Correlation of flow harmonics and mean transverse momentum in 5.02 TeV $p+Pb$ and $Pb+Pb$ collisions and event-plane dependence of HBT radii in high-multiplicity $p+Pb$ collisions with the ATLAS detector

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Correlation of flow harmonics and mean transverse momentum in 5.02 TeV $p+Pb$ and $Pb+Pb$ collisions

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The idea

- Relate initial state quantity (event mean $[p_T]$) with evolution towards the final state (flow harmonics)
- Known that the correlation exists (ALICE Phys. Rev. C93, 034916)
- Pearson correlation coefficient $R$ distorted by the limited event multiplicity
- A modified correlator $\rho$ proposed (P. Bozek Phys. Rev. C93 044908)
  - Replaces variances by dynamic counterparts $\text{Var}_{\text{dyn}} c_k$
  - Reproduces true $R$ even with limited event multiplicity
    $\rightarrow$ detector independent measurement

- Is the correlation present & positive or negative?
  - Is it strong? Is it the same for all harmonics?
  - Is it the same in Pb+Pb an p+Pb?

\[
R = \frac{\text{cov}(v_n\{2\}^2, [p_T])}{\sqrt{\text{Var}(v_n\{2\}^2)} \sqrt{\text{Var}([p_T])}},
\]

\[
\rho = \frac{\text{cov}(v_n\{2\}^2, [p_T])}{\sqrt{\text{Var}(v_n\{2\}^2)_{\text{dyn}} \sqrt{c_k}}},
\]

\[
\text{Var}(v_n\{2\}^2)_{\text{dyn}} = \langle \text{corr}\{4\} \rangle - \langle \text{corr}\{2\} \rangle^2
\]

\[
c_k = \frac{1}{N_{\text{pair}}} \sum_i \sum_{j \neq i} (p_{T,i} - \langle [p_T] \rangle)(p_{T,j} - \langle [p_T] \rangle)
\]
Details

- Dataset: $\sqrt{s_{NN}} = 5.02$ TeV,
  2015 Pb+Pb 22$\mu$b$^{-1}$, 2013 p+Pb 28nb$^{-1}$
- Distinct sets of particles for $[p_T]$ and $v_n\{2\}^2$
- Rapidity gaps to suppress non-flow
- Analysis in narrow bins of multiplicity in forward regions
  - Mapped to $N_{\text{ch}}$ and $N_{\text{part}}$
- Several $p_T$ intervals: hydrodynamics region, energy loss region & region to test sensitivity to multiplicity change

\[ \rho = \frac{\text{cov}(v_n\{2\}^2, [p_T])}{\sqrt{\text{Var}(v_n\{2\}^2)_{\text{dyn}}} \sqrt{c_k}}. \]
Ingredients of the $\rho$ for $\nu_2$ in $Pb+Pb$

Significant variation with centrality
Trend follows the $\nu_2$ magnitude
Negative in peripheral events!

$$\rho = \sqrt{\text{Magnitude of } \nu_2 \text{ fluctuations}}$$

Magnitude of $\nu_2$ fluctuations
Similar trend to $\nu_2$
Different $p_T$ ordering as compared to cov

$\rho$ quantifies magnitude of $[p_T]$ fluctuations
Nontrivial $p_T$ interval ordering, different than for cov and $\text{Var}_{\text{dyn}}$

$c_k$ quantifies magnitude of $[p_T]$ fluctuations
Nontrivial $p_T$ interval ordering, different than for cov and $\text{Var}_{\text{dyn}}$
Correlation coefficient $\rho$ for $v_2$

Negative correlation for $v_2$ in peripheral collisions → related to ecc. ~ $1/r$

Gentle rise in mid central → stronger hydrodynamic response to initial eccentricities - interplay between radial and elliptic flow

Fall in most central events

Hydrodynamics 1+3D (Phys. Rev. C93 044908), reproduces the behaviour qualitatively
Correlation coefficient $\rho$ for $\nu_3$ and $\nu_4$

Correlation for $\nu_3$ is weaker compared to $\nu_2$
Positive except for $N_{\text{part}} < 100$ and $p_T > 1\text{GeV}$
Above $N_{\text{part}} \approx 100$ steady rise

Significant correlation for $\nu_4$
The trend is inverted as compared to $\nu_2$ and $\nu_3$
Change of the trend in central events
$\rightarrow$ nonlinear hydro response to initial geometry fluctuations?
Ingredients of $\rho$ for $v_2$ in $\rho+Pb$

\[
\rho = \sqrt{\text{Var}(v_2^2)_{ch} \times 10^6}
\]

Negative covariance, will determine sign of $\rho$
The $\rho$ for $v_2$ in $p+Pb$ vs $Pb+Pb$

The $[p_T]$ fluctuations are of similar magnitude in $p+Pb$ and peripheral $Pb+Pb$ when matched $N_{ch}$

The difference in the $\rho$ values driven by the flow
The $\rho$ for $v_2$ in $p+Pb$ vs $Pb+Pb$

The $[p_T]$ fluctuations are of similar magnitude on $p+Pb$ and peripheral $Pb+Pb$ when matched $N_{ch}$

The difference in the $\rho$ values driven by the flow

The $\rho$ for $v_2$ is negative in high multiplicity $p+Pb$ collisions, for $N_{ch} < 100$, compatible with $Pb+Pb$

No geometry driven trend observed in $p+Pb$ compared to a clear effect in $Pb+Pb$
The $\rho$ for $v_2$ in $p+Pb$ vs $Pb+Pb$

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Favours small dimensions of the initial state -> higher pressure ($[p_T]$), low eccentricity ($v_2$)
Event-plane dependence of HBT radii in high-multiplicity in 5.02 TeV $p+Pb$ collisions with the ATLAS detector

ATLAS-CONF-2017-008
The idea

- Many observables point to the collective behaviour of the system created in $p+Pb$ collisions
  - Competitive theoretical explanations available, hydrodynamics vs “glasma” models
- By measuring the shape of the fireball we can provide useful input
- Technique:
  - Measure the HBT radii with pions ($0.2 < k_T < 0.3$ GeV - late ev. stag) as a function of angular distance of $k_T$ from $\Psi_2 - 2(\phi_k - \Psi_2)$
  - In bins of flow vector magnitude $|\vec{q}_2|$

- Is there any modulation visible in $p+Pb$? How significant?
- Does it depend on the $|\vec{q}_2|$, does it become $\simeq 0$ for $|\vec{q}_2| \simeq 0$?
- Does it resemble the modulation in $A+A$?
Analysis

- Events selection: 28\text{nb}^{-1} of \(p+Pb\) data from 2013
- High multiplicity \(N_{ch} > 130\)
- Very careful treatment of detector effects applied
- \(p_{T,min} = 0.1\) GeV, same-, mixed- events distribution corrected for \(\Psi_2\) resolution (U. W. Heinz Phys. Rev. 044903),

\[ c_{BE}(q) \text{ includes corrections for:} \]
final state - Bowler-Sinyukov
jets - opposite-sign + scaling from MC

- **Extracted modulation amplitude for:**
  \(R_{out}\) - along \(k_T\), \(R_{side}\) - \(\perp k_T\), \(R_{os}\), \(R_{long}\) - along \(z\)

\[
C_{BE}(q) = 1 + e^{-\|Rq\|}
\]

\[
R = \begin{pmatrix}
    R_{out} & R_{os} & 0 \\
    R_{os} & R_{side} & 0 \\
    0 & 0 & R_{long}
\end{pmatrix}
\]

\[
R_i = R_{i,0} \left( 1 + 2 \frac{R_{i,2}}{R_{i,0}} \cos[2(\phi_k - \Psi_2)] \right)
\]

\[
R_{os} = 2R_{os,2} \sin[2(\phi_k - \Psi_2)]
\]
Extracted radii

large $|\vec{q}_2|$

+arbitrary shifts for visibility

small $|\vec{q}_2|$

point - data

lines - cos/sin fits
Extracted radii

\[ R_{\text{out}} \] vs \( 2(\phi_\perp - \Psi) \)

\[ R_{\text{side}} \] vs \( 2(\phi_\perp - \Psi) \)

ATLAS Preliminary
\( p + \text{Pb} 2013, 28 \text{ nb}^{-1} \)
\( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \)

<table>
<thead>
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<th>( \langle N_{\text{ch}} \rangle ) = 186</th>
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<td>0.2 &lt; ( k_T &lt; 0.3 \text{ GeV} )</td>
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\[ R_{\text{out}} \] vs \( \Psi \)

\[ R_{\text{side}} \] vs \( \Psi \)

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Extracted radii
Extracted radii (cont)

![Graph showing extracted radii](image-url)

- Preliminary ATLAS +Pb 2013, 28 nb⁻¹
- p+Pb 2013, 28 nb⁻¹
- $\langle N_{\text{ch}} \rangle = 186$
- $0.2 < k_T < 0.3$ GeV
- $|s_{NN}| = 5.02$ TeV

Fit function

$R_{\text{long}}$
Extracted radii (cont)

\[ \frac{R_{\text{long}}}{R_{\text{long}0}} \]

\[ \langle N_{\text{ch}} \rangle = 186 \]

\[ 0.2 < k_{T} < 0.3 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ 2(k_{x} - \Psi_{2}) \]

\[ \text{ATLAS Preliminary} \]

\[ p+\text{Pb 2013}, 28 \text{ nb}^{-1} \]

\[ \text{Fit function} \]

\[ \det(\mathbf{R}_T) \]

\[ \text{ATLAS Preliminary} \]

\[ p+\text{Pb 2013}, 28 \text{ nb}^{-1} \]

\[ \langle N_{\text{ch}} \rangle = 186 \]

\[ 0.2 < k_{T} < 0.3 \text{ GeV} \]

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ 2(k_{x} - \Psi_{2}) \]

\[ \text{Fit function} \]
Extracted radii (cont)
Conclusions

- ATLAS measured correlations of $v_n$ with event mean-$p_T$ in $Pb+Pb$ and $p+Pb$
  - Significant values for all harmonics in central $Pb+Pb$
  - Very different magnitudes and behaviour with centrality for $v_2$, $v_3$ and $v_4$
  - For peripheral $Pb+Pb$ collisions and $p+Pb$ the $\rho$ for $v_2$ correlation is negative and $\sim$ compatible
  - Hydrodynamical simulations predicted such behaviour in $Pb+Pb$, useful insight into initial conditions in $p+Pb$
- ATLAS measured azimuthal variation of HBT radii in $p+Pb$
  - Found significant radii modulation
  - Magnitude of $|\vec{q}_2|$ does not affect observed radii, except for very symmetric events
  - Qualitatively reassemble observations in $A+A$ systems
  - Naturally explained by hydrodynamics

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Thank you