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# Measurement of the Top Quark Mass In All-Jet Events

DØ Collaboration

## Abstract

We describe a measurement of the mass of the top quark from the purely hadronic decay modes of  $t\bar{t}$  pairs using all-jet data produced in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV at the Fermilab Tevatron Collider. The data, which correspond to an integrated luminosity of  $110.2 \pm 5.8$  pb<sup>-1</sup>, were collected with the DØ detector from 1992 to 1996. We find a top quark mass of  $178.5 \pm 13.7$  (stat)  $\pm 7.7$  (syst) GeV/ $c^2$ .

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The mass of the top quark ( $m_t$ ) is a key parameter of the standard model (SM). Knowledge of its value is essential for determining quantum corrections to the theory and for limiting the predicted range of Higgs boson masses [1, 2]. In this letter we report a new measurement of  $m_t$  by the DØ collaboration in the process  $p\bar{p} \rightarrow t\bar{t}$  for the case in which the top and antitop quarks each decay to a  $W$  boson and a  $b$  quark, followed by the hadronic decay of both  $W$  bosons. At lowest order in perturbative QCD, this leads to a final state of six quark jets, referred to as the all-jets channel of  $t\bar{t}$  production.

Measurements of  $m_t$  have been reported by the DØ and CDF collaborations based on Run I data (1992–1996) from the Fermilab Tevatron Collider, with a  $p\bar{p}$  center-of-mass energy of 1.8 TeV. For the all-jets final state, CDF has reported a top quark mass of  $186 \pm 10$  (stat)  $\pm 12$  (syst) GeV/ $c^2$  [3]. CDF, combining leptonic and hadronic  $W$  boson decay channels, has measured an average top quark mass of  $175.9 \pm 4.8$  (stat)  $\pm 4.9$  (syst) GeV/ $c^2$  [4]. The DØ average for  $m_t$ , based on leptonic decay channels of one or both of the  $W$  bosons, is  $179.0 \pm 3.5$  (stat)  $\pm 3.8$  (syst) GeV/ $c^2$  [5]. Combining all published measurements yields an average value of  $178.0 \pm 4.3$  GeV/ $c^2$  for the mass of the top quark [5].

The all-jets decay channel has the largest branching fraction of all  $t\bar{t}$  decay channels (46%) and is the most kinematically constrained final state, since no energetic neutrinos are produced [6]. If the jets could be correctly associated with their original partons, there would be no ambiguity in the analysis. However, the association cannot be made unambiguously. The events of interest contain six or more high transverse momentum jets, two of which originate from  $b$  quarks. The dominant background arises from other QCD processes that produce six or more jets. DØ measured the  $t\bar{t}$  production cross section in the all-jets decay channel to be  $7.1 \pm 2.8$  (stat)  $\pm 1.5$  (syst) pb, assuming a top quark mass of 172.1 GeV/ $c^2$  that was previously determined by DØ from other decay channels [7]. This cross section corresponds to roughly 360  $t\bar{t} \rightarrow jets$  events produced at DØ during Run I.

The DØ detector and our methods of triggering, identifying particles, and reconstructing events are described elsewhere [8, 9]. The measurement reported here is based on  $110.2 \pm 5.8$  pb $^{-1}$  of data from Run I of the Fermilab Tevatron Collider, at a  $p\bar{p}$  center-of-mass energy of 1.8 TeV. The events were selected with a trigger that required at least five jets of cone radius  $\mathcal{R} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ , where  $\phi$  and  $\eta$  are the azimuthal angle and pseudorapidity, respectively. Each jet was required to have transverse energy

( $E_T$ ) greater than 10 GeV and  $|\eta| < 2.5$ . The triggered sample contains approximately 2 million events, with an estimated signal-to-background ratio of about 1 to 7000. Further selection criteria were applied to this sample, including criteria to suppress Main Ring noise, to ensure good jet energy resolution, and to remove events consistent with light-quark backgrounds. Events containing a reconstructed electron or muon outside a jet cone of radius  $\mathcal{R} = 0.5$  were excluded to avoid overlap with other  $t\bar{t}$  decay channels. In addition, we required events to contain at least six jets with  $E_T > 10$  GeV and  $|\eta| < 2.5$ . The  $E_T$  of each jet was scaled to give, on average, the correct (true) jet energy. For more information on the DØ jet algorithm, see Ref. [10]. For information on the jet energy scale correction see Ref. [11]

These criteria led to the selection of a sample containing 165,373 multi-jet events with an estimated signal-to-background ratio of about 1 to 1000. Since  $t\bar{t}$  events contain a  $b\bar{b}$  pair, whereas such pairs are relatively rare in background events, the signal-to-background ratio can be improved by selecting events with at least one jet that may have arisen from the fragmentation of a  $b$  quark that subsequently decayed to a muon, either directly, or indirectly via the chain  $b \rightarrow c \rightarrow \mu$ . The tagging of  $b$ -jets using embedded muons is effective at suppressing background relative to signal because 15–20% of  $t\bar{t}$  events are so tagged whereas only 2% of the multijet events in the selected sample satisfy the  $b$ -tagging requirements. In this analysis, a  $b$ -jet was defined as any  $\mathcal{R} = 0.5$  cone jet, with  $E_T > 10$  GeV and  $|\eta| < 1.0$ , that contained a muon with  $p_T > 4$  GeV/ $c$  within its cone. The tag requirement reduced the sample to 3,043  $b$ -tagged events, with an estimated signal-to-background ratio of approximately 1 to 100. More details on  $b$  tagging are given in Ref. [12].

To determine the properties of all-jets events from  $t\bar{t}$  production, extensive Monte Carlo studies were done. The  $t\bar{t}$  signal events were generated using the HERWIG V5.7 [13] program and propagated through a detailed detector simulation, based on GEANT V3.15 [14], and reconstructed with the standard DØ reconstruction program. We found that the mean of the invariant masses of two triplets of jets formed from the six highest- $E_T$  jets,  $M \equiv \left(\frac{m_{t_1+m_{t_2}}}{2}\right)$ , provided a satisfactory discriminant for distinguishing  $t\bar{t}$  signal from background [15]. We chose the two jet triplets to be those that minimized the quantity

$$\chi^2 = \left(\frac{m_{t_1} - m_{t_2}}{2 \times \sigma_{m_t}}\right)^2 + \left(\frac{M_{W_1} - M_{W_0}}{\sigma_{M_W}}\right)^2 + \left(\frac{M_{W_2} - M_{W_0}}{\sigma_{M_W}}\right)^2, \quad (1)$$

where  $M_{W_0} = 77.5$  GeV/ $c^2$  is the mean value of the reconstructed  $W$  boson



mass in the all-jets  $t\bar{t}$  Monte Carlo events processed through the DØ detector simulation and reconstruction programs, and  $m_{t_1}$ ,  $m_{t_2}$  and  $M_{W_1}$ ,  $M_{W_2}$  are the calculated masses of the reconstructed jets that correspond to candidate top quarks and  $W$  bosons, respectively, computed from the jet triplets and, within each triplet, the jet doublets. The standard deviations,  $\sigma_{m_t} \approx 31$  GeV/ $c^2$  and  $\sigma_{M_W} \approx 21$  GeV/ $c^2$ , are the average root mean square (RMS) values of the mass distributions determined using HERWIG Monte Carlo events generated with top quark masses of 140, 180 and 220 GeV/ $c^2$ . Minimizing  $\chi^2$  provides the correct combination of jets in about 40% of the  $t\bar{t}$  Monte Carlo events.

The top quark mass was measured through the best fit of different admixtures of signal and background to the observed mass distribution. The fitting technique used is similar to that of Ref. [16], which takes account of the finite size of every sample in the fit. The posterior probability density  $p(m_t, \sigma_{t\bar{t}}|\text{Data})$ , computed assuming a flat prior in mass and in the  $t\bar{t}$  cross section, is calculated for a set of mass values  $m_t$ . For each  $m_t$  value, the posterior probability density, numerically identical (in this case) to the likelihood  $L$ , was maximized by varying  $\sigma_{t\bar{t}}$  to give the “maximized likelihood”,  $L_{max}(m_t)$  as a function of the hypothesized top quark mass,  $m_t$ . The “best fitted mass”,  $m_{fit}$ , was taken to be the location of the minimum of the negative log-likelihood curve  $-\ln L_{max}(m_t)$ .

The templates for the top quark signal were generated using a Monte Carlo simulation of  $t\bar{t}$  events for a discrete set of masses in the range of 110 to 310 GeV/ $c^2$  in 10 GeV/ $c^2$  steps, that is, at 21 mass values. The background was modeled using *untagged* events, that is, multijet data that passed all selection criteria except those that define the  $b$ -tag. For each untagged event  $i$ , a weight  $w_i$  is calculated, which reflects the probability of tagging that event, such that the sum  $\sum_i w_i$  over all untagged events provides an estimate of the background, that is, the number of non- $t\bar{t}$   $b$ -tagged events within the 3,043 event sample. The event weight is the sum of the  $b$ -tag rate *per jet*, which is assumed to depend only on the  $E_T$  and  $\eta$  of the jet, and on the muon detection efficiency. The tag-rate ( $t_R$ ) is assumed to factorize as follows:

$$t_R = T(E_T, \eta, R) = N(R)f(E_T, R)g(\eta, R), \quad (2)$$

where

$$f(E_T, R) = a_0 + a_1 E_T^{1/2}, \quad (3)$$

$$g(\eta, R) = p_0 + p_1 |\eta|^2 \quad (4)$$

and  $N(R)$  is an overall normalization constant. The forms of  $f(E_T, R)$  and  $g(\eta, R)$  were determined empirically. The tag-rate is divided into 5 bins as a function of run number ( $R$ ) according to the 5 major changes in muon system efficiency. For each of the 5 run bins, jets were selected with  $E_T > 10$  GeV and  $|\eta| \leq 1.0$ . Histograms were made of the  $E_T$  of the tagged jets and the  $E_T$  of the untagged jets in the data, and their ratio (bin by bin) was fit using  $f(E_T, R)$ . Similarly, the distributions of the ratio of tagged and untagged  $|\eta|$  histograms were fit using  $g(\eta, R)$ . The tag-rate was normalized to return the number of observed tagged events in the data.  $\chi^2$  tests show very good agreement between the tagged data and the predicted background. More details on this method are given in Ref. [15].

Since the jets in  $t\bar{t}$  events tend to be more energetic, have a more isotropic momentum flow, and have larger transverse energies than those in light-quark events, we can enrich the event sample further by event discrimination based on a suitable set of kinematic variables. For this analysis, we used the following eight variables:  $E_{T5} \times E_{T6}$ ,  $|\eta_{W1} \times \eta_{W2}|$ ,  $\sqrt{\hat{s}}$ ,  $\mathcal{A}$ ,  $\mathcal{S}$ ,  $N_{jet}^{E_T}$ ,  $H_{T3}/H_T$ , and  $H_T/H$ , where  $E_{T1}$  to  $E_{T6}$  and  $E_1$  to  $E_6$  are the transverse energies and energies, respectively, of the six jets, ordered in decreasing  $E_T$ ;  $\eta_{W1}$  and  $\eta_{W2}$  are the pseudorapidities of the two hypothesized  $W$  bosons;  $\sqrt{\hat{s}}$  is the invariant mass of the  $N_{jets}$  system;  $\mathcal{A}$ , the aplanarity, is  $\frac{3}{2}$  of the smallest eigenvalue of the normalized laboratory-frame momentum tensor [17] of all the jets;  $\mathcal{S}$ , the sphericity, is  $\frac{3}{2}$  of the sum of the smallest and next-smallest eigenvalues of the same tensor;  $N_{jet}^{E_T}$  is the number of jets above a given  $E_T$  threshold, over the range 10 GeV to 55 GeV, weighted by the threshold [18];  $H_T = \sum_j E_{Tj}$ ;  $H_{T3} = H_T - E_{T1} - E_{T2}$ ; and  $H = \sum_j E_j$ , where the sums are over all  $\mathcal{R} = 0.5$  cone jets with  $|\eta| < 2.5$  and  $E_T > 10$  GeV. Figure 1 shows comparisons of distributions in each of the kinematic variables between background and a  $t\bar{t}$  Monte Carlo signal for  $m_t = 180$  GeV/ $c^2$ . The distributions of kinematic variables for events with  $b$ -jets are consistent with those without  $b$ -jets.

The above variables were combined into a single discriminant, calculated using a neural network (NN) [19] with eight inputs, a single hidden layer with three nodes, and a single output  $D_{NN}$ . The network was trained and tested with independent samples of HERWIG Monte Carlo  $t\bar{t}$  signal events, at top quark masses of 140, 180 and 220 GeV/ $c^2$ , and untagged events for the background, with the target for background set at 0 and at 1 for the signal. Roughly equal numbers of training events were used at each mass.

These events (in all, 11,423 for signal and 8,143 for background) were used only for training the neural network and producing a single set of network parameters. These events were not used in the subsequent analysis.

Figure 2 shows  $D_{NN}$  for the 3,043 event data sample and for background normalized to the same number of events. Also shown for comparison is the expected  $t\bar{t}$  Monte Carlo signal for  $m_t = 180 \text{ GeV}/c^2$  multiplied by a factor of ten. The final event sample used in the fit to the top mass was defined by a cutoff in  $D_{NN}$ , which was chosen to minimize the uncertainty on the extracted top mass. For a given cutoff on  $D_{NN}$ , and a given mass value  $m_t$ , a distribution was composed by adding the background mass distribution to the signal mass distribution, with the signal normalized to the theoretical cross section [20]. An ensemble of  $\sim 100$  fake mass distributions was created by sampling from the combined distribution. The fitting procedure was applied to each fake mass distribution to yield a fitted mass  $m_{fit}$ . We thereby obtained a distribution of fitted masses, characterized by a mean and an RMS, for the given  $D_{NN}$  cutoff and the given value of  $m_t$ . The procedure was repeated for different  $D_{NN}$  cutoffs and for top quark mass values of 155, 165, 175, 185 and 195  $\text{GeV}/c^2$ . We found that the cutoff  $D_{NN} > 0.97$  minimizes the RMS in the fitted mass distributions for the five top quark masses considered.

When applied to the 3,043 events, the requirement of  $D_{NN} > 0.97$  reduced the dataset to a final sample of 65 events. Figure 3 shows a comparison between the observed mass distribution in the data and the sum of background and 175  $\text{GeV}/c^2$  top quark signal scaled to the observed number of top events (see below). The fitting procedure, with 21 mass values, was applied to the observed mass distribution to yield a mass estimate, which was corrected for a bias [15] of 2.6  $\text{GeV}/c^2$  using the relationship

$$m_{fit} = 0.712 m_t + 53.477 \text{ GeV}/c^2, \quad (5)$$

determined from the Monte Carlo studies. The uncertainties (also bias-corrected) were defined to be the 68% interval about the minimum in the log-likelihood curve. A systematic uncertainty of 5% arises from the discrepancy between the jet energy scale in Monte Carlo simulations and that in data [11]. The fitting of the tag-rate function introduces a normalization uncertainty of 14.9%. The systematic uncertainty also receives a contribution from the bin-by-bin uncertainty due to the limited number of untagged events used to model the background. The effect of these systematic uncertainties on the measured top quark mass was obtained by repeating the fits

varying the nominal values by their systematic uncertainties. The effect of a small signal contribution to the background sample was checked and found not to affect the determination of the top quark mass.

The insert in Figure 3 shows the negative log-likelihood as a function of the top quark mass for six points near the minimum. After bias correction, we find a top quark mass of  $178.5 \pm 13.7$  (stat)  $\pm 7.7$  (syst)  $\text{GeV}/c^2$ . As a consistency check of our measurement, given the measured top quark mass, we can estimate the  $t\bar{t}$  production cross section at that mass. The estimated signal in the 65-event sample is  $16.6 \pm 7$  events. This corresponds to a total cross section of  $11 \pm 5$  pb, which is consistent with the measured  $D\bar{O}$   $t\bar{t}$  production cross section of  $5.6 \pm 1.4$  (stat)  $\pm 1.2$  (syst) pb for a top quark mass of  $172.1 \text{ GeV}/c^2$  [21].

In summary, we have measured the mass of the top quark, using the purely hadronic decay modes in  $t\bar{t}$  events, to be  $178.5 \pm 13.7$  (stat)  $\pm 7.7$  (syst)  $\text{GeV}/c^2$ . This is in good agreement with top quark mass measurements in other decay channels.

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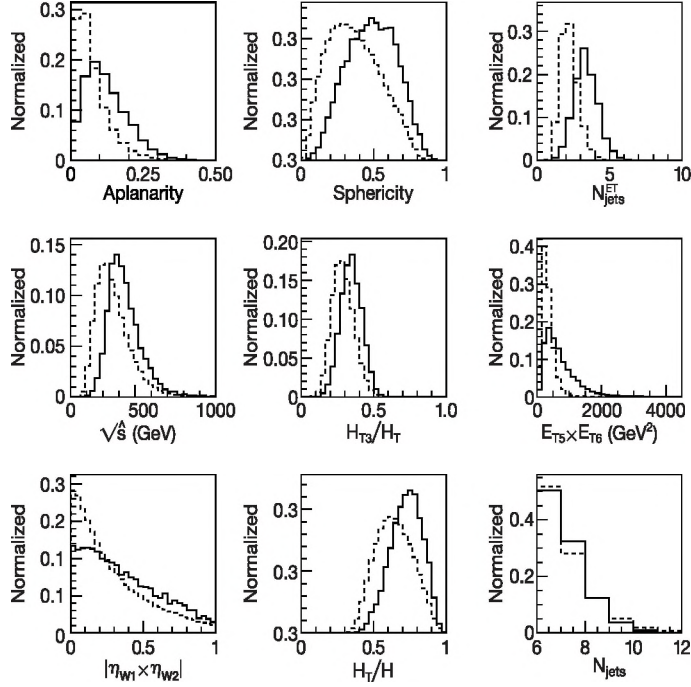


Figure 1: Histograms of kinematic variables for  $t\bar{t}$  Monte Carlo signal (solid) and background (dashed) normalized to the same area. The Monte Carlo signal samples were generated with a top quark mass of  $180 \text{ GeV}/c^2$ . The variables are described in the text.

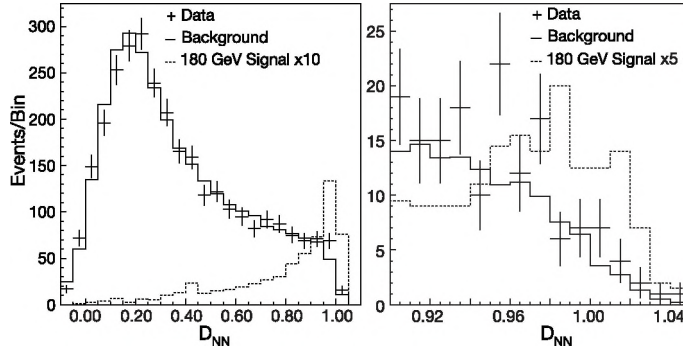


Figure 2: (a)  $D_{NN}$  is plotted for data and background. Also shown is the  $D_{NN}$  expected for a  $180 \text{ GeV}/c^2$  top quark Monte Carlo signal scaled up by a factor of ten. (b)  $D_{NN}$  in finer bins from 0.90 to 1.05, for data, background and  $180 \text{ GeV}/c^2$  top quark Monte Carlo signal scaled up by a factor of five.

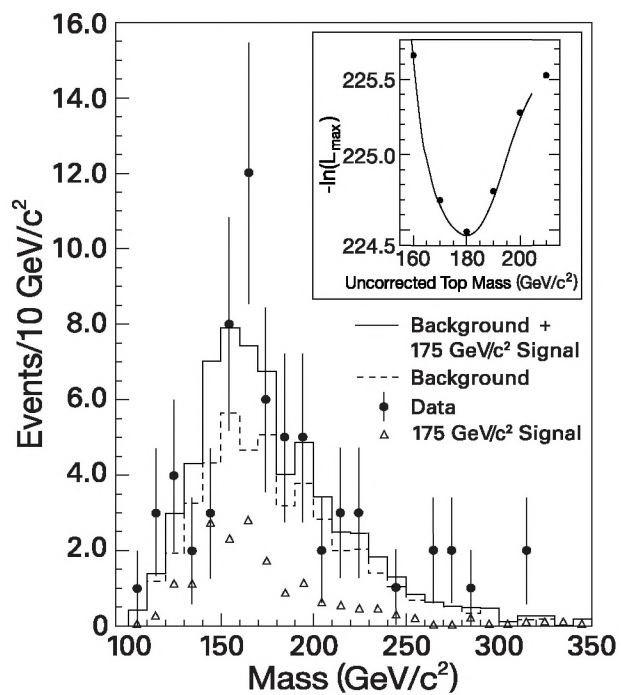


Figure 3: Data and the sum of background and Monte Carlo signal plotted as a function of the mean mass,  $M$ . Insert is  $-\ln L_{max}$  as a function of the top quark mass.