IDENTIFIED PION INTERFEROMETRY IN HEAVY-ION COLLISIONS AT CERN

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Abstract

$\pi^+\pi^+$ correlations from S + Pb collisions at 200 GeV/c per nucleon, measured by the focusing spectrometer of the NA44 experiment at CERN, are presented. The large data set, particularly at small values of Q_{inv} , allows determination of the detailed shape of the correlation function. We construct the background by event mixing, and correct for resolution, Coulomb interaction, and distortion of single-particle spectra which produce effects large compared to the statistical errors at small Q_{inv} . An exponential, rather than Gaussian, source distribution is slightly favoured, but both are statistically acceptable.

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1 INTRODUCTION

Two-particle intensity interferometry can provide information on the space-time extent of the particle-emitting source [1, 2, 3], and shed light on the dynamical evolution of heavy-ion collisions. This technique of analysis follows the approach of Hanbury-Brown and Twiss (HBT) [1]. Results from early experiments indicate that pions are emitted from a source of approximately the same radius as the projectile at BNL energies [4, 5], but from a larger source in the higher energy collisions explored at CERN [5, 6]. Additionally, intensity interferometry may yield information about the time span of particle emission, and provide evidence for the existence of a first-order phase transition in these collisions [7]. Such analyses require good resolution and high statistics in the two-particle distributions. The physics interpretation needs a good understanding of the connection between a functional form to fit to the data and the corresponding space-time distribution of the emitting source.

NA44 is a second generation experiment, building on the results of the early surveys. It is optimized for the study of identified single- and two-particle distributions at mid-rapidity. The spectrometer is a focusing spectrometer, a design which optimizes the acceptance for pairs of particles with small momentum difference. This allows small statistical uncertainties in the two-particle correlation function in the region of the signal from Bose-Einstein correlations. These small statistical errors demand good control of the systematic errors. We describe corrections in detail. Additionally, we apply a Coulomb correction based on the integration of Coulomb waves [8], in the place of the more common but less accurate Gamow correction. Our high statistics allow a study of the shape of the correlation function. Most of the previous studies have integrated over the transverse momentum of the mesons and analysed the correlation in the four-momentum difference of the two particles. We follow that procedure here to obtain a basis for comparison. In subsequent publications we shall give results for the multi-dimensional analyses, which are more sensitive to interesting dynamics, and for kaons and higher p_T pions, which are less diluted by resonance decay. A Gaussian parametrization is frequently applied to fit two-particle correlation functions [3]; however an exponential distribution could arise owing to particle-production dynamics such as string-breaking [9] or decay of resonances [8, 10, 11].

2 EXPERIMENTAL SET-UP

The layout of the experiment is shown in Fig. 1. There are three dipole magnets (D1, D2, and D3) and three quadrupoles (Q1, Q2, and Q3); the first two dipoles select the momentum and the last one, which is not shown in the figure, is used for momentum calibration. The quadrupoles are configured in such a way that the momentum of the particle is strongly correlated with the position on hodoscope No. 1. Only one charge state can be detected in the spectrometer at one time. The momentum range selected by the spectrometer covers a band of $\pm 20\%$ at its nominal momentum setting. As an example, the 4 GeV/c setting accepts tracks in the momentum range $3.2 < p < 4.8$ GeV/c. The angular coverage is approximately -0.3° to 4.5° in the horizontal and $\pm 0.3^\circ$ in the vertical plane.

The beam rate and time-of-flight start signal are determined using two systems: a Cherenkov beam counter, labelled CX, and a scintillating optical fibre hodoscope, labelled BCF. The intrinsic time resolution of the scintillating fibre array [12] is about 85 ps, whilst for the Cherenkov beam counter [13] it is about 35 ps. A forward calorimeter is available for triggering on missing energy. A silicon multiplicity detector is used to

measure the charged-particle distribution with 2π acceptance in the pseudorapidity range $1.5 < \eta < 3.3$. Finally, a forward scintillator, T_0 , is used as a trigger device, to signal ‘minimum bias’ events (at least one minimum ionizing particle) or ‘central’ events, for which the particle multiplicity recorded in T_0 is large. Our minimum bias data, however, contain a bias toward small impact parameters owing to the requirement of finding two particles in the spectrometer acceptance. The events with the lowest multiplicities in the silicon detector have been excluded during the off-line analyses in order to ensure that our ‘target out’ contribution is negligible.

The spectrometer uses three highly segmented scintillator hodoscopes, named H1, H2, and H3 [14], divided into 50, 60, and 50 vertical slats, respectively. Photomultiplier tubes are mounted on either end of the slats to optimize the time-of-flight resolution, and to allow determination of the y -position of each particle using the time difference between top and bottom.

In this analysis we use only the time measured on H3 for particle identification with a time resolution of approximately 100 ps. The Cherenkov detectors are used for differentiation between π , K, and p (C1, freon-12 at 1.3 and 3.0 atm), and to separate e and π (C2, nitrogen/neon mixture at atmospheric pressure). They are implemented in the trigger in either ‘veto’ or ‘require’ mode, or used in the off-line analyses.

Four wire chambers are used for momentum calibration in conjunction with the third dipole magnet. A uranium–scintillator calorimeter, which was not used in this analysis, allows identification of e, π , and μ .

3 DATA ANALYSIS

The data sample contains 227,000 reconstructed π^+ pairs from S + Pb collisions at 200 GeV/c per nucleon. The single-particle acceptance curve is shown in Fig. 2a, and spans the rapidity range from 3.1 to 4.1, and a p_T range up to 0.4 GeV/c. The lead-target thickness was 2 mm, i.e. 1% of an interaction length. There was no centrality (small impact parameter) requirement in this data sample. However, the two-particle trigger itself favours central events.

Tracks are reconstructed from hit positions on the three hodoscopes, with pattern recognition constrained by straight-line trajectories after the magnets. The χ^2 in the vertical direction provides additional track-quality information. Particles are identified based on the Cherenkov pulse heights and the time-of-flight. Figure 2b shows the distribution of flight times. Contamination of $\pi\pi$ pairs by πK was estimated to be less than 2%. Pairs hitting neighbouring slats on the hodoscopes are not used in this data sample to avoid the possibility of two tracks being reconstructed from a single particle. The Q_{inv} resolution for two particles is 13 MeV and bins of size 10 MeV/c are employed for the correlation study.

The raw correlation function is determined using

$$C_{raw}(\vec{k}_1, \vec{k}_2) = \frac{R(\vec{k}_1, \vec{k}_2)}{B(\vec{k}_1, \vec{k}_2)}, \quad (1)$$

where $\vec{k}_i$ are the particle momenta. The ‘real distribution’ $R(\vec{k}_1, \vec{k}_2)$ is the distribution of the relative momentum, and the ‘background distribution’ $B(\vec{k}_1, \vec{k}_2)$ is constructed from tracks mixed randomly from all events contained in $R(\vec{k}_1, \vec{k}_2)$. The background distribution is generated as follows: for each event in $R(\vec{k}_1, \vec{k}_2)$, ten pairs of events are selected randomly to form the background pairs. In these pairs, one particle in each event is selected randomly

to create a new ‘event’ for the $B(\vec{k}_1, \vec{k}_2)$ distribution. As in the real distribution, events from $B(\vec{k}_1, \vec{k}_2)$ are rejected when the tracks have neighbouring hits on the hodoscopes. Thus, the effects due to the loss of close-by pairs cancel for the two-particle correlation. There are 1,903,000 events in the background sample which is normalized to 227,000 events. The statistical error is dominated by the data sample.

This event-mixing technique is equivalent to creating background pairs from the single-particle spectrum arising from the real pairs,

$$B(\vec{k}_1) = \sum_{\vec{k}_2} R(\vec{k}_1, \vec{k}_2), \quad (2)$$

$$B(\vec{k}_1, \vec{k}_2) = B(\vec{k}_1) \otimes B(\vec{k}_2). \quad (3)$$

$B(\vec{k}_1, \vec{k}_2)$ will be treated as being created from the single-particle spectrum $B(\vec{k}_1)$ for the discussion of the HBT analysis in the following sections.

Our background sample is distorted compared to the ideal uncorrelated two-particle spectrum owing to the effect of the two-particle correlations on the single-particle spectrum [15]. The correct single-particle spectrum can be obtained by use of the observed correlations and the two-particle spectrum,

$$B_{SPC}(\vec{k}_1) = \sum_{\vec{k}_2} \frac{R(\vec{k}_1, \vec{k}_2)}{C_{SPC}(\vec{k}_1, \vec{k}_2)}, \quad (4)$$

where C_{SPC} is the fitted two-particle correlation corrected for the distortion of the single-particle spectrum. Since it is not possible to know the two-particle correlations in advance, an iterative procedure is needed to obtain them and the ‘correlation-free’ single-particle spectrum. The initial single-particle spectrum, $B_{SPC}^0(\vec{k}_1)$, is taken from the two-particle event sample,

$$B_{SPC}^0(\vec{k}_1) = \sum_{\vec{k}_2} R(\vec{k}_1, \vec{k}_2), \quad (5)$$

$$B_{SPC}^{i+1}(\vec{k}_1) = \sum_{\vec{k}_2} \frac{R(\vec{k}_1, \vec{k}_2)}{C_{SPC}^i(\vec{k}_1, \vec{k}_2)}, \quad (6)$$

$$B^{i+1}(\vec{k}_1, \vec{k}_2) = B_{SPC}^{i+1}(\vec{k}_1) \otimes B_{SPC}^i(\vec{k}_2), \quad (7)$$

$$C_{SPC}^{i+1}(\vec{k}_1, \vec{k}_2) = \frac{R(\vec{k}_1, \vec{k}_2)}{B^i(\vec{k}_1, \vec{k}_2)}, \quad (8)$$

with $i = 0, 1, \dots$, where $B_{SPC}^{i+1}(\vec{k}_1)$ is the single-particle reference sample created from the $\pi^+\pi^+$ data set corrected with the two-particle correlations C_{SPC}^i calculated from the last iteration, and $B^i(\vec{k}_1, \vec{k}_2)$ is the two-particle reference sample created from the corrected single-particle reference sample, $B_{SPC}^i(\vec{k}_1)$. C_{SPC} is well represented by a Gaussian distribution,

$$C_{SPC}(Q_{inv}) = A(1 + \lambda e^{-Q_{inv}^2 R_{inv}^2}) \quad (9)$$

and this was used in the iterative procedure. Finally, the correction factor, K_{SPC} , is calculated as

$$K_{SPC}(Q_{inv}) = \frac{B^i(Q_{inv})}{B^0(Q_{inv})}, \quad (10)$$

with $B^i(Q_{inv})$ from the final iteration.

The procedure is similar to the approach in Ref. [16]. In Monte Carlo simulations, we find convergence to the input parameters within four or five iterations. When this correction is applied to the experimental data, the results converge inside the experimental statistical error within four iterations.

This technique corrects the distortion of the single-particle spectrum due to the two-particle correlations of the particles that are in the acceptance of the detectors, although it does not fully correct the distortion due to the correlations with particles outside the acceptance. We estimate this to have only a small effect on the single-particle spectrum. We do not consider screening effects due to particles of opposite charge in a high-particle-density environment. Such effects might influence the Coulomb correction considerably [17].

4 RESULTS

The measured two-particle correlation (1) is related to the true correlation by

$$C_{corr}(\vec{k}_1, \vec{k}_2) = C_{raw}(\vec{k}_1, \vec{k}_2) \times K_{SPC}(\vec{k}_1, \vec{k}_2) \times K_{acceptance}(\vec{k}_1, \vec{k}_2), \quad (11)$$

where $K_{SPC}(\vec{k}_1, \vec{k}_2)$ corrects for the distortion of the single-particle spectrum as discussed above and $K_{acceptance}(\vec{k}_1, \vec{k}_2)$ is the correction for the distortion of the two-particle spectrum by the momentum resolution and the two-particle acceptance of the detectors. $K_{acceptance}$ is calculated from the known resolution of the spectrometer. All three corrections, K_{coul} (see below), K_{SPC} , and $K_{acceptance}$, depend on the source size and the fitting results, so an iterative approach is required.

For π^+ pairs, the two-particle correlations arise from two different origins, the Coulomb interaction and the Bose–Einstein effect. In order to get the Bose–Einstein correlation alone, C_{corr} should be corrected for the Coulomb interaction,

$$C_{HBT}^{data}(\vec{k}_1, \vec{k}_2) = C_{corr}(\vec{k}_1, \vec{k}_2) \times K_{coul}(\vec{k}_1, \vec{k}_2), \quad (12)$$

where C_{HBT}^{data} is the Bose–Einstein correlation of the experimental data and K_{coul} is the correction for the Coulomb interaction; K_{coul} is calculated by using a Coulomb wave-function integration [8], a procedure which is more accurate than the standard Gamow correction. It is not possible to use the Coulomb wave-function integration exactly for the exponential parametrization of the source distribution owing to the divergence of the integration of the Fourier transform of an exponential function. The Coulomb wave-function integration for the exponential parametrization is therefore calculated with the Gaussian source model.

The data, correction factors, and final C_{HBT} are shown in Table 1. The momentum resolution reduces the Coulomb dip visible in the first bin in C_{corr} , leading to a relatively large acceptance correction. The Coulomb correction applies to the particles originating in the interaction volume, whilst there are some fraction of pions in our sample which come from decays of relatively long-lived resonances such as the η , or from the small number of tracks from π – μ decay which pass reconstruction. We do not correct for this effect explicitly, but include it in the assignment of the systematic errors. We also allow for an uncertainty in the effective integration of the Coulomb correction over the rapidly varying event population in that bin.

Two different functions are used for fitting, with

$$C_{HBT}^{Gaussian}(Q_{inv}) = A(1 + \lambda e^{-Q_{inv}^2 R_{inv}^2}) \quad (13)$$

Table 1: Table of experimental results and corrections

Q_{inv} (MeV/c)	C_{raw}	SPC correction	Acceptance correction	C_{corr}	Coulomb correction	C_{HBT}^{data}	$\delta C_{statistic}$	$\delta C_{systematic}$
5	1.169	1.220	0.514	0.733	1.565	1.148	0.031	0.126
15	1.143	1.224	0.710	0.994	1.161	1.154	0.011	0.032
25	1.136	1.226	0.720	1.003	1.074	1.077	0.008	0.029
35	1.080	1.224	0.706	0.933	1.037	0.968	0.007	0.026
45	1.034	1.223	0.702	0.887	1.020	0.905	0.007	0.023
55	1.004	1.220	0.701	0.858	1.012	0.868	0.008	0.017
65	0.992	1.217	0.698	0.842	1.009	0.849	0.008	0.016
75	0.970	1.214	0.701	0.826	1.007	0.831	0.008	0.012
85	0.979	1.210	0.705	0.835	1.005	0.840	0.008	0.012
95	0.942	1.206	0.700	0.796	1.005	0.799	0.008	0.007
110	0.946	1.200	0.713	0.809	1.003	0.812	0.006	0.006
130	0.942	1.189	0.716	0.802	1.003	0.805	0.007	0.004
150	0.937	1.179	0.720	0.796	1.002	0.797	0.007	0.004
170	0.946	1.170	0.718	0.795	1.002	0.796	0.008	0.004
190	0.945	1.160	0.726	0.797	1.001	0.797	0.009	0.004
225	0.934	1.139	0.739	0.785	1.001	0.785	0.007	0.004
275	0.947	1.108	0.768	0.805	1.001	0.807	0.012	0.004
325	0.901	1.080	0.790	0.769	1.001	0.770	0.022	0.004
375	0.890	1.054	0.798	0.749	1.000	0.749	0.059	0.004

Table 2: Fitted results of Gaussian and exponential parametrizations

Parametrization	Normalization	λ	R_{inv} (fm)	χ^2/N_{dof}
Gaussian	0.800 ± 0.002	0.46 ± 0.04	4.50 ± 0.31	18.1/16
Exponential	0.794 ± 0.004	0.77 ± 0.08	3.54 ± 0.33	12.0/16

for the Gaussian parametrization and

$$C_{HBT}^{exp}(Q_{inv}) = A(1 + \lambda e^{-2Q_{inv}R_{inv}}) \quad (14)$$

for the exponential parametrization. The fitted parameters are listed in Table 2 and shown together with the data in Fig. 3, where a renormalization to the Gaussian fitting result has been applied (i.e. divided by 0.80). If the standard Gamow correction is used instead of the Coulomb wave-function correction applied here, the resulting parameters for the Gaussian fit are $\lambda = 0.52 \pm 0.04$, $R_{inv} = 4.12 \pm 0.20$ fm.

It is seen that the Gaussian fit deviates from the data mainly around 80 MeV, whilst the exponential fit is excellent.

The Gaussian fit ¹⁾ allows comparison with other experiments and models, despite its larger χ^2 . The value in Table 2 is much larger than that obtained in experiments on hadron collisions, consistent with the picture that we are measuring a geometrical effect related to the large dimensions of the nuclear system. However, it is not much larger than

1) It is important to note that the R_{inv} in the Gaussian is very often introduced in such a way that the value is $\sqrt{2}$ larger than in this paper. We have decided to adhere to the definition used in Ref. [18].

the radius of the sulfur projectile, defining the size of the interaction volume in a central collision with a lead target. It must be noted that R_{inv} is not a direct measure of a physical size as it also contains a time component. We note that there is not much change from the radius observed in collisions of silicon projectiles at the lower energies of the AGS [18], and thus conclude that there is little evidence for a large expansion of a pion gas before freeze out.

Although the fit to the exponential function yields a better χ^2 , it is possible that the actual shape of the correlation is neither exponential nor Gaussian. The correlations as a function of Q_{inv} may reflect kinematic effects arising from the spectrometer acceptance [18]. Pions arising from the decay of resonances add a pion source with an effectively longer lifetime and populate the correlation function at small Q_{inv} , modifying the shape so that it appears more exponential [10]. The overall strength of the correlation, reflected in the λ parameter, is lowered by pions from long-lived resonances (e.g. η) as they have no Bose-Einstein correlation effect with the promptly emitted pions [19].

We have investigated the correlation function with very high statistics and carefully analysed the systematic errors in our data sample. Such data allow a more detailed study of the emitting source than has been previously possible. Further interpretation of the fine details of the shape of the correlation will be available after careful investigation of the effects of resonances and analysis in terms of directional correlations rather than Q_{inv} .

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Figure 1: The NA44 experimental set-up.

Figure 2: a): The single-particle response in y and p_T . The ϕ acceptance (not shown) decreases from 2π at $p_T = 0.0$ GeV/c to 0.1 at $p_T = 0.4$ GeV/c. b) Time-of-flight spectrum at H3.

□

Figure 3: $CHBT$ as a function of Q_{inv} . The systematic and statistical errors have been added in quadrature.