Top Quark Mass from the Tevatron Collider [a]

L. Brigliadori
on behalf of CDF and D0 Collaborations
Dipartimento di Fisica dell' Università di Bologna
Viale Berti-Pichat 6/2, 40127 - Bologna, Italy
luca.brigliadori@bo.infn.it

The discovery of the top quark in 1995 has been one of the great successes of the CDF and D0 experiments at the Tevatron collider. Since then, both collaborations have measured the properties of the top quark in many channels and using different methods. The results obtained for the top quark mass are competitive with those from the CERN Large Hadron Collider, and the first combination of measurements from the two colliders has recently been performed to obtain a relative uncertainty of 0.44%. In these proceedings a selected review of the most recent or relevant results obtained by the CDF and D0 Collaborations is presented, together with the first "World Average".

1 Introduction

Since the first observation of the top quark (t) by the CDF and D0 experiments at the Tevatron collider in 1995 [1,2] the large value of its mass (M_{top}) represents a striking property of this particle. If the scalar boson recently observed by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) [3] is identified as the SM Higgs boson, the top quark is by far the heaviest particle in the SM with the three generations of fermions observed so far. This makes its contribution to higher order corrections to many electroweak observables dominant so that a precise knowledge of M_{top} is fundamental in checking the consistency of theoretical predictions of the SM by the electroweak fits [4]. This and other reasons pushed the CDF and D0 collaborations to measure M_{top} in all possible topologies related to top quark pair ($t\bar{t}$) events production and to improve the used techniques. Shortly after the Tevatron shutdown in September 2011, the whole samples of data collected by the experiments, corresponding to about $10\,\mathrm{fb}^{-1}$ of $p\bar{p}$ collisions each, became available for analyses, allowing therefore to reach the smallest achievable statistical uncertainty.

2 Top Quark Production, Decay and Signatures

In the Run II of the Tevatron collider, started in March 2001, bunches of protons and antiprotons were brought into collision with a center-of-mass energy, $\sqrt{s}$, equal to 1.96 TeV and data were collected by the multipurpose CDF and D0 detectors [5,6]. At this energy top quarks are predominantly produced in $t\bar{t}$ pairs by $q\bar{q}$ annihilation ($\sim 85\%$ of the times) or gluon-gluon fusion ($\sim 15\%$). In the SM framework they decay to a W boson and a b-quark with a branching ratio (BR) very close to 100% so that the different final states of $t\bar{t}$ ("signal") events can usually be classified by the decays of the W boson pair to leptons ($W \to \ell\nu_l$) or quarks ($W \to q_1\bar{q}_2$) as the "di-lepton channel" (BR $\simeq 9\%$), the "lepton + jets channel" (BR $\simeq 45\%$) and the "all-hadronic

[a] The status of the M_{top} measurements presented here dates back to the time of the XLIXth Rencontres de Moriond 2014, i.e. to March 2014. At the moment of submitting this note a new, very precise result obtained by the D0 Collaboration has just been made public (arXiv:1405.1756, May 2014)

channel" (or all-jets channel, BR $\simeq$ 46%). The signal signatures used in analyzing the data correspond to the final states and have similar nomenclature, but usually the "di-lepton" and "lepton + jets" analyses consider only events with electrons and muons directly produced from the W decays, excluding therefore events with taus and reducing the BR's to about 5% and 30%, respectively. In order to cover all the possible kind of events a "missing transverse energy + jets" ($\not\!\!E_T$ + jets) signature is also defined.

The current theoretical predictions for the $t\bar{t}$ production cross section at $\sqrt{s} = 1.96\,\text{TeV}$ are in the range 7.0$\div$7.6 pb for $\text{M}_{\text{top}} = 172.5\,\text{GeV}$ [7] so that at the Tevatron one signal event was produced in about 10^{10} inelastic $p\bar{p}$ collisions. This makes the measurement of any of the top quark properties a really challenging task, requiring tools and selection techniques exploiting at the best the peculiar features of the signal. An important example is the identification of jets generated by b-quarks ("b-tagging"), fundamental in reducing the background yield and also the combinatoric problem related to possible jet-to-quark assignments. In measuring M_{top}, the reconstruction of the kinematics of the event is crucial. The estimate of the parton energy requires an accurate knowledge of the correction to be applied to the measured jet energy (Jet Energy Scale, JES), due to instrumental effects or jet clustering algorithms.

3 Measurement Techniques

Apart from the peculiarities of each individual measurement and with a few exceptions, two main techniques are used by the CDF and D0 collaborations to extract the value of M_{top} from a sample of selected events : the *Matrix Element Method* (ME) and the *Template Method* (TMT).

In the ME, the probability that a set $\vec{y}$ of variables is observed is evaluated as a function of the possible event kinematics $\vec{x}$ (depending on M_{top} for $t\bar{t}$) at parton level, given "transfer functions" $\mathcal{W}(\vec{y}, \vec{x})$ taking into account detector effects and the event reconstruction. In the TMT a set of event observables, $\vec{y}$, sensitive to M_{top} is considered and their *expected* distributions are used as references ("templates") for the data in the measurement. In both methods a likelihood, written as the product of individual event probabilities, is then usually maximized as a function of M_{top} to extract the value which gives the largest probability to observe the selected set of events.

By now, a well established and important feature of most analyses is the calibration of the JES simultaneously (*in situ*) with the M_{top} measurement, constraining the four-momenta of jets assigned to a W by its well known mass. This technique allows a part of the JES uncertainty to scale down with the data statistics.

4 M_{top} Measurements by the CDF and D0 Experiments

In this section a brief summary of most recent results obtained by the two Tevatron Collaboration as it concerns M_{top} is presented. A more complete overview can be found in [8]. The measurements by the CDF Collaboration have recently been updated in all channels to include the full set of data collected by the detector. The integrated luminosity of the data samples can change as a function of the main triggers and subdetectors involved in the event selection and reconstruction. All these new analyses are based on TMT and, when possible, include the *in situ* JES calibration. At present, analyses from the D0 experiment are based to integrated luminosities up to $5.4\,\text{fb}^{-1}$, i.e. about half of the available statistics, but new results are expected soon.

4.1 Di-Lepton Channel

The fully leptonic channel usually provides the candidate samples with the best signal-to-background ratio (S/B) because of the presence of two energetic, high-p_T leptons and the b-jets. Moreover the combinatoric problem in assigning jets to partons is small. Unfortunately it suffers of a small BR and the kinematics of the events is underconstrained because the reconstructed $\not\!\!E_T$ results from two undetected neutrinos. As there is no W decaying to hadrons, the *in situ* JES calibration cannot be performed in this channel.

The updated TMT analysis from the CDF Collaboration [9] is based on 9.1 fb^{-1} of data. Two different event variables are considered: a top quark mass (M_t^{reco}), reconstructed by the so-called "Neutrino Weighting Algorithm" (NWA), and an "alternative" mass (M_t^{alt}) which is not based on the energies of jets to be insensitive to the JES, so that its distribution is not affected by the corresponding uncertainty. An hybrid variable (M_t^{eff}), obtained as a weighted sum of M_t^{reco} and M_t^{alt}, is then defined to build the template distributions used in the measurement. The likelihood fit to the data gives $\mathrm{M_{top}} = 170.80 \pm 3.25\,\mathrm{GeV}$, with a total relative precision of $\approx 1.9\%$. Figure 1, left, shows the fitted templates for events with no b-tagged jet.

Two different results are combined by the D0 Collaboration to obtain a better measurement in this channel. The result of a ME analysis performed on 5.4 fb^{-1} of data [10] is combined with one using TMT with NWA [11] and based on a total of 5.3 fb^{-1}. An example of templates used in the latter analysis is shown in Fig. 1 right. A peculiarity of this analysis is that the JES is calibrated using the value obtained in the lepton + jets channel [12]. The final result is $\mathrm{M_{top}} = 173.9 \pm 2.4\,\mathrm{GeV}$, with a precision of $\approx 1.4\%$.

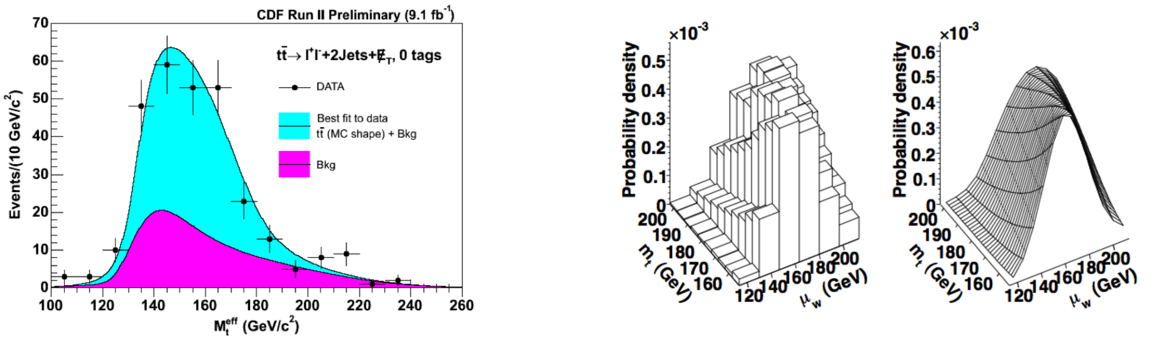

Figure 1 – Left: observed data and fitted templates for events with no b-tagged jet in the CDF $\mathrm{M_{top}}$ measurement in the di-lepton channel [9]. Right: example of templates (both histogram and the corresponding smooth parametrization) as a function of the input top quark mass as used in the di-lepton measurement by D0 [12]

4.2 Lepton + Jets Channel

The final state including one charged lepton and jets can be considered the "golden channel" as it concerns the measurements of the top quark properties. In fact it offers the best compromise between the purity of selected samples and the available statistics because of its large BR. This allows the experiments to achieve their best results in this channel.

The result obtained by the CDF Collaboration with the most recent analysis [13] and 8.7 fb^{-1} of data represents the most precise individual $\mathrm{M_{top}}$ measurement from the Tevatron experiments so far, reaching a precision $\sigma_{\mathrm{M_{top}}}/\mathrm{M_{top}} \approx 0.6\%$. It exploits the TMT technique based on the simultaneous fit of three different distributions to the data. One of them, the invariant mass of the jets assigned to the quarks from the W decaying to hadrons in the event reconstruction, m_{jj}, is used to calibrate the JES. The fit to the data gives $\mathrm{M_{top}} = 172.85 \pm 1.11\,\mathrm{GeV}$. Figure 2 shows the fitted templates compared to observed data.

The result described in [12] is the most precise measurement obtained by the D0 Collaboration at present, even if it is based on a total integrated luminosity of 3.6 fb^{-1} only. The main analysis is performed on 2.6 fb^{-1} and then combined with a previous result obtained with 1.0 fb^{-1}. A likelihood based on the ME method is maximized, including the *in situ* JES calibration and the final combination gives $\mathrm{M_{top}} = 174.94 \pm 1.49\,\mathrm{GeV}$ so that $\sigma_{\mathrm{M_{top}}}/\mathrm{M_{top}} \simeq 0.9\%$.

4.3 All-Hadronic Channel

The all-hadronic channel has the advantage of the large BR and the possibility to reconstruct completely the event kinematics because ideally no particle from the $t\bar{t}$ system escapes the detector. The major downside is the huge background from QCD multijet production which greatly dominates the signal even after the application of specific triggers.

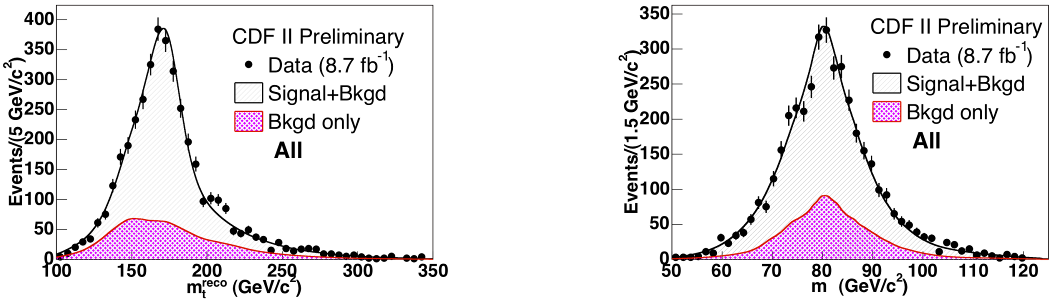

Figure 2 – Fitted templates are compared to observed data in the CDF analysis [13] for two out of the three used variables : the reconstructed top quark mass ($m_t^{\rm reco}$, left plot) and the invariant mass of jets assigned to the W boson (m_{jj}, right plot)

Measurements in this channel has been so far performed by the CDF Collaboration only, even if a result from the D0 experiment should be available soon. The analysis was updated very recently [14] and the new result is based on $9.3\,{\rm fb}^{-1}$ of data. An event selection exploiting a Neural Network with 13 input kinematic and jet shapes variables is used, together with the requirement of at least one b-tagged jet, to obtain a good signal-to-background ratio in this difficult channel. Two variables, a "top quark mass" $m_t^{\rm rec}$ and a "W mass" $m_W^{\rm rec}$, are reconstructed event by event and their distributions are used as templates. The result from the likelihood fit, including JES calibration, is $\rm M_{top} = 175.07 \pm 1.96\,GeV$, with a precision $\approx 1.1\%$. Figure 3 shows examples of $m_t^{\rm rec}$ templates and the fitted distributions compared to data.

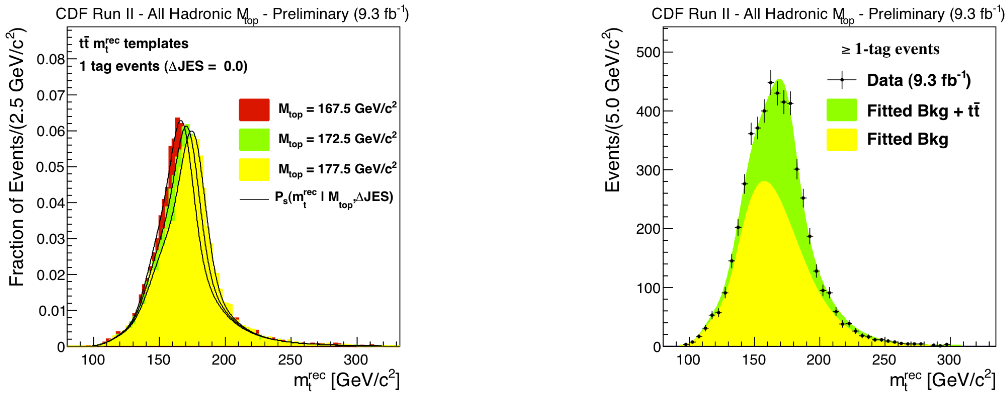

Figure 3 – Left : examples of templates used in the CDF measurement in the all-hadronic channel[14] as a function on the input $\rm M_{top}$. Right : distribution of the $m_t^{\rm rec}$ variable as observed in the data is compared to the fitted templates.

4.4 $\not\!\!E_T$ + jets Channel

As outlined in Sec. 2 the $\not\!\!E_T$ + jets signature is usually defined to be complementary to all the other measurement channels, with large $\not\!\!E_T$ (differently from the all-hadronic channel) and no energetic and isolated lepton (to reject events falling in the usual leptonic channels).

In this channel a result obtained by CDF with the full dataset ($8.7\,{\rm fb}^{-1}$) is available [15]. The analysis presents features similar to both the all-hadronic one [14], as it concerns the background modeling and kinematical event selection, and to the lepton + jets [13], as the same variables are reconstructed for the templates. In the event reconstruction the $\not\!\!E_T$ is totally assigned to the W boson decaying leptonically, assuming that also the charged lepton escapes detection. The result is $\rm M_{top} = 173.93 \pm 1.85\,GeV$ yielding a precision of 1.1%.

5 Systematic Uncertainties

Given the final amount of data collected by the experiments most of the measurements of $\rm M_{top}$ at the Tevatron are limited by systematic uncertainties. During the years the CDF and

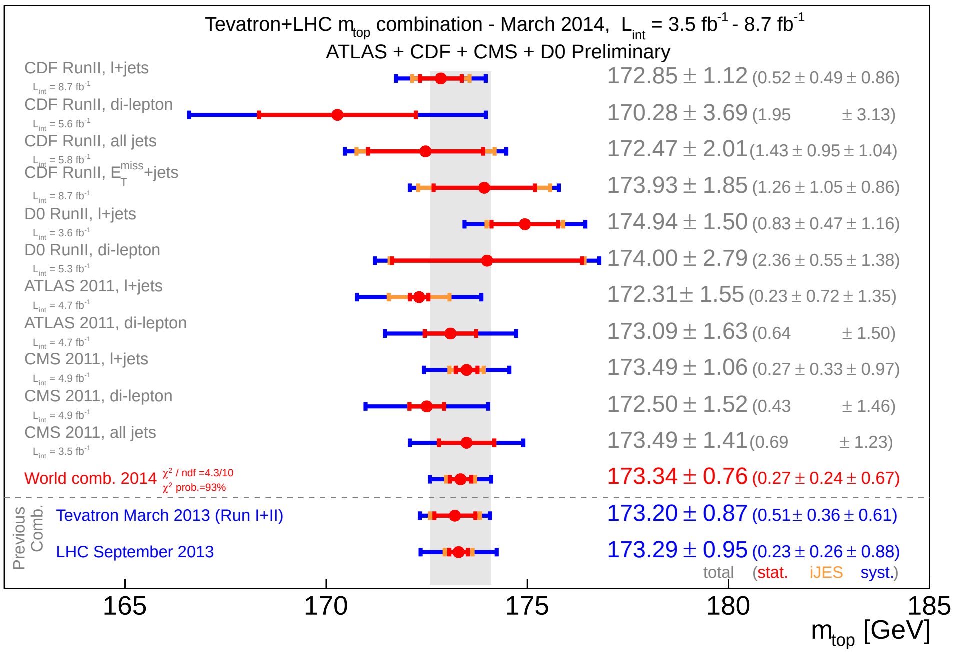

Figure 4 – Input measurements to the M_{top} World Average and result of their combination. The individual Tevatron (reported in Sec. 6) and LHC combined values are also reported

D0 collaborations have performed a strong joint effort to define a common way to evaluate the systematics, to improve the knowledge of important effects, to avoid overlaps and double countings and to define properly the possible correlations between the various sources. The most important uncertainties are related to Monte Carlo simulation of signal and background processes and include the choice of the event generator and e.g. the modeling of initial and final state radiation, color reconnections and parton distribution functions.

6 Tevatron M_{top} Combination and First World Average

The CDF and D0 experiments regularly combine their best results from each channel both internally (*i.e.* within each experiment separately) and in a unique number representing the Tevatron M_{top} average. In such combinations correlations among uncertainties for different results are properly taken into account.

The last Tevatron combination has been performed in March 2013 [16] and includes most, but not all the results reported in these proceedings. The value obtained is $M_{top} = 173.20 \pm 0.87$ GeV with a χ^2/d.o.f. probability of 67%, denoting a good agreement among all measurements. The relative precision is $\approx 0.50\%$. As it concerns the individual combinations, the CDF Collaboration just updated its result using all the measurements with the full statistics obtaining $M_{top} = 173.16 \pm 0.93$ GeV [17], while D0 presently uses no more than 5.4 fb^{-1} of data to obtain $M_{top} = 175.08 \pm 1.47$ GeV [8].

In March 2014 the very first combination of measurements obtained both at the Fermilab Tevatron and the CERN LHC colliders has been finalized by the ATLAS, CDF, CMS and D0 Collaborations. This combination concerns just the top quark mass and includes the best measurements in each channel obtained by the four experiments during the Run II of the Tevatron (for CDF and D0, but the most recent updates presented here are excluded) and with the data collected during the 2011 Run of the LHC (pp collisions at $\sqrt{s} = 7$ TeV) by ATLAS and CMS [18].

The first M_{top} World Average is $M_{top} = 173.34 \pm 0.76$ GeV, obviously representing the best measurement for this fundamental parameter of the SM so far, with a precision $\approx 0.44\%$. This result improves by 13% the best combination from a single collider and by 28% the best individual measurement used as an input in the combination, as can be appreciated by the summary reported in Fig. 4. A special effort has been required from the collaborations in dealing with the systematic uncertainties, in order to find a common pattern for their classification and reliable estimates of the correlations, given the differences in detector effects, Monte Carlo simulations and analysis techniques. Many assumptions have been checked to verify the stability of the central value and its uncertainty.

7 Conclusions

The Fermilab Tevatron collider has been shut down in September 2011. The CDF and D0 Collaborations are finalizing the measurements of the top quark mass, one of main goals of their physics program, using the full available data statistics, amounting to about $10\,\mathrm{fb}^{-1}$. The precision reached by the single measurements and in their combination is by far beyond the goal planned for the Tevatron Run II, and, even if not all of them have been updated to the whole statistics yet, the final absolute uncertainty on $\mathrm{M_{top}}$ from the Tevatron experiments is below 1 GeV, with a precision $\approx 0.5\%$, very competitive with the measurements obtained at the LHC. In these proceedings a selected review of the most recent results from CDF and D0 has been presented, together with the first combination of measurements between the Tevatron and LHC Collaborations, resulting in the first "$\mathrm{M_{top}}$ World Average": $\mathrm{M_{top}} = 173.34 \pm 0.76\,\mathrm{GeV}$, pushing the knowledge of this fundamental parameter of the SM close to the 0.4% level.

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