EPJ Web of Conferences **60**, 16007 (2013)
DOI: 10.1051/epjconf/20136016007

Top quark mass measurements with CMS

Hamed Bakhshiansohi[1,a] on behalf of the CMS Collaboration

[1] *IPM, Tehran, Iran*

Abstract. We present a review of latest top quark mass measurement results from the CMS experiment. All decay modes of $t\bar{t}$ events including dileptonic, lepton + jets and full hadronic channels are used to measure the top quark mass. The combined result is also presented. CMS has studied the dependence of the top mass measurement to different kinematic variables. The latest result of the top and antitop mass difference obtained by the full 2012 dataset is reported.

1 Introduction

Precise measurement of the properties of the top quark is essential to test the Standard Model (SM). The top quark mass is one of the most important inputs to the global electroweak fits [1]. After the discovery of the Higgs boson [2] [3], more precise measurement of the parameters of the SM, especially the top quark mass which is the heaviest particle observed so far, is crucial to check the consistency of the SM. The top quark mass (m_t) has been measured by CDF and D0 collaborations with great precision, resulting in the combined value $m_t = 173.20 \pm 0.87 \mathrm{GeV/c^2}$ [4] as the current world average. Measurement of the top mass by the CMS experiment[5] at the Large Hadron Collider (LHC) in addition to providing an independent cross-check to the Tevatron results helps to achieve a more precise m_t value.

2 Top mass measurement

In proton-proton collisions the top quarks are mostly produced in the top-antitop pairs ($t\bar{t}$). The top quark decays most of the time into a b quark and a W boson. Therefore the $t\bar{t}$ events can be categorized according to the decay of the W bosons. If both W bosons decay into leptons (e or μ) the event is categorized as dilepton ($t\bar{t} \to b\bar{b}l\nu_l l'\nu_{l'}$). Although just 4% of $t\bar{t}$ events decay into dileptons, the low background rate is an advantage of the study of this channel. The lepton + jets channel, where just one W boson decays leptonically, has a moderate background rate together with a considerably more branching fraction. The most probable $t\bar{t}$ decay mode is when both W bosons decay hadronically. Due to the nature of hadron colliders in which so many QCD events are produced, the most challenging channel is the fully hadronic decays of $t\bar{t}$ events.

During 2011 run of LHC at $\sqrt{s} = 7\,\mathrm{TeV}$, the CMS experiment has recorded an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$ of data. This data was used to perform the top quark mass measurement.

2.1 Dileptonic channel

The existence of two leptons in the final state of $t\bar{t}$ decay results in a high purity selection. The two neutrinos scape detection, together resulting in an energy imbalance measured as Missing Transverse Energy (MET). CMS has used two methods to resolve the MET ambiguity and extract the top quark mass from the full 2011 dataset.

2.1.1 Analytical Matrix Weighting Technique

For different top mass hypotheses the $t\bar{t}$ event is reconstructed by solving a set of analytical kinematic equations [6]. All event solutions are weighted according to the probability of finding the leptons at their observed energy given the top quark mass hypothesis. For each event, the top mass with the maximum summed weight value is chosen as the reconstructed top quark mass, m_{AMWT}. A likelihood function is constructed comparing the distribution of m_{AMWT} in data and simulation with different top quark masses between 161.5 and 184.5 GeV. The top mass is read by maximizing the likelihood function. Figure 1 illustrates the distribution of m_{AMWT} for the $m_t = 172.5\,\mathrm{GeV}$ hypothesis in simulation. It also includes the likelihood function for different top quark masses. The measurement, yielding $m_t = 172.5 \pm 0.4(\mathrm{stat.}) \pm 1.5(\mathrm{syst.})\mathrm{GeV}$, is dominated by systematic uncertainties.

2.1.2 Endpoint method

The M_{T2} variable [7] is an extension to the M_T variable where two invisible particles exist in the final state. Its kinematic endpoint carries information about the mass of the particles involved in the decay chain. With a proper choice of the subsystem, upstream (ISR), visible (b-tagged jets) and child (leptons and neutrinos), one can measure the top quark mass in the dilepton final state [8]. Two background sources are taken into account: physics

a. e-mail: Hamed.Bakhshian@cern.ch

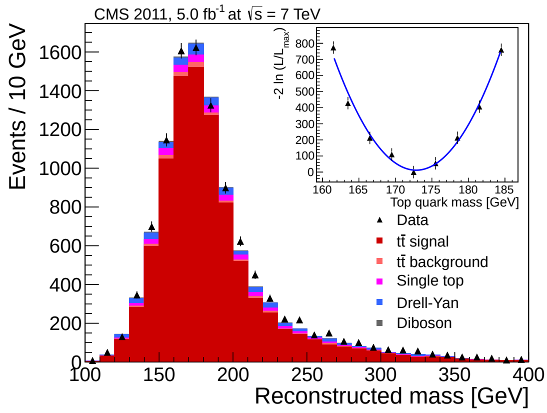


Figure 1: The distribution of the reconstructed mass in data and simulation for the top-quark mass hypothesis which maximizes the likelihood. The behavior of the likelihood function is shown in the inset.

backgrounds with negligible effect on the mass extraction and b-jet misidentification estimated from a control data sample. An unbinned maximum likelihood fit is performed on the M_{T2} distribution resulting in $m_t = 173.9 \pm 0.9(\text{stat})^{+1.6}_{-2.0}(\text{syst})$. The main sources of systematic uncertainties are found to be the Jet Energy Scale (JES) and Jet Energy Resolution (JER). In the same analysis, the masses of the W boson and ν are measured using different definitions for the subsystems.

2.2 Lepton + jets channel

The full 2011 data sample has been searched for lepton + jets decays of $t\bar{t}$ events, corresponding to an integrated luminosity of 5.0 fb^{-1} [9]. The selected events have at least 4 jets and 2 b-tagged jets. A kinematic fit is used to constrain the event to the hypothesis for the production of a pair of a heavy particle decaying to a W boson and a b quark. The reconstructed mass of the two W bosons are fixed to 80.4 GeV. Two b-tagged jets are used as candidates for the b quarks in the $t\bar{t}$ hypothesis and the two leading untagged jets are assumed as the W boson decay products. For each event two permutations are possible. The goodness-of-fit probability (P_{gof}) can be assigned to each permutation using the value of the χ^2 of the fit and if it is lower than 0.2 the permutation is rejected. The accepted permutations are weighted according to the value of P_{gof}. The distribution of the reconstructed mass of the top quark before and after the P_{gof} selection and weighting are displayed in figures 3a and 3b respectively.

To extract the top-quark mass, the ideogram method is used. This method which has been used by DELPHI [10], D0 [11] and CDF [12] collaborations to measure the masses of the W boson and top-quark, determines the JES and the mass simultaneously in a joint likelihood fit to the selected events. The likelihood in the ideogram method is evaluated from analytic expressions obtained and calibrated using simulated events. The 2D likelihood obtained from data is shown in figure 2. The top mass and JES are obtained by maximizing the likelihood function to be $m_t = 174.28 \pm 1.00(stat. + JES) \pm 1.23(syst.)$ and $JES = 0.991 \pm 0.008(stat.) \pm 0.013(syst.)$. Color reconnection effects, b-tagged jets energy scale and p_T and η dependent JES are found to be the main sources of systematic uncertainties.

2.3 Fully hadronic channel

About 70% of the 2011 data sample corresponding to 3.54 fb^{-1} of data has been used to measure the top-quark mass in the fully hadronic final state. Events with at least 6 reconstructed jets are selected. A kinematic fit is applied and the permutations with lowest χ^2 value are chosen. An additional criterion on the distance of the two bottom quark candidates is imposed to reduce the multijet background from $b\bar{b}$ production. The number of events passing each selection step and the signal fractions are given in Table 1. The event mixing method is used to model the backgrounds.

Table 1: Number of events and the expected signal fraction in the data sample after each selection step.

Selection step	Events	Signal fraction
At least 6 jets	786 741	2%
At least two b tags	26 304	17%
$P_{\text{gof}} > 0.09$	3 691	39%
$\Delta R_{b\bar{b}} > 1.5$	2 418	51%

A similar ideogram method as the lepton+jet analysis is used to construct a likelihood function that allows to determine the top-quark mass and JES simultaneously. Two estimations of the top-quark mass are obtained using this

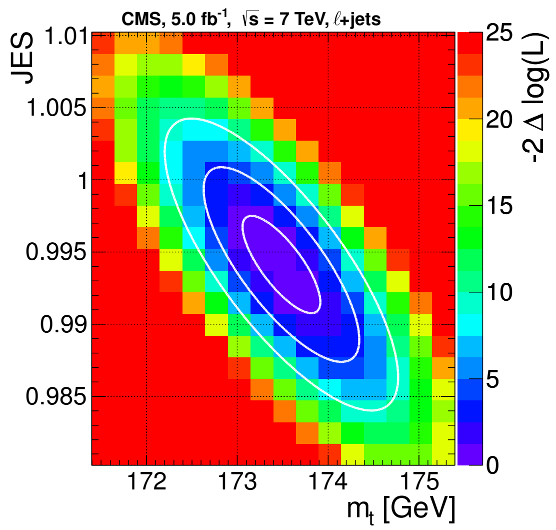
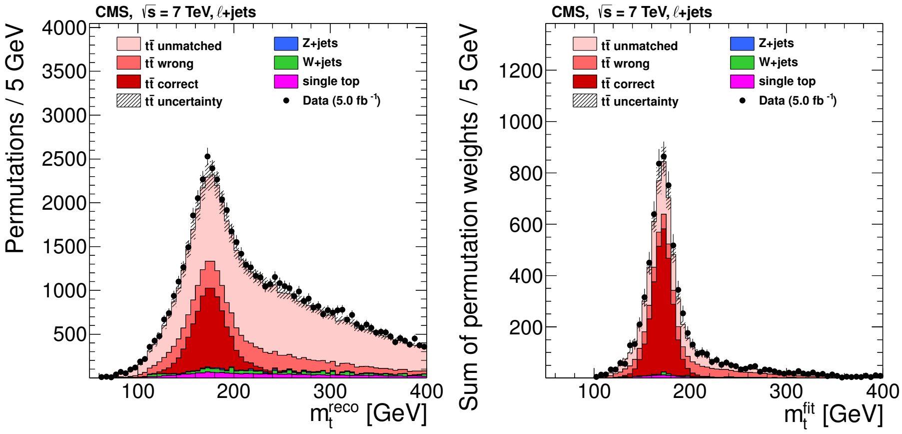


Figure 2: The 2D likelihood measured by the lepton+jets selected events. The ellipses correspond to statistical uncertainties on m_t and JES of one, two, and three standard deviations.



(a) (b)

Figure 3: The reconstructed top-quark mass for the hadronically decaying top quark before (a) and after (b) applying the $P_{\rm gof}$ selection and weighting.

likelihood function, one with a fixed JES (1D) and one simultaneously with the JES(2D). The result of the 1D measurement is $m_t = 173.49 \pm 0.69(stat.) \pm 1.25(syst.)$. The 2D measurement leads to $m_t = 174.28 \pm 1.00(stat. + JES) \pm 1.23(syst.)$ and $JES = 0.991 \pm 0.008(stat.) \pm 0.013(syst.)$.

2.4 Combination

All the results from different decay channels except the results from the end-point method (described in Section 2.1.2) are combined together using the Best Linear Unbiased Estimator method (BLUE) [13]. The results from 2010 data sample are used too in the combination [14, 15]. The resulting combination is

$$m_{\rm t} = 173.36 \pm 0.38\ ({\rm stat.}) \pm 0.91\ ({\rm syst.})\,{\rm GeV}$$

Figure 4 shows a comparison of all obtained value and the CMS combination with the Tevatron combined results.

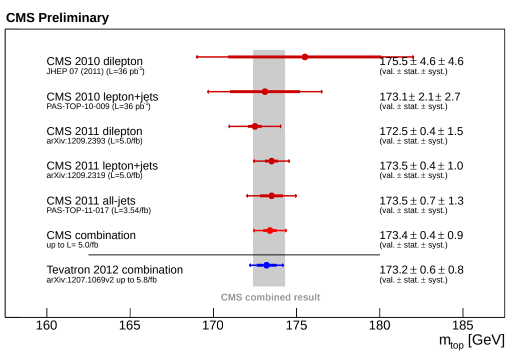


Figure 4: Comparison between CMS and Tevatron combinations, The Tevatron combined result is updated in March 2013 by 8.7fb^{-1} to $m_t = 173.2 \pm 0.87$ [4]

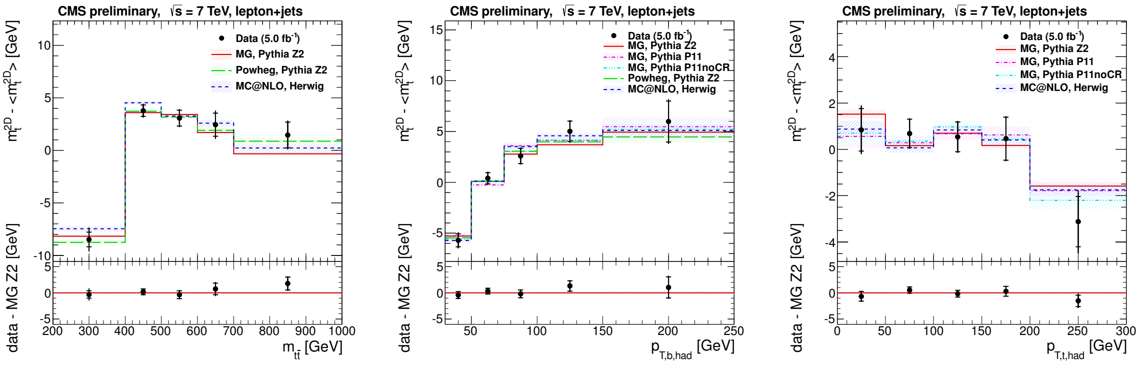
3 Dependence of Top Quark Mass Measurement on Event Kinematics

The differential behavior of the m_t observable versus different kinematic variables is investigated for the first time by the CMS collaboration [16]. This study is essential to test if the current generators can describe correctly the m_t observable in different regions of phase space. It is also important to have a correct interpretation of the top-mass measurements because the pole mass for the top-quark as an unstable and colored particle is not well-defined. The event selection and the top mass reconstruction are similar to the lepton+jets channel analysis described in Section 2.2 which is the most precise single measurement. The top-quark mass is measured versus 12 variables to study the bias of the top quark mass measurement versus 3 different possible kinematic sources : color reconnection effects, initial/final state radiation and the kinematics of the b-quark. The value of the χ^2 reported in Table 2 represents how well data and MC are in agreement.

Table 2: All the variables used to study the dependence of Top Quark Mass Measurement on 3 different biases.

	Observable	$m_t^{2D}\chi^2$	Ndf
Color Recon.	$\Delta R_{q\bar{q}}$	1.49	3
	$\Delta\phi_{q\bar{q}}$	2.89	3
	$p_{T,t,had}$	2.41	4
	$\lvert\eta_{t,had}\rvert$	3.17	3
ISR/FSR	H_T	2.24	4
	$m_{t\bar{t}}$	2.25	4
	$p_{t\bar{t}}$	2.18	4
	# Jets	1.56	2
b. quark kin.	$p_{T,b,had}$	2.17	4
	$\lvert\eta_{b,had}\rvert$	0.48	2
	$\Delta R_{b\bar{b}}$	8.01	3
	$\Delta\phi_{b\bar{b}}$	6.86	3

The top quark mass versus three different kinematic variables is shown in Figure 5. As shown in Table 2 we conclude that within the precision of the current data, no



(a) (b) (c)

Figure 5: Differential measurement of the top-quark mass as a function of (a) the invariant mass of the $t\bar{t}$ system, (b) the p_T of the b-quark and (c) the p_T of the top-quark. The quadratic sum of the statistic and systematic uncertainties of data is presented. The hatched areas represent the statistical uncertainties on the simulated quantities.

mis-modeling effect due to color reconnection effects, initial/final state radiation and the kinematics of the b-quark is observed.

4 top - antitop mass difference

CMS experiment has measured the difference of the top-quark and anti-top quark masses using the full 2012 data sample, corresponding to an integrated luminosity of 18.92 fb^{-1} of 8 TeV proton-proton collision [17]. This measurement tests the CPT invariance which is one of the basic assumptions behind the theory of the Standard Model. A similar event selection and ideogram method as described in Section 2.2 is used separately for positive and negative lepton charges. Some of the systematic uncertainties which are relevant for the absolute value of top mass cancel in this measurement. The $m_t - m_{\bar{t}}$ is found to be

$$\Delta m_t = -272 \pm 196(stat.) \pm 122(syst.)\text{MeV}$$

which is consistent with 0. The main sources of the systematic uncertainties are b vs. $\bar{b}$ jet response, background composition and b vs. $\bar{b}$ tagging efficiency.

5 Conclusions

The latest top-quark mass measurement results obtained by the CMS collaboration are presented. For the first time CMS has studied the dependence of Top Quark Mass Measurement on event kinematics and a very good agreement between data and MC is observed. The most precise measurement of Δm_t which is compatible with 0 was presented.

References

[1] M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Kennedy, R. Kogler, K. Mönig, M. Schott, J. Stelzer, The European Physical Journal C **72**, 1 (2012)

[2] CMS Collaboration, Physics Letters B **716**, 30 (2012)

[3] ATLAS Collaboration, Physics Letters B **716**, 1 (2012)

[4] Tevatron Electroweak Working Group and CDF and D0 Collaborations, *Combination of cdf and do results on the mass of the top quark using up to 8.7 fb^{-1} at the tevatron* (2013), http://arxiv.org/abs/1305.3929

[5] CMS Collaboration, Journal of Instrumentation **3**, S08004 (2008)

[6] CMS Collaboration, The European Physical Journal C **72**, 1 (2012)

[7] C. Lester, D. Summers, Physics Letters B **463**, 99 (1999)

[8] CMS Collaboration, *Measurement of masses in the $t\bar{t}$ system by kinematic endpoints in pp collisions at $\sqrt{s}$ = 7 TeV* (2013), http://arxiv.org/abs/1304.5783

[9] CMS Collaboration, Journal of High Energy Physics **2012**, 1 (2012)

[10] DELPHI Collaboration, Eur.Phys.J. **C55**, 1 (2008), 0803.2534

[11] D0 Collaboration, Phys.Rev. **D75**, 092001 (2007), hep-ex/0702018

[12] CDF Collaboration, Phys.Rev.Lett. **98**, 142001 (2007), hep-ex/0612026

[13] CMS Collaboration, Tech. Rep. CMS-PAS-TOP-11-018, CERN, Geneva (2012)

[14] CMS Collaboration, Tech. Rep. CMS-PAS-TOP-10-009, CERN, Geneva (2011)

[15] CMS Collaboration, Journal of High Energy Physics **2011**, 1 (2011)

[16] CMS Collaboration, Tech. Rep. CMS-PAS-TOP-12-029, CERN, Geneva (2013)

[17] CMS Collaboration, Tech. Rep. CMS-PAS-TOP-12-031, CERN, Geneva (2013)