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

30th Workshop on Nuclear Dynamics – WWND
Galveston, Texas
6-12 April 2014

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Observed long-range correlations in high multiplicity events in p+p and p+Pb

Near-side ridge structure observed at LHC for high multiplicity p+p (7 TeV) and p+Pb (5.02 TeV) collisions suggest that these small systems are large enough (and last long enough) for significant medium effects previously only seen in A+A collisions

- Two theories on the origin of ridge structure:
CGC framework: Observed two-ridge structure is as a result of quantum interference effects between correlated gluons due to gluon saturation at small impact parameters.
Viscous hydro model: Observed collective effects could be due to fluctuations of initial state carried through final-state hydrodynamic evolution

(2) 3+1-dimensional hydrodynamic model

Flow hydro results compared to the experimental d+Au results at RHIC at both 0-5% and 0-20% centrality

Elliptic and triangular flow hydro results compared to experimental p+Pb results at LHC at 0-2% and 0-20% centrality

arXiv:1306.3439
Motivation for HBT studies in d+Au

- With two equally successful interpretations of the near-side ridge structure, need for an independent check of the role of final-state interactions

- HBT measurements are well studied and show characteristic patterns due to collective effects in A+A collisions

- Similar measurements can provide constraint for final-state effects in p+A collisions

- Common trends in A+A and p+A systems in HBT measurements would be a strong indication of final-state effects in p+A systems
HBT Methodology

Based on quantum interference of identical particles whose space-momentum correlation can be expressed as:

\[ C_2(q,k) - 1 = \int (d^3r)kn(r)\left[|\psi(k,r)|^2 - 1\right] \]

\[ q = p_1 - p_2 \quad k = (p_1 + p_2)/2 \]

Space-time information extracted by fitting \( C_2(q_i) \) with:

\[ C_2(q_{\text{side}}, q_{\text{out}}, q_{\text{long}}) = 1 + \lambda \exp\left(-R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2\right) \]

Here, \( q \) is decomposed in the longitudinal co-moving system (LCMS): \( q_{\text{side}}, q_{\text{out}}, q_{\text{long}} \)

\( q_{\text{side}} \) - is perpendicular to the beam direction

\( q_{\text{out}} \) - is parallel to the average transverse momentum of pair or \( k_T \)

\( q_{\text{long}} \) - is along beam direction

\( R_{\text{side}} \) - carries information about the geometrical size of the dynamic system, \( R_{\text{geom}} \)

\( R_{\text{out}} \) - encodes information about the size and the emission duration of the system at freeze-out, \( \Delta\tau \)

\( R_{\text{long}} \) - provides information about the lifetime of the system, \( \tau \)
The PHENIX Experiment

Zero Degree Calorimeter (ZDC) & Beam Beam Counter (BBC)
Vertex and centrality determination

Drift Chamber (DC) & Pad Chamber (PC)
Tracking information

Electromagnetic Calorimeter (EMC)
Lead Scintillator Sectors (Six Total)
PID information

Time-of-Flight Detector (TOF)
PID information

With their good timing resolution, the EMC and TOF detectors provide for very good PID capabilities.
Centrality and PID Determination

Centrality  
determined from total charge  
 deposited in BBC

\[ N_{\text{part}} \quad \text{and} \quad R_{\text{bar}} \quad \text{obtained from MC-Glauber simulation of each centrality class.} \]

\[ R_{\text{bar}} \]  
is the initial transverse size of the  
 system defined as:  
\[ 1/R_{\text{bar}} = \sqrt{1/\sigma_x^2+1/\sigma_y^2} \]

\[ \sigma_x, \sigma_y \] : RMS widths of density distributions

PID done using the time-of-flight method  
Very good pion separation obtained in both d+Au and Au+Au systems
### Analysis Summary and Outline

#### Analysis outline

- Select particles
- Build correlation functions ($C_2(q)$)
  - Apply appropriate cuts to remove spurious correlations
- Fit to extract for HBT radii in 3-D and study as a function of:
  - collision centrality
  - average transverse mass ($m_T$) for each collision system
- Fit HBT radii $m_T$ dependence to obtain geometrical radius and system lifetime

#### Analysis summary

<table>
<thead>
<tr>
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<th>Analysis done for charged pions for:</th>
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<tbody>
<tr>
<td>$\sqrt{s_{NN}} = 200$ GeV Au+Au</td>
<td>3.5 billion events</td>
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<tr>
<td>$\sqrt{s_{NN}} = 200$ GeV d+Au</td>
<td>1.8 billion events</td>
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PID: 2σ for pion acceptance; 3σ for kaon rejection

- $k_T$ range: $0.2 < k_T < 0.7$ GeV/c
- $k_T$ average: 0.39 GeV/c (for collision geometry dependence)
Correlation Functions

In both d+Au and Au+Au, correlation functions were generated in 3-D and projected for \( q_{\text{side}} \), \( q_{\text{out}} \), and \( q_{\text{long}} \) in different centrality and \( k_T \) selections.

\[
C_2(q_{\text{side}}, q_{\text{out}}, q_{\text{long}}) = 1 + \lambda \exp\left(-R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2\right)
\]

- In both d+Au and Au+Au, correlation functions were generated in 3-D and projected for \( q_{\text{side}} \), \( q_{\text{out}} \), and \( q_{\text{long}} \) in different centrality and \( k_T \) selections.
- \((R_{\text{out}}, R_{\text{side}}, R_{\text{long}})\) were obtained and compared at similar \( N_{\text{part}} \) values in d+Au (central collisions) and Au+Au (peripheral collisions) for \( m_T \) dependence. The centrality dependence was also studied.

Excellent fits to the correlation functions found in both d+Au and Au+Au
HBT measurements in Au+Au: $N_{\text{part}}^{1/3}$ dependence

Au+Au collisions show a linear increase of HBT radii with an increase in $N_{\text{part}}^{1/3}$.
HBT measurements in Au+Au: $m_T$ dependence

Au+Au collisions show a systematic decrease of the HBT radii with an increase in $m_T$. This trend indicates a radially expanding source.
dependence of HBT radii in d+Au vs. Au+Au

- The $m_T$ dependence was studied for similar values of $N_{\text{part}}$ in d+Au and Au+Au

- Decreasing trend with $m_T$ in all HBT radii for both d+Au and Au+Au

- Similar trend found in Au+Au and Pb+Pb systems – indicative of an expanding source

- Fits done based on the blast wave model to extract: $R_{\text{geom}}$ – Geometrical radius at freeze-out $\tau_0$ – System lifetime

Freeze-out temperature and expansion velocities obtained from blast wave fit to $p_T$ spectra for identified charge hadrons: 
- d+Au: $T = 0.118 \pm 0.02; \beta = 0.42 \pm 0.03 \text{c}$
- Au+Au: $T = 0.123 \pm 0.02; \beta = 0.38 \pm 0.08 \text{c}$
The $m_T$ dependence for $R_{\text{out}}/R_{\text{side}}$ was also studied for similar values of $N_{\text{part}}$ in d+Au and Au+Au.

- Ratio found to be flat (close to unity).
- This trend suggests a system, both in d+Au and Au+Au, with a very short emission duration.
$m_T$ dependence of freeze-out volume: d+Au vs. Au+Au

- The freeze-out volume is proportional to $R_{\text{out}} \times R_{\text{side}} \times R_{\text{long}}$
- The d+Au freeze-out volume found to be smaller than Au+Au
- Fall-off with $m_T$ is comparable to that in Au+Au within systematic error

\[ \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \quad \pi^+\pi^+ \& \quad \pi^-\pi^- \]
\[ <N_{\text{part}}> = 16.7; \]
HBT studies of the collision geometry dependence of d+Au vs. Au+Au
The $N_{\text{part}}$ dependence of HBT radii: $d+Au$ vs. $Au+Au$

- The $N_{\text{part}}$ dependence was studied at the same average $k_T$.

- A similar linear increase with $N_{\text{part}}^{1/3}$ seen in $R_{\text{out}}$ and $R_{\text{side}}$ for both systems.

- A slight slope difference in $R_{\text{long}}$ could be from differences in longitudinal dynamics between $d+Au$ and $Au+Au$.

- Results suggest that strong correlation between transverse size and initial geometry common in $d+Au$ and $Au+Au$.

- Dependence of transverse expansion rate with collision geometry similar in the two systems.
$R_{\text{side}}$ vs. $R_{\text{bar}}$

- Expansion time ($\tau$) proportional to $R_{\text{bar}}$

  therefore

- $R_{\text{bar}}$ better scaling variable for HBT radii

- $R_{\text{side}}$ has linear relationship with $R_{\text{bar}}$ (so does $R_{\text{out}}$)

- Similar slopes for d+Au and Au+Au
  - Probably larger slope for Pb+Pb since stronger expansion rate at 2.76 TeV expected

This dependence emphasizes the role of final-state re-scattering effects in d+Au typical of a hydrodynamic evolution scenario.
Summary and Conclusion

- Two differing theories on the origin of the two-ridge structure in p+p and p+A systems
  1. Initial effects from interference of correlated gluons due to gluon saturation
  2. Final-state hydrodynamic effects

- HBT studies provide an independent check of existing models

- $m_T$ dependence of HBT radii shows decreasing trend with increase in $m_T$ for d+Au and Au+Au indicative of expanding source. $R_o/R_s$ is flat and about unity suggesting a short emission duration

- d+Au system also found to be smaller than Au+Au and with shorter lifetime

- Similar dependence of transverse expansion rate with collision geometry evident in both systems

- $R_{side}$ found to have linear relationship with $R_{bar}$ and a similar slope for both d+Au and Au+Au systems.

- Results strongly suggest that final-state re-scattering effects play important role in d+Au