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

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ABSTRACT

Measurements of the yield and nuclear modification factor, R_{AA}, for inclusive jet production are performed using 0.49 nb^{-1} of Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV and 25 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.

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

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

where N_{jet} and σ_{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_{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 nb^{-1} of Pb+Pb data

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collected at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in 2015 and 25 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 nb^{-1} of Pb+Pb data collected at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV in 2011 and 4.0 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.[1] 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 collisions, the highest-threshold jet trigger sampled the full delivered luminosity while all lower threshold triggers were prescaled.

Table 1
The mean number of participants, $\langle N_{\mathrm{part}}\rangle$, the mean nuclear thickness function, $\langle T_{\mathrm{AA}}\rangle$, and their uncertainties (see Section 5) for different centrality intervals.

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

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, 2.9×10^7 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, $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$, at the electromagnetic energy scale. The $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ 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 $\Sigma E_{\mathrm{T}}^{\mathrm{FCal}}$ distribution is used to evaluate $\langle T_{\mathrm{AA}}\rangle$ and the number of nucleons participating in the collision, $\langle N_{\mathrm{part}}\rangle$, 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 $\langle N_{\mathrm{part}}\rangle$ and $\langle T_{\mathrm{AA}}\rangle$.

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

[1] 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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

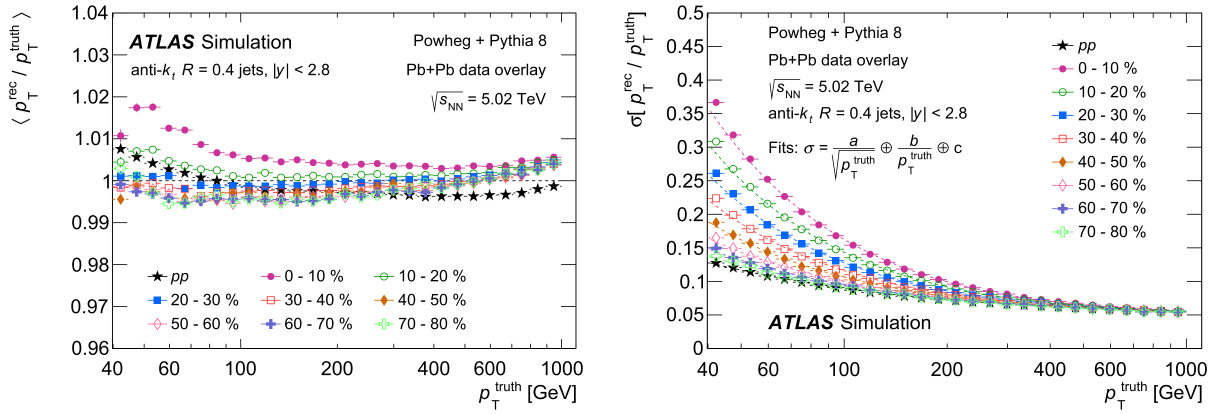

Fig. 1. The left panel shows the JES as a function of p_T^{truth} and the right panel shows the JER as a function of p_T^{truth} in MC samples. Both are for jets with $|y| < 2.8$. The curves in the right panel show fits to Eq. (1) for pp, and Pb+Pb in eight centrality intervals (0–10%, 10–20%, 20–30%, 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, μ 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 ϕ 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 (Ψ_n) of the Fourier components of the azimuthal angle distributions as:

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

where ϕ 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 ρ and the v_n values. In the initial estimate of ρ 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 ρ 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 ρ[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^{rec}/p_T^{truth}) in the MC simulation. Here p_T^{rec} and p_T^{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^{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,

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

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 $\sqrt{s_{NN}} =$

[2] The average ρ is ≈270 GeV and ≈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$^{1/2}$]	b [GeV]	c
70–80%	0.75 ± 0.01	2.5 ± 0.2	0.050 ± 0.001
0–10%	0.76 ± 0.02	14.4 ± 0.1	0.049 ± 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 $p_T^{trk} > 4$ GeV within $\Delta R = 0.4$ of the jet and requiring a minimum value of $\sum p_T^{trk}$. A threshold of $\sum p_T^{trk} = 8$ GeV is used throughout the analysis. Thresholds of $\sum p_T^{trk}$ 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 then 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 $\langle T_{AA}\rangle$ 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 $\sum p_T^{trk}$ of track jets. This ratio is called $\langle r_{trk}\rangle$. The data-to-MC ratio of $\langle r_{trk}\rangle$ 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.

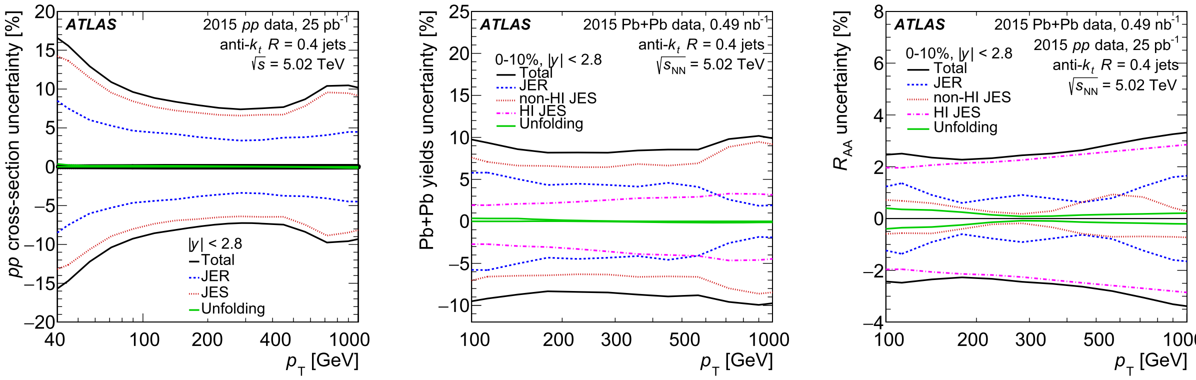

Fig. 2. Systematic uncertainties, for pp jet cross-section (left), Pb+Pb jet yields (middle) and jet R_{AA} (right). Systematic uncertainties on pp luminosity and $\langle T_{AA}\rangle$, which affect the overall normalisation of measured distributions, are not shown.

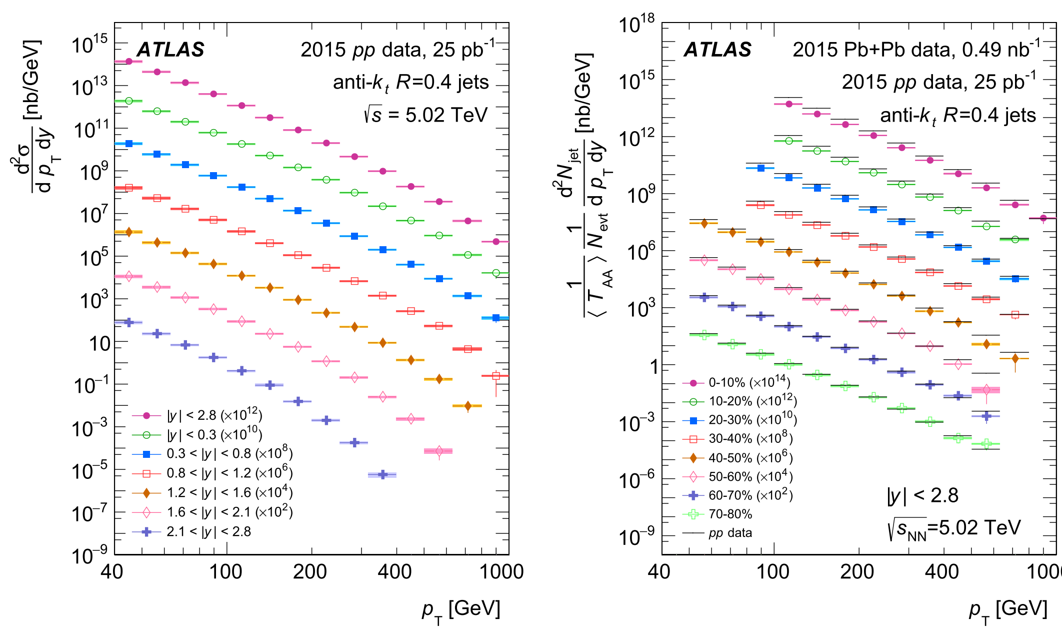

Fig. 3. Left: Inclusive jet cross-section in pp collisions as a function of jet p_T in different $|y|$ intervals scaled by successive powers of 10^2. Right: Per-event inclusive jet yield in Pb+Pb collisions normalised by $\langle T_{AA}\rangle$ as a function of jet p_T in different centrality intervals 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

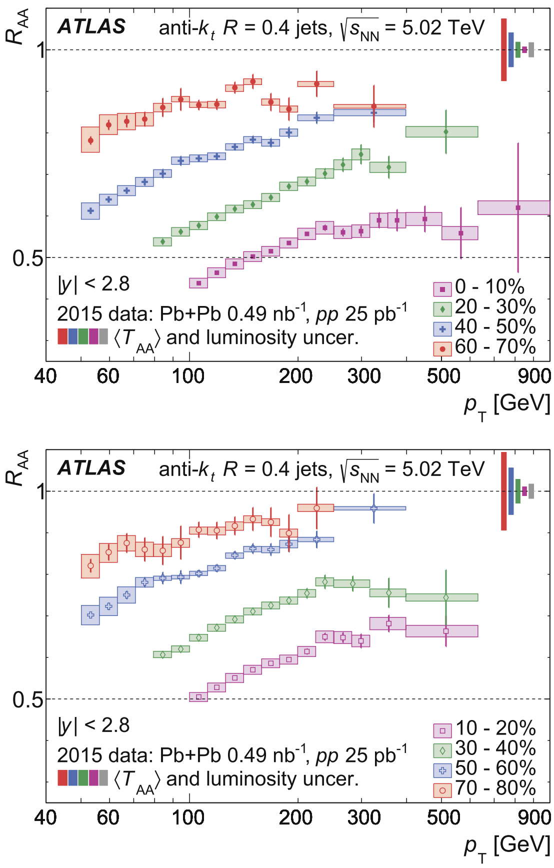

Fig. 4. Upper panel: The R_{AA} values as a function of jet p_T for jets with $|y| < 2.8$ for four centrality intervals (0–10%, 20–30%, 40–50%, 60–70%). Bottom panel: The R_{AA} values as a function of jet p_T for jets with $|y| < 2.8$ for four other centrality intervals (10–20%, 30–40%, 50–60%, 70–80%). 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.

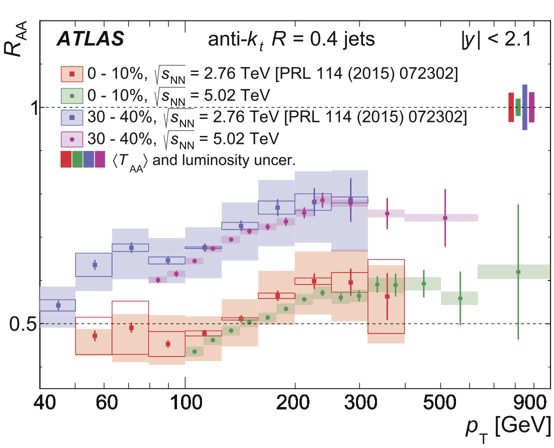

Fig. 5. The R_{AA} values as a function of jet p_T for jets with $|y| < 2.1$ in 0–10% and 30–40% centrality intervals compared to the same quantity measured in $\sqrt{s_{NN}} =$ 2.76 TeV Pb+Pb collisions [9]. The error bars represent statistical uncertainties, the shaded boxes around the data points 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.

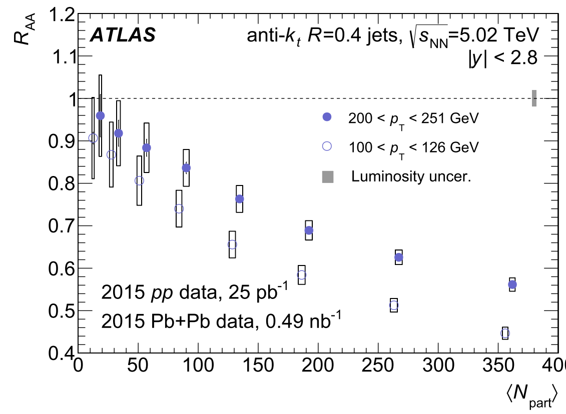

Fig. 6. The R_{AA} values for jets with $100 < p_T < 126$ GeV and $200 < p_T < 251$ GeV for rapidity $|y| < 2.8$ evaluated as a function of $\langle N_{part}\rangle$. For legibility, the $\langle N_{part}\rangle$ values are shifted by -7 and $+7$ for $100 < p_T < 126$ GeV selection and $200 < p_T < 251$ 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 ± 0.07 and 0.68 ± 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$_G$) [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$_G$ 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$_G$ model which uses $g = 2.2$. For

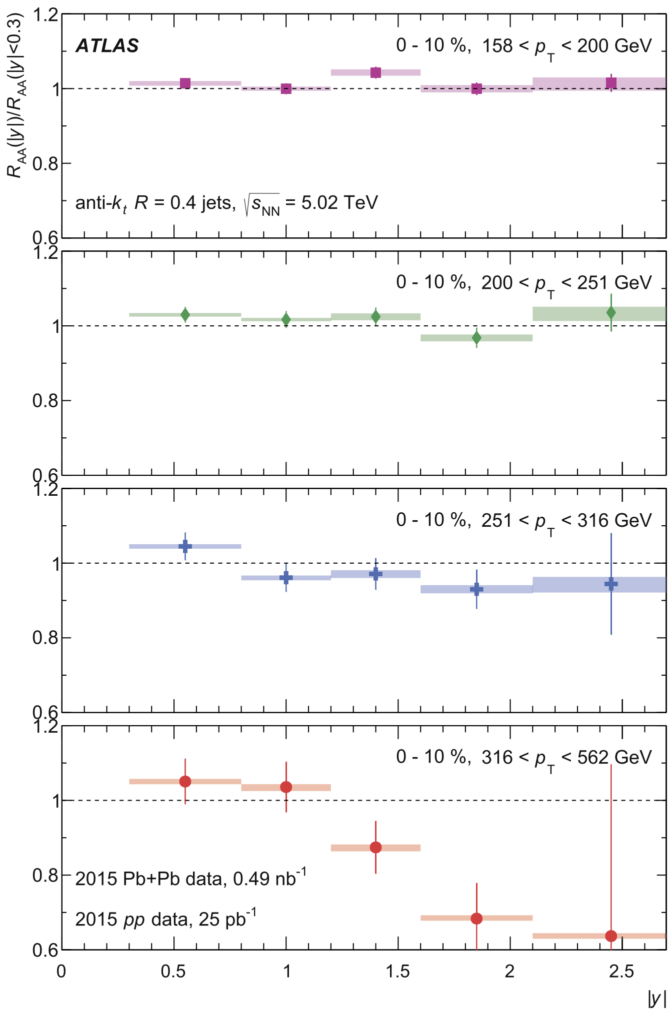

Fig. 7. The ratio of R_{AA} to the R_{AA} value for $|y| < 0.3$ as a function of $|y|$ for jets in four p_T intervals ($158 < p_T < 200$ GeV, $200 < p_T < 251$ GeV, $251 < p_T < 316$ GeV, and $316 < p_T < 562$ GeV) shown for the 10% most central Pb+Pb collisions. The error bars represent statistical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

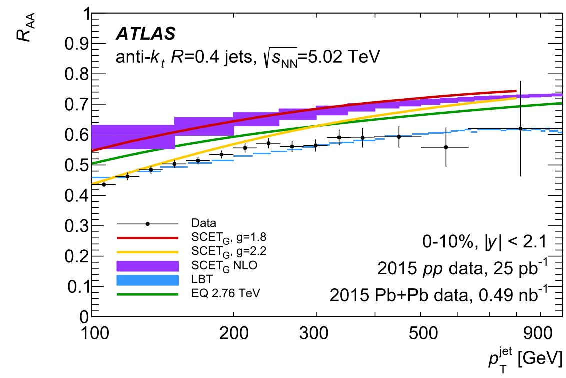

Fig. 8. The R_{AA} values as a function of jet p_T for the 0–10% centrality interval and $|y| < 2.1$ compared with theory predictions. The uncertainties of the data points are the combined statistical and systematic uncertainties. The vertical width of the distribution shown for the LBT and SCET$_G$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

$p_T \gtrsim 250$ 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 nb^{-1} of Pb+Pb collision data and 25 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_t 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 peripheral 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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