ (stat) GeV/c^2. As Fig. 1(a) indicates, the cutoff chosen in P_{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_{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.

The total number of $t\bar{t}$ events in the 91-event sample is deduced to be $(11 \pm 3)/(0.71 \times 0.70 \times 0.87) = 25 \pm 7$, where 11 is the number of extracted (using c_1 and c_2) events, and the corrections are for: (*i*) acceptance (0.71), (*ii*) events with more than 4 jets (0.70), and (*iii*) $t\bar{t}$ 4-jets events that appear as background because a leading-order matrix element does not represent them correctly (0.87). The number of $t\bar{t}$ events is consistent with that found in the previous analysis [6]. The uncertainties in the quoted efficiencies are negligible compared with the statistical uncertainty in the total number of $t\bar{t}$ events.

Table I: Systematic uncertainties on the measurement of M_t.

Model for $t\bar{t}$	1.1 GeV/c^2
Model for backgound(W+jets)	1.0 GeV/c^2
Noise and multiple interactions	1.3 GeV/c^2
Jet energy scale	3.3 GeV/c^2
Parton distribution function	0.1 GeV/c^2
Acceptance correction	0.3 GeV/c^2
Bias correction	0.5 GeV/c^2
Total	3.9 GeV/c^2

In the previous analysis [6], γ+jet events were used to check the energy scale in the experiment relative to MC simulation. This calibration had an uncertainty of δE= 0.025 E + 0.5 GeV. Consequently, we rescaled the energies of all jets in our sample by $\pm\delta E$, redid the analysis, and the average of the two rescaled results for M_t ($\delta M_t = (3.0 + 3.5)/2 \approx 3.3$ GeV/c^2) is taken as the systematic error due to the uncertainty in the jet energy scale (JES). Additional contributions to the systematic uncertainty are listed in Table I, and details on the evaluation of these systematic errors and further description of the analysis technique can be found in Ref.[17].

Our method provides substantial improvements in both the statistical and systematic uncertainties. This is due to two main differences relative to the previous analysis: (i) each event now has an individual probability as a function of the mass parameter, and therefore well-measured events having a narrower likelihhod contribute more to the extraction of the top quark mass than those that are poorly measured, and (ii) all possible jet and neutrino combinations are included, which guarantees that all signal events contribute to the measurement.

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 significant improvement in statistical uncertainty over the previous measurement [6] that is equivalent to a factor of 2.4 more data.

From the differences in the two analyses, and from statistical fluctuations arising from using a subsample of the original data, we expect the difference between the original and the new mass measurement to be on the order of 4 GeV/c^2. Thus, the two results differ by less than two standard deviations. The current analysis is also less sensitive to the calibration of the JES, and leads to an improved systematic uncertainty. The new result is:

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

Combining the two uncertainties in quadrature, we obtain $M_t = 180.1 \pm 5.3$ GeV/c^2, which has an uncertainty comparable to all the previous measurements of DØ and CDF [3] combined.

Using the procedure described in Ref.[18], 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:

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

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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