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Source Parameters Deduced from Bose-Einstein Correlations of Two and Three Soft Pions in Symmetric Heavy-Ion Interactions at 650 A MeV

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The analysis of Bose-Einstein correlations for systems of two and three low-momentum pions in interactions of Au+Au and Nb+Nb at 650 A MeV kinetic energy are presented. The data were taken with the Plastic Ball spectrometer. The pion-emitting source sizes obtained from specific three-pion correlations are significantly smaller than those extracted from two-pion correlations. The dependence of the source parameters on the multiplicity of produced pions was examined. The low-p_t pions are emitted from a larger region than the high-p_t ones.

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1. Introduction

Identical pion interferometry, analogous to the Hanbury-Brown and Twiss method in astronomy [1], has become a commonly recognized tool for studying the coherence and the dimensions of pion sources. An enhancement in the production of identical pions being close in phase space is expected from the requirement of a symmetric wave-function under particle transposition. With specific assumptions on the distribution of pion point-sources, the width of this enhancement is used to estimate the spatial and temporal dimensions of the pion-emitting region, whereas the height of the interference peak is believed to reflect the degree of coherence of the pion sources. The height of the interference peak is usually decreased by resonance production, Coulomb repulsion, strong final-state interactions, local charge compensation, experimental acceptance etc. Some of these factors are difficult to account for quantitatively and consequently the information about the coherence of pions obtained from interferometric measurements is less reliable than the extracted source sizes.

The usefulness of the intensity interferometry tool in relativistic ion collisions has already been convincingly demonstrated (for a review see [2]). There exist interferometric data from equal-mass light-ion interactions, and from interactions between projectiles of light and medium mass and heavy target nuclei. To our knowledge only one interferometric study of symmetric heavy-ion collisions has been reported so far [3].

In this article we continue our study of two-pion correlations [3] and present the analysis of the interference of three positive pions, produced in Nb+Nb and Au+Au collisions. The data was taken with the Plastic Ball spectrometer and the incident kinetic energy of the projectile nuclei was 650 A MeV. We recall here the main findings on two-pion correlations reported in our previous paper [3]. Assuming a Gaussian distribution of the sources, both in space and time dimensions, and using the variables $q=|\mathbf{p}_1-\mathbf{p}_2|$ and $q_0=|E_1-E_2|$ where $\mathbf{p}_i$ and E_i are the momentum and energy of the ith pion in the centre-of-mass system, we obtained the radii of 3.4 ± 0.4 fm and 4.8 ± 0.6 fm and the life-times of 3.6 ± 0.8 fm/c and 5.7 ± 0.7 fm/c for the Nb+Nb and Au+Au collisions, respectively. We have not seen any significant dependence of the source size on the total charged-particle multiplicity. Selection of low cms-momentum pions

($p < 80$ MeV/c) revealed a large source size of about 10 fm for the Au+Au interactions and a size of about 4.5 fm for the Nb+Nb system. For larger pion momenta the source size decreased, the decrease being stronger for Au+Au collisions.

2. Experiment

The data we are presenting here have been obtained by using the Plastic Ball spectrometer [4] at the Bevalac. The Plastic Ball consists of 815 $\Delta E - E$ detector modules surrounding the target and covering 97% of the 4π solid angle. Each of the modules represents a particle identifying telescope with a slow ΔE and a fast E detector which are read out via the same photomultiplier. The ΔE detector is a CaF_2(Eu) crystal with a characteristic decay time of 1 µs for the emission of the scintillation light and it is read out through the E counter which consists of plastic scintillator material. The light emission of the plastic scintillator is approximately 100 times faster than that of the CaF_2(Eu) so that 90% of the E signal is collected within 10 ns. The thickness of the CaF_2(Eu) crystal is 4 mm and the plastic E scintillator has a length of 35.6 cm. The telescope is capable of identifying charged fragments up to helium isotopes and positive pions. The most forward angular range of the detector (9°–30°), called the Mall, has a granularity which is two times finer than the rest of the sphere. The angular separation of the centres of adjacent modules in the Mall is 3.5 degrees. The positive pions in the kinetic energy range of 20–100 MeV can be identified by using $\Delta E - E$ technique. Because of the relatively low yield of pions as compared to baryons, the additional positive pion identification is made by means of their sequential decay $\pi^+ \to \mu^+ \to e^+$. The e^+-energies extend up to 53 MeV and are easily measured in the plastic scintillator. A discriminator detects the second spike corresponding to the e^+ and a TDC measures the delay time between the π^+ and e^+ signals. The TDC covers the range between 250 ns and 10 µs and about 90% of all $\pi^+ \to \mu^+ \to e^+$ decays can be recorded, provided the e^+ deposits an energy greater than 1 to 2 MeV in the scintillator. This requirement leads to the loss of a few percent of the π^+'s. It may occur that a positron penetrates into an adjacent tube and this could simulate a pion signal if it coincides with a baryonic signal in the same tube. This effect manifests itself as a spike at $\Delta t < 60$ ns in an otherwise quite flat Δt spectrum, Δt being the time difference between the π^+ and e^+ signals. In order to discard those accidentals, a cut at $\Delta t = 60$ ns has been applied. The following analysis will be based on 102000 and 67000 events with two or more particles identified as positive pions for the Nb+Nb and Au+Au interactions, respectively. The total number of two-pion combinations were 126000 and 90000 for the Nb+Nb and Au+Au systems, respectively, whereas for pion triplets the corresponding numbers were 13000 and 14000.

3. Variables and Reference Distributions

To deduce the size of the pion source certain assumptions regarding the boson emitting region have to be made. In our previous analysis of two-pion correlations [3] we used a model which assumes a Gaussian distribution of point-like pion sources in the spatial and temporal variables. The corresponding variables were the three-momentum difference $q = |\mathbf{p}_1 - \mathbf{p}_2|$ and the energy difference $q_0 = |E_1 - E_2|$. The Gaussian widths in space and time are separately characterized by the estimated parameters. These variables, however, can not be easily generalized to the three-particle case. We adopt here the Q_{12}-variable, defined for the two-particle case as the four-momentum transfer squared, which is simply related to the effective mass of the pair:

$$Q_{12}^2 = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 - (2m_\pi)^2 = M^2 - (2m_\pi)^2$$

For particles of close energies, Q_{12} is approximately equal to q. By analogy, for three-pion correlations the corresponding formula reads:

$$\begin{aligned} Q_{123}^1 &= Q_{12}^2 + Q_{23}^2 + Q_{13}^2 \\ &= (E_1 + E_2 + E_3)^2 - (\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3)^2 - (3m_\pi)^2 \end{aligned}$$

We shall analyze both two- and three-pion correlation functions by fitting them to the following expression:

$$C(Q) = N[1 + \lambda \exp(-Q^2 r^2/2)] \tag{1}$$

where the parameter r characterizes the spatial and temporal dimensions of the pion emitting region and λ, called "chaoticity," measures the degree of coherence of the pion sources.

Special attention has been devoted to construct the uncorrelated reference distribution. In the two-pion case it has been calculated by random selection of pions from different events with close total charged-particle multiplicities and the same pion multiplicity [3]. When studying three-pion system, our intention was to look for specific three-pion correlations, irreducible to two-pion ones. The reference sample was generated *by random selection of a single pion from* *one event and a random pion pair from another event,* the latter event having the same charged-pion multiplicity and about the same total multiplicity of charged particles as the first one. This procedure *conserves two-pion effects in the reference distribution.* To construct the correlation function, the experimental distributions were divided by the normalized reference distributions. The reference samples used in our correlation analysis consisted of one million pion pairs and 225 thousands triplets for each reaction. To account for possible distortion of the correlation function by electromagnetic interaction of pions, we have incorporated the Gamov factor [5], defined for a pair of pions as:

$$G(\eta)=\eta/[\exp(\eta)-1]$$

where $\eta=2\pi\alpha m_\pi/\tilde{q}$ with α being the fine structure constant and $\tilde{q}$ the invariant relative momentum of the pion pair. The two-pion reference distribution has been corrected by weighting each pair with $1/G(\eta)$. As Gamov factor for three-pion analysis we used the following approximation [8]:

$$G(123)=G(12)\,G(23)\,G(13)$$

where $G(ij)$ is the two-particle Gamov factor of the ith and jth pions. No attempt has been made to account for the strong $\pi^+\pi^+$ and $\pi^+\pi^+\pi^+$ final-state interactions. Precise FSI calculations are hardly possible at present. It has been shown recently by Suzuki [13], that an uncorrected two-pion correlation function underestimates the Bose-Einstein enhancement by about 20%, although the significance of this number is not clear due to the lack of understanding of the pion-production dynamics. The separation of final-state interactions and the mechanisms responsible for the pion production, as it has been pointed out in [14], is intrinsically ambiguous. The validity of these calculations was, however, disputed by Bowler [15].

4. Basic Characteristics of the Interactions

We will first present the multiplicity and inclusive momentum distributions. The multiplicities of charged particles are given in the variable $n_r \equiv \mathcal{N}_{ch}/\mathcal{N}_{1/2}$, which we will refer to as the "reduced multiplicity". Here $\mathcal{N}_{ch}$ is the charged-particle multiplicity of the event and $\mathcal{N}_{1/2}$ is the value for which the multiplicity distribution of the studied reaction have decreased to half the plateau value. In Fig. 1 the normalized n_r distributions are shown for events in which the multiplicity of positive pions is equal to two, $n_\pi=2$ (open circles), or greater than two, $n_\pi>2$ (black points), for the Nb+Nb interactions. Figure 2 displays the corresponding data for Au+Au collisions. It can be seen from the figures that the selection of events with $n_\pi>2$ slightly favours more central collisions as compared to the $n_\pi=2$ events. In Fig. 3 the inclusive momentum distribution of pions in the centre-of-mass system are shown for all events (Fig. 3a), for events with $n_\pi=2$ (Fig. 3b) and for those

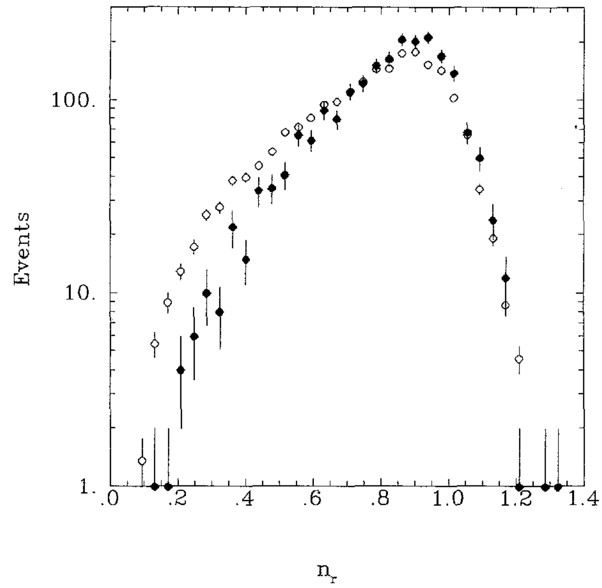


Fig. 1. The normalized distributions of the reduced charged particle multiplicity in the Nb+Nb interactions for events with two (open circles) and more than two (black points) positive pions in the final state

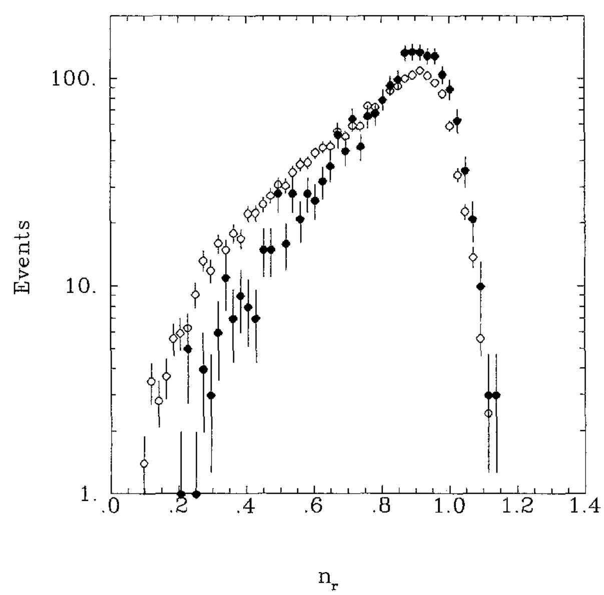
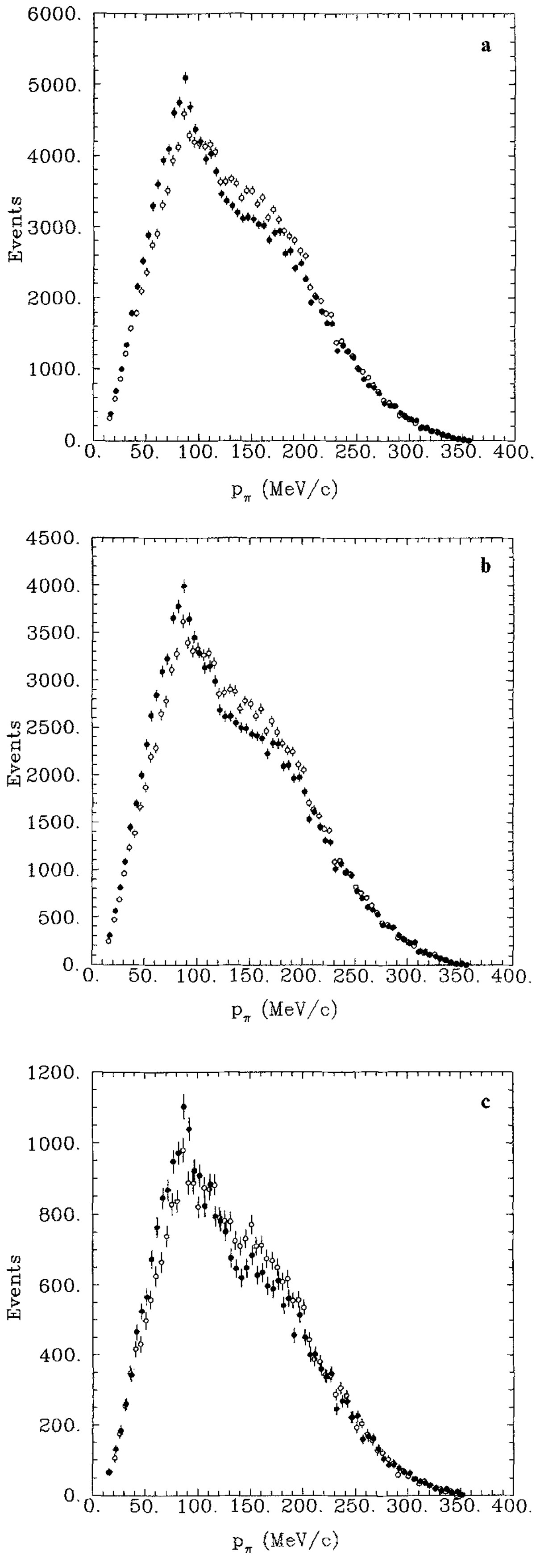


Fig. 2. The same as in Fig. 1 but for Au+Au interactions



with $n_\pi > 2$ (Fig. 3c). The open (black) points refer to the Nb+Nb(Au+Au) interactions. The distributions are normalized. For each of the event selections, the pion momentum spectrum stemming from the Au+Au interactions is somewhat softer than the one from the Nb+Nb collisions. The same tendency is seen for the transverse momentum distributions as shown in Fig. 4a–c.

5. Two-pion Correlations

The two-pion correlation analysis which we previously reported [3] was performed with variables different from the ones used in this work. We have therefore reanalyzed the two-pion data, using the Q variable, which enables us to compare the source parameters obtained from the two- and three-pion correlations. Data for two-pion correlations are displayed in Figs. 5–7 and 8 and in Table 1. In all the figures the data are corrected for electromagnetic interactions. In Table 1 we also list the values of estimated parameters in the former $q = |\mathbf{p}_1 - \mathbf{p}_2|$ representation, where $\mathbf{p}_1$ and $\mathbf{p}_2$ are the momenta of the two pions in the centre-of-mass system. When comparing the numbers one sees that both parametrizations give quite similar results. This is not surprising since the energy difference of the pions in the pairs giving rise to the interference effect is small. In all cases we list the source parameters obtained with and without correction for electromagnetic interactions. As it can be seen from Table 1, only the coherence factor λ is significantly influenced by the Gamov corrections, whereas for the source sizes the difference is typically about 0.1 fm which is negligible as compared to the errors of the fit.

In Fig. 5 the two-pion correlation functions and results of the fits of expression (1) are shown for the full Nb+Nb sample (Fig. 5a), for the $n_\pi = 2$ sample (Fig. 5b) and for the $n_\pi > 2$ selection (Fig. 5c). The same data for Au+Au interactions are presented in Fig. 6a–c. The Nb+Nb system exhibits a smaller two-pion source size ($r = 3.5 \pm 0.2$ fm) than does the Au+Au system ($r = 5.3 \pm 0.5$ fm). In the latter reaction we obtain a significantly larger source for the $n_\pi = 2$ event sample ($r = 7.1 \pm 1.9$ fm) than for the case of $n_\pi > 2$ ($r = 3.1 \pm 0.3$ fm). As can be seen from Fig. 5c, for the Nb+Nb system, pion pairs from the $n_\pi > 2$

Fig. 3. **a** The momentum distributions of pions in the cms of the collision for the events with two or more pions. Open circles refer to Nb+Nb and black points to Au+Au interactions. The distributions are normalized. **b** The same as in **a** but for events with only two detected pions. **c** The same as in **a** but for events with more than two detected pions

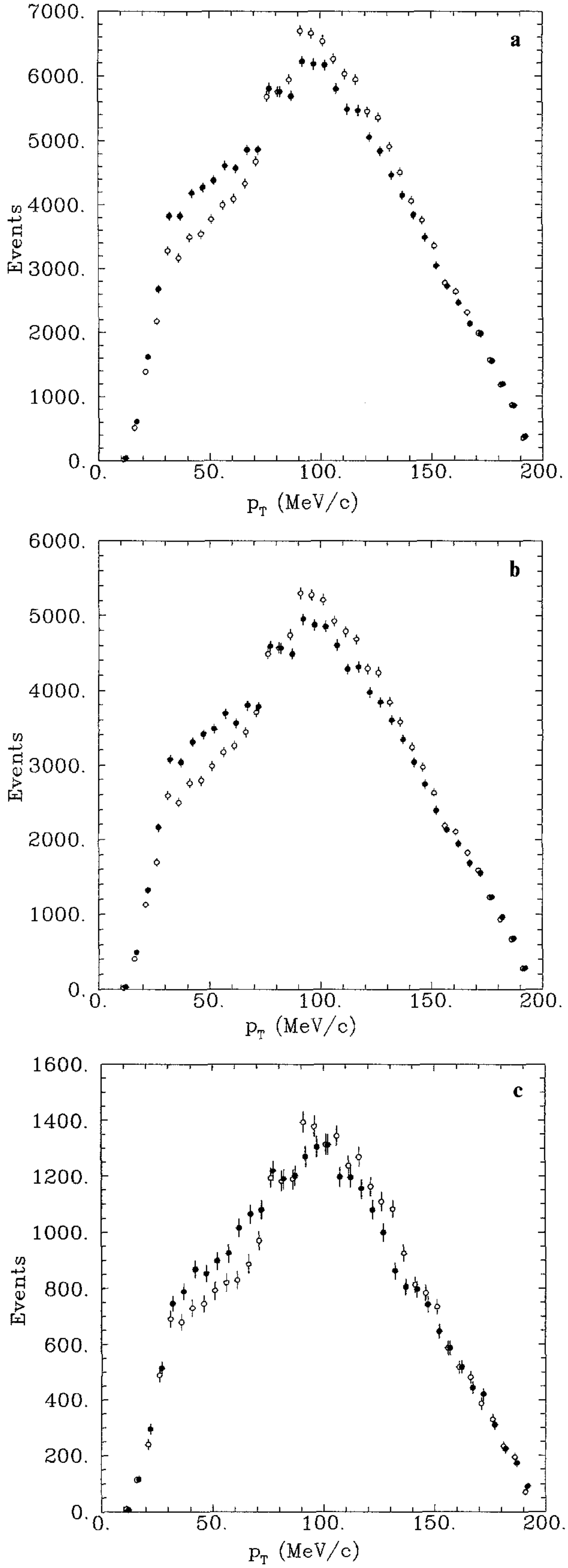


Fig. 4. **a** The normalized transverse momentum distributions of pions for all events with two or more pions. Open circles refer to Nb+Nb and black points to Au+Au interactions. **b** The same as in **a** but for events with only two detected pions. **c** The same as in **a** but for events with more than two detected pions

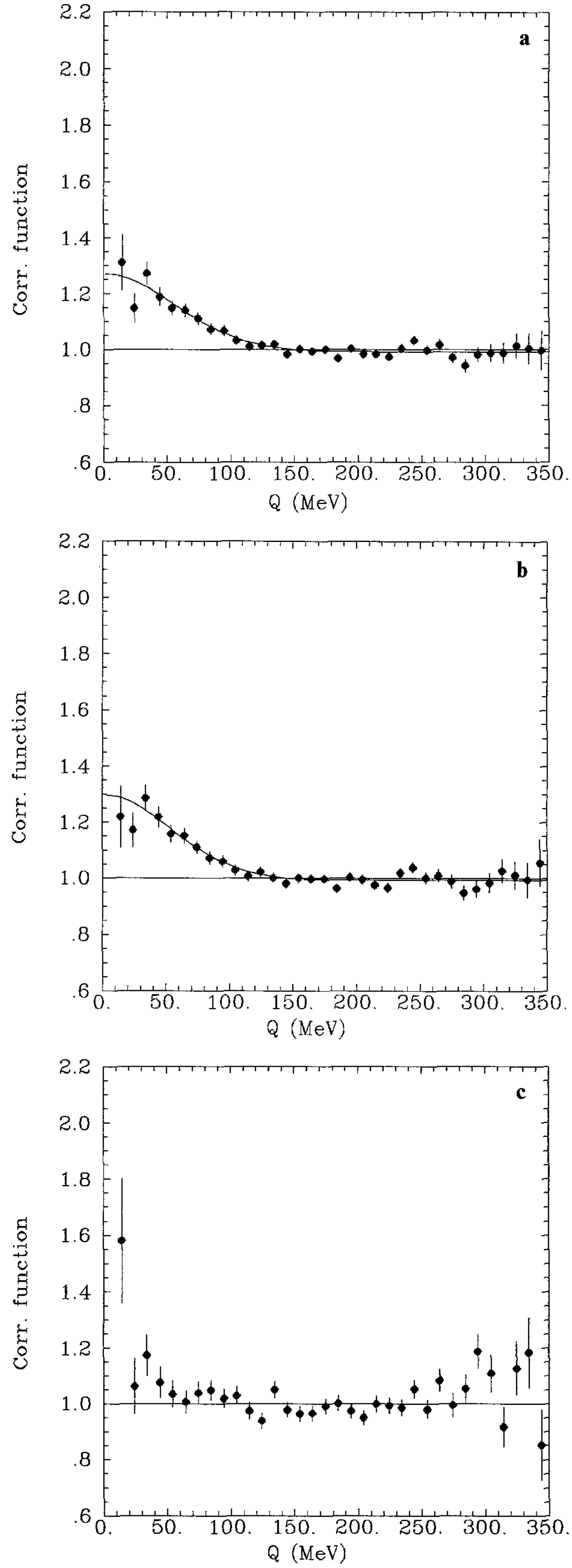
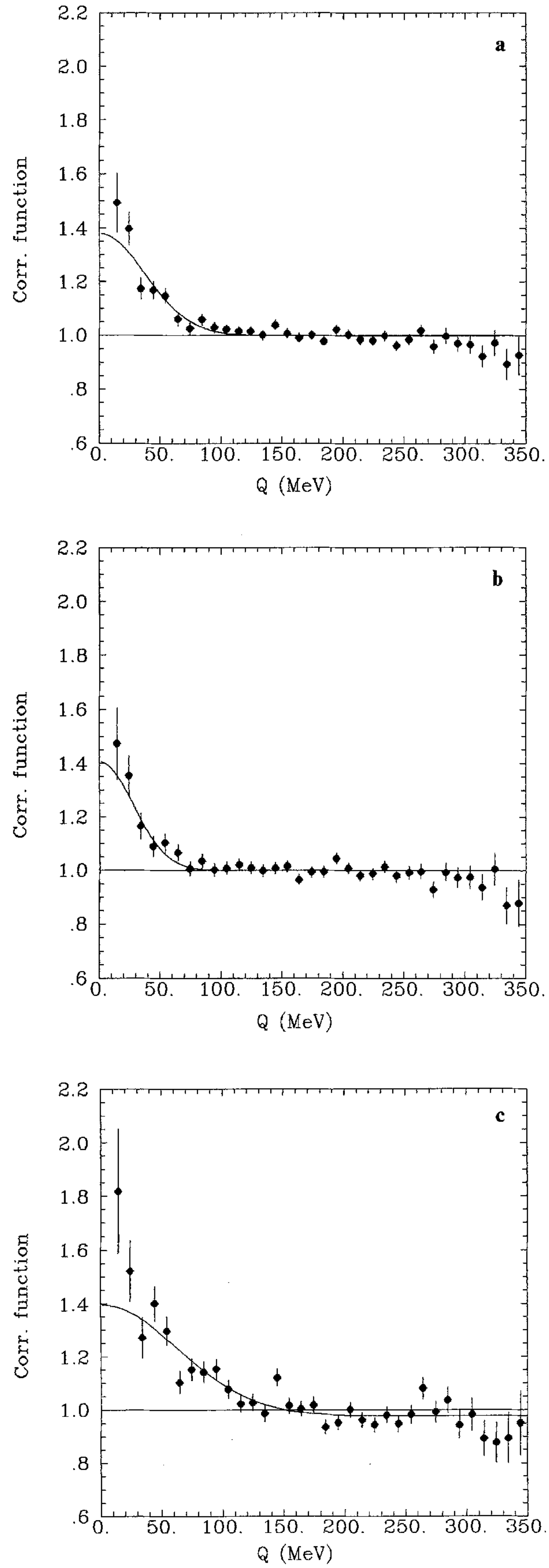


Fig. 5. **a** The two-pion correlation function for all Nb+Nb interactions. The curve represents the best fit to the Gaussian model. **b** The same as in **a** but for events with more than two detected pions. **c** The same as in **a** but for events with more than two detected pions



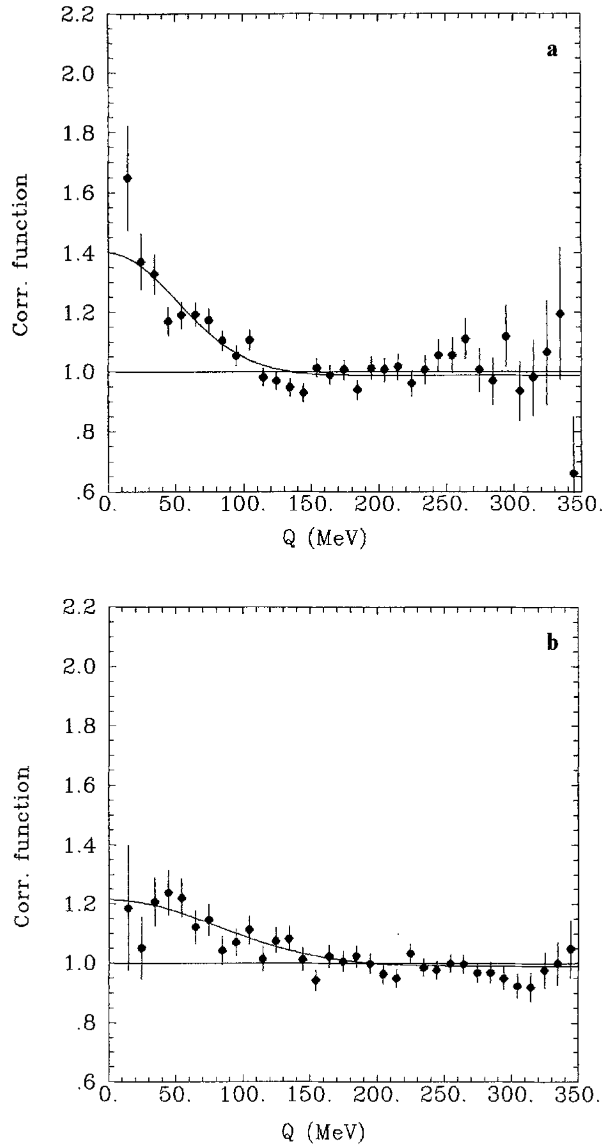


Fig. 7. **a** The two-pion correlation function for all Nb+Nb interactions with a transverse pion-momentum selection of $p_t < 100$ MeV/c. **b** The same as in **a** but with the $p_t > 100$ MeV/c selection

event selection show no significant correlation. In order to study the p_t dependence of the correlations we selected pions with $p_t < 100$ MeV/c and $p_t > 100$ MeV/c. Figure 7a and b present the two-pion correlation function calculated with different p_t selection of pions for the Nb+Nb system and Fig. 8a and b show the same analysis for the Au+Au interactions. In both cases the significant dependence of the pion emitting region on the transverse momentum,

Fig. 6. **a** The two-pion correlation function for all Au+Au interactions. The curve represents the best fit to the Gaussian model. **b** The same as in **a** but for events with only two detected pions. **c** The same as in **a** but for events with more than two detected pions

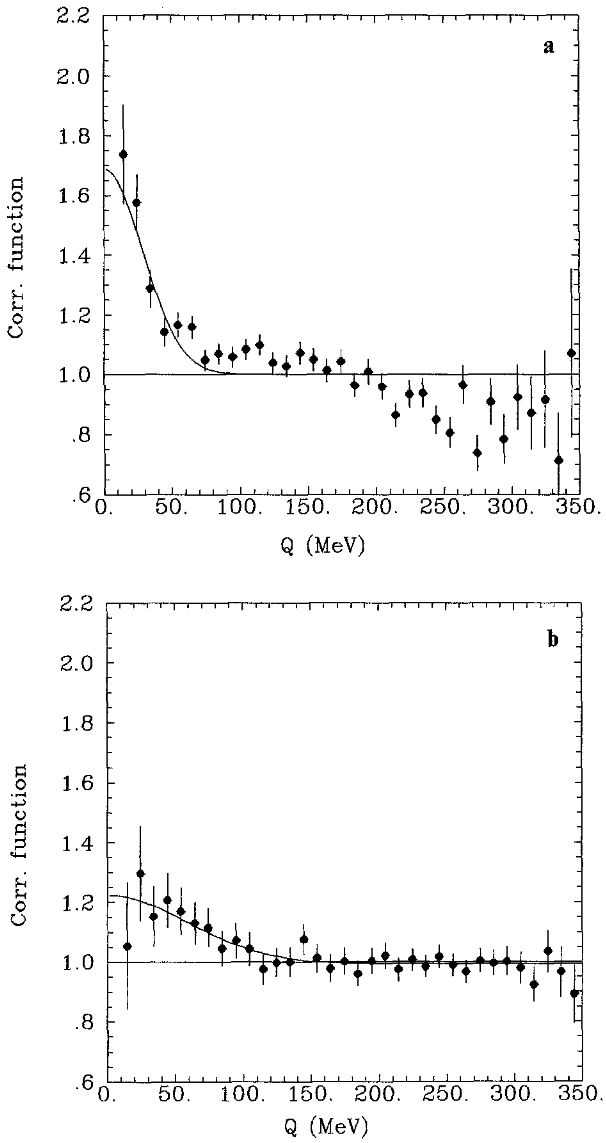


Fig. 8. **a** The two-pion correlation function for all Au+Au interactions with a transverse pion-momentum selection of $p_t < 100$ MeV/c. **b** The same as in **a** but with the $p_t > 100$ MeV/c selection

selection is observed. The pions with the larger transverse momenta are emitted from a smaller source. The dependence of the source size on p_t is more pronounced for Au+Au interactions, $r = 7.0 \pm 1.0$ fm for $p_t < 100$ MeV/c and $r = 3.3 \pm 0.7$ fm for $p_t > 100$ MeV/c. This behaviour is still evident for the Nb+Nb system where the corresponding radii are 3.9 ± 0.3 fm and 2.5 ± 0.4 fm, respectively.

6. Three-pion Correlations

All the results for pionic triplets are shown in Figs. 9 and 10. As in two-pion case, only with correction for electromagnetic interactions are presented in the figures together with the best fits of expression (1). The parameters from the fits to both the corrected an the uncorrected correlation functions are listed in Table 2. The numbers in Table 2 show that, as was the case for the two-pion analysis, source radii are marginally affected by electromagnetic interaction in the final state. The chaoticity parameter, λ, is much more influenced by the Coulomb repulsion in pion triplets than in pairs.

In Fig. 9a and b the correlation functions for the Nb+Nb and the Au+Au systems are shown. For the Au+Au interactions we obtain a radius of 1.51 ± 0.13 fm. The enhancement in the correlation function for Nb+Nb is very weak and results mainly from Gamov corrections. We obtain a radius of 0.9 ± 0.4 fm for the Nb+Nb system, however, the significance of this number is rather limited as can be judged from Fig. 9a. As it was mentioned earlier we have not seen any dependence of the two-pion source radius on the total charged-particle multiplicity [3]. Leaving aside the Nb+Nb system, for which the magnitude of the Bose-Einstein effect does not allow any multiplicity selection, we divided the Au+Au three-pion sample into two intervals of the reduced multiplicity, n_r being less or greater than 0.7 (Fig. 10a, b). We obtain a radius of about 1.5 fm in both intervals of n_r, thus confirming our previous observation made for the like-pion pairs [3].

7. Conclusions and Comments

To summarize the results of this analysis, we note the following observations:

(*i*) There are significant three-pion correlations for the Au+Au system and a weak signal for the Nb+Nb interactions. For the Au+Au and Nb+Nb collisions the three-pion source sizes are 1.5 ± 0.1 fm and 0.9 ± 0.4 fm, respectively. These numbers characterize a specific three-pion effect as the two-pion residual correlations are excluded by conserving them in the reference distributions.

(*ii*) There is a strong dependence of two-pion correlations on the pion multiplicity for the Au+Au interactions: the two-pion source size for the $n_\pi = 2$ events is larger than that for the $n_\pi > 2$ events. For the Nb+Nb interactions we do not see any significant Bose-Einstein correlations when we select events with $n_\pi > 2$.

(*iii*) We do not see any significant dependence of the source radius on the multiplicity of charged particles.

Table 1. Two-pion correlations

Sample	No corrections			Corrected		
	λ	r(fm)	χ^2/NDF	λ	r(fm)	χ^2/NDF
Nb+Nb, Q-variable						
Overall	0.174±0.022	3.38±0.28	1.3	0.279±0.026	3.53±0.22	1.0
$n_\pi=2$	0.203±0.028	3.63±0.31	1.3	0.306±0.032	3.70±0.25	1.0
$p_t<100$	0.293±0.040	3.71±0.34	1.5	0.415±0.049	3.85±0.31	1.2
$p_t>100$	0.140±0.031	2.11±0.47	1.2	0.228±0.041	2.46±0.40	0.9
Au+Au, Q-variable						
Overall	0.232±0.058	5.42±0.82	1.1	0.380±0.061	5.26±0.54	1.3
$n_\pi=2$	0.256±0.131	7.27±1.94	0.8	0.406±0.100	7.09±1.92	0.9
$n_\pi>2$	0.316±0.048	3.38±0.31	1.7	0.428±0.052	3.14±0.31	1.9
$p_t<100$	0.501±0.061	7.01±1.57	2.0	0.690±0.098	6.98±1.00	1.9
$p_t>100$	0.172±0.070	3.59±0.98	0.4	0.231±0.069	3.33±0.69	0.4
Nb+Nb, q-variable						
Overall	0.207±0.025	3.39±0.29	1.5	0.323±0.039	3.51±0.19	1.3
$n_\pi=2$	0.243±0.030	3.59±0.27	1.4	0.351±0.034	3.65±0.22	1.4
$p_t<100$	0.307±0.043	3.60±0.35	1.4	0.431±0.050	3.71±0.29	1.4
$p_t>100$	0.159±0.036	2.16±0.48	1.1	0.229±0.042	2.31±0.39	1.1
Au+Au, q-variable						
Overall	0.221±0.042	4.79±0.57	1.6	0.376±0.069	4.81±0.45	2.6
$n_\pi=2$	0.212±0.097	6.26±1.49	1.3	0.363±0.087	6.68±0.92	1.5
$n_\pi>2$	0.329±0.048	3.29±0.29	1.5	0.442±0.051	3.04±0.27	2.5
$p_t<100$	0.519±0.062	6.91±0.56	1.8	0.695±0.078	7.01±0.67	2.0
$p_t>100$	0.142±0.055	2.79±0.78	0.9	0.252±0.074	3.07±0.63	0.8

(*iv*) There is a distinct transverse momentum dependence of the two-pion source size. Low-p_t pions are emitted from a larger region than the high-p_t ones.

There exist many two-pion interferometry measurements in the literature and very few three-pion studies, especially for nucleus-nucleus collisions, and there is none for symmetric heavy-ion interactions. The authors of [7] reported an enhancement in the three-pion effective mass at threshold when studying the interactions of deuterium, alpha and carbon nuclei with Ta target at 4.2 A GeV/c. They do not ascribe any source parameters to the observed correlations. Analysis of negative like-pion triplets for heavier Ar $+Pb_3O_4$ and Ar+KCl systems are presented in [8] at 1.8 and 1.5 A GeV, respectively. The authors observe larger sources than we do and larger chaoticity parameters. They also report approximately the same source radii for pion pairs and triplets, which is in disagreement with our finding that the source size is smaller for pion triplets. There are, however, apart from the differences in the beam-target configurations and incident energies between their and our experiment, the differences in experimental cuts made on the pion momentum. In [8] a cut on the pion momenta of $p_{\text{lab}}>100$ MeV/c was applied to remove possible experimental artefacts, whereas in our analysis, due to the acceptance of the Plastic Ball spectrometer, only soft pions in the momentum range of (77–195) MeV/c were analysed. Also, due to acceptance, the angular range of the pions in the laboratory system was between 9° and 160° [4].

Few other three-pion interferometry results are known but from elementary collisions. For negative pions originating from the 40 GeV/c π^--p interactions [9] a peak has been observed at a low effective-mass value of three identical pions and this finding was interpreted as a Bose-Einstein effect. No estimates of the source parameters have been attempted in this work. The authors studying proton-proton interactions at the ISR [11] have not found any three-pion Bose-Einstein effect. Identical pions from four different e^+e^- experiments [10, 14] exhibit very distinct three- and two-pion Bose-Einstein correlations, revealing significantly smaller source radii for the pion triplets than for the pion pairs, in qualitative agreement with our findings.

For the Nb+Nb case the three-pion effect is very weak and, when selecting events with $n_\pi>2$, the two-pion effect is marginal. This finding, if taken at face value, indicates a larger coherence for the Nb+Nb pion-emitting sources as compared to the Au+Au system. One possible explanation why the coher-

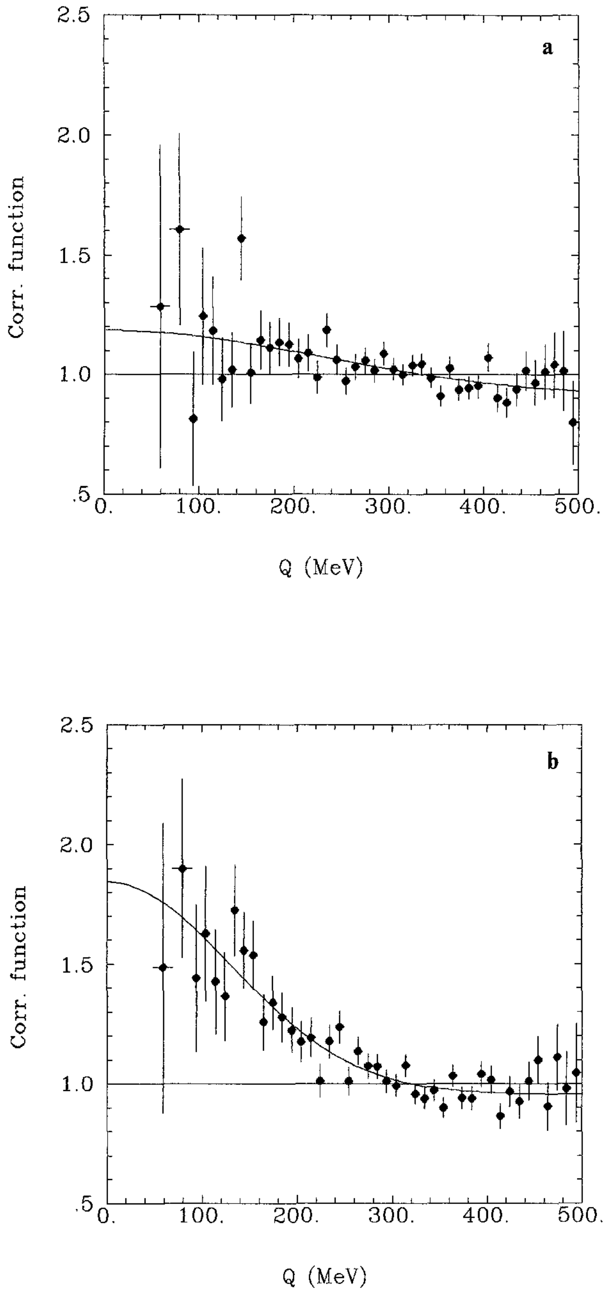


Fig. 9. a The three-pion correlation function for the Nb+Nb interactions. The curve represents the best fit to the Gaussian model. **b** The same as in **a** but for Au+Au interaction

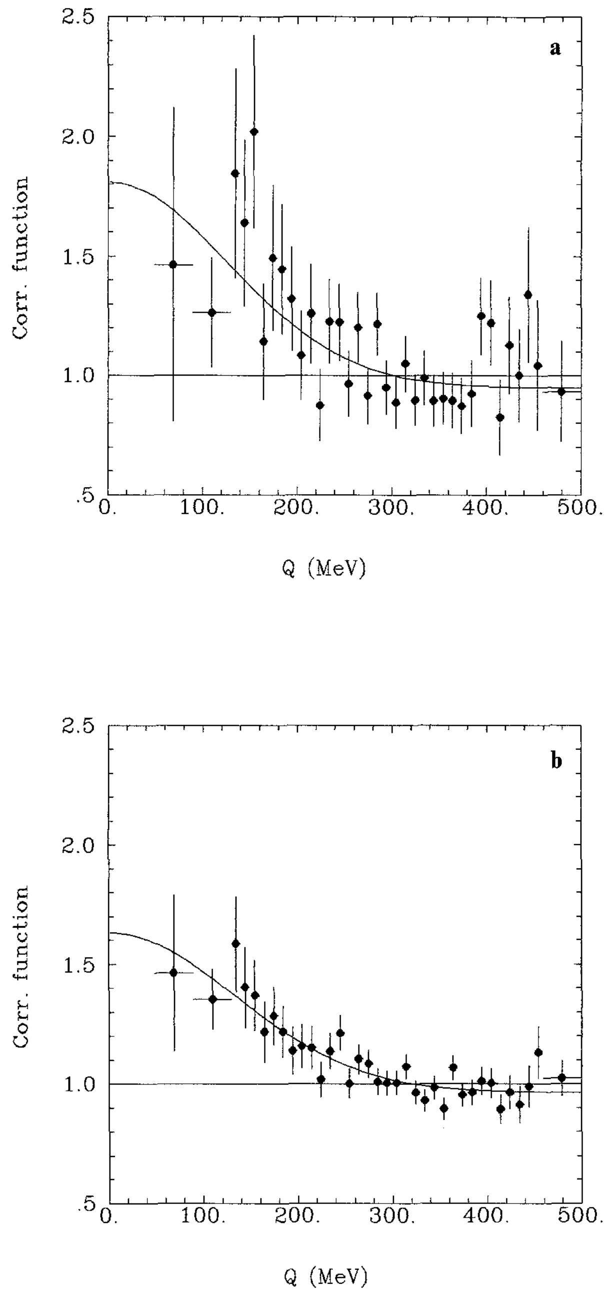


Fig. 10. a The three-pion correlation function for the Au+Au with selection of events with $n_\pi<0.7$. The curve represents the best fit to the Gaussian model. **b** The same as in **a** but with the $n_\pi>0.7$ selection

ence could be smaller for the Au+Au data might be the interference of the many soft pion sources present in heavier systems which eliminates the coherence. This mechanism was pointed out by Gyulassy et al. [5].

Our present results on the p_t dependence of the source size, as well the previous report [3] on its cms momentum dependence, are in qualitative agreement with the findings presented in [12], where the source size was reported to decrease from 6 to 3 fm over the 450 MeV/c interval of the average momentum of the pions in the pair. These results may support the idea of collective expansion associated with cooling of the pion emitting source [6].

Table 2. Three-pion correlations

Sample	No corrections			Corrected		
	λ	r(fm)	χ^2/NDF	λ	r(fm)	χ^2/NDF
Nb+Nb						
Overall				0.306 ± 0.092	0.87 ± 0.43	0.9
Au+Au						
Overall	0.639 ± 0.103	1.46 ± 0.14	1.2	0.929 ± 0.138	1.51 ± 0.13	1.0
$n_r < 0.7$	0.613 ± 0.223	1.50 ± 0.31	1.0	0.905 ± 0.290	1.55 ± 0.27	0.9
$n_r > 0.7$	0.463 ± 0.111	1.47 ± 0.21	0.8	0.693 ± 0.136	1.48 ± 0.17	0.8

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