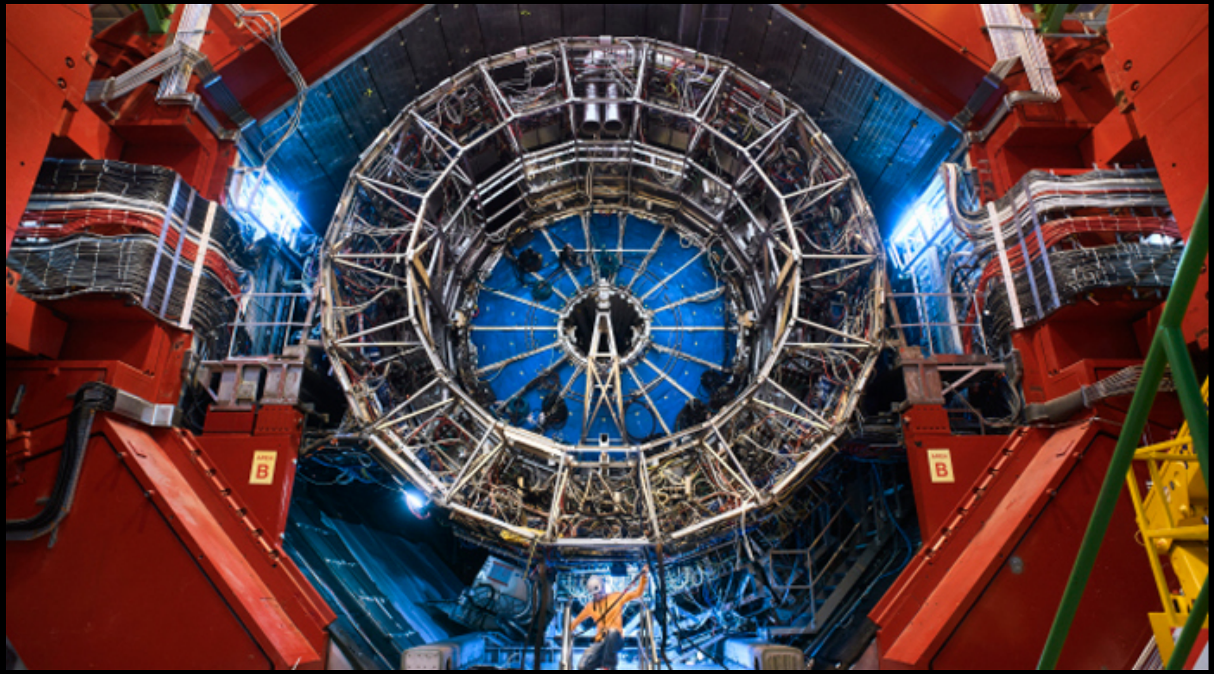
Go beyond the standard anisotropic flow study at the LHC



You Zhou (周铀)

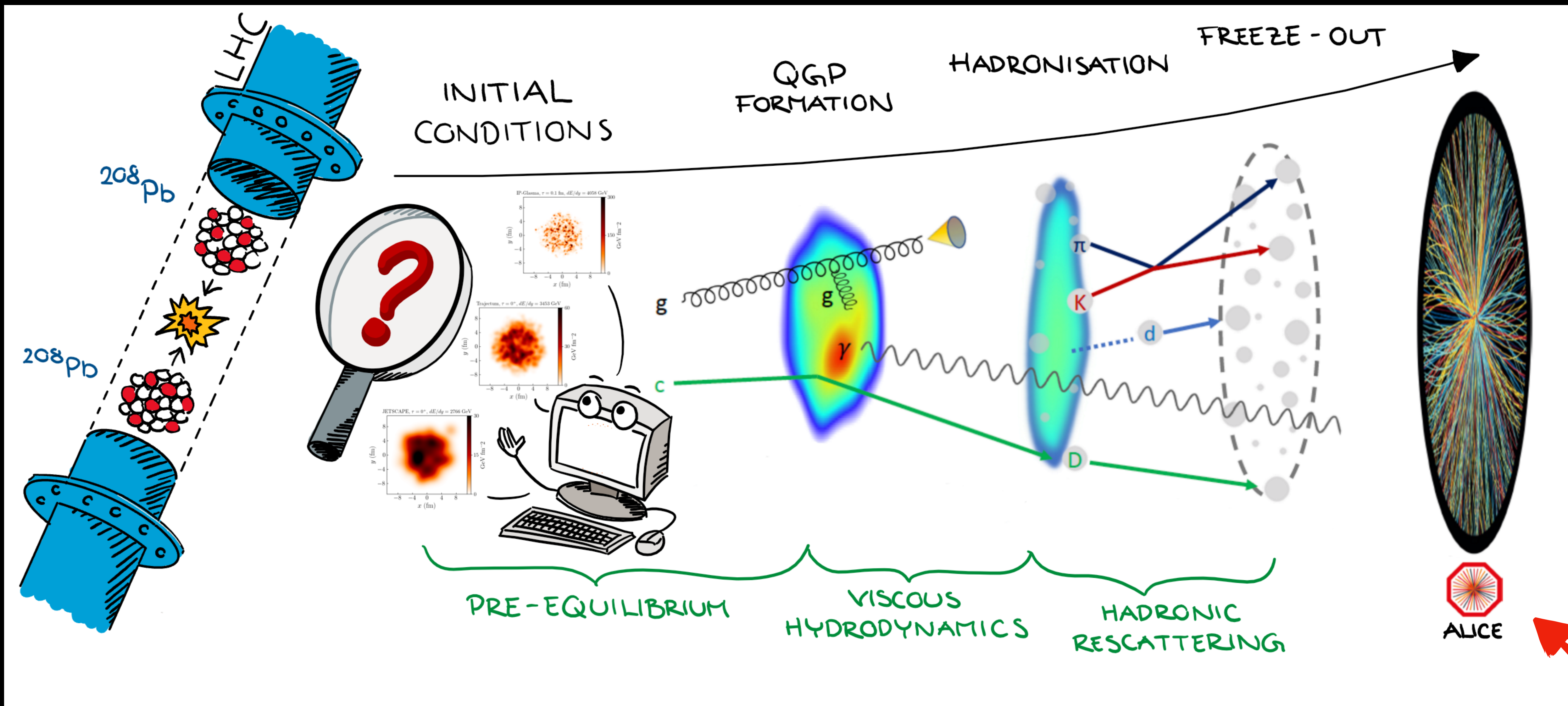
Niels Bohr Institute

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

INDEPENDENT RESEARCH FUND DENMARK

Evolution in the *Little Bang*



TH

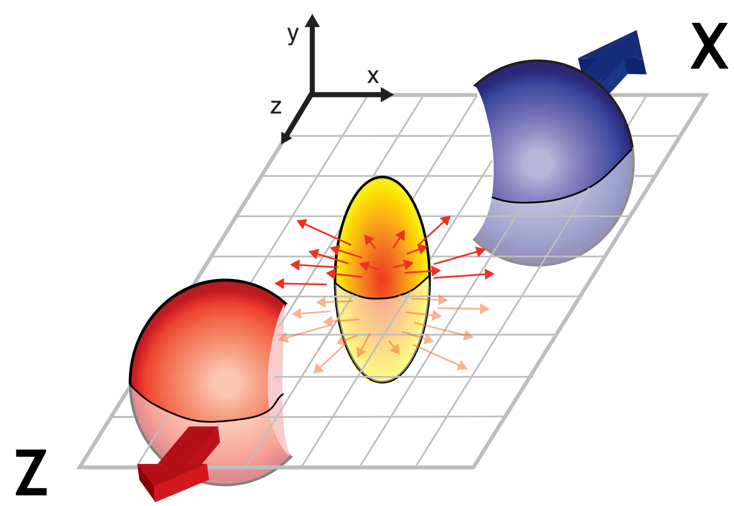
IC → Hydro → Rescattering → Final

IC → Partonic/hadronic transport → Final

Elliptic flow

- Spatial eccentricity in the initial state converted to momentum anisotropic particle distributions
  - known as ***elliptic flow***
  - reflect initial **eccentricity** and **transport properties** of QGP

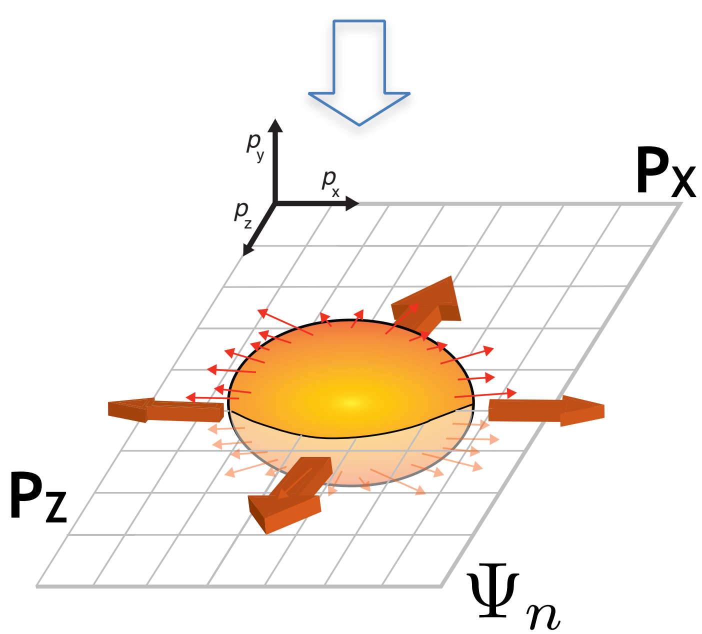
J.Y. Ollitrault, PRD46 (1992) 229
S. Voloshin, Y. Zhang, ZPC70 (1996) 665



$$\varepsilon_{\mathrm{RP}} = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$$

coordinate space Eccentricity

system expansion



$$v_2 = \langle \cos 2(\phi - \Psi_{\mathrm{RP}})\rangle$$

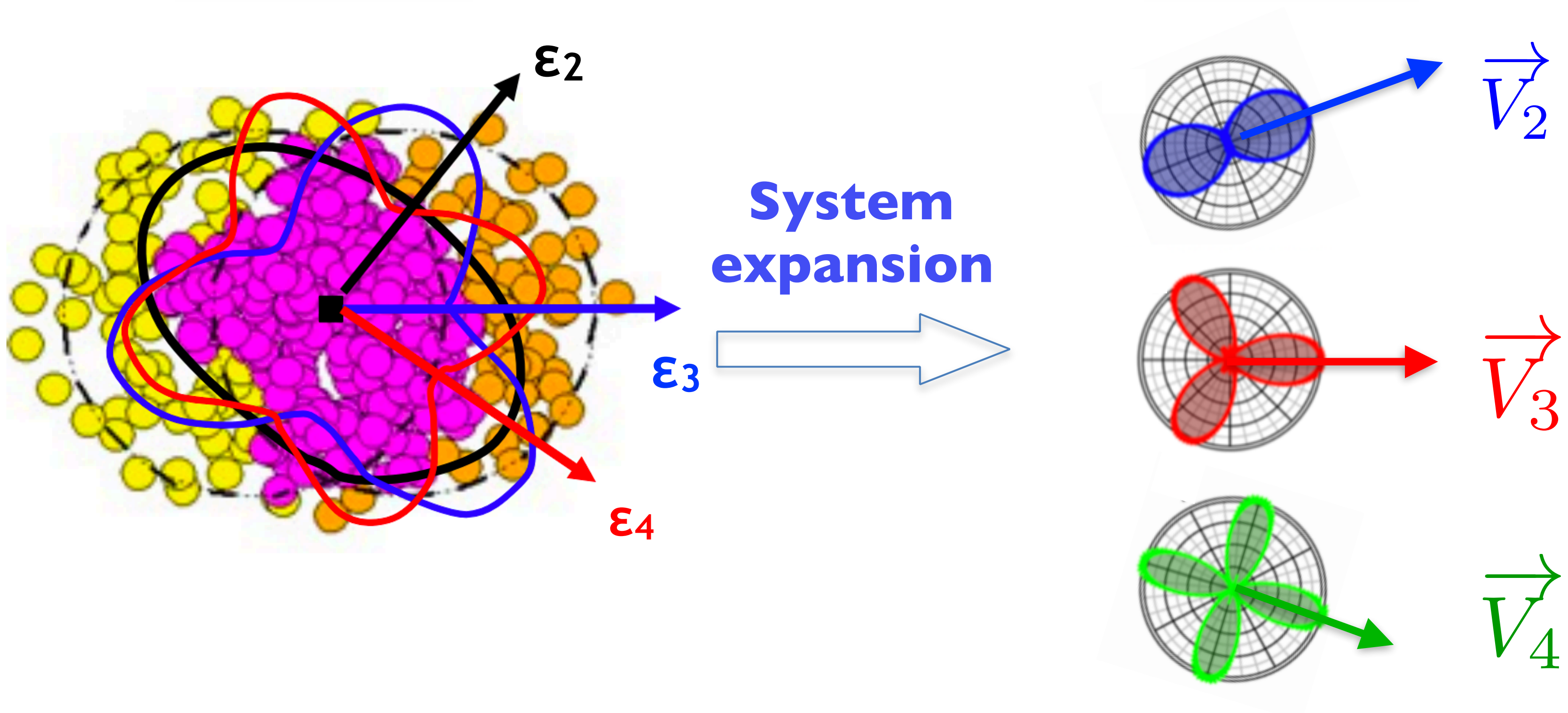
momentum space Elliptic Flow

From initial anisotropy to anisotropic flow

Initial state

Final state

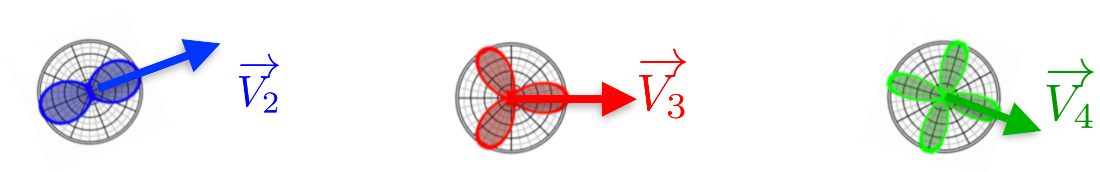
B. Alver, G. Roland, PRC 81 (2010) 054905



$$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, ..., \Phi_m, \Phi_n, \Phi_k, ...) \Rightarrow P(v_m, v_n, v_k, ..., \Psi_m, \Psi_n, \Psi_k, ...)$$

How does v_n fluctuate	How does ψ_n fluctuate	How do v_n and v_m correlate	How do ψ_n and ψ_m correlate
$P(v_n)$	$P(\Psi_n)$	$P(v_m, v_n, v_k, ...)$	$P(\Psi_m, \Psi_n, \Psi_k, ...)$

Two-particle azimuthal correlations



❖ What we *want* to measure:

$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

Ψ_n is unknown in experiment

❖ What we *hope* to get from 2-particle azimuthal correlation

$$\langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle = \langle\langle \cos n\left[(\varphi_1 - \Psi_n) - (\varphi_2 - \Psi_n)\right] \rangle\rangle$$

$$= \langle\langle \cos n(\varphi_1 - \Psi_n) \cdot \cos n(\varphi_2 - \Psi_n) \rangle\rangle \; \cancel{+ \langle\langle \sin n(\varphi_1 - \Psi_n) \cdot \sin n(\varphi_2 - \Psi_n) \rangle\rangle}$$

= 0 due to symmetry

$$= \langle v_n^2 \rangle$$

- Get the RMS value of v_n distribution without knowing Ψ_n

❖ What we *actually get* from 2-particle azimuthal correlation in experiment

$$\langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle = \langle v_n^2 + \delta_2 \rangle$$

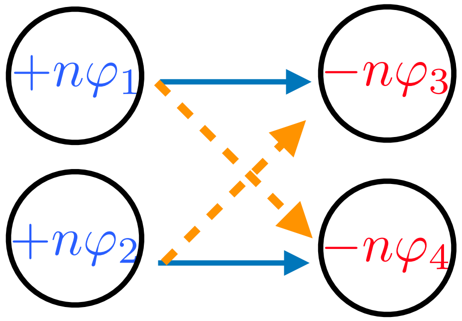
→ *Nonflow (resonance decay, jets etc)*

$$\delta_2 \sim 1/M$$

Multi-particle correlation/cumulant

Flow analysis from multiparticle azimuthal correlations

Nicolas Borghini, Phuong Mai Dinh, and Jean-Yves Ollitrault
Phys. Rev. C **64**, 054901 – Published 25 September 2001



❖ Example: 4-particle cumulant

$$c_n\{4\} = \langle\langle \cos n(\varphi_1+\varphi_2-\varphi_3-\varphi_4)\rangle\rangle - \langle\langle \cos n(\varphi_1-\varphi_3)\rangle\rangle\,\langle\langle \cos n(\varphi_2-\varphi_4)\rangle\rangle - \langle\langle \cos n(\varphi_1-\varphi_4)\rangle\rangle\,\langle\langle \cos n(\varphi_2-\varphi_3)\rangle\rangle$$

$$= \langle v_n^4 + 4v_n^2\delta_2 + 2\delta_2^2 + \delta_4\rangle - 2\langle (v_n^2+\delta_2)^2\rangle = \langle -v_n^4 + \delta_4 \rangle = -v_n\{4\}^4$$

Nonflow (of 4-particles) $\delta_4 \sim 1/M^3$

❖ Using multi-particle cumulant, one can largely suppress nonflow contaminations

$$v_n\{2\}^2 = v_n^2 + \sigma_v^2 + \delta_n^2$$

$$v_n\{4\}^2 \approx v_n^2 - \sigma_v^2$$

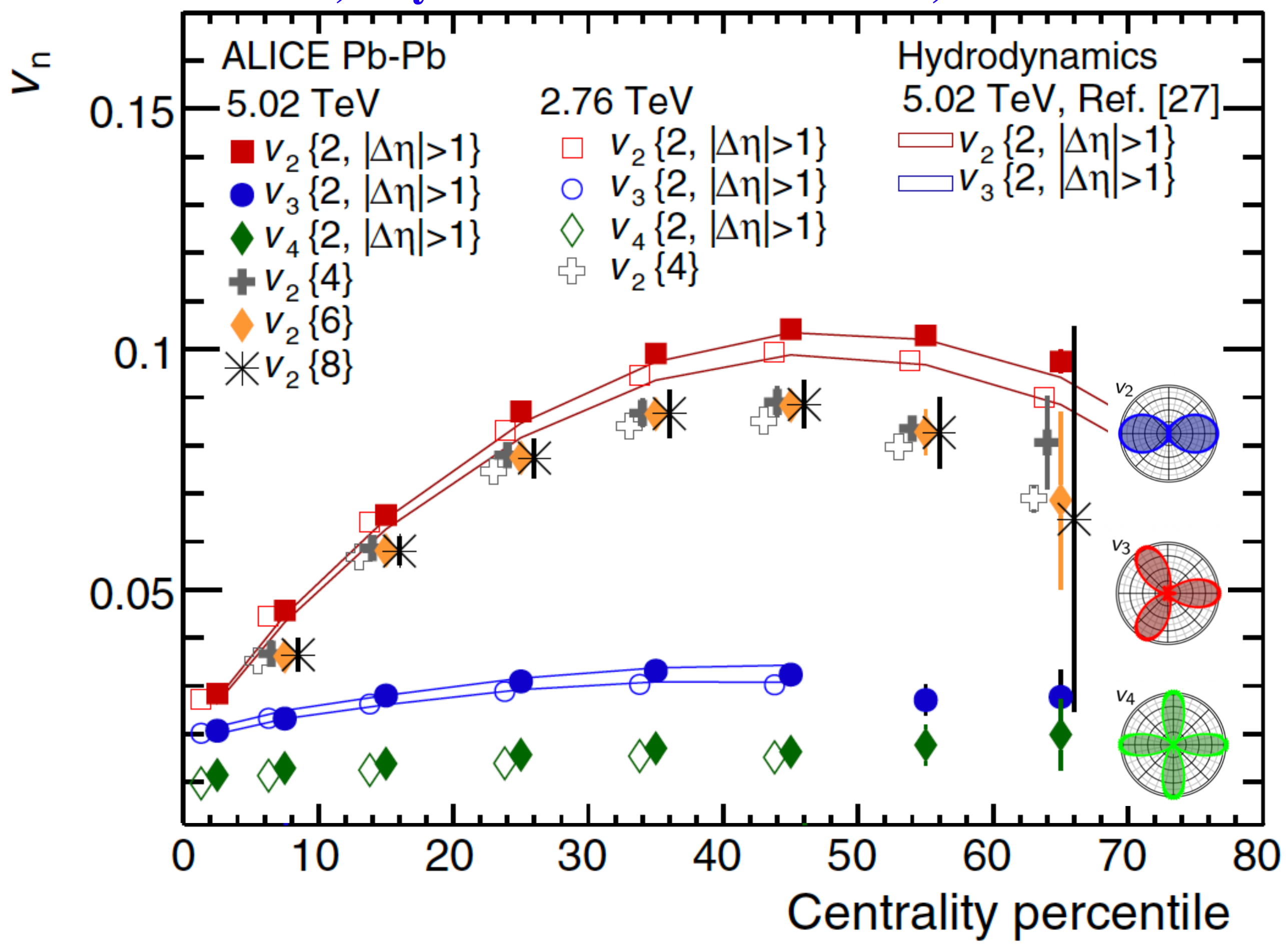
$$v_n\{6\}^2 \approx v_n^2 - \sigma_v^2$$

$$v_n\{8\}^2 \approx v_n^2 - \sigma_v^2$$

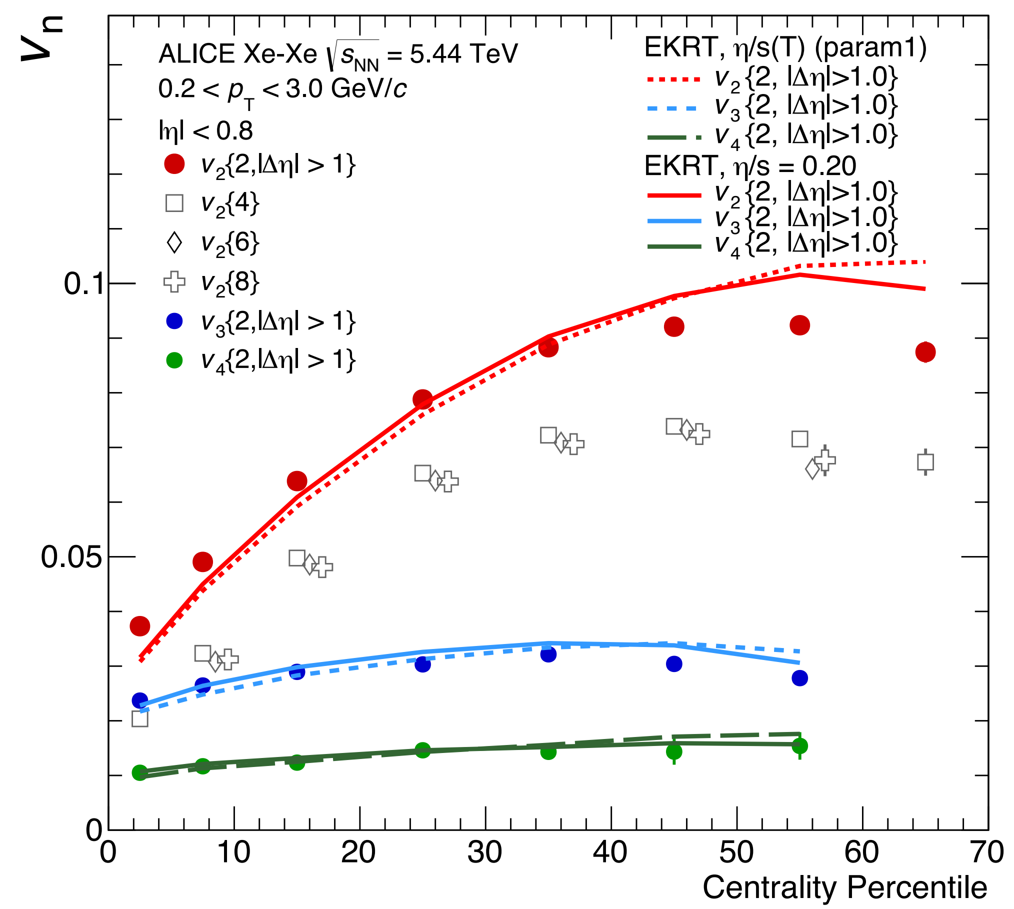
(For Gaussian fluctuations and $\sigma_v \ll v_n$)

Anisotropic flow at the LHC

ALICE, Physical Review Letters 116, 132302



ALICE, Physics Letters B784 (2018) 82

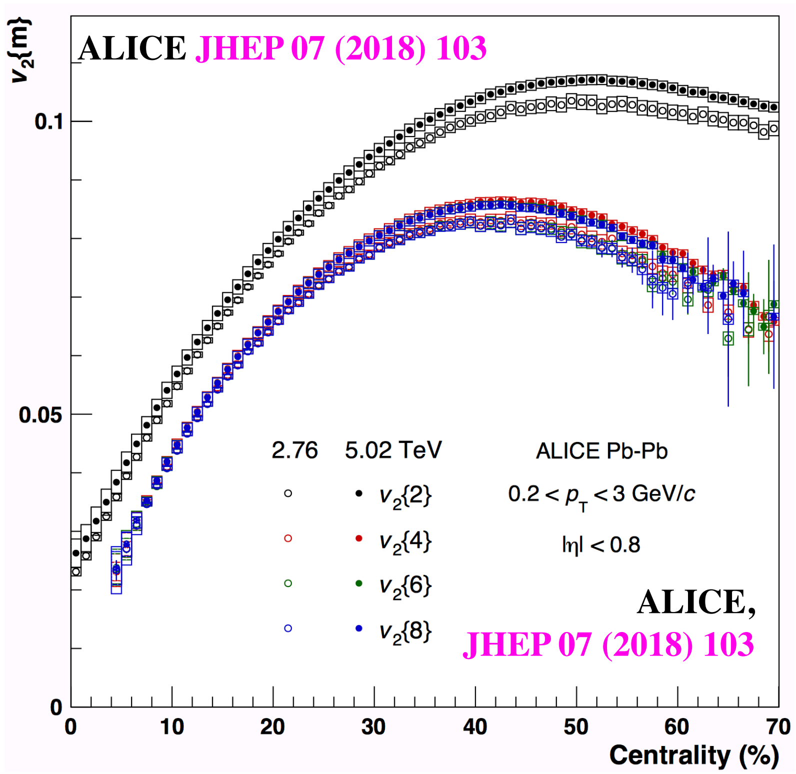


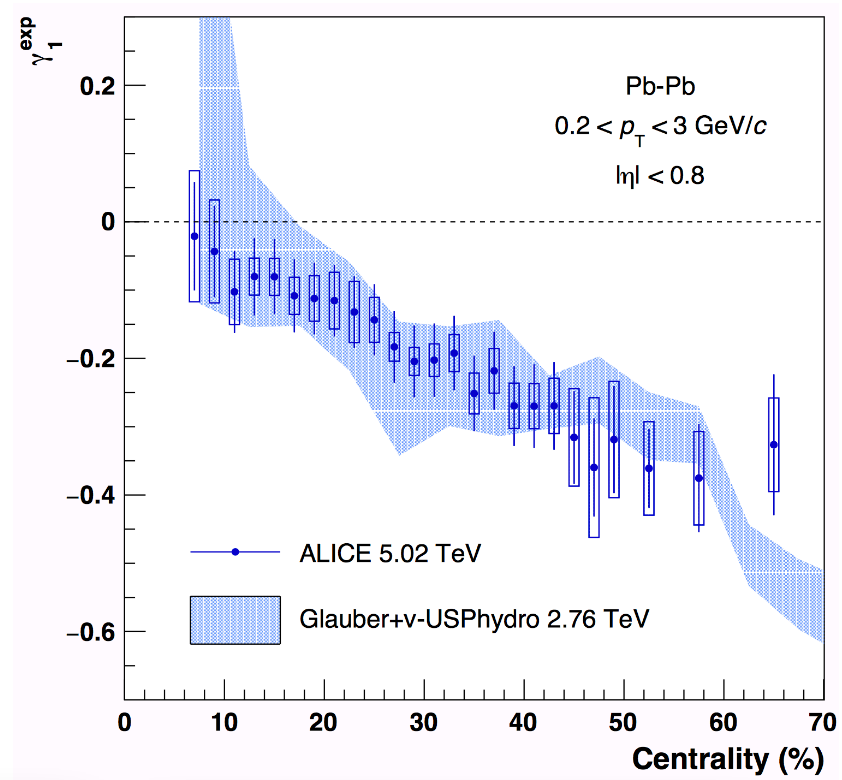
- Flow measurements at the top LHC energies agree with hydrodynamic predictions
  - **The Quark-Gluon Plasma behaves like a perfect fluid**

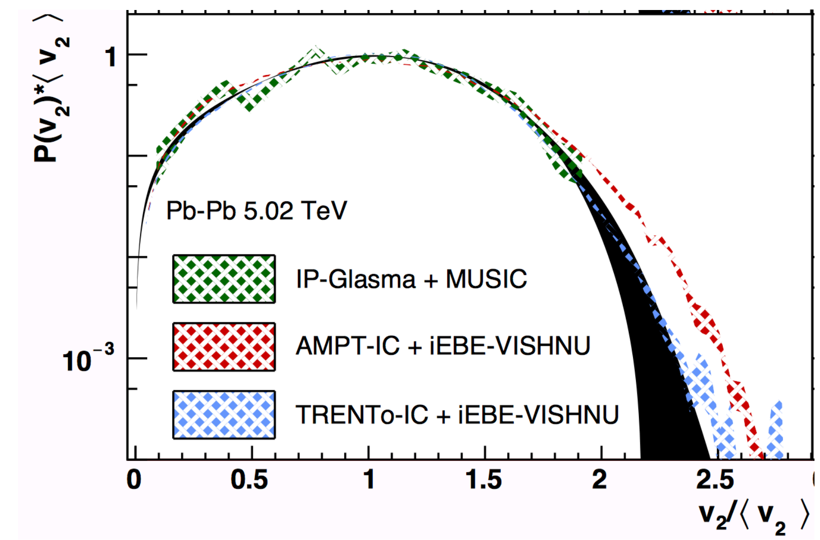
How does v_n fluctuate

$P(v_n)$ and $P(\varepsilon_n)$

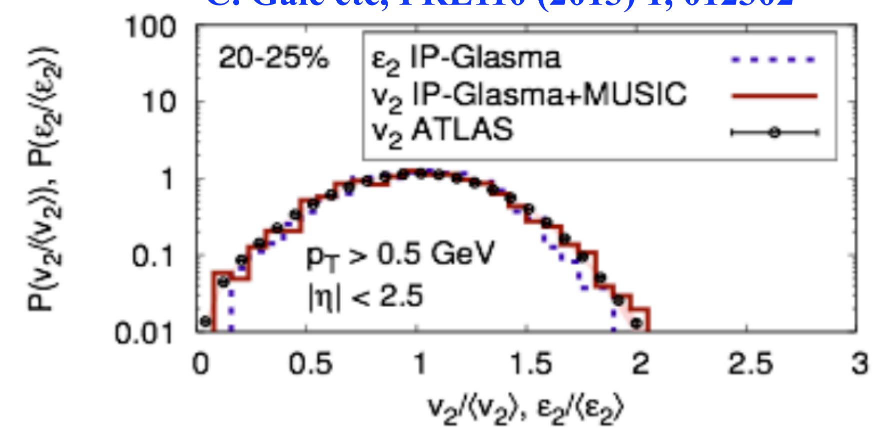
$v_n\{m\}$ → Moments → $p(v_n)$ → $p(\varepsilon_n)$







C. Gale etc, PRL110 (2013) 1, 012302



$$v_n\{2\} = \sqrt[2]{\langle v_n^2\rangle},$$
$$v_n\{4\} = \sqrt[4]{2\langle v_n^2\rangle^2 - \langle v_n^4\rangle},$$
$$v_n\{6\} = \sqrt[6]{\langle v_n^6\rangle - 9\langle v_n^2\rangle\langle v_n^4\rangle + 12\langle v_n^2\rangle^3},$$
$$v_n\{8\} = \sqrt[8]{\langle v_n^8\rangle - 16\langle v_n^2\rangle\langle v_n^6\rangle - 18\langle v_n^4\rangle^2 + 144\langle v_n^2\rangle^2\langle v_n^4\rangle - 144\langle v_n^2\rangle^4}.$$

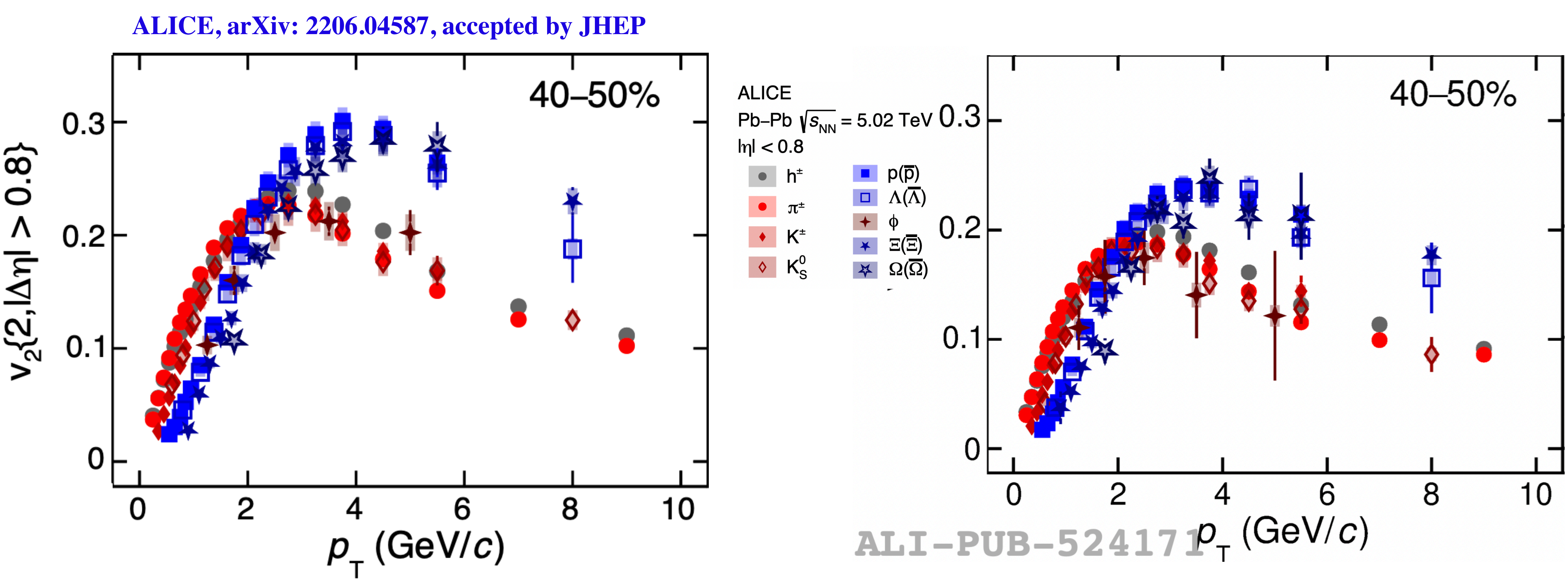
$$\gamma_1^{\rm exp} = -6\sqrt{2}\, v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}$$

$$\gamma_2 \simeq \gamma_2^{\rm expt} \equiv -\frac{3}{2}\frac{v_2\{4\}^4 - 12 v_2\{6\}^4 + 11 v_2\{8\}^4}{(v_2\{2\}^2 - v_2\{4\}^2)^2}$$

$$v_n \propto \varepsilon_n$$
$$P(v_n/\langle v_n\rangle) \approx P(\varepsilon_n/\langle \varepsilon_n\rangle)$$

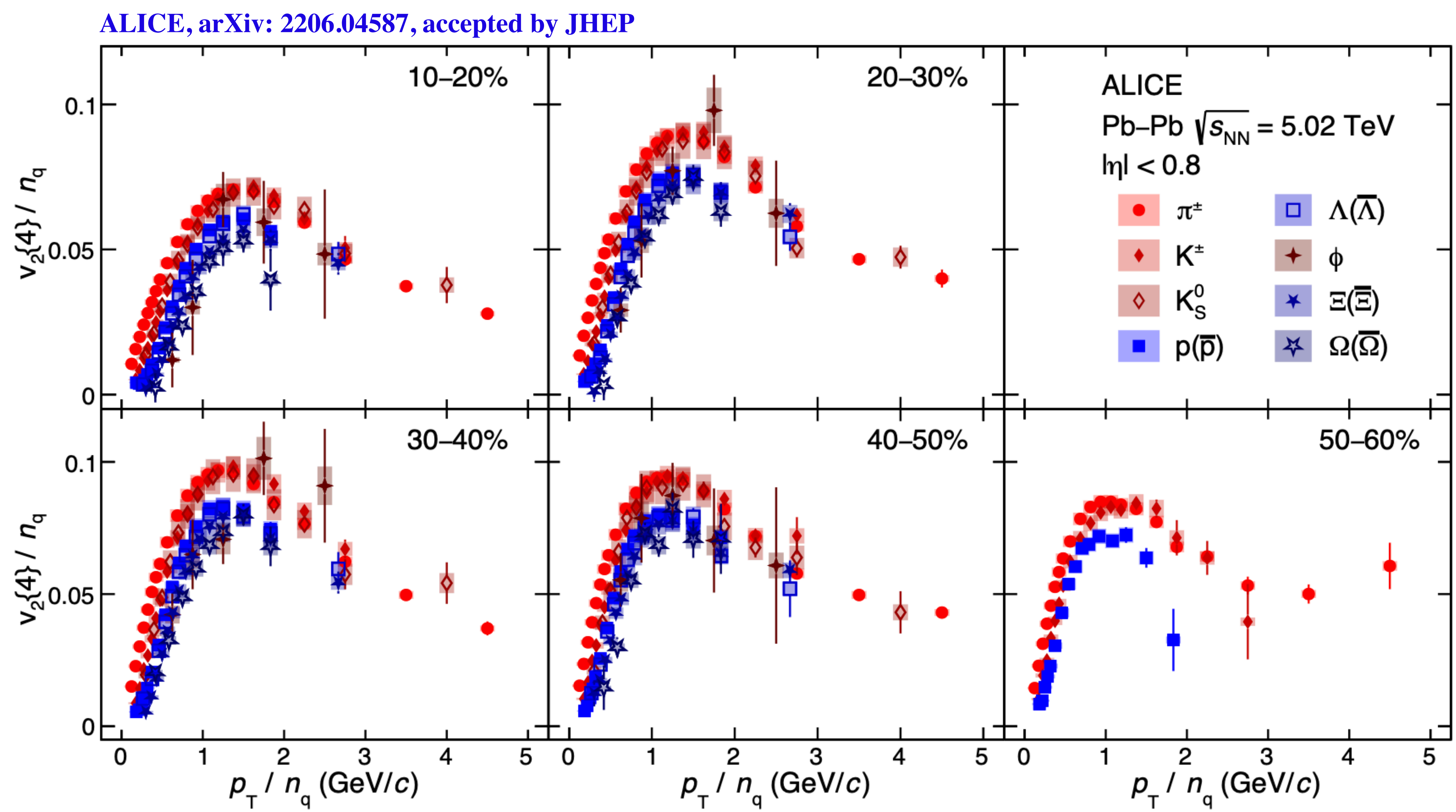
- Investigating $p(v_2)$ with multi-particle cumulants
  - Ultra-higher order cumulants e.g. $v_2\{10\}\{12\}\{14\}\{16\}$ is implemented for HL-LHC,
  - Possibility to construct a more precise p.d.f. with higher moments

PID flow



- $v_2\{2\}$ and $v_2\{4\}$ for $\pi^\pm$, $K^\pm$, K^0_S, p(p), Λ(Λ), ϕ, Ξ(Ξ), Ω(Ω)
  - Low p_T : mass ordering
  - Intermediate p_T: baryon-meson grouping
  - Quantitatively described by CoLBT model with hydro+coal+frag (not shown)

NCQ scaling



- Number of constituent quark (NCQ) scaling is not observed neither in $v_2\{2\}/n_q$ nor $v_2\{4\}/n_q$ at the LHC
  - Is NCQ scaling to simplified to probe the partonic collectivity?
  - Can one use NCQ scaling to search for the critical point at RHIC-BES?

PID flow fluctuations

❖ Flow fluctuations with $v_n\{2\}$ and $v_n\{4\}$

$$v_n^2\{2\} = \langle v_n \rangle^2 + \sigma_{v_n}^2,$$
$$v_n^2\{4\} \approx \langle v_n \rangle^2 - \sigma_{v_n}^2,$$

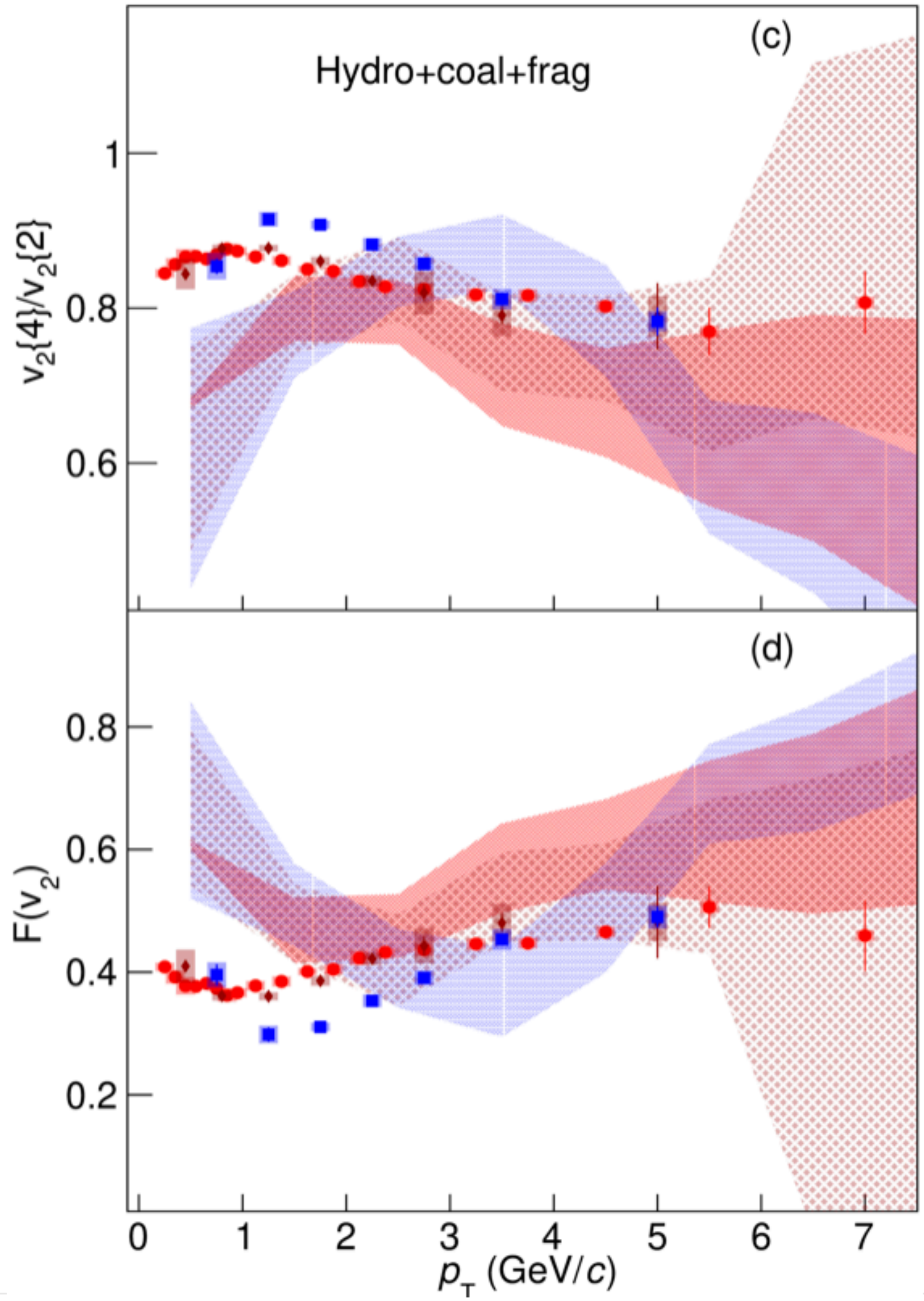
→ $v_n\{4\}/v_n\{2\}$

→ $$F(v_n) = \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}}$$

❖ Characteristic p_T and particle species dependence of $v_2\{4\}/v_2\{2\}$ and $F(v_2)$

- Contributions not only from initial eccentricity fluctuations (p_T independent) but also system dynamic evolutions

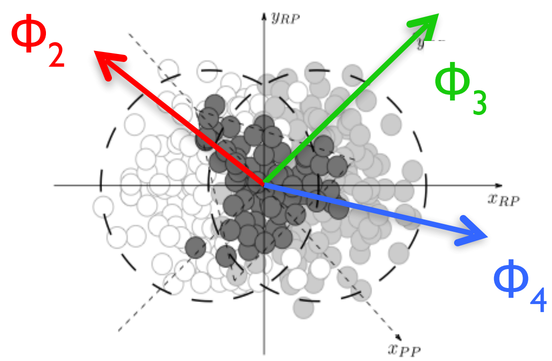
ALICE, arXiv: 2206.04587, accepted by JHEP



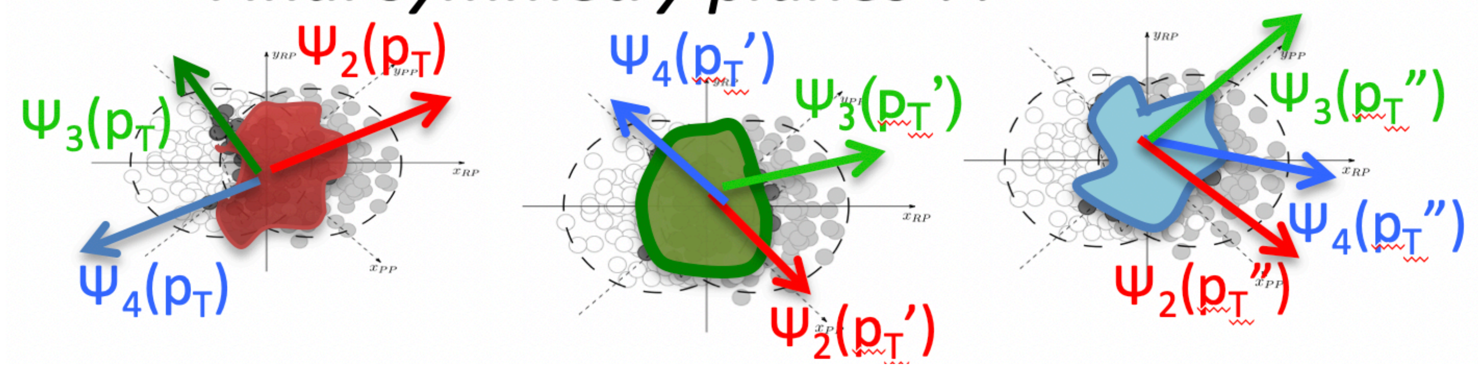
How does ψ_n fluctuate

Flow vector fluctuations

Initial symmetry planes



Final symmetry planes ??



$$v_n\{2\} = \frac{\langle v_n(p_{\rm T})\ v_n \cos n[\Psi_n(p_{\rm T}) - \Psi_n]\rangle}{\sqrt{\langle v_n^2\rangle}}$$

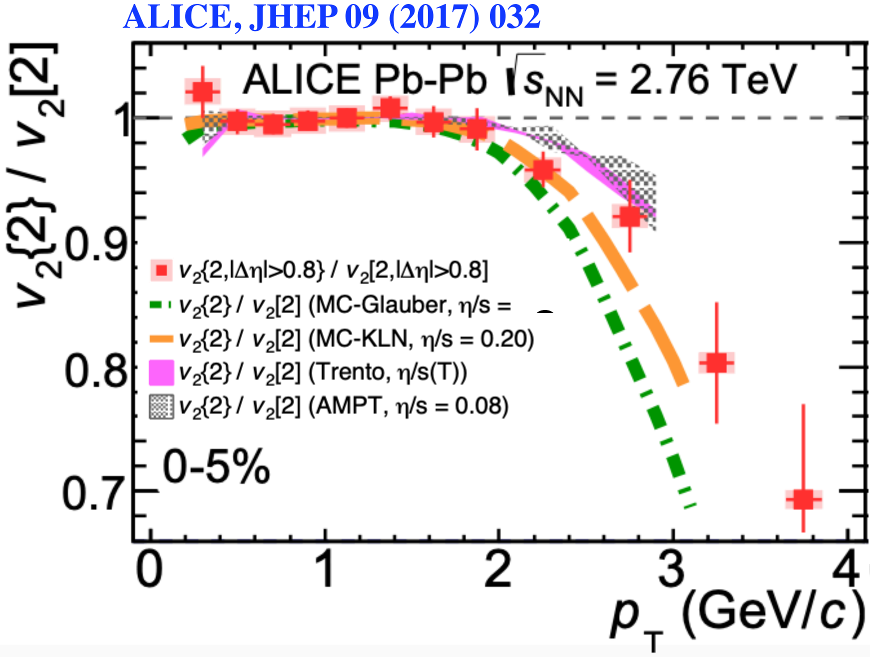
$$v_n[2] = \sqrt{\langle v_n^2(p_{\rm T})\rangle}$$

$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_{\rm T}^a)\ v_n \cos n[\Psi_n(p_{\rm T}^a) - \Psi_n]\rangle}{\sqrt{\langle v_n^2(p_{\rm T}^a)\rangle}\sqrt{\langle v_n^2\rangle}}$$

→ Flow angle fluctuations

→ Flow magnitude fluctuations

ALICE, JHEP 09 (2017) 032



- ❖ $v_2\{2\}/v_2[2] < 1$, indicates presence of flow angle and magnitude fluctuations
- ❖ How can we disentangle the two contributions and quantify each of them?

U. Heinz etc, PRC87, 034913 (2013)
F. G. Gardim etc, PRC87, 031901(R) (2013)

Flow angle and magnitude fluctuations

☆ **New observable to measure** **flow angle fluctuations:**

$$F(\Psi_n^a, \Psi_n) = \frac{\langle\langle \cos[n(\varphi_1^a + \varphi_2^a - \varphi_3 - \varphi_4)] \rangle\rangle}{\langle\langle \cos[n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4)] \rangle\rangle}$$

$$= \frac{\langle v_n^2(p_T^a)\ v_n^2 \cos 2n[\Psi_n(p_T^a) - \Psi_n] \rangle}{\langle v_n^2(p_T^a) v_n^2 \rangle}$$

$$\approx \langle \cos 2n[\Psi_n(p_T^a) - \Psi_n] \rangle$$

$F(\Psi_n^a, \Psi_n) < 1$ indicates p_T-dependent **flow angle fluctuations**

☆ **New observable to measure** **flow magnitude fluctuations:**

$$\frac{\langle\langle \cos n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4) \rangle\rangle}{\langle\langle \cos n(\varphi_1^a - \varphi_3^a) \rangle\rangle \langle\langle \cos n(\varphi_2 - \varphi_4) \rangle\rangle} = \frac{\langle v_n^2(p_T^a)\ v_n^2 \rangle}{\langle v_n^2(p_T^a) \rangle \langle v_n^2 \rangle}$$

p_T-integrated baseline: $\langle v_n^4 \rangle / \langle v_n^2 \rangle^2$

Deviations from baseline indicate the p_T-dependent **flow magnitude fluctuations**

arXiv > nucl-ex > arXiv:2211.13651

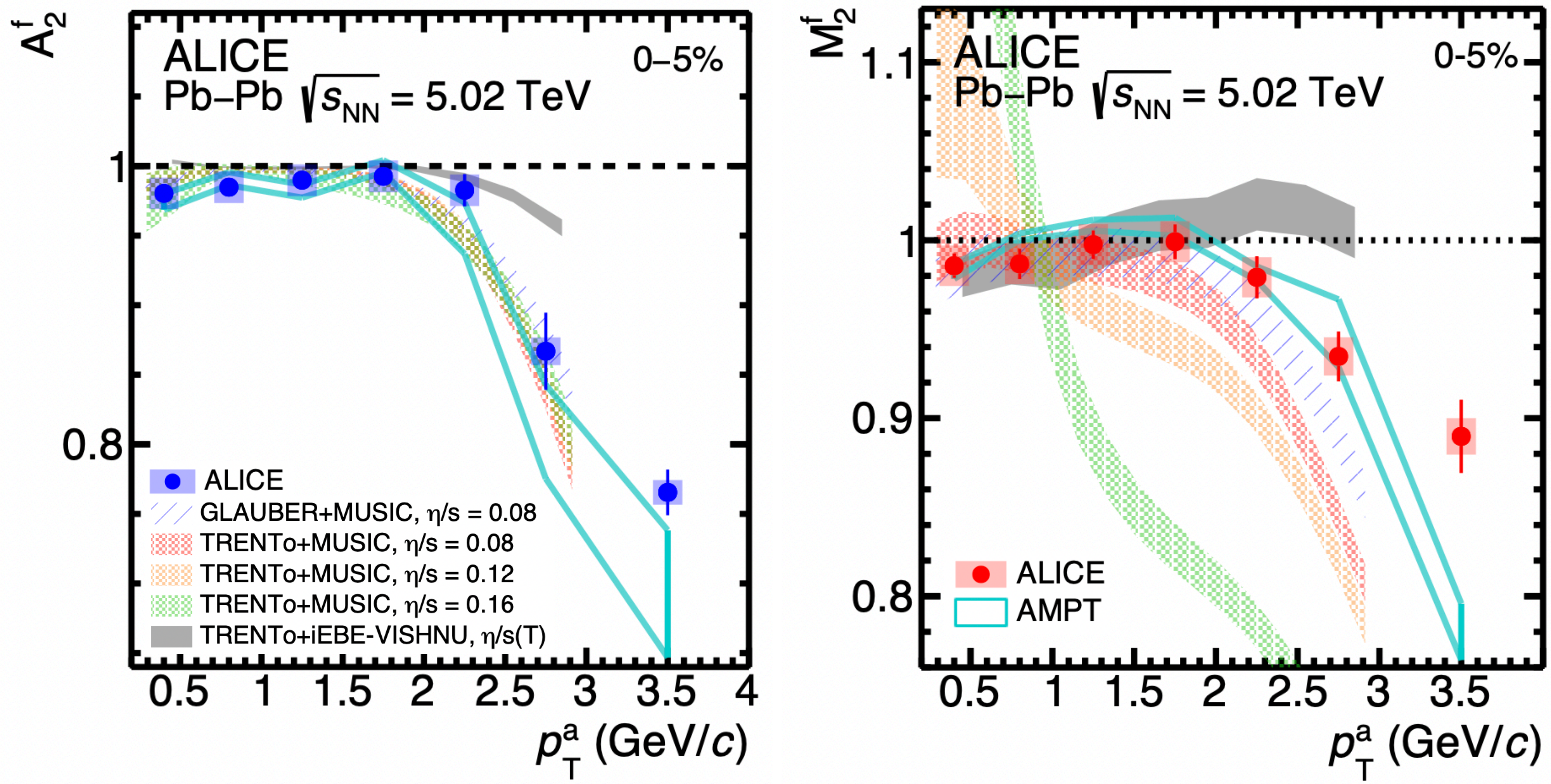
Nuclear Experiment

[Submitted on 24 Nov 2022]

Transverse momentum decorrelation of the flow vector in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Emil Gorm Nielsen, You Zhou

Observation of flow angle and flow magnitude fluctuations



ALICE, arXiv: 2206.04574

iEBE-VISHNU: W. Zhao etc, EPJC77 (2017) 645

MUSIC: P. Bozek etc, PRC105 (2022) 034904

- Large deviations from unity of both A_2^f and M_2^f → **First observation of flow angle and flow magnitude fluctuations!**
- Comparison with theoretical models suggest observables are sensitive to **initial state** and the **QGP properties.**

How do v_n and v_m correlate

Symmetric Cumulant

Flow with 2-particle correlation:

$$\langle\langle \cos(n\varphi_1 - n\varphi_2)\rangle\rangle = \langle v_n^2 \rangle$$

Flow with 4-particle correlation:

$$\langle\langle \cos(n\varphi_1 + n\varphi_2 - n\varphi_3 - n\varphi_4)\rangle\rangle = \langle v_n^4 \rangle$$

Flow with 4-particle cumulant:

$$\langle\langle \cos(n\varphi_1 + n\varphi_2 - n\varphi_3 - n\varphi_4)\rangle\rangle - \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle \, \langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle - \langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle \, \langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle = c_n\{4\}$$

PHYSICAL REVIEW C **89**, 064904 (2014)

Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations

Ante Bilandzic,[1] Christian Holm Christensen,[1] Kristjan Gulbrandsen,[1] Alexander Hansen,[1] and You Zhou[2,3]
[1]*Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[2]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3]*Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

Symmetric cumulants:

$$\langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c$$
$$= \langle\langle \cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle - \langle\langle \cos[m(\varphi_1 - \varphi_2)]\rangle\rangle \, \langle\langle \cos[n(\varphi_1 - \varphi_2)]\rangle\rangle$$
$$= \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle \,.$$

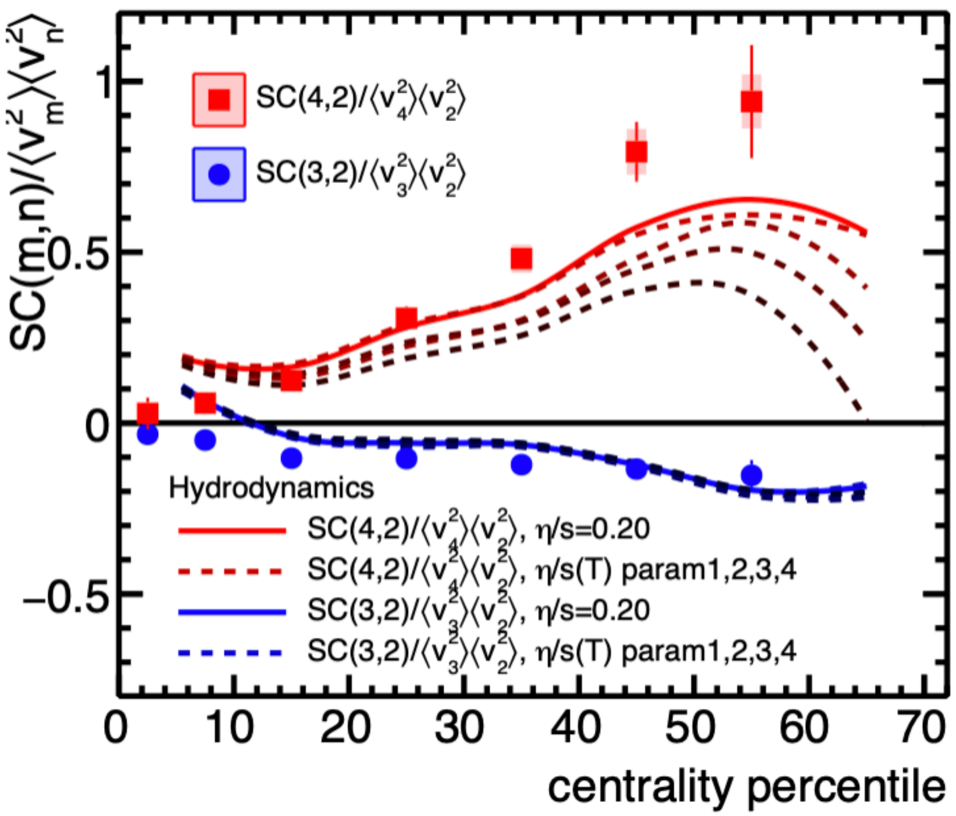
By construction not sensitive to:

- non-flow effects, due to usage of 4-particle cumulant
- inter-correlations of various symmetry planes (Ψ_n and Ψ_m correlations)

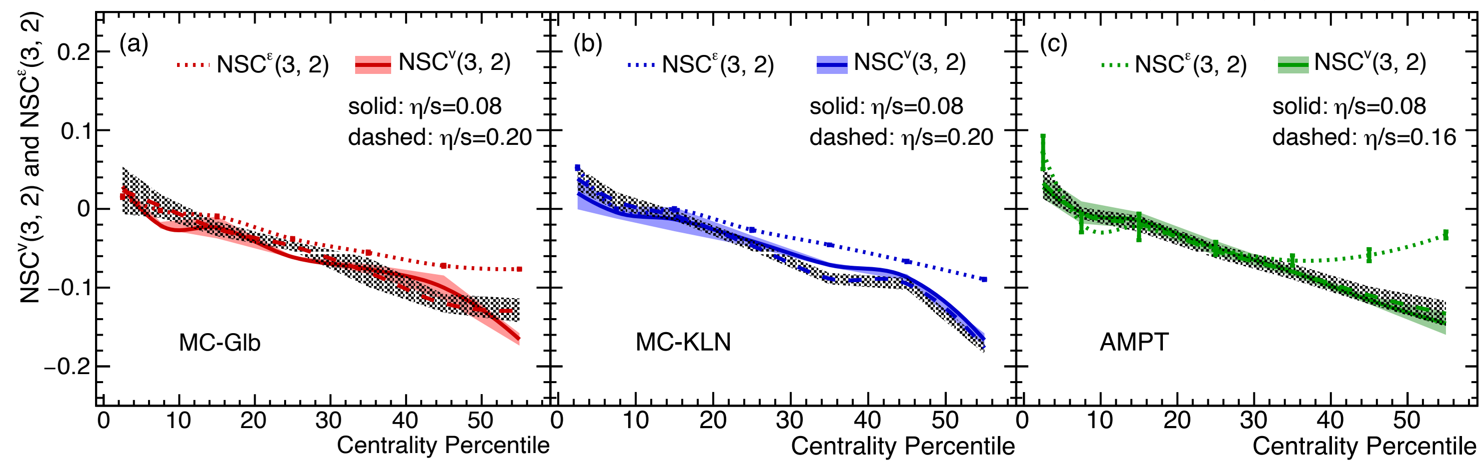
(Normalized) Symmetric Cumulant

Normalized Symmetric cumulants: $NSC(m,n) = \frac{SC(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$

ALICE, PRL117, 182301 (2016)



X. Zhu etc, PRC95, 044902 (2017)



$v_2 \propto \varepsilon_2$
$v_3 \propto \varepsilon_3$

$\Rightarrow \quad \frac{\langle v_3^2\, v_2^2 \rangle}{\langle v_3^2 \rangle \langle v_2^2 \rangle} \approx \frac{\langle \varepsilon_3^2\, \varepsilon_2^2 \rangle}{\langle \varepsilon_3^2 \rangle \langle \varepsilon_2^2 \rangle}$

$NSC^{v}(3,2)$ $\quad NSC^{\varepsilon}(3,2)$

- Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations
  - Although hydro describes v_n fairly well, there is not a single centrality for which a given η/s parameterization describes simultaneously SC and NSC -> tighter constraints!
  - NSC(3,2) measurements provide direct access into the initial conditions (despite details of systems evolution)
  - what is the general correlation between any order of v_n^k and v_m^p and the correlations among multiple flow coefficients

$P(v_m, v_n, v_k, \ldots)$

PHYSICAL REVIEW C **103**, 024913 (2021)

Generic algorithm for multiparticle cumulants of azimuthal correlations in high energy nucleus collisions

Zuzana Moravcova, Kristjan Gulbrandsen,[*] and You Zhou[†]
Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark

❖ Multi-particle mixed harmonic cumulants
- correlation between v_m^k, v_n^l and v_p^q
- correlation between v_m^k and v_n^l

Mixed harmonic cumulants with 4-particles

$$\mathrm{MHC}(v_m^2, v_n^2) = \mathrm{SC}(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

Mixed harmonic cumulants with 6-particles

$$\begin{aligned}\mathrm{MHC}(v_2^4, v_3^2) &= \langle\langle e^{i(2\varphi_1+2\varphi_2+3\varphi_3-2\varphi_4-2\varphi_5-3\varphi_6)}\rangle\rangle_c \\ &= \langle v_2^4\, v_3^2\rangle - 4\langle v_2^2\, v_3^2\rangle\langle v_2^2\rangle - \langle v_2^4\rangle\langle v_3^2\rangle \\ &\quad +4\langle v_2^2\rangle^2\langle v_3^2\rangle.\end{aligned}$$

$$\begin{aligned}\mathrm{MHC}(v_2^2, v_3^4) &= \langle\langle e^{i(2\varphi_1+3\varphi_2+3\varphi_3-2\varphi_4-3\varphi_5-3\varphi_6)}\rangle\rangle_c \\ &= \langle v_2^2\, v_3^4\rangle - 4\langle v_2^2\, v_3^2\rangle\langle v_3^2\rangle - \langle v_2^2\rangle\langle v_3^4\rangle \\ &\quad +4\langle v_2^2\rangle\langle v_3^2\rangle^2.\end{aligned}$$

$$\begin{aligned}\mathrm{MHC}(v_2^2, v_3^2, v_4^2) &= \langle\langle e^{i(2\varphi_1+3\varphi_2+4\varphi_3-2\varphi_4-3\varphi_5-4\varphi_6)}\rangle\rangle_c \\ &= \langle v_2^2\, v_3^2\, v_4^2\rangle - \langle v_2^2\, v_3^2\rangle\langle v_4^2\rangle - \langle v_2^2\, v_4^2\rangle\langle v_3^2\rangle \\ &\quad -\langle v_3^2\, v_4^2\rangle\langle v_2^2\rangle + 2\langle v_2^2\rangle\langle v_3^2\rangle\langle v_4^2\rangle.\end{aligned}$$

Mixed harmonic cumulants with 8-particles

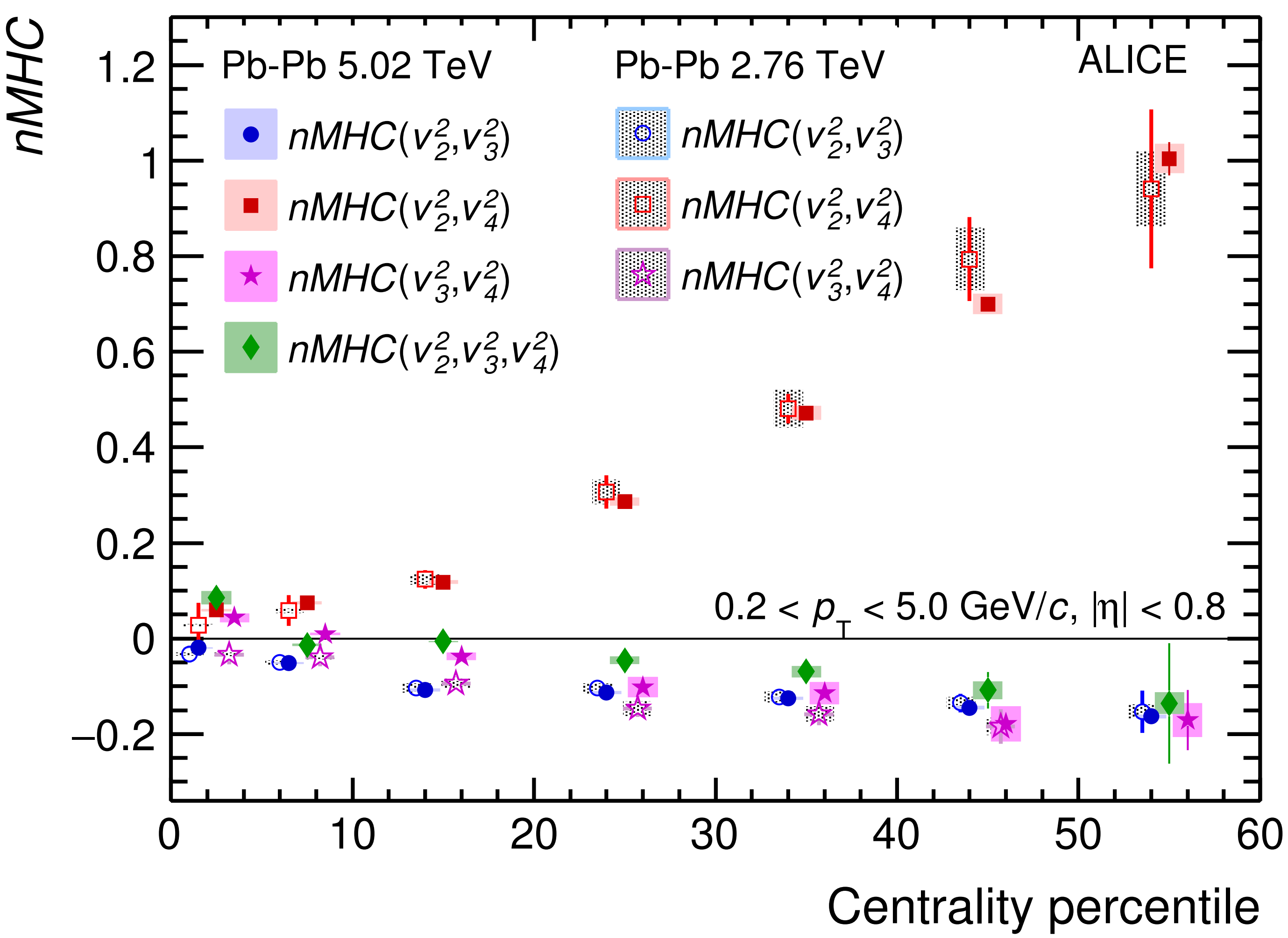
$$\begin{aligned}\mathrm{MHC}(v_2^6, v_3^2) &= \langle\langle e^{i(2\varphi_1+2\varphi_2+2\varphi_3+3\varphi_4-2\varphi_5-2\varphi_6-2\varphi_7-3\varphi_8)}\rangle\rangle_c \\ &= \langle v_2^6\, v_3^2\rangle - 9\langle v_2^4\, v_3^2\rangle\langle v_2^2\rangle - \langle v_2^6\rangle\langle v_3^2\rangle \\ &\quad -9\langle v_2^4\rangle\langle v_2^2\, v_3^2\rangle - 36\langle v_2^2\rangle^3\langle v_3^2\rangle \\ &\quad +18\langle v_2^2\rangle\langle v_3^2\rangle\langle v_2^4\rangle + 36\langle v_2^2\rangle^2\langle v_2^2\, v_3^2\rangle.\end{aligned}$$

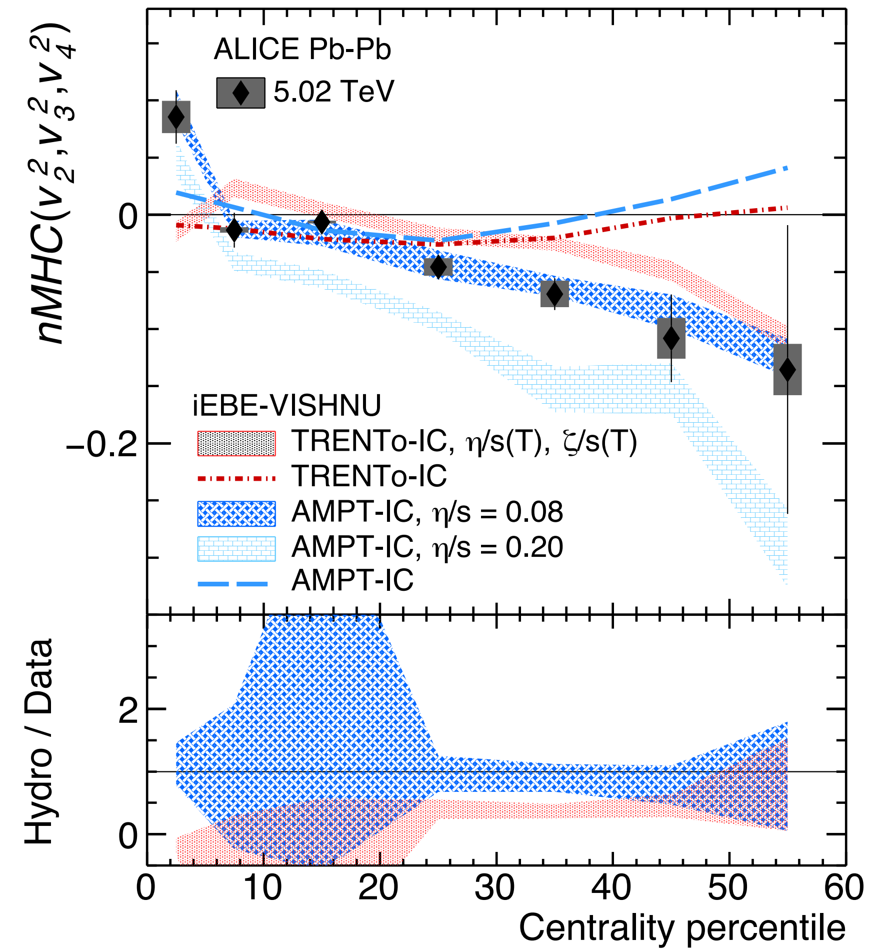
$$\begin{aligned}\mathrm{MHC}(v_2^4, v_3^4) &= \langle\langle e^{i(2\varphi_1+2\varphi_2+3\varphi_3+3\varphi_4-2\varphi_5-2\varphi_6-3\varphi_7-3\varphi_8)}\rangle\rangle_c \\ &= \langle v_2^4\, v_3^4\rangle - 4\langle v_2^4\, v_3^2\rangle\langle v_3^2\rangle \\ &\quad -4\langle v_2^2\, v_3^4\rangle\langle v_2^2\rangle - \langle v_2^4\rangle\langle v_3^4\rangle \\ &\quad -8\langle v_2^2\, v_3^2\rangle^2 - 24\langle v_2^2\rangle^2\langle v_3^2\rangle^2 \\ &\quad +4\langle v_2^2\rangle^2\langle v_3^4\rangle + 4\langle v_2^4\rangle\langle v_3^2\rangle^2 \\ &\quad +32\langle v_2^2\rangle\langle v_3^2\rangle\langle v_2^2\, v_3^2\rangle.\end{aligned}$$

$$\begin{aligned}\mathrm{MHC}(v_2^2, v_3^6) &= \langle\langle e^{i(2\varphi_1+3\varphi_2+3\varphi_3+3\varphi_4-2\varphi_5-3\varphi_6-3\varphi_7-3\varphi_8)}\rangle\rangle_c \\ &= \langle v_2^2\, v_3^6\rangle - 9\langle v_2^2\, v_3^4\rangle\langle v_3^2\rangle - \langle v_3^6\rangle\langle v_2^2\rangle \\ &\quad -9\langle v_3^4\rangle\langle v_2^2\, v_3^2\rangle - 36\langle v_2^2\rangle\langle v_3^2\rangle^3 \\ &\quad +18\langle v_2^2\rangle\langle v_3^2\rangle\langle v_3^4\rangle + 36\langle v_3^2\rangle^2\langle v_2^2\, v_3^2\rangle.\end{aligned}$$

Correlations between $v_m^2, v_n^2, v_k^2, \ldots$

ALICE, PLB818 (2021) 136354





$$
\begin{aligned}
\mathrm{MHC}(v_2^2, v_3^2, v_4^2) &= \langle\langle e^{i\,(2\varphi_1+3\varphi_2+4\varphi_3-2\varphi_4-3\varphi_5-4\varphi_6)}\rangle\rangle_c \\
&= \langle v_2^2\, v_3^2\, v_4^2\rangle - \langle v_2^2\, v_3^2\rangle\langle v_4^2\rangle - \langle v_2^2\, v_4^2\rangle\langle v_3^2\rangle \\
&\quad -\langle v_3^2\, v_4^2\rangle\langle v_2^2\rangle + 2\,\langle v_2^2\rangle\langle v_3^2\rangle\langle v_4^2\rangle.
\end{aligned}
$$

- Non-zero value of *nMHC(v_2^2, v_3^2, v_4^2)* in Pb-Pb collisions
  - Highly non-trivial correlations among three flow coefficients

How do ψ_n and ψ_m correlate

ψ_n correlations: $P(\psi_m, \psi_n, \psi_k)$

Flow with 2-particle correlation:

$$\langle\langle \cos(n\varphi_1 - n\varphi_2)\rangle\rangle = \langle v_n^2 \rangle$$

Flow with 4-particle correlation:

$$\langle\langle \cos(n\varphi_1 + n\varphi_2 - n\varphi_3 - n\varphi_4)\rangle\rangle = \langle v_n^4 \rangle$$

How about 3-particle correlation: $\langle\langle \cos(k\varphi_1 + m\varphi_2 - n\varphi_3)\rangle\rangle$

If k+m != n, $\langle\langle \cos(k\varphi_1 + m\varphi_2 - n\varphi_3)\rangle\rangle = 0$

If k+m = n, $\langle\langle \cos(k\varphi_1 + m\varphi_2 - n\varphi_3)\rangle\rangle = \langle v_k v_m v_n \cos(k\Psi_k + m\Psi_m - n\Psi_n)\rangle$

-> Example: $\langle\langle \cos(2\varphi_1 + 2\varphi_2 - 4\varphi_3)\rangle\rangle = \langle v_2^2\, v_4 \cos(4\Psi_2 - 4\Psi_4)\rangle$ -> Correlations between ψ_2 and ψ_4

Further reading

Physics Letters B 744 (2015) 82–87

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

v_4, v_5, v_6, v_7: Nonlinear hydrodynamic response versus LHC data

Li Yan *, Jean-Yves Ollitrault

Institut de physique théorique, Université Paris Saclay, CNRS, CEA, F-91191 Gif-sur-Yvette, France

A R T I C L E I N F O

Article history:
Received 12 February 2015
Accepted 18 March 2015
Available online 23 March 2015
Editor: W. Haxton

A B S T R A C T

Higher harmonics of anisotropic flow (v_n with $n \geq 4$) in heavy-ion collisions can be measured either with respect to their own plane, or with respect to a plane constructed using lower-order harmonics. We explain how such measurements are related to event-plane correlations. We show that CMS data on v_4 and v_6 are compatible with ATLAS data on event-plane correlations. If one assumes that higher harmonics are the superposition of non-linear and linear responses, then the linear and non-linear parts can be isolated under fairly general assumptions. By combining analyses of higher harmonics with analyses of v_2 and v_3, one can eliminate the uncertainty from initial conditions and define quantities that only involve nonlinear hydrodynamic response coefficients. Experimental data on v_4, v_5 and v_6 are in good agreement with hydrodynamic calculations. We argue that v_7 can be measured with respect to elliptic and triangular flow. We present predictions for v_7 versus centrality in Pb–Pb collisions at the LHC.

Physics Letters B 773 (2017) 68–80

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Linear and non-linear flow mode in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration *

A R T I C L E I N F O

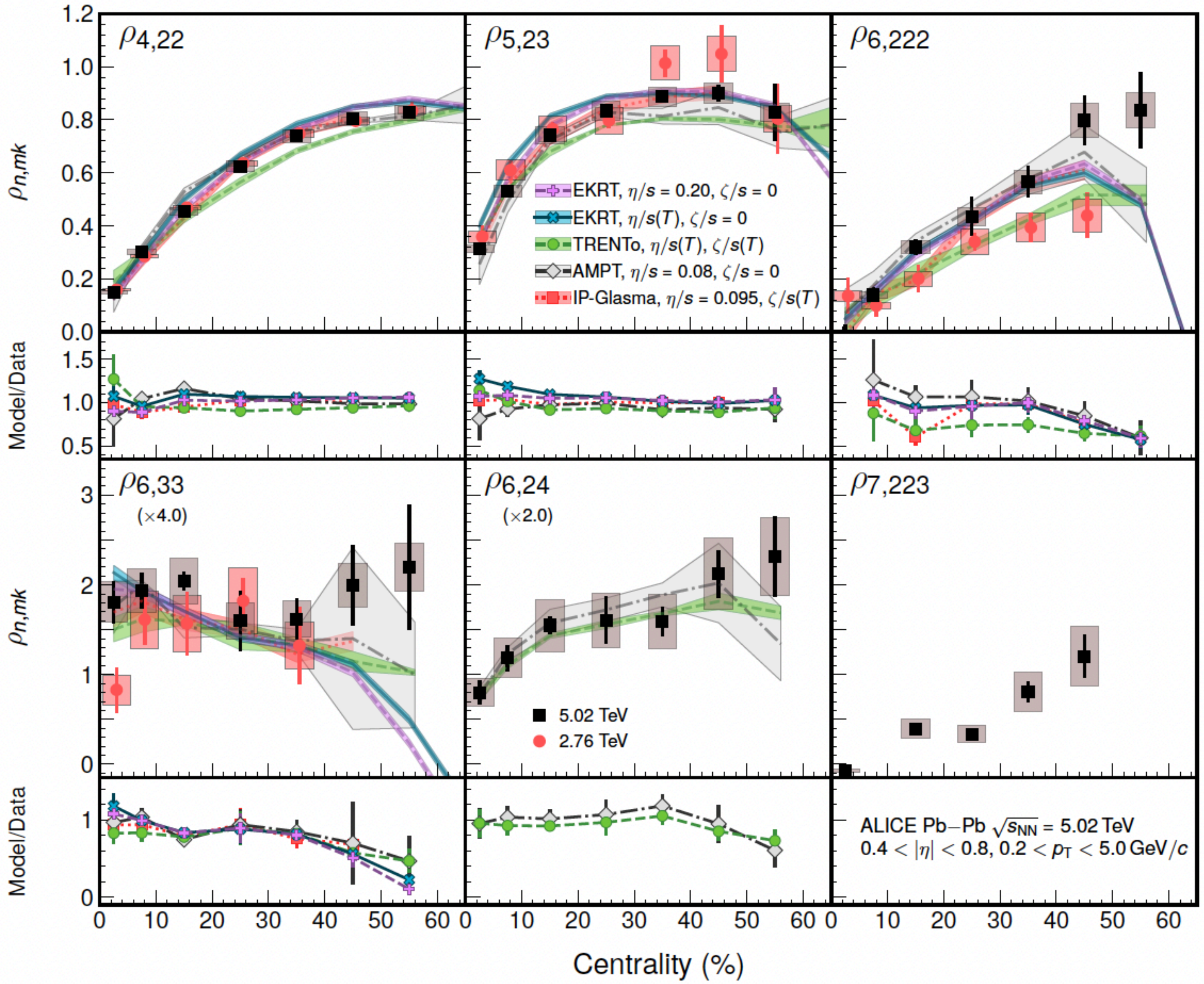
Article history:
Received 22 May 2017
Received in revised form 10 July 2017
Accepted 27 July 2017
Available online 4 August 2017
Editor: L. Rolandi

A B S T R A C T

The second and the third order anisotropic flow, V_2 and V_3, are mostly determined by the corresponding initial spatial anisotropy coefficients, ε_2 and ε_3, in the initial density distribution. In addition to their dependence on the same order initial anisotropy coefficient, higher order anisotropic flow, V_n ($n > 3$), can also have a significant contribution from lower order initial anisotropy coefficients, which leads to mode-coupling effects. In this Letter we investigate the linear and non-linear modes in higher order anisotropic flow V_n for $n = 4, 5, 6$ with the ALICE detector at the Large Hadron Collider. The measurements are done for particles in the pseudorapidity range $|\eta| < 0.8$ and the transverse momentum range $0.2 < p_T < 5.0$ GeV/c as a function of collision centrality. The results are compared with theoretical calculations and provide important constraints on the initial conditions, including initial spatial geometry and its fluctuations, as well as the ratio of the shear viscosity to entropy density of the produced system.

ψ_n correlations: $P(\psi_m, \psi_n, \psi_k)$

ALICE, PLB773 (2017) 68, JHEP05 (2020) 085

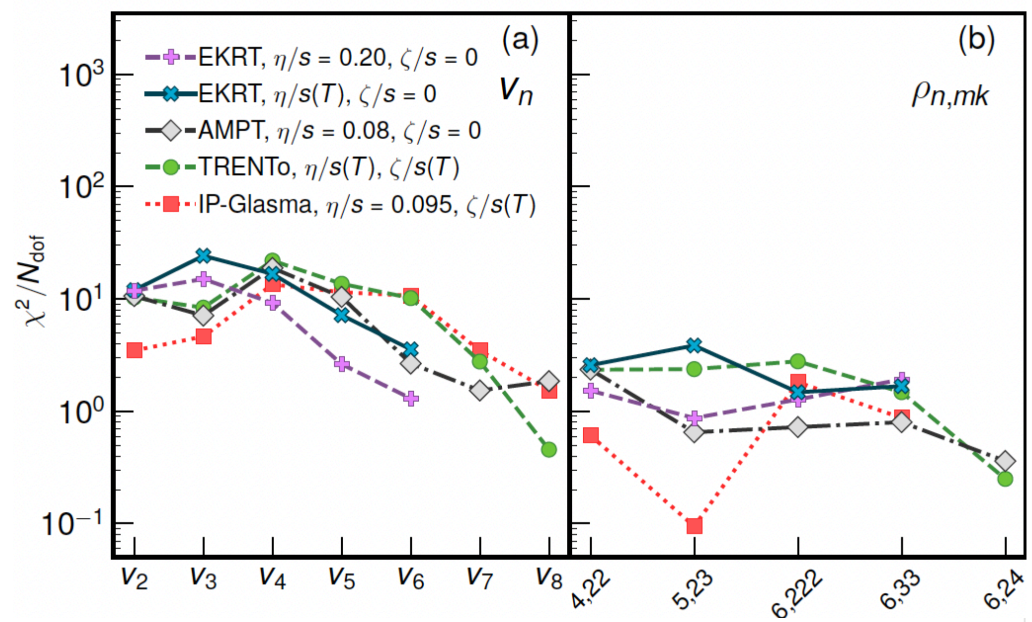


$\rho_{422} \approx \langle \cos(4\Psi_4 - 4\Psi_2) \rangle$

$\rho_{532} \approx \langle \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2) \rangle$

$\rho_{6222} \approx \langle \cos(6\Psi_6 - 6\Psi_2) \rangle$

$\rho_{633} \approx \langle \cos(6\Psi_6 - 6\Psi_3) \rangle$

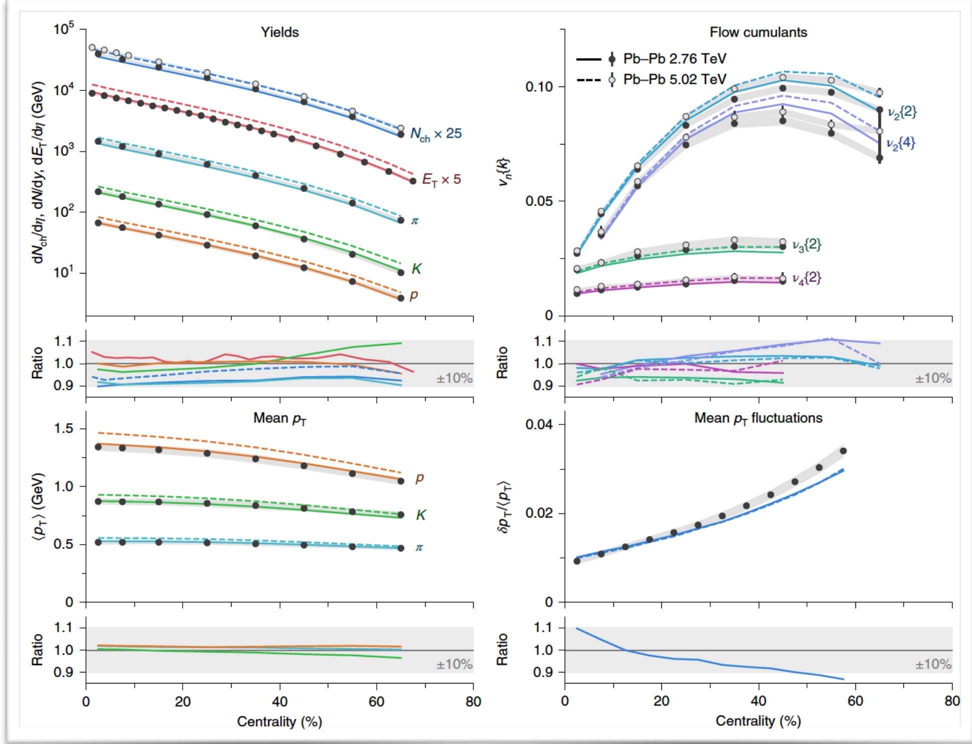


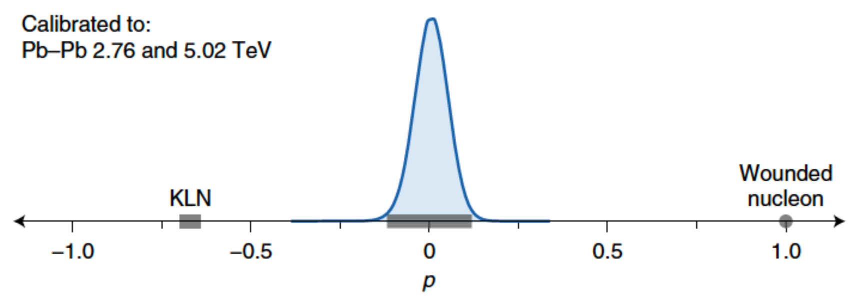
EKRT, PRC93, 024907 (2016)
TRENTo, EPJC77 (2017) 645
AMPT, EPJC77 (2017) 645
IP-Glasma, PRC95, 064913 (2017)

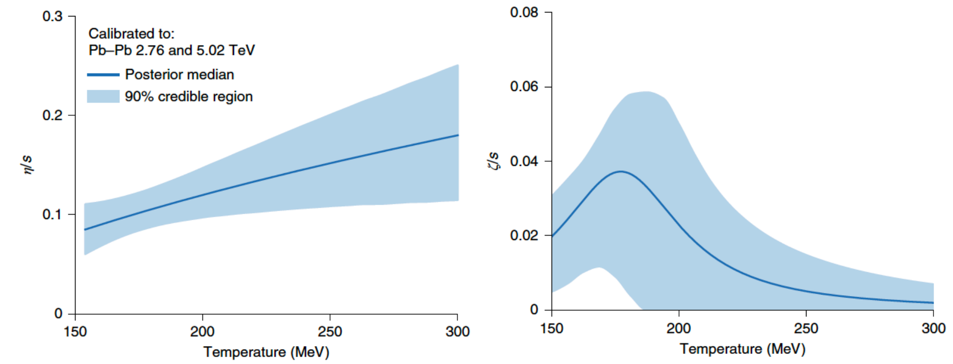
- ρ_{mn}, probes the symmetry plane correlations
  - No energy dependence between measurements except $\rho_{6,222}$
  - Among many models, TRENTo model does not work well in $\rho_{n,mk}$

Bayesian analyses with simple v_n

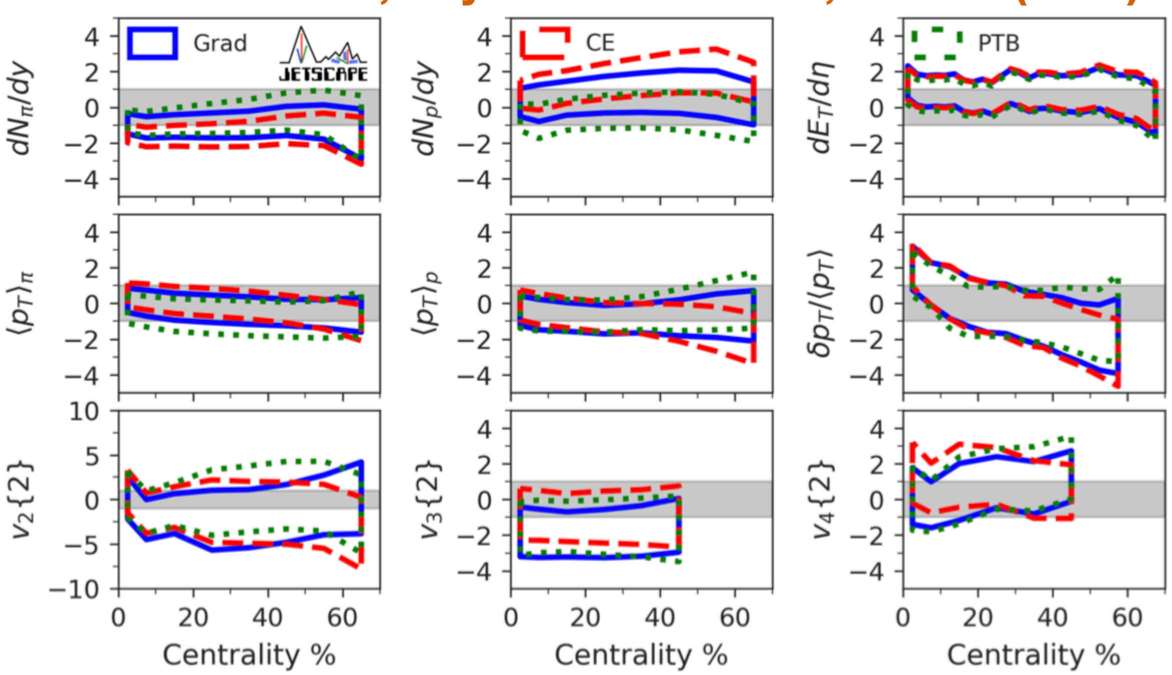
J.E. Bernhard etc, Nature Physics,15, 1113 (2019)

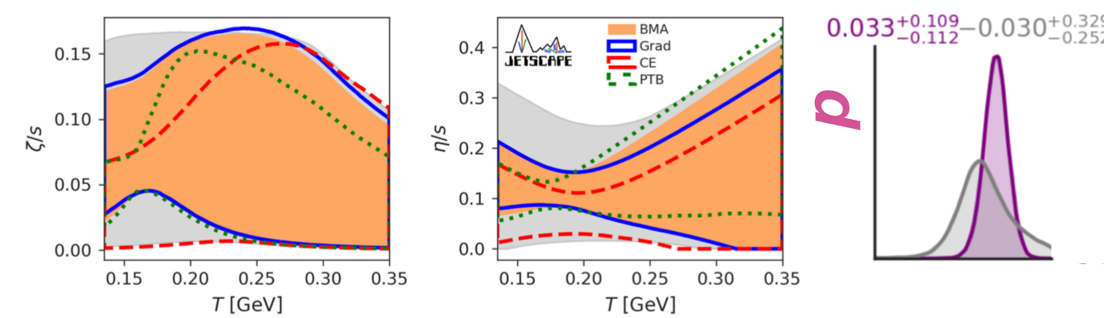




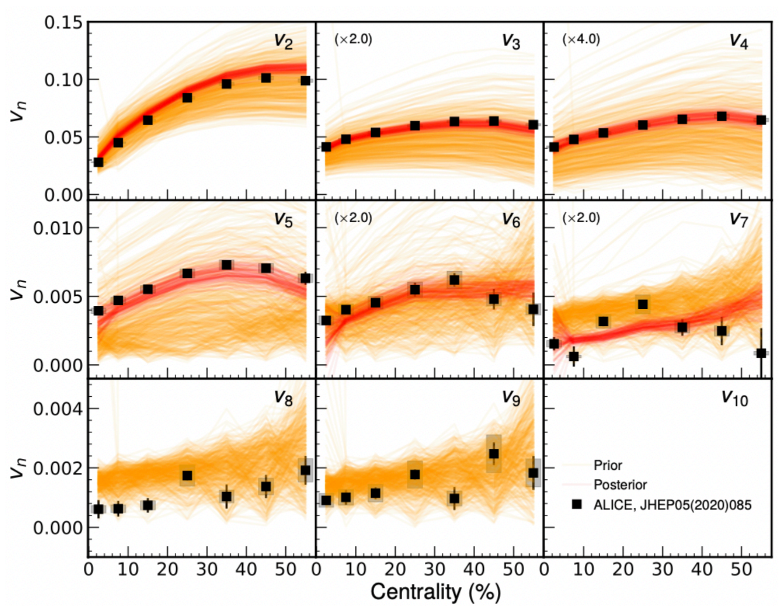


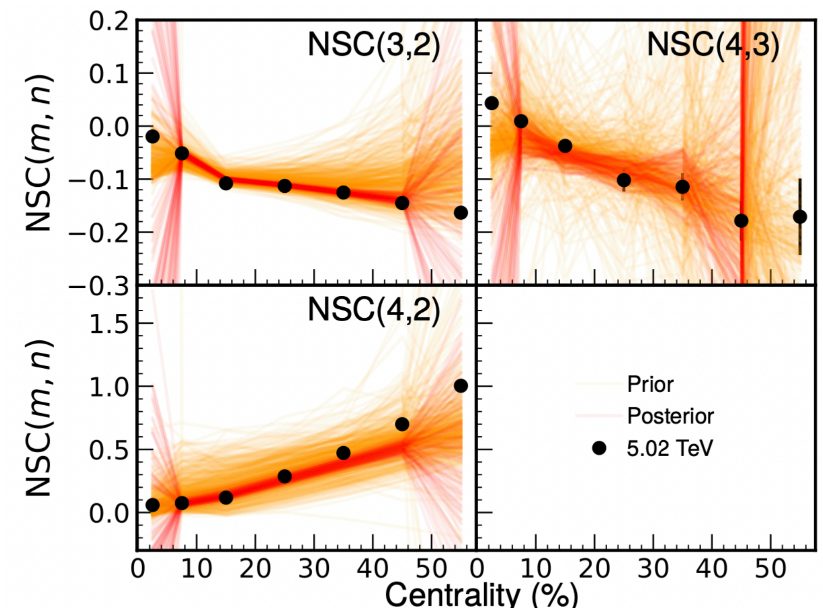
JETSCAPE, Phys. Rev. Lett. 126, 242301 (2021)

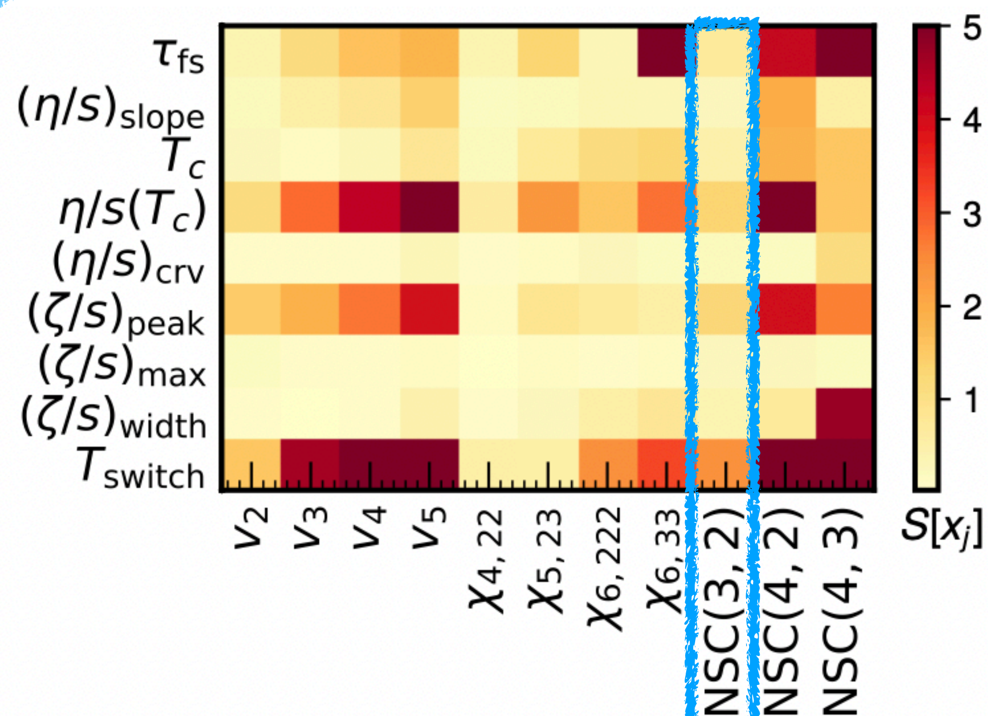


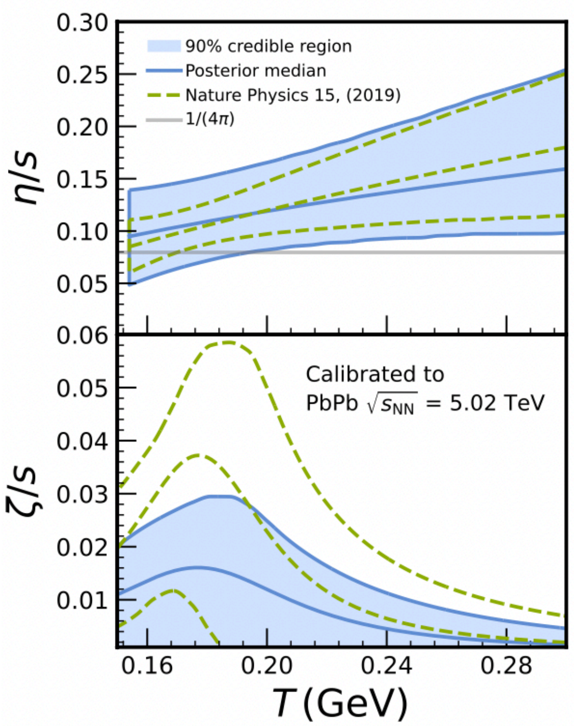


Bayesian analysis with more flow observables









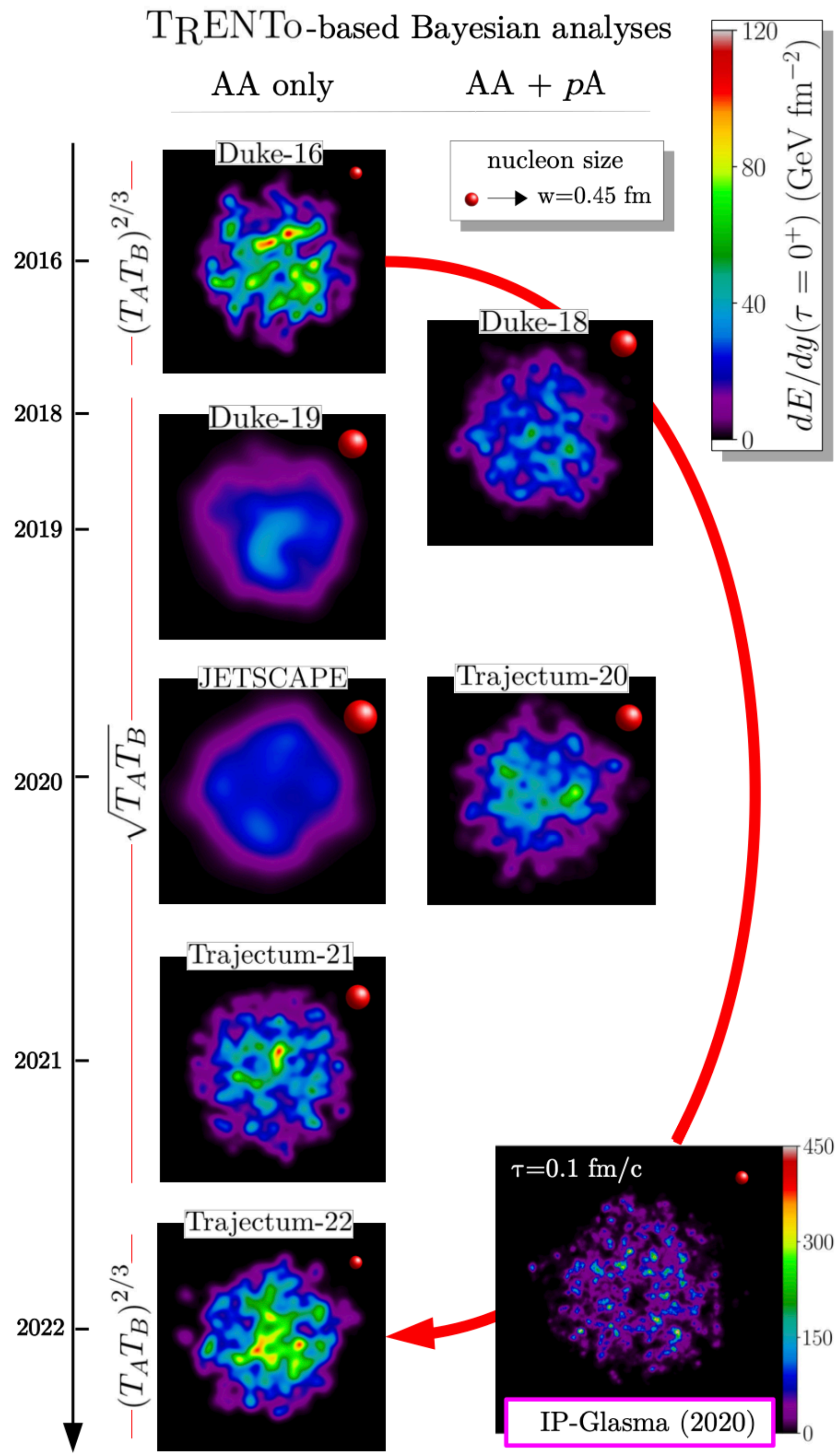
Initial conditions

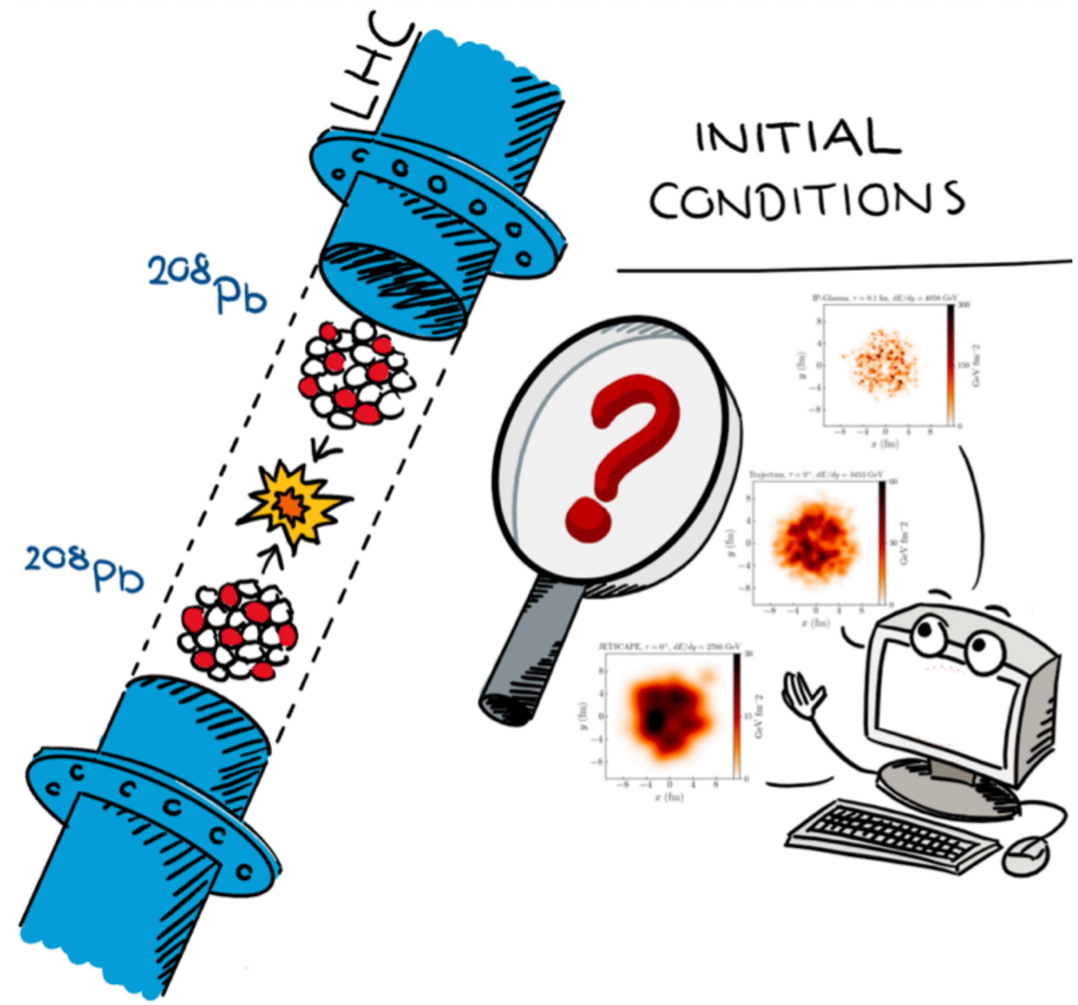
Parameter	MAP value
Norm	21.06
p	0.0077
σ_k	0.881
d^3_{min}	0.975
τ_{fs}	0.901
T_c	0.147
T_{switch}	0.160

J.E. Parkkila etc, PRC104, 054904

Similar study by including differential flow data, see: G. Nijs, W. Van der Schee, PRL126, 202301 (2021)

IC: state of the art (?)





How can we access the initial conditions in EXP ?

$[p_T]$ - v_n correlations

❖Shape of the fireball: Anisotropic flow

❖Size of the fireball: radial flow, $[p_{\rm T}]$

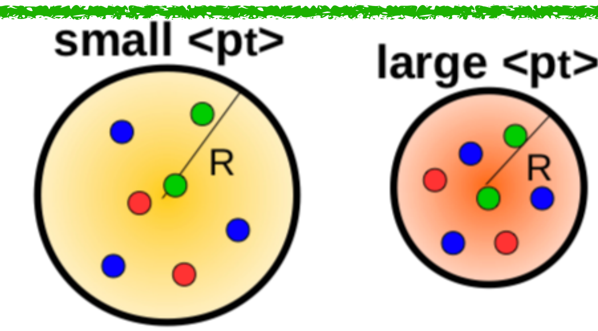
❖Initial geometry and fluctuations of shape and size

❖Final state: correlation between v_n and $p_{\rm T}$

$$V_n \propto \mathcal{E}_n$$

$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto \frac{dE}{E}$$

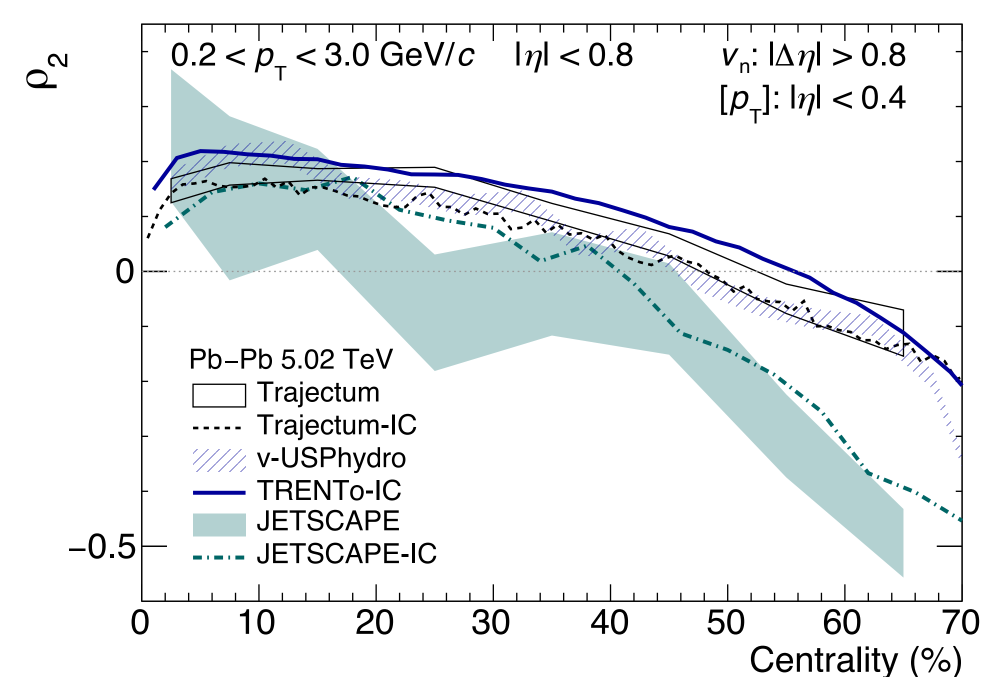
$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto -\frac{dR}{R}$$



$$\rho(v_n^2,[p_{\rm T}]) = \frac{cov(v_n^2,[p_{\rm T}])}{\sqrt{var(v_n^2)}\sqrt{var([p_{\rm T}])}}$$

P. Bozek etc, PRC96 (2017) 014904

$$\rho(v_n^2,[p_{\rm T}]) \approx \rho(\varepsilon_n^2, E_0^{-1})$$



☆ $cov(v_n^2,[p_{\rm T}])$: 3-particle correlation (2 azimuthal, 1 $[p_T]$)

$$\left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j}(p_{{\rm T},k}-\langle\langle p_{\rm T}\rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_{\rm evt}$$

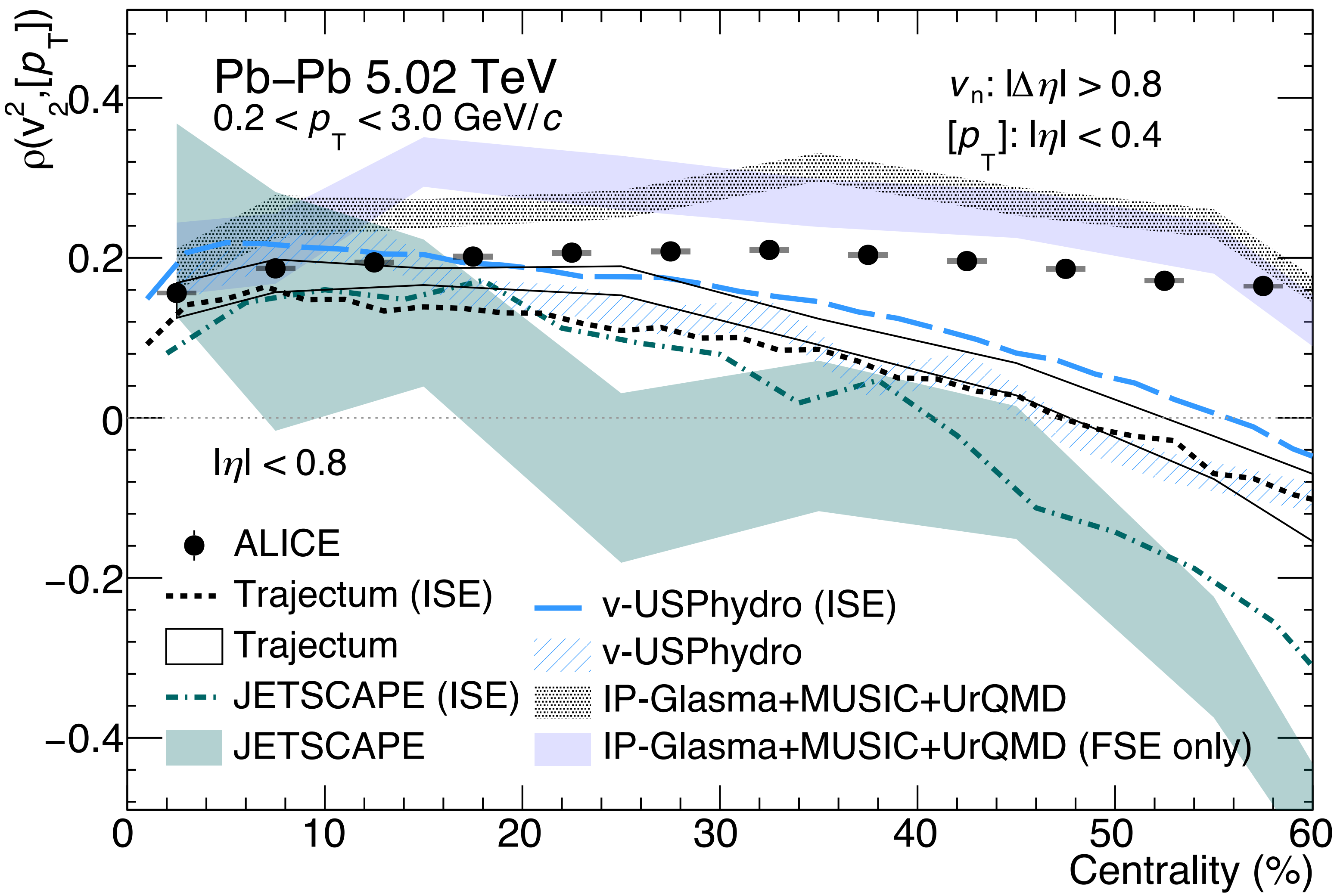
☆ $\sqrt{var(v_n^2)}$: 2 and 4-particle azimuthal correlations

$$= v_n\{2\}^4 - v_n\{4\}^4$$

☆ $\sqrt{var([p_{\rm T}])}$: 2-particle $[p_T]$ correlations

$$\left\langle \frac{\sum_{i\neq j} w_i w_j (p_{{\rm T},i}-\langle\langle p_{\rm T}\rangle\rangle)(p_{{\rm T},j}-\langle\langle p_{\rm T}\rangle\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle_{\rm evt}$$

ρ2 in Pb-Pb



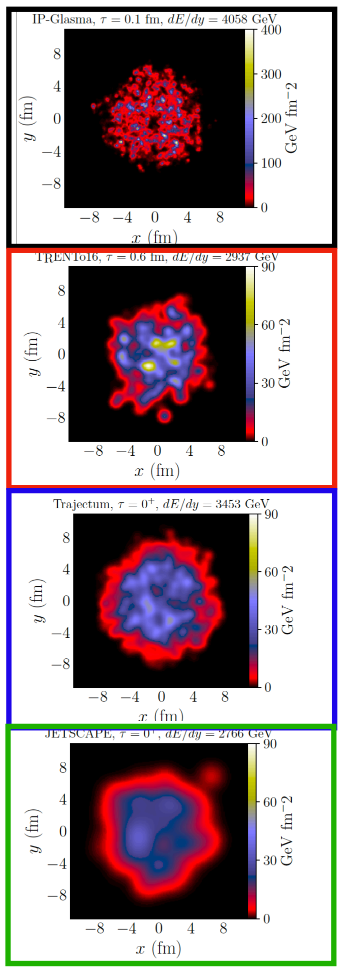
ALICE, PLB 834 (2022) 137393
v-USPhydro, PRC103 (2021) 2, 024909
IP-Glasma, PRC102, 034905 (2020)
JETSCAPE, PRL126, 242301 (2021)
Privation communication
Trajectum, PRL126, 202301 (2021)
Privation communication

- ❖ TRENTo-IC based calculations all show strong centrality dependence, negative values for centrality >40%
  - v-USPhydro, Trajectum, JETSCAPE
- ❖ The difference is from the initial stage: geometric effects or initial momentum anisotropy (CGC)?
  - No significant difference between the "full IP-Glasma" and "FSE only" for the presented centralities
  - Difference not from initial momentum anisotropy and confirm the different geometric effects

Difference in IP-Glasma and TRENTo: potential explanations

❖ Sensitive to the nucleon width parameter (size of nucleon)

- IP-Glasma ~ 0.4; v-USPhydro ~ 0.5; Trajectum~0.7; JETSCAPE (TRENTo) ~ 1.1
- w(IP-Glasma) < w(v-USPhydro) < w(Trajectum) < w(JETSCAPE)
- New constraints on the ***nucleon size***

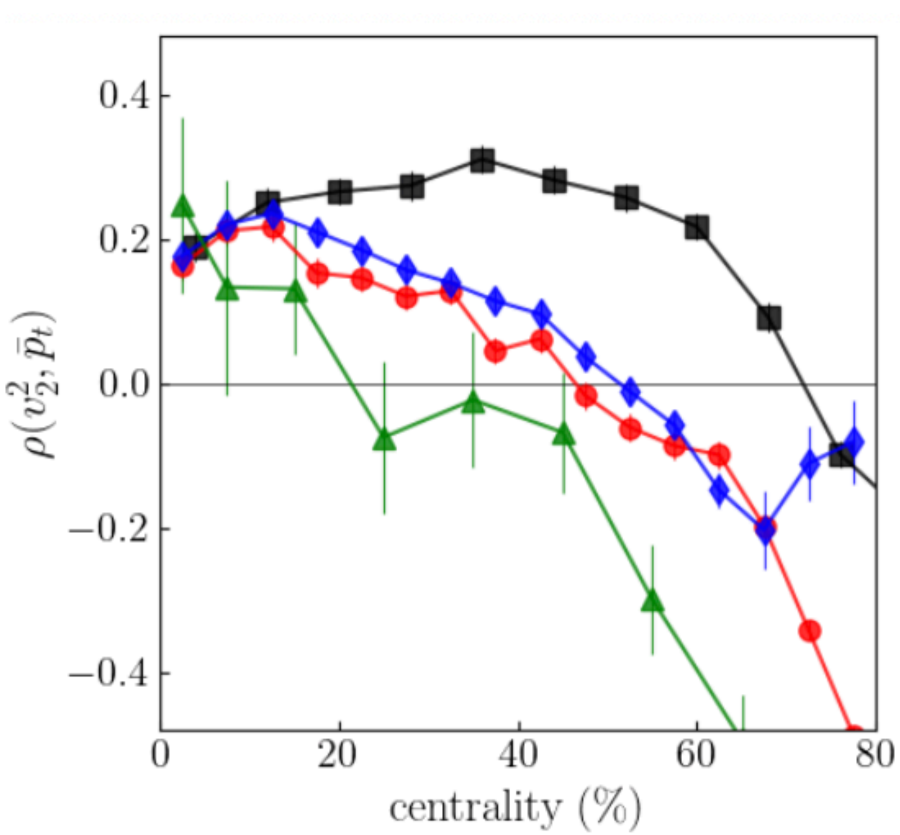


w ~ 0.4

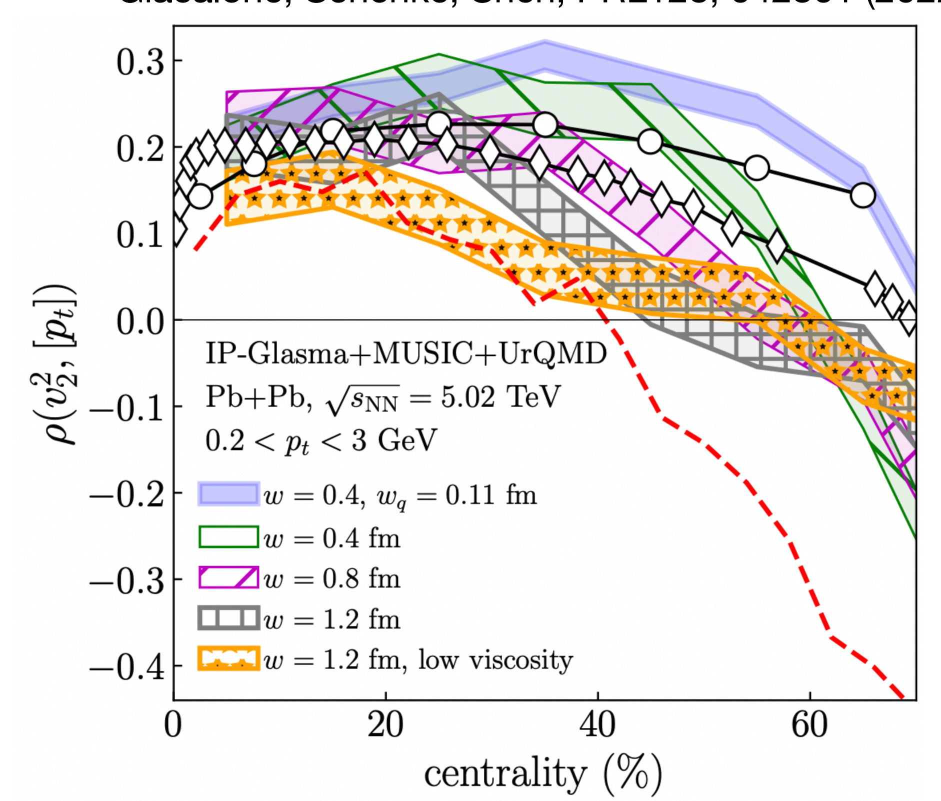
w ~ 0.5

w ~ 0.7

w ~ 1.1



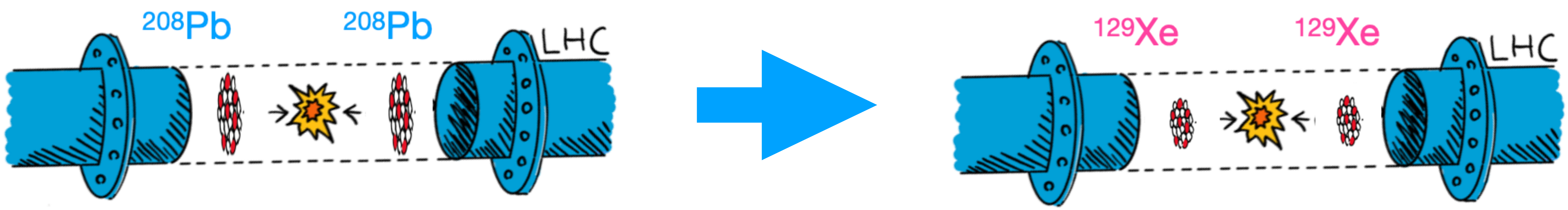
Giacalone, Schenke, Shen, PRL128, 042301 (2022)

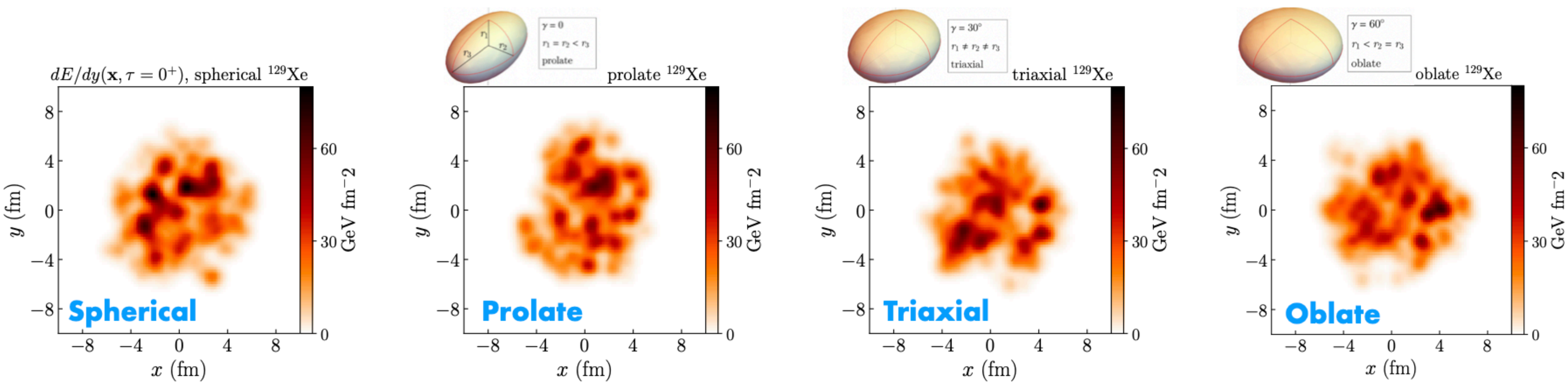


❖ Different types of thickness functions

- TRENTo $\left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$ with p≈0 $\sqrt{T_A T_B}$ IP-Glasma $T_A T_B$ type

Nuclear structure at relativistic energies





How does v_n fluctuate

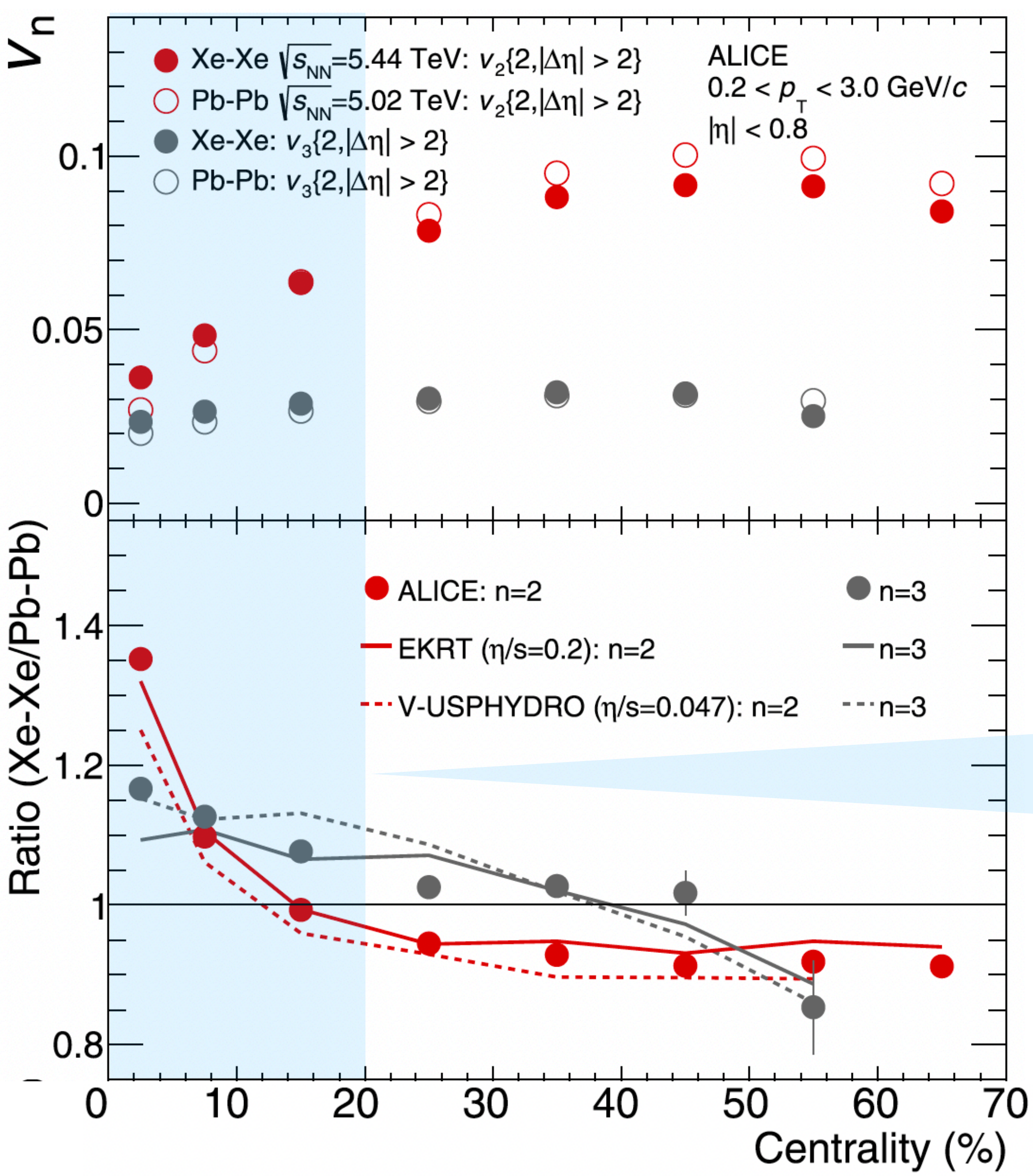
How does ψ_n fluctuate

How do v_n and v_m correlate

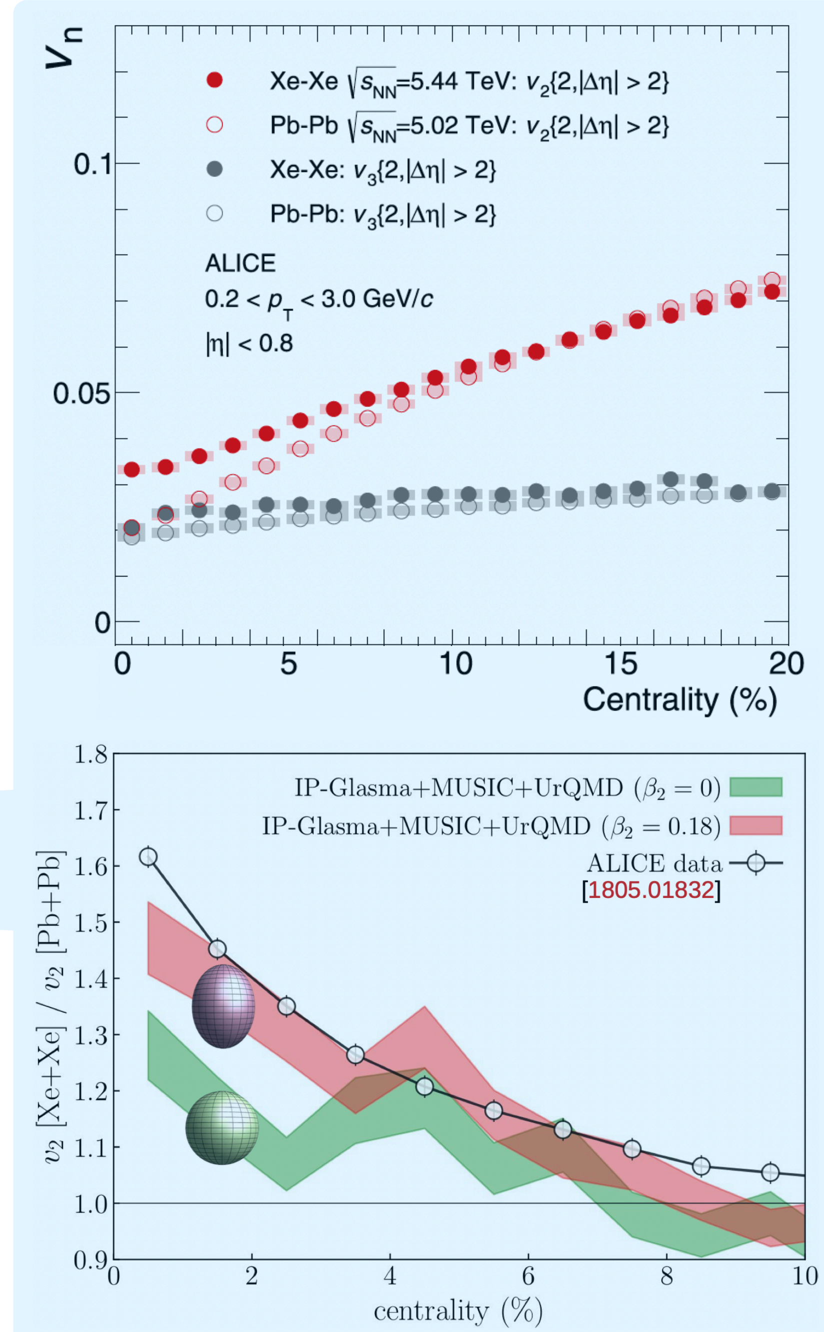
How do ψ_n and ψ_m correlate

Probe deformation of ^{129}Xe at the LHC

ALICE, Physics Letters B 784 (2018) 82
EKRT: K.J. Eskola etc, PRC 97(3) (2018) 034911
v-USPhydro: G. Giacalone etc, PRC 97 (2018) 034904



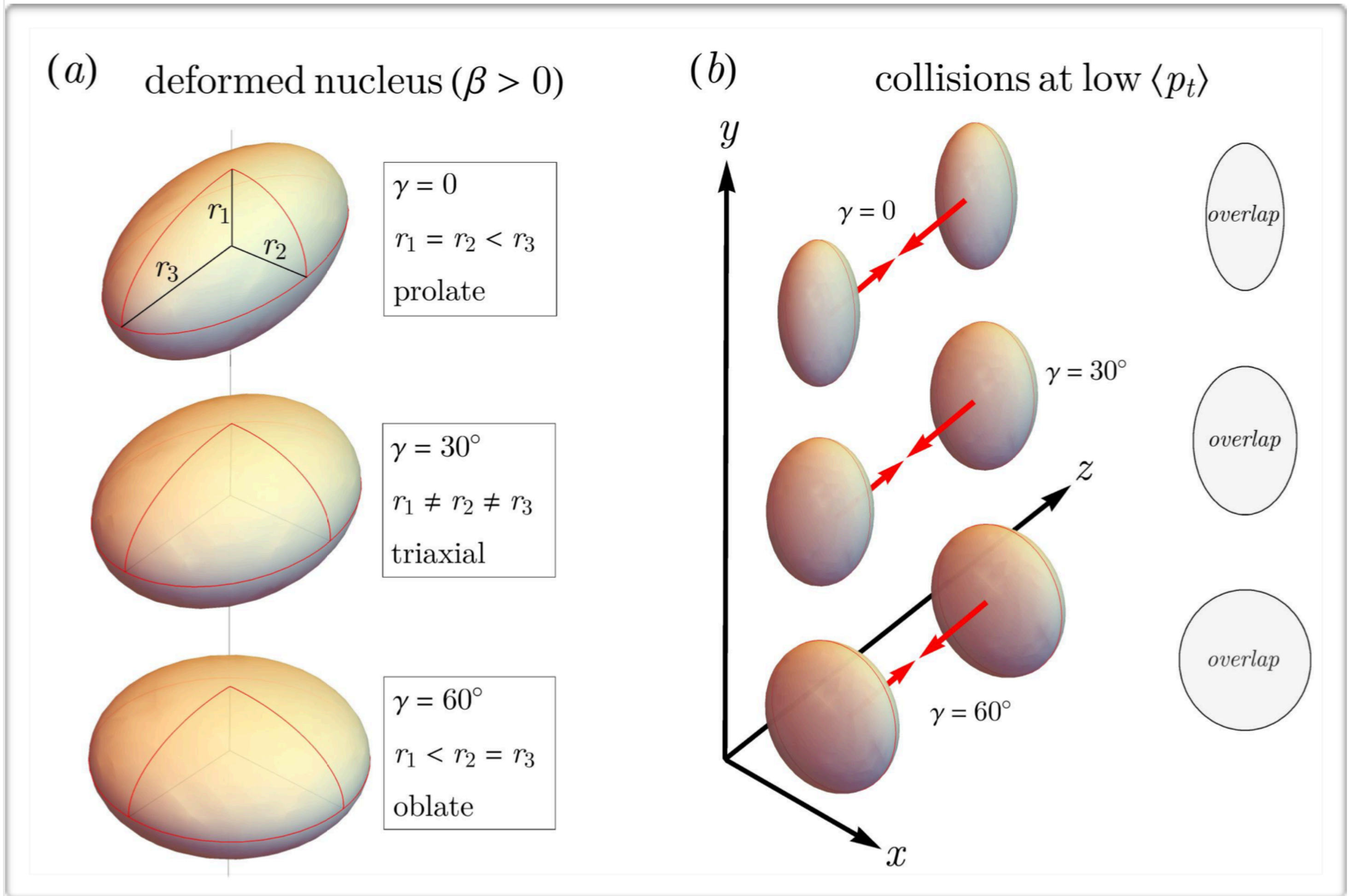
Zoom-in

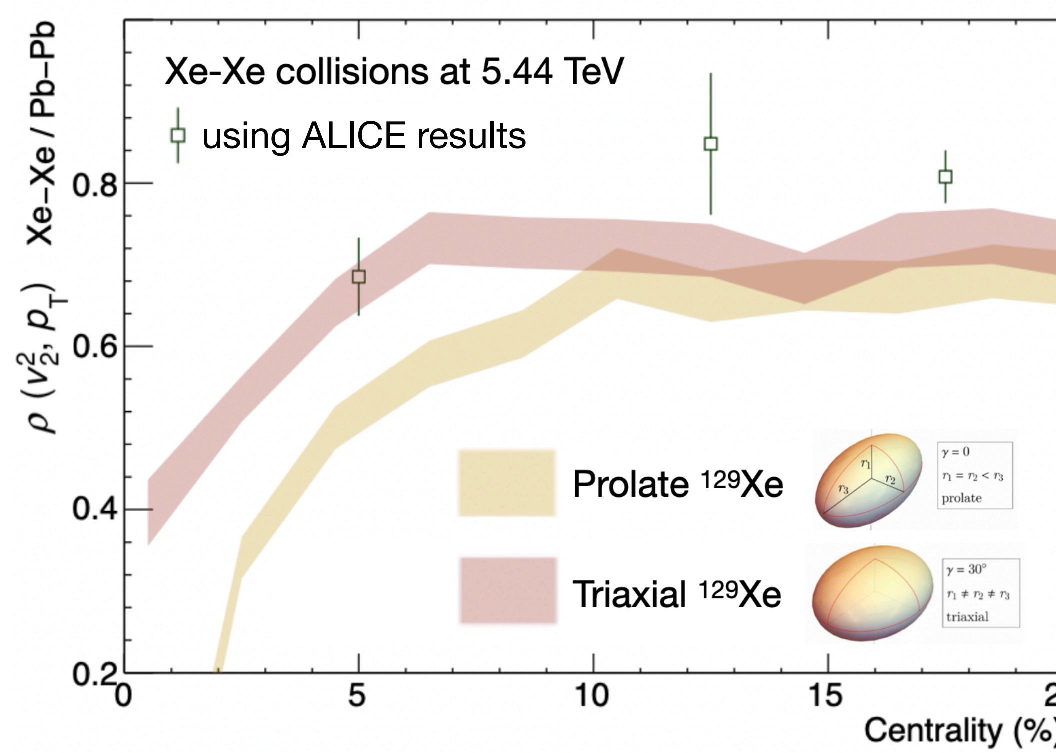


- Significant v_2 enhancement in central Xe-Xe collisions, originated from large deformation
- Help to constrain β_2

Probe triaxial structure of Xe

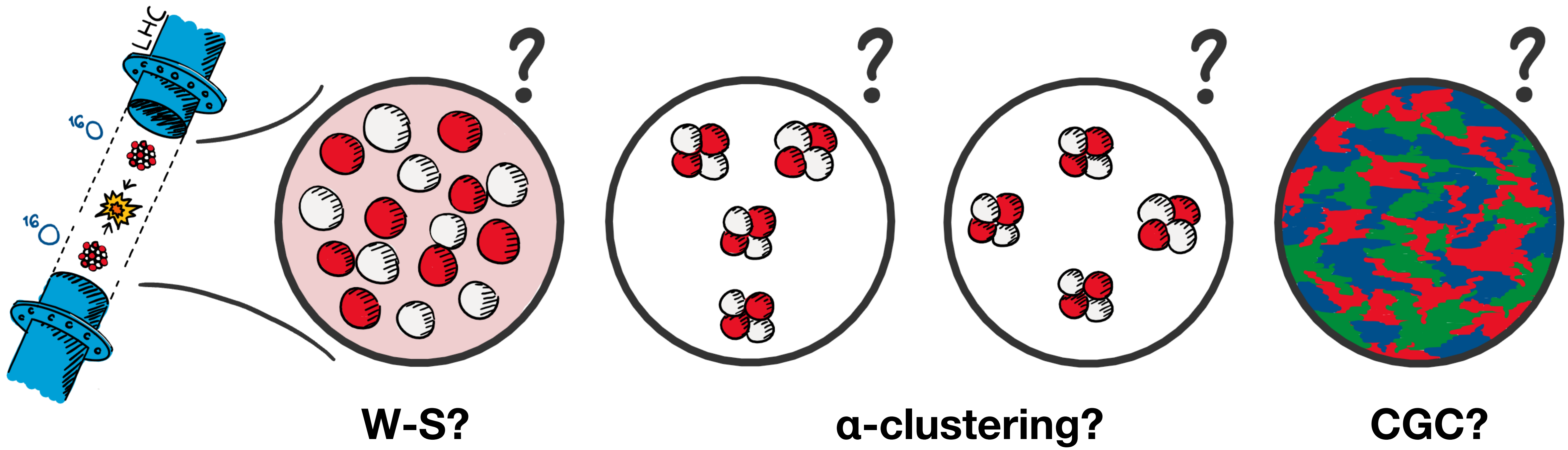
B. Bally etc, *Phys. Rev. Lett.* 128 (2022) 8, 082301





- ❖ Better agreement between LHC data and calculations with γ = 26.93°
  - Indication of triaxial structure of ^{129}Xe at high energy collisions at the LHC
  - New connection of high-energy heavy-ion physics to low-energy nuclear (structure) physics

O-O collisions at LHC Run 3



O-O projection studies

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN

ALICE-PUBLIC-2021-004

ALICE physics projections for a short oxygen-beam run at the LHC

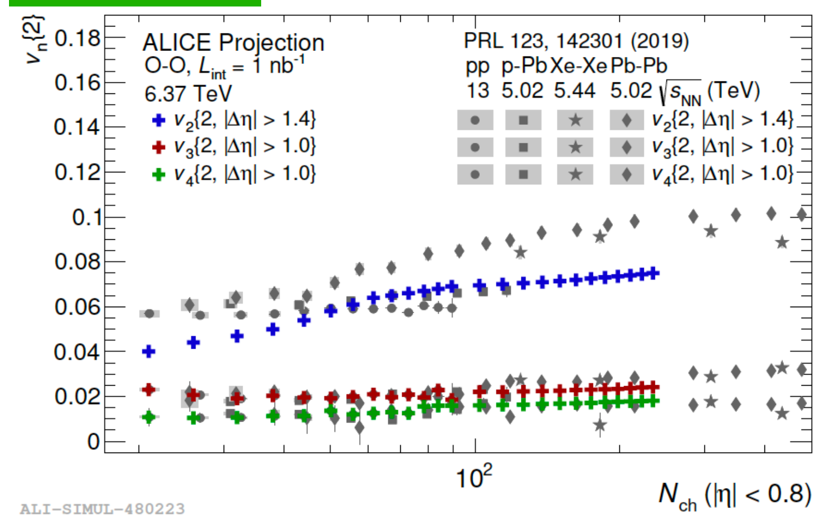
ALICE Collaboration*

Abstract

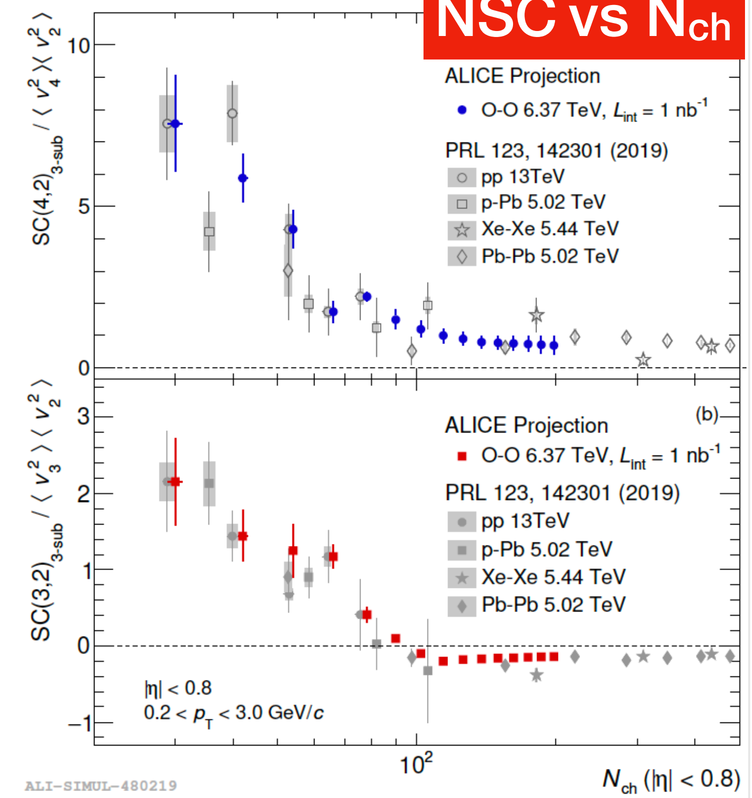
This document collects performance projections for a selection of measurements that can be carried out with a short O–O run during the LHC Run 3. The baseline centre-of-mass energy per nucleon–nucleon collision is $\sqrt{s_{\rm NN}}$ = 6.37 TeV and measurement uncertainties are given for the integrated luminosity $L_{\rm int}$ = 1 nb^{-1}. Some projections for p–O collisions are also included. These studies were presented at the CERN workshop on Opportunities of O–O and p–O collisions at the LHC [1,2].

(did not consider the structure of ^{16}O)

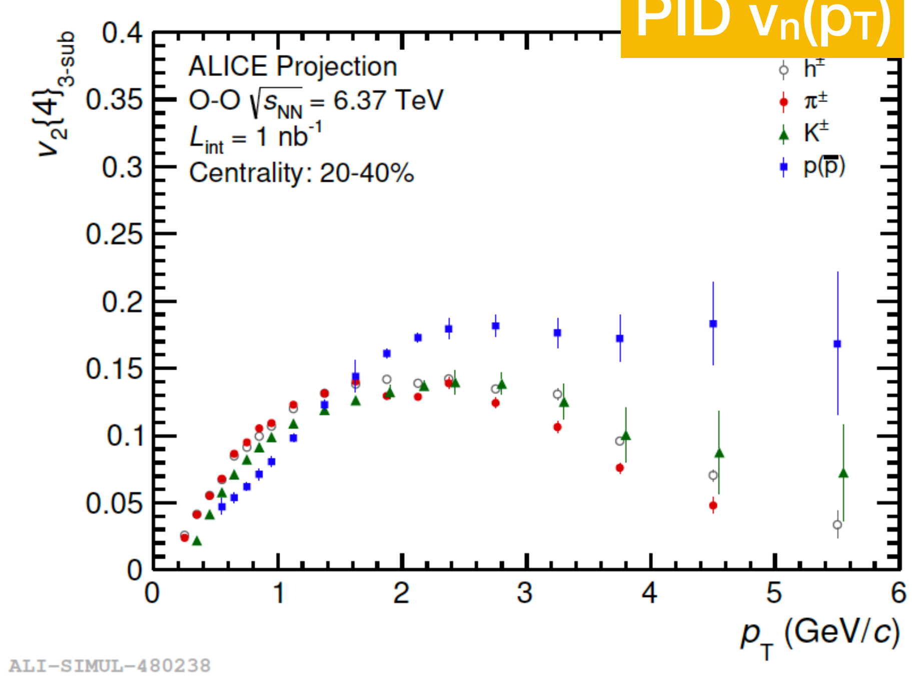
v_n vs N_{ch}



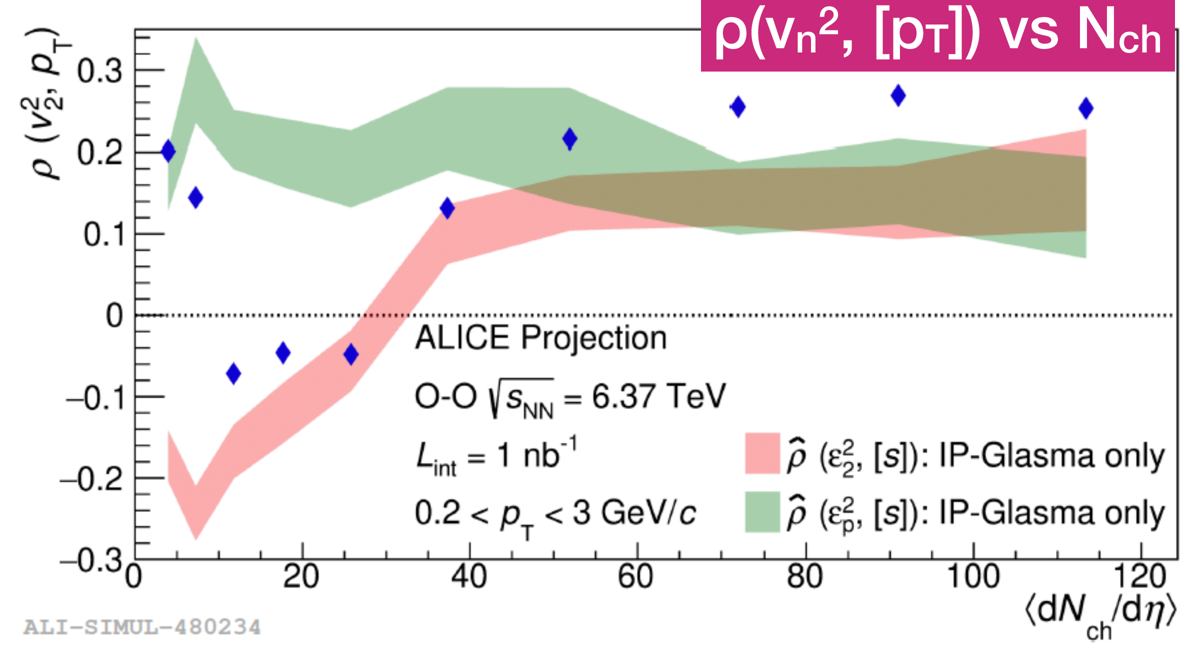
NSC vs N_{ch}



PID $v_n(p_T)$



$\rho(v_n^2, [p_T])$ vs N_{ch}



More on NS at RHIC and the LHC

BNL

RIKEN BNL Research Center
Physics Opportunities from the RHIC Isobar Run
This workshop will be held virtually.
January 25–28, 2022

link

GSI

EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 1/2)

30 May 2022 to 3 June 2022
Heidelberg University

link

GSI

EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 2/2)

12-14 October 2022
Heidelberg University

link

CEA Saclay

Deciphering nuclear phenomenology across energy scales

Back to the ESNT page

20-23 September 2022

PROGRAM ESNTprogram19Sept2022DefVf.pdf

link

INT

INSTITUTE for NUCLEAR THEORY

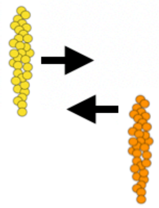
INT PROGRAM INT-23-1A

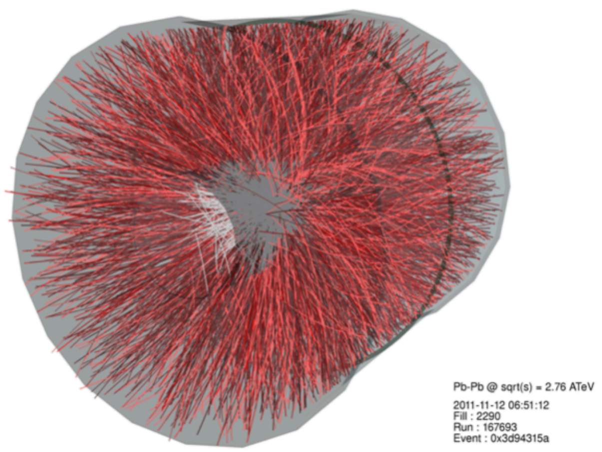
Intersection of nuclear structure and high-energy nuclear collisions

link

Small system

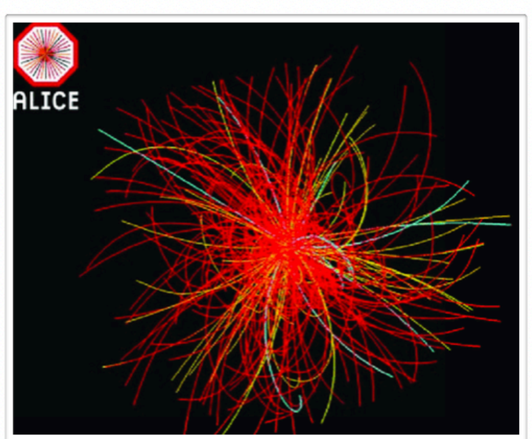
Pb-Pb collisions



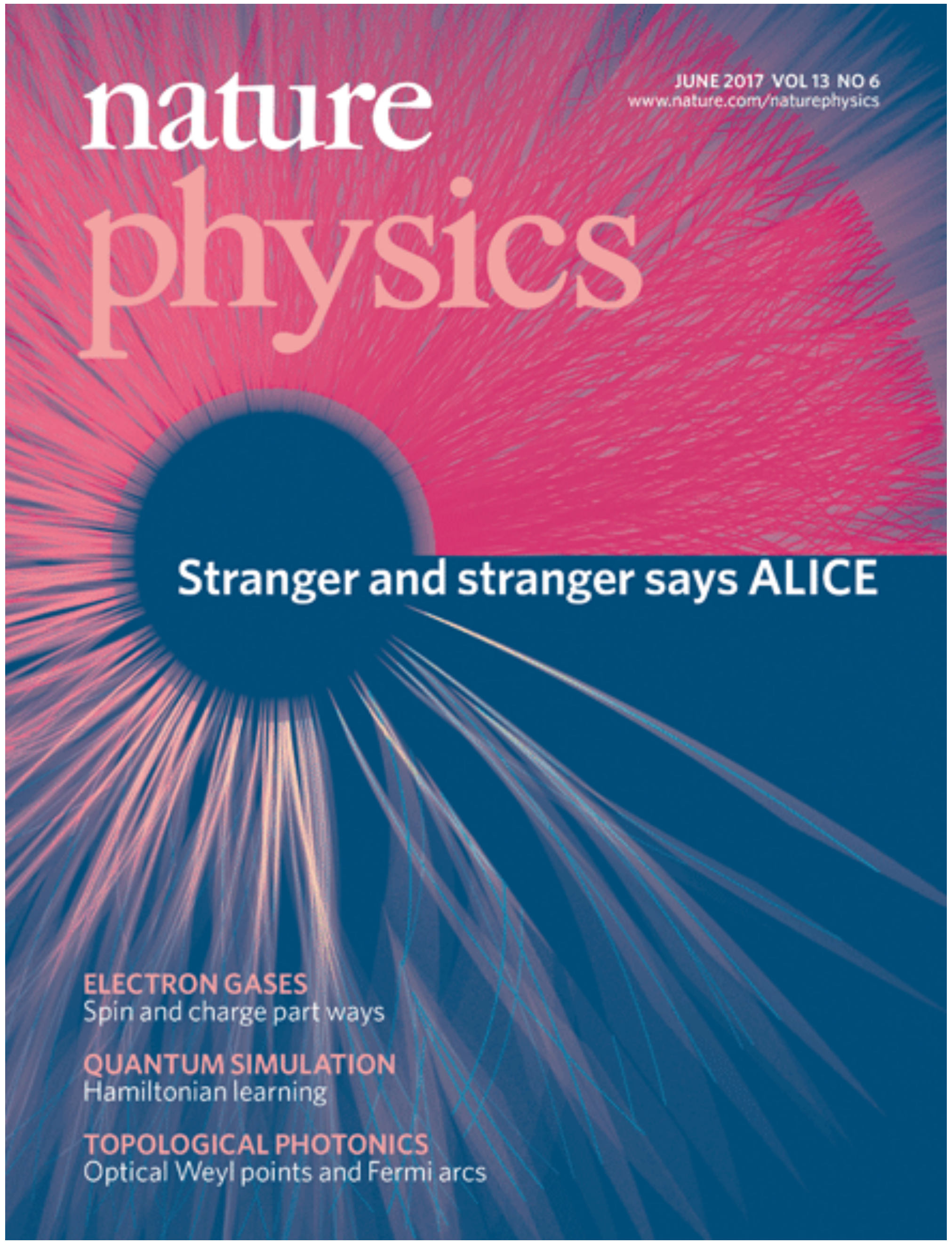


(peripheral Pb-Pb)
~100 charged particles produced

pp



(high multiplicity pp)
~100 charged particles produced



For many years, the proton-proton collision was used as "*reference data*" where no QGP is expected …
But !

CERN yellow report

CERN-LPCC-2018-07
February 26, 2019

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

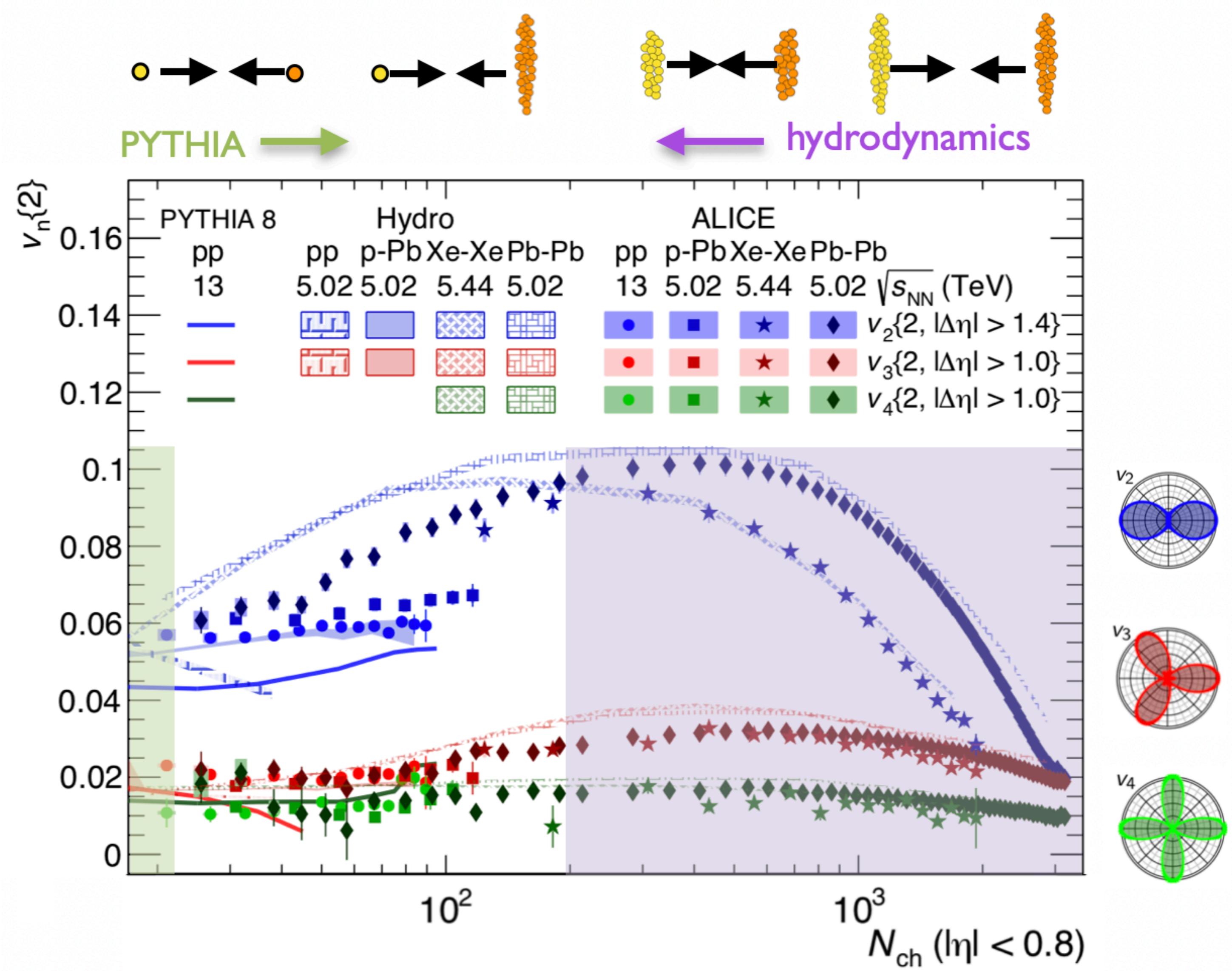
Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)
Low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
Particle ratios Statistical model	GC level $\gamma_s^{GC} = 1$, 10–30%	GC level except Ω $\gamma_s^{GC} \approx 1$, 20–40%	GC level except Ω MB: $\gamma_s^{C} < 1$, 20–40%
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Charge-dependent correlations	yes	yes	yes
Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)
Non-linear flow modes	up to v_6	not measured	not measured
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured
Direct photons at low p_T	yes	not measured	not observed
Jet quenching through dijet asymmetry	yes	not observed	not observed
Jet quenching through R_{AA}	yes	not observed	not observed
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed†	suppressed	not measured

❖A lot should be done, but have not been done

- How does v_n fluctuate
- How does ψ_n fluctuate
- How do v_n and v_m correlate
- How do ψ_n and ψ_m correlate

❖LHC Run3 enables new possibilities (with many times more data)

Multi-particle correlations across systems



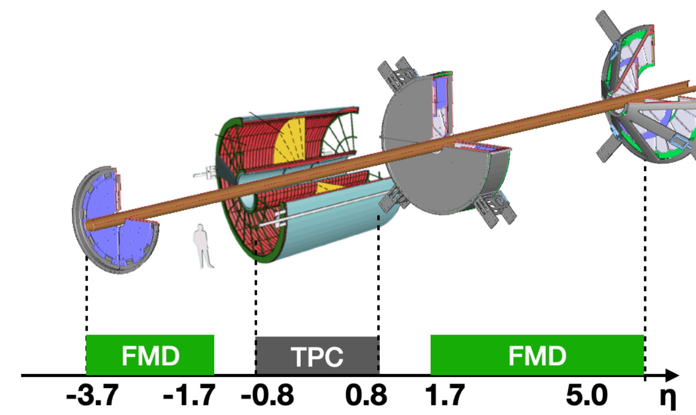
ALICE, Physical Review Letters 123, 142301 (2019)

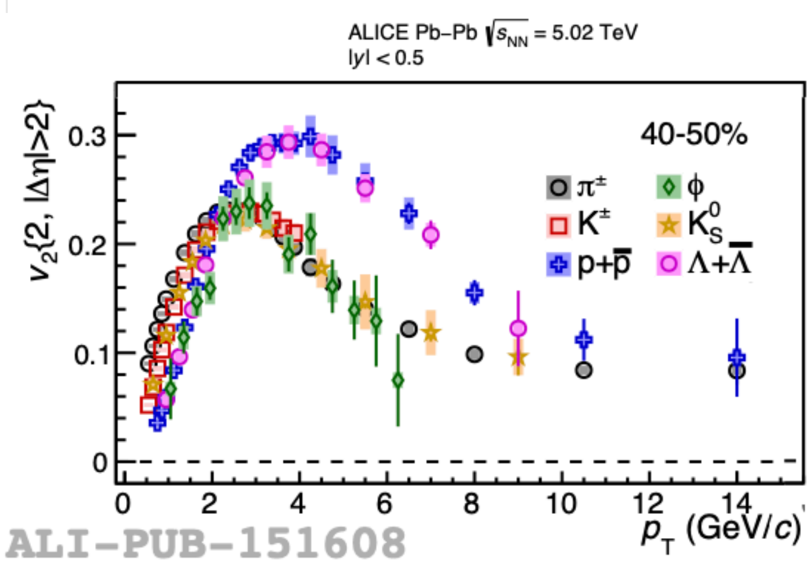
- ❖ Discovery of flow in small collisions systems (proton-lead, proton-proton collisions)
- ❖ Challenges two paradigms at once!
  - How far down in system size does the "Standard model of heavy ions" (hydrodynamics) remain?
  - Can the standard tool for minimum bias pp (PYTHIA) remain standard?

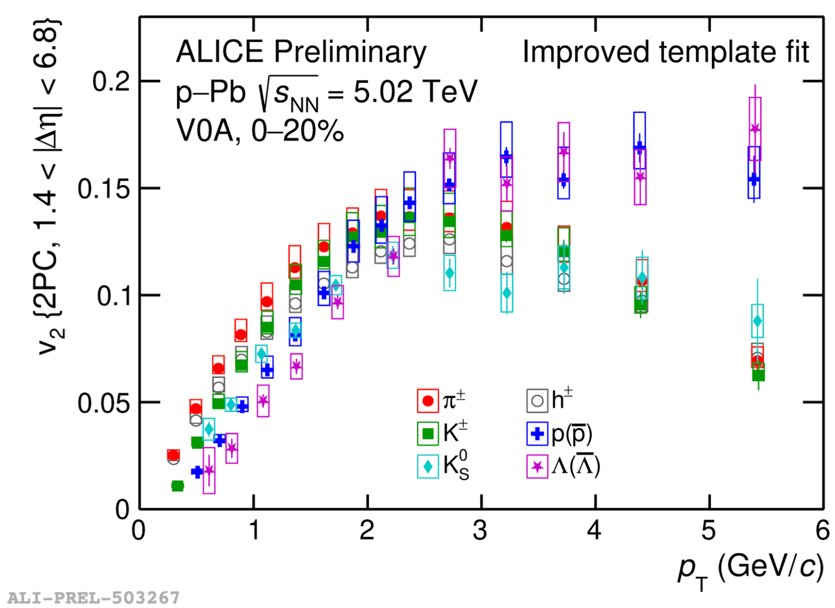
Similarity in PID flow

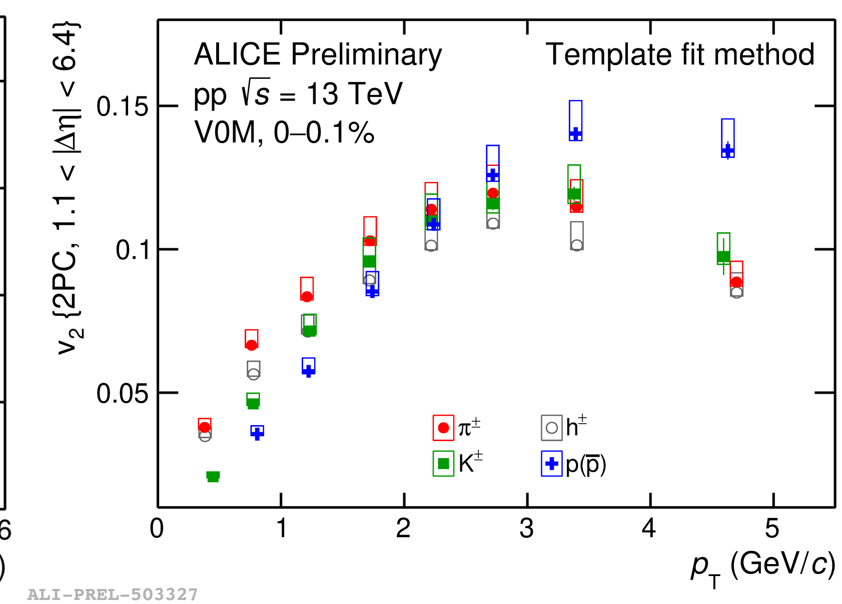
❖ Flow of identified particles, using long-range di-hadron correlations, in p-Pb and pp collisions

- ***Mass ordering*** in low p_T region (described by hydrodynamics)
- ***Baryon-meson v_2 splitting*** at intermediate p_T region by > 3σ
- Characteristic flow behaviours in Pb-Pb collisions, have been observed in p-Pb and pp collisions





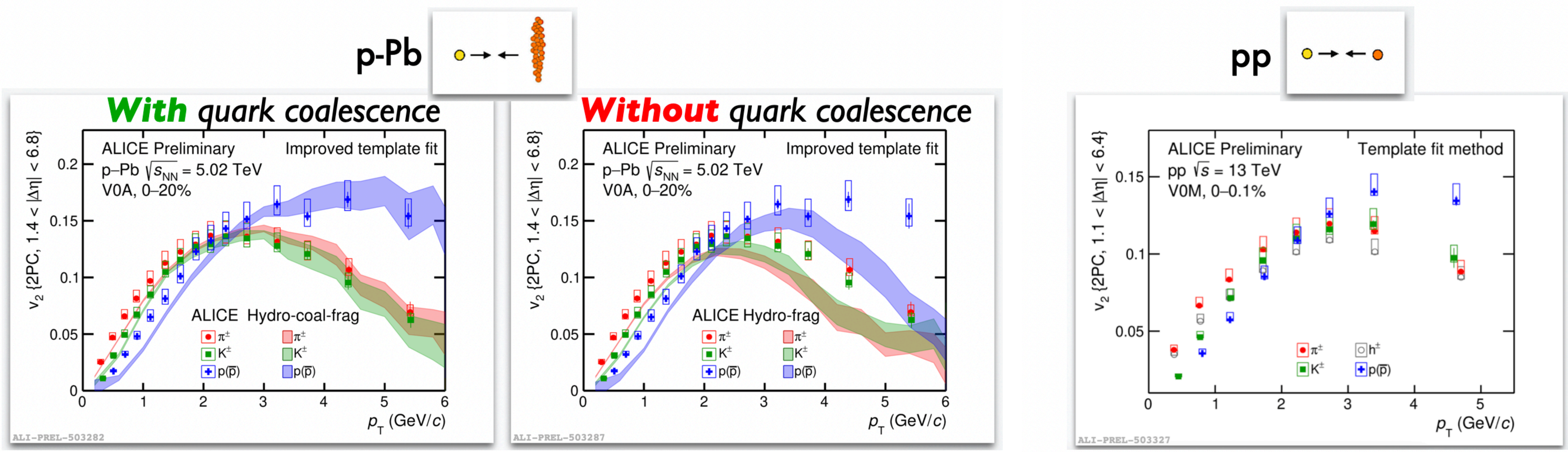




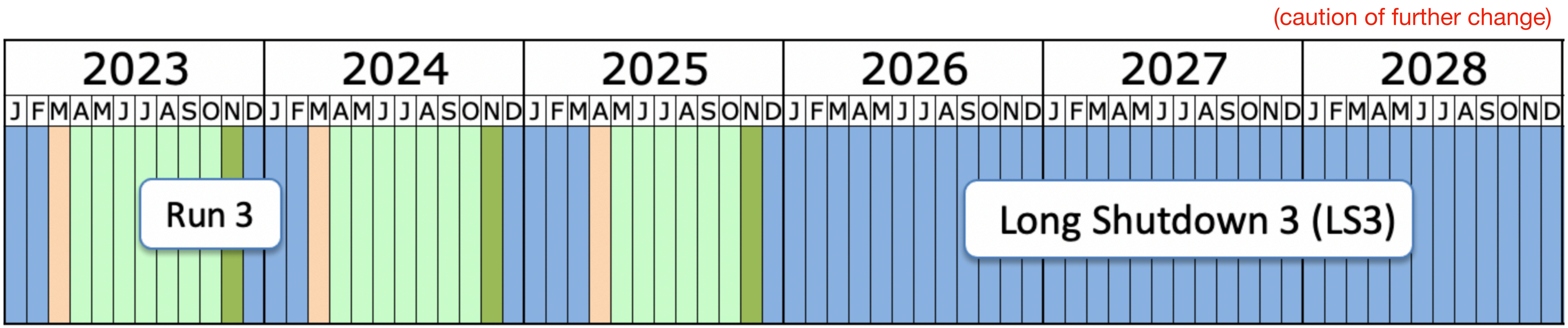
Partonic flow in small systems

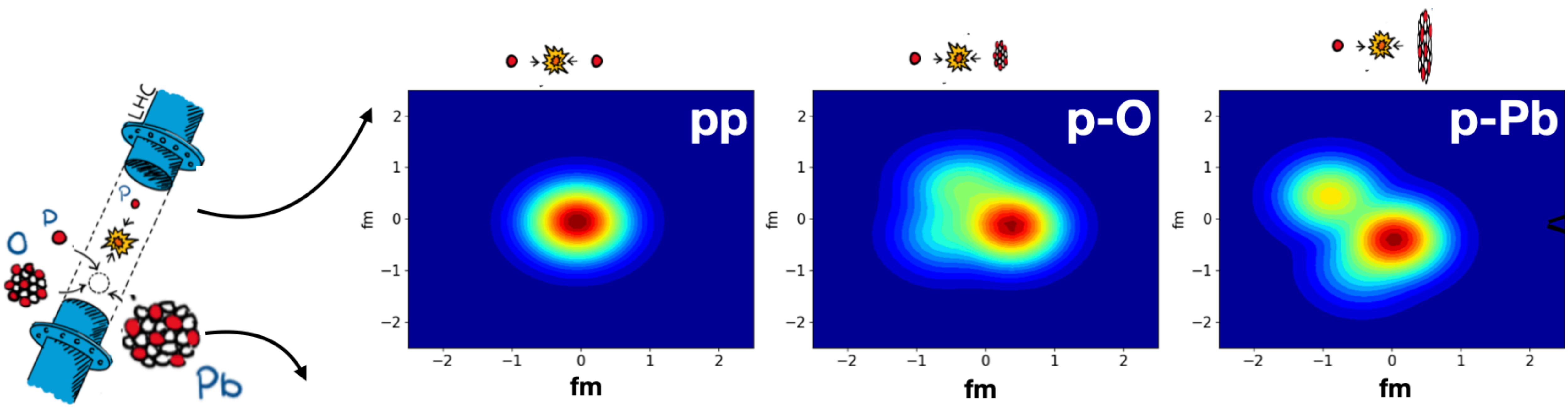
❖ Flow of identified particles in p-Pb and pp collisions

- Mass ordering in low p_T region (described by hydrodynamics)
- Baryon-meson v_2 splitting at intermediate p_T region by > 3σ
- Model without quark coalescence cannot qualitatively describe trends seen in data
- **Discovery** of partonic (quark & gluon) flow in small systems -> a small droplet of QGP



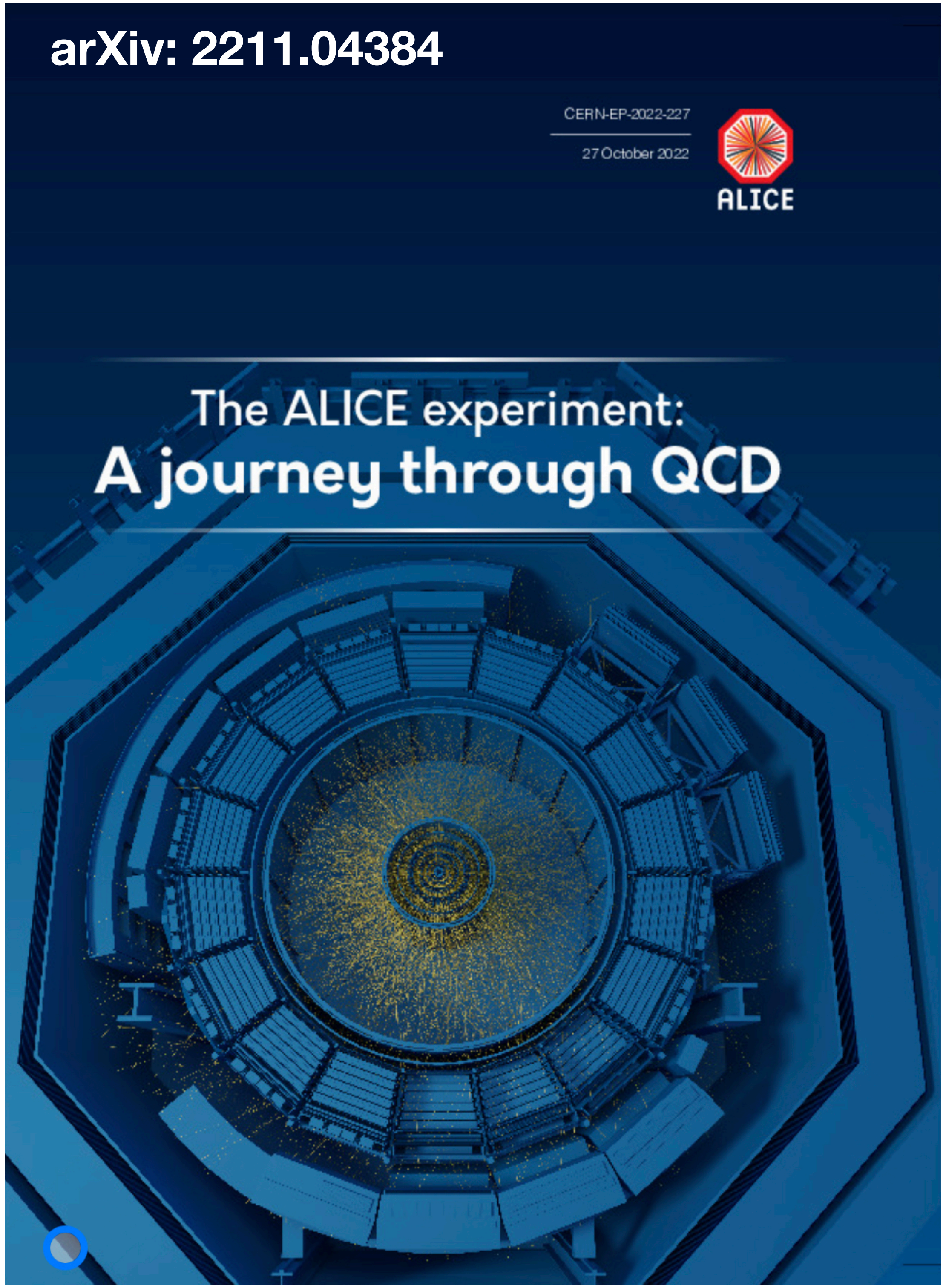
New possibilities





- **Constrain the initial conditions of small systems**
- **Turn on/off the QGP matter ?**

ALICE flow results (further reading)



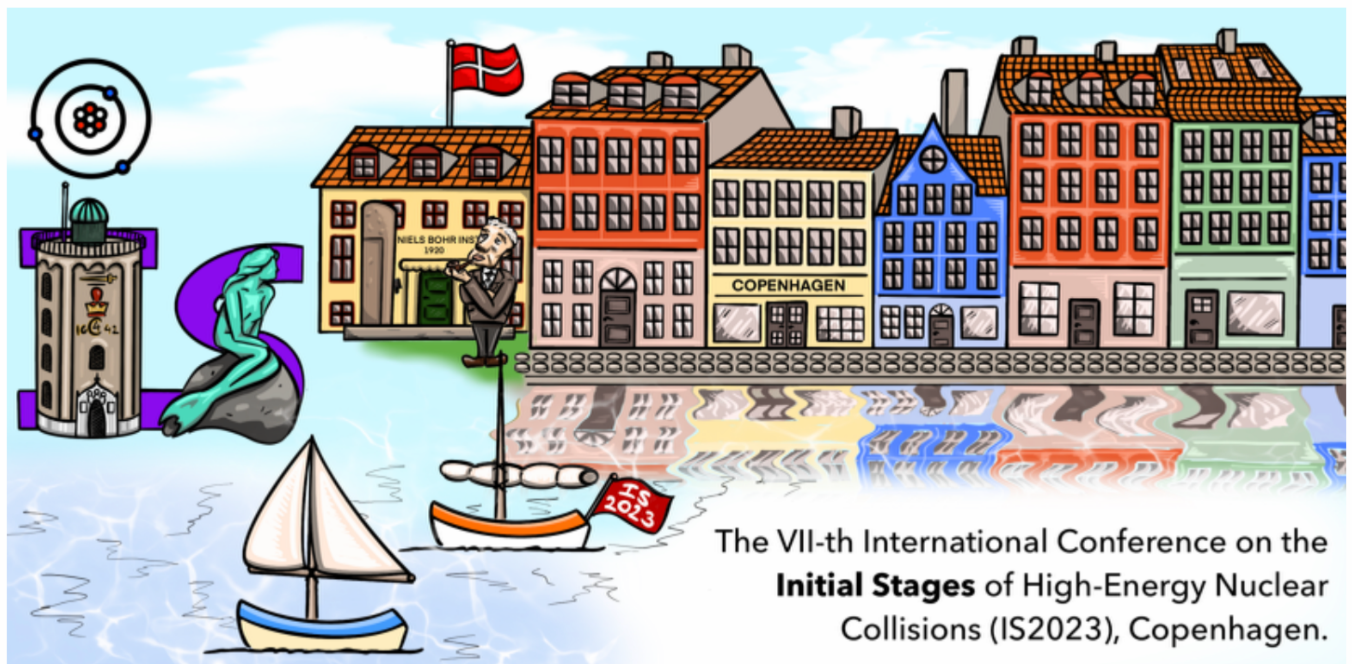
Initial Stages 2023

The VII-th International Conference on the Initial Stages of High-Energy Nuclear Collisions : Initial Stages 2023

19–23 Jun 2023
Copenhagen
Europe/Copenhagen timezone

Enter your search term

- Overview
- Call for Abstracts
- Scientific Programme
- Programme and Nordic Organisation Committee
- International Advisory Committee
- Important dates
- Previous Stages



Abstract submission deadline: March 10th, 2023

50+ junior supports (encourage all students and young postdocs to attend)

- **Hotels in Copenhagen during the entire conference for FREE**
- **Reduced conference fee**

New positions at NBI (Copenhagen)

INDEPENDENT RESEARCH FUND DENMARK

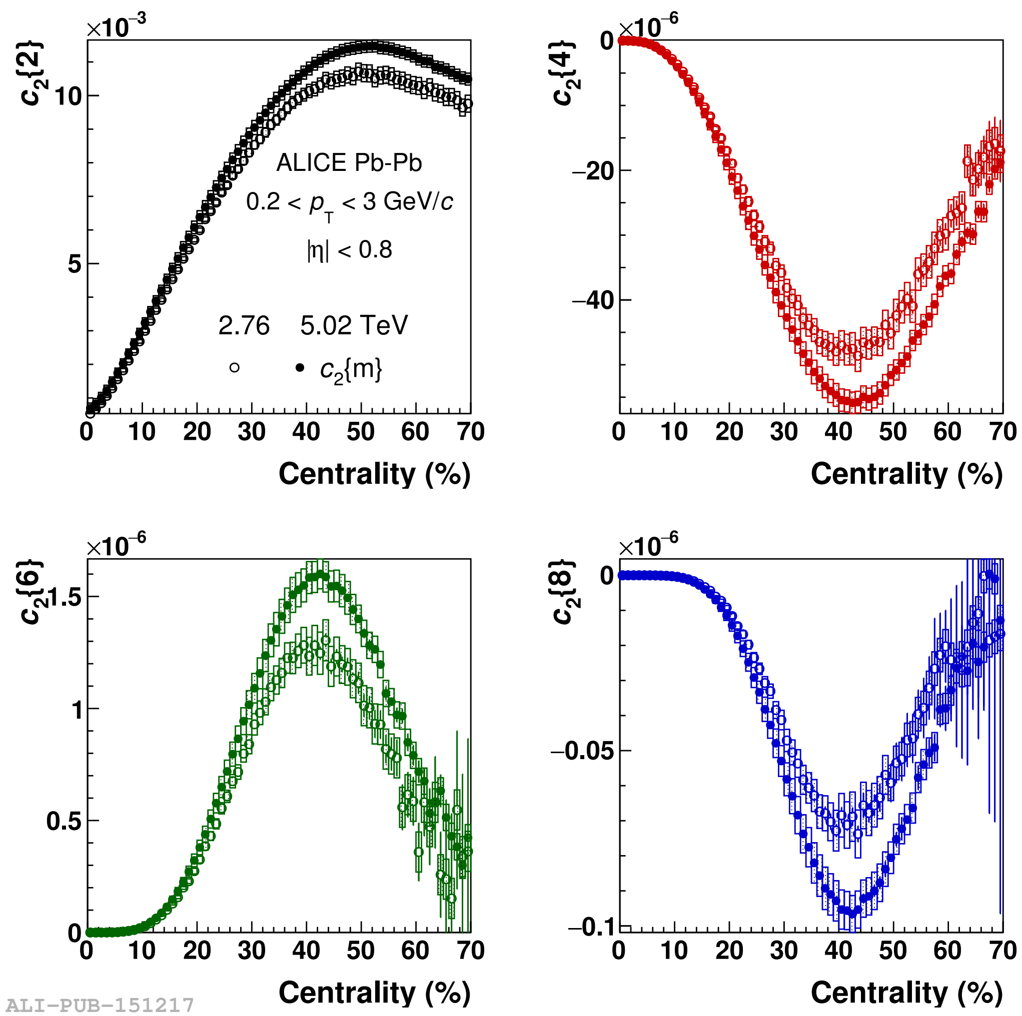
erc European Research Council

My research group expects to hire ***1 Postdoc and 2 PhD students*** after this summer
(Will call for applicants this spring)
If you have interests, don't hesitate to contact me: you.zhou@cern.ch

Backup

$P(v_n)$ from multi-particle cumulants of v_n

ALICE, JHEP 07 (2018) 103



$p(\varepsilon_n)$ → System Expansion → $p(v_n)$

↑

$v_n\{2\}, v_n\{4\}, v_n\{6\}, v_n\{8\}, v_n\{10\}, v_n\{12\}$ …

Multi-particle ***correlations*** of single harmonic v_n

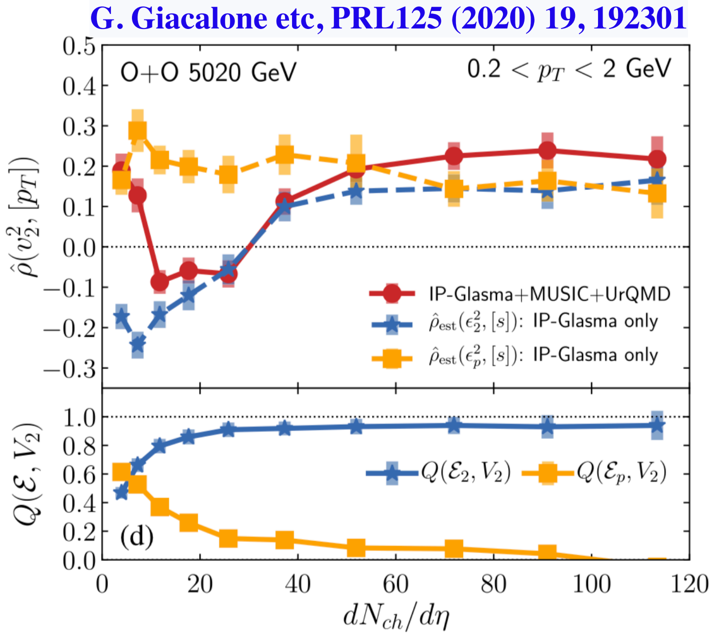
$$\langle\langle \cos(n\phi_1 - n\phi_2 + n\phi_3 - n\phi_4)\rangle\rangle = \left\langle v_n^4 \cos(n\Phi_n - n\Phi_n + n\Phi_n - n\Phi_n)\right\rangle = \left\langle v_n^4\right\rangle$$

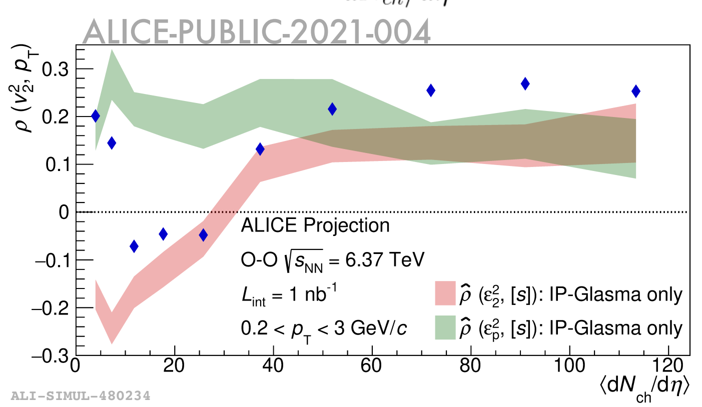
Multi-particle ***cumulants*** of single harmonic v_n

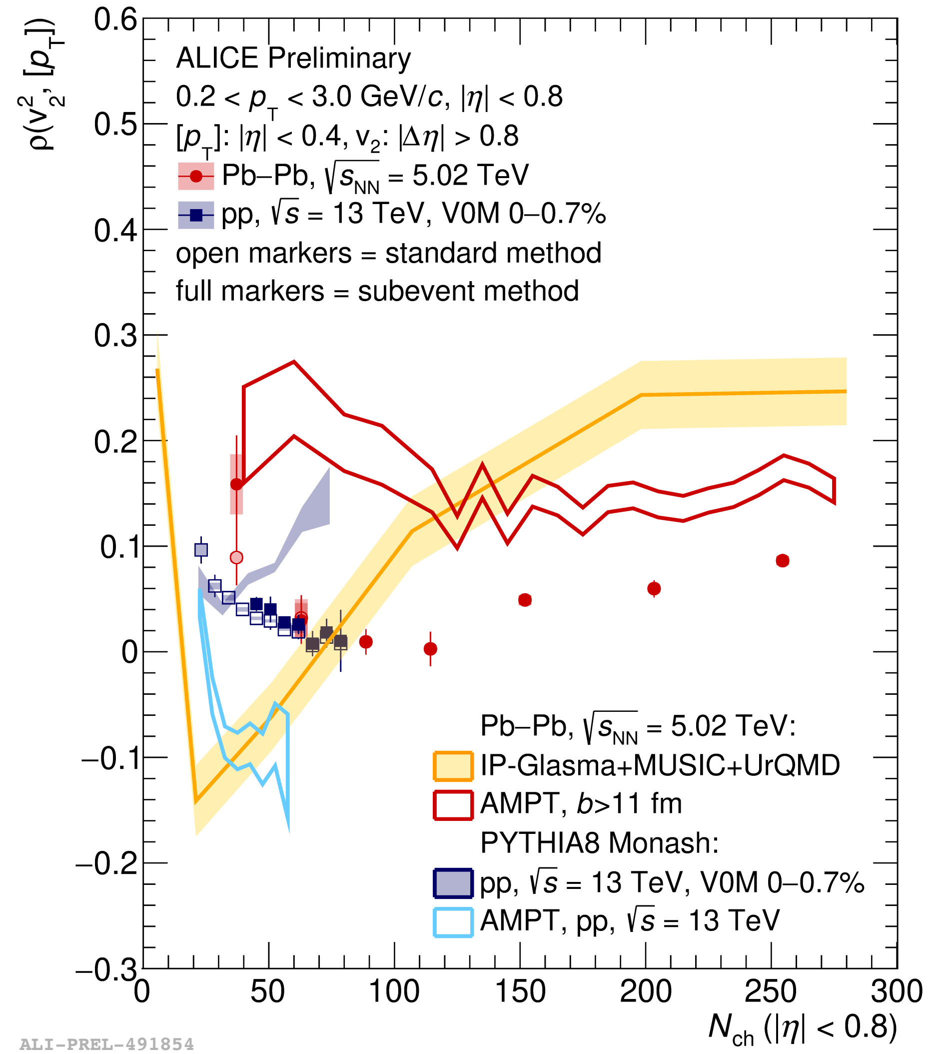
$$\begin{aligned}\langle\langle \cos(n\phi_1 - n\phi_2 + n\phi_3 - n\phi_4)\rangle\rangle_c &= \langle \cos(n\phi_1 - n\phi_2 + n\phi_3 - n\phi_4)\rangle \\ &- \langle\langle \cos(n\phi_1 - n\phi_2)\rangle\rangle \langle\langle \cos(n\phi_3 - n\phi_4)\rangle\rangle \\ &- \langle\langle \cos(n\phi_1 - n\phi_4)\rangle\rangle \langle\langle \cos(n\phi_2 - n\phi_3)\rangle\rangle \\ &= \left\langle v_n^4\right\rangle - 2\left\langle v_n^2\right\rangle^2\end{aligned}$$

$$\begin{aligned}v_n\{2\} &= \sqrt[2]{\langle v_n^2\rangle}, \\ v_n\{4\} &= \sqrt[4]{2\langle v_n^2\rangle^2 - \langle v_n^4\rangle}, \\ v_n\{6\} &= \sqrt[6]{\langle v_n^6\rangle - 9\langle v_n^2\rangle\langle v_n^4\rangle + 12\langle v_n^2\rangle^3}, \\ v_n\{8\} &= \sqrt[8]{\langle v_n^8\rangle - 16\langle v_n^2\rangle\langle v_n^6\rangle - 18\langle v_n^4\rangle^2 + 144\langle v_n^2\rangle^2\langle v_n^4\rangle - 144\langle v_n^2\rangle^4}.\end{aligned}$$

More results in smaller colliding systems

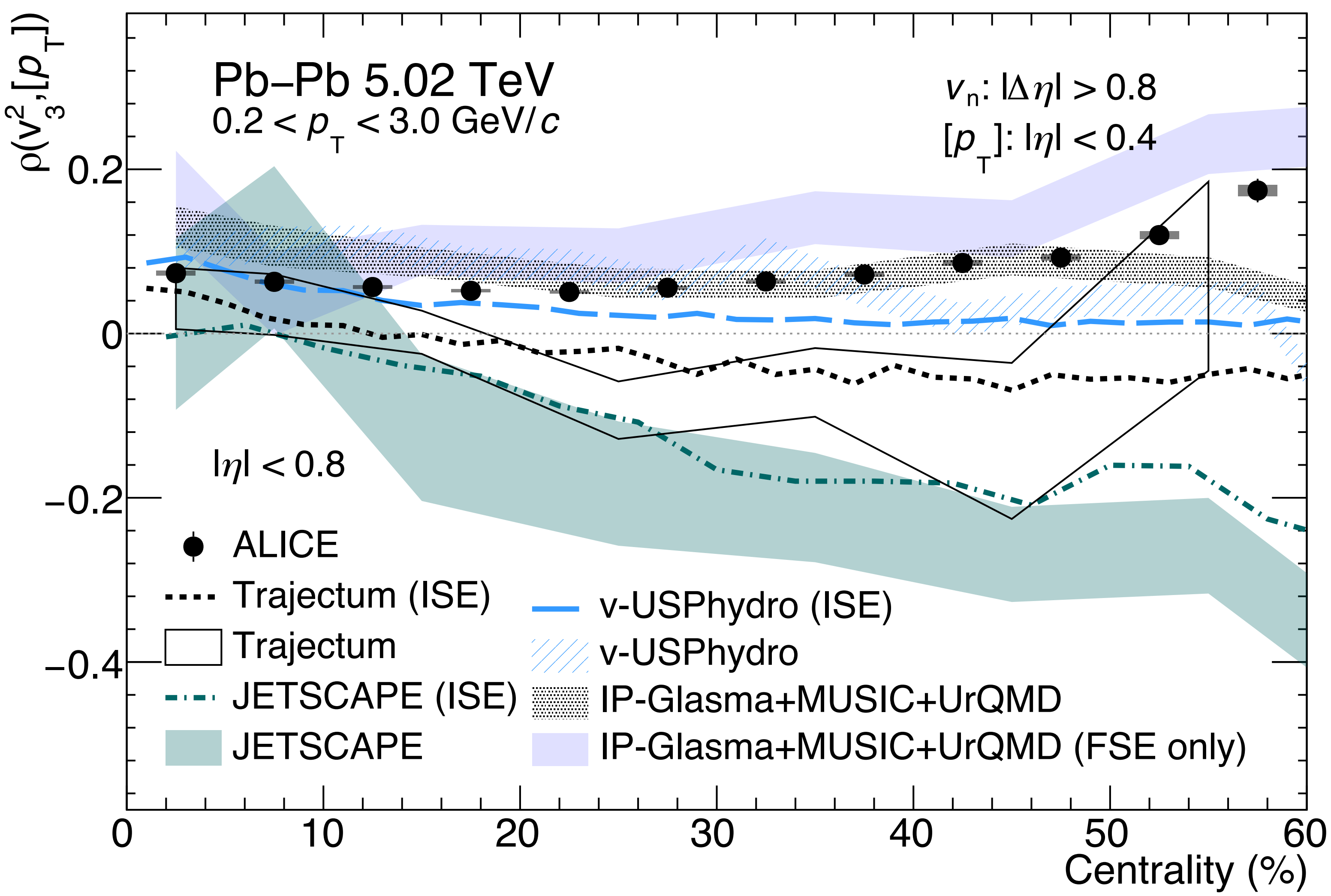






- Search for the initial momentum anisotropy (IMA) in smaller colliding systems
  - Peripheral Pb-Pb collisions
    - Slope changes for N_{ch} ~ 100 for data and ~ 20 for IP-Glasma calculations
    - Both AMPT and IP-Glasma+hydro predicts slope changes -> not unique signature of IMA?
  - pp collisions:
    - Decreasing trend with increasing N_{ch}, results are consistent with the one in Pb-Pb
    - AMPT generates stronger anti-correlations, PYTHIA predicted a wrong N_{ch} dependence
    - Non-flow is a main challenge, many important studies by J. Jia, C. Zhang, J. Nagle etc

ρ_3 in Pb-Pb



ALICE, PLB 834 (2022) 137393
v-USPhydro, PRC103 (2021) 2, 024909
IP-Glasma, PRC102, 034905 (2020)
JETSCAPE, PRL126, 242301 (2021) Privation communication
Trajectum, PRL126, 202301 (2021) Privation communication

- ρ_3 values:
  - positive
  - have a modest centrality dependence for the presented centralities,
  - better described by IP-Glasma,
  - TRENTo predicts negative ρ_3, getting worse for Trajectum and JETSCAPE calculations
- model shows that ρ_3 is not sensitive to β_2
- Difference of full IP-Glasma and FSE only, indication of potential contributions from IMA in peripheral?

Higher-order correlations

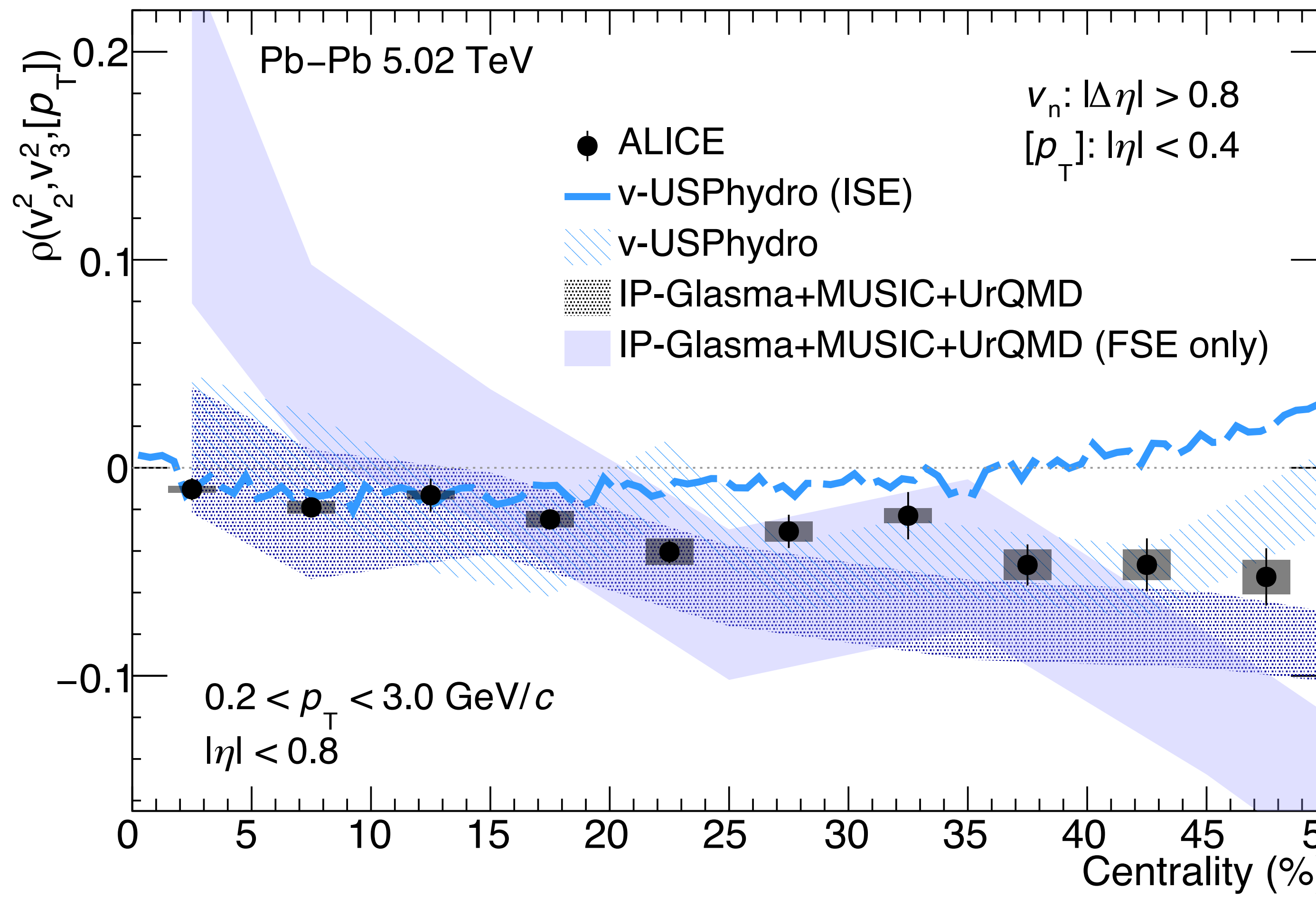
❖ The **first** measurement of higher-order $[p_T]$, v_2 and v_3 correlations **P. Bozek etc, PRC104 (2021) 1, 014905**

$$\rho(v_{\rm m}^2, v_{\rm n}^2, [p_{\rm T}]) = \frac{C(v_{\rm m}^2, v_{\rm n}^2, [p_{\rm T}])}{\sqrt{{\rm Var}(v_{\rm m}^2)}\sqrt{{\rm Var}(v_{\rm n}^2)}\sqrt{c_k}} - \frac{\langle v_{\rm m}^2\rangle}{\sqrt{{\rm Var}(v_{\rm m}^2)}}\cdot\rho_{\rm n} - \frac{\langle v_{\rm n}^2\rangle}{\sqrt{{\rm Var}(v_{\rm n}^2)}}\cdot\rho_{\rm m} - \frac{\langle [p_{\rm T}]\rangle}{\sqrt{c_{\rm k}}}\cdot\frac{SC({\rm m},{\rm n})}{\sqrt{{\rm Var}(v_{\rm m}^2)}\sqrt{{\rm Var}(v_{\rm n}^2)}}$$

❖ the first ρ_{23} measurement is non-zero
- negative for the presented centrality
- anti-correlations between two flow coefficients and $[p_T]$

❖ ρ_{23} from IP-Glasma and v-USPhydro are different for centrality >40%
- Weaker centrality dependence of full IP-Glasma while strong dependence for FSE only, indication?
- More simulations are needed

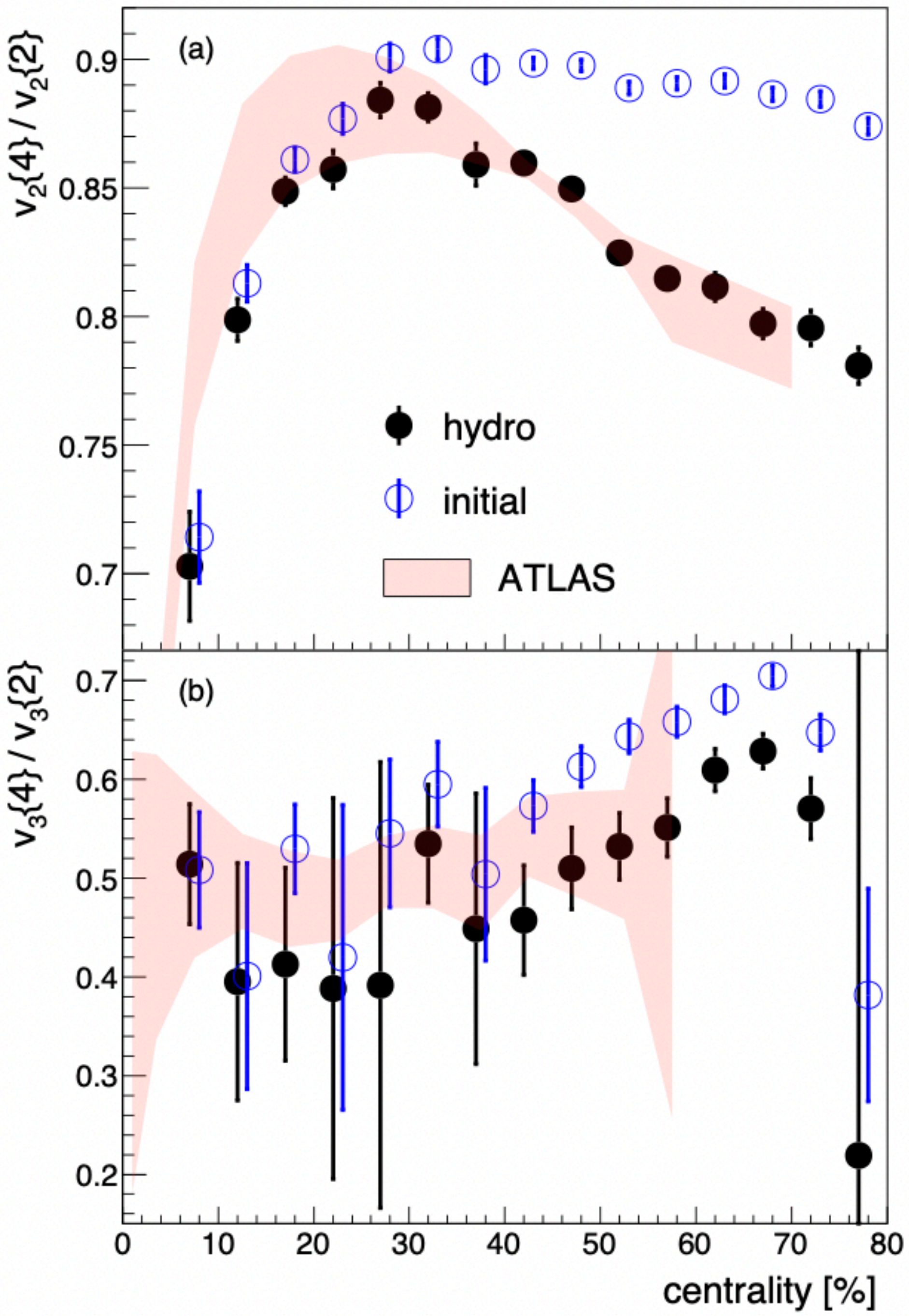
❖ Not conclusive on which model works better due to sizeable uncertainties from model calculations

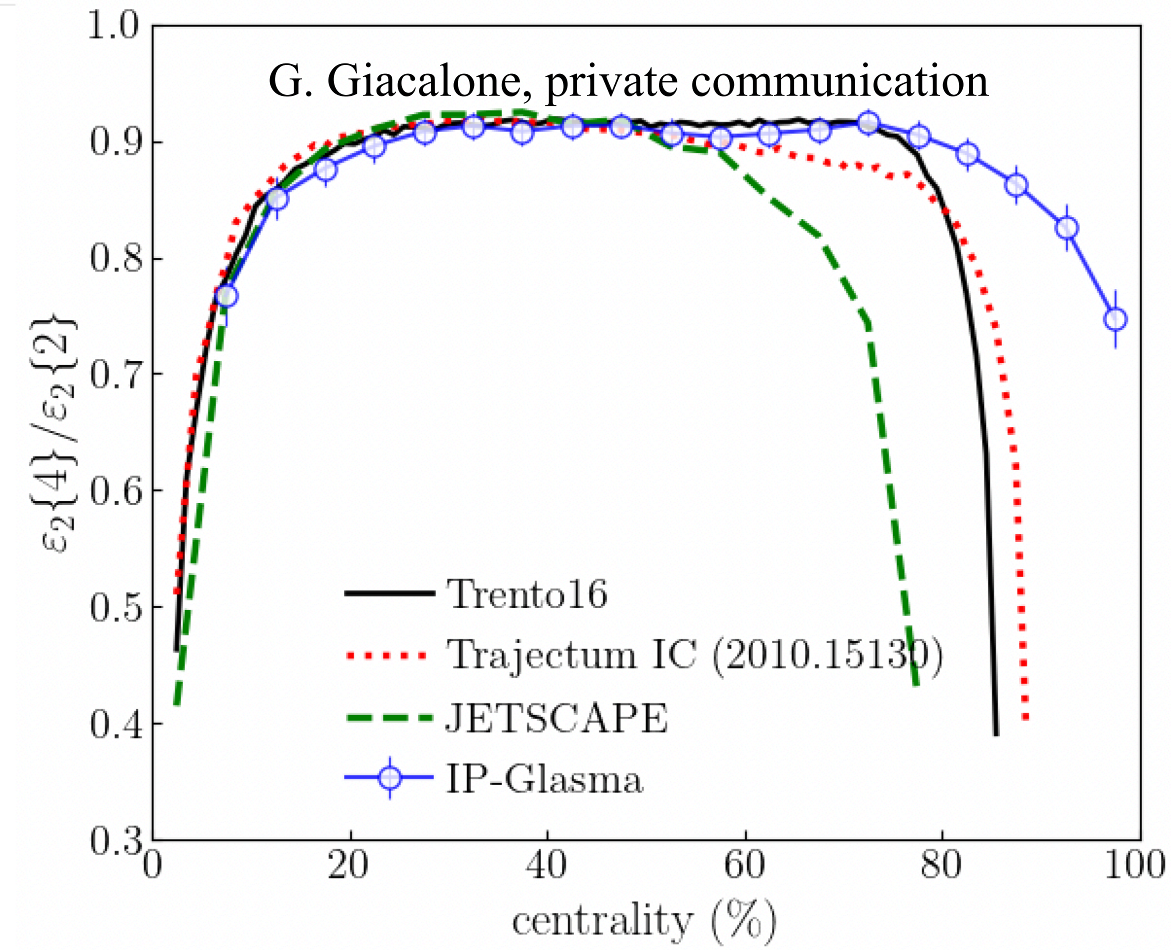


Event-by-event v_n fluctuations

$$v_n \propto \varepsilon_n \qquad \frac{v_n\{4\}}{v_n\{2\}} = \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}}$$

G. Giacalone etc, PRC95, 054910 (2017)



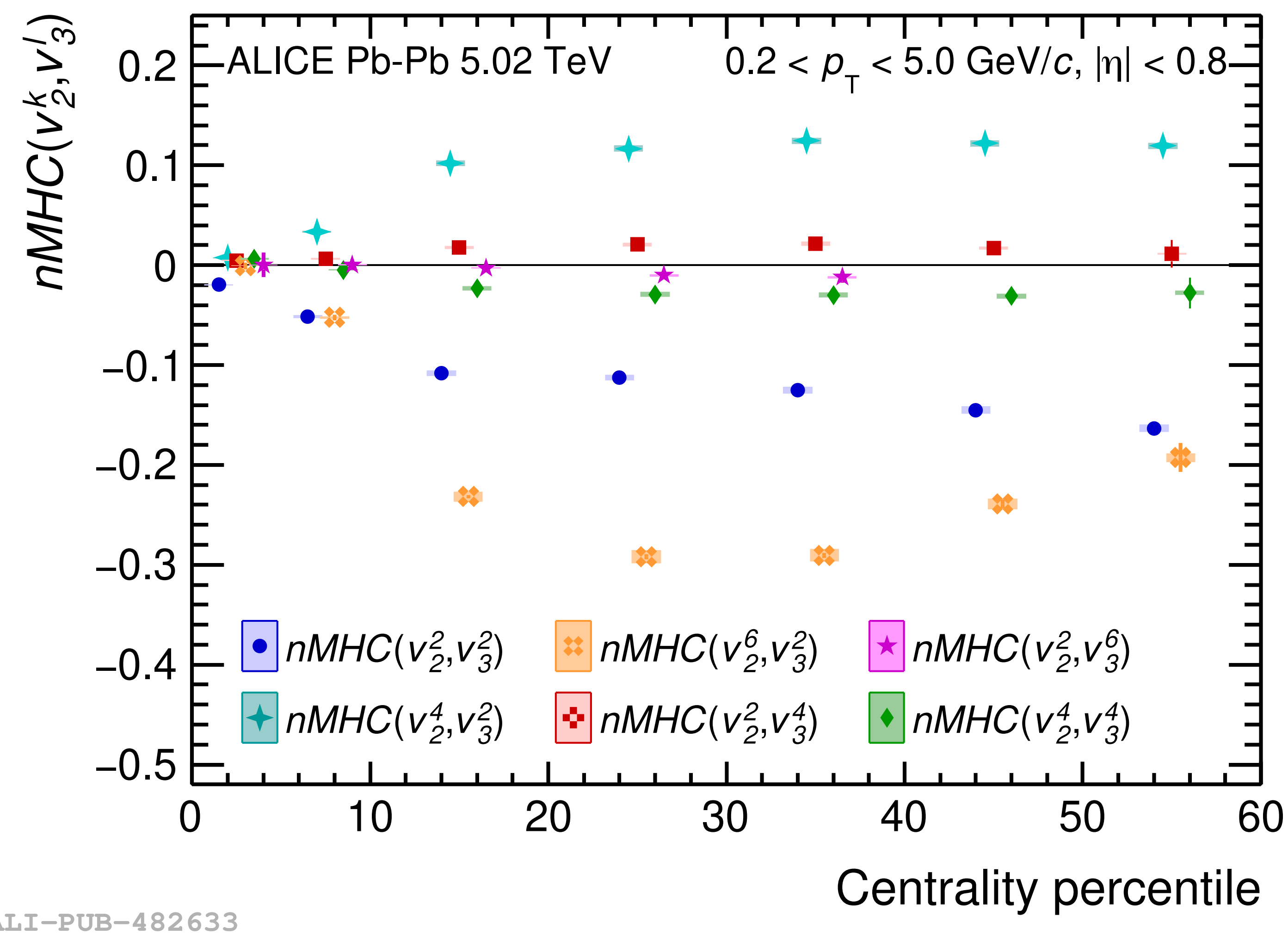


Minor difference from IS models

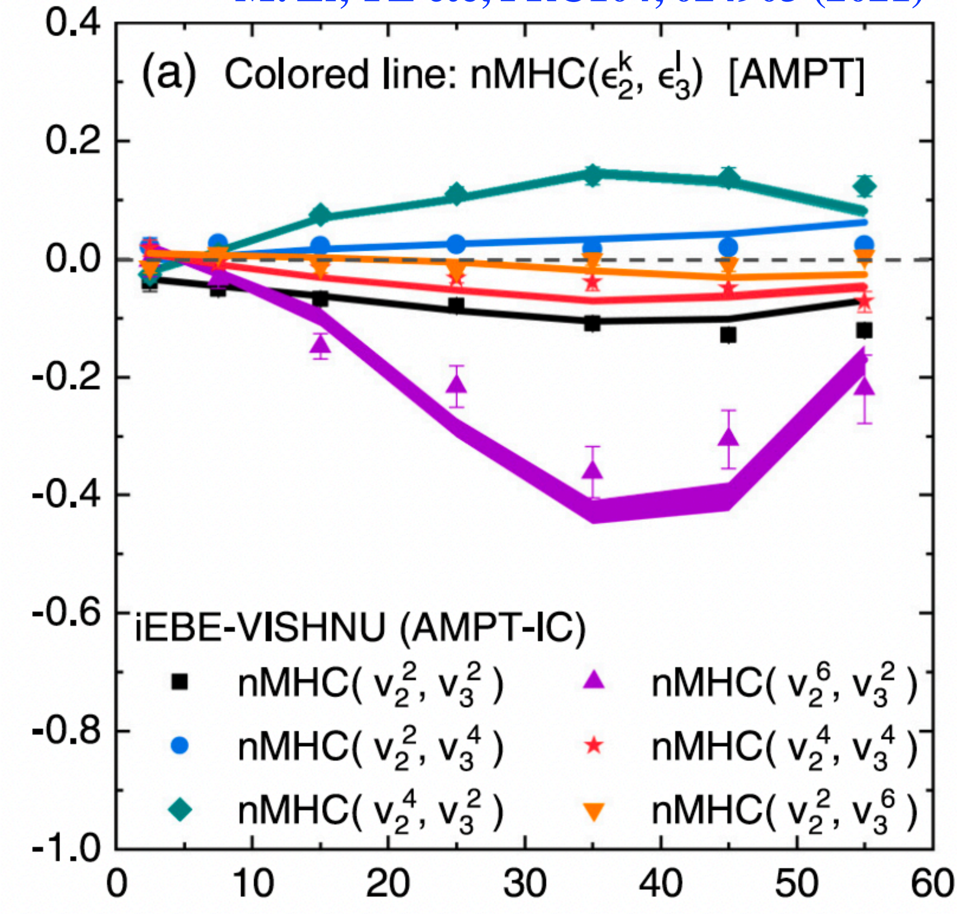
- Despite the precision of the data, the differences of $\varepsilon_n\{4\}/\varepsilon_n\{2\}$ from various initial state models are minor
  - The peripheral collision should not be used as $v_n \propto \varepsilon_n$ does not hold

Correlations between v_2^k and v_3^L

ALICE, PLB818 (2021) 136354



M. Li, YZ etc, PRC104, 024903 (2021)



- First measurement of correlations between higher order moments of v_2 and v_3
  - characteristic -, +, - signs observed for 4-, 6- and 8-particle cumulants of ***mixed harmonic***
  - Final state results quantitatively reproduced by the initial state correlations
  - Experimental data provides direct constraints on the correlations of higher order moments of eccentricity coefficients

Various initial state models

Credits: G. Giacalone

– **“sharp” models: IP-GLASMA and TRENTo 2016**

[Schenke, Shen, Tribedy **2005.14682**]

[Bass, Bernhard, Moreland **1605.03954**]

Nucleons have a width of ~0.5fm (trento), 3 sub-nucleons with size ~0.1fm (IP-Glasma). Trento is used for the entropy density at the beginning of hydro.

– **“fat” models: TRENTo 2019 and JETSCAPE**

[Bass, Bernhard, Moreland **Nature Phys. 15 (2019)**]

[JETSCAPE Collaboration **2011.01430**, **2010.03928**]

[Parkkila, Onnerstad, Kim **2106.05019**]

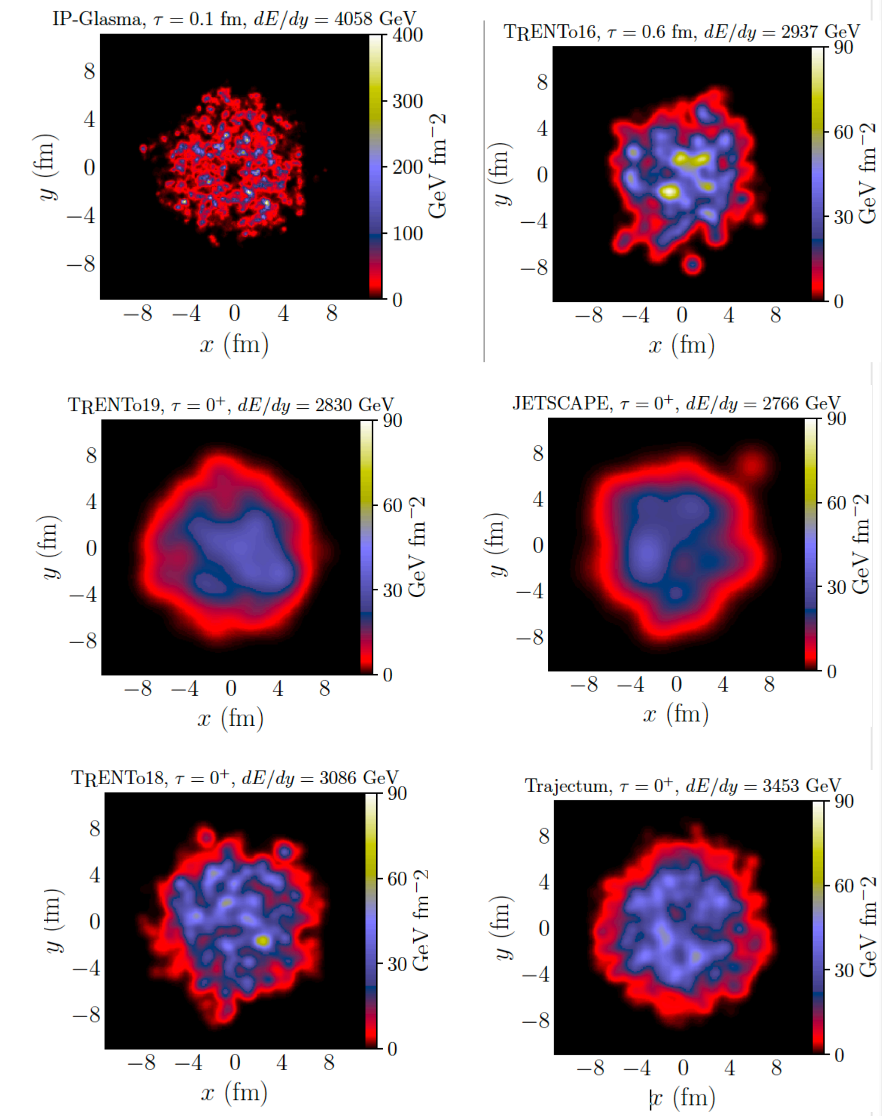
The Trento parametrization is now used for the energy density at tau=0+. There is no substructure. The nucleon width is now ~1fm. Very smooth profiles.

– **“bumpy” models: TRENTo 2018 and Trajectum**

[Bass, Bernhard, Moreland **1808.02106**]

[Nijs, van der Schee, Gürsoy, Snellings **2010.15130**, **2010.15134**]

The Trento parametrization is the energy density at tau=0+. Substructure is included: 4-6 constituents with width ~0.4fm. Profiles with some lumpiness.



Initial Stages 2023

Banquet

Reception

IAC dinner

Boat tour

50+ junior supports (encourage all students and young postdocs to attend)

- **Hotels in Copenhagen during the entire conference for FREE**
- **Reduced conference fee**