Measurements of anisotropic flow and flow fluctuations in Xe-Xe and Pb-Pb collisions with ALICE

arXiv:1804.02944, arXiv:1805.01832

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Netherlands Organisation for Scientific Research

What is flow?

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2 \sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]$$

Flow: momentum anisotropies in azimuthal angle, quantified by coefficients v_n

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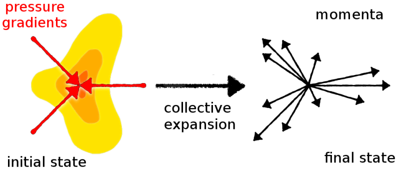
- Soft sector (low p_T, $\lesssim 2$ GeV/c): multiple interactions between partons (a.k.a. "collectivity") convert initial-state (IS) spatial anisotropies into final-state momentum ones



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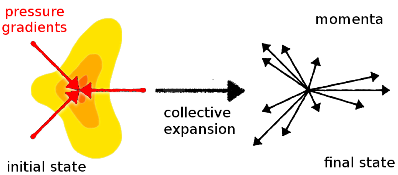

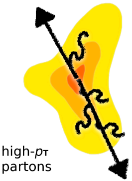

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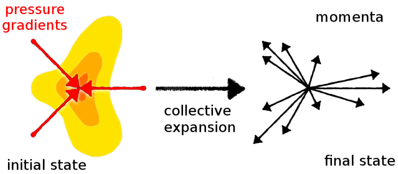
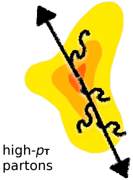
- Common origin: spatial anisotropies from geometry of the collision and IS fluctuations





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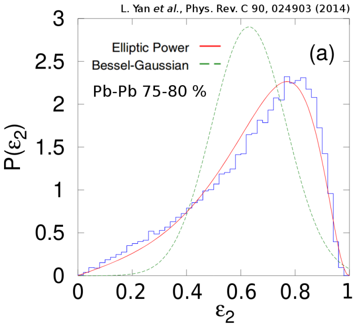

Distribution of IS eccentricity ε_2 in MC-Glauber

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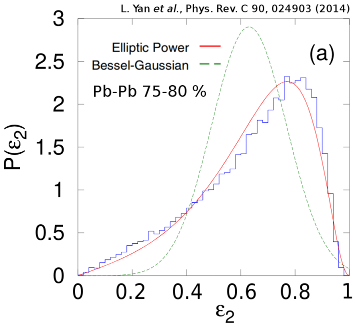
- How does flow depend on system size / transverse energy density?



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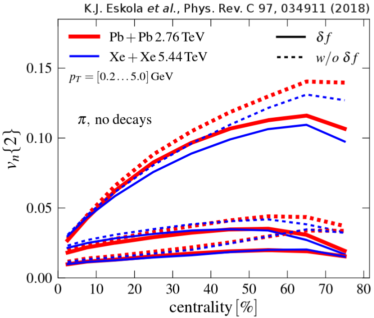

Predictions for v_n ($n = 2, 3, 4$) in Xe–Xe collisions, with (continuous line) and without (dashed line) viscous corrections

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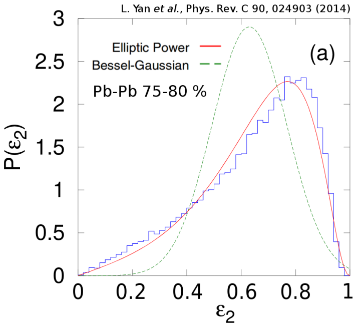
$\longrightarrow$ **two new ALICE papers: arXiv:1804.02944, arXiv:1805.01832**



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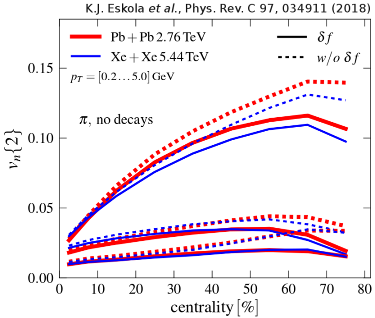

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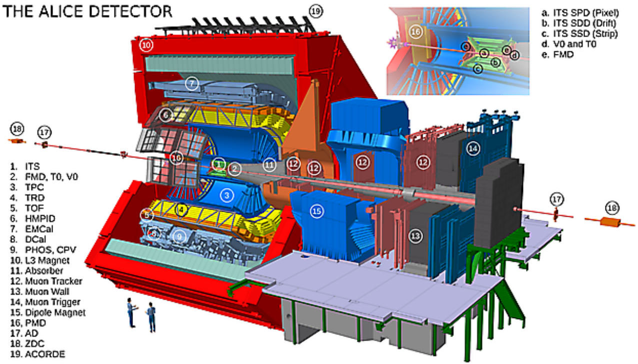


Data samples

system	$\sqrt{s_{\rm NN}}$ (TeV)	events ($\times 10^6$)	$\mathcal{L}_{\rm int}$ (μb^{-1})
Pb-Pb	2.76	13	2
Pb-Pb	5.02	78	13
Xe-Xe	5.44	1	

Detectors employed

- **I**nner **T**racking **S**ystem: tracking, vertexing, triggering
- **T**ime **P**rojection **C**hamber: tracking, vertexing
- **V0**: triggering, event plane and centrality determination
  V0A: $2.8 < \eta < 5.1$
  V0C: $-3.7 < \eta < 1.7$

Track selection

- **inclusive charged particles**
- $|\eta| < 0.8$
- $0.2 < p_{\rm T} < 50$ GeV/c

What do we measure?

Multi-particle cumulants (*à la* Generic Framework[1])

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

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

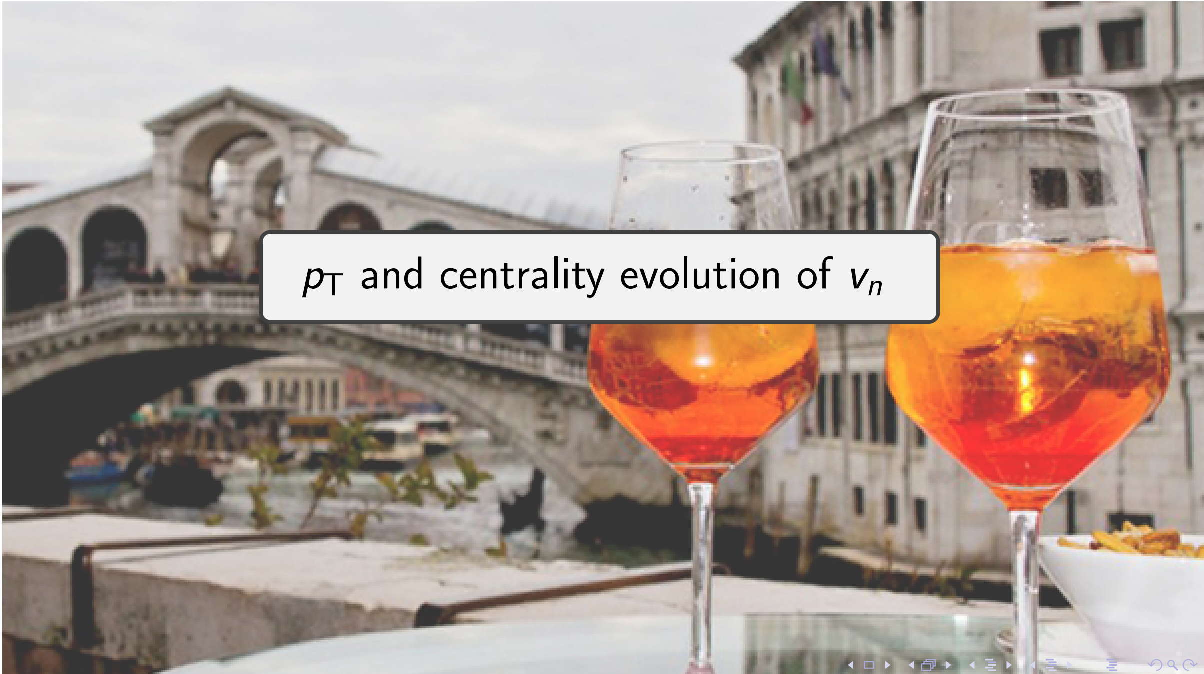
2-particle cumulant with **Scalar Product** method

- Correlating tracks with Q-vectors at forward (backward) rapidity from V0A (V0C)
- Non-flow suppressed by large η-gap ($|\Delta\eta| > 2$)

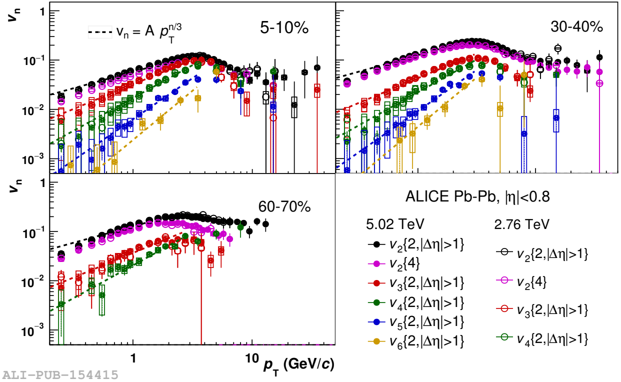
$$v_n\{2, |\Delta\eta| > 2\} = \frac{\langle u_n Q_n^{\mathrm{V0A}*} \rangle}{\sqrt{\frac{\langle Q_n^{\mathrm{V0A}} Q_n^{*} \rangle \langle Q_n^{\mathrm{V0A}} Q_n^{\mathrm{V0C}*} \rangle}{\langle Q_n Q_n^{\mathrm{V0C}*} \rangle}}}, \qquad u_n, Q_n = \sum_j w_j e^{in\varphi_j}$$

[1] A. Bilandzic *et al.*, Phys. Rev. C 89, 064904 (2014)

p_{T} and centrality evolution of v_n



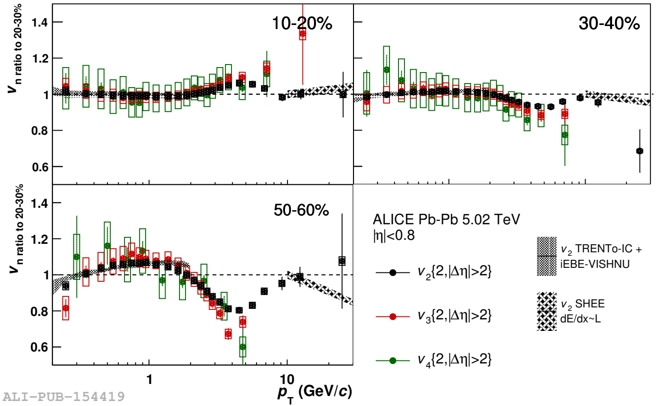
Power-law scaling



- $v_n(p_T)$ unchanged between $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV
- **Simple power-law scaling**: $v_n(p_T) \sim p_T^{n/3}$ at low p_T for $n = 2$-6
- **Unexpected**: in ideal hydro $v_n(p_T) \sim p_T^n$ [1]

[1] N. Borghini and J.Y. Ollitrault, PLB 642 (2006) 227-231

Centrality evolution

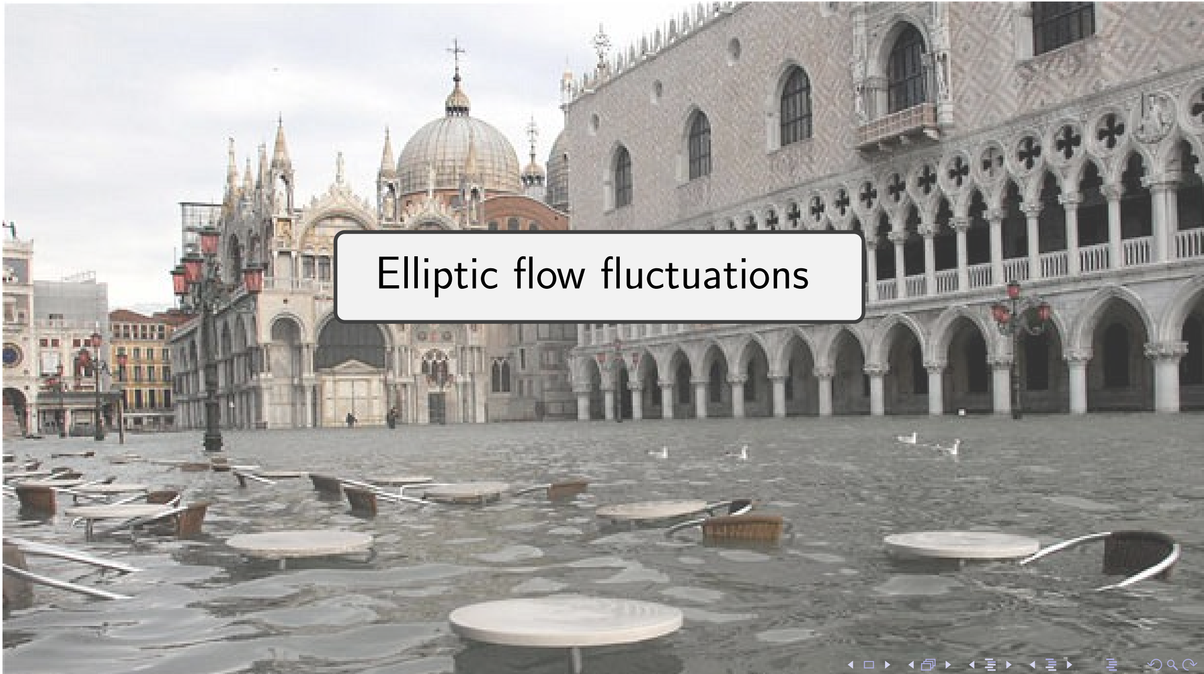


$$v_n(p_T)_{\text{ratio to 20-30\%}} = \frac{v_n(p_T)}{v_n(p_T)[20\text{-}30\%]}\frac{v_n[20\text{-}30\%]}{v_n},$$

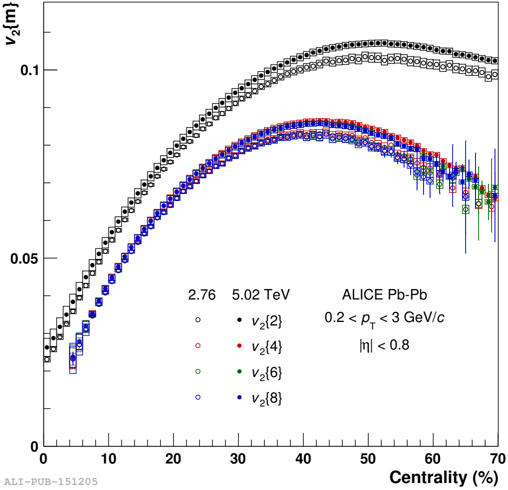
$$v_n \equiv v_n(0.2 < p_T < 3 \text{ GeV}/c)$$

- Ratio at **low and high** p_T consistent with 1: **common origin (IS geometry)**
- Deviations at intermediate p_T: radial flow shifting the maximum of v_n
- Does not depend on change in particle composition of the inclusive charged particle sample (see backup)

Elliptic flow fluctuations

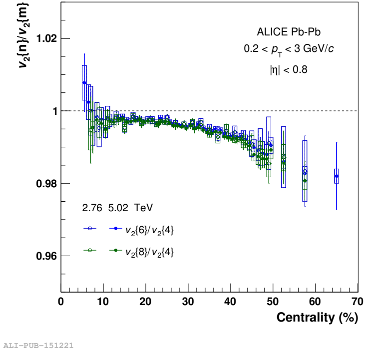


Cumulants



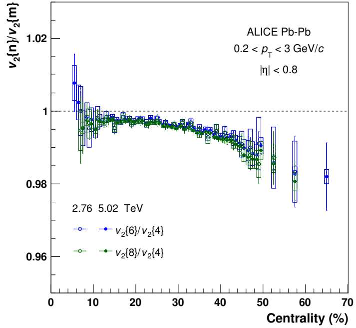
- v_2 from **multi-particle cumulants** $v_2\{2,4,6,8\}$ has **different sensitivities to fluctuations**: possible to extract information on the flow p.d.f. from their combination
- differences between $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV from increase in $\langle p_T \rangle$

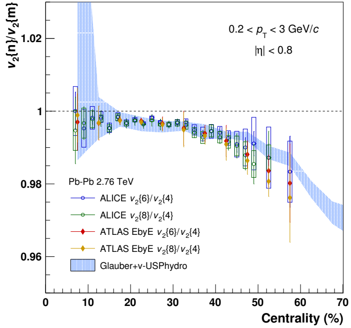
Ratios of cumulants



- Ratios $\mathbf{v_2\{6\}/v_2\{4\}}$ and $\mathbf{v_2\{8\}/v_2\{4\}}$ below unity: **non-Gaussian fluctuations** ($v_2\{8\}/v_2\{6\}$ in backup)
- Small but finite centrality dependence: decreasing from central to peripheral

[1] ATLAS, Eur. Phys. J. C (2014) 74: 3157
[2] G. Giacalone *et al.*, Phys. Rev. C 95, 014913 (2017)





- Ratios $\mathbf{v_2\{6\}/v_2\{4\}}$ and $\mathbf{v_2\{8\}/v_2\{4\}}$ below unity: **non-Gaussian fluctuations** ($v_2\{8\}/v_2\{6\}$ in backup)
- Small but finite centrality dependence: decreasing from central to peripheral
- Consistency between results at $\sqrt{s_{NN}} = 2.76$ (ATLAS[1]) and 5.02 TeV: **no significant energy and p_T dependence**; consistent with hydro model predictions[2]

[1] ATLAS, Eur. Phys. J. C (2014) 74: 3157
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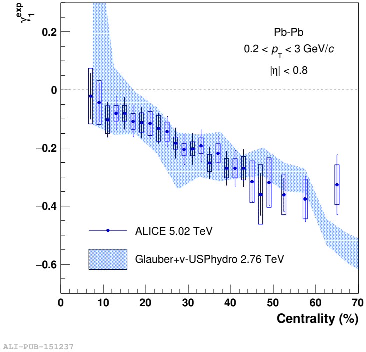

$$\gamma_1^{\text{exp}} = -6\sqrt{2}v_2\{4\}^2(v_2\{4\} - v_2\{6\})/(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}$$

- **Negative skewness** of v_2, suppressed for more central collisions. Consistent with hydro model predictions[1].

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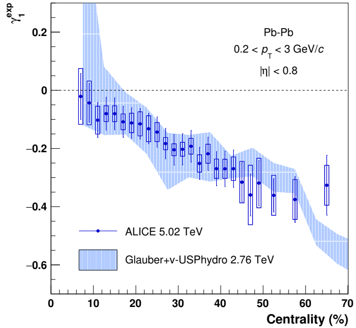

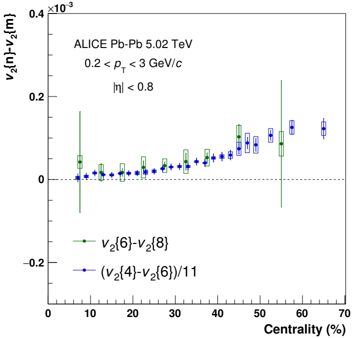

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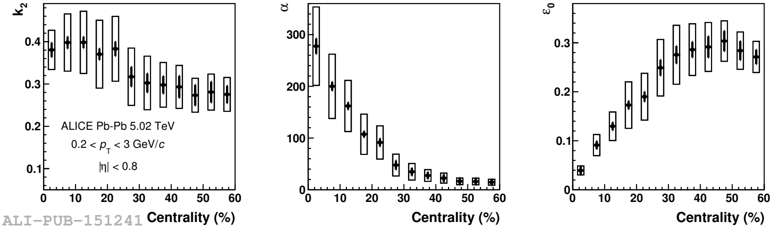
- **Negative skewness** of v_2, suppressed for more central collisions. Consistent with hydro model predictions[1].
- Differences between $v_2\{4, 6, 8\}$ also sensitive to higher order moments (**kurtosis**): contribution **not significant**, $< 4 \times 10^{-4}$ at 95% C.L.

[1] G. Giacalone *et al.*, Phys. Rev. C 95, 014913 (2017)

Elliptic-Power fits



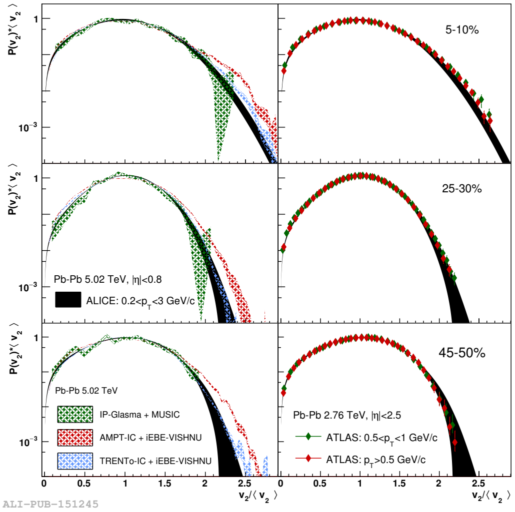
The full flow p.d.f. $P(v_2)$ can be extracted **fitting the cumulants** $c_2\{2, |\Delta\eta| > 1\}$, $c_2\{4, 6, 8\}$ with the **Elliptic Power distribution**[1,2]

$$P(v_2) = \frac{1}{k_2} P(\varepsilon_2) = 2\,\alpha\,\varepsilon_2\,(1-\varepsilon_2^2)^{\alpha-1}\,(1-\varepsilon_0^2)^{\alpha+1/2}\,\frac{1}{\pi}\int_0^{\pi}(1-\varepsilon_2\varepsilon_0\cos\varphi)^{-2\alpha-1}\,d\varphi,$$

Free parameters: α (fluctuations), ε_0 (average eccentricity), k_2 (hydro response, defined as $v_2 = k_2\varepsilon_2$). All equations in backup.

[1] L. Yan and J.Y. Ollitrault, Phys. Rev. Lett. 112, 082301 (2014)

[2] L. Yan *et al.*, Phys. Rev. C 90, 024903 (2014)



- $P(v_2)$ **rescaled by** $\langle v_2 \rangle$ in agreement with ATLAS results[1] at $\sqrt{s_{NN}} = 2.76$ TeV and different p_T range: flow fluctuations depend minorily on energy and p_T (at low p_T)
- **Good agreement** with hydro models employing **IP-Glasma initial-conditions**[2,3], in a wide centrality range

All centralities in backup.

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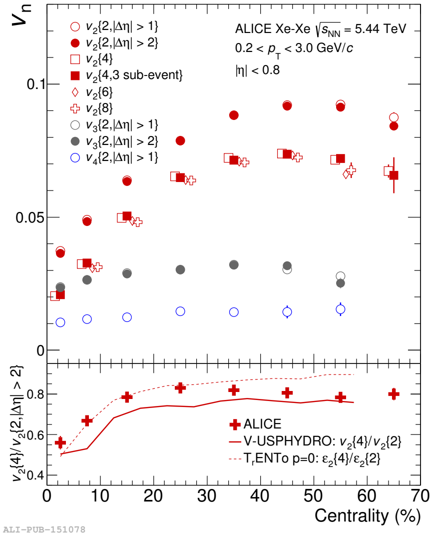
[1] ATLAS, JHEP 11 (2013) 183
[2] S. McDonald *et al.*, PRC 95, 064913 (2017)
[3] W. Zhao *et al.*, EPJ C77 no.9, 645 (2017)

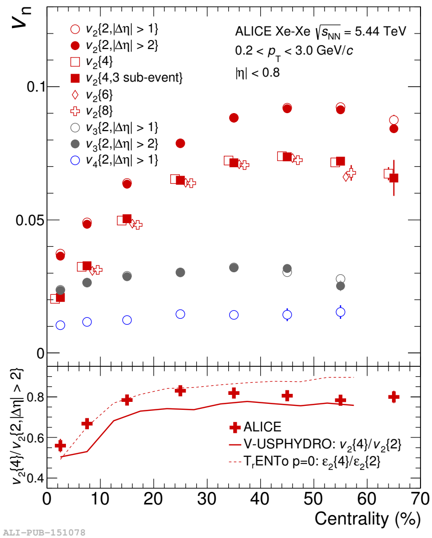
Flow in Xe–Xe



- **First measurements** of v_2, v_3, v_4 in Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV
- $v_2\{4\}/v_2\{2\}$ sensitive to **flow fluctuations**: qualitatively described by initial conditions, some tension with hydro model predictions[1]

[1] G. Giacalone *et al.*, Phys. Rev. C 97, 034904 (2018)

Centrality dependence



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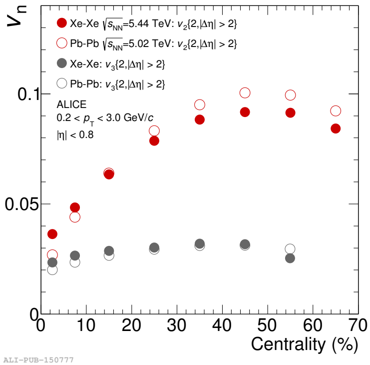
- $v_2\{4\}/v_2\{2\}$ sensitive to **flow fluctuations**: qualitatively described by initial conditions, some tension with hydro model predictions[1]
- Models include **nuclear deformation** β_2, which modifies Wood-Saxon as

$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{(r - R_0 - R_0\,\beta_2\,Y_{20}(\theta))/a}}$$

ρ_0 density at center, R_0 nuclear radius, r distance from center, Y_{20} Bessel function of secon kind, a skin depth

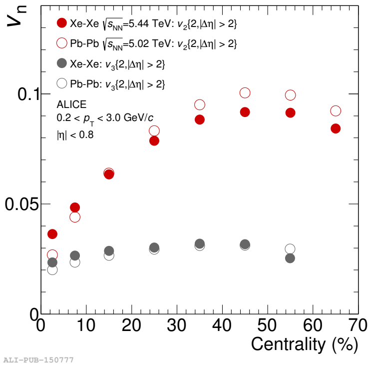
Effect: $\sim 20\%$ larger $v_2\{2\}$ in central, decreasing towards peripheral

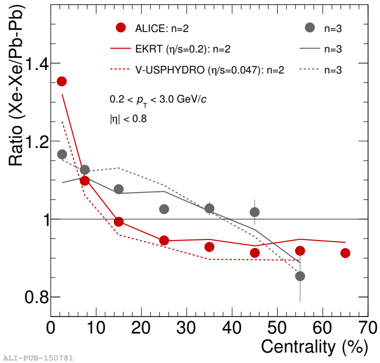
[1] G. Giacalone *et al.*, Phys. Rev. C 97, 034904 (2018)



v_n in Xe–Xe vs Pb–Pb

[1]K.J. Eskola *et al.*, Phys. Rev. C 97, 034911 (2018); G. Giacalone *et al.*, Phys. Rev. C 97, 034904 (2018)





v_n in Xe–Xe vs Pb–Pb

- v_2: larger $\lesssim 35\%$ in central $\rightarrow$ larger IS fluctuations + nuclear deformation; smaller $\sim 10\%$ in semi-central and peripheral $\rightarrow$ smaller radial flow and/or larger viscous effects

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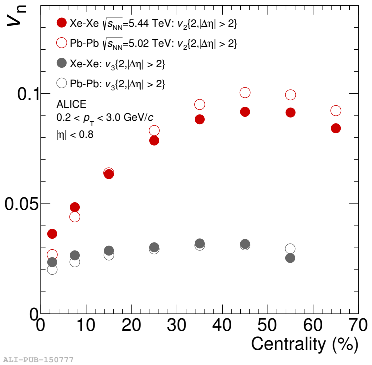

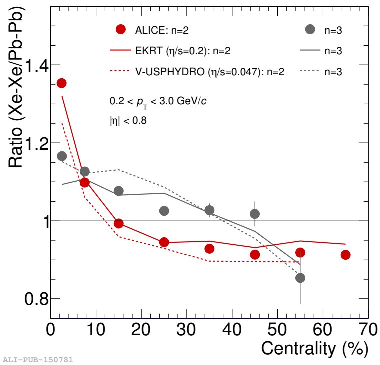

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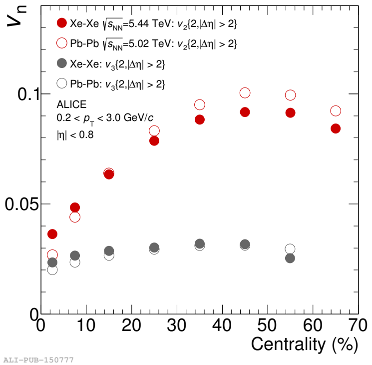

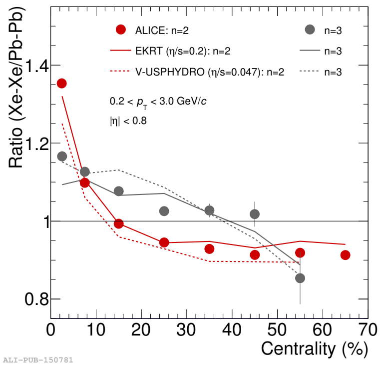

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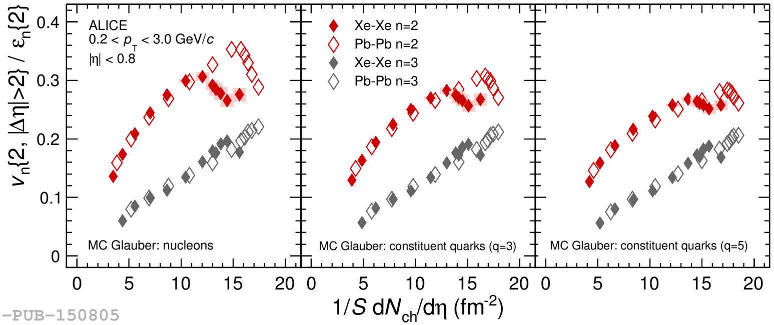
Quantitatively described by models[1] up to a few %. Finer centrality bins in backup

[1] K.J. Eskola *et al.*, Phys. Rev. C 97, 034911 (2018); G. Giacalone *et al.*, Phys. Rev. C 97, 034904 (2018)

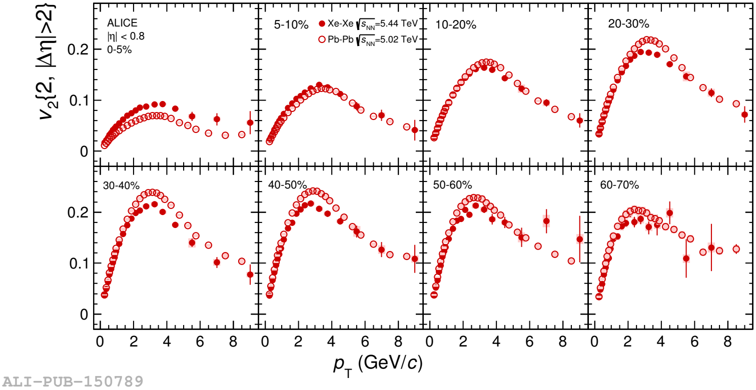


Transverse energy density quantified as $1/S\ \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ [1], from IS models

- **Hydro predicts** v_n/ε_n to **increase** with $1/S\ \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, same for Xe–Xe and Pb–Pb
- **Not observed** for most models **in central collisions**: deficiencies in estimating ε_2?

More models and details of the calculation in backup

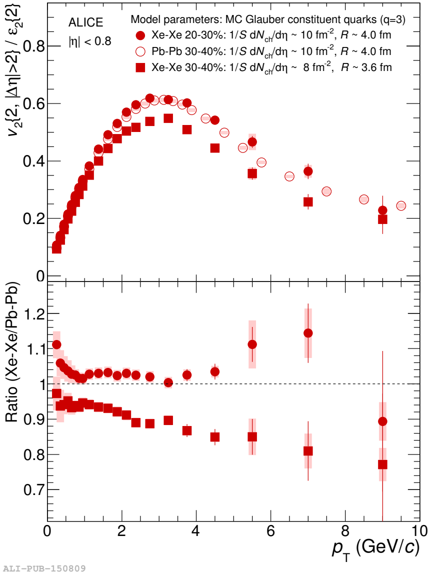
[1] S transverse area, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ charged particle density



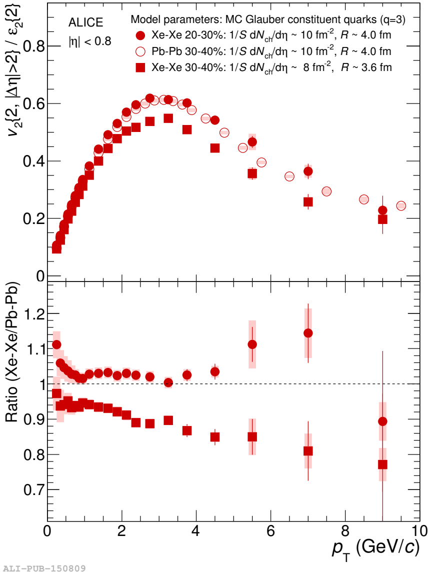
$v_2(p_T)$ in Xe–Xe vs Pb–Pb ($v_3(p_T)$ in backup)

- same trend w.r.t. centrality: larger in central, smaller otherwise
- larger differences at intermediate p_T (see next slide)
- differences not arising from difference in energy (see slide 6)

p_T-dependence and transverse density

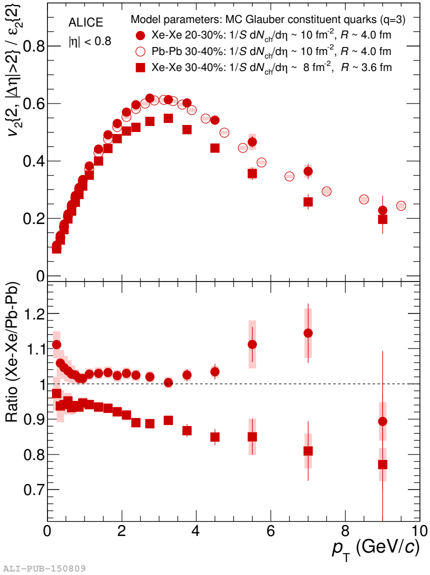


$v_2(p_T)$ in Xe–Xe vs Pb–Pb, mid-central collisions



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

- Two centrality classes with similar $1/S\ dN_{ch}/d\eta$ consistent with each other $\rightarrow$ **transverse energy scaling does not depend on p_T**



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

- Two centrality classes with similar $1/S\ dN_{ch}/d\eta$ consistent with each other
  $\rightarrow$ **transverse energy scaling does not depend on p_T**
- At fixed centrality / eccentricity, **differences increase with p_T**
  $\rightarrow$ viscous effects and/or radial flow

Conclusions

v_n of inclusive charged particles in Pb–Pb and Xe–Xe

arXiv:1804.02944, arXiv:1805.01832

v_n of inclusive charged particles in Pb–Pb and Xe–Xe

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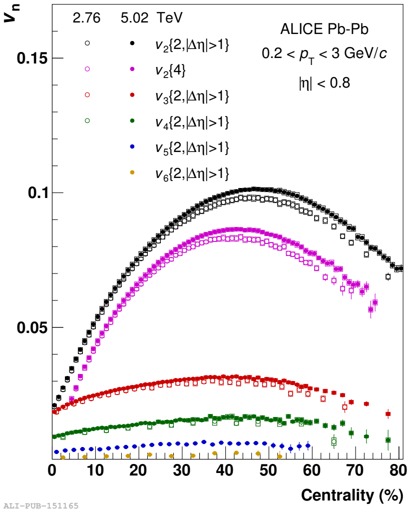
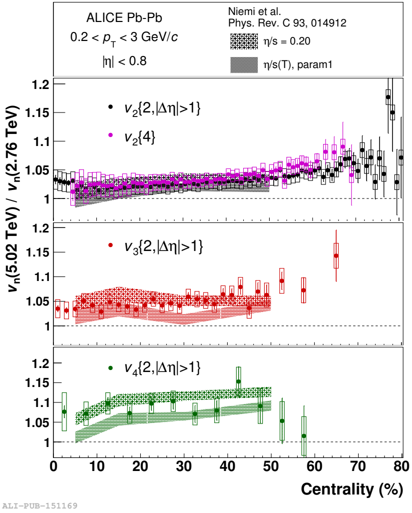
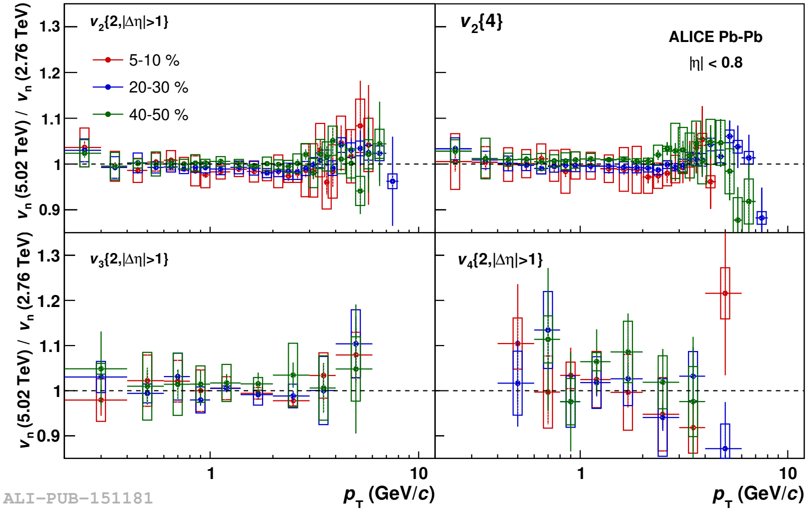
- First measurement of flow in Xe–Xe: evidence of nuclear deformations at play
- Comparing Xe–Xe to Pb–Pb
  - Approximate transverse energy scaling observed, broken in central collisions
  - Differences attributed to larger IS fluctuations, smaller radial flow and/or larger viscous effects

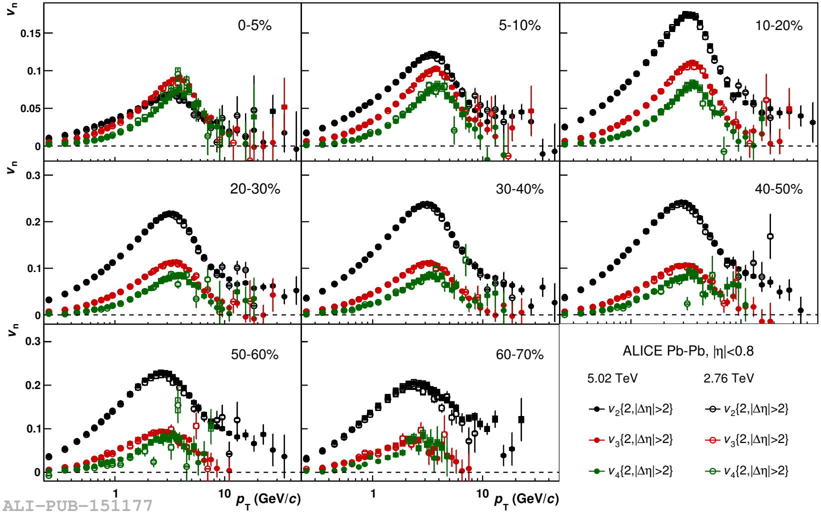

TOURISM IS
THE OPIUM
OF THE PEOPLE

Flow in Pb-Pb: energy dependence



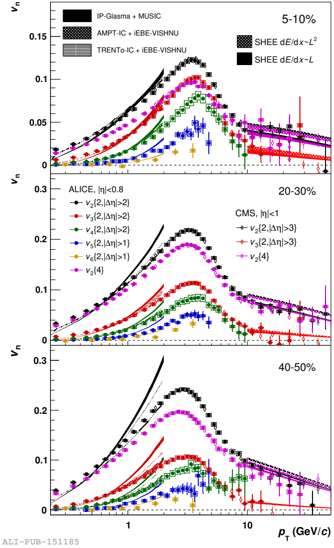



$v_2\{2,|\Delta\eta|>1\}$
5-10 %
20-30 %
40-50 %
$v_2\{4\}$
ALICE Pb-Pb
$|\eta| < 0.8$
$v_3\{2,|\Delta\eta|>1\}$
$v_4\{2,|\Delta\eta|>1\}$
v_n (5.02 TeV) / v_n (2.76 TeV)
1.3
1.2
1.1
1
0.9
1
10
p_T (GeV/c)
ALI-PUB-151181

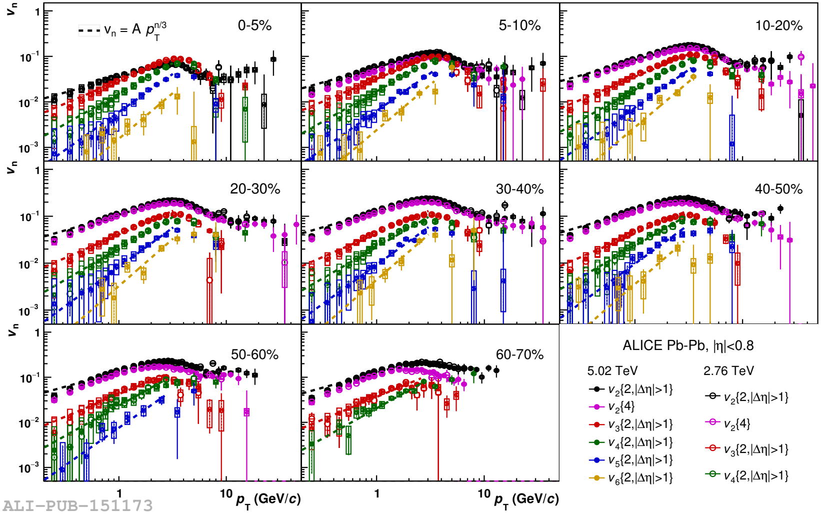


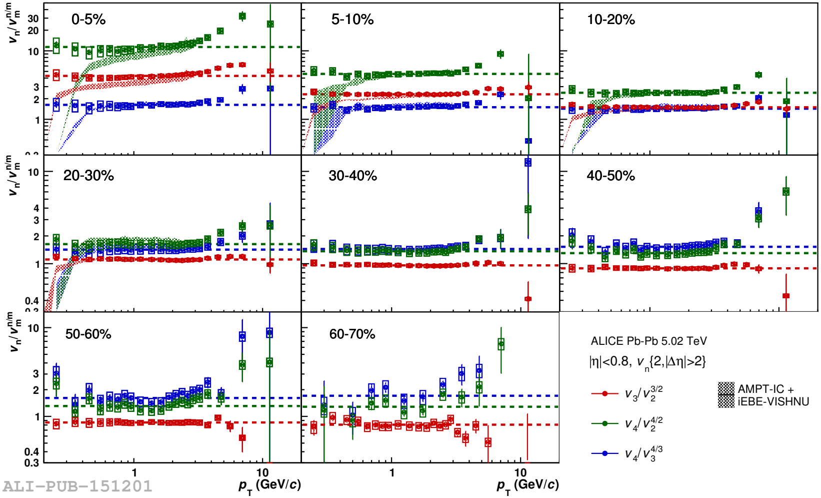
v_n
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
ALICE Pb-Pb, |η|<0.8
5.02 TeV
2.76 TeV
$v_2\{2,|\Delta\eta|>2\}$
$v_3\{2,|\Delta\eta|>2\}$
$v_4\{2,|\Delta\eta|>2\}$
p_T (GeV/c)
ALI-PUB-151177

Flow in Pb-Pb: model comparison



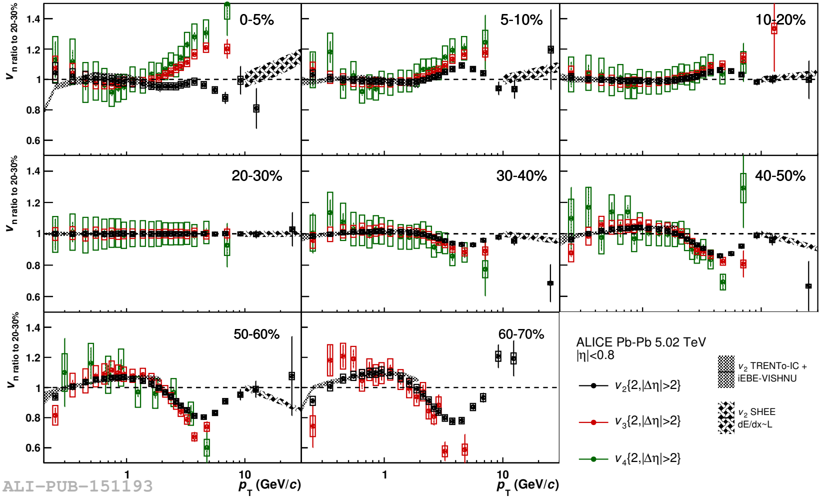
Flow in Pb-Pb: power-law scaling



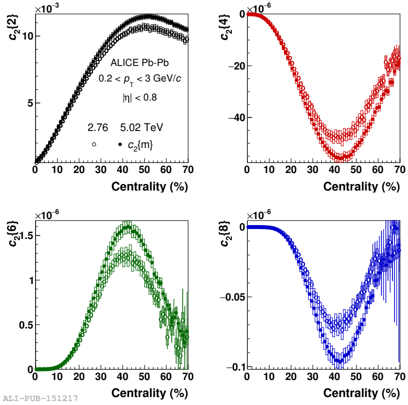


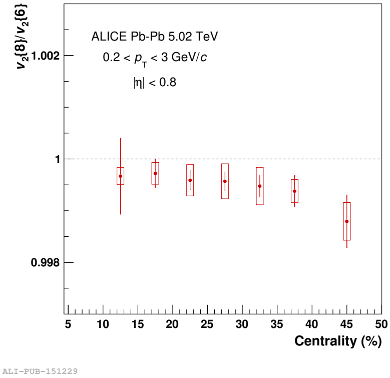
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
$v_n/v_m^{n/m}$
p_T (GeV/c)
ALI-PUB-151201
ALICE Pb-Pb 5.02 TeV
$|\eta|<0.8$, $v_n\{2,|\Delta\eta|>2\}$
$v_3/v_2^{3/2}$
$v_4/v_2^{4/2}$
$v_4/v_3^{4/3}$
AMPT-IC +
iEBE-VISHNU

Flow in Pb-Pb: centrality evolution



Flow fluctuations: cumulants





Cumulants $c_2\{2,4,6,8\}$ fit with functions[1]

$$
\begin{aligned}
c_2\{2\} =& k_2^2 \left(1 - f_1\right), \\
c_2\{4\} =& - k_2^4 \left(1 - 2\,f_1 + 2\,f_1^2 - f_2\right), \\
c_2\{6\} =& k_2^6 \left(4 + 18\,f_1^2 - 12\,f_1^3 + 12 f_1\left(3 f_2 - 1\right) - 6\,f_2 - f_3\right), \\
c_2\{8\} =& - k_2^8 (33 - 288\,f_1^3 + 144\,f_1^4 - 66\,f_2 + 18\,f_2^2 - 24\,f_1^2(-11 + 6\,f_2) \\
& - 12\,f_3 + 4\,f_1(-33 + 42\,f_2 + 4\,f_3) - f_4)
\end{aligned}
$$

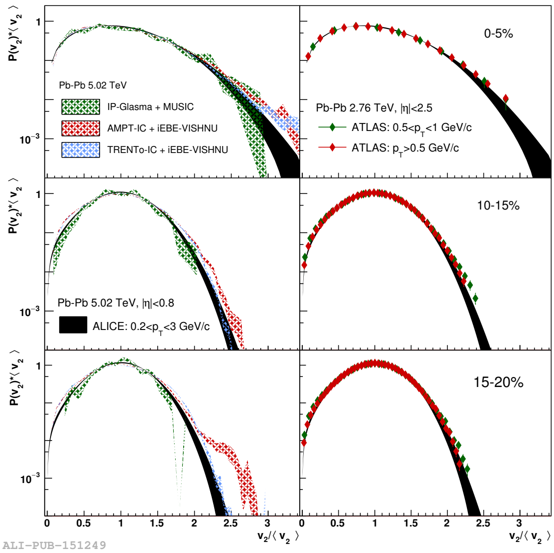
where

$$
f_k \equiv \langle (1-\varepsilon_n^2)^k \rangle = \frac{\alpha}{\alpha + k} (1-\varepsilon_0^2)^k \, {}_2F_1\left(k + \frac{1}{2}, k; \alpha + k + 1, \varepsilon_0^2\right)
$$

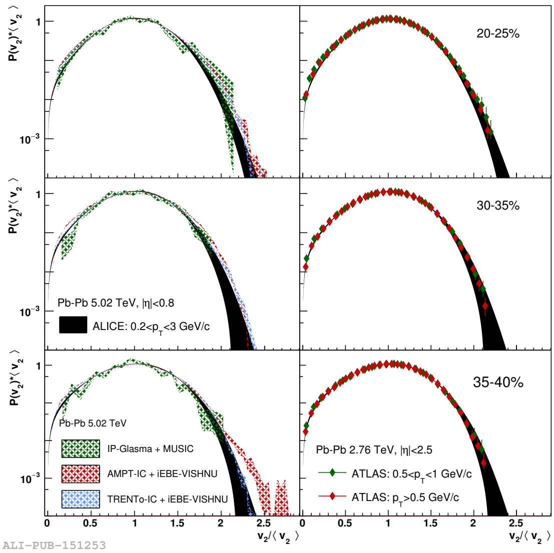
and ${}_2F_1$ is the hypergeometric function

[1] L. Yan *et al.*, Phys. Rev. C 90, 024903 (2014)

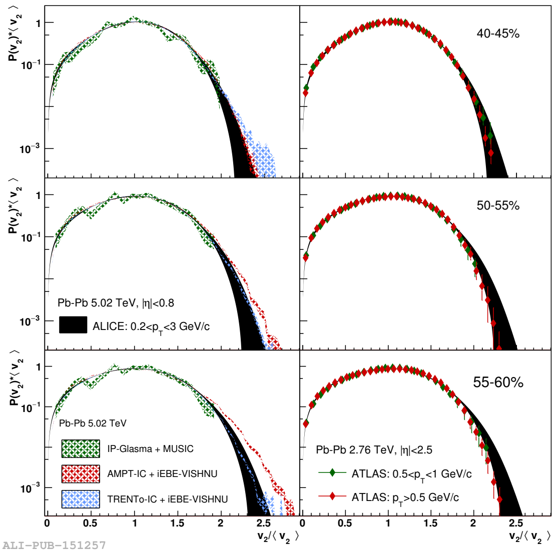
Flow fluctuations: flow p.d.f.



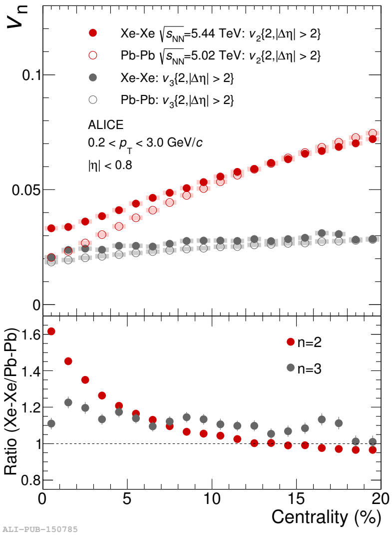
Flow fluctuations: flow p.d.f.



Flow fluctuations: flow p.d.f.



Flow in Xe–Xe: finer centrality bins



Transverse energy density determined from IS models as

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\varphi)\rangle^2 + \langle r^n \sin(n\varphi)\rangle^2}}{\langle r^n\rangle}$$

$$\varepsilon_2\{2\} = \sqrt{\langle \varepsilon_n^2 \rangle}$$

$$S = 4\pi\, \sigma_x \sigma_y$$

where x, y, and φ, r are the cartesian and polar coordinates of the source, respectively, properly re-centered so that $\langle x\rangle = \langle y\rangle = 0$

- S normalized so that the average energy density coincides with N_{part}/S
- A nuclear deformation $\beta_2 = 0.18 \pm 0.02$ is assumed for ^{129}Xe, extrapolated from available measurements[1]
- Centrality in IS models is defined as percentiles of entropy density / multiplicity distributions, matched to the measured charged particle distributions used to define centrality in ALICE[2,3]

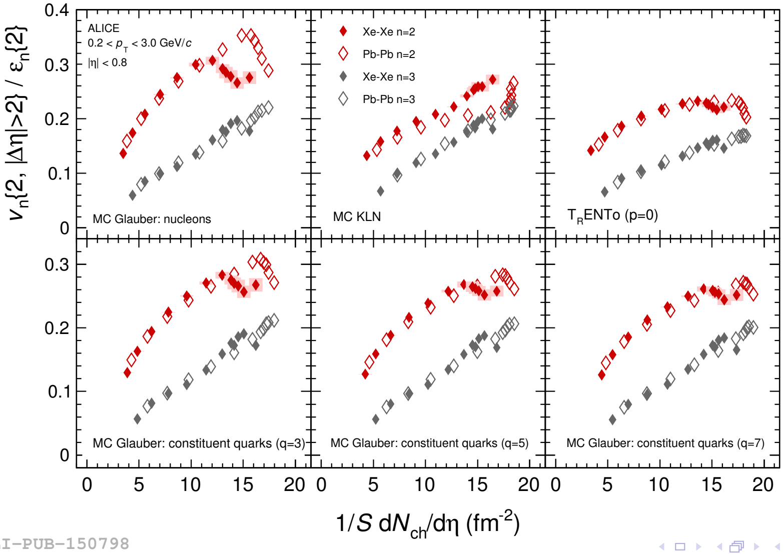
S is normalized so that the average energy density coincide with N_{part}/S

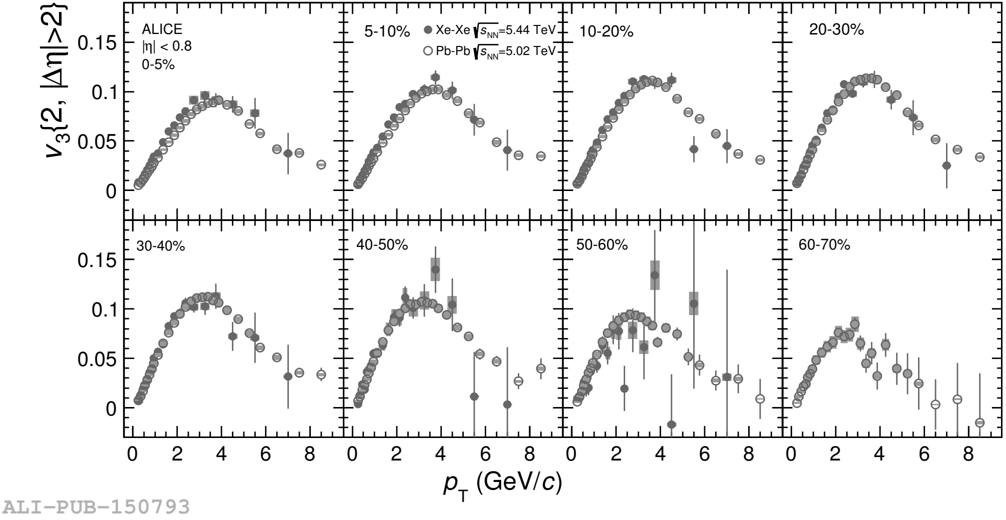
[1] S. Raman *et al.*, Atom. Data Nucl. Data Tabl. 78 (2001) 1-128; P. Moller *et al.*, Atom. Data Nucl. Data Tabl. 109-110 (2016) 1-204; E. Zoltan *et al.*, Nucl. Data Shee. 129 (2015) 191-436.

[2] ALICE-PUBLIC-2018-003

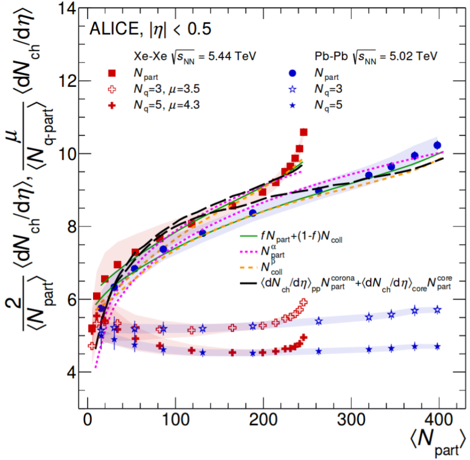
[3] ALICE, Phys. Rev. Lett. 116, 222302 (2016)

Transverse density dependence

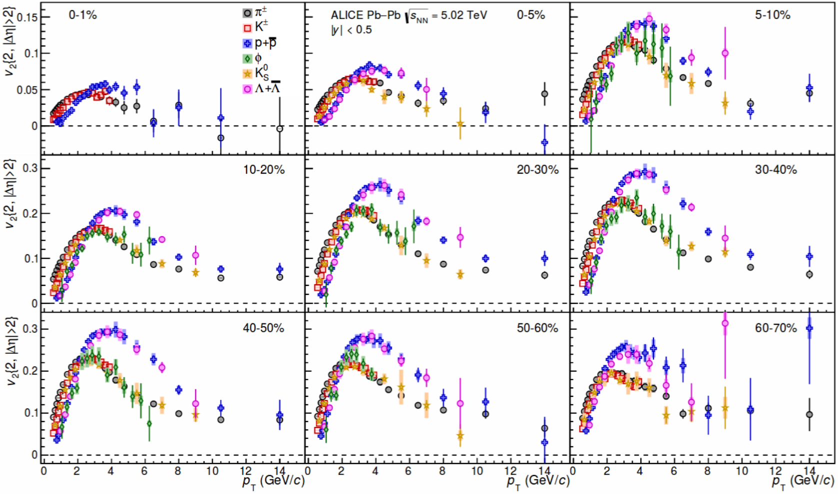



ALICE
|η| < 0.8
0-5%
5-10%
Xe-Xe √sNN=5.44 TeV
Pb-Pb √sNN=5.02 TeV
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
v3{2, |Δη|>2}
0.15
0.1
0.05
0
0
2
4
6
8
pT (GeV/c)
ALI-PUB-150793

$dN_{ch}/d\eta$ in Xe–Xe

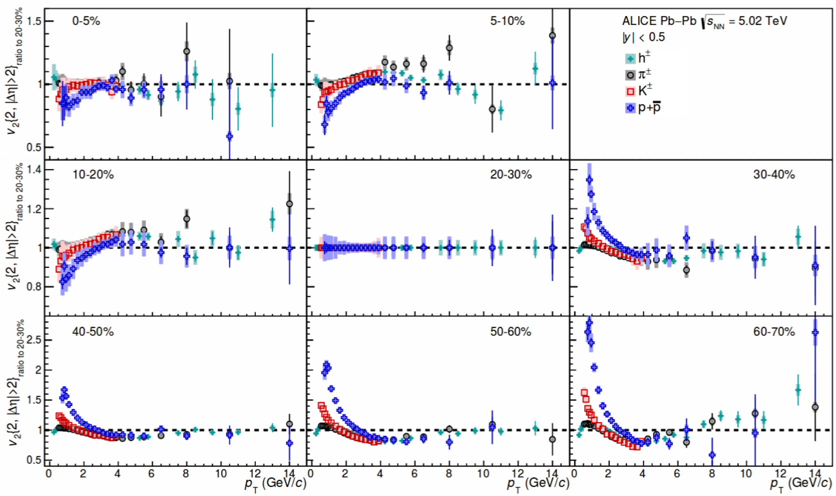


arXiv:1805.04432



arXiv:1805.04390

PID flow in Pb–Pb: centrality evolution



arXiv:1805.04390