Experimental overview of fluctuations in initial stages

Klaudia Burka
Institute of Nuclear Physics PAN

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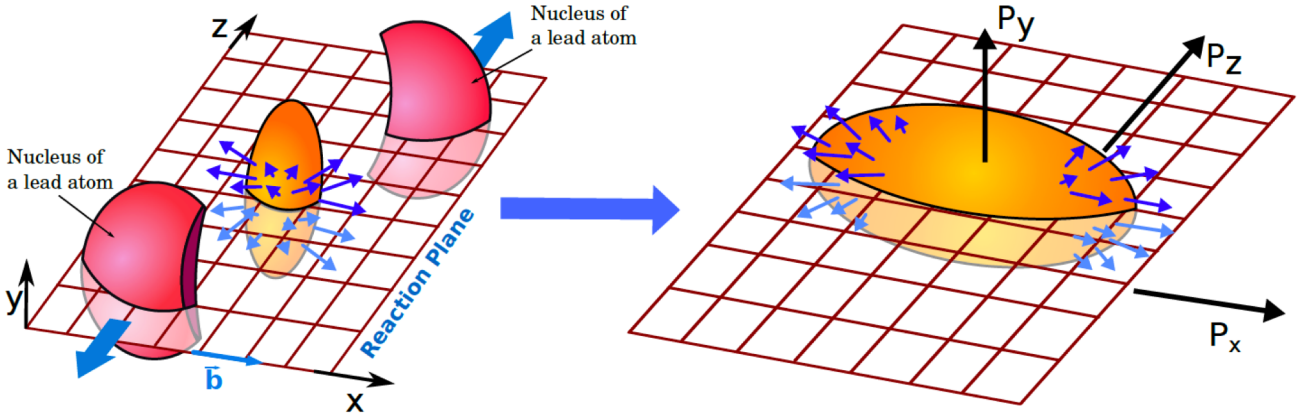
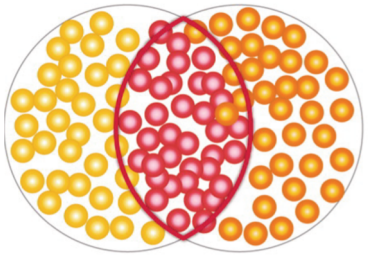
Introduction



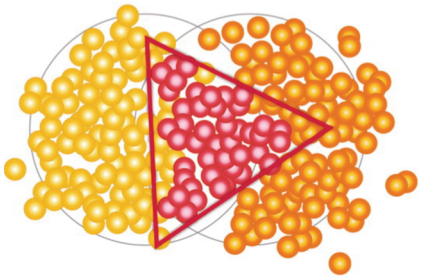
Initial spacial anisotropy → **Momentum-space anisotropy**

- Particle distribution over azimuthal angle: $\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Psi_n)]$
- v_n coefficients driven by:
  - Initial geometry
  - Medium properties
- v_2 → elliptical shape of the collision zone
- Initial state fluctuations studied by:
  - Higher order v_n
  - Multi-particle cumulants



System symmetry → elliptic flow, v_2

Fluctuations → triangular flow, v_3



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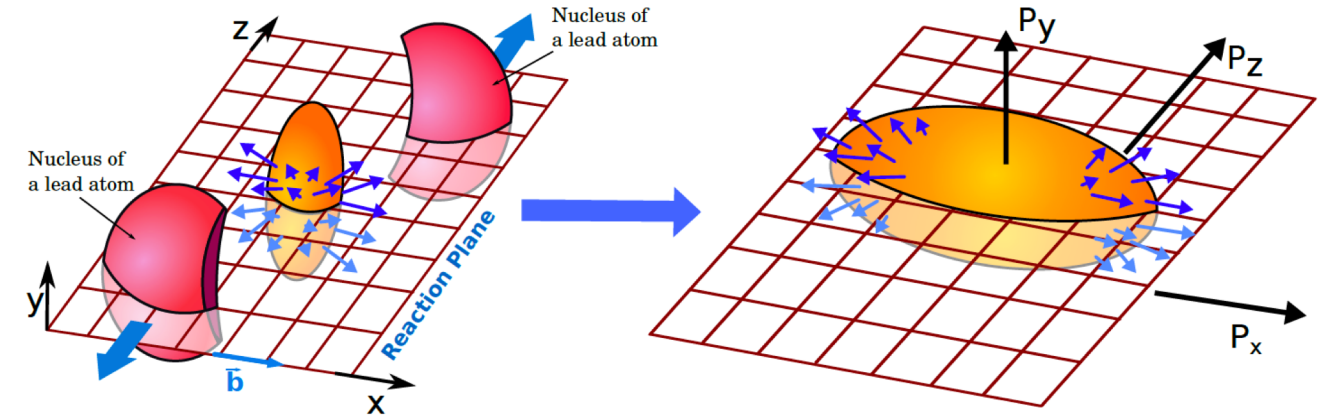


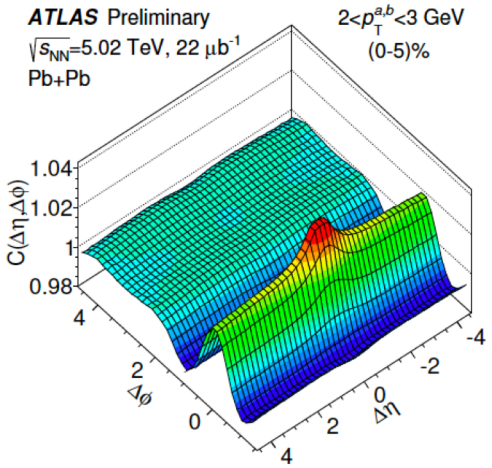
- Simultaneous measurements of v_2, v_3, v_4, … provide better understanding of initial states and medium properties
- Comparison of v_n measured with different methods is direct probe of flow fluctuations
- Xe+Xe collisions provide a chance to bridge the gap between large and small systems

Methodology

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

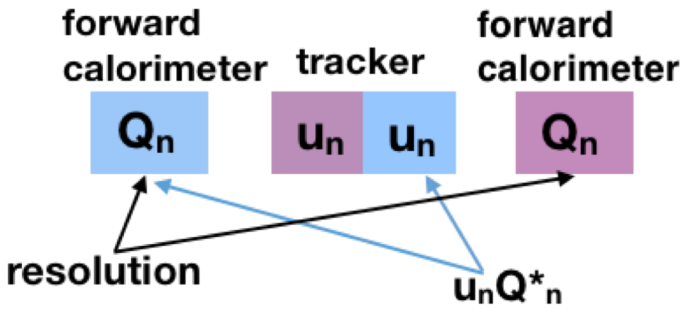
- Correlating tracks with Q-vectors at forward rapidities
- Non-flow suppressed by large Δη-gap (Δη>2)

arXiv:0809.2949 [nucl-ex]



$$u_n, Q_n = \sum_j w_j e^{in\phi_j}$$

$$v^2_2\{2\} = \langle v_2 \rangle^2 + \sigma^2_v$$



✧ Multi-particle cumulants:

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

$$v^2_2\{4\} \approx \langle v_2 \rangle^2 - \sigma^2_v$$

$$v_n\{2\} = \sqrt[2]{\langle v_n^2 \rangle},$$

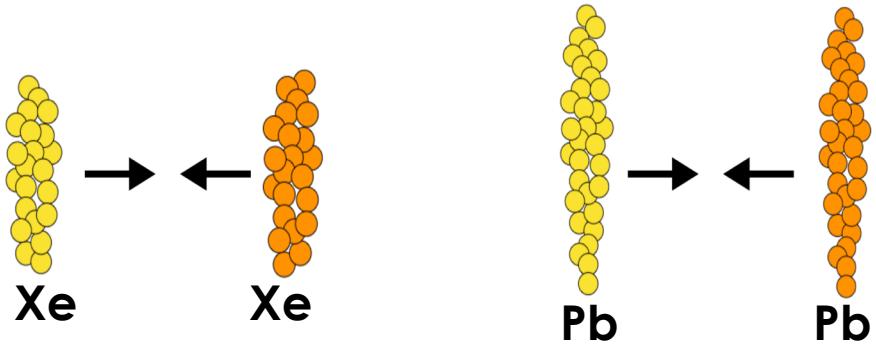
$$v_n\{4\} = \sqrt[4]{2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle},$$

$$v_n\{6\} = \sqrt[6]{\langle v_n^6 \rangle - 9\langle v_n^2 \rangle \langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3}$$

Phys.Rev. C63 (2001) 054906

From Quark Matter 2018

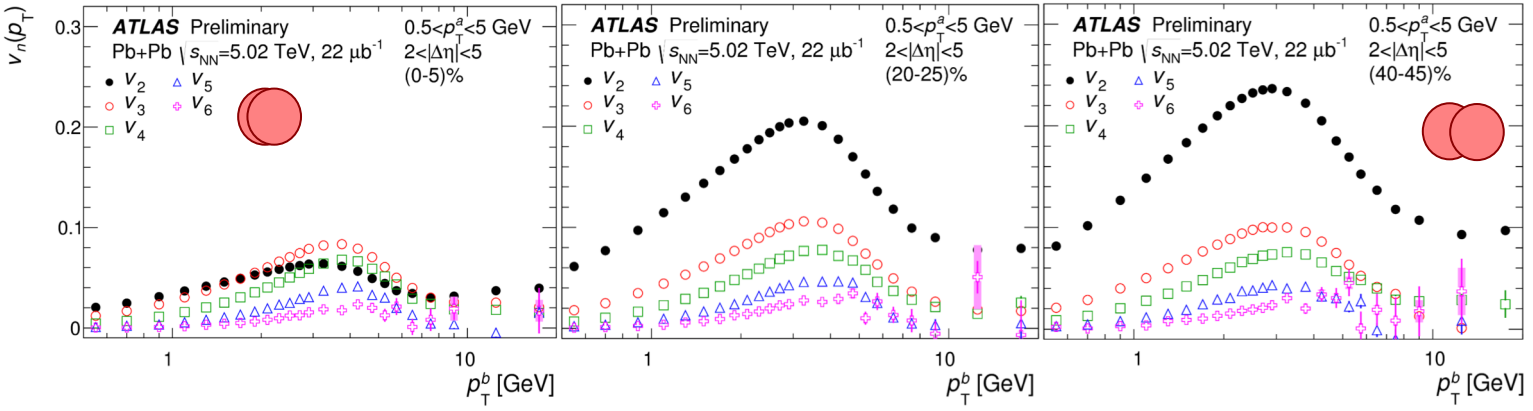
Recent results of v_n measured in Xe+Xe and Pb+Pb systems at the LHC:



- **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**

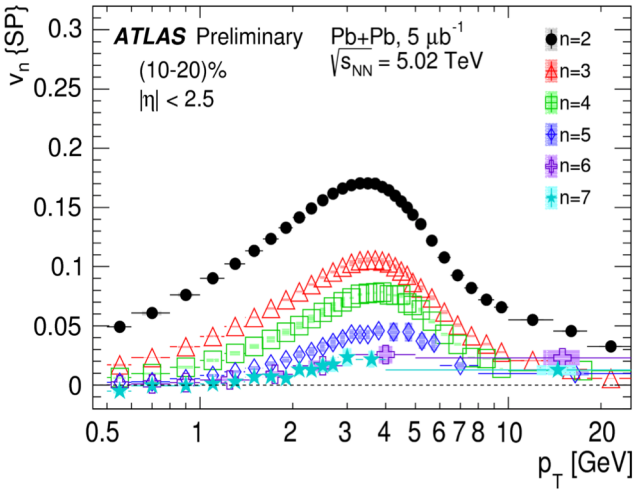
Pb+Pb collisions

$v_n(p_T)$@Pb+Pb 5.02 TeV

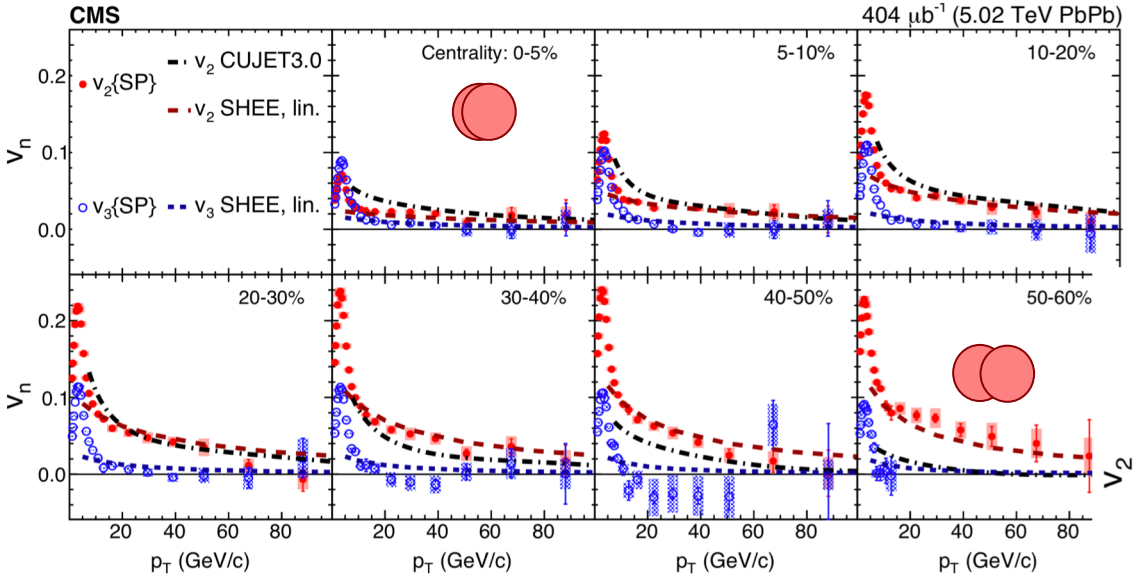


- Measurement of the v_n in Pb+Pb at $\sqrt{s_{NN}}$ =5.02 TeV allowed to reach high p_T of 25 GeV
- Harmonics measured up to n=7 with SP
- Weak η dependence
- The v_n at $\sqrt{s_{NN}}$=2.76 and 5.02TeV energies are similar

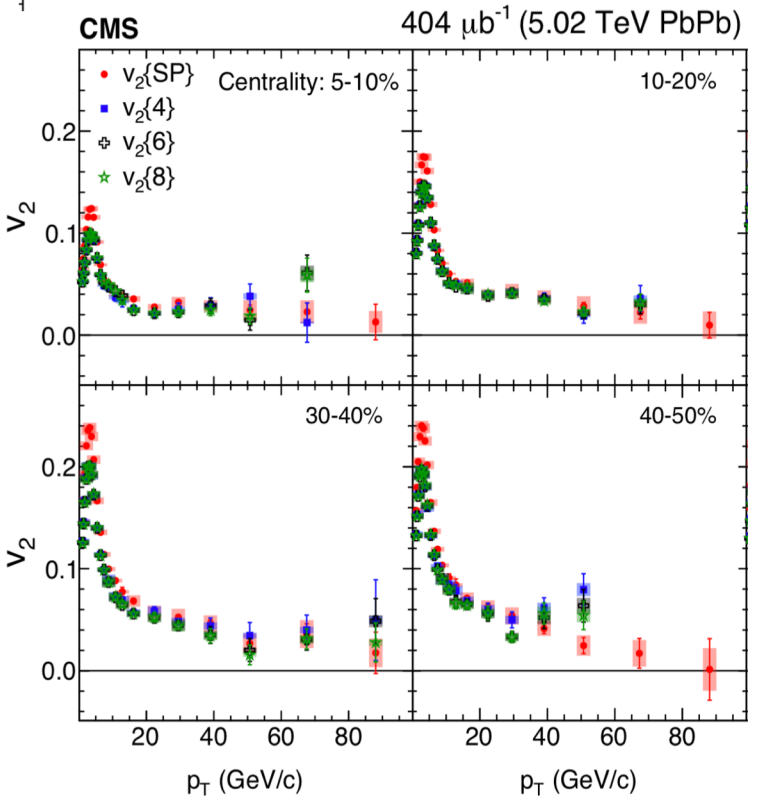
ATLAS-CONF-2016-105



$v_n(p_T)$@Pb+Pb 5.02 TeV

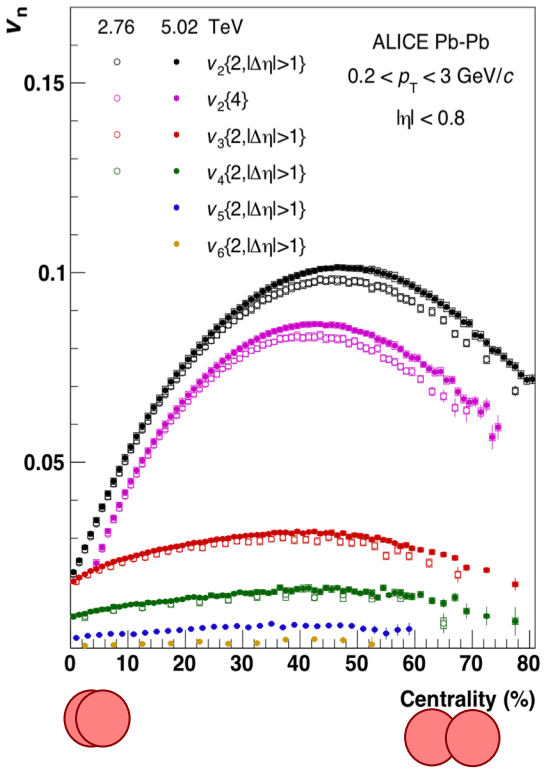


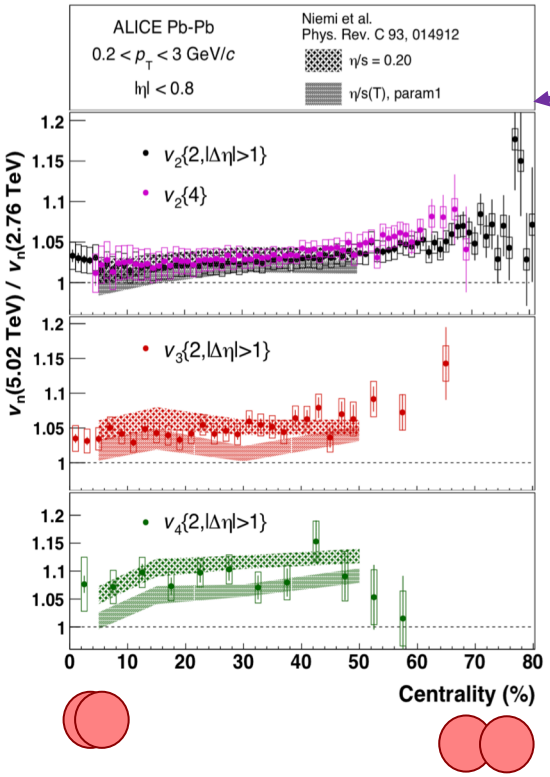
Phys. Lett. B 776 (2017) 195



- 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~60-80 GeV
- v_3 values are consistent with zero for p_T>20 GeV

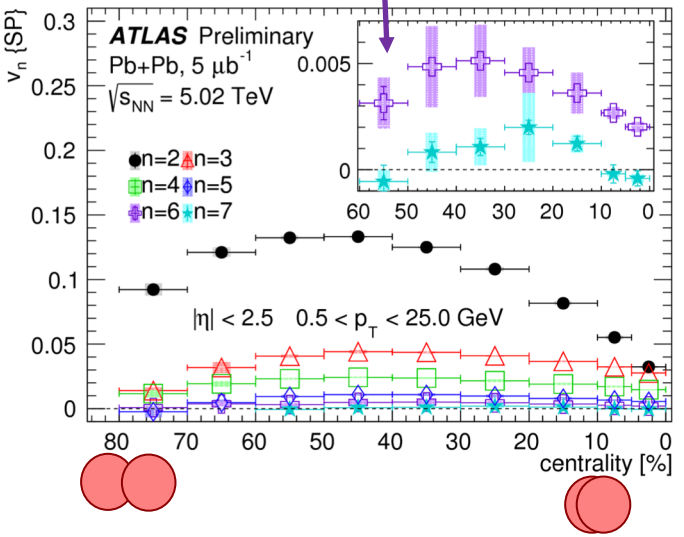
v_n(centrality)@Pb+Pb 5.02 TeV





ALICE: arXiv:1804.02944

ATLAS-CONF-2016-105



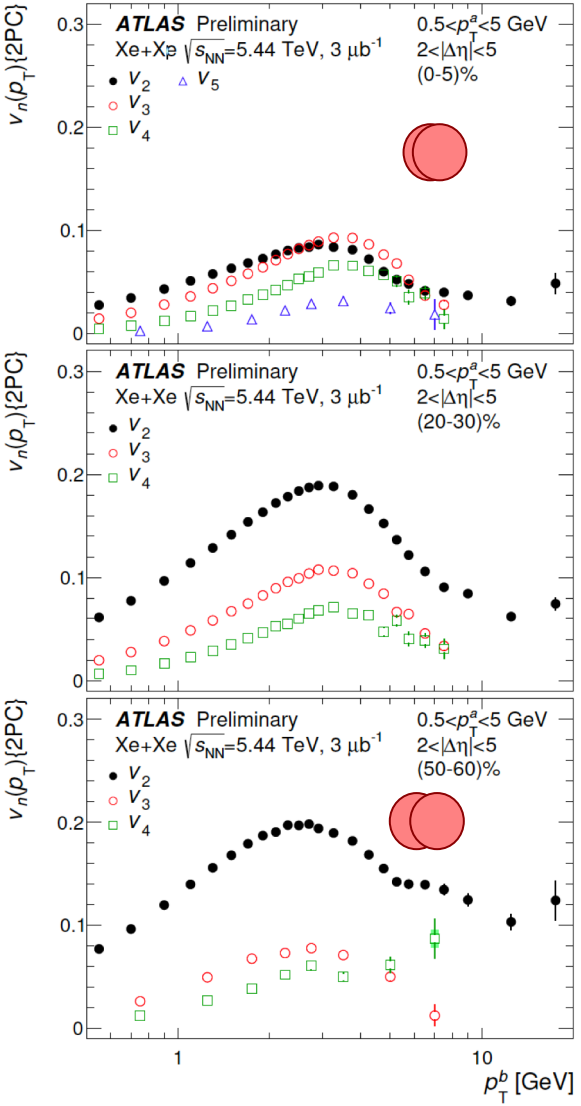
- Clear hierarchy $v_{n+1} > v_n$ is observed
  - v_2 is strongly dependent on event centrality and is largest in mid-central events (30-50%)
  - higher order v_n show weak centrality dependence
- ALICE: The relative variation of these flow coefficients between 2.76 & 5.02 TeV
  - All harmonics are observed to increase with energy, between about 2 and 10%

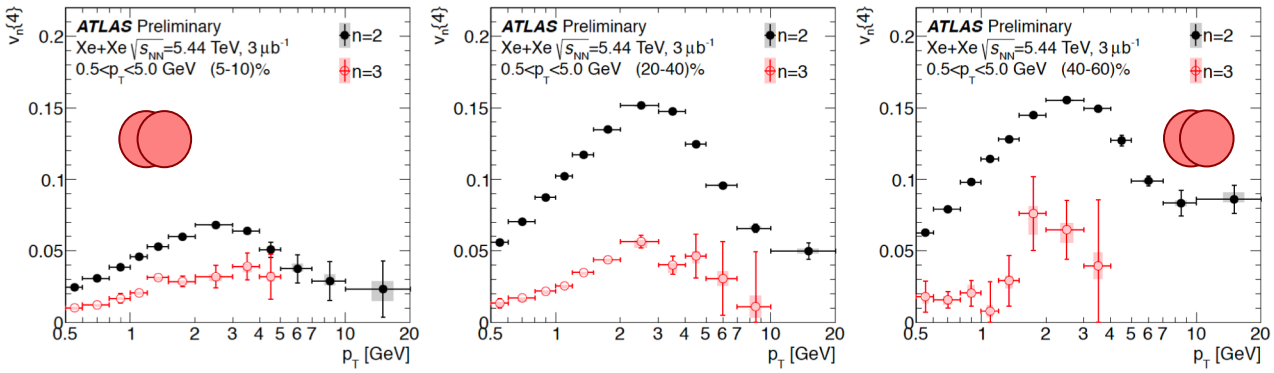
Xe+Xe collisions

$v_n(p_T)$@Xe+Xe 5.44 TeV

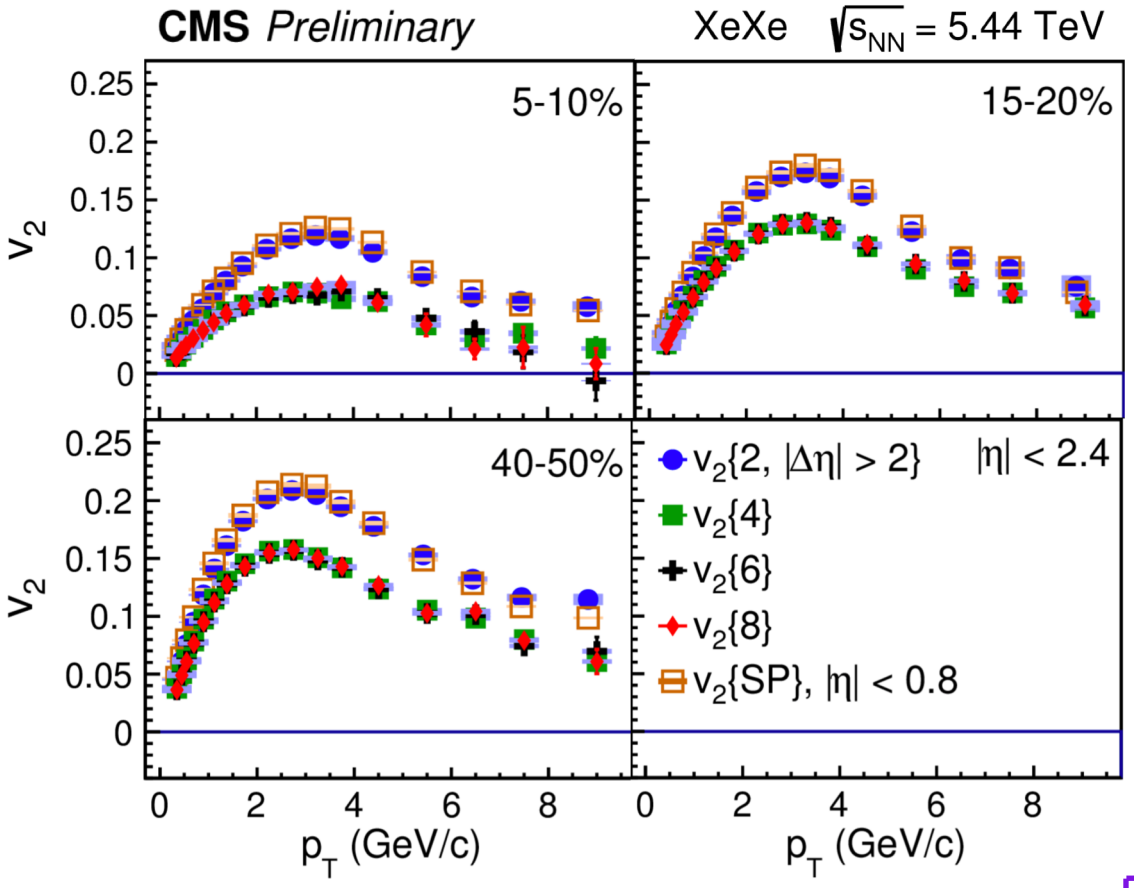
- Measured v_n up to n=5, wide p_T range (20 GeV for v_2)
- Typical p_T dependence is observed
- v_2 dominant except the most central collisions
- v_n measured with higher order correlations smaller
  - suppressed non-flow
  - impact of fluctuations

ATLAS-CONF-2018-011





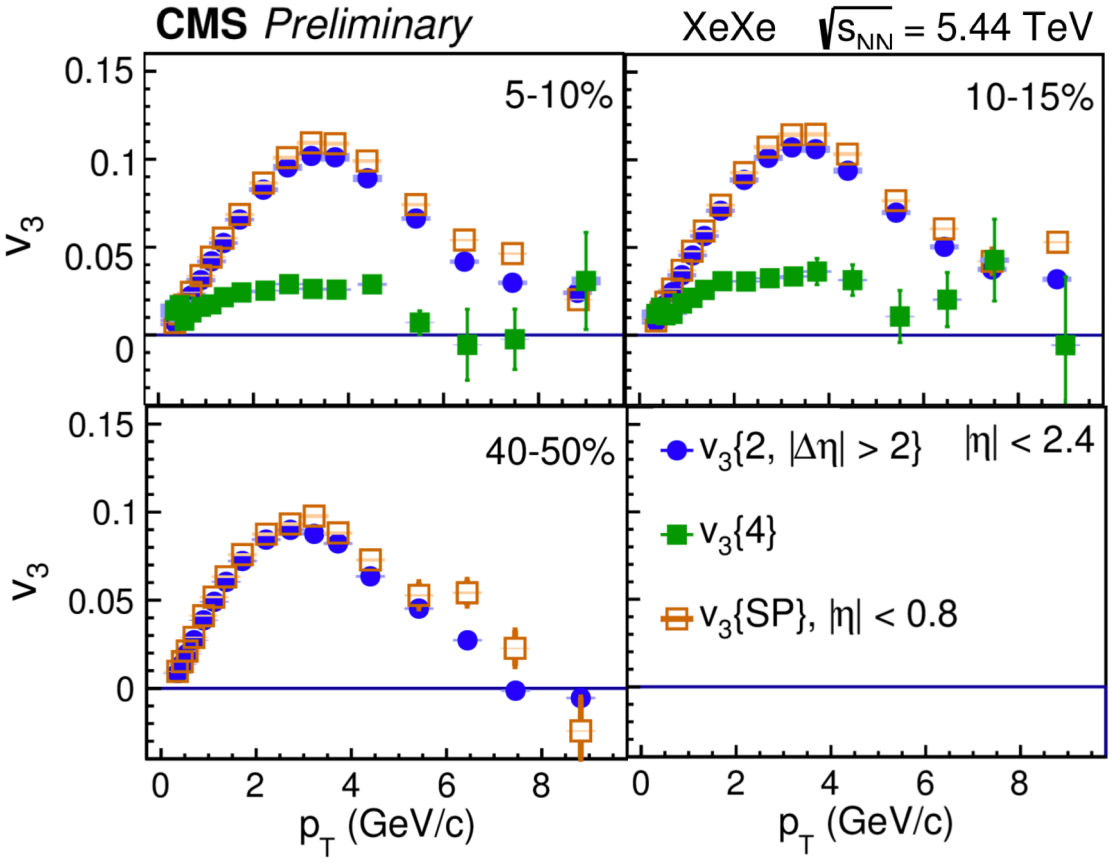
$v_2(p_T)$@Xe+Xe 5.44 TeV



- $v_2\{2\} > v_2\{4\}$
  - Event-by-event fluctuations
- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
  - Collectivity

CMS-PAS-HIN-18-001

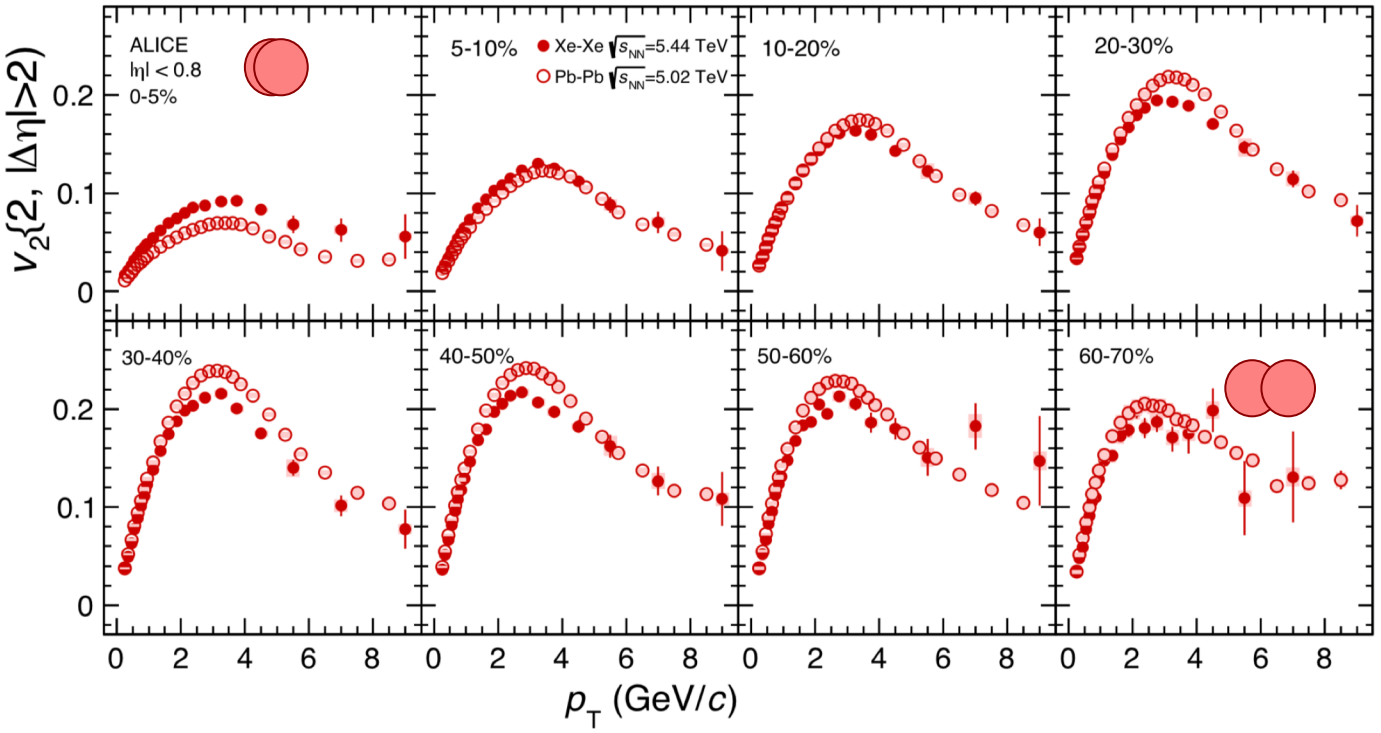
$v_3(p_T)$@Xe+Xe 5.44 TeV



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

CMS-PAS-HIN-18-001

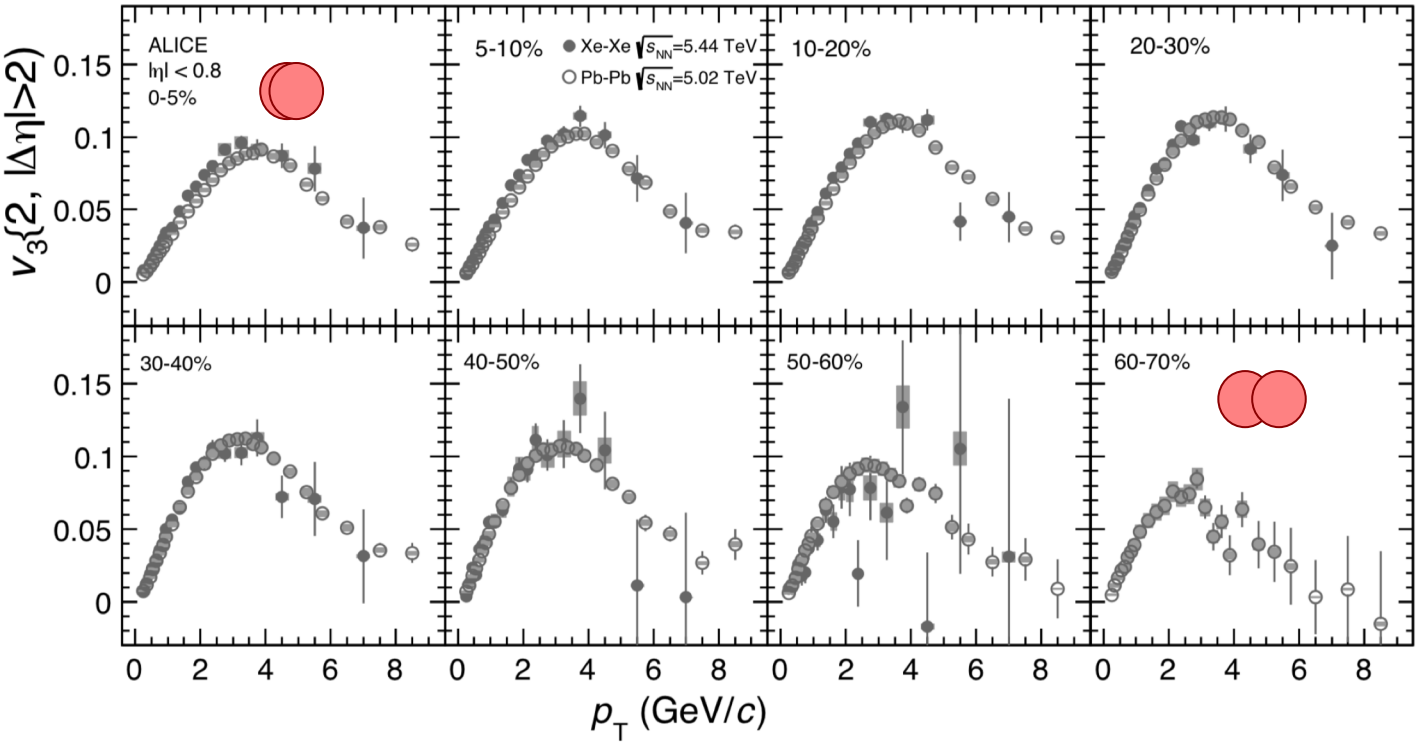
$v_2(p_T)$@Xe+Xe 5.44 TeV vs. @Pb+Pb 5.02 TeV



- v_2 in Xe+Xe vs. Pb+Pb
  - v_2[Xe+Xe] larger than v_2[Pb+Pb] in central events
  - Larger differences at intermediate p_T

ALICE: arXiv:1805.01832

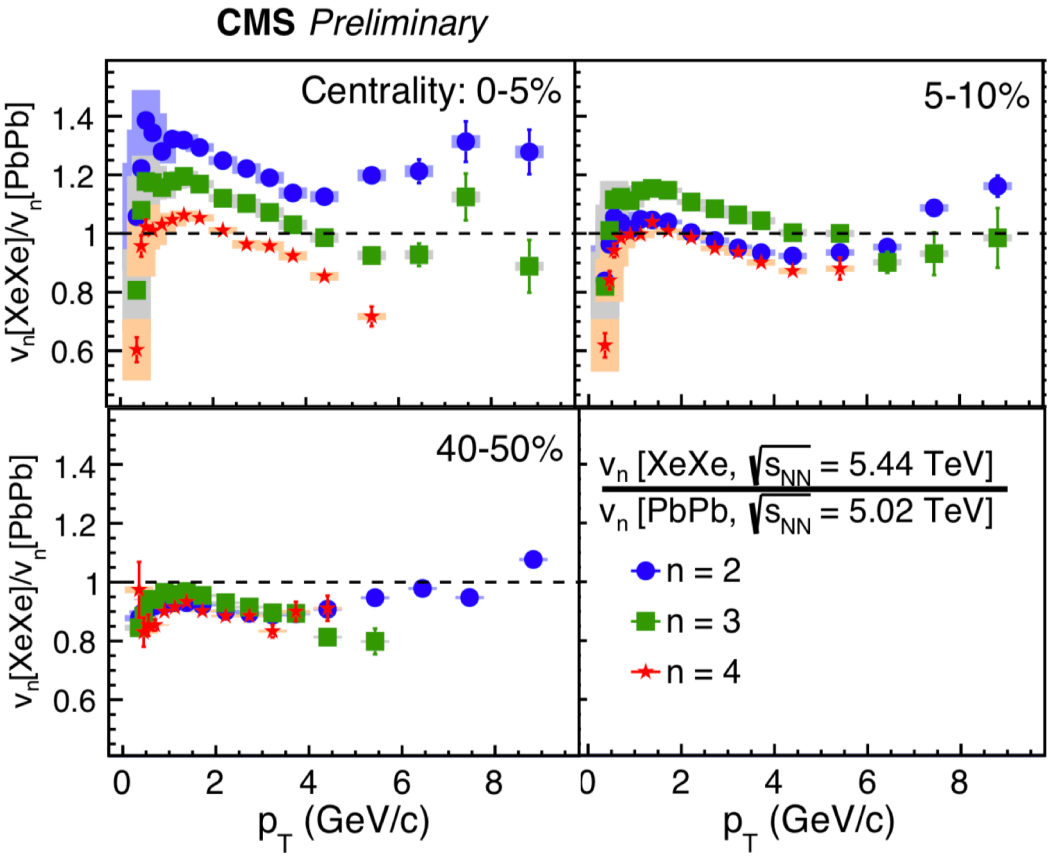
$v_3(p_T)$@Xe+Xe 5.44 TeV vs. @Pb+Pb 5.02 TeV



ALICE: arXiv:1805.01832

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

$v_n(p_T)$@Xe+Xe 5.44 TeV vs. @Pb+Pb 5.02 TeV



- Central collisions: v_n[Xe+Xe] larger than v_n[Pb+Pb]
  - Main effect: fluctuations
- Peripheral collisions: v_n[Pb+Pb] larger than v_n[Xe+Xe]
  - Viscous effects are dominant

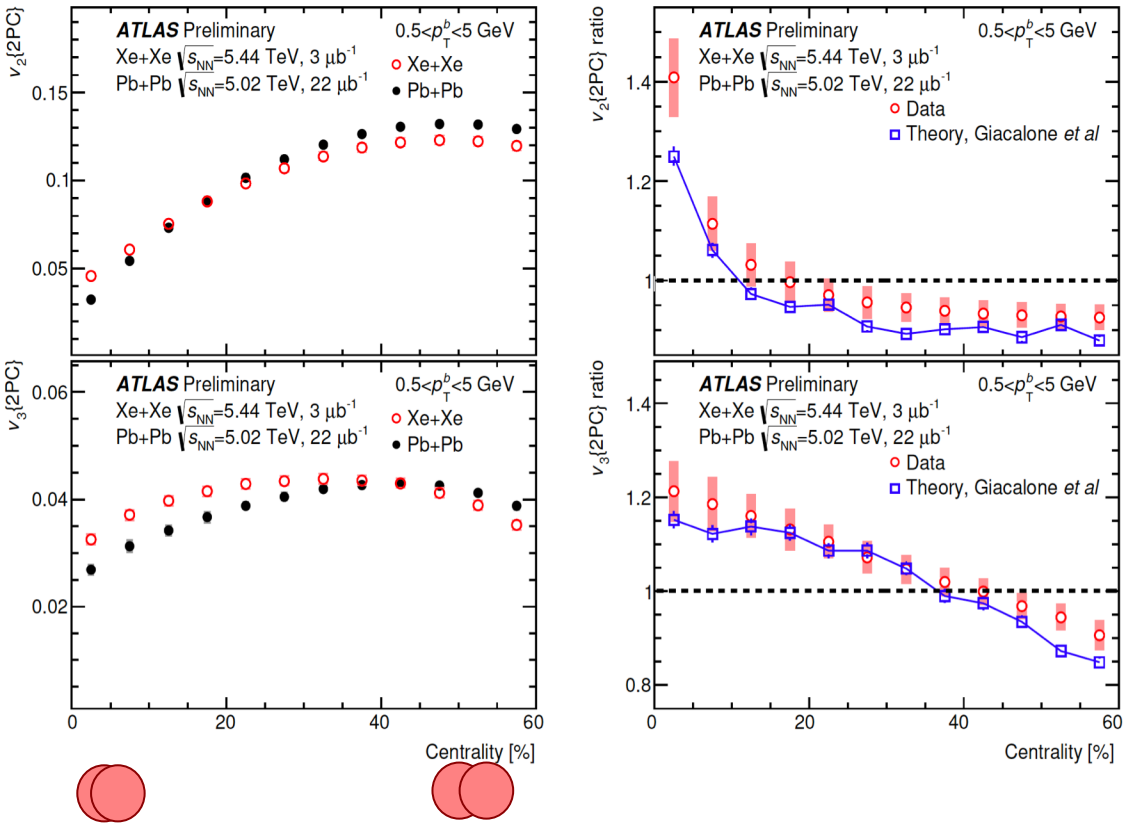
Xe+Xe: CMS-PAS-HIN-18-001

Pb+Pb: CMS-PAS-HIN-16-018

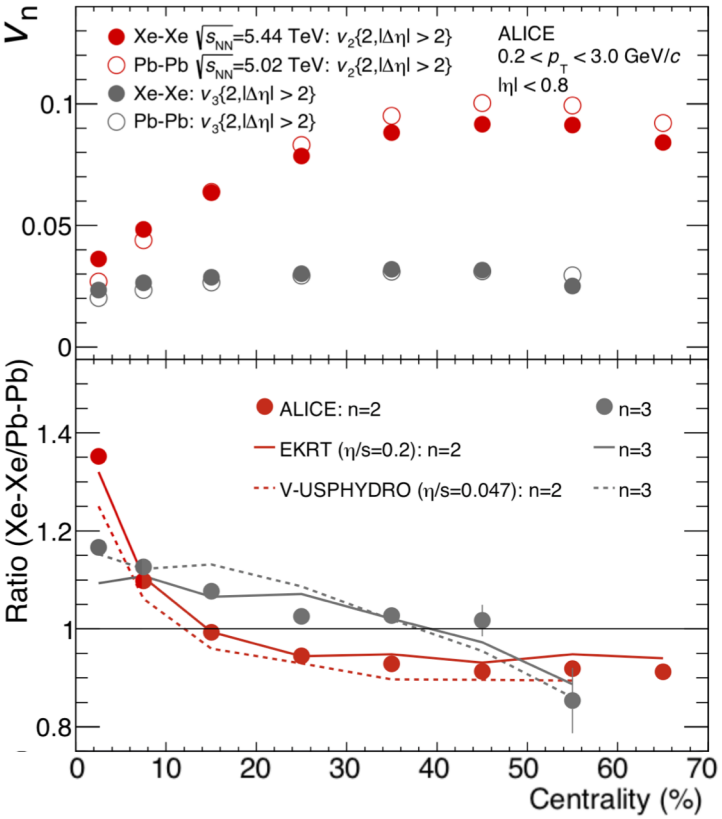
v_n(centrality)@Xe+Xe 5.44 TeV vs. v_n(centrality)@Pb+Pb 5.02 TeV

- Integrated v_2 is higher in most central events for Xe+Xe collisions
  - Elongated Xe shape
  - Smaller N_{part} → 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

ATLAS-CONF-2018-011



v_n(centrality)@Xe+Xe 5.44 TeV
v_n(centrality)@Pb+Pb 5.02 TeV



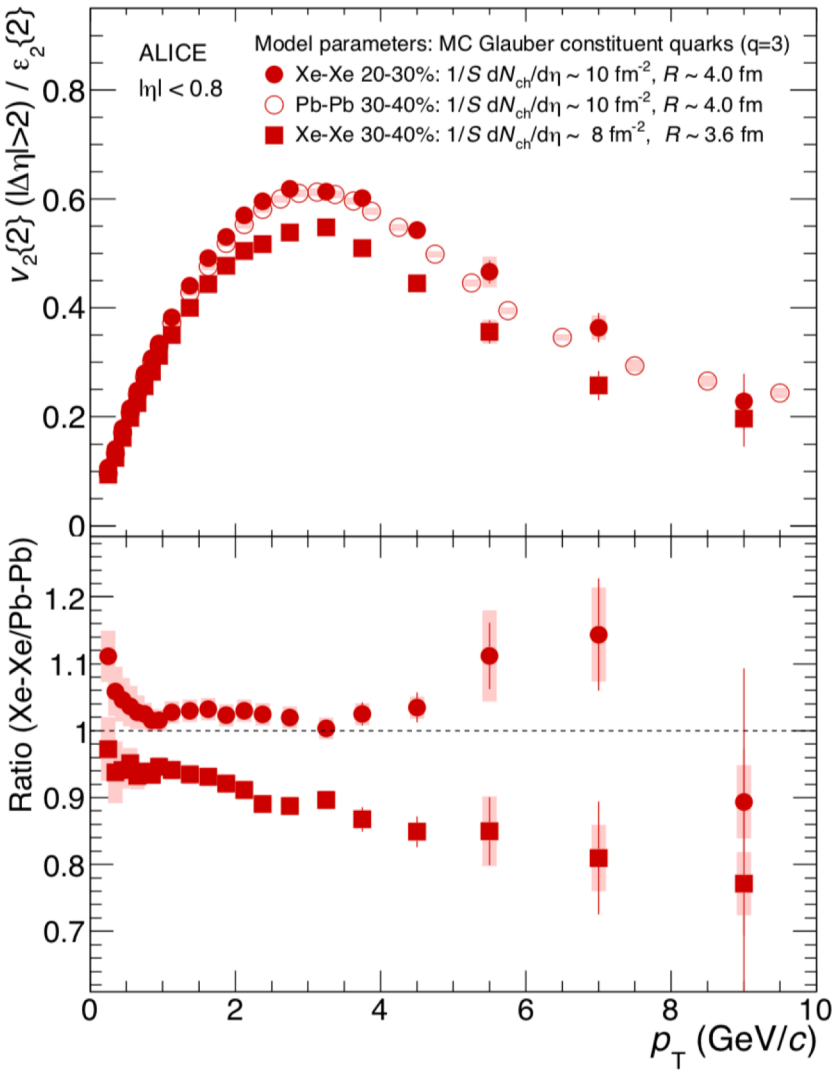
ALICE: arXiv:1805.01832

- 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
  - Dierences attributed to larger initial state fuctuations, smaller radial flow and/or larger viscous efects

$v_n(p_T)$@Xe+Xe 5.44 TeV vs. @Pb+Pb 5.02 TeV



ALICE: arXiv:1805.01832

- $v_2(p_T)$ 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