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Azimuthally-differential pion femtoscopy relative to the third harmonic event plane in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV

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ABSTRACT

Azimuthally-differential femtoscopic measurements, being sensitive to spatio-temporal characteristics of the source as well as to the collective velocity fields at freeze out, provide very important information on the nature and dynamics of the system evolution. While the HBT radii oscillations relative to the second harmonic event plane measured recently reflect mostly the spatial geometry of the source, model studies have shown that the HBT radii oscillations relative to the third harmonic event plane are predominantly defined by the velocity fields. In this Letter, we present the first results on azimuthally-differential pion femtoscopy relative to the third harmonic event plane as a function of the pion pair transverse momentum $k_{\rm T}$ for different collision centralities in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. We find that the $R_{\rm side}$ and $R_{\rm out}$ radii, which characterize the pion source size in the directions perpendicular and parallel to the pion transverse momentum, oscillate in phase relative to the third harmonic event plane, similar to the results from 3+1D hydrodynamical calculations. The observed radii oscillations unambiguously signal a collective expansion and anisotropy in the velocity fields. A comparison of the measured radii oscillations with the Blast-Wave model calculations indicate that the initial state triangularity is washed-out at freeze out.

1. Introduction

Heavy-ion collisions at LHC energies create a hot and dense medium known as the quark–gluon plasma (QGP) [1]. The QGP fireball first expands, cools, and then freezes out into a collection of final-state hadrons. Correlations among the particles carry information about the space–time extent of the emitting source, and are imprinted on the final-state spectra due to a quantum-mechanical interference effect [2]. Commonly known as intensity or Hanbury–Brown–Twiss (HBT) interferometry, the correlation of two identical particles at small relative momentum, is an effective tool to study the space–time ("femtoscopic") structure of the emitting source in relativistic heavy-ion collisions [3]. The initial state of a heavy-ion collision is characterized by spatial anisotropies that lead to anisotropies in pressure gradients, and consequently to azimuthal anisotropies in final particle distributions, commonly called anisotropic flow. Anisotropic flow is usually characterized by a Fourier decomposition of the particle azimuthal distribution and quantified by the flow coefficients v_n and the corresponding symmetry plane angles Ψ_n [4]. Elliptic flow is quantified by the second flow harmonic coefficient v_2, whereas triangular flow [5] is quantified by v_3. Due to the position–momentum correlations in particle emission [6], the particles emitted at a particular angle relative to the flow plane carry information about the source as seen from that corresponding direction; these correlations also lead to the HBT radii to be sensitive to the collective velocity fields, from which information about the dynamics of the system evolution can be extracted.

Azimuthally-differential femtoscopic measurements can be performed relative to the direction of different harmonics event planes [7,8]. The measurements of the HBT radii with respect to the first harmonic event plane (directed flow) at the AGS [9] revealed that the source was tilted relative to the beam direction [10]. The HBT radii variations relative to the second harmonic event plane angle (Ψ_2) provide information on the pion source elliptic eccentricity at freeze-out. The recent ALICE measurements [11] indicate that due to the strong in-plane expansion the final-state source elliptic eccentricity is more than a factor 2–3 smaller compared to the initial-state. While the HBT radii modulations relative to Ψ_2 are defined mostly by the source geometry, the azimuthal dependence of the HBT radii relative to the third harmonic event plane (Ψ_3) originate predominantly in the anisotropies of the collective velocity fields – for a triangular, but static source the radii do not exhibit any oscillations [12]. Models studies [13,14] show that the anisotropy in expansion velocity as well as the system geometrical shape can be strongly constrained by azimuthally differential femtoscopic measurements relative to

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Ψ_3. The HBT radii oscillations relative to the third harmonic event plane have been first observed in Au–Au collisions at RHIC energy by the PHENIX Collaboration [15]. Unfortunately, due to large uncertainties these measurements did not allow to obtain detailed information on the origin of the observed oscillations.

In this Letter, the first azimuthally-differential femtoscopic measurement relative to the third harmonic event plane in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV from the ALICE experiment are presented. We compare our results to the toy-model calculations from [13] to get an insight on the role of the anisotropies in the velocity fields and the system shape. In addition, we compare our results to a $3+1$D hydrodynamical calculations [14] and a Blast-Wave Model [16] for a quantitative characterization of the final source shape.

2. Data analysis

The analysis was performed over the data sample recorded in 2011 during the second Pb–Pb running period at the LHC. Approximately 2 million minimum bias events, 29.2 million central trigger events, and 34.1 million semi-central trigger events were used. The minimum bias, semi-central, and central triggers used all require a signal in both V0 detectors [17]. The V0 detector, also used for the centrality determination [18], is a small angle detector of scintillator arrays covering pseudorapidity ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ for a collision vertex occurring at the center of the ALICE detector. The results of this analysis are reported for collision centrality classes expressed as ranges of the fraction of the inelastic Pb–Pb cross section: 0–5%, 5–10%, 10–20%, 20–30%, 30–40%, and 40–50%. Events with the primary event vertex along the beam direction $|V_z| < 8$ cm were used in this analysis to ensure a uniform pseudorapidity acceptance. A detailed description of the ALICE detector can be found in [19,20]. The Time Projection Chamber (TPC) has full azimuthal coverage and allows charged-particle track reconstruction in the pseudorapidity range $|\eta| < 0.8$, as well as particle identification via the specific ionization energy loss $\mathrm{d}E/\mathrm{d}x$ associated with each track. In addition to the TPC, the Time-Of-Flight (TOF) detector was used for identification of particles with transverse momentum $p_{\rm T} > 0.5$ GeV/c.

The TPC has 18 sectors covering full azimuth with 159 pad rows radially placed in each sector. Tracks with at least 80 space points in the TPC were used in this analysis. Tracks compatible with a decay in flight (kink topology) were rejected. The track quality was determined by the χ^2 of the Kalman filter fit to the reconstructed TPC clusters [21]. The χ^2 per degree of freedom was required to be less than 4. For primary track selection, only trajectories passing within 3.2 cm from the primary vertex in the longitudinal direction and 2.4 cm in the transverse direction were used. Based on the specific ionization energy loss in the TPC gas compared with the corresponding Bethe–Bloch curve, and the time of flight in TOF, a probability for each track to be a pion, kaon, proton, or electron was determined. Particles for which the pion probability was the largest were used in this analysis. This resulted in an overall purity above 95%, with small contamination from electrons in the region where the $\mathrm{d}E/\mathrm{d}x$ for the two particle types overlap. Pions were selected in the pseudorapidity range $|\eta| < 0.8$ and $0.15 < p_{\rm T} < 1.5$ GeV/c.

The correlation function $C(\mathbf{q})$ was calculated as

$$C(\mathbf{q}) = \frac{A(\mathbf{q})}{B(\mathbf{q})}, \tag{1}$$

where $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$ is the relative momentum of two pions, $A(\mathbf{q})$ is the distribution of particle pairs from the same event, and $B(\mathbf{q})$ is the background distribution of uncorrelated particle pairs. The background distribution is built by using the mixed-event technique [22] in which pairs are made out of particles from three different events with similar centrality (less than 2% difference), event-plane angle (less than 6° difference), and event vertex position along the beam direction (less than 4 cm difference). Both the $A(\mathbf{q})$ and $B(\mathbf{q})$ distributions were measured differentially with respect to the third harmonic event-plane angle $\Psi_{\rm EP,3}$. Note, that measurements relative to $\Psi_{\rm EP,3}$ will smear any contribution from elliptic flow as the elliptic and triangular event planes are uncorrelated [23]. The third harmonic event-plane angle $\Psi_{\rm EP,3}$ was determined using TPC tracks. To avoid auto-correlation each event was split into two subevents ($-0.8 < \eta < 0$ and $0 < \eta < 0.8$). Pairs were chosen from one subevent and the third harmonic event-plane angle $\Psi_{\rm EP,3}$ was estimated using the particles from the other subevent, and vice-versa, with the event plane resolution determined from the correlations between the event planes determined in different subevents [4]. Requiring a minimum value in the two-track separation parameters $\Delta\varphi^* = |\varphi_1^* - \varphi_2^*|$ and $\Delta\eta = |\eta_1 - \eta_2|$ reduces two-track reconstruction effects such as track splitting or track merging. The quantity φ^* is defined in this analysis as the azimuthal angle of the track in the laboratory frame at the radial position of 1.6 m inside the TPC. Splitting is the effect when one track is reconstructed as two tracks, and merging is the effect of two tracks being reconstructed as one. Also, to reduce the splitting effect, pairs that share more than 5% of the TPC clusters were removed from the analysis. It is observed that at large relative momentum the correlation function is a constant, and the background pair distribution is normalized such that this constant is equal to unity. The analysis was performed for different collision centralities in several ranges of $k_{\rm T}$, the magnitude of the pion-pair transverse momentum $\mathbf{k}_{\rm T} = (\mathbf{p}_{\rm T,1} + \mathbf{p}_{\rm T,2})/2$, and in bins of $\Delta\varphi = \varphi_{\rm pair} - \Psi_{\rm EP,3}$, where $\varphi_{\rm pair}$ is the pair azimuthal angle. The Bertsch–Pratt [3,24] out–side–long coordinate system was used with the *long* direction pointing along the beam axis, *out* along the transverse pair momentum, and *side* being perpendicular to the other two. The three-dimensional correlation function was analyzed in the Longitudinally Co-Moving System (LCMS) [25], in which the total longitudinal momentum of the pair is zero, $p_{1,\rm L} = -p_{2,\rm L}$.

To isolate the Bose–Einstein contribution in the correlation function, effects due to final-state Coulomb repulsion must be taken into account. For that, the Bowler–Sinyukov fitting procedure [26,27] was used in which the Coulomb weight is only applied to the fraction of pairs (λ) that participate in the Bose–Einstein correlation. In this approach, the correlation function is fitted by

$$C(\mathbf{q}, \Delta\varphi) = N[(1-\lambda) + \lambda K(\mathbf{q})(1 + G(\mathbf{q}, \Delta\varphi))], \tag{2}$$

where N is the normalization factor. The function $G(\mathbf{q}, \Delta\varphi)$ describes the Bose–Einstein correlations and $K(\mathbf{q})$ is the Coulomb part of the two-pion wave function integrated over a source function corresponding to $G(\mathbf{q})$. In this analysis the Gaussian form of $G(\mathbf{q}, \Delta\varphi)$ [28] was used

$$\begin{aligned} G(\mathbf{q}, \Delta\varphi) = \exp\Big[& -q_{\rm out}^2 R_{\rm out}^2(\Delta\varphi) - q_{\rm side}^2 R_{\rm side}^2(\Delta\varphi) \\ & - q_{\rm long}^2 R_{\rm long}^2(\Delta\varphi) - 2q_{\rm out}q_{\rm side} R_{\rm os}^2(\Delta\varphi) \\ & - 2q_{\rm side}q_{\rm long} R_{\rm sl}^2(\Delta\varphi) - 2q_{\rm out}q_{\rm long} R_{\rm ol}^2(\Delta\varphi)\Big], \end{aligned} \tag{3}$$

where the parameters $R_{\rm out}$, $R_{\rm side}$, and $R_{\rm long}$ are traditionally called HBT radii in the *out*, *side*, and *long* directions. The cross-terms $R_{\rm os}^2$, $R_{\rm sl}^2$, and $R_{\rm ol}^2$ describe the correlation in the *out-side*, *side-long*, and *out-long* directions, respectively.

The systematic uncertainties on the extracted radii, discussed below, vary in $k_{\rm T}$ and centrality. They include uncertainties related

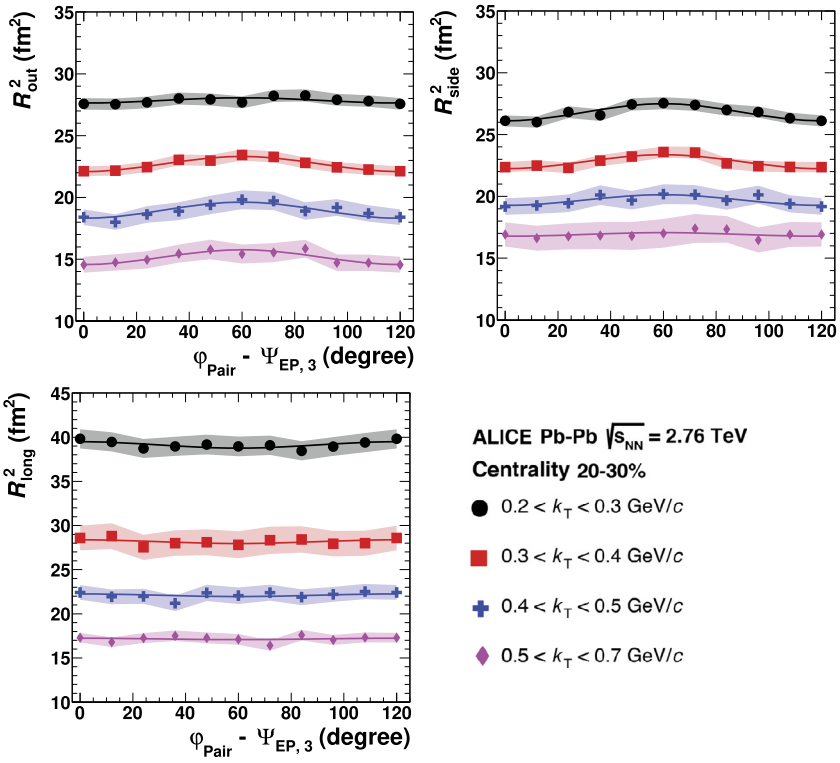

Fig. 1. The azimuthal dependence of $R^2_{\rm out}$, $R^2_{\rm side}$, and $R^2_{\rm long}$ as a function of $\Delta\varphi = \varphi_{\rm pair} - \Psi_3$ for centrality percentile 20–30% and four different $k_{\rm T}$ ranges. Solid lines represent the fit to the functional forms of Eq. (4). The shaded bands show the systematic uncertainty.

to the tracking efficiency and track quality, momentum resolution, different values for pair cuts ($\Delta\varphi^*$ and $\Delta\eta$), and correlation function fit ranges [29]. Similarly to the azimuthally inclusive analysis [29], different pair cuts were used, with the default values chosen based on a Monte Carlo study. The difference in the results from using different pair cuts rather than the default pair cuts were included in the systematic uncertainties (1–4%). For different $k_{\rm T}$ and centrality ranges, different fitting ranges of correlation function were used as the width of the correlation function depends on $k_{\rm T}$ and centrality range. The difference in the results from using different fit ranges are due to the contamination of electrons in the particle identification and the non-perfect Gaussian source (1–3%). We also studied the difference in the results by using positive and negative pion pairs separately as well as data obtained with two opposite magnetic field polarities of the ALICE L3 magnet. They have been analyzed separately and a small difference in the results (less than 3%) has been also accounted for in the systematic uncertainty. The total systematic uncertainties were obtained by adding in quadrature the contributions from all various sources mentioned above. The systematic uncertainty associated with the event plane determination is negligible compared to other systematic uncertainties; the procedure for the reaction plane resolution correction of the results is described in the next section.

3. Results

Fig. 1 presents the dependence of $R^2_{\rm out}$, $R^2_{\rm side}$, and $R^2_{\rm long}$ on the pion emission angle relative to the third harmonic event plane for centrality 20–30% and different $k_{\rm T}$ ranges. Note that $R^2_{\rm out}$ and $R^2_{\rm side}$ exhibit in-phase oscillations (for a quantitative analysis, see below). Within the uncertainties of the measurement, $R^2_{\rm long}$ oscillations, if any, are insignificant. Oscillations of $R^2_{\rm ol}$ and $R^2_{\rm sl}$ radii (not shown) are found to be consistent with zero, as expected due to the source symmetry in longitudinal direction, and are not further investigated. The curves represent the fits to the data using the functions [12]:

$$\begin{aligned} R^2_{\mu}(\Delta\varphi) &= R^2_{\mu,0} + 2R^2_{\mu,3}\cos(3\Delta\varphi) \quad (\mu = \text{out, side, long}), \\ R^2_{\rm os}(\Delta\varphi) &= R^2_{\rm os,0} + 2R^2_{\rm os,3}\sin(3\Delta\varphi). \end{aligned} \tag{4}$$

Fitting the radii's azimuthal dependence with the functional forms of Eq. (4) allows us to extract the average radii and the amplitudes of oscillations. The χ^2 per number of degree of freedom is 0.3–1.8 depending on $k_{\rm T}$ and centrality range. The results for the average radii $R^2_{\rm out,0}$, $R^2_{\rm side,0}$, and $R^2_{\rm os,0}$ were found to be consistent with those reported previously in [11] in azimuthally inclusive analysis. The extracted amplitudes of oscillations have to be corrected for the finite event plane resolution. There exist several methods for such a correction [30], which produce consistent results [31] well within uncertainties of this analysis. The results shown below have been obtained with the simplest method first used by the E895 Collaboration [9], in which the amplitude of oscillation is divided by the event plane resolution. In this analysis the event plane resolution correction factor is about 0.6–0.7, depending on centrality.

Fig. 2 shows the oscillation parameters $R^2_{\rm out,3}$, $R^2_{\rm side,3}$, $R^2_{\rm long,3}$, and $R^2_{\rm os,3}$ for different centrality and $k_{\rm T}$ ranges. All radii oscillations exhibit weak centrality dependence, likely reflecting the weak centrality dependence of the triangular flow itself. The $k_{\rm T}$ dependence is different for different radii oscillations: while the magnitudes of $R^2_{\rm out,3}$ and $R^2_{\rm os,3}$ are smallest for the smallest $k_{\rm T}$ range, it is opposite for $R^2_{\rm side,3}$ (and, possibly for $R^2_{\rm long,3}$), where the oscillations become stronger. The parameter $R^2_{\rm long,3}$ is consistent with zero within the systematic uncertainties while $R^2_{\rm os,3}$ is positive for all centralities and $k_{\rm T}$ ranges except for the lowest $k_{\rm T}$ range 0.2–0.3 GeV/c. Note that $R^2_{\rm out,3}$ and $R^2_{\rm side,3}$ are negative for

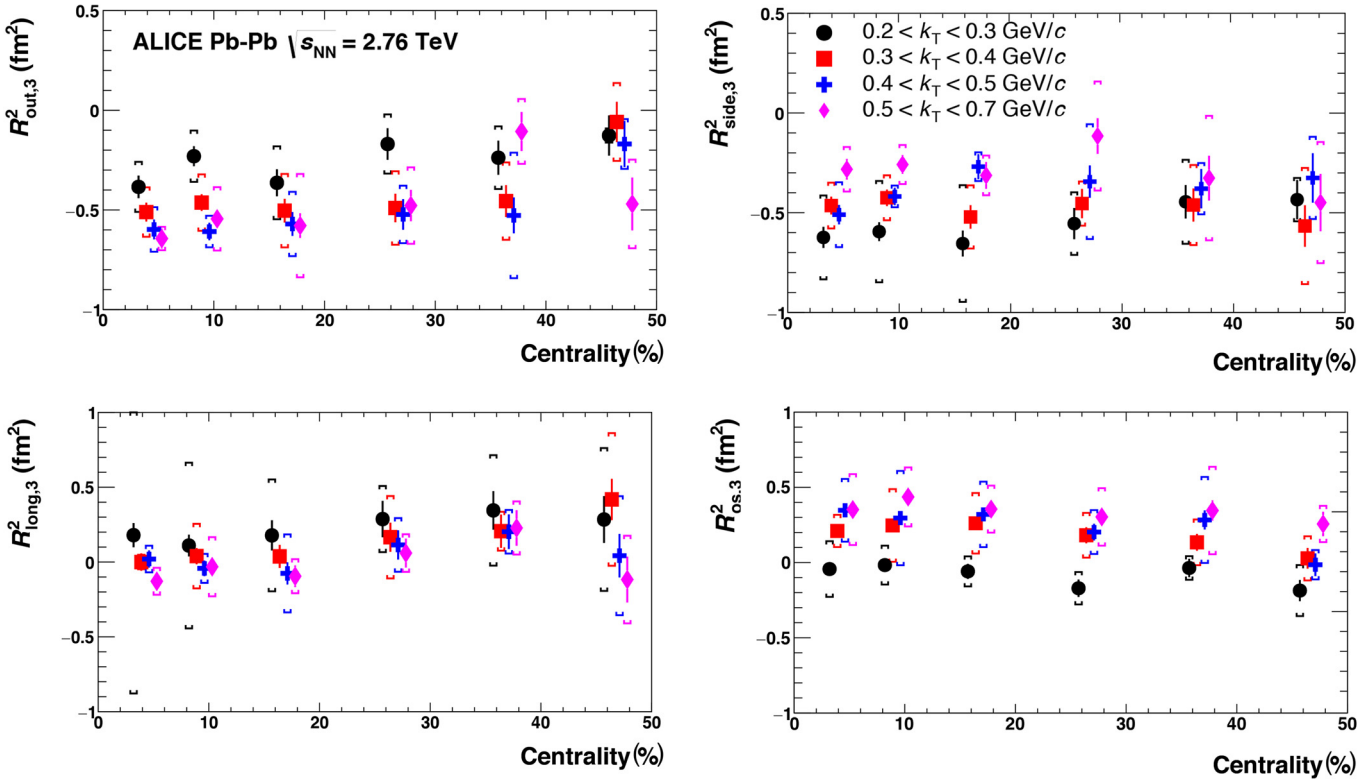

Fig. 2. The amplitudes of radii oscillations $R^2_{\mathrm{out},3}$, $R^2_{\mathrm{side},3}$, $R^2_{\mathrm{long},3}$, and $R^2_{\mathrm{os},3}$ versus centrality percentiles for four k_{T} ranges. Square brackets indicate systematic uncertainties.

all centralities and k_{T} ranges. In the toy model simulations [13] such phases of radii oscillations were observed only in the so-called "flow anisotropy dominated case" (a circular source with the radial expansion velocity including the third harmonic modulation) and not for "geometry dominated" case (triangular shape source with radial expansion velocity proportional to radial distance from the center, with corners having largest expansion velocity).

Fig. 3 shows the relative amplitudes of radius oscillations $R^2_{\mathrm{out},3}/R^2_{\mathrm{side},0}$, $R^2_{\mathrm{side},3}/R^2_{\mathrm{side},0}$, and $R^2_{\mathrm{os},3}/R^2_{\mathrm{side},0}$. Similar to the previous analyses and theoretical calculations [14] we report all the radii oscillations relative to the side radius the least affected by the emission time duration. There exist no obvious centrality dependence. As the average radii decrease with increasing k_{T}, the k_{T} dependence of relative oscillation amplitudes appear much stronger for "out" and "out-side" radii, while "side" radius relative amplitude exhibits no k_{T} dependence with the uncertainties. The shaded bands in Fig. 3 indicate the results of 3+1D hydrodynamical calculations [14]. These calculations assume constant shear viscosity to entropy ratio $\eta/s = 0.08$ and bulk viscosity that is nonzero in the hadronic phase $\zeta/s = 0.04$, and the initial density from a Glauber Monte Carlo model. The parameters of the model, were tuned to reproduce the measured charged particle spectra, the elliptic and triangular flow. We find that the relative amplitudes $R^2_{\mathrm{side},3}/R^2_{\mathrm{side},0}$ agree with these results rather well, while the relative amplitudes $R^2_{\mathrm{out},3}/R^2_{\mathrm{side},0}$ and $R^2_{\mathrm{os},2}/R^2_{\mathrm{side},0}$ agree only qualitatively. According to the 3+1D hydrodynamical calculations, the negative signs of $R^2_{\mathrm{side},3}$ and $R^2_{\mathrm{out},3}$ parameters are an indication that the initial triangularity has been washed-out or even reversed at freeze-out due to triangular flow [14].

To investigate further on the final source shape, we compare our results to the Blast-Wave model calculations [16]. In that model, the spatial geometry of the pion source at freeze-out is parameterized by

$$R(\phi) = R_0\left(1 - \sum_{n=2}^{\infty} a_n \cos(n(\phi - \Psi_n))\right), \tag{5}$$

where Ψ_n's denote the orientations of the n-th order symmetry planes. The amplitudes a_n and the phases Ψ_n are model parameters. The magnitude of the transverse expansion velocity is parameterized as $v_t = \tanh\rho$, where the transverse rapidity ρ [13,16] is

$$\rho(\tilde{r}, \phi_b) = \rho_0 \tilde{r}\left(1 + \sum_{n=2}^{\infty} 2\rho_n \cos\left(n(\phi_b - \Psi_n)\right)\right). \tag{6}$$

Here $\tilde{r} = r/R(\phi)$, and $\phi_b(\phi)$ is the transverse boost direction assumed to be perpendicular to the surface of constant $\tilde{r}$. The results of this model presented below were obtained assuming a kinetic freeze-out temperature of 120 MeV, and maximum expansion rapidity $\rho_0 = 0.8$, tuned to describe single particle spectra. Fig. 4 shows the relative amplitudes of the radius oscillations $R^2_{\mathrm{out},3}/R^2_{\mathrm{out},0}$, and $R^2_{\mathrm{side},3}/R^2_{\mathrm{side},0}$ as a function of Blast-wave model third-order parameters, spatial anisotropy a_3 and transverse flow anisotropy ρ_3. Thin dashed lines represent the lines of constant relative amplitudes, with numbers next to lines indicating the relative amplitude values. Thick dashed lines show the ALICE results for $R^2_{\mathrm{out},3}/R^2_{\mathrm{out},0}$ and $R^2_{\mathrm{side},3}/R^2_{\mathrm{side},0}$ with the thickness of the lines indicating the uncertainties. The intersection of the two dashed lines corresponds to a_3 and ρ_3 parameters consistent with ALICE measurements. The ALICE data and the Blast-Wave model calculations correspond to pairs with $k_{\mathrm{T}} = 0.6$ GeV/c and the centrality range 5–10%. The comparison have been also performed for other centralities and the corresponding Blast-Wave model parameters have been deduced. Fig. 5 presents the final source spatial and transverse flow anisotropies for different centrality ranges from matching the ALICE data with the Blast-Wave model calculations. The contours correspond to one sigma uncertainty as derived from

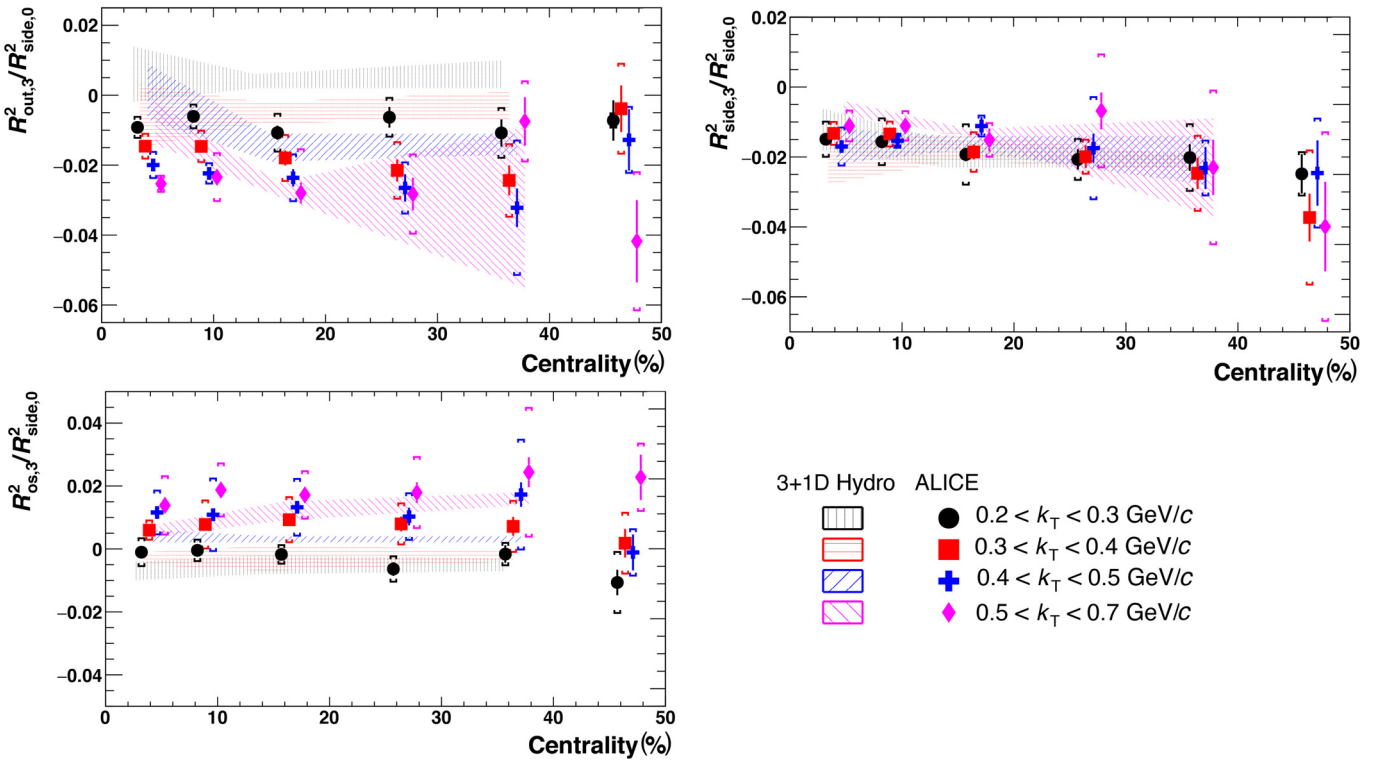

Fig. 3. Amplitudes of the relative radii oscillations $R^2_{out,3}/R^2_{side,0}$, $R^2_{side,3}/R^2_{side,0}$, and $R^2_{os,2}/R^2_{side,0}$ versus centrality for four k_T ranges. Square brackets indicate systematic uncertainties. The shaded bands are the 3+1D hydrodynamical calculations [14] and the width of the bands represent the uncertainties in the model calculations.

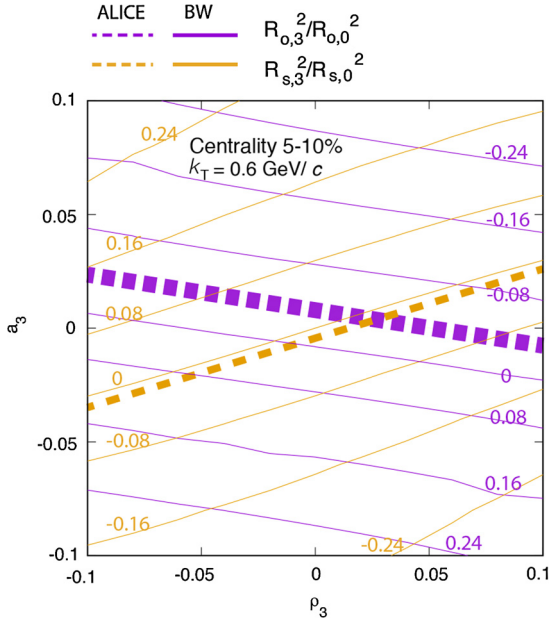

Fig. 4. The relative amplitudes of the radius oscillations $R^2_{out,3}/R^2_{out,0}$, and $R^2_{side,3}/R^2_{side,0}$ on the third-order anisotropies in space (a_3) and transverse flow (ρ_3) for the centrality range 5–10% and $k_T = 0.6$ GeV/c from the Blast-Wave model [16]. The thin dashed lines show the lines of a constant relative amplitude, in magenta for $R^2_{out,3}/R^2_{out,0}$ and in dark yellow for $R^2_{side,3}/R^2_{side,0}$. The thick lines show the corresponding ALICE results, with width of the lines representing the experimental uncertainties. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

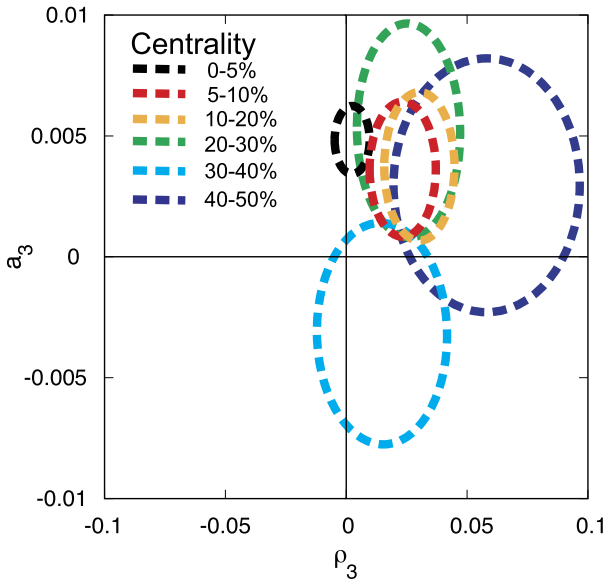

Fig. 5. Blast-Wave model [16] source parameters, final spatial (a_3) and transverse flow (ρ_3) anisotropies, for different centrality ranges, as obtained from the fit to ALICE radii oscillation parameters. The contours represent the one sigma uncertainty.

the fit of the model to the data. It is observed that the final source anisotropy is close to zero, significantly smaller than the initial triangular eccentricities that are typically of the order of 0.2–0.3. The negative values of the final source anisotropy would be interpreted as that the triangular orientation at the initial-state is reversed at freeze out.

4. Summary

We have reported a measurement of two-pion azimuthally-differential femtoscopy relative to the third harmonic event plane in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The observed oscillations

of the HBT radii unambiguously indicate a collective expansion of the system and anisotropy in collective velocity fields at freeze-out. Clear in-phase oscillations of $R_{\rm out}$ and $R_{\rm side}$, with both $R^2_{\rm out,3}$ and $R^2_{\rm side,3}$ parameters (as defined in Eq. (4)) being negative, have been observed for all centralities and $k_{\rm T}$ ranges. According to model calculations [13] the observed $R_{\rm out}$ and $R_{\rm side}$ in-phase oscillations are characteristics of the source with strong triangular flow and close to zero spatial anisotropy. This conclusion is further confirmed by a detailed comparison of our results with the Blast-Wave model calculations [16], from which the parameters of the source, the spatial anisotropy and modulations in the radial expansion velocity, have been derived, with spatial triangular anisotropy being more than an order of magnitude smaller than the typical initial anisotropy values. The oscillation amplitudes exhibit weak centrality dependence, and in general decrease with decreasing $k_{\rm T}$ except for $R^2_{\rm side,3}$ which on opposite is the largest in the smallest $k_{\rm T}$ bin. The results of the 3+1D hydrodynamic calculations [14] are in a good qualitative agreement with our measurements but, quantitatively, the model predicts a stronger dependence of $R^2_{\rm out,3}$ oscillations on $k_{\rm T}$ than observed in the data.

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