Source breakup dynamics in Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV via three-dimensional two-pion source imaging

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A three-dimensional (3D) correlation function obtained from mid-rapidity, low \( p_T \), pion pairs in central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV is studied. The extracted model-independent source function indicates a long range tail in the directions of the pion pair transverse momentum (out) and the beam (long). Model comparisons to these distensions indicate a proper breakup time \( \tau_0 \sim 9 \) fm/c and a mean proper emission duration \( \Delta \tau \sim 2 \) fm/c, leading to sizable emission time differences \( \langle |\Delta t_{LCM}| \rangle \approx 12 \) fm/c) partly due to resonance decays. They also suggest an outside-in “burning” of the emission source reminiscent of many hydrodynamical models.

PACS numbers: PACS 25.75.Ld
Collisions between heavy nuclei at ultra-relativistic energies produce transient systems with energy densities much greater than that required to decompose bulk nuclear matter into quarks and gluons. Such systems were predicted to have long lifetimes if a first order phase transition occurred during their formation or decay.

A number of interferometry studies have been made to search for signals of long time delays in emissions from actual reaction sources. For a Gaussian source function, assumed in the traditional Hanbury Brown Twiss (HBT) methodology, this would be signaled by an increase in the width $R$ of the emission source function in the out direction of the Bertsch-Pratt coordinate system i.e $R_{\text{out}}/R_{\text{side}} >> 1$. No such result has been found by these HBT studies, and the reported Gaussian source functions are spheroidal with $R_{\text{out}} \approx R_{\text{side}}$ in the longitudinally co-moving system (LCMS) [4]. However, a recent study with a 1D source imaging technique has observed a long non-Gaussian tail in the radial source function and attributed it to possible lifetime effects [8, 9]. This suggests that further study of the source image may give new insights into the reaction dynamics leading to source breakup.

Here, we extract and perform a detailed study of the 3D two-pion source function using the technique proposed by Danielewicz and Pratt. Namely, the 3D correlation function is first decomposed into a basis of Cartesian surface-spherical harmonics to extract the coefficients, also called moments, of the expansion. In turn, they are then imaged or fitted with a trial function to extract the 3D source function, which is then used to probe the emission dynamics of the two-pion source produced.

Au+Au data (at $\sqrt{S_{NN}}=200$ GeV) was recorded during 2004 with the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC). The collision vertex $z$ (along the beam axis) was constrained to $|z| < 30$ cm of the nominal crossing point. Charged pions were detected in the east and west central arms of PHENIX, each of which subtends 90° in azimuth $\phi$, and ±0.35 units of pseudo-rapidity $\eta$. Tracking and momentum reconstruction were accomplished with the drift chamber and two layers of multi-wire proportional chambers with pad readout (PC1 and PC3). Particle momenta were measured with a resolution $\sigma_p/p = 0.7\% \pm 1.0\%$ (GeV/c).

Pion identification was achieved for $p_T \lesssim 2.0$ GeV/c and $p_T \lesssim 1$ GeV/c in the time of flight and electromagnetic calorimeter, respectively. For this analysis, mid-rapidity pion pairs were selected with $0.2 < p_T < 0.36$ GeV/c from semi-central ($0-20\%$) Au+Au collisions at $\sqrt{S_{NN}}=200$ GeV, where $p_T$ is half the pion pair transverse momentum. Track merging and splitting effects were removed by appropriate cuts on both the real and mixed pair distributions. Systematic variations of these cuts were explored to obtain systematic error estimates; on average, they are well within the statistical uncertainty. Hence, the pair cuts do not introduce any significant bias in the correlation function.

The 3D correlation function $C(q) = N_{\text{fgd}}(q)/N_{\text{bkg}}(q)$ was constructed as a ratio of 3D relative momentum distribution for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs in the same event $N_{\text{fgd}}(q)$ to that from mixed events $N_{\text{bkg}}(q)$. $C(q)$ is normalized to unity for $50 < |q| < 100$ MeV/c. Here, $q = |p_1 - p_2|$, where $p_1$ and $p_2$ are the momentum 4-vectors in the pair center of mass system (PCMS). The Lorentz transformation of $q$ from the laboratory frame to the PCMS is made by a transformation to the pair LCMS along the beam direction followed by a transformation to the PCMS along the pair transverse momentum.

To obtain the moments, the 3D correlation function $C(q)$, is expanded in a Cartesian surface-spherical harmonic basis [10, 11]

$$C(q) - 1 = R(q) = \sum_{l} \sum_{\alpha_1,\ldots,\alpha_l} R_{\alpha_1,\ldots,\alpha_l}^{(l)}(q) A_{\alpha_1,\ldots,\alpha_l}^{(l)}(\Omega_q),$$

where $l = 0, 1, 2, \ldots$, $\alpha_i = x, y$ or $z$, $A_{\alpha_1,\ldots,\alpha_l}^{(l)}(\Omega_q)$ are Cartesian harmonic basis elements; $\Omega_q$ is the solid angle in $q$ space; $R_{\alpha_1,\ldots,\alpha_l}^{(l)}(q)$ are Cartesian correlation moments given by Eq. (2); and $q$ is the modulus of $q$.

$$R_{\alpha_1,\ldots,\alpha_l}^{(l)}(q) = \frac{(2l+1)!!}{l!} \int d\Omega_q A_{\alpha_1,\ldots,\alpha_l}^{(l)}(\Omega_q) R(q).$$

Here, the coordinate axes are oriented so that $z$ (long) is parallel to the beam direction, $x$ (out) points in the direction of the total momentum of the pair in the LCMS.

Correlation moments, for each order $l$, can be calculated from the measured 3D correlation function using Eq. (2). Eq. (1) is truncated at $l = 6$ and expressed in terms of independent even moments only. As expected from symmetry considerations, odd moments were found to be consistent with zero within statistical uncertainty; higher order moments were found to be negligible. Up to order 6, there are 10 independent moments: $R^{(0)}, R^{(2)}_{\alpha_1\alpha_2}, R^{(4)}_{\alpha_1\alpha_2}, R^{(6)}_{\alpha_1\alpha_2}, R^{(4)}_{\alpha_1\alpha_2\alpha_2\alpha_2}, R^{(6)}_{\alpha_1\alpha_2\alpha_2\alpha_2\alpha_2}$, and $R^{(8)}_{\alpha_1\alpha_2\alpha_2\alpha_2\alpha_2\alpha_2\alpha_2}$ where $R^{(2)}_{\alpha_1\alpha_2}$ is shorthand for $R^{(2)}_{\alpha_1\alpha_2\alpha_2}$ etc (the dependent moments are obtained from the independent ones).

These independent moments were extracted as a function of $q$, by fitting the truncated series to the measured 3D correlation function with the moments as the parameters of the fit.

Figure 1 shows the correlation moments $R_{\alpha_1,\ldots,\alpha_l}^{(l)}$ up to order $l = 6$. In panel (a), $R^{(0)}(q)$ is shown along with $R(q) = C(q) - 1$; both represent angle-averaged correlation functions, but they are obtained by very different methods. For $R^{(0)}(q)$ one uses Eq. (2) and the 3D correlation function directly as in Ref. [4].

The very good agreement between $R^{(0)}(q)$ and $R(q)$ underlines the absence of any significant angular acceptance issues and attests to the reliability of the moment extraction technique used. Figures (b)-(j) show results for the
FIG. 1: Experimental correlation moments $R_l(q)$ for $l=0, 2, 4, 6$. Panel (a) also shows a comparison between $R_l(q)$ and $R(q)$. Systematic errors are less than the statistical errors. The solid lines indicate the fit with the Hump function Eq. (6).

moments $l=2, 4$ and 6. Contributions decrease with increasing $l$ in each direction and are relatively small for $l=6$. This justifies the truncation of the series Eq. (11) at $l=6$. The 3D source function $S(r)$ is obtained from these moments via imaging or fitting as discussed below.

Analogous to Eq. (11), $S(r)$ can be expanded in a Cartesian Surface-spherical harmonic basis (Eq. (3))

$$S(r) = \sum_{l} \sum_{\alpha_1 \ldots \alpha_l} S_{\alpha_1 \ldots \alpha_l}(r) A_{\alpha_1 \ldots \alpha_l}(\Omega_r).$$  

(3)

Substitution of the series for $R(q)$ and $S(r)$ into the 3D Koonin-Pratt equation (4):

$$C(q) - 1 = R(q) = \int drrK(q, r)S(r),$$  

(4)

gives a set of 1D relations (Eq. (5)) [10, 11]

$$R_{\alpha_1 \ldots \alpha_l}(q) = 4\pi \int drr^2 K(q, r) S_{\alpha_1 \ldots \alpha_l}(r),$$  

(5)

which connects the correlation moments $R_{\alpha_1 \ldots \alpha_l}(q)$ and source moments $S_{\alpha_1 \ldots \alpha_l}(r)$. $S(r)$ gives the probability of emitting a pair of particles with a separation vector $r$ in the PCMS. The 3D Kernel, $K(q, r)$, incorporates Coulomb interaction and Bose-Einstein symmetrization. Strong interaction is assumed to be negligible for pions. The 1D imaging code of Brown and Danielewicz [3, 4, 7] was used to numerically invert each correlation moment $R_{\alpha_1 \ldots \alpha_l}(q)$ to extract the corresponding source moment $S_{\alpha_1 \ldots \alpha_l}(r)$; the latter were then combined as in Eq. (4) to obtain the source function.

The 3D source function can also be extracted by directly fitting the 3D correlation function with an assumed functional form for $S(r)$. This corresponds to a simultaneous fit of the ten independent moments. A 4-parameter 3D Gaussian (ellipsoid) fit, using MINUIT minimization, gives a poor result ($\chi^2$/ndf=3.7). The solid line in Fig. 1 shows the result of a fit to the independent moments with an empirical Hump function given by

$$S^H(r_x, r_y, r_z) = \lambda \exp[-f_s(x^2 + y^2 + z^2) - f_1(x^2 + y^2)^{2/3} + z^2]^{1/3},$$  

(6)

where $\lambda, r_0, r_x, y, r_z, r_x, r_y, r_z, r_0, r_y, r_z$ are fit parameters and $f_s = 1/\{1 + (r/r_0)^2\}$, $f_1 = 1 - f_s$. This 8-parameter Hump function achieves a better fit to the data ($\chi^2$/ndf=1.4). Smearing the track momenta by the measured resolution has a negligible effect on the data points and fits.

Figure 2(a)-(c) shows a comparison of profiles of the two-pion 3D source function in the $x, y$ and $z$ directions ($S(x), S(y)$ and $S(z)$) obtained via fitting (line) and source imaging (squares). Source image extraction makes no assumption for the shape of the 3D source function; whereas, moment fitting explicitly assumes a shape. Therefore, the good agreement from the two extraction methods confirms the sufficiency of the Hump function but not its uniqueness.

The function $S(r_x)$ is characterized by a long tail, which is resolved up to $\sim 60$ fm, in contrast to $S(r_y)$ and $S(r_z)$ which range up to $\sim 25$ fm. This difference is also reflected in the respective correlation profiles (Fig. 2(d)-(f)) obtained by summation of the data (circle), fit (line) and image (square) moments up to order $l=6$ (Coulomb effects are not removed). The broader $S(r_x)$ is associated with the narrower $C(q_x)$ (Fig. 2(a) and (d)), as expected.

The extended tail lies along the total momentum of the pair in the PCMS. Thus, the relative emission times between the pions (including those from resonances), as well as the source geometry, will contribute directly to...
The lifetime of the source contributes to the range of \( S(r_x) \), and \( S(r_y) \) reflects its mean transverse geometric size. The difference between \( S(r_x) \) and \( S(r_y) \) is thus driven by the combination of the emission time difference, the freeze-out dynamics and the kinematic (Lorentz) \( \gamma \) boost, which is especially important in the out direction.

The event generator Therminator \cite{14, 15} can shed more light on the source breakup and emission dynamics. It gives thermal emission from a longitudinally oriented cylinder of radius \( r_{\text{max}} \), includes all known resonance decays, assumes Bjorken longitudinal boost invariance and Blast-Wave transverse expansion with radial velocity \( v_r \) semi-linear in \( \rho \), i.e. \( v_r(\rho) = (\rho/\rho_{\text{max}})/(\rho/\rho_{\text{max}} + v_t) \), where \( v_t = 1.41 \). A differential fluid element is a ring defined by cylindrical coordinates \( r \) and \( \rho \); it breaks up at proper time \( \tau \) in its rest frame or at time \( t \) in the lab frame, where \( t^2 = \tau^2 + z^2 \). The freeze-out hypersurface is given by \( \tau = \tau_0 + a\rho \), where \( \tau_0 \) is the proper breakup time for \( \rho = 0 \) and \( a \) is the space-time correlation parameter. In Blast-Wave mode, Therminator sets \( a = -0.5 \) for source emission or “burning” from outside in as in many hydrodynamical models.

Using a set of parameters tuned to fit charged pion and kaon spectra \cite{17}, pion pairs from Therminator were obtained with the effects of all known resonance decay processes on and off. These pairs were then transformed to the PCMS, following the same set of kinematic cuts and Lorentz transformations as in the data analysis, to obtain \( S(r_i) \) distributions for comparison with the data.

Figure 3 shows that the 3D source function generated by Therminator calculations (solid triangles) with \( \tau_0 = 8.55 \text{ fm}/c, \rho_{\text{max}} = 8.92 \text{ fm} \) and other previously tuned parameters \cite{17} underestimates \( S(r_x), S(r_y) \) and \( S(r_z) \). Open triangles (Fig. 3) show that resonance decays reproduce \( S(r_y) \) ((b)) and extend the calculated source function in \( x \) ((a)) as expected, but not enough to account for the long tails in \( S(r_x) \) and \( S(r_z) \). This suggests that the latter have substantial contribution from pion pairs with significantly longer emission time differences. Attempts to fit the distributions by only increasing \( \tau_0 \) or with \( \alpha \geq 0 \) failed, suggesting a fireball burning from outside in.

The generated distribution of time differences can also be lengthened by sampling pions from a family of hypersurfaces defined by a range of values of proper breakup times \( \tau' \). One such parametrization consists of replacing \( \tau \) by \( \tau' \) chosen from an exponential distribution \( dN/d\tau' = \theta(\tau' - \tau) \exp[-(\tau' - \tau)/a] \). In this parametrization, the width of the distribution \( \Delta \tau \) represents the mean proper emission duration in the rest frame. Figure 3 shows that this approach, with \( \Delta \tau = 2 \text{ fm}/c \) (open circles), leads to a fairly good match to the observed source profiles in all three directions. A 10\% change in \( \Delta \tau \) spoils this match.

Figure 3(d) shows the relative emission time distribution in the LCMS, \( \Delta \tau_{\text{LCM}} \), for pion pairs from events with the parameterizations indicated. For a fixed \( \tau_0 = 8.55 \text{ fm}/c \) (\( \Delta \tau = 0 \)) and resonance decays excluded, the distribution \( \Delta \tau_{\text{LCM}} \) is narrow, \( \langle |\Delta \tau_{\text{LCM}}| \rangle = 2.4 \text{ fm}/c \). The addition of resonance decays adds a long tail and gives \( \langle |\Delta \tau_{\text{LCM}}| \rangle = 8.8 \text{ fm}/c \). Replacing \( \tau \) with the ex-
ponential distribution $\tau'$ with $\Delta \tau = 2$ fm/c, results in a $\Delta t_{\text{LCM}}$ distribution which is significantly broadened to give $\langle |\Delta t_{\text{LCM}}| \rangle = 11.8$ fm/c. The wider distribution of time delays is needed to reproduce the source distributions. This implies a finite non-zero proper emission duration in the emission rest frame. Note that this $\Delta t_{\text{LCM}}$ distribution broadening has only a small effect on $S(r_y)$.

Figure 3 shows that substantial time differences $\Delta t_{\text{LCM}}$ are required by the source distensions; however, the interplay between proper time and breakup dynamics is model dependent. The picture which emerges from the data, in the context of the Therminator model, is consistent with that of an expanding fireball with proper breakup time $\tau_0 \sim 9$ fm/c, which hadronizes and emits particles over a short but non-zero mean proper emission duration $\Delta \tau = 2$ fm/c.

In summary, a new model-independent, three-dimensional source imaging technique has been applied to extract the 3D pion emission source function in the PCMS frame from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The source function has a much greater extent in the out ($x$) and long ($z$), than in the side ($y$) direction. Therminator model comparison indicates a fireball burning from outside in with proper lifetime $\tau_0 \sim 9$ fm/c and a mean emission duration $\Delta \tau \sim 2$ fm/c, leading to significant relative emission times ($\langle |\Delta t_{\text{LCM}}| \rangle \approx 12$ fm/c), including those due to resonance decay.

We thank the staff of the Collider-Accelerator and Physics Departments at BNL for their vital contributions. We thank P. Danielewicz and S. Pratt for their interest and input. We acknowledge support from the Office of Nuclear Physics in DOE Office of Science and NSF (U.S.A.), MEXT and JSPS (Japan), CNPq and FAPESP (Brazil), NSFC (China), IN2P3/CNRS, and CEA (France), BMBF, DAAD, and AvH (Germany), OTKA (Hungary), DAE (India), ISF (Israel), KRF and KOSEF (Korea), MES, RAS, and FFAE (Russia), VR and KAW (Sweden), U.S. CRDF for the FSU, US-Hungarian NSF-OTKA-MTA, and US-Israel BSF.

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