



# Measurement of the mass difference between top and anti-top quarks in $pp$ collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector



ATLAS Collaboration\*

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## ABSTRACT

A measurement of the mass difference between top and anti-top quarks is presented. In a  $4.7 \text{ fb}^{-1}$  data sample of proton–proton collisions at  $\sqrt{s} = 7$  TeV recorded with the ATLAS detector at the LHC, events consistent with  $t\bar{t}$  production and decay into a single charged lepton final state are reconstructed. For each event, the mass difference between the top and anti-top quark candidate is calculated. A two  $b$ -tag requirement is used in order to reduce the background contribution. A maximum likelihood fit to these per-event mass differences yields  $\Delta m \equiv m_t - m_{\bar{t}} = 0.67 \pm 0.61$  (stat)  $\pm 0.41$  (syst) GeV, consistent with CPT invariance.

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## 1. Introduction

The CPT symmetry<sup>1</sup> required by a locally gauge-invariant quantum field theory dictates that the masses of all particles and their anti-particles be exactly equal. Any deviation from this would have major implications for particle physics, implying a non-local field theory [1]. Searches for CPT violation both in the  $B$  meson sector [2–5] and with  $K$  mesons [6–8] have not yielded any deviations from the Standard Model (SM). The top quark has the unique property of decaying before hadronization, making it the only quark for which a direct measurement of its mass is possible. The CDF Collaboration measured the mass difference between top and anti-top quarks to be  $\Delta m \equiv m_t - m_{\bar{t}} = 3.3 \pm 1.4 \pm 1.0$  GeV [9], approximately 2 standard deviations away from zero. The D0 Collaboration measured  $\Delta m = 0.8 \pm 1.8 \pm 0.5$  GeV [10], in agreement with the SM value. The CMS Collaboration recently measured  $\Delta m = -0.44 \pm 0.46 \pm 0.27$  GeV [11], also in agreement with the SM value. The CDF and D0 analyses used both the top and anti-top quarks within each event to measure  $\Delta m$ . In the CMS measurement, the masses of the top and anti-top quarks with hadronic  $W$  boson decays are extracted from two separate samples, split using the lepton charge, and subtracted from one another. In this Letter, the ATLAS Collaboration presents a measurement of this mass difference. The top and anti-top quarks are each taken from the same event, in which a  $t\bar{t}$  pair is produced and decays in the lepton+ jets channel.

## 2. ATLAS detector

ATLAS [12] is a general-purpose particle physics detector with cylindrical geometry covering nearly the entire solid angle around the collision point. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane, where  $\phi$  is the azimuthal angle around the beam pipe. The pseudorapidity is defined as  $\eta \equiv -\ln \tan(\theta/2)$ , where  $\theta$  is the polar angle. The transverse mass ( $m_T$ ) of any two objects is defined as  $m_T \equiv \sqrt{2E_T^1 E_T^2 (1 - \cos \Delta\phi)}$ , where  $E_T$  is the object's transverse energy, defined in the plane transverse to the beam axis.

The inner detector (ID) systems, located closest to the interaction region, are immersed in a 2 T axial magnetic field and provide charged particle tracking in the range  $|\eta| < 2.47$ . The ID systems consist of a high-granularity silicon pixel detector and a silicon microstrip tracker, as well as a transition radiation tracker. Located outside the solenoid, electromagnetic calorimetry is provided by barrel and endcap lead/liquid-argon calorimeters, and hadronic calorimetry by the steel/scintillating-tile sampling calorimeters in the central region, and liquid-argon calorimeters in the endcap/forward regions. Comprising separate trigger and high-precision tracking chambers, the muon spectrometer measures the deflection of muons in a magnetic field with a field integral from 2–8 Tm, generated by one barrel and two endcap superconducting air-core toroids. A three-level trigger system is used to select and record interesting events. The level-1 hardware trigger uses a subset of detector information to reduce the event rate resulting from the peak LHC bunch crossing rate of 20 MHz in 2011 to a value of at most 65 kHz. The level-1 trigger is followed by two software-based trigger levels, level-2 and the event filter, which together reduce the event rate to a few hundred Hz for permanent storage and offline analysis.

\* E-mail address: atlas.publications@cern.ch.

<sup>1</sup> CPT is the combination of three symmetries; Charge conjugation (C), Parity (P) and Time reversal (T).

### 3. Data sample and event selection

This analysis uses  $4.7 \pm 0.2 \text{ fb}^{-1}$  [13] of proton–proton collision data recorded by the ATLAS experiment at  $\sqrt{s} = 7 \text{ TeV}$  in 2011. The selected events used in this analysis must contain the signature of a  $t\bar{t}$  event decaying in the lepton + jets channel. Exactly one charged lepton is required – either a single electron with  $E_T > 25 \text{ GeV}$ , or a single muon with  $p_T > 20 \text{ GeV}$ , where  $p_T$  is the object’s transverse momentum, defined in the plane transverse to the beam axis. Energy deposits are selected as electron candidates based on their shower shapes in the electromagnetic calorimeters and on the presence of a good-quality track pointing to them. Electron candidates are required to pass the “tight” quality cuts described in Ref. [14], to fall inside a well-instrumented region of the detector, and to be well isolated from other objects in the event. Muons are required to pass “tight” muon quality cuts [15–17], to be well measured in both the ID and the muon spectrometer, and to be isolated from other objects in the event. Events with an electron (muon) are required to have been triggered by an electron (muon) trigger with an  $E_T$  ( $p_T$ ) threshold of 20 (18) GeV. The selection requirements ensure that triggered events are on the trigger efficiency plateau [18,19].

Jets are reconstructed in the calorimeter using the anti- $k_t$  algorithm [20,21] with a radius parameter of 0.4, starting from energy deposits grouped into noise-suppressed topological clusters [22,23]. Jets are required to satisfy  $p_T > 25 \text{ GeV}$  and  $|\eta| < 2.5$ . Events with jets arising from problematic regions in the calorimeters, beam backgrounds and cosmic rays are rejected [24]. Additional corrections are applied after the default ATLAS jet energy calibration [24] to restore on average the partonic energies in  $t\bar{t}$  events. Jets from the decay of long-lived heavy-flavor hadrons are selected by using a multivariate tagging algorithm ( $b$ -tagging) [25,26]. The transverse momentum of neutrinos is inferred from the magnitude of the missing transverse momentum ( $E_T^{\text{miss}}$ ) [27].

In addition to the requirement of exactly one charged lepton, the signal selection for this analysis requires four or more jets, at least two of which must be  $b$ -tagged. The selected lepton is required to match a trigger object that caused the event to be recorded. To suppress backgrounds from multi-jet events,  $E_T^{\text{miss}}$  must be larger than 30 (20) GeV in the electron (muon) channel. Further reduction of the multi-jet background in the electron channel is achieved by requiring the transverse mass ( $m_T$ ) of the lepton and  $E_T^{\text{miss}}$  to be  $> 30 \text{ GeV}$ . In the muon channel,  $E_T^{\text{miss}} + m_T > 60 \text{ GeV}$  is required.

### 4. Simulated samples and background estimation

The ATLAS detector simulation [28], based on GEANT4 [29], is used to process simulated signal and background events. Simulated minimum bias collisions are overlaid on top of the hard scatter process, and events are reweighted so that the distribution of the average number of interactions (typically 5–20, see Ref. [30]) per bunch crossing matches the distribution observed in data.

Simulated samples of  $t\bar{t}$  events are produced using PYTHIA v6.425 [31] with  $\Delta m$  ranging from  $-15 \text{ GeV}$  to  $+15 \text{ GeV}$ . In total, 15 such samples are used, with decreasing granularity at large  $|\Delta m|$ . Near  $\Delta m = 0$ , the granularity is  $0.3 \text{ GeV}$ .<sup>2</sup> In these samples, the average top quark mass ( $\frac{m_t + m_{\bar{t}}}{2}$ ) is set to  $172.5 \text{ GeV}$ . The underlying-event tune used is AUET2B [32], and the parton distribution function (PDF) set is MRST [33]. Despite being a leading order generator, PYTHIA is used because it allows generation

<sup>2</sup> In total, 15 signal samples were generated with a  $\Delta m$  of  $\pm 15$ ,  $\pm 10$ ,  $\pm 5$ ,  $\pm 3$ ,  $\pm 1$ ,  $\pm 0.6$ ,  $\pm 0.3$  and  $0 \text{ GeV}$ .

of events where the masses of the top and anti-top quarks are not equal. Non-zero widths as predicted by the SM for the corresponding top and anti-top quark masses are included in the event generation.

Pseudo-experiments and additional checks for systematic uncertainties are performed with a SM  $t\bar{t}$  sample with  $\Delta m = 0$  generated using MC@NLO [34,35] v4.01 interfaced to HERWIG v6.520 [36] and JIMMY v4.31 [37]. Except for multi-jet processes, Monte Carlo simulations are used to study and estimate the backgrounds. The background from production of single  $W$  bosons in association with jets is studied using ALPGEN v2.13 [38] interfaced to HERWIG and JIMMY. The MLM matching scheme [39] is used to form inclusive  $W$  + jets samples, taking appropriate care to remove overlapping events in heavy-flavor phase space stemming from both the hard scatter and the showering. Diboson events are generated using HERWIG. Single-top events are generated using MC@NLO in the  $s$ - and  $Wt$ -channels, and ACERMC v3.8 [40] in the  $t$ -channel. The distribution of the multi-jet background is taken from a control region in data where leptons are required to be semi-isolated and have large impact parameter ( $d_0$ ) and impact parameter significance ( $d_0$  divided by its uncertainty) with respect to the collision vertex. The semi-isolated selection requires the scalar  $p_T$  sum for tracks in a cone of 0.3 around the electron (muon) divided by its  $E_T$  ( $p_T$ ) to be between 0.1 and 0.3. The normalization of this background is obtained from a likelihood fit to the  $E_T^{\text{miss}}$  distribution in data [41].

### 5. Kinematic fits

In order to measure a quantity sensitive to the mass difference  $\Delta m$  between the top and anti-top quarks, the kinematic  $\chi^2$  fitter described below is used to reconstruct the  $t\bar{t}$  system from the observed lepton,  $E_T^{\text{miss}}$  and jets. The assignment of the selected jets to the partons from the  $t\bar{t}$  decay uses knowledge of the over-constrained  $t\bar{t}$  system with the reconstructed top/anti-top quark mass difference ( $\Delta m^{\text{fit}}$ ) as a free parameter in each event. In the kinematic fitter, the  $p_T$  of the lepton and jets is allowed to fluctuate within uncertainties determined from simulated  $t\bar{t}$  events. The average top quark mass is fixed, but the individual  $t$  and  $\bar{t}$  masses are allowed to fluctuate while being constrained by the predicted top quark width. The masses of the two reconstructed  $W$  bosons are also allowed to vary within the  $W$  boson width. The fit is applied by examining all jet–parton assignments (from among the five leading jets) consistent with the  $b$ -jet assignment and minimizing the following  $\chi^2$ :

$$\chi^2 = \sum_{i=\ell, A \text{ jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{E_U^{\text{fit}}} - p_j^{E_U^{\text{meas}}})^2}{\sigma_{E_U}^2} + \sum_{k=jj,\ell\nu} \frac{(m_k^{\text{fit}} - m_W)^2}{\sigma_W^2} + \frac{(m_{b\ell\nu}^{\text{meas}} - (m_t + \frac{(m_{b\ell\nu}^{\text{fit}} - m_{bjj}^{\text{fit}})}{2}))^2}{\sigma_t^2} + \frac{(m_{bjj}^{\text{meas}} - (m_t - \frac{(m_{b\ell\nu}^{\text{fit}} - m_{bjj}^{\text{fit}})}{2}))^2}{\sigma_t^2}, \quad (1)$$

$$\Delta m^{\text{fit}} = q_\ell \times (m_{b\ell\nu}^{\text{fit}} - m_{bjj}^{\text{fit}}) \quad (2)$$

**Table 1**

The observed number of events in data, the expected numbers of events from signal and background processes and the total number of events, after all selection requirements. Uncertainties shown include statistical and total systematic uncertainties added in quadrature.

Channel	Muon	Electron
Data	8854	4941
SM $t\bar{t} \rightarrow W^+bW^-\bar{b}$	$7700^{+1600}_{-1700}$	$4500^{+900}_{-1000}$
$W/Z$ + jets	$320 \pm 90$	$160 \pm 40$
Single top	$300 \pm 50$	$170 \pm 30$
Diboson	$5 \pm 1$	$3 \pm 1$
Multi-jet	$220 \pm 110$	$110 \pm 60$
Total expected (SM)	$8550^{+1800}_{-1700}$	$4900^{+900}_{-1000}$

where  $p_T^{i,\text{fit}}$  and  $p_T^{i,\text{meas}}$  are the fitted and measured  $p_T$  of the jets and the charged lepton, and  $\sigma_i$  is the uncertainty on those values. The unclustered energy in the calorimeter ( $E_U$ ) is defined as a quantity that includes all energy not associated with the primary lepton or the jets and is used to correct  $E_T^{\text{miss}}$ . The width of the  $W$  boson ( $\sigma_W$ ) is set to the PDG value [42], and the top quark width ( $\sigma_t$ ) is set to the value predicted from theory. The top quark mass ( $m_t$ ) is fixed to 172.5 GeV, and the  $W$  boson mass ( $m_W$ ) is set to  $m_W = 80.42$  GeV. The value of  $m_k^{\text{fit}}$  is the fitted dijet (lepton–neutrino) mass from the hadronic (leptonic)  $W$  boson decay, and  $m_{b\ell\nu}^{\text{fit}}$  and  $m_{bjj}^{\text{fit}}$  are the fitted top quark masses with leptonically and hadronically decaying  $W$  bosons. The value of the mass difference between the hadronic- and leptonic-side top quarks is a free parameter in the fit. In each event, the single jet–parton assignment with the lowest  $\chi^2$  is used, and the fitted value of  $\Delta_m^{\text{fit}}$  is taken as an observable to measure the true  $\Delta m$ . As seen in Eq. (2),  $\Delta_m^{\text{fit}}$  is calculated from the product of the lepton charge ( $q_\ell$ ) and the difference between  $m_{b\ell\nu}^{\text{fit}}$  and  $m_{bjj}^{\text{fit}}$ . Events with  $\chi^2 > 10$  for the best jet–parton assignment are considered to be poorly measured or background, and are rejected. The value of this cut is chosen based on studies of simulated signal events, and the efficiency of the  $\chi^2$  selection is estimated in simulation to be 55% for  $t\bar{t}$  signal events and 31% for background events. Table 1 shows the expected and observed number of events after all selection requirements, including the  $\chi^2$  cut, are applied.

Distributions of  $\Delta_m^{\text{fit}}$  are produced for all background samples as well as for a number of simulated  $t\bar{t}$  samples generated with different  $\Delta m$ .

The  $\Delta_m^{\text{fit}}$  distributions in the signal samples are parameterized in templates by fitting the sum of two Gaussians, where the narrow one corresponds to the correct jet–parton pairing, and the wide one corresponds to an incorrect pairing. The widths of the two Gaussians are quadratic functions of  $\Delta m$  (symmetric about  $\Delta m = 0$ ). The means of the two Gaussians are fit to linear functions of  $\Delta m$ . The relative weight of the two Gaussians is fit to a quadratic function symmetric about  $\Delta m = 0$ . Fig. 1 shows the parameterization for five different values of  $\Delta m$ . The  $\Delta_m^{\text{fit}}$  distributions for all background samples are combined with relative weights according to the SM prediction, into a single template distribution that is fit with a Gaussian, as shown in Fig. 2. The choice of background parameterization has only a small impact on the fits due to the small background in the double  $b$ -tag channel. The signal and background templates are used to model the probability density distributions in  $\Delta m$ .

## 6. Likelihood fit

An unbinned extended maximum likelihood fit to the distribution of  $\Delta_m^{\text{fit}}$  is performed to extract  $\Delta m$ , as well as the expected number of signal ( $n_s$ ) and background ( $n_b$ ) events in the data.

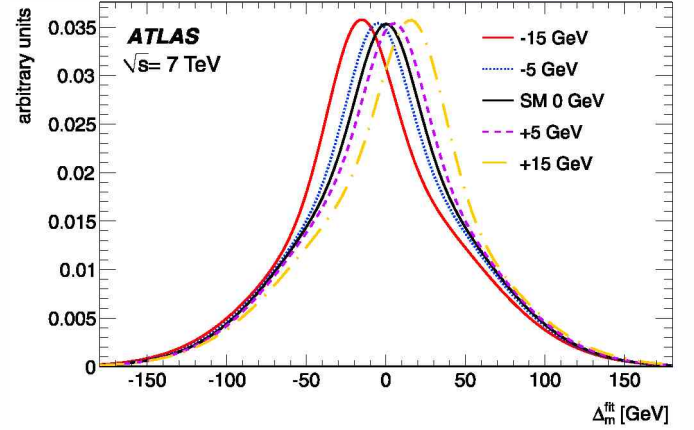


Fig. 1. Parameterization of  $\Delta_m^{\text{fit}}$  for simulated  $t\bar{t}$  samples with different values of  $\Delta m$ .

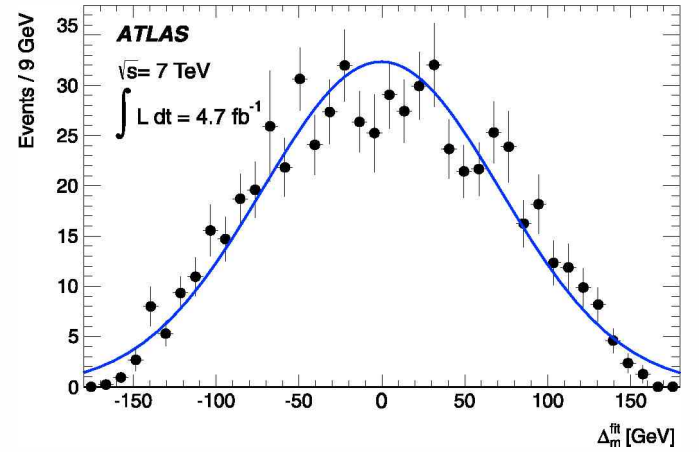


Fig. 2. Parameterized background template.

Given the data  $D$ , which contain  $N$  values of  $\Delta_m^{\text{fit}}$ , the probability distribution function for signal ( $p_s$ ) and background ( $p_b$ ) are used to write down a likelihood ( $L$ ):

$$L(D|n_s, n_b, \Delta m) = q(N, n_s + n_b) \times \prod_{i=1}^N \frac{n_s p_s(\Delta_m^{\text{fit},i}|\Delta m) + n_b p_b(\Delta_m^{\text{fit},i})}{n_s + n_b} \quad (3)$$

where  $q(N, n_s + n_b)$  is the Poisson probability to observe  $N$  events given  $n_s + n_b$  expected events and the product over  $i$  is over the  $N$  reconstructed events. The likelihood is maximized over all three parameters ( $n_s, n_b, \Delta m$ ). Ensembles of pseudo-experiments are run to ensure that the fits are unbiased and return correct statistical uncertainties. The widths of pull distributions are consistent with unity. Due to the use of PYTHIA to generate templates and MC@NLO to run ensemble tests, a 175 MeV offset is applied to all pseudo-experiments (and to the nominal fit result) to return an unbiased measurement, with the statistical uncertainty of 50 MeV on this calibration taken as a systematic uncertainty. The 175 MeV offset is the average difference between the MC@NLO samples with the top and anti-top quark masses reweighted to the distributions in PYTHIA for a given mass difference. When running pseudo-experiments, events are drawn directly from the simulated samples and not from the parameterizations in order to check for any potential bias.

The extended maximum likelihood fit is applied to the full 2011 dataset, yielding the result shown in Fig. 3. The value of 175 MeV

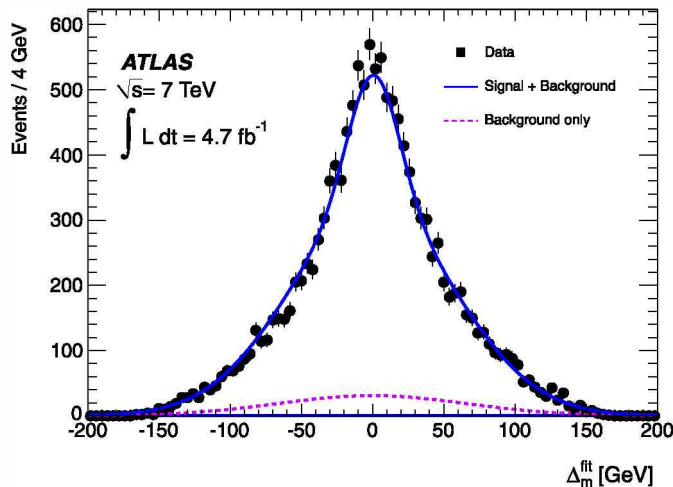


Fig. 3. Reconstructed top/anti-top quark mass difference with the best maximum likelihood fit for signal and background overlaid.

Table 2  
Systematic uncertainties.

Systematic uncertainty	$\Delta(\Delta m)$ [GeV]
$b/\bar{b}$ decay uncertainties	0.34
$K^+/K^-$ calorimeter response asymmetry	0.08
Residual $b$ vs $\bar{b}$ differences	0.08
$b$ -tagging	0.08
Mis-tagging as a $b$ -quark jet	0.05
Jet energy scale	0.04
$b$ -jet energy scale	0.05
Jet energy resolution	0.03
Parton shower	0.08
MC generator	0.08
ISR/FSR	0.07
Calibration method	0.05
Non- $t\bar{t}$ normalization	0.04
Non- $t\bar{t}$ shape	0.04
Parton distribution function	0.02
Lepton energy scale asymmetry	< 0.01
Electron reconstruction & identification	0.02
Muon reconstruction & identification	0.04
Top mass input	0.04
Total	0.41

quoted above is subtracted from the result to correct for this bias, giving a measured top/anti-top quark mass difference of  $m_t - m_{\bar{t}} = 0.67 \pm 0.61$  (stat). The  $\chi^2$  per degree of freedom for Fig. 3 is 1.2.

## 7. Systematic uncertainties

Due to cancellations from measuring the mass difference and not the individual quark masses, most systematic effects yield small uncertainties on the final measurement. Systematic uncertainties are evaluated by performing pseudo-experiments with pseudo-data that reflect a variation due to the potential source of uncertainty considered, and comparing the extracted  $\Delta m$  to the one obtained with default pseudo-data. A list of all systematic uncertainties and their effects on the measurement are summarized in Table 2. The total systematic uncertainty of 0.41 GeV on the measured  $\Delta m$  is dominated by the uncertainty from the choice of  $b$  fragmentation model, which can induce different detector response to jets from  $b$ - and  $\bar{b}$ -quarks in simulation. The various systematic uncertainties are discussed in more detail below.

Systematic uncertainties on  $\Delta m$  due to differences in the detector response to jets from  $b$ - and  $\bar{b}$ -quarks are difficult to evaluate with in-situ methods in the  $t\bar{t}$  environment due to correlations with  $\Delta m$ . Based on the evaluation of the jet energy scale uncertainty from single-hadron response measurements [43], most differences between the calorimeter response to the two types of jets are expected to be small; exceptions are discussed below. One such difference could come from the different responses to positively and negatively charged kaons, which occur at different rates in jets from  $b$ - and  $\bar{b}$ -quarks. The interaction cross sections for  $K^+$  and  $K^-$  in the calorimeters are different. Such effects are studied by comparing convolutions of the kaon spectra in  $b$ - and  $\bar{b}$ -jets from  $t\bar{t}$  events with the expected calorimeter response to kaons simulated with various hadron shower simulation models, as specified in Ref. [43]. The resulting uncertainty is 80 MeV. Uncertainties due to fragmentation and the decay of  $b$ -hadrons can also lead to uncertainties in the particle content and hadron momentum spectra, and thus in the calorimeter response. This uncertainty is evaluated by comparing POWHEG samples that use EVTGEN [44] and PYTHIA to decay  $b$ -hadrons, and is estimated to be 340 MeV. The EVTGEN particle decay simulation implements different hadron decay models and up-to-date  $b$ -hadron decay tables. An additional 80 MeV is assigned to account for any residual difference in response between jets from  $b$  and  $\bar{b}$  quarks due to effects not considered above. Parton shower and additional fragmentation uncertainties are estimated by comparing POWHEG samples interfaced with HERWIG to those interfaced with PYTHIA.

Other uncertainties are small compared to those from differences between jets from  $b$ - and  $\bar{b}$ -quarks. The uncertainty on  $\Delta m$  from the uncertainty on the  $b$ -tagging efficiency is measured by varying the  $b$ -tag scale factors, which correct simulated efficiencies to those measured in data, within  $1\sigma$  of their uncertainties. The systematic effects from uncertain light- and  $b$ -jet energy scales and resolutions are small, as they affect the top and anti-top quark masses in the same way [45,46]. Generator uncertainties are estimated by comparing pseudo-experiments using MC@NLO and POWHEG. A systematic uncertainty on the amount of QCD radiation is derived from ACERMC  $t\bar{t}$  samples that have varying amounts of initial- and final-state radiation [47]. Uncertainties from the template parameterization are estimated by varying the parameters within their uncertainties, and are found to be small. The systematic uncertainties due to background shape and rate are estimated by replacing the  $W$  + jets background used in pseudo-experiments with the shape from the multi-jet background and by varying the normalization within uncertainties. A small systematic uncertainty due to the parton distribution functions of the proton is evaluated by taking the envelope of the MSTW2008NLO [48], NNPDF2.3 [49] and CTEQ6.6 [50] PDF set uncertainties, following the PDF4LHC recommendations [51]. Asymmetries due to lepton energy scales are negligible. A systematic uncertainty on the top quark mass of 40 MeV is estimated by comparing pseudo-experiments where the input average top quark mass is shifted up and down by 1.5 GeV. Other systematic uncertainties considered are those caused by the uncertainty on the lepton identification and reconstruction.

## 8. Conclusions

The analysis described in this Letter is the first measurement by ATLAS of the mass difference between the top and anti-top quarks using event-by-event quantities in  $t\bar{t}$  events. It is based on  $4.7 \text{ fb}^{-1}$  of 7 TeV proton–proton collisions at the LHC. The mass difference,  $\Delta m$ , is calculated using a kinematic  $\chi^2$  fitter. The measured mass difference is  $\Delta m \equiv m_t - m_{\bar{t}} = 0.67 \pm 0.61$  (stat)  $\pm 0.41$  (syst) GeV, consistent with the SM expectation of no mass difference.

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G. Aad<sup>48</sup>, T. Abajyan<sup>21</sup>, B. Abbott<sup>112</sup>, J. Abdallah<sup>12</sup>, S. Abdel Khalek<sup>116</sup>, O. Abdinov<sup>11</sup>, R. Aben<sup>106</sup>, B. Abi<sup>113</sup>, M. Abolins<sup>89</sup>, O.S. AbouZeid<sup>159</sup>, H. Abramowicz<sup>154</sup>, H. Abreu<sup>137</sup>, Y. Abulaiti<sup>147a,147b</sup>, B.S. Acharya<sup>165a,165b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, T.N. Addy<sup>56</sup>, J. Adelman<sup>177</sup>, S. Adomeit<sup>99</sup>, T. Adye<sup>130</sup>, S. Aefsky<sup>23</sup>, T. Agatonovic-Jovin<sup>13b</sup>, J.A. Aguilar-Saavedra<sup>125b,b</sup>, M. Agustoni<sup>17</sup>, S.P. Ahlen<sup>22</sup>, A. Ahmad<sup>149</sup>, F. Ahmadov<sup>64,c</sup>, M. Ahsan<sup>41</sup>, G. Aielli<sup>134a,134b</sup>, T.P.A. Åkesson<sup>80</sup>, G. Akimoto<sup>156</sup>, A.V. Akimov<sup>95</sup>, M.A. Alam<sup>76</sup>, J. Albert<sup>170</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>70</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>64</sup>, F. Alessandria<sup>90a</sup>, C. Alexa<sup>26a</sup>, G. Alexander<sup>154</sup>, G. Alexandre<sup>49</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>165a,165c</sup>, M. Aliev<sup>16</sup>, G. Alimonti<sup>90a</sup>, L. Alio<sup>84</sup>, J. Alison<sup>31</sup>, B.M.M. Allbrooke<sup>18</sup>, L.J. Allison<sup>71</sup>, P.P. Allport<sup>73</sup>, S.E. Allwood-Spiers<sup>53</sup>, J. Almond<sup>83</sup>, A. Aloisio<sup>103a,103b</sup>, R. Alon<sup>173</sup>, A. Alonso<sup>36</sup>, F. Alonso<sup>70</sup>, A. Althaiser<sup>35</sup>, B. Alvarez Gonzalez<sup>89</sup>, M.G. Alviggi<sup>103a,103b</sup>, K. Amako<sup>65</sup>,

Y. Amaral Coutinho<sup>24a</sup>, C. Amelung<sup>23</sup>, V.V. Ammosov<sup>129,\*</sup>, S.P. Amor Dos Santos<sup>125a</sup>, A. Amorim<sup>125a,d</sup>,  
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 C.F. Anders<sup>58b</sup>, G. Anders<sup>58a</sup>, K.J. Anderson<sup>31</sup>, A. Andreazza<sup>90a,90b</sup>, V. Andrei<sup>58a</sup>, X.S. Anduaga<sup>70</sup>,  
 S. Angelidakis<sup>9</sup>, P. Anger<sup>44</sup>, A. Angerami<sup>35</sup>, F. Anghinolfi<sup>30</sup>, A.V. Anisenkov<sup>108</sup>, N. Anjos<sup>125a</sup>,  
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R. Yoosoofmiya <sup>124</sup>, K. Yorita <sup>172</sup>, R. Yoshida <sup>6</sup>, K. Yoshihara <sup>156</sup>, C. Young <sup>144</sup>, C.J.S. Young <sup>119</sup>, S. Youssef <sup>22</sup>,  
D.R. Yu <sup>15</sup>, J. Yu <sup>8</sup>, J. Yu <sup>113</sup>, L. Yuan <sup>66</sup>, A. Yurkewicz <sup>107</sup>, B. Zabinski <sup>39</sup>, R. Zaidan <sup>62</sup>, A.M. Zaitsev <sup>129,ad</sup>,  
A. Zaman <sup>149</sup>, S. Zambito <sup>23</sup>, L. Zanello <sup>133a,133b</sup>, D. Zanzi <sup>100</sup>, A. Zaytsev <sup>25</sup>, C. Zeitnitz <sup>176</sup>, M. Zeman <sup>127</sup>,  
A. Zemla <sup>39</sup>, K. Zengel <sup>23</sup>, O. Zenin <sup>129</sup>, T. Ženiš <sup>145a</sup>, D. Zerwas <sup>116</sup>, G. Zevi della Porta <sup>57</sup>, D. Zhang <sup>88</sup>,  
H. Zhang <sup>89</sup>, J. Zhang <sup>6</sup>, L. Zhang <sup>152</sup>, X. Zhang <sup>33d</sup>, Z. Zhang <sup>116</sup>, Z. Zhao <sup>33b</sup>, A. Zhemchugov <sup>64</sup>,  
J. Zhong <sup>119</sup>, B. Zhou <sup>88</sup>, L. Zhou <sup>35</sup>, N. Zhou <sup>164</sup>, C.G. Zhu <sup>33d</sup>, H. Zhu <sup>33a</sup>, J. Zhu <sup>88</sup>, Y. Zhu <sup>33b</sup>, X. Zhuang <sup>33a</sup>,  
A. Zibell <sup>99</sup>, D. Zieminska <sup>60</sup>, N.I. Zimin <sup>64</sup>, C. Zimmermann <sup>82</sup>, R. Zimmermann <sup>21</sup>, S. Zimmermann <sup>21</sup>,  
S. Zimmermann <sup>48</sup>, Z. Zinonos <sup>54</sup>, M. Ziolkowski <sup>142</sup>, R. Zitoun <sup>5</sup>, L. Živković <sup>35</sup>, G. Zobernig <sup>174</sup>,  
A. Zoccoli <sup>20a,20b</sup>, M. zur Nedden <sup>16</sup>, G. Zurzolo <sup>103a,103b</sup>, V. Zutshi <sup>107</sup>, L. Zwalinski <sup>30</sup>

<sup>1</sup> School of Chemistry and Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany, NY, United States

<sup>3</sup> Department of Physics, University of Alberta, Edmonton, AB, Canada

<sup>4</sup> <sup>(a)</sup> Department of Physics, Ankara University, Ankara; <sup>(b)</sup> Department of Physics, Gazi University, Ankara; <sup>(c)</sup> Division of Physics, TOBB University of Economics and Technology, Ankara;

<sup>(d)</sup> Turkish Atomic Energy Authority, Ankara, Turkey

<sup>5</sup> LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France

<sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States

<sup>7</sup> Department of Physics, University of Arizona, Tucson, AZ, United States

<sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington, TX, United States

<sup>9</sup> Physics Department, University of Athens, Athens, Greece

<sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece

<sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

<sup>12</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain

<sup>13</sup> <sup>(a)</sup> Institute of Physics, University of Belgrade, Belgrade; <sup>(b)</sup> Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

<sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway

<sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States

<sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany

<sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

<sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>19</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics, Dogus University, Istanbul; <sup>(c)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey

<sup>20</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

<sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany

<sup>22</sup> Department of Physics, Boston University, Boston, MA, United States

<sup>23</sup> Department of Physics, Brandeis University, Waltham, MA, United States

- 24 <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
- 25 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
- 26 <sup>(a)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(b)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(c)</sup> University Politehnica Bucharest, Bucharest; <sup>(d)</sup> West University in Timisoara, Timisoara, Romania
- 27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- 28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- 29 Department of Physics, Carleton University, Ottawa, ON, Canada
- 30 CERN, Geneva, Switzerland
- 31 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
- 32 <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- 33 <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Physics Department, Shanghai Jiao Tong University, Shanghai, China
- 34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- 35 Nevis Laboratory, Columbia University, Irvington, NY, United States
- 36 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- 37 <sup>(a)</sup> INFN Gruppo Collegato di Cosenza; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- 38 <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- 39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
- 40 Physics Department, Southern Methodist University, Dallas, TX, United States
- 41 Physics Department, University of Texas at Dallas, Richardson, TX, United States
- 42 DESY, Hamburg and Zeuthen, Germany
- 43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- 44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- 45 Department of Physics, Duke University, Durham, NC, United States
- 46 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- 47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
- 48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- 49 Section de Physique, Université de Genève, Geneva, Switzerland
- 50 <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- 51 <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- 52 Il Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- 53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- 54 Il Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- 55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
- 56 Department of Physics, Hampton University, Hampton, VA, United States
- 57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
- 58 <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany; <sup>(c)</sup> ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Heidelberg
- 59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 60 Department of Physics, Indiana University, Bloomington, IN, United States
- 61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 62 University of Iowa, Iowa City, IA, United States
- 63 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
- 64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 66 Graduate School of Science, Kobe University, Kobe, Japan
- 67 Faculty of Science, Kyoto University, Kyoto, Japan
- 68 Kyoto University of Education, Kyoto, Japan
- 69 Department of Physics, Kyushu University, Fukuoka, Japan
- 70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 71 Physics Department, Lancaster University, Lancaster, United Kingdom
- 72 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- 77 Department of Physics and Astronomy, University College London, London, United Kingdom
- 78 Louisiana Tech University, Ruston, LA, United States
- 79 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 80 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 81 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 82 Institut für Physik, Universität Mainz, Mainz, Germany
- 83 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 84 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 85 Department of Physics, University of Massachusetts, Amherst, MA, United States
- 86 Department of Physics, McGill University, Montreal, QC, Canada
- 87 School of Physics, University of Melbourne, Victoria, Australia
- 88 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
- 89 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
- 90 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- 91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- 93 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
- 94 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- 96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia

- <sup>98</sup> D.V. Skobel'syn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- <sup>99</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>100</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>101</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>102</sup> Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>103</sup> <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
- <sup>104</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
- <sup>105</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- <sup>106</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>107</sup> Department of Physics, Northern Illinois University, DeKalb, IL, United States
- <sup>108</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- <sup>109</sup> Department of Physics, New York University, New York, NY, United States
- <sup>110</sup> Ohio State University, Columbus, OH, United States
- <sup>111</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>112</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
- <sup>113</sup> Department of Physics, Oklahoma State University, Stillwater, OK, United States
- <sup>114</sup> Palacký University, RCPTM, Olomouc, Czech Republic
- <sup>115</sup> Center for High Energy Physics, University of Oregon, Eugene, OR, United States
- <sup>116</sup> LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>117</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>118</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>119</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>120</sup> <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>121</sup> Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
- <sup>122</sup> Petersburg Nuclear Physics Institute, Gatchina, Russia
- <sup>123</sup> <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>124</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
- <sup>125</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal; <sup>(b)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
- <sup>126</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- <sup>127</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>128</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>129</sup> State Research Center Institute for High Energy Physics, Protvino, Russia
- <sup>130</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>131</sup> Physics Department, University of Regina, Regina, SK, Canada
- <sup>132</sup> Ritsumeikan University, Kusatsu, Shiga, Japan
- <sup>133</sup> <sup>(a)</sup> INFN Sezione di Roma I; <sup>(b)</sup> Dipartimento di Fisica, Università La Sapienza, Roma, Italy
- <sup>134</sup> <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>135</sup> <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>136</sup> <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies, Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
- <sup>137</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- <sup>138</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
- <sup>139</sup> Department of Physics, University of Washington, Seattle, WA, United States
- <sup>140</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>141</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>142</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany
- <sup>143</sup> Department of Physics, Simon Fraser University, Burnaby, BC, Canada
- <sup>144</sup> SLAC National Accelerator Laboratory, Stanford, CA, United States
- <sup>145</sup> <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- <sup>146</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>147</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden
- <sup>148</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>149</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States
- <sup>150</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>151</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>152</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>153</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- <sup>154</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>155</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>156</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- <sup>157</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>158</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>159</sup> Department of Physics, University of Toronto, Toronto, ON, Canada
- <sup>160</sup> <sup>(a)</sup> TRIUMF, Vancouver, BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto, ON, Canada
- <sup>161</sup> Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- <sup>162</sup> Department of Physics and Astronomy, Tufts University, Medford, MA, United States
- <sup>163</sup> Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
- <sup>164</sup> Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States
- <sup>165</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>166</sup> Department of Physics, University of Illinois, Urbana, IL, United States
- <sup>167</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>168</sup> Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- <sup>169</sup> Department of Physics, University of British Columbia, Vancouver, BC, Canada
- <sup>170</sup> Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada



- <sup>171</sup> Department of Physics, University of Warwick, Coventry, United Kingdom  
<sup>172</sup> Waseda University, Tokyo, Japan  
<sup>173</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel  
<sup>174</sup> Department of Physics, University of Wisconsin, Madison, WI, United States  
<sup>175</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany  
<sup>176</sup> Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany  
<sup>177</sup> Department of Physics, Yale University, New Haven, CT, United States  
<sup>178</sup> Yerevan Physics Institute, Yerevan, Armenia  
<sup>179</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

- <sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom.  
<sup>b</sup> Also at Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa, Portugal.  
<sup>c</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.  
<sup>d</sup> Also at Faculdade de Ciências and CFNUL, Universidade de Lisboa, Lisboa, Portugal.  
<sup>e</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.  
<sup>f</sup> Also at TRIUMF, Vancouver, BC, Canada.  
<sup>g</sup> Also at Department of Physics, California State University, Fresno, CA, United States.  
<sup>h</sup> Also at Novosibirsk State University, Novosibirsk, Russia.  
<sup>i</sup> Also at Department of Physics, University of Coimbra, Coimbra, Portugal.  
<sup>j</sup> Also at Università di Napoli Parthenope, Napoli, Italy.  
<sup>k</sup> Also at Institute of Particle Physics (IPP), Canada.  
<sup>l</sup> Also at Department of Physics, Middle East Technical University, Ankara, Turkey.  
<sup>m</sup> Also at Louisiana Tech University, Ruston, LA, United States.  
<sup>n</sup> Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.  
<sup>o</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.  
<sup>p</sup> Also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States.  
<sup>q</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.  
<sup>r</sup> Also at Instituto Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.  
<sup>s</sup> Also at Department of Physics, University of Cape Town, Cape Town, South Africa.  
<sup>t</sup> Also at CERN, Geneva, Switzerland.  
<sup>u</sup> Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.  
<sup>v</sup> Also at Manhattan College, New York, NY, United States.  
<sup>w</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.  
<sup>x</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.  
<sup>y</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.  
<sup>z</sup> Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.  
<sup>aa</sup> Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.  
<sup>ab</sup> Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.  
<sup>ac</sup> Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France.  
<sup>ad</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.  
<sup>ae</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland.  
<sup>af</sup> Also at Departamento de Física, Universidade de Minho, Braga, Portugal.  
<sup>ag</sup> Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.  
<sup>ah</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.  
<sup>ai</sup> Also at DESY, Hamburg and Zeuthen, Germany.  
<sup>aj</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy.  
<sup>ak</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.  
<sup>al</sup> Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.  
<sup>am</sup> Also at Nevis Laboratory, Columbia University, Irvington, NY, United States.  
<sup>an</sup> Also at Physics Department, Brookhaven National Laboratory, Upton, NY, United States.  
<sup>ao</sup> Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.  
<sup>ap</sup> Also at Department of Physics, Oxford University, Oxford, United Kingdom.  
<sup>aq</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.  
<sup>ar</sup> Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.  
<sup>as</sup> Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.  
<sup>\*</sup> Deceased.