Measurements of the azimuthal anisotropy of jets and high-$p_T$ charged particles in Pb+Pb collisions with the ATLAS detector

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The heavy-ion collisions produce a hot, dense medium, and high-momentum partons from the collision traverse this medium while losing energy to it. This talk presents new measurements of the azimuthal dependence with respect to the event plane of single jet yields and high momentum charged particles yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. As the distance traversed by the partons in the medium is dependent on the angle with respect to the event plane at which the partons are produced, these measurements give insight into the path-length dependence of parton energy loss. The magnitude of angular modulation is quantified by the parameter $v_n$ with respect to the nth-order event plane. In this talk we will present these two measurements that show $v_2$, $v_3$, and $v_4$ as a function of $p_T$ and collision centrality. In both measurements, a non-zero value of $v_2$ are observed. A non-zero $v_3$ is observed in the jet measurement while the charged particle $v_3$ remains zero. Both measurements explore a higher transverse momentum regime and higher-order harmonics than current measurements benefiting from the high statistics 2018 Pb+Pb heavy ion data recorded by ATLAS. These measurements provide new information about the path-length dependence of jet quenching.
1. Introduction

The primary aim of the heavy-ion program at the Large Hadron Collider (LHC) is to produce and study the quark-gluon plasma (QGP). Jets originating from hard parton scatterings interact with the QGP and are expected to experience energy loss that is dependent on the amount of QGP that the jet travels through, which leads to a dependence of the jet yield on the azimuthal angle with respect to the event plane [1].

This azimuthal anisotropy in yield can be quantified via \( v_n \) values, defined by:

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n)),
\]

where \( \Psi_n \) is the \( n \)th order event plane and \( \phi \) is the azimuthal angle of the object. In addition to being measured by reconstructing the event planes directly [2], \( v_n \) can also be measured using the scalar-product method (SP) [3].

Measurements of \( v_n \) using jets [4, 5] and high-\( p_T \) charged particles [6, 7] in Pb+Pb collisions have been previously performed. These proceedings utilized the large dataset of Pb+Pb collisions collected in 2015 and 2018, and extended \( v_n \) measurements to higher-order for jets \( v_n \) and to higher-\( p_T \) for charged particles \( v_n \), providing new information about the energy loss dependence on path-length and the initial geometry. For more details on the analysis results described in these proceedings, see Ref. [8] and Ref. [9].

2. Datasets

The jets analysis utilized 2.2 nb\(^{-1} \) Pb+Pb data collected in 2015 and 2018, and measured \( v_n \) over the \( p_T \) range of 71–398 GeV and the rapidity range of \( |y| < 1.2 \). Jets are reconstructed using the anti-\( k_T \) algorithm [10] with radius \( R = 0.2 \). The charged particles analysis utilized 1.72 nb\(^{-1} \) Pb+Pb data collected in 2018, and measured \( v_n \) over \( p_T \) range 1–200 GeV and the pseudorapidity range of \( |\eta| < 2.5 \).

3. Azimuthal anisotropy measurements of jets

This analysis uses the event-plane method to determine \( v_n \) as described in Ref. [11] and used in previous measurements [12, 13]. The observed \( n \)th order event-plane angles, \( \Psi_n^{\text{obs}} \), are determined by the azimuthal variation of transverse energy in the forward calorimeters from pseudorapidity range \( 4.0 < |\eta| < 4.9 \). Figure 1 shows an example of the angular distribution of jets with respect to the \( \Psi_2 \), \( \Psi_3 \) and \( \Psi_4 \) planes. The statistical uncertainties are shown as error bars and the systematic uncertainties are shown as boxes (as in all figures).

\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 \( z \)-axis. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \). The rapidity is defined as \( y = 0.5 \ln [(E + p_z)/(E - p_z)] \) where \( E \) and \( p_z \) are the energy and \( z \)-component of the momentum along the beam direction respectively. Transverse momentum and transverse energy are defined as \( p_T = p \sin \theta \) and \( E_T = E \sin \theta \), respectively. The angular distance between two objects with relative differences \( \Delta \eta \) in pseudorapidity and \( \Delta \phi \) in azimuth is given by \( \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \).}
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Figure 1: Angular distribution of jets with respect to the $\Psi_2$, $\Psi_3$ and $\Psi_4$ planes, $n|\Psi_{n}^{\text{obs}} - \psi|$, for jets with $71 < p_T < 79$ GeV in the 10–20% centrality bin [9].

Figure 2: Left: the $v_2$ values for $R = 0.2$ jets as a function of centrality for jets in several $p_T$ ranges, as indicated in the legend [9]. Right: The $v_2$, $v_3$, and $v_4$ as a function of centrality for jets with $p_T$ 71–398 GeV [9].

The $v_2$ values as a function of centrality for different $p_T$ selections are shown on the left hand side of Figure 2. The $v_2$ values are consistent with zero in the most central collisions, and positive for all other centrality bins over the full $p_T$ range. The centrality dependence for the $v_2$, $v_3$, and $v_4$ for the full $p_T$ range of the measurement, 71—398 GeV, is shown in the right hand side plot of Figure 2. The $v_3$ is positive and on the order of 0.01 for central and mid-central collisions, and consistent with zero in the most peripheral collisions. The value of $v_4$ is compatible with zero.

A comparison with previous charged particle and jet measurements of $v_2$ and $v_3$ is made in Figure 3. The jet $v_2$ shows no obvious collision energy dependence, and shows a similar but scaled $p_T$ dependence in comparison to charged particle $v_2$. $v_3$ shows agreement with previous analysis in overlapped $p_T$ region.

4. Azimuthal anisotropy measurements of charged particles

Utilizing the large dataset of Pb+Pb collisions in 2018, $v_2$, $v_3$ and $v_4$ were measured in charged particles to very high $p_T$ for centrality range 0–40% using the SP method. The SP method is discussed in Ref. [14] and Ref. [3]. Results using this method have been published by ATLAS in Ref. [7, 15]. The charged particle $v_n$ measurements in these proceedings impose a pseudorapidity gap of at least 3.2 between the event plane determination and the particles of interest, thus suppressing non-flow correlations [16].
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Figure 3: The jet $v_2$ (left) and $v_3$ (right) as a function of $p_T$ in 20–40% centrality collisions [9] with previous measurements. See the charged particle (h$^+$) results from CMS in Ref. [6], the jet results from ATLAS at $\sqrt{s_{NN}} = 2.76$ TeV in Ref. [4], and the jet results from ALICE at $\sqrt{s_{NN}} = 2.76$ TeV in Ref. [5].

Figure 4: The $v_n$ values as a function of charged-particle $p_T$ for 10–20% central Pb+Pb collisions [8].

Figure 5: The $v_2$, $v_3$, and $v_4$ values as a function of particle $p_T$ [8], for the 10–20% centrality interval, compared with previous ATLAS [7] and CMS [6] measurements. For $v_4$, only ATLAS [7] measurements are available.

Figure 4 shows the $v_2$, $v_3$, and $v_4$ values as a function of $p_T$ for the selected centrality bin 10–20%. As shown in Figure 4, for $p_T > 100$ GeV $v_2$ values remain positive for all but the 0–5% centrality intervals. $v_3$ values are consistent with zero over the $p_T$ range 20 − 200 GeV. $v_4$ values are consistent with zero at high $p_T$. The charged particle $v_n$ values measured here were compared with previous measurements [6, 7] in Pb+Pb collisions at the same collision energy and found to be consistent, as shown for 10–20% central collisions in Figure 5.

Figure 6 shows the centrality dependence of the $v_n$ coefficients for selected $p_T$ intervals above
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Figure 6: The $v_2$ (left) and $v_3$ (right) values as a function of centrality for charged particles in selected $p_T$ ranges [8].

35 GeV. The centrality dependence of $v_2$ in these ranges is very similar to that expected from the QGP geometry, with the $v_2$ magnitude increases from central to mid-central bins. For $v_3$, the results are consistent with zero, independent of centrality, for $p_T > 35$ GeV.

5. Conclusion

These proceedings present the measurements of azimuthal anisotropies of jets and charged particles in Pb+Pb collisions at 5.02 TeV using data taken by the ATLAS detector. The harmonics of azimuthal anisotropies, $v_n$, are measured differentially in $p_T$ for $n = 2, 3, 4$. In the charged particle analysis, high-$p_T$ charged particles are used as a proxy for jets. $v_2$ measured by jets and charged particles exhibit qualitatively similar centrality and $p_T$ dependence. Positive $v_3$ is observed in mid-central jet measurements while for charged particle measurements, which was conducted over wider pseudorapidity range, $v_3$ stays zero of the same centrality. Measurements of $v_4$ are consistent with zero in high-$p_T$ region for both probes. Comparison with previous measurements and theoretical models are also made. These two analyses have greatly extended the scope of $v_n$ measurements, and provide new information to constrain the path-length dependence of jet quenching, and facilitate the development of currently missing theoretical calculations on particle flows.

References


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