Correlations and fluctuations in large and small systems at the LHC energies

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3rd Initial Stages 2016, Lisbon, Portugal

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- Correlations between flow harmonics in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - Experimental measurements of correlations on event-planes and flow harmonics
  - Correlations of flow harmonics from e-by-e VISH2+1 hydrodynamics
- Azimuthal correlations in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
  - Azimuthal correlations from hadronic cascade model, UrQMD
- Investigating anisotropic collectivity in pp collisions at the LHC energies
  - Initial conditions
  - Event-by-event hybrid approach iEBE−VISHNU in pp collisions at 7 and 13 TeV
- Summary
Correlations between flow harmonics in Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV
**Introduction**

**Anisotropic flow:** initial anisotropic geometry and its fluctuations


\[ \langle \cos(4(\Psi_2 - \Psi_4)) \rangle \]

\[ \langle \cos(8(\Psi_2 - \Psi_4)) \rangle \]

\[ \langle \cos(12(\Psi_2 - \Psi_4)) \rangle \]

\[ \langle \cos(6(\Psi_2 - \Psi_3)) \rangle \]

\[ \langle \cos(6(\Psi_2 - \Psi_6)) \rangle \]

\[ \langle \cos(8(\Psi_2 - \Psi_5)) \rangle \]

\[ \langle \cos(10(\Psi_2 - \Psi_5)) \rangle \]

\[ \langle \cos(12(\Psi_3 - \Psi_4)) \rangle \]

\[ \langle \cos(12(\Psi_3 - \Psi_4)) \rangle \]

\[ \langle \cos(10(\Psi_2 - \Psi_5)) \rangle \]
**Introduction**

**Anisotropic flow:** initial anisotropic geometry and its fluctuations

- Correlations of event-plane angles


**MC-Glb., \( \eta/s = 0.08 \)**

**MC-KLN, \( \eta/s = 0.2 \)**

**ATLAS data**

**N_{\text{part}}**

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**Correlations of flow harmonics**

\[ \langle \cos(m\phi_1 + n\phi_2 - m\phi_3 - n\phi_4) \rangle \]

\[ \langle \cos(2\phi_2 + 3\phi_3 - 5\phi_5) \rangle \]

\[ \langle \cos(-10\phi_2 + 4\phi_3 + 6\phi_6) \rangle \]

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**Centrality percentile**

0 10 20 30 40 50 60 70

\( SC(m,n) \)

\( 2 \)

\( 1 \)

\( 0 \)

\( 1 \)

\( 2 \)

\( 3 \)

\( 6 - 10 \times \)

\( = 2.76 \text{ TeV} \)

\( NN \)

\( \text{ALICE Pb-Pb} \)

**SC(4,2)**

**SC(3,2)**

**HIJING**

**SC(4,2)**

**SC(3,2)**

(\( \text{Symmetric 2-harmonic 4-particle Cumulant} \))

ALICE, 1604.07663

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Xiangrong Zhu (PKU)

Correlations and fluctuations in large and small systems

May 24, 2016 4 / 28
**Introduction**

**Anisotropic flow:** initial anisotropic geometry and its fluctuations

- Correlations of event-plane angles


\[ \langle \cos(4(\Psi_2 - \Psi_4)) \rangle \]

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\[ \langle \cos(12(\Psi_2 - \Psi_4)) \rangle \]

\[ \langle \cos(6(\Psi_2 - \Psi_4)) \rangle \]

MC-Glb., \( \eta/s = 0.08 \)

MC-KLN, \( \eta/s = 0.2 \)

ATLAS data

**Correlations of flow harmonics**

\[ SC(m,n) = \langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4) \rangle_c \]

= \( \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle \)

- correlation between \( v_2 \) and \( v_4 \)

- anti-correlation between \( v_2 \) and \( v_3 \)

\( SC(m,n) \) from HIJING are compatible with zero

ALICE, 1604.07663v1

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Event-by-event hydrodynamics VISH2+1

To investigate the initial conditions dependence of correlations of flow harmonics, MC-Glauber, MC-KLN and AMPT initial conditions are used.

$v_n$ from hydrodynamics with AMPT initial conditions and $\eta/s=0.08$ are compatible with data.
Event-by-event hydrodynamics qualitatively describes the centrality dependence.

- Signs of $SC_v(3, 2)$ and $SC_v(4, 2)$ are same as the $SC^\epsilon(3, 2)$ and $SC^\epsilon(4, 2)$.
- $SC_v(3, 2)$ and $SC_v(4, 2)$ are sensitive to both $\eta/s$ and initial conditions.
Centrality dependence of $SC(m, n)$

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MC-Glb: $s = 0.08$
- Solid: $\eta/s = 0.08$
- Dashed: $\eta/s = 0.20$

MC-KLN: $s = 0.08$
- Solid: $\eta/s = 0.08$
- Dashed: $\eta/s = 0.20$

AMPT: $s = 0.08$
- Solid: $\eta/s = 0.08$
- Dashed: $\eta/s = 0.16$
Centrality dependence of $SC(m, n)$

- $v_5$ and $v_2$, $v_5$ and $v_3$ are correlated, and $v_4$ and $v_3$ are anti-correlated
- Signs of $SC^v(5, 2)$ and $SC^v(5, 3)$ are same as the $SC^e(5, 2)$ and $SC^e(5, 3)$
- Signs of $SC^v(4, 3)$ are opposite from $SC^e(4, 3)$
  \[ \iff \text{understood with } v_4 e^{i4\Psi} = a_0 \varepsilon_4 e^{i4\Phi_4} + a_1 (\varepsilon_2 e^{i2\Phi_2})^2 \]

Centrality dependence of $SC(m, n)$

- $(a)$ Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV curves: VISH2+1
- $(b)$ $MC-KLN$ solid: $\eta/s=0.08$ dashed: $\eta/s=0.20$
- $(c)$ $AMPT$ solid: $\eta/s=0.08$ dashed: $\eta/s=0.16$

- $(d)$ $v_5$ and $v_2$, $v_5$ and $v_3$ are correlated, and $v_4$ and $v_3$ are anti-correlated
- $(e)$ $v_5$ and $v_3$ are anti-correlated

\[ \epsilon_4 \Psi_4 = a_0 \epsilon_4 e^{-} + a_1 (\epsilon_2 e^{-}) \]

Centrality dependence of $SC(m, n)$

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- Signs of $SC^v(5, 2)$ and $SC^v(5, 3)$ are same as the $SC^e(5, 2)$ and $SC^e(5, 3)$

- Signs of $SC^v(4, 3)$ are opposite from $SC^e(4, 3)$

\[ \Leftarrow \text{understood with } v_4 e^{i4\Psi} = a_0 \varepsilon_4 e^{i4\Phi_4} + a_1 (\varepsilon_2 e^{i2\Phi_2})^2 \]

Normalized Symmetric Cumulants $NSC(m, n)$

Further, we calculate $NSC^v(m, n) = \frac{SC^v(m, n)}{\langle v^2 \rangle} = \frac{\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$

- $NSC^v(3, 2)$ are insensitive to $\eta/s$ and initial conditions, and also roughly fit the measurements from ALICE.
- $NSC^v(4, 2)$, $NSC^v(5, 2)$, $NSC^v(5, 3)$ are sensitive to $\eta/s$ and initial conditions.
Pearson correlation coefficients

$C(v_m, v_n)$ was first proposed by H. Niemi in PRC 87, 054901 (2013)

$C=1$ or $-1$: $v_m$ and $v_n$ is linearly correlated or anti-correlated, and $C=0$: uncorrelated

$$C(v_m^2, v_n^2) = \frac{\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle}{\sqrt{\langle v_m^4 \rangle - \langle v_m^2 \rangle^2} \sqrt{\langle v_n^4 \rangle - \langle v_n^2 \rangle^2}}$$

- None of the $v_m$ and $v_n$ pairs are linearly correlated or linearly anti-correlated
Pearson correlation coefficients

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None of the $v_m$ and $v_n$ pairs are linearly correlated or linearly and correlated.
Azimuthal correlations in p+Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV
Collective flow in p+Pb? – Experimental Observations

Where does the correlations (collective flow) in 5.02 TeV p+Pb collisions come from?

- **Initial State?**
  T. Lappi, et al., JHEP 1601 (2016) 061

- **QGP?**

- **Hadronic matter?**

  ![UrQMD Baseline Calculations](image)


**Assumption:**
p+Pb collisions only produce hadronic systems without reach the threshold of the QGP formation
Sizeable values of $v_2\{2\}$ with different pseudo-rapidity gap.

With large pseudo-rapidity gap, $v_2\{2\}$ from UrQMD is comparable with the experimental data.
Remarkable mass ordering is produced by UrQMD like ALICE data.
Multi-particle cumulants of $v_2$ from UrQMD


- 2-particle correlations of $v_2$: $c_2\{2\} = \langle\langle 2 \rangle\rangle = \langle\langle e^{i2(\phi_1 - \phi_2)} \rangle\rangle = \langle v_2^2 + \delta_2^2 \rangle$

- The UrQMD systems are largely influenced by non-flow effects

- Non-flow effects: $\delta \sim 1/M$, $M$ multiplicity in one event

- $c_2\{2\}$ is positive.
Multi-particle cumulants of \( v_2 \) from UrQMD

- ALICE results of \( c_2^{(4)} \) becomes negative when centrality < 10%.
- But, \( c_2^{(4)} \) from UrQMD keeps positive at all centrality bins.
- UrQMD simulations for \( p+Pb \) collisions are non-flow dominant.
- In \( p+Pb \) collisions, effects from initial state and/or QGP are needed to generate collectivity.
Where is the mass ordering from?

- Hadronic interactions can generate a mass ordering of $v_2(p_T)$ of identified particles.
- $v_2$ mass-ordering is not necessarily associated with strong fluid-like expansions.
Investigating anisotropic collectivity in pp collisions at the LHC energies
Introduction

“Ridge”-like structure in high multiplicity pp collisions at the LHC

(d) CMS $N \geq 110$, $1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$

CMS Preliminary pp $\sqrt{s} = 13 \text{ TeV}$

$N_{\text{offline}} \geq 105$

$1 < p_T < 3 \text{ GeV/c}$

Anisotropy harmonics from pp collisions

CMS-FSQ-15-002

ATLAS, report in Initial Stages 2016

CMS-FSQ-15-002
Anisotropy harmonics from pp collisions

CMS Preliminary

ATLAS, report in Initial Stages 2016

ATLAS, report in Initial Stages 2016
**Event-by-event hybrid approach iEBE-VISHNU**

**iEBE-VISHNU hybrid approach:** VISH2+1+UrQMD

- **Initial conditions:** HIJING 2.0 \cite{Phys. Lett. B 711 (2012) 301}

  hard parton jets and the soft interaction between nucleon remnants
  \[\Rightarrow\text{treated as independent strings} \Rightarrow \text{hot spots}\]

- **hot spot:** Gaussian distribution with $\sigma$
- **initial energy density:** Gaussian smearing with $\sigma$ to all partons in hot spots

\[
\begin{align*}
\text{hot spots before smearing} & \quad \text{before smearing} & \quad \text{after smearing}
\end{align*}
\]
$p_T$-spectra of $\pi$, $K$ and $\rho$

$\eta/s = 0.10$  
$\eta/s = 0.16$  
$\eta/s = 0.08$

- Different $\tau_0$ are used to fit well the $p_T$-spectra.
- Roughly reproduce the $p_T$-spectra slopes for all three hadron species.
- iEBE–VISHNU gives reasonable radial flow in high multiplicity pp collisions.

Anisotropic momentum vs multiplicity in pp collisions

Preliminary

Our calculations roughly reproduce the measurements from CMS at $N_{ch} [20, 120]$

Positive $c_2\{2\}$ at full $N_{ch}$, but negative $c_3\{2\}$ at $N_{ch} < 100$ like CMS data.

Negative $c_2\{4\}$ at $N_{ch} > 100$. More statistics is needed.
Correlations between flow harmonics in Pb+Pb collisions at the LHC

- Symmetric Cumulants $SC(m,n)$, normalized SC $NSC(m,n)$, and Pearson correlation coefficients $C(v_m^2,v_n^2)$ with $m(n) = 2 \sim 5$ are studied.
- $SC(m,n)$ are sensitive to both $\eta/s$ and initial conditions.
- Hydrodynamic $SC(3,2)$ and $SC(4,2)$ qualitatively describe the data.
- $NSC(3,2)$ and $C(v_3^2,v_2^2)$ are mainly determined by corresponding correlations in the initial state.

Correlations in p+Pb collisions

- UrQMD simulations shows hadronic interactions can not produce flow data measured in experiments; effects from initial state and /or QGP are needed.
- $v_2$ mass-ordering is observed in UrQMD, which is the consequence of hadronic interactions.
- Mass-ordering is not necessarily associated with strong fluid-like expansions.

Investigating collective flow in pp collisions

- Initial conditions from HIJING 2.0 + Event-by-Event hybrid approach iEBE-VISHNU is used to studied pp collisions.
- Our calculations roughly reproduce the measurements at 7 TeV from the CMS.
- Positive $c_2\{2\}$ and negative $c_2\{4\}$ are also observed from our calculations.
- More statistics is needed to study $c_3\{2\}$, $c_2\{4\}$ and $c_3\{4\}$.
Summary

- **Correlations between flow harmonics in Pb+Pb collisions at the LHC**
  - Symmetric Cumulants $SC(m, n)$, normalized SC $NSC(m, n)$, and Pearson correlation coefficients $C(v_m^2, v_n^2)$ with $m(n) = 2 \sim 5$ are studied.
  - $SC(m, n)$ are sensitive to both $\eta/s$ and initial conditions.
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Thanks for your attention!
Backup
**Initial conditions from HIJING 2.0**

**HIJING**: hard parton jets and the soft interaction between nucleon remnants
⇒ treated as independent strings

- Partons from each string build a hot spot
  - The center of the hot spots:
    
    $$n_p(r) = \frac{n_0}{1 + e^{(r-R_0)/d}}$$

    
    $$n_0 = 0.17/fm^3, R_0=0.56 \text{ fm}, \text{ and } d=0.112 \text{ fm}$$

  - The spatial parton distribution in each hot spot:
    
    $$f(r) = e^{-r/r_0}$$

    
    $$r_0$$ gives the size of the hot spots

- Initial energy density profiles: a Gaussian smearing of partons within $$|\eta_s| < 1$$

  $$\varepsilon(x, y) = K \sum_i \frac{E^*}{2\pi\sigma^2\tau_0 \Delta \eta_s} \exp(-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma^2})$$

  - $$K$$: normalization factor, $$\sigma$$: Gaussian smearing factor, $$E^*$$: Lorentz invariant energy of partons
Eccentricity $\varepsilon_2$ and $\varepsilon_3$ of the initial conditions

- sizeable $\varepsilon_2$ and $\varepsilon_3$
- hot spot size and smearing factor dependence
- collision energy independent