New insights of multi-particle azimuthal correlations via differential studies in high-multiplicity p-Pb collisions

Maxime Guilbaud

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Parallel session: QCD in small systems

7/2/17
New insights of multi-particle azimuthal correlations with symmetric cumulants in p-p, p-Pb, and Pb-Pb

Maxime Guilbaud(1)

On behalf of the CMS collaboration

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Parallel session: QCD in small systems
7/2/17
Hydrodynamic flow in A-A collisions

\[ f(p_T, \phi, \eta) \sim 1 + 2 \cdot \sum_n v_n(p_T, \eta) \cdot \cos[n(\phi - \Psi_n)] \]
Hydrodynamic flow in A-A collisions

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- \( v_n \) depends on:
  - Initial state geometry and its fluctuations
  - Medium transport coefficients (\( \eta/s, \ldots \))
New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb

Hydrodynamic flow in A-A collisions

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- \( v_n \) depends on:
  - Initial state geometry and its fluctuations
  - Medium transport coefficients (\( \eta/s, \ldots \))

- \( v_n \) well understood in A-A collisions with hydro.
  - Diagonal terms (\( v_n^2 \))
Can we do better?

- Correlations between flow harmonics
  - access details about:
    - Medium response ($\eta/s$, ...)
    - Initial correlations (geometry + fluctuations)
Can we do better?

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- How to study non-diagonal terms ($v_n v_m$)?
  - Mixed harmonic
    - see S.Tuo’s talk tomorrow 8.50 am
**v_n coefficient correlations**

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  - Event-shape engineering

q_2 cut:
- Same centrality (initial geometry)
- Different ellipticity

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**PhysRevC.92, 034903**  
ATLAS results
**v_n coefficient correlations**

**Can we do better?**

- Correlations between flow harmonics access details about:
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**Something else?**

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PhysRevC.92, 034903

ATLAS results
Symmetric Cumulants (SC) in A-A

Correlation between harmonics:

\[ SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \]

ALICE results

**PhysRevLett.117, 182301**
Symmetric Cumulants (SC) in A-A

- Correlation between harmonics:
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- Symmetric Cumulant (SC) developed by ALICE
  - New observable
  - Base on 4-particle cumulant technique
  - Non-flow free at first order

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**PhysRevLett.117, 182301**
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\[ SC(2,3) < 0 \Rightarrow v_2 \text{ and } v_3 \text{ are anti-correlated} \]
\[ SC(2,4) > 0 \Rightarrow v_2 \text{ and } v_4 \text{ are correlated} \]

PhysRevLett.117, 182301  ALICE results
Normalized SC in A-A

- SC normalized by $<\varepsilon_n^2>,<\varepsilon_m^2>$
  - Only $<v_n^2>,<v_m^2>$ accessible experimentally
  - Normalized by $v_n$ magnitude

PhysRevLett.117, 182301
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- Odd-Even correlation: IS fluctuation
- Even-Even correlation: medium response + IS fluctuation

PhysRevLett.117, 182301
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- Apples-to-apples comparison across systems (p-p, p-Pb and Pb-Pb)
- Stringent constraints on models!
  - Giacalone et al. arXiv 1605.08303
  - Gardim et al. arXiv 1608.02982
  - Norhona-Holster et al. arXiv 1609.05171
  - Welsh et al. arXiv 1605.09418

ALICE results
PhysRevLett.117, 182301

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb

7/2/17
Normalized SC in A-A

- SC normalized by \( \langle \varepsilon_n^2 \rangle, \langle \varepsilon_m^2 \rangle \)
  - Only \( \langle v_n^2 \rangle, \langle v_m^2 \rangle \) accessible experimentally
  - Normalized by \( v_n \) magnitude

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**PhysRevLett.117, 182301**

**ALICE results**

**What about small colliding systems?**
Ridge in small systems

- Ridge observed in all systems
  - See Z.Chen’s talk tomorrow 11.40 am

<table>
<thead>
<tr>
<th>CMS pp</th>
<th>$\sqrt{s} = 13$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>105 $\leq N_{\text{offline}}^{\text{trg}} &lt; 150$</td>
<td></td>
</tr>
<tr>
<td>$1 &lt; p_T^{\text{trg}}, p_T^{\text{assoc}} &lt; 3$ GeV/c</td>
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</tr>
</tbody>
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<tr>
<th>CMS pPb</th>
<th>$\sqrt{s_{\text{NN}}} = 5.02$ TeV, $220 \leq N_{\text{offline}}^{\text{trk}} &lt; 260$</th>
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<th>CMS PbPb</th>
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PhysLettB.2013.06, 028, PhysLettB.2016.12, 009

CMS results
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CMS results

PhysLettB.2013.06, 028, PhysLettB.2016.12, 009

- Fourier coefficients \( (v_n) \) extracted with:
  - 2-particle correlations + low multiplicity subtraction
  - Multi-particle cumulants
Ridge in small systems

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NEW!!!
- Fourier coefficients ($v_n$) extracted with:
  - 2-particle correlations + low multiplicity subtraction
  - Multi-particle cumulants

What about correlations?
More insights on the Ridge nature with SCs

CMS results

PhysLettB.2013.06, 028, PhysLettB.2016.12, 009

CMS pp $\sqrt{s} = 13$ TeV
105 $\leq N_{\text{off}}^{\text{ offline}} < 150$
1 $< p_T^{\text{ trig}}$, $p_T^{\text{ assoc}} < 3$ GeV/c

CMS Preliminary
pPb 8.16 TeV, $330 \leq N_{\text{off}}^{\text{ offline}} < 360$
1 $< p_T^{\text{ trig}} < 3$ GeV/c
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(a) CMS PbPb $\sqrt{s_{\text{nn}}} = 2.76$ TeV, $220 \leq N_{\text{off}}^{\text{ offline}} < 260$
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Fourier harmonics and multi-particle cumulants in small systems

- Measurement of Fourier harmonics with multi-particle cumulants
  - See Z. Chen’s talk tomorrow 11.40 am

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**Graphical Data**

CMS

- *pp* $\sqrt{s} = 13$ TeV
  - $v_2^{\text{sub}}_{\{2, |\Delta\eta|>2\}}$
  - $v_2\{4\}$
  - $v_2\{6\}$
  - $v_2\{8\}$
  - $v_2\{LYZ\}$

- *pPb* $\sqrt{s}_{\text{NN}} = 5$ TeV
- *PbPb* $\sqrt{s}_{\text{NN}} = 2.76$ TeV

**Legend**

- $0.3 < p_T < 3.0$ GeV/c
- $|\eta| < 2.4$

**Graphs**

- Offline track multiplicity $N_{\text{trk}}$

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PhysLettB.2016.12, 009

7/2/17

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
Fourier harmonics and multi-particle cumulants in small systems

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What about correlations between harmonics?
SC in small systems

- SC can be measured in small system (p-p and p-Pb)
  - Never measured
  - Little knowledge
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J. Quian, U. Heinz (eccentricity correlation only) arXiv 1605.09418

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Anti-correlation predicted in p-Pb

\begin{align*}
\sigma_g &= 0.25\text{fm} \\
\sigma_g &= 0.3\text{fm} \\
\sigma_g &= 0.3\text{fm}, \theta = 0.75 \\
\sigma_g &= 0.4\text{fm}
\end{align*}
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![Graphs showing SC(2,3) vs Centrality for p+p@13 TeV and p+Pb@5.02 TeV with different values of \( \sigma_g \) and \( \theta \).]
SC in small systems

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Correlation predicted in p-p Related to the number of fluctuating sources
SC in small systems

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High multiplicity data in small system needed!!!
New p-Pb data at 8.16 TeV

Large sample of high-multiplicity events collected for p-p (13 TeV: 2.2 pb\(^{-1}\)) and p-Pb (5.02 & 8.16 TeV: 35 nb\(^{-1}\)/186 nb\(^{-1}\)) so far!!!
New p-Pb data at 8.16 TeV

Large sample of high-multiplicity events collected for p-p (13 TeV: 2.2 pb\(^{-1}\)) and p-Pb (5.02 & 8.16 TeV: 35 nb\(^{-1}\)/186 nb\(^{-1}\)) so far!!!

Large gain in the number of high multiplicity events from 5.02 to 8.16 TeV!!!
2-particle correlation technique

2D correlation function

CMS Preliminary

pPb 8.16 TeV, 330 \leq N_{\text{trk}}^{\text{offline}} < 360

1 < p_T^{\text{trig}} < 3 \text{ GeV/c}

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7/2/17

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
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\[
\frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left[ 1 + \sum_n 2V_n \Delta \cos(n\Delta\phi) \right]
\]

1D correlation function

CMS Preliminary
pPb 8.16 TeV, 330 ≤ N < 360

1 < p_T^{\text{trig}} < p_T^{\text{assoc}} < 3 \text{ GeV/c}

Projection on ΔΦ

Fourier fit

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
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\[
V_n = \sqrt{V_n\Delta}
\]

Extract single particle v_n

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
$v_n$ as a function of multiplicity

CMS-PAS-HIN-16-022
$v_n$ as a function of multiplicity

CMS Preliminary

8.16 TeV 5.02 TeV

$p\text{Pb}$

$v_{n\text{sub}}^{v_n}$ $v_{n\text{sub}}^{v_n}$ $0.3 < p_T < 3 \text{ GeV/c}$

CMS Preliminary

5.02 TeV

$Pb\text{Pb}$

$v_{n\text{sub}}^{v_n}$ $v_n$

$0.3 < p_T < 3 \text{ GeV/c}$

CMS-PAS-HIN-16-022
\( v_n \) as a function of multiplicity

- Similar pattern observed across systems for \( v_n \)

---

**CMS-PAS-HIN-16-022**

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
$v_n$ as a function of multiplicity

- Similar pattern observed across systems for $v_n$
- Very small energy dependence observed for p-Pb results
\( v_n \) as a function of multiplicity

- Similar pattern observed across systems for \( v_n \)
- Very small energy dependence observed for p-Pb results

These results will be used to normalize SCs
Symmetric cumulant

Based on 4-particle cumulant technique

Diagonal terms

$$\langle \langle 4 \rangle \rangle_{n,n} \equiv \left\langle \cos \left[ n (\phi_1 + \phi_2 - \phi_3 - \phi_4) \right] \right\rangle$$

Non-diagonal terms

$$\langle \langle 4 \rangle \rangle_{n,m} \equiv \left\langle \cos \left[ n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4 \right] \right\rangle$$
Symmetric cumulant

Based on 4-particle cumulant technique

- **Diagonal terms**
  \[ \langle \langle 4 \rangle \rangle_{n,n} \equiv \langle \langle \cos[n(\phi_1 + \phi_2 - \phi_3 - \phi_4)] \rangle \rangle \]

- **Non-diagonal terms**
  \[ \langle \langle 4 \rangle \rangle_{n,m} \equiv \langle \langle \cos[n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4] \rangle \rangle \]

- **Symmetric cumulant**
  \[ SC(n,m) = \langle \langle 4 \rangle \rangle_{n,m} - \langle \langle 2 \rangle \rangle_{n} \cdot \langle \langle 2 \rangle \rangle_{m} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \]

Correlators are expressed in terms of Q-vectors
\[ Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i} \]
SC comparison with ALICE

Very good agreement with ALICE using the same cuts

CMS PAS-HIN-16-022

PbPb

CMS Preliminary

CMS ALICE

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

$| \eta | < 0.8$

$0.2 < p_T < 5$ GeV/c

centrality (%)
Very good agreement with ALICE using the same cuts

$|\eta| < 0.8$

$0.2 < p_T < 5$ GeV/c

$\text{CMS-PAS-HIN-16-022}$

$\text{SC(2,3)}$: $v_2$, $v_3$ anti-correlated
SC comparison with ALICE

Very good agreement with ALICE using the same cuts

CMS-PAS-HIN-16-022

CMS Preliminary

PbPb

SC(n,m)

CMS ALICE

\( \eta \) < 5 GeV/c

\( 0.2 < p_T < 5 \) GeV/c

\( |h| < 0.8 \)

\( v_2, v_3 \) anti-correlated

\( v_2, v_4 \) correlated

\( v_2 \), \( v_3 \) anti-correlated

\( v_2 \), \( v_4 \) correlated

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
SC as a function of multiplicity

CMS-PAS-HIN-16-022
SC as a function of multiplicity

CMS-PAS-HIN-16-022
**SC as a function of multiplicity**

- **Similar pattern observed across systems for SC**

![Graphs showing SC as a function of multiplicity for different collision systems.](image)

**CMS-PAS-HIN-16-022**
SC as a function of multiplicity

Similar pattern observed across systems for SC

Very small energy dependence observed for p-Pb results

Normalization needed for a fair comparison

CMS-PAS-HIN-16-022
Similar behavior in p-Pb and PbPb

Points to similar IS fluctuations
SC normalized

SC normalized by $\langle v_n^2 \rangle . \langle v_m^2 \rangle$

- Similar behavior in p-Pb and PbPb
- Points to similar IS fluctuations
- First calculations ($\varepsilon_n$ correlations only)
  - Right sign
  - Magnitude is off

New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
Similar behavior in p-Pb and PbPb

Ordering observed:
  p-p > p-Pb > Pb-Pb

May point to different transport properties

SC normalized by $<v_n^2>.<v_m^2>$

- Ordering observed:
  - p-p > p-Pb > Pb-Pb

- May point to different transport properties

- Similar behavior in p-Pb and PbPb
- Points to similar IS fluctuations
- First calculations ($\varepsilon_n$ correlations only)
  - Right sign
  - Magnitude is off
The new p-Pb 8.16 TeV results reach a multiplicity regime never explored so far.

Symmetric cumulants were measured in p-p, p-Pb and Pb-Pb as a function of multiplicity:

- \( v_2 \) & \( v_3 \)
  - Similar behavior observed across systems
  - Points to similar IS fluctuation contribution

- \( v_2 \) & \( v_4 \)
  - \( p-p > p-Pb > PbPb \)
  - May point to different transport properties

Stringent constraints on the model calculations.
New insights of multi-particle azimuthal correlation with SC in p-p, p-Pb, and Pb-Pb
Symmetric Cumulant (SC): multiplicity fluctuation and normalization

To avoid multiplicity fluctuation we follow this procedure:

<table>
<thead>
<tr>
<th>$N_{trk}^{off}$</th>
<th>$W_{11} \text{ SC}_{11}$</th>
<th>$W_{12} \text{ SC}_{12}$</th>
<th>$W_{13} \text{ SC}_{13}$</th>
<th>$W_{1M} \text{ SC}_{1M}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{trk}^{off}$</td>
<td>$W_{21} \text{ SC}_{21}$</td>
<td>$W_{22} \text{ SC}_{22}$</td>
<td>$W_{33} \text{ SC}_{33}$</td>
<td>$W_{NM} \text{ SC}_{NM}$</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{trk}^{off}$</td>
<td>$W_{N1} \text{ SC}_{N1}$</td>
<td></td>
<td></td>
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</table>

- To insure an apple-to-apple comparison across system, SCs are usually normalized by $\langle v_n^2 \rangle \langle v_m^2 \rangle$ from 2-particle correlation analysis.
  - Large gap needed to get as close as possible to $\langle \epsilon_n^2 \rangle \langle \epsilon_m^2 \rangle$