Measurement of the correlation between flow harmonics of different order in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ATLAS

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Introduction and Motivation

- Event shape dependence of flow harmonics.
  - Helps understand change in medium response with event shape.
  - Disentangle system size and system shape dependence.
  - $v_2 - v_n$ and $v_3 - v_n$ correlations (study of non-linear response).
Introduction and Motivation

• Event shape dependence of flow harmonics.
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  • Disentangle system size and system shape dependence.
  • $v_2 - v_n$ and $v_3 - v_n$ correlations (study of non-linear response).

• Correlations between Event Planes of different orders studied previously (ATLAS: PRC 90, 024905 (2014)).

• Not reproduced by initial state correlations.
  • Additional constraints on medium response.

• Event shape selected analysis helps to understand these correlations better.
Both ellipticity and system size change with centrality!
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Within a given centrality $v_n$ varies over a wide range.
• Both ellipticity and system size change with centrality!
• Event shape selection allows to control the shape of the events (ellipticity, triangularity etc), but without changing centrality.
• Can study correlations of many observables with the system shape, eg jet properties, flow correlations etc.
i) Bin events in centrality classes.
ii) For each centrality class, bin into event-shape classes based on magnitude of $q_m$ vector.
iii) Calculate $v_n$ and $v_m - v_n$ correlations using tracks in ID (using 2PC from pairs with $\Delta \eta > 2$).

\[ q_m = q_m e^{im \Psi_m^{obs}} \]
\[ = \frac{\sum E_{Tj} e^{-im \phi_j}}{\sum E_{Tj}} - \langle q_m \rangle_{evts} \]
Events are binned into \( q \)-vector classes based on the magnitude of \( q_2 \) or \( q_3 \) in FCal.
Event Shape Selection

- Events are binned into $q$-vector classes based on the magnitude of $q_2$ or $q_3$ in FCal.
- Good correlation between $q_n$ in forward detector and $v_n$ in mid-rapidity.
v_2 at intermediate p_T

- v_2 at intermediate p_T plot against v_2 at low p_T. Each point is for a centrality interval.

- For same v_2 at low p_T, smaller v_2 at higher p_T, for peripheral events.

- Effect of larger viscosity in peripheral classes.

Does the correlation depend on event-shape?
• Similar plot, but now in each centrality many points corresponding to the event-shape classes.

• Within a centrality ratio between low $p_T$ and intermediate $p_T$, $v_2$ remains same.

• Slope changes with centrality.

• Suggests viscous effects controlled by system size and independent of event ellipticity.
• Similar plot, for $v_3$.

• Within a centrality ratio between low $p_T$ and intermediate $p_T$ $v_3$ remains same.

• Slope changes with centrality.

• Suggests viscous effects controlled by system size and independent of event triangularity.
- Can study $v_n$ as a function of $v_m$ at fixed centralities.

- Colored markers are from different event shape classes.

- Anti-correlation between $v_2$ and $v_3$, particularly in mid-central and peripheral event classes.

- Initial state effects or from final state interactions?

\[ v_2 - v_3 \text{ correlation} \]
$v_2 - v_3$ correlation: Comparison with initial state correlations

- $ε_2 - ε_3$ correlation from initial state models show similar behavior.

- Some deviations though, particularly in most central classes.
Non-linear increase of $v_4$ with $v_2$.

$v_4$ is expected to have non-linear correlation with $v_2$, $v_4 \propto v_2^2$.
- From initial geometry, $\epsilon_4 \propto \epsilon_2^2$
- Due to non-linear medium response.
- From freeze-out due to anisotropic flow profile.

Can also have a contribution from quadrangular geometry uncorrelated with $\epsilon_2$, $\epsilon_4^{True}$.

Do initial state models capture this correlation?
• $v_4$ gets two contributions: $v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^{True}} + c_1 v_2^2 e^{i4\Phi_2}$
  $c_0$ captures response to $\epsilon_4^{True}$ and $c_1 v_2^2$, the non-linear contribution.

• $v_4$ can be fit with a function, $v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}$

• Fits work quite well to the data

• Also shown are $\epsilon_2 - \epsilon_4$ correlations from MC Glauber and MC-KLN: initial state models fail to describe data.
$v_2 - v_4$ correlation: Linear and non-linear components

- Weak centrality dependence for the linear component, strong centrality dependence for non-linear component.
- Linear and non-linear terms are argued to have different sensitivities to viscosity (D. Teaney, L. Yan PhysRevC.86.044908)

\[
v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^{True}} + c_1 v_2^2 e^{i4\Phi_2}
\]
\[
v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}; \quad v_4^L = c_0, \quad v_4^{NL} = c_1 v_2^2
\]
\(v_2 - v_4\) correlation: Linear and non-linear components

- Linear and non-linear components may also be calculated from EP correlations.

\[
v_4^{NL} = v_4 \langle \cos 4(\Phi_4 - \Phi_2) \rangle
\]

\[
v_4 = \sqrt{c_0^2 + c_1^2 v_2^4}; \quad v_4^L = c_0, \quad v_4^{NL} = c_1 v_2^2
\]

- Consistent results between the two methods!
$v_5$ gets a contribution also from $v_2 v_3$: $v_5 e^{i5\Phi_5} = c_0 e^{i\Phi_5^{True}} + c_1 v_2 v_3 e^{i(3\Phi_3+2\Phi_2)}$

- $\epsilon_2 - \epsilon_5$ correlations from initial state models do not describe the data.
- The fit, $v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2}$ can be used to extract linear and non-linear components.
- Also good agreement with EP results.
• Significant $v_n$ harmonics observed in $p+Pb$.
• $v_n$ shown for similar multiplicity event classes.
• Difference in $v_2$ magnitude reflects difference in initial ellipticity.
• $v_3$ magnitudes similar since driven by fluctuations in both systems.
• $v_4$ larger in Pb+Pb than p+Pb.
Non-linear response in p+Pb?

- $v_n$ in p+Pb and Pb+Pb found to have similar $p_T$ dependence.
- $v_2$ is different by a constant scale factor change in average geometry.
- $v_3$ driven by fluctuations, no scale factor needed.
- $v_4$ driven by fluctuations, but also by $v_2$ differ by a scale factor (J.Jia IS2014).
• $v_4$ driven by fluctuations, but also by $v_2$ differ by a scale factor \( (J.\text{Jia IS2014}) \).

\[
v_4^{\text{pPb}} = v_4^{L^2} \{\text{pPb}\} + v_4^{NL^2} \{\text{pPb}\}
= v_4^{L^2} \{\text{PbPb}\} + a^2 c^2 v_2^4 \{\text{PbPb}\}
= (1 - b^2) v_4^2 \{\text{PbPb}\} + a^2 b^2 v_2^4 \{\text{PbPb}\}
= (1 - b^2 + a^4 b^2) v_4^2 \{\text{PbPb}\} \approx 0.66^2 v_4^2 \{\text{PbPb}\}
\]

\( a = 0.66, \ b = \langle \cos 4(\Phi_2 - \Phi_4) \rangle \approx 0.84 \)
Presented results of correlations of flow harmonics with event shape.

- Correlation between $v_n$ at different $p_T$
  - Correlation between $v_2$ ($v_3$) at different $p_T$ has strong centrality dependence.
  - But independent of event shape.
  - Suggests viscous effects controlled by system size, not system shape.

- Anti correlation between $v_2$ and $v_3$.
  - Mostly described by $\epsilon_2 - \epsilon_3$ correlations from initial state models.
- Non-linear correlation between $v_2$ and higher order harmonics.
  - Initial state models fail to describe the observed correlations.
  - Fits with a two component function with linear and non-linear response terms.
  - Linear component has weak centrality dependence, non-linear component has strong centrality dependence.
  - Consistent with results from EP correlations.

- $v_4$ values from p+Pb also suggest contribution from non-linear response to geometry.
  - Supports the geometric and collective origin of ridge in p+Pb collisions.
Back Up
• $v_n / \sqrt{\epsilon_n^2}$ as a function of $N_{\text{part}}$.

• For $n=4$ and $n=5$, both linear and total $v_n$ are shown.

• For linear component, larger variation can be seen with centrality.

• Indicates larger viscous damping for higher order harmonics.
Event shape selection

- $v_n$ as function of $p_T$ for different shape selected event classes selected on $q_2$ (left) and $q_3$ right.
**v_2 - v_4 correlation**

- \( v_4 \) gets two contributions: \( v_4 e^{i4\Phi_4} = c_0 e^{i\Phi_4^{true}} + c_1 v_2^2 e^{i4\Phi_2} \)

- The fit, \( v_4 = \sqrt{c_0^2 + c_1^2 v_2^4} \) can be used to extract linear and non-linear components.

- Linear and non-linear components are argued to have different sensitivities to viscosity of the medium \((D. Teaney, L. Yan, PhysRevC.86.044908)\)
\[ v_5 e^{i5\Phi_5} = c_0 e^{i\Phi_5^{True}} + c_1 v_2 v_3 e^{i(3\Phi_3+2\Phi_2)} \]

\[ v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2} \quad ; \quad v_5^L = c_0, \quad v_5^{NL} = c_1 v_2 v_3 \]

- Linear and non-linear components may also be calculated from EP correlations.

\[ v_5^{NL} = v_5 \langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle \]

\[ v_5^L = \sqrt{v_5^2 - (v_5^{NL})^2} \]

- Weak centrality dependence for the linear component, strong centrality dependence for the non-linear component.
- Consistent with EP correlation results.
• Similar analysis can be done using $q_3$ selected events.
• For e.g. can use to extract linear and non-linear components in $v_5$.
• Gives consistent results!
• More results in \(\text{arXiv:1504.01289}\)

\[
v_5 e^{i5\Phi_5} = c_0 e^{i\Phi_5^{\text{True}}} + c_1 v_2 v_3 e^{i(3\Phi_3 + 2\Phi_2)}
\]

\[
v_5 = \sqrt{c_0^2 + (c_1 v_2 v_3)^2} ; \quad v_5^L = c_0 , \quad v_5^{NL} = c_1 v_2 v_3
\]