Measurement of elliptic and higher order flow harmonics in 2.76 TeV Pb-Pb collisions with the ATLAS detector

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Abstract.

We present the measurements of charged particle azimuthal anisotropy in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at LHC. These anisotropies are quantified by the Fourier harmonics $v_n$ and are important observables in heavy ion collisions containing information about the initial geometry as well as the transport properties of the produced medium. The measurements are done in broad ranges of transverse momentum pseudorapidity and centrality via the event plane and two-particle correlation methods using 8 $\mu$b$^{-1}$ of Pb-Pb data. We show that for central and mid-central collisions and at low and intermediate $p_T$, the long range structures in two-particle correlations are entirely accounted for by the collective flow. Some interesting scaling relations between the $v_n$ are also shown.

1. Introduction

A central goal of the heavy ion program at the Large Hadron Collider (LHC) is to understand the properties of the hot and dense matter produced in relativistic heavy ion collisions, commonly termed as the quark gluon plasma. One of the ways to study its properties is to perform high accuracy measurements of the azimuthal yields of the produced particles. Due to anisotropic pressure gradients, the “fireball” produced in the collisions expands differently in different directions with more particles emitted along the larger gradients. This anisotropy in the particle yields can be expressed as a Fourier series:

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n^a \cos(n(\phi - \Phi_n))$$  \hspace{1cm} (1)

where $\phi$ is the azimuthal angle of the produced particles, $v_n$ is the magnitude of the $n^{th}$ order harmonic flow and $\Phi_n$ is the orientation of the corresponding harmonic plane [1]. The superscript ‘$a$’ is used to indicate particle species, $p_T$ bin and centrality.

The elliptic flow $v_2$ has been studied extensively as it usually dominates other coefficients, being strongly influenced by the elliptic geometry of the overlap region between the colliding nuclei. However, the initial geometry of the produced fireball may have angular moments of several orders: elliptic, triangular and higher orders due to fluctuations in the spatial positions of the nucleons in the colliding nuclei. These higher order moments in the initial geometry can give rise to measurable higher order flow ($n > 3$).
A better understanding of the higher order $v_n$ can explain the origin of the ridge, an elongated structure along $\Delta \eta$ at $\Delta \phi \sim 0$ [2] and the so-called “mach-cone”, a double hump structure on the away-side [3] seen in two-particle correlations. These were initially interpreted as response of the medium to the energy deposited by the quenched jets. However, recent studies [4] have shown that higher order flow harmonics make a significant contribution to these structures. The $v_n$ can also be used to obtain information about the initial geometry and transport properties of the medium, for instance the viscosity to entropy ratio [5, 6, 7].

The $v_n$ can be measured by the event plane (EP) method where one determines the orientation of the harmonic planes $\Phi_n$ and then, by measuring the yield of the particles about these planes, obtains the $v_n$. They can also be measured by the two-particle correlation (2PC) method where one measures the relative yield of associated (or partner) particles with respect to trigger particles in $\Delta \phi = \phi_{\text{trigger}} - \phi_{\text{partner}}$ and $\Delta \eta = \eta_{\text{trigger}} - \eta_{\text{partner}}$. The 2PC correlation function can be expanded in a Fourier series in $\Delta \phi$ as:

$$C(\Delta \phi) \propto 1 + 2 \sum_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b) \cos(n \Delta \phi)$$  \hspace{1cm} (2)

where the superscripts $a$ and $b$ label the trigger and partner particles. If the only contribution to correlations comes from collective flow, then the Fourier coefficients $v_{n,n}$ are equal to the product of the individual single particle $v_n$ [8]:

$$v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a) \times v_n(p_T^b)$$  \hspace{1cm} (3)

Using Eq.3, one can obtain the $v_n$ from the 2PC. The above relation is violated if non-flow effects, like jets, are present. Thus before extracting the flow harmonics from the correlations, one must ensure that most (if not all) of the non-flow effects are removed.

All the results presented in this proceeding are for inclusive charged hadrons reconstructed in Minimum Bias events using the ATLAS inner detector [9] covering the pseudorapidity range $|\eta| < 2.5$. For the event plane analysis, the harmonic planes are determined using the Q-vector method [1], with the Q-vectors measured using the forward calorimeter (FCal) which lies at $|\eta| \in (3.3, 4.8)$. Details of the results presented here can be found in [10].

2. Event plane analysis

Figure 1 shows the $v_n$ as a function of centrality from EP method in 5% centrality bins plus a (0-1)% super-central bin, for two different $p_T$ ranges. The $v_2$ has a much stronger centrality dependence as compared to the other harmonics. For non-central events, $v_2$ becomes much larger than the other $v_n$ due to the elliptical geometry of the fireball. The other $v_n$, mainly driven by event-by-event fluctuations in the initial geometry have a weaker centrality dependence. In most central events (top 5%) and at sufficiently high $p_T$, $v_3$, $v_4$ and even $v_5$ can become larger than or comparable to $v_2$.

Figure 2 shows $v_n$ as a function of $p_T$ for two different centralities. For all centralities the $v_n$ have a similar trend, they increase to reach a maximum between $3 \text{ GeV} < p_T < 4 \text{ GeV}$ and then decrease. This is interpreted as the driving mechanism being the $v_n$ changing from collective flow at low $p_T$ to path-length dependent suppression at high $p_T$. In the (0-5)% central events, $v_3$ and $v_4$ become larger than $v_2$ at $p_T \sim 2 \text{ GeV}$ and 3 GeV respectively.

A scaling, previously observed at RHIC [11] is seen in the $p_T$ dependence of $v_n$: $v_n^{1/n} = k_n v_2^{1/2}$ where $k_n$ are only weakly dependent on $p_T$. This is shown in in the left panels of Fig.3 for several different centralities. The centrality dependence of the $k_n$ is shown in the right panel of Fig.3 for $p_T \in (2, 3) \text{ GeV}$. They vary weakly with centrality in mid-central and peripheral events, but increase strongly in central events.
Figure 1. Flow harmonics $v_n$ as a function of centrality in 5% centrality bins plus a (0-1)% most central bin (the right most point) for two $p_T$ bins. The shaded bands indicate systematic uncertainties.

Figure 2. Flow harmonics $v_n$ as a function of $p_T$ for two centrality bins. The shaded bands indicate the systematic uncertainties.

Figure 3. Left panels: $v_n^{1/n}/v_2^{1/2}$ as function of $p_T$ in different bins of centrality. Right panel: $v_n^{1/n}/v_2^{1/2}$ vs centrality for $p_T \in (2,3)\text{GeV}$.

In Fig.4 the $\eta$ dependence of the $v_n$ is shown for $p_T \in (2,3) \text{GeV}$. In this $p_T$ interval, $v_2$ decreases by at most 5% from $\eta = 0$ to $\eta = 2.5$, for $n > 2$ the decrease is slightly larger. In general, there is a weak dependence of the $v_n$ on $\eta$ in central and mid-central collisions. Eq.3 stated that ignoring non-flow effects, the 2PC $v_{n,n}$ is the product of the single particle $v_n$. This relation is only true if there is no $\eta$ dependence of the $v_n$ (or approximately true if the $\eta$ dependence is weak). The weak $\eta$ dependence justifies the use of Eq.3.
3. Two-particle correlations

Fig. 5 shows the 2PC in $\Delta \eta - \Delta \phi$ space for $p_T^a, p_T^b \in (2, 3) \text{ GeV}$ for three centrality bins. Such correlations, where both trigger and partner particle have same $p_T$ range, are termed as fixed-$p_T$ correlations. The near-side jet peak reported in [2] is clearly visible at $(\Delta \eta, \Delta \phi) \sim (0, 0)$ across all centralities and is more prominent in peripheral events. The near-side ridge has a weak $\Delta \eta$ dependence in central and mid-central collisions. The strength of the ridge increases from central to mid-central collisions and then decreases for peripheral collisions, completely disappearing in the (80-90)% centrality class, leaving behind only the near-side jet peak. In the (0-5)% central collisions (one can see a double hump structure on the away-side which transforms into a ridge-like structure in the (20-30)% mid-central collisions. In the (80-90)% peripheral collisions, it is replaced by the away-side jet. The presence of the near-side jet biases the values of the flow harmonics obtained from the two-particle correlations. This bias can be minimized by requiring a $|\Delta \eta| > 2.0$ cut between the trigger and the associated particle in the correlations.

The left panel in Fig. 6 shows the the one-dimensional $\Delta \phi$ correlation corresponding to the first panel of Fig. 5 for $2 < |\Delta \eta| < 5$. As the trigger and partner particle $p_T$ ranges are chosen to be the same, Eq. 3 becomes:

$$v_{n,n}(p_T^a, p_T^b) = v_n^2(p_T^n)$$  \hspace{1cm} \text{(4)}$$

Using this relation, the values of $v_n$ and its uncertainties are calculated from $v_{n,n}$ and are plotted as a function of $n$ in the panel c) of Fig. 6. The $v_n$ values are plotted up to $n = 15$. However,
the analysis is limited to \( n \leq 6 \) because for higher \( n \) the systematic and statistical uncertainties are large compared to the extracted value of \( v_n \).

**Figure 6.** Left Panel: The \( \Delta \phi \) correlation function (black points) for \( 2 < |\Delta \eta| < 5 \), overlaid with contributions from individual Fourier components and their sum. Right Panel: \( v_n \) vs. \( n \) (The bars and bands indicate statistical and systematic uncertainties respectively). The lower sub panel shows \( v_n \) for \( n \geq 7 \) in a linear scale.

Next step is to compare the \( v_n \) values obtained from the 2PC and the EP methods and check the validity of the factorization relation, Eq.3. But before that, it is already possible to check where the factorization will break down using the 2PC results. From Eq.2 it is seen that if collective flow dominated the 2PC, then the near-side peak must be larger than the away-side peak (as all harmonics add up at \( \Delta \phi = 0 \)). From Fig.7 it is seen that this is roughly true up to 50% centrality (for \( 3 \text{ GeV} < p_T^a, p_T^b < 4 \text{ GeV} \)) beyond which the away-side peak becomes larger indicating a break-down of the \( v_{n,n} \) factorization.

Similarly, in Fig.8 the \( p_T \) evolution of the correlations is shown for (0-10)% central events. At low \( p_T \) the correlation is driven by flow and the near-side peak is larger than the away-side. However, for \( p_T^a, p_T^b > 6 \text{ GeV} \), the 2PCs are dominated by the away-side peak, due to the strong influence of the away-side jet. Thus already from the 2PC, it is possible to estimate that the factorization will break down at high \( p_T (>6 \text{ GeV}) \) and in peripheral events (>)50% centrality.

**Figure 7.** Centrality dependence of \( \Delta \phi \) correlations for \( p_T^a, p_T^b \in (3,4)\text{GeV} \) and \( \Delta \eta \in (2,5) \). The superimposed solid lines (thick-dashed lines) indicate contributions from individual \( v_{n,n} \) components (sum of the first six components).

4. Comparison of \( v_n \) obtained from 2PC and EP methods

The left panels of Fig.9 compare the \( v_2 \) from fixed-\( p_T \) 2PC method with those from the EP method for (0-10)% central events. The two methods agree within 5% to 15% for \( v_2 \) for \( p_T < 4 \text{ GeV} \). Deviations are observed for \( p_T > 4-5 \text{ GeV} \), presumably due to contributions from the away-side jet.
Figure 8. Fixed-\(p_T\) correlation functions in the (0-10)\% centrality interval for several \(p_T\) ranges with \(2 < |\Delta \eta| < 5\).

Figure 9. Left panel: comparison between the fixed-\(p_T\) \(v_2(p_T)\) and EP \(v_2(p_T)\). Right panel: Comparison of \(v_2(p_T)\) obtained for four different reference \(p_T\) ranges (0.5-1, 1-2, 2-3, 3-4 GeV) with the EP values. The error bars indicate the statistical uncertainties only. The dashed lines in the ratio plots indicate a ±10\% band to guide the eye. All results are for the (0-10)\% centrality interval.

The \(v_n\) values obtained from fixed-\(p_T\) correlations (where trigger and partner particle are in same \(p_T\) range) can be cross-checked using correlations where the trigger and partner particle have different \(p_T^T\) and \(p_T^B\) values. Such correlations are termed as mixed-\(p_T\) correlations. The \(v_n(p_T^B)\) of the partner can be obtained as:

$$v_n(p_T^B) = v_{n,n}(p_T^T, p_T^B)/v_n(p_T^T)$$  \hspace{1cm} (5)

Equation 5 can be checked by measuring the same \(v_n(p_T^B)\) for different \(v_n(p_T^T)\). This is illustrated for \(v_2\) in the right panel of Fig.9. It is seen that factorization of \(v_{n,n}\) works well for \(n=2\) and the values of \(v_2(p_T^B)\) are reasonably independent of \(p_T^T\). Further it is seen that when \(p_T^T\) is below 3 GeV, the agreement of the 2PC values with the EP method extend out to much higher \(p_T^B\).

This shows that, as long as the reference \(p_T^T\) is low, the factorization relation is valid and hence the \(v_n\) can be measured to high \(p_T\) via the 2PC method.

Next, the validity of the factorization relation is checked for the other harmonics. In Fig.10 the \(v_1-v_6\) for \(p_T^B\) in (1.0, 1.5) GeV are plotted as a function of \(|\Delta \eta|\) for four different \(p_T^T\) bins for the (10-20)% centrality bin. Consider harmonics 2-6 for now. At low \(|\Delta \eta|\) different triggers give
different values for $v_n(p_T^b)$ showing that the scaling relation Eq.3 (or Eq.5) breaks down due to the influence of the near-side jet. However, for $|\Delta \eta| > 1.0$, all trigger-partner combinations give nearly identical values of $v_n(p_T^b)$ even though the trigger $v_n$ values vary over a large range. This validates Eq.3 and Eq.5, and shows that indeed the Fourier components ($n = 2$ to $n = 6$) in the 2PCs at large $|\Delta \eta|$ are due to collective flow.

Coming back to $v_{1,1}$, from the first panel of Fig.10, it is seen that for $v_{1,1}$ the factorization does not hold for any value of the $\Delta \eta$ gap. This is because the $v_{1,1}$ is influenced by global momentum conservation effects which must be accounted for before Eq.3 can be used. A detailed study of the $v_{1,1}$ in ATLAS, accounting for the momentum conservation effects to obtain the $v_{1,1}$ has been presented in a separate talk in this conference by J. Jia, details of which can be found in [10].

Figure 10. Flow harmonic $v_n(p_T^b)$ as a function of $|\Delta \eta|$ for $p_T^b \in (1, 1.5)$ GeV, calculated for four different reference $p_T^b$ ranges (0.5-1, 1-2, 2-3, and 3-4 GeV). The error bars indicate the statistical uncertainties only.

The left panel of Fig.11 shows the centrality dependence of the $v_n$ obtained from the two methods. For clarity only the statistical errors are shown. From the ratio plots in the bottom panels one can see that the values for $v_2$, $v_3$ and $v_4$ agree within 5% for central and mid-central collisions. For $v_5$ and $v_6$ they agree within 10% and 15% respectively and are consistent within the systematic uncertainties quoted in [10].

For central and mid-central collisions and $p_T < 4$ GeV, the two-particle correlation with $|\Delta \eta| > 2$ gap and EP method give consistent values of $v_n$. This indicates that the structures in two-particle correlations at large $\Delta \eta$ including the ridge and cone can be entirely accounted for by collective flow. To demonstrate this clearly, the EP $v_n$ values are used to reconstruct the 2PC which are then compared to the measured 2PC. The reconstructed $v_{n,n}$ are calculated according to Eq.3 as the product of the $v_n$ obtained using the EP method:

$$v_{n,n}^{\text{reco}} = v_n^{EP} \times v_n^{EP}$$

Since $v_1$ measurements were not made using the EP method, the $v_{1,1}$ component of the reconstructed correlation function is taken to be the same as that of the measured correlation function. The overall normalization of the reconstructed correlation function is taken to be
the same as that of the measured correlation function $N_0^{2PC}$. The final expression for the reconstructed correlation function can be written as:

$$C^{reco}(\Delta \phi) = N_0^{2PC} \left( 1 + 2v_{1,1}^{2PC} \cos(\Delta \phi) + 2 \sum_{n=2}^{6} v_n^{EP} v_n^{EP} \cos(n \Delta \phi) \right)$$  \hfill (7)

In the right panel of Fig.11 a reconstructed correlation function is for (0-1)% central collisions and $p_T^a, p_T^b \in (2,3)$ GeV is compared to the corresponding measured correlation. The measured 2PC is well reproduced with both the near-side ridge as well as the away-side double hump.

5. Summary

To summarize, consistent values of the flow harmonics $v_n$ were measured by EP and 2PC (with large $\Delta \eta$ gap) methods over larger $p_T$ and $\eta$ ranges and to higher orders than previously done at RHIC. An approximate scaling: $v_1^{1/n} \propto v_2^{1/2}$ was shown to hold. It was shown that the ridge and cone seen in 2PC for $|\Delta \eta| > 2.0$ for $p_T < 4.0$ GeV can be entirely accounted for by the collective flow of the medium without invoking additional physics models.

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