Rapidity and $k_T$ dependence of HBT correlations in Au+Au collisions at 200 GeV with PHOBOS

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Abstract. Two-particle correlations of identical charged pion pairs from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were measured by the PHOBOS experiment at RHIC. Data for the most central (0–15%) events were analyzed with Bertsch-Pratt (BP) and Yano-Koonin-Podgoretskii (YKP) parameterizations using pairs with rapidities of $0.4 < y < 1.3$ and transverse momenta $0.1 < k_T < 1.4$ GeV/c. The Bertsch-Pratt radii decrease as a function of pair transverse momentum. The pair rapidity $Y_{\pi\pi}$ roughly scales with the source rapidity $Y_{YKP}$, indicating strong dynamical correlations.

Identical-particle correlation measurements (Hanbury-Brown and Twiss, HBT) yield valuable information on the size, shape, duration, and spatiotemporal evolution of the emission source in heavy ion collisions. Experimentally, the correlation function $C(q)$ is defined as

$$C(q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$

where $P(p_1, p_2)$ is the probability of a pair being detected with relative four-momentum $q = p_1 - p_2$, and $P(p_1)$ and $P(p_2)$ are the single particle probabilities. The numerator
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is determined directly from data, while the denominator is constructed using the standard event-mixing technique.

The data reported here were collected using the PHOBOS two-arm magnetic spectrometer during RHIC Run II (2001). Details of the setup have been previously described in [1]. The spectrometer arms are each equipped with 16 layers of silicon sensors, providing charged particle reconstruction both outside and inside a 2 T magnetic field. The primary event trigger was provided by two sets of 16 scintillator paddle counters, which covered a pseudorapidity range $3 < |\eta| < 4.5$. Details of event selection and centrality determination can be found in [2, 3]. The 0–15% most central events were used in this analysis, equivalent to $\langle N_{\text{part}} \rangle = 310$ as determined by a Glauber model.

The details of the track reconstruction algorithm can be found in [4]. Events with a reconstructed primary vertex position between $-12 \text{ cm} < z_{\text{vtx}} < 10 \text{ cm}$ along the beam direction were selected in order to optimize vertex-finding precision, track reconstruction efficiency, and momentum resolution. Only particles which traversed the entire spectrometer were used in the analysis. A $3\sigma$ cut on the distance of closest approach with respect to the primary vertex ($dca_{\text{vtx}} < 0.35 \text{ cm}$) was then applied. The final track selection was based on the $\chi^2$ probability of a full track fit, taking into account multiple scattering and energy loss. The momentum resolution is $\Delta p/p \sim 1\%$ after all cuts. To identify pions, a cut three RMS deviations away from the expected mean value of the specific ionization $\langle dE/dx \rangle$ for pions was applied. Contamination from other particle species was studied using HIJING 1.35 [5] and a GEANT 3.21 simulation of the full detector. The contamination from $K^{\pm}K^{\pm}$, $pp$, and $\pi\pi$ pairs is less than 1%; non-identical pairs contribute less than 10% throughout the entire $k_T$ range.

To reject ghost pairs, only one shared hit in the weak-field region and two shared hits in the strong-field region were allowed per pair. A two-particle acceptance cut was applied to both data and background; the criterion for pair acceptance was defined by $\Delta \phi + 2\Delta \theta > 0.05 \text{ rad}$, where $\Delta \phi$ and $\Delta \theta$ are the relative pair separation in azimuthal and polar angle, respectively. About 7.3 million $\pi^+\pi^+$ and 5.5 million $\pi^-\pi^-$ pairs survive all cuts.

Systematic errors were determined by changing two-particle acceptance cuts, cuts in azimuthal separation, random seeds used in mixed-event background generation, as well as varying the definition of “event class” to create background events from pairs within narrow and broad vertex ranges.

Because the event mixed background is the product of tracks from different events, it does not a priori include any multiparticle correlations. In order to study the HBT correlation, it is necessary to apply a weight to account for the Coulomb effect. The Coulomb correction can be expressed solely as a function of relative 4-momentum $q$,

$$F_R(q) = \frac{F_c(q)}{F_{\text{pl}}(q)} = \frac{\int d\vec{r}|\psi_c(\vec{r})|^2 S(\vec{r})}{\int d\vec{r}|\psi_{\text{pl}}(\vec{r})|^2 S(\vec{r})}$$

where $S(\vec{r})$ is the relative separation of the particle pair, and $\psi_c$ and $\psi_{\text{pl}}$ are the Coulomb and plane wave-functions, respectively. A closed-form approximation and numerical correction for this relation was derived in [6] for $\lambda = 1$. For a variable $\lambda$,

$$F_R(q, \lambda) = \frac{(1 - \lambda) + \lambda(1 + e^{-q^2 R^2}) F_R(q)}{1 + \lambda e^{-q^2 R^2}}$$

This prescription is nearly equivalent to the corrections applied by the CERES, STAR, and PHENIX experiments [7, 8, 9]; our results showed no significant change using either correction method. The method is applied iteratively, successively fitting distributions of the correlation function $C(q)$ and iteratively applying the fit value $R$ to a new $S(\vec{r})$. Typically 2 or 3 iterations are sufficient for convergence.
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$C(q)$ is typically fit to a Gaussian source in three dimensions, the so-called Bertsch-Pratt parameterization [10],

$$C(q) = 1 + \lambda e^{-(q_0^2 R_0^2 + q_z^2 R_z^2 + q_x^2 R_x^2 + 2 q_x q_0 R_{0z})}$$

The correlation function was also fit to the YKP parameterization [11],

$$C(q) = 1 + \lambda e^{-(q_0^2 R_0^2 + \gamma(q_0 - \beta q_T)^2 R_0^2 + \gamma(q_\parallel - \beta q_T)^2 R_0^2)}$$

where $\beta$ is the longitudinal velocity of the source and $\gamma = 1/\sqrt{1 - \beta^2}$, $q_\perp$ and $q_\parallel$ the relative 3-momentum difference projected in the transverse and longitudinal directions respectively, and $q_T$ the relative difference in energy. In order to compare with lower energy, the data presented was fit in the longitudinal co-moving system (LCMS) frame.

![Figure 1. Bertsch-Pratt radii as a function of pair transverse momentum $k_T$ for Au+Au at 200 GeV from PHOBOS, STAR and PHENIX. The boxes represent PHOBOS systematic error.](image)

In Fig. 1 the Bertsch-Pratt radii are presented as a function of pair transverse momentum $k_T$ for $\pi^-\pi^-$ pairs. For comparison, data from STAR and PHENIX at $\sqrt{s_{NN}} = 200$ GeV are also shown. The PHOBOS data were analyzed in the LCMS frame within the rapidity range $0.4 < y < 1.3$, while the other data are at mid-rapidity ($-0.5 < y < 0.5$). The three-dimensional correlation functions were fit to Eq. (4) using the log-likelihood method. $R_s$ weakly varies as a function of $k_T$, while $R_o$ and $R_\ell$ decrease rapidly with increasing $k_T$.

In Fig. 2 the extracted value of the source rapidity $Y_{YKP}$ is plotted as a function of pair rapidity for $\pi^+\pi^+$ pairs with $0.1 < k_T < 1.4$ GeV/c. The data from NA49 at lower energy is also plotted; however, it should be noted the presented NA49 data covers only $0.1 < k_T < 0.2$ GeV/c. The pair rapidity strongly scales with source rapidity, indicating the presence of strong position-momentum correlations. The solid line at $Y_{YKP} = Y_{\pi\pi}$ represents a class of models including, but not limited to, boost invariance.
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Figure 2. Source rapidity ($Y_{YKP}$) as a function of pair rapidity ($Y_{\pi\pi}$) for PHOBOS (circles) and NA49 (squares) [12]. The line at $Y_{YKP} = Y_{\pi\pi}$ is drawn to guide the eye. The boxes represent PHOBOS systematic error.

In conclusion, we have extracted HBT parameters from Au+Au collisions at $\sqrt{s_{NN}} = 200$ using two different parameterizations of the correlation function. The Bertsch-Pratt parameters show good agreement between three experiments with very different acceptances. From the YKP analysis, the pair rapidity scales strongly with the source rapidity, indicating a source with strong position-momentum correlations.

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