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Soft probes of p+Pb and Pb+Pb collisions in the ATLAS experiment at the LHC

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Abstract. Collective flow and azimuthal correlation measurements of particles in the p_{T} region $\lesssim$ 10 GeV provide valuable information in constraining the initial conditions and expansion dynamics of the system produced in heavy-ion collisions. ATLAS collaboration has recently measured correlations between flow harmonics in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, using an event-shape selection procedure, and has separated the components arising from linear and non-linear hydrodynamic evolution in higher order harmonics (v_4 and v_5). A brief overview of these results are presented in these proceedings. Recently, azimuthal correlations extending to large pseudorapidity differences ("ridge"), similar to that seen in heavy-ion collisions, was observed in p+Pb collisions at LHC. These proceedings also present a measurement of the Fourier harmonics associated with the ridge correlations (v_1 to v_5) in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV by ATLAS collaboration. The results are compared with v_n in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with similar event multiplicities. Reasonable agreement is observed after accounting for the difference in the average p_{T} of particles produced in the two collision systems, consistent with a recent hydrodynamic calculation.

1. Introduction

The particles produced in heavy-ion collisions at RHIC and LHC show azimuthal anisotropy that extend over large pseudorapidity (η) [1, 2]. In AA collisions these long-range correlations are well described by a hydrodynamic expansion resulting from the anisotropic initial density distribution [3, 4]. The azimuthal anisotropy in particle production is often expanded in a Fourier series, $\frac{dN}{d\phi} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n))$. The second and third harmonics in the Fourier expansion arise from a linear response to the corresponding initial eccentricities, ϵ_n, i.e $v_n \propto \epsilon_n$ [5]. However higher-order harmonics contain non-linear contributions from lower-order harmonics [5, 6]. Using an event-shape selection procedure, ATLAS collaboration has measured the correlations between flow harmonics in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The correlation between higher and lower-order harmonics show non-linear correlations, consistent with expectations from hydrodynamics. The linear and non-linear components are separated from the measured correlations for different centrality intervals. A brief discussion of these results are presented in these proceedings.

Recently, azimuthal correlations extending to large pseudorapidity differences (referred to as "ridge"), similar to that observed in heavy-ion collisions, was observed in p+Pb collisions at LHC [7, 8, 9] and d+Au collisions at RHIC [10]. The theoretical understanding of the origin of these correlations is still a matter of debate [11, 12]. ATLAS collaboration has done a detailed measurement of the first five Fourier harmonics ($v_1 - v_5$) associated with the ridge correlations in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. These proceedings discuss the ATLAS v_n results in p+Pb collisions. A comparison between v_n from p+Pb collisions and Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$

= 2.76 TeV with similar event multiplicity is also included. Reasonable agreements are observed after accounting for the difference in the average p_{T} of particles produced in the two collision systems, consistent with a recent hydrodynamic calculation, thus suggesting a similar or perhaps common origin of these correlations in both systems.

2. Flow correlations in Pb+Pb collisions

Correlation between flow harmonics in heavy-ion collisions can be studied using an event-shape analysis. The event-shape selection is done using the transverse energy (E_{T}) distribution in the ATLAS [13] forward calorimeter (FCal) in $3.3 < |\eta| < 4.9$. For each event, the energy distribution is expanded in a Fourier series, $2\pi\frac{dE_{\mathrm{T}}}{d\phi} = (\sum E_{\mathrm{T}})(1 + 2\sum_{n=1}^{\infty} q_n cos(n(\phi - \psi_n)))$. The reduced flow vector, q_n, represents the E_{T} weighted observed flow coefficients. In each centrality class, events are classed into different ellipticity bins according to the value of the observed elliptic flow, q_2. The v_n values are then calculated for each of these q_2 classes using tracks in the Inner Detector (ID, $|\eta| < 2.5$), using a two-particle correlation method.

The left panel in Figure 1 shows the v_4 values measured in the ID, as a function of the v_2 values measured in the ID for different q_2 classes. The results for different centrality classes are shown. The observed non-linear correlation between v_4 and v_2 is found to be well described by a two component fit, motivated by hydrodynamics [5], of the form $v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$. The middle panel shows the extracted linear ($v_n^L = c_0$) and non-linear components ($v_n^{NL} = \sqrt{v_n^2 - c_0^2}$), for $n = 4$, as a function of the number of participants. The values from a similar decomposition using the results from event-plane correlation measurements [14] are also shown. Good agreement can be seen between both, suggesting that the correlations between flow magnitudes arise from the correlations between the flow angles. Right panel shows a similar decomposition for v_5, from a fit of the form $v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$ to the measured correlation between v_5 and v_2. More results related to the analysis along with a detailed description of the procedure and systematics can be found elsewhere [15].

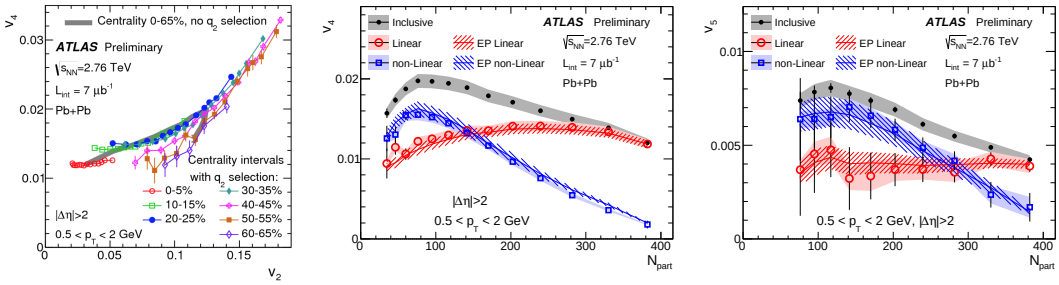

Figure 1. (Left) Correlation between v_2 and v_4, both measured in $0.5 < p_{\mathrm{T}} < 2$ GeV, for different centrality intervals. The data points in each centrality interval correspond to different q_2 bins. (Middle) N_{part} dependence of v_4 and the extracted linear and non-linear components associated with it. Also shown are the linear and non-linear components calculated from event-plane correlations. (Right) Similar plot for v_5. Error bars and shaded bands represent statistical and systematic uncertainties, respectively. [15]

3. Ridge in p+Pb collisions

The long-range correlations in p+Pb are studied using two-particle correlation constructed using the charged particle tracks reconstructed in the ID. A recoil subtraction procedure, similar to that described in [9], is applied at the per-trigger yield level by subtracting the per-trigger yield above uncorrelated pairs in a "peripheral" event class − defined as having $E_{\mathrm{T}} < 10$ GeV in the FCal on the Pb-going side. The recoil subtracted distribution is then expanded in a Fourier

series, and the two particle harmonic coefficients $v_{n,n}$ in the expansion are used to compute the single particle coefficients v_n, assuming factorization: $v_n(p_{\rm T}^{\rm a}) = v_{n,n}(p_{\rm T}^{\rm a}, p_{\rm T}^{\rm b})/\sqrt{v_{n,n}(p_{\rm T}^{\rm b}, p_{\rm T}^{\rm b})}$. A detailed description of the analysis procedure and systematic uncertainties along with a complete set of results can be found in [16].

The v_n values extracted from the subtracted distribution, for $n = 2$, 3, 4 and 5, as a function of the transverse momentum are shown in the left panel of Figure 2, for events with $220 \leq N_{\rm ch}^{\rm rec} < 260$. The v_n values increase with $p_{\rm T}$ in the low $p_{\rm T}$ region, reach a maximum around $3 - 5$ GeV and then decrease with further increase in $p_{\rm T}$, but remain positive in the measured range. This is similar to the $p_{\rm T}$ dependence of v_n harmonics measured in heavy-ion collisions [17]. The magnitude of v_n is found to decrease with increasing harmonic number n. The second panel of Figure 2 shows the first order harmonic, v_1, as a function of $p_{\rm T}^{\rm a}$. The values are obtained assuming factorization, but accounting for the sign change of v_1 at low $p_{\rm T}$. Good agreements are found between the v_1 values extracted using three different $p_{\rm T}^{\rm b}$ ranges. The v_1 is negative at low $p_{\rm T}$, crosses zero ~ 1.5 GeV and then increase to 0.1 in the $4 - 6$ GeV range. A similar $p_{\rm T}$ dependence for v_1 (with $v_1(p_{\rm T})$ crossing zero ~ 1.1 GeV) was observed in Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [17].

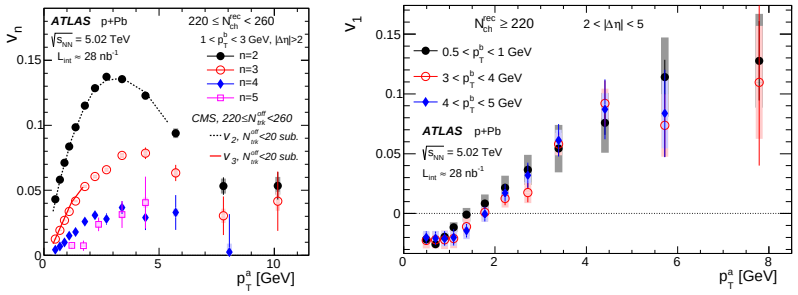

Figure 2. (Left) v_n for $n = 2{-}5$ as a function of $p_{\rm T}^{\rm a}$ for associated particles in the range $1 < p_{\rm T}^{\rm b} < 3$ GeV and $2 < |\Delta\eta| < 5$ for events with $220 \leq N_{\rm ch}^{\rm rec} < 260$. (Right) v_1 as a function of $p_{\rm T}^{\rm a}$ for different associated $p_{\rm T}$ selections for events with $220 \leq N_{\rm ch}^{\rm rec} < 260$. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively [16].

The left-panels of Figure 3 compares the v_n values from p+Pb collision in the event-activity class $220 \leq N_{\rm ch}^{\rm rec} < 260$ with those from Pb+Pb collisions in 55−60% centrality from [17]. The two event classes are selected such that they have similar efficiency corrected number of tracks with $p_{\rm T} > 0.5$ GeV and $|\eta| < 2.5$. The larger v_2 values in Pb+Pb collisions can be attributed to the elliptic collision geometry of the Pb+Pb system, while the larger v_4 values could be due to the non-linear coupling between v_2 and v_4 in the collective expansion [15]. The v_3 data for Pb+Pb collisions are similar in magnitude to those in p+Pb collisions which could be expected if v_3 arises from density fluctuations in both systems. A scaling relation between the v_n of p+Pb and Pb+Pb systems was proposed recently in [18]. It is argued that the $v_n(p_{\rm T})$ in p+Pb and $v_n(p_{\rm T}/K)$ in Pb+Pb systems should be proportional to each other at a given $p_{\rm T}$, with $K = 1.25$ being the ratio of mean $p_{\rm T}$ in the two collision systems. The right panels of Figure 3 show the comparison between $v_n(p_{\rm T})$ in p+Pb and $v_n(p_{\rm T}/K)$ in Pb+Pb. The $v_2(p_{\rm T}/K)$ and $v_4(p_{\rm T}/K)$ in Pb+Pb are also scaled vertically by an empirical factor of 0.66. The two sets of values are found to agree well with each other after the scaling of $p_{\rm T}$ axis.

4. Conclusions

Event-shape selection are used to measure correlations between flow harmonics and to separate linear and non-linear components in higher harmonics (v_4 and v_5). The linear and non-linear

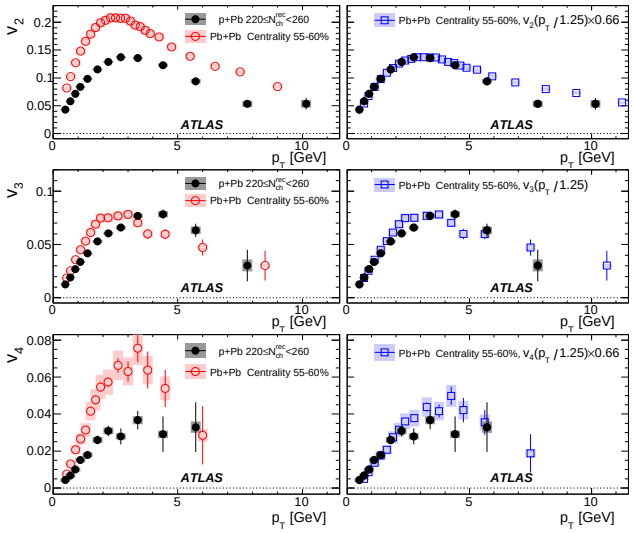

Figure 3. v_2 (top row), v_3 (middle row) and v_4 (bottom row) data compared between p+Pb collisions with $220 \leq N_{\rm ch}^{\rm rec} < 260$ in this analysis and Pb+Pb collisions in 55-60% centrality from [17]. Left column shows the original data with their statistical (error bars) and systematic uncertainties (shaded boxes). In right column, the same Pb+Pb data are rescaled horizontally by a constant factor of 1.25, and the v_2 and v_4 are also down-scaled by an empirical factor of 0.66 to match the p+Pb data [16].

components are extracted as function of centrality and show good agreement with the linear and non-linear components evaluated from event-plane correlation measurements. The first five Fourier harmonics associated with the ridge correlations in p+Pb collisions are measured. The v_n values show similar $p_{\rm T}$ dependence as the v_n from heavy-ion collisions. The $v_n(p_{\rm T})$ values from p+Pb collisions (for n =2, 3 and 4) are compared to those from Pb+Pb collisions for event class with similar average multiplicity. After applying a scale factor of $K = 1.25$, that accounts for the difference of mean $p_{\rm T}$ in the two collision systems, the $v_n(p_{\rm T}/K)$ from Pb+Pb is found to have similar shape as the $v_n(p_{\rm T})$ from p+Pb collisions. This could suggest that the long-range correlations in p+Pb and Pb+Pb systems are driven by similar dynamics.

5. References

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