HBT measurement with respect to event plane in Pb-Pb at 2.76TeV collisions from ALICE

2016.Sep.23
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JPS meeting @ University of Miyazaki
Space time evolution and azimuthal anisotropy

A powerful probe of hydrodynamic evolution

Azimuthal anisotropy

\[ v_n = \langle \cos [n (\phi - \Psi_n)] \rangle \]

Event plane

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

Source shape @ freeze out

- A lot of parameters contributes to the final source shape
- Initial eccentricity, collective flow, evolution time and viscosity
- To quantify the properties of QGP, a precise understanding of spatial and temporal evolution is required
Method to measure the source size with two identical particles

- Quantum interference between two identical particles
- **Unique tool** to measure source size at kinetic freeze out
- Geometrical source size ≠ HBT radii = “Length of homogeneity”

\[ C_2(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \]

\[ C_2(q) = 1 + \lambda \exp(-R^2q^2) \]

3D HBT analysis

Bertsch Pratt parametrization

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

- \( R_{long} \): source size along the longitudinal direction (beam direction)
- \( R_{out} \): source along the pair transverse momentum + emission duration
- \( R_{side} \): source size along the perpendicular to \( R_{out} \)
- \( \lambda \): chaoticity = (in coherence) – (resonance) – (Background)
Azimuthally sensitive HBT with respect to $\Psi_2$

- Dividing the pair angle relative to the $\Psi_2$ in azimuthal plane
- Differential azimuthal angle HBT measurements explores spatial deformation of the source
- Hydrodynamical model shows oscillation in azimuthal angle dependence of HBT radii (out-of-plane extended source shape)

Hydrodynamic model
Au+Au 130GeV

Azimuthal angle dependence of HBT radii

nucl-th/0305084

Azimuthally sensitive HBT gives us more detailed information of space-time evolution
Azimuthal angle dependence of HBT w.r.t. $\Psi_2$

- $R_{\text{out}}$ has explicit oscillation and $R_{\text{side}}$ has weak oscillation
- $R_{\text{out}}$ and $R_{\text{side}}$ oscillate out-of-phase
  - Initial elliptic shape still remains at freeze out (out-of-plane extended source)
  - Fit function
    - $R^2_{\mu,0} + 2R^2_{\mu,n} \cos(n(\Phi_{\text{pair}} - \Psi_n))$
    - $R^2_{\mu,0}$: Average HBT radii
    - $R^2_{\mu,n}$: $n$th order Oscillation

- Final source eccentricity is obtained by relative amplitude from Blast Wave model
  - (Phys. Rev. C 70, 044907)
  - The magnitude of $R_{\text{out}} R_{\text{side}}$ relative amplitude decreases from central to peripheral collisions

- $R^2_{\text{out,2}} / R^2_{\text{side,0}}$
  - Final source eccentricity
    - $\varepsilon_{\text{final}} = 2 R^2_{\text{side,2}} / R^2_{\text{side,0}}$

- Contributing factors to $\varepsilon_{\text{final}}$
  - initial geometry
  - collective flow
  - freeze out time
Triangular deformation via HBT

- **AMPT and Blast wave model** (S. Voloshin, J. Phys. G38, 124097)
  - HBT w.r.t. $\Psi_3$ shows finite oscillation in expanding source, but almost no oscillation in static source

- **HBT w.r.t. $\Psi_3$ measured @ PHENIX Au+Au 200GeV** (Phys.Rev.Lett. 112 222301)
  - Same oscillation sign of $R_{out}$ and $R_{side}$ → Relative amplitude negative value

- **HBT w.r.t. $\Psi_3$ in LHC energy**
  - Difference between RHIC and LHC
    - Larger radial flow & evolution duration
    - Viscosity
  - Hydrodynamic model (P. Bozek, J. Phys. G38, 124097)
    - Relative amplitude of $R_{side}$ is negative
    - Triangular deformation is washed-out or even reversed
In this analysis

- **VZERO**
  - Trigger & centrality
  - $V0_A : 2.8 < \eta < 5.1$
  - $V0_C : -3.7 < \eta < -1.7$

- **TPC & ITS**
  - Tracking & PID
  - Vertex
  - $|\eta_{\text{track}}| < 0.8$

- **TOF**
  - PID
  - $|\eta_{\text{track}}| < 0.8$

- **FMD**
  - Event plane
  - $FMD_A : 1.7 < \eta < 5.0$
  - $FMD_C : -3.4 < \eta < -1.7$
Event plane via FMD

The FMD Detector
- Silicon strip detector
- 3 sub detector: FMD1, FMD2, FMD3
- 2 types of rings: inner and outer
  - inner: 20 sectors (0 < φ < 2π)
  - outer: 40 sectors (0 < φ < 2π)

Event plane resolution
- Event plane resolution are extracted with 3 sub event method

\[
\text{Res} \{\Psi_n\} = \sqrt{\frac{\langle \cos(n(\Psi^A_n - \Psi^B_n)) \rangle}{\langle \cos(n(\Psi^A_n - \Psi^C_n)) \rangle}}
\]

FMD event plane and HBT measurement
- 3rd order harmonics, FMD resolution is approximately 15% better than V0
  - This excellent resolution allows us precise measurement of higher order event plane
- Rapidity gap between HBT measurement and E.P. is |Δη| > 0.9
  - HBT → Mid-rapidity (-0.8 < η < 0.8)
  - Event Plane → Forward rapidity (-3.4 < η < -1.7, 1.7 < η < 5.0)
Analysis method for HBT

- 2.76 TeV Pb-Pb collisions
- Particle Identification
  - Charged pions are identified with TPC and TOF combined PID
- Correlation function
  \[ C_2 = \frac{R(q)}{M(q)} \]
  - R(q) : real pairs
  - M(q) : mixed pairs (made by event mixing)
  - q : relative momentum
- Event mixing class
  - Event with similar centrality, Z-vertex and \( \Psi_3 \) angle are used
- Fit function
  \[ C_2 = N \left[ (1 - \lambda) + \lambda K_c \left(1 + \exp \left(G\right)\right)\right] \]
  \[ G = -R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2 - R_{os}^2 q_{out} q_{side} - R_{ol}^2 q_{out} q_{long} - R_{sl}^2 q_{side} q_{long} \]
  ✓ K_c is Coulomb correction factor
- Event plane
  - \( \Psi_3 \) is determined via FMD (1.7 < \( \eta \) < 5.0, -3.4 < \( \eta \) < -1.7)
- Momentum resolution correction
  - Estimated with HIJING and GEANT
Azimuthal angle dependence of HBT w.r.t. $\Psi_3$

**Fit function**

$$R^{2}_{\mu,0} + 2 R^{2}_{\mu,3} \cos(3(\varphi_{\text{pair}} - \Psi_3))$$

- $R^{2}_{\mu,0}$: Average HBT radii
- $R^{2}_{\mu,3}$: Oscillation amplitude

**Average HBT radii**
- ✓ centrality dependence

**Azimuthal angle dependence**
- ✓ $R_{\text{out}}$ has explicit oscillation
- ✓ $R_{\text{side}}$ has small oscillation
- ✦ $R_{\text{out}}$ and $R_{\text{side}}$ oscillate in-phase
  - unlike HBT w.r.t. $\Psi_2$
- ✓ $R_{\text{long}}$ and $\lambda$ have no oscillation
- ✓ Small centrality dependence
  - similar to $v_3$

**Pb-Pb 2.76TeV in ALICE**

Charged pion pair
(-0.8 < $\eta$ < 0.8)

Event plane is determined with FMD

- ALICE work in progress
Initial $\varepsilon_3$ vs Relative amplitude

- $R^2_{\text{out,3}} / R^2_{\text{out,0}}$
  - Relative amplitude of $R^2_{\text{out}}$ is positive
  - $-2R^2_{\text{out,3}} / R^2_{\text{out,0}}$ increase with increasing initial $\varepsilon_3$

- $R^2_{\text{side,3}} / R^2_{\text{side,0}}$
  - Relative amplitude of $R^2_{\text{side}}$ is negative ($\varepsilon_{\text{initial}} < 0.25$)
  - No centrality dependence can be seen

- $R^2_{\text{long,3}} / R^2_{\text{long,0}}$
  - Relative amplitude of $R^2_{\text{long}}$ has almost no amplitude
**Hydrodynamic model comparison**

**ALICE Pb-Pb 2.76TeV**

- $R^2_{\text{side,3}} / R^2_{\text{side,0}}$
  - $N_{\text{part}}$ dependence of $R^2_{\text{side,3}} / R^2_{\text{side,0}}$ can be reproduced by 3+1D hydrodynamic model within the systematic uncertainty
  - $R^2_{\text{out,3}} / R^2_{\text{side,0}}$ and $R^2_{\text{os,3}} / R^2_{\text{side,0}}$ will be compared with hydrodynamic model
  - Need $k_T$ dependence !!

**3+1D Hydrodynamic model**

- $R^2_{\text{side,3}} / R^2_{\text{side,0}}$
  - $0.2 < k_T < 2.0$
  - ALICE work in progress

(P. Bozek, J. Phys. G38, 124097)
Summary

✧ Azimuthal angle dependence of HBT radii w.r.t. Ψ₃
  • $R_{\text{out}}$ and $R_{\text{side}}$ oscillate in-phase
  • Explicit oscillation of $R_{\text{out}}$ and small oscillation of $R_{\text{side}}$ can be seen
  • $R_{\text{long}}$ and $\lambda$ have almost no oscillation

✧ Relative amplitude of squared HBT radii
  • $-2R_{\text{out},3}^2/R_{\text{out},0}^2$ is positive in centrality 10-50% and small centrality dependence
  • $2R_{\text{side},3}^2/R_{\text{side},0}^2$ is negative in centrality 10-40%

✧ Hydro dynamical model comparison
  • Bozek $R_{\text{side},3}^2/R_{\text{side},0}^2$ calculation shows good agreement within Syst. error

Outlook

✧ Azimuthal angle dependence of HBT w.r.t. Ψ₃ in centrality 0-10% is ongoing
✧ $k_T$ dependence of HBT w.r.t. Ψ₃ for more precise understanding
✧ Azimuthally sensitive HBT with Event shape engineering (J. Schukraft et al., arXiv:1208.4563)
  ✓ Selecting of event by event $v_n$ by the magnitude of flow vector
  ➡ Impact on final source shape by larger triangular flow (initial $\varepsilon_3$)
Backup

\[ N(q, \phi_j) = N_{\text{exp}}(q, \phi_j) + 2 \sum_{n=1}^{n_{\text{bins}}} \xi_{n,m}(\Delta) \left[ N_{c,n}^{\text{exp}}(q) \cos(n\phi_j) + N_{s,n}^{\text{exp}}(q) \sin(n\phi_j) \right] \]

\[ N_{c,n}^{\text{exp}}(q) \cos(n\phi_j) = \langle N_{\text{exp}}(q, \phi_j) \cos(n\phi) \rangle = \frac{1}{n_{\text{bins}}} \sum_{n=1}^{n_{\text{bins}}} N_{\text{exp}}(q, \phi_j) \cos(n\phi_j) \]

\[ N_{s,n}^{\text{exp}}(q) \sin(n\phi_j) = \langle N_{\text{exp}}(q, \phi_j) \sin(n\phi) \rangle = \frac{1}{n_{\text{bins}}} \sum_{n=1}^{n_{\text{bins}}} N_{\text{exp}}(q, \phi_j) \sin(n\phi_j) \]

\[ \xi_{n,m}(\Delta) = \frac{n\Delta/2}{\sin(n\Delta/2) \left( \cos \left( n \left( \Psi_n^m - \Psi_n^{\text{true}} \right) \right) \right)} \]

**Event plane resolution correction**

- correction for q-distribution with EP resolution