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Measurement of the top-quark mass in all-jets $t\bar{t}$ events in pp collisions at $\sqrt{s} = 7$ TeV

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Abstract The mass of the top quark is measured using a sample of $t\bar{t}$ candidate events with at least six jets in the final state. The sample is selected from data collected with the CMS detector in pp collisions at $\sqrt{s} = 7$ TeV in 2011 and corresponds to an integrated luminosity of 3.54 fb^{-1}. The mass is reconstructed for each event employing a kinematic fit of the jets to a $t\bar{t}$ hypothesis. The top-quark mass is measured to be 173.49 ± 0.69 (stat.) ± 1.21 (syst.) GeV. A combination with previously published measurements in other decay modes by CMS yields a mass of 173.54 ± 0.33 (stat.) $\pm$ 0.96 (syst.) GeV.

1 Introduction

The mass of the top quark (m_t) is an essential parameter of the standard model. Its measurement also provides an important benchmark for the performance and calibration of the Compact Muon Solenoid (CMS) detector [1] at the CERN Large Hadron Collider (LHC). The top-quark mass has been determined with high precision at the Fermilab Tevatron [2] to be $m_t = 173.18 \pm 0.94$ GeV. Measurements have been carried out in several top-quark decay channels using different methods, with the most precise single measurement at the Tevatron being that performed by the CDF Collaboration [3] in the lepton+jets final state using a template method yielding $m_t = 172.85 \pm 1.11$ GeV.

In this article a measurement is presented using a sample of $t\bar{t}$ candidate events with six or more reconstructed jets in the final state. It represents the first mass measurement in the all-jets channel performed by the CMS Collaboration. The all-jets decay mode has a larger signal yield than the dilepton and lepton+jets channels. However, with only jets in the final state, this channel is dominated by a multijet background and this measurement requires dedicated triggers and tight selection criteria. This measurement complements the latest measurements by the CMS Collaboration in the lepton+jets and dilepton channels that yield $m_t = 173.49 \pm 1.07$ GeV [4] and $m_t = 172.5 \pm 1.5$ GeV [5], respectively. The most precise measurement in the all-jets channel so far is by the CDF Collaboration yielding $m_t = 172.5 \pm 2.0$ GeV [6].

The event selection is very similar to the one used for the CMS $t\bar{t}$ cross section measurement in the same final state, requiring at least six jets [7]. Analogously to the CMS measurement of the top-quark mass in the lepton+jets channel [4], the analysis employs a kinematic fit of the decay products to a $t\bar{t}$ hypothesis and likelihood functions for each event ("ideograms") that depend on the top-quark mass only or on both the top-quark mass and the jet energy scale.

2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. The bore of the solenoid is equipped with various particle detection systems. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle, θ, is measured from the positive z axis and the azimuthal angle, ϕ, is measured in the x–y plane in radians.

Charged-particle trajectories are measured with silicon pixel and strip trackers, covering the pseudorapidity range $|\eta| < 2.5$, where $\eta \equiv -\ln[\tan(\theta/2)]$. A lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume. The HCAL, when combined with the ECAL, measures jets with a resolution $\Delta E/E \approx 100\,\%/\sqrt{E\,[\mathrm{GeV}]} \oplus 5\,\%$. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry that extends the coverage to $|\eta| < 5$. Muons are measured up to $|\eta| < 2.4$ using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A two-level trigger system selects the final states pertinent to this analysis. A detailed description of the CMS detector is available elsewhere [1].

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3 Data samples and event selection

The analyzed data sample has been collected in 2011 in pp collisions at $\sqrt{s} = 7$ TeV using two different multijet triggers and corresponds to an integrated luminosity of $3.54 \pm 0.08\,\text{fb}^{-1}$ [8]. The first trigger requires the presence of at least four jets built only from the energies deposited in the calorimeters with transverse momenta $p_T \geq 50$ GeV and the presence of a fifth calorimeter jet with $p_T \geq 40$ GeV. An additional requirement of a sixth calorimeter jet with $p_T \geq 30$ GeV was added during the data taking and this second trigger collected $3.19\,\text{fb}^{-1}$ of data.

Our procedure uses simulated events to estimate the composition of the data sample, to determine and calibrate the ideograms, and to evaluate the systematic uncertainties. The $t\bar{t}$ signal events have been generated for nine different top-quark mass values ranging from 161.5 to 184.5 GeV with the MADGRAPH 5.1.1.0 matrix element generator [9], PYTHIA 6.424 parton showering [10] using the Z2 tune [11], and a full GEANT4 [12] simulation of the CMS detector. The matching between the matrix elements (ME) and the parton shower evolution (PS) is done by applying the MLM prescription described in Ref. [13]. The simulation includes the effects of additional overlapping minimum-bias events (pileup) so that the distribution of the number of proton interactions per bunch crossing matches the corresponding distribution in data. Furthermore, the jet energy resolution in simulation has been scaled to match the resolution observed in data [14].

Jets are formed by clustering the particles reconstructed by a particle-flow algorithm [15] using the anti-k_T algorithm [16,17] with a radius parameter of 0.5. The particle-flow technique combines information from all subdetectors to reconstruct individual particles including muons, electrons, photons, charged hadrons, and neutral hadrons. It typically improves the jet energy resolution to 15 % at 10 GeV, 8 % at 100 GeV, and 4 % at 1 TeV. An additional advantage of this technique is that it facilitates pileup removal by discarding charged particles associated with vertices other than the primary and secondary vertices from the primary collision. Jet energy corrections are applied to all the jets in data and simulation [14]. These corrections are derived from simulation and are defined as a function of the transverse momentum density of an event [17–19] as well as of the p_T and η of the reconstructed jet. By these means a uniform energy response at the particle level with low pileup dependence is obtained. A residual correction, measured from the momentum balance of dijet and γ+jet/Z+jet events, is applied to the jets in data. To reduce the contamination by false jets from detector noise or by electrons reconstructed as jets, the fractions of the jet energy from photons, electrons, and neutral hadrons are required to be below 99 %, and the fraction of the jet energy from charged hadrons is required to be greater than zero.

Since hadronically decaying top-quark pairs lead to six quarks in the final state, events are selected with at least four jets with $p_T > 60$ GeV, a fifth jet with $p_T > 50$ GeV, and a sixth jet with $p_T > 40$ GeV. Additional jets are considered only if they have $p_T > 30$ GeV. All jets are required to be within pseudorapidity $|\eta|$ of 2.4, where the tracker acceptance ends. The Combined Secondary Vertex tagger with the Tight working point (CSVT) [20] is used to tag jets originating from bottom quarks. The CSVT working point corresponds to an efficiency of approximately 60 %, while the misidentification probability for jets originating from light quarks (uds) and gluons is only 0.1 %. We require at least two b-tagged jets. After these initial event selection criteria, 26,304 candidate events are selected in the data.

4 Kinematic fit

For the final selection of candidate $t\bar{t}$ events, a kinematic least-squares fit [21] is applied. It exploits the characteristic topology of $t\bar{t}$ events: two W bosons that can be reconstructed from the untagged jets and two top quarks that can be reconstructed from the W bosons and the b-tagged jets. The reconstructed masses of the two top quarks are constrained to be equal. In addition, the mass of both W bosons in the event is constrained to 80.4 GeV [22] in the fit leading to $n_{\text{dof}} = 3$ degrees of freedom. Gaussian resolutions are used for the jet energies in the kinematic fit. They are separately determined for jets originating from light quarks and bottom quarks as functions of p_T and η using simulated $t\bar{t}$ events.

To find the correct combination of jets, the fit procedure is repeated for every experimentally distinguishable jet permutation. This is done using all (six or more) jets that pass the selection. In the data, 8,810 events have exactly seven selected jets, 3,259 events have eight jets, and 1,183 events have nine or more jets. All b-tagged jets are taken as bottom-quark candidates, the untagged jets serve as light-quark candidates. If the fit converges for more than one of the possible jet permutations, the one with the smallest fit χ^2 is chosen. After the kinematic fit, all events with a goodness-of-fit probability of $P_{\text{gof}} = P(\chi^2, n_{\text{dof}} = 3) > 0.09$ are accepted.

To further reduce the multijet background with $b\bar{b}$ production, an additional criterion on the separation of the two bottom-quark candidates, $\Delta R_{b\bar{b}} = \sqrt{(\Delta\phi_{b\bar{b}})^2 + (\Delta\eta_{b\bar{b}})^2} > 1.5$, is imposed. The number of events in data passing each selection step, the expected fraction of signal events in the data sample assuming a $t\bar{t}$ cross section of 163pb [23], and the selection efficiency for signal are given in Table 1.

To extract the mass, the events are weighted by their goodness-of-fit probabilities increasing the fraction of $t\bar{t}$ events to 54 % and improving the resolution of the fitted top-quark mass. We classify the $t\bar{t}$ events based on the jet-parton associations in simulation. Partons are matched to a jet if they are separated by less than 0.3 in η–ϕ space. Three different

Table 1 Number of events, the predicted signal fraction in the data sample, and the selection efficiency for signal after each selection step. The predicted signal fraction is derived from simulation assuming a $t\bar{t}$ cross section of 163 pb [23] and a top-quark mass of 172.5 GeV

Selection step	Events	Sig. frac. (%)	Sel. eff. for signal (%)
At least 6 jets	786,741	3	3.48
At least two b tags	26,304	17	0.91
$P_{\mathrm{gof}} > 0.09$	3,691	39	0.30
$\Delta R_{b\bar{b}}$	2,418	51	0.25

categories are distinguished in the following way: correct permutations *cp* (27.9 %), wrong permutations *wp* (22.6 %) where at least one jet is not associated to the correct parton from the $t\bar{t}$ decay, and unmatched permutations *un* (49.4 %). The last case contains events in which at least one quark from the $t\bar{t}$ decay cannot be matched unambiguously to a selected jet. For correct permutations, the kinematic fit and the weighting procedure improve the resolution of the fitted top-quark masses from 13.6 to 7.9 GeV. Furthermore, the requirement on the goodness-of-fit probability removes 76 % of the signal events classified as unmatched permutations enhancing the fraction of correct permutations from 10 to 27.9 %.

5 Background modeling

The multijet background is estimated using an event mixing technique. All events after the b-tagging selection are taken as input. The jets are mixed between the different events based on their position in a p_{T}-ordered list in the event in which they were recorded; every jet in the events in the multijet background model originates from a different event in the data, with the p_{T}-ordered position preserved. No duplicate jets, in terms of their p_{T}-ordering, are allowed. In addition, it is required that at least two b-tagged jets are found in every new event. The kinematic fit to a $t\bar{t}$ hypothesis is performed on each mixed event and the same P_{gof} and $\Delta R_{b\bar{b}}$ selection is applied. This procedure was validated on particle-level jets using $b\bar{b}$ events generated with PYTHIA. The distributions of the fitted top-quark mass $m_{\mathrm{t}}^{\mathrm{fit}}$ and the mean of the two reconstructed W-boson masses agree well between the generated $b\bar{b}$ events and the modeled events from event mixing on the same sample.

As can be seen in Table 1, the input sample has an expected fraction of 17 % $t\bar{t}$ events. The impact of this contamination on the background prediction is evaluated with simulated $t\bar{t}$ events and its minor effect on the background modeling is treated as a systematic uncertainty.

We normalize the simulated $t\bar{t}$ sample and the background prediction to data with an expected signal fraction f_{sig} from simulation. This signal fraction f_{sig} depends on the $t\bar{t}$ cross section and the selection efficiency for $t\bar{t}$ events for different top-quark masses. It varies between 50 and 55 % for top-quark masses within three standard deviations of the Tevatron average top-quark mass [2] for three different predictions of the $t\bar{t}$ cross section [23–25]. Adding to this the uncertainty in the luminosity and the systematic uncertainties in the selection efficiency [7], we assume $f_{\mathrm{sig}} = (54 \pm 4\,(\mathrm{th.}) \pm 1\,(\mathrm{lum.}) \pm 10\,(\mathrm{syst.}))\,\%$ for this analysis.

Figure 1 compares data and the expectation from simulation and background for the fitted top-quark mass $m_{\mathrm{t}}^{\mathrm{fit}}$, the mean of the two reconstructed W-boson masses per event $m_{\mathrm{W}}^{\mathrm{reco}}$, the goodness-of-fit probability P_{gof} , and the distance between the two b-tagged jets $\Delta R_{b\bar{b}}$. Overall, the agreement is good within the uncertainties.

6 Ideogram method

Since the jet energy scale (JES) is the leading systematic uncertainty in previous top-quark mass measurements, we construct a likelihood function that allows the determination of the JES and the top-quark mass simultaneously by a joint fit to all selected events in data. The JES is estimated from the invariant masses of the jets associated with the W bosons exploiting the precise knowledge of the W-boson mass from previous measurements [22]. Based on this likelihood function, we perform two different estimations of the top-quark mass: one with a fixed JES (henceforth "1D analysis") and a second with a simultaneous estimation of the JES (henceforth "2D analysis"). The 2D analysis is similar to the measurements of the top-quark mass in the all-jets channel by the CDF Collaboration [6] and in lepton+jets final states by the CMS Collaboration [4].

The observable used for measuring m_{t} is the top-quark mass $m_{\mathrm{t}}^{\mathrm{fit}}$ obtained from the fitted four-momenta of the jets after the kinematic fit. We take the mean of the two reconstructed W-boson masses before they are constrained by the kinematic fit $m_{\mathrm{W}}^{\mathrm{reco}}$ as an estimator for measuring in situ an additional global JES beyond that of the standard CMS jet energy corrections. The likelihood calculation in the ideogram method [26–28] is done by evaluation of analytic expressions for the probability densities. These expressions are derived and calibrated using simulated events and the modeled background from event mixing.

A likelihood to estimate the top-quark mass and JES given the observation of a data sample can be defined as:

$$\mathcal{L}\,(m_{\mathrm{t}}, \mathrm{JES}|\mathrm{sample}) \propto P\,(\mathrm{sample}|m_{\mathrm{t}}, \mathrm{JES}) = \prod_{\mathrm{events}} P\left(m_{\mathrm{t}}^{\mathrm{fit}}, m_{\mathrm{W}}^{\mathrm{reco}}|m_{\mathrm{t}}, \mathrm{JES}\right)^{w_{\mathrm{event}}}. \quad (1)$$

The event weight $w_{\mathrm{event}} \propto P_{\mathrm{gof}}$ is introduced in order to lower the impact of unmatched and background events. The sum of all event weights is normalized to the number of events.

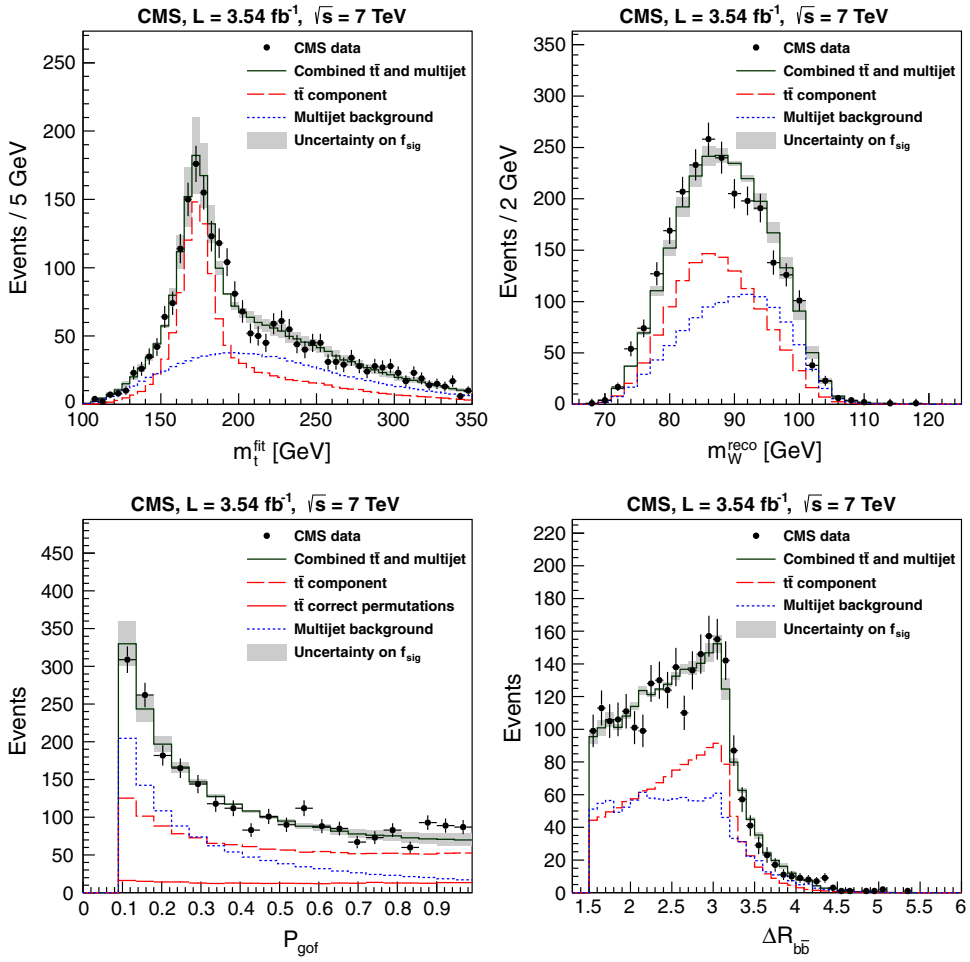

Fig. 1 *Upper left* Reconstructed top-quark mass from the kinematic fit, *upper right* average reconstructed W-boson mass, *lower left* goodness-of-fit probability, and *lower right* the separation of the two b-tagged jets after all selection steps. The simulated $t\bar{t}$ signal and the background from event mixing are normalized to data. The *band* indicates the correlated uncertainty from the signal fraction f_{sig}. The top-quark mass used in the simulation is 172.5 GeV and the nominal jet energy scale is applied

Due to the mass constraint on the W boson in the fit, the correlation coefficient between m_t^{fit} and m_W^{reco} is only -0.08 for correct permutations in simulation. Hence, we treat m_t^{fit} and m_W^{reco} as uncorrelated and the probability $P(m_t^{fit}, m_W^{reco}|m_t, \text{JES})$ from Eq. (1) is factorized into

$$\begin{aligned} &P\left(m_t^{fit}, m_W^{reco}|m_t, \text{JES}\right) \\ &\quad = f_{sig} \cdot P_{sig}\left(m_t^{fit}, m_W^{reco}|m_t, \text{JES}\right) \\ &\qquad + \left(1 - f_{sig}\right) \cdot P_{bkg}\left(m_t^{fit}, m_W^{reco}\right) \\ &\quad = f_{sig} \cdot \sum_j f_j P_j\left(m_t^{fit}|m_t, \text{JES}\right) \cdot P_j\left(m_W^{reco}|m_t, \text{JES}\right) \\ &\qquad + \left(1 - f_{sig}\right) \cdot P_{bkg}\left(m_t^{fit}\right) \cdot P_{bkg}\left(m_W^{reco}\right), \end{aligned}$$

where f_j with $j \in \{cp, wp, un\}$ is the relative fraction of the three different permutation cases. The relative fractions f_j and the probability density functions P_j for signal are determined from simulated $t\bar{t}$ events generated for nine different top-quark mass ($m_{t,\,gen}$) values and three different JES values (0.96, 1.00, and 1.04). For the probability density functions, the m_t^{fit} distributions are fitted with a Breit–Wigner function convolved with a Gaussian resolution function for the *cp* case and with the sum of a Landau function and a Gaussian function with common means for the *wp* and *un* cases for different generated top-quark masses and jet energy scales. The corresponding m_W^{reco} distributions are distorted by the jet-selection criteria and the goodness-of-fit probability requirement and weighting because permutations with a reconstructed W-boson mass close to 80.4 GeV are preferred by the kinematic fit. The m_W^{reco} distributions are therefore fitted with asymmetric generalized Gaussian functions. The dependence of the parameters of the fitted functions on $m_{t,\,gen}$ and JES is then expressed in a linear function of the generated top-quark mass, JES, and the product of the two.

As the background is modeled from data, the probability density distributions for the background depend neither on the top-quark mass nor the JES. Its m_t^{fit} distribution is fitted by the sum of a Gamma function and a Landau function and its m_W^{reco} distribution by an asymmetric Gaussian function.

In the 1D analysis, where the JES is not measured simultaneously, the top-quark mass is estimated from the minimization of $-2\ln\{\mathcal{L}(m_t, \text{JES} = 1|\text{sample})\}$. In the 2D analysis the most likely top-quark mass and JES are obtained by mini-

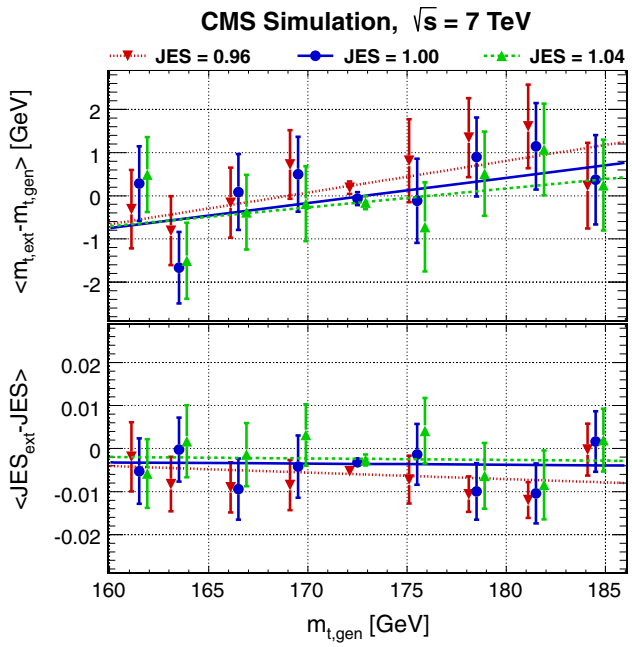

Fig. 2 Difference between the extracted top-quark mass $m_{\mathrm{t,\,ext}}$ and the generated top-quark mass $m_{\mathrm{t,\,gen}}$, (*upper*) and between the extracted and generated values of JES (*lower*) before calibration, for different generated top-quark masses and three different JES values. The *lines* correspond to linear fits which are used to correct the final likelihoods. The mass points for different JES values are shifted horizontally for clarity

mizing $-2\ln\{\mathcal{L}(m_{\mathrm{t}}, \mathrm{JES}|\mathrm{sample})\}$. We fit a parabola (elliptic paraboloid) to extract the minimum and 1σ uncertainty from the 1D (2D) log-likelihoods.

7 Analysis calibration

The method is tested for possible biases and for the correct estimation of the statistical uncertainty using pseudo-experiments. For each combination of nine different generated top-quark masses and three jet energy scales, we conduct 10,000 pseudo-experiments using simulated $\mathrm{t\bar{t}}$ events and modeled background events from event mixing on data. We extract $m_{\mathrm{t,\,ext}}$ and $\mathrm{JES_{ext}}$ from each pseudo-experiment, which corresponds to an integrated luminosity of 3.54 fb^{-1}. This results in 27 calibration points in the $m_{\mathrm{t,\,gen}}$-JES plane.

The biases are defined as

$$\text{mass bias} = \left\langle m_{\mathrm{t,\,ext}} - m_{\mathrm{t,\,gen}} \right\rangle;$$
$$\text{JES bias} = \langle \mathrm{JES_{ext}} - \mathrm{JES} \rangle\,.$$

Both mass and JES bias are plotted as a function of $m_{\mathrm{t,\,gen}}$ for all three different JES values in Fig. 2. The bias is fit with a linear function for each generated JES value. Additional small corrections for calibrating the top-quark mass $m_{\mathrm{t,\,cal}}$ and the jet energy scale $\mathrm{JES_{cal}}$ are derived as linear functions of both the extracted top-quark mass and JES from these fits. As shown in Fig. 3 (top), no further corrections are needed for the calibrated top-quark mass $m_{\mathrm{t,\,cal}}$ and for the calibrated jet energy scale $\mathrm{JES_{cal}}$.

Using pseudo-experiments with the calibrated likelihood, we fit a Gaussian function to the distribution of the pulls defined as

$$\text{pull} = \frac{m_{\mathrm{t,\,cal}} - m_{\mathrm{t,\,gen}}}{\sigma\left(m_{\mathrm{t,\,cal}}\right)},$$

where $\sigma(m_{\mathrm{t,\,cal}})$ is the statistical uncertainty in an individual $m_{\mathrm{t,\,cal}}$ for a pseudo-experiment generated at $m_{\mathrm{t,\,gen}}$. As depicted in Fig. 3 (bottom), we find a mass pull width of 1.19, meaning that our method underestimates the statistical uncertainty. We correct for this by dividing $-2\ln\{\mathcal{L}(m_{\mathrm{t}}, \mathrm{JES}|\mathrm{sample})\}$ by the square of the found mass pull width. From these pseudo-experiments, the statistical uncertainty in the measured top-quark mass is expected to be 0.64 ± 0.03 GeV for the 1D analysis and 0.95 ± 0.03 GeV for the 2D analysis.

8 Systematic uncertainties

An overview of the different sources of systematic uncertainties is shown in Table 2 for the 1D analysis with a fixed JES and the 2D analysis where we estimate the top-quark mass and JES simultaneously. The effect of a source on the efficiency to select $\mathrm{t\bar{t}}$ events and hence on the signal fraction f_{sig} is taken into account in the evaluation. In general, the largest observed shifts in the top-quark mass and JES when varying the parameters studied are quoted as systematic uncertainties. If the statistical uncertainty in a shift is larger than the observed shift value we quote the statistical uncertainty in the shift instead. The different systematic uncertainties considered as relevant for this measurement and the method to evaluate them are:

Fit calibration: We propagate the statistical uncertainty of the calibration to the final measured quantities.

Jet energy scale: The effect of the uncertainty in the jet energy corrections is estimated by scaling all jet energies up and down according to their overall uncertainty [14]. The scaling leads to an average JES shift of 1.2 %. We take the largest difference in measured top-quark mass as a systematic uncertainty. The systematic uncertainty in the measured JES for the 2D analysis is obtained by comparing the measured JES for the scaled samples with the expected JES shift of 1.2 %.

b-JES: The different energy responses for jets originating from light quarks (uds), bottom quarks, and gluons have been studied in simulation. It is found that the b-jet response is intermediate between the light-quark and gluon jet responses [14]. Hence, the flavor uncertainty assumed for the JES determination [14] to cover the transition from a gluon-dominated to a light-quark-

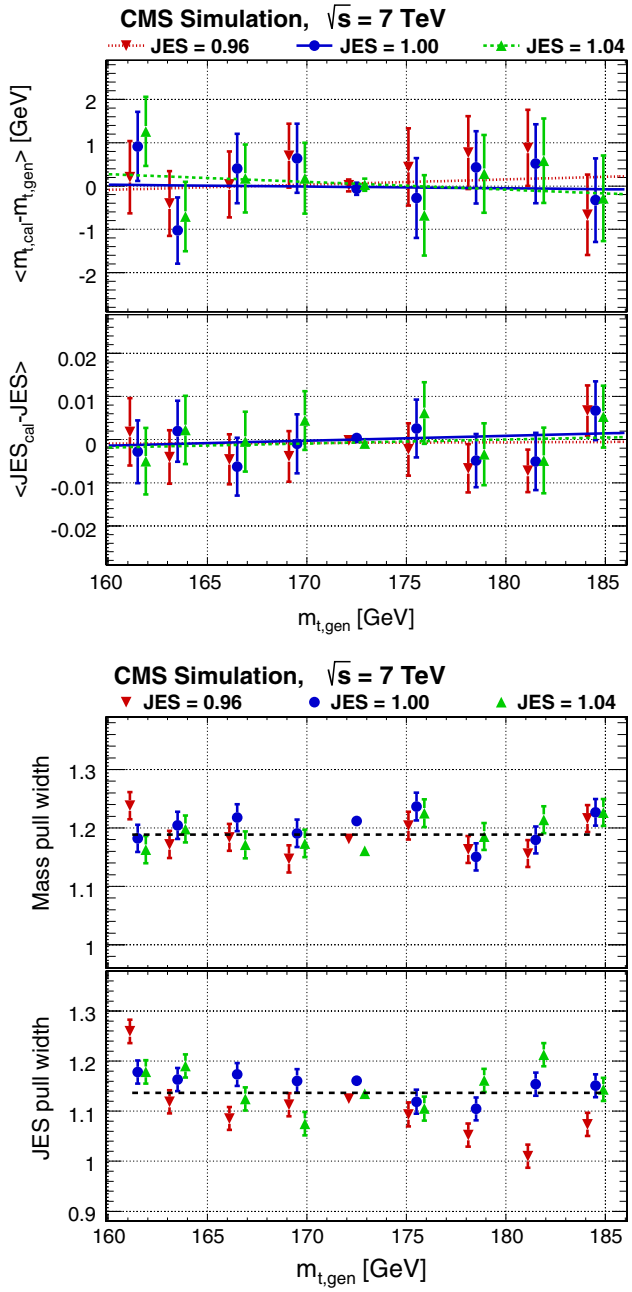

Fig. 3 *Top* Difference between the calibrated top-quark mass $m_{\mathrm{t,\,cal}}$ and the generated top-quark mass $m_{\mathrm{t,\,gen}}$, and between the calibrated and the generated values of JES after calibration for different generated top-quark masses and three different JES values; *bottom* width of the pull distribution for the calibrated top-quark mass and for the calibrated JES for different generated top-quark masses and three different JES values. The *colored lines* (*top*) correspond to linear fits for individual values of JES and the *black line* (*bottom*) corresponds to a constant fit to all calibration points. The mass points for different JES values are shifted horizontally for clarity

dominated sample also covers the transition from a sample of light quarks to one of bottom quarks. Thus, the energies of all b jets are scaled up and down by this flavor uncertainty in simulation that ranges from 0.2 to 1.2 %.

Jet energy resolution: The jet energy resolution in simulation is degraded by 7–20 % depending on η to match the resolutions found in [14]. To account for the resolution uncertainty, two additional shifts corresponding to $\pm 1\sigma$ are evaluated.

b tagging: The threshold on the CSVT tagger is varied in order to reflect an uncertainty of the b-tag efficiency of 3 % [20].

Trigger: The uncertainty in the turn-on of the jet triggers in data is estimated by raising the jet p_{T} cuts on the 4th, 5th, and 6th jets separately by 2 GeV in the $\mathrm{t\bar{t}}$ simulation. Each increase lowers the selection efficiency by 7–10 % covering the uncertainty of 5 % found in a dedicated study for the $\mathrm{t\bar{t}}$ cross section measurement in this channel [7]. We quote the quadratic sum of the observed shifts in top-quark mass and JES from each increase as systematic uncertainty.

Pileup: To estimate the uncertainties associated with the determination of the number of pileup events and with the weighting procedure, the average number of expected pileup events (8.1) is varied by ±5 %.

Parton distribution functions: The simulated events have been generated using the CTEQ 6.6L parton distribution functions (PDFs) [29]. The uncertainty in this PDF set is described by up/down variation of 22 orthogonal parameters resulting in 22 pairs of additional PDFs. The events are weighted for agreement with the additional PDFs and half of the difference in top-quark mass and JES of each pair is quoted as systematic uncertainties. The systematic uncertainties stemming from each pair are added in quadrature.

Renormalization and factorization scale: The dependence of the result on the renormalization and factorization scale used in the $\mathrm{t\bar{t}}$ simulation is studied by varying the scale choice for the hard scattering and for parton showering by a factor 0.5 and 2.0. The variation of these parameters in simulation reflects also the uncertainty in the amount of initial state and final state radiation.

ME-PS matching threshold: In the $\mathrm{t\bar{t}}$ simulation, the matching threshold used for interfacing the matrix elements generated with MADGRAPH and the PYTHIA parton showering is varied by factors of 0.5 and 2.0 compared to the default threshold.

Underlying event: Non-perturbative QCD effects are taken into account by tuning PYTHIA to measurements of the underlying event [11]. The uncertainties are estimated by comparing in simulation two tunes with increased and decreased underlying event activities to a central tune (the Perugia 2011 tune to the Perugia 2011 mpiHi and Perugia 2011 Tevatron tunes [30]).

Color reconnection effects: The uncertainties that arise from different modeling of color reconnection effects [31] are estimated by comparing in simulation an under-

Table 2 Overview of systematic uncertainties. The total is defined by adding in quadrature the contributions from all sources, by choosing for each the larger of the estimated shift or its statistical uncertainty, as indicated by the bold script

	1D analysis	2D analysis	
	δ_{m_t} (GeV)	δ_{m_t} (GeV)	δ_{JES}
Fit calibration	**0.13**	**0.14**	**0.001**
Jet energy scale	**0.97** $\pm$ 0.06	0.09 $\pm$ **0.10**	**0.002** $\pm$ 0.001
b-JES	**0.49** $\pm$ 0.06	**0.52** $\pm$ 0.10	**0.001** $\pm$ 0.001
Jet energy resolution	**0.15** $\pm$ 0.06	**0.13** $\pm$ 0.10	**0.003** $\pm$ 0.001
b tagging	0.05 $\pm$ **0.06**	0.04 $\pm$ **0.10**	**0.001** $\pm$ 0.001
Trigger	**0.24** $\pm$ 0.06	**0.26** $\pm$ 0.10	**0.006** $\pm$ 0.001
Pileup	0.05 $\pm$ **0.06**	0.09 $\pm$ **0.10**	**0.001** $\pm$ 0.001
Parton distribution functions	0.03 $\pm$ **0.06**	0.07 $\pm$ **0.10**	**0.001** $\pm$ 0.001
Renormalization and factorization scale	0.08 $\pm$ **0.22**	0.31 $\pm$ **0.34**	**0.005** $\pm$ 0.003
ME-PS matching threshold	**0.24** $\pm$ 0.22	0.29 $\pm$ **0.34**	0.001 $\pm$ **0.003**
Underlying event	**0.20** $\pm$ 0.12	**0.42** $\pm$ 0.20	**0.004** $\pm$ 0.002
Color reconnection effects	0.04 $\pm$ **0.15**	**0.58** $\pm$ 0.25	**0.006** $\pm$ 0.002
Multijet background	**0.13** $\pm$ 0.06	**0.60** $\pm$ 0.10	**0.006** $\pm$ 0.001
Total	1.21	1.23	0.013

lying event tune with color reconnection to a tune without it (the Perugia 2011 and Perugia 2011NoCR tunes [30]). Multijet background: After the final selection, a signal fraction of 54 % is expected from simulation. The signal fraction is varied between 49 and 59 %, corresponding to the uncertainties of the theoretical predictions of the $t\bar{t}$ cross section, the value of the top-quark mass, and the luminosity. In addition, we study the effect of $t\bar{t}$ events in the input sample used for the event mixing. To estimate the effect, the event mixing is performed in simulation on a $t\bar{t}$ sample and alternative probability density distributions are derived from this sample for the background. This variation also accounts for the small shape differences observed for the event mixing technique on the additional $b\bar{b}$ sample.

As expected, the main systematic uncertainty in the 1D analysis stems from the uncertainty in the jet energy scale and the 2D analysis reduces this uncertainty to a small p_T- and η-dependent JES uncertainty, but leads to a larger statistical uncertainty in the measured top-quark mass. Within the statistical precision of the uncertainty evaluation, most other systematic uncertainties are compatible. The variation of the signal fraction f_{sig} contributes 0.11 GeV (0.10 GeV) to the systematic uncertainty on the multijet background in the 1D (2D) analysis justifying that f_{sig} is kept fixed in the likelihood method. However, the 2D analysis has increased uncertainties for color reconnection effects and the shape of the multijet background. Due to the W-boson mass constraint in the kinematic fit, only the color reconnection effects for the b quarks affect the 1D analysis. For the 2D analysis, the JES estimation from the reconstructed W-boson masses results in an additional dependence on color reconnection effects for the light quarks and, hence, an increased systematic uncertainty. Similarly, the additional uncertainty in the modeling of the distribution of the reconstructed W-boson masses for the background gets propagated into the measured top-quark mass for the multijet background uncertainty.

Overall, the systematic uncertainties for both methods are very similar in size. This is in contrast to the CMS measurement in the lepton+jets channel [4] where the simultaneous fit of the top-quark mass and the JES leads to a reduction of the systematic uncertainty by 40 %. However, the jets are required to have a higher minimum transverse momentum in the all-jets channel, which leads to a reduced uncertainty in the JES in the 1D analysis compared to the previous work [4]. In addition, the tighter jet criteria in the all-jets measurement have a stronger impact on the m_W^{reco} distribution, making the JES estimation more sensitive to changes in the simulation.

9 Results

From the selected 2,418 events we measure with the jet energy scale fixed to the nominal value of JES = 1:

$$m_t = 173.49 \pm 0.69\,(\text{stat.}) \pm 1.21\,(\text{syst.})\,\text{GeV}$$

The overall uncertainty of the presented 1D analysis is 1.39 GeV. The likelihood profile used in the 1D analysis is shown in Fig. 4 (left).

A simultaneous fit of the top-quark mass and JES to the same data yields:

$$m_t = 174.28 \pm 1.00\,(\text{stat.} + \text{JES}) \pm 1.23\,(\text{syst.})\,\text{GeV}$$
$$\text{JES} = 0.991 \pm 0.008\,(\text{stat.}) \pm 0.013\,(\text{syst.}).$$

The measured JES confirms the JES for particle-flow jets in data measured in events where a Z boson or photon is

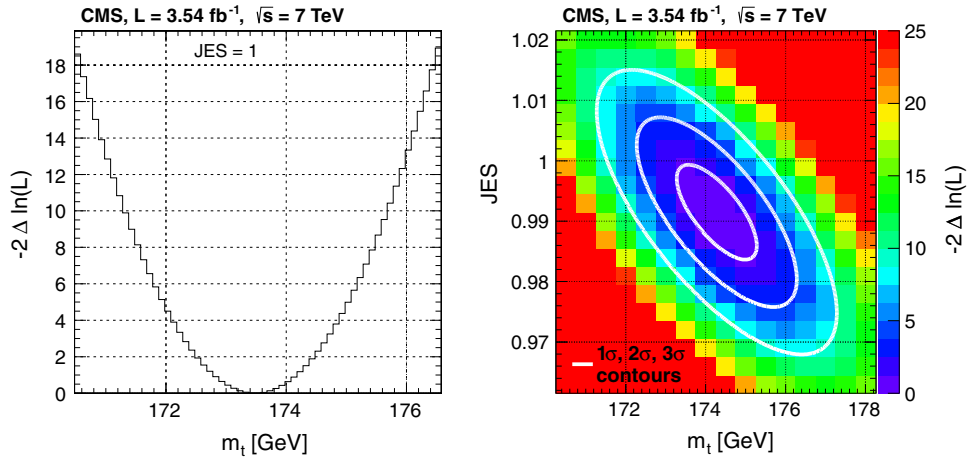

Fig. 4 *Left* The 1D likelihood profile with the JES fixed to unity and *right* the 2D likelihood. The *contours* correspond to 1σ, 2σ, and 3σ statistical uncertainties

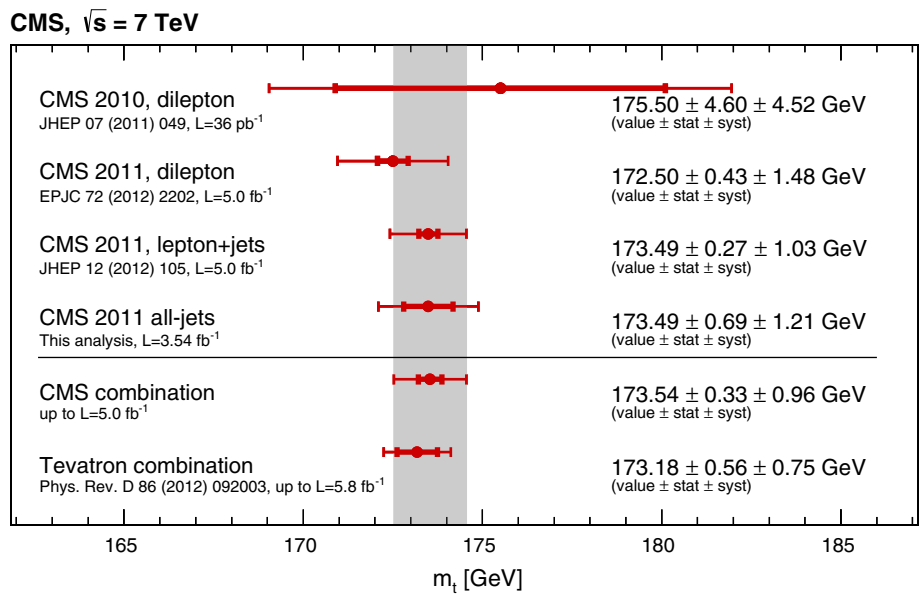

Fig. 5 Overview of the CMS top-quark mass measurements, their combination that is also shown as the *shaded band*, and the Tevatron average. The *inner error bars* indicate the statistical uncertainty, the *outer error bars* indicate the total uncertainty. The statistical uncertainty in the in situ fit for the JES is treated as a systematic uncertainty

produced together with one jet [14]. In the 2D analysis the overall uncertainty in the top-quark mass is 1.58 GeV. As the top-quark mass and JES are measured simultaneously, the uncertainty in the top-quark mass combines the statistical uncertainties arising from both components. Figure 4 (right) shows the 2D likelihood obtained from data. The measured top-quark masses in both analyses are in agreement, but the 1D analysis has a better precision than the 2D analysis.

We use the Best Linear Unbiased Estimate technique [32] to combine the 1D result presented in this paper with the CMS measurements in the dilepton channel based on 2010 [33] and 2011 [5] data, and the measurement in the lepton+jets channel [4]. Most of the systematic uncertainties listed in Table 2 are assumed to be fully correlated among the four input measurements. Exceptions are the uncertainties in pileup, for which we assign full correlation between the 2011 analyses but no correlation with the 2010 analysis, since the pileup conditions and their treatments differ. In addition, the statistical uncertainty in the in situ fit for the JES and the uncertainties in the mass calibration, the background normalization from control samples in data in the dilepton, and the background prediction in the all-jets analysis are treated as uncorrelated systematic uncertainties. The combination of the four measurements yields a mass of $m_t = 173.54 \pm 0.33\,(\text{stat.}) \pm 0.96\,(\text{syst.})$ GeV. It has a χ^2 of 1.4 for three degrees of freedom, which corresponds to a probability of 71 %.

Figure 5 gives an overview of the input measurements and the combined result.

10 Summary

A measurement of the top-quark mass is presented using events with at least six jets in the final state, collected by CMS in pp collisions at $\sqrt{s} = 7$ TeV in 2011. The complete

kinematic properties of each event are reconstructed using a constrained fit to a $t\bar{t}$ hypothesis. For each selected event a likelihood is calculated as a function of assumed values of the top-quark mass. From a data sample corresponding to an integrated luminosity of 3.54 fb^{-1}, 2,418 candidate events are observed and the mass of the top quark is measured to be $m_t = 173.49 \pm 0.69\,(\text{stat.}) \pm 1.21\,(\text{syst.})$ GeV. This result for m_t is consistent with the Tevatron average [2], with the ATLAS measurement in the lepton+jets channel [34], and with CMS measurements in the lepton+jets [4] and dilepton [5] channels. To date, this measurement constitutes the most precise determination of the top-quark mass in the all-jets channel. A combination with the three previously published CMS measurements [4,5,33] yields a mass of $m_t = 173.54 \pm 0.33\,(\text{stat.}) \pm 0.96\,(\text{syst.}) = 173.54 \pm 1.02$ GeV, consistent with the Tevatron average [2] and with similar precision.

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