Correlation of flow harmonics and mean transverse momentum in 5.02 TeV p +Pb and Pb+Pb collisions and event-plane dependence of HBT radii in high-multiplicity p +Pb collisions with the ATLAS detector

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Abstract

To assess the properties of the quark-gluon plasma formed in heavy ion collisions, correlations between the mean transverse momentum, $[p_T]$, and the magnitude of the flow harmonics, v_n , are measured by the ATLAS experiment at the LHC. The analysis uses data samples of Pb+Pb and p +Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, corresponding to integrated luminosities of $22 \mu\text{b}^{-1}$ and 28nb^{-1} , respectively. The correlations are measured using a modified Pearson coefficient that is independent of multiplicity fluctuations. To suppress any short-range correlations, the $[p_T]$ is measured at mid-rapidity and the flow harmonics are measured at forward rapidity. In Pb+Pb collisions, significant (non-zero) values of the correlation coefficients are observed for all studied harmonics, which show a strong centrality dependence but vary only weakly with the charged particle p_T range used in the measurement. On the other hand, in p +Pb collisions, the correlation coefficient measured for the 2nd harmonic is found to show only a weak centrality dependence. The predictions of a 3+1D viscous-hydrodynamic model are found to be qualitatively consistent with the data, indicating hydrodynamic origin of these correlations in p +Pb collisions. As an independent test for the hydrodynamic description of collectivity observed in p +Pb collisions, measurements of two-pion HBT correlations as a function of the angle of the pion pair with respect to the second-order event plane angle are presented. The HBT correlation functions, corrected for event plane resolution, are measured as a function of q_{out} , q_{side} and q_{long} in intervals of pair transverse momentum and second-order flow-vector magnitude. The correlation functions are fit using the Bowler-Sinyukov form with the exponential HBT correlation function. The extracted HBT radii, R_{out} , R_{side} and R_{long} and a significant out-side cross-term are found to exhibit significant modulation with respect to the second-order event plane, similar to that observed in heavy-ion collisions. Results of the measurements and physics implications of the result, will be discussed.

Keywords: flow, correlations, HBT, interferometry

1. Correlation of flow harmonics and mean transverse momentum in p +Pb and Pb+Pb collisions

The ATLAS experiment [1] measured correlation between the average momentum of charged particles $[p_T]$ and the magnitude of flow harmonics, v_n . The measurement is performed in Pb+Pb and p +Pb collisions

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at centre-of-mass energy per nucleon pair of 5.02 TeV. The event activity classes are defined by charged-particle multiplicity in the interval $0.5 < p_T < 5$ GeV and $|\eta| < 2.5$. Modification of charged-particle p_T spectra was already observed by the ALICE collaboration in events with different magnitude of observed flow in the same centrality class [2]. The existence of such correlation indicates a link between the initial-state quantity, $[p_T]$, and the v_n encoding the system evolution. In the ATLAS measurement a Pearson's correlation coefficient is obtained [3]. The coefficient depends among others on detector performance or selection of kinematic requirements applied on charged particles. Thus a modified variant of it, ρ , that ensures independence on the event multiplicity [4], is used in practice.

The ρ thus facilitates comparisons across the experiments and to the theory predictions. It is defined as

$$\rho = \frac{\text{cov}(v_n\{2\}^2, [p_T])}{\sqrt{\text{var}(v_n\{2\}^2)_{\text{dyn}}} \sqrt{c_k}}, \quad (1)$$

where the covariance, dynamical variance $\text{var}(v_n\{2\}^2)_{\text{dyn}}$ and the c_k are averages over events as denoted by $\langle \rangle$ and are defined as

$$\text{cov}(v_n\{2\}^2, [p_T]) = \left\langle \frac{1}{N_{\text{pairs}}} \sum_{k,j} e^{in\phi_k - in\phi_j} ([p_T] - \langle [p_T] \rangle) \right\rangle \quad (2)$$

$$\text{var}(v_n\{2\}^2)_{\text{dyn}} = v_n\{2\}^4 - v_n\{4\}^4 \quad (3)$$

$$c_k = 1/N_{\text{pairs}} \left\langle \sum_i \sum_{j \neq i} (p_{T,i} - \langle [p_T] \rangle)(p_{T,j} - \langle [p_T] \rangle) \right\rangle \quad (4)$$

where N_{pairs} is the number of particle pairs and ϕ is the particle azimuthal angle. In the calculation of the $\text{var}(v_n\{2\}^2)_{\text{dyn}}$, particles from opposite forward and backward sides of the detector, $|\eta| > 0.75$, are used to remove the non-flow effects. The $[p_T]$ is obtained using particles within $|\eta| < 0.5$. In the calculation of the covariance the central and forward regions are combined to ensure suppression of short-range correlations. For more details about this study and the above equations see [3]. The measurements are performed for three intervals of p_T to probe different regions of spectra: $0.5 < p_T < 2$ GeV which is well described by hydrodynamics, $p_T < 5$ GeV to observe an impact of the energy loss on ρ and the region with the increased lower threshold from 0.5 to 1 GeV (0.3 to 0.5 GeV in case of p +Pb) to test sensitivity to significant change in multiplicity. The covariance, dynamical variance for v_2 and c_k for Pb+Pb collisions are shown in Figure 1. A non-monotonic N_{ch} dependence is observed for covariance and variance. Also a nontrivial ordering for various p_T intervals can be observed. The coefficient ρ is shown in Figure 2 for Pb+Pb and p +Pb systems. It is anticipated that a more compressed initial stage leads to a larger $[p_T]$. At the same time, a compressed source has smaller initial asymmetry and as a consequence smaller magnitude of v_2 develops during the system evolution. Indeed, a negative correlation coefficient for v_2 is observed in peripheral Pb+Pb and in p +Pb collisions. In case of Pb+Pb data for more central collisions a significant positive correlation is observed suggesting a constructive interplay of the initial-stage energy density with the hydrodynamic evolution. In the very central events a change of the trends is observed. It can be attributed to the dominance of the fluctuations as a source of the v_2 . The correlation coefficient for p +Pb collisions resembles that one from the most peripheral Pb+Pb collisions, suggesting a common evolution path given similar initial

Fig. 1. The covariance, $\text{cov}(v_2\{2\}^2, [p_T])$ (left), dynamical variance, $\text{var}(v_2\{2\}^2)_{\text{dyn}}$ (center), and c_k (right) as a function of the number of charged particles N_{ch} [3].

Fig. 2. (from left to right and top to bottom) The modified correlation coefficient ρ for second flow harmonics in p +Pb collisions as a function of N_{ch} and for Pb+Pb collisions as a function of N_{part} , for the second, third and fourth flow harmonics and three p_T intervals as indicated in the legend [3].

conditions. Higher order harmonics feature different trends with centrality as compared to ρ for v_2 . For the $\rho(v_3\{2\}^2, [p_T])$ a steady rise is observed with growing multiplicity whereas for v_4 an opposite trend is seen. The results are compared to predictions obtained from hydrodynamical simulations [4]. A quantitative agreement is found supporting the hydrodynamic interpretation of the observed ρ .

2. Event-plane dependence of HBT radii in high-multiplicity in p +Pb collisions

The collective behaviour symptomatic to the quark-gluon plasma (QGP) signature is confirmed in the collisions of small systems at relativistic energies at the LHC. Competing theoretical models featuring hydrodynamics [5] and so called color-glass-condensate [6] are trying to explain the data. To be able to distinguish between the two, a more direct measurement of the azimuthal Hanbury Brown and Twiss (HBT) radii variation in the central p +Pb collisions is conducted with the ATLAS experiment [7]. In the measurement the events are categorised according to the magnitude of the observed flow in the event that is proxied by the value of the second order flow vector, $\vec{q}_2$, defined as

$$\vec{q}_2 = \frac{(\sum_i E_{T,i} \cos(2\phi_i), \sum_i E_{T,i} \sin(2\phi_i))}{\sum_i E_i}, \quad (5)$$

where $E_{T,i}$ is the transverse energy of the i -th calorimeter tower and ϕ_i is its azimuthal angle in the laboratory frame. The azimuthal angle of $\vec{q}_2$ defines the event-plane angle Ψ_2 with respect to which the azimuthal analysis is performed. For each charged pion pairs (a, b) the mean pair momentum vector, $\mathbf{k} = (\mathbf{p}_a + \mathbf{p}_b)/2$ is calculated. Next, the correlation function is obtained independently in eight bins of $\mathbf{k}$ azimuthal angle, ϕ , relative to Ψ_2 as follows

$$c(q) = \frac{dN_{ab}}{d^3\mathbf{p}_a d^3\mathbf{p}_b} / \frac{dN_a}{d^3\mathbf{p}_a} \frac{dN_b}{d^3\mathbf{p}_b} = \frac{A(\mathbf{q})}{B(\mathbf{q})} \quad (6)$$

where A and B are distributions obtained using tracks from the same and mixed events, respectively, and the vector $\mathbf{q} = \mathbf{p}_a - \mathbf{p}_b$ is the relative momentum of the pair. Distributions A and B are corrected for Ψ_2 resolution and the finite number of azimuthal bins [8]. Precautions are made in the event mixing procedure to match the vertex position as well as the orientation of the Ψ_2 angle. The correlation function is fitted with the Bowler-Sinyukov form [9, 10] to extract the HBT radii, the R matrix is parameterized with four ingredients R_{out} , R_{side} , mixed term R_{os} and R_{long} [11]. Further details can be found in Ref. [7]. The R matrices are obtained as a function of the azimuthal distance from Ψ_2 and fitted with the form $R = 2R_2 \sin 2(\phi - \Psi_2)$ or $R = R_o + 2R_2 \cos 2(\phi - \Psi_2)$ to obtain the amplitude of the variations R_2 . Figure 3 shows R_{side} , R_{out} and

R_{long} . A significant modulation, consistent across the range of $|\vec{q}_2|$ is observed for them. Other radii (not shown) also exhibit modulation with the amplitude distinct from zero indicating an asymmetric fireball at freezeout. Thus the results favour the hypothesis of the hydrodynamic evolution of the medium in $p+\text{Pb}$ collisions.

Fig. 3. (top) The HBT radii R_{out} (left), R_{side} (centre) and R_{long} (right) modulation with the distance from the Ψ_2 in bins of $|\vec{q}_2|$. (bottom) The amplitude of the modulation extracted from the cosine fits as a function of $|\vec{q}_2|$ [7].

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