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

The CMS Collaboration

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 $173.49 \pm 0.69$ (stat.) $\pm 1.21$ (syst.) GeV. A combination with previously published measurements in other decay modes by CMS yields a mass of $173.54 \pm 0.33$ (stat.) $\pm 0.96$ (syst.) GeV.

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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 a dedicated trigger 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

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, $\theta$, is measured from the positive $z$ axis and the azimuthal angle, $\phi$, is measured in the $x$-$y$ plane in radians.

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. 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 $\Delta E/E \approx 100%/\sqrt{E[\text{GeV}]} \oplus 5\%$. 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].
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 $3.54 \pm 0.08$ 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 jet with $p_T \geq 40$ GeV. An additional requirement of a sixth jet with $p_T \geq 30$ GeV was added during the data taking and this second trigger collected $3.19$ fb$^{-1}$ of data.

Our procedure uses simulated events for the $t\bar{t}$ signal, the mass extraction, and the evaluation of 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 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 compared to calorimeter-based jets 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 $\eta$ 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 $\gamma$+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, 26304 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 $\eta$ 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. 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 $\chi^2$ 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 from $b\bar{b}$ production, an additional criterion on the separation of the two bottom-quark candidates, $\Delta R_{bb} = \sqrt{(\Delta\phi_{bb})^2 + (\Delta\eta_{bb})^2} > 1.5$, 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 163 pb [23], and the selection efficiency for signal are given in Table 1.

<table>
<thead>
<tr>
<th>Selection step</th>
<th>Events</th>
<th>Sig. frac.</th>
<th>Sel. eff. for signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>At least 6 jets</td>
<td>786741</td>
<td>3%</td>
<td>3.48%</td>
</tr>
<tr>
<td>At least two b tags</td>
<td>26304</td>
<td>17%</td>
<td>0.91%</td>
</tr>
<tr>
<td>$P_{\text{gof}} &gt; 0.09$</td>
<td>3691</td>
<td>39%</td>
<td>0.30%</td>
</tr>
<tr>
<td>$\Delta R_{bb} &gt; 1.5$</td>
<td>2418</td>
<td>51%</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

To reconstruct 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 reconstructed 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 $\eta$-$\phi$ space. Three different 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 reconstructed top-quark mass from 13.6 GeV to 7.9 GeV.

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 $P_{\text{gof}}$ and $\Delta R_{bb}$
Ideogram Method

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 \( m_t^{\text{fit}} \) 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 \( m_W^{\text{reco}} \) 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] 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:

\[
L (m_t, \text{JES}| \text{sample}) \propto P (\text{sample}| m_t, \text{JES}) = \prod_{\text{events}} P \left( m_t^{\text{fit}}, m_W^{\text{reco}} | m_t, \text{JES} \right)^{w_{\text{event}}}.
\]  

(1)

The event weight \( w_{\text{event}} \propto P_{\text{gof}} \) 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.

Due to the mass constraint on the W boson in the fit, the correlation coefficient between \( m_t^{\text{fit}} \) and \( m_W^{\text{reco}} \) is only \(-0.08\) for correct permutations in simulation. Hence, \( m_t^{\text{fit}} \) and \( m_W^{\text{reco}} \) can be
Figure 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 $f_{\text{sig}}$. The top-quark mass used in the simulation is 172.5 GeV and the nominal jet energy scale is applied.
treated as uncorrelated and the probability $P\left( m_t^{\text{fit}}, m_W^{\text{reco}} | m_t, \text{JES} \right)$ from Eq. (1) is factorized into

\[
P\left( m_t^{\text{fit}}, m_W^{\text{reco}} | m_t, \text{JES} \right) = f_{\text{sig}} \cdot P_{\text{sig}} \left( m_t^{\text{fit}}, m_W^{\text{reco}} | m_t, \text{JES} \right) \\
+ \left( 1 - f_{\text{sig}} \right) \cdot P_{\text{bkg}} \left( m_t^{\text{fit}}, m_W^{\text{reco}} \right) \\
= f_{\text{sig}} \cdot \sum_j f_j P_j \left( m_t^{\text{fit}} | m_t, \text{JES} \right) \cdot P_j \left( m_W^{\text{reco}} | m_t, \text{JES} \right) \\
+ \left( 1 - f_{\text{sig}} \right) \cdot P_{\text{bkg}} \left( m_t^{\text{fit}} \right) \cdot P_{\text{bkg}} \left( m_W^{\text{reco}} \right),
\]

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 ($m_t, \text{gen}$) values and three different JES values (0.96, 1.00, and 1.04). For the probability density functions, the $m_t^{\text{fit}}$ 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 $m_W^{\text{reco}}$ distributions are distorted by the jet-selection criteria and the 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 $m_W^{\text{reco}}$ distributions are therefore fitted with asymmetric generalized Gaussian functions. The dependence of the parameters of the fitted functions on $m_t, \text{gen}$ 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 $m_t^{\text{fit}}$ distribution is fitted by the sum of a Gamma function and a Landau function and its $m_W^{\text{reco}}$ 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 $-2 \ln \{ L( m_t, \text{JES} = 1 | \text{sample}) \}$. In the 2D analysis the most likely top-quark mass and JES are obtained by minimizing $-2 \ln \{ L( m_t, \text{JES} | \text{sample}) \}$.

### 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 $t\bar{t}$ events and modeled background events from event mixing. We extract $m_t, \text{ext}$ and $\text{JES}_{\text{ext}}$ from each pseudo-experiment, which corresponds to an integrated luminosity of 3.54 fb$^{-1}$. This results in 27 calibration points in the $m_t, \text{gen}$-JES plane.

The biases are defined as

\[
\text{mass bias} = \left\langle m_t, \text{ext} - m_t, \text{gen} \right\rangle; \\
\text{JES bias} = \left\langle \text{JES}_{\text{ext}} - \text{JES} \right\rangle.
\]

Both mass and JES bias are plotted as a function of $m_t, \text{gen}$ 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 $m_t, \text{cal}$ and the jet energy scale $\text{JES}_{\text{cal}}$ are derived.
as linear functions of both the extracted top-quark mass and JES from these fits. As shown in Fig. 3 (left), no further corrections are needed for the calibrated top-quark mass \( m_{t, \text{cal}} \) and for the calibrated jet energy scale \( \text{JES}_{\text{cal}} \).

Figure 2: Difference between the extracted top-quark mass \( m_{t, \text{ext}} \) and the generated top-quark mass \( m_{t, \text{gen}} \) (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.

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

\[
\text{pull} = \frac{m_{t, \text{cal}} - m_{t, \text{gen}}}{\sigma (m_{t, \text{cal}})},
\]

where \( \sigma (m_{t, \text{cal}}) \) is the statistical uncertainty in an individual \( m_{t, \text{cal}} \) for a pseudo-experiment generated at \( m_{t, \text{gen}} \). As depicted in Fig. 3 (right), we find a mass pull width of 1.19, meaning that our method underestimates the statistical uncertainty. We incorporate corrections for this directly into the evaluation of the likelihood. 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 \( t \bar{t} \) events and hence on the signal fraction \( f_{\text{sig}} \) 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:
**Figure 3**: (left) Difference between the calibrated top-quark mass \( m_{t, \text{cal}} \) and the generated top-quark mass \( m_{t, \text{gen}} \), and between the calibrated and the generated values of JES after calibration for different generated top-quark masses and three different JES values; (right) 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 correspond to linear fits for individual values of JES and the black line corresponds to a linear (left) or constant (right) fit to all calibration points. The mass points for different JES values are shifted horizontally for clarity.

**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-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% to 20% depending on \( \eta \) 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 t\( t \) simulation. Each
increase lowers the selection efficiency by 7 to 10% covering the uncertainty of 5% found in a dedicated study for the $t\bar{t}$ 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 $\pm 5\%$.

**Parton distribution functions:** The simulated events have been generated using the CTEQ 6.6L parton distribution functions (PDFs) [27]. 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 $t\bar{t}$ 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 $t\bar{t}$ 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 [28]).

**Color reconnection effects:** The uncertainties that arise from different modeling of color reconnection effects [29] are estimated by comparing in simulation an underlying event tune with color reconnection to a tune without it (the Perugia 2011 and Perugia 2011NoCR tunes [28]).

**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 $\eta$-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. However, the 2D analysis has increased uncertainties for color reconnection effects and the modeling of the multijet background. Due to the W-boson mass constraint in
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.

<table>
<thead>
<tr>
<th>Source</th>
<th>1D analysis</th>
<th>2D analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m_t$ (GeV)</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.97 ± 0.06</td>
<td>0.09 ± 0.10</td>
</tr>
<tr>
<td>b-JES</td>
<td>0.49 ± 0.06</td>
<td>0.52 ± 0.10</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.15 ± 0.06</td>
<td>0.13 ± 0.10</td>
</tr>
<tr>
<td>b tagging</td>
<td>0.05 ± 0.06</td>
<td>0.04 ± 0.10</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.24 ± 0.06</td>
<td>0.26 ± 0.10</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.05 ± 0.06</td>
<td>0.09 ± 0.10</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>0.03 ± 0.06</td>
<td>0.07 ± 0.10</td>
</tr>
<tr>
<td>Renormalization and factorization scale</td>
<td>0.08 ± 0.22</td>
<td>0.31 ± 0.34</td>
</tr>
<tr>
<td>ME-PS matching threshold</td>
<td>0.24 ± 0.22</td>
<td>0.29 ± 0.34</td>
</tr>
<tr>
<td>Underlying event</td>
<td>0.20 ± 0.12</td>
<td>0.42 ± 0.20</td>
</tr>
<tr>
<td>Color reconnection effects</td>
<td>0.04 ± 0.15</td>
<td>0.58 ± 0.25</td>
</tr>
<tr>
<td>Multijet background</td>
<td>0.13 ± 0.06</td>
<td>0.60 ± 0.10</td>
</tr>
<tr>
<td>Total</td>
<td>1.21</td>
<td>1.23</td>
</tr>
</tbody>
</table>

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 $m_{W}^{\text{reco}}$ distribution, making the JES estimation more sensitive to changes in the simulation.

9 Results

From the selected 2418 events we measure with the jet energy scale fixed to the nominal value of JES = 1:

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

The overall uncertainty of the presented 1D analysis is 1.39 GeV. The likelihood 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:

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

$$ \text{JES} = 0.991 \pm 0.008 \text{ (stat.)} \pm 0.013 \text{ (syst.).} $$
The measured JES confirms the JES for particle-flow jets in data measured in events where a Z boson or photon is produced together with one jet \cite{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.

![Figure 4](image_url)

Figure 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.

We use the Best Linear Unbiased Estimate technique \cite{30} to combine the 1D result presented in this paper with the CMS measurements in the dilepton channel based on 2010 \cite{31} and 2011 \cite{5} data, and the measurement in the lepton+jets channel \cite{4}. Most of the systematic uncertainties listed in Table 2 are assumed to be fully correlated among the three 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 \( m_t = 173.54 \pm 0.33 \text{ (stat.)} \pm 0.96 \text{ (syst.)} \text{ GeV} \). It has a \( \chi^2 \) 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 \( \sqrt{s} = 7 \text{ TeV} \) 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\(^{-1} \), 2418 candidate events are observed and the mass of the top quark is measured to be \( m_t = 173.49 \pm 0.69 \text{ (stat.)} \pm 1.21 \text{ (syst.)} \text{ GeV} \). This result for \( m_t \) is consistent with the Tevatron average \cite{2}, with the AT-
Figure 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.

LAS measurement in the lepton+jets channel \[32\], 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 \[4,5,31\] yields a mass of \(m_t = 173.54 \pm 0.33 \text{ (stat.)} \pm 0.96 \text{ (syst.)} = 173.54 \pm 1.02 \text{ GeV}\), consistent with the Tevatron average \[2\] and with similar precision.

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References


A  The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
C.A. Bernardes b, F.A. Dias a, T.R. Fernandez Perez Tomei a, E.M. Gregores b, C. Lagana a, F. Marinho a, P.G. Mercadante b, S.F. Novaes a, Sandra S. Padula a

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev2, P. Iaydjiev2, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova
University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Y. Guo, Q. Li, W. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, C.A. Carrillo Montoya, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina, D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim, Y. Assran, A. Ellithi Kamel, M.A. Mahmoud, A. Radi

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Muntel, M. Murumaa, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia
V. Roinishvili

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

University of Athens, Athens, Greece
L. Gouskos, T.J. Merzimekis, A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece
X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horvath, B. Radics, F. Sikler, V. Veszpremi, G. Vesztergombi, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
S.K. Swain

Panjab University, Chandigarh, India

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, P. Saxena, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research - EHEP, Mumbai, India
Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy

INFN Sezione di Catania, Università di Catania, Catania, Italy
S. Albergo, M. Chiorboli, S. Costa, F. Giordano, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
G. Barbagli, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, S. Frosali, E. Gallo, S. Gonzi, V. Gori, P. Lenzi, M. Meschini, S. Paoletti, G. Sguazzoni, A. Tropiano

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Università di Genova, Genova, Italy
P. Fabbricatore, R. Musenich, S. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy

INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Università della Basilicata (Potenza), Università G. Marconi (Roma), Napoli, Italy

INFN Sezione di Padova, Università di Padova, Università di Trento (Trento), Padova, Italy
INFIN Sezione di Pavia $^a$, Università di Pavia $^b$, Pavia, Italy
M. Gabusi$^{a,b}$, S.P. Ratti$^{a,b}$, C. Riccardi$^{a,b}$, P. Vitulo$^{a,b}$

INFIN Sezione di Perugia $^a$, Università di Perugia $^b$, Perugia, Italy
M. Biasini$^{a,b}$, G.M. Bilei$^a$, L. Fanò$^{a,b}$, P. Lariccia$^{a,b}$, G. Mantovani$^{a,b}$, M. Menichelli$^a$, A. Nappi$^{a,b}$, F. Romeo$^{a,b}$, A. Saha$^a$, A. Santocchia$^{a,b}$, A. Spiezia$^{a,b}$

INFIN Sezione di Pisa $^a$, Università di Pisa $^b$, Scuola Normale Superiore di Pisa $^c$, Pisa, Italy
K. Androsov$^{a,29}$, P. Azzurri$^a$, G. Bagliesi$^a$, T. Boccali$^a$, G. Broccolo$^{a,c}$, R. Castaldi$^a$, R.T. D’Agnolo$^{a,c,2}$, R. Dell’Orso$^a$, F. Fiori$^{a,c}$, L. Foà$^{a,c}$, A. Giassi$^a$, M.T. Grippo$^a$, A. Kraan$^a$, F. Ligabue$^{a,c}$, T. Lomtadze$^a$, L. Martini$^{a,29}$, A. Messineo$^{a,b}$, F. Palla$^a$, A. Rizzi$^{a,b}$, A.T. Serban$^a$, P. Spagnolo$^a$, P. Squillacioti$^a$, T. Tenchini$^a$, G. Tonelli$^{a,b}$, A. Venturi$^a$, P.G. Verdini$^a$, C. Vernieri$^{a,c}$

INFIN Sezione di Roma $^a$, Università di Roma $^b$, Roma, Italy
L. Barone$^{a,b}$, F. Cavallari$^a$, D. Del Re$^{a,b}$, M. Diemoz$^a$, M. Grassi$^{a,b,2}$, E. Longo$^{a,b}$, F. Margaroli$^{a,b}$, P. Meridiani$^a$, F. Micheli$^{a,b}$, S. Nourbakhsh$^{a,b}$, G. Origantini$^{a,b}$, R. Paramatti$^a$, S. Rahatlou$^{a,b}$, L. Soffi$^{a,b}$

INFIN Sezione di Torino $^a$, Università di Torino $^b$, Università del Piemonte Orientale (Novara) $^c$, Torino, Italy
N. Amapane$^{a,b}$, R. Arcidiacono$^{a,c}$, S. Argiro$^{a,b}$, M. Arneodo$^{a,c}$, C. Biino$^a$, N. Cartiglia$^a$, S. Casasso$^{a,b}$, M. Costa$^{a,b}$, N. Demaria$^a$, C. Mariott$^a$, S. Maselli$^a$, E. Migliore$^{a,b}$, V. Monaco$^{a,b}$, M. Musich$^a$, M.M. Obertino$^{a,c}$, G. Ortona$^{a,b}$, N. Pastrone$^a$, M. Pelliccioni$^{a,2}$, A. Potenza$^{a,b}$, A. Romero$^{a,b}$, M. Ruspa$^{a,c}$, R. Sacchi$^{a,b}$, A. Solano$^{a,b}$, A. Staiano$^a$, U. Tamponi$^a$

INFIN Sezione di Trieste $^a$, Università di Trieste $^b$, Trieste, Italy
S. Belforte$^a$, V. Candelise$^{a,b}$, M. Casarsa$^a$, F. Cosutti$^{a,2}$, G. Della Ricca$^a$, B. Gobbo$^a$, C. La Licata$^{a,b}$, M. Marone$^{a,b}$, D. Montanino$^{a,b}$, A. Penzo$^a$, A. Schizzi$^{a,b}$, A. Zanetti$^a$

Kangwon National University, Chunchon, Korea
S. Chang, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, Y.D. Oh, H. Park, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, S.K. Park, Y. Roh

University of Seoul, Seoul, Korea
M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Vilnius University, Vilnius, Lithuania
I. Grigelionis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

National Centre for Nuclear Research, Swierk, Poland

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³, L. Dudko, A. Gribushin, V. Klyukhin, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, N. Tsirova

Universität Zürich, Zurich, Switzerland
C. Amsler, V. Chiochia, C. Favaro, M. Ivova Rikova, B. Kilminister, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Taroni, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan

National Taiwan University (NTU), Taipei, Taiwan

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Suwonjandee

Cukurova University, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey

Bogazici University, Istanbul, Turkey
E. Gülmez, B. Isildak, M. Kaya, S. Ozkorucuklu, N. Sonmez

Istanbul Technical University, Istanbul, Turkey
H. Bahtiyar, E. Barlas, K. Cankocak, Y.O. Günaydın, F.I. Vardarlı, M. Yücel

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom
Brunel University, Uxbridge, United Kingdom

Baylor University, Waco, USA
J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev
University of Colorado at Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fairfield University, Fairfield, USA
D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

Florida International University, Miami, USA

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA
The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA
A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA
L. Antonelli, B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, G. Williams, B.L. Winer, H. Wolfe

Princeton University, Princeton, USA
E. Berry, P. Elmer, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, S.A. Koay, D. Lopes

University of Puerto Rico, Mayaguez, USA
E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA

Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, USA

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA
M.W. Arenton, S. Boute, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov
University of Wisconsin, Madison, USA

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil
7: Also at California Institute of Technology, Pasadena, USA
8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9: Also at Zewail City of Science and Technology, Zewail, Egypt
10: Also at Suez Canal University, Suez, Egypt
11: Also at Cairo University, Cairo, Egypt
12: Also at Fayoum University, El-Fayoum, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Now at Ain Shams University, Cairo, Egypt
15: Also at National Centre for Nuclear Research, Swierk, Poland
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at The University of Kansas, Lawrence, USA
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at Tata Institute of Fundamental Research - EHEP, Mumbai, India
22: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
23: Now at King Abdulaziz University, Jeddah, Saudi Arabia
24: Also at University of Visva-Bharati, Santiniketan, India
25: Also at University of Ruhuna, Matara, Sri Lanka
26: Also at Sharif University of Technology, Tehran, Iran
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
31: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
32: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
33: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
34: Also at INFN Sezione di Roma, Roma, Italy
35: Also at University of Athens, Athens, Greece
36: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
37: Also at Paul Scherrer Institut, Villigen, Switzerland
38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
39: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
40: Also at Gaziosmanpasa University, Tokat, Turkey
41: Also at Adiyaman University, Adiyaman, Turkey
42: Also at Cag University, Mersin, Turkey
43: Also at Mersin University, Mersin, Turkey
44: Also at Izmir Institute of Technology, Izmir, Turkey
45: Also at Ozyegin University, Istanbul, Turkey
46: Also at Kafkas University, Kars, Turkey
47: Also at Suleyman Demirel University, Isparta, Turkey
48: Also at Ege University, Izmir, Turkey
49: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
50: Also at Kahramanmaras Sütçü İmam University, Kahramanmaras, Turkey
51: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
52: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
53: Also at Utah Valley University, Orem, USA
54: Now at University of Edinburgh, Scotland, Edinburgh, United Kingdom
55: Also at Institute for Nuclear Research, Moscow, Russia
56: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
57: Also at Argonne National Laboratory, Argonne, USA
58: Also at Erzincan University, Erzincan, Turkey
59: Also at Yildiz Technical University, Istanbul, Turkey
60: Also at Texas A&M University at Qatar, Doha, Qatar
61: Also at Kyungpook National University, Daegu, Korea