TOP QUARK MASS MEASUREMENTS AT THE TEVATRON

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We present recent measurements of the mass of the top quark performed at the Tevatron $p\bar{p}$ collider at a center-of-mass energy of 1.96 TeV. These measurements use the full Run II data samples corresponding to an integrated luminosity of up to 9.3 fb^{-1}. We also report the first world combination of the measurements from the Large Hadron Collider and Tevatron experiments resulting in a top mass of 173.34 ± 0.76 GeV with a relative precision of 0.44%.

1 Introduction

The top quark discovered in 1995 by the CDF and D0 Collaborations at the Fermilab Tevatron proton-antiproton ($p\bar{p}$) collider [1] is the heaviest fundamental particle among observed. Due to its large mass, the top quark has a very short lifetime, about one order of magnitude smaller than the hadronization time scale, implying it can decay before hadronization takes place. This feature allows the top quark properties to be directly measured and thereby the top quark sector provides a unique place to study bare quark. In addition, a large Yukawa coupling of almost unity indicates that the top quark may play a crucial role in electroweak symmetry breaking.

The mass of the top quark (m_t or m_{top}) is a fundamental parameter of the standard model (SM) of particle physics because it is connected with the masses of the W boson and the Higgs boson in the electroweak theory [2] as shown in Fig. 1. Therefore, precise measurements of the mass of the top quark provide a crucial test of the internal consistency of the SM and could hint at physics beyond the SM. The value of the top quark also has cosmological implications through the so-called vacuum stability of the universe [3].

2 Experimental Methods

At hadron colliders, the dominant production mode of top quarks is the $t\bar{t}$ pair creation via the strong interaction. In the SM, the top quark decays almost always to a W boson and a b quark. $t\bar{t}$ events can be categorized into three final states depending on how the W bosons decay: i) dilepton final states where both W bosons decay leptonically; ii) lepton+jets where one of the W bosons decays leptonically while the other hadronically; and iii) all-jets where both W bosons decay hadronically.

The most common techniques utilized for the measurement of the top quark mass at the Tevatron are two fold: template method and matrix element method.

2.1 Template Methods

The template method interprets the distributions of a set of variables which are sensitive to the top quark mass, e.g. reconstructed mass, as probability densities. Distributions of such

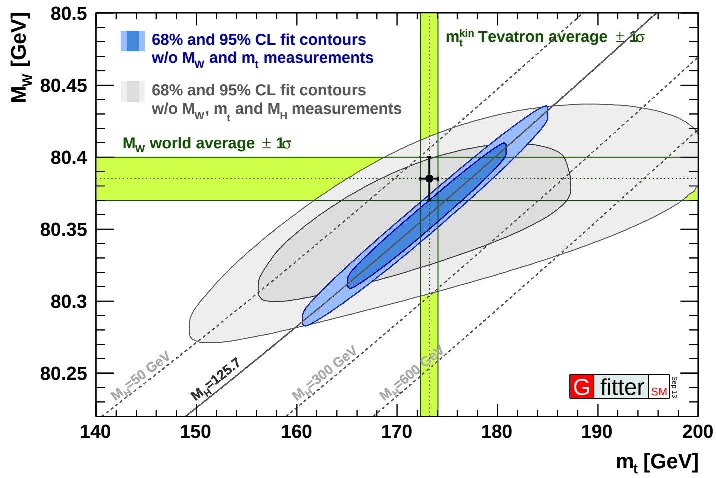

Figure 1 – Contours of 68% and 95% confidence level obtained from the EW global fit in the (M_W, m_t) plane. The narrower blue and wider gray regions are the results of the fit including and excluding the Higgs mass measurements, respectively. The vertical and horizontal bands represent the 1σ bands of the world averages of M_W and m_t [4].

observables, referred to as templates, are constructed from simulated events for different top quark masses and then the likelihood fit is performed to the data to extract the top quark mass.

2.2 Matrix Element Methods

Exploring the topology of the event, the matrix element (ME) method calculates the probability of each event being signal for a given mass hypothesis. The probability is written by

$$P_{sgn}(x;H) = \frac{1}{\sigma_{obs}} \int f_{PDF}(\epsilon_1) f_{PDF}(\epsilon_2) d\epsilon_1 d\epsilon_2 \frac{(2\pi)^4 |M(y,H)|^2}{\epsilon_1 \epsilon_2 s} d\Phi_6 W(x,y), \tag{1}$$

where σ_{obs} denotes the observable cross section, f_{PDF} the parton distribution function (PDF), ϵ_1 and ϵ_2 the momentum fractions of the incoming partons from the protons and antiprotons, $\sqrt{s}$ the center of mass energy, $M(y,H)$ the leading order matrix element for a given mass hypothesis (H), and $d\Phi_6$ the infinitesimal volume element of the 6-body phase space. The finite detector resolution is taken into account by the transfer functions $W(x,y)$ that provide the normalized probability of a set of parton four-momenta y to be measured as x. In general, the ME technique yields a better statistical sensitivity since it makes a maximal use of the topological and kinematic information in the event.

2.3 In-situ Jet Energy Scale Calibration

One of the largest uncertainties on measurements of the top quark mass stems from the uncertainty on the jet energy scale (JES). For lepton+jets and all-jets analysis channels, this particular uncertainty can be reduced using a mass constraint of the W boson. The JES can be calibrated for each event by requiring the invariant mass of the reconstructed W boson in the dijet system to be consistent with the mass of the W boson of 80.4 GeV. Referred to as *in-situ* JES calibration, this provides an additional scaling to jet energy for signal events, k_{JES}, which is extracted simultaneously with the top quark mass.

3 New Measurements

Since the Tevatron combination of the top quark mass measurements in 2013 [5], there have been a few updated results from the Tevatron experiments.

3.1 Measurements in Dilepton Final States

CDF finalizes the analysis in the dilepton channel using the template method with the full statistics corresponding to an integrated luminosity of 9.1 fb^{-1} [6]. A "hybrid variable" consisting of two independent variables is introduced: one that is most sensitive to the top quark mass (reconstructed m_t) and the other that is sensitive to the top quark mass but insensitive to the JES (such as angle of leptons or jets). A weighted sum of these two variables is used to construct the templates. The weight is determined to be optimal for the measurement. This new variable allows a reduction of the convoluted uncertainty (stat$\oplus$JES) by 12% with respect to the result using only the reconstructed m_t.

The selected events are divided into two subsamples according to the number of b-tagged jets (non-tagged vs. tagged). The likelihood function is defined as a product of individual likelihood functions obtained for these independent subsamples. The top quark mass is extracted by performing an unbinned likelihood fit of the templates to data. The obtained result is $m_{\rm top} = 170.80 \pm 1.83(\text{stat.}) \pm 2.69(\text{syst.}) = 170.80 \pm 3.25$ GeV and the resulting top mass distributions are shown in Fig. 2. The dominant systematic uncertainty of 2.4 GeV is due to the JES.

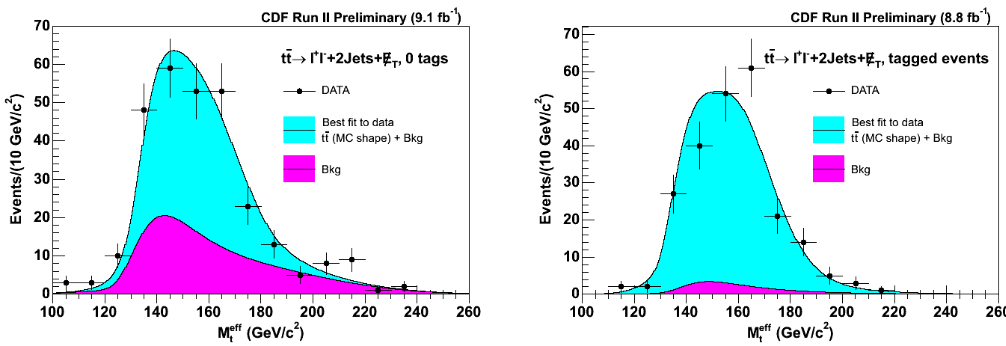

Figure 2 – Reconstructed top quark mass distributions from an unbinned likelihood fit for non-tagged (left) and tagged (right) subsamples.

3.2 Measurements in All-jets Final States

CDF also performs the measurement of the top quark mass in the all-jets final states using the template method with the Run II full dataset of 9.3 fb^{-1} [7]. The event selection is tuned to maximize the signal fraction in the sample using a neural network technique based on 13 kinematic input variables. The selected events are subdivide in events with exactly one tagged jet (1-tag sample) and two or more tagged jets (2-tag sample). The kinematics of the event are reconstructed by minimizing a constrained kinematic fit χ^2 to the top quark and W boson decays. The measurement relies on the comparison of mass distributions of the reconstructed top quark and W boson in the data to expected distributions from signal Monte Carlo (MC) and data-driven background events. It also employs the simultaneous (*in situ)* JES calibration and the top quark mass is extracted through an unbinned likelihood technique. By minimizing the negative log-likelihood in a 2D space between m_t and ΔJES, the top quark mass of $m_{\rm top} = 175.07 \pm 1.19(\text{stat.})\,^{+1.55}_{-1.58}(\text{syst.})$ GeV is obtained with a corresponding resolution of $\sigma(m_{\rm top})/m_{\rm top} = 1.1\%$. Figure 3 shows the distributions of reconstructed m_t and m_W, and the behavior of the likelihood as a function of the measured $m_{\rm top}$ and ΔJES parameters. The main systematic uncertainties from the residual JES and trigger simulation are evaluated to be about 0.6 GeV.

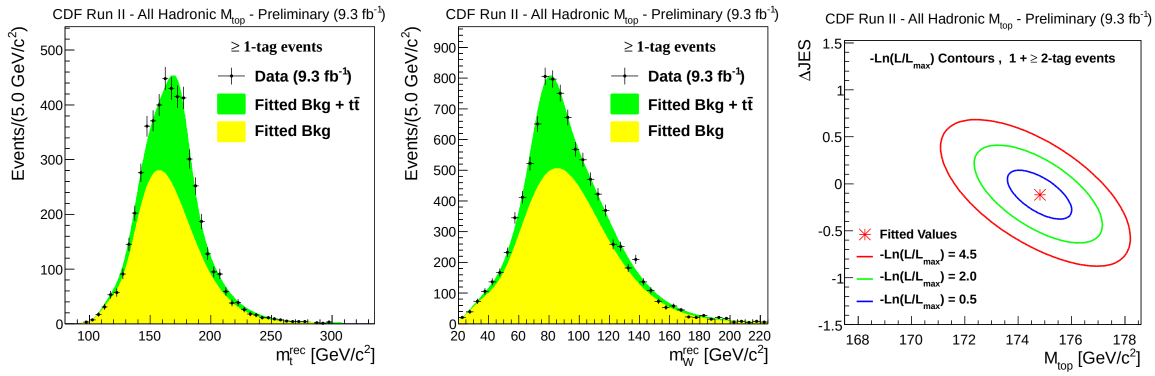

Figure 3 – Distributions of m_t (left) and m_W (middle) as obtained in the data (black points) are compared to the probability density functions from signal and background for the inclusive $\geq 1b$-tagged sample. Contours of the measured likelihood in the m_{top} and ΔJES parameter space (right) corresponding to one, two and three standard deviations. The fitted central values, corresponding to the maximum likelihood (or minimum ln L), are also shown

3.3 CDF Combination

The final combination of the measurements of the top quark mass performed at the CDF experiment is reported [7]. Three published results using 0.1 fb^{-1} of data in collisions at $\sqrt{1.8}$ TeV during Run I (1992-1996) [11,12,13] are combined with three published [14,15,18] and two preliminary measurements, described above, based on data corresponding to $8.7 - 9.3$ fb^{-1} during Run II (2001-2011). The combination is performed using two independent methods: a numerical χ^2 minimization and the analytic best linear unbiased estimator (BLUE) [9,10]. It is verified that they yields consistent results for the combination. Taking the correlations of systematic uncertainties among different input measurements into account, the BLUE determines the coefficients (weights) to be used in a linear combination of the measurements by minimizing the total uncertainty of the combined result.

The resulting CDF average mass of the top quark is $m_{\text{top}} = 173.16 \pm 0.57(\text{stat.}) \pm 0.74(\text{syst.})$ GeV with a total uncertainty of 0.93 GeV. The input measurements and the resulting CDF mass of the top quark are summarized in Fig. 4. The mass of the top quark is measured with a relative precision of 0.54%, limited by the systematic uncertainties with dominant contributions from the uncertainties on the jet energy scale and signal modeling. Since the combination is achieved using measurements based on the full Tevatron dataset, this is the final report from the CDF collaboration on the top quark mass.

4 World Combination

Collaborations from the Tevatron and Large Hadron Collider (LHC) experiments perform a world combination of the top quark mass measurements. The chosen inputs to the combination correspond to the best measurements per channel of each experiment. They consist of six results from the Tevatron collider based on Run II $p\bar{p}$ data collected at $\sqrt{s} = 1.96$ TeV [a], and five results from the LHC based on pp data at $\sqrt{s} = 7$ TeV. An overview of the input m_{top} measurements used in this combination is shown in Table 1.

The combination is performed using the BLUE method. Both statistical and systematic uncertainties are assumed to follow Gaussian probability density functions and their correlations among different channels, experiments, and colliders are taken into account. Systematic uncertainties on m_{top} are classified into three categories: i) JES, ii) theory and signal modeling, and iii) detector modeling, background contamination and environment. Realistic estimates of

[a] Only a partial set of Tevatron measurements is used in the world combination.

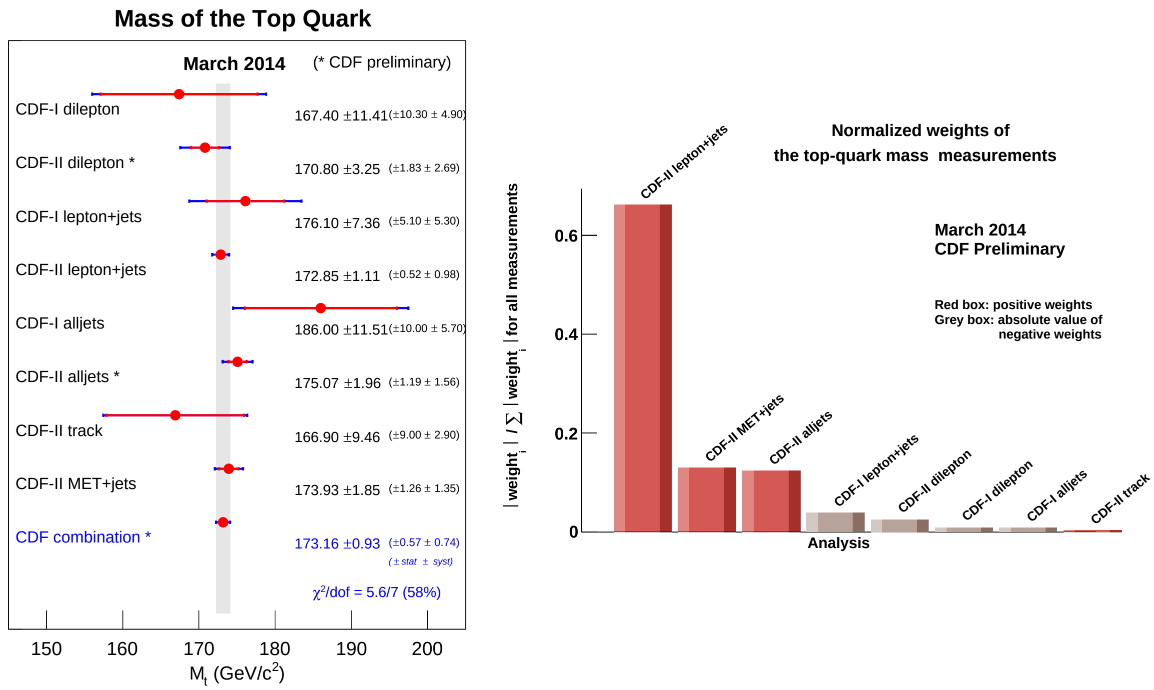

Figure 4 – Summary of the input measurements and resulting combination of the top quark mass from the CDF experiment (left) and relative weights of the input measurements in the combination (right).

the correlations among measurements within the same experiment or across experiments and uncertainty treatments are made.

Using the BLUE method, taking statistical and systematic uncertainties and their correlations into account, the resulting combination yields $m_t = 173.34 \pm 0.27(\text{stat.}) \pm 0.71(\text{syst.})$ GeV with a total uncertainty of 0.76 GeV. The χ^2 of the combination is 4.3 for 10 degrees of freedom and the corresponding probability is 93%. Figure 5 summaries the inputs and the results of the combination.

The corresponding relative precision is 0.44% corresponding to the most precise evaluation of the top quark mass. The world combination achieves an improvement of the total uncertainty of 13% relative to the previous most precise combination [5]. The total uncertainty of the com-

Table 1: Overview of the 11 input measurements used in this m_{top} combination and the baseline MC programs for $t\bar{t}$ signal events. All experiments use the Pythia program for parton evolution.

Experiment	Final state	L_{int} [fb^{-1}]	$m_{\text{top}} \pm$ (stat.) $\pm$ (syst.) [GeV]	MC	Ref.
CDF	letpon+jets	8.7	$172.85 \pm 0.52 \pm 0.99$	Pythia	15
	dilepton	5.6	$170.28 \pm 1.95 \pm 3.13$		16
	all jets	5.8	$172.47 \pm 1.43 \pm 1.41$		17
	$\not\!\!E_T$+jets	8.7	$173.93 \pm 1.26 \pm 1.36$		18
D0	letpon+jets	3.6	$174.94 \pm 0.83 \pm 1.25$	Alpgen	19
	dilepton	5.3	$174.00 \pm 2.36 \pm 1.49$		20
ATLAS	letpon+jets	4.7	$172.31 \pm 0.23 \pm 1.53$	Powheg	21
	dilepton	4.7	$173.09 \pm 0.64 \pm 1.50$		22
CMS	letpon+jets	4.9	$173.49 \pm 0.27 \pm 1.03$	Madgraph	23
	dilepton	4.9	$172.50 \pm 0.43 \pm 1.46$		24
	all jets	3.5	$173.49 \pm 0.69 \pm 1.23$		25

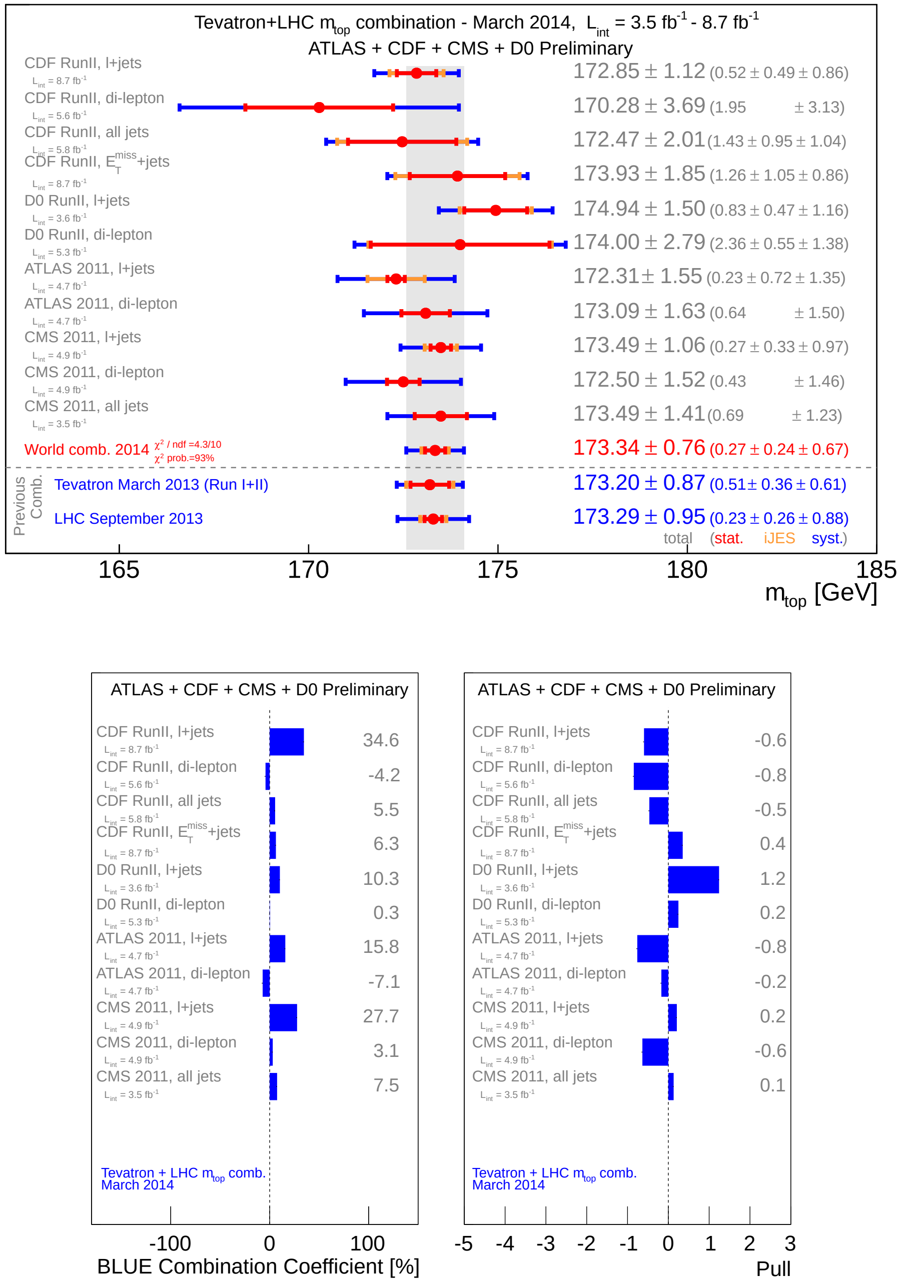

Figure 5 – Input measurements and result of their combination compared with the Tevatron and LHC combinations [5,26] (top). For each measurement, the iJES contributions (when applicable) are reported separately. The gray vertical band reflects the total uncertainty on the combined value of $m_{\rm top}$. The BLUE combination coefficients and pulls of the input measurements are shown on the bottom left and right, respectively.

bination is 0.76 GeV, and is currently dominated by systematic uncertainties due to modeling of the $t\bar{t}$ signal events and *in situ* jet energy calibration. Effects of using alternative correlation assumptions on the final result are evaluated by performing stability cross checks and found to be small compared to the current $m_{\rm top}$ precision.

5 Summary

Recent measurements of the mass of the top quark performed at the Tevatron experiments are presented. They utilize the full statistics of the $p\bar{p}$ collision data during Run II corresponding to up to 9.3 fb^{-1}. The first world combination of the top quark mass measurements from four experiments from Tevatron and LHC is reported. This yields $m_{top} = 173.34 \pm 0.27(\text{stat}) \pm 0.71(\text{syst})$ GeV and provides the most precise determination of the top quark mass. More precise results are expected by the Tevatron and LHC Collaborations.

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