TWO-PARTICLE CORRELATIONS IN AU+AU COLLISIONS AT THE AGS

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Abstract

Two-particle correlation functions for positive and negative pions as well as protons have been measured in Au+Au collisions at 10.8 GeV/c per nucleon. The weakness of the pion-proton correlations suggests that the pion and proton sources are separated in space or time. A double-gaussian fit to the raw two-pion correlation functions yields the size of the pion halo. Is is compared to the RQMD prediction. The phase space density of pions at freeze-out is extracted from the parameters of three-dimensional two-pion correlations. The phase space density is used to test thermalization.

1 Introduction

The two-particle correlation function $C(\vec{p}_1, \vec{p}_2)$, defined as the ratio of the two-particle density and a product of single particle densities, can be used to obtain information about the space-time-momentum distribution $S(\vec{r}, t, \vec{p})$ of particles at freeze-out (source function) in nuclear collisions [1]. The correlations of identical pions and kaons are governed by the Bose-Einstein statistics and by mutual Coulomb interaction. These correlations, after the Coulomb correction, show a peak at $\vec{p}_1 = \vec{p}_2$, the width of which is inversely proportional to the size of the source. Analysis of C as a function of different components of the momentum difference yields the source dimensions in different directions. The two-proton correlation is a product of the Fermi statistics as well as the mutual Coulomb and strong interactions. This correlation contains a peak at the relative momentum $Q_{inv}/2 = \sqrt{-(p_2 - p_1)^2}/2 \approx 20$ MeV/c, the amplitude of which is roughly inversely proportional to the volume of the proton source. In the following I present recent results from the E877 collaboration on such correlations and discuss their interpretation.

2 Experiment

The experiment took place at the AGS in Fall 1993. The reaction was ^{197}Au + ^{197}Au at 10.8 GeV/c per nucleon. The experimental setup (Fig. 1) consisted of a forward spectrometer measuring momenta of pions and protons, and calorimeters which give centrality and orientation of the reaction plane, also used to generate a centrality trigger. The spectrometer acceptance window for pions was located close to the beam rapidity $y_B = 3.14$. The setup allowed a simultaneous measurement of positive and negative particles. The momentum resolution was $\Delta p_t \approx 4$ MeV/c for pions with small p_t. The mean p_t of all analyzed pions was about 0.1 GeV/c and the mean rapidities were 3.19 and 3.11 for π^+ and π^-, respectively.

We used the relative momentum in the pair c.m. system Q to construct one-dimensional correlation functions. For equal mass particles Q is equal to Q_{inv} which is defined as $\sqrt{(\mathbf{p_2} - \mathbf{p_1})^2 - (E_2 - E_1)^2}$. The three-dimensional correlations were analyzed in the beam rapidity frame $y_B = 3.14$ which is close to the average rapidities of accepted pions. The variables q_{out}, q_{side} and q_{long}, used in the 'out-side-long' analysis, are three components of the momentum difference vector $\vec{q} = \vec{p}_2 - \vec{p}_1$. Here q_{long} is the component parallel to the beam, q_{side} is perpendicular to the beam and to the average pair momentum $\vec{P}$, and q_{out} is perpendicular to q_{long} and q_{side} [2, 3]. A more detailed description of the setup and data analysis can be found in [4].

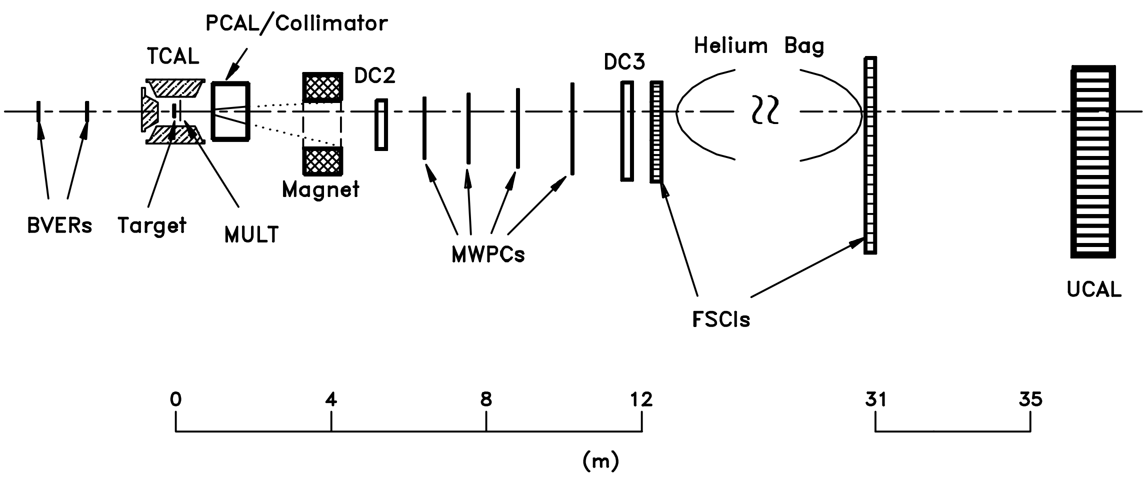

Fig. 1. The E877 setup at the AGS.

3 Pion-proton correlation puzzle

The measured one-dimensional correlations functions, obtained with a proper treatment of the two-track resolution but not corrected for Coulomb and momentum resolution, are presented as black dots in Fig. 2. The line in Fig. 2 represents a calculation in which the RQMD event generator was used to generate particle positions and momenta. The generated particles were combined

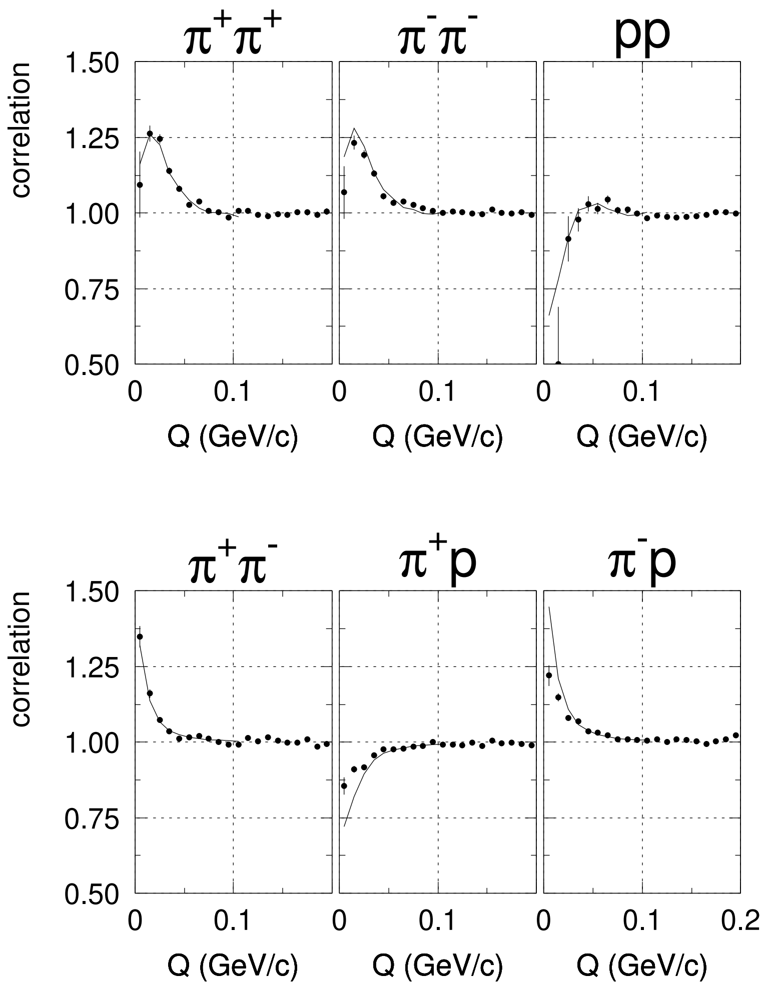

Fig. 2. Experimental one-dimensional correlation functions (points) compared to the RQMD calculation (line). RQMD correctly accounts for the size of the pion and proton sources but fails to describe the pion-proton correlations.

into pairs. For each pair we used the code by Lednicky [5] to calculate the weighting factor which incorporates the effects of quantum statistics as well as mutual Coulomb and nuclear interactions. It appears that while the calculation agrees quite well with the data for two-pion and two-proton correlation functions, it overestimates both pion-proton correlations. This indicates that the average pion-proton separation in the experiment is larger than in RQMD even if RQMD accounts correctly for the sizes of the pion and proton sources. Such a separation could be a result of collective transverse motion of pions in the opposite direction from that of protons (negative pion flow) which has been observed recently. This hypothesis can be verified by a rapidity dependent analysis (the effect should disappear at midrapidity) or by a multidimensional analysis of the pion-proton correlations with respect to the reaction plane.

Of course, other (less attractive) explanations are possible, like a data analysis error (we were looking for it but found nothing) or a wrong description of the pion-proton interaction in the Lednicky code.

4 Pion halo

The agreement of the two-pion correlation data with RQMD suggests that the strength of the correlation is determined by the shape of the pion source and not by the coherent production of pairs of identical pions. In the core-halo model [6] the pion source consists of a small ($\sigma \approx$ 5-6 fm) core of pions produced directly or via decay of short-lived resonances like Δ or ρ, and a much bigger halo of pions from long-lived resonances like ω or η'. In the simplest approach such a source can be described by a sum of two Gaussians. Three parameters, the fraction of pions from the core f and the sizes (sigma) of the core and halo components, R_c and R_h respectively, contain the full information of the pion source. The parameter f is related to the standard two-pion correlation parameter λ by $f^2 = \lambda$. We fitted these source parameters to the three experimental two-pion correlation functions. This was done by generating pairs of particles with positions picked at random from the source function described above. The momenta were generated randomly using the experimental momentum distributions. For each pair the Lednicky code was used to calculate a weighting factor containing the Bose-Einstein effect, Coulomb and strong interactions. Then the momenta of the two particles were smeared out by the experimental momentum resolution. The weighting factor was used to increment a histogram bin corresponding to the Q calculated from the smeared momenta. The theoretical correlation obtained in this way was compared to the experimental one, and the χ^2 was calculated. The parameters were adjusted until the χ^2 minimum was found. The parameters obtained from the fit were f=0.74±0.04, R_c=(5.4±0.3) fm and R_h=(36±16) fm. A similar fit to the proton-proton correlation, assuming a single-Gaussian source, yielded the sigma of R_p=(4.9±1.0) fm. The quoted errors are systematical uncertainties from the two-track resolution correction and the momentum resolution. They are subject to improvement. The statistical errors are smaller. The fitted correlation functions are shown together with the corresponding fit functions

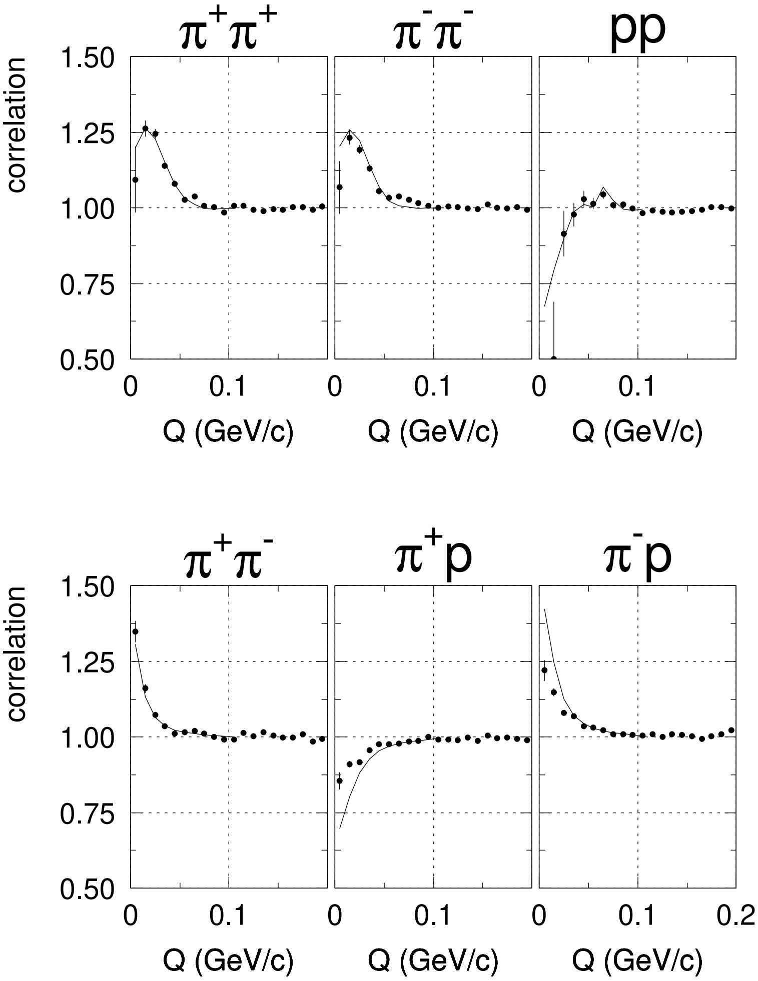

Fig. 3. Experimental one-dimensional correlation functions (same as in Fig. 2) and the fit function (line). The fit function is based on a Monte Carlo generator (see text).

in the first four panels of Fig. 3. The pion-proton correlations calculated using the same source parameters, on the other hand, disagree with the data similarly as in the case of RQMD (two last panels of Fig. 3).

The convergence of the fit for pions means that the data is sensitive to the size of halo. The obtained size of 36 fm is not very different from 20 fm extracted from RQMD for negative pions within the E877 acceptance.

5 Pion phase space density

The standard two-pion correlation analysis consists in fitting a Coulomb corrected three-dimensional correlation function by

$$C(q_o, q_s, q_l) = 1 + \lambda \exp(-{R_o}^2{q_o}^2 - {R_s}^2{q_s}^2 - {R_l}^2{q_l}^2 - 2|R_{ol}|R_{ol}q_oq_l). \qquad (1)$$

The results of the fit are shown in Fig. 4 and Table 1.

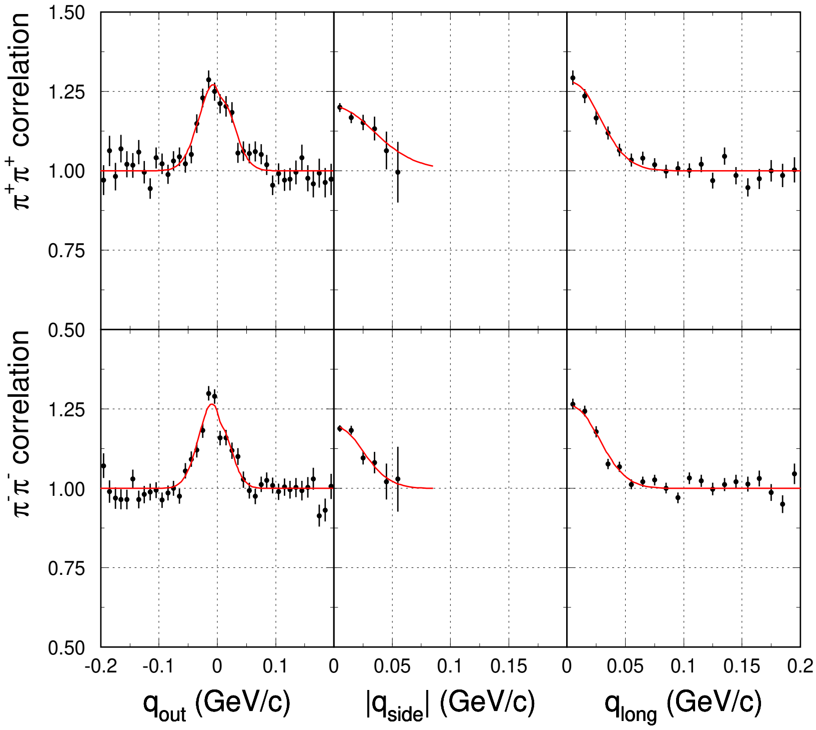

Fig. 4. Gaussian fit to three-dimensional two-pion correlation functions.

Table 1: Parameters of the fit to three-dimensional correlation functions.

	λ	R_{out}(fm)	R_{side}(fm)	R_{long}(fm)	R_{ol}(fm)
$\pi^+\pi^+$	0.50±0.04	5.1±0.4	3.8±0.7	5.5±0.4	2.3±0.6
$\pi^-\pi^-$	0.53±0.03	5.9±0.3	5.8±0.6	6.0±0.3	3.7±0.4

It has been shown recently that the parameters of the two-meson correlation function are related to the meson phase space density at freeze-out [7]. The relation is direct in the sense that it does not require the introduction of a *source volume*. Let us briefly sketch the idea.

The pion phase space density $f(\vec{r},\vec{p})$ is defined as the number of pions per h^3 volume in 6-dim phase space. The pion source function $g(\vec{r},t,\vec{p})$, on the other hand, is the number of pions which have their last interaction in an $\hbar^3$ volume in 6-dim phase space per unit time. Under the assumption that all pions with momentum $\vec{p}$ have their last interaction at the same time t_0, the relation between f and g is given by

$$g(\vec{r},t,\vec{p}) = \delta(t-t_0) f(\vec{r},\vec{p})/(2\pi)^3. \tag{2}$$

Now, let us define the mean freeze-out phase space density of pions with momentum $\vec{p}$ as

$$< f >_{\vec{p}} := \frac{\int d^3r \; [f(\vec{r},\vec{p})]^2}{\int d^3r \; f(\vec{r},\vec{p})} \; . \tag{3}$$

The denominator of (3) is easy to calculate:

$$\int d^3r \; f(\vec{r},\vec{p}) = (2\pi)^3 \; \frac{d^3n}{d^3p} \; . \tag{4}$$

In order to calculate the numerator, please note that

$$\begin{aligned} &(2\pi)^3 \int d^3q \int d^4r_1 \int d^4r_2 \; g(\vec{r}_1,t_1,\vec{p}_1) \; g(\vec{r}_2,t_2,\vec{p}_2) \; \cos(q\Delta r) \\ &= (2\pi)^{-3} \int d^3r_1 \int d^3r_2 \; f(\vec{r}_1,\vec{p}_1) \; f(\vec{r}_2,\vec{p}_2) \int d^3q \cos(q\Delta r) \\ &= \int d^3r [f(\vec{r},\vec{p})]^2 \; . \end{aligned}$$

Thus the mean phase space density at freeze-out is given by

$$< f >_{\vec{p}} = \left(\frac{d^3n}{d^3p}\right)^{-1} \int d^3q \int d^4r_1 \int d^4r_2 \; g(\vec{r}_1,t_1,\vec{p}_1) \; g(\vec{r}_2,t_2,\vec{p}_2) \cos(q\Delta r) \; . \tag{5}$$

But from Pratt's Formula

$$\int d^4r_1 d^4r_2 \; g(\vec{r}_1, t_1, \vec{p}_1) g(\vec{r}_2, t_2, \vec{p}_2) \cos(q\Delta r) = \frac{d^6 n}{d^3p_1 d^3p_2} - \frac{d^3n}{d^3p_1}\frac{d^3n}{d^3p_2} \tag{6}$$

and thus

$$< f >_{\vec{p}} = \left(\frac{d^3n}{d^3p}\right)^{-1} \int d^3q \left[\frac{d^6 n}{d^3p_1 d^3p_2} - \frac{d^3n}{d^3p_1}\frac{d^3n}{d^3p_2}\right] \tag{7}$$

or, even simpler,

$$< f >_{\vec{p}} = \frac{d^3n}{d^3p} \int d^3q \, [C(\vec{q}) - 1] \; . \tag{8}$$

If we parametrize the correlation function as in Eq.(1), then

$$< f >_{\vec{p}} = \frac{d^3n}{d^3p} \; \frac{\sqrt{\pi}^3 \lambda}{R_s\sqrt{R_o^2 R_l^2 - R_{ol}^4}} \tag{9}$$

or, if R_{ol} can be neglected,

$$< f >_{\vec{p}} = \frac{d^3n}{d^3p} \; \frac{\sqrt{\pi}^3 \lambda}{R_o R_s R_l} \tag{10}$$

This phase space density could be compared to a theoretical prediction assuming local equilibrium, i.e. to the Bose-Einstein distribution function. However, pions from long-lived resonances (halo), which result in $\lambda < 1$, decrease the mean phase space density. This component of the source function is of course not thermalized and should be left out from the comparison. In order to calculate the mean phase space density of core pions only, i.e. of pions produced directly or via Δ or ρ decays, we first consider a case without halo:

$$< f >_{\vec{p}} = \frac{d^3n}{d^3p} \; \frac{\sqrt{\pi}^3}{R_o R_s R_l} \tag{11}$$

Thus

$$< f >_{\vec{p}}^{core} = \left(\frac{d^3n}{d^3p}\right)^{core} \left(\frac{\sqrt{\pi}^3}{R_o R_s R_l}\right)^{core} \tag{12}$$

But the fraction of pions from the core can be calculated from λ:

$$\left(\frac{d^3n}{d^3p}\right)^{core} = \sqrt{\lambda} \; \frac{d^3n}{d^3p} \tag{13}$$

and thus the core phase space density is

$$<f>_{\vec{p}}^{core} = \frac{d^3n}{d^3p} \; \frac{\sqrt{\pi}^3\sqrt{\lambda}}{R_o R_s R_l} \; . \tag{14}$$

By the way, the overall density is a weighted average of the core and halo densities:

$$<f>_{\vec{p}} = \sqrt{\lambda} <f>_{\vec{p}}^{core} + (1-\sqrt{\lambda}) <f>_{\vec{p}}^{halo} \; . \tag{15}$$

Since the halo is much larger than the core, $<f>_{\vec{p}}^{halo} = 0$, and

$$<f>_{\vec{p}} = \sqrt{\lambda} <f>_{\vec{p}}^{core} \tag{16}$$

which, consistently, leads back to Eq.(10).

The core phase space density can be compared to the Bose-Einstein distribution function (for each pion species):

$$f^{\mathrm{BE}}(\mathbf{p}) = \frac{1}{\exp(m_t \cosh(y-y_S)/T) - 1} \tag{17}$$

with the pion transverse mass m_t and rapidity y, and the source rapidity y_S. The comparison is simplified by the fact that the experimental differential multiplicity can also be parametrized by the Bose-Einstein function:

$$\frac{d^3n}{d^3p} = \frac{A}{\exp(m_t/T_{\mathrm{eff}}) - 1} \tag{18}$$

with two fit parameters: effective transverse temperature T_{eff} and normalization A. Neglecting transverse flow (see discussion below) we assume that $T_{\mathrm{eff}} = T/\cosh(y-y_S)$. Consequently, the comparison between $\langle f\rangle_{\mathbf{p}}^{\mathrm{core}}$ and $f^{\mathrm{BE}}(\mathbf{p})$ is reduced to the comparison between the parameters of the two-pion correlation function and the normalization of the pion spectra A:

$$\frac{\langle f\rangle_{\mathbf{p}}^{\mathrm{core}}}{f^{\mathrm{BE}}(\mathbf{p})} = A\frac{\sqrt{\pi}^3\sqrt{\lambda}}{R_o R_s R_l} \tag{19}$$

Using the correlation parameters from Table 1 and A obtained from a Bose-Einstein fit to transverse spectra in the rapidity range 3.0–3.3, we evaluated the experimental-to-thermal density ratio of 0.95±0.21 and 1.00±0.16 for π^+ and π^-, respectively. Thus the experimental pion phase space density is consistent with the presence of local equilibrium.

It should be noted that the normalization A was obtained by fitting the entire measured transverse momentum spectra $0 < p_t < 0.6$ GeV/c. Since the spectra have a somewhat concave shape, A depends on the range of the fit: low (high) p_t's yield high (low) A. By doing a Monte Carlo simulation we found that an addition of transverse flow with $\beta = 0.3$ gives a better fit of the experimental data. This amount of flow would decrease the reference phase space density, and thus increase the quoted experimental-to-thermal ratios, by 20%. Another uncertainty comes from the fact that the present analysis entirely neglected the contribution of Δ decays to pion production. This would be more acceptable if the entire analysis could be done at $p_t > 0.3$ GeV/c where the Δ decay contribution is small. A p_t and y dependent analysis is planned for the high-statistics data sets taken in the 94' and 95' runs of E877.

6 Summary

The relative weakness of the pion-proton correlations as compared to other particle combinations suggests that the pion and proton sources are separated. A double-gaussian fit to the raw two-pion correlation functions yields a halo size comparable to the halo from RQMD. The three-dimensional analysis allows to calculate the average phase space density of pions at freeze-out. This density is consistent with local equilibrium.

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