Centrality and rapidity dependence of inclusive jet production in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector


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Centrality and rapidity dependence of inclusive jet production in $\sqrt{s_{NN}} = 5.02$ TeV proton–lead collisions with the ATLAS detector

ATLAS Collaboration

1. Introduction

Proton–lead ($p + \text{Pb}$) collisions at the Large Hadron Collider (LHC) provide an excellent opportunity to study hard scattering processes involving a nuclear target [1]. Measurements of jet production in $p + \text{Pb}$ collisions provide a valuable benchmark for studies of jet quenching in lead–lead collisions by, for example, constraining the impact of nuclear parton distributions on inclusive jet yields. However, $p + \text{Pb}$ collisions also allow the study of possible violations of the QCD factorisation between hard and soft processes which may be enhanced in collisions involving nuclei.

Previous studies in deuteron–gold ($d + \text{Au}$) collisions at the Relativistic Heavy Ion Collider (RHIC) observed such violations, manifested in the suppressed production of very forward hadrons with transverse momenta up to 4 GeV [2–4]. Studies of forward di-hadron angular correlations at RHIC also showed a much weaker dijet signal in $d + \text{Au}$ collisions than in $pp$ collisions [4,5]. These effects have been attributed to the saturation of the parton distributions in the gold nucleus [6–8], to the modification of the nuclear parton distribution function [9], to the higher-twist contributions to the cross-section enhanced by the forward kinematics of the measurement [10], or to the presence of a large nucleus [11]. The extended kinematic reach of $p + \text{Pb}$ measurements at the LHC allows the study of hard scattering processes that produce forward hadrons or jets over a much wider rapidity and transverse momentum range. Such measurements can determine whether the factorisation violations observed at RHIC persist at higher energy and, if so, how the resulting modifications vary as a function of particle or jet momentum and rapidity. The results of such measurements could test the competing descriptions of the RHIC results and, more generally, provide new insight into the physics of hard scattering processes involving a nuclear target.

This paper reports the centrality dependence of inclusive jet production in $p + \text{Pb}$ collisions at a nucleon–nucleon centre-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV. The measurement was performed using a dataset corresponding to an integrated luminosity of 278 nb$^{-1}$ recorded in 2013. The $p + \text{Pb}$ jet yields were
The centrality of $p + Pb$ collisions was characterised using the total transverse energy measured in the pseudorapidity $\eta$ interval $-4.9 < \eta < -3.2$ in the direction of the lead beam. Whereas in nucleus–nucleus collisions centrality reflects the degree of nuclear overlap between the colliding nuclei, centrality in $p + Pb$ collisions is sensitive to the multiple interactions between the proton and nucleons in the lead nucleus. Centrality has been successfully used at lower energies in $d + Au$ collisions at RHIC as an experimental handle on the collision geometry [2,13,14].

A Glauber model [15] was used to determine the average number of nucleon–nucleon collisions, $\langle N_{\text{coll}} \rangle$, and the mean value of the overlap function, $T_{pA}(b) = \int_{-\infty}^{\infty} \rho(b,z)dz$, where $\rho(b,z)$ is the nucleon density at impact parameter $b$ and longitudinal position $z$, in each centrality interval. Per-event jet yields, $(1/N_{\text{evt}})(d^2N_{\text{jet}}/dp_Tdy^*)$, were measured as a function of jet centre-of-mass rapidity $y$, and transverse momentum $p_T$, where $N_{\text{jet}}$ is the number of jets measured in $N_{\text{evt}} p + Pb$ events analysed. The centrality dependence of the per-event jet yields was evaluated using the nuclear modification factor,

$$R_{pPb} \equiv \frac{1}{T_{pA}} \frac{(1/N_{\text{evt}}) \ d^2N_{\text{jet}}/dp_Tdy^*}{d^2\sigma_{pp}/dp_Tdy^*}_{\text{cent}},$$

(1)

for a given centrality selection “cent”, where $d^2\sigma_{pp}/dp_Tdy^*$ is determined using the jet cross-section measured in pp collisions at $\sqrt{s} = 2.76$ TeV. The factor $R_{pPb}$ quantifies the absolute modification of the jet rate relative to the geometric expectation. In each centrality interval, the geometric expectation is the jet rate that would be produced by an incoherent superposition of the number of nucleon–nucleon collisions corresponding to the mean nuclear thickness in the given class of $p + Pb$ collisions.

Results are also presented for the central-to-peripheral ratio,

$$R_{CP} \equiv \frac{1}{R_{\text{coll}}} \frac{(1/N_{\text{evt}}) \ d^2N_{\text{jet}}/dp_Tdy^*}_{\text{cent}}$$

$$\frac{(1/N_{\text{evt}}) \ d^2N_{\text{jet}}/dp_Tdy^*}_{\text{peri}},$$

(2)

where $R_{\text{coll}}$ represents the ratio of $\langle N_{\text{coll}} \rangle$ in a given centrality interval to that in the most peripheral interval, $R_{\text{coll}} \equiv [N_{\text{cent}}]/[N_{\text{peri}}]$. The $R_{CP}$ ratio is sensitive to relative deviations in the jet rate from the geometric expectation between the $p + Pb$ event centralties. The $R_{pPb}$ and $R_{CP}$ measurements are presented as a function of inclusive jet $y^*$ and $p_T$. For the 2013 $p + Pb$ run, the LHC was configured with a 4 TeV proton beam and a 1.57 TeV per-nucleon Pb beam that together produced collisions with $\sqrt{s_{NN}} = 5.02$ TeV and a rapidity shift of the centre-of-mass frame of 0.465 units relative to the ATLAS rest frame. The run was split into two periods, with the directions of

the proton and lead beams being reversed at the end of the first period. The first period provided approximately 55% of the integrated luminosity with the Pb beam travelling to positive rapidity and the proton beam to negative rapidity, and the second period provided the remainder with the beams reversed. The analysis in this paper uses the events from both periods of data-taking and $y^*$ is defined so that $y^* > 0$ always refers to the downstream proton direction.

2. Experimental setup

The measurements presented in this paper were performed using the ATLAS inner detector (ID), calorimeters, minimum-bias trigger scintillator (MBTS), and trigger and data acquisition systems [16]. The ID measures charged particles within $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors, and a straw-tube transition radiation tracker, all immersed in a 2 T axial magnetic field [17]. The calorimeter system consists of a 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 electromagnetic and hadronic forward calorimeters (FCal) covering $3.2 < |\eta| < 4.9$. The EM calorimeters use lead plates as the absorbers and are segmented longitudinally in shower depth into three compartments with an additional presampler layer in front for $|\eta| < 1.8$. The granularity of the EM calorimeter varies with layer and pseudorapidity. The middle sampling layer, which typically has the largest energy deposit in EM showers, has a $\Delta \eta \times \Delta \phi$ granularity of 0.025 x 0.025 within $|\eta| < 2.5$. The hadronic calorimeter uses steel as the absorber and has three segments longitudinal in shower depth with cell sizes $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ for $|\eta| < 2.5^2$ and $0.2 \times 0.2$ for $2.5 < |\eta| < 4.9$. The two FCal modules are composed of tungsten and copper absorbers with LAr as the active medium, which together provide ten interaction lengths of material. The MBTS detects charged particles over 2.1 < $|\eta| < 3.9$ using two hodoscopes of 16 counters each, positioned at $z = \pm 3.6$ m.

The $p + Pb$ and pp events used in this analysis were recorded using a combination of minimum-bias (MB) and jet triggers [18]. In $p + Pb$ data-taking, the MB trigger required hits in at least one counter in each side of the MBTS detector. In pp collisions the MB condition was the presence of hits in the pixel and microstrip detectors reconstructed as a track by the high-level trigger system. Jets were selected using high-level jet triggers implemented with a reconstruction algorithm similar to the procedure applied in the offline analysis. In particular, it used the anti-$k_t$ algorithm with $R = 0.4$, a background subtraction procedure, and a calibration of the jet energy to the full hadronic scale. The high-level jet triggers were seeded from a combination of low-level MB and jet hardware-based triggers. Six jet triggers with transverse energy thresholds ranging from 20 GeV to 75 GeV were used to select jets within $|\eta| < 3.2$ and a separate trigger with a threshold of 15 GeV was used to select jets with $3.2 < |\eta| < 4.9$. The triggers were prescaled in a fashion which varied with time to accommodate the evolution of the luminosity within an LHC fill.

3. Data selection

In the offline analysis, charged-particle tracks were reconstructed in the ID with the same algorithm used in pp collisions [19]. The $p + Pb$ events used for this analysis were required to have

\[ \text{An exception is the third (outermost) sampling layer, which has a segmentation of 0.2 x 0.1 up to } |\eta| = 1.7. \]
4. Centrality determination

The centrality of the $p + $Pb events selected for analysis was characterised by the total transverse energy $\Sigma E_T^{Pb}$ in the FCal module on the Pb-going side. The $\Sigma E_T^{Pb}$ distribution for minimum-bias $p + $Pb collisions passing the event selection described in Section 3 is presented in Fig. 1. Following standard techniques [20], centrality intervals were defined in terms of percentiles of the $\Sigma E_T^{Pb}$ distribution after accounting for an estimated inefficiency of $(2 \pm 2)\%$ for inelastic $p + $Pb collisions to pass the applied event selection. The following centrality intervals were used in this analysis, in order from the most central to the most peripheral: 0–10%, 10–20%, 20–30%, 30–40%, 40–60%, and 60–90%, with the 60–90% interval serving as the reference for the $R_{cp}$ ratio. Events with a centrality beyond 90% were not used in the analysis, since the uncertainties on the composition of the event sample and in the determination of the geometric quantities are large for these events.

A Glauber Monte Carlo (MC) [15] analysis was used to calculate $R_{coll}$ and $T_{PA}$ for each centrality interval. First, a Glauber MC program [21] was used to simulate the geometry of inelastic $p + $Pb collisions and calculate the probability distribution of the number of nucleon participants $N_{part}$, $P(N_{part})$. The simulations used a Woods–Saxon nuclear density distribution and an inelastic nucleon–nucleon cross-section, $\sigma_{NN}$, of $70 \pm 5$ mb. Separately, PYTHIA 8 [22,23] simulations of 4 TeV on 15.7 TeV pp collisions provided a detector-level $\Sigma E_T^{Pb}$ distribution for inelastic–nucleon–nucleus collisions, to be used as input to the Glauber model. This distribution was fit to a gamma distribution.

Then, an extension of the wounded-nucleon (WN) [24] model that included a non-linear dependence of $\Sigma E_T^{Pb}$ on $N_{part}$ was used to define $N_{part}$-dependent gamma distributions for $\Sigma E_T^{Pb}$, with the constraint that the distributions reduce to the PYTHIA distribution for $N_{part} = 2$. The non-linear term accounted for the possible variation in the effective FCal acceptance resulting from an $N_{part}$-dependent backward rapidity shift of the produced soft particles with respect to the nucleon–nucleon frame [25]. The gamma distributions were summed over $N_{part}$ with a $P(N_{part})$ weighting to produce a hypothetical $\Sigma E_T^{Pb}$ distribution. That distribution was fit to the measured $\Sigma E_T^{Pb}$ distribution shown in Fig. 1 with the parameters of the extended WN model allowed to vary freely. The best fit, which contained a significant non-linear term, successfully described the $\Sigma E_T^{Pb}$ distribution in data over several orders of magnitude. From the results of the fit, the distribution of $N_{part}$ and the corresponding $\langle N_{part} \rangle$ were calculated for each centrality interval. The resulting $R_{coll}$ and $T_{PA}$ values and corresponding systematic uncertainties, which are described in Section 8, are shown in Table 1.

5. Monte Carlo simulation

The performance of the jet reconstruction procedure was evaluated using a sample of 36 million events in which simulated $\sqrt{s} = 5.02$ TeV pp hard-scattering events were overlaid with minimum-bias $p + $Pb events recorded during the 2013 run. Thus the sample contains an underlying event contribution that is identical in all respects to the data. The simulated events were generated using PYTHIA 8 [22] (version 6.425, AUET2B tune [26], CTEQ6L1 parton distribution functions [27]) and the detector effects were fully simulated using GEANT4 [28,29]. These events were produced for different $p_T$ intervals of the generator-level (“truth”) $R = 0.4$ jets. In total, the generator-level spectrum spans $10 < p_T < 10^2$ GeV. Separate sets of 18 million events each were generated for the two different beam directions to take into account any z-axis asymmetries in the detector. For each beam direction, the four-momenta of the generated particles were longitudinally boosted by a rapidity of $\pm0.465$ to match the corresponding beam conditions. The events were simulated using detector conditions appropriate to the two periods of the 2013 $p + $Pb run and reconstructed using the same algorithms as were applied to the experimental data. A sep-
arate 9-million-event sample of fully simulated 2.76 TeV PYTHIA pp hard scattering events (with the same version, tune and parton distribution function set) was used to evaluate the jet performance in \( \sqrt{s} = 2.76 \) TeV pp collisions during 2013 data-taking.

6. Jet reconstruction and performance

The jet reconstruction and underlying event subtraction procedures were adapted from those used by ATLAS in Pb + Pb collisions, which are described in detail in Refs. [30,31], and are summarised here along with any substantial differences from the referenced analyses.

An iterative procedure was used to obtain an event-by-event estimate of the underlying event energy density while excluding contributions from jets to that estimate. The modulaion of the underlying event energy density to account for potential elliptic flow was not included in this analysis. Jets were reconstructed from the anti-\( k_{t} \) algorithm with \( R = 0.4 \) applied to calorimeter cells grouped into \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \) towers, with the final jet kinematics calculated from the background-subtracted energy in the cells contained in the jet. The rate of jets reconstructed from the underlying event fluctuations of soft particles was negligible in the kinematic range studied and therefore no attempt to reject them was made. The mean subtracted transverse energy in \( p + Pb \) collisions was 2.4 GeV (1.4 GeV) for jets with \( |y^*| < 1 \ (|y^*| > 3) \). In \( pp \) collisions, this procedure simply subtracts the underlying event pedestal deposited in the calorimeter which can arise, in part, from the presence of additional \( pp \) interactions in the same crossing (in-time pileup).

Following the above jet reconstruction, a small correction, typically a few percent, was applied to the transverse momentum of those jets which did not overlap with a region excluded from the background determination and thus were erroneously included in the initial estimate of the underlying event background. Then, the jet energies were corrected to account for the calorimeter energy response using an \( \eta \)- and \( p_T \)-dependent multiplicative factor that was derived from the simulations [32]. Following this calibration, a final multiplicative in situ calibration was applied to account for differences between the simulated detector response and data. The measured \( p_T \) of jets recoiling against objects with an independently calibrated energy scale – such as Z bosons, photons, or jets in a different region of the detector – was investigated. The in situ calibration, which typically differed from unity by a few percent, was derived by comparing this \( p_T \) balance in \( pp \) data with that in simulations in a fashion similar to that used previously within ATLAS [33].

The jet reconstruction performance was evaluated in the simulated samples by applying the same subtraction and reconstruction procedure as was applied to data. The resulting reconstructed jets with transverse momentum \( p_T^{\text{gen}} \) were compared with their corresponding generator jets, which were produced by applying the anti-\( k_t \) algorithm to the final-state particles produced by PYTHIA, excluding muons and neutrinos. Each generator jet was matched to a reconstructed jet, and the \( p_T \) difference between the two jets was studied as a function of the generator jet transverse momentum, \( p_T^{\text{gen}} \), and generator jet rapidity \( y^* \), and in the six \( p + Pb \) event centrality intervals.

The reconstruction efficiency for jets having \( p_T^{\text{gen}} > 25 \) GeV was found to be greater than 99%. The performance was quantified by the means and standard deviations of the \( \Delta p_T/p_T \) \( (= p_T^{\text{jet}}/p_T^{\text{gen}} - 1) \) distributions, referred to as the jet energy scale closure and jet energy resolution respectively. The closure in \( p + Pb \) events was less than 2% for \( p_T^{\text{gen}} > 25 \) GeV jets and was better than 1% for \( p_T^{\text{gen}} > 100 \) GeV jets. At low \( p_T^{\text{gen}} \), the energy scale closure and resolution exhibited a weak \( p + Pb \) centrality dependence, with differences in the closure of up to 1% and differences in the resolution of up to 2% in the most central 0–10% events relative to the 60–90% peripheral events. At high jet \( p_T \), the response was centrality independent within sensitivity. In \( pp \) events, the closure was less than 1% in the entire kinematic range studied.

In order to quantify the degree of \( p_T \)-bin migration introduced by the detector response and reconstruction procedure, response matrices were populated by recording the \( p_T \) values of each generator–reconstructed jet pair. Separate matrices were constructed for each \( y^* \) interval and \( p + Pb \) centrality interval used in the analysis. The \( p_T \) bins used were chosen to increase with \( p_T \) such that the width of each bin was \( \approx 0.25 \) of the bin low edge. Using this binning, the proportion of jets with reconstructed \( p_T \) in the same bin as their truth \( p_T \) monotonically increased with truth \( p_T \) and was 50–70%.

7. Data analysis

A combination of minimum-bias and jet triggered \( p + Pb \) events were selected for analysis as described in Section 2. The sampled luminosity (defined as the luminosity divided by the mean luminosity-weighted prescale) of the jet triggers increased with increasing \( p_T \) threshold. Offline jets were selected for the analysis by requiring a match to an online jet trigger. The efficiency of the various triggers was determined with respect to the minimum-bias trigger and to lower threshold jet triggers. For simplicity, each \( p_T \) bin used jets selected by only one jet trigger. In a given \( p_T \) bin, jets were selected by the highest-threshold jet trigger for which the efficiency was determined to be greater than 99% in the bin. No additional corrections for the trigger efficiency were applied.

The double-differential per-event jet yields in \( p + Pb \) collisions were constructed via

\[
\frac{1}{N_{\text{ext}}} \frac{d^2N_{\text{jet}}}{dp_T dy^*} = \frac{1}{N_{\text{ext}}} \frac{N_{\text{jet}}}{\Delta p_T \Delta y^*},
\]

where \( N_{\text{ext}} \) is the total (unprescaled) number of MB \( p + Pb \) events sampled, \( N_{\text{jet}} \) is the yield of jets corrected for all detector effects and the instantaneous trigger prescale during data-taking, and \( \Delta p_T \) and \( \Delta y^* \) are the widths of the \( p_T \) and \( y^* \) bins. The centrality-dependent yields were constructed by restricting \( N_{\text{ext}} \) and \( N_{\text{jet}} \) to come from \( p + Pb \) events within a given centrality interval. The double-differential cross-section in \( pp \) collisions was constructed via

\[
\frac{d^2\sigma}{dp_T dy^*} = \frac{1}{L_{\text{int}}} \frac{N_{\text{jet}}}{\Delta p_T \Delta y^*},
\]

where \( L_{\text{int}} \) is the total integrated luminosity of the jet trigger used in the given \( p_T \) bin. The \( p_T \) binning in the \( pp \) cross-section was chosen such that the \( x_t = 2p_T/\sqrt{s} \) binning between the \( p + Pb \) and \( pp \) datasets is the same.

Both the per-event yields in \( p + Pb \) collisions and the cross-section in \( pp \) collisions were restricted to the \( p_T \) range where the MC studies described in Section 6 show that the efficiency for a truth jet to remain in the same \( p_T \) bin is \( \geq 50\% \). This \( p_T \) range was rapidity dependent, with the lowest \( p_T \) bin edge used ranging from 50 GeV in the most backward rapidity intervals studied to 25 GeV in the most forward intervals.

The measured \( p + Pb \) and \( pp \) yields were corrected for jet energy resolution and residual distortions of the jet energy scale which result in \( p_T \)-bin migration. For each rapidity interval, the yield was corrected by the use of \( p_T \)-dependent (and, in the \( p + Pb \) case, centrality-dependent) bin-by-bin correction factors \( C(p_T, y^*) \) obtained from the ratio of the reconstructed to the truth jet \( p_T \) distributions for jets originating in a true \( y^* \) bin, according to
\[ C(\pT, y^*) = \frac{N_{\text{jet}}^{\text{true}}(\pT, y^*)}{N_{\text{jet}}^{\text{reco}}(\pT, y^*)}, \]

where \( N_{\text{jet}}^{\text{true}}(\pT, y^*) \) is the number of true jets in the given \( \pT(\pT^{\text{reco}}) \) bin in the corresponding MC samples.

Since the determination of the correction factors \( C(\pT, y^*) \) is sensitive to the shape of the jet spectrum in the MC sample, the response matrices used to generate them were reweighted to provide a better match between the reconstructed distributions in data and simulated events. The spectrum of generator jets was weighted jet-by-jet by the ratio of the reconstructed spectrum in data to that in simulation. This ratio was found to be approximately linear in the logarithm of reconstructed \( \pT \). A separate reweighting was performed for the \( p + \text{Pb} \) jet yield in each centrality interval, resulting in changes of \( \leq 10\% \) from the original correction factors before reweighting. The resulting corrections to the \( p + \text{Pb} \) and \( pp \) yields were at most 30\%, and were typically \( \leq 10\% \) for jets with \( \pT > 100 \text{ GeV} \). These corrections were applied to the detector-level yield \( N_{\text{jet}}^{\text{reco}} \) to give the particle-level yield via

\[ N_{\text{jet}} = C(\pT, y^*) N_{\text{jet}}^{\text{reco}}. \]

A \( \sqrt{s} = 5.02 \text{ TeV} \) \( pp \) reference jet cross-section was constructed through the use of the corrected 2.76 TeV \( pp \) cross-section and a previous ATLAS measurement of the \( x_T \)-scaling between the inclusive jet cross-sections at \( \sqrt{s} = 2.76 \text{ TeV} \) (measured using 0.20 pb\(^{-1}\) of data collected in 2011) and 7 TeV (measured using 37 pb\(^{-1}\) of data collected in 2010) [34]. In this previous analysis, the \( \sqrt{s} \)-scaled ratio \( \rho \) of the 2.76 TeV cross-section to that at 7 TeV was evaluated at fixed \( x_T \).

\[ \rho(x_T, y^*) = \left( \frac{2.76 \text{ TeV}}{7 \text{ TeV}} \right)^3 \frac{d^2\sigma/\sqrt{s}}{dp_T dy^*} = \frac{76 \text{ TeV}}{2.76 \text{ TeV}} \left( \frac{d^2\sigma/\sqrt{s}}{dp_T dy^*} \right). \]

where \( d^2\sigma/\sqrt{s}/dp_T dy^* \) is the \( pp \) jet cross-section at the given centre-of-mass energy \( \sqrt{s} \), and the numerator and denominator are each evaluated at the same \( x_T \) (but different \( \pT = x_T \sqrt{s}/2 \)). Equation (7) can be rearranged to define the cross-section at \( \sqrt{s} = 7 \text{ TeV} \) in terms of that at 2.76 TeV times a multiplicative factor and divided by \( \rho \).

The \( \sqrt{s} = 5.02 \text{ TeV} \) \( pp \) cross-section at each \( \pT \) and \( y^* \) value was constructed by scaling the corrected \( \sqrt{s} = 2.76 \text{ TeV} \) \( pp \) cross-section measured at the equivalent \( x_T \) according to

\[ \frac{d^2\sigma}{dp_T dy^*} = \rho(x_T, y^*) \cdot 0.643 \left( \frac{2.76 \text{ TeV}}{5.02 \text{ TeV}} \right) \frac{d^2\sigma}{dp_T dy^*}. \]

where the power \( -\ln(2.76/5.02)/\ln(2.76/7) \approx -0.643 \) interpo-
lates between 2.76 TeV and 7 TeV to 5.02 TeV using a power-law collision energy dependency at each \( \pT \) and \( y^* \). Since the jet energy scale and \( x_T \)-interpolation uncertainties are large for the \( pp \) data at large rapidities \((|y^*| > 2.8)\), a \( \sqrt{s} = 5.02 \text{ TeV} \) reference is not constructed in that rapidity region.

The \( pp \) jet cross-section at \( \sqrt{s} = 2.76 \text{ TeV} \) measured with the 2013 data was found to agree with the previous ATLAS measurement of the same quantity [34] within the systematic uncertainties.

8. Systematic uncertainties

The \( R_{\text{CP}} \) and \( R_{\text{PP}} \) measurements are subject to systematic uncertainties arising from a number of sources: the jet energy scale and resolution, differences in the spectral shape between data and simulation affecting the bin-by-bin correction factors, residual inefficiency in the trigger selection, and the estimates of the geometric uncertainties \( R_{\text{coll}} \) (in \( R_{\text{CP}} \)) and \( T_{\text{pA}} \) (in \( R_{\text{PP}} \)). In addition to these sources of uncertainty, which are common to the \( R_{\text{CP}} \) and \( R_{\text{PP}} \) measurements, \( R_{\text{PP}} \) is also subject to uncertainties from the \( x_T \)-interpolation of the \( \sqrt{s} = 2.76 \text{ TeV} \) pp cross-section to the \( \sqrt{s} = 5.02 \text{ TeV} \) centre-of-mass energy and from the integrated luminosity of the \( pp \) dataset.

Uncertainties in the jet energy scale and resolution influence the correction of the \( p + \text{Pb} \) and \( pp \) jet spectra. The uncertainty in the scale was taken from studies of the \( \text{in situ} \) calorimeter response and systematic variations of the jet response in simulation [32], as well as studies of the relative energy scale difference between the jet reconstruction procedure in heavy-ion collisions and the procedure used by ATLAS for inclusive jet measurements in 2.76 TeV and 7 TeV \( pp \) collisions [34,35]. The total energy scale uncertainty in the measured \( \pT \) range was \( < 4\% \) for jets in \(|y^*| < 2.8 \), and \( < 7\% \) for jets in \(|y^*| > 2.8 \). The sensitivity of the results to the uncertainty in the energy scale was evaluated separately for ten distinct sources of uncertainty. Each source was treated as fully uncorrelated with any other source, but fully correlated with itself in \( \pT \), \( \eta \), and \( \phi \). The uncertainty in the resolution was taken from \( \text{in situ} \) studies of the dijet energy balance [36]. The resolution uncertainty generally was \(< 10\% \), except for low-\( \pT \) jets where it was \(< 20\% \). The effects on the \( R_{\text{CP}} \) and \( R_{\text{PP}} \) measurements were evaluated through an additional smearing of the energy of reconstructed jets in the simulation such that the resolution uncertainty was added to the original resolution in quadrature.

The resulting systematic uncertainties on \( R_{\text{CP}} \) (\( \delta R_{\text{CP}} \)) and \( R_{\text{PP}} \) (\( \delta R_{\text{PP}} \)) were evaluated by producing new response matrices in accordance with each source of the energy scale uncertainty and the resolution uncertainty, generating new correction factors, and calculating the new \( R_{\text{CP}} \) and \( R_{\text{PP}} \) results. Each energy scale and resolution variation was applied to all rapidity bins and to both the \( p + \text{Pb} \) and \( pp \) response matrices simultaneously. The uncertainty on \( R_{\text{CP}} \) and \( R_{\text{PP}} \) from the total energy scale uncertainty was determined by adding the effects of the ten energy scale uncertainty sources in quadrature. Since the correction factors for the \( p + \text{Pb} \) spectra in different centrality intervals were affected to a similar degree by variations in the energy scale and resolution, the effects tended to cancel in the \( R_{\text{CP}} \) ratio, and the resulting \( \delta R_{\text{CP}} \) were small. The resulting \( \delta R_{\text{PP}} \) values were somewhat larger than the \( \delta R_{\text{CP}} \) values due to the relative centre-of-mass shift between the \( p + \text{Pb} \) and \( pp \) collision systems. The centrality dependence of the energy scale and resolution uncertainties in \( p + \text{Pb} \) events was negligible.

To achieve better correspondence with the data, the simulated jet spectrum was reweighted to match the spectral shape in data before deriving the bin-by-bin correction factors as described above. To determine the sensitivity of the results to this reweighting procedure, the slope of the fit to the ratio of the detector-level spectrum in data to that in simulation was varied by the fit uncertainty, and the correction factors were recomputed with this alternative weighting. The resulting \( \delta R_{\text{PP}} \) and \( \delta R_{\text{CP}} \) from the nominal values were included in the total systematic uncertainty.

As the jet triggers used for the data selection were evaluated to have greater than 99\% efficiency in the \( \pT \) regions where they are used to select jets, an uncertainty of 1\% was chosen for the centrality selected \( p + \text{Pb} \) yields and the \( pp \) cross-section in the range \( 20 < \pT < 125 \text{ GeV} \). This uncertainty was taken to be uncorrelated between the centrality-selected \( p + \text{Pb} \) yields and the \( pp \) cross-section, resulting in a 1.4\% uncertainty on the \( R_{\text{CP}} \) and \( R_{\text{PP}} \) measurements.

The geometric quantities \( R_{\text{coll}} \) and \( T_{\text{pA}} \) and their uncertainties are listed in Table 1. These uncertainties arise from uncertainties in the geometric modelling of \( p + \text{Pb} \) collisions and in modelling the \( N_{\text{part}} \) dependence of the forward particle production measured by \( \Sigma E_T \). In general, the uncertainties were asymmetric.
Uncertainties in R_{coll} were largest for the ratio of the most central to the most peripheral interval (0–10%/60–90%), where they were +17/−6%, and smallest in the 40–60%/60–90% ratio, where they were +4/−3%. Uncertainties in T_{ppb} were largest in the most central (0–10%) and most peripheral (60–90%) centrality intervals, where the upper or lower uncertainty was as high as 10%, and smaller for intervals in the middle of the p + Pb centrality range, where they reached a minimum of +3/−2% for the 20–30% interval.

The x_t-interpolation of the √s = 2.76 TeV pp jet cross-section to 5.02 TeV is sensitive to uncertainties in ρ(ψ(x_t, y^*)), the √s-scaled ratio of jet spectra at 2.76 and 7 TeV. Following Eq. (8), the uncertainty in the interpolated pp cross-section (dσ/5.02 TeV) at fixed x_t is related to the uncertainty in ρ (dρ) via (dσ/5.02 TeV)/σ = 0.643(dρ/ρ), where dρ was taken from Ref. [34]. The values of dρ ranged from 5% to 23% in the region of the measurement and were generally larger at lower x_t and at larger rapidities.

The integrated luminosity for the 2013 pp dataset was determined by measuring the interaction rate with several ATLAS subdetectors. The absolute calibration was derived from three van der Meer scans [37] performed during the pp data-taking in 2013 in a fashion similar to that used previously within ATLAS [38] for pp data-taking at higher energies. The systematic uncertainty on the integrated luminosity was estimated to be 3.1%.

The uncertainties from the jet energy scale, jet energy resolution, reweighting and x_t-interpolation are p_T and y^* dependent, while the uncertainties from the trigger, luminosity, and geometric factors are not. The total systematic uncertainty on the R_{ppb} measurement ranges from 7% at mid-rapidity and high p_T to 18% at forward rapidities and low p_T. In most p_T and rapidity bins, the dominant systematic uncertainty on R_{ppb} is from the x_t-interpolation. The p_T- and y^*-dependent systematic uncertainties on R_{CP} are small. Near mid-rapidity or at high p_T, they are 2%, rising to approximately 12% at low p_T in forward rapidities. Thus, in most of the kinematic region studied, the dominant uncertainty on R_{CP} is from the geometric factors R_{coll}.

9. Results

Fig. 2 presents the fully corrected per-event jet yield as a function of p_T in 0–90% p + Pb collisions, for each of the jet centre-of-mass rapidity ranges used in this analysis. At mid-rapidity, the yields span over eight orders of magnitude.

The jet nuclear modification factor R_{ppb} for 0–90% p + Pb events is presented in Fig. 3 in the eight rapidity bins for which the pp reference was constructed. At most rapidities studied, the R_{ppb} values show a slight (∼10%) enhancement above one, although many bins are consistent with unity within the systematic uncertainties. At mid-rapidity, the R_{ppb} values reach a maximum near 100 GeV. No large modification of the total yield of jets relative to the geometric expectation (under which R_{ppb} = 1) is observed. The data in Fig. 3 are compared to a next-to-leading order perturbative QCD calculation of R_{ppb}, with the EPS09 parameterisation of nuclear parton distribution functions [9], using CT10 [39] for the free proton parton distribution functions and following the procedure for calculating jet production rates in p + Pb collisions described in Refs. [1,40]. The data are slightly higher than the calculation, but generally compatible with it within systematic uncertainties.

The central-to-peripheral ratio R_{CP} for jets in p + Pb collisions is summarised in Fig. 4, where the R_{CP} values for three centrality intervals are shown in all rapidity ranges studied. The R_{CP} ratio shows a strong variation with centrality relative to the geometric expectation, under which R_{CP} = 1. The jet R_{CP} for 0–10%/60–90% events is smaller than one at all rapidities for jet p_T > 100 GeV and at all p_T at sufficiently forward (proton-going, y^* > 0) rapidities. Near mid-rapidity, the 40–60%/60–90% R_{CP} values are consistent with unity up to 100–200 GeV, but indicate a small suppression at higher p_T. In all rapidity intervals studied, R_{CP} decreases with increasing p_T and in increasingly more central collisions. Furthermore, at fixed p_T, R_{CP} decreases systematically at more forward rapidities. At the highest p_T in the most forward rapidity bin, the 0–10%/60–90% R_{CP} value is ∼0.2. In the backward rapidity direction (lead-going, y^* < 0), R_{CP} is found to be enhanced by 10–20% for low-p_T jets.

Fig. 5 summarises the jet R_{ppb} in central, mid-central and peripheral events in all rapidity intervals studied. The patterns observed in the centrality-dependent R_{ppb} values are a consequence of the near-geometric scaling of the minimum-bias R_{ppb} values along with the strong modifications of the central-to-peripheral ratio R_{CP}. At sufficiently high p_T, R_{ppb} in central events is found to be suppressed (R_{ppb} < 1) and in peripheral events to be enhanced (R_{ppb} > 1). Generally, these respective deviations from the geometric expectation (under which R_{ppb} = 1 for all centrality intervals) increase with p_T and, at fixed p_T, increase as the rapidity becomes more forward. Thus, the large effects in R_{CP} are consistent with a combination of modifications that have opposite sign in the centrality-dependent R_{ppb} values but have little effect on the centrality-inclusive (0–90%) R_{ppb} values. At backward-going rapidities (y^* < 0) the R_{ppb} value for low-p_T jets in all centrality intervals is consistent with unity within the uncertainties.
Given the observed suppression pattern as a function of jet rapidity, in which the suppression in $R_{CP}$ at fixed $p_T$ systematically increases at more forward-going rapidities, it is natural to ask if it is possible to find a single relationship between the $R_{CP}$ values in the different rapidity intervals which is a function of jet kinematics alone. To test this, the $R_{CP}$ values in each rapidity bin were plotted against the quantity $p_T \times \cosh(y^*) \approx E$, where $(y^*)$ is the centre of the rapidity bin and $E$ is the total energy of the jet. In relativistic kinematics, the total energy of a particle is given by $E = m_T \cosh(y^*)$, where the transverse mass $m_T = \sqrt{m^2 + p_T^2}$.

In the kinematic range studied, the mass of the typical jet is sufficiently small relative to its transverse momentum that approximating the transverse mass, $m_T$, with the $p_T$ is reasonable. The $0$–$10\%$ jet yields $R_{CP}$ versus $p_T \times \cosh(y^*)$ is shown for all ten rapidity ranges in Fig. 6. When plotted against this variable, the $R_{CP}$ values in each of the five forward-going rapidities $(y^* > +0.8)$ fall along the same curve, which is approximately linear in the logarithm of $E$. This trend is also observed in the two most forward of the remaining rapidity intervals (−0.3 < $y^*$ < +0.8), but the $R_{CP}$ values at backward rapidities (−0.8 < $y^*$ < −0.3) do not follow this trend. This pattern is also observed in other centrality intervals, albeit with a different slope in $E$ for each centrality interval.

These patterns suggest that the observed modifications may depend on the initial parton kinematics, such as the longitudinal momentum fraction of the parton originating in the proton, $x_p$. In particular, a dependence on $x_p$ would explain why the data follow a consistent trend vs. $p_T \times \cosh(y^*)$ at forward rapidities (where jet production at a given jet energy $E$ is dominated by $x_p \sim E/(\sqrt{s}/2)$ partons in the proton) but do not do so at backward rapidities (where the longitudinal momentum fraction of the parton originating in the lead nucleus, $x_p$, as well as $x_p$ are both needed to relate the jet and parton kinematics).

By analogy with Fig. 6 where the $R_{CP}$ values are plotted versus $p_T \times \cosh(y^*)$, the $R_{PPb}$ values in the four most forward-going bins studied are plotted against this variable in Fig. 7. The $R_{PPb}$ values in central and peripheral events are shown separately. Although the systematic uncertainties are larger on $R_{PPb}$ than on $R_{CP}$, the observed behaviour for jets with $p_T > 150$ GeV is consistent with the nuclear modifications depending only on the approximate total jet energy $p_T \times \cosh(y^*)$. In central (peripheral) events, the $R_{PPb}$ values at forward rapidities are consistent with a rapidity-independent decreasing (increasing) function of $p_T \times \cosh(y^*)$. Thus, the single trend in $R_{CP}$ versus $p_T \times \cosh(y^*)$ at forward rapidities appears to arise from opposite trends in the central and peripheral $R_{PPb}$, both a single function of $p_T \times \cosh(y^*)$. 

**Fig. 3.** Measured $R_{PPb}$ values for $R = 0.4$ jets in 0–90% $p + Pb$ collisions. Each panel shows the jet $R_{PPb}$ in a different rapidity range. Vertical error bars represent the statistical uncertainty while the boxes represent the systematic uncertainties on the jet yields. The shaded box at the left edge of the $R_{PPb} = 1$ horizontal line indicates the systematic uncertainty in $T_{sh}$ and the $pp$ luminosity in quadrature. The shaded band represents a calculation using the EPS09 nuclear parton distribution function set.

**Fig. 4.** Measured $R_{CP}$ values for $R = 0.4$ jets in $p + Pb$ collisions in central (stars), mid-central (diamonds) and mid-peripheral (crosses) events. Each panel shows the jet $R_{CP}$ in a different rapidity range. Vertical error bars represent the statistical uncertainty while the boxes represent the systematic uncertainties on the jet yields. The shaded boxes at the left edge of the $R_{CP} = 1$ horizontal line indicate the systematic uncertainty in $T_{sh}$ and the $pp$ luminosity in quadrature. The shaded bands represent a calculation using the EPS09 nuclear parton distribution function set.
Fig. 5. Measured $R_{\text{pPb}}$ values for $R = 0.4$ jets in $p + \text{Pb}$ collisions in central (stars), mid-central (diamonds) and peripheral (crosses) events. Each panel shows the jet $R_{\text{pPb}}$ in a different rapidity range. Vertical error bars represent the statistical uncertainty while the boxes represent the systematic uncertainties on the jet yields. The shaded boxes at the right edge of the $R_{\text{pPb}} = 1$ horizontal line indicate the systematic uncertainties on $T_{\text{pA}}$ and the $pp$ luminosity added in quadrature for (from left to right) peripheral, mid-central and central events.

The results presented here use the standard Glauber model with fixed $\sigma_{\text{NN}}$ to estimate the geometric quantities. The impact of geometric models which incorporate event-by-event changes in the configuration of the proton wavefunction [41] has also been studied. Using the so-called Glauber-Gribov Colour Fluctuation model to determine the geometric parameters amplifies the effects seen with the Glauber model. In this model, the suppression in central events and the enhancement in peripheral events would be increased.

10. Conclusions

This paper presents the results of a measurement of the centrality dependence of jet production in $p + \text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV over a wide kinematic range. The data were collected with the ATLAS detector at the LHC and correspond to 27.8 nb$^{-1}$ of integrated luminosity. The centrality of $p + \text{Pb}$ collisions was characterised using the total transverse energy measured in the forward calorimeter on the Pb-going side covering the interval $-4.9 < \eta < -3.2$. The average number of nucleon–nucleon collisions and the mean nuclear thickness factor were evaluated for each centrality interval using a Glauber Monte Carlo analysis.

Results are presented for the nuclear modulation factor $R_{\text{pPb}}$ with respect to a measurement of the inclusive jet cross-section in $\sqrt{s} = 2.76$ TeV $pp$ collisions corresponding to 4.0 pb$^{-1}$ of integrated luminosity. The $pp$ cross-section was $x_1$-interpolated to 5.02 TeV using previous ATLAS measurements of inclusive jet production at 2.76 and 7 TeV. Results are also shown for the central-to-peripheral ratio $R_{CP}$. The centrality-inclusive $R_{\text{pPb}}$ results for 0–90% collisions indicate only a modest enhancement over the geometric expectation. This enhancement has a weak $p_T$ and rapidity dependence and is generally consistent with predictions from the modification of the parton distribution functions in the nucleus, which is small in the kinematic region probed by this measurement.

The results of the $R_{CP}$ measurement indicate a strong centrality-dependent reduction in the yield of jets in central collisions relative to that in peripheral collisions, after accounting for the effects of the collision geometries. In addition, the reduction becomes more pronounced with increasing jet $p_T$ and at more forward (downstream proton) rapidities. These two results are reconciled by the centrality-dependent $R_{\text{pPb}}$ results, which show a suppression in central collisions and enhancement in peripheral collisions, a pattern which is systematic in $p_T$ and $y^*$. The $R_{CP}$ and $R_{\text{pPb}}$ measurements at forward rapidities are also reported as a function of $p_T \times \cosh(y^*)$, the approximate total jet energy. When plotted this way, the results from different rapidity intervals follow a similar trend. This suggests that the mechanism responsible for the observed effects may depend only on the total jet energy or, more generally, on the underlying parton–parton kinematics such as the fractional longitudinal momentum of the parton originating in the proton.

If the relationship between the centrality intervals and proton–lead collision impact parameter determined by the geometric models is correct, these results imply large, impact parameter-dependent changes in the number of partons available for hard scattering. However, they may also be the result of a correlation between the kinematics of the scattering and the soft interactions resulting in particle production at backward (Pb-going) rapidities [42,43].

Recently, the effects observed here have been hypothesised as arising from a suppression of the soft particle multiplicity in collisions producing high energy jets [44]. Independently, it has also been argued that proton configurations containing a large-x parton interact with nucleons in the nucleus with a reduced cross-section, resulting in the observed modifications [45]. In any case the presence of such correlations would challenge the usual factorisation-based framework for describing hard scattering processes in collisions involving nuclei.

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Fig. 6. Measured $R_{CP}$ values for $R = 0.4$ jets in 0–10% $p + Pb$ collisions. The panel on the left shows the five rapidity ranges that are the most forward-going, while the panel on the right shows the remaining five. The $R_{CP}$ values at each rapidity are plotted as a function of $p_T \times \cosh(y^*)$, where ($y^*$) is the midpoint of the rapidity bin. Vertical error bars represent the statistical uncertainty while the boxes represent the systematic uncertainties on the jet yields. The shaded box at the left edge (in the left panel) and right edge (in the right panel) of the $R_{CP} = 1$ horizontal line indicates the systematic uncertainty on $R_{coll}$.

Fig. 7. Measured $R_{pb}$ values for $R = 0.4$ jets in $p + Pb$ collisions displayed for multiple rapidity ranges, showing 0–10% events in the left panel and 60–90% events in the right panel. The $R_{pb}$ at each rapidity is plotted as a function of $p_T \times \cosh(y^*)$, where ($y^*$) is the midpoint of the rapidity bin. Vertical error bars represent the statistical uncertainty while the boxes represent the systematic uncertainties on the jet yields. The shaded box at the left edge of the $R_{pb} = 1$ horizontal line indicates the systematic uncertainties on $T_{AP}$ and the $pp$ luminosity added in quadrature.

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References


1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany, NY, United States
3 Department of Physics, University of Alberta, Edmonton, AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara;
5 Turkish Atomic Energy Authority, Ankara, Turkey
6 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
7 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
8 Department of Physics, University of Arizona, Tucson, AZ, United States
9 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
10 Physics Department, University of Athens, Athens, Greece
11 Physics Department, National Technical University of Athens, Zografou, Greece
12 Instituto de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, MA, United States
23 Department of Physics, Brandeis University, Waltham, MA, United States
24 (a) Universidad Federal do Rio de Janeiro CPPEE/UF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of São Paulo del Rei (UFSP), São Paulo del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) 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 (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu;
34 School of Physics, Shandong University, Shandong; (d) Physics Department, Shanghai Jiao Tong University, Shanghai, China
35 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
36 Nevis Laboratory, Columbia University, Irvington, NY, United States
37 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
38 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
39 (a) ACH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
40 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
41 Physics Department, Southern Methodist University, Dallas, TX, United States
42 Physics Department, University of Texas at Dallas, Richardson, TX, United States
43 DESY, Hamburg and Zeuthen, Germany
44 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
45 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
46 Department of Physics, Duke University, Durham, NC, United States
47 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
48 INFN Laboratori Nazionali di Frascati, Frascati, Italy
49 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
50 Section de Physique, Université de Genève, Geneva, Switzerland
51 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
52 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
53 Il Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
54 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
55 Il Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
56 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
57 Department of Physics, Hampton University, Hampton, VA, United States
58 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
59 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 Department of Physics, Indiana University, Bloomington, IN, United States
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City, IA, United States
64 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

* Deceased.