# Transverse Momentum Dependence of Bose-Einstein Correlations in 200*A* GeV/*c* S + *A* Collisions

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The NA35 experiment has collected a high statistics set of momentum analyzed negative hadrons near and forward of midrapidity for central collisions of 200*A* GeV/*c* $^{32}$S + S, Cu, Ag, and Au. Using momentum space correlations to study the size of the source of particle production, the transverse source radii are found to decrease by ~40% at midrapidity and ~20% at forward rapidity while the longitudinal radius $R_L$ is found to decrease by ~50% as $p_T$ increases over the interval $50 < p_T < 600$ MeV/*c*. Calculations using a microscopic phase space approach (relativistic quantum molecular dynamics) reproduce the observed trends of the data.

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The motivation for studying particle production in relativistic heavy ion collisions is the expectation of finding novel collective phenomena not directly attributable to a superposition of independent nucleon-nucleon collisions. Our emphasis is on identifying characteristics of hadron production in these collisions which appear to depend upon the presence of hadronic matter. The NA35 experiment at the CERN Super Proton Synchrotron (SPS) [1] has reported preliminary results on the evolution of the two-pion Bose-Einstein correlation function with rapidity [2] which have been shown to be consistent with a collective longitudinal scaling expansion scenario. In this Letter we present the results of a second generation two-particle correlation measurement in which a systematic study of the evolution of the two-particle correlation function as a function of pair transverse momentum is performed to probe the space-time evolution of the source in relativistic heavy ion collisions at 200*A* GeV/*c* [3].

Traditionally, the tendency of Bose particles emanating from a chaotic source of spatial extent $R$ to *clump* in momentum space over a scale of momentum difference $q \leq \hbar/R$ has been used to infer the space-time extent of particle production [4]. Under ideal conditions the two-particle correlation function, experimentally defined as the ratio of the actual measured relative momentum distribution $A(q)$ to a so-called background distribution $B(q)$ modeling two-particle phase space in the absence of the Bose symmetrization,

$$C_2(q) \equiv A(q)/B(q) = 1 + \lambda|\tilde{\rho}(q)|^2, \qquad (1)$$

is used in order to infer the source extent subject to the assumption of a plausible static pion spatial source distribution $\rho(\vec{r})$ with Fourier transform $\tilde{\rho}(\vec{q})$. It has been shown that this simple picture breaks down whenever there exist strong correlations between particle emission points and their momenta [5]. Under these circumstances, the correlation function becomes a function of the pair momenta. The dynamical evolution of a central ultrarelativistic heavy ion collision is expected to lead to such a situation in expansion scenarios with a high degree of collectivity [5–7]. Thus the dependence on pion pair momentum of the correlation function becomes a diagnostic of source evolution scenarios. Additionally, through the Wigner function formalism [8], it is now possible to make direct comparisons between the predictions of microscopic dynamical models and experimental data [9]. Previously, we have demonstrated [2,3] that in central collisions of 200*A* GeV/$c$ sulphur projectiles with S, Ag, and Au targets, the dependence of the *longitudinal* projection of the correlation function upon laboratory rapidity $y$, and pion pair momentum are consistent with Sinyukov's prediction [6] for a longitudinal "scaling" expansion scenario. Thus subsequent experiments should concentrate on the evolution of the *transverse* projections of the correlation function with either the transverse momenta of the pions in the pair $p_T$ or the pair mean transverse momentum $k_T$, in order to assess the mechanism of transverse expansion during the hadron production process. In particular, the theoretical work of Pratt and Bertsch *et al.* [5] has proposed that such transverse direction correlation observables exhibit a dramatic sensitivity to deconfined plasma formation in the primordial state, before expansion. Thus in this Letter we investigate the dependence on $p_T$ of the transverse projections of the two-pion correlation function in central S + S, Cu, Ag, and Au collisions. We shall show that such $p_T$ dependences exist at midrapidity, are relatively weaker at higher rapidity, and that microscopic dynamical models such as relativistic quantum molecular dynamics (RQMD) [10] offer a qualitative description of this momentum dependence.

The NA35 experimental setup at the CERN SPS [1] consists of a streamer chamber in a large volume dipole ("vertex") magnet, and a time projection chamber (TPC) [11], installed in the field-free region between the streamer chamber and the veto calorimeter. In this Letter we shall only consider TPC data. A beam of 200*A* GeV/$c$ $^{32}$S ions from the CERN SPS was normally incident upon Au, Ag, Cu, and S targets, 8 cm upstream of the streamer chamber (in the fringe field of the vertex magnet), of thickness 940, 750, 460, and 1165 mg/cm$^2$, respectively (corresponding to 1.1%, 1.2%, 1.0%, and 3.8% of an interaction length). A hardware trigger selected events corresponding to the lowermost 6%, 3%, 3%, and 3%, respectively, of the energy spectrum detected by a veto calorimeter covering the beam fragmentation region (effective laboratory opening angles of less than 0.3°). This anticoincidence trigger on the number of projectile spectators served as a central collision trigger with an impact parameter sensitivity on the level of 2–3 fm [12]. There were approximately $31 \times 10^3$, $44 \times 10^3$, $28 \times 10^3$, and $30 \times 10^3$ events respectively recorded for each of the systems. All negatively charged hadrons with $2.5 < y < 4.5$ are detected in the TPC. Three-dimensional space points for all tracks traversing the TPC were recorded. Their straight line trajectories were reconstructed in the TPC volume and then projected through the magnetic field to the target spot, resulting in momentum analysis and charge determination, as well as the rejection of nonvertex tracks. Two settings of the magnetic field (with 4.5 and 2.25 T m total bending power) lead to acceptances of the TPC for negative hadrons which overlap at $y \approx 3.5$ and, together, achieve a wide and uniform coverage of the longitudinal phase space, $2.5 < y < 4.5$. The transverse momentum acceptance is $0.05 < p_T < 1.8$ GeV/$c$. However, since the negative hadron pair statistics become marginal toward high $p_T$, we restrict the analysis to $p_T < 600$ MeV/$c$. Finally, the single- and two-particle momentum resolutions of the TPC system can be characterized as $\delta p/p^2 \approx 0.8 \times 10^{-3}$ (GeV/$c$)$^{-1}$ with $\delta q \approx 10-15$ MeV/$c$ in each component of the two-pion momentum difference.

The correlation functions are constructed as the ratio of the observed, or *actual*, and the so-called *background* two particle phase space distributions, $C_2 \equiv A(q_S, q_O, q_L)/B(q_S, q_O, q_L)$. The momentum difference $q$ is resolved into $q_L$ parallel and $q_T$ perpendicular to the beam direction; $q_T$ is further resolved into $q_O$ parallel to the pair momentum sum, and $q_S$ perpendicular to it [5]. The background distribution is constructed from an ensemble of randomized events which are generated according to the observed multiplicity distribution using an event-mixing prescription. The background distribution is corrected, on a pairwise basis, for the dipion Coulomb interaction using the standard Gamow penetration factor [13,14]. In order to accommodate the overall two-track resolution both the actual and background distributions are subjected to a cut which excludes tracks with neighbors closer than 2.5 cm at the TPC midplane. A Monte Carlo study indicates that this procedure causes no significant biases of the correlation function at low relative momentum, and hence a two-particle acceptance correction [15] is unnecessary. The pulse height information from the TPC permits the estimate of the contamination from kaons and electrons in the momentum analyzed negative track sample to be less than 15%. Our Monte Carlo studies indicate that secondary strange hadron decay pions lead to a further 10% contamination of the negative track samples. The principal impact of all contaminations is a significant underestimate, relative to the theoretical value of unity, of the extracted intercept parameter, $\lambda$ [Eq. (1)] [16].

The three-dimensional correlation functions are fit by a Gaussian functional form

$$C_2(q_S, q_O, q_L) = N[1 + \lambda e^{1/2\{-q_S^2 R_S^2 - q_O^2 R_O^2 - q_L^2 R_L^2\}}], \quad (2)$$

using the principle of maximum likelihood with $q_L$ boosted into the center of the respective rapidity interval. The parameters $R_S$, $R_O$, and $R_L$ are a measure of the source size dimensions in configuration space and correspond to a Woods-Saxon shape description of nuclear density distributions [17,18]. The results, for each of the systems studied, are shown in Figs. 1–3. A fully detailed report on the present investigations including a detailed analysis of the rapidity dependence of source radii are given elsewhere [16]. Concerning the evolution of the longitudinal component of the correlation function with $p_T$ shown in Fig. 1 we see in all systems a distinct and significant trend in which the longitudinal source radius $R_L$ decreases with $p_T$. This trend is somewhat larger in the calculations employing the microscopic RQMD model [10] which also yields larger absolute values of the source radii. The RQMD calculations implemented a simulation of the experimental central collision trigger conditions, and were filtered by the experiment acceptances. The evolution of $R_L$ with $p_T$ is also consistent with predictions of a scaling hydrodynamic expansion description of the particle production process [6,7]. The main point of the present investigation is in the *transverse* source parameters as observed in the evolution of the so-called $R_S$ and $R_O$ components of the correlation function; results are presented in Figs. 2 and 3. Figure 2 shows the radii $R_S$ and $R_O$ at midrapidity resulting from fits of the correlation functions, employing Eq. (2). Since the dependence on transverse momentum can be analyzed either in successive windows of the transverse momentum $p_T$ of pions contributing to the correlation functions or in bins of the average momentum $k_T = \frac{1}{2} \mid \vec{p}_{1T} + \vec{p}_{2T} \mid$ of the pion pair, we show the dependence on both $p_T$ and $k_T$ for didactic purposes. For both representations we observe similar radii that exhibit a decrease with increasing transverse momentum. Figure 2 thus suggests that the transverse momentum dependence of the transverse source parameters exists, and that, as expected, no essential difference emerges from considering either the $p_T$ or the $k_T$ representation. Turning, finally, to the target mass systematics of the data at forward rapidities, we show in Fig. 3 the $k_T$ dependence of the sideward and outward source radii for central S + S, Ag, and Au collisions. These data are from

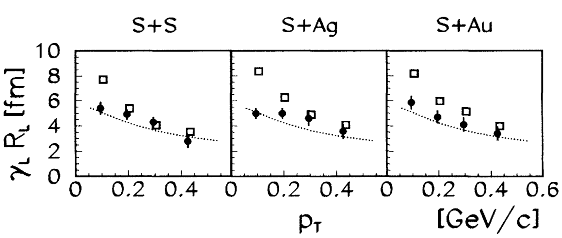


FIG. 1. Transverse pion momentum dependence of the longitudinal source radius $R_L$ (computed in the $y = 4$ c.m. frame) obtained from the longitudinal projection of the two-pion correlation function. The rapidity interval is $3.5 < y < 4.5$. Data given by full circles, RQMD results by open squares. The dotted lines represent the $m_T^{-1/2}$ dependence ($m_T^2 = m_0^2 + p_T^2$) expected from the scaling expansion model.

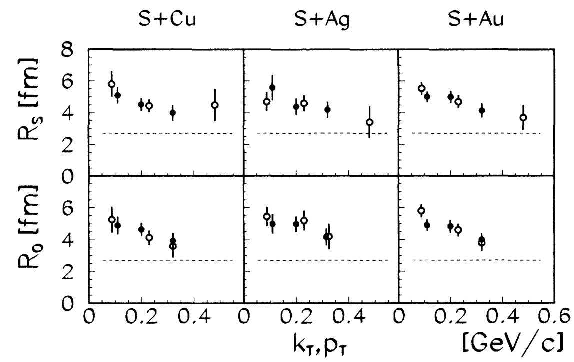


FIG. 2. Transverse pair momentum dependence of the transverse source size parameters, $R_{\rm side}$ and $R_{\rm out}$, for the reactions S + Cu, S + Ag, and S + Au in the rapidity interval $2.5 < y < 3.5$. The dashed lines represent the effective primordial reaction volume radius. Both the $p_T$ (open circles) and $k_T$ (full circles) dependences of the radii are shown.

the high magnetic field TPC run and refer to the rapidity domain $3.5 < y < 4.5$. We note that $R_O$ $R_O \approx R_S$ as in Fig. 2, both radii gathering at about 4 fm for all systems: slightly smaller than what we observe at midrapidity (Fig. 2). The $k_T$ dependence is weaker than in Fig. 2, but the data are consistent with a slight (20%) decrease toward higher transverse momentum, both in the $R_S$ and $R_O$ parameters. The RQMD results [10] (also shown in Fig. 3) fit our data for $R_S$ quite well. They overestimate the absolute values of $R_O$ but reproduce the $k_T$ dependence. From Figs. 2 and 3 we further conclude that the system at freeze-out is (only) 1–2 fm larger in transverse direction than the initial volume given by the effective transverse dimension of the projectile-target overlapping density profiles, corresponding to the central collision trigger geometry. This primordial radial source size [19], with an average value of $R = 2.7$ fm is indicated by the dashed lines in Figs. 2 and 3.

In summary, it has been the purpose of this investigation to search for a widening of two-pion correlation

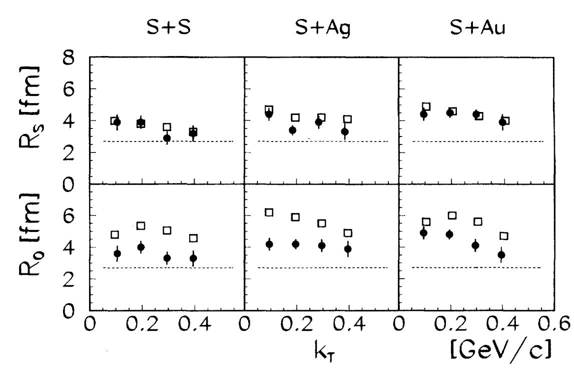


FIG. 3. Transverse pair momentum dependence of the transversal source size parameters, $R_{\rm side}$ and $R_{\rm out}$, referring to the rapidity interval $3.5 < y < 4.5$. Results of RQMD calculations are given by open squares. The dashed lines show the primordial reaction volume radius.

functions with pion transverse momentum, leading to a decrease in the extracted "source radii" for higher $p_T$ or $k_T$. This effect was demonstrated by theoretical investigations [5] to be a sensitive test of collective expansion: Pratt considered the isentropic expansion of a hadron-filled sphere initially at an energy density of 2 GeV/fm$^3$ and freezing out at 120 MeV (not an unreasonable formation and decay scenario). He found both $R_O$ and $R_S$ to fall by more than a factor of 2 in going from $k_T \approx 0$ to $k_T = 600$ MeV/$c$ due to a pronounced radial collective flow. Such behavior was indeed seen at the much lower Bevalac energies [20]. Our data do not exhibit such a dramatic $k_T$ dependence. The dependence is stronger at midrapidity than at forward rapidity. Our S + Au data at $y \approx 3$ agree with the S + Pb results of NA44 [21]. What we observe is consistent with earlier predictions for both string-motivated and Bjorken or thermal descriptions of the reaction dynamics [7] and with recent hydrodynamic calculations that include a phase transition with a modest latent heat difference [22]. On the other hand, our data for the longitudinal direction (Fig. 1) are indeed perfectly compatible with a collective, isentropic longitudinal "scaling" expansion, showing effects that are as strong as expected [5,6]. We are led to the conclusion that different mechanisms appear to drive the longitudinal and transverse expansions of the initial reaction volume: Collective transverse flow depends on rapidity and average, its signals are weaker than those, supporting longitudinal flow. The observed qualitative agreement of the microscopic RQMD model with the momentum evolution of both the longitudinal and transverse source parameters (Figs. 1 and 3) may suggest a first plausible explanation. The correlation between longitudinal momentum and position may result, not from a pressure driven hydrodynamic expansion, but from the relativistic kinematics of particle production from decaying strings which are oriented along the beam direction at the high SPS energy. RQMD seems to even overestimate this effect (see Fig. 1). The net outcome may well resemble that of a Bjorken-Sinyukov collective model. The transverse expansion, however, may indeed be thermal (i.e., driven by rescattering) and of relatively short duration (the density falling rapidly because of the predominantly longitudinal expansion). This scenario is implied by the RQMD model. These observations at 200A GeV may also be reconcilable with recent reports of a more pronounced transverse expansion at the lower Brookhaven AGS energy [23], where longitudinal collectivity should be less predominant. We note, however, that a second tentative explanation stems from the agreement of the hydrodynamical model calculations of Bolz *et al.* [22] with our data [16]. In this calculation the longitudinal expansion is manifestly collective but the transverse expansion is slowed down by the inward shock wave mechanism, characteristic of a mixed phase of plasma and hadrons. Intuitively one hesitates to apply such a model to collisions induced by the surface–dominated, small sulphur projectile. The next generation of experiments, with lead beams at the same energy, will help to finally clarify the expansion scenario.

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