Measurement correlations between elliptic and higher-order flow harmonics in 2.76 TeV Pb+Pb collisions using the ATLAS detector

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Abstract. Measurements of correlations between elliptic and higher order flow harmonics in 2.76 TeV Pb+Pb collisions are presented. The correlations are measured as a function of centrality, as well as the ellipticity of the collision geometry. The origin of the measured correlations are determined by comparing to initial geometry models, and by fitting the data to functions whose forms are motivated by hydrodynamic considerations. The correlations are shown to give an insight into understanding of the initial geometry and expansion mechanism of the medium produced in heavy ion collisions.

1. Introduction and measurements

The medium produced in heavy ion collisions has spatial anisotropies of many orders characterized by the eccentricities ϵ_n . These eccentricities are transferred by collective expansion into anisotropies of the final particle distributions, quantified by the flow harmonics v_n [1]. The v_n , thus contain information about the initial geometry, as well as the expansion mechanism of the produced medium, and are important observables. Previous measurements have studied in detail the mean v_n as function of centrality [1], as well as the fluctuations in v_n at fixed centrality [2]. The v_n fluctuations within a given centrality bin are largely driven by the event-by-event fluctuations in the positions of the colliding nucleons. From these measurements, it is seen that the range over which the v_n fluctuate within one centrality interval is much larger than the variation of the mean v_n across all centralities. Thus, in order to completely understand the v_n , they must be studied not only as a function of centrality but also as a function of changing geometry at fixed centrality: this is called “event-shape-selected” v_n measurement [3].

Such shape-selected measurements can reveal several hidden correlations. For example, model calculations show that in the initial geometry, ϵ_2 and ϵ_3 are anti-correlated at fixed centrality [4]. This would lead to anti-correlation between v_2 and v_3 , as they are proportional to ϵ_2 and ϵ_3 respectively. Correlations between harmonics can also be generated dynamically as higher order harmonics can be driven by lower order eccentricities. For example, v_4 receives a “linear”-contribution from ϵ_4 and a “non-linear” contribution from ϵ_2 [5]. This would naturally lead to correlation between the magnitudes and phases of v_4 and v_2 as both are driven by ϵ_2 . The shape-selected v_n measurements can reveal the effects of such initial geometry correlations and non-linear hydrodynamic response.

The ATLAS detector due to its large acceptance is ideal for such shape-selected measurements. This analysis makes use of the ATLAS Forward calorimeter (FCal) for

Figure 1. Left Plot: An example of the q_2 -binning for the (0-1)% centrality bin. Right Plot: The 2PC for the (0-5)% centrality bin for three different q_2 bins. Figure taken from [6].

determining the event centrality and for event-shape selection. Charged particle tracks measured in the Inner Detector (ID), which has a pseudorapidity coverage of $\eta < 2.5$, are used to measure the v_n , which are in turn used for the v_n - v_2 correlations. The event-shape selection is implemented in the following manner: the observed E_T weighted v_2 in FCal (called q_2) is used to categorize events into q_2 -bins, centrality by centrality. The left panel of Fig. 1 shows the q_2 categorization for the (0-1)% centrality bin. Events with larger q_2 will have larger v_2 because of the global nature of collision geometry. For each q_2 -bin, v_2 - v_5 are measured using the ID tracks via two-particle correlations (2PC). The measurements described here are detailed in [6].

The right panel of Fig. 1 shows the 2PC in $\Delta\phi$ for the (0-5)% centrality range. Shown are the correlations for the 10% events with largest q_2 (red), 10% events with smallest q_2 (blue) and the 2PC without any binning in q_2 (black). Clear differences are seen in the 2PC for different q_2 -classes at fixed centrality. For example, a double hump is clearly seen on the away side for the events with smallest q_2 (blue), which is not seen in the inclusive case. This is because the lowest 10% q_2 case, the v_2 is small so the v_3 component dominates the 2PC and leads to this double-hump structure. This plot clearly demonstrates that there is large variation in geometry within a centrality interval, and that the event-shape selection is a natural way to study these fluctuations. From these 2PCs the v_n are extracted for each centrality and q_2 -bin using the factorization formula which states that the Fourier coefficients of the 2PC are products of the single-particle v_n [1].

The left panel of Fig. 2 shows the correlation between intermediate- p_T v_2 ($3 < p_T < 4$ GeV) and low- p_T v_2 ($0.5 < p_T < 2$ GeV) for several different centralities. The gray band indicates the inclusive correlation, while the points indicate the q_2 -selected results. The lines are linear fits to guide the eye. As one moves along the curves, the centrality remains fixed, but the event-geometry becomes more and more elliptic. The thick grey band indicates the inclusive correlation, where each 5% centrality bin is treated as a single point. It is seen that the correlation between intermediate and low- p_T for fixed centrality but changing event geometry is fairly linear. This is in complete contrast to the inclusive correlation (grey-band) where the correlation curves downward in a “boomerang”-like trajectory. The boomerang structure indicates that at the same value of the low- p_T v_2 , peripheral events have a lower value of the intermediate- p_T v_2 . This perhaps indicates that the viscous effects, which increase with p_T are more dominant in peripheral events. On the other hand, the linear correlation at fixed centrality but changing geometry indicates that once the system size has been fixed, changing the elliptic eccentricity does not alter viscous effects. Otherwise the correlations for the individual centralities would curve downward like the inclusive case.

The middle panel of Fig. 2 shows similar plots for the v_3 - v_2 correlation. A clear anti-

Figure 2. Correlation between v_n and the v_2 for p_T in (0.5,2.0) GeV (see text for details). Figure taken from [6].

correlation is seen between v_2 and v_3 at fixed centrality, but changing event-geometry that is much different than the how the inclusive correlation (grey-band) behaves. Clear non-linear correlations are seen in v_4 - v_2 case, shown in the last panel of Fig. 2, indicated by upward bending of v_4 at large v_2 . This non-linearity cannot be seen clearly in the inclusive correlations (grey-band).

To evaluate whether the observed correlations result from initial-state geometry, or from coupling between the harmonics in the hydrodynamic expansion, the results are compared to ϵ_n - ϵ_2 correlations in initial geometry models. This is shown in Fig. 3, where the measured v_3 - v_2 , v_4 - v_2 and v_5 - v_2 correlations in the (30-35)% centrality range are compared to the corresponding ϵ_n - ϵ_2 correlations calculated in Glauber and MC-KLN models [7]. For the v_3 - v_2 case, both initial geometry models describe the measured correlations reasonably well, indicating that this correlation is primarily an initial-geometry effect. However significant deviation is seen in the other two cases, indicating that they are perhaps generated during hydrodynamic expansion. Hydrodynamic calculations, as well as recent ATLAS measurements of event-plane correlations show that the harmonic v_4 receives non-linear contributions from ϵ_2 which couples it to v_2 [5]. Taking into consideration this non-linear contribution, the v_4 can be parameterized as [6]:

$$v_4 = \sqrt{a_0 \epsilon_4^2 + (c_1 \epsilon_2^2)^2} = \sqrt{c_0^2 + (c_1 v_2^2)^2} \quad (1)$$

where c_0 , is a measure of the contribution to v_4 from ϵ_4 , and $c_1 v_2^2$ is a measure of the non-linear response to ϵ_2 which is proportional to ϵ_2^2 . These two are termed as the linear and non-linear components of v_4 respectively. The v_4 - v_2 correlation shown in Fig. 3 is fit with Eq. 1, shown by the red-line. It is seen that the parameterized fit describes the data quite well, indicating that the two-component parameterization in Eq. 1 works quite well. Similarly, the v_5 - v_2 correlation is fit by a two-component model parameterization:

$$v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2} \quad (2)$$

where, as before, c_0 is a measure of the contribution to v_5 from ϵ_5 (linear component) and $c_1 v_2 v_3$ is a measure of the non-linear response to $\epsilon_2 \epsilon_3$ which couples v_5 to $v_2 v_3$. The fit shown in the last panel of Fig. 3 by the red line, describes the data quite well, unlike the two models based on purely initial-state geometry.

Similar fits are done for all centrality bins and the linear and non-linear components of v_4 and v_5 are extracted for each centrality. These are plotted as function of number of participating nucleons, N_{part} , in Fig. 4, by mapping the centralities to N_{part} [2]. Also shown are the total

Figure 3. Comparison of the measured v_3 - v_2 (left plot), v_4 - v_2 (center plot) and v_5 - v_2 (right plot) correlations to the corresponding ϵ_n - ϵ_2 correlations calculated in Glauber (black continuous line) and MC-KLN (dashed line) initial geometry models, and to parameterized fits (red line) (see text for details). Figure taken from [6].

Figure 4. Left (Center) Plot: The linear component, non-linear component and total v_4 (v_5) as a function of N_{part} . The symbols represent the results obtained from the event-shape analysis while the continuous curves represent similar results derived from the event-plane correlations measured by ATLAS [5]. The shaded (hashed) bands represent the systematic uncertainties in the two measurements. Right Plot: The ratio of the $v_n/\sqrt{\epsilon_n^2}$ as a function of N_{part} for $n=2$ -6. For v_4 and v_5 the ratio is shown for both the total v_n as well as the linear component of v_n . Figures taken from [6].

v_4 and v_5 . As mentioned before, physically, the linear component is the part of v_4 (v_5) that is largely driven by ϵ_4 (ϵ_5), and is uncorrelated with lower-order harmonics. It is seen that in most central events the linear component dominates, while with decreasing centrality the non-linear component becomes more important, indicating that a large fraction of the measured v_4 and v_5 are actually generated by ϵ_2 and $\epsilon_2\epsilon_3$ respectively. Also shown for comparisons in Fig. 4 are the linear and non-linear components of v_4 and v_5 obtained from event-plane correlation measurements, where the correlation between the phases of v_4 - v_2 and between the phases of v_5 - v_3 - v_2 were measured [5, 6]. The results from the two very independent measurements compare quite well.

The last panel of Fig. 4 compares the $v_n/\text{rms-}\epsilon_n$ ratios for the inclusive v_n values. The idea behind making these plots is that this ratio is sensitive to viscosity and should be smaller when

viscous effects are larger. For v_4 and v_5 , the ratio is shown for the linear component as well as the total v_n . In the literature one can find several such comparisons [2], however this is the first time where the linear components for v_4 and v_5 are used in the ratios, which is a more appropriate quantity, as it compares only that part of v_4 (v_5) that is driven directly by ϵ_4 (ϵ_5). The linear component shows greater variation, indicating larger viscous dampening for higher harmonics, with decreasing centrality.

2. Summary

Measurements of the correlation between v_n ($n=2-5$) and v_2 over broad centrality ranges were presented. Using the correlations between the low- p_T v_2 and intermediate- p_T v_2 , it was shown that the viscous effects in heavy ion collisions depend on only the size of the colliding system but not on its geometry. An anti-correlation was observed between v_3 and v_2 at fixed centrality but changing event ellipticity that could be entirely attributed to initial geometry effects. The v_4 - v_2 and v_5 - v_2 correlations were shown to be different than those expected from initial-geometry models. However, the measured correlations were well described by two-component parameterized fits, whose form is expected from hydrodynamic considerations. From these two-component fits, the linear and non-linear components of v_4 and v_5 were extracted. It was shown that the linear components dominate in most central events, while the non-linear components become more important in mid-central and peripheral events.

References

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