Anisotropic flow fluctuations relative to participant and spectator planes in heavy-ion collisions with ALICE

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new: ALICE-PUBLIC-2022-008
Knowledge of initial state important to extract QGP properties based on final state observables.

Event-by-event fluctuations quantified by participant eccentricities $\varepsilon_n$ and symmetry planes $\Psi_n$.

Detailed studies of QGP need experimental constraints of the initial state.
Studying participant plane fluctuations

Elliptic flow using multi-particle cumulants

\[ v_2^2 \neq v_2^4 = v_2^{2m} = v_2^{\Psi_{RP}} \]

\[ v_2^2 > v_2^4 > v_2^{2m} > v_2^{\Psi_{RP}} \]

Shape of elliptic flow fluctuations

• Bessel-Gaussian model (BGM)\(^1\)

\[ v_2^2 \neq v_2^4 = v_2^{2m} = v_2^{\Psi_{RP}} \]

• Elliptic-Power model (EPM)\(^2\)

\[ v_2^2 > v_2^4 > v_2^{2m} > v_2^{\Psi_{RP}} \]

\(^1\)Voloshin et al. PLB 659 (2008) 537

\(^2\)Yan et al. PRC 90 (2014) 024903

More on PP fluctuations:

V. Vislavicius T07 07.04@12:15
Spectators and initial state fluctuations

Spectators quickly decouple from participants before QGP formation.

In case of small fluctuations of spectator planes
\[ \Psi_{SP}^P \approx \Psi_{SP}^T \approx \Psi_{SP} \approx \Psi_{RP} \]

Elliptic flow relative to \( \Psi_{SP} \) allows to study:

- \( v_2\{2\} > v_2\{4\} \approx v_2\{\Psi_{SP}\} \approx v_2\{\Psi_{RP}\} \)
- Initial state models
ALICE setup

spectator neutron measurement
|η| > 8.8

centrality determination
A side: 2.8 < η < 5.1
C side: -3.7 < η < -1.7

A side (η>0) ZDC

v0

event and track reconstruction
|η| < 0.8
p_T > 0.2 GeV/c

C side (η<0) ZDC

Data samples

<table>
<thead>
<tr>
<th></th>
<th>Pb–Pb</th>
<th>Xe–Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>√s_{NN}</td>
<td>2.76 TeV</td>
<td>5.44 TeV</td>
</tr>
<tr>
<td></td>
<td>10 million</td>
<td>1 million</td>
</tr>
</tbody>
</table>

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Spectator measurement with the neutron ZDC

Transverse energy distribution of neutrons reconstructed on each side event-by-event using the 4 ZDC Channels.

Picture of the front face of ZDC

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Elliptic flow relative to the spectator plane $v_2\{\Psi_{SP}\}$

$\Psi_{SP}$ estimated from outward deflection of neutron spectators (directed flow) \textit{PRL} \textbf{111} (2013) 232302

Decorrelated from plane of all spectators & $\Psi_{RP}$ because nuclear recoils release

- Neutrons
- Protons
- Nuclear fragments (deflected in LHC)

Mixed harmonic\textsuperscript{1} observable $v_2\{\Psi_{SP}\} = \frac{1}{3} \left( \frac{\langle x^T x^C x^A \rangle}{\langle x^C x^A \rangle} + \frac{\langle x^T y^C y^A \rangle}{\langle y^C y^A \rangle} + \sqrt{\frac{\langle y^T y^C x^A \rangle\langle y^T x^C y^A \rangle}{\langle x^C x^A \rangle\langle y^C y^A \rangle}} \right) \text{sgn}(...)$

$q_n = x_n + iy_n = \sum w_j \exp in\varphi_j$

$\langle ... \rangle =$ event average

\textsuperscript{1}Selyuzhenkov \textit{et al.} \textit{PRC} \textbf{77} (2008) 034904

$T := \text{tracks} \ (|\eta| < 0.8) \ C := \text{ZDC} \ (\eta < -8.8) \ A := \text{ZDC} \ (\eta > 8.8)$

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Elliptic flow: participant vs. spectator plane

\[ v_2\{2, \Delta \eta > 1\} = \sqrt{\langle \cos 2(\varphi_1 - \varphi_2) \rangle} \]
\[ v_2\{\Psi_{SP}\} = \langle \cos 2(\varphi - \Psi_{SP}) \rangle \]
\[ v_2\{4\} = \left[ 2\langle \cos 2(\varphi_1 - \varphi_2) \rangle \right]^2 - \frac{1}{4} \langle \cos 2(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle \]

Close to Bessel-Gaussian Model (BGM) \( v_2\{2\} \neq v_2\{4\} = v_2\{\Psi_{SP}\} \)

But splitting between \( v_2\{\Psi_{SP}\} \) and \( v_2\{4\} \) observed
Participant vs. spectator plane fluctuations

$v_2\{2, |\Delta \eta| > 1\}/v_2\{4\}$

$v_2\{\Psi_{SP}\}/v_2\{4\}$
Participant vs. spectator plane fluctuations

$\frac{v_2\{2, |\Delta \eta| > 1\}}{v_2\{4\}}$

$\frac{v_2\{\Psi_{SP}\}}{v_2\{4\}}$

Central: ratio $> 1$

- Fewer spectator neutrons
- Correlation of $\Psi_{SP}$ & $\Psi_2$
- Correlated local particle production reducing $v_2\{4\}$
Participant vs. spectator plane fluctuations

\[ v_2\{2, |\Delta \eta| > 1\}/v_2\{4\} \]

\[ v_2\{\Psi_{SP}\}/v_2\{4\} \]

**Central: ratio > 1**
- Fewer spectator neutrons
- Correlation of \( \Psi_{SP} \) & \( \Psi_2 \)
- Correlated local particle production reducing \( v_2\{4\} \)

**Midcentral: ratio ≥ 1**
- \( \Psi_{SP} \neq \Psi_{RP} \): non-trivial decorrelation due to loss of fragments and protons

ALICE Preliminary Pb–Pb √s\(_{NN}\) = 2.76 TeV
\( p_T > 0.2 \text{ GeV/c} \)
\( |\eta| < 0.8 \)

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Participant vs. spectator plane fluctuations

Central: ratio > 1
• Fewer spectator neutrons
• Correlation of $\Psi_{SP}$ & $\Psi_2$
• Correlated local particle production reducing $v_2\{4\}$

Midcentral: ratio $\geq 1$
• $\Psi_{SP} \neq \Psi_{RP}$: non-trivial decorrelation due to loss of fragments and protons

Peripheral: ratio $\leq 1$
• Fewer spectator neutrons (bound into fragments)
• Fewer participants: deviations from BGM
Participant vs. spectator plane fluctuations

\[ v_2\{2, |\Delta \eta| > 1\}/v_2\{4\} \]

\[ v_2\{\Psi_{SP}\}/v_2\{4\} \]

Central: ratio > 1
- Fewer spectator neutrons
- Correlation of \( \Psi_{SP} \) & \( \Psi_2 \)
- Correlated local particle production reducing \( v_2\{4\} \)

Midcentral: ratio ≥ 1
- \( \Psi_{SP} \neq \Psi_{RP} \): non-trivial decorrelation due to loss of fragments and protons

Peripheral: ratio ≤ 1
- Fewer spectator neutrons
- Fewer participants: deviations from BGM

Comparison to Models
- Incomplete initial state description
- Effects of QGP evolution

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ALI-PREL-518236
System size dependence of $\Psi_2$ & $\Psi_{SP}$ fluctuations

Similar trends in Pb–Pb and Xe–Xe

Xe–Xe: statistics limits significance of $v_2(\Psi_{SP})/v_2(4)$ deviation from unity
Weak $p_T$-dependence suggests common origin of fluctuations at low and intermediate $p_T$

Slopes (2 $-$ 4$\sigma$ significance) indicate $p_T$-dependent decorrelation of flow magnitude & angles
\( \nu_2/\varepsilon_2 \) scaling in hydrodynamics

Ideal fluid evolution \( \nu_2 \propto \kappa \varepsilon_2 \)

\( \kappa \) hydrodynamic response of QGP

- \( \frac{\nu_2}{\varepsilon_2} \propto \) initial energy density \( \approx \frac{1}{S} \frac{dN_{ch}}{d\eta} \)
- Deviation from scaling due to
  - Later stages of evolution: freeze-out
  - Viscosities

In viscous hydrodynamics \( \nu_2/\varepsilon_2 \) depends on

- Centrality: sensitive due to lifetime of QGP
- Viscosity: strong sensitivity
- Colliding system: weak dependence
$v_2/\varepsilon_2$ scaling with ALICE at the LHC

Ideal fluid evolution $v_2 \propto \kappa \varepsilon_2$

- $\kappa$ hydrodynamic response of QGP
- $\frac{v_2}{\varepsilon_2} \propto$ initial energy density $\approx \frac{1}{S} \frac{dN_{ch}}{d\eta}$
- Deviation from scaling due to
  - Later stages of evolution: freeze-out
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In viscous hydrodynamics $v_2/\varepsilon_2$ depends on

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System size dependence of $v_2/\varepsilon_2$ scaling

- $\varepsilon_2$ and transverse area ($S$) from TRENTo:

- $dN_{\text{ch}}/d\eta$ from ALICE:
  * Xe-Xe PLB 790 (2019) 35
  * Pb-Pb PRL 106 (2011) 032301

Individual fits to each $v_2/\varepsilon_2$ ratio for participant and spectator planes

- Scaling well described by linear function
- Each $v_2/\varepsilon_2$ has a different slope
System size dependence of $v_2/\varepsilon_2$ scaling

Difference of $(7.0 \pm 0.9)\%$ observed between Pb-Pb and Xe-Xe collisions

• Additional $+1.8\%$ from choice of $T_{\text{RENTo}}$ tune: LHC data\(^1\) versus LHC+RHIC data\(^2\)

Sensitive to details of initial state and QGP viscosity

\(^1\) Bernhard et al. Nat. Phys. 15 (2019) 1113
\(^2\) JETSCAPE collaboration PRC 103 (2021) 054904
Summary

first measurement of $v_2\{\Psi_{SP}\}$ at the LHC

$v_2\{\Psi_{SP}\}/v_2\{4\}$

• Large deviations of models indicate an incomplete description of fluctuations
• Weak $p_T$-dependence suggests common origin of fluctuations
• Small non-zero slopes indicate $p_T$-dependent flow vector decorrelation

$v_2/\varepsilon_2$ in Pb–Pb and Xe–Xe collisions

• Observed difference is sensitive to details of initial state and QGP viscosity