PROCEEDINGS OF SCIENCE

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 $\sqrt{s_{\rm NN}}$ = 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.

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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[1] 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 Ψ_n is the n^{th} order event plane and ϕ 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 meaesurements 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, Ψ_n^{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 Ψ_2, Ψ_3 and Ψ_4 planes. The statistical uncertainties are shown as error bars and the systematic uncertainties are shown as boxes (as in all figures).

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector, and the z-axis along the beam pipe. The x-axis points from the IP to the center 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 $\eta = -\ln\tan(\theta/2)$. 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 $E_{\mathrm{T}} = E\sin\theta$, 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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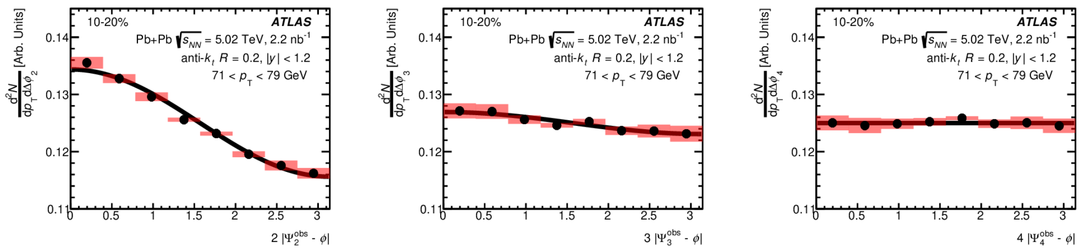

Figure 1: Angular distribution of jets with respect to the Ψ_2, Ψ_3 and Ψ_4 planes, $n|\Psi_n^{obs} - \psi|$, for jets with $71 < p_T < 79$ GeV in the 10–20% centrality bin [9].

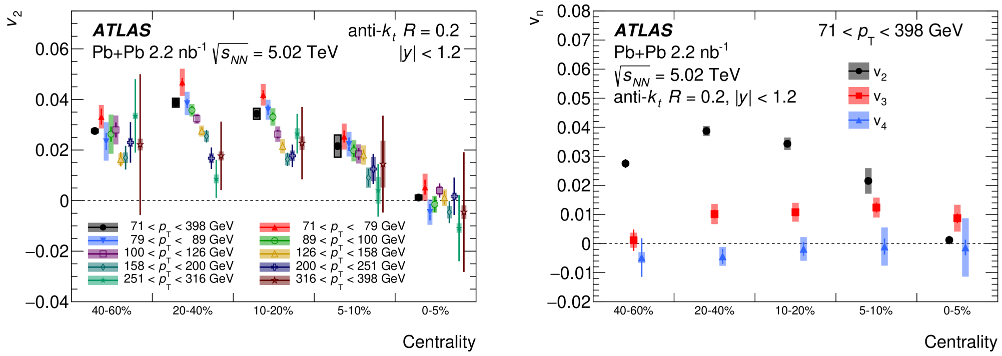

Figure 2: Left: the v_2 values for $R = 0.2$ jets as a function of centrality for jets in several p_T ranges, as indicated in the legend [9]. Right: The v_2, v_3, and v_4 as a function of centrality for jets with p_T 71–398 GeV [9].

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].

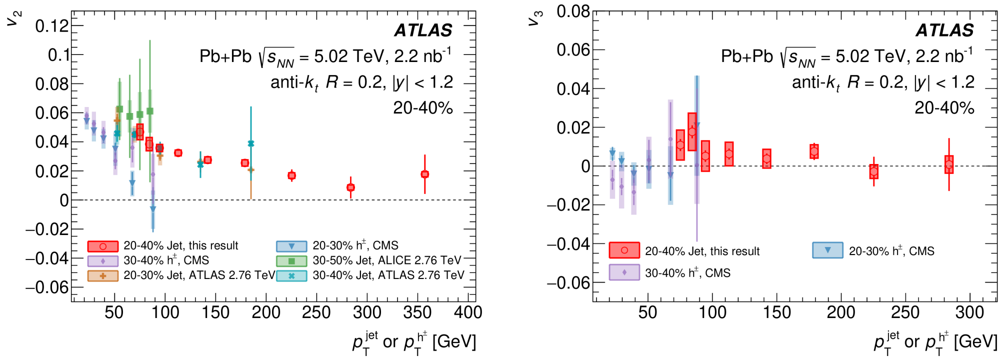

Figure 3: The jet v_2 (left) and v_3 (right) as a function of p_T in 20–40% centrality collisions [9] with previous measurements. See the charged particle ($h^{\pm}$) results from CMS in Ref. [6], the jet results from ATLAS at $\sqrt{s_{NN}}$ = 2.76 TeV in Ref. [4], and the jet results from ALICE at $\sqrt{s_{NN}}$ = 2.76 TeV in Ref. [5].

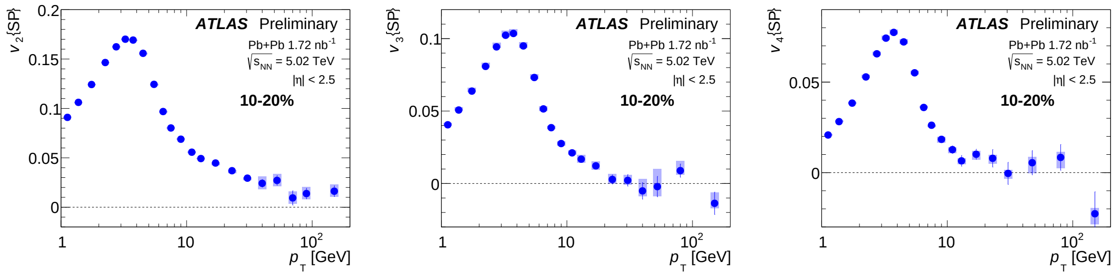

Figure 4: The v_n values as a function of charged-particle p_T for 10–20% central Pb+Pb collisions [8].

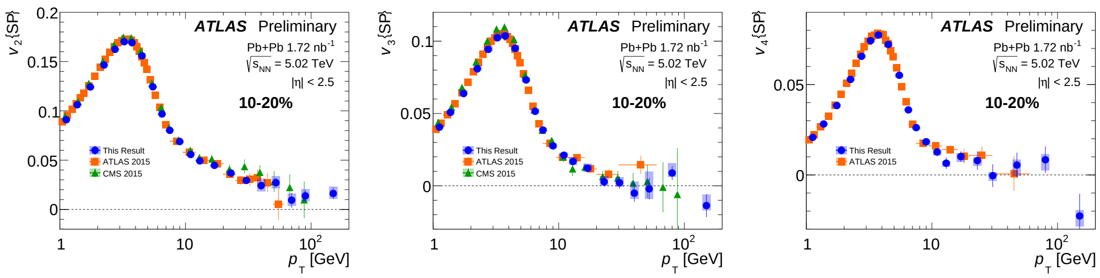

Figure 5: The v_2, v_3, and v_4 values as a function of particle p_T [8], for the 10–20% centrality interval, compared with previous ATLAS [7] and CMS [6] measurements. For v_4, only ATLAS [7] measurements are available.

Figure 4 shows the v_2, v_3, and v_4 values as a function of p_T for the selected centralty 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

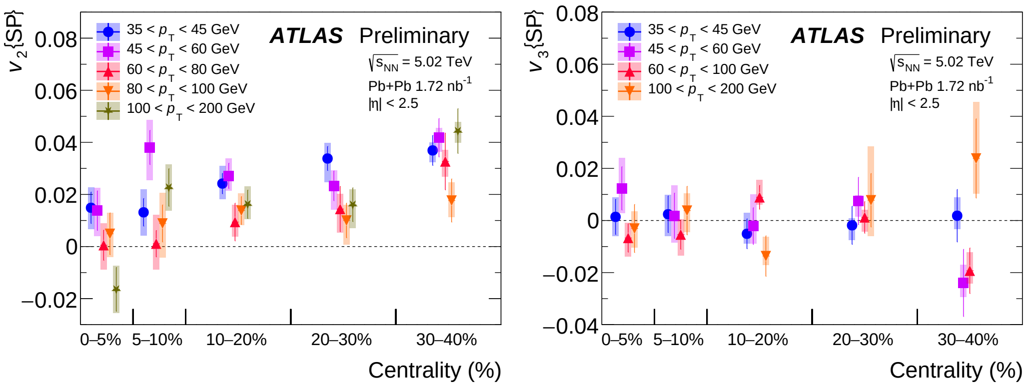

Figure 6: The v_2 (left) and v_3 (right) values as a function of centrality for charged particles in selected p_T ranges [8].

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 TeVusing 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.

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