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**Two-pion Bose–Einstein correlations in central Pb–Pb collisions
at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$**

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Abstract

The first measurement of two-pion Bose–Einstein correlations in central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ at the Large Hadron Collider is presented. We observe a growing trend with energy now not only for the longitudinal and the outward but also for the sideward pion source radius. The pion homogeneity volume and the decoupling time are significantly larger than those measured at RHIC.

*See Appendix A for the list of collaboration members

1 Introduction

Matter at extremely high energy density created in central collisions of heavy ions at the Large Hadron Collider (LHC) is the main object of study of ALICE (A Large Ion Collider Experiment) [1, 2, 3]. Under these conditions the Quark-Gluon Plasma (QGP), a state characterized by partonic degrees of freedom, is thought to be formed [4, 5, 6, 7, 8, 9, 10]. The highly compressed strongly-interacting system created in these collisions is expected to undergo longitudinal and transverse expansion. The first measurement of the elliptic flow in the Pb–Pb system at the LHC confirmed the presence of strong collective motion and the hydrodynamic behavior of the system [11]. While the hydrodynamic approach is rather successful in describing the momentum distributions of hadrons in ultrarelativistic nuclear collisions (for recent reviews of hydrodynamic models see Refs. [12, 13, 14, 15, 16]), the spatial distributions of decoupling hadrons are more difficult to reproduce [17] and thus provide important model constraints on the initial temperature and equation of state of the system [18]. Experimentally, the expansion rate and the spatial extent at decoupling are accessible via intensity interferometry, a technique which exploits the Bose–Einstein enhancement of identical bosons emitted close by in phasespace. This approach, known as Hanbury Brown–Twiss analysis (HBT) [19, 20], has been successfully applied in e^+e^- [21], hadron–hadron and lepton–hadron [22], and heavy-ion [18] collisions.

In this Letter, we report on the first measurement of HBT radii for heavy-ion collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV at the LHC and discuss the space-time properties of the system generated at these record energies in the context of systems created at lower energies, measured over the past quarter of a century [18]. Like with such studies at RHIC and SPS energies, our measurements should provide strong constraints for models that aspire to describe the dynamic evolution of heavy ion collisions at the LHC.

2 Experiment and data analysis

The data were collected in 2010 during the first lead beam running period of the LHC. The runs used in this analysis were taken with beams of either 4 or 66 bunches colliding at the ALICE interaction point. The bunch intensity was typically 7×10^7 Pb ions per bunch. The luminosity varied within $0.5 - 8 \times 10^{23} \text{ cm}^{-2}\text{s}^{-1}$.

The detector readout was activated by a minimum-bias interaction trigger based on signals measured in the forward scintillators (VZERO) and in the Silicon Pixel Detector (SPD), in coincidence with the LHC bunch-crossing signal. The VZERO counters are placed along the beam line at +3.3 m and -0.9 m from the interaction point. They cover the region $2.8 < \eta < 5.1$ (VZERO-A) and $-3.7 < \eta < -1.7$ (VZERO-C) and record the amplitude and arrival time of signals produced by charged particles. The inner and outer layers of the SPD cover the central pseudorapidity regions $|\eta| < 2$ and $|\eta| < 1.4$, respectively. The detector has a total of 9.8 million pixels read out by 1200 chips. Each chip provides a fast signal if at least one of its pixels is hit. The signals from the 1200 chips are combined in a programmable logic unit. The minimum-bias interaction trigger required at least two out of the following three conditions: i) at least two pixel chips hit in the outer layer of the SPD, ii) a signal in VZERO-A, iii) a signal in VZERO-C. More details of the trigger and run conditions are discussed in Ref. [23].

For the present analysis we have used 1.6×10^4 events selected by requiring a primary vertex reconstructed within ± 12 cm of the nominal interaction point and applying a cut on the sum of the amplitudes measured in the VZERO detectors corresponding to the most central 5% of the hadronic cross section. The charged-particle pseudorapidity density measured in this centrality class is $\langle dN_{\text{ch}}/d\eta \rangle = 1601 \pm 60$ (syst.) as published in Ref. [24] where the centrality determination and the measurement of charged-particle pseudorapidity density are described in detail. The correlation analysis was performed using charged-particle tracks detected in the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). The ITS extends over $3.9 < r < 43$ cm and contains, in addition to the two SPD layers described above, two layers of Silicon Drift Detectors and two layers of Silicon Strip Detectors, with 1.33×10^5 and

2.6×10^6 readout channels, respectively. The TPC is a cylindrical drift detector with two readout planes on the endcaps. The active volume covers $85 < r < 247$ cm and $-250 < z < 250$ cm in the radial and longitudinal directions, respectively. A high voltage membrane at $z = 0$ divides the active volume into two halves and provides the electric drift field of 400 V/cm, resulting in a maximum drift time of 94 μ s. With the solenoidal magnetic field of 0.5 T the momentum resolution for particles with $p_T < 1$ GeV/c is about 1%. Tracks at the edge of the acceptance were removed by restricting the analysis to the region $|\eta| < 0.8$. Good track quality was ensured by requiring the tracks to have at least 90 clusters in the TPC (out of a maximum of 159), to have at least two matching hits in the ITS (out of a maximum of 6), and to point back to the primary interaction vertex within 1 cm. In order to reduce the contamination of the pion sample by electrons and kaons, that would dilute the Bose-Einstein enhancement in the correlation function, we applied a cut on the specific ionization (dE/dx) in the TPC gas. In central Pb–Pb collisions the dE/dx resolution of the TPC is better than 7%.

3 Two-pion correlation functions

The two-particle correlation function is defined as the ratio $C(\mathbf{q}) = A(\mathbf{q})/B(\mathbf{q})$, where $A(\mathbf{q})$ is the measured distribution of the difference $\mathbf{q} = \mathbf{p}_2 - \mathbf{p}_1$ between the three-momenta of the two particles \mathbf{p}_1 and \mathbf{p}_2 , and $B(\mathbf{q})$ is the corresponding distribution formed by using pairs of particles where each particle comes from a different event (event mixing) [25]. Every event was mixed with five other events, and for each pair of events all pion candidates from one event were paired with all pion candidates from the other. The correlation functions were studied in bins of transverse momentum, defined as half the modulus of the vector sum of the two transverse momenta, $k_T = |\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$. The momentum difference is calculated in the longitudinally co-moving system (LCMS), where the longitudinal pair momentum vanishes, and is decomposed into $(q_{\text{out}}, q_{\text{side}}, q_{\text{long}})$, with the “out” axis pointing along the pair transverse momentum, the “side” axis perpendicular to it in the transverse plane, and the “long” axis along the beam (Bertsch–Pratt convention [26, 27]).

Track splitting (incorrect reconstruction of a signal produced by one particle as two tracks) and track merging (reconstructing one track instead of two) generally lead to structures in the two-particle correlation functions if not properly treated. With the particular track selection used in this analysis, the track splitting effect is negligible and the track merging leads to a 20-30% loss of track pairs with a distance of closest approach in the TPC of 1 cm or less. We have solved this problem by including in $A(\mathbf{q})$ and $B(\mathbf{q})$ only those track pairs that are separated by at least 1.2 cm in $r\Delta\phi$ or at least 2.4 cm in z at a radius of 1.2 m. We have checked that with this selection one recovers the flat shape of the correlation function in Monte Carlo simulations that do not include Bose–Einstein enhancement.

Projections of three-dimensional $\pi^- \pi^-$ correlation functions $C(q_{\text{out}}, q_{\text{side}}, q_{\text{long}})$ for seven k_T bins from 0.2 to 1.0 GeV/c are shown in Fig. 1. The correlation functions for positive pion pairs look similar. The Bose–Einstein enhancement peak is manifest at low $q = |\mathbf{q}|$. The peak width increases when going from low to high transverse momenta. The three-dimensional correlation functions were fitted by an expression [28] accounting for the Bose–Einstein enhancement and for the Coulomb interaction between the two particles:

$$\begin{aligned} C(\mathbf{q}) &= \mathcal{N} [(1 - \lambda) + \lambda K(q_{\text{inv}})(1 + G(\mathbf{q}))], \\ G(\mathbf{q}) &= \exp(-(R_{\text{out}}^2 q_{\text{out}}^2 + R_{\text{side}}^2 q_{\text{side}}^2 + R_{\text{long}}^2 q_{\text{long}}^2 + \\ &\quad + 2|R_{\text{ol}}|R_{\text{ol}}q_{\text{out}}q_{\text{long}})), \end{aligned} \quad (1)$$

with λ describing the correlation strength, and R_{out} , R_{side} , and R_{long} being the Gaussian HBT radii. The parameter R_{ol} , that quantifies the cross term between q_{out} and q_{long} , was found to be consistent with zero, as expected for measurements at midrapidity in a symmetric system. This term was therefore set equal to zero in the final fits. The factor $K(q_{\text{inv}})$ is the squared Coulomb wave function averaged over a spherical

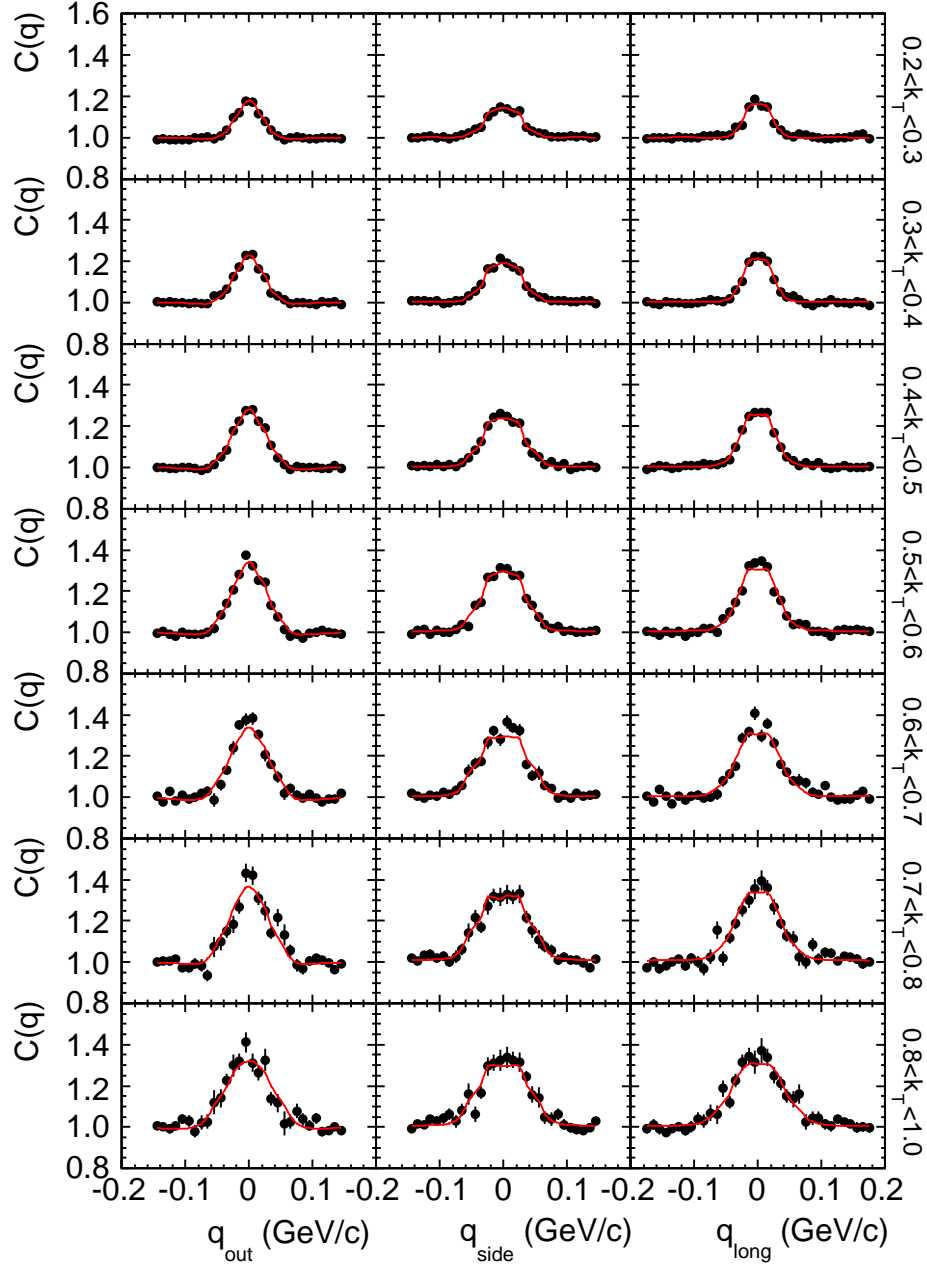


Fig. 1: Projections of the three-dimensional $\pi^-\pi^-$ correlation function (points) and of the respective fits (lines) for seven k_T intervals. When projecting on one axis the other two components were required to be within $(-0.03, 0.03)$ GeV/c. The k_T range is indicated on the right-hand side axis in GeV/c.

source [29] of size equal to the mean of R_{out} , R_{side} , and R_{long} ; its argument q_{inv} , for pairs of identical pions, is equal to q calculated in the pair rest frame. The Coulomb effect is taken to be attenuated by the same factor λ as the Bose–Einstein peak. The fit function is shown as a solid line in Fig. 1.

The obtained radii have been corrected for the finite momentum resolution that smears out the correlation peak. The effect was studied by applying weights to pairs of tracks in simulated events so as to produce the correlation function expected for a given set of the HBT radii. The weights were calculated using the original Monte Carlo momenta. The reconstructed radii were found to differ from the input ones by up to 4%, depending on the radius and k_T . The corresponding correction was applied to the experimental HBT radii.

4 Systematic uncertainties

The systematic uncertainties on the HBT parameters were estimated by comparing the results obtained by varying the analysis procedure. Not requiring the ITS hits in the tracking leads to a variation of the transverse and longitudinal radii of up to 3% and 8%, respectively. Variation of the pion identification criteria within a reasonable range introduces radius variations of up to 5%. Changing the fit range in q from 0-0.3 GeV/ c to 0-0.5 GeV/ c results in a reduction of all three radii by about 3%. Increasing the two-track separation cut by 50% results in a change of the radii by up to 3%. Generating the denominator of the correlation function by rotating one of the two tracks by 180° rather than by event mixing results in an increase of 6% for R_{side} at low k_T and up to 4% for R_{out} and R_{long} . The systematic error connected with the Coulomb correction was evaluated by modifying the source radius used for the correction by ± 2 fm. This was found to affect mostly R_{out} which changed by up to 4%. The correction for the momentum resolution is about 4%. The corresponding uncertainty on the final radii, tested by modifying the momentum resolution by 20%, is negligible. Finally, a study performed with an independent analysis code, including a different pair selection criterion (accepting only those 50% of the pairs for which the $r\Delta\phi$ separation between the two tracks increases with the radius, and requiring that the separation is at least 2 cm at the entrance to the TPC), yields transverse radii and R_{long} that differ by up to 5% and 8%, respectively. The total systematic errors are estimated by adding up the mentioned contributions in quadrature and are largest (9-10%) for the transverse radii in the lowest k_T bin and for R_{long} above 0.65 GeV/ c .

5 Transverse momentum dependence of the radii

The HBT radii extracted from the fit to the two-pion correlation functions and corrected for the momentum resolution as described in the previous section are shown as a function of $\langle k_T \rangle$ in Table 1 and in Fig. 2. The fit parameters for positive and negative pion pairs agree within statistical errors and therefore the averages are presented here. The HBT radii for the 5% most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV are found to be significantly (10-35%) larger than those measured by STAR in central Au–Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV [30]. The increase is beyond systematic errors and is similarly strong for R_{side} and R_{long} . As also observed in heavy-ion collision experiments at lower energies [18], the HBT radii show a decreasing trend with increasing k_T . This is a characteristic feature of expanding particle sources since the HBT radii describe the homogeneity length rather than the overall size of the particle-emitting system [31, 32, 33, 34]. The homogeneity length is defined as the size of the region that contributes to the pion spectrum at a particular three-momentum \mathbf{p} . The R_{out} radius is comparable with R_{side} and the k_T dependence of the ratio $R_{\text{out}}/R_{\text{side}}$ is flat within the systematic errors. R_{long} is seen to be somewhat larger than R_{out} and R_{side} and to decrease slightly faster with increasing k_T .

The extracted λ -parameter is found to range from 0.5 to 0.7 and increases slightly with k_T . Somewhat

Table 1: Pion HBT radii for the 5% most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, as function of $\langle k_T \rangle$. The first error is statistical and the second is systematic.

$\langle k_T \rangle$ (GeV/ c)	R_{out} (fm)	R_{side} (fm)	R_{long} (fm)
0.26	$6.92 \pm 0.12 \pm 0.61$	$6.36 \pm 0.12 \pm 0.54$	$8.03 \pm 0.15 \pm 0.42$
0.35	$6.03 \pm 0.08 \pm 0.48$	$6.13 \pm 0.09 \pm 0.26$	$7.31 \pm 0.10 \pm 0.39$
0.44	$5.15 \pm 0.07 \pm 0.30$	$5.49 \pm 0.08 \pm 0.30$	$6.23 \pm 0.09 \pm 0.41$
0.54	$4.79 \pm 0.08 \pm 0.34$	$5.14 \pm 0.09 \pm 0.26$	$5.67 \pm 0.10 \pm 0.35$
0.64	$4.56 \pm 0.10 \pm 0.29$	$4.73 \pm 0.11 \pm 0.25$	$5.30 \pm 0.12 \pm 0.40$
0.75	$4.29 \pm 0.12 \pm 0.34$	$4.48 \pm 0.13 \pm 0.20$	$4.90 \pm 0.15 \pm 0.50$
0.88	$4.02 \pm 0.14 \pm 0.26$	$4.35 \pm 0.14 \pm 0.34$	$4.43 \pm 0.15 \pm 0.45$

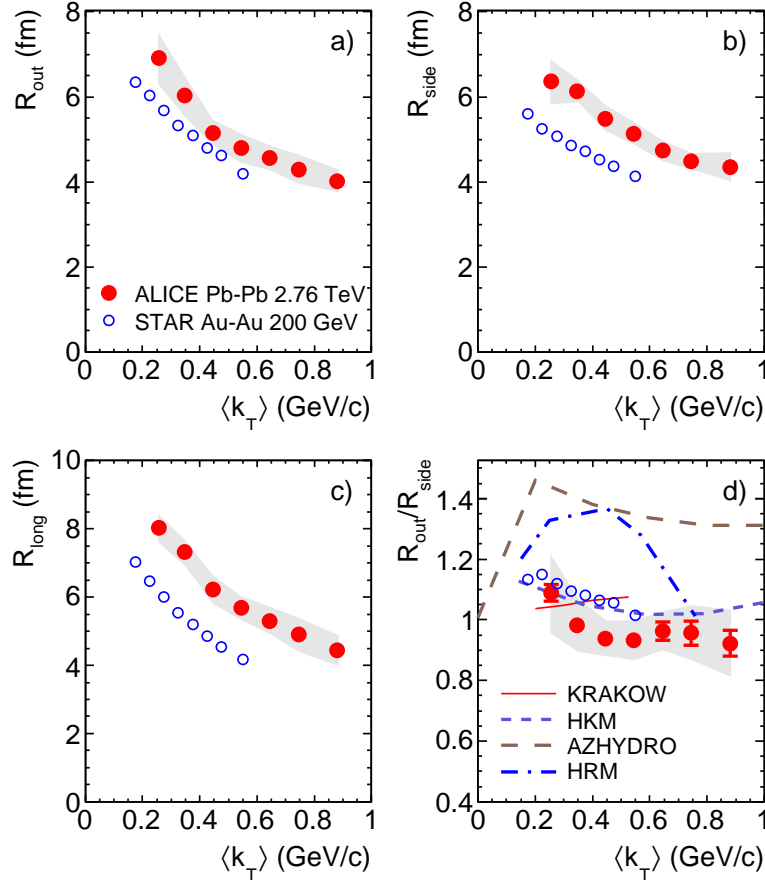


Fig. 2: Pion HBT radii for the 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, as function of $\langle k_T \rangle$ (red filled dots). The shaded bands represent the systematic errors. For comparison, parameters for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [30] are shown as blue open circles. (The combined, statistical and systematic, errors on these measurements are below 4%.) The lines show model predictions (see text).

lower values but a similar k_T dependence were observed in Au–Au collisions at RHIC [30].

6 Beam energy dependence of the radii

In Fig. 3, we compare the three radii at $\langle k_T \rangle = 0.3$ GeV/c with experimental results at lower energies. The values of the radii at this k_T were obtained by parabolic interpolation. Following the established practice [18] we plot the radii as functions of $\langle dN_{ch}/d\eta \rangle^{1/3}$. In this representation the comparison is not affected by slight differences between the mass numbers of the colliding nuclei and between centralities. For E895 and NA49, $dN_{ch}/d\eta$ has been approximated using the published rapidity densities. The reference frame dependence of $dN_{ch}/d\eta$ is neglected. The errors on the E895 points are statistical only. For the other experiments the error bars represent the statistical and systematic uncertainties added in quadrature. For the ALICE point the error is dominated by the systematic uncertainties.

The ALICE measurement significantly extends the range of the existing world systematics of HBT radii. The trend of R_{long} growing approximately linearly with the cube root of the charged-particle pseudorapidity density, established at lower energies, continues at the LHC (Fig. 3-c). The situation is similar with R_{out} (Fig. 3-a) which also grows with energy albeit slower than R_{long} . For R_{side} , that is most directly related to the transverse size of the pion source and is less affected by experimental uncertainties, an increase is observed beyond systematic errors (Fig. 3-b). At lower energies a rather flat behavior with a shallow minimum between AGS and SPS energies was observed and interpreted as due to the transition

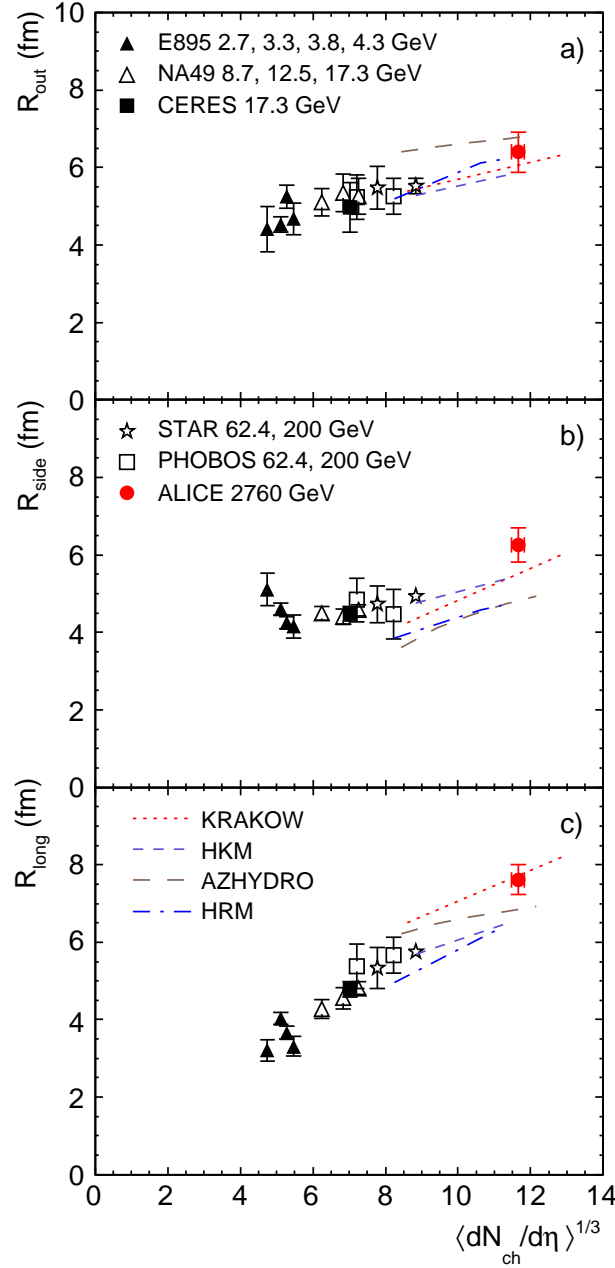


Fig. 3: Pion HBT radii at $k_T = 0.3$ GeV/ c for the 5% most central Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV (red filled dot) and the radii obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43]. Model predictions are shown as lines.

from baryon to meson dominance at freeze-out [44]. An increase of R_{side} at high energy is consistent with that interpretation.

Available model predictions are compared to the experimental data in Figs. 2-d and 3. Calculations from three models incorporating a hydrodynamic approach, AZHYDRO [45], KRAKOW [46, 47], and HKM [48, 49], and from the hadronic-kinematics-based model HRM [50, 51] are shown. An in-depth discussion is beyond the scope of this Letter but we notice that, while the increase of the radii between RHIC and the LHC is roughly reproduced by all four calculations, only two of them (KRAKOW and HKM) are able to describe the experimental R_{out}/R_{side} ratio.

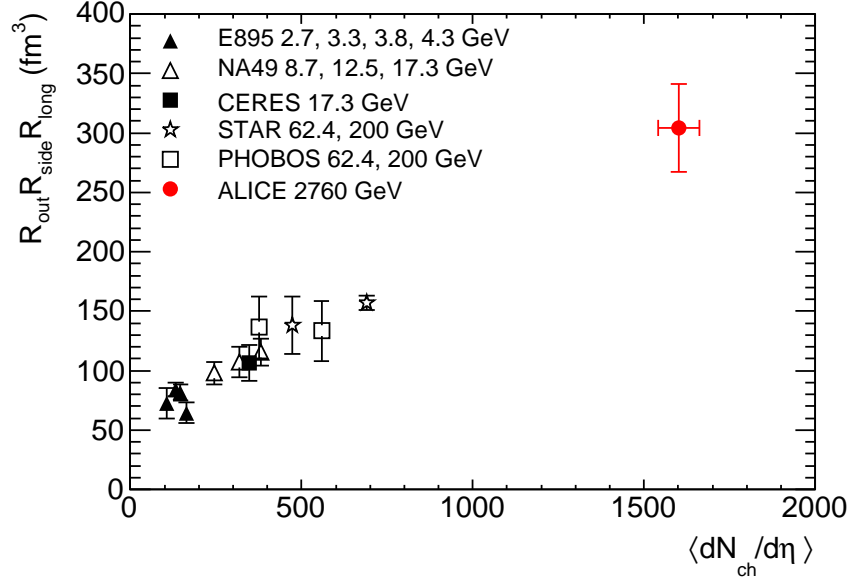


Fig. 4: Product of the three pion HBT radii at $k_T = 0.3$ GeV/ c . The ALICE result (red filled dot) is compared to those obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43].

The systematics of the product of the three radii is shown in Fig. 4. The product of the radii, which is connected to the volume of the homogeneity region, shows a linear dependence on the charged-particle pseudorapidity density and is two times larger at the LHC than at RHIC.

Within hydrodynamic scenarios, the decoupling time for hadrons at midrapidity can be estimated in the following way. The size of the homogeneity region is inversely proportional to the velocity gradient of the expanding system. The longitudinal velocity gradient in a high energy nuclear collision decreases with time as $1/\tau$ [52]. Therefore, the magnitude of R_{long} is proportional to the total duration of the longitudinal expansion, i.e. to the decoupling time of the system [31]. Quantitatively, the decoupling time τ_f can be obtained by fitting R_{long} with

$$R_{long}^2(k_T) = \frac{\tau_f^2 T}{m_T} \frac{K_2(m_T/T)}{K_1(m_T/T)}, \quad m_T = \sqrt{m_\pi^2 + k_T^2}, \quad (2)$$

where m_π is the pion mass, T the kinetic freeze-out temperature taken to be 0.12 GeV, and K_1 and K_2 are the integer order modified Bessel functions [31, 53]. The decoupling time extracted from this fit to the ALICE radii and to the values published at lower energies are shown in Figure 5. As can be seen, τ_f scales with the cube root of charged-particle pseudorapidity density and reaches 10–11 fm/ c in central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. It should be kept in mind that while Eq. (2) captures basic features of a longitudinally expanding particle-emitting system, in the presence of transverse expansion and a finite chemical potential of pions it may underestimate the actual decoupling time by about 25% [54]. An uncertainty is connected to the value of the kinetic freeze-out temperature used in the fit $T = 0.12$ GeV. Setting T to 0.1 GeV [55, 36, 30, 56] and 0.14 GeV [57] leads to a τ_f value that is 13% higher and 10% lower, respectively.

7 Summary

We have presented the first analysis of the two-pion correlation functions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC. The pion source radii obtained from this measurement exceed those measured at RHIC by 10–35%. The increase is beyond systematic errors and is present for both the longitudinal and

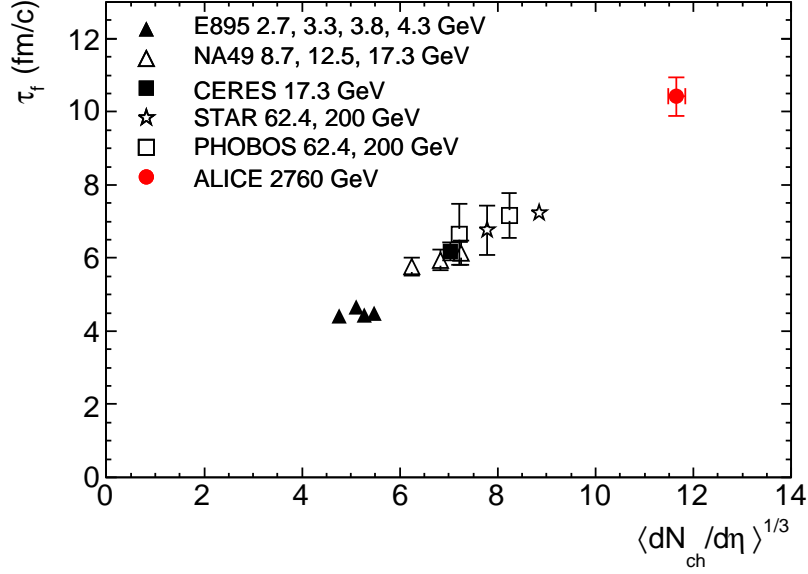


Fig. 5: The decoupling time extracted from $R_{long}(k_T)$. The ALICE result (red filled dot) is compared to those obtained for central gold and lead collisions at lower energies at the AGS [35], SPS [36, 37, 38], and RHIC [39, 40, 41, 42, 30, 43].

transverse radii. The homogeneity volume is found to be larger by a factor of two. The decoupling time for midrapidity pions exceeds 10 fm/c which is 40% larger than at RHIC. These results, taken together with those obtained from the study of multiplicity [23, 24] and the azimuthal anisotropy [11], indicate that the fireball formed in nuclear collisions at the LHC is hotter, lives longer, and expands to a larger size at freeze-out as compared to lower energies.

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