Flow and Centrality fluctuations in ATLAS

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Based on arXiv:1904.04808
Origin of flow/centrality fluctuations

Many collisions

Each with own evolution

\[
\frac{dN}{d\phi} = N_a \left[ 1 + 2 \sum_n v_{n,a} \cos(n(\phi - \Phi_{n,a})) \right]
\]

\[
\frac{dN}{d\phi} = N_b \left[ 1 + 2 \sum_n v_{n,b} \cos(n(\phi - \Phi_{n,b})) \right]
\]

\[
\frac{dN}{d\phi} = N_c \left[ 1 + 2 \sum_n v_{n,c} \cos(n(\phi - \Phi_{n,c})) \right]
\]

Event by event fluctuations:

- Same N can have different shapes \(\Rightarrow\) flow fluctuation
- Same N can have different sizes \(\Rightarrow\) centrality fluctuation

\[
p(N), p(v_n), p(v_n, v_m), p(\Phi_n, \Phi_m)...
\]
Observables for flow fluctuations

- **Cumulants for** \( p(v_n) \)

\[
\begin{align*}
    c_n\{2\} &= \langle v_n^2 \rangle \\
    c_n\{4\} &= \langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2 \\
    c_n\{6\} &= \langle v_n^6 \rangle - 9\langle v_n^4 \rangle \langle v_n^2 \rangle + 12\langle v_n^2 \rangle^3
\end{align*}
\]

\[
    n c_n\{4\} = \frac{c_n\{4\}}{c_n\{2\}^2} = -\left(\frac{v_n\{4\}}{v_n\{2\}}\right)^4
\]

\[
    n c_n\{6\} = \frac{c_n\{6\}}{4 c_n\{2\}^3} = \left(\frac{v_n\{6\}}{v_n\{2\}}\right)^6
\]

- **Mixed-harmonic cumulants for** \( p(v_n,v_m) \). Not discussed here, see 1904.04808

\[
    nsc_{n,m}\{4\} = \frac{\langle v_n^2 v_m^2 \rangle}{\langle v_n^2 \rangle \langle v_m^2 \rangle} - 1
\]

\[
    nac_n\{3\} = \frac{\langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle}{\langle v_2^2 \rangle \sqrt{v_4^2}}
\]

All results cross-checked with subevent method to ensure non-flow is negligible

- **Current paradigm:** \( V_n \propto \varepsilon_n \)

\[
\begin{align*}
    \frac{v_n\{4\}}{v_n\{2\}} &= \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}} \\
    \frac{v_n\{6\}}{v_n\{4\}} &= \frac{\varepsilon_n\{6\}}{\varepsilon_n\{4\}}
\end{align*}
\]

L. Yan, J. Ollitrault arXiv:1312.6555

Fine splitting of \( v_n\{2k\} \) reflects the fine splitting of \( \varepsilon_n\{2k\} \) between \( k=1,2,3 \ldots \)
$v_2$ and $v_3$ from 4-particle cumulants

- Clear $p_T$ dependence in cumulant ratios $\Rightarrow$

- $v_2\{4\}/v_2\{2\}$ decreases with $p_T$, $v_3\{4\}/v_3\{2\}$ increases with $p_T$

Role of initial-state sub-leading eccentricity or final state fluctuations?
Excellent agreement among experiments
- but much better precision
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- but much better precision

Clear $p_T$ dependence seen
- Increase in central region
- Decrease in peripheral region

$$\frac{v_2\{6\}}{v_2\{4\}} \neq \frac{\varepsilon_2\{6\}}{\varepsilon_2\{4\}}$$

Excellent agreement among experiments but much better precision
Clear $p_T$ dependence seen
- Increase in central region
- Decrease in peripheral region

Role of initial-state sub-leading eccentricity or final state fluctuations?
Constraining the initial-state fluctuations

- $v_2\{6\}/v_2\{4\}$ vs. $v_2\{4\}/v_2\{2\}$ has weaker $p_T$ dependence $\Rightarrow$ more related to IS geometry
Constraining the initial-state fluctuations

- $v_2^6/v_2^4$ vs. $v_2^4/v_2^2$ has weaker $p_T$ dependence more related to IS geometry
- 2-component Glauber model agrees better with Pb+Pb data
- Glauber model fails in peripheral region, where data approach fluctuation-driven model

**Fluctuation-driven model** describes pPb

**CMS**

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**ATLAS**

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

- 0.5$<p_T<$5 GeV
- 1.0$<p_T<$5 GeV
- 1.5$<p_T<$5 GeV
- 2.0$<p_T<$5 GeV

Standard method

- Standard Glauber
- Two-component Glauber
- Fluctuation-driven model

**Peripheral**

- 65%

**Central**

- 5%

- 25%
\( v_4 \) from 4-particle cumulants

- \( c_4\{4\} \) changes sign around 25% centrality, also depends on \( p_T \).
- \( v_4 \) has non-linear contribution from \( v_2 \): \( V_4 = V_{4L} + \chi V_2^2 \propto \epsilon_4 + k \epsilon_2^2 \), but not enough quantitatively

\[
nc_4\{4\} = -\left( \frac{v_4\{4\}}{v_4\{2\}} \right)^4
\]

G. Giacalone, L. Yan, J. Noronha-Hostler, J. Ollitrault, 1608.06022
$v_4$ from 4-particle cumulants

- $c_4\{4\}$ changes sign around 25% centrality, also depends on $p_T$.
- $v_4$ has non-linear contribution from $v_2$: $V_4 = v_{4L} + \chi V_2^2 \propto \epsilon_4 + k\epsilon_2^2$, but not enough quantitatively.
- $v_4\{4\}/v_4\{2\} \sim 0.5$ in central region, magnitude reach $>1$ in peripheral region.

$n c_4\{4\} = -\left(\frac{v_4\{4\}}{v_4\{2\}}\right)^4$

Implies large non-Gaussian fluctuation in peripheral collisions!
Centrality in A+A collisions

- Many variables to quantify centrality/volume.
  - At initial state: $b, N_{part}, xN_{part} + (1-x)N_{coll}, N_{qp}, \ldots$
  - At final state: $N_{ch}, E_T, N_{neutron}, \ldots$

Initial state sources: $V$

Final state particles: $N$

Experimental use:

- $|\eta| < 1$
  - Subevent B
  - Measurement
- $3 < |\eta| < 5$
  - Subevent A
  - Event selection
How to detect centrality fluctuation?

If no fluctuation:

\[ \langle \text{cent}_1 \rangle \text{ in narrow slices of cent}_2 \]

\[ \langle \text{cent}_2 \rangle \text{ in narrow slices of cent}_1 \]
How to detect centrality fluctuation?

with fluctuation:

\[ \langle \text{cent}_2 \rangle \text{ increases more slowly with cent}_1, \]
\[ \text{due to poorer centrality resolution or more centrality fluctuation of cent}_1. \]

\[ \langle \text{cent}_1 \rangle \text{ in narrow slices of cent}_2 \]

This relation remains linear

\[ \langle \text{cent}_2 \rangle \text{ in narrow slices of cent}_1 \]

Non-linearity expected in ultra-central region
Observation of centrality resolution in the data

5.02 TeV Pb+Pb

$|\eta|<2.5$ has poorer centrality resolution than $3<|\eta|<5$

Cent in $3<|\eta|<5$

Cent in $|\eta|<2.5$
Impact centrality fluctuation for flow observables

\[ p(v_n \mid N) = \sum_{\text{cent}_{\text{true}}} p(v_n \mid \text{cent}_{\text{true}}) \otimes p(\text{cent}_{\text{true}} \mid N) \]

Even if \( <E_T> \) and \( <N_{ch}> \) are same, \( p_1(v_n) \) and \( p_2(v_n) \) could still be different

\[ c_n\{4\} = \langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2 \]
Centrality fluctuation and $v_2$-slope in ultra-central collisions
Centrality fluctuation and $v_2$-slope in ultra-central collisions

arXiv:1803.01812

Larger centrality fluctuation for $N_{ch}$-bin(mid-$\eta$) than for $E_T$-bin(forward-$\eta$)

Significant centrality decorrelation along $\eta$
Effects of centrality fluctuation on higher-order cumulants

\[ nc_n \{4\} = - \left( \frac{v_n \{4\}}{v_n \{2\}} \right)^4 \]

- Direct comparison: difference largest in UCC, persists to mid-central collisions
  \[ nc_2\{4,N_{ch}\} (\Sigma E_T) \text{ obtained by map } N_{ch} \text{ to } \langle \Sigma E_T \rangle \]

- Sign change in UCC!

CF influences \( c_n \{4\} \) over a broad centrality range!
Effects of centrality fluctuation on higher-order cumulants

\[ n c_n \{4\} = -\left( \frac{v_n\{4\}}{v_n\{2\}} \right)^4 \]

- Direct comparison: difference largest in UCC, persists to mid-central collisions

\[ nc_2\{4,N_{ch}\} (\Sigma E_T) \text{ obtained by map } N_{ch} \text{ to } <\Sigma E_T> \]

- Sign change in UCC!

CF influences \( c_n\{4\} \) over a broad centrality range!

Glauber study show multiplicity smearing change sign of eccentricity cumulants
Centrality/size fluctuation in central collision

Modification of dynamic fluctuations in ultra-central collisions seen in several observables

$v_2^2$ fluctuation

$v_2^2<p_T>$ correlation

$<p_T>$ fluctuation

ATLAS
Pb+Pb 5.02 TeV, 470 μb$^{-1}$

Provide a way to study the nature of centrality and particle production mechanism
Summary

- Space-time dynamics of HI collisions studied via flow fluctuations and centrality fluctuations

- Flow cumulants show $p_T$ dependence $\rightarrow \varepsilon_n$ not the only source for flow fluctuations
  - Provide new constrains on the initial-state fluctuations.

  Intriguing sign change of $c_4\{4\}$ in mid-central collisions: mixing between $v_2$ and $v_4$?

- Flow fluctuations sensitive to centrality resolution or volume fluctuations
  - Reflected by sign-change of many cumulants observables in UCC

Flow fluctuations can be used to elucidate nature of centrality & particle production mechanism
Anti-corr. between \( v_2 \) & \( v_3 \) \( \Rightarrow \) reflects anti-corr. between \( \varepsilon_2 \) & \( \varepsilon_3 \) ; strong \( p_T \) dependence

Correlation between \( v_2 \) & \( v_4 \) \( \Rightarrow \) mode-mixing of \( V_4 = V_{4L} + \chi V_2^2 \); weak \( p_T \) dependence
Centrality fluctuation effects is large for $v_2$-$v_3$ correlation

CF effects much smaller for $v_2$ - $v_4$ correlation, still visible in UCC
Four-particle cumulant for $v_1$

- Rapidity-even $v_1$ from dipolar fluctuations

$v_1\{2\}$ changes sign at $p_T \sim 1.2$ GeV, $v_1\{4\}$ measurable only at large $p_T$
Four-particle cumulant for $v_1$

- Rapidity-even $v_1$ from dipolar fluctuations
- $c_1\{4\} < 0$ observed at high $p_T$.
  \[ c_1\{4\} = \langle v_1^4 \rangle - 2\langle v_1^2 \rangle^2 \]
- $v_1\{4\}$ increase from central to peripheral.
  - Ranges from 1 to 4%