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Evidence for Non-Gaussian Tail in 3-Dimensional Pion Emission Source at SPS

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The NA49 experiment at CERN SPS has acquired a huge data set of Pb+Pb events over a broad range of energy and centrality during the last several years. This high statistics data set, coupled with a state-of-the-art analysis technique, allows for the first model-independent extraction and energy scan of 3D emission sources for pion pairs at SPS energies. These 3D pion emission sources provide new insights into the nature of a long-range source previously reported by PHENIX at RHIC. Preliminary results indicate that the pion source function is essentially Gaussian from 20 AGeV to 80 AGeV but it displays significant non-Gaussian tails at 158 AGeV.

Keywords: Correlation; Interferometry; Intensity interferometry; Cartesian harmonics; Anisotropic correlation

I. INTRODUCTION

A deconfined phase of nuclear matter is expected to be formed at the high energy densities created in relativistic heavy ion collisions [1]. It is widely believed that important signatures of such a phase are reflected in the space-time extent and shape of particle emission source functions.

Recently, 1-Dimensional source imaging techniques [2,3] have revealed a non-trivial long range structure in the two-pion emission source at RHIC [4,5]. The origins of this structure are still unclear. The presence/absence of such a structure in the pion emission sources in heavy ion collisions at intermediate SPS energies could yield important information which could help resolve the structure's origins. The NA49 Collaboration has carried out Pb+Pb collisions over a wide range of bombarding energies at the CERN SPS during the last decade [6]. Such a rich data set provides a unique opportunity to search for this long range structure at the SPS and study its evolution with beam energy with a view to unraveling its nature.

In this paper, preliminary 3D emission source images for pions produced in central Pb+Pb collisions over the incident energy range 20 to 158 AGeV are presented. The results are discussed in the context of a Gaussian shape assumption.

II. EXPERIMENTAL SETUP AND DATA ANALYSIS

The data presented here were taken by the NA49 Collaboration during the years 1996-2002. The incident beams of 20, 80, 158 AGeV were provided by the CERN SPS accelerator. The NA49 Large Acceptance Hadron Detector [7] achieves large acceptance precision tracking ($\delta p/p^2 \approx (0.3 - 7) \cdot 10^{-4} \text{ (GeV/c)}^{-1}$ [7]) and particle identification using time projection chambers. Charged particles are detected by the tracks left in the TPC and identified by the energy deposited in the TPC gas. Mid-rapidity particle identification is further enhanced by a time-of-flight wall (resolution 60 ps). Event centrality is determined by a forward calorimeter which measures the energy of spectator matter.

3D correlation functions, $C(\mathbf{q})$, were obtained as the ratio of

pair to uncorrelated reference distributions in relative momentum \mathbf{q} for $\pi^-\pi^-$ pairs. Here, $\mathbf{q} = \frac{(\mathbf{p}_1 - \mathbf{p}_2)}{2}$ is half of the relative momentum between the two particles in the Pair Center-of-Mass System (PCMS) frame. The pair distribution was obtained using pairs of particles from the same event and the uncorrelated distribution was obtained by pairing particles from different events.

Track merging and splitting effects were removed by appropriate cuts on both the pair and uncorrelated distributions. The pair cuts require the two particles in each pair to be separated by at least 2.2 cm over 50 pad rows in the main vertex TPC. A 20% increase in this minimum separation results in the correlation data points fluctuating within the statistical errors. Hence, the systematic uncertainty associated with the pair cuts is deemed smaller than the statistical uncertainty.

The effects of track momentum resolution were assessed by jittering the momentum of the tracks in the data by the maximum resolution, $\delta p/p^2 \approx 7 \cdot 10^{-4} \text{ (GeV/c)}^{-1}$ [7]. The resulting re-computed 3D correlation function incorporates twice the effect of the momentum resolution and was found to be identical to the raw un-smearred correlation function for incident beam energies up to 80 AGeV. This is not surprising, considering that the mean momentum of the low p_T tracks used is 1.2 GeV/c, resulting in a momentum resolution of $\delta p/p \approx (1.2 \times 7 \cdot 10^{-4}) = 0.1\%$. Such a small momentum resolution has no observable effect on the correlation function.

At 158 AGeV, the above smearing procedure results in the correlation peak in the region $q < 10 \text{ MeV}$ to be slightly smeared. This tends to reduce the imaged source intensity at large radii. Hence, the preliminary results presented here would be a lower limit of the actual source function.

In the cartesian harmonic decomposition technique [8, 9], the 3D correlation function is expressed as

$$fC(\mathbf{q}) - 1 = R(\mathbf{q}) = \sum_l \sum_{\alpha_1 \dots \alpha_l} R_{\alpha_1 \dots \alpha_l}^l(q) A_{\alpha_1 \dots \alpha_l}^l(\Omega_{\mathbf{q}}) \quad (1)$$

where $l = 0, 1, 2, \dots$, $\alpha_i = x, y$ or z , $A_{\alpha_1 \dots \alpha_l}^l(\Omega_{\mathbf{q}})$ are cartesian harmonic basis elements ($\Omega_{\mathbf{q}}$ is solid angle in \mathbf{q} space) and $R_{\alpha_1 \dots \alpha_l}^l(q)$ are cartesian correlation moments given by

$$R_{\alpha_1 \dots \alpha_l}^l(q) = \frac{(2l+1)!!}{l!} \int \frac{d\Omega_{\mathbf{q}}}{4\pi} A_{\alpha_1 \dots \alpha_l}^l(\Omega_{\mathbf{q}}) R(\mathbf{q}) \quad (2)$$

The coordinate axes are oriented so that z is parallel to the beam (long) direction, x points in the direction of the total momentum of the pair in the LCMS frame (out) and y is perpendicular to the other two axes (side).

The correlation moments, for each order l , are calculated from the measured 3D correlation function using Eq. (2). Each independent correlation moment is then imaged using the 1D Source Imaging code of Brown and Danielewicz [2, 3] to obtain the corresponding source moment for each order l . Thereafter, the total source function is calculated by combining the source moments for each l as in Eq. (3)

$$S(\mathbf{r}) = \sum_l \sum_{\alpha_1 \dots \alpha_l} S_{\alpha_1 \dots \alpha_l}^l(r) A_{\alpha_1 \dots \alpha_l}^l(\Omega_{\mathbf{r}}) \quad (3)$$

III. RESULTS

Figure 1 shows the $l = 0$ (R^0) and $l = 2$ (R_{xx}^2 and R_{yy}^2) moments for mid-rapidity ($|y_L - y_0| < 0.35$, where y_L is particle laboratory rapidity and y_0 is CM rapidity), low p_T ($0.0 < p_T < 0.2$ GeV/c) $\pi^+ \pi^-$ pairs from 20 AGeV central (7%) Pb+Pb collisions as a function of the relative momentum q in the PCMS frame. Higher order moments are either zero or negligible. The Lorentz transformation of \mathbf{q} from the laboratory frame to the PCMS is done by a Lorentz transformation to the pair Locally Co-Moving System frame (LCMS) along the beam direction followed by a transformation to the PCMS along the direction of transverse momentum of the pair.

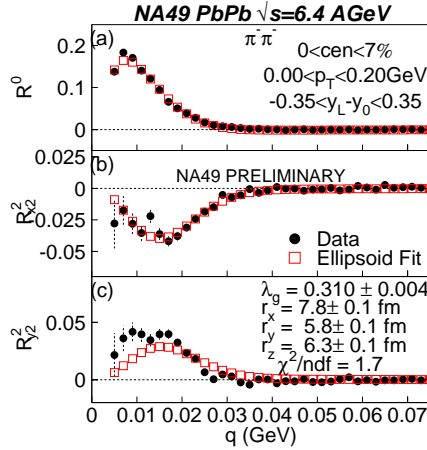


FIG. 1: (a) $l = 0$ and $l = 2$ ((b) and (c)) moments for mid-rapidity low p_T $\pi^+ \pi^-$ pairs from 20 AGeV central Pb+Pb collisions as a function q . Data are shown as solid circles while the squares represent the result of a simultaneous fit of the moments with an ellipsoid shape.

The data points are shown in solid circles and the open squares represent the result of a simultaneous fit to the independent moments with a ellipsoid shape (3D Gaussian). The fit parameters are shown in the bottom panel. The extracted

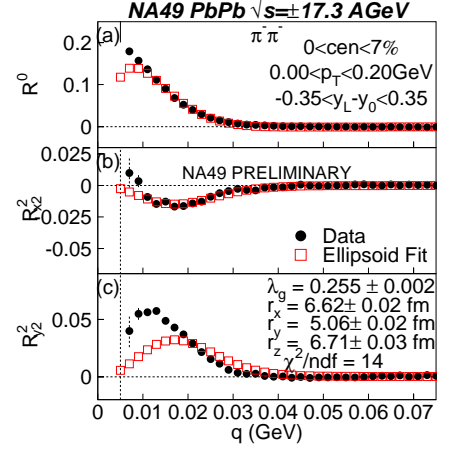


FIG. 2: Same as Fig.1 but for 158 AGeV Pb+Pb collisions.

data moments are fairly well represented by the Gaussian shape.

Figure 2 shows the corresponding moments for $\pi^+ \pi^-$ pairs from 158 AGeV Pb+Pb collisions. In this case, the fit result shows that the data moments are not adequately described by the Gaussian assumption: R^0 and R_{xx}^2 exhibit significant discrepancies between the data and the fit moments.

For the low p_T pairs considered, the only significant source moments are found for multiplicities $l = 0$ and 2. Hence, the total source functions in the x , y and z directions are simply the sum of the 1D source S^0 and the corresponding $l = 2$ moment S_{ii}^2 where $i = x, y$ or z . Fig. 3(a)-(c) shows the total

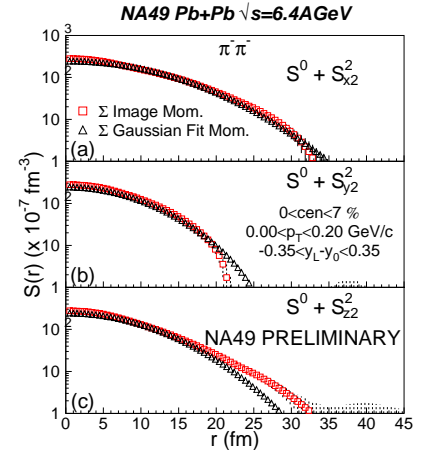


FIG. 3: Total source function in (a) x (out) (b) y (side) (c) z (long) direction for low p_T mid-rapidity $\pi^+ \pi^-$ pairs from central Pb+Pb collisions at $\sqrt{s} = 6.4$ AGeV (Incident beam energy = 20 AGeV). Squares represent source image while triangles represent Gaussian assumption fit function result.

source function for mid-rapidity, low p_T pion pairs from central Pb+Pb collisions at 20 AGeV (i.e $\sqrt{s} = 6.4$ AGeV). The source image is shown in squares while the triangles represent an ellipsoid (3D Gaussian) shape fit to the 3D correlation

function. The source image and the Gaussian fit agree reasonably well in all 3 directions.

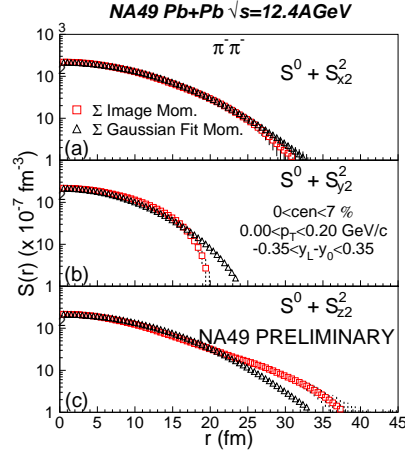


FIG. 4: Same as Fig.3 but for $\sqrt{s} = 12.4$ AGeV (Beam energy = 80 AGeV).

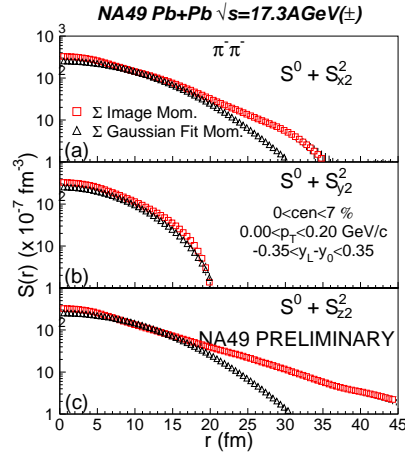


FIG. 5: Same as Fig.3 but for $\sqrt{s} = 17.3$ AGeV (Beam energy = 158 AGeV). Result is average over runs with +ve and -ve magnetic field.

The same conclusion is reached from Fig. 4(a)-(c) for low p_T pion pairs from central Pb+Pb collisions at 80 AGeV ($\sqrt{s} = 12.4$ AGeV) respectively.

However, at 158 AGeV incident energy ($\sqrt{s} = 17.3$ AGeV), Fig. 5(a),(c) show that there are significant deviations of the source image from the Gaussian fit in the x and z directions respectively: the source image seems to exhibit a non-Gaussian tail which extends beyond the range of the Gaussian fit for $r > 17$ fm in the out and long directions.

IV. DISCUSSION

The evolution of the pion source image with increasing beam energy indicates that the source function is essentially Gaussian from 20 AGeV to 80 AGeV but it displays very prominent non-Gaussian tails at 158 AGeV in the out and long directions. Hence, the long range structure, first observed at RHIC ($\sqrt{s} = 200$ AGeV) [5], is already manifest at much lower energies at the SPS. This points to the expectation that there are new physics processes which set in between 80 AGeV ($\sqrt{s} = 12.4$ AGeV) and 158 AGeV ($\sqrt{s} = 17.3$ AGeV) which result in the non-Gaussian tails in this energy regime.

Could the non-Gaussian tails observed at 158 AGeV be due to resonance decays such as the ω meson? Although a quantitative issue, the resonance population does not change significantly from $\sqrt{s} = 12.4$ AGeV to $\sqrt{s} = 17.3$ AGeV. Hence, it is unlikely that resonance decays could account for the observed non-Gaussian tail at 158 AGeV.

V. CONCLUSIONS

The NA49 Collaboration has performed the first extraction of emission source functions for mid-rapidity, low p_T pions produced in central Pb+Pb collisions over the beam energy range 20-158 AGeV at SPS. Preliminary results indicate that the source functions are essentially Gaussian from 20 to 80 AGeV. However, at 158 AGeV the pion source function displays non-Gaussian tails in the out and long directions. It is unlikely that these non-Gaussian tails originate from secondary pions produced in resonance decays.

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