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TWO PION CORRELATIONS AT SPS ENERGIES*

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Recent results of identical pion correlations from the NA45/CERES, NA49, and NA57 CERN SPS experiments are discussed including their beam energy and transverse momentum dependence. The emphasis is put on the Hanbury–Brown Twiss (HBT) pion correlations analyzed with respect to the reaction plane orientation reported by the CERES Collaboration D. Adamova *et al.*, *Phys. Rev.* **C78**, 064901 (2008). The mean free path of pions at freeze-out D. Adamova *et al.*, *Phys. Rev. Lett.* **90**, 022301 (2003) is presented updated by the recent results from the SPS experiments.

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1. Introduction

The two-pion correlations from CERN SPS have already more then two decades of history. Since the beginning of the SPS operation in 1986, when ^{16}O ions were accelerated to 60 AGeV, many experiments were looking at the two particle correlations observables [1–3]. Such observables provide unique access to the spatial extension and dynamics of the source of particles emitted during heavy ion collisions. The experimental correlation function $C_2(\boldsymbol{q},\boldsymbol{k})$ is usually defined as the ratio of the signal distribution $S(\boldsymbol{q},\boldsymbol{k})$ to the background distribution $B(\boldsymbol{q},\boldsymbol{k})$, commonly calculated via event mixing technique (for a recent review see [4]). The ratio $C_2(\boldsymbol{q},\boldsymbol{k})$ depends on the momentum difference $\boldsymbol{q}=\boldsymbol{p}_2-\boldsymbol{p}_1$ and on the mean pair momentum $\boldsymbol{k}=(\boldsymbol{p}_1+\boldsymbol{p}_2)/2$. The width of the correlation function at $\boldsymbol{q}=0$ is inversely proportional to the source radius. Nowadays, with improving experimental capability of measuring particles emitted during heavy ion collisions, a new frontier has opened in the HBT analysis. Measurement of the emission

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source anisotropy in the collisions with finite impact parameters, detailed analysis of the HBT radii as a function of the pair momentum and rapidity, or even event-by-event source radii reconstruction become possible. Although the latter has not been reported yet by any of the SPS experiments the other interferometry techniques have been successfully applied to the CERN SPS data. The recent results of identical pion correlation analyses performed within three CERN SPS experiments, CERES, NA49, and NA57, are discussed in these proceedings.

2. Experimental setups and analysis approaches

The lead-beam program started at the CERN SPS in 1994, and for almost a decade the SPS accelerator provided a broad spectrum of energies to explore the physics of heavy ion collisions. The three CERN SPS experiments, CERES, NA49, and NA57, described in detail in [5, 6] and [7], respectively, collected a large amount of data during this period. The two-pion correlation analysis was performed on the data acquired for almost all energies provided by SPS, as listed in Table I. The latter also presents other general information about the experiments, *e.g.* colliding system, acceptance, and the particle identification method. The CERES energies 12.3 and 17.2 GeV per nucleon pair refer to the HBT analysis performed with the improved momentum resolution, a better understanding of the two-track resolution, and the full available data set [8, 9] in comparison to the first study reported in [3]. CERES and NA49 used Time Projection Chamber (TPC) detectors to identify charged particles, while NA57 used a high granularity telescope of silicon pixel planes. Comparing experimental setups, only CERES possessed cylindrical symmetry making the setup ideally suited to address azimuthal anisotropies. On the other hand, the wide acceptance of the NA49 experiment allowed for the detailed study of the HBT radii dependency on the rapidity. Combined, these detectors cover a broad range of femtoscopic results at SPS energies.

TABLE I

Characteristics of the chosen SPS experiments. The energies marked with an asterisk refer to data being re-analyzed (see text for details).

Detector	System	Energy $\sqrt{s_{\rm NN}}$ (GeV)	Acceptance y	Particle ID
CERES	Pb+Au	8.7, 12.3*, 17.2*	1.5–2.5	via dE/dx
NA49	Pb+Pb	6.3, 7.6, 8.7, 12.5, 17.3	1.0–6.0	h^-h^-
NA57	Pb+Pb	8.8	2.4–3.2	h^-h^-

The detailed information about event, track, and pair selection for two-pion analysis performed by the CERES, NA49 and NA57 experiments reported in this review can be found in [8, 9], [10], [11], respectively. The correlation functions were calculated in the longitudinally co-moving frame (LCMS) defined by the vanishing z-component of the pair momentum. The momentum difference $\boldsymbol{q}$ in this frame was decomposed into the "out", "side", and "long" components as suggested by Bertsch–Pratt [12]. The obtained two-pion Bose–Einstein (BE) correlation functions were parametrized by a three-dimensional Gauss function

$$G(\boldsymbol{q}) = \exp\Big\{ -\sum_{i,j} R_{ij}^2 q_i q_j \Big\}, \qquad (1)$$

with the indices i, j={out, side, long}. However, at this stage the three experiments start to follow their own specific analysis approach for extraction of the HBT radii. The main differences are:

- individual approach for treatment of the Coulomb repulsion,
- no common bins for centrality selection,
- fitting technique; maximum likelihood assuming Poisson distribution used by CERES and NA57 while NA49 used χ^2 minimalization.

3. Energy dependence of the HBT radii and the universal pion freeze-out

The mean transverse momentum dependence of the recently measured HBT radii from three SPS experiments is shown in Fig. 1, supporting the scenario of a collectively expanding particle source. At the top SPS energy new results from CERES agree within experimental uncertainties with the previous CERES HBT analysis [3] and with the one reported by NA49 Collaboration [10]. The minor discrepancy in $R_{\rm out}$ between CERES and NA49 experiments, visible for the highest $\boldsymbol{k}_\perp$ bin, could be attributed to the difference in the analysis approaches mentioned in Sec. 2. The similarity in the HBT radii measured by the CERES and NA49 experiments at the collision energy $\sqrt{s_{\rm NN}} \simeq 12.3$ GeV is not reflected in the case of the pion interferometry analysis at $\sqrt{s_{\rm NN}} \simeq 8.7$ GeV. Recent HBT results from the NA57 experiment are closer to the NA49 measurement.

A subtle variation of the HBT radii measured at different beam energies, lead to a possible explanation in terms of a universal pion freeze-out condition proposed by the CERES Collaboration [13]. The mean free path of pions at freeze-out $\lambda_{\rm f}$ is defined as the ratio of the freeze-out volume $V_{\rm f}$ to the product of the particle numbers N and the cross-sections σ of the

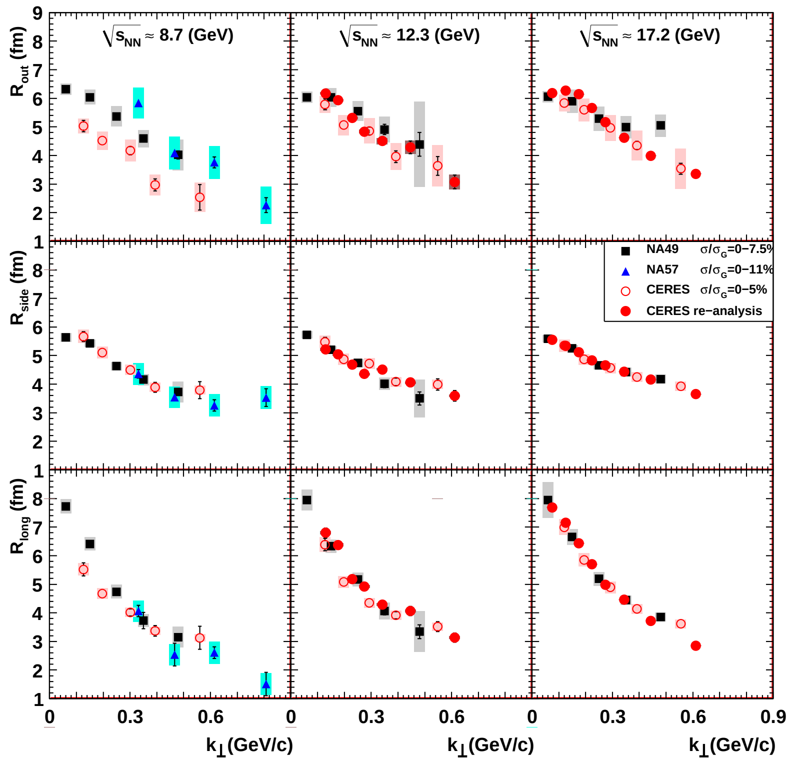

Fig. 1. The dependence of the HBT radii on mean transverse momentum — comparison between three SPS experiments. The corresponding event centralities are depicted in the legend (both CERES results obtained at $\sigma/\sigma_{\rm G} = 0$–$5\,\%$). The HBT radii measured by NA57 at $\boldsymbol{k}_\perp$=1.16 GeV/c are not shown. The color boxes correspond to systematics errors.

surrounding medium. Assuming azimuthal symmetry in the central collisions it is possible to calculate the freeze-out volume based on the measured HBT radii (for details see Eq. (2) in [13]). The recently published results of the pion interferometry from a wide variety of beam energies and collision systems give an opportunity to express them in the context of the freeze-out volume as shown in Fig. 2(a). The full circles correspond to the preliminary results from the re-analysis of the CERES data collected at energies 12.3 and 17.2 GeV per nucleon pair. The calculated mean free path of pions is shown in Fig. 2(b). For all beam energies measured the mean free path of pions is consistent with a constant value of about $\sim$1.0 fm supporting the universal pion freeze-out condition. The limited acceptance of NA57 experiments for measurement of the low momentum pion pairs did not allow a calculation of the $\lambda_{\rm f}$ at the collision energy $\sqrt{s_{\rm NN}} \simeq 8.7$ GeV where a visible discrepancy still remains between SPS results.

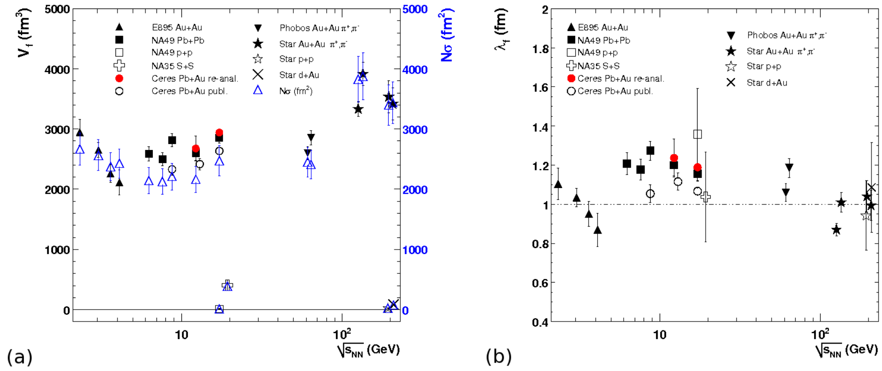

Fig. 2. (a) Beam energy dependence of the freeze-out volume and the total cross-section times the number of particle contained in $V_{\rm f}$ (see [13] for details). (b) Excitation function of the pion mean free path. Data taken from [2, 10, 13–23] has been slightly shifted for better visibility.

4. Azimuthal dependence of the pion source radii

The fireball created during a heavy ion collision at finite impact parameter is initially elongated in the direction perpendicular to the reaction plane. This initial asymmetry could be reduced or even reversed due to larger pressure gradient in-plane than out-of-plane. Therefore, it is interesting to look for a possible anisotropy of the pion source seen by the measured HBT radii with respect to the reaction plane as a possible signature of the source eccentricity at decoupling time. Such measurement at maximum SPS energy in Pb+Au collisions was recently reported by the CERES Collaboration [8]. In this analysis pion pairs were sorted into eight bins according to their azimuthal angle with respect to the reaction plane orientation $\Phi^* = \Phi_{\rm pair} - \Psi_{\rm RP}$. The latter was estimated based on the preferred direction of the particle emission, with a resolution of about 30°–34°. For each of the $\Phi^* = \Phi_{\rm pair} - \Psi_{\rm RP}$ bins the correlation function was generated and fitted as described in Section 2. The squared radii of the fits were parametrized by Eq. (25) from [24]. Such parametrization allowed for the measurement of the second Fourier coefficients, $R^2_{i,2}$ (with the indices $i = \{\text{out, side, long}\}$), describing the eccentricity of the observed pion source. The extracted second Fourier coefficients were corrected for the finite reaction plane resolution. Results for the centrality range $\sigma/\sigma_{\rm G} = 15$–$25\,\%$, together with the results from other beam energies, are shown in Fig. 3. The systematic error in case of the CERES analysis was estimated to be $0.3\,{\rm fm}^2$. The measured anisotropies in the transverse plane (out-side) indicate a pion source elongated out-of-plane. However, the smaller magnitude of the $R_{\rm side}$ oscillation comparing to

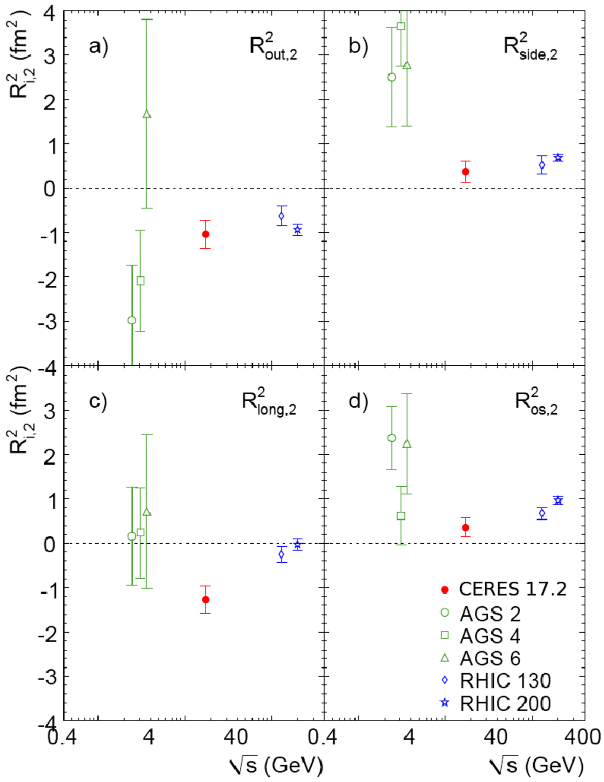

Fig. 3. Beam energy dependence of the pion source "out", "side", "long", and "out-side" anisotropies in Au+Au and Pb+Au collisions at the 15–25% event centrality. The data were taken from [25], [8], and [26, 27] representing the AGS, SPS, and RHIC energies, respectively.

the $R_{\rm out}$ might suggest that not only the source geometry but also the azimuthal dependence of the emission time needs to be considered. However, this scenario is not supported by the fact that the data follows the sum rule from Ref. [24]. The negative anisotropy of the $R_{\rm long}$ could imply a sensitivity of this radius to fluctuations of the azimuthal particle density. However, the finite oscillation of the $R^2_{\rm long,2}$ persisting in the limit of central collisions indicates that the knowledge about the mechanism leading to this effect is still incomplete. The source eccentricity, defined as $\varepsilon \equiv (R_y^2 - R_x^2)/(R_y^2 + R_x^2)$, can be experimentally approximated via $\varepsilon \simeq 2R^2_{\rm side,2}/R^2_{\rm side,0}$. Its value measured at SPS is about 0.043 which is significantly less than the one measured at AGS and somewhat lower than the one at RHIC, leading to a non-monotonic dependence on the collision energy.

5. Summary

Recent results of the two-pions intensity interferometry from three CERN SPS experiments were presented. The HBT radii measured at energies 12.3 and 17.2 GeV per nucleon pair agree well within experimental errors. The results obtained at $\sqrt{s_{\rm NN}} \simeq 8.7$ GeV by CERES differ from those reported by NA49 and NA57. A re-analysis of the CERES data collected at $\sqrt{s_{\rm NN}} = 8.7$ GeV is in progress. The first analysis of the two-pion HBT interferometry relative to the reaction plane orientation in Pb+Au collisions at the top SPS energy was reported by CERES Collaboration. The geometrical pion source eccentricity exhibits a non-monotonical dependence on the beam energy, similarly as the freeze-out volume. While the latter was explained in the context of a transition from baryon- to meson- dominated matter, such an implication for source anisotropies in noncentral collisions have not yet been considered. All these results make the low-energy scan at RHIC an interesting perspective.

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