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New results on fully corrected dijet asymmetry in Pb+Pb collisions with ATLAS

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Abstract

The phenomenon of events containing highly asymmetric dijet pairs is one of the most striking results in heavy ion physics, providing the first direct observation of in-medium jet energy loss at the Large Hadron Collider. Detailed measurements of a centrality-dependent dijet imbalance in 2.76 TeV Pb+Pb collisions using data collected by the ATLAS detector in the 2011 LHC heavy ion run are presented. The new analysis provides a measurement, fully corrected for detector effects to the particle level, of the centrality- and leading jet transverse momentum- (p_{T}-) dependence of the dijet p_{T} balance distribution, compared to an analogous measurement in pp collisions at the same center-of-mass energy.

Keywords: heavy ion physics, jet quenching, dijet asymmetry, energy loss

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1. Introduction

Since the beginning of the heavy ion physics program at the Large Hadron Collider (LHC), measurements of the energy balance of dijets in lead–lead (Pb+Pb) collisions have been a valuable way to probe the differential energy loss of fast partons traversing the hot nuclear medium. Since the outgoing partons from a hard parton–parton scattering early in the collision generally traverse a different path length, they lose different amounts of energy. This phenomenon is typically quantified through the distribution of the dijet asymmetry values $A_{\mathrm{J}} \equiv (p_{\mathrm{T},1} - p_{\mathrm{T},2})/(p_{\mathrm{T},1} + p_{\mathrm{T},2})$ and dijet p_{T} balance ratio $x_{\mathrm{J}} \equiv p_{\mathrm{T},2}/p_{\mathrm{T},1}$, where $p_{\mathrm{T},1}$ and $p_{\mathrm{T},2}$ indicate the transverse momentum of the leading and subleading jet in the event, respectively.

Inital measurements of A_{J} and x_{J} distributions in Pb+Pb collisions showed that they are modified in a centrality-dependent manner due to this path-length dependent energy loss [1], while remaining unmodified in p+Pb collisions [2]. Although these have generated much theoretical interest [3], the measured distributions have typically not been corrected for detector effects, making direct comparisons with jet quenching calculations ambiguous. Recent advances in jet measurement techniques in heavy ion collisions, including a quantitative determination of the heavy ion jet energy scale in ATLAS [4], have enabled more sophisticated measurements. This proceedings presents an updated measurement of the dijet p_{T} balance ratio in Pb+Pb and pp collisions [5] as a function of centrality and leading jet p_{T}, in which the distributions have been fully corrected to the particle level. Together with measurements of modified single and multi-jet production rates [6], these observables can provide a more complete picture of energy loss in the hot nuclear medium.

[1] A list of members of the ATLAS Collaboration and acknowledgements can be found at the end of this issue.

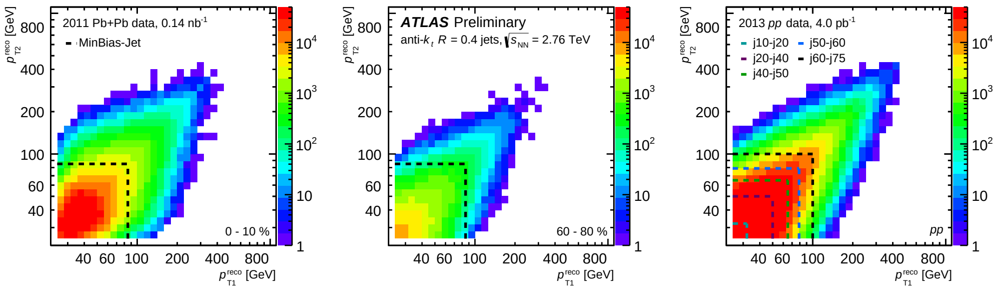

Fig. 1. Symmetrized distributions of the leading and subleading jet p_{T} in central (left) and peripheral (center) Pb+Pb collisions and in *pp* collisions (right), from Ref. [5]. The dashed lines indicate boundaries used in selecting different triggers.

2. Data selection and jet reconstruction

The data used in this work comprise 0.14 nb^{-1} of Pb+Pb data at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and 4.0 pb^{-1} of *pp* data at $\sqrt{s} = 2.76$ TeV delivered by the LHC in 2011 and 2013, respectively. The ATLAS detector is described in detail in Ref. [7]. The hermetic, large-acceptance calorimeter system, which includes liquid argon (LAr) electromagnetic and hadronic calorimeters, and a steel-scintillator hadronic calorimeter, provided the jet energy measurement. The Pb+Pb data were selected using a combination of a minimum bias trigger, defined by a minimum amount of energy in the calorimeter system or a coincidence in the zero-degree calorimeters situated far downstream of the interaction point, and a hardware-based jet trigger. The centrality of Pb+Pb collisions is characterized using the sum of transverse energy in the forward calorimeter modules, situated at $3.2 < |\eta| < 4.9$[2]. In *pp* collisions, the data were selected using high-level jet triggers with increasing p_{T} thresholds, in which the highest-threshold trigger sampled the full luminosity.

Jets were reconstructed according to a procedure that closely follows those used for previous measurements in Pb+Pb and *pp* collisions [8]. Calorimeter cells were collected into $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ towers at the electromagnetic scale. An iterative procedure was used to determine the underlying event (UE) energy density in an η- and calorimeter layer-dependent manner, while excluding jets from that estimate. For this measurement, the UE estimation procedure was extended to allow for possible third- and fourth-order modulations of the energy density due to flow. Jets were defined by the application of the anti-k_t algorithm with $R = 0.4$ to the towers, with the kinematics of the jet updated to remove the UE contribution. The jet p_{T} was corrected for the response of the calorimeter with a calibration derived from simulation and for an additional, small data-to-simulation difference derived from *in situ* studies of the jet response [4].

3. Data analysis, corrections and systematics

Events selected for analysis were required to have the leading and sub-leading jet within $|\eta| < 2.1$, with $p_{\mathrm{T},1} > 100$ GeV and $p_{\mathrm{T},2} > 25$ GeV. Furthermore, the dijet configuration was required to be back-to-back as given by $|\Delta\phi| > 7\pi/8$. The triggered samples were weighted by their respective luminosity (in *pp* collisions) or corrected for their respective scaledowns (in Pb+Pb collisions) and used to populate the two-jet $(p_{\mathrm{T},1}, p_{\mathrm{T},2})$ spectrum. Each $p_{\mathrm{T},1}$ range was populated using only the highest-statistics trigger which was efficient in that range. The resulting distributions were symmetrized along the $p_{\mathrm{T},1} = p_{\mathrm{T},2}$ axis to allow the unfolding to properly treat instances where the leading/subleading classification switched due to the fluctuations in the UE and response. Figure 1 shows representative two-jet distributions in Pb+Pb and *pp* collisions.

[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

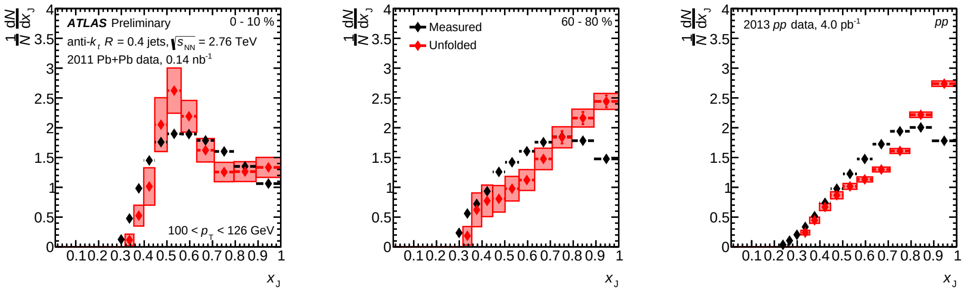

Fig. 2. Example of per-dijet x_J distributions at the detector-level (black) and after unfolding to the particle level (red), shown for $p_{T,1} > 100$ GeV dijets in central (left) and peripheral (center) Pb+Pb collisions and in pp collisions (right), from Ref. [5].

Due to the presence of low-p_T reconstructed jets which arise from UE fluctuations in Pb+Pb collisions, the $(p_{T,1}, p_{T,2})$ distribution contains a residual contribution from the combinatoric pairing of leading jets with UE fluctuations. These pairings were found to occur when the UE fluctuations sit atop third- and fourth-order flow maxima, and the residual contribution was therefore modeled as $C(\Delta\phi) = Y(1 + 2c_3 \cos 3\Delta\phi + 2c_4 \cos 4\Delta\phi)$. For each $(p_{T,1}, p_{T,2})$ interval, the values of c_3, c_4 and Y were constrained in the region $\Delta\phi < 1.4$ and used to estimate and subtract the combinatoric contribution in the signal region $\Delta\phi > 7\pi/8$. This contribution was 10% at the lowest x_J values in central collisions, and smaller elsewhere.

Monte Carlo simulations of hard scattering events, including a full GEANT4 simulation of the detector, were used to evaluate the performance of the dijet measurement [9]. Pythia was used to generate pp event samples [10], and a separate sample of Pythia events was overlaid onto Pb+Pb minimum bias data. To include possible correlations in the response of the leading and subleading jets, four-dimensional response matrices were generated between the particle-level and reconstructed jet pairs. A Bayesian unfolding procedure [11] was used to correct the bin migration in the measured $(p_{T,1}, p_{T,2})$ distributions. The number of iterations was chosen by checking the stability against additional iterations and performing a refolding test.

For each $p_{T,1}$ and centrality selection, the unfolded $(p_{T,1}, p_{T,2})$ distributions were projected into x_J distributions. Figure 2 shows an example of x_J distributions before and after the unfolding procedure. Systematic uncertainties on the results were evaluated in the following ways: response matrices were generated with variations in the jet energy scale and resolution (most important at high-p_T and in central collisions); the number of unfolding iterations was varied and the prior x_J distribution in simulation was reweighted (most important at low-p_T and in peripheral collisions); the two-jet response was factorized into the product of the single jet response; and the procedure for determining the combinatoric dijet contribution was varied.

4. Dijet asymmetry results

Figure 3 summarizes the corrected dijet p_T balance distributions. The left-most panels of Figure 3 show how the x_J distribution for $100 < p_{T,1} < 126$ GeV dijets evolves with selections on event centrality. In the most peripheral Pb+Pb collisions, the x_J distributions are largest at unity and fall off at lower x_J values. They are consistent with the analogous distributions in pp collisions and indicate predominantly balanced dijet configurations. With increasingly more-central event selections, the x_J distribution shifts to lower values of x_J, indicating a higher prevalence of very asymmetric dijet configurations. In the most central events, the x_J distributions develop a peak near $x_J \approx 0.5$. Thus, in these events the most common dijet configuration after quenching is when the subleading jet has half the p_T of the leading jet.

The right-most panels of Figure 3 show how the x_J distribution in the most central collisions evolves with selections on the leading jet p_T. As shown above, for $100 < p_{T,1} < 126$ GeV dijets, the x_J distribution in 0-10% Pb+Pb events is substantially different from that in pp collisions. However, for systematically higher $p_{T,1}$ selections, the x_J distributions in Pb+Pb collisions shift to larger values of x_J. For $p_{T,1} > 200$ GeV, the x_J distribution in central events is peaked at unity, and is qualitatively similar to that in pp collisions. This

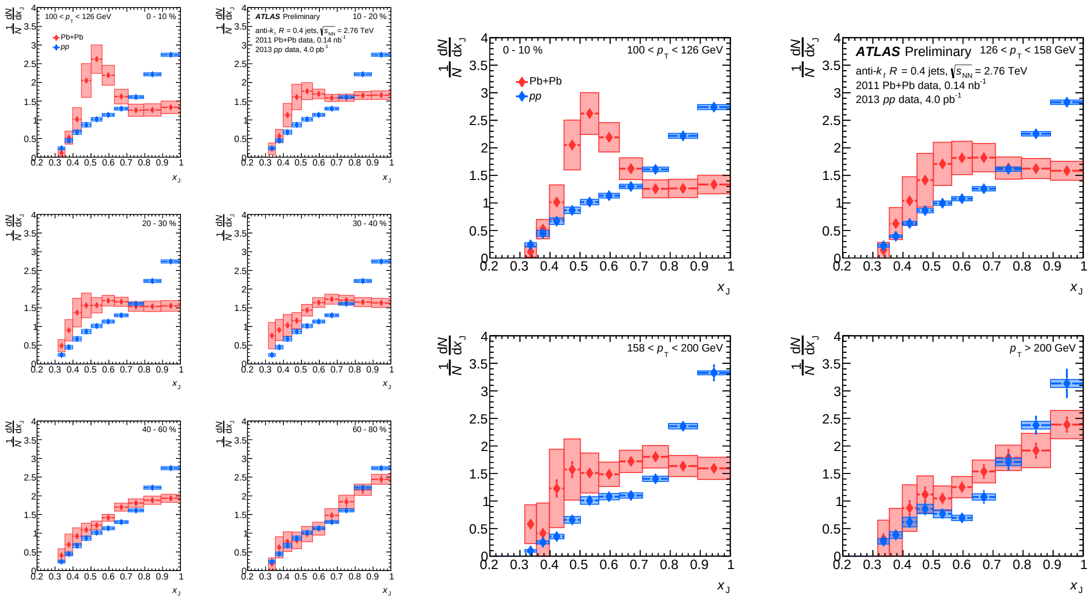

Fig. 3. Per-dijet pair x_J distributions in Pb+Pb (red) and pp collisions (blue), fully corrected to the particle level, from Ref. [5]. The vertical lines and boxes show the statistical and systematic uncertainties, respectively. *a*) $p_{T,1} > 100$ GeV dijet events, each panel showing a different Pb+Pb centrality selection. *b*) 0-10% Pb+Pb events, each panel showing a different selection on $p_{T,1}$.

indicates that for systematically higher selections on the leading jet p_T, while both jets may be individually quenched, the most likely dijet configurations are nevertheless balanced. The observed $p_{T,1}$ dependence may suggest, for example, a decrease in the fractional energy loss with increasing p_T.

5. Conclusion

This work presents an updated measurement of the dijet transverse momentum balance distributions in Pb+Pb collisions with the ATLAS detector at the LHC. The distributions have been corrected for detector effects to the particle level, and are presented as a function of the event centrality and leading jet p_T. For dijets with $p_{T,1} > 100$ GeV in the most central collisions, the typical configurations are strongly asymmetric compared to that in pp collisions at the same collision energy. However, in peripheral collisions or at higher $p_{T,1}$ (> 200 GeV), the distributions are qualitatively similar to those in pp collisions, providing insight into the differential path-length-dependent energy loss in the hot nuclear matter created in these collisions.

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