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THE FLOW HARMONICS MEASUREMENT WITH THE EVENT PLANE AND MULTI-PARTICLE CUMULANT METHODS IN Pb+Pb COLLISIONS AT 2.76 TeV IN ATLAS*

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The ATLAS results on charged particles flow harmonics in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are presented. Elliptic flow and higher order flow harmonics, v_n (for $n = 2$–4), are measured using two methods: standard event plane and multi-particle cumulants (up to the 8^{th} order). Results for elliptic flow are shown in a wide range of pseudorapidity ($|\eta| < 2.5$), transverse momentum ($0.5 < p_{\mathrm{T}} < 20$ GeV) and centrality (0–80%). The measurement techniques are discussed in terms of non-flow effects. It is shown that four-particle correlations suppress most of non-flow contributions.

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1. Introduction

Quark–Gluon Plasma (QGP) is under a thorough investigation in heavy-ion experimental programme since its discovery at RHIC [1–4]. The ATLAS Collaboration, together with other LHC experiments, have dedicated a significant part of its operational time to heavy-ion collisions. During the first data taking period (Run 1), in the years 2010–2013, the ATLAS experiment collected 7 $\mu\mathrm{b}^{-1}$ in 2010 and 158 $\mu\mathrm{b}^{-1}$ in 2011 of Pb + Pb data at $\sqrt{s_{NN}} = 2.76$ TeV. This paper summarizes ATLAS results on flow harmonics measurements using the early lead–lead data from 2010.

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It is generally expected that the presence of QGP medium leads to large anisotropies in the observed azimuthal angle distributions of produced particles, which are customarily expanded into Fourier series [5, 6]

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N_0}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\phi - \Phi^{\mathrm{RP}}\right)\right]\right], \qquad (1)$$

where v_n coefficients are called flow harmonics of n^{th} order, ϕ is azimuthal angle of a particle and Φ^{RP} is the reaction plane angle. Flow harmonics are used to characterize the large azimuthal anisotropy observed at the RHIC [1–4] and LHC [7–10] energies. The second Fourier coefficient, v_2, known as *elliptic flow*, is sensitive to the initial spatial asymmetry of the almond-shaped overlapping zone of colliding nuclei, whereas consecutive harmonics are related to initial spatial fluctuations of the zone. In general, flow harmonics are defined with the relation: $v_n = \langle \cos[n(\phi - \Phi^{\mathrm{RP}})]\rangle$. However, as the real reaction plane angle could not be directly extracted from experiment, several measurement techniques were developed to estimate v_n [5, 6].

The azimuthal angle distributions of particles produced during collisions are not only affected by collective flow correlations but also by correlations not related to the initial geometry such as contributions from jet production, resonance decays and energy or momentum conservation. It is essential to separate the pure flow signal from non-flow components. This paper is focused on two methods which provide different ways of such separation.

2. Flow harmonics measurement

The ATLAS detector [11] is composed of several sub-detectors that surround the interaction point. In the flow analysis, two sub-detectors are used. The most essential one is the Inner Detector (ID) which reconstructs tracks with $p_{\mathrm{T}} > 0.5$ GeV in the pseudorapidity region ($|\eta| < 2.5$) and has a full acceptance in the azimuthal angle. The ID detector is immersed in a 2 T solenoidal magnetic field. The second sub-detector is a two-arm Forward Calorimeter (FCal) symmetrically located at both sides of the interaction point ($3.2 < |\eta| < 4.9$). In heavy-ion analyses, the FCal detector is used to determine centrality of the collision as well as to estimate event plane angles. In ATLAS, centrality is defined with the total transverse energy deposited in FCal. The FCal $\sum E_{\mathrm{T}}$ distribution is partitioned into intervals, each consists of a percentage of the total inelastic Pb+Pb cross section (*e.g.* 0–10% denotes the bin with 10% of the most central events with the largest FCal $\sum E_{\mathrm{T}}$).

2.1. The event plane method

A standard technique adopted in flow measurements is the event plane method (EP) [5]. In ATLAS, it is based on the correlation of azimuthal angles of tracks reconstructed in ID, ϕ, with EP angles Ψ_n^{P} and Ψ_n^{N} determined separately for each FCal arm located at positive and negative η, respectively [7]. In this method, the flow harmonics are calculated as follows:

$$v_n = \frac{\left\langle \cos\left(n\left[\phi - \Psi_n^{\mathrm{N|P}}\right]\right)\right\rangle}{\sqrt{\left\langle \cos\left(n\left[\Psi_n^{\mathrm{N}} - \Psi_n^{\mathrm{P}}\right]\right)\right\rangle}} \,. \tag{2}$$

In the numerator, where the average is calculated over tracks, Ψ_n^{P} or Ψ_n^{N} is selected to be in the opposite η-hemisphere to a particle of azimuthal angle ϕ. Therefore, in the EP method, there is a large η-gap ($|\Delta\eta| > 3.2$) between tracks used to calculate v_n and the FCal arm used for the EP angle determination. This separation leads to a reduction of short range non-flow correlations distorting the collective flow measurement. The denominator is related to the resolution of the reaction plane angle estimation [6].

2.2. The multi-particle cumulant method

A systematic approach to investigate the impact of non-flow correlations (*e.g.* from resonance decays or jets) on the v_n estimation is provided by the multi-particle correlations method which exploits a direct relation between azimuthal angle correlations of $2k$ particles and the $2k^{\mathrm{th}}$ moments of v_n distributions [12, 13]

$$\langle \mathrm{corr}_n\{2k\}\rangle = \langle \cos\left[n\left(\phi_1 + ... + \phi_k - \phi_{k+1} - ... - \phi_{2k}\right)\right]\rangle = \left\langle v_n^{2k}\right\rangle \,. \tag{3}$$

It was observed [14] that using higher order ($2k$) cumulants of the multi-particle correlations eliminates the correlations of fewer than $2k$ particles. Therefore, higher order cumulants suppress the non-flow contributions which are typically of lower order. For example, four-particle cumulant, $c_n\{4\} = \langle \mathrm{corr}_n\{4\}\rangle - 2\,\langle \mathrm{corr}_n\{2\}\rangle^2$, suppresses two-particle non-flow correlations, so that only genuine four-particle correlations are left for v_n calculations. In the analysis, cumulants were obtained up to the 8^{th} order with the Generating Function Cumulant method [12, 13]. The method significantly limits the required computing time. Flow harmonics for two- and four-particle cumulants are defined as: $v_n\{2\} = \sqrt{c_n\{2\}}$, $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$ [13].

3. Results

The ATLAS results presented in this section are from Ref. [14]. Figure 1 shows the second Fourier harmonic, v_2, integrated over a wide range of pseudorapidity ($|\eta| < 2.5$) as a function of transverse momentum p_{T}. Each panel represents a different centrality interval with the most central bin, 0–2%, in the top left plot. The comparison is done between elliptic flow extracted from EP, $v_2\{\mathrm{EP}\}$, and multi-particle cumulant $v_2\{2k\}$ (where $k = 1, 2, 3, 4$) methods.

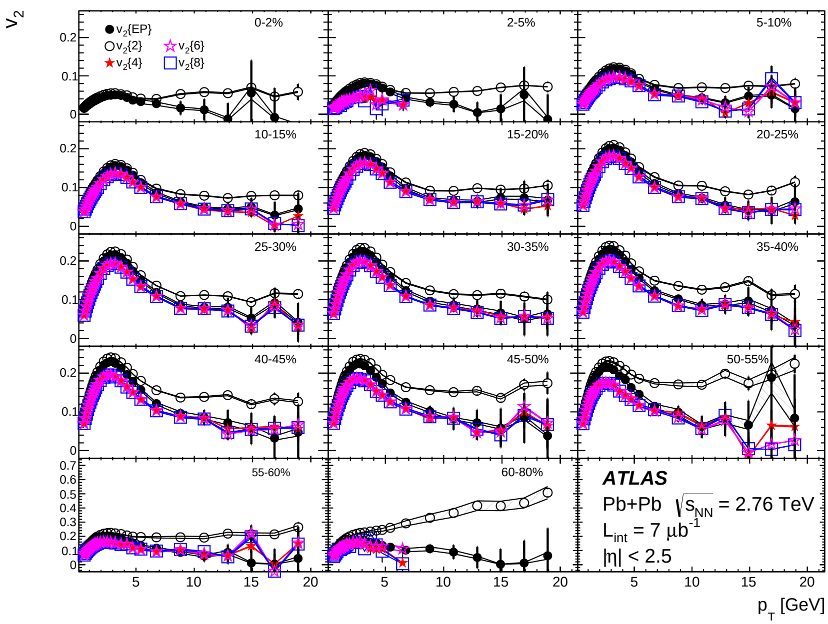

Fig. 1. The $v_2(p_{\mathrm{T}})$ integrated over full pseudorapidity range ($|\eta| < 2.5$) in several centrality bins, as indicated on each panel. The comparison is done between $v_2\{\mathrm{EP}\}$ and two-, four-, six- and eight-particle cumulant harmonics [14]. Statistical and systematical uncertainties are marked as vertical bars and bands, respectively.

Due to low statistics, the panel for the most central bin presents only $v_2\{\mathrm{EP}\}$ and $v_2\{2\}$ results. EP measurements give systematically lower flow values when compared to the two-particle cumulant results. It is due to the suppression of short-range correlations in the EP method by exploiting the large η-gap in this approach. One should also notice the significant flow reduction between two- and higher-particle correlation results. Furthermore, four-, six- and eight-particle cumulant harmonics are consistent with each other. It could be concluded that most of the non-flow correlations are already removed in four-particle cumulants.

Figure 2 presents the centrality dependence of elliptic flow measured with multi-particle cumulant method and integrated over large p_{T} (0.5 GeV $< p_{\mathrm{T}} <$ 20 GeV) and pseudorapidity ($|\eta| < 2.5$) ranges. The centrality is defined by the number of participating nucleons in a nuclear reaction, $\langle N_{\mathrm{part}} \rangle$, which is assigned to each FCal $\sum E_{\mathrm{T}}$ centrality bin [6]. The more central collision, the larger $\langle N_{\mathrm{part}} \rangle$ is. The tendency is the same as for $v_2(p_{\mathrm{T}})$: flow values are reduced for higher order particle correlations. Lower panel shows ratios of v_2 from six- and eight-particle cumulants to four-particle cumulant. A good agreement, within measurement uncertainties, between $v_2\{4\}$ and v_2 of higher order cumulants is observed. This indicates that non-flow effects are effectively excluded starting from four-particle correlations.

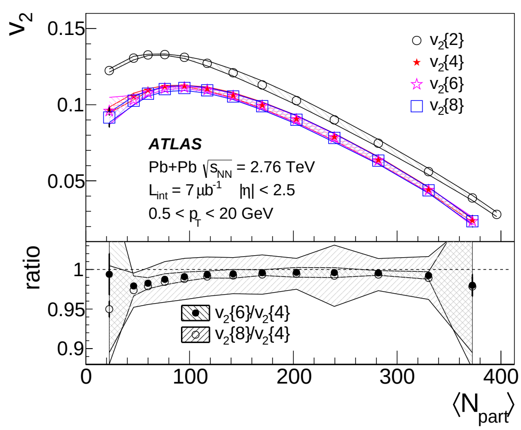

Fig. 2. The centrality dependence of the elliptic flow $v_2\{2,4,6,8\}$ integrated over 0.5 GeV $< p_{\mathrm{T}} <$ 20 GeV and $|\eta| < 2.5$. Lower panel shows the ratio of $v_2\{6\}$ and $v_2\{8\}$ to $v_2\{4\}$ [14].

Results for third and fourth flow harmonics are shown in Fig. 3. Due to large statistical uncertainties, v_3 is presented in two broad centrality intervals, 0–25% and 25–60%, while v_4 only in one most central bin 0–25%. Cumulant results are shown up to four-particle correlation. Along with elliptic flow, higher order flow harmonics reveal the sensitivity to non-flow effects. As expected, the $v_{3,4}\{4\}$ is significantly lower than two-particle correlations $v_{3,4}\{2\}$ and $v_{3,4}\{\mathrm{EP}\}$. Furthermore, it is observed that the difference between $v_{3,4}\{4\}$ and $v_{3,4}\{\mathrm{EP}\}$ is much larger than the difference between $v_2\{4\}$ and $v_2\{\mathrm{EP}\}$. This implies that the fluctuations of higher order flow harmonics are much larger than fluctuations of the second flow harmonic.

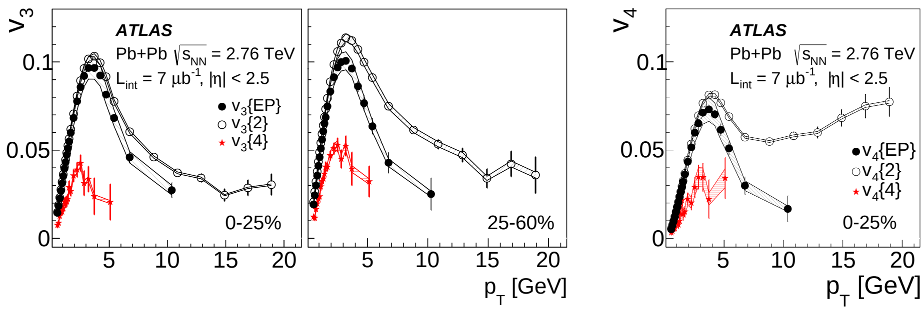

Fig. 3. The transverse momentum dependence of third (two left panels) and fourth (right panel) flow harmonics. The v_3 is shown in two wide centrality bins, 0–25% and 25–60%, due to lower statistics. The v_4 is shown only in one bin of 0–25%. The comparison is done between EP and two- and four-particle cumulant methods [14].

4. Summary

High precision measurements of azimuthal anisotropy in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were performed by the ATLAS experiment. Three flow harmonics, v_2, v_3 and the v_4 were measured using the multi-particle cumulant and the event plane methods. The $v_2\{2,4,6,8\}$ and $v_2\{\mathrm{EP}\}$ harmonics were obtained in a broad range of centrality (0–80%), pseudorapidity ($|\eta| < 2.5$) and transverse momentum ($0.5 < p_{\mathrm{T}} < 20$ GeV). Using higher order cumulants allows effectively reduce the contribution of non-flow correlations in flow harmonics. Efficient non-flow subtraction is already obtained using the four-particle correlation.

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