Experimental overview of fluctuations in initial stages

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Introduction

- Particle distribution over azimuthal angle:
  - $v_n$ coefficients driven by:
    - Initial geometry
    - Medium properties
  - $v_2 \rightarrow$ elliptical shape of the collision zone

- Initial state fluctuations studied by:
  - Higher order $v_n$
  - Multi-particle cumulants

\[
\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Psi_n)]
\]

System symmetry $\rightarrow$ elliptic flow, $v_2$

Fluctuations $\rightarrow$ triangular flow, $v_3$
Simultaneous measurements of $v_2$, $v_3$, $v_4$, ... provide better understanding of initial states and medium properties.

Comparison of $v_n$ measured with different methods is direct probe of flow fluctuations.

Xe+Xe collisions provide a chance to bridge the gap between large and small systems.
Methodology

✧ **Two-particle correlations (2PC) and Scalar-product (SP) methods**

- Correlating tracks with Q-vectors at forward rapidities
- Non-flow suppressed by large $\Delta \eta$-gap ($\Delta \eta > 2$)

\[
u_2(2) = \langle v_2 \rangle^2 + \sigma_v^2
\]

✧ **Multi-particle cumulants**:

- Correlating tracks at mid-rapidity with each other
- Analytically suppress non-flow
- Sensitive to flow fluctuations

\[
u_n(4) \approx \langle v_2 \rangle^2 - \sigma_v^2
\]

**References**


arXiv:0809.2949 [nucl-ex]
Recent results of $v_n$ measured in Xe+Xe and Pb+Pb systems at the LHC:

**ATLAS**
- Xe+Xe@5.44TeV: ATLAS-CONF-2018-011
- Pb+Pb@5.02TeV: ATLAS-CONF-2016-105

**ALICE**
- Xe+Xe@5.44TeV: arXiv:1805.01832
- Pb+Pb@5.02&2.74 TeV: arXiv:1804.02944

**CMS**
- Xe+Xe@5.44TeV: HIN-18-001
- Pb+Pb@5.02TeV: HIN-16-018, Phys. Lett. B 776 (2017) 195
Pb+Pb collisions
$v_n(p_T)@\text{Pb+Pb} \ 5.02 \text{ TeV}$

- Measurement of the $v_n$ in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV allowed to reach high $p_T$ of 25 GeV
- Harmonics measured up to $n=7$ with SP
- Weak $\eta$ dependence
- The $v_n$ at $\sqrt{s_{NN}}=2.76$ and 5.02 TeV energies are similar
$v_n(p_T)@Pb+Pb$ 5.02 TeV

- $v_n$ at high-$p_T$: up to 100 GeV
  - Multi-particle $v_2 \{4,6,8\}$
  - $v_2 \{SP\}$ & $v_3 \{SP\}$
- At low $p_T$ results follow the trend:
  $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Positive $v_2$ values up to $p_T \sim 60-80$ GeV
- $v_3$ values are consistent with zero for $p_T > 20$ GeV
Clear hierarchy $v_{n+1} > v_n$ is observed

- $v_2$ is strongly dependent on event centrality and is largest in mid-central events (30-50%)
- higher order $v_n$ show weak centrality dependence

ALICE: The relative variation of these flow coefficients between 2.76 & 5.02 TeV

- All harmonics are observed to increase with energy, between about 2 and 10%
Xe+Xe collisions
$v_n(p_T)@Xe+Xe$ 5.44 TeV

- Measured $v_n$ up to $n=5$, wide $p_T$ range (20 GeV for $v_2$)
- Typical $p_T$ dependence is observed
- $v_2$ dominant except the most central collisions
- $v_n$ measured with higher order correlations smaller
  - suppressed non-flow
  - impact of fluctuations

**ATLAS-CONF-2018-011**
$v_2(p_T)@Xe+Xe$ 5.44 TeV

- $v_2\{2\} > v_2\{4\}$
  - Event-by-event fluctuations

- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
  - Collectivity

CMS Preliminary

$XeXe \sqrt{s_{NN}} = 5.44$ TeV

CMS-PAS-HIN-18-001
$v_3(p_T)@Xe+Xe$ 5.44 TeV

- $v_3\{2\} > v_3\{4\}$
- Event-by-event fluctuations
- Larger than for $v_2$

CMS Preliminary

$\sqrt{s_{NN}} = 5.44$ TeV

CMS-PAS-HIN-18-001
\( v_2(p_T)@\text{Xe+Xe} \) 5.44 TeV vs. \( \sqrt{s} @\text{Pb+Pb} \) 5.02 TeV

- \( v_2 \) in Xe+Xe vs. Pb+Pb
  - \( v_2[\text{Xe+Xe}] \) larger than \( v_2[\text{Pb+Pb}] \) in central events
  - Larger differences at intermediate \( p_T \)

\[ \text{ALICE: arXiv:1805.01832} \]
$v_3(p_T)@\text{Xe+Xe \ 5.44 TeV vs. @Pb+Pb \ 5.02 TeV}$

✧ Overall good agreement between Xe+Xe and Pb+Pb

ALICE: arXiv:1805.01832
$v_n(p_T)@\text{Xe+Xe}$ 5.44 TeV vs. @\text{Pb+Pb} 5.02 TeV

- **Central collisions:**
  - $v_n[\text{Xe+Xe}]$ larger than $v_n[\text{Pb+Pb}]$
  - Main effect: fluctuations

- **Peripheral collisions:**
  - $v_n[\text{Pb+Pb}]$ larger than $v_n[\text{Xe+Xe}]$
  - Viscous effects are dominant

- CMS - PAS - HIN - 18 - 001
- CMS - PAS - HIN - 16 - 018

23/05/18

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$v_n(\text{centrality})@\text{Xe+Xe} 5.44 \text{ TeV}$

vs.

$v_n(\text{centrality})@\text{Pb+Pb} 5.02 \text{ TeV}$

- Integrated $v_2$ is higher in most central events for Xe+Xe collisions
  - Elongated Xe shape
  - Smaller $N_{\text{part}} \rightarrow$ larger fluctuations

- Reduced value in mid-central and peripheral
  - smaller initial eccentricities
  - viscous corrections

- $v_3$: the increase in most central events is less pronounced

- Ratio is similar for different $p_T$ intervals

- Consistent with predictions
\[ v_n(\text{centrality})@\text{Xe+Xe} \ 5.44 \ TeV \]
\[ v_n(\text{centrality})@\text{Pb+Pb} \ 5.02 \ TeV \]

- **\( v_2 \):** larger < 35\% in central
  - larger IS fluctuations + nuclear deformation

- **\( v_2 \):** smaller ~10\% in semi-central and peripheral
  - smaller radial flow and/or larger viscous effects

- **\( v_3 \):** larger in all centralities, decreasing from central to peripheral
  - larger IS fluctuations

- Quantitatively described by models up to a few \%
Summary

✧ A lot of new, interesting results!
  • Not enough time to show everything

✧ First measurement of flow in Xe+Xe by ATLAS, ALICE and CMS

✧ Comparing Xe+Xe to Pb+Pb
  • Approximate transverse energy scaling observed, broken in central collisions
  • Differences attributed to larger initial state fluctuations, smaller radial flow and/or larger viscous effects
$v_n(p_T)@Xe+Xe$ 5.44 TeV vs. @Pb+Pb 5.02 TeV

- $v_2(p_T)$ in Xe+Xe vs. Pb+Pb, mid-central collisions

- At fixed centrality differences increase with $p_T$
  - viscous effects and/or radial flow

- Two centrality classes with similar transverse densities consistent with each other

ALICE: arXiv:1805.01832

Model parameters: MC Glauber constituent quarks ($q=3$)
- Xe-Xe 20-30%: $1/S \frac{dN_{ch}}{d\eta} \sim 10$ fm$^{-2}$, $R \sim 4.0$ fm
- Pb-Pb 30-40%: $1/S \frac{dN_{ch}}{d\eta} \sim 10$ fm$^{-2}$, $R \sim 4.0$ fm
- Xe-Xe 30-40%: $1/S \frac{dN_{ch}}{d\eta} \sim 8$ fm$^{-2}$, $R \sim 3.6$ fm