Azimuthal angle dependence of HBT radii with respect to the Event Plane in Au+Au collisions at PHENIX

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Space-time extent at freeze-out reflects the characteristics of system evolution, such as the strength of the expansion, the expansion time, hadron rescattering, and so on.

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

- 1956s, R. Hanbury Brown and R. Twiss measured the angular diameter of Sirius.
- 1960, Goldhaber et al. correlation among identical pions in p+\(\bar{p}\)
- Quantum interference between two identical particles

\[
\Psi_{12} = \frac{1}{\sqrt{2}} [\Psi(x_1, p_1)\Psi(x_2, p_2) \pm \Psi(x_2, p_1)\Psi(x_1, p_2)]
\]

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

Spatial distribution \(\rho\)

\[
\rho(r) \sim \exp\left(-\frac{r^2}{2R^2}\right)
\]

\(\sim 1/R\)
Azimuthal angle dependence

- Angle dependence of HBT radii relative to Reaction Plane reflects the source shape at kinetic freeze-out.
- Initial spatial anisotropy causes momentum anisotropy (flow anisotropy)
  - One may expect in-plane extended source at freeze-out
- Final source eccentricity will depend on initial eccentricity, flow profile, expansion time, and viscosity etc.
HBT radii w.r.t Reaction Plane at RHIC

\[ R_{s,n}^2 = \langle R_{s,n}^2 (\Delta \phi) \rangle \cos^2 \theta \]  
\[ \varepsilon_{\text{final}} = 2 \frac{R_{s,2}^2}{R_{s,0}^2} \]

- \( \varepsilon_{\text{final}} \approx \varepsilon_{\text{initial}}/2 \)
- Strong expansion to in-plane, but still elliptical shape.
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
$\phi$ : azimuthal angle of emitted particles
**Centrality dependence of \( v_n \) and initial \( \varepsilon_n \)**

Higher harmonic flow \( v_n \)

![Graph showing higher harmonic flow](Image)

**Initial source anisotropy \( \varepsilon_n \)**

![Graph showing initial source anisotropy](Image)

- Weak centrality dependence of \( v_3 \) unlike \( v_2 \)
- Initial \( \varepsilon_3 \) has finite values and weaker centrality dependence than \( \varepsilon_2 \)
- Triangular component in source shape exists at final state?
  - Measurement of HBT radii relative to \( \Psi_3 \)
Beam line

Central Arm & Magnet
Event Plane Determination

Determined by anisotropic flow itself

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

Event plane is determined by Reaction Plane Detector (RXNP)

 Resolution: \( <\cos(n(\Psi_n - \Psi_{\text{real}}))> \)
- \( n=2 : \sim 0.75 \)
- \( n=3 : \sim 0.34 \)
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 \( \pi \) within 2\( \sigma \)
  - ♦ \( \pi/K \) separation up to ~1 GeV/c

EMC here!

Phenix Detector

Particle Identification by PbSc-EMC

Mass square

Momentum × charge
3D-Analysis

- “Out-Side-Long” frame
  - Bertsch-Pratt parameterization
  - Longitudinal Center of Mass System ($p_{z1}=p_{z2}$)

$C_2 = 1 + \lambda G$

$\lambda$ : chaoticity  $R_\mu$ : HBT radii

$G = \exp(-R^2q^2)$

$= \exp(-R_x^2q_x^2 - R_y^2q_y^2 - R_z^2q_z^2 - \Delta \tau^2 q_0^2)$

$= \exp(-R_s^2q_s^2 - R_o^2q_o^2 - R_l^2q_l^2 - \Delta \tau^2 q_0^2)$

$L^\text{LCMS}$

$\approx \exp(-R_s^2q_s^2 - (R_o^2 + \beta_T^2 \Delta \tau^2)q_o^2 - R_l^2q_l^2)$

$= R_o^2$

including cross term

$G = \exp(-R_s^2q_s^2 - R_o^2q_o^2 - R_l^2q_l^2 - 2R^2 q_s q_o)$

- Core-Halo model

$C_2 = C_2^{\text{core}} + C_2^{\text{halo}}$

$= N[\lambda(1 + G)F_{\text{coul}}] + [1 - \lambda]$

$N$: normalization factor
$F_{\text{coul}}$: Coulomb correction factor
Correction of Event Plane Resolution

- Smearing effect by finite resolution of the event plane

- Correction for q-distribution


PRC.66, 044903(2002)

- model-independent correction

- Checked by MC-simulation

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

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

Strengthened by finite resolution of the event plane

Smeared

Corrected!
HBT radii w.r.t 3rd-order event plane

- $R_o$ clearly shows a finite oscillation w.r.t $\Psi_3$ in most central event, while $R_s$ does not show such a oscillation.

- What makes this $R_o$ oscillation?

  - $\Delta \tau$ depends on azimuthal angle?
  - $R_o$ is sensitive to $\Delta \tau$ & $\beta_T$
  - $C_2 = 1 + \lambda \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_o q_s)$
  - $R_o^2 = R_o^*^2 + \beta_T^2 \Delta \tau^2$

  - effect of flow anisotropy?
  - difference of “width” and “thickness”?
Possible explanation

- HBT radii w.r.t $\Psi_3$ with Gaussian model
  ✨ C. Plumberg et al., PRC88, 044914 (2013)
  ✨ Next talk: C. Plumberg

- with/without triangularly deformed flow/geometry

- “Deformed flow” shows finite $R_o$ oscillation and very small $R_s$ oscillation

- Qualitatively agreement with the data seen in most-central collisions
k_T dependence of HBT radii w.r.t. Ψ_3

- Charged pions in Au+Au 200 GeV
  - 20-60% centrality
  - 5 k_T bins within 0.2-1.5 GeV/c
- Fitted with the following Eq.:
  \[
  R_{\mu}^2 = R_{\mu,0}^2 + 2R_{\mu,3}^2 \cos[3(\phi - \Psi_3)] \\
  R_{os}^2 = 2R_{os,3}^2 \sin[3(\phi - \Psi_3)]
  \]
  \[\mu = s, o, l\]
- No clear k_T dependence for R_s
- Same sign of the R_o oscillation in all k_T bins
$m_T$ dependence of 3$^{rd}$-order oscillation amplitudes

- $R_{s,3}^2$ are around zero, and does not show any clear $m_T$ dependence.
- $R_{o,3}^2$ has finite negative values in both centrality.
  - In 20-60%, it seems to decrease with $m_T$. 

![Graph showing $R_{s,3}^2$ and $R_{o,3}^2$ versus $<m_T>$]
Comparison with the 3\textsuperscript{rd}-order Gaussian model

- Trend of $R_{o,3}^2$ seems to be explained by “deformed flow” in both centralities.
  - Note that model curves are scaled by 0.3 for the comparison with the data
- $R_{s,3}^2$ seems to show a slight opposite trend to “deformed flow”.
  - Zero~negative value at low $m_T$, and goes up to positive value at higher $m_T$
- Contribution from spatial anisotropy seems to be small.
Time evolution of spatial anisotropy

- **MC-KLN + Hydrodynamic model**
  - Parameters are not tuned.
- **15-20% centrality**

**Graphs:**
- Inflection points represent that the \(n^{\text{th}}\)-order deformation of the source turns over.
- Interesting that \(\varepsilon_3\) turns over earlier than \(\varepsilon_2\).
Summary

- Azimuthal angle dependence of HBT radii with respect to 3rd-order event plane have been presented.
  - Finite oscillation of $R_o^2$ and very weak oscillation of $R_s^2$ seen in most central event may be explained by the triangular flow anisotropy rather than spatial anisotropy.
  - $R_{o,3}^2$ shows a monotonic decrease with $m_T$.
    - Similar trend to “deformed flow” model
  - $R_{s,3}^2$ does not show any clear $m_T$ dependence, but seems to have opposite trend to “deformed flow” model.
- The result indicate that initial triangularity may be significantly diluted.
Thank you for your attention!