Measurement of the top quark mass at CMS

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1 Introduction

The top quark mass is an important parameter of the standard model (SM) and it affects predictions of SM observables via radiative corrections. A precise measurement of the top quark mass is crucial since it constitutes one of the most important inputs to the global electroweak fits [1], which provide constraints on the model itself, including indirect limits on the mass of the Higgs boson. The mass of the top quark has been measured very precisely by the Tevatron experiments, and the current world average is $173.3 \pm 0.6\,(\mathrm{stat.}) \pm 0.9\,(\mathrm{syst.})$ GeV/c^2 [2].

We present here a measurement of the top quark mass based on the data sample collected in 2010 by the Compact Muon Solenoid (CMS) experiment [3] at the LHC. This corresponds to an integrated luminosity of 35.9 ± 1.4 pb^{-1}. This measurement is performed in the lepton+jets channel [4], in which one W boson decays leptonically and the other into quarks, and the dilepton channel [5], in which both W bosons decay into leptons. Although these measurements do not yet have the level of precision reached at the Tevatron, they represent important milestones in our understanding of the detector and physics reconstruction performance, providing benchmarks on the way to precision measurements of top quark properties.

2 Measurement in the lepton+jets channel

In this channel, the final state is composed of four jets, one energetic isolated lepton (electron or muon) and missing transverse energy. Events are required to pass either a single electron trigger or single muon trigger. The minimum E_{T} value for electron trigger ranged from 10 GeV to 22 GeV, while the minimum p_{T} value for muon trigger ranged from 9 GeV to 15 GeV.

After offline reconstruction, events are selected requiring exactly one isolated lepton (electron or muon) with $p_{\mathrm{T}} > 20$ GeV/c and $|\eta| < 2.1$ for muons and $p_{\mathrm{T}} > 30$ GeV/c, $|\eta| < 2.5$ for electrons, and at least four jets ($p_{\mathrm{T}} > 30$ GeV/c, $|\eta| < 2.4$). The jets and the missing transverse energy ($\not\!\!E_{\mathrm{T}}$) are reconstructed with the particle flow algorithm [6].

The analysis method is a simplified version of the Ideogram technique that was used by D0 for the top quark mass measurement in the same channel [7].

First, a constrained kinematic fit [8] is used to reconstruct the complete kinematics of the event under the hypothesis that it is a $t\bar{t}$ event decaying into a lepton+jets final state. There are 12 combinations to pair the four reconstructed jets with the quarks from $t\bar{t}$ decay. For each combination, the jet four-momenta are corrected back to the parton level according to the flavour hypothesis [9]. Further, there are two possible solutions for the z-component of the neutrino four-momentum, leading to a total of 24 possible combinations. The event is rejected if there is no solution with a fit-$\chi^2 > 10$. In data, the number of selected events is 303 in the electron+jets and 334 in the muon+jets channels.

For each event in the sample, a likelihood to observe the event is then calculated as a function of the assumed top quark mass. The likelihood contains a term corresponding to the probability of the event to be a $t\bar{t}$ event, and another term corresponding to the probability of the event to be a background event. The event observables used in the likelihood are the number of b-tagged jets, the fitted mass, its estimated uncertainty, and the fit-χ^2.

The probabilities are calculated as a weighted sum over all possible combinations. For each combination, the relative weight is given by the likelihood that the jet permutation hypothesis is compatible with the result from the kinematic fit, and the likelihood that it is compatible with the information from the b-tagging algorithm.

The $t\bar{t}$ signal probability contains two terms. The first term represents the probability that a solution has the correct jets to quarks assignment. It is taken as a convolution of a Gaussian resolution function and a relativistic Breit-Wigner distribution. The second term represents the probability that a solution does not have the correct jets to quarks assignment. It is derived by fitting a Crystal Ball function to the mass distribution of solutions which have a wrong jets to quark assignment in $t\bar{t}$ simulation.

The background probability density is derived from a fit to the distribution of fitted masses in W+jets background simulation.

Finally, the overall sample likelihood is calculated by combining the event likelihoods of all events in the sample. The estimated mass and its statistical uncertainty are derived from a parabolic interpolation using the three likelihood points closest to the minimum. The dominant sources of uncertainty are the overall jet energy scale (JES) and a b-jet specific energy scale [10].

The combined likelihood of the electron and muon channels yields the following result:

$$m_{\mathrm{top}} = 173.1 \pm 2.1\ (\mathrm{stat})^{+2.4}_{-2.1}\ (\mathrm{JES}) \pm 1.4\ (\mathrm{other\ syst})\ \mathrm{GeV/c}^2.$$

3 Measurement in the dilepton channel

The same triggers are used in this channel as in the lepton+jets channel. After offline reconstruction, events are selected with two isolated, oppositely charged leptons (electrons or muons) with $p_{\mathrm{T}} > 20$ GeV/c and $|\eta| < 2.5$ ($|\eta| < 2.4$ for muons), at least two jets with $E_T > 30$ GeV and $|\eta| < 2.4$, and $\not\!\!E_{\rm T} > 20$ (30) GeV for $e\mu$ ($ee/\mu\mu$) events. The selected leptons and jets are required to originate from the same primary interaction vertex. Events with same-flavour lepton pairs in the dilepton mass region $76 < m_{ll} < 106$ GeV/c^2 are removed to suppress the dominant Z+jet background. Dilepton pairs from heavy flavor resonances and low-mass Drell-Yan are also removed by requiring a minimum invariant mass of 12 GeV/c^2. In the data, 102 events are selected.

The top quark mass is measured with two methods, a full kinematic analysis (KINb) and an analytical matrix weighting technique (AMWT), which have been improved over those used at the Tevatron [11, 12]. A key difference with respect to previous measurements is the choice of the jets used to reconstruct the top candidates. Because of initial state radiation, the two leading jets may not be those that originate from the decays of the top quarks. Therefore, b-tagged jets in an event are used in the reconstruction, even if they are not the leading jets. When no jet is b-tagged, the two leading jets are used. If there is a single b-tagged jet in the event, it is supplemented by the leading untagged jet. It is demonstrated using Monte Carlo simulation that the proportion of events in which the jets used for the reconstruction are correctly matched is increased significantly.

In the KINb method, the kinematic equations describing the $t\bar{t}$ system are solved many times per event for each lepton-jet combination. Each time, the jet $p_{\rm T}$, the $\not\!\!E_{\rm T}$ direction, and the longitudinal momentum of the $t\bar{t}$ system $p_z^{t\bar{t}}$ are varied independently according to their resolutions to scan the kinematic phase space compatible with the $t\bar{t}$ system. The jet $p_{\rm T}$ and $\not\!\!E_{\rm T}$-direction resolutions are obtained from the data; the $p_z^{t\bar{t}}$ description, which is minimally dependent on m_{top}, is taken from simulation. Solutions with the lowest invariant mass of the $t\bar{t}$ system are accepted if the mass difference between the two top quark masses is less than 3 GeV/c^2. The combination with the largest number of solutions is chosen, and the mass value m_{KINb} is estimated by a Gaussian fit in a 50 GeV/c^2 window around the most probable value.

In the AMWT, the kinematic equations describing the $t\bar{t}$ system are also solved many times per event using an analytical method [13]. In each event, there are two possible lepton-jet pairings with up to four solutions for each pairing. Because the system is under-constrained, solutions are obtained for all values of m_{top} in the range 100 to 300 GeV/c^2 in 1 GeV/c^2 steps. In addition, the event is reconstructed 1,000 times varying the jet $p_{\rm T}$ and the $\not\!\!E_{\rm T}$ direction according to their resolutions. In order to determine a preferred value of the top quark mass, a weight based on kinamatic quantitie and the parton distribution function is assigned to each solution [14]. For each value of the top quark mass, the weights are added for all solutions. For each event, the m_{top} hypothesis with maximum averaged weight is taken as the reconstructed top quark mass m_{AMWT}. Events that have no solutions or that have a maximum weight below a threshold value are discarded.

For both methods, a likelihood fit of the reconstructed mass distribution is made

Method	Measured $m_{\rm top}$ (in GeV/c^2)	Weight
AMWT	$175.8 \pm 4.9\,(\text{stat.}) \pm 4.5\,(\text{syst.})$	0.65
KINb	$174.8 \pm 5.5\,(\text{stat.})^{+4.5}_{-5.0}\,(\text{syst.})$	0.35
Combined	$175.5 \pm 4.6\,(\text{stat.}) \pm 4.6\,(\text{syst.})$	$\chi^2/\text{dof} = 0.040$ (p-value = 0.84)

Table 1: Summary of measured top quark mass in the dilepton channel with the contributing weights to the combined mass value.

to obtain an unbiased estimate of m_{top}. The signal and background templates are obtained from simulation. For the signal tempates, samples generated with m_{top} values between 151 and 199 GeV/c^2 in steps of 3 GeV/c^2 are used. A unique template is used for each b-tag category, where the mass distribution of each individual contribution is added according to its expected relative contribution. The relative contribution of Z+jet events to the total background is determined from data near the Z-peak.

The two independent measurements from the KINb and AMWT methods are then combined with the Best Linear Unbiased Estimation (BLUE) method [15]. The statistical correlations estimated from simulated samples with a top quark mass of 172 GeV/c^2 is 0.57. Systematic uncertainties common to the methods are assumed to be 100% correlated. The combined top quark mass is given in Tab. 1 together with the individual measurements. As before, the dominant sources of uncertainty are the overall jet energy scale and a b-jet specific energy scale [16].

4 Combination of the lepton+jets and dilepton measurements

The combination of the measurements in the lepton+jets and dilepton channels is performed using the BLUE method. Since the event samples used for both measurements are constructed to be non-overlapping, the statistical uncertainty in each measurement is uncorrelated. The systematic uncertainties that are common to both measurements are considered to be fully correlated, with the exception of the JES. The lepton+jets measurement uses a later version of JES calibration compared to the version used in the dilepton channel. The combined result is:

$$m_{\rm top} = 173.4 \pm 1.9 \text{ (stat)} \pm 2.7 \text{ (syst) GeV}/c^2$$

5 Conclusion

Two separate measurements of the top quark mass from $t\bar{t}$ decays were performed in the lepton+jets and the dilepton channel. These measurements used an integrated luminosity of 36 pb^{-1}. The combination of the two measurements yields $m_{top} = 173.4 \pm 1.9$ (stat) ± 2.7 (syst) GeV/c^2.

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