Study of inclusive jet yields in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

The ATLAS Collaboration

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Measurements of the yield and nuclear modification factor, $R_{\text{AA}}$, for inclusive jets are performed using 25 pb$^{-1}$ of $pp$ data at $\sqrt{s} = 5.02$ TeV and 0.49 nb$^{-1}$ of Pb+Pb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The jets are reconstructed with the anti-$k_t$ algorithm, with $R = 0.4$, and are measured over the transverse momentum range of 100–1000 GeV in six rapidity intervals covering $|y| < 2.8$. The magnitude of the $R_{\text{AA}}$ increases with increasing $p_T$ and with decreasing centrality of the Pb+Pb collision. The $R_{\text{AA}}$ is independent of rapidity at low $p_T$ and it decreases with increasing rapidity at high $p_T$. 

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1 Introduction

Heavy-ion collisions at ultra-relativistic energies produce a hot, dense medium of strongly interacting nuclear matter understood to be composed of deconfined color charges that is commonly called a quark-gluon plasma (QGP) [1–4]. Products of hard scattering of quarks and gluons occurring in these collisions evolve as parton showers that propagate through the heavy ion medium. Full parton shower or its constituents emit medium-induced gluon radiation and as a consequence the resulting jet loses energy. This phenomenon is termed “jet quenching” [5–7]. It can be observed as the suppression of the jet production relative to a \( pp \) reference and modification of the jet internal structure. Generally, the energy loss of partons traversing QGP will result in a reduction in the jet yield at fixed transverse momentum \( (p_T) \). Thus, the jets are observed to be suppressed in central collisions relative to peripheral or \( pp \) collisions. The inclusive jet suppression has previously been measured at the LHC in \( \sqrt{s_{NN}} = 2.76 \) TeV Pb+Pb collisions in the hard scattering rate [8–11].

The centrality dependence of measured hard scattering rates must be normalized by the nuclear thickness function, \( \langle T_{AA} \rangle \), that accounts for the geometric enhancement of per-collision nucleon-nucleon luminosity to allow for a proper assessment of the quenching effects. Such an assessment is quantified by the nuclear modification factor

\[
R_{AA} = \frac{1 \, \frac{d^2N_{\text{jet}}}{d\eta dy_{\text{cent}}}}{\langle T_{AA} \rangle \frac{d^2\sigma_{\text{jet}}}{dp_T dy_{pp}}} ,
\]

where \( N_{\text{tot}} \) 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 [9, 10]. This implies a suppression of jet yields by roughly a factor of two in central collisions with respect to expectations from scaled \( pp \) collisions at the same center-of-mass energy. Two interesting features were revealed by those studies, \( R_{AA} \) increases only very slowly with increasing jet \( p_T \); \( R_{AA} \) exhibits no dependence on the rapidity\(^1\) of the jet.

This note describes new measurements of jet yields performed with 0.49 nb\(^{-1}\) of Pb+Pb data collected in 2015 at \( \sqrt{s_{NN}} = 5.02 \) TeV and 25 pb\(^{-1}\) of \( pp \) data collected at \( \sqrt{s} = 5.02 \) TeV in the same year. This new study extends the original measurement to higher transverse momentum and rapidity. It should provide needed inputs for a more detailed understanding of jet suppression, especially its dependence on the collision energy.

2 Experimental setup

The measurements presented in this note were performed using the ATLAS calorimeter, trigger and data acquisition systems [12]. The calorimeter system consists of a sampling liquid argon (LAr) electromagnetic (EM) calorimeter covering \( |\eta| < 3.2 \), a steel–scintillator sampling hadronic calorimeter covering

\(^1\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \). Rapidity \( y \) is defined as \( y = 0.5 \ln \frac{E + p_T}{E - p_T} \) where \( E \) and \( p_T \) are the energy and the component of the momentum along the beam direction.
$|\eta| < 1.7$, 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. The EM calorimeters are segmented longitudinally in shower depth into three layers with an additional pre-sampler layer. The EM calorimeters have a granularity that varies with layer and pseudorapidity, but which is generally much finer than that of the hadronic calorimeter. The minimum-bias trigger scintillators (MBTS) \cite{12} detect charged particles over $2.1 < |\eta| < 3.9$ using two segmented counters each segment placed at $z = \pm 3.6$ m. Each counter provides measurements of both the pulse heights and arrival times of ionization energy deposits.

A multi-level trigger system was used to select the Pb+Pb and $pp$ collisions analyzed here. The first, hardware based trigger stage Level-1, is implemented with custom electronics. The next level is the software based High Level Trigger (HLT). The jets were selected by the HLT seeded by Level-1 jet, minimum bias, or total energy triggers. 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 \cite{13}. The HLT jet trigger used a jet reconstruction algorithm similar to that applied in the offline analysis and selected events containing jets with a range of transverse energy thresholds up to 100 GeV in Pb+Pb collisions and up to 85 GeV in $pp$ collisions. In both $pp$ and Pb+Pb collisions, the highest threshold jet trigger sampled the full delivered luminosity while all lower thresholds were prescaled. Jets that are used in this analysis were selected from jet triggers in the region of jet $p_T$ for which the trigger efficiencies are greater than 99%.

3 Collision data, MC sample and event selection

The collision data used in this analysis were recorded during the LHC Run 2 in 2015. The data consist of 25 pb$^{-1}$ of $pp$ data at $\sqrt{s} = 5.02$ TeV and 0.49 nb$^{-1}$ of Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV.

The impact of the 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 \cite{14, 15}. Two MC samples were used in this study. The first one was Powheg+Pythia 8 \cite{16, 17} dijet sample at $\sqrt{s} = 5.02$ TeV with the A14 ATLAS tune \cite{18} and the CT10 NLO (PDFs) \cite{19}. In total, $29 \times 10^6$ dijet events, spanning a range of the jet transverse momentum 20–1300 GeV, were simulated. The second MC sample consisted of the same signal dijet events as those used in the first sample but embedded into real minimum-bias heavy ion events. This data was combined with the signal from Powheg+Pythia 8 simulation at the digitization stage, and then reconstructed as a combined event. This MC sample provided the same kinematic coverage as the first sample and the same number of events.

The level of overall event activity or “centrality” in heavy ion collisions was characterized using the sum of the total transverse energy in the forward calorimeter, $\Sigma E_{T}^{\text{FCal}}$, at the electromagnetic scale. The $\Sigma E_{T}^{\text{FCal}}$ distribution was divided into percentiles of the total inelastic cross-section for Pb+Pb collisions. The minimum bias trigger and event selection were estimated to sample 84.5% of the total inelastic cross-section, with an uncertainty of 1%. For this analysis the data has been divided into eight centrality classes, 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, and 70-80%, where 0-10% are the most central collisions, with the highest $\Sigma E_{T}^{\text{FCal}}$.

The geometric parameters of the collisions were quantified using the Glauber model \cite{20}. The MC implementation of this model was used to determine the mean number of nucleons participating in the collision, $\langle N_{\text{part}} \rangle$, the nuclear thickness function, $\langle T_{AA} \rangle$, and their uncertainties (including the uncertainties
<table>
<thead>
<tr>
<th>Centrality range</th>
<th>$\langle N_{\text{part}} \rangle$</th>
<th>$\langle T_{\text{AA}} \rangle$ [1/mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-80%</td>
<td>15.4 ± 1.0</td>
<td>0.22 ± 0.02</td>
</tr>
<tr>
<td>60-70%</td>
<td>30.6 ± 1.6</td>
<td>0.57 ± 0.04</td>
</tr>
<tr>
<td>50-60%</td>
<td>53.9 ± 2.0</td>
<td>1.28 ± 0.07</td>
</tr>
<tr>
<td>40-50%</td>
<td>87.0 ± 2.3</td>
<td>2.63 ± 0.11</td>
</tr>
<tr>
<td>30-40%</td>
<td>131.4 ± 2.6</td>
<td>4.94 ± 0.15</td>
</tr>
<tr>
<td>20-30%</td>
<td>189.2 ± 2.8</td>
<td>8.64 ± 0.17</td>
</tr>
<tr>
<td>10-20%</td>
<td>264.1 ± 2.8</td>
<td>14.3 ± 0.18</td>
</tr>
<tr>
<td>0-10%</td>
<td>358.8 ± 2.2</td>
<td>23.4 ± 0.20</td>
</tr>
</tbody>
</table>

Table 1: The mean number of participants, $\langle N_{\text{part}} \rangle$ and the nuclear thickness function, $\langle T_{\text{AA}} \rangle$ and their uncertainties for different centrality intervals.

on the nuclear density, the nucleon-nucleon cross-section, and the estimated sampling efficiency) for the centrality classes used here. These are shown in Table 1.

4 Jet reconstruction and analysis procedure

The jet reconstruction in $pp$ and Pb+Pb collisions closely follows the procedures described in Refs. [8, 21] including the underlying event (UE) subtraction procedure which is applied in Pb+Pb collisions. A brief summary is given here. First, the jets were reconstructed using the anti-$k_t$ algorithm [22], which is implemented in the FastJet software package [23] with $R = 0.2$. The jets were formed by combining $\Delta \eta \times \Delta \phi = 0.1 \times \frac{\pi}{32}$ “towers” that were constructed using energy deposits in nearby calorimeter cells. A background subtraction procedure was applied that uses the UE average transverse energy density, $\rho$, and the magnitude ($v_n$) and phases ($\Psi_n$) of the modulation due to harmonic flow. The background is modulated in this way because global azimuthal correlations in the particle production arise from the hydrodynamical evolution of the medium as defined by Eq. 2 where $\phi$ is the azimuthal angle of the jet.

$$\frac{dE_T}{d\eta d\phi} \approx \frac{dE_T}{d\eta} (1 + \sum_n v_n \cos (n(\phi - \Psi_n)))$$

(2)

The modulation is dominated by the lowest order harmonics, $v_2$ and $v_3$ [24]. In the reconstruction used for Run 1 results, the background subtraction only accounted for the contributions of elliptical flow ($v_2$) to the UE [8]. In Run 2 results, the third and fourth harmonics were also used to further improve the UE estimation. It was found that the inclusion of $v_3$ and $v_4$ (especially $v_3$) substantially improved the jet energy resolution. Once each of the phases and magnitudes for $n = 2 - 4$, where $n$ indicates the order of the flow harmonic, were determined using the entire calorimeter, the subtraction was applied cell-by-cell within each jet. An iterative procedure was used to remove the effects of jets on the $\rho$ and the estimation of the magnitude of the flow harmonics. First the average UE density and the flow harmonics were estimated from the transverse energy of cells within $|\eta| < 3.2$. The background was subtracted cell-by-cell within the jet to obtain the subtracted jet kinematics. Then the $\rho$ and $v_n$ were recalculated by excluding any cells within $\Delta R < 0.4$ of seed jets that were defined to be the jets with transverse energy, $E_T > 30$ GeV. These were then used to evaluate a new subtracted energy by applying these to the original cells and then calculating new jet kinematics. In this final step, $R = 0.4$ jets were also reconstructed which are used in this analysis.
The performance of the jet reconstruction was characterized by evaluating the jet energy scale (JES) and resolution (JER), which are the mean and width of the jet response \( \frac{p_T^{\text{reco}}}{p_T^{\text{truth}}} \) in the MC simulations. Hereafter “truth” denotes MC generator-level jets reconstructed from final-state particles using techniques described in Ref. [25]. The response was generated by matching the truth to reconstructed jets in the MC within a cone of \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.2 \). The ratio of the reconstructed \( p_T \) to the truth \( p_T \) was evaluated as a function of the truth \( p_T \). The performance of the jet reconstruction is summarized in Figure 1, where the left and right panels show the JES and JER, respectively. The ratio, or closure, between the truth and reconstructed \( p_T \) in the MC is demonstrated by the value of the JES in the left panel of Figure 1 and is shown to be about 1% at high \( p_T \). This also has a small centrality dependence at high \( p_T \) which is expected. The JER has been parameterized as

\[
\sigma = \frac{a}{\sqrt{p_T^{\text{truth}}}} \otimes \frac{b}{p_T^{\text{reco}}} \otimes c, \tag{3}
\]

where \( a, b, \) and \( c \) are free parameters. The first and last terms in the right-hand side of Eq. 3 are sensitive to aspects of the detector response and are expected to be independent of centrality, while the second (\( b \)) term is driven by fluctuations uncorrelated with the jet \( p_T \). This “noise” term is often understood in terms of electronic or pileup noise, but in all but the most peripheral HI collisions, both of these contributions are small compared to the magnitude of the UE fluctuations. The JER for different centrality intervals and for \( pp \) collisions is shown on the right in Figure 1. Fits using Eq. 3 are indicated with dashed lines. The JER is largest in the more central collisions, as expected from the larger magnitudes of the total transverse energy in the UE. The JER is \( \approx 16\% \) at 100 GeV in central collisions and decreases with increasing \( p_T \) to a constant at about 5-6\% for jets with \( p_T \) greater than 500 GeV.

The effect of the subtraction procedure on JES relative to the \( n = 2 \) and \( n = 3 \) phase \( n|\Psi_n - \phi| \), where \( \Psi_n \) is the phase of the harmonic modulation due to flow as described above and shown in Eq. 2 and \( \phi \) is the azimuthal angle of the jet, is shown in the left and right panel of Figure 2, respectively. The open black points on each figure show the angular dependence without including harmonic flow in the UE subtraction. The filled points show the impact of including the harmonic flow correction, resulting in only a small residual dependence on event plane angle, substantially improving the jet energy resolution.
Figure 2: The jet energy scale as a function of $2|\Psi_2 - \Phi_{\text{truth}}|$ (left) and $3|\Psi_3 - \Phi_{\text{truth}}|$ (right) for jets with a truth $p_T$ between 100-200 GeV. The black unfilled points are for centrality of 0-10% without the harmonic flow subtraction. The filled points show the JES with the harmonic flow subtraction applied for different centralities, namely 0-10% (black circles), 20-30% (red squares), 40-50% (blue diamonds), and 60-70% (green crosses).

The jet cross-section in $pp$ collisions, jet yields and $R_{AA}$ in Pb+Pb collisions were measured for jets with $p_T > 100$ GeV in the following jet rapidity intervals: $|y| < 0.3$, $0.3 < |y| < 0.8$, $0.8 < |y| < 1.2$, $1.2 < |y| < 1.6$, $1.6 < |y| < 2.1$, $2.1 < |y| < 2.8$. The individual uncorrected jet spectra were corrected using the iterative Bayesian unfolding method [26, 27], which accounts for the bin migration due to the finite jet energy resolution and for other detector effects. The response matrices used as the input to the unfolding were built from truth level jets that were matched to reconstructed jets in the MC. The unmatched truth jets were used as part of the prior and are incorporated as an inefficiency after the unfolding. The truth jets and reconstructed jets were selected to have $p_T > 40$ GeV and $p_T > 80$ GeV, respectively. The response matrices were generated separately for $pp$ and Pb+Pb and for each rapidity and centrality interval. The responses were reweighted along the truth jet axis to better represent the data by a data-to-MC ratio of the reconstructed jet $p_T$ spectra. The number of iterations in the unfolding was chosen based on the stability of the result with respect to changing the number of iterations. It was found that three iterations are sufficient for all the centrality and rapidity intervals both in Pb+Pb and $pp$ collisions.

The unfolding procedure was verified by evaluating a closure test in the MC, defined as the ratio between the unfolded and original distributions, before simulating the detector response. This ratio is consistent with unity for all the rapidity and centrality intervals in the kinematic selection considered for the analysis. The unfolding procedure was further tested by performing a ‘refolding’, where the unfolded results is smeared using the response matrix, and compared with the uncorrected simulated distributions. The stability of the unfolding was confirmed by observing no large deviations between the uncorrected and refolded distributions.
5 Systematic uncertainties

The following sources of systematic uncertainties were identified for this analysis: jet energy scale, jet energy resolution, uncertainty due to the unfolding procedure, uncertainty on the determination of the $\langle T_{AA} \rangle$ values and the uncertainty on the $pp$ luminosity.

Uncertainties on the $R_{AA}$ can be categorized into two classes: uncertainties that are common for the numerator and denominator of the $R_{AA}$ and uncertainties that differ between the numerator and denominator of the $R_{AA}$. For uncertainties common to both the numerator and denominator of the $R_{AA}$, the uncertainties were taken as correlated. For uncorrelated uncertainties, the uncertainty was added in quadrature.

The strategy for determining the JES and its uncertainty for heavy ion jets is discussed in detail in Ref. [28]. The JES for heavy ion (HI) jets was established by calibrating them with respect to standard “EM+JES” jets used in $pp$ collisions [29]. This calibration was performed using 13 TeV $pp$ data where the jet energy scale and its uncertainty had previously been evaluated [30, 31]. This JES was then adapted to 5.02 TeV. Several components of the JES uncertainty were considered. The main component was described by a set of eleven independent nuisance parameters which include effects from uncertainties derived through in-situ calibration and which were derived for EM+JES jets [29]. The flavor components include the uncertainty in flavor composition of jets and the uncertainty due the sensitivity of the response to jets of different flavors. The components were derived using the same procedure as for the EM+JES jets, but the flavor fractions were evaluated at 5.02 TeV center-of-mass energy. The cross-calibration serves as an alternative derivation of the in-situ calibration of HI jets while also accounting for any residual differences arising from the difference in the reconstruction procedures themselves. These components of the JES uncertainty were taken to be correlated between $Pb+Pb$ and $pp$ collisions.

The quenching component of the JES reflects a modification of parton showers by the $Pb+Pb$ environment. The resulting jets may have different flavor compositions, or more generally different particle content. The impact of the quenching on the measured jet $p_T$ was evaluated by defining the $p_T$ ratio of calorimeter jets and corresponding track jets, which match the calorimeter jets within $\Delta R < 0.4$. This ratio is called $r_{trk}$. The data-to-MC ratio of $r_{trk}$ was evaluated and then compared between $pp$ and $Pb+Pb$, which showed a small shift. This shift represents the typical difference in the JES in $Pb+Pb$ collisions and $pp$ collisions. It is 0.5% in the most central and linearly decreases to 0% at 60% centrality. This difference constitutes a heavy ion specific component of the JES uncertainty.

For each component of the JES uncertainty a new response matrix was obtained by shifting the reconstructed jet $p_T$. These response matrices were then used to unfold the data. A difference between the data unfolded with the new response matrix and the original response matrix was used to determine the systematic uncertainty.

Similarly to the JES uncertainty, the systematic uncertainty due to the jet energy resolution was also obtained by performing the unfolding with modified response matrices. The modified response matrices were generated for both $pp$ and $Pb+Pb$ collisions with the JER uncertainty which was quantified in $pp$ collisions using data-driven techniques [30]. An additional uncertainty which is specific for the heavy ion environment was used, which is the uncertainty related to the impact of fluctuations in the UE to the JER. Both these components were used to smear the reconstructed jet momentum in the MC and regenerate the response matrices.

The results presented in this note were obtained using the unfolding procedure with response matrices which were reweighted to better characterize the data as described in Section 4. To assess the sensitivity
to the input MC distributions the unfolding was also run without the reweighting. The difference between the nominal results and results obtained with response matrices without the reweighting was used to calculate the uncertainty due to the unfolding procedure. The response without reweighting, which has a smooth simple slope with respect to the data, provides a reasonable variation of how the prior could be different.

The uncertainty on the $\langle T_{AA}\rangle$ arises from geometric modeling uncertainties (e.g. nucleon-nucleon inelastic cross-section, Woods-Saxon parameterization of the nucleon positions) and the uncertainty on the fraction of selected inelastic Pb+Pb collisions (the “efficiency” uncertainty). The values of these uncertainties along with $\langle T_{AA}\rangle$ are tabulated in Tab. 1.

The integrated luminosity determined for 2015 $pp$ data was calibrated based on data from dedicated beam-separation scans, known as Van der Meer scans. Determination of systematic uncertainty followed the procedure described in Ref. [32], leading to a relative uncertainty of 5.4%.

Typical uncertainties are summarized in Figure 3 for $pp$ jet cross-section on the left, Pb+Pb jet yields in the middle and the $R_{AA}$ on the right. In the $pp$ cross-section the largest uncertainty is from the JES between 7-10% depending on the $p_T$ of the jet. The JES is also the largest contribution to the uncertainty in central Pb+Pb where it is also between 7-10%. The uncertainties on the $R_{AA}$ are smaller than those on the cross-sections and yields because the correlated systematics uncertainties that are common for $pp$ and Pb+Pb mostly cancel in the ratio. The largest contribution to the uncertainty on the $R_{AA}$ is the heavy ion component of the JES uncertainty which is approximately 3%.

6 Results

The inclusive jet cross-section obtained from $pp$ collision data is shown in the left panel of Figure 4. The cross-section is reported for six intervals of rapidity. The error bars in the figure represent statistical uncertainties while the shaded boxes represent systematic uncertainties. Systematic uncertainties also include the uncertainty due to the luminosity which is correlated for all the data points.

The right panel of Figure 4 shows the Pb+Pb jet yields scaled by $\langle T_{AA}\rangle$, which are shown for four selected centrality intervals for jets with $|y|<2.8$. For a direct comparison with the jet production in $pp$ collisions,
The nuclear modification factor evaluated as a function of jet $p_T$ is shown in the upper panel of Figure 5 for four centrality selections. The $R_{AA}$ is evaluated for jets with $p_T$ in the interval of 100–1000 GeV and $|y| < 2.8$. The higher $p_T$ intervals are combined in the cross section and yields before evaluating the $R_{AA}$ because of the large statistical uncertainties at high $p_T$. A clear suppression of the jet production in central Pb+Pb collisions with respect to $pp$ collisions can be seen. In 0-10% central collisions the $R_{AA}$ is approximately 0.45 near $p_T = 100$ GeV. The $R_{AA}$ is observed to grow slowly with increasing jet momentum reaching a value of approximately 0.6 for jets with $p_T$ around 800 GeV. The error bars in the figure represent the statistical uncertainties. Shaded boxes represent fully correlated systematic uncertainties for which all the data-points can move upward or downward for a given change in the uncertainty. The open boxes represent uncorrelated systematic uncertainties for which individual data points can vary independently.

The $R_{AA}$ evaluated for jets with $|y| < 2.1$ can be compared with a previous measurement performed at $\sqrt{S_{NN}} = 2.76$ TeV [9]. This is shown for the centrality selection of 0-10% in the bottom panel of Figure 5. The two measurements are observed to agree within their uncertainties.

The $\langle N_{\text{part}} \rangle$ dependence of the $R_{AA}$ is shown in Figure 6 for jets with $|y| < 2.8$ and $100 < p_T < 125$ GeV. A smooth evolution of the $R_{AA}$ is seen with the largest values in the most peripheral collision and the smallest values in the most central collisions. The error band here represents the correlated systematic uncertainties included in the figure are the values of $pp$ cross-section which are shown without systematic uncertainties for readability.

The solid lines represent the $pp$ cross-section for the same rapidity selection scaled by the same factor to allow for a comparison with the Pb+Pb data at different centralities. The error bars represent statistical uncertainties, shaded boxes represent systematic uncertainties including uncertainties on $\langle T_{AA} \rangle$ and luminosity.

Figure 4: Left: Inclusive jet cross-section in $pp$ data evaluated as a function of jet $p_T$ scaled by successive powers of $10^2$. Right: Per event jet yield in Pb+Pb collisions, multiplied by $\langle T_{AA} \rangle$, as a function of jet $p_T$ scaled by successive powers of $10^2$. The highest $p_T$ intervals are combined in the cross section and yields before evaluating the $R_{AA}$. The error bars represent statistical uncertainties, shaded boxes represent systematic uncertainties including uncertainties on $\langle T_{AA} \rangle$ and luminosity.
Figure 5: Upper panel: The $R_{AA}$ as a function of jet $p_T$ for jets with $|y| < 2.8$ for three centrality bins. Bottom panel: The $R_{AA}$ as a function of jet $p_T$ for jets with $|y| < 2.1$ in 0-10% central collisions compared to the same quantity measured in $\sqrt{s_{NN}} = 2.76$ Pb+Pb collisions published in Ref. [9]. The error bars represent statistical uncertainties, the shaded boxes around the data points represent correlated systematic uncertainties, open boxes represent uncorrelated systematic uncertainties. In the upper panel, the colored shaded boxes at unity represent $\langle T_{AA} \rangle$ uncertainties and the gray shaded box represents the uncertainty on $pp$ luminosity. The horizontal width on the shaded boxes represent the width of the $p_T$ interval and the horizontal width on the open boxes are arbitrary for better visibility. In the bottom panel, the colored shaded boxes at unity represent the combined $\langle T_{AA} \rangle$ uncertainties with the uncertainties on $pp$ luminosity. error bars on the
uncertainties which include also the uncertainty on \( \langle T_{AA} \rangle \). The open boxes represent uncorrelated systematic uncertainties. The statistical uncertainties are smaller than the data points for all \( R_{AA} \) values.

The rapidity dependence of the \( R_{AA} \) is shown in Figure 7 by evaluating the ratio of the \( R_{AA} \) as a function of rapidity to the \( R_{AA} \) at \( |y| < 0.3 \). This representation was chosen because all systematic uncertainties largely cancel in the ratio. This is shown in intervals of increasing values of \( p_T \) in the four panels. The rapidity dependence is shown to be flat with rapidity at lower \( p_T \). As the \( p_T \) is increased the \( R_{AA} \) starts to decrease with rapidity and this decrease is the most significant in the highest \( p_T \) interval. This is the first time a significant rapidity dependence has been observed.
Figure 7: The ratio of the $R_{AA}$ as a function of $|y|$ to the $R_{AA}$ at $|y| < 0.3$ for jets with centrality of 0-10% in the following $p_T$ bins on each panel: $158 < p_T < 200$ GeV (red squares), $200 < p_T < 251$ GeV (blue diamonds), $251 < p_T < 316$ GeV (green crosses), and $316 < p_T < 562$ GeV (purple stars). The error bars represent statistical uncertainties, the shaded boxes around the data points represent correlated systematic uncertainties.
7 Summary

In this note measurements of jet cross-sections in pp collisions, inclusive jet yields in Pb+Pb collisions and the jet $R_{AA}$ are presented. The measurements were performed using pp and Pb+Pb collisions at the nucleon-nucleon (pp) center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV collected by the ATLAS detector at the LHC. Jets reconstructed using the anti-$k_t$ algorithm, with $R = 0.4$, were measured over the transverse momenta range of 100–1000 GeV in six rapidity intervals with $|y| < 2.8$. The jet yields measured in heavy ion collisions are scaled by the nuclear thickness function and are observed to be suppressed with respect to the jet cross-section measured in pp collisions. The magnitude of the $R_{AA}$ monotonically decreases moving from peripheral to central collisions. The $R_{AA}$ is flat with rapidity at low $p_T$ and then decreases with rapidity at high $p_T$. The rapidity dependence at high $p_T$ is observed for the first time as a consequence of the availability of a high-statistics data set while the previous measurement was statistically limited at high $p_T$ and forward rapidity. The magnitude of the suppression as well as its evolution with jet $p_T$ and rapidity are consistent with those reported in the similar measurement performed in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the kinematic region where the two measurements overlap.

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

References


