Measurement of Quantum Interference of Two Identical Particles with respect to the Event Plane in Relativistic Heavy Ion Collisions at RHIC-PHENIX

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High Energy Nuclear Physics Group

TAC seminar, Dec 20th/2012
Introduction
- HBT Interferometry
- Motivation

Analysis
- PHENIX Detectors
- Analysis Method

Results & Discussion
- HBT measurement with respect to 2nd-/3rd-order event plane
- Blast-wave model

Summary
Introduction
Quark Gluon Plasma (QGP)

- State at a few µ-seconds after Big Bang
- Quarks and gluons are reconfined from hadrons

Probably here

- QGP will be created at extreme temperature and energy density

http://www.scientificamerican.com/
Relativistic Heavy Ion Collisions

- Relativistic Heavy Ion Collider is an unique tool to create QGP.
  - Brookhaven National Laboratory in U.S.A
  - Two circular rings (3.8 km in circumference)
  - Various energies: 19.6, 27, 39, 62.4, 200 GeV
  - Various species: p+p, d+Au, Cu+Cu, Cu+Au, Au+Au, U+U

<table>
<thead>
<tr>
<th>Year</th>
<th>Species/Energy</th>
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<tbody>
<tr>
<td>2001</td>
<td>Au+Au 130GeV</td>
</tr>
<tr>
<td>2002</td>
<td>Au+Au, p+p 200GeV</td>
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<tr>
<td>2003</td>
<td>d+Au 200GeV, p+p 20GeV</td>
</tr>
<tr>
<td>2004</td>
<td>Au+Au 200, 62.4GeV</td>
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<tr>
<td>2005</td>
<td>Cu+Cu 200, 62.4, 22.4GeV</td>
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<td>2006</td>
<td>p+p 200, 62.4GeV</td>
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<td>2007</td>
<td>Au+Au 200GeV</td>
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<tr>
<td>2008</td>
<td>d+Au, p+p 200GeV</td>
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<td>2009</td>
<td>p+p 200, 500GeV</td>
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<td>2010</td>
<td>Au+Au 200, 62.4, 39, 7.7GeV</td>
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<td>2011</td>
<td>Au+Au 200, 27, 19.6GeV</td>
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<tr>
<td>2012</td>
<td>U+U 193GeV, Cu+Au 200GeV</td>
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</tbody>
</table>

**Energy density**
- Lattice QCD calculation
  - $T_c \sim 170$ MeV
  - $\epsilon_c \sim 1$ GeV/fm$^3$
- Au+Au 200GeV @RHIC
  - $\epsilon_{Bj} \sim 5$ GeV/fm$^3 > \epsilon_c$
Space-Time Evolution

1. Collision occurs
2. Partonic thermalization
3. Phase transition
   Hadronization
4. Chemical freeze-out
5. Thermal freeze-out

How fast the system thermalizes and evolves?
How much the system size?
What is the nature of phase transition?
**HBT Interferometry**

- **HBT effect** is quantum interference between two identical particles.
- **R. Hanbury Brown and R. Twiss**
  - In 1956, they measured the angular diameter of Sirius.
- **Goldhaber et al.**
  - In 1960, they observed the correlations among identical pions in p+anti-p collision independent of HBT.

\[ C_2 = \frac{\left| \Psi_{12}(p_1, p_2) \right|^2}{\left| \Psi_1(p_1) \right|^2 \left| \Psi_2(p_2) \right|^2} \approx 1 + \left| \tilde{\rho}(q) \right|^2 \]

\[ = 1 + \lambda \exp(-\Delta r^2 q^2) \]

\[ q = p_1 - p_2 \quad [\text{GeV/c}] \]
What does HBT radii depend on?

- Centrality
  - HBT radii depends on the size of collision area.
- Average pair momentum $k_T$
  - Case of “static source”: measuring the whole size
  - Case of “expanding source”: measuring “homogeneity region”

\[
\vec{k}_T = \frac{1}{2}(\vec{p}_{T1} + \vec{p}_{T2})
\]

\[
\vec{q}_{out} \parallel \vec{k}_T, \vec{q}_{side} \perp \vec{k}_T
\]
Comparison of models and the past HBT results

Introduction

- STAR, Au+Au 200 GeV
- First-order phase transition with no prethermal flow, no viscosity
- Including initial flow
- Using stiffer equation of state
- Adding viscosity
- Including all features

PRL.102, 232301(2009)

Hydrodynamic model can reproduce the past HBT result!
HBT can provide constraints on the model!
HBT with respect to Reaction Plane

- Azimuthal HBT can give us the source shape at freeze-out.
- Final eccentricity is determined by initial eccentricity, pressure gradient (velocity profile) and expansion time etc.
Higher Harmonic Flow and Event Plane

- Initial density fluctuations cause higher harmonic flow $v_n$
- Azimuthal distribution of emitted particles:
  \[
  \frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2) + 2v_3 \cos 3(\phi - \Psi_3) + 2v_4 \cos 4(\phi - \Psi_4)
  \]
  \[
  v_n = \langle \cos n(\phi - \Psi_n) \rangle
  \]

$v_n$ : Strength of higher harmonic flow
$\Psi_n$ : Higher harmonic event plane plane
$\phi$ : Azimuthal angle of emitted particles
HBT vs Higher Harmonic Event Plane

- The idea is to expand azimuthal HBT to higher harmonic event planes.
  - may show the fluctuation of the shape at freeze-out.
  - provide more constraints on theoretical models about the system evolution.

Hydrodynamic model calculation

\[ R_{ij}^2, \text{fm}^2 \]

\[ \Psi_3 \]

S. Voloshin at QM2011

\[ T=100[\text{MeV}], \rho=r' \rho_{\max}(1+\cos(n\phi)) \]
Motivation

- Study the properties of time-space evolution of the heavy ion collision via azimuthal HBT measurement.
  - Measurement of charged pion/kaon HBT radii with respect to 2nd-order event plane, and Comparison of the particle species
  - Measurement of HBT radii with respect to 3rd-order event plane to reveal the detail of final state and system evolution.
# My Activity

<table>
<thead>
<tr>
<th>2006(M1)</th>
<th>2007(M2)</th>
<th>2010(D1)</th>
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</thead>
<tbody>
<tr>
<td>MRPC construction</td>
<td>RXNP construction</td>
<td>Di-jet Calorimeter construction</td>
</tr>
<tr>
<td>Installed MRPC &amp; RXNP</td>
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</tr>
</tbody>
</table>

3 years later

Azimuthal HBT analysis using Run4 data

Start azimuthal HBT analysis using Run7 data

<table>
<thead>
<tr>
<th>2011(D2)</th>
<th>2012(D3)</th>
</tr>
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<tbody>
<tr>
<td>Talk WPCF2011</td>
<td>Talk JPS fall</td>
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<tr>
<td>Talk JPS spring</td>
<td>Talk HIC in LHC era</td>
</tr>
<tr>
<td>Talk QM2012</td>
<td>Poster Radon Workshop</td>
</tr>
</tbody>
</table>

Summer Challenge @KEK

Summer Challenge @KEK

Shift taking & Detector Expert for Run11 @BNL

Shift taking & Detector Expert for Run12 @BNL

preliminary result
Centrality dependence of $\pi/K$ HBT w.r.t $\Psi_2$

preliminary result
Centrality dependence of $\pi$ HBT w.r.t $\Psi_3$

preliminary result
$m_T$ dependence of $\pi$ HBT w.r.t $\Psi_2$
Analysis
**PHENIX Detectors**

- **Beam-Beam Counter** \( |\eta| = 3\sim 4 \)
  - Quartz radiator + 64 PMTs

- **Central arms** \( |\eta| < 0.35 \)
  - DC, PCs, TOF, EMCAL

- **Reaction Plane Detector** \( |\eta| = 1\sim 2.8 \)
  - 2 rings of 24 scintillators

- **Zero Degree Calorimeter**
  - Spectator neutron energy

**Analysis**

- Minimum Bias Trigger
- Start time
- Collision z-position
- Centrality
- Event Planes
- Tracking, Momentum
- Particle Identification

**Diagram**

- Southern detector with a beam line and collision point
- Northern detector with a beam line and collision point
- Reaction plane detector indicated with a red ellipse

*Images of detector components shown:*
- Central arm setup
- Beam-Beam counter setup
- Reaction plane detector setup

Takafumi Nida, TAC seminar, Dec 20, 2012
Centrality

- Centrality is used to classify events instead of impact parameter.
  - 0% to 100% ↔ central to peripheral collision
- BBC measures charged particles coming from participant.
Event Plane

- Event plane was determined by Reaction Plane Detector
- Resolution: \( \langle \cos (n(\Psi_n - \Psi_{\text{real}})) \rangle \)
  - \( n=2 \): \( \sim 0.75 \)
  - \( n=3 \): \( \sim 0.34 \)
Track Reconstruction

- **Drift Chamber**
  - Momentum determination
  \[ p_T \sim \frac{K}{\alpha} \]
  - \( K \): field integral
  - \( \alpha \): incident angle

- **Pad Chamber (PC1)**
  - Associate DC tracks with hit positions on PC1

- **Outer detectors (PC3, TOF, EMCal)**
  - Extend the tracks to outer detectors
**Particle IDentification**

- **EMC-PbSc is used.**
  - Timing resolution ~ 600 ps

- **Time-Of-Flight method**
  
  \[ m^2 = p^2 \left( \left( \frac{ct}{L} \right)^2 - 1 \right) \]
  
  - \( p \): momentum
  - \( L \): flight path length
  - \( t \): time of flight

- **Charged \( \pi/K \) within 2\( \sigma \)**
  - \( \pi/K \) separation up to ~1 GeV/c
  - \( K/\rho \) separation up to ~1.6 GeV/c
Correlation Function

- Experimental Correlation Function $C_2$ is defined as:
  - $R(q)$: Real pairs at the same event.
  - $M(q)$: Mixed pairs selected from two different/similar events.

$$C_2 = \frac{R(q)}{M(q)}$$

$q = p_1 - p_2$

- $R(q)$ includes HBT effects, Coulomb interaction and detector inefficient effect, while $M(q)$ doesn’t include HBT, Coulomb.
3D HBT radii

- “Out-Side-Long” system
  - Bertsch-Pratt parameterization
  - LCMS (Longitudinal Center of Mass System) frame is used.

\[ C_2 = 1 + \lambda G \]
\[ G = \exp(-R_{inv}^2q_{inv}^2) \]
\[ = \exp(-R_{side}^2q_{side}^2 - R_{out}^2q_{out}^2 - R_{long}^2q_{long}^2 - 2R_{os}^2q_{side}q_{out}) \]

- \( \lambda \): chaoticity
- \( R_{side} \): transverse size
- \( R_{out} \): transverse size + emission duration
- \( R_{os} \): cross term between “out” and “side”
- \( R_{long} \): longitudinal size

\( R_{out} \) includes temporal information on emission duration of particles!
Pair Selection

- **Ghost Tracks**
  - A single particle is reconstructed as two tracks

- **Merged Tracks**
  - Two particles is reconstructed as a single track

**Distance of pion pairs at DC**

**Distance of pion pairs at EMC**

- Removed
- 1
- 1
Coulomb Interaction

- Coulomb repulsion for like-sign pairs reduces pairs at low-q.
  - Estimated by Coulomb wave function
    \[
    \left[ -\frac{\hbar^2 \nabla^2}{2\mu} + \frac{Z_1 Z_2 e^2}{r} \right] \Psi(r) = E \Psi(r) \quad \gamma = \frac{m e^2}{\hbar^2 q} Z_1 Z_2
    \]
- The correction was applied in fit function for \( C_2 \)
  - Core-Halo model
    \[
    C_2 = C_2^{\text{core}} + C_2^{\text{halo}}
    \]
    \[
    = N [\lambda (1 + G) F_{\text{coul}}] + [1 - \lambda]
    \]

\( F_{\text{coul}} \): Coulomb term
\( G \): Gaussian term
Correction of Event Plane Resolution

- Smearing effect by finite resolution of the event plane

- Resolution correction
  - correction for q-distribution

\[
A_{\text{corr}}(q, \Phi_j) = A_{\text{uncorr}}(q, \Phi_j) + 2\sum\zeta_{n,m}[A_c \cos(n\Phi_j) + A_s \sin(n\Phi_j)]
\]

\[
\zeta_{n,m} = \frac{n\Delta/2}{\sin(n\Delta/2)}(\cos(n(\Psi_m - \Psi_{\text{real}})))
\]

Event Plane Resolution

- original
- uncorrected
- corrected

Simulation
Results & Discussion
Azimuthal HBT w.r.t 2nd order event plane

Initial spatial eccentricity

Momentum anisotropy $v_2$

What is the final eccentricity?

Results & Discussion
Centrality dependence of pion HBT radii w.r.t. $\Psi_2$

- Oscillation are seen for $R_{\text{side}}$, $R_{\text{out}}$, $R_{\text{os}}$.
- $R_{\text{out}}$ has strong oscillation in all centrality.

\begin{itemize}
  \item Oscillation are seen for $R_{\text{side}}$, $R_{\text{out}}$, $R_{\text{os}}$.
  \item $R_{\text{out}}$ has strong oscillation in all centrality.
\end{itemize}
Centrality dependence of kaon HBT radii w.r.t $\Psi_2$

- charged kaons also have similar trends!
Eccentricity at freeze-out

- $\varepsilon_{\text{final}} \approx \varepsilon_{\text{initial}}/2$ for pion
  - This indicates that source expands to in-plane direction, and still elliptical shape.
  - PHENIX and STAR results are consistent.

- $\varepsilon_{\text{final}} \approx \varepsilon_{\text{initial}}$ for kaon
  - Kaon may freeze-out sooner than pion because of less cross section.
  - Due to the difference of $m_T$ between $\pi/K$?
**m_T dependence of \( \varepsilon_{\text{final}} \)**

\[
m_T = \sqrt{k_T^2 + m^2}
\]

- \( \varepsilon_{\text{final}} \) of pions increases with \( m_T \) in most/mid-central collisions
- Still difference between \( \pi/K \) in 20-60% even at the same \( m_T \)
  - Indicates sooner freeze-out time of K than \( \pi \)?
**$m_T$ dependence of relative amplitude**

- **Relative amplitude of $R_{out}$ in 0-20% doesn’t depend on $m_T$**
  - Does it indicate the difference of **emission duration** between in-plane and out-of-plane at low $m_T$?
Azimuthal HBT w.r.t 3rd order event plane

Initial spatial fluctuation

What is final shape?

- Note that no anisotropy is observed by HBT in static source.
Azimuthal HBT radii w.r.t $\Psi_3$

- $R_{\text{side}}$ is almost flat
- $R_{\text{out}}$ have a oscillation in most central collisions
Comparison of 2\textsuperscript{nd} and 3\textsuperscript{rd} order component

- In 0-10\%, $R_{\text{out}}$ have stronger oscillation for $\Psi_2$ and $\Psi_3$ than $R_{\text{side}}$
  
- This oscillation indicates different emission duration between 0°/60° w.r.t $\Psi_3$ or depth of the triangular shape?

Average of radii is set to “10” or “5” for w.r.t $\Psi_2$ and w.r.t $\Psi_3$

Results & Discussion
Relative amplitude of $R_{\text{side}}$

- Relative amplitude of $R_{\text{side}}$ w.r.t $\Psi_3$ is zero within systematic error.

$$R_s^2 \quad \quad \quad \quad R_{s,0}^2 \quad \quad \quad \quad R_{s,3}^2$$

$\varphi_{\text{pair}} - \Psi_3$

The width of the “homogeneity” seems to be the same between 0°/60° w.r.t $\Psi_3$ unlike the depth(+emission duration).

$
\varepsilon_{3,\text{final}} = 2 \frac{R_{s,3}^2}{R_{s,0}^2}
$

Results & Discussion
Blast wave model

- **Hydrodynamic model assuming radial flow**
  - Well described at low $p_T$ for spectra & elliptic flow
  - Expand to HBT: **PRC 70, 044907 (2004)**
  - Physical parameters are treated as free parameters.

7 free parameters

- $T_f$: temperature at freeze-out
- $\rho_0, \rho_2$: transverse rapidity
- $R_x, R_y$: transverse sizes (shape)
- $\tau_0, \Delta \tau$: system lifetime and emission duration

\[
\frac{dN}{d\tau} \sim \exp \left( -\frac{(\tau - \tau_0)^2}{2\Delta \tau^2} \right)
\]

Assuming a Gaussian distribution peaked at $\tau_0$ and with a width $\Delta \tau$, and source size doesn’t change with $\tau$.  

**PRC 70, 044907 (2004)**
Fit by Blast wave model

- Spectra and $v_2$ are used to reduce parameters.

In this model, $\Delta \tau$ doesn’t depend on azimuthal angle.

$R_{\text{out}}$ and $R_{\text{os}}$ doesn’t seem to be fitted well.

Need to plot the systematic error.

In this model, $\Delta \tau$ doesn’t depend on azimuthal angle.
Extracted freeze-out parameters

- Size($R_x, R_y$) and $R_y/R_x$ seem to be valid.
- $\tau$ and $\Delta \tau$ increases with going to centrality.
Summary

- **Azimuthal HBT radii w.r.t 2nd-order event plane**
  - Final eccentricity increases with increasing $m_T$, but not enough to explain the difference between $\pi/K$.
    - Difference may indicate faster freeze-out of $K^\pm$ due to less cross section.
  - Relative amplitude of $R_{out}$ in 0-20% doesn’t depend on $m_T$.
    - It may indicate the difference of emission duration between in-plane and out-of-plane.

- **Azimuthal HBT radii w.r.t 3rd-order event plane**
  - $R_{side}$ doesn’t seem to have azimuthal dependence.
  - While $R_{out}$ clearly has finite oscillation in most central collisions.
    - It may indicate the difference of emission duration between $\Delta\phi=0^\circ/60^\circ$ direction or depth of the triangular shape.

- **Balst wave model**
  - System lifetime and emission duration seems to get longer in central collisions.
Back up
Centrality dependence of $v_3$ and $\varepsilon_3$

- Weak centrality dependence of $v_3$
- Initial $\varepsilon_3$ has centrality dependence

---

Final $\varepsilon_3$ has any centrality dependence?
PHENIX Detectors

RXN in: $1.5 < |\eta| < 2.8$
& out: $1.0 < |\eta| < 1.5$

MPC: $3.1 < |\eta| < 3.7$

BBC: $3.0 < |\eta| < 3.9$

ZDC/SMD

dN/d\eta

Analysis
Image of initial/final source shape
Spatial anisotropy by Blast wave model

- **Blast wave fit for spectra & \( v_n \)**
  - Parameters used in the model
    - \( T_f \): temperature at freeze-out
    - \( \rho_0 \): average velocity
    - \( \rho_n \): anisotropic velocity
    - \( s_n \): spatial anisotropy
    - \( s_2 \) and \( s_3 \) correspond to final eccentricity and triangularity
    - \( s_2 \) increase with going to peripheral collisions
    - \( s_3 \) is almost zero
  - Similar results with HBT

- Initial vs Final spatial anisotropy

Poster, Board #195
Sanshiro Mizuno
Relative amplitude of HBT radii

- Relative amplitude is used to represent “triangularity” at freeze-out
- Relative amplitude of $R_{out}$ increases with increasing $N_{part}$

$\star$ Triangular component at freeze-out seems to vanish for all centralities (within systematic error)
Charged hadron $v_n$ at PHENIX

- $v_2$ increases with increasing centrality, but $v_3$ doesn’t
- $v_3$ is comparable to $v_2$ in 0-10%
- $v_4$ has similar dependence to $v_2$
\( v_3 \) breaks degeneracy

\[
\begin{align*}
\text{(a) } p_T &= 0.75-1.0 \text{ GeV/c} \\
\text{(b) } p_T &= 1.75-2.0 \text{ GeV/c} \\
\text{(c) } p_T &= 0.75-1.0 \text{ GeV/c} \\
\text{(d) } p_T &= 1.75-2.0 \text{ GeV/c}
\end{align*}
\]

- \( v_3 \) provides new constraint on hydro-model parameters
  - Glauber & \( 4\pi \eta/s=1 \) : works better
  - KLN & \( 4\pi \eta/s=2 \) : fails
Azimuthal HBT radii for kaons

- Observed oscillation for $R_{\text{side}}$, $R_{\text{out}}$, $R_{\text{os}}$
- Final eccentricity is defined as $\varepsilon_{\text{final}} = 2R_{s,2} / R_{s,0}$
  \[ R_{s,n}^2 = \langle R_{s,n}^2 (\Delta \phi) \cos(n\Delta \phi) \rangle \]  
  PRC70, 044907 (2004)

\[ \lambda_{3D} \]
PHENIX Preliminary

\[ R_{\text{os}}^2 \]

Au+Au 200GeV $K^+K^+K^-K^-$
- 0-20%
- 20-60%

@WPCF2011
$k_T$ dependence of azimuthal pion HBT radii in 20-60%

- Oscillation can be seen in $R_s$, $R_o$, and $R_{os}$ for each $kT$ regions
$k_T$ dependence of azimuthal pion HBT radii in 0-20%
The past HBT Results for charged pions and kaons

- Centrality / $m_T$ dependence have been measured for pions and kaons
  - No significant difference between both species

![Graphs showing centrality and $m_T$ dependences for charged pions and kaons]
Analysis method for HBT

- **Correlation function**
  \[ C_2 = \frac{R(q)}{M(q)} \]
  - Ratio of real and mixed q-distribution of pairs
  - q: relative momentum

- **Correction of event plane resolution**

- **Coulomb correction and Fitting**
  - By Sinyukov’s fit function
  - Including the effect of long lived resonance decay
  \[ C_2 = C_2^{\text{core}} + C_2^{\text{halo}} \]
  \[ = N[\lambda(1 + G)F] + [1 - \lambda] \]
  \[ G = \exp(-R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2 - 2R_{\text{os}}^2 q_{\text{side}} q_{\text{out}}) \]
Azimuthal HBT radii for pions

- Observed oscillation for $R_{\text{side}}$, $R_{\text{out}}$, $R_{\text{os}}$
- Rout in 0-10% has oscillation
  ✧ Different emission duration between in-plane and out-of-plane?

![Graphs showing oscillations in Rside, Rout, Rlong and λ_3D for PHENIX and PHENIX Preliminary](image)
Model predictions

Blast-wave model

\[ T = 100 \text{[MeV]}, \quad \rho = r' \rho_{\text{max}} (1 + \cos(n\phi)) \]

Both models predict weak oscillation will be seen in \( R_{\text{side}} \) and \( R_{\text{out}} \).