A Comparison of HBT Measurements for $d + Au$ and $Au + Au$ collision systems at $\sqrt{s_{NN}} = 200$ GeV

Alex Mwai for the PHENIX Collaboration
Department of Chemistry, Stony Brook University, Stony Brook, NY 11794-3800
E-mail: alexmwai@bnl.gov

Abstract. Two-pion Bose-Einstein correlations are a valuable tool for studying the space-time extent of emission sources in $p + A$, $d + A$, and $A + A$ collisions. In recent work, PHENIX has extracted the 3-D HBT radii as a function of centrality and transverse-pair mass ($m_T$) for the $d + Au$ and $Au + Au$ collision systems. A comparison of the radii for both systems indicate strong similarities in the detailed dependencies on centrality and $m_T$, suggestive of important final-state re-scattering effects in the reaction dynamics for the $d + Au$ and $Au + Au$ systems. The measurements also point to a smaller freeze-out size and system lifetime in $d + Au$ as compared to $Au + Au$.

1. Introduction

A double-ridge structure has recently been reported for high multiplicity 2-D hadron correlations in $p + p$ and $p + A$ systems at the LHC [4, 1, 27, 22]. The observation of this structure suggests that the $p + p$ and $p + A$ systems might be large enough and be sufficiently long-lived for significant medium effects to form, such as those previously seen in $A + A$ collisions [10, 5].

Two theories have been presented as to the origin of the double-ridge structure: The Color Glass Condensate (CGC) framework argues that the structure is as a result of quantum interference effects between correlated gluons due to gluon saturation at small impact parameter [23, 24]. The 3+1-D viscous hydrodynamic model, on the other hand, suggests that the collective effects observed could be attributed to fluctuations in the initial state that are then carried through the final-state hydrodynamic evolution [20, 32].

Hanbury Brown-Twiss (HBT) interferometry is a useful technique for studying the space-time extent of pion-emitting sources [25, 18]. The HBT measurements dependence on transverse mass and collision centrality in $A + A$ systems have been extensively studied, and are known to show characteristics that point to the influence of final-state re-scattering effects [12, 8, 2]. Similar HBT measurements for $p + p$ and $p + A$ systems can therefore provide a useful and independent check of proposed models. Specifically, observation of common trends in $A + A$ and $p + A$ systems for the HBT measurements would be an indication of the strong role that final-state re-scattering effects has in $p + A$ systems [21]. In these proceedings, we present two-pion HBT measurement results for the $d + Au$ collision system at $\sqrt{s_{NN}} = 200$ GeV using the PHENIX detector. The measurements are studied for their dependence on the transverse mass as well as the collision geometry. These results are also compared...
with similar measurements done for the $Au + Au$ collision system at $\sqrt{s_{NN}} = 200$ GeV, as well as the $\sqrt{s_{NN}} = 2.76$ TeV $Pb + Pb$ collision system results from LHC.

2. Analysis

This analysis is done using data collected by the PHENIX detector. The $Au + Au$ results are from the 2007 running period while the $d + Au$ results are from the 2008 running period. In total, 3.5 billion events are utilized for $Au + Au$ and 1.8 billion events for $d + Au$. The collision vertex was determined using the Zero Degree Calorimeter (ZDC) and restricted to $|z| < 30$ cm along the beam direction. The collision centrality classes were selected from the distribution of the charge deposited in the Beam Beam Counter (BBC). Charged particle tracking was done using both the Drift Chamber (DC) and the Pad Chambers (PC), with the 3-D trajectories of the particles reconstructed from a model based on hits in the two subsystems [11].

PID in this analysis was done using the Time-of-Flight detector (ToF) and the Electromagnetic Calorimeter (EMC). Both detectors provide for very good timing resolution ($\sigma_{t} \sim 110$ psec and $\sigma_{t} \sim 400$ psec respectively) and sufficient azimuthal angle coverage ($\Delta \phi < \pi/2$) [14, 15]. Charged pions were identified to within 2 standard deviations of their mass squared distribution peak to ensure purity.

The two-particle correlation function is defined as $C_2(q) = A(q)/B(q)$. Here, $A(q)$ is the same charge pair distribution in relative momentum for pions from the same event while $B(q)$ is a background distribution obtained from pairing same charge pions from different events, but with similar binning in vertex and centrality as the $A(q)$ distribution. Pairs in both distributions were built in vertex bins of 3 cm and centrality bins of 5%. The relative momentum, $q$, is defined as $\overrightarrow{p}_1 - \overrightarrow{p}_2$ where $\overrightarrow{p}_1$ and $\overrightarrow{p}_2$ are the momenta for the particles in the pair. To remove spurious correlations due to effects of track splitting as well as detector resolution limitations, cuts were applied in DC, PC, and EMC to both the $A(q)$ and $B(q)$ distributions. These cuts were rigorously studied for each centrality selection, and applied for each collision system independently. The 3-D correlation functions were projected in the Bertsch-Pratt parameterization [16, 31] such that $q_{long}$ is projected along the beam direction, $q_{out}$ is parallel to the average transverse momentum of the pair ($k_T$), and $q_{side}$ is orthogonal to $q_{out}$ and $q_{long}$. $k_T$ is defined as $(\overrightarrow{p}_{T,1} + \overrightarrow{p}_{T,2})/2$ where $\overrightarrow{p}_{T,1}$ and $\overrightarrow{p}_{T,2}$ are the transverse momenta of the particles. Figure 1 shows a selection of the correlation functions for $Au + Au$ and $d + Au$ at comparable number of participants ($N_{part}$) selections (15.7 $\pm$ 1.6 and 16.7 $\pm$ 1.1 respectively) and an average $k_T$ of 0.39 GeV/c.

The obtained correlation functions were studied for their dependence on the expansion dynamics of the system in the form of the transverse mass given as $m_T = \sqrt{E_T + m_\pi}$ where $m_\pi$ is the pion mass. The correlation functions were also studied for their dependence in the collision centrality in the form of $N_{part}$ and the initial transverse size ($\overline{R}$). These two quantities were determined for each centrality selection using Monte-Carlo Glauber calculations [29, 30]. $\overline{R}$ is obtained from the root-mean-square widths of density distributions in 2-D, $\sigma_x$, $\sigma_y$, and defined as $1/\overline{R} = \sqrt{(1/\sigma_x^2) + (1/\sigma_y^2)}$ [17]. Since $\overline{R}$ is proportional to $\tau$, the expansion time of the system, it is a more natural scaling variable for the system size as measured in HBT as compared to $N_{part}$ [36, 28]. To allow for a more quantitative comparison of the two systems, the correlation functions were fit with the Sinyukov fit function [19, 37]. This fit function allows for the extraction of the HBT radii while compensating for
Final State Interactions (FSI), which in this study are dominated by Coulomb pair repulsion at small $q$.

$$C_2(q) = N[\lambda(1 + G(q))F_c + (1 - \lambda)]$$

$$G(q) \approx \exp(-R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2)$$  \hspace{1cm} (1)$$

$N$ is a normalization factor and $\lambda$ is a measure of the chaoticity. $F_c$ is a correction for the FSI. $R_{\text{side}}$ carries information about the geometrical transverse size of the system. $R_{\text{out}}$ carries information about both the transverse size and the particle emission duration of the system, $\Delta \tau$, while from $R_{\text{long}}$, we can extract information about the lifetime of the system, $\tau$.

3. Results

3.0.1. $m_T$ dependence Figure 2 shows the $m_T$ dependence of $R_{\text{out}}$, $R_{\text{side}}$, and $R_{\text{long}}$ for $Au + Au$ and $d + Au$ collision systems at similar $N_{\text{part}}$ values. A decreasing trend with an increase in $m_T$ is evident for both collision systems. This trend has previously been shown to be characteristic of an expanding source [26]. To further extract information about the geometrical size ($R_{\text{geom}}$) and lifetime of the system ($\tau$), blastwave model fits [33] were made to the curves for $R_{\text{side}}$ and $R_{\text{long}}$ with the fit functions:

$$R_{\text{side}} = R_{\text{geom}} / \sqrt{1 + \beta^2 (m_T/T)},$$  \hspace{1cm} (2)$$
Figure 2. \( R_{\text{out}}, R_{\text{side}}, \) and \( R_{\text{long}} \) dependence on \( m_T \) for central \( d + Au \) and peripheral \( Au + Au \). Dashed lines are blastwave fits to the curves.

### Table 1. \( R_{\text{geom}} \) and \( \tau \) values for \( d + Au \) and \( Au + Au \) obtained from blastwave model fits to curves for \( R_{\text{side}} \) and \( R_{\text{long}} \) in figure 2.

|          | \( d + Au \)      | \( Au + Au \)   |
|----------|-------------------|-----------------|
| \( R_{\text{geom}} \) (fm) | 2.7±0.03±0.2(sys) | 3.8±0.04±0.2(sys) |
| \( \tau \) (fm/c)        | 2.8±0.03±0.4(sys) | 4.2±0.04±0.3(sys) |

\[ R_{\text{long}} = \tau \sqrt{(T/m_T)}[(K_2(m_T/T))]/(K_1(m_T/T))] \] (3)

\( T \) (0.118 ± 0.02 GeV and 0.123 ± 0.02 GeV for \( d + Au \) and \( Au + Au \) respectively), the freeze-out temperature and \( \beta \) (0.42 ± 0.03 and 0.38 ± 0.08 c for \( d + Au \) and \( Au + Au \) respectively), the surface velocity are the input parameters. \( T \) and \( \beta \) are obtained from blastwave fits to the \( p_T \) spectra for identified charged hadrons [6] while \( K_2 \) and \( K_1 \) are modified Bessel functions. The values given in table 1 show that \( d + Au \) has both a smaller transverse size and system lifetime as compared to \( Au + Au \).

The smaller size of the \( d + Au \) system as compared to the \( Au + Au \) can also be seen in the freeze-out volume which is proportional to the product \( R_{\text{out}} \times R_{\text{side}} \times R_{\text{long}} \). Figure 3 shows \( R_{\text{out}} \times R_{\text{side}} \times R_{\text{long}} \) dependence on \( m_T \) for \( d + Au \) and \( Au + Au \) systems. While \( d + Au \) indicates a smaller freeze-out volume as compared to \( Au + Au \), the fall-off with \( m_T \) for both systems is comparable.

\( R_{\text{out}}/R_{\text{side}} \) has traditionally been used as a proxy for \( \Delta \tau \) for a pion-emitting source [13, 35, 34, 7]. Figure 4 shows the \( R_{\text{out}}/R_{\text{side}} \) dependence on \( m_T \) for the \( d + Au \) and \( Au + Au \) systems. The ratio is found to be flat and close to unity, suggesting that the two systems both exhibit a very short emission duration.
Figure 3. $R_{out} \times R_{side} \times R_{long}$ dependence on $m_T$ for $d + Au$ and $Au + Au$ systems.

Figure 4. The $R_{out}/R_{side}$ ratio dependence on $m_T$ for central $d + Au$ and peripheral $Au + Au$ collisions.
3.0.2. Collision geometry dependence

To investigate the collision geometry dependence, $R_{\text{out}}$, $R_{\text{side}}$, and $R_{\text{long}}$ were studied for their dependence on $N_{\text{part}}$ and $R_{\text{T}}$.

$N_{\text{part}}$ dependence

The $N_{\text{part}}$ dependence for both $d + Au$ and $Au + Au$ collision systems was done at $k_T \approx 0.39$ GeV/c. Figure 5 shows this dependence. A similar linear increase in both $R_{\text{out}}$ and $R_{\text{side}}$ is observed for both collision systems. $R_{\text{long}}$ shows a slight difference in slope which could be due to differences in the longitudinal dynamics for $d + Au$ and $Au + Au$. These results suggest that there is a common strong correlation between the transverse size and the initial geometry in both collision systems. The results also indicate that the dependence of the transverse expansion rate with collision geometry is similar in $d + Au$ and $Au + Au$ systems.

$R_{\text{T}}$ dependence

Figure 6 shows the $R_{\text{T}}$ dependence of $R_{\text{side}}$ for the $d + Au$ and $Au + Au$ collision systems, as well as ALICE $Pb + Pb$ at 2.76 TeV and STAR $Au + Au$ at 200 GeV [3, 9]. For all systems, $R_{\text{side}}$ shows a linear relationship with $R_{\text{T}}$. $d + Au$ and $Au + Au$ collision systems have similar slopes while the $Pb + Pb$ results demonstrate a larger slope which could be attributed to the stronger expansion rate expected at 2.76 TeV. A good match between the 200 GeV $Au + Au$ PHENIX and STAR measurements is also seen in the comparison. These results strongly emphasize the role of final-state re-scattering effects in $d + Au$ which is typical of a hydrodynamic evolution scenario.
4. Summary and Conclusion

We have, in this proceedings, presented new PHENIX results on HBT measurements for the $d + Au$ and $Au + Au$ collision systems at $\sqrt{s_{NN}} = 200$ GeV. The HBT radii for the two systems show comparable trends both for their $m_T$ and collision centrality dependence. The $d + Au$ system was also found to have both a smaller size and shorter lifetime as compared to the $Au + Au$ system. $R_{side}$ in the $d + Au$ and $Au + Au$ systems, as well as $Pb + Pb$ at $\sqrt{s_{NN}} = 2.76$ TeV, shows a linear relationship with the initial transverse size but with a larger slope for the $Pb + Pb$ collision system. The difference in slope could be due to the larger expansion rate at the higher LHC energy. In conclusion, these results indicate that final-state re-scattering effects play an important role in the $d + Au$ collision system.

References

[1] Georges Aad et al. Observation of Associated Near-side and Away-side Long-range Correlations in $\sqrt{s_{NN}}=5.02$ TeV Proton-lead Collisions with the ATLAS Detector. Phys.Rev.Lett., 110:182302, 2013.

[2] K. Aamodt et al. Two-pion Bose-Einstein correlations in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys.Lett., B696:328–337, 2011.

[3] K. Aamodt et al. Two-pion Bose-Einstein correlations in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Phys.Lett., B696:328–337, 2011.
[4] Betty Abelev et al. Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys.Lett.*, B719:29–41, 2013.

[5] B.I. Abelev et al. Long range rapidity correlations and jet production in high energy nuclear collisions. *Phys.Rev.*, C80:064912, 2009.

[6] B.I. Abelev et al. Systematic Measurements of Identified Particle Spectra in $pp, d^+Au$ and Au+Au Collisions from STAR. *Phys.Rev.*, C79:034909, 2009.

[7] J. Adams et al. Azimuthally sensitive HBT in Au + Au collisions at $s(NN)^{1/2} = 200$-GeV. *Phys.Rev.Lett.*, 93:012301, 2004.

[8] J. Adams et al. Pion interferometry in Au+Au collisions at $s(NN)^{1/2} = 200$-GeV. *Phys.Rev.*, C71:044906, 2005.

[9] J. Adams et al. Pion interferometry in Au+Au collisions at $s(NN)^{1/2} = 200$-GeV. *Phys.Rev.*, C71:044906, 2005.

[10] A. Adare et al. Dihadron azimuthal correlations in Au+Au collisions at $s(NN)^{1/2} = 200$-GeV. *Phys.Rev.*, C78:014901, 2008.

[11] K. Adcox et al. PHENIX central arm tracking detectors. *Nucl.Instrum.Meth.*, A499:489–507, 2003.

[12] S.S. Adler et al. Bose-Einstein correlations of charged pion pairs in Au + Au collisions at $s(NN)^{1/2} = 200$-GeV. *Phys.Rev.Lett.*, 93:152302, 2004.

[13] S.S. Adler et al. Bose-Einstein correlations of charged pion pairs in Au + Au collisions at $s(NN)^{1/2} = 200$-GeV. *Phys.Rev.Lett.*, 93:152302, 2004.

[14] M. Aizawa et al. PHENIX central arm particle ID detectors. *Nucl.Instrum.Meth.*, A499:508–520, 2003.

[15] L. Aphecetche et al. PHENIX calorimeter. *Nucl.Instrum.Meth.*, A499:521–536, 2003.

[16] G.F. Bertsch. Pion Interferometry as a Probe of the Plasma. *Nucl.Phys.*, A498:173C–180C, 1989.

[17] R.S. Bhalerao, Jean-Paul Blaizot, Nicolas Borghini, and Jean-Yves Ollitrault. Elliptic flow and incomplete equilibration at RHIC. *Phys.Lett.*, B627:49–54, 2005.

[18] David H. Boul, Claus-Konrad Gelbe, and Byron K. Jennings. Intensity interferometry in subatomic physics. *Rev. Mod. Phys.*, 62:553–602, Jul 1990.

[19] M.G. Bowler. Coulomb corrections to Bose-Einstein correlations have been greatly exaggerated. *Phys.Lett.*, B270:69–74, 1991.

[20] Piotr Bozek. Collective flow in p-Pb and d-Pd collisions at TeV energies. *Phys.Rev.*, C85:014911, 2012.

[21] Piotr Bozek and Wojciech Broniowski. Size of the emission source and collectivity in ultra-relativistic p-Pb collisions. *Phys.Lett.*, B720:250–253, 2013.

[22] Serguei Chatrchyan et al. Observation of long-range near-side angular correlations in proton-lead collisions at the LHC. *Phys.Lett.*, B718:795–814, 2013.

[23] Kevin Dusling and Raju Venugopalan. Azimuthal collimation of long range rapidity correlations by strong color fields in high multiplicity hadron-hadron collisions. *Phys.Rev.Lett.*, 108:262001, 2012.

[24] Kevin Dusling and Raju Venugopalan. Comparison of the color glass condensate to dihadron correlations in proton-proton and proton-nucleus collisions. *Phys.Rev.*, D87(9):094034, 2013.
[25] R. Hanbury Brown and R. Q. Twiss. A Test of a New Type of Stellar Interferometer on Sirius. *Nature*, 178(4541):1046–1048, November 1956.

[26] M. Herrmann and G.F. Bertsch. Source dimensions in ultrarelativistic heavy ion collisions. *Phys. Rev.*, C51:328–338, 1995.

[27] Vardan Khachatryan et al. Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC. *JHEP*, 1009:091, 2010.

[28] Roy A. Lacey, Yi Gu, X. Gong, D. Reynolds, N.N. Ajitanand, et al. Is anisotropic flow really acoustic? 2013.

[29] Roy A. Lacey, Rui Wei, N.N. Ajitanand, and A. Taranenko. Initial eccentricity fluctuations and their relation to higher-order flow harmonics. *Phys. Rev.*, C83:044902, 2011.

[30] Michael L. Miller, Klaus Reygers, Stephen J. Sanders, and Peter Steinberg. Glauber modeling in high energy nuclear collisions. *Ann. Rev. Nucl. Part. Sci.*, 57:205–243, 2007.

[31] S. Pratt. Pion Interferometry of Quark-Gluon Plasma. *Phys. Rev.*, D33:1314–1327, 1986.

[32] Guang-You Qin and Berndt Müller. Elliptic and triangular flow anisotropy in deuteron-gold collisions at RHIC and proton-lead collisions at the LHC. *Phys. Rev.*, C89:044902, 2014.

[33] Fabrice Retiere and Michael Amna Lisa. Observable implications of geometrical and dynamical aspects of freeze out in heavy ion collisions. *Phys. Rev.*, C70:044907, 2004.

[34] Dirk H. Rischke. Hydrodynamics and collective behavior in relativistic nuclear collisions. *Nucl. Phys.*, A610:88C–101C, 1996.

[35] Dirk H. Rischke and Miklos Gyulassy. The Time delay signature of quark - gluon plasma formation in relativistic nuclear collisions. *Nucl. Phys.*, A608:479–512, 1996.

[36] Edward Shuryak and Ismail Zahed. High-multiplicity pp and pA collisions: Hydrodynamics at its edge. *Phys. Rev.*, C88(4):044915, 2013.

[37] Yu. Sinyukov, R. Lednicky, S.V. Akkelin, J. Pluta, and B. Erazmus. Coulomb corrections for interferometry analysis of expanding hadron systems. *Phys. Lett.*, B432:248–257, 1998.