



# Measurement of the nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector

The ATLAS Collaboration <sup>\*</sup>



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## ABSTRACT

Measurements of the yield and nuclear modification factor,  $R_{AA}$ , for inclusive jet production are performed using  $0.49 \text{ nb}^{-1}$  of Pb+Pb data at  $\sqrt{s_{NN}} = 5.02$  TeV and  $25 \text{ pb}^{-1}$  of  $pp$  data at  $\sqrt{s} = 5.02$  TeV with the ATLAS detector at the LHC. Jets are reconstructed with the anti- $k_t$  algorithm with radius parameter  $R = 0.4$  and are measured over the transverse momentum range of 40–1000 GeV in six rapidity intervals covering  $|y| < 2.8$ . The magnitude of  $R_{AA}$  increases with increasing jet transverse momentum, reaching a value of approximately 0.6 at 1 TeV in the most central collisions. The magnitude of  $R_{AA}$  also increases towards peripheral collisions. The value of  $R_{AA}$  is independent of rapidity at low jet transverse momenta, but it is observed to decrease with increasing rapidity at high transverse momenta.

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## 1. Introduction

Heavy-ion collisions at ultra-relativistic energies produce a hot, dense medium of strongly interacting nuclear matter understood to be composed of unscreened colour charges which is commonly called a quark–gluon plasma (QGP) [1–4]. Products of the hard scattering of quarks and gluons occurring in these collisions evolve as parton showers that propagate through the hot medium. Parton shower constituents emit medium-induced gluon radiation or suffer from elastic scattering processes and as a consequence they lose energy, leading to the formation of lower-energy jets. This phenomenon is termed “jet quenching” [5–7]. It has been directly observed as the suppression of the jet yields in Pb+Pb collisions compared to jet yields in  $pp$  collisions [8–11], the modification of jet internal structure [12–15], and a significant modification of the transverse energy balance in dijet [16–18] and multijet systems [19].

The energy loss of partons propagating through the QGP results in a reduction of the jet yield at a given transverse momentum ( $p_T$ ). This together with the falling shape of the jet  $p_T$  spectrum lead to the observed suppression of jets in collisions of nuclei relative to  $pp$  collisions. Central heavy-ion collisions have an enhanced hard-scattering rate due to the larger geometric overlap between the colliding nuclei, resulting in a larger per-collision nucleon–nucleon flux. To quantitatively assess the quenching effects, the hard-scattering rates measured in Pb+Pb collisions are normalised by the mean nuclear thickness function,  $\langle T_{AA} \rangle$ , which accounts for

this geometric enhancement [20]. The magnitude of the inclusive jet suppression in nuclear collisions relative to  $pp$  is quantified by the nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \left. \frac{d^2 N_{\text{jet}}}{dp_T dy} \right|_{\text{cent}}}{\langle T_{AA} \rangle \left. \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \right|_{pp}},$$

where  $N_{\text{jet}}$  and  $\sigma_{\text{jet}}$  are the jet yield in Pb+Pb collisions and the jet cross-section in  $pp$  collisions, respectively, both measured as a function of transverse momentum,  $p_T$ , and rapidity,  $y$ , and where  $N_{\text{evt}}$  is the total number of Pb+Pb collisions within a chosen centrality interval.

A value of  $R_{AA} \approx 0.5$  in central collisions was reported in Pb+Pb measurements at  $\sqrt{s_{NN}} = 2.76$  TeV by the ATLAS and CMS Collaborations for jet  $p_T$  above 100 GeV [9,10]. These measurements therefore show a suppression of jet yields by a factor of two in central collisions relative to the corresponding  $pp$  yields at the same centre-of-mass energy. Also a clear centrality dependence is observed. Two unexpected features [21] also emerge from those studies:  $R_{AA}$  increases only very slowly with increasing jet  $p_T$ , and no dependence of  $R_{AA}$  on jet rapidity is observed. Measurements by the ATLAS and CMS Collaborations can be complemented by the measurement by the ALICE Collaboration which reports  $R_{AA}$  for jets measured in  $p_T$  interval of 30–120 GeV in central Pb+Pb collisions [22].

This Letter describes the new measurements of yields of  $R = 0.4$  anti- $k_t$  jets [23] performed with  $0.49 \text{ nb}^{-1}$  of Pb+Pb data

<sup>\*</sup> E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

collected at  $\sqrt{s_{NN}} = 5.02$  TeV in 2015 and  $25 \text{ pb}^{-1}$  of  $pp$  data collected at  $\sqrt{s} = 5.02$  TeV in the same year. This new study closely follows the first measurement by the ATLAS Collaboration [9] performed using  $0.14 \text{ nb}^{-1}$  of Pb+Pb data collected at  $\sqrt{s_{NN}} = 2.76$  TeV in 2011 and  $4.0 \text{ pb}^{-1}$  of  $pp$  data collected at  $\sqrt{s} = 2.76$  TeV in 2013. Higher luminosity, increased centre-of-mass energy, and improved analysis techniques allowed to extend the measurement to more than two times higher transverse momenta, and to larger rapidities. This new measurement provides input relevant to a detailed theoretical description of jet suppression, especially its dependence on the collision energy, centrality, jet  $p_T$ , and rapidity.

## 2. Experimental setup

The ATLAS experiment [24] at the LHC features a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a nearly full coverage in solid angle.<sup>1</sup> The measurements presented here were performed using the ATLAS inner detector, calorimeter, trigger and data acquisition systems.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the pseudorapidity range  $|\eta| < 2.5$ . The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track. It is followed by the silicon microstrip tracker (SCT) which comprises four cylindrical layers of double-sided silicon strip detectors in the barrel region, and nine disks in each endcap. These silicon detectors are complemented by the transition radiation tracker, a drift-tube-based detector, which surrounds the SCT and has coverage up to  $|\eta| = 2.0$ .

The calorimeter system consists of a sampling lead/liquid-argon (LAr) electromagnetic (EM) calorimeter covering  $|\eta| < 3.2$ , a steel/scintillator sampling hadronic calorimeter covering  $|\eta| < 1.7$ , a LAr hadronic calorimeter covering  $1.5 < |\eta| < 3.2$ , and two LAr forward calorimeters (FCal) covering  $3.1 < |\eta| < 4.9$ . The hadronic calorimeter has three sampling layers longitudinal in shower depth in  $|\eta| < 1.7$  and four sampling layers in  $1.5 < |\eta| < 3.2$ , with a slight overlap. The EM calorimeter is segmented longitudinally in shower depth into three compartments with an additional presampler layer.

A two-level trigger system [25] was used to select the Pb+Pb and  $pp$  collisions analysed here. The first level (L1) is a hardware-based trigger stage which is implemented with custom electronics. The second level is the software-based high-level trigger (HLT). The events were selected by the HLT which was seeded by a L1 jet trigger, total energy trigger, or zero-degree calorimeter (ZDC) trigger. The total energy trigger required a total transverse energy measured in the calorimeter system to be greater than 5 GeV in  $pp$  interactions and 50 GeV in Pb+Pb interactions. The ZDC trigger required a presence of at least one neutron on both sides of ZDC ( $|\eta| > 8.3$ ). The HLT jet trigger used a jet reconstruction algorithm similar to the Pb+Pb one applied in offline analyses. It selected events containing jets with transverse energies exceeding a threshold, using a range of thresholds up to 100 GeV in Pb+Pb collisions and up to 85 GeV in  $pp$  collisions. In both the  $pp$  and Pb+Pb col-

**Table 1**

The mean number of participants, ( $N_{\text{part}}$ ), the mean nuclear thickness function, ( $T_{AA}$ ), and their uncertainties (see Section 5) for different centrality intervals.

Centrality range	$\langle N_{\text{part}} \rangle$	$\langle T_{AA} \rangle$ [1/mb]
70–80%	$15.4 \pm 1.0$	$0.22 \pm 0.02$
60–70%	$30.6 \pm 1.6$	$0.57 \pm 0.04$
50–60%	$53.9 \pm 1.9$	$1.27 \pm 0.07$
40–50%	$87.0 \pm 2.3$	$2.63 \pm 0.11$
30–40%	$131.4 \pm 2.6$	$4.94 \pm 0.15$
20–30%	$189.1 \pm 2.7$	$8.63 \pm 0.17$
10–20%	$264.0 \pm 2.8$	$14.33 \pm 0.17$
0–10%	$358.8 \pm 2.3$	$23.35 \pm 0.20$

lisions, the highest-threshold jet trigger sampled the full delivered luminosity while all lower threshold triggers were prescaled.

In addition to the jet trigger, two triggers were used in Pb+Pb collisions to select minimum-bias events. The minimum-bias trigger required either more than 50 GeV transverse energy recorded in the whole calorimeter system by L1 trigger or a signal from the ZDC trigger and a track identified by the HLT.

## 3. Data and Monte Carlo samples, and event selection

The impact of detector effects on the measurement was determined using a simulated detector response evaluated by running Monte Carlo (MC) samples through a GEANT4-based detector simulation package [26,27]. Two MC samples were used in this study. In the first one, multi-jet processes were simulated with POWHEG-BOX v2 [28–30] interfaced to the PYTHIA 8.186 [31,32] parton shower model. The CT10 PDF set [33] was used in the matrix element while the A14 set of tuned parameters [34] was used together with the NNPDF2.3LO PDF set [35] for the modelling of the non-perturbative effects. The EvtGen 1.2.0 program [36] was used for the properties of b- and c-hadron decays. In total,  $2.9 \times 10^7$  hard-scattering events at  $\sqrt{s} = 5.02$  TeV were simulated at the NLO precision, spanning a range of jet transverse momenta from 20 to 1300 GeV. The second MC sample consists of the same signal events as those used in the first sample but embedded into minimum-bias Pb+Pb data events. This minimum-bias sample was combined with the signal from POWHEG+PYTHIA8 simulation at the digitisation stage, and then reconstructed as a combined event. So-called “truth jets” are defined by applying the anti- $k_T$  algorithm with radius parameter  $R = 0.4$  to stable particles in the MC event generator’s output, defined as those with a proper lifetime greater than 10 ps, but excluding muons and neutrinos, which do not leave significant energy deposits in the calorimeter.

The level of overall event activity or centrality in Pb+Pb collisions is characterised using the sum of the total transverse energy in the forward calorimeter,  $\Sigma E_T^{\text{FCal}}$ , at the electromagnetic energy scale. The  $\Sigma E_T^{\text{FCal}}$  distribution is divided into percentiles of the total inelastic cross-section for Pb+Pb collisions with 0–10% centrality interval classifying the most central collisions. The minimum-bias trigger and event selection are estimated to sample 84.5% of the total inelastic cross-section, with an uncertainty of 1%. A Glauber model analysis of the  $\Sigma E_T^{\text{FCal}}$  distribution is used to evaluate  $\langle T_{AA} \rangle$  and the number of nucleons participating in the collision,  $\langle N_{\text{part}} \rangle$ , in each centrality interval [20,37,38]. The centrality intervals used in this measurement are indicated in Table 1 along with their respective calculations of  $\langle N_{\text{part}} \rangle$  and  $\langle T_{AA} \rangle$ .

Jets used in this analysis are reconstructed either in minimum-bias events or in events selected by inclusive jet triggers in the region of jet  $p_T$  for which the trigger efficiencies are greater than 99%. Events are required to have a reconstructed vertex within 150 mm of the nominal interaction point along the beam axis. Only events taken during stable beam conditions and satisfying

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Rapidity  $y$  is defined as  $y = 0.5 \ln[(E + p_z)/(E - p_z)]$  where  $E$  and  $p_z$  are the energy and the component of the momentum along the beam direction, respectively. Angular distance is measured in units of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

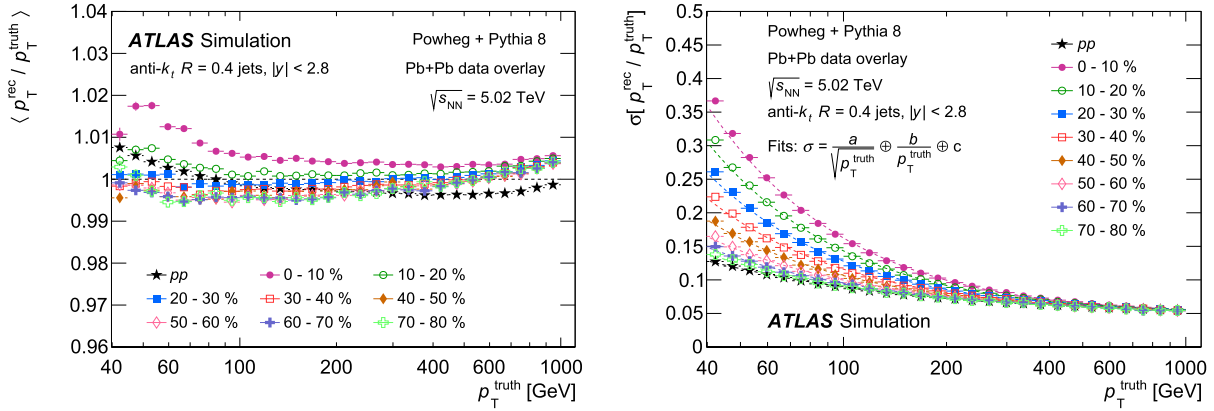


Fig. 1. The left panel shows the JES as a function of  $p_T^{\text{truth}}$  and the right panel shows the JER as a function of  $p_T^{\text{truth}}$  in MC samples. Both are for jets with  $|y| < 2.8$ . The curves in the right panel show fits to Eq. (1) for  $pp$ , and Pb+Pb in eight centrality intervals (0–10%, 10–20%, 20–30%, 30–40%, 40–50%, 50–60%, 60–70%, and 70–80%).

detector and data-quality requirements, which include the ID and calorimeters being in nominal operation, are considered. The average number of  $pp$  inelastic interactions per bunch crossing was  $\mu < 1.4$ . In Pb+Pb collisions,  $\mu$  was smaller than  $10^{-4}$ .

#### 4. Jet reconstruction and analysis procedure

The reconstruction of jets in  $pp$  and Pb+Pb collisions closely follows the procedures described in Refs. [8,39] including the underlying event (UE) subtraction procedure. A brief summary is given here. Jets are reconstructed using the anti- $k_t$  algorithm, which is implemented in the `FastJet` software package [40]. The jets are formed by clustering  $\Delta\eta \times \Delta\phi = 0.1 \times \pi/32$  logical “towers” that are constructed using energy deposits in enclosed calorimeter cells. A background subtraction procedure based on the UE average transverse energy density,  $\rho(\eta, \phi)$ , which is calorimeter-layer dependent, was applied. The  $\phi$  dependence is due to global azimuthal correlations between the produced particles (typically referred to as “flow”). These correlations arise from the hydrodynamic response of the medium to the geometry of the initial collision. The flow contribution to the transverse energy of towers can be described by the magnitude ( $v_n$ ) and phase ( $\Psi_n$ ) of the Fourier components of the azimuthal angle distributions as:

$$\frac{d^2 E_T}{d\eta d\phi} = \frac{dE_T}{d\eta} \left( 1 + 2 \sum_n v_n \cos(n(\phi - \Psi_n)) \right),$$

where  $\phi$  is the azimuthal angle of the tower and  $n$  indicates the order of the flow harmonic. The modulation is dominated by  $v_2$  and  $v_3$  [41]. In this analysis, the second, third and fourth harmonics are used to further improve the UE estimation. An iterative procedure is used to remove the effects of jets on  $\rho$  and the  $v_n$  values. In the initial estimate of  $\rho$  and  $v_n$ , these are estimated from the transverse energy of calorimeter cells within  $|\eta| < 3.2$ . The background is subtracted from calorimeter-layer-dependent transverse energies within towers associated with the jet to obtain the subtracted jet kinematics. Then  $\rho$  and  $v_n$  values are recalculated by excluding towers within  $\Delta R = 0.4$  of seed jets. Seed jets are defined as calorimeter jets with subtracted  $p_T > 25$  GeV, which are reconstructed with radius parameter  $R = 0.2$ , and  $R = 0.4$  track jets with  $p_T > 10$  GeV, which are reconstructed from charged-particle tracks recorded in the ID. These new  $\rho^2$  and  $v_n$  values

are then used to evaluate a new subtracted energy using the original towers, and the new jet kinematic variables are calculated. A final correction depending on rapidity and  $p_T$  is applied to obtain the correct hadronic energy scale for the reconstructed jets. Jets are calibrated using an MC-based procedure which is the same as for the “EM+JES” jets used in the analysis of  $pp$  collisions [42]. This calibration is followed by a “cross-calibration” which relates the jet energy scale (JES) of Pb+Pb jets to the JES of  $pp$  jets [43].

The performance of the jet reconstruction was characterised by evaluating the JES and jet energy resolution (JER), which are correspondingly the mean and width of the jet response ( $p_T^{\text{rec}}/p_T^{\text{truth}}$ ) in the MC simulation. Here  $p_T^{\text{rec}}$  and  $p_T^{\text{truth}}$  are the transverse momenta of the reconstructed jet and truth jet, respectively. The performance of the jet reconstruction in the simulation is summarised in Fig. 1, where the left and right panels show the JES and JER, respectively. The JES is shown as a function of  $p_T^{\text{truth}}$  in the left panel of Fig. 1. It deviates from unity by less than 1% in the kinematic region of the measurement. No rapidity dependence of the JES is observed. A weak centrality dependence of the JES is corrected by the unfolding procedure described later in this section. To express the different contributions, the JER is parameterised by a quadrature sum of three terms,

$$\sigma \left( \frac{p_T^{\text{rec}}}{p_T^{\text{truth}}} \right) = \frac{a}{\sqrt{p_T^{\text{truth}}}} \oplus \frac{b}{p_T^{\text{truth}}} \oplus c. \quad (1)$$

The first parameter ( $a$ ) and third parameter ( $c$ ) in Eq. (1) are sensitive to the detector response and are expected to be independent of centrality, while the second parameter ( $b$ ) is centrality dependent and it is driven by UE fluctuations uncorrelated with the jet  $p_T$ . The JER for different centrality intervals and for  $pp$  collisions is shown in the right panel of Fig. 1. Fits using Eq. (1) are indicated with dashed lines. The JER is largest in the more central collisions, as expected from stronger fluctuations of the transverse energy in the UE. The JER is about 16% for  $p_T = 100$  GeV in central collisions and decreases with increasing  $p_T$  to 5–6% for jets with  $p_T$  greater than 500 GeV. The parameters  $a$  and  $c$  in the fit are found to be independent of centrality while the values of  $b$  are consistent with the expected magnitude of UE fluctuations. The fit parameters are listed in Table 2 for the most central and most peripheral Pb+Pb collisions.

The jet cross-section in  $pp$  collisions, jet yields and  $R_{AA}$  in Pb+Pb collisions are measured in the following absolute rapidity ranges: 0–0.3, 0.3–0.8, 0.8–1.2, 1.2–1.6, 1.6–2.1, 2.1–2.8, and two inclusive intervals, 0–2.1 and 0–2.8. The interval of 0–2.1 is used to make comparisons with the measurement of  $R_{AA}$  at  $\sqrt{s_{NN}} =$

<sup>2</sup> The average  $\rho$  is  $\approx 270$  GeV and  $\approx 10$  GeV in 0–10% and 70–80% Pb+Pb collisions, respectively.

**Table 2**  
The fitted parameters  $a$ ,  $b$ , and  $c$  (Eq. (1)) for the most central and most peripheral collisions.

Centrality range	$a$ [GeV <sup>1/2</sup> ]	$b$ [GeV]	$c$
70–80%	$0.75 \pm 0.01$	$2.5 \pm 0.2$	$0.050 \pm 0.001$
0–10%	$0.76 \pm 0.02$	$14.4 \pm 0.1$	$0.049 \pm 0.001$

2.76 TeV [9]. The more forward region ( $|y| > 2.8$ ) is not included in the study due to deterioration of the jet reconstruction performance. In Pb+Pb peripheral and  $pp$  collisions, results are reported for  $p_T > 50$  GeV and  $p_T > 40$  GeV, respectively. In mid-central collisions and central collisions, results are reported for  $p_T > 80$  GeV and  $p_T > 100$  GeV, respectively. A higher value of the minimum jet  $p_T$  in more central Pb+Pb collisions, compared to peripheral or  $pp$  collisions, was used to reduce the contribution of jets reconstructed from fluctuations of the underlying events (“UE jets”). These UE jets were removed by considering the charged-particle tracks with  $p_T^{\text{trk}} > 4$  GeV within  $\Delta R = 0.4$  of the jet and requiring a minimum value of  $\sum p_T^{\text{trk}}$ . A threshold of  $\sum p_T^{\text{trk}} = 8$  GeV is used throughout the analysis. Thresholds of  $\sum p_T^{\text{trk}}$  ranging from 5 to 12 GeV were found to change  $R_{AA}$  by much less than 1% in the considered kinematic region.

The jet  $p_T$  spectra are unfolded using the iterative Bayesian unfolding method [44] from the RooUnfold software package [45], which accounts for bin migration due to the jet energy response. The response matrices used as the input to the unfolding are built from generator-level (truth) jets that are matched to reconstructed jets in the simulation. The unmatched truth jets are incorporated as an inefficiency corrected for after the unfolding. In the first  $p_T$  bin reported in this analysis (100–126 GeV and 50–63 GeV for 0–10% and 70–80% Pb+Pb collisions, respectively), the relative number of unmatched truth jets is 12% and 32% in 0–10% and 70–80% collisions, respectively. The response matrices were generated separately for  $pp$  and Pb+Pb collisions and for each rapidity and centrality interval. To better represent the data, the response was reweighted along the truth-jet axis by a data-to-MC ratio. The number of iterations in the unfolding was chosen so that the result is stable when changing the number of iterations by one. Three iterations were used for  $pp$  collisions while four iterations were used in all the centrality and rapidity intervals for Pb+Pb collisions. The unfolding procedure was tested by performing a refolding, where the unfolded results were convolved with the response matrix, and compared with the input spectra. The refolded spectra were found to deviate from input spectra by less than 5% in all centrality classes.

## 5. Systematic uncertainties

The following sources of systematic uncertainties were identified for this analysis: uncertainties of the jet energy scale and jet energy resolution, uncertainty due to the unfolding procedure, uncertainty of the determination of the mean nuclear thickness function ( $T_{AA}$ ) values, and the uncertainty of the  $pp$  luminosity. Systematic uncertainties of the measured distributions can be categorised into two classes: bin-wise correlated uncertainties and uncertainties that affect the overall normalisation of distributions. Uncertainties due to the determination of  $\langle T_{AA} \rangle$  and  $pp$  luminosity belong to the second class, all other uncertainties belong to the first.

The strategy for determining the JES uncertainty for Pb+Pb jets is described in Ref. [43]. The JES uncertainty has two components: the centrality-dependent component, applicable in Pb+Pb collisions, and a centrality-independent component, applicable in both the  $pp$  and Pb+Pb collisions. The centrality-independent JES

uncertainty was derived by using in situ studies of calorimeter response [46], and studies of the relative energy scale difference between the jet reconstruction procedure in Pb+Pb collisions [43] and  $pp$  collisions [42]. The centrality-dependent component of the JES uncertainty accounts for possible differences in the calorimeter response due to jets in the Pb+Pb environment. It was evaluated by measuring the ratio of  $p_T$  of calorimeter jets to  $\sum p_T^{\text{trk}}$  of track jets. This ratio is called  $\langle r_{\text{trk}} \rangle$ . The data-to-MC ratio of  $\langle r_{\text{trk}} \rangle$  was evaluated and then compared between  $pp$  and Pb+Pb collisions, where it shows a small shift. This shift may be attributed to a modification of the jet fragmentation pattern in the Pb+Pb environment which may lead to a change of the calorimeter response of jets reconstructed in the Pb+Pb collisions compared to jets reconstructed in  $pp$  collisions. Consequently, this shift represents a typical difference in the JES between Pb+Pb collisions and  $pp$  collisions. It is 0.5% in the most central collisions and decreases linearly to be 0% beyond the 50–60% centrality interval. This difference is taken to be the Pb+Pb-specific component of the JES uncertainty.

Each component that contributes to the JES uncertainty was varied separately and a modified response matrix was obtained by shifting the reconstructed jet  $p_T$ . These response matrices were then used to unfold the data. The difference between the data unfolded with the new response matrix and the nominal response matrix is used to determine the systematic uncertainty.

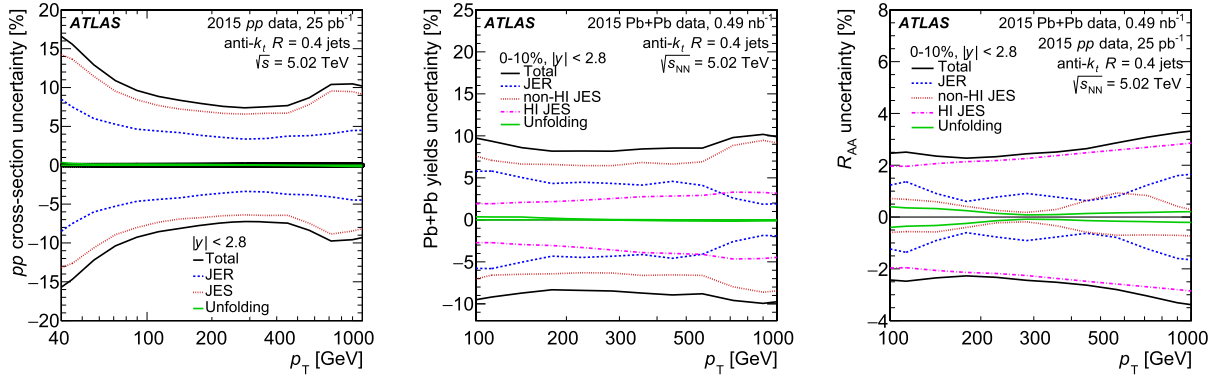
Similarly to the JES uncertainty, the systematic uncertainty due to the JER was obtained by performing the unfolding with modified response matrices. The modified response matrices were generated for both the  $pp$  and Pb+Pb collisions with the JER uncertainty which was quantified in  $pp$  collisions using data-driven techniques [47]. An additional uncertainty specific for the Pb+Pb environment is used, which is the uncertainty related to the impact of fluctuations of the UE on the JER. Both of these components are used to smear the reconstructed jet momentum in the MC events and regenerate the response matrices.

The results are obtained using the unfolding procedure with response matrices which were reweighted along the reconstructed jet axis to better characterise the data, as described in Section 4. The difference between the nominal results and results obtained with response matrices without the reweighting is used to calculate the uncertainty due to the unfolding procedure.

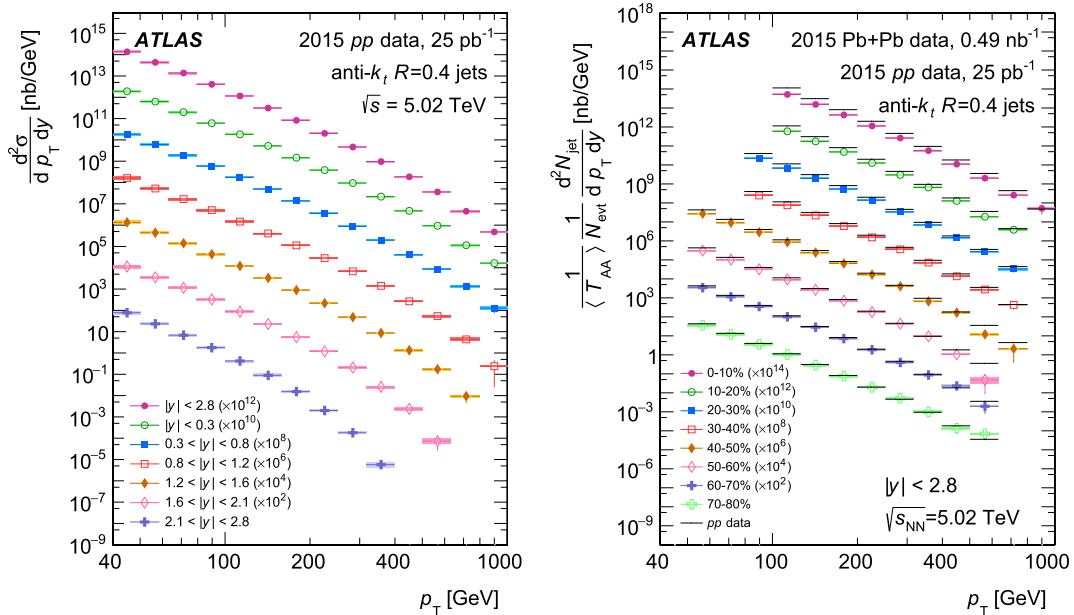
The uncertainty of the mean nuclear thickness function arises from geometric modelling uncertainties (e.g. nucleon–nucleon inelastic cross-section, Woods–Saxon parameterisation of the nucleon distribution [20]) and the uncertainty of the fraction of selected inelastic Pb+Pb collisions. The values of these uncertainties are presented in Table 1.

The integrated luminosity determined for 2015  $pp$  data was calibrated using data from dedicated beam separation scans. The relative systematic uncertainty is 1.9%, determined using procedures described in Ref. [48].

The relative,  $p_T$ -dependent systematic uncertainties are summarised in Fig. 2 for the  $pp$  jet cross-section on the left, the Pb+Pb jet yields in the middle and the  $R_{AA}$  values on the right. In the  $pp$  cross-section the largest uncertainty is from the JES, ranging from 7% to 15% depending on the  $p_T$  of the jet. The JES is also the largest contribution to the uncertainty in central Pb+Pb collisions where the results are reported only for jets with  $p_T > 100$  GeV and where it is as large as 10%. The uncertainties of the  $R_{AA}$  values are smaller than those of the cross-sections and yields because the correlated systematic uncertainties that are common to  $pp$  and Pb+Pb collisions mostly cancel out in the ratio. The largest contribution to the uncertainty of the  $R_{AA}$  values is the Pb+Pb component of the JES uncertainty, which reaches 3% at the highest jet  $p_T$ .



**Fig. 2.** Systematic uncertainties, for  $pp$  jet cross-section (left), Pb+Pb jet yields (middle) and jet  $R_{AA}$  (right). Systematic uncertainties on  $pp$  luminosity and  $\langle T_{AA} \rangle$ , which affect the overall normalisation of measured distributions, are not shown.



**Fig. 3.** Left: Inclusive jet cross-section in  $pp$  collisions as a function of jet  $p_T$  in different  $|y|$  intervals scaled by successive powers of  $10^2$ . Right: Per-event inclusive jet yield in Pb+Pb collisions normalised by  $\langle T_{AA} \rangle$  as a function of jet  $p_T$  in different centrality intervals scaled by successive powers of  $10^2$ . The solid lines represent central values of  $pp$  cross-section for the same rapidity selection scaled by the same factors to allow a comparison with the Pb+Pb data at different centralities. The error bars represent statistical uncertainties, shaded boxes represent systematic uncertainties.

## 6. Results

The inclusive jet cross-section obtained from  $pp$  collision data is shown in the left panel of Fig. 3. The cross-section is reported for six intervals of rapidity spanning the range  $|y| < 2.8$  and for the whole  $|y| < 2.8$  interval. The error bars in the figure represent statistical uncertainties while the shaded boxes represent systematic uncertainties. The systematic uncertainties also include the uncertainty due to the luminosity, which is correlated for all the data points.

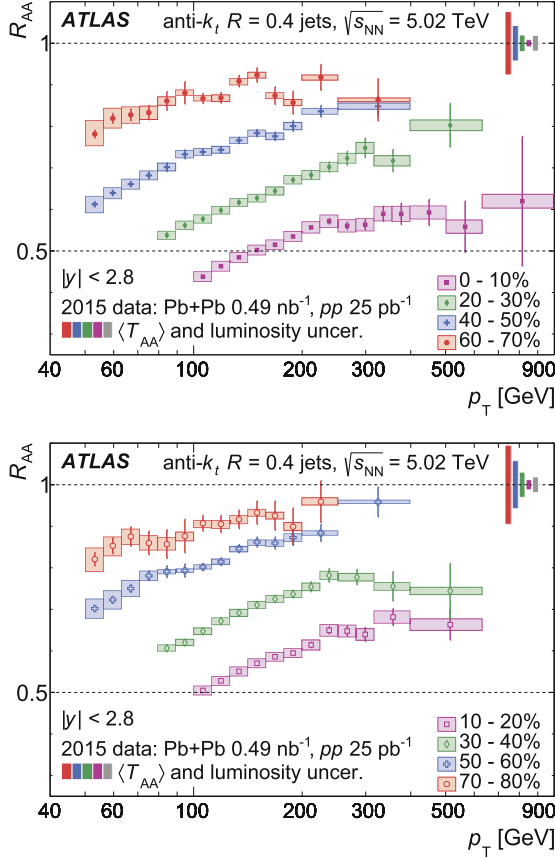
The right panel of Fig. 3 shows the differential per-event Pb+Pb jet yields scaled by  $1/\langle T_{AA} \rangle$ , which are presented for eight centrality intervals for jets with  $|y| < 2.8$ . The solid lines represent the  $pp$  jet cross-sections for the same rapidity interval; the jet yields fall below these lines, showing the jet suppression.

The nuclear modification factor evaluated as a function of jet  $p_T$  is presented in the two panels of Fig. 4, each showing four centrality selections indicated in the legend. The  $R_{AA}$  value is obtained for jets with  $|y| < 2.8$  and with  $p_T$  in up to 15 intervals between 50 and 1000 GeV, depending on centrality. The higher  $p_T$

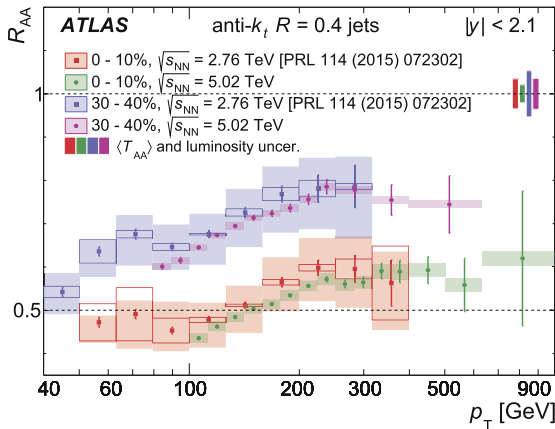
intervals are combined in the cross-section and yields before evaluating  $R_{AA}$  because of the large statistical uncertainties at high  $p_T$ . A clear suppression of jet production in central Pb+Pb collisions relative to  $pp$  collisions is observed. In the 0–10% centrality interval,  $R_{AA}$  is approximately 0.45 at  $p_T = 100$  GeV, and is observed to grow slowly (quenching decreases) with increasing jet  $p_T$ , reaching a value of 0.6 for jets with  $p_T$  around 800 GeV.

The  $R_{AA}$  value observed for jets with  $|y| < 2.1$  is compared with the previous measurement at  $\sqrt{s_{NN}} = 2.76$  TeV [9]. This is shown for the 0–10% and 30–40% centrality intervals in Fig. 5. The two measurements are observed to agree within their uncertainties in the overlapping  $p_T$  region. The apparent reduction of the size of systematic uncertainties in the new measurement is driven by collecting the  $pp$  and Pb+Pb data during the same LHC running period.

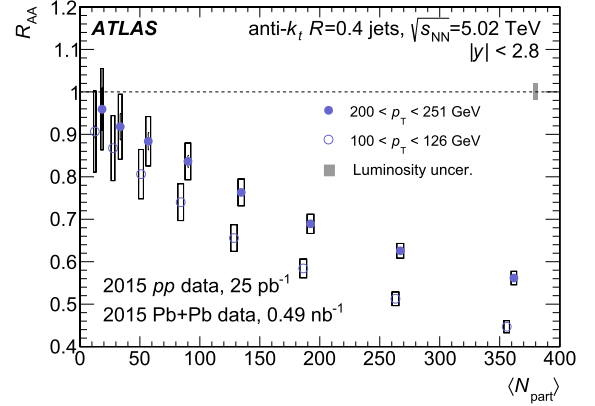
The  $\langle N_{part} \rangle$  dependence of  $R_{AA}$  is shown in Fig. 6 for jets with  $|y| < 2.8$  and for two representative  $p_T$  intervals:  $100 < p_T < 126$  GeV and  $200 < p_T < 251$  GeV. The open boxes around the data points represent the bin-wise correlated systematic uncertainties which include also the uncertainty of  $\langle T_{AA} \rangle$ . A smooth



**Fig. 4.** Upper panel: The  $R_{AA}$  values as a function of jet  $p_T$  for jets with  $|y| < 2.8$  for four centrality intervals (0–10%, 20–30%, 40–50%, 60–70%). Bottom panel: The  $R_{AA}$  values as a function of jet  $p_T$  for jets with  $|y| < 2.8$  for four other centrality intervals (10–20%, 30–40%, 50–60%, 70–80%). The error bars represent statistical uncertainties, the shaded boxes around the data points represent bin-wise correlated systematic uncertainties. The coloured and grey shaded boxes at  $R_{AA} = 1$  represent fractional  $\langle T_{AA} \rangle$  and  $pp$  luminosity uncertainties, respectively, which both affect the overall normalisation of the result. The horizontal size of error boxes represents the width of the  $p_T$  interval.



**Fig. 5.** The  $R_{AA}$  values as a function of jet  $p_T$  for jets with  $|y| < 2.1$  in 0–10% and 30–40% centrality intervals compared to the same quantity measured in  $\sqrt{s_{NN}} = 2.76$  TeV Pb+Pb collisions [9]. The error bars represent statistical uncertainties, the shaded boxes around the data points represent bin-wise correlated systematic uncertainties. For  $\sqrt{s_{NN}} = 2.76$  TeV measurement, the open boxes represent uncorrelated systematic uncertainties. The coloured shaded boxes at  $R_{AA} = 1$  represent the combined fractional  $\langle T_{AA} \rangle$  and  $pp$  luminosity uncertainty. The horizontal size of error boxes represents the width of the  $p_T$  interval.

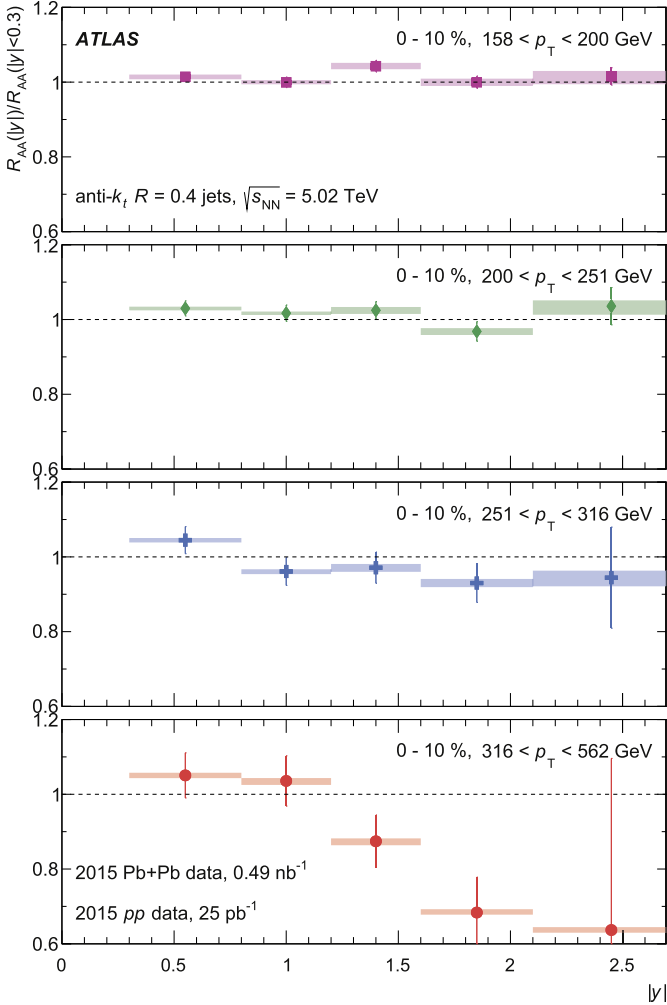


**Fig. 6.** The  $R_{AA}$  values for jets with  $100 < p_T < 126$  GeV and  $200 < p_T < 251$  GeV for rapidity  $|y| < 2.8$  evaluated as a function of  $\langle N_{part} \rangle$ . For legibility, the  $\langle N_{part} \rangle$  values are shifted by  $-7$  and  $+7$  for  $100 < p_T < 126$  GeV selection and  $200 < p_T < 251$  GeV selection, respectively. The error bars represent statistical uncertainties. The heights of the open boxes represent systematic uncertainties. The widths of the open boxes represent the uncertainties in the determination of  $\langle N_{part} \rangle$ . The grey shaded box at unity represents the uncertainty of the  $pp$  integrated luminosity.

evolution of  $R_{AA}$  is observed, with the largest values of  $R_{AA}$  in the most peripheral collisions and the smallest values of  $R_{AA}$  in the most central collisions. The magnitude of  $R_{AA}$  is observed to be larger for jets in higher  $p_T$  interval for  $\langle N_{part} \rangle \gtrsim 50$ . For  $\langle N_{part} \rangle \lesssim 50$  the difference is not statistically significant.

The rapidity dependence of  $R_{AA}$  is shown in Fig. 7 as the ratio of  $R_{AA}$  to its value measured for  $|y| < 0.3$ . This representation was chosen because all systematic uncertainties largely cancel out in the ratio. The distributions are reported in intervals of increasing values of  $p_T$  in the four panels. The ratio is constant in rapidity at lower  $p_T$ . As the  $p_T$  increases, the value of  $R_{AA}$  starts to decrease with rapidity and the decrease is most significant in the highest  $p_T$  interval of 316–562 GeV. In this  $p_T$  interval, the value of the  $R_{AA}$  ratio is  $0.83 \pm 0.07$  and  $0.68 \pm 0.13$  in the rapidity regions of  $|y| = 1.2$ –2.8 and  $|y| = 1.6$ –2.8, respectively. This decrease was predicted in Ref. [49] as a consequence of a steepening of jet  $p_T$  spectra in the forward rapidity region.

A comparison of the  $R_{AA}$  values with theoretical predictions is provided in Fig. 8. The  $R_{AA}$  values obtained as a function of jet  $p_T$  are compared with five predictions for jets with  $|y| < 2.1$  where theory calculations are available: the Linear Boltzmann Transport model (LBT) [50], three calculations using the Soft Collinear Effective Theory approach (SCET<sub>G</sub>) [51–54], and the Effective Quenching model (EQ) [49]. The LBT model combines a kinetic description of parton propagation with a hydrodynamic description of the underlying medium evolution while keeping track of thermal recoil partons from each scattering and their further propagation in the medium [50]. The SCET<sub>G</sub> approach uses semi-inclusive jet functions [55] evaluated with in-medium parton splittings computed using soft collinear effective theory. It provides three predictions with two different settings of the strong coupling constant associated with the jet–medium interaction ( $g = 2.2$  and  $g = 1.8$ ) and the calculation at NLO accuracy. The EQ model incorporates energy loss effects through two downward shifts in the  $p_T$  spectrum based on a semi-empirical parameterisation of jet quenching effects. One shift is applied to quark-initiated jets and a larger shift to gluon-initiated jets. The EQ model requires experimental data in order to extract the parameters of the energy loss. The same parameters of the jet energy loss as for  $\sqrt{s_{NN}} = 2.76$  TeV data [49] are used here. All the models are capable of reproducing the general trends seen in the data. For  $p_T \lesssim 250$  GeV, the data agrees best with the SCET<sub>G</sub> model which uses  $g = 2.2$ . For

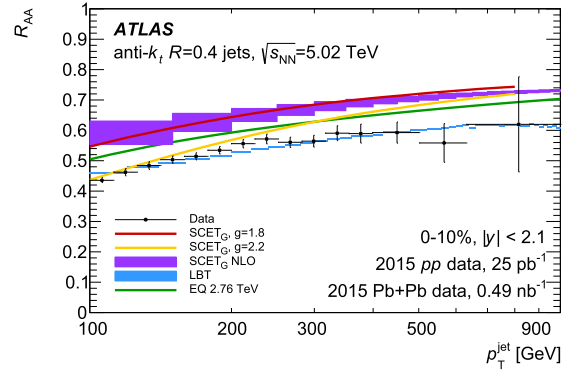


**Fig. 7.** The ratio of  $R_{AA}$  to the  $R_{AA}$  value for  $|y| < 0.3$  as a function of  $|y|$  for jets in four  $p_T$  intervals ( $158 < p_T < 200$  GeV,  $200 < p_T < 251$  GeV,  $251 < p_T < 316$  GeV, and  $316 < p_T < 562$  GeV) shown for the 10% most central Pb+Pb collisions. The error bars represent statistical uncertainties, the shaded boxes around the data points represent systematic uncertainties.

$p_T \gtrsim 250$  GeV the LBT model describes the data better. Disagreement between the data and the EQ model using the parameters of the jet energy loss from 2.76 TeV Pb+Pb data can be explained as a consequence of stronger quenching in 5.02 TeV Pb+Pb collisions.

## 7. Summary

Measurements of inclusive jet yields in Pb+Pb collisions, jet cross-sections in  $pp$  collisions, and the jet nuclear modification factor,  $R_{AA}$ , are performed using  $0.49 \text{ nb}^{-1}$  of Pb+Pb collision data and  $25 \text{ pb}^{-1}$  of  $pp$  collision data collected at the same nucleon-nucleon centre-of-mass energy of 5.02 TeV by the ATLAS detector at the LHC. Jets, reconstructed using the anti- $k_r$  algorithm with radius parameter  $R = 0.4$ , are measured over the transverse momentum range of 40–1000 GeV in six rapidity intervals covering  $|y| < 2.8$ . The jet yields measured in Pb+Pb collisions are suppressed relative to the jet cross-section measured in  $pp$  collisions scaled by the mean nuclear thickness function,  $\langle T_{AA} \rangle$ . The magnitude of  $R_{AA}$  increases with increasing jet transverse momentum, reaching a value of approximately 0.6 at 1 TeV in the most central collisions. The magnitude of  $R_{AA}$  also increases towards periph-



**Fig. 8.** The  $R_{AA}$  values as a function of jet  $p_T$  for the 0–10% centrality interval and  $|y| < 2.1$  compared with theory predictions. The uncertainties of the data points are the combined statistical and systematic uncertainties. The vertical width of the distribution shown for the LBT and SCET<sub>G</sub> NLO models represents the uncertainty of the theory prediction.

eral collisions. The  $R_{AA}$  value is independent of rapidity at low jet  $p_T$ . For jets with  $p_T \gtrsim 300$  GeV a sign of a decrease with rapidity is observed. The magnitude of the jet suppression as well as its evolution with jet  $p_T$  and rapidity are consistent with those reported in a similar measurement performed with Pb+Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV in the kinematic region where the two measurements overlap.

The results presented here extend previous measurements to significantly higher transverse momenta and larger rapidities of jets and improve on the precision of the measurement. This allows precise and detailed comparisons of the data to theoretical models of jet quenching. These new results can also be used as additional input to understand the centre-of-mass energy dependence of jet suppression.

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## The ATLAS Collaboration

M. Aaboud<sup>34d</sup>, G. Aad<sup>99</sup>, B. Abbott<sup>124</sup>, O. Abdinov<sup>13,\*</sup>, B. Abeloos<sup>128</sup>, D.K. Abhayasinghe<sup>91</sup>, S.H. Abidi<sup>164</sup>, O.S. AbouZeid<sup>39</sup>, N.L. Abraham<sup>153</sup>, H. Abramowicz<sup>158</sup>, H. Abreu<sup>157</sup>, Y. Abulaiti<sup>6</sup>, B.S. Acharya<sup>64a,64b,o</sup>, S. Adachi<sup>160</sup>, L. Adamczyk<sup>81a</sup>, J. Adelman<sup>119</sup>, M. Adersberger<sup>112</sup>, A. Adiguzel<sup>12c,ah</sup>, T. Adye<sup>141</sup>, A.A. Affolder<sup>143</sup>, Y. Afik<sup>157</sup>, C. Agheorghiesei<sup>27c</sup>, J.A. Aguilar-Saavedra<sup>136f,136a</sup>, F. Ahmadov<sup>77,af</sup>, G. Aielli<sup>71a,71b</sup>, S. Akatsuka<sup>83</sup>, T.P.A. Åkesson<sup>94</sup>, E. Akilli<sup>52</sup>, A.V. Akimov<sup>108</sup>, G.L. Alberghi<sup>23b,23a</sup>, J. Albert<sup>173</sup>, P. Albicocco<sup>49</sup>, M.J. Alconada Verzini<sup>86</sup>, S. Alderweireldt<sup>117</sup>, M. Aleksa<sup>35</sup>, I.N. Aleksandrov<sup>77</sup>, C. Alexa<sup>27b</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>124</sup>, B. Ali<sup>138</sup>, G. Alimonti<sup>66a</sup>, J. Alison<sup>36</sup>, S.P. Alkire<sup>145</sup>, C. Allaire<sup>128</sup>, B.M.M. Allbrooke<sup>153</sup>, B.W. Allen<sup>127</sup>, P.P. Allport<sup>21</sup>, A. Aloisio<sup>67a,67b</sup>, A. Alonso<sup>39</sup>, F. Alonso<sup>86</sup>, C. Alpigiani<sup>145</sup>, A.A. Alshehri<sup>55</sup>, M.I. Alstaty<sup>99</sup>, B. Alvarez Gonzalez<sup>35</sup>, D. Álvarez Piqueras<sup>171</sup>, M.G. Alviggi<sup>67a,67b</sup>, B.T. Amadio<sup>18</sup>, Y. Amaral Coutinho<sup>78b</sup>, L. Ambroz<sup>131</sup>, C. Amelung<sup>26</sup>, D. Amidei<sup>103</sup>, S.P. Amor Dos Santos<sup>136a,136c</sup>, S. Amoroso<sup>44</sup>, C.S. Amrouche<sup>52</sup>, C. Anastopoulos<sup>146</sup>, L.S. Ancu<sup>52</sup>, N. Andari<sup>142</sup>, T. Andeen<sup>11</sup>, C.F. Anders<sup>59b</sup>, J.K. Anders<sup>20</sup>, K.J. Anderson<sup>36</sup>, A. Andreazza<sup>66a,66b</sup>, V. Andrei<sup>59a</sup>, C.R. Anelli<sup>173</sup>, S. Angelidakis<sup>37</sup>, I. Angelozzi<sup>118</sup>, A. Angerami<sup>38</sup>, A.V. Anisenkov<sup>120b,120a</sup>, A. Annovi<sup>69a</sup>, C. Antel<sup>59a</sup>, M.T. Anthony<sup>146</sup>, M. Antonelli<sup>49</sup>, D.J.A. Antrim<sup>168</sup>, F. Anulli<sup>70a</sup>, M. Aoki<sup>79</sup>, J.A. Aparisi Pozo<sup>171</sup>, L. Aperio Bella<sup>35</sup>, G. Arabidze<sup>104</sup>, J.P. Araque<sup>136a</sup>, V. Araujo Ferraz<sup>78b</sup>, R. Araujo Pereira<sup>78b</sup>, A.T.H. Arce<sup>47</sup>, R.E. Ardell<sup>91</sup>, F.A. Arduh<sup>86</sup>, J.-F. Arguin<sup>107</sup>, S. Argyropoulos<sup>75</sup>, A.J. Armbruster<sup>35</sup>, L.J. Armitage<sup>90</sup>, A. Armstrong<sup>168</sup>, O. Arnaez<sup>164</sup>, H. Arnold<sup>118</sup>, M. Arratia<sup>31</sup>, O. Arslan<sup>24</sup>, A. Artamonov<sup>109,\*</sup>, G. Artoni<sup>131</sup>, S. Artz<sup>97</sup>, S. Asai<sup>160</sup>, N. 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Bannoura<sup>179</sup>, L. Barak<sup>158</sup>, W.M. Barbe<sup>37</sup>, E.L. Barberio<sup>102</sup>, D. Barberis<sup>53b,53a</sup>, M. Barbero<sup>99</sup>, T. Barillari<sup>113</sup>, M.-S. Barisits<sup>35</sup>, J. Barkeloo<sup>127</sup>, T. Barklow<sup>150</sup>, N. Barlow<sup>31</sup>, R. Barnea<sup>157</sup>, S.L. Barnes<sup>58c</sup>, B.M. Barnett<sup>141</sup>, R.M. Barnett<sup>18</sup>, Z. Barnovska-Blenessy<sup>58a</sup>, A. Baroncelli<sup>72a</sup>, G. Barone<sup>26</sup>, A.J. Barr<sup>131</sup>, L. Barranco Navarro<sup>171</sup>, F. Barreiro<sup>96</sup>, J. Barreiro Guimarães da Costa<sup>15a</sup>, R. Bartoldus<sup>150</sup>, A.E. Barton<sup>87</sup>, P. Bartos<sup>28a</sup>, A. Basalaeu<sup>134</sup>, A. Bassalat<sup>128</sup>, R.L. Bates<sup>55</sup>, S.J. Batista<sup>164</sup>, S. Batlamous<sup>34e</sup>, J.R. Batley<sup>31</sup>, M. Battaglia<sup>143</sup>, M. Bauge<sup>70a,70b</sup>, F. Bauer<sup>142</sup>, K.T. Bauer<sup>168</sup>, H.S. Bawa<sup>150,m</sup>, J.B. 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Chen<sup>29</sup>, J. Chen<sup>58a</sup>, J. Chen<sup>38</sup>, S. Chen<sup>133</sup>, S.J. Chen<sup>15c</sup>, X. Chen<sup>15b.as</sup>, Y. Chen<sup>80</sup>, Y-H. Chen<sup>44</sup>, H.C. Cheng<sup>103</sup>, H.J. Cheng<sup>15d</sup>, A. Cheplakov<sup>77</sup>, E. Cheremushkina<sup>140</sup>, R. Cherkaoui El Moursli<sup>34e</sup>, E. Cheu<sup>7</sup>, K. Cheung<sup>62</sup>, L. Chevalier<sup>142</sup>, V. Chiarella<sup>49</sup>, G. Chiarelli<sup>69a</sup>, G. Chiodini<sup>65a</sup>, A.S. Chisholm<sup>35</sup>, A. Chitan<sup>27b</sup>, I. Chiu<sup>160</sup>, Y.H. Chiu<sup>173</sup>, M.V. Chizhov<sup>77</sup>, K. Choi<sup>63</sup>, A.R. Chomont<sup>128</sup>, S. Chouridou<sup>159</sup>, Y.S. Chow<sup>118</sup>, V. Christodoulou<sup>92</sup>, M.C. Chu<sup>61a</sup>, J. Chudoba<sup>137</sup>, A.J. Chuinard<sup>101</sup>, J.J. Chwastowski<sup>82</sup>, L. Chytka<sup>126</sup>, D. Cinca<sup>45</sup>, V. Cindro<sup>89</sup>, I.A. Cioară<sup>24</sup>, A. Ciocio<sup>18</sup>, F. Ciotto<sup>67a,67b</sup>, Z.H. Citron<sup>177</sup>, M. Citterio<sup>66a</sup>, A. Clark<sup>52</sup>, M.R. Clark<sup>38</sup>, P.J. Clark<sup>48</sup>, C. Clement<sup>43a,43b</sup>, Y. Coadou<sup>99</sup>, M. Cobl<sup>64a,64c</sup>, A. Coccaro<sup>53b,53a</sup>, J. Cochran<sup>76</sup>, A.E.C. Coimbra<sup>177</sup>, L. Colasurdo<sup>117</sup>, B. Cole<sup>38</sup>, A.P. Colijn<sup>118</sup>, J. Collot<sup>56</sup>, P. Conde Muiño<sup>136a,136b</sup>, E. Coniavitis<sup>50</sup>, S.H. Connell<sup>32b</sup>, I.A. Connelly<sup>98</sup>, S. Constantinescu<sup>27b</sup>, F. Conventi<sup>67a.av</sup>, A.M. Cooper-Sarkar<sup>131</sup>, F. Cormier<sup>172</sup>, K.J.R. Cormier<sup>164</sup>, M. Corradi<sup>70a,70b</sup>, E.E. Corrigan<sup>94</sup>, F. Corriveau<sup>101.ad</sup>, A. Cortes-Gonzalez<sup>35</sup>, M.J. Costa<sup>171</sup>, D. Costanzo<sup>146</sup>, G. Cottin<sup>31</sup>, G. Cowan<sup>91</sup>, B.E. Cox<sup>98</sup>, J. Crane<sup>98</sup>, K. Cranmer<sup>121</sup>, S.J. 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Zacharis<sup>10</sup>, E. Zaffaroni<sup>52</sup>, R. Zaidan<sup>14</sup>, A.M. Zaitsev<sup>140,am</sup>, T. Zakareishvili<sup>156b</sup>, N. Zakharchuk<sup>44</sup>, J. Zalieckas<sup>17</sup>, S. Zambito<sup>57</sup>, D. Zanzi<sup>35</sup>, D.R. Zariповas<sup>55</sup>, S.V. Zeiřner<sup>45</sup>, C. Zeitnitz<sup>179</sup>, G. Zemaityte<sup>131</sup>, J.C. Zeng<sup>170</sup>, Q. Zeng<sup>150</sup>, O. Zenin<sup>140</sup>, D. Zerwas<sup>128</sup>, M. Zgubič<sup>131</sup>, D.F. Zhang<sup>58b</sup>, D. Zhang<sup>103</sup>, F. Zhang<sup>178</sup>, G. Zhang<sup>58a</sup>, H. Zhang<sup>15c</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>15c</sup>, L. Zhang<sup>58a</sup>, M. Zhang<sup>170</sup>, P. Zhang<sup>15c</sup>, R. Zhang<sup>58a</sup>, R. Zhang<sup>24</sup>, X. Zhang<sup>58b</sup>, Y. Zhang<sup>15d</sup>, Z. Zhang<sup>128</sup>, P. Zhao<sup>47</sup>, X. Zhao<sup>41</sup>, Y. Zhao<sup>58b,128,ai</sup>, Z. Zhao<sup>58a</sup>, A. Zhemchugov<sup>77</sup>, B. Zhou<sup>103</sup>, C. Zhou<sup>178</sup>, L. Zhou<sup>41</sup>, M.S. Zhou<sup>15d</sup>, M. Zhou<sup>152</sup>, N. Zhou<sup>58c</sup>, Y. Zhou<sup>7</sup>, C.G. Zhu<sup>58b</sup>, H.L. Zhu<sup>58a</sup>, H. Zhu<sup>15a</sup>, J. Zhu<sup>103</sup>, Y. Zhu<sup>58a</sup>, X. Zhuang<sup>15a</sup>, K. Zhukov<sup>108</sup>, V. Zhulanov<sup>120b,120a</sup>, A. Zibell<sup>174</sup>, D. Zieminska<sup>63</sup>, N.I. Zimine<sup>77</sup>, S. Zimmermann<sup>50</sup>, Z. Zinonos<sup>113</sup>, M. Zinser<sup>97</sup>, M. Ziolkowski<sup>148</sup>, G. Zobernig<sup>178</sup>, A. Zoccoli<sup>23b,23a</sup>, K. Zoch<sup>51</sup>, T.G. Zorbas<sup>146</sup>, R. Zou<sup>36</sup>, M. Zur Nedden<sup>19</sup>, L. Zwalinski<sup>35</sup>

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

- <sup>2</sup> Physics Department, SUNY Albany, Albany, NY, United States of America
- <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> Istanbul Aydin University, Istanbul; <sup>(c)</sup> Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
- <sup>5</sup> LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
- <sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America
- <sup>7</sup> Department of Physics, University of Arizona, Tucson, AZ, United States of America
- <sup>8</sup> Department of Physics, University of Texas at Arlington, Arlington, TX, United States of America
- <sup>9</sup> Physics Department, National and Kapodistrian University of Athens, Athens, Greece
- <sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece
- <sup>11</sup> Department of Physics, University of Texas at Austin, Austin, TX, United States of America
- <sup>12</sup> <sup>(a)</sup> Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; <sup>(b)</sup> Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; <sup>(c)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(d)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- <sup>13</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>14</sup> Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
- <sup>15</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Physics Department, Tsinghua University, Beijing; <sup>(c)</sup> Department of Physics, Nanjing University, Nanjing; <sup>(d)</sup> University of Chinese Academy of Science (UCAS), Beijing, China
- <sup>16</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia
- <sup>17</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>18</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America
- <sup>19</sup> Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
- <sup>20</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>21</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>22</sup> Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
- <sup>23</sup> <sup>(a)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; <sup>(b)</sup> INFN Sezione di Bologna, Italy
- <sup>24</sup> Physikalisches Institut, Universität Bonn, Bonn, Germany
- <sup>25</sup> Department of Physics, Boston University, Boston, MA, United States of America
- <sup>26</sup> Department of Physics, Brandeis University, Waltham, MA, United States of America
- <sup>27</sup> <sup>(a)</sup> Transilvania University of Brasov, Brasov; <sup>(b)</sup> Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; <sup>(d)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; <sup>(e)</sup> University Politehnica Bucharest, Bucharest; <sup>(f)</sup> West University in Timisoara, Timisoara, Romania
- <sup>28</sup> <sup>(a)</sup> Faculty of Mathematics, Physics and 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>29</sup> Physics Department, Brookhaven National Laboratory, Upton, NY, United States of America
- <sup>30</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>31</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>32</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>33</sup> Department of Physics, Carleton University, Ottawa, ON, Canada
- <sup>34</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 (CNESTEN), 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, Rabat, Morocco
- <sup>35</sup> CERN, Geneva, Switzerland
- <sup>36</sup> Enrico Fermi Institute, University of Chicago, Chicago, IL, United States of America
- <sup>37</sup> LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
- <sup>38</sup> Nevis Laboratory, Columbia University, Irvington, NY, United States of America
- <sup>39</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>40</sup> <sup>(a)</sup> Dipartimento di Fisica, Università della Calabria, Rende; <sup>(b)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- <sup>41</sup> Physics Department, Southern Methodist University, Dallas, TX, United States of America
- <sup>42</sup> Physics Department, University of Texas at Dallas, Richardson, TX, United States of America
- <sup>43</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> Oskar Klein Centre, Stockholm, Sweden
- <sup>44</sup> Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
- <sup>45</sup> Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>46</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>47</sup> Department of Physics, Duke University, Durham, NC, United States of America
- <sup>48</sup> SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>49</sup> INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>50</sup> Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
- <sup>51</sup> II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
- <sup>52</sup> Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
- <sup>53</sup> <sup>(a)</sup> Dipartimento di Fisica, Università di Genova, Genova; <sup>(b)</sup> INFN Sezione di Genova, Italy
- <sup>54</sup> II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>55</sup> SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>56</sup> LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
- <sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States of America
- <sup>58</sup> <sup>(a)</sup> Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; <sup>(b)</sup> Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; <sup>(c)</sup> School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; <sup>(d)</sup> Tsung-Dao Lee Institute, Shanghai, China
- <sup>59</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>60</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>61</sup> <sup>(a)</sup> Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>62</sup> Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- <sup>63</sup> Department of Physics, Indiana University, Bloomington, IN, United States of America
- <sup>64</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>65</sup> <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- <sup>66</sup> <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>67</sup> <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>68</sup> <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>69</sup> <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

- 70 <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 71 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 72 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 73 <sup>(a)</sup> INFN-TIFPA; <sup>(b)</sup> Università degli Studi di Trento, Trento, Italy
- 74 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 75 University of Iowa, Iowa City, IA, United States of America
- 76 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States of America
- 77 Joint Institute for Nuclear Research, Dubna, Russia
- 78 <sup>(a)</sup> Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; <sup>(b)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;
- <sup>(c)</sup> Universidade Federal de São João del Rei (UFSJ), São João del Rei; <sup>(d)</sup> Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
- 79 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 80 Graduate School of Science, Kobe University, Kobe, Japan
- 81 <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
- 82 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- 83 Faculty of Science, Kyoto University, Kyoto, Japan
- 84 Kyoto University of Education, Kyoto, Japan
- 85 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- 86 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 87 Physics Department, Lancaster University, Lancaster, United Kingdom
- 88 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- 89 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- 90 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- 91 Department of Physics, Royal Holloway University of London, Egham, United Kingdom
- 92 Department of Physics and Astronomy, University College London, London, United Kingdom
- 93 Louisiana Tech University, Ruston, LA, United States of America
- 94 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 95 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- 96 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
- 97 Institut für Physik, Universität Mainz, Mainz, Germany
- 98 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- 99 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
- 100 Department of Physics, University of Massachusetts, Amherst, MA, United States of America
- 101 Department of Physics, McGill University, Montreal, QC, Canada
- 102 School of Physics, University of Melbourne, Victoria, Australia
- 103 Department of Physics, University of Michigan, Ann Arbor, MI, United States of America
- 104 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States of America
- 105 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 106 Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
- 107 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 108 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- 109 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 110 National Research Nuclear University MEPhI, Moscow, Russia
- 111 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 112 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- 113 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- 114 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 115 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 116 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States of America
- 117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- 118 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- 119 Department of Physics, Northern Illinois University, DeKalb, IL, United States of America
- 120 <sup>(a)</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk; <sup>(b)</sup> Novosibirsk State University Novosibirsk, Russia
- 121 Department of Physics, New York University, New York, NY, United States of America
- 122 Ohio State University, Columbus, OH, United States of America
- 123 Faculty of Science, Okayama University, Okayama, Japan
- 124 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America
- 125 Department of Physics, Oklahoma State University, Stillwater, OK, United States of America
- 126 Palacký University, RPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
- 127 Center for High Energy Physics, University of Oregon, Eugene, OR, United States of America
- 128 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- 129 Graduate School of Science, Osaka University, Osaka, Japan
- 130 Department of Physics, University of Oslo, Oslo, Norway
- 131 Department of Physics, Oxford University, Oxford, United Kingdom
- 132 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- 133 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States of America
- 134 Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia
- 135 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States of America
- 136 <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas – LIP; <sup>(b)</sup> Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Departamento de Física, Universidade de Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 137 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- 138 Czech Technical University in Prague, Prague, Czech Republic
- 139 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- 140 State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia
- 141 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- 142 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- 143 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States of America
- 144 <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

- <sup>145</sup> Department of Physics, University of Washington, Seattle, WA, United States of America  
<sup>146</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom  
<sup>147</sup> Department of Physics, Shinshu University, Nagano, Japan  
<sup>148</sup> Department Physik, Universität Siegen, Siegen, Germany  
<sup>149</sup> Department of Physics, Simon Fraser University, Burnaby, BC, Canada  
<sup>150</sup> SLAC National Accelerator Laboratory, Stanford, CA, United States of America  
<sup>151</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden  
<sup>152</sup> Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, United States of America  
<sup>153</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom  
<sup>154</sup> School of Physics, University of Sydney, Sydney, Australia  
<sup>155</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan  
<sup>156</sup> <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  
<sup>157</sup> Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel  
<sup>158</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel  
<sup>159</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece  
<sup>160</sup> International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan  
<sup>161</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan  
<sup>162</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan  
<sup>163</sup> Tomsk State University, Tomsk, Russia  
<sup>164</sup> Department of Physics, University of Toronto, Toronto, ON, Canada  
<sup>165</sup> <sup>(a)</sup> TRIUMF, Vancouver, BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto, ON, Canada  
<sup>166</sup> Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan  
<sup>167</sup> Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America  
<sup>168</sup> Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America  
<sup>169</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden  
<sup>170</sup> Department of Physics, University of Illinois, Urbana, IL, United States of America  
<sup>171</sup> Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain  
<sup>172</sup> Department of Physics, University of British Columbia, Vancouver, BC, Canada  
<sup>173</sup> Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada  
<sup>174</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany  
<sup>175</sup> Department of Physics, University of Warwick, Coventry, United Kingdom  
<sup>176</sup> Waseda University, Tokyo, Japan  
<sup>177</sup> Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel  
<sup>178</sup> Department of Physics, University of Wisconsin, Madison, WI, United States of America  
<sup>179</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany  
<sup>180</sup> Department of Physics, Yale University, New Haven, CT, United States of America  
<sup>181</sup> Yerevan Physics Institute, Yerevan, Armenia

<sup>a</sup> Also at Borough of Manhattan Community College, City University of New York, NY; United States of America.

<sup>b</sup> Also at California State University, East Bay; United States of America.

<sup>c</sup> Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.

<sup>d</sup> Also at CERN, Geneva; Switzerland.

<sup>e</sup> Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.

<sup>f</sup> Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

<sup>g</sup> Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.

<sup>h</sup> Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); Spain.

<sup>i</sup> Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.

<sup>j</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.

<sup>k</sup> Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.

<sup>l</sup> Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

<sup>m</sup> Also at Department of Physics, California State University, Fresno CA; United States of America.

<sup>n</sup> Also at Department of Physics, California State University, Sacramento CA; United States of America.

<sup>o</sup> Also at Department of Physics, King's College London, London; United Kingdom.

<sup>p</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.

<sup>q</sup> Also at Department of Physics, Stanford University; United States of America.

<sup>r</sup> Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.

<sup>s</sup> Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

<sup>t</sup> Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

<sup>u</sup> Also at Giresun University, Faculty of Engineering, Giresun; Turkey.

<sup>v</sup> Also at Graduate School of Science, Osaka University, Osaka; Japan.

<sup>w</sup> Also at Hellenic Open University, Patras; Greece.

<sup>x</sup> Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Romania.

<sup>y</sup> Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.

<sup>z</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.

<sup>aa</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.

<sup>ab</sup> Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.

<sup>ac</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.

<sup>ad</sup> Also at Institute of Particle Physics (IPP); Canada.

<sup>ae</sup> Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.

<sup>af</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

<sup>ag</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.

<sup>ah</sup> Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.

<sup>ai</sup> Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.

<sup>aj</sup> Also at Louisiana Tech University, Ruston LA; United States of America.

<sup>ak</sup> Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.

<sup>al</sup> Also at Manhattan College, New York NY; United States of America.

<sup>am</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.

<sup>an</sup> Also at National Research Nuclear University MEPhI, Moscow; Russia.

<sup>ao</sup> Also at Near East University, Nicosia, North Cyprus, Mersin; Turkey.

<sup>ap</sup> Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.

<sup>aq</sup> Also at School of Physics, Sun Yat-sen University, Guangzhou; China.

<sup>ar</sup> Also at The City College of New York, New York NY; United States of America.

<sup>as</sup> Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.

<sup>at</sup> Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.

<sup>au</sup> Also at TRIUMF, Vancouver BC; Canada.

<sup>av</sup> Also at Università di Napoli Parthenope, Napoli; Italy.

\* Deceased.