Measurement of dijet $p_T$ correlations in Pb+Pb and $pp$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector

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Abstract

Measurements of dijets in both Pb+Pb and $pp$ collisions at a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV are presented. The measurements were performed with the ATLAS detector at the LHC using data samples with integrated luminosities of 0.14 nb$^{-1}$ and 4.0 pb$^{-1}$ for the Pb+Pb and $pp$ data samples, respectively. Jets were reconstructed using the anti-$k_t$ algorithm with $R = 0.4$. A background subtraction procedure was applied to correct the jet for the large underlying event present in Pb+Pb collisions. Measurements are reported of the normalized yields $\frac{1}{N} \frac{dN}{dx_J}$, where $x_J = p_{T2}/p_{T1}$ and $p_{T1}$ and $p_{T2}$ are the leading and subleading jet transverse momenta, respectively. The results are presented as a function of $p_{T1}$ and collision centrality. The results were obtained by measuring the two-dimensional $p_{T1}$-$p_{T2}$ distributions and applying an unfolding procedure to account for experimental resolution in the measurement of both jets’ transverse momenta simultaneously. The distributions are found to be similar in peripheral Pb+Pb collisions and $pp$ collisions, but highly modified in central Pb+Pb collisions. The results are consistent with expectations from partonic energy loss.
1 Introduction

Jets have long been considered an important tool to study the matter produced in ultra-relativistic heavy-ion collisions. In these collisions, a hot medium of deconfined color charges is produced known as the quark-gluon plasma (QGP). Jets produced in the initial stages of the collision lose energy as they travel through the medium. This phenomenon, known as jet quenching, was first observed at RHIC [1, 2]. The first measurements using fully reconstructed jets in Pb+Pb collisions at the LHC provided a direct observation of this phenomenon [3]. In Pb+Pb collisions the transverse momentum ($p_T$) balance between dijet pairs was found to be distorted, resulting from events in which the two jets suffer different amounts of energy loss. This measurement was the experimental realisation of some of the initial pictures of jet quenching and signatures of a deconfined medium [4].

Subsequent measurements of jets in Pb+Pb collisions have improved the understanding of properties of quenched jets and the empirical features of the quenching mechanism [5–13]. Significant theoretical advances have also occurred in this period, and while a complete description of jet quenching is not available, some models are capable of reproducing its key features and providing testable predictions. Measurements of the dijet asymmetry $A_J \equiv (p_{T1} - p_{T2})/(p_{T1} + p_{T2})$ where $p_{T1}$ and $p_{T2}$ are the transverse momenta of the jets with the highest and second highest $p_T$ in the event, respectively, have been crucial in facilitating these developments. The experimental results demonstrate that the measured asymmetries in central collisions, where the geometric overlap of the colliding nuclei is almost complete, show a centrality dependence beyond that expected from detector-specific experimental effects [3, 8, 9]. However, such effects, in particular the resolution of the measured jet $p_{T}$, must be corrected for in order for the measurement to be directly compared to theoretical calculations. Unfolding procedures have been applied to correct for such effects for single jet results [6]; however the dijet result requires a two-dimensional unfolding to account for migration in the $p_T$ of each jet separately. The measurement reported in this note is the first unfolded Pb+Pb dijet measurement and thus is the first that can be directly compared to theoretical models.

This note presents a measurement of dijet $p_T$ correlations in Pb+Pb and $pp$ collisions at a nucleon-nucleon centre-of-mass energy of 2.76 TeV performed with the ATLAS detector. Jets are reconstructed with the anti-$k_t$ algorithm with $R = 0.4$ [14]. A background subtraction procedure to account for the effects of the large underlying event (UE) present in Pb+Pb collisions on the measured jet kinematics is applied. The momentum balance of the dijet system was expressed by the variable $x_J \equiv p_{T2}/p_{T1}$. Measurements of $\frac{1}{N} \frac{dN}{dx_J}$ are presented as a function of $p_{T1}$ and collision centrality. The results were obtained by first measuring the $p_{T1}, p_{T2}$ distribution and unfolding in the two-dimensional space. The binning in the $p_{T1}, p_{T2}$ distribution was chosen such that the bin boundaries correspond to fixed ranges of $x_J$, and the $\frac{1}{N} \frac{dN}{dx_J}$ results were obtained by projecting into these $x_J$ bins.

This note is organised as follows. Sections 2 and 3 describe the ATLAS detector and the data samples used in this analysis, respectively. The procedure used to reconstruct jets is discussed in Section 4. Section 5 describes the data analysis including the dijet pair selection, while the unfolding and projection to $x_J$ procedures are described in Section 6. The systematic uncertainties on the measurement are presented in Section 7 followed by a presentation of the results in Section 8. Finally, Section 9 presents the conclusions drawn from the measurement.
2 Experimental setup

The measurements presented in this paper were performed using the ATLAS inner detector, calorimeter and trigger systems [15]. The inner detector system provides measurements of charged particles over the range $|\eta| < 2.5$\footnote{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 center 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 $\eta = -\ln\tan(\theta/2)$.}. It is composed of silicon pixel detectors in the innermost layers, followed by silicon microstrip detectors and a straw-tube tracker, all immersed in a 2 T axial magnetic field provided by a solenoid. The minimum-bias trigger scintillators (MBTS) measure charged particles over $2.1 < |\eta| < 3.9$ using two planes of counters placed at $z = \pm 3.6$ m and were used to provide timing measurements used in the event selection [16].

The ATLAS calorimeter system consists of a liquid argon (LAr) electromagnetic (EM) calorimeter ($|\eta| < 3.2$), a steel-scintillator sampling hadronic calorimeter ($|\eta| < 1.7$), a LAr hadronic calorimeter ($1.5 < |\eta| < 3.2$), and a forward calorimeter (FCal) ($3.2 < |\eta| < 4.9$). The hadronic calorimeter has three longitudinal sampling layers and has a $\Delta\eta\times\Delta\phi$ granularity of $0.1\times0.1$ for $|\eta| < 2.5$ and $0.2\times0.2$ for $2.5 < |\eta| < 4.9$\footnote{An exception is the third sampling layer that has a segmentation of $0.2\times0.1$ up to $|\eta| = 1.7$.}. The EM calorimeters are longitudinally segmented into three compartments with an additional pre-sampler layer. The EM calorimeter has a granularity that varies with layer and pseudorapidity, but which is generally much finer than that of the hadronic calorimeter. The first layer has high $\eta$ granularity (between 0.003 and 0.006) that can be used to identify photons and electrons. The middle sampling layer, which typically has the largest energy deposit in EM showers, has a granularity of $0.025\times0.025$ over $|\eta| < 2.5$. A total transverse energy (TE) trigger is implemented by requiring a hardware-based determination of the total transverse energy in the calorimeter system, $E_{T}^{\text{tot}}$, to be above a threshold.

The zero-degree calorimeters (ZDCs) are located symmetrically at $z = \pm 140$ m and cover $|\eta| > 8.3$. In Pb+Pb collisions the ZDCs primarily measure “spectator” neutrons: neutrons from the incident nuclei that do not interact hadronically. A ZDC coincidence trigger is implemented by requiring the summed pulse height from each ZDC to be above a threshold set below the single neutron peak.

3 Data and Monte Carlo samples

The Pb+Pb data used in this measurement were obtained using a combination of jet and minimum-bias triggers. The minimum-bias trigger was defined by a logical OR of the TE trigger with a threshold of $E_{T}^{\text{tot}} > 50$ GeV and the ZDC coincidence trigger, and was fully efficient in the range of centralities presented here. The jet trigger first selected events satisfying the TE trigger with a threshold of $E_{T}^{\text{tot}} > 20$ GeV. A jet reconstruction procedure was then applied using the anti-$k_t$ algorithm with $R = 0.2$ and utilising a UE subtraction procedure similar to that used in the offline reconstruction described in Section 4. Events with at least one jet with $E_T > 20$ GeV at the electromagnetic scale [17] were selected by the jet trigger. The use of $R = 0.2$ in the trigger, as opposed to the value of $R = 0.4$ used in the measurement, was necessitated by operational requirements during data taking, and the effects of the different $R$ values on the trigger efficiency are discussed in Section 5. The minimum-bias trigger operated with a prescale of approximately 18 while no prescale was applied to the jet trigger. After accounting for these prescales,
the recorded events correspond to integrated luminosities of 0.008 and 0.14 nb$^{-1}$, for the minimum-bias and jet-triggered samples, respectively.

Events were further subjected to criteria designed to remove non-collision background and inelastic electromagnetic interactions between the nuclei. Events were required to have a reconstructed primary vertex and have a timing difference of less than 5 ns between the times measured by the two MBTS planes. After the trigger and event selection criteria, the resulting data samples contain 53 and 14 million events in the minimum-bias and jet triggered samples, respectively. The average number of collisions per bunch-crossing (pile-up) in the Pb+Pb data sample was less than 0.001, and the effects of multiple collisions were neglected in the data analysis.

The centrality of the Pb+Pb collisions was characterised by the total transverse energy measured in the FCal modules, $\sum E_{T}^{\text{FCal}}$. The $\sum E_{T}^{\text{FCal}}$ distribution obtained in minimum-bias collisions was partitioned into separate ranges of $\sum E_{T}^{\text{FCal}}$ referred to as centrality classes [16, 18, 19]. Each class was defined by the fraction of the distribution contained by the interval, e.g. the 0–10% centrality class contains the 10% of minimum-bias events with the largest $\sum E_{T}^{\text{FCal}}$. The centrality boundaries used in this analysis are 0%, 10%, 20%, 30%, 40%, 60% and 80%.

The $pp$ data sample is composed of events selected using the ATLAS jet trigger [20]. It applied the anti-$k_t$ algorithm with $R = 0.4$ and used a series of different $p_T$ thresholds each selected with a different prescale. The events were further required to contain at least one primary reconstructed vertex. The average number of $pp$ collisions per bunch-crossing varied between 0.3 and 0.6 during data taking. The sample corresponds to a luminosity of 4.0 pb$^{-1}$.

The impact of experimental effects on the measurement was evaluated using the Geant4-simulated detector response [21, 22] in a Monte Carlo (MC) sample of $pp$ hard-scattering events. Dijet events at $\sqrt{s} = 2.76$ TeV were generated using Pythia version 6.423 [23] with parameters chosen according to the AUET2B tune [24]. Separate samples were generated for the Pb+Pb and $pp$ analyses, with the simulated detector conditions chosen to match those present during the recording of the respective data samples. The pile-up contribution present in the $pp$ data sample was accounted for by overlaying minimum-bias $pp$ collisions produced at the same rate present in the data, generated by Pythia 8 [25] using the A2 [26] tune with MSTW2008LO PDF sets. In the Pb+Pb sample, the UE contribution to the detector signal was accounted for by overlaying the simulated events with minimum-bias Pb+Pb data. The vertex positions of each simulated event were selected to match the data event used in the overlay. Through this procedure the MC sample contains contributions from underlying event fluctuations and harmonic flow that match those present in the data. The combined signal was then reconstructed using the same procedure as was applied to the data. So-called truth jets were defined by applying the anti-$k_t$ algorithm with $R = 0.4$ to stable particles in the generator 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. To fully populate the kinematic range considered in the measurement, hard scattering events were generated for separate intervals of $\hat{p}_T$, the transverse momentum of outgoing partons in the $2 \rightarrow 2$ hard-scattering, and combined using weights proportional to their respective cross sections.

An additional sample was produced using the Pyquen generator [27] to study the detector response to quenched jets. This generator applies medium-induced energy loss to parton showers produced by Pythia. It was used to generate a sample of jets with fragmentation functions that differ from those in the nominal Pythia sample in a fashion consistent with measurements of fragmentation functions in quenched jets [11–13].
4 Jet reconstruction

The procedure used to reconstruct jets in heavy-ion collisions is described in detail in Ref. [5] and is briefly summarised here. First, energy deposits in the calorimeter cells are assembled into $\Delta \eta \times \Delta \phi = 0.1 \times \frac{\pi}{32}$ logical towers. Jets arse formed from the towers by applying the anti-$k_t$ algorithm [14] as implemented in the FastJet software package [28].

The background subtraction procedure first determined the UE average transverse energy density, $\rho$, as well as the magnitudes and phases of the harmonic modulation due to flow. In Ref. [5], only the second-order harmonic modulation ($n = 2$) was considered, but in this measurement the procedure has been extended to account for $n = 3$ and 4 harmonic modulations as well. Once these quantities have been determined, the subtraction is applied to each tower within the jet. The $\rho$ and flow quantities can be biased if the energy in a jet is included in their calculation. This may result in an over-subtraction of the average UE contribution to the jet energy or incomplete removal of the harmonic modulation. To mitigate such effects, an iterative procedure is used remove the contribution of actual jets from the estimate of the background. The typical background subtracted from the jets varies between a few GeV in peripheral collisions to 150 GeV in the most central collisions.

A calibration factor, derived from MC studies, is then applied after the subtraction to account for non-compensation of the hadronic response. A final in situ calibration is applied to account for known differences between the detector response in data and in the MC sample used to derive the initial calibration [29]. This calibration is derived in 8 TeV pp data and adapted to the different beam energy and pile-up conditions relevant for the samples considered here. It uses the balance between dijet pairs in different $\eta$ regions of the detector to provide an evaluation of the relative response to jets as a function of $\eta$. It subsequently uses jets recoiling against well calibrated objects such as $Z$ bosons and photons to provide constraints on the absolute energy measurement.

5 Data analysis

In this analysis, jet pairs were formed from the two highest $p_T$ jets in the event with $p_T > 25$ GeV and $|\eta| < 2.1$. The pair was required to have $\Delta \phi > 7\pi/8$. For events selected by a jet trigger, the leading jet was required to match a jet identified by the trigger algorithm responsible for selecting the jet. The two-dimensional $p_T^1 - p_T^2$ distributions obtained from different triggered samples were combined such that intervals of $p_T^1$ are populated by a single trigger. In the pp data analysis, the trigger with the most events that was more than 99% efficient for selecting a jet with $p_T > p_T^1$ was used, with the reciprocal of the luminosity for the respective trigger samples used as a weight.

The Pb+Pb jet trigger efficiency has a broad turn-on as a function of $p_T$ since the trigger jets were identified using $R = 0.2$ and had no energy scale calibration applied. This effect is the strongest in central collisions where the UE fluctuations are the largest and further weaken the correlation between jets reconstructed with $R = 0.2$ and 0.4. In the most central collisions, the single jet efficiency does not reach a plateau until $p_T \sim 90$ GeV. The jet-triggered sample was used where the efficiency was found to be greater than 97% which occurs at a $p_T$ of approximately 85 GeV in the most central collisions. A trigger efficiency correction was applied in the region where there is an inefficiency.

In addition to the dijet signal, the measured $p_T^1 - p_T^2$ distribution receives contributions from so-called combinatoric pairs. Such pairs arise when another jet in the event, uncorrelated with the hard-scattering
process that produced the dijet, fullfills the pair requirements through random association. Such jets may originate from independent hard scatterings or with upward UE fluctuations identified as jets, referred to as UE jets. The rate for such occurrences is highest in the most central collisions, and the reduction in the true sub-leading jet $p_T$ due to quenching effects further enhances the likelihood of forming a combinatoric pair.

The shape of the $\Delta \phi$ distribution for the combinatoric pairs is influenced by the harmonic flow. As the jet spectrum is steeply falling, the most likely jets to be observed at a given $p_T$ value are those where the UE underneath the jet is above average background. If the effects of the modulation of the UE are not fully accounted for in the background subtraction, more jets will be observed at angles corresponding to the flow maxima. Thus combinatoric dijet pairs, without any underlying angular correlation, are expected to acquire a modulation to their $\Delta \phi$ distribution determined by the dominant flow harmonics \cite{30}. Although the second, third and fourth order harmonic modulation are considered in the jet reconstruction procedure described in Section 4, only the effects of the second order modulation on the $\Delta \phi$ distribution were observed to be completely removed. The residual effects are an indication that the method of estimating the modulation of the UE underneath the jet is less accurate for the higher order harmonics than for $n = 2$.

To account for the residual modulation, the combinatoric contribution was assumed to be of the form \( C(\Delta \phi) = Y (1 + 2c_3 \cos 3\Delta \phi + 2c_4 \cos 4\Delta \phi) \). The $c_3$ and $c_4$ values were determined by fitting the $\Delta \phi$ distributions over the range $0 < \Delta \phi < \pi/2$ where the real dijet contribution is expected to be small. The region near $\Delta \phi \sim 0$ is also expected to receive real dijet contributions arising from split jets. To remove this contribution, this fit to obtain $c_3$ and $c_4$ was performed only using dijet pairs with a separation of $|\Delta \eta| > 1.5$. Once $c_3$ and $c_4$ were obtained, the $\Delta \phi$ distribution without this $|\Delta \eta|$ requirement was fit over the range $1 < \Delta \phi < 1.4$ to obtain $Y$. All fits were performed separately in each $p_{T_1} - p_{T_2}$ interval. The expected contribution in the signal region was obtained by integrating $C(\Delta \phi)$ from $7\pi/8$ to $\pi$ and subtracting the yield from each $p_{T_1} - p_{T_2}$ bin. The background subtraction is most significant in central collisions where the fraction subtracted from the total yield in the signal region is as large as 10% for small $x_J$ and is less than 1% for $x_J$ values greater than 0.5. The background contribution in more peripheral collisions is less than 1% for all values of $x_J$.

In a given event, the $p_T$ resolution may result in the jet with the highest true $p_T$ in the event being measured with the second highest $p_T$ and vice-versa. To properly account for such migration effects, $p_{T_1} - p_{T_2}$ distributions were symmetrised prior to the unfolding by apportioning half of the yield in a given $p_{T_1} - p_{T_2}$ bin, after combinatoric subtraction, to another bin related to the original by $p_{T_1} \leftrightarrow p_{T_2}$. The two-dimensional distributions after symmetrisation are shown in Fig. 1 for central and peripheral Pb+Pb collisions and for $pp$ collisions.

6 Unfolding

The calorimetric response to jets was evaluated in the MC sample by matching truth and reconstructed jets; the nearest reconstructed and truth jets within $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.4$ were considered to be a match. The response is typically characterised in terms of the jet energy scale (JES) and jet energy resolution (JER). These quantities describe the mean and width of the $p_T^{\text{reco}}$ distributions at fixed $p_T^{\text{truth}}$, expressed as a fraction of $p_T^{\text{truth}}$. Generally, the mean of $p_T^{\text{reco}}$ and $p_T^{\text{truth}}$ differ by less than a percent, independent of $p_T^{\text{truth}}$ and centrality. This indicates that the subtraction of the average UE contribution to the jet energy is under good experimental control. The JER receives contributions both from the response
of the calorimeter and from local UE fluctuations about the mean in the region of the jet. The latter contribution dominates at low \( p_T \) with the resolution as large as 40\% at \( p_T \approx 30 \text{ GeV} \) in the most central collisions. By contrast the JER is only 20\% in peripheral collisions, or similarly in \( pp \) collisions, at the same \( p_T \). At larger \( p_T \) values the relative contribution of the UE fluctuations to the jet \( p_T \) diminishes, and the JER is dominated by detector effects, reaching a constant, centrality-independent value of 8\% for \( p_T > 300 \text{ GeV} \).

The migration in the two-dimensional \( p_{T1},p_{T2} \) distribution was accounted for by applying a two-dimensional Bayesian unfolding to the data \([31]\). This procedure utilised a response matrix obtained by applying the same pair selections to the MC sample as in the data analysis (except the trigger requirement) and recording the values of \( p_{T1}^{\text{reco}} \) and \( p_{T2}^{\text{reco}} \) and the transverse momenta of the corresponding matched truth jets \( p_{T1}^{\text{truth}} \) and \( p_{T2}^{\text{truth}} \). The full four-dimensional response behaves similarly to the factorised product of separate single jet response distributions, and the migration effects can be understood in terms of the above discussion. While this provides intuition for the nature of the unfolding problem, such a factorisation is not explicitly assumed, and any correlations between the response of the two jets are accounted for in the procedure.

The Bayesian unfolding method is an iterative procedure that requires both a choice in number of iterations, \( n_{\text{iter}} \), and assumption of a prior for the underlying true distribution. The value of \( n_{\text{iter}} \) was selected by evaluating the tradeoff between the amplification of statistical fluctuations (large \( n_{\text{iter}} \)) and residual bias in the unfolded distribution due to the original choice of prior (small \( n_{\text{iter}} \)). The latter was studied by applying the response matrix to the unfolded result (refolding) and comparing the resulting distribution to the input data as a consistency check. Based on these considerations \( n_{\text{iter}} \) was chosen to be 26 in the Pb+Pb analysis. In the \( pp \) analysis 15 iterations was found to be suitable. The prior in both the Pb+Pb and the \( pp \) response matrices was generated from the truth \( p_{T1},p_{T2} \) distribution in Pythia.

After unfolding, the leading/sub-leading distinction was restored by reflecting the distribution over the line \( p_{T1} = p_{T2} \); for each bin with \( p_{T2} > p_{T1} \) the yield was moved to the corresponding bin with \( p_{T2} < p_{T1} \). Bins with \( p_{T2} = p_{T1} \) were not affected by this procedure. The two-dimensional distribution was constructed using binning along each axis such that the upper edge of the \( i \)th bin obeys,

\[
p_{T_i} = p_{T_0} \alpha^i, \quad \alpha = \left( \frac{p_{T_n}}{p_{T_0}} \right)^{1/n},
\]

Figure 1: The symmetrised two-dimensional \( p_{T1},p_{T2} \) distributions for Pb+Pb data in the 0–10\% (left) and 60–80\% (center) centrality bins and for \( pp \) data (right). The dashed lines indicate the boundaries used in selecting the different triggers. The Pb+Pb data distributions have their combinatoric contribution subtracted.
where \( n \) is the total number of bins and \( p_{T0} \) and \( p_{Tn} \) are the minimum and maximum ranges covered by the binning, respectively. With these choices of binning, the range of \( x_J \) values in any given \( p_{T1}-p_{T2} \) bin is fully contained within two adjacent \( x_J \) bins. In this analysis, half of the yield in each \( p_{T1}-p_{T2} \) bin was apportioned to each of the \( x_J \) bins. The exception are the bins along the diagonal. These bins contribute solely to the \( x_J \) bin with bin edges \((\alpha^{-1}, 1)\). The effects of such a mapping on the \( x_J \) distribution were studied and found to not significantly distort the shape of the distribution for a variety of input \( x_J \) distributions.

### 7 Systematic uncertainties

Systematic uncertainties attributed to the response matrix used in the unfolding arise due to uncertainties in the JES and JER. To account for these effects, new response matrices were constructed with a systematically-varied relationship between the truth and reconstructed jet kinematics. The data were then unfolded using the new response and the result compared with the nominal.

In the \( pp \) data analysis, the JES uncertainty was described by a set of 11 independent nuisance parameters; these include effects from uncertainties derived through the \textit{in situ} calibration \cite{29}. The calorimetric response to jets initiated by the fragmentation of quarks and gluons was observed to differ in the MC sample used in the calibration. Potential inaccuracies in the MC sample to describe both this flavor-dependent response and the relative abundances of quark and gluon jets were accounted for using separate nuisance parameters. A source of uncertainty related to the adaptation of the \textit{in situ} calibration derived at \( \sqrt{s} = 8 \) TeV to 2.76 TeV \cite{32} was also included.

In the \( Pb+Pb \) data analysis, two additional uncertainties on the JES were considered. The first accounted for differences in the detector operating conditions in the \( Pb+Pb \) data and the \( pp \) data. This was derived by using charged particles reconstructed in the inner detector to provide an independent check on the JES, which only uses information from the calorimeter. For each jet, all reconstructed tracks within \( \Delta R < 0.4 \) and having \( p_{T\text{trk}} > 2 \) GeV, were associated with the jet and the scalar sum of the track transverse momenta was evaluated. The ratio of this sum to the jet’s \( p_T \) was evaluated both in data and in the MC sample, and a double ratio was formed between the two quantities. This double ratio was compared between that obtained in peripheral \( Pb+Pb \) data and \( pp \) data. The precision of the comparison is limited by the poor statistics in the peripheral \( Pb+Pb \) data and high jet \( p_T \), and a conservative \( p_T \)- and \( \eta \)-independent uncertainty of 1.46% was assigned to account for potential differences.

A centrality-dependent JES uncertainty to account for potential differences in the detector response to quenched jets was estimated to be up to 1% in the most central collisions and decreasing linearly with centrality percentile to 0% in the 60–80% centrality class. This was estimated by comparing the detector response evaluated in the \textsc{Pythia} and \textsc{PyQuen} MC samples. This estimate was checked in data using a study with tracks similar to the one described above, but comparing central and peripheral \( Pb+Pb \) collisions and accounting for the measured variation of the fragmentation function with centrality.

The uncertainty attributed to the JER was obtained by adding Gaussian fluctuations to each reconstructed jet \( p_T \) value when populating the response matrix. The magnitude of this uncertainty was fixed by a comparison of the data and MC descriptions of the JER in 8 TeV data \cite{33, 34}. Since the MC sample was constructed using the data overlay procedure, it is expected that the centrality dependence of the JER should be well described in the MC. This was checked by studying the distribution of UE fluctuations using random, jet-sized groups of calorimeter towers in \( Pb+Pb \) data. The standard deviations of these
distributions describe the typical UE contribution beneath a jet. The centrality dependence of the UE fluctuations was compared to that of the JER in the MC sample. A systematic uncertainty was included to account for the observed differences, although as expected, these differences were much smaller than the centrality-independent contribution.

Sensitivity to the number of iterations used in the unfolding was tested by varying the value by ±4, and using the variation in the unfolded results to assign an uncertainty. A separate uncertainty was applied to account for the observed differences, although as expected, these differences were much smaller than the centrality-independent contribution.

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The method of populating the response matrix, using samples with different $p_T$ ranges and applying a weighting, suffers from the fact that large fluctuations may occur in bins where two samples contribute with one containing many fewer counts but a much larger cross section. As the response matrix is sparsely populated (containing $40^4$ bins), such fluctuations could introduce instabilities in the unfolding. To evaluate the sensitivity to such effects, along with any other defects in the response, a new response matrix was constructed as a factorised product of single jet response distributions, i.e. assuming the response in $p_{T1}$ and $p_{T2}$ were independent. The data were unfolded using this new response and the differences in the unfolded distributions were taken as a systematic.

Finally, uncertainties on the combinatoric contribution were evaluated by varying the region of $\Delta\phi$ used to estimate that contribution from 1.0–1.4 to 1.1–1.5. Generally the combinatoric subtraction contribution is smaller than the others in all $p_T$ and centrality bins, and is only greater than 5% at values of $x_J < 0.4$.

Each contribution to the uncertainty and thus the total uncertainty tends to decrease with increasing $x_J$. The total uncertainty at $x_J \sim 1$ reaches approximately 15% in most $p_T$ and centrality bins in the Pb+Pb data. For $x_J < 0.4$, the relative uncertainty becomes large, but this region represents only a small contribution to the total $\frac{1}{N} \frac{dN}{dx_J}$ distribution. The JES uncertainty is the largest contribution. In the Pb+Pb data it reaches values of approximately 10% and 15% at $x_J \sim 1$ and $x_J = 0.5$, respectively. The unfolding (number of iterations, refolding, reweighting and response population) and JER contributions to the uncertainties are typically between 5 and 10%, but in the most central bins the unfolding uncertainty can become as large as a the JES contribution. The contributions to the uncertainty in the $pp$ data follow similar trends as described for the Pb+Pb data, but are typically smaller by a factor of two.

8 Results

The unfolded $\frac{1}{N} \frac{dN}{dx_J}$ distributions are shown Figure 2, for pairs with 100 < $p_{T1}$ < 126 GeV for different centrality intervals. The distribution in $pp$ collisions is shown on each panel for comparison. In the 60–80% centrality bin, where the effects of quenching are expected to be the smallest, the Pb+Pb data are generally consistent with the $pp$ data. In more central Pb+Pb collisions, the distributions become significantly broader than that in $pp$ collisions and the peak at $x_J \sim 1$, corresponding to nearly-symmetric dijet events, is reduced. The distribution becomes almost flat over the range 0.5 < $x_J$ < 1, before developing a peak at $x_J \sim 0.5$ in the most central collisions.
Figure 2: The $\frac{1}{N} \frac{dN}{dx_j}$ distributions for pairs with $100 < p_T < 126$ GeV for different collision centralities. The Pb+Pb data is shown in red, while the pp distribution is shown for comparison in blue, and is the same in all panels. Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes.
Figure 3: The $\frac{1}{N} \frac{dN}{dx_j}$ distributions for different selections on $p_T$, shown for the 0–10% centrality bin (red) and for $pp$ (blue). Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes.

Figure 3 shows the $\frac{1}{N} \frac{dN}{dx_j}$ for 0–10% Pb+Pb collisions and $pp$ collisions for different selections on $p_T$. In $pp$ collisions, the $x_j$ distribution becomes increasingly narrow, indicating that higher $p_T$ dijets tend to be better balanced in momentum (fractionally). The $x_j$ distribution begins to fall more steeply from $x_j \sim 1$, but appears to flatten at intermediate values of $x_j$. The modifications observed in the Pb+Pb data lessen with increasing $p_T$ and for pairs with $p_T > 200$ GeV the maximum at $x_j \sim 1$ is restored.

9 Conclusion

This note has presented a measurement of dijet differential $x_j$ distributions in $pp$ and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The measurement was performed differentially in leading jet transverse momentum, $p_T$, and in collision centrality. The measured distributions were unfolded to account for the effects of experimental resolution on the two-dimensional $p_T$-$p_T$ distributions and then projected into bins of fixed $x_j$. The distributions show a larger contribution of asymmetric dijet pairs in Pb+Pb data compared to that
in pp data, a feature that grows with centrality which is consistent with expectations of medium-induced energy loss due to jet quenching. In the 0–10% centrality bin at 100 < \( p_T \) < 126 GeV, the \( x_J \) distributions develop a significant peak at \( x_J \sim 0.5 \) indicating that the most probable configuration for dijets is for them to be highly imbalanced. This is in sharp contrast to the situation in the pp data where the most probable values are near \( x_J \sim 1 \). The centrality-dependent modifications evolve smoothly from central to peripheral collisions, and the results in the 60–80% centrality bin and the pp data are generally consistent. At larger values of \( p_T \) the \( x_J \) distributions are observed to narrow and the differences between the distribution central Pb+Pb and the pp data lessen. This is consistent with a picture in which the fractional energy loss decreases with jet \( p_T \). The features in the data are compatible with those observed in previous measurements of dijets in Pb+Pb collisions [3, 8, 35], however, the trends in this measurement are clear due to the application of the unfolding procedure. This result constitutes an important benchmark for theoretical models of jet quenching and the dynamics of relativistic heavy-ion collisions.

References

Additional figures

Figure 4: The $\frac{1}{N} \frac{dN}{dJ_x}$ distributions for pairs with $126 < p_T < 158$ GeV for different collision centralities. The Pb+Pb data is shown in red, while the pp distribution is shown for comparison in blue, and is the same in all panels. Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes.
Figure 5: The $\frac{1}{N} \frac{dN}{dx_J}$ distributions for different selections on $p_T$, shown for the 20–30% centrality bin (red) and for $pp$ (blue). Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes.
Figure 6: The $\frac{1}{N} \frac{dN}{dx}$ distributions for different selections on $p_T$, shown for the 60–80% centrality bin (red) and for $pp$ (blue). Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown with shaded boxes.

Figure 7: The $\frac{1}{N} \frac{dN}{dx}$ before (black) and after unfolding (red) shown for $100 < p_T < 126$ GeV, for 0–10% (left), 60–80% (center) Pb+Pb collisions and for $pp$ collisions (right). Statistical uncertainties are indicated by the error bars while systematic uncertainties are shown for the unfolded results with shaded boxes.