Flow fluctuations in large systems (Xe and Pb) with ATLAS detector

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for the ATLAS Collaboration
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Flow fluctuation and cumulant

- Flow fluctuates from event to event
  - Initial geometry
  - Hydro evolution
- Cumulant $c_n\{2k\}$ measures $p(\nu_n)$
  - Suppresses non-flow
    - $\nu_n\{4\} \equiv 4\sqrt{-c_n\{4\}}$
- Many sources $\Rightarrow \nu_n \sim Gauss(\bar{\nu}_n, \delta_n)$
  - $\nu_n\{2\} = \sqrt{\bar{\nu}_n^2 + \delta_n^2}$
  - $\nu_n\{4\} = \nu_n\{6\} = \cdots = \bar{\nu}_n$
- System comparisons; $\nu_1\{4\}$ and $\nu_4\{4\}$ in Pb+Pb
- $\nu_2\{4\}$ in ultra-central: role of centrality fluctuation
Mass number of Xe is halfway of Pb and $p$;
If $v_2 \sim Gauss(\bar{v}_n, \delta_n)$: $v_2\{6\}/v_2\{4\} = 1$
$v_2$ in Xe+Xe deviates further from Gauss: deformed nucleus?
\textbf{ATLAS Preliminary}

- Xe+Xe $\sqrt{s_{\text{NN}}}=5.44$ TeV, 3 \( \mu \text{b}^{-1} \)
- Pb+Pb $\sqrt{s_{\text{NN}}}=5.02$ TeV, 22 \( \mu \text{b}^{-1} \)

- $0.5<p_{T}<5.0$ GeV

\begin{itemize}
  \item $c_3\{4\}$ doesn’t scale with centrality between Xe and Pb
  \item No avg. geometry for $v_3$;
\end{itemize}
\( \nu_3 \) 

- \( c_3 \{4\} \) doesn’t scale with centrality between Xe and Pb
- No avg. geometry for \( \nu_3 \);
- \( c_3 \{4\} \) scales with \( \langle N_{\text{part}} \rangle \)
  - Fluctuation driven by \# of sources \( N_{\text{part}} \)
- Similar observation for \( c_4 \{4\} \) (see backup)
• To measure 4-particle $v_1$
  • High $p_T$ cut needed: $v_1\{2PC\}$ changes sign at $p_T = 1.2$ GeV;
  • Free of 2PC momentum conservation: $c_1\{4\} = \langle 4 \rangle - 2 \langle 2 \rangle^2$;
To measure 4-particle $v_1$

- High $p_T$ cut needed: $v_1 \{2\text{PC}\}$ changes sign at $p_T = 1.2$ GeV;
- Free of 2PC momentum conservation: $c_1 \{4\} = \langle 4 \rangle - 2 \langle 2 \rangle^2$;
- Negative $c_1 \{4\}$ observed in high $p_T$, peripheral collision
$c_4\{4\} > 0$ and increase towards to peripheral: non-flow?
\[ c_4 \{4\} > 0 \text{ and increase towards to peripheral: non-flow?} \]
$c_4\{4\} > 0$ and increase towards to peripheral: non-flow?

3-subevent measures the same: not due to non-flow.
• $c_4\{4\} > 0$ and increase towards to peripheral: non-flow?
• 3-subevent measures the same: not due to non-flow.
• Linear and non-linear components: $v_4 = v_{4L} + \beta_{2,2}v_2^2$
  • $c_4\{4\} < 0$ in mid-central $\Leftarrow v_{4L}$
  • $c_4\{4\} > 0$ in peripheral $\Leftarrow v_2^2$
• Collectivity can also give $c_n\{4\} > 0$
Centrality and $p_T$ dependence of $c_2\{4\}$

- Centrality dependence $\Leftarrow \bar{v}_2 \Leftarrow$ Geometry
- $p_T$ dependence $\Leftarrow \bar{v}_2(p_T)$
Centrality and $p_T$ dependence of $c_2\{4\}$

- Centrality dependence $\Leftarrow \bar{v}_2 \Leftarrow$ Geometry
- $p_T$ dependence $\Leftarrow \bar{v}_2(p_T)$
  - Require all particles in the same $p_T$ range;
  - Not affected by flow $p_T$-decorrelation;
- But how about flow fluctuation? Need to suppress $\bar{v}_2$. 

This measurement
• In UCC: $\bar{v}_2 \rightarrow 0$, largest relative flow fluctuation;
• ATLAS applied UCC triggers: $\times 20$ statistics over MinBias;
• In UCC: $\bar{v}_2 \rightarrow 0$, largest relative flow fluctuation;
• ATLAS applied UCC triggers: $\times 20$ statistics over MinBias;
• $c_2\{4\} > 0$ in UCC $\Rightarrow$ non-Gaussian flow fluctuation
  • Why?
Initial stage and hydro response

- On the model side
  - Gaussian $p(\varepsilon_2) \Rightarrow$ Gaussian $p(v_2) \Rightarrow c_2\{4\} \leq 0$
- But we observed $c_2\{4\} > 0$
  - Non-flow contribution?
Two methods consistent: **not due to non-flow.**

Pileup effects have also been suppressed.
Initial stage
sources $N_{part}$
Centrality (volume) Fluctuation (CF)

Initial stage sources $N_{part}$

Final stage particles $N_{ch}$

$p(n)$
Centrality (volume) Fluctuation (CF)

- Fluctuation of particle production $p(n)$
  - Same $N_{part}$ ⇒ different $N_{ch}$
  - Same $N_{ch}$ ⇒ different $N_{part}$

Initial stage sources $N_{part}$

Final stage particles $N_{ch}$

Not detector effect!
Fluctuation of particle production $p(n)$

- Same $N_{part}$ ⇒ different $N_{ch}$
- Same $N_{ch}$ ⇒ different $N_{part}$

In the experiment
- First calculate $\mathcal{O}bs(N_{ch})$
- Then map to $\langle N_{part} \rangle$
- Flow is driven by initial stage $N_{part}$

$\mathcal{O}bs(\langle N_{part} \rangle)$ introduces CF

CF affects all fluctuation measurements, but never been studied in flow
How to test centrality fluctuation in data?

\[ c_n\{4\} \equiv \langle \langle 4 \rangle \rangle - 2\langle \langle 2 \rangle \rangle^2 \]

Calculated event-by-event

Averaged over many events
How to test centrality fluctuation in data?

\[ c_n\{4\} \equiv \left( \langle \langle 4 \rangle \rangle - 2\langle \langle 2 \rangle \rangle^2 \right) \]

Calculated event-by-event

Averaged over many events

- Particle production depends on \( \eta \)

<table>
<thead>
<tr>
<th>Binning defined by</th>
<th>Observable</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCal: 3.2 &lt;</td>
<td>( \eta )| &lt; 4.9</td>
</tr>
<tr>
<td>ID:</td>
<td>( \eta | &lt; 2.5, p_T ) cut</td>
</tr>
</tbody>
</table>

Test relative CF by comparing \( c_2\{4\} \) binned by \( \Sigma E_T \) and \( N_{ch}^{\text{rec}} \)
How to test centrality fluctuation in data?

\[ c_n\{4\} \equiv \left\langle \left\langle 4 \right\rangle \right\rangle - 2\left\langle \left\langle 2 \right\rangle \right\rangle^2 \]

- Calculated event-by-event
- Averaged over many events

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- Particle production depends on \(\eta\)

Test relative CF by comparing \(c_2\{4\}\) binned by \(\Sigma E_T\) and \(N_{ch}^{rec}\)

- \(p(N_{ch}^{rec})\) broader than \(p(\Sigma E_T)\)
- CF effect: \(\Sigma E_T < N_{ch}^{rec}\)
- Prediction
  - \(c_2\{4, \Sigma E_T\} < c_2\{4, N_{ch}^{rec}\}\)

arXiv:1803.01812
\( c_{2\{4\}, \Sigma E_T} \) and centrality fluctuation

\[ c_{2\{4\}, \Sigma E_T} < c_{2\{4\}, N_{\text{ch}}^{\text{rec}}} \]: CF affects flow cumulant;

\( c_{2\{4\}} \rightarrow 0 \) in very most-central: smaller CF effect;
- $c_2\{4\}$: CF mostly affects central;
- $c_2\{4\}$: CF mostly affects central;
- $c_3\{4\}$: CF affects most centralities.
Summary I

- Non-Gauss: Xe and Pb
- $N_{part}$ scaling between Xe and Pb
Summary I

• Non-Gauss: Xe and Pb

\[ c_1\{4\} < 0: \text{dipolar fluctuation} \]

\[ c_4\{4\} > 0: \text{non-linear} \]
• Ultra-central collision: perfect to study flow fluctuation
  • $c_2\{4\} > 0$ in ultra-central;
  • CF probably causes $c_2\{4\} > 0$;
  • CF affects $c_3\{4\}$ in most centralities;

\begin{figure}
\centering
\begin{subfigure}[b]{0.4\textwidth}
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  \includegraphics[width=\textwidth]{c2_4.png}
  \caption{$c_2\{4\}$}
  \label{fig:c2_4}
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  • $c_2\{4\} > 0$ in ultra-central;
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  • CF affects $c_3\{4\}$ in most centralities;

• Suggestions to minimize centrality fluctuation
  1. Choose observables insensitive to CF (use models);
  2. Define centrality by observables with small CF (forward $\eta$?);
  3. Model-data comparison requires same binning $\Rightarrow$ CF cancels;
• Cumulant is **sensitive** to fluctuation: easy to extract **signal**;
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• But sometimes it is **too sensitive**: significant **other effects**...
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• Cumulant is sensitive to fluctuation: easy to extract signal;
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**QM17**

- **ATLAS**
  - $pp$ $13$ TeV, $0.9$ pb$^{-1}$
  - $0.3 < p_T < 3$ GeV

**QM18**

- **ATLAS** Preliminary
  - $1.0 < p_T < 5$ GeV

- Pb+Pb $5.02$ TeV, $22$-$470$ $\mu$b$^{-1}$
Outlook

- Cumulant is **sensitive** to fluctuation: easy to extract signal;
- But sometimes it is **too sensitive**: significant other effects...

- $c_2\{4\}$ independent of $N_{ch}$?
  - Larger CF in small system
  - $N_{ch}$ not a good indicator for “centrality”?
ATLAS Preliminary

Xe+Xe $\sqrt{s_{NN}}=5.44$ TeV, 3 $\mu$b$^{-1}$

$0.5<p_T<5.0$ GeV

$\frac{v_{2\{4\}}}{v_{2\{2PC\}}}$

Centrality [%]

0 10 20 30 40 50 60 70 80
ATLAS Preliminary

Xe+Xe \( \sqrt{s_{NN}} = 5.44 \) TeV, \( 3 \mu b^{-1} \)

0.5<\( p_T \)<5.0 GeV  (20-40)%

\( n=2 \)

\( n=3 \)

---

ATLAS Preliminary

Xe+Xe \( \sqrt{s_{NN}} = 5.44 \) TeV, \( 3 \mu b^{-1} \)

0.5<\( p_T \)<5.0 GeV  (40-60)%

\( n=2 \)

\( n=3 \)
ATLAS Preliminary

Xe+Xe $\sqrt{s_{NN}}=5.44$ TeV, 3 $\mu$b$^{-1}$

$0.5<p_T<5.0$ GeV

Centrality [%]

Correlator

$\times 10^{-6}$

$\times 10^{-6}$

Centrality [%]
Preliminary ATLAS
Xe+Xe \( \sqrt{s_{\text{NN}}} = 5.44 \) TeV, 3 \( \mu b^{-1} \)

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ATLAS Preliminary
Xe+Xe $\sqrt{s_{NN}}=5.44$ TeV, 3 $\mu$b$^{-1}$
Pb+Pb $\sqrt{s_{NN}}=5.02$ TeV, 22 $\mu$b$^{-1}$
$0.5<p_T<5.0$ GeV
• Definitions of centrality
  • Ideally, defined by initial stage: $N_{part}$ or $b$;
  • In experiment, defined by final stage: $E_T$ or $N_{ch}$;
• To compare data with models, map $\langle N_{ch} \rangle$ to $\langle N_{part} \rangle$;
• But it does NOT always work for cumulant.

Cumulant is sensitive to flow fluctuation, but sometimes it is TOO sensitive…

• 4-particle cumulant: $c_{n\{4\}} \equiv \langle \langle 4 \rangle \rangle - 2\langle \langle 2 \rangle \rangle^2$

Calculated event-by-event in each centrality

Centrality definition $\Rightarrow$ flow fluctuation $\Rightarrow c_{2\{4\}}$
• Since $p(v_2)$ depends on $N_{\text{part}}$: $p(v_2, N_{\text{part}}^0) \neq p(v_2, \langle N_{\text{part}} \rangle = N_{\text{part}}^0)$

\[ c_2\{4, N_{\text{part}}^0\} \neq c_2\{4, \langle N_{\text{part}} \rangle = N_{\text{part}}^0\} \]

Centrality resolution has potential effects on cumulants.

• Assume $v_2 \sim \varepsilon_2$, such effects can be shown in MC-Glauber

\[ \varepsilon_2\{4, N_{\text{part}}^0\} \neq \varepsilon_2\{4, \langle N_{\text{part}} \rangle = N_{\text{part}}^0\} \]

arXiv:1803.01812
In very central collision, centrality resolution becomes better.
• Centrality resolution too poor: $N_{ch}$ not a good indicator for geometry?