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 $\sqrt{s_{NN}} = 2.76$ 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 $\sqrt{s_{NN}} = 5.02$ TeV by ATLAS collaboration. The results are compared with $v_n$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ 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 ($\eta$) [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, $dN/d\phi \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n))$. The second and third harmonics in the Fourier expansion arise from a linear response to the corresponding initial eccentricities, $\epsilon_n$, 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 $\sqrt{s_{NN}} = 2.76$ 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 ($v_1$ to $v_5$) associated with the ridge correlations in $p$+Pb collisions at $\sqrt{s_{NN}} = 5.02$ 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 $\sqrt{s_{NN}}$
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, $2\pi dE_T/d\phi = (\sum E_T(1 + 2\sum_{n=1}^{\infty} q_n \cos(n(\phi - \psi_n)))$.

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, $v_2$. 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 $v_2$ 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 ($v_4^L = c_0$) and non-linear components ($v_4^{NL} = \sqrt{v_2^4 - c_0^2}$), 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](image)

Figure 1. (Left) Correlation between $v_2$ and $v_4$, both measured in $0.5 < p_T < 2$ GeV, for different centrality intervals. The data points in each centrality interval correspond to different $q_2$ bins. (Middle) $N_{\text{part}}$ 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 $E_T < 10$ GeV in the FCal on the Pb-going side. The recoil subtracted distribution is then expanded in a Fourier

= 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.
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: $v_n(p_T^2) = v_{n,n}(p_T^2, p_T^2) / \sqrt{v_{n,n}(p_T^2, p_T^2)}$. 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 $220 \leq N_{ch}^{rec} < 260$. The $v_n$ values increase with $p_T$ in the low $p_T$ region, reach a maximum around $3 - 5$ GeV and then decrease with further increase in $p_T$, but remain positive in the measured range. This is similar to the $p_T$ 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 $p_T^2$. The values are obtained assuming factorization, but accounting for the sign change of $v_1$ at low $p_T$. Good agreements are found between the $v_1$ values extracted using three different $p_T^2$ ranges. The $v_1$ is negative at low $p_T$, crosses zero $\sim 1.5$ GeV and then increase to 0.1 in the $4 - 6$ GeV range. A similar $p_T$ dependence for $v_1$ (with $v_1(p_T)$ crossing zero $\sim 1.1$ GeV) was observed in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [17].

![Figure 2](image.png)

Figure 2. (Left) $v_n$ for $n = 2−5$ as a function of $p_T^2$ for associated particles in the range $1 < p_T^2 < 3$ GeV and $2 < |\Delta \eta| < 5$ for events with $220 \leq N_{ch}^{rec} < 260$. (Right) $v_1$ as a function of $p_T^2$ for different associated $p_T$ selections for events with $220 \leq N_{ch}^{rec} < 260$. 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 $220 \leq N_{ch}^{rec} < 260$ 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 $p_T > 0.5$ 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 $v_1$ 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 $v_n(p_T)$ in $p+$Pb and $v_n(p_T/K)$ in Pb+Pb systems should be proportional to each other at a given $p_T$, with $K = 1.25$ being the ratio of mean $p_T$ in the two collision systems. The right panels of Figure 3 show the comparison between $v_n(p_T)$ in $p+$Pb and $v_n(p_T/K)$ in Pb+Pb. The $v_2(p_T/K)$ and $v_4(p_T/K)$ 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 $p_T$ 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 $220 \leq N_{ch}^{p+p} < 260$ 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 $p_T$ dependence as the $v_n$ from heavy-ion collisions. The $v_n (p_T)$ 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 $p_T$ in the two collision systems, the $v_n (p_T/K)$ from Pb+Pb is found to have similar shape as the $v_n (p_T)$ 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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