Charged hadron spectra and dijet $p_T$ correlations measured in Xe+Xe collisions at $\sqrt{s_{_{NN}}} = 5.44$ TeV with the ATLAS detector

The ATLAS Collaboration

The Large Hadron Collider recorded 3 $\mu$b$^{-1}$ of Xe+Xe data in 2017 at a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{_{NN}}} = 5.44$ TeV. To probe the physics of “jet quenching” in heavy-ion collisions with nuclei lighter than lead, measurements using these data are presented, namely the transverse momentum asymmetry of dijet pairs and the rates for production of charged particles. The dijet transverse momentum imbalance is characterized by the ratio of sub-leading to leading jet transverse momenta, $x_J = p_{T2}/p_{T1}$. Distributions of $x_J$ are measured using dijet pairs having $p_{T1} > 100$ GeV and are not unfolded to the particle level. A centrality-dependent modification relative to $\sqrt{s} = 5.02$ TeV $pp$ collisions is observed. It is consistent with that measured in 5.02 TeV Pb+Pb collisions, either when compared in the same centrality interval, or when compared using common intervals of forward calorimeter transverse energy. Charged particle per-event yields are measured as a function of transverse momentum in different intervals of Xe+Xe collision centrality and compared to $pp$ charged-particle cross-sections measured at $\sqrt{s} = 5.02$ TeV, extrapolated to 5.44 TeV. Nuclear modification factors, $R_{AA}$, obtained from the Xe+Xe and $pp$ data show a centrality-dependent suppression of the charged-particle yield with characteristics qualitatively similar to that observed in Pb+Pb collisions.
1 Introduction

Jets and high \( p_T \) hadrons produced in hard scattering processes provide an important probe of the properties of the quark gluon plasma created in high-energy nuclear (A+A) collisions [1, 2]. The products of the hard scattering evolve as parton showers that propagate through the medium and experience in-medium energy loss in a process referred to as "jet quenching". Previous measurements show that the yield of jets [3, 4] as well as charged hadrons [5–9] are suppressed in the heavy-ion (HI) collisions relatively to the \( pp \) collisions at Large Hadron Collider (LHC) energies. In addition, measurements of the dijet asymmetry [10–13] show that the two jets typically lose different amounts of energy in the medium and provide insight into the physics of parton energy loss in the quark-gluon plasma.

A short Xe+Xe run in 2017 provided the first heavy-ion collisions with nuclei lighter than Pb at the LHC. The possibility of studying jet quenching in collisions of nuclei lighter than Pb is attractive as the underlying event is smaller in the most central collisions where the collision geometry is the most symmetric. The decrease in the number of nucleons or the nuclear radius between Pb and Xe nuclei may be expected to affect the amount of jet quenching through a reduction in both the overall energy density and the path lengths of the hard-scattered partons in the medium. However, there are different ways to compare observables sensitive to jet quenching between different collision systems. In this note, Xe+Xe and Pb+Pb results are compared using common collision centrality intervals — for which the two colliding systems have similar degree of overlap – as well as common intervals of total forward transverse energy – for which the two systems have a similar number of participants. The latter comparison has the advantage that the underlying event in Pb+Pb and Xe+Xe collisions may be similar. Thus inferences may be made from such comparisons without resorting to a full unfolding or detector response.

The dijet asymmetry \( x_J \) is defined as:

\[
x_J = \frac{p_{T2}}{p_{T1}},
\]

where \( p_{T1} \) is the leading jet transverse momentum and \( p_{T2} \) is the sub-leading jet transverse momentum.

The suppression of charged hadrons is measured using the nuclear modification factor, \( R_{AA} \):

\[
R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{1/N_{\text{evt}} d^2N_{\text{Xe+Xe}}/d\eta dp_T}{d^2\sigma_{pp}/d\eta dp_T},
\]

where \( 1/N_{\text{evt}} d^2N_{\text{Xe+Xe}}/d\eta dp_T \) is the differential yield of charged particles measured in Xe+Xe collisions per event; \( d^2\sigma_{pp}/d\eta dp_T \) is the differential proton–proton cross-section; and \( \langle T_{AA} \rangle \) is the nuclear thickness function, which is defined by the collision geometry of the overlapping nuclei and which accounts for the fact that in a given nucleus–nucleus collision, a nucleon may interact with more than one nucleon from the other nucleus. The variables \( \eta \) and \( p_T \) denote particle pseudorapidity and transverse momentum.\(^1\)

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\(^1\) 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 upwards. Cylindrical coordinates \( (r, \phi) \) are used in the transverse plane, \( \phi \) being the azimuthal angle around the \( z \)-axis. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \). Angular distance is measured in units of \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \).
This note presents measurements of the dijet $x_J$ distributions and the charged hadron $R_{AA}$ in $\sqrt{s_{NN}} = 5.44$ TeV Xe+Xe collisions. The $x_J$ distributions, not corrected for experimental resolution, are compared to Pb+Pb and $pp$ collisions at a nucleon–nucleon centre-of-mass energy of 5.02 TeV. The fully-corrected $R_{AA}$ is calculated using charged particle cross-sections from $\sqrt{s} = 5.02$ TeV $pp$ collisions and is compared to the Pb+Pb $R_{AA}$ at $\sqrt{s_{NN}} = 5.02$ TeV.

2 ATLAS detector

The measurements presented in this note are performed using the ATLAS inner detector (ID), calorimeter system, muon spectrometers, trigger system and data acquisition system [14]. The ID measures the trajectories of charged particles with a combination of a silicon pixel detector (Pixel), including the innermost “insertable B-layer” (IBL) [15, 16], a silicon micro-strip detector (SCT), and a straw-tube transition radiation tracker (TRT), all of which are immersed in a 2T axial magnetic field. A particle emerging from the IP within $|\eta| < 2$ typically crosses 4 pixel layers, 4 double sided micro-strip layers and 36 straw tubes.

The calorimeter system consists of a sampling 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. 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 is much finer than that of the hadronic calorimeter.

The muon spectrometer covers $|\eta| < 2.7$. It uses monitored drift tubes, cathode strip chambers, resistive plate chambers and thin gap chambers. The first two systems provide a high-precision measurement of $p_T$, and the latter two systems are used also for triggering.

Data are recorded with a multi-stage trigger system [17]. Events are selected using custom-electronics hardware-based level-1 triggers (L1) and then processed by a high-level trigger (HLT) to further reduce the accepted event rate and to provide additional purity.

3 Data sets, event selection, and MC samples

The data sets used in this analysis consist of $3 \mu$b$^{-1}$ of Xe+Xe data at $\sqrt{s_{NN}} = 5.44$ TeV, $36 \text{ pb}^{-1}$ of $pp$ data at $\sqrt{s} = 5.02$ TeV, both recorded in 2017, and $0.49 \text{ nb}^{-1}$ of Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV recorded in 2015.

Events in $pp$ collisions were selected by an HLT trigger that was seeded by a jet identified by the L1 jet trigger with transverse momentum greater than 20 GeV. The HLT trigger selected events containing jets with transverse energy of at least 85 GeV.

The Xe+Xe events were recorded using a combination of two triggers designed to select minimum-bias (MB) collisions. They were required either to have the total transverse energy deposited in the calorimeters at L1 to be more than 4 GeV or to have at least one track reconstructed in the ID.
Figure 1: The $\Sigma E^{F\text{Cal}}_T$ distributions in $\text{Xe}+\text{Xe}$ in round and $\text{Pb}+\text{Pb}$ in square points. The lines on the figure indicate the respective centrality intervals for each collision system: 0–10%, 10–20%, 20–30%, 30–40%, 40–60%, and 60–80%.

Events in $\text{Pb}+\text{Pb}$ collisions were required to have at least 50 GeV of total transverse energy in the calorimeter at L1, and a presence of a jet with transverse energy of at least 75 GeV was required at the HLT. In both $pp$ and $\text{Pb}+\text{Pb}$, the HLT jet trigger used a jet reconstruction algorithm similar to that used in the offline analysis. The measurement is performed in the jet transverse momentum region where the triggers are fully efficient.

In addition to the trigger selections, events were required to have a reconstructed primary vertex and pass criteria that ensure events with good quality. In the $\text{Xe}+\text{Xe}$ analysis, a small number of recorded events consistent with two $\text{Xe}+\text{Xe}$ interactions in the same bunch crossing (pile-up) were removed based on the tight correlation between the $\Sigma E^{F\text{Cal}}_T$ and the number of reconstructed tracks associated with the primary vertex. The minimum-bias trigger and event selection were estimated to sample 82.4% (84.5%) of the total inelastic cross-section in $\text{Xe}+\text{Xe}$ ($\text{Pb}+\text{Pb}$) collisions, with an uncertainty of 1% in both cases [18, 19].

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, $\Sigma E^{F\text{Cal}}_T$, at the electromagnetic scale. The distributions of the $\Sigma E^{F\text{Cal}}_T$ are shown in Figure 1 for both $\text{Xe}+\text{Xe}$ and $\text{Pb}+\text{Pb}$ collisions. The $\Sigma E^{F\text{Cal}}_T$ distributions are divided into percentiles of the total inelastic cross-section. The percentiles are labeled such that smaller percentiles correspond to more head-on (central) collisions where the nuclei overlap significantly (smaller impact parameter) and the large percentiles correspond to collisions with small overlap that are referred to as peripheral (larger impact parameter).

The procedure to generate the distribution of $\text{Xe}+\text{Xe}$ collision geometries is similar to that in $\text{Pb}+\text{Pb}$ collisions [19]. A Monte Carlo (MC) Glauber model simulation [20, 21] is used to estimate the mean number of nucleons participating in the collision, $\langle N_{\text{part}} \rangle$, the nuclear thickness function, $T_{AA}$, and their uncertainties. For the nominal analysis, version 2.4 of the TGlauberMC package is used, with the Xe-129 nuclear wave function described by a Woods-Saxon distribution with parameters obtained from applying
Table 1: The nuclear thickness function, \( T_{AA} \), and the mean number of participants, \( \langle N_{\text{part}} \rangle \), and their uncertainties for different centrality intervals in 5.44 TeV Xe+Xe collisions.

<table>
<thead>
<tr>
<th>Centrality</th>
<th>( T_{AA} ) [mb(^{-1})]</th>
<th>( \langle N_{\text{part}} \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5%</td>
<td>13.89±0.09</td>
<td>237.4±0.6</td>
</tr>
<tr>
<td>0–10%</td>
<td>12.38±0.08</td>
<td>223.0±0.9</td>
</tr>
<tr>
<td>5–10%</td>
<td>10.87±0.07</td>
<td>207±1</td>
</tr>
<tr>
<td>5–15%</td>
<td>9.68±0.08</td>
<td>194±1</td>
</tr>
<tr>
<td>10–15%</td>
<td>8.49±0.08</td>
<td>180±1</td>
</tr>
<tr>
<td>10–20%</td>
<td>7.54±0.09</td>
<td>167±2</td>
</tr>
<tr>
<td>15–30%</td>
<td>5.1±0.1</td>
<td>131±2</td>
</tr>
<tr>
<td>20–25%</td>
<td>5.1±0.1</td>
<td>130±2</td>
</tr>
<tr>
<td>20–30%</td>
<td>4.5±0.1</td>
<td>120±2</td>
</tr>
<tr>
<td>30–40%</td>
<td>2.55±0.09</td>
<td>84±2</td>
</tr>
<tr>
<td>40–50%</td>
<td>1.37±0.06</td>
<td>56±2</td>
</tr>
<tr>
<td>50–60%</td>
<td>0.69±0.04</td>
<td>35±1</td>
</tr>
<tr>
<td>55–70%</td>
<td>0.40±0.03</td>
<td>24±1</td>
</tr>
<tr>
<td>60–80%</td>
<td>0.23±0.02</td>
<td>15.5±0.9</td>
</tr>
</tbody>
</table>

a \( A^{1/3} \) scaling to the average parameters obtained from Sb-121 and Sb-123. The value of the nucleon–nucleon inelastic cross-section, \( \sigma_{NN} \), was set to 71 ± 3 mb, motivated by recent measurements of total cross-sections at LHC energies [22, 23].

The \( \sum E_{\text{TFCal}} \) distribution in Xe+Xe events of a fixed geometric configuration is taken to be a multiple convolutions of the distribution in pp collisions, itself modeled as a Gaussian function with free parameters, according to the two-component model [24]. The hypothetical \( \sum E_{\text{TFCal}} \) distribution for minimum-bias events is expressed as the sum of the distributions over the number of binary nucleon–nucleon collisions, \( N_{\text{coll}} \), and the number of participating nucleons, \( N_{\text{part}} \).

This hypothetical distribution is fit to the data in the region above \( \sum E_{\text{TFCal}} > 40 \text{ GeV} \). This minimum \( \sum E_{\text{TFCal}} \) was chosen conservatively using an analysis of pseudorapidity gap distributions in these events [25] to ensure that the event sample was free of electromagnetic and other processes that are not included in the Glauber model. The best fit was achieved with a value of the two-component model parameter \( x = 0.09 \), identical that found for 2011 [18] and 2015 [19] Pb+Pb data, and indicates that 82.4% of the inelastic Xe+Xe cross-section is contained above \( \sum E_{\text{TFCal}} = 40 \text{ GeV} \). The mean number of participants and the nuclear thickness function in Xe+Xe collisions are summarized in Table 1.

### 3.1 MC samples

Various MC simulations were used to understand the performance of the ATLAS detector and correct the data for detector effects. The generated events were passed through a full Geant4 simulation [26] of the ATLAS detector for all the MC samples described below. The impact of the detector effects on the Xe+Xe measurements were determined using PYTHIA 8.215 [27] with the A14 set of tuned parameters [28] and NNPDF2.3 LO parton density functions [29]. The PYTHIA hard-scattering events were then overlaid onto HIJING-simulated [30] Xe+Xe collisions at \( \sqrt{s_{\text{NN}}} = 5.44 \text{ TeV} \) generated at five fixed vertex positions. The resulting events were reconstructed using the same software as used for the data [31]. For the dijet measurement, three samples were simulated, each corresponding to a different \( p_{\text{T}} \) range of the leading jet.
For the charged hadron measurement, twelve samples were simulated, each corresponding to a different \( p_T \) range of the leading charged particle. There are \( 5 \cdot 10^6 \) and \( 3 \cdot 10^6 \) events in the dijet and charged hadron samples, respectively.

A similar dijet sample as described above, but for collisions at \( \sqrt{s} = 5.02 \) TeV without the HIJING overlay, and using the 2017 pp data conditions, was used for studies of pp collisions.

Two MC samples were used for studies of the 5.02 TeV Pb+Pb data. The first was a Powheg +Pythia 8 [27, 32] dijet sample at \( \sqrt{s} = 5.02 \) TeV. Five slices were generated, each corresponding to a different \( p_T \) range of the leading jet producing a total of \( 29 \cdot 10^6 \) dijet events. The second MC sample consists of the same signal dijet events as those used in the first sample but embedded into real minimum-bias Pb+Pb events.

In order to extrapolate existing pp data [6] from \( \sqrt{s} = 5.02 \) TeV to \( \sqrt{s} = 5.44 \) TeV for the charged hadron measurement, \( 2 \times 12 \) Pythia 8 dijet samples were generated \((2 \times 19.2 \cdot 10^6\) events\), with samples corresponding to the different \( p_T \) ranges of the leading charged particle, as in the case of Xe+Xe events.

## 4 Reconstruction

### 4.1 Jets

The jet reconstruction in pp, Xe+Xe and Pb+Pb collisions closely follows the procedures described in Refs. [3, 33] including the underlying event (UE) subtraction procedure that is applied in Pb+Pb collisions. Jets are reconstructed using the anti-\( k_t \) algorithm [34], which is implemented in the FastJet software package [35] with \( R = 0.4 \). The subtraction is performed cell-by-cell inside \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \) calorimeter towers within the jet using an iterative procedure where the background due to the UE is modulated by harmonic flow [36]. The energies in the towers are obtained by summing the energies of calorimeter cells at the electromagnetic energy scale within the tower boundaries. Then, a jet \( \eta \)- and \( p_T \)-dependent correction factor to the \( p_T^{\text{jet}} \) derived from the simulation samples is applied to correct for the calorimeter energy response [37]. An additional correction based on \textit{in situ} studies of jets recoiling against photons, Z bosons, and jets in other regions of the calorimeter is applied [19, 38]. The same jet reconstruction procedure without the azimuthal modulation of the UE is also applied to pp collisions.

The performance of the jet reconstruction is described for Pb+Pb jets at 5.02 TeV in Ref. [4] and for Xe+Xe and pp jets here, and is characterized by the jet energy scale (JES) and resolution (JER), which are the mean and width of the jet response \((p_T^{\text{rec}}/p_T^{\text{true}})\) in the MC simulations. Here, and through the remainder of the note, “truth” denotes MC generator-level jets reconstructed from primary particles\(^2\) using techniques described in Ref. [39]. The response is generated by matching the truth to reconstructed jets in the MC within a cone of \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3 \). The JES varies from 4% from unity at low \( p_T \) to \( \sim 1\% \)

\(^2\) Particles with a lifetime longer than \( 0.3 \times 10^{-10} \) s produced promptly in nucleon–nucleon interactions, or in decays of particles with shorter lifetimes, are considered to be primary. This includes strange baryons. All other particles are considered to be secondary.
from unity for $p_T > 60 \text{ GeV}$. It also has a small centrality dependence. The JER can be parameterized as

$$\sigma[p_T^{\text{reco}}/p_T^{\text{truth}}] = \frac{a}{\sqrt{p_T^{\text{truth}}}} \otimes \frac{b}{p_T^{\text{truth}}} \otimes c.$$  \hspace{1cm} (3)

The parameters $a$ and $c$ are sensitive to aspects of the detector response and are expected to be independent of centrality, while the parameter $b$ is driven by fluctuations uncorrelated with the jet $p_T$. This “noise” term is often understood in terms of electronic or pile-up 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 is shown in Figure 2 for different Xe+Xe centrality intervals and for $pp$ collisions. Fits using Eq. 3 are indicated with dashed line, where $a$ and $c$ are found to be centrality independent while all of the centrality dependence is in $b$. The JER is largest in the more central collisions, as expected from the larger magnitudes of the total transverse energy in the UE.

Jet measurements are affected by the presence of the finite jet energy resolution. The term in Eq. 3 containing the parameter $b$ includes a contribution from UE fluctuations. These fluctuations do not depend on jet $p_T$ but depend on the collision centrality, centre-of-mass energy, and colliding species. The measurement of the dijet asymmetry is not corrected for resolution effects by the unfolding procedure. However, the $x^d_\text{meas}$ distributions measured in Xe+Xe collisions are compared to the $x^d_\text{meas}$ distributions in the Pb+Pb collisions. The two colliding systems could differ in the size of the fluctuations of the UE for events in the same centrality interval and also for events with the same $\sum E_T^{\text{FCal}}$.

The UE fluctuations are evaluated in minimum-bias Pb+Pb and Xe+Xe data using calorimeter towers with transverse energy $E_T$ at the electromagnetic scale before subtraction of the UE. The towers inside the pseudorapidity range of $|\eta| < 2.8$ are used. The transverse energies $E_T$ are evaluated in individual $(1 \times 1)$ towers that are further combined into “windows” in $(\eta, \phi)$ of size $7 \times 7$ towers. The area of these windows corresponds approximately to the area of jets reconstructed with distance parameter $R = 0.4$. The average
and standard deviation of the \( E_T \) distribution (\( \langle E_T \rangle \) and \( \sigma(E_T) \), respectively) are then evaluated in fine \( \sum E_T^{\text{FCal}} \) intervals within each event.

At a given value of \( \sum E_T^{\text{FCal}} \) the \( \sigma(E_T) \) distribution is relatively narrow and the distribution can be characterized by the mean standard deviation, \( \overline{\sigma}(E_T) \). The measured \( \overline{\sigma}(E_T) \) distributions for single towers and for \( 7 \times 7 \) windows are shown in the top panels of Figure 3 for both the Xe+Xe and Pb+Pb collisions. The lower panels show the ratio of Pb+Pb to Xe+Xe \( \overline{\sigma}(E_T) \) values.

For single towers and \( 7 \times 7 \) windows, the \( \overline{\sigma}(E_T) \) are larger in Pb+Pb collisions than in Xe+Xe collisions at the same \( \sum E_T^{\text{FCal}} \). The ratio of the values is as large as 3\% for single towers and 13\% for \( 7 \times 7 \) windows, however the trends are similar between the two collision systems. The differences between the fluctuations in Pb+Pb and Xe+Xe collisions represent the difference in the UE contributions to the JER.

### 4.2 Charged particles

Charged particle tracks in Xe+Xe events are reconstructed [40] in the pseudorapidity region \(|\eta| < 2.5\) and over the full azimuthal region. At least one hit is required in one of the two innermost layers of the Pixel detector if the reconstructed track passed through an active sensor. Tracks are required to not have missing hits in the Pixel and SCT detectors, if such hits are expected from the track trajectory. Tracks with \(|\eta| < 1.65\) are required to have at least 9 hits in the Pixel and the SCT detectors combined, and at least 11 hits for tracks with \(|\eta| > 1.65\). To ensure a good matching to the primary vertex, the significances \( d_0/\sigma_{d_0} \) and \( z_0 \sin \theta/\sigma_{z_0 \sin \theta} \) may not exceed 3, where \( d_0 \) and \( z_0 \sin \theta \) are transverse and longitudinal distances of closest approach of the track to the primary vertex in the transverse plane, respectively, and \( \sigma_{d_0} \) and \( \sigma_{z_0 \sin \theta} \) are their corresponding uncertainties.

Due to the large number of relatively low-\( p_T \) tracks that can be mis-reconstructed as high-\( p_T \) tracks in the high track density environment of heavy-ion collisions, tracks with \( p_T > 40\text{ GeV} \) are required to be
matched to jets. A track $p_T$ may not be much higher than the $p_T^{\text{jet}}$ to which it is matched. However, finite jet energy resolution must be taken into account. A momentum balance requirement $p_T < 1.3 \times p_T^{\text{jet}}$ has to be satisfied by each track–jet pair, otherwise the track is rejected from the analysis.

5 Analysis

The following two subsections describe the procedures for the dijet and charged hadron analyses.

5.1 Dijets

The analysis is performed using the same methods as in the 2.76 TeV dijet measurement [41], but this current result has not been unfolded for detector effects. In summary, jet pairs are formed from the two highest-$p_T$ jets in the event where the leading jet, or $p_T^1$, is required to be greater than 100 GeV and the sub-leading jet, or $p_T^2$, is required to be greater than $p_T > 35$ GeV. Both jets are restricted to $|\eta| < 2.1$. The pair is required to have $\Delta\phi > 7\pi/8$, where $\Delta\phi$ is the difference in azimuthal angle of the two jets. For events selected by a jet trigger, the leading jet is required to match a jet identified by the trigger algorithm responsible for selecting the jet where the trigger is fully efficient. The results are presented as area-normalized distributions of $1/N \frac{dN}{dx_{\text{meas}}}$.

The measurement is performed in Xe+Xe collisions at 5.44 TeV and compared to Pb+Pb collisions and $pp$ collisions at 5.02 TeV. The analysis is performed in the following intervals of leading jet $p_T^1$: 100–126 GeV, 126–158 GeV, 158–200 GeV, and >200 GeV. The measurement is performed in the centrality intervals: 0–10%, 10–20%, 20–30%, 30–40%, 40–60%, and 60–80% and intervals of $\Sigma E_T^{\text{FCal}}$: >2.99 TeV, 2.05–2.99 TeV, 1.37–2.05 TeV, 0.88–1.37 TeV, 0.29–0.88 TeV, and <0.29 TeV.

The analysis compares both the centrality and $\Sigma E_T^{\text{FCal}}$ dependence in Xe+Xe and Pb+Pb because the former is a comparison of the geometry and the latter is a comparison of the density. Figure 1 shows the $\Sigma E_T^{\text{FCal}}$ distributions compared between Pb+Pb and Xe+Xe with the centrality interval in each collision system indicated by vertical lines in the figure. The centrality intervals for Pb+Pb correspond to larger values of $\Sigma E_T^{\text{FCal}}$ than Xe+Xe. The analysis as a function of $\Sigma E_T^{\text{FCal}}$ was performed applying the Pb+Pb intervals to the Xe+Xe data indicated by the dotted lines.

When comparing Xe+Xe to Pb+Pb at fixed $\Sigma E_T^{\text{FCal}}$, a smearing is applied to the jet $p_T$ based on the difference between the fluctuations at a fixed value of $\Sigma E_T^{\text{FCal}}$ in Xe+Xe and Pb+Pb (see Section 4). An additional smearing due to the difference between the fluctuations at the different values of $\Sigma E_T^{\text{FCal}}$ in the different centrality intervals is applied when comparing the distributions at fixed centrality intervals.

5.2 Charged hadrons

Apart from the simpler trigger setup in Xe+Xe data taking, this analysis closely follows previous Pb+Pb ATLAS studies [3, 4] where more analysis details can be found.

Since the main observables in this analysis are the charged hadron spectra, leptons arising from the decays of heavy vector bosons are excluded from the measured spectra. Tracks forming part of reconstructed
muons are identified, and the contribution from stable leptons is subtracted twice from the measured spectra, assuming that electrons contribute the same as muons.

The measured charged particle spectra are corrected for several effects. All corrections are estimated from MC simulations. The first correction is for secondary and fake tracks. These are tracks matched to secondary particles or they are spurious combinations of hits not associated with a single particle. This correction is estimated as a function of track $p_T$ and $|\eta|$. It is no more than 1% at $p_T \approx 1$ GeV and diminishing with increasing $p_T$. The second correction is for the $p_T$ resolution and track reconstruction efficiency. Bin-by-bin unfolding is used to correct for possible $p_T$ mismeasurement and for the track reconstruction efficiency, i.e. to account for generated particles that do not result in reconstructed and selected tracks. This correction is also estimated as a function of $p_T$ and $|\eta|$. It is around 75% at low $p_T$ ($p_T \approx 1$ GeV), mid-rapidity ($|\eta| \lesssim 1$) and in peripheral collisions. Efficiencies at higher $|\eta|$ are lower by no more than 15% (in absolute scale). An additional reduction of no more than 15% is obtained in the most central collisions. A small continuous increase of the efficiency with the increasing $p_T$ is observed.

To extrapolate the measured $pp$ cross-section [6] from $\sqrt{s} = 5.02$ TeV to $\sqrt{s} = 5.44$ TeV, the ratio of PYTHIA-generated cross-sections at these two centre-of-mass energies was evaluated as a function of $p_T$ and $|\eta|$. The ratio shows that the cross section increases by about 4% at $p_T \approx 1$ GeV over the whole $\eta$ region. However, at the highest $p_T$ measured, the increase should be about 17% in $|\eta| \lesssim 1.2$ and about 26% at the highest $|\eta|$ measured.

6 Systematic uncertainties

The following two subsections describe the systematic uncertainties that are considered for the dijet and charged hadron analyses.

6.1 Dijets

The main sources of systematic uncertainties identified for this analysis are on the jet energy scale and jet energy resolution. The uncertainties on the jet energy scale can arise from discrepancies between the MC where the jet calibration was derived and the data. Also, there are heavy-ion specific uncertainties due to differences in the jet energy scale at different centralities associated with modification of jets in heavy-ion collisions. There is an additional uncertainty due to a residual non-closure in the MC. The procedure for determining the JES and its uncertainty for heavy-ion jets is discussed in detail in Ref. [42]. The strategy and description of each systematic uncertainty are discussed in detail in Ref. [4].

To account for systematic uncertainties due to the disagreement between the JER in data and MC, Gaussian fluctuations are added to each reconstructed jet $p_T$. A systematic uncertainty on the intrinsic JER accounts for uncertainty between the data and MC. An additional HI jet specific uncertainty is included that accounts for differences in the $pp$ and HI jet reconstruction procedure.

The systematic uncertainties on the $x_1^{\text{meas}}$ distributions have been evaluated as a function of jet $p_T$ and collisions centrality separately for Xe+Xe, Pb+Pb, and $pp$. The only difference is that Xe+Xe and Pb+Pb have a centrality dependent JES that is derived separately in each collision system and described in Ref. [4]. The variations are performed at the reconstructed level, and the entire analysis procedure is repeated for
The systematic uncertainties are evaluated by varying individual sources and comparing the results to the results of the default analysis. The correlated components are varied consistently in numerator and denominator in order to estimate the uncertainty on $R_{AA}$. 

6.2 Charged hadrons

The systematic uncertainties are evaluated by varying individual sources and comparing the results to the results of the default analysis. The correlated components are varied consistently in numerator and denominator in order to estimate the uncertainty on $R_{AA}$. 

The Pb+Pb and $pp$ results are only used as a comparison to the Xe+Xe results so only the uncertainties that are different between them and the Xe+Xe results are actually shown on the data points. The breakdown of the systematic uncertainty is shown in Figure 4 for the $100 < p_T < 126$ GeV interval in $pp$ collisions and for the 0–10% centrality interval in Xe+Xe and Pb+Pb collisions. For the Xe+Xe results in the left panel, the systematic uncertainties are shown for both the JES and JER contributions as well as the combination. For the Pb+Pb results in the centre panel, the systematics uncertainties that are uncorrelated with those in Xe+Xe collisions are shown. This includes the difference between the non-closure in the JES evaluated in the MC in Pb+Pb and Xe+Xe collisions and the heavy-ion specific JES uncertainty due to quenching in Pb+Pb collisions. For the $pp$ results in the right panel, the systematic uncertainties that are uncorrelated with those in Xe+Xe collisions are shown. Similarly, this includes the difference between the non-closure in the JES evaluated in the MC in $pp$ and Xe+Xe collisions and the heavy-ion specific JES uncertainty due to quenching in Xe+Xe collisions. The uncertainty tends to decrease with increasing $x^\text{meas}_J$. The total uncertainty at $x^\text{meas}_J \sim 1$ reaches approximately 10% in the Xe+Xe data. For $x^\text{meas}_J < 0.4$, the relative uncertainty on Xe+Xe becomes large, but this region represents only a small contribution to the total $1/N \, dN/dx^\text{meas}_J$ distribution.
The track-selection uncertainty reflects possible differences in performance of the track reconstruction in
data and MC. The requirements mentioned in Section 5.2 were tightened by requiring an additional hit in
Pixel and SCT detectors combined and more strict requirements on $d_0$ and $z_0$, or loosened by requiring
only 7 hits in Pixel and SCT together and less strict requirement on $d_0$ and $z_0$. The same changes were
applied consistently to data and MC simulation. This results in an uncertainty on the cross-section of 1% 
at $p_T \approx 1$ GeV and up to 5% at $p_T \approx 100$ GeV.

The systematics uncertainty due to fake and secondary tracks is estimated to be 30% of the secondary
and fake rate [43]. The resulting uncertainty is less than 1% at low $p_T$ and becomes negligible at around
10 GeV.

The secondary and fake rate, the track momentum resolution, and track reconstruction efficiency rely on
a matching of the reconstructed tracks to generated particles. To account for ambiguities in the matching
procedure, the matching probability is varied to assess a systematic uncertainty. The uncertainty is about
1% over the whole $p_T$ range measured.

The uncertainty of the bin-by-bin unfolding results from three contributions. The first contribution
accounts for the fit used to smooth the corrections. The difference between the values of the fit and the
actual values of the bin-by-bin correction is propagated into the uncertainty. This contribution is constant
in $p_T$ at around 7%. The second contribution comes from the iterative procedure that is used in the
bin-by-bin unfolding. This procedure is used to account for the difference between the shape of the $p_T$
distributions in simulated events and data. The analysis was repeated without reweighting the simulated
spectra. The difference between these two approaches is taken as the systematic uncertainty, and is as large
as 2% in the region around 7 GeV. The track reconstruction efficiency also depends on the description of
the inactive material. This inactive material was varied in the MC simulations. The resulting uncertainty
is between 1% at low $|\eta|$ and 6% at high $|\eta|$.

Three sources of systematic uncertainties in the geometric quantities $N_{\text{part}}$ and $T_{\text{AB}}$ were considered:
the value of $\sigma_{\text{NN}}$ was changed by $\pm 3$ mb. Alternative descriptions of the Xe nuclear wavefunction,
including one derived by scaling measurements of $^{132}$Xe [44] were used. Finally, the two-component
model parameter $x$ was varied within a range that still produced a reasonable fit to the data. Under this last
variation, the fraction of the cross-section with $\sum E_{\text{Cal}}^T > 40$ GeV changed by $\pm 1\%$. The uncertainties
on the $\langle T_{\text{AA}} \rangle$ and $\langle N_{\text{part}} \rangle$, are largest in the peripheral centrality interval where they are 8% and 6%,
respectively. In the most central interval, they are less than 1%.

7 Results

7.1 Dijets

The distributions of $1/N dN/dx_{j_1}^{\text{meas}}$ at $100 < p_{T1} < 126$ GeV in different centrality intervals at the
reconstructed level are shown in Figure 5. They are compared to $pp$ collisions at the same centre-of-mass
energy. The centrality dependence is similar to that seen in 2.76 TeV Pb+Pb collisions where the jets
are more asymmetric in more central collisions as compared to $pp$ collisions but become similar in more
peripheral collisions [41]. The difference is that these results have not been unfolded for detector effects.
Figure 6 shows results for the 0–10% centrality interval for different $p_{T1}$ intervals. The dependence on
leading jet $p_T$ is similar to that seen in 2.76 TeV Pb+Pb collisions[41], where the distributions become
more similar to $pp$ with increasing leading jet $p_T$. 

12
The Xe+Xe distributions of $1/N \frac{dN}{dx_{\text{meas}}^J}$ at $100 < p_T < 126$ GeV are compared to 5.02 TeV Pb+Pb results in Figure 7. The centrality dependence is shown, where each collision system has been partitioned into its own centrality intervals. The $x_{\text{meas}}^J$ distributions in the two collision systems are observed to be consistent within uncertainties. The black line on the figures shows the effect of the addition smearing applied to the Xe+Xe data using the fluctuation analysis described in Section 4. The curve shows that the smearing has no impact on the distribution. Figure 8 shows results for the 0–10% centrality interval for different leading jet $p_T$ intervals. Again, the Xe+Xe and Pb+Pb data are consistent within statistical and systematic uncertainties.

The $1/N \frac{dN}{dx_{\text{meas}}^J}$ distributions in Xe+Xe collisions are also evaluated in the same $\Sigma E_{\text{T Cal}}$ intervals as the Pb+Pb analysis. The centrality dependence is shown in Figure 9 and the leading jet $p_T$ dependence for 0—10% centrality is shown in Figure 10. These results show that Xe+Xe and Pb+Pb $x_{\text{meas}}^J$ distributions are still consistent within statistical and systematic uncertainties. The black line represents the results of the fluctuations analysis described in Section 4 again, but now for the $\Sigma E_{\text{T Cal}}$ intervals. Once again, including the fluctuations has little substantive impact on the distribution.
Figure 5: The $1/N \mathrm{d}N/\mathrm{d}x^\text{meas}$ distributions for jet pairs with $100 < p_T < 126$ GeV in different centrality intervals. The Xe+Xe data are shown as circles, while the pp distribution is shown for comparison as diamonds, and is the same in all panels. Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes. The Xe+Xe systematic uncertainties include all of the JES and JER uncertainties on Xe+Xe data. The pp systematic uncertainties include only the uncertainties that are uncorrelated between Xe+Xe and pp collisions.
Figure 6: The $1/N \frac{dN}{dx_\text{meas}}$ distributions for jets with different selections on $p_T$, shown for Xe+Xe in the 0–10% centrality interval (circles) and for $pp$ (diamonds). Statistical uncertainties are indicated by the error bars, and systematic uncertainties are shown with shaded boxes. The Xe+Xe systematic uncertainties include all of the JES and JER uncertainties on Xe+Xe data. The $pp$ systematic uncertainties include only the uncertainties that are uncorrelated between Xe+Xe and $pp$ collisions.
Figure 7: The $1/N\,dN/dx_j^{\text{meas}}$ distributions for jet pairs with $100 < p_T < 126$ GeV in different centrality intervals. The Xe+Xe data are shown in circles, while the Pb+Pb distribution is shown for comparison in diamonds. Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes. The Xe+Xe systematic uncertainties include all of the JES and JER uncertainties on Xe+Xe data. The Pb+Pb systematic uncertainties include only the uncertainties that are uncorrelated between Xe+Xe and Pb+Pb collisions. The black line represents the inclusion of additional fluctuations based on the results of the fluctuations analysis described in Section 4.
Figure 8: The $1/N \, dN/dx_{J^\text{meas}}$ distributions for jets with different selections on $p_T$, shown for the 0–10% centrality interval for Xe+Xe (circles) and for Pb+Pb (diamonds). Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes. The Xe+Xe systematic uncertainties include all of the JES and JER uncertainties on Xe+Xe data. The Pb+Pb systematic uncertainties include only the uncertainties that are uncorrelated between Xe+Xe and Pb+Pb collisions. The black line represents the inclusion of additional fluctuations based on the results of the fluctuations analysis described in Section 4.
Figure 9: The $1/N \, dN/d\chi_j^{\text{meas}}$ distributions for jet pairs with $100 < p_T < 126$ GeV shown in different intervals of $\Sigma E_{T}^{\text{FCal}}$ for Xe+Xe (circles) and for Pb+Pb (diamonds). Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes. The Xe+Xe systematic uncertainties include all of the JES and JER uncertainties on Xe+Xe data. The Pb+Pb systematic uncertainties include only the uncertainties that are uncorrelated between Xe+Xe and Pb+Pb collisions. The black line represents the results of the fluctuations analysis described in Section 4. The bottom right panel is missing the Xe+Xe points since the Xe+Xe $\Sigma E_{T}^{\text{FCal}}$ distribution does not extend into this interval (see Figure 1).
Figure 10: The $1/N \frac{dN}{dx_{\text{meas}}}$ distributions for jets with different selections on $p_{T1}$, shown for $2.05 < \Sigma E_{T}^{\text{FCal}} < 2.99$ TeV for Xe+Xe (circles) and for Pb+Pb (diamonds). Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes. The Xe+Xe systematic uncertainties include all of the JES and JER uncertainties on Xe+Xe data. The Pb+Pb systematic uncertainties include only the uncertainties that are uncorrelated between Xe+Xe and Pb+Pb collisions. The black line represents the results of the fluctuations analysis described in Section 4.
7.2 Charged hadrons

Charged hadron spectra measured in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV over the full $|\eta| < 2.5$ range are shown in Figure 11 with filled markers as a function of transverse momentum in five centrality intervals: 0-5%, 10-20%, 30-40%, 50-60%, and 60-80%. The results are shown for several intervals of collision centrality and are divided by the corresponding $\langle T_{AA} \rangle$ and also by constant scale factors applied for visual clarity. The $pp$ differential cross-section, extrapolated to $\sqrt{s} = 5.44$ TeV, is also plotted in the figure. The original $pp$ cross-section is taken from Ref. [4]. By comparing the $pp$ results and the Xe+Xe results in the 0–5% centrality interval, a deficit in the number of particles in the Xe+Xe spectrum at $p_T \sim 7$ GeV is visible.

![Figure 11: Charged hadron production cross-sections as a function of $p_T$ measured in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV for five centrality intervals: 0–5%, 10–20%, 30–40%, 50–60% and 60–80%. The cross-section measured in $pp$ collisions and extrapolated to the same centre-of-mass energy is also shown. The statistical uncertainties are shown as the bars (mostly smaller than the marker size), and systematic uncertainties are shown by the boxes. The results are scaled down by constant factors for clarity.](image)

Figure 12 shows the nuclear modification factor, $R_{AA}$, constructed according to Eq. 2, in the same five centrality intervals as shown for the spectra. The $p_T$ dependence of the $R_{AA}$ shows a characteristic curvature which becomes more pronounced for more central collisions. It increases with increasing $p_T$ reaching a maximum at around 2 GeV and then decreases to a minimum at around 7 GeV. Above this $p_T$,
the $R_{AA}$ values increase up to around 60 GeV, where the behaviour is difficult to ascertain due to the low statistics.

Figure 12: Nuclear modification factor, $R_{AA}$, as a function of $p_T$ measured in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV for five centrality intervals: 0–5%, 10–20%, 30–40%, 50–60% and 60–80%. The statistical uncertainties are shown as the bars, and systematic uncertainties are shown by the brackets.

Figure 13 shows the nuclear modification factor $R_{AA}$ measured in Xe+Xe collisions and in Pb+Pb collisions as a function of the mean number of participation nucleons, $\langle N_{\text{part}} \rangle$, in three momentum intervals. These intervals correspond to the local minimum in the region $6.7 < p_T < 7.7$ GeV, to the interval where $R_{AA}$ has an intermediate value, in the region $26 < p_T < 30$ GeV, and to the highest $p_T$ measured, $p_T > 60$ GeV. In all momentum intervals $R_{AA}$ decreases with $\langle N_{\text{part}} \rangle$, however the decrease is the strongest for the local minimum.

Figure 14 shows the nuclear modification factor $R_{AA}$ as a function of $p_T$ in three centrality intervals measured in Xe+Xe collisions (closed markers), together with another three centrality intervals of Pb+Pb [6] (open markers). Although having different centrality, the $\langle N_{\text{part}} \rangle$ for the intervals of the same marker style are comparable. The Xe+Xe results show stronger suppression than Pb+Pb results for the central events, however milder suppression is seen for the peripheral events. Also, the shape of the $R_{AA}$ appears to be systematically different.

Figure 15 shows the nuclear modification factor $R_{AA}$ as a function of $p_T$ in three centrality intervals measured in Xe+Xe collisions (closed markers), together with another three centrality intervals of Pb+Pb [6] (open markers). The intervals of the same centrality have the same marker styles. The Xe+Xe results show milder suppression than Pb+Pb results. At low $p_T$ the difference is very small for the most central collisions and the discrepancies rise with increasing $p_T$ or decreasing centrality.

Figure 16 shows the nuclear modification factor $R_{AA}$ as a function of $p_T$ in the 0–10% Xe+Xe centrality interval together with a theoretical prediction. It was evaluated in a similar manner as in Ref. [45] however the modification of in-medium parton showers was evaluated in a 2+1D viscous hydrodynamics as in Ref. [46]. The model was rudimentarily compared to the Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV and the lower edge exhibits an underestimation of the data. Nevertheless, the shape and normalisation of the $R_{AA}$ are well described by the theoretical calculation.
Figure 13: Nuclear modification factor, $R_{AA}$, as a function of $\langle N_{\text{part}} \rangle$ for selected ranges of $p_T$ measured in Xe+Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV (closed markers) and in Pb+Pb collisions at 5.02 TeV (open markers). The statistical uncertainties are shown as the bars, and systematic uncertainties are shown by the brackets. The width of the brackets represents the systematic uncertainty of $\langle N_{\text{part}} \rangle$. The lines are to help guide the eye.

Figure 14: Nuclear modification factor, $R_{AA}$, as a function of $p_T$ measured in Xe+Xe collisions at $\sqrt{s_{\text{NN}}} = 5.44$ TeV (closed markers) and in Pb+Pb collisions at 5.02 TeV (open markers). The intervals of comparable $\langle N_{\text{part}} \rangle$ have the same marker styles. The statistical uncertainties are shown as the bars, and systematic uncertainties are shown by the brackets.
Figure 15: Nuclear modification factor, $R_{AA}$, as a function of $p_T$ measured in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV (closed markers) and in Pb+Pb collisions at 5.02 TeV (open markers). The intervals of the same centrality have the same marker styles. The statistical uncertainties are shown as the bars, and systematic uncertainties are shown by the brackets.

Figure 16: Nuclear modification factor, $R_{AA}$, as a function of $p_T$ measured in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV in the 0–10% centrality interval. The statistical uncertainties are shown as the bars, and systematic uncertainties are shown by the brackets. The theoretical prediction [45, 46] is shown with the shaded band.
8 Conclusion

This note presents a measurement of dijet $x_T^{\text{meas}}$ distributions in $pp$ collisions at $\sqrt{s} = 5.02$ TeV, Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV and Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The measurement is performed differentially in leading-jet transverse momentum, $p_T^1$, and in collision centrality and $\Sigma E_T^{\text{FCal}}$ using data from the ATLAS detector at the LHC. The distributions show a larger contribution of asymmetric dijets in the more central Xe+Xe collisions compared to that in $pp$ data. This difference becomes less pronounced in more peripheral collisions and in 60–80% the Xe+Xe and in the $pp$ data are consistent. This trend is consistent with in-medium energy loss due to jet quenching and is also consistent with previous measurements of jet imbalance in Pb+Pb collisions by the ATLAS and CMS collaborations. The distributions in Xe+Xe were found to be consistent with Pb+Pb when compared in their respective centrality intervals indicating no significant dependence on the geometry of the event. They were also found to be consistent at fixed values of $\Sigma E_T^{\text{FCal}}$.

This note also presents a measurement of the charged hadron spectra and the nuclear modification factor, $R_{AA}$, in Xe+Xe data at nucleon–nucleon pair collisions energy of $\sqrt{s_{NN}} = 5.44$ TeV. The $R_{AA}$ measured as a function of $p_T$ shows a characteristic dependence that becomes more pronounced for more central collisions. The $R_{AA}$ is compared between Xe+Xe and Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV. Even though they have different centralities, the $\langle N_{\text{part}} \rangle$ for the same $p_T$ intervals are comparable. The Xe+Xe data show more suppression than the Pb+Pb data in more central collisions, and less suppression in more peripheral collisions.

References


The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.


25


Appendix

Figure 17: The dependence of nuclear modification factor $R_{AA}$ on $p_T$. The intervals of comparable $\langle N_{\text{part}} \rangle$ have the same marker styles.

Figure 18: The dependence of nuclear modification factor $R_{AA}$ on $p_T$. The intervals of comparable FCal $E_T$ have the same marker styles.
Figure 19: The dependence of nuclear modification factor $R_{AA}$ on $p_T$. The intervals of comparable $\langle N_{\text{coll}} \rangle$ have the same marker styles.
Figure 20: The dependence of nuclear modification factor $R_{AA}$ on $p_T$. The intervals of the same centrality have the same marker styles.