# TOP QUARK MASS MEASUREMENTS AT THE TEVATRON

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We present the most recent measurements of the mass of the top quark from Tevatron and the combination of the measurements from CDF and DØ, which yield a top mass of $173.20 \pm 0.51$ *(stat.)* $\pm 0.71$ *(syst.)* GeV/$c^2$.

## 1 Introduction

The top quark ($t$) is the heaviest elementary particle observed so far. Its decay width of $2.0^{+0.5}_{-0.4}$GeV [1] settles the top quark in a unique position among the quarks, since it decays before "dressing" into a hadron. This feature allows a direct study of the properties of the top quark, including its mass, by the detection of its decay products, without the complication of the soft QCD interactions happening in a hadron.

The mass of the top quark is a free parameter of the Standard Model (SM). Its value affects the contributions of $t$ loop diagrams, for example in radiative corrections to $W$ and $H$ masses. A precise knowledge of its mass can provide a stringent test on the SM [2].

## 2 Experimental Methods

Top quarks are produced in $p\bar{p}$ interactions singly by weak interaction and more abundantly in $t\bar{t}$ pairs by strong interaction. The latter, with a measured cross section [3] of about $7.65 \pm 0.42$ pb at $\sqrt{s} = 1.96$ TeV, is the production channel of choice for measuring the mass of the top quark.
Each of the two top quarks decays into a quark ($b$ quark in more than 99% of the decays) and a $W$ boson. The presence of $b$ quarks in the events provides an important mean to discriminate the $t\bar{t}$ events, since the jets originating from $b$ quark can have very characteristic features as the presence of a soft lepton and of a displaced decay vertex. Specific algorithms can identify these jets ("$b$-tagged jets"), typically achieving an efficiency within $50 - 80\%$.
The two $W$ bosons from the $t\bar{t}$ decay define the experimental signature of the events. The final state where only one $W$ boson decays into a charged lepton and its neutrino ("semileptonic") provides one fully reconstructed top quark and a sizeable branching fraction. The presence of the lepton allows for a sensible reduction of the background contamination.

The presence of a $W$ boson decaying in jets is a remarkable feature for the top mass measurements. The uncertainty on the scale of the jet energy is $1-2\%$, and it affects directly the measured mass. The mass can be measured beyond that precision only by an alternative calibration of the jet energy. The mass of the $W$ boson has been measured independently [4] with an uncertainty of $\approx 15\,\mathrm{MeV}/c^2$. Therefore the $W$ boson decaying in two jets can provide a very precise scale reference for the jet energy. The top mass measurements exploit this feature by measuring also the residual jet energy scale bias, $\Delta_{\mathrm{JES}}$, for the selected data sample ("calibration *in situ*").

The most common techniques for the measurement of the mass of the top quark follow a shared pattern. Each event satisfying the selection criteria is assigned a likelihood, which describes its compatibility with a $t\bar{t}$ event of a given top mass $m_t$. This likelihood can be a function of other parameters in addition to $m_t$, for example $\Delta_{\rm JES}$. The estimator of $m_t$ is extracted from the maximization of a sample likelihood which includes contributions from each of the events. Finally, a calibration procedure relying on the simulation removes any bias from the estimator and delivers the measurement of the top mass. The methods differ in the choice of the event likelihood.

An important consequence of the calibration procedure is the dependency of the measurement from the definition of the top mass implemented in the simulations. Conversely, a precise measurement of the top mass contributes to the full understanding of those implementations [5].

The *Matrix Element method* exploits the full topology of the event. Its likelihood is based to the leading order $q\bar{q} \to t\bar{t}$ scattering matrix element, $\mathcal{M}\,(y, m_t)$, including the $t\bar{t}$ decay. Since neither the initial nor the final state of the process described by $\mathcal{M}$ are observable, two layers are needed to connect $\mathcal{M}$ with the initial $p\bar{p}$ and the set of the detected objects (for example, four jets and one lepton).

The *templates method* relies on a few observables which are sensitive to the top mass. Distributions of these observables ("templates") are extracted from signal samples simulated with different top masses and from background samples. These distributions are used as probability densities to compute the likelihood for each event to be a signal event with a given mass. Correlations between the observables can be included by the use of multi-dimensional distributions. Multi-dimensional templates require large simulated samples to avoid statistical fluctuations. This limits the number of observables which can be included by this method.

The most precise measurements of the Tevatron experiments have historically been from events with semileptonic signature, using the Matrix Element method. The measurement from CDF, on 5.6 $\rm fb^{-1}$ of data, now superseded, had achieved a precision of 0.7% ($173.0 \pm 0.9$ *(stat.+JES)* $\pm$ $0.9$ *(syst.)* GeV/$c^2$ [6]). The measurement from DØ on 3.6 $\rm fb^{-1}$ of data achieved a precision of 0.85% ($174.9 \pm 1.1$ *(stat.+JES)* $\pm$ $1.0$ *(syst.)* GeV/$c^2$ [7]). The precision of both is limited by the statistical uncertainties. The combination from the two experiments from July 2012 yields to $m_t$=$173.18 \pm 0.56$ *(stat.)* $\pm$ $0.75$ *(syst)* GeV/$c^2$ [8]. By comparison, the most precise result from LHC, combination of CMS and ATLAS results, is $173.3 \pm 0.5$ *(stat.)* $\pm$ $1.3$ *(syst)* GeV/$c^2$ [9]. Also in this case, it is the systematic uncertainties which limit the precision of the measurement.

## 3 New Measurements

### *3.1 From Events with One Lepton and Jets*

CDF has measured the mass of the top quark from the full dataset of 8.7 $\rm fb^{-1}$ using a selection of events with one charged lepton ($e$ or $\mu$) and four or more jets [10]. This analysis uses the templates method, based on three observables and including their correlations. There are up to 12 possible assignments for each of the four reconstructed jets to the four quarks in the $t\bar{t} \to b\bar{b}q\bar{q}'\ell\bar{\nu}_\ell$ ($b$-tagged jets will not be assigned to light quarks). For each of the assignments a $\chi^2$ quantity is evaluated, which describes how compatible the event is with a $t\bar{t}$ configuration where the two $W$ bosons have the nominal mass of $M_W = 80.39\,{\rm GeV}/c^2$ and the two $t$ quarks have the same mass, a free parameter $m_t^{\rm reco}$. The first two observables chosen for the templates are $m_t^{\rm reco}$ from the assignment with the lowest $\chi^2$ (Fig. 1), and from the assignment with the second lowest $\chi^2$. The third observable is chosen as the invariant mass of two jets which is closest to the known $M_W$ value. All and only the jets which are not $b$-tagged are considered.

The measured top mass is

$$m_t = 172.85 \pm 0.71\ \textit{(stat.+JES)} \pm 0.85\ \textit{(syst.)}\ {\rm GeV}/c^2.$$

The energy scale shift $\Delta_{\rm JES}$ from the calibration in situ is found to be consistent with zero. The systematic uncertainty is dominated by the residual uncertainty on jet energy scale and by the signal modelling, also including a contribution from an alternative parton shower model.

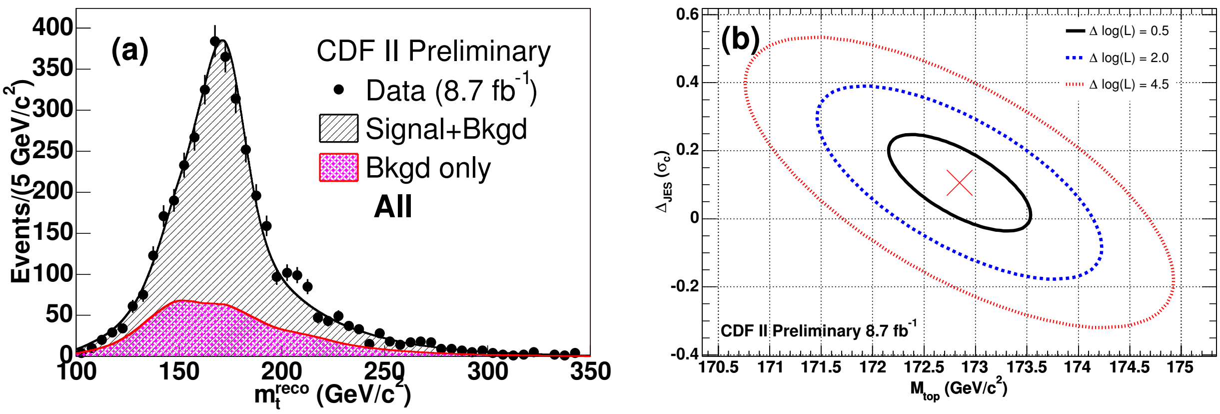



Figure 1: Measurement on 8.7 fb$^{-1}$ of CDF data using events with lepton and jets: *(a)* template distributions of $m_t^{\rm reco}$ for background and signal with $m_t$=173.0 GeV/$c^2$, compared with data; *(b)* minimum of the sample likelihood, with contours corresponding to one, two and three standard deviations.

### *3.2 From Events with No Lepton and Jets*

CDF has performed a measurement from a selection of events with no electron nor muon, and large momentum imbalance [11]. The simulation shows that such events have large contribution from $t\bar{t}$ processes where the lepton is present but not reconstructed.

The analysis is performed on the full CDF dataset of 8.7 fb$^{-1}$, using a template method similar to the one used in the analysis of events with one lepton (Fig. 2). The main differences are in the details of the formulation of the $\chi^2$, modified to take into account the lack of information about one of the two $W$ bosons, and the strategy for the reduction of background contamination. The final state without leptons is dominated by non-resonant multi-jet events. The requirement of at least one $b$-tagged jet is necessary to reduce the background. Further reduction is achieved by using a multivariate discriminant, which yields to a signal over background ratio of 2:1.

The result of the analysis is a top mass

$$m_t = 173.9 \pm 1.6\ (stat.{+}JES) \pm 0.9\ (syst.)\ \mathrm{GeV}/c^2$$

whose precision is limited by the statistical uncertainty. This measurement can't compete in precision with the previous one, but it contributes in the combination with other measurements.

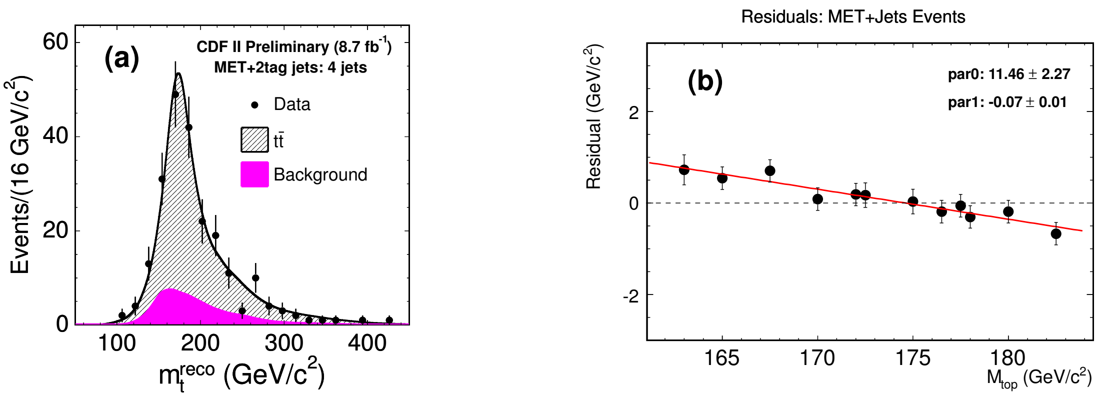



Figure 2: Measurement on 8.7 fb$^{-1}$ of CDF data using events with large momentum imbalance and jets: *(a)* template distributions of $m_t^{\rm reco}$ for background and signal with $m_t$=173.0 GeV/$c^2$ compared with data for the events with four jets, two of them $b$-tagged; *(b)* calibration curve for the top mass estimator: bias on top mass as function of the top mass chosen in the simulated sample.

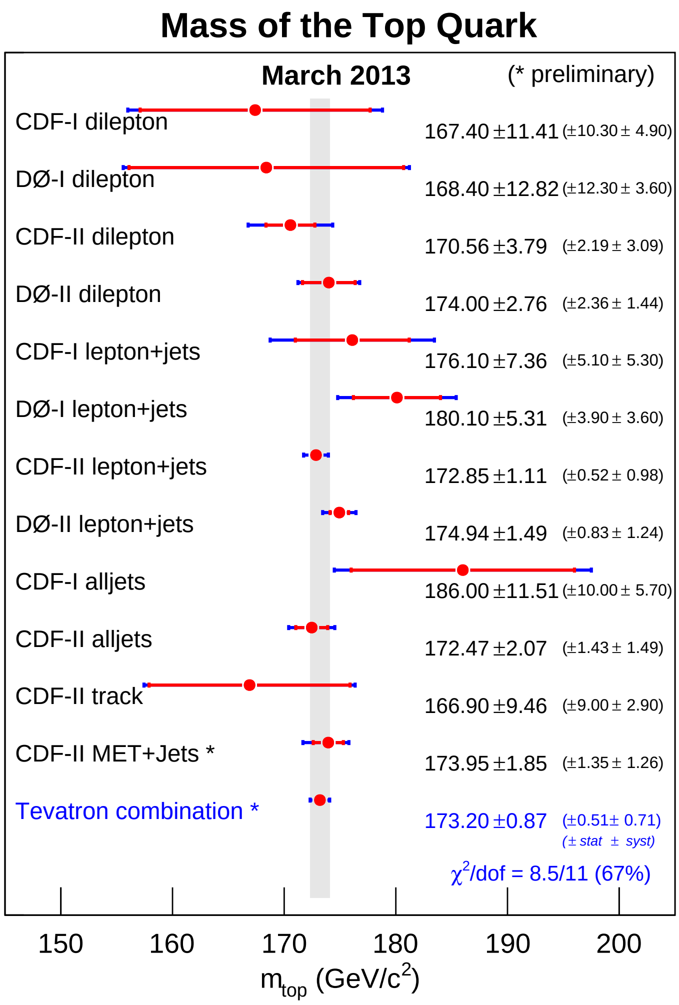
## 4 Tevatron Combination

A joint CDF and DØ working group performs combinations of top quark measurements, including mass, $t\bar{t}$ production cross section and other properties.

The combination technique for the top mass measurements is based on a Best Linear Unbiased Estimator[12], relying on the assumption that each source of uncertainty is assumed to be described by a normal distribution. The method requires the detailed knowledge of the correlation of the uncertainties between all the measurements to be combined. The uncertainties are split in 14 categories, defined so that the correlations within each of them are well defined. The categories include seven related to jet energy scale, two about detector modelling, two about background modelling; the remaining ones are the signal modelling, the modelling of the underlying event and the calibration method.

The choice of measurements follows two guidelines. The measurements must be as independent as possible, and the most precise available. Their independence guarantees that their statistical uncertainty is uncorrelated, and it maximises the available information. Therefore the 12 measurements chosen (Table 1) span the two Tevatron experiments, the two Tevatron runs and many final states, including the two measurements presented in this report.

Table 1: Summary of the 12 mass measurements from Tevatron in the March 2013 top mass combination, and the combination result.




The result of the combination[13] is

$$m_t = 173.20 \pm 0.51\ (stat.) \pm 0.71\ (syst.)\ \mathrm{GeV}/c^2 = 173.20\ \pm 0.87\ \mathrm{GeV}/c^2$$

wose precision of 0.50% qualifies it as the most precise estimation of the top mass to date.

The precision of the combination is dominated, as the most precise among the contributing measurements, by the uncertainties on the energy scale of the jets and on the signal modelling.

## 5 Summary

The precision of the measurements of the top mass keeps being improved by the Tevatron experiments. To date, the top mass is know with an uncertainty of 870 MeV/$c^2$ (0.5%), with the contribution of the first measurements from the full dataset by CDF. Further improvements are expected with the inclusion of the remaining Tevatron analyses currently in preparation.
The most precise single measurements have been since long time limited by the systematic uncertainties. The leap in precision can be only achieved by the better understanding of the signal modelling, common to all measurements, and by the combination of measurements with different and independent uncertainties. The largest gain comes with the contributions from different experiments. It must be stressed that all the measurements are consistent, regardless of the detector, technique or events signature, including the measurements from the LHC $pp$ events. This indicates the combination of all the measurements from Tevatron and LHC as the necessary mean to improve the precision of the measurement of the top mass from hadron collisions.

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