Azimuthal angle dependence of HBT radii in Au+Au collisions at RHIC-PHENIX

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Quark Gluon Plasma (QGP)

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

QGP will be created at extreme temperature and energy density

Relativistic heavy ion collisions is a unique way to study the QGP

from BNL web site

http://www.scientificamerican.com/
Space-time extent at freeze-out reflects the properties of system evolution, such as the phase transition, hydrodynamic expansion and hadron rescattering etc.

HBT interferometry is a powerful tool to study the space-time evolution in Heavy Ion collisions.
HBT Interferometry

- R. Hanbury Brown and R. Twiss
  - In 1956, the angular diameter of Sirius was measured.
- Goldhaber et al.
  - In 1960, correlation among identical pions in p+p collision was observed.
- Quantum interference between two identical particles

Wave function for 2 bosons (fermions):
\[ \Psi_{12} = \frac{1}{\sqrt{2}} [\Psi(x_1, p_1)\Psi(x_2, p_2) \pm \Psi(x_2, p_1)\Psi(x_1, p_2)] \]

Spatial distribution \( \rho \):
\[ \rho(r) \sim \exp(-\frac{r^2}{2R^2}) \]

\[ C_2 = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \approx 1 + |\tilde{\rho}(q)|^2 = 1 + \exp(-R^2 q^2) \]
Azimuthal angle dependence

- HBT w.r.t Reaction Plane give us source shape at freeze-out.
  - R.P defined by beam axis and vector between centers of colliding nuclei
- Final eccentricity is determined by initial eccentricity, velocity profile and expansion time etc.
  - Initial anisotropy causes momentum anisotropy

\[ R_{\text{in-plane}} > R_{\text{out-of-plane}} \]

\[ R_{\text{in-plane}} = R_{\text{out-of-plane}} \]
Higher Harmonic Flow and Event Plane

- Initial density fluctuations cause higher harmonic flow $v_n$
- Azimuthal distribution of emitted particles:

\[
\frac{dN}{d\phi} \propto 1 + 2v_2\cos(2(\phi - \Psi_2)) + 2v_3\cos(3(\phi - \Psi_3)) + 2v_4\cos(4(\phi - \Psi_4))
\]

$v_n$: strength of higher harmonic flow
$\Psi_n$: higher harmonic Event plane
$\phi$: azimuthal angle of emitted particles

What is final shape?
3D HBT radii

“Out-Side-Long” frame

- Bertsch-Pratt parameterization
- Longitudinal Center of Mass System \( (p_{z1}=p_{z2}) \)

\[ C_2 = 1 + \lambda G \]
\[ G = \exp\left( -R^2 q^2 \right) \]
\[ = \exp\left( -R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2 - \Delta \tau^2 q_0^2 \right) \]
\[ \approx \exp\left( -R_{\text{side}}^2 q_{\text{side}}^2 - \left( R_{\text{out}}^2 + \beta T \Delta \tau^2 \right) q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2 \right) \]
\[ = R_{\text{out}}^2 \]
\[ G = \exp\left( -R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{long}}^2 q_{\text{long}}^2 - 2R_{\text{os}} q_{\text{side}} q_{\text{out}} \right) \]

\( \lambda \) : chaoticity
\( R_{\text{side}} \) : transverse HBT radius
\( R_{\text{out}} \) : transverse HBT radius + \( \Delta \tau \) (emission duration)
\( R_{\text{long}} \) : longitudinal HBT radius
\( R_{\text{os}} \) : cross term for \( \phi \)-dependent analysis
HBT radii w.r.t 2nd-order event plane

\[ R_{s,n} = \langle R_s^2(\Delta \phi) \cos(n\Delta \phi) \rangle \]

\[ \varepsilon_{\text{final}} = 2R_{s,2}^2/R_{s,0}^2 \]

- \( \varepsilon_{\text{final}} \approx \varepsilon_{\text{initial}}/2 \) for pion
  - expansion to in-plane, but still elliptical at freeze-out
  - consistent with STAR experiment
- \( \varepsilon_{\text{final}} \approx \varepsilon_{\text{initial}} \) for kaon
  - emission region we’re looking at is different?
**m_T dependence**

- HBT does not measure the whole size but the emission region for expanding source
  - HBT radii depend on pair transverse momentum mass m_T
  - Kaon has higher m_T than pion
- R_{s,2}^2/R_{s,0}^2 shows difference even at the same m_T in 20-60%
  - m_T scaling works well for average radius of π/K (PRL103.142301(2009))
  - Different freeze-out dynamics for both species?

**Diagram:**

- Graph showing 2R_{s,2}^2/R_{s,0}^2 and -2R_{0,2}^2/R_{0,0} vs. \langle m_T \rangle [GeV/c]
- PHENIX Preliminary: Au+Au 200GeV

\[ m_T = \sqrt{k_T^2 + m^2} \]
**HBT radii w.r.t 3\textsuperscript{rd}-order event plane**

- **$R_{\text{out}}$** clearly shows a finite oscillation w.r.t $\Psi_3$ in most central event
  - Strength w.r.t $\Psi_3$ is comparable to w.r.t $\Psi_2$
- **What make this $R_{\phi}$ oscillation?**
  - Triangular spatial shape?
  - Triangular flow?
    - $v_3$ is comparable to $v_2$ in most central
  - Emission duration?

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**PHENIX**

preliminary

Au+Au 200GeV 0-10%

- $\pi^+\pi^+\pi^-\pi^-$
  - $w.r.t \Psi_2$
  - $w.r.t \Psi_3$

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

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PRL.107.252301
Centrality dependence of relative amplitudes

- Oscillation of $R_s$ shows is almost zero within systematic error
  ✶ Slightly negative value in peripheral ?
- $R_o$ has finite oscillation except peripheral event
Possible explanation of $R_\circ$ oscillation

- HBT w.r.t $\Psi_3$ with toy model have been reported in arXiv:1306.1485[nucl-ex] (2013)
  - assuming Gaussian source with triangular geometric deformation and triangular flow

**triangular** source
- without flow anisotropy
- spherical source
- with flow anisotropy

- Close to “flow dominated” case?
- Need to check the $k_T$ dependence to constraint $\varepsilon_3/\beta_3$
Summary

- Azimuthal angle dependence of HBT radii with respect to 2\textsuperscript{nd}- and 3\textsuperscript{rd}-order event plane have been presented.
  - Final eccentricity of kaons shows higher value than that of pion even at the same \( m_T \)
  - Oscillation of \( R_o \) w.r.t \( \Psi_3 \) have been observed in most central event, while \( R_s \) doesn't show any signal beyond systematic error
    - \( R_o \) oscillation may be explained by triangular flow

Outlook

- \( k_T \) dependence of oscillation amplitudes w.r.t \( \Psi_3 \) will be measured, which will provides us information on the relative magnitude of geometrical and flow anisotropy
Back up
PHENIX Detectors

✫ Particle Identification by EMCal
✦ π/K separation up to ~1GeV
✫ Centrality by Beam-Beam Counter
✦ measure charge sum from participants
✫ Event plane $\Psi_n$ determined by RxNP
✦ $\text{Res}(\Psi_2) \sim 0.75$, $\text{Res}(\Psi_3) \sim 0.32$

Reaction Plane Detector (RxNP)

24 scintillator segments

beam axis

$\Psi_n = \frac{1}{n} \tan^{-1} \left( \frac{\sum w_i \cos(n\phi_i)}{\sum w_i \sin(n\phi_i)} \right)$

$\text{Res}(\Psi_n) = \langle \cos n(\Psi_n(\text{meas}) - \Psi_n(\text{true})) \rangle$

Residential Energy Distribution

- n=2 RXN
- n=3 RXN
- n=4 RXN
- n=2 MPC
- n=3 MPC
PHENIX Detectors

\[ C_2 = \frac{R(q)}{M(q)} \]

*R(q), M(q)*: relative momentum dist. for real and mixed pairs

** \( \gg \) ** PID by EMC&TOF

- charged \( \pi/K \) are selected

** \( \star \) ** \( \Psi_n \) by forward detector RXN
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
    - $p_z$ is determined

- Outer detectors (PC3, TOF, EMCaI)
  - 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 \(\pi/\text{K}\) within 2\(\sigma\)**
  - ♦ \(\pi/\text{K}\) separation up to \(~1\) GeV/c
  - ♦ \(\text{K}/\rho\) 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 different events.

  Event mixing was performed using events with similar z-vertex, centrality, E.P.

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

  $q = p_1 - p_2$

  - Real pairs include HBT effects, Coulomb interaction and detector inefficient effect.
  - Mixed pairs doesn’t include HBT and Coulomb effects.

  $C_2 = R/M$

relative momentum dist.

HBT effect
Coulomb repulsion
m_T dependence of $\varepsilon_{\text{final}}$

- $\varepsilon_{\text{final}}$ of pions increases with m_T in most/mid-central collisions
- There is still difference between $\pi$/$K$ for mid-central collisions even in same m_T
- Indicates sooner freeze-out time of K than $\pi$?
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?
Azimuthal HBT radii w.r.t $\Psi_3$

- $R_{\text{side}}$ is almost flat
- $R_{\text{out}}$ have a oscillation in most central collisions

PHENIX Preliminary
Au+Au 200GeV $\pi^+\pi^+$ & $\pi^0\pi^-$

- 0-10%
- 10-20%
- 20-30%
- 30-60%
Image of initial/final source shape
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 $v_2$
The past HBT Results for charged pions and kaons

- Centrality / $m_T$ dependence have been measured for pions and kaons
  - higher transverse mass $m_T$ for kaons leads to smaller radii compared to pions
    - pion $<m_T> \sim 0.47$ GeV/c
    - kaon $<m_T> \sim 0.89$ GeV/c
  - $m_T$ scaling works well
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 $R_{\text{side}}$, $R_{\text{out}}$, $R_{\text{long}}$, and $R_{\text{os}}$](image-url)
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)