Measurements of $p_T$-differential $v_2$ and $v_3$ using multi-particle cumulants in Pb-Pb and Xe-Xe collisions

Vytautas Vislavicius for the ALICE Collaboration
Hydrodynamical flow in heavy-ion collisions

Heavy-ion collision geometry

- Partial overlap between colliding projectiles, spatial anisotropy of colliding nucleons give rise to pressure gradients...
- ... which result in anisotropies in (produced) particle azimuthal angular distributions
- -> Particles “flow”
Hydrodynamical flow in heavy-ion collisions

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- ...which result in anisotropies in (produced) particle azimuthal angular distributions
  -> Particles “flow”
  — Elliptic flow ($v_2$), triangular flow ($v_3$), etc...

Studying the flow of final state hadrons we can learn about medium properties and initial conditions in heavy-ion collisions
How do we measure flow?

Several techniques: Fourier decomposition, Q-cumulants...

From 2-particle correlations:

\[ c_n(2) = \langle \langle 2 \rangle \rangle_n = \langle v_n^2 \rangle \]
\[ d_n(2)(p_T) = \langle \langle 2' \rangle \rangle_n = \langle v_n(p_T) \cdot v_n \rangle \]
\[ v_n(2)(p_T) = \frac{d_n(2)(p_T)}{\sqrt{c_n(2)}} \]
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Can also calculate from 4-particle correlation:

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

\[ d_n\{4\}(p_T) = \langle \langle 4' \rangle \rangle_n - 2\langle \langle 2 \rangle \rangle \langle \langle 2' \rangle \rangle_n \]

\[ v_n\{4\}(p_T) = \frac{d_n\{4\}(p_T)}{\sqrt[3]{-c_n\{4\}}} \]

Short-range correlations (e.g. jets) introduce bias in correlation function -> Non-flow

To suppress short-range correlations, introduce \( \eta \) gap, only construct pairs from opposite regions:
The ALICE detector

A Large Ion Collider Experiment: multi-purpose detector at the LHC with excellent tracking & particle identification capabilities in a wide $p_T$ range (0.1 GeV/c to ~20 GeV/c for PID, up to 50 GeV/c for unidentified)

- Inner Tracking System (ITS)
  - Tracking
  - Triggering
  - PID
- Time-Projection Chamber
  - Tracking
  - PID
- V0 detector
  - V0A ($2.8 < \eta < 5.1$)
  - V0C ($-3.7 < \eta < -1.7$)
- Triggering
- Multiplicity estimation
\( \rho_T \)-differential \( v_n\{m\} \) in Pb-Pb collisions

Plethora of \( v_2\{2,4,6,8\} \) measurements in ALICE, with different \( \eta \) gaps,

![Graphs showing \( v_2 \) and \( v_4 \) at different \( \eta \) gaps for Pb-Pb collisions at 5.02 TeV, with ALICE Preliminary results for V0M 5-10\%, 10-20\%, 20-30\%, and 30-40\%.](image-url)
$p_T$-differential $v_n\{m\}$ in Pb-Pb collisions

Plethora of $v_2\{2,4,6,8\}$ measurements in ALICE, with different $\eta$ gaps, and also $v_3\{2,4\}$
$p_T$-differential $v_n(m)$ in Pb-Pb collisions

$v_n(m)$ in central Pb—Pb collisions:
- $v_2(2)$ larger than $v_2(4,6,8)$: fluctuations and non-flow
- Non-flow in $v_2(2)$ suppressed by $\eta$-gap; $v_2(4,6,8)$ not affected by $\eta$-gap
$p_T$-differential $v_n\{m\}$ in Pb-Pb collisions

$v_2\{m\}$ in central Pb—Pb collisions:
- $v_2\{2\}$ larger than $v_2\{4, 6, 8\}$: fluctuations and non-flow
- $v_2$ sensitive to geometry, increases when going peripheral

- Non-flow in $v_2\{2\}$ suppressed by $\eta$-gap; $v_2\{4, 6, 8\}$ not affected by $\eta$-gap
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$v_3\{m\}$ in Pb—Pb collisions:
- At high $p_T$ dominated by non-flow, suppressed with $\eta$-gap

• Non-flow in $v_2\{2\}$ suppressed by $\eta$-gap; $v_2\{4,6,8\}$ not affected by $\eta$-gap

![Graph showing $v_3/m$ vs $p_T$](image)
\( p_T \)-differential \( v_n\{m\} \) in Pb-Pb collisions

\( v_2\{m\} \) in central Pb—Pb collisions:
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\( v_3\{m\} \) in Pb—Pb collisions:
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- Less sensitive to geometry (compared to \( v_2 \)), more sensitive to colliding nucleon fluctuations

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![Graph showing \( v_3\{2\}, v_3\{2, |\eta|>0\}, v_3\{2, |\eta|>1\}, v_3\{4\} \) vs. \( p_T \) in Pb-Pb collisions.](attachment:image.png)
**\( \rho_T \)-differential \( v_n\{m\} \) in Pb-Pb collisions**

**\( v_2\{m\} \) in central Pb—Pb collisions:**
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**Non-flow in \( v_2\{2\} \) suppressed by \( \eta \)-gap; \( v_2\{4,6,8\} \) not affected by \( \eta \)-gap**

What about smaller systems, eg Xe—Xe?

**arXiv:1903.01790 [nucl-ex]**

![Graph showing data for \( v_2\{m\} \) and \( v_3\{m\} \) in Pb—Pb collisions](image)
\( p_T \)-differential \( v_n^m \) in Xe-Xe collisions

\( v_2 \) in Xe—Xe: similar trends to those seen in Pb—Pb collisions

- \( v_2^{\{4,6\}} < v_2^{\{2\}} \), fluctuations and non-flow
- \( \eta \)-gap suppresses non-flow, larger gap required

- In peripheral collisions, \( v_2^{\{2\}} \) is dominated by non-flow

\begin{align*}
\text{ALICE Preliminary} \\
\text{Xe-Xe, } \sqrt{s_{\text{NN}}} = 5.44 \text{ TeV} \\
\text{V0M 30-50\%}
\end{align*}

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\text{ALICE Preliminary} \\
\text{Xe-Xe, } \sqrt{s_{\text{NN}}} = 5.44 \text{ TeV} \\
\text{V0M 50-70\%}
\end{align*}
**ρ_T-differential v_n{m} in Xe-Xe collisions**

$v_2$ in Xe—Xe: similar trends to those seen in Pb—Pb collisions

- $v_2\{4,6\} < v_2\{2\}$, fluctuations and non-flow
- $\eta$-gap suppresses non-flow, larger gap required

- In peripheral collisions, $v_2\{2\}$ is dominated by non-flow

And similar for $v_3$, ...

![Graphs showing $v_3(2)$ vs $p_T$ for Xe-Xe collisions at different energy and centrality.]
$p_T$-differential $v_2$ PDFs

What can we learn from these measurements?

- If $v_2\{m\} \propto \varepsilon_2$, then
  \[
  \frac{v_2\{4\}}{v_2\{6,8\}} = \text{const, independent of } p_T
  \]

- If the probability density function of $v_2$ is given by the Bessel-Gaussian distribution, then
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  $$\frac{v_2\{4\}}{v_2\{6,8\}} = \text{const}, \text{ independent of } p_T$$
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But we find:
- $v_2$ distribution not described by the Bessel-Gaussian distribution
- Non-trivial evolution with $p_T$, -> Sensitive to medium transport parameters?
$p_T$-differential $\nu_2$ PDFs

$\nu_2$ PDF: sensitive to geometry and evolution of the system. How does it look?
— Can calculate different moments of the distribution from $\nu_2 \{m\}$[1]:
  - Skewness ($\gamma_1$) $\sim$ -0.3 at low $p_T$ (cf hydro [2])
  - Kurtosis ($\gamma_2$) small, positive at low $p_T$, tails larger than Gaussian
  - Higher $p_T$ ($\gtrsim 3$): $\gamma_1$ and $\gamma_2$ consistent with 0, $\nu_2$ PDF approaches normal distribution

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Summary

• $p_T$-differential measurements of flow coefficients using 6- and 8-particle correlations done for the first time in ALICE

• $v_2\{6\}$ and $v_2\{8\}$ show deviations from $v_2\{4\}$, indicating that the underlying PDF is not described by the Bessel-Gaussian distribution

• $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{4\}$ ratios show non-trivial evolution with $p_T$
  -> Might point to needed refinement of the traditional linear relation between $v_n$ and $\varepsilon_n$

• Probability density function of $v_2$ is not constant in $p_T$ (large left tail at low $p_T$, approaching normal distribution at ~3 GeV/c)
Backup
$\rho_T$-differential $v_n\{m\}$ in Pb-Pb collisions

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