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

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

(1)

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 3σ 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 $p\bar{p}$ 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 $q$,

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

where $S(\vec{r})$ is the relative separation of the particle pair, and $\psi_c$ and $\psi_{pl}$ 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],

$$C(q) = 1 + \lambda e^{-(q^2 R_o^2 + q^2 R_s^2 + q^2 R_\ell^2 + 2q_o q_s R_{os}^2)}$$

(4)

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

$$C(q) = 1 + \lambda e^{-(q^2 R_o^2 + \gamma^2 (q - \beta q_T)^2 R_{\parallel}^2 + \gamma^2 (q_t - \beta q_s)^2 R_{\tau}^2)}$$

(5)

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.

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 [8] and PHENIX [9] 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 [12] 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.](image)

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.

This work was partially supported by U.S. DOE grants DE-AC02-98CH10886, DE-FG02-93ER40802, DE-FC02-94ER40818, DE-FG02-94ER40865, DE-FG02-99ER41099, and W-31-109-ENG-38, by U.S. NSF grants 9603486, 0072204, and 0245011, by Polish KBN grant 2-P03B-10323, and by NSC of Taiwan under contract NSC 89-2112-M-008-024.

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