Anisotropic flow measured from multi-particle azimuthal correlations

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Anisotropic flow

- For ideal geometry event anisotropy in momentum space is quantified solely with even cosine terms
- S. Voloshin and Y. Zhang, Z.Phys.C70,1996:
  \[ v_n = \langle \cos(n(\varphi - \Psi_{\text{RP}})) \rangle \]
- There is only one ‘geometrical’ symmetry plane
- Harmonics \( v_n \) quantify anisotropic flow:
  - \( v_1 \) is directed flow, \( v_2 \) is elliptic flow, \( v_3 \) is triangular flow, etc.
Flow fluctuations

- Event-by-event fluctuations in the positions of participating nucleons result in non-zero odd harmonics:

\[ \Psi_{RP} \Rightarrow \Psi_n \]

\[ \nu_n = \langle \cos(n(\varphi - \Psi_n)) \rangle \]

- Each harmonic \( \nu_n \) has its own symmetry plane \( \Psi_n \)

- Experimental consequences of e-b-e flow fluctuations:
  - \( \langle \nu_n^k \rangle \) is not the same as \( \langle \nu_n \rangle^k \)

- What is the underlying probability density function (p.d.f.) of e-b-e flow fluctuations?

- What is the relation between different symmetry planes \( \Psi_n \)?
Analysis outline

- **Data sample:**
  - 2010 + 2011 Pb-Pb events at 2.76 TeV
  - Acceptance $|\eta| < 0.8$

- **Charged particle tracking:**
  - Time Projection Chamber (TPC)

- **Systematic uncertainties:**
  - Non-flow
  - Centrality determination
  - Inefficiencies in detectors azimuthal acceptance
  - Variation of track quality cuts
p.d.f. of flow fluctuations

- **Equivalence:** p.d.f. $\Leftrightarrow$ moments $\Leftrightarrow$ cumulants
  - Cumulants measure genuine multi-particle correlations
  - If for the $1^{\text{st}}$ ($\langle v \rangle$) and $2^{\text{nd}}$ ($\sigma_v$) moments $(\sigma_v/\langle v \rangle)^2 \ll 1$ is satisfied, then all multi-particle cumulants for any p.d.f. are the same
  - For $v_2$: $(\sigma_v/\langle v \rangle)^2 < 0.25$ for mid-central collisions (A. Hansen talk)
  - Odd harmonics originate from fluctuations and $(\sigma_v/\langle v \rangle)^2 \ll 1$ is never satisfied

- **Bessel-Gaussian p.d.f:** All higher moments degenerated
  \[ v_n\{4\} = v_n\{6\} = v_n\{8\} = \ldots \]
  \[
  f(v) = \frac{v}{b^2} \exp \left( -\frac{v^2 + a^2}{2b^2} \right) I_0 \left( \frac{va}{b^2} \right) 
  \]
  \[
  v\{2\} = \sqrt{a^2 + 2b^2}
  \]
  \[
  v\{4, 6, \ldots\} = a
  \]

*Voloshin et al.: PLB 659, 537 (2008)*
Directed flow vs centrality

\( v_1 \{4\} \) and \( v_1 \{6\} \) are similar within the uncertainties.
Triangular flow vs centrality

$v_3\{4\}$ and $v_3\{6\}$ are consistent for all centralities
What is the p.d.f. of flow fluctuations?

- Established experimentally that $v_n\{4\} \sim v_n\{6\} \Rightarrow$ p.d.f. of e-b-e flow fluctuations must have non-negligible 3\textsuperscript{rd}/higher moments (when compared to the 1\textsuperscript{st}/2\textsuperscript{nd} moment)

- Bessel-Gaussian function is an example of p.d.f. with $v_n\{4\} = v_n\{6\}$
Strong centrality dependence of $v_2\{4\}$ - contribution from $v_2$ wrt. $\Psi_{RP}$

Weak centrality dependence of $v_3\{4\}$ typical for pure flow fluctuations
Correlation between symmetry planes

- Observables to probe correlation between symmetry planes:

\[ \langle \cos(n_1 \varphi_1 + \cdots + n_k \varphi_k) \rangle = v_{n_1} \cdots v_{n_k} \cos(n_1 \Psi_1 + \cdots + n_k \Psi_k) \]

Bhalerao, Luzum, Ollitrault  PRC 84 034910 (2011)

- Teaney & Yan proposed: \( \langle \cos(\varphi_a - 3 \varphi_b + 2\Psi_2) \rangle \)

- Experimentally, we measure:

\[
\begin{align*}
\langle \cos(\varphi_a - 3 \varphi_b + 2\varphi_c) \rangle &= \langle \cos(\varphi_a - 3 \varphi_b + 2\Psi_2) \rangle \langle \cos(2\varphi_c - 2\Psi_2) \rangle \\
&= \langle \cos(\varphi_a - 3 \varphi_b + 2\Psi_2) \rangle \times v_2
\end{align*}
\]

Teaney, Yan  PRC 83, 064904 (2011)
\[ \langle \cos(\varphi_a - 3\varphi_b + 2\varphi_c) \rangle = \langle \cos(\varphi_a - 3\varphi_b + 2\Psi_2) \rangle \times \nu_2 \]

Observe non-zero 3-particle correlation
\[ \langle \cos(\varphi_a - 3\varphi_b + 2\varphi_c) \rangle = \langle \cos(\varphi_a - 3\varphi_b + 2\Psi_2) \rangle \times v_2 \]

- Measured correlations have different structure than expected from MC Glauber + ideal hydro model calculations

Teaney, Yan PRC 83, 064904 (2011)
5-particle mixed harmonic cumulants:

\[
\langle \cos(3\varphi_1 + 3\varphi_2 - 2\varphi_3 - 2\varphi_4 - 2\varphi_5) \rangle_c = \langle \cos(3\varphi_1 + 3\varphi_2 - 2\varphi_3 - 2\varphi_4 - 2\varphi_5) \rangle \\
\approx v_3^2 v_2^3 \cos[6(\Psi_3 - \Psi_2)]
\]

\[
\langle \cos(2\varphi_1 + 2\varphi_2 - 2\varphi_3 - \varphi_4 - \varphi_5) \rangle_c = \langle \cos(2\varphi_1 + 2\varphi_2 - 2\varphi_3 - \varphi_4 - \varphi_5) \rangle \\
- 2 \langle \cos(2\varphi_1 - \varphi_2 - \varphi_3) \rangle \langle \cos(2\varphi_1 - 2\varphi_2) \rangle \\
\approx -v_2^3 v_1^2 \cos[2(\Psi_2 - \Psi_1)]
\]

\[
\langle \cos(3\varphi_1 + 2\varphi_2 - 2\varphi_3 - 2\varphi_4 - \varphi_5) \rangle_c = \langle \cos(3\varphi_1 + 2\varphi_2 - 2\varphi_3 - 2\varphi_4 - \varphi_5) \rangle \\
- 2 \langle \cos(3\varphi_1 - 2\varphi_2 - \varphi_3) \rangle \langle \cos(2\varphi_1 - 2\varphi_2) \rangle \\
\approx -v_3 v_2^3 v_1^2 \cos[3\Psi_3 - 2\Psi_2 - \Psi_1]
\]

- All 5-particle cumulants which are sensitive to $v_2^3$
What is the relation between symmetry planes $\Psi_n$?

- Observe non-zero genuine 5-particle correlation
- Correlation strength is related to three-plane correlations
Established experimentally that $v_n\{4\} \sim v_n\{6\} \Rightarrow$ p.d.f. of e-b-e flow fluctuations must have non-negligible 3\textsuperscript{rd}/higher moments when compared to the 1\textsuperscript{st}/2\textsuperscript{nd} moment

- Supports Bessel-Gaussian shape of the p.d.f.

- Weak centrality dependence of $v_3\{4\}$ vs $p_T$ is consistent with its origin from flow fluctuations

- Mixed harmonic 3-particle correlation exhibits different structure than what is expected from MC Glauber + ideal-hydro model calculations (Teaney, Yan PRC 83, 064904 (2011))

- Observe non-zero 5-particle correlations
  - Probe 3-plane correlations
Thanks!
Transverse momentum dependence of $v_3\{4\}$