Insights into the initial conditions and evolution of hadronic collisions with flow observables

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From collisions to measurements
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- Overlap between colliding nuclei:
  ⇒ Initial state, geometry & its fluctuations
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• Hydrodynamic expansion of QGP:
  ➔ Radial and anisotropic flow, sensitive to initial state and properties of QGP

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What can we learn about the initial state and properties of QGP from the measurements of radial and anisotropic flow?
$v_2$ of baryons and mesons in Pb—Pb

- Measurements of $v_2$:
  - Baryon/meson ordering and crossing

![Graph showing $v_2$ vs. $p_T$ for different particles in Pb—Pb collisions](image)
\( \nu_2 \) of baryons and mesons in Pb–Pb comparison to hydro model

- Measurements of \( \nu_2 \):
  - Baryon/meson ordering and crossing
  - Hydro + fragmentation:
    - underestimates the data in most cases
    - Baryon/meson crossing predicted
    - Arises from species-dependent \( p_T \) cut, where fragmentation dominates over hydro
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- Measurements of $v_2$:
  ⇒ Baryon/meson ordering and crossing
- Hydro + fragmentation:
  ✗ Underestimates the data in most cases
  ✓ Baryon/meson crossing predicted
  ⇒ Arises from species-dependent $p_T$ cut, where fragmentation dominates over hydro
- Hydro + coalescence + fragmentation:
  ✓ Significantly better description of data
- But crossing is not unique to coalescence!
$v_2$ fluctuations of baryons and mesons in Pb–Pb collisions

- Emerging $p_T$ dependence from central to peripheral collisions
- Baryon/meson grouping in semi-central collisions
  - Different from that observed for $v_2$
  - Could point to a different origin of this observation

\[ F(v_2) = \frac{\sigma(v_2)}{v_2} \]

 ALICE, arXiv:2206.04587 [nucl-ex]
\( \nu_2 \) fluctuations: skewness and kurtosis in Pb—Pb collisions

Measure \( \nu_2 \) with multiparticle cumulants:

\( \Rightarrow \) Sensitive to underlying \( \nu_2 \) probability density function (PDF) and thus initial geometry

- Skewness (\( \gamma_1 \)) decreasing with centrality, PDF becoming less symmetric
- Kurtosis (\( \gamma_2 \)) increasing with centrality, tails become "fatter"

Do \( \gamma_1, \gamma_2 \) probe initial geometry exclusively?
**$\nu_2$ fluctuations: skewness and kurtosis in Pb—Pb collisions**

Measure $\nu_2$ with multiparticle cumulants:

⇒ Sensitive to underlying $\nu_2$ probability density function (PDF) and thus initial geometry

- Skewness ($\gamma_1$) decreasing with centrality, PDF becoming less symmetric
- Kurtosis ($\gamma_2$) increasing with centrality, tails become “fatter”

Do $\gamma_1$, $\gamma_2$ probe initial geometry exclusively?

Not necessarily!

- Both $\gamma_1$ and $\gamma_2$ show evolution with $p_T$

⇒ Suggests that $\nu_2$ PDF is modified by the evolution of QGP
Flow vector fluctuations in Pb—Pb

Flow factorisation ratio

\[ r_n = \frac{\langle v^a_n v^n_t \cos[n (\Psi^a_n - \Psi^n_t)] \rangle}{\sqrt{\langle v^a_n, 2 \rangle \langle v^n_t, 2 \rangle}} \]

(trigger and associated)
Flow vector fluctuations in Pb—Pb

Flow factorisation ratio

\[ r_n = \frac{\langle v_a^i v_n^i \cos[n(\Psi_n^a - \Psi_n^t)] \rangle}{\sqrt{\langle v_n^{a,2} \rangle \langle v_n^{t,2} \rangle}} \]

(trigger and associated)

Largest fluctuations in central Pb—Pb collisions at high \( p_T \) ⇒ large event-by-event fluctuations in the initial state

\[ \langle v_n^{a,2} \rangle \langle v_n^{t,2} \rangle \]
Flow factorisation ratio $r_n = \frac{\langle v^a_n v^t_n \cos[n (\Psi^a_n - \Psi^t_n)] \rangle}{\sqrt{\langle v^a_n \rangle^2 \langle v^t_n \rangle^2}}$

(trigger and associated)

Largest fluctuations in central Pb—Pb collisions at high $p_T \Rightarrow$ large event-by-event fluctuations in the initial state

Deviations from $r_n = 1$ can be due to:

- **Flow angle fluctuations,**
  $$\langle \cos \left[ n (\Psi^a_n - \Psi^t_n) \right] \rangle \neq 1$$

- **Flow magnitude fluctuations,**
  $$\langle v^a_n v^t_n \rangle \neq \sqrt{\langle v^a_n \rangle^2 \langle v^t_n \rangle^2}$$

- Cannot be measured directly, but upper/lower limits can be estimated
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  \]

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**Flow angle fluctuations**

- Sensitive to fluctuations in initial state, little sensitivity to $\eta/s$
Flow vector fluctuations in Pb—Pb

Flow factorisation ratio

\[ r_n = \frac{\langle v_n^a v_n^t \cos[n (\Psi_n^a - \Psi_n^t)] \rangle}{\sqrt{\langle v_n^a \rangle^2 \langle v_n^t \rangle^2}} \]

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  \[ \langle v_n^a v_n^t \rangle \neq \sqrt{\langle v_n^a \rangle^2 \langle v_n^t \rangle^2} \]

- Cannot be measured directly, but upper/lower limits can be estimated

\[ r_n = 1 \langle \cos \left[ n (\Psi_n^a - \Psi_n^t) \right] \rangle \neq 1 \]

\[ \langle v_n^a \rangle \langle v_n^t \rangle \neq \langle v_n^a \rangle \langle v_n^t \rangle \]

• Sensitive to fluctuations in initial state, little sensitivity to \( \eta/s \)
• Strong sensitivity to shear viscosity, but only in the most central collisions
Flow vector fluctuation limits in Pb—Pb

Flow factorisation ratio (trigger and associated)

Largest fluctuations in central Pb—Pb collisions at high \( p_T \) ⇒ large event-by-event fluctuations in the initial state

- At least 40% of fluctuations in central collisions originate from flow angle fluctuations
- Above 30% centrality, flow magnitude fluctuations are suppressed

First measurement separating flow angle and magnitude fluctuations ⇒ Challenges the assumption of a common symmetry plane

\[ \langle \cos 2[\Psi_2(p_T^A)-\Psi_2] \rangle_{\text{min}} \]

\[ \langle v_2(p_T^A)v_2 \rangle / \langle (v_2^2(p_T^A))^{1/2} \max \rangle \]

\[ v_2(2)/v_2[2] \]

ALICE, \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \), 3 < \( p_T^A < 4 \text{ GeV/c} \)

Data

AMPT

\[ \text{relative contribution} \]

\[ \text{absolute contribution} \]
Correlation between $[p_T]$ and $v_2$

- Shape of the fireball: anisotropic flow, $\varepsilon_n \rightarrow v_n$
- Size of the fireball: radial flow, $[p_T], 1/R \rightarrow [p_T]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between $v_n$ and $[p_T]$

$\Rightarrow$ Study with Pearson correlation coefficient:

$$
\rho_n \left( v_n^2, [p_T] \right) = \frac{\text{cov} \left( v_n^2, [p_T] \right)}{\sqrt{\text{var} \left( v_n^2 \right)} \sqrt{\text{var} \left( [p_T] \right)}}
$$
Correlation between \([p_T]\) and \(v_2\)
and deformation of nuclei

- Shape of the fireball: anisotropic flow, \(\varepsilon_n \rightarrow v_n\)
- Size of the fireball: radial flow, \([\rho_T]\), \(1/R \rightarrow [p_T]\)
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\]

\(\Rightarrow\) \(\rho_2\) is significantly smaller in central collisions of deformed Xe nuclei (deformation parameter \(\beta_2 \approx 0.16\)) compared to spherical Pb (\(\beta_2 \approx 0\))

Correlation between $[p_T]$ and $\nu_2$
at low multiplicity

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- Size of the fireball: radial flow, $[p_T]$, $1/R \rightarrow [p_T]$
- Initial state: geometry and fluctuations of shape and size
- Final state: correlation between $\nu_n$ and $[p_T]$

⇒ Study with Pearson correlation coefficient:

$$\rho_n\left(\nu_n^2, [p_T]\right) = \frac{\text{cov}\left(\nu_n^2, [p_T]\right)}{\sqrt{\text{var}\left(\nu_n^2\right)} \sqrt{\text{var}\left([p_T]\right)}}$$
Correlation between $[p_T]$ and $v_2$

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$$

Low multiplicity: geometry $\rightarrow$ initial momentum correlations

$\Rightarrow$ Change of slope sign $\rightarrow$ presence of CGC?
Correlation between $[p_T]$ and $v_2$ in Pb—Pb and Xe—Xe collisions

• $\rho_2$ slightly larger in Pb—Pb compared to Xe—Xe

• Comparison to models:
  – Below 20% centrality, all models provide a decent description
  – More peripheral $\rightarrow$ best described by models with IP-Glasma

• Xe—Xe:
  – $\beta_2 = 0.162$ gives better description in most central collisions, similar to $\beta_2 = 0$ in more peripheral
Correlation between $[p_T]$ and $v_2$

in Pb–Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb–Pb:
- Decreasing + increasing trend at low multiplicity
Correlation between $[p_T]$ and $v_2$ in Pb—Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb—Pb:

• Decreasing + increasing trend at low multiplicity

• Sensitive to $p_T$ interval...

Three-subevent method
Pb+Pb 5.02 TeV, 22µb$^{-1}$
$|\eta| < 2.5$

ATLAS
$\Sigma E_T$-based

Centrality [%]

$0.5 < p_T < 5.0$ GeV

$0.5 < p_T < 2.0$ GeV

ATLAS, 2205.00039 [nucl-ex]
Correlation between $[p_T]$ and $v_2$ in Pb—Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb—Pb:

- Decreasing + increasing trend at low multiplicity
- Sensitive to $p_T$ interval...
- and pseudorapidity range...

ATLAS, 2205.00039 [nucl-ex]
Correlation between $[p_T]$ and $v_2$

in Pb—Pb at low multiplicity

$\rho(v_2^2, [p_T])$ in Pb—Pb:

• Decreasing + increasing trend at low multiplicity

• Sensitive to $p_T$ interval…

• and pseudorapidity range…

• and even the multiplicity estimator

Three-subevent method
Pb+Pb 5.02 TeV, 22µb⁻¹
$0.5 < p_T < 5.0$ GeV
$|\eta| < 2.5$
Correlation between \([p_T]\) and \(v_2\) comparison to models

\[ \rho(v_2^2, [p_T]) \] in Pb—Pb:

- **IP-glasma+MUSIC+UrQMD:**
  - Slope change around 20 charged tracks, significantly lower than in data
- **AMPT:**
  - Change of slope also observed, although at significantly higher \(N_{\text{ch}}\)

\[ \Rightarrow \text{Slope change not exclusive to IP-Glasma} \]

\[ \rho(v_2^2, [p_T]) \] in pp:

- Consistent with Pb—Pb at similar \(N_{\text{ch}}\)
- Underestimated by AMPT, overestimated by PYTHIA
Summary

• Relative flow fluctuations: emerging $p_T$ dependence in peripheral collisions

• Higher moments of $v_2$ PDF: evolution with centrality and $p_T$ suggests sensitivity to initial geometry and transport properties of QGP

• First ever measurement separating flow angle and flow magnitude fluctuations
  ➔ Dominated by flow angle fluctuations
  ➔ Challenges the assumption of a single event-averaged symmetry plane

• Correlations between $[p_T]$ and $v_2$:
  ➔ Highly sensitive to kinematic cuts and multiplicity estimator
  ➔ Data better described by models with IP-Glasma in initial conditions
  ➔ Observed decreasing trend at small $N_{ch}$ in Pb—Pb collisions
  ➔ Change of slope at low $N_{ch}$ sensitive to interplay between initial conditions and geometry
Backup
From collisions to measurement

- Overlap between colliding nuclei:
  ⇒ Initial state, geometry & its fluctuations

- Hydrodynamic expansion of QGP:
  ⇒ Radial and anisotropic flow, sensitive to initial state and properties of QGP

⇒ (Non-)Gaussian probability density function of $v_n$
  sensitive to initial state eccentricity $\varepsilon_n$
⇒ $v_n$ fluctuations measured w.r.t. averaged $\Psi_n$
$\nu_2$ fluctuations and $\nu_2$ ratios in Pb–Pb collisions
$\nu_2$ fluctuations and $\nu_2$ ratios in Pb—Pb collisions
Define flow factorisation as

\[ r_n = \frac{V_n(\Delta p_T^a, p_T^t)}{\sqrt{V_n(\Delta p_T^a, p_T^a) \cdot V_n(\Delta p_T^t, p_T^t)}} = \frac{\langle v_n^a v_n^t \cos[n(\Psi_n^a - \Psi_n^t)] \rangle}{\sqrt{\langle v_n^a v_n^t \rangle^2}} \]

Deviations from \( r_n = 1 \) can be due to:

- **Flow magnitude fluctuations**, 
  \[ \langle v_n^a v_n^t \rangle \neq \sqrt{\langle v_n^a v_n^t \rangle^2} \]

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- Cannot measure directly, but can measure upper/lower limits!
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For deformed nuclei

Significantly smaller $\rho_2$ in central Xe—Xe, compared to Pb—Pb
⇒ Deformation $\beta$ reduces $\rho_2$

Study with Pearson correlation coefficient:
\[
\rho_n \left( \nu_n^2, [p_T] \right) = \frac{\text{cov} \left( \nu_n^2, [p_T] \right)}{\sqrt{\text{var} \left( \nu_n^2 \right)} \sqrt{\text{var} \left( [p_T] \right)}}
\]

\[D_{WS}(r) = \frac{D_0}{1 + e^{(r-R_0(1+\beta Y_{20}))/a}}\]

\[\beta > 0\]
\[\beta < 0\]

\[\begin{align*}
\text{Pb—Pb: } & \beta \approx 0 \\
\text{Xe—Xe: } & \beta \approx 0.16
\end{align*}\]

Correlation between $[p_T]$ and $\nu_2$

- Shape of the fireball: anisotropic flow, $\varepsilon_n \rightarrow \nu_n$
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For deformed nuclei

Significantly smaller $\rho_2$ in central Xe—Xe, compared to Pb—Pb

$\Rightarrow$ Deformation $\beta$ reduces $\rho_2$

Probing the initial state

- Low multiplicity: geometry $\rightarrow$ initial momentum correlations
  $\Rightarrow$ Change of slope sign $\rightarrow$ presence of CGC?

Study with Pearson correlation coefficient:

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