Azimuthally differential pion femtoscopy relative to the second and third harmonic in Pb-Pb 2.76 TeV collisions from ALICE

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Outline

- Introduction
- ALICE at LHC
- Azimuthal HBT:
  - second harmonic
  - third harmonic
  - Event shape engineering
- Summary

arXiv:1702.01612
**Introduction: HBT**

- **HBT**: Hanbury Brown and Twiss \(^1\)
- A very powerful tool to study the source space-time extension in heavy-ion collisions

### Theory

\[
C(q) = 1 + \exp(-R_{inv}^2 q_{inv}^2)
\]

- \(q_{inv} = \sqrt{|\vec{q}|^2 - q_0^2}\)
- \(q_0 = E_1 - E_2\)
- \(\vec{q} = \vec{p}_1 - \vec{p}_2\)

### Experiment

\[
C(q) = \frac{A(q)}{B(q)}
\]

- \(A(q)\) is the measured (same-event) pair distribution in relative momentum
- \(B(q)\) is the measured (mixed-event) pair distribution in relative momentum

The source size is inversely proportional to the correlation function width

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\(^1\) Hanbury-Brown R, Twiss RQ. Nature 178:1046 (1956)
**Introduction: 3D HBT radii**

- **Bowler and Sinyukov:**

  \[ C(\vec{q}) = N[(1 - \lambda) + \lambda K(q_{inv})(1 + G(\vec{q}))] \]

  where:
  - \( N \): normalization
  - \( K \): Coulomb correction
  - \( \lambda \): chaoticity

  \[ G(\vec{q}) = \exp(-q_{out}^2 R_{out}^2 - q_{side}^2 R_{side}^2 - q_{long}^2 R_{long}^2 - 2q_{out}q_{side}R_{os}^2) \]

  \[ \vec{k}_T = (\vec{p}_{T,1} + \vec{p}_{T,2})/2 \]
  \[ q_{out} || \vec{k}_T \]
  \[ q_{side} \perp \vec{k}_T \]

- **Symbols:**
  - \( R_{out} \): source size along the pair transverse momentum direction
  - \( R_{side} \): source size perpendicular to pair transverse momentum direction
  - \( R_{long} \): longitudinal size
  - \( R_{os} \): out-side cross term

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Final eccentricity can be measured by azimuthal HBT w.r.t second harmonic event plane

- It depends on initial eccentricity, lifetime and dynamics of the source evolution
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Motivation: Azimuthal HBT w.r.t $v_2$ plane

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- It depends on initial eccentricity, lifetime and dynamics of the source evolution

Initial spatial anisotropy

in-plane expansion elliptic flow ($v_2$)

reaction plane

Initial source

$v_2$ plane ($\Psi_2$)

$\varepsilon_2 > 0$ out-of-plane

$\varepsilon_2 < 0$ in-plane
Final eccentricity can be measured by azimuthal HBT w.r.t second harmonic event plane

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Final eccentricity can be measured by azimuthal HBT w.r.t second harmonic event plane
- It depends on initial eccentricity, lifetime and dynamics of the source evolution
Main tracking device: Time Projection Chamber (TPC),
- $|\eta| < 0.8$; $0.2 < k_T < 0.7$ (GeV/c)

Trigger, centrality and event plane: V0
- Centrality: 0-50%

Flow vector for ESE: Forward Multiplicity Detector

Particle identification (PID): TPC ($dE/dx$) & TOF (time of flight)
- Pions

TOF was included in the PID starting from $p = 0.6$ GeV/c

$-3.7 < \eta_{V0C} < -1.7$  $2.8 < \eta_{V0A} < 5.1$
$-0.9 < \eta_{TPC} < 0.9$  $-3.4 < \eta_{FMDC} < -1.7$
$1.7 < \eta_{FMDA} < 5.0$
As the value of $k_T$ increases, the radii decrease.

- Space-momentum correlation = collective radial flow
Results: Azimuthal HBT w.r.t $v_2$ plane

- $R_{out}^2$ vs. $\phi_{pair} - \Psi_{EP,2}$ (rad)
- $R_{side}^2$ vs. $\phi_{pair} - \Psi_{EP,2}$ (rad)

As the value of $k_T$ increases, the radii decrease.

- Space-momentum correlation = collective radial flow

$\Delta \varphi = 0$

$\Delta \varphi = \phi_{pair} - \Psi_{EP,2}$

$R_{out}$ and $R_{side}$ oscillate out-of-phase
Results: Azimuthal HBT w.r.t $v_2$ plane

As the value of $k_T$ increases, the radii decrease.

- Space-momentum correlation = collective radial flow

\[ \phi_{\text{pair}} - \Psi_{\text{EP,2}} \text{ (rad)} \]

\[ R_{\text{out}}^2 (\text{fm}^2) \]

\[ R_{\text{side}}^2 (\text{fm}^2) \]

ALICE 20-30% Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

\[ \Delta \varphi = 90^\circ \]

$R_{\text{out}}$ and $R_{\text{side}}$ oscillate out-of-phase

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Amplitudes of the relative radii oscillations depend strongly on centrality and weakly on $k_T$. 

Centrality dependence similar to that at RHIC
Results: Azimuthal HBT w.r.t $v_2$ plane

Final eccentricity is smaller than the initial eccentricity, but remains positive (still out-of-plane extended)

\[ 0 < \varepsilon_{\text{final (LHC)}} < \varepsilon_{\text{final (RHIC)}} < \varepsilon_{\text{initial}} \]

\[ \varepsilon_{\text{final}} \approx \frac{2R^2_{\text{side},2}}{R^2_{\text{side},0}} \]

The 3+1D hydro calculations agree qualitatively but predict a more isotropic final source.
Motivation: Azimuthal HBT w.r.t $v_3$ plane

Initial geometry  Final source shape

ψ_3

Motivation: Azimuthal HBT w.r.t $v_3$ plane

For non-expanding source:

$$R_{side}^2 = \langle x_{side}^2 \rangle = \langle x^2 \rangle \sin^2 \phi + \langle y^2 \rangle \cos^2 \phi - \langle xy \rangle \sin 2\phi$$

no $R_{side}$ oscillations should be observed w.r.t $\Psi_3$
Motivation: Azimuthal HBT w.r.t. $v_3$ plane

For non-expanding source:

$$R_{\text{side}}^2 = \langle x_{\text{side}}^2 \rangle = \langle x^2 \rangle \sin^2 \phi + \langle y^2 \rangle \cos^2 \phi - \langle xy \rangle \sin 2\phi$$

Triangular flow leads to Radii oscillations

Radii oscillations will confirm the collective nature of triangular flow

References:

Radii oscillations were observed for all centralities

$R_{\text{out}}$ and $R_{\text{side}}$ oscillate in-phase
Amplitudes of the relative radii oscillations for $R_{\text{out}}$ agree qualitatively with hydro while $R_{\text{side}}$ and $R_{\text{os}}$ agree quantitatively.

Results: Azimuthal HBT w.r.t $v_3$ plane

Toy model shows in-phase oscillations of $R_{\text{out}}$ and $R_{\text{side}}$ for $k_T > 0.6$ GeV

$R_{\text{side}}$ and $R_{\text{out}}$ oscillate in-phase, similar to that at higher $k_T$ in the toy model in triangular flow dominated scenario

geometry dominated case ($v_3=0$)  Triangular flow dominated case ($\varepsilon_3=0$)

Event shape engineering

- New tool to select the initial source geometry \([1]\) by the magnitude of the flow vector \(Q_n\)

\[
|Q_n| = \sqrt{Q_{n,x}^2 + Q_{n,y}^2}
\]

\[
Q_{n,x} = \sum w_i \cos n\varphi_i
\]

\[
Q_{n,y} = \sum w_i \sin n\varphi_i
\]

\[
q_n = \frac{|Q_n|}{\sqrt{M}}
\]

\(M\): the multiplicity of the events

Effect of large \(q_n\) selection on \(v_n\)

In selected events \(v_2\) is increased about 25% and \(v_3\) about 15%
Event shape engineering

Large $q_2$ selection significantly enhances the amplitude of oscillations for $R_{out}$, $R_{side}$ slightly enhanced.

Large $q_3$ selection slightly affects the oscillations of the HBT radii.
Event shape engineering

Large $q_2$ selection significantly enhances the amplitudes of the relative radii oscillations of $R_{out}$, and produces slight enhancement for $R_{side}$

- larger initial elliptic source

Large $q_3$ selection slightly affects the amplitudes of the relative radii oscillations

$Pb-Pb \sqrt{s_{NN}}=2.76$ TeV

$\pi^+\pi^+$ and $\pi^0\pi^0$ pair combined

$k_T$: 0.2-1.5 (GeV/c)

$q$ vector cut via FMD A+C side

- 20% large $q_2$ cut, $n=2$
- No $q_2$ cut, $n=2$
- 20% large $q_3$ cut, $n=3$
- No $q_3$ cut, $n=3$
Azimuthal HBT w.r.t $v_2$ plane:
- Final eccentricity is smaller than the initial eccentricity, but remains positive (still out-of-plane), $0 < \varepsilon_{\text{final (LHC)}} < \varepsilon_{\text{final (RHIC)}} < \varepsilon_{\text{initial}}$

Azimuthal HBT w.r.t $v_3$ plane:
- First measurements of the HBT radii oscillations w.r.t $\Psi_3$ at ALICE have been presented
- Our results show similar signs of oscillations for $R_{\text{out}}$ and $R_{\text{side}}$ as in the triangular flow dominated case of the toy model

Event shape engineering
- $v_2$ is enhanced with large $q_2$ selection
  - significantly enhances the amplitude of oscillations for $R_{\text{out}} \sim 20\%$
  - slightly enhances $R_{\text{side}}$ amplitude of oscillations
- $v_3$ is enhanced with $q_3$ selection about $\sim 15\%$
  - slightly affects the relative amplitude of oscillations of HBT radii
Thank you
Backup slides
$R_{long}$ relative amplitudes of oscillations

ALICE Preliminary
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$R^2_{long,3}/R^2_{long,0}$ vs Centrality %

- 0.2 < $k_T$ < 0.3 GeV/c
- 0.3 < $k_T$ < 0.4 GeV/c
- 0.4 < $k_T$ < 0.5 GeV/c
- 0.5 < $k_T$ < 0.7 GeV/c
ESE for all radii

Pb-Pb $\sqrt{s_{\text{NN}}}=2.76$ TeV

$\pi^+\pi^+$ and $\pi\pi$ pair combined

$k_T:0.2-1.5$(GeV/$c$)

q vector cut via FMD A+C side

- $2R^2_{\text{out,0}}/R^2_{\text{out,0}}$
- $2R^2_{\text{side,0}}/R^2_{\text{side,0}}$
- $2R^2_{\text{long,0}}/R^2_{\text{long,0}}$

20% large $q_2$ cut, n=2
No $q_2$ cut, n=2
20% large $q_3$ cut, n=3
No $q_3$ cut, n=3
Third harmonic event plane results

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$\pi^+\pi^+ \text{ and } \pi^+\pi^- \text{ combined}$

$k_T : 0.2-1.5$ (GeV/c)

- centratlity0-5%
- centraltiy5-10%
- centraltiy10-20%
- centraltiy20-30%
- centraltiy30-40%
- centraltiy40-50%

Systematic uncertainties
J. Jia et al., arXiv:1403.6077

Initial shape $\varepsilon_2$

Flow vector $q_2$

AMPT Pb+Pb 2.76 TeV

(c) 0.640

0 0.1 0.2 0.3

0 1000 2000 3000 4000
ALICE Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

SC(m, n)

$3 \times 10^{-6}$

Centrality percentile

HIJING

- SC(4,2)
- SC(3,2)

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Results: Azimuthal HBT w.r.t $v_2$ plane

Average radii are larger for more central collisions which is related to the initial eccentricity.

$R_{\text{out}}$, $R_{\text{side}}$, and $R_{\text{long}}$ have clear centrality and $k_T$ dependence.

3+1D Hydro agrees qualitatively with ALICE data points.

**ALICE Pb-Pb 2.76 TeV**

- $0.2 < k_T < 0.3$ GeV/c
- $0.3 < k_T < 0.4$ GeV/c
- $0.4 < k_T < 0.5$ GeV/c
- $0.5 < k_T < 0.7$ GeV/c

**3+1D Hydro Pb-Pb 2.76 TeV**

- $0.2 < k_T < 0.3$ GeV/c
- $0.3 < k_T < 0.4$ GeV/c
- $0.4 < k_T < 0.5$ GeV/c
- $0.5 < k_T < 0.7$ GeV/c