Two-particle correlations in Au+Au collisions at AGS energy

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Two-particle correlation functions have been measured in Au+Au collisions at the AGS. The one-dimensional correlations are compared to the RQMD predictions. A multi-dimensional analysis of two-pion correlations allows to extract the average phase space density of pions at freeze-out and the pion source velocity.

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 related 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 inversely related to the proton source volume. In the following we 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 E877 setup at the AGS consisted of beam counters, calorimeters and a forward spectrometer (Fig. 1). The beam counters determined the horizontal beam angle and position, discriminated against contamination due to upstream interactions and delivered the time of flight (TOF) start signal. The Target and Participant Calorimeters (TCal and PCal) measured the amount and distribution of transverse energy in the backward and forward hemispheres, respectively, which allowed determination of the centrality and of the orientation of the reaction plane. The central collision trigger, used in the experiment, was derived from PCal. The particles used in the HBT analysis were measured in the forward spectrometer. The spectrometer acceptance window for pions was located close to the beam rapidity y_B = 3.14 (Fig. 2). 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.

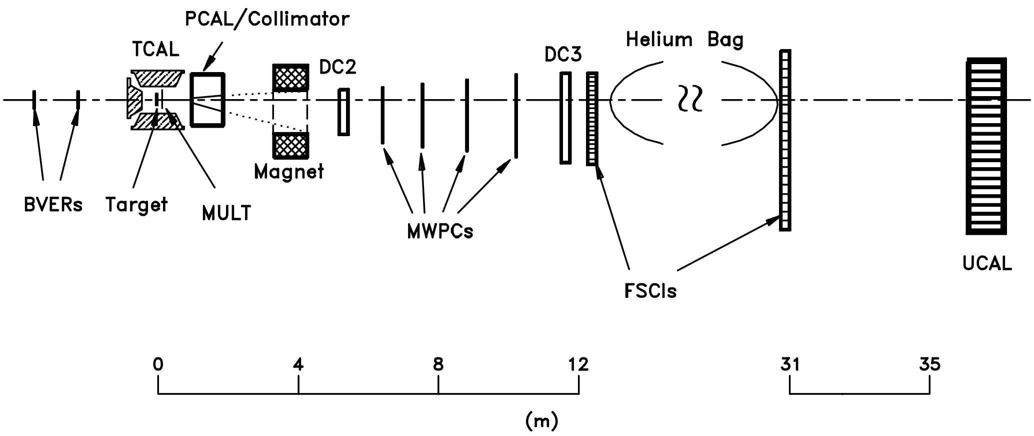

Figure 1. The E877 setup at the AGS.

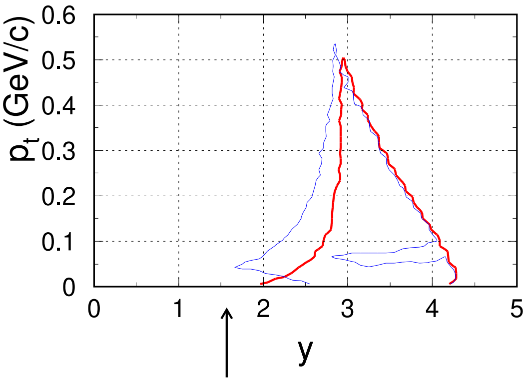

Figure 2. Forward spectrometer acceptance for π^+ (thick line) and π^- (thin line) for one magnet polarity. The arrow shows midrapidity.

3. DATA ANALYSIS

The basic idea of the offline analysis was straightforward. Events containing two beam particles were removed by cutting on pulse height in the beam detectors. About 1 million events survived the subsequent centrality cut at the level of 10% of the geometrical cross-section. For all spectrometer tracks in these events we required that they vertically pointed to the target (pointing to the target horizontally had been assumed during the momentum reconstruction) and did not pass close to the edge of the acceptance. We suppressed double hits in the TOF stop scintillators by cutting on pulse height. Pairs of 'good' particles were used to get the numerator of the correlation function C (signal). The denominator (background) was obtained by event mixing. For the signal and background pairs we required that the tracks did not share a TOF stop scintillator and that their separation in the two drift chambers (DC2 and DC3 in Fig. 1), which were used to determine the momentum, exceeded 1 cm for the first and 2 cm for the second drift chamber. This way the correlation functions were not distorted by the finite two track resolution. For identical bosons the background pairs were weighted with the Coulomb correction factor. The correlation function was normalized to unity at its flat part.

We used the relative momentum in the pair c.m. frame Q to construct one-dimensional correlation functions. For equal mass particles Q is equal to Q_{inv}. 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]. In the 'moving Gaussian source' analysis the correlation function $C(q_x, q_y, q_z, q_0)$ has been constructed. The variables q_x and q_y are the components parallel and perpendicular to the reaction plane, both perpendicular to the beam, $q_z = q_{long}$ and q_0 is the energy difference: $q_0 = E_2 - E_1$. The positive x is defined by the direction of the transverse flow in the forward hemisphere.

There are several points in the data analysis which require special attention. The following list, containing brief description of these difficulties, was made with a two-pion analysis in mind. Some of the points are relevant also to other particle combinations.

Two track efficiency. The detector's ability of distinguishing a pair of close tracks from a single track falls with decreasing track separation. If not corrected, this inefficiency significantly distorts the correlation function. We deal with this problem by rejecting from the signal and the background distributions all pairs which are too close (as described above). The loss of statistics in C is insignificant.

Track order in event. The tracks are written on tape in an order dictated by the data acquisition code. This order is destroyed in event mixing which can lead to broad structures in the correlation function if the variables used depend on the sign of the momentum difference (like q_{out},q_{side} or q_{long}). In our analysis we always rearrange the particles such that $q_{long} > 0$.

Background fluctuations. As a consequence of event mixing, one particle can contribute more that once to the background distribution. This causes fluctuations larger than Poissonian in the number of background pairs [4,5]. We generate 50 times more background than signal pairs to keep the background error, in spite of the additional fluctuations, much smaller than the signal error.

Normalization. The correlation functions should be carefully normalized to unity in the flat part corresponding to large relative momenta. Even a small deviation from unity can cause a large error in the fitted parameters (if the fit function does not contain a normalization parameter). Particularly, it is incorrect to normalize by total numbers of signal and background pairs: the resulting correlation would lie below unity in the flat part.

Singles distortion. One can define the correlation function in two different ways: as the two-particle distribution divided by the same distribution in the absence of the Bose-Einstein effect ("like-to-unlike"), and as the two-particle distribution divided by the product of singles spectra ("doubles-to-singles") [6]. The first definition is the one that can be linked to the source function. The second is usually applied to experimental data (event mixing). The two definitions are equivalent only if the singles spectra are not affected by the two-particle correlations. There are two reasons [7] why they could be:

1. For high phase space densities (of the order of 1) the two-particle Bose-Einstein correlations can cause a low-p_t enhancement [8]. This effect has nothing to do with the apparatus used to detect particles. Its magnitude increases with increasing multiplicity. Most probably it is insignificant at the AGS energy (see below).
2. If a two-particle trigger is being used, the particles at the edge of the acceptance have lower chances of being detected. This results in a distortion of the single particle spectra and, consequently, of the background distribution. This effect would not occur if the apparatus had full acceptance (no edges). Its significance decreases with increasing average particle multiplicity (in experiments with a high mean multiplicity every reaction would cause a trigger). It is irrelevant in our case because we did not use a two-particle trigger.

Combination of different measurements. Our data have been taken with two (roughly opposite) magnetic field settings resulting in two different acceptances (Fig. 2). We decided to combine these data sets at the level of the correlation function. There are several ways to do this, some of them being incorrect:

1. Add the two signal and the two background distributions, divide the total signal by the total background and normalize.
2. Add the two signal and the two *normalized* backgrounds, divide the total signal by the total background.
3. Calculate the average of the two correlations using one over the (statistical) error squared as the weighting factor.
4. Calculate the average of the two correlations using the number of background pairs divided by the normalization factor as the weighting factor.

The method 3 is incorrect for the same reason as fitting by Least Square (see below). The methods 2 and 4 are correct and equivalent. Also method 1 becomes correct and equivalent to 2 and 4 if the normalization factor (the signal/background ratio at large relative momenta Q_{inv} >100 MeV/c) in the two measurements has the same value. In our analysis we kept the normalization factor constant (1/50) and used method 1.

Fitting. Fitting by the Least Square method and using the square root of the number of counts as an estimator of the error introduces a systematic bias by overestimating the significance of bins with a low number of counts [9]. The magnitude of this bias depends on statistics. Maximum Likelihood method should be applied instead. We used MINUIT [10] to minimize the negative logarithmic likelihood function

$$-2\log\mathcal{L}(\vec{A}) = 2\sum_i [C_iN_i - n_i\log(C_iN_i) + \log(n_i!)]\ , \tag{1}$$

where n_i and N_i are the numbers of signal and background pairs in the relative momentum bin i, and C_i is the correlation hypothesis for a given set of fit parameters $\vec{A}$. The last term in Eq. (1) does not depend on $\vec{A}$ and, consequently, can be omitted. In this case, the value at the minimum after subtracting $n_i - n_i\log n_i$ can be used to describe the goodness-of-fit in a χ^2-like manner [11].

Coulomb correction. The usually applied Gamow correction does not take into account the finite source size. The radii obtained from a fit to the Gamow corrected two-pion correlations are (in our case) smaller by about 5% and the correlation strength λ larger by 15-20%, as compared to results obtained with the finite-source Coulomb correction, calculated by averaging the squared Coulomb wave function over a Gaussian source distribution. In addition, Gamow corrected correlations have a non-zero slope at high relative momenta which leads to normalization problems [12].

Momentum resolution. The finite momentum resolution of the spectrometer smears out the correlation peak and apparently decreases both the fitted radii and λ. In our case the error is about 10% in the radius parameters and 20% in λ. The presented data are not corrected for it.

4. ONE-DIMENSIONAL π–π, K–K, p–p and π–p CORRELATIONS

The one-dimensional correlations as a function of relative momentum evaluated in the pair c.m. system Q, not corrected for mutual Coulomb interaction, are shown in Fig. 3. In the $\pi^+\pi^+$ and $\pi^-\pi^-$ correlations the Bose-Einstein peak prevails over the Coulomb repulsion. In the K^+K^+ correlation the two contributions seem to cancel. The non-identical particle correlations are dominated by Coulomb effect. The solid line is a result of a calculation in which events generated by the RQMD cascade [13] were processed through the code supplied by the Nantes group [14] and through a momentum smearing routine. The Nantes code calculates for each particle pair a weighting factor containing effects of quantum statistics, Coulomb and strong interactions. There is quite a good agreement between the calculation and data for pions. This suggests that the low intercept value λ of about 0.5 (0.6 after the momentum resolution correction) is caused by the pions from long-lived resonances [15] (included in RQMD) and not by coherent pion production (absent in RQMD). Consequently, λ should not be called "incoherence" or "chaoticity parameter" but simply "correlation strength" [16]. Also, an agreement between RQMD and the measured two-pion correlations implies that RQMD correctly describes the pion distribution at freeze-out. An analysis of RQMD events yields a pion density at freeze-out of ρ_π=0.17/fm^3. Thus our measurement is consistent with this density.

In the correlations that include protons one sees a discrepancy between the data and the calculations. We are working on understanding the origin of this difference.

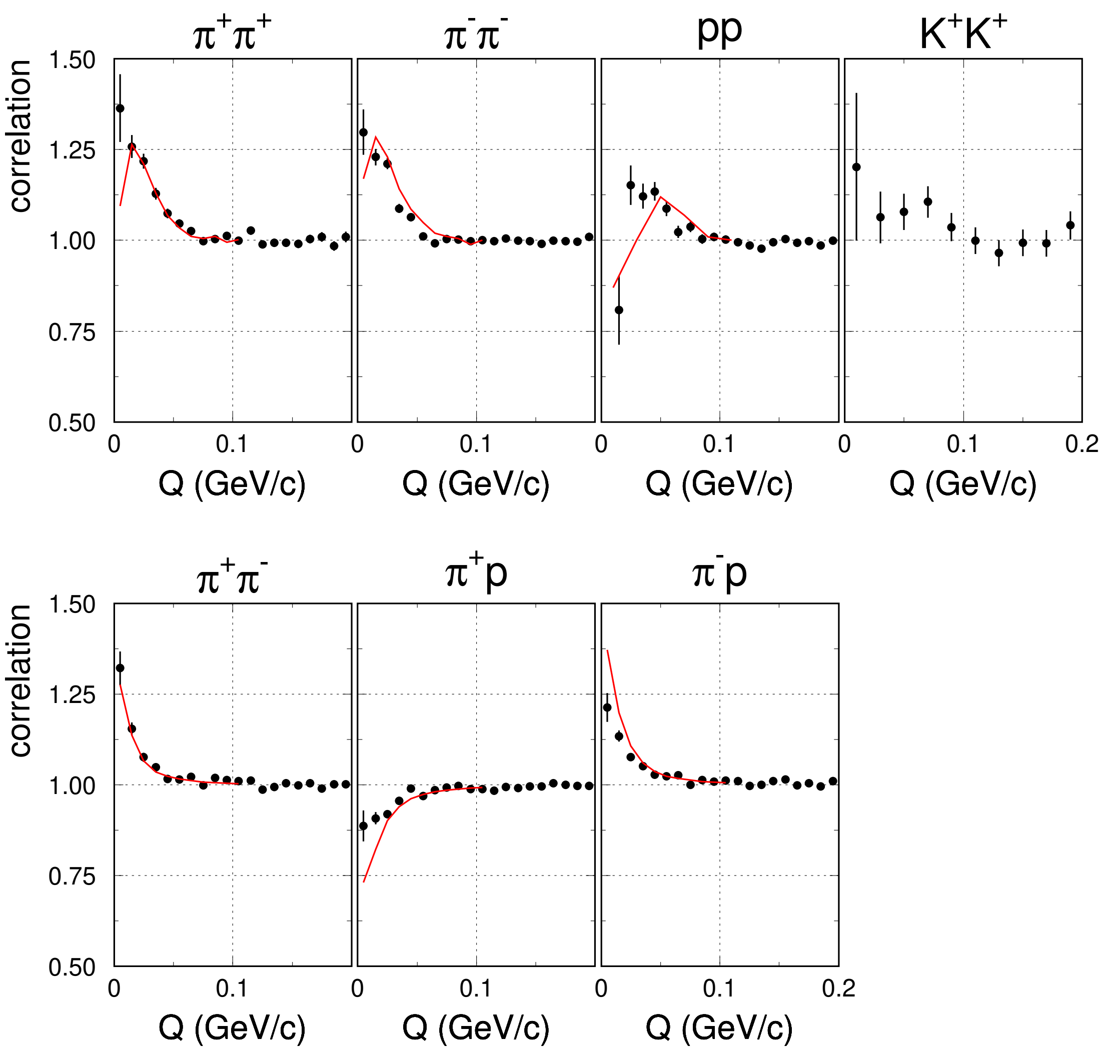

Figure 3. One-dimensional correlation functions, not corrected for Coulomb effect.

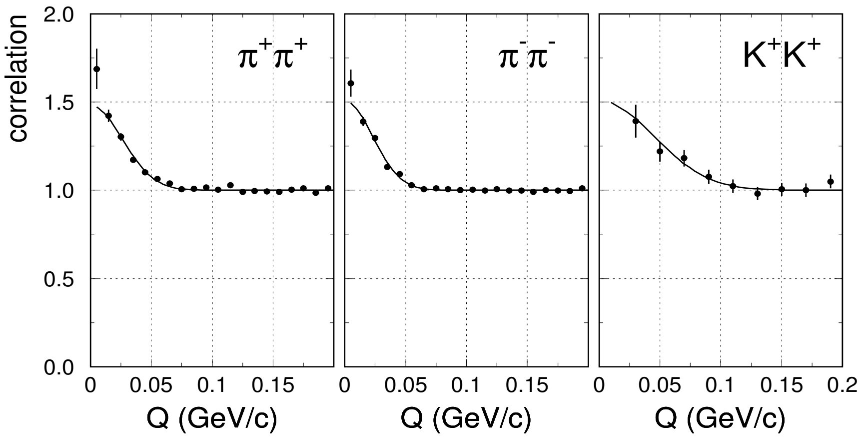

Figure 4. Gaussian fit to one-dimensional two-meson Coulomb-corrected correlation functions.

The Coulomb corrected two-pion and two-kaon correlations (Fig. 4) were fitted by

$$C(Q_{inv}) = 1 + \lambda \exp\left(-R^2 {Q_{inv}}^2\right) \tag{2}$$

The parameters λ and R obtained from the fits are given in Table 1. The radius parameter determined for the kaon source is smaller than the value for pions which is in agreement with published results of other experiments [17,18]. This difference could be caused by longitudinal expansion. The low value of λ for kaons is caused by the contamination of the kaon sample by misidentified particles. This contamination does not affect R.

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

	λ	R (fm)
$\pi^+\pi^+$	0.48±0.04	5.4±0.3
$\pi^-\pi^-$	0.51±0.03	6.2±0.2
K^+K^+	0.51±0.13	3.1±0.5

5. THREE-DIMENSIONAL π–π CORRELATIONS AND PHASE SPACE DENSITY

In the 'out-side-long' analysis, performed in the $y_{anal} = 3.14$ frame, the correlations have been fitted by

$$\begin{aligned} C(q_{out}, q_{side}, q_{long}) &= 1 + \lambda \exp(-{R_{out}}^2 {q_{out}}^2 - {R_{side}}^2 {q_{side}}^2 + \\ &\quad -{R_{long}}^2 {q_{long}}^2 - 2|R_{ol}| R_{ol} q_{out} q_{long}) \end{aligned} \tag{3}$$

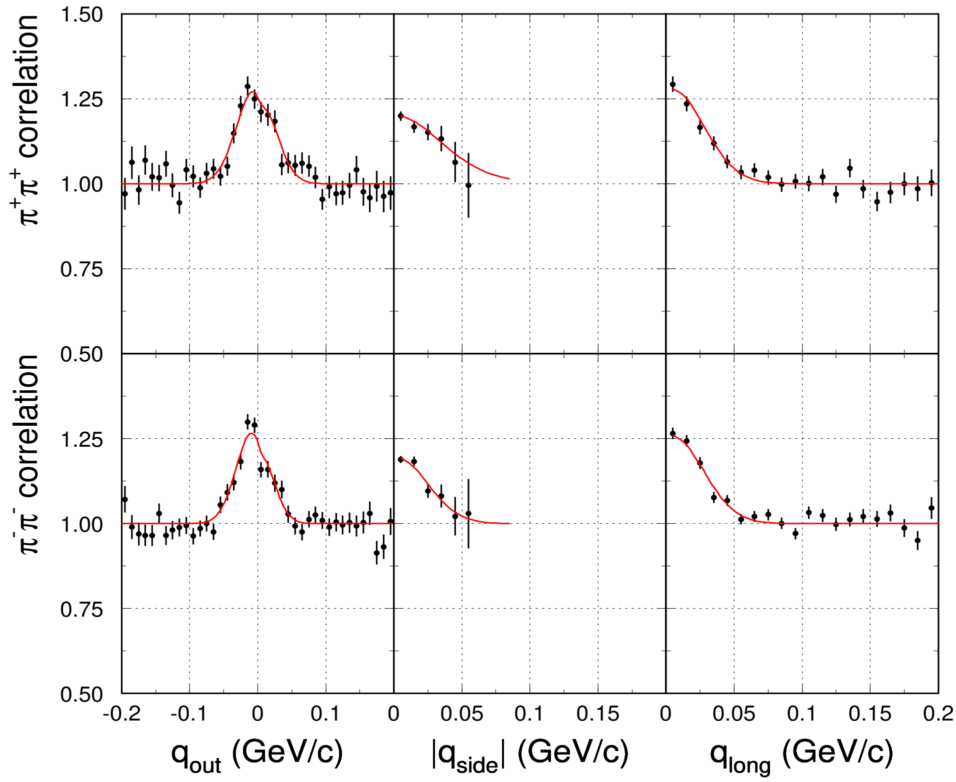

Figure 5. Gaussian fit to three-dimensional two-pion correlation functions.

The projections of the correlation and of the fit, obtained by averaging over the two other components of $\vec{q}$ in the range from -50 MeV/c to 50 MeV/c with a weighting factor equal to the number of mixed pairs, are shown in Fig. 5. The particles were labeled such that $q_{long}>0$. The sign of q_{side} has been ignored. The asymmetric shape of the projection $C(q_{out})$, well reproduced by the fit, is caused by the acceptance and the finite width of the projection window. The parameters obtained from the fit are given in Table 2. The results are not corrected for the finite momentum resolution.

Table 2
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 two-meson correlation function is directly related to the meson phase space density (defined as the number of particles per unit volume h^3 in six-dimensional phase space) at freeze-out [19]. Using the results from this publication we obtained the following formula:

$$< f >_{\vec{p}} = \frac{d^3n}{d^3p} \cdot \frac{\sqrt{\pi}^3 \lambda}{R_{out} R_{side} R_{long}} \tag{4}$$

where $< f >_{\vec{p}}$ is the phase space density of pions with momentum $\vec{p}$, averaged over the spatial coordinates, d^3n/d^3p is the differential pion multiplicity and $\lambda, R_{out}, R_{side}$ and R_{long} are the numbers obtained from the 'out-side-long' fit to the correlation function. This phase space density can be compared to a theoretical prediction assuming local equilibrium, i.e. to the Bose-Einstein distribution function. However, pions from long-lived resonances, which result in $\lambda < 1$ [15,16], 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. One can show that averaging only over the core of the source function and neglecting the tails gives a formula similar to Eq.(4) but containing $\sqrt{\lambda}$ instead of λ:

$$< f >_{\vec{p}}^{core} = \frac{d^3n}{d^3p} \cdot \frac{\sqrt{\pi}^3 \sqrt{\lambda}}{R_{out} R_{side} R_{long}} \tag{5}$$

We applied this formula to calculate the average phase space density in the core of the source function for pions with $p_t = 0$. The correlation parameters λ, R_{out}, R_{side} and R_{long} were taken from Table 2. The values of d^3n/d^3p were determined by extrapolating the pion transverse spectra from the range 0.02 GeV/c $< p_t <$ 0.2 GeV/c to $p_t = 0$. The results are shown in Fig. 6. The positive and negative pions have similar values. The phase space density is significantly lower than unity which means that (in our acceptance) the pion multiplicity is not being enhanced significantly by the Bose-Einstein quantum effect. The density increases with decreasing pion rapidity and could reach about 0.5 at

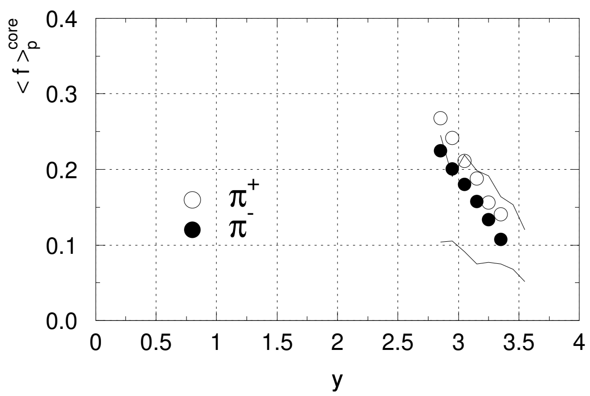

Figure 6. Measured pion phase space density at freeze-out (solid and open points). The data are preliminary. The statistical errors are smaller than the symbols. The overall normalization uncertainty is of the order of 30%. The solid lines represent a calculation for π^- assuming a local equilibrium (Eq.(6)). The upper (lower) line was obtained using T from a fit to the high (low) momentum part of the π^- transverse spectrum.

midrapidity $y_{NN} = 1.57$ (rough extrapolation by eye). The solid lines in Fig. 6 are the phase space densities calculated for negative pions at $p_t = 0$ (i.e. at $m_t = m_\pi$), assuming a local Bose-Einstein distribution:

$$f^{BE}(p_t = 0) = \frac{1}{\exp(m_\pi/T) - 1} \tag{6}$$

As the parameter T we used the temperatures obtained from a Bose-Einstein fit to the transverse π^- spectrum at a given rapidity. Since the experimental transverse momentum spectra are somewhat concave as compared to the Bose-Einstein function, the fitted temperature depends on the range of the fit. Fitting in the range 0.02 GeV/c $< p_t <$ 0.2 GeV/c and 0.2 GeV/c $< p_t <$ 0.6 GeV/c gives the lower and the upper curve in Fig. 6, respectively. These two lines bracket the data. Thus the measured phase space density is roughly consistent with local equilibrium, with the local temperature equal to the slope of the transverse spectrum in its intermediate part. On the other hand, the non-thermal shape of the transverse spectra, and also the fact that the lines in Fig. 6 are less steep than the data, mean that the presented picture, in which every rapidity bin is independently thermalized, is oversimplified. It would be interesting to compare the measured phase space density to more realistic models.

6. FOUR-DIMENSIONAL π–π CORRELATIONS AND PION SOURCE VELOCITY

We tried to determine the duration of pion emission by fitting a two-dimensional Gaussian curve to $(C(|\vec{q}|, |q_0|) - 1)$. Our attempt failed because of a very non-Gaussian shape of the correlation: the maximum was spread along the diagonal $|\vec{q}| = |q_0|$ instead of being confined to small $\vec{q}$ and q_0. We found that this shape was caused by a cross-term between q_{long} and q_0, the strength of which depended on the reference frame in which the data were analyzed (Fig. 7). In the $y_{anal} = 2.73$ frame the cross-term disappears which means that the source function in this frame has no correlation between the time and the position. Thus 2.73 is the rapidity of the source which emits pions within the E877 spectrometer acceptance.

While the shape of the correlation depends on the difference between the rapidities of the analysis frame and of the pion source, the distribution of the available pair statistics is governed by the difference between the rapidity of the analysis frame and pion pair rapidity[1]. That is why in the $y_{anal} = 1.57$ frame, which is far away (in y) from both the pions and the pion source, both the correlation peak and the pair statistics are concentrated on the diagonal.

[1] I thank H. Appelshäuser for calling my attention to this fact.

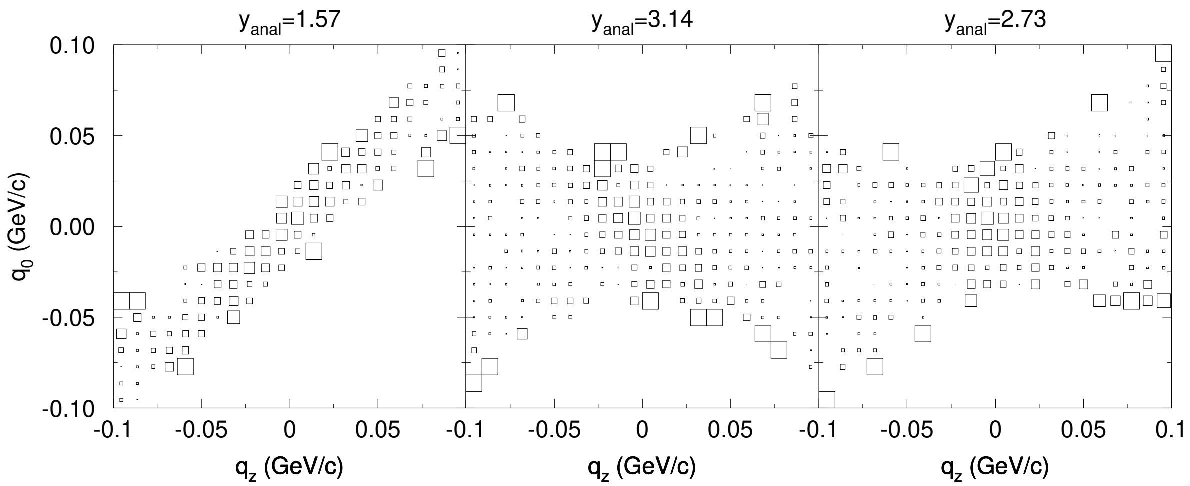

Figure 7. Two-pion correlation (combined positive and negative pions) as a function of q_z and q_0, with a 50 MeV/c cut on $|q_{out}|$ and $|q_{side}|$. The same data set has been analyzed in three different frames: midrapidity $y_{anal} = 1.57$, beam rapidity $y_{anal} = 3.14$ and a frame moving with $y_{anal} = 2.73$.

Instead of analyzing data in different frames and trying to fit $(C-1)$ by a Gaussian function we can include the source velocity in the fit function ('moving Gaussian source' analysis). In addition to the longitudinal velocity, we allow the source to move in the transverse direction in the reaction plane. The fit function becomes

$$C(q_x, q_y, q_z, q_0) = 1 + \lambda \exp(-R_x^2 q_x'^2 - R_y^2 q_y'^2 - R_z^2 q_z'^2 - \tau^2 q_0'^2), \tag{7}$$

where (q_x', q_y', q_z', q_0') are (q_x, q_y, q_z, q_0) boosted by $(\beta_x, 0, \beta_z)$. Here z is parallel to the beam and x (y) is the transverse direction in (perpendicular to) the reaction plane. The positive x is defined by the direction of the transverse flow in the forward hemisphere. The parameters obtained from the fits are given in Table 3. The source appears rather spherical and the duration of the emission is rather short. The source rapidity y, calculated from the fitted β_z values, is between midrapidity and the rapidity of the analyzed pions. The uncertainty of β_x is too big to make a statement about the transverse motion of the source. If taken seriously, the negative sign of β_x would mean that the transverse motion of the pion source and the transverse flow of protons have opposite directions.

Constraining the fit parameters to $R_x = R_y$ and $\beta_x = 0$ makes our fit function identical

Table 3
Parameters of the fit to four-dimensional correlation functions in the y_{anal}=3.14 reference frame. The last column (source rapidity y) is in LAB.

	λ	R_x(fm)	R_y(fm)	R_z(fm)	τ(fm/c)	β_x(fm)	$y(\beta_z)$(fm)
π^+	0.52±0.04	4.6±0.5	4.8±0.4	5.3±0.4	3.2±2.1	-0.07±0.12	2.9±0.1
π^-	0.50±0.03	4.9±0.4	5.5±0.4	5.3±0.4	0.0±1.5	-0.10±0.09	2.5±0.1

to the one used by the GIBS Collaboration at Dubna [20] and recently proposed in [21] (Yano-Koonin-Podgoretskii fit). The parameters obtained under these restrictions are given in Table 4.

The determined source velocity should be interpreted as the velocity of the freeze-out 'surface' in the three-dimensional coordinate space. The 'thickness' of this 'surface' is described by τ. In a hydrodynamical picture, if the freeze-out happens simultaneously in the local frame of a fluid element, this velocity would be equal to the velocity of the fluid element.

Table 4
Parameters of the fit to four-dimensional correlation functions assuming $R_x = R_y = R_t$ and $\beta_x = 0$ (Yano-Koonin-Podgoretskii fit). As in Table 3, analysis was done in the y_{anal}=3.14 frame. The source rapidity y has been transformed to LAB.

	λ	R_t(fm)	R_z(fm)	τ(fm/c)	$y(\beta_z)$(fm)
π^+	0.54±0.04	4.8±0.3	5.4±0.4	2.7±2.3	2.8±0.1
π^-	0.50±0.03	5.1±0.3	5.2±0.4	0.0±1.7	2.5±0.1

7. CONCLUSION

We presented the current status of the HBT analysis of the E877 Au+Au data. The one-dimensional correlations for different particle combinations form a consistent picture which, especially for pions, can be reproduced by a RQMD+SUBATECH calculation. This agreement means that $\lambda < 1$ is caused by resonances and not by coherent pion emission.

Two novel techniques have been applied to two-pion data. First, a fit to three-dimensional correlations, combined with the measured differential multiplicities, allows to calculate the average pion phase space density at freeze-out. The preliminary values are consistent with the numbers expected for local equilibrium. Secondly, a fit to the four-dimensional correlations (with q_0 as the fourth independent variable) gives the source velocity and the local source dimensions. This analysis reveals a pion source moving with 0.6-0.8 of the beam rapidity (in midrapidity frame) which is a strong evidence for longitudinal expansion.

The data analyzed so far are a small fraction (5%) of all recorded events. The available statistics will allow to analyze data binned by (p_t, y, ϕ) of the pair. Such a six-dimensional analysis will give access to the complete information contained in the two-particle correlations.

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