



# Identical pion intensity interferometry in central Au + Au collisions at 1.23A GeV



HADES Collaboration

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## ABSTRACT

We investigate identical pion HBT intensity interferometry in central Au+Au collisions at 1.23A GeV. High-statistics  $\pi^-\pi^-$  and  $\pi^+\pi^+$  data are measured with HADES at SIS18/GSI. The radius parameters, derived from the correlation function depending on relative momenta in the longitudinally comoving system and parametrized as three-dimensional Gaussian distribution, are studied as function of transverse momentum. A substantial charge-sign difference of the source radii is found, particularly pronounced at low transverse momentum. The extracted source parameters agree well with a smooth extrapolation of the center-of-mass energy dependence established at higher energies, extending the corresponding excitation functions down towards a very low energy.

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Two-particle intensity interferometry of hadrons is widely used to study the spatio-temporal size, shape and evolution of their sources created in heavy-ion collisions or other reactions involving hadrons (for a review see Ref. [1]). The technique, pioneered by Hanbury Brown and Twiss [2] to measure angular radii of stars, later on named HBT interferometry, is based on the quantum-statistical interference of identical particles. Goldhaber et al. [3] first applied intensity interferometry to hadrons. In heavy-ion collisions, the intensity interferometry does not allow to measure directly the reaction volume, as the emission source, changing in shape and size in the course of the collision, is affected by density and temperature gradients and dynamically generated space-momentum correlations (e.g. radial expansion after the compression phase or resonance decays). Thus, intensity interferometry generally does not yield the proper source size, but rather an effective “length of homogeneity” [1]. It measures source regions in which particle pairs are close in momentum, so that they are correlated as a consequence of their quantum statistics or due to their two-body interaction. In general, the sign and strength of the correlation is affected by (i) the strong interaction, (ii) the Coulomb interaction if charged particles are involved, and (iii) the quantum statistics in the case of identical particles (Fermi–Dirac suppression for fermions, Bose–Einstein enhancement for bosons). In the case of  $\pi\pi$  correlations, the mutual strong interaction was found to be minor [4] compared to the effects (ii) and (iii).

Pion freeze-out dynamics may be relevant to ongoing searches for the QCD critical point in the  $T-\mu_B$  plane, where  $T$  and  $\mu_B$  are the temperature and the baryon-chemical potential. Systems with  $\mu_B$  above the critical point are expected to undergo a first-order phase transition which might be visible in a non-monotonic behavior of various source parameters. However, it is also conceivable that the initial temperatures of the system, which can be reached in heavy-ion collisions at high  $\mu_B$ , are not high enough to create a deconfined partonic state. In this scenario a first order phase boundary cannot be reached experimentally. A recently published excitation function of HBT source radii [5] from the domain of the Relativistic Heavy Ion Collider (RHIC) down to lower collision energies indicates such a non-monotonic energy dependence around center-of-mass energies of  $\sqrt{s_{NN}} < 10$  GeV. Even though a part of this behavior can be related to the strong impact of different pair transverse momentum intervals involved in the source parameter compilation of Ref. [5], to a certain extent the deviation of the data points from a monotonic trend remains at low energies. Here, new precision data, especially at low collision energies of  $\sqrt{s_{NN}} < 5$  GeV, can contribute to the clarification of this excit-

ing observation before definite conclusions on a change in physics can be drawn.

It is worth emphasizing that only preliminary data [6] of identical-pion HBT data exist for a large symmetric collision system (like Au+Au or Pb+Pb) at a beam kinetic energy of about 1A GeV (fixed target,  $\sqrt{s_{NN}} = 2.3$  GeV).<sup>6</sup> For the somewhat smaller system La+La, studied at 1.2A GeV with the HISS spectrometer at the Lawrence Berkeley Laboratory (LBL) Bevalac, pion correlation data were reported by Christie et al. [7,8]. An oblate shape of the pion source and a correlation of the source size with the system size were found. Also, pion intensity interferometry for small systems (Ar+KCl, Ne+NaF) was studied at 1.8A GeV at the LBL Bevalac using the Janus spectrometer by Zajc et al. [9]. Both groups made first attempts to correct the influence of the pion-nuclear Coulomb interaction on the pion momenta. The effect on the source radii, however, were found negligible for their experiments.

In this letter we report on the first investigation of  $\pi^-\pi^-$  and  $\pi^+\pi^+$  correlations at low relative momenta in Au+Au collisions at 1.23A GeV, continuing our previous femtoscopic studies of smaller collision systems [10–12]. The experiment was performed with the **H**igh **A**cceptance **D**i-**E**lectron **S**pectrometer (HADES) at the Schwerionensynchrotron SIS18 at GSI, Darmstadt. HADES [13], although primarily optimized to measure di-electrons [14], offers also excellent hadron identification capabilities [15–18]. HADES is a charged particle detector consisting of a six-coil toroidal magnet centered around the beam axis and six identical detection sections located between the coils and covering polar angles between 18° and 85°. Each sector is equipped with a Ring-Imaging Cherenkov (RICH) detector followed by two layers of Mini-Drift Chambers (MDCs), two in front of and two behind the magnetic field, as well as a scintillator Time-Of-Flight detector (TOF) (45°–85°) and Resistive Plate Chambers (RPC) (18°–45°). Both timing detectors, TOF and RPC, allow for good particle identification, i.e. proton-pion separation. (Due to their low yield, kaons hardly affect the pion selection at SIS energies.) TOF, RPC, and Pre-Shower detectors (behind RPC, for  $e^\pm$  identification) were combined into a Multiplicity and Electron Trigger Array (META). Several triggers are implemented. The minimum bias trigger is defined by a signal in a diamond START detector in front of the 15-fold segmented gold target. In addition, online Physics Triggers (PT) are used, which are based on hardware thresholds on the TOF signals, proportional to

<sup>6</sup> Throughout this publication A GeV refers to the mean kinetic beam energy.

the event multiplicity, corresponding to at least 20 (PT3) hits in the TOF. About 2.1 billion PT3 triggered Au+Au collisions corresponding to the 40% most central events are taken into account for the correlation analysis. The centrality determination is based on the summed number of hits detected by the TOF and the RPC detectors. The measured events are divided in centrality classes corresponding to successive 10% regions of the total cross section [19]. Here, we report only on results of the 0–10% class; the entire centrality dependence of pion source parameters analyzed as function of azimuthal angle w.r.t. the reaction plane will be part of an extended forthcoming paper, while yields and phase-space distributions of charged pions are to be presented in a separate report.

Generally, the two-particle correlation function is defined as the ratio of the probability  $P_2(\mathbf{p}_1, \mathbf{p}_2)$  to measure simultaneously two particles with momenta  $\mathbf{p}_1$  and  $\mathbf{p}_2$  and the product of the corresponding single-particle probabilities  $P_1(\mathbf{p}_1)$  and  $P_1(\mathbf{p}_2)$  [1],

$$C(\mathbf{p}_1, \mathbf{p}_2) = \frac{P_2(\mathbf{p}_1, \mathbf{p}_2)}{P_1(\mathbf{p}_1)P_1(\mathbf{p}_2)}. \quad (1)$$

Experimentally this correlation is formed as a function of the momentum difference between the two particles of a given pair and quantified by taking the ratio of the yields of ‘true’ pairs ( $Y_{\text{true}}$ ) and uncorrelated pairs ( $Y_{\text{mix}}$ ).  $Y_{\text{true}}$  is constructed from all particle pairs in the selected phase space interval from the same event.  $Y_{\text{mix}}$  is generated by event mixing, where particle 1 and particle 2 are taken from different events. Care was taken to mix particles from similar event classes in terms of multiplicity, vertex position and reaction plane angle. The events are allowed to differ by not more than 10 units in the number of the RPC+TOF hit multiplicity of  $\geq 182$  (i.e. corresponding to the uncertainty of the centrality class 0–10% [19]), 1.2 mm in the z-vertex coordinate (amounting to less than one third of the spacing between target segments), and 30 degrees in azimuthal angle (to be compared to the event plane resolution of  $\langle \cos \Phi \rangle = 0.612$ ), respectively.

The momentum difference is decomposed into three orthogonal components as suggested by Podgoretsky [20], Pratt [21] and Bertsch [22]. The three-dimensional correlation functions are projections of equation (1) into the (out, side, long)-coordinate system, where ‘out’ means along the pair transverse momentum,  $\mathbf{k}_t = (\mathbf{p}_{t,1} + \mathbf{p}_{t,2})/2$ , ‘long’ is parallel to the beam direction z, and ‘side’ is oriented perpendicular to the other directions. The particles forming a pair are boosted into the longitudinally comoving system (LCMS), where the z-components of the momenta cancel each other,  $p_{z1} + p_{z2} = 0$ . Note that in other publications also the pair comoving system ( $\mathbf{p}_1 + \mathbf{p}_2 = 0$ ) is frequently used. The LCMS choice allows for an adequate comparison with correlation data taken at very different, usually much higher, collision energies, where the distribution of the rapidity,  $y = \tanh^{-1}(\beta_z)$ , of produced particles is found to be not as narrow as in the present case but largely elongated. (Here,  $\beta_z = p_z/E$ ,  $E = \sqrt{p^2 + m_0^2}$  and  $m_0$  are the longitudinal velocity, the total energy and the rest mass of the particle, respectively. We use units with  $\hbar = c^2 = 1$ .) Hence, the experimental correlation function is given by

$$C(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}) = \mathcal{N} \frac{Y_{\text{true}}(q_{\text{out}}, q_{\text{side}}, q_{\text{long}})}{Y_{\text{mix}}(q_{\text{out}}, q_{\text{side}}, q_{\text{long}})}, \quad (2)$$

where  $q_i = (p_{1,i} - p_{2,i})/2$  ( $i = \text{‘out’}, \text{‘side’}, \text{‘long’}$ ) are the relative momentum components, and  $\mathcal{N}$  is a normalization factor which is fixed by the requirement  $C \rightarrow 1$  at large relative momenta, where the correlation function is expected to flatten out at unity. Note that, as in our previous intensity interferometry analyses [10–12], we use the above low-energy convention of  $q$  which is common

also in studies of proton-proton correlations, in contrast to the high-energy convention of  $\pi\pi$  correlations,  $Q = 2q$ . The statistical errors of equation (2) are dominated by those of the true yield, since the mixed yield is generated with much higher statistics.

Two-track reconstruction defects (e.g. track splitting and merging effects) that are particularly important to HBT analyses were corrected by appropriate selection conditions on the META-hit and MDC-layer levels, i.e. by discarding pairs which hit the same META cell, and by excluding for particle 2 three successive wires symmetrically around the MDC wire fired by particle 1. This method was tested with simulations carrying neither quantum-statistical nor Coulomb effects, based on UrQMD [23], Geant [24] and a detailed description of the detector response, to firmly exclude any close-track effect. Also broader exclusion windows have been tested, but no significant improvement was found. These simulations also showed that there are no significant long-range correlations, usually attributed either to energy-momentum conservation in correlation analyses of small systems or to minijet-like phenomena at high energies.

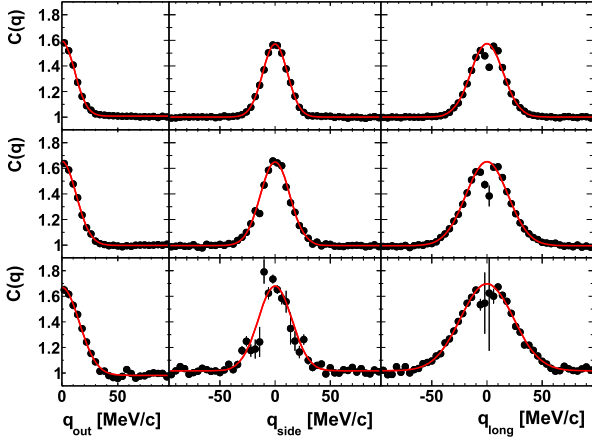
The data are divided into seven  $k_t$  bins from 50 to 400 MeV/c. The three-dimensional experimental correlation function is then fitted with the function

$$C_{\text{fit}}(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}) = N \left[ (1 - \lambda) + \lambda K_C(\hat{q}, R_{\text{inv}}) C_{\text{qs}}(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}) \right], \quad (3)$$

where

$$C_{\text{qs}}(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}) = 1 + \exp(-2q_{\text{out}}R_{\text{out}})^2 - (2q_{\text{side}}R_{\text{side}})^2 - (2q_{\text{long}}R_{\text{long}})^2 \quad (4)$$

represents the quantum-statistical part of the correlation function. The parameters  $N$  and  $\lambda$  in Eq. (3) are a normalization constant and the fraction of correlated pairs, respectively, and  $\hat{q} = q_{\text{inv}}(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}, k_t)$  is the average value of the invariant momentum difference,  $q_{\text{inv}} = \frac{1}{2} \sqrt{(\mathbf{p}_1 - \mathbf{p}_2)^2 - (E_1 - E_2)^2}$ , for given intervals of the relative momentum components and  $k_t$ . The range of the one- and three-dimensional fits extends in  $q_{\text{inv}}$  from 6 MeV/c to 80 MeV/c. Log-likelihood minimization [25] was used in all fits to the correlation functions. The influence of the mutual Coulomb interaction in Eq. (3) is separated from the Bose-Einstein part by including in the fits the commonly used Coulomb correction by Sinyukov et al. [26]. The Coulomb factor  $K_C$  results from the integration of the two-pion Coulomb wave function squared over a spherical Gaussian source of fixed radius. This radius is iteratively approximated by the result of the corresponding fit to the correlation function. In Eq. (3), the non-diagonal elements comprising the combinations ‘out’-‘side’ and ‘side’-‘long’ vanish for symmetry reasons [27] when azimuthally and rapidity integrated correlations functions are studied [28,29], as it is done in the present investigation. The ‘out’-‘long’ component, however, can have a finite value depending on the degree of symmetry of the detector-accepted rapidity distribution w.r.t. midrapidity ( $y_{\text{cm}} = 0.74$ ). We studied this effect by including in Eq. (4) an additional term  $-2q_{\text{out}}(2R_{\text{out long}})^2 q_{\text{long}}$ , where the prefactor accounts for both non-diagonal terms, ‘out’-‘long’ and ‘long’-‘out’. We found only marginal differences in the fits which delivered, for all transverse-momentum classes, rather small values of  $R_{\text{out long}}^2 < 1 \text{ fm}^2$ . For all results presented here, we restricted the pair rapidity to an interval  $|y - y_{\text{cm}}| < 0.35$ , within which  $dN/dy$  does not vary by more than 10%, and limited ourselves to the fit function with the Bose-Einstein part (Eq. (4)) consisting of diagonal elements only and added the small deviations to the systematic errors. The effect of finite momentum resolutions of the



**Fig. 1.** Projections of the Coulomb-corrected three-dimensional  $\pi^-\pi^-$  correlation function (dots) and of the respective fits (dashed curves) for the  $k_t$  intervals of 100–150 MeV/c (top), 200–250 MeV/c (middle), and 300–350 MeV/c (bottom). The left, center, and right panels give the ‘out’, ‘side’, and ‘long’ directions, respectively. The unplotted  $q$  components are integrated over  $\pm 12$  MeV/c.

HADES tracking system is studied with dedicated simulations. Typical Gaussian resolution values of  $\sigma_q(q_{\text{inv}} = 20 \text{ MeV}/c) \simeq 2 \text{ MeV}/c$  are estimated. Incorporating a corresponding correction into the fit function by convolution of Eq. (3) with a Gaussian resolution function leads to radius shifts of about  $\delta R/R \simeq +2\%$ .

Fig. 1 shows one-dimensional projections of the Coulomb-corrected  $\pi^-\pi^-$  correlation function together with corresponding fits with Eq. (3) for various  $k_t$  intervals. (Due to the permutability of particles 1 and 2, one of the  $q$  projections can be restricted to positive values.) The peak due to the Bose–Einstein enhancement becomes evident at low  $|q|$ . Its width increases with increasing  $k_t$ . The correlation functions for  $\pi^+\pi^+$  pairs look similar. The main systematic uncertainties of the results presented below arise from the slight fluctuations of the fit results when varying the fit ranges ( $\sim 0.1\text{--}0.3 \text{ fm}$ ), from the forward–backward differences of the fit results w.r.t. midrapidity within similar transverse momentum intervals ( $\sim 0.03\text{--}0.1 (0.2) \text{ fm}$  for  $R_{\text{inv}}$ ,  $R_{\text{side}}$ ,  $R_{\text{long}}$  ( $R_{\text{out}}$ )), and from the differences when switching on/off the ‘out’-‘long’ component in the fit function ( $\sim 0.05\text{--}0.2 \text{ fm}$ ). Finally, all systematic error contributions are added quadratically. In Fig. 2 they are shown as hatched bands.

To separate a potential source radius bias introduced by the Coulomb force the charged pions experience in the field of the charged fireball, we follow the ansatz used in Ref. [30],

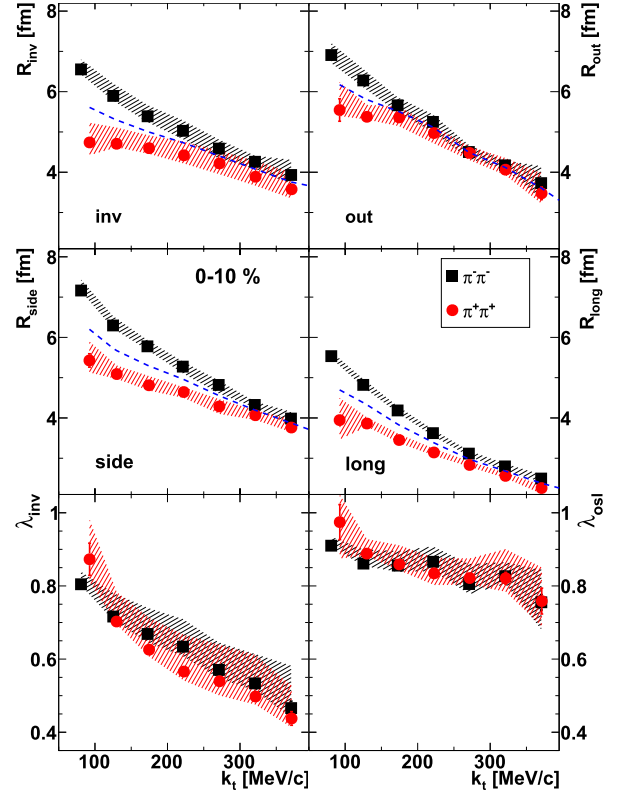
$$E(\mathbf{p}_f) = E(\mathbf{p}_i) \pm V_{\text{eff}}(\mathbf{r}_i), \quad (5)$$

where  $E$  is the total energy,  $\mathbf{p}_i$  ( $\mathbf{p}_f$ ) is the initial (final) momentum and  $\mathbf{r}_i$  is the initial position of the pion in the Coulomb potential  $V_{\text{eff}}$  with positive (negative) sign for  $\pi^+$  ( $\pi^-$ ). With

$$\frac{R_{\pi^\pm\pi^\pm}}{R_{\pi^0\pi^0}} \approx \frac{q_i}{q_f} = \frac{|\mathbf{p}_i|}{|\mathbf{p}_f|} = \sqrt{1 \mp 2 \frac{V_{\text{eff}}}{|\mathbf{p}_f|} \sqrt{1 + \frac{m_\pi^2}{\mathbf{p}_f^2} + \frac{V_{\text{eff}}^2}{\mathbf{p}_f^2}}}, \quad (6)$$

where  $q_i$  ( $q_f$ ) is the initial (final) relative momentum, and with  $V_{\text{eff}}/k_t \ll 1$ , it turns out that the constructed squared source radius for pairs of neutral pions (denoted by  $\tilde{\pi}^0\tilde{\pi}^0$  in the following in contrast to the case where  $\pi^-\pi^-$  and  $\pi^+\pi^+$  data are combined) is simply the arithmetic mean of the corresponding quantities of the charged pions,

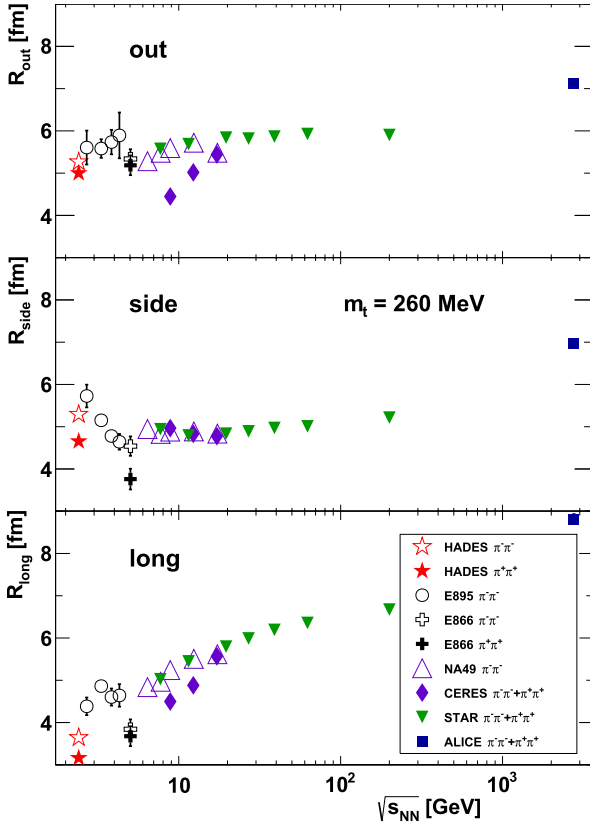
$$R_{\tilde{\pi}^0\tilde{\pi}^0}^2 = \frac{1}{2}(R_{\pi^+\pi^+}^2 + R_{\pi^-\pi^-}^2), \quad (7)$$



**Fig. 2.** Source parameters as function of pair transverse momentum,  $k_t$ , for central (0–10%) Au+Au collisions at 1.23A GeV. The upper left, upper right, center left, and center right panels display the invariant, out, side, and long radii, respectively. The lower left and lower right panels show the corresponding  $\lambda$  parameters resulting from the fits to the one- and three-dimensional correlation functions, respectively. Black squares (red circles) are for pairs of negative (positive) pions. Blue dashed lines represent constructed radii of neutral pion pairs (see text). Error bars and hatched bands represent the statistical and systematic errors, respectively.

which is valid for all radius components (even though in the ‘out’ direction, Eq. (6) looks slightly different). Finally, the constructed  $\pi^0\pi^0$  correlation radii are derived from cubic spline interpolations of the  $k_t$  dependence of both the corresponding experimental  $\pi^-\pi^-$  and  $\pi^+\pi^+$  data. This interpolation is necessary because – as result of different detector acceptances – the charged pion pairs exhibit slightly different average transverse momenta, even though they are measured in identical  $k_t$  intervals.

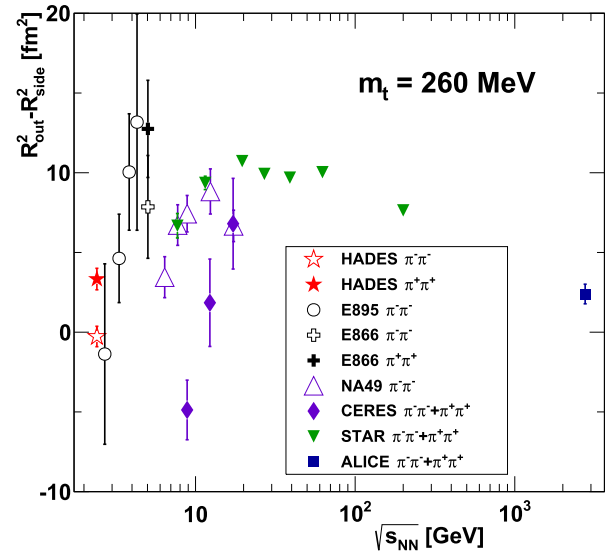
Fig. 2 shows the dependence on average  $k_t$  (determined for  $q_{\text{inv}} < 50 \text{ MeV}/c$ ) of the one-dimensional (invariant) and three-dimensional source radii for  $\pi^-\pi^-$  (black squares) and  $\pi^+\pi^+$  (red circles) pairs. While for low transverse momentum the Coulomb interaction with the fireball leads to an increase (a decrease) of the source size derived for negative (positive) pion pairs, at large transverse momentum apparently the Coulomb effect fades away. The effect is smallest for  $R_{\text{out}}$ . Note that the charge splitting of the source radii was early predicted by Barz [31,32] who investigated the combined effects of nuclear Coulomb field, radial flow, and opaqueness on two-pion correlations for a large collision system such as Au+Au in the 1A GeV energy regime. Earlier experimental works at the Bevalac employing a three-body Coulomb correction found the effect negligible for their studies of smaller systems [7–9]. The parameter  $\lambda$  derived from the fits with Eq. (3) appears rather independent of charge sign and decreases only slightly with increasing transverse momentum, cf. lower right panel of Fig. 2. It fits well into a preliminary evolution with  $\sqrt{s_{\text{NN}}}$  established previously [5], except the lowest E895 data point. In contrast,  $\lambda$  resulting from the fits to the one-dimensional



**Fig. 3.** Excitation function of the source radii  $R_{\text{out}}$  (upper panel),  $R_{\text{side}}$  (central panel), and  $R_{\text{long}}$  (lower panel) for pairs of identical pions with transverse mass of  $m_t = 260$  MeV in central collisions of Au+Au or Pb+Pb. Squares represent data by ALICE at LHC ( $\pi^- \pi^- + \pi^+ \pi^+$ ) [37], full triangles STAR at RHIC ( $\pi^- \pi^- + \pi^+ \pi^+$ ) [5], diamonds are for CERES at SPS ( $\pi^- \pi^- + \pi^+ \pi^+$ ) [38], open triangles are for NA49 at SPS ( $\pi^- \pi^-$ ) [39], open circles are  $\pi^- \pi^-$  data by E895 at AGS [1,28], and open (full) crosses involve  $\pi^- \pi^-$  ( $\pi^+ \pi^+$ ) data of E866 at AGS [40], respectively. The present data of HADES at SIS18 for pairs of  $\pi^- \pi^-$  ( $\pi^+ \pi^+$ ) are given as open (full) stars. Statistical errors are displayed as error bars; if not visible, they are smaller than the corresponding symbols.

( $q_{\text{inv}}$ -dependent) correlation function, exhibits a significant decrease with  $k_t$  (cf. lower left panel), probably pointing to the fact that the one-dimensional fit function is not adequate. Note that deviations from Gaussian source shapes will be studied in a forthcoming paper by applying the method of source imaging [33,34], or by using Lévy source parameterizations [35].

The excitation functions of  $R_{\text{out}}$ ,  $R_{\text{side}}$ , and  $R_{\text{long}}$  for pion pairs produced in central collisions are displayed in Fig. 3. All shown radius parameters have been obtained by interpolating the existing measured data points to the same transverse mass of  $m_t = \sqrt{k_t^2 + m_\pi^2} = 260$  MeV at which data points by STAR at RHIC [5] are available. The statistical errors are properly propagated and quadratically added with systematic differences of linear and cubic-spline interpolations. Extrapolations were not necessary at this  $m_t$  value. Corresponding excitation functions at other transverse masses show similar dependencies. Surprisingly,  $R_{\text{out}}$  and  $R_{\text{side}}$  vary hardly more than 40% over three orders of magnitude in center-of-mass energy. Only  $R_{\text{long}}$  exhibits a systematic increase by about a factor of two to three when going in energy from SIS18 via AGS, SPS, RHIC to LHC. Note that in the excitation functions of Ref. [5] not all, particularly AGS, data points were properly corrected for their  $k_t$  dependence. While the HADES  $R_{\text{out}}$  and  $R_{\text{side}}$  data for negative pions completely agree with the lowest E895 data at 2A GeV,  $R_{\text{long}}$  deviates from the corresponding



**Fig. 4.** Excitation function of  $R_{\text{out}}^2 - R_{\text{side}}^2$ , as calculated from the data points shown in Fig. 3.

E895 data point. Both data are, however, in accordance with the overall smooth trend within  $2\sigma$ . (The low-energy CERES data of  $R_{\text{out}}$  and the E866 data point of  $R_{\text{long}}$  for  $\pi^- \pi^-$  pairs appear to be outliers.)

The combination of  $R_{\text{out}}^2$  and  $R_{\text{side}}^2$  can be related to the emission time duration [36],  $(\Delta\tau)^2 \approx (R_{\text{out}}^2 - R_{\text{side}}^2)/(\beta_t^2)$ , where  $\beta_t$  is the transverse pair velocity. The excitation function of  $R_{\text{out}}^2 - R_{\text{side}}^2$  is shown in Fig. 4. Up to now almost all measurements below 10 GeV are characterized by large errors and scatter sizeably. (Here, the outlying low-energy CERES data are solely caused by the deviation in  $R_{\text{out}}$ , cf. top panel of Fig. 3.) The new HADES data show that the difference of source parameters in the transverse plane almost vanishes at low collision energies. With increasing energy, it reaches a maximum at  $\sqrt{s_{\text{NN}}} \sim 20\text{--}30$  GeV and afterwards decreases towards zero at LHC energies. One would conclude that in the 1A GeV energy region pions are emitted into free space during a short time span of less than one to two fm/c. However, also the opaqueness of the source affects  $R_{\text{out}}^2 - R_{\text{side}}^2$  which could cause it to become negative, thus compensating the positive contribution from the emission time [32].

The excitation function of the freeze-out volume,  $V_{\text{fo}} = (2\pi)^{3/2} R_{\text{side}}^2 R_{\text{long}}$ , is given in Fig. 5. Note that this definition of a three-dimensional Gaussian volume does not incorporate  $R_{\text{out}}$  since generally this length is potentially extended due to a finite value of the aforementioned emission duration. From the above HADES data, we estimate a volume of about  $1300 \text{ fm}^3$  for pairs of constructed neutral pions. The volume of homogeneity steadily increases with energy, but is merely a factor four larger at LHC. Extrapolating  $V_{\text{fo}}$  to  $k_t = 0$  yields a value of about  $3900 \text{ fm}^3$ .

The large scatter of data points in Fig. 5 below  $\sqrt{s_{\text{NN}}} = 10$  GeV is intriguing and might indicate a non-trivial energy dependence of the radius parameters in this region. However, the simplest interpretation would be to assume instead that the energy dependence is smooth. (Note that the difference of the HADES  $\pi^- \pi^-$  data and the lowest E895 data point at 2A GeV is primarily caused by the deviation in  $R_{\text{long}}$ .) If, however, the variation of the data at low energies, most prominently seen in the non-monotonicity of  $R_{\text{side}}$  (cf. Fig. 3), is to be taken seriously, new experimental and theoretical efforts are needed to clarify the situation, as could be done with the future experiments CBM at SIS100/FAIR in Darmstadt [41] and MPD at NICA in Dubna [42] or with the STAR fixed-target pro-

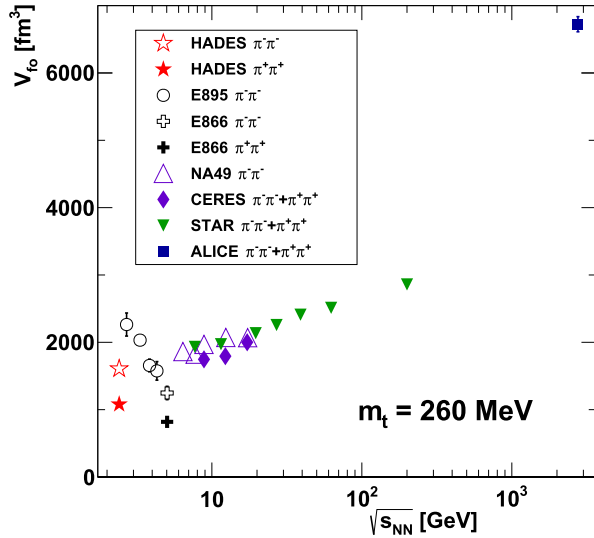


Fig. 5. Excitation function of the freeze-out volume,  $V_{fo} = (2\pi)^{3/2} R_{side}^2 R_{long}$ , as calculated from the data points shown in Fig. 3.

gram [43]. Finally, we want to recall that in Figs. 3, 4, and 5 we display statistical uncertainties only; the systematic ones were not available for all experiments.

In summary, we presented high-statistics  $\pi^-\pi^-$  and  $\pi^+\pi^+$  HBT data for central Au+Au collisions at 1.23A GeV. The three-dimensional Gaussian emission source is studied in dependence on transverse momentum and found to follow the trends observed at higher collision energies, extending the corresponding excitation functions down to the very low part of the energy scale. Substantial differences of the source radii for pairs of negative and positive pions are found, especially at low transverse momenta, an effect which is not observed at higher collision energies. A clear hierarchy of the three Gaussian radii is seen in our data, i.e.  $R_{long} < R_{side} \approx R_{out}$ , independent of transverse momentum. Furthermore, a surprisingly small variation of the space–time extent of the pion emission source over three orders of magnitude in center-of-mass energy,  $\sqrt{s_{NN}}$ , is observed. Our data indicate that the very smooth trends observed at ultra-relativistic energies continue towards very low energies. While both  $R_{out}$  and  $R_{long}$  steadily decrease with decreasing  $\sqrt{s_{NN}}$ , a weak non-monotonic energy dependence of  $R_{side}$  can not be excluded.

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