

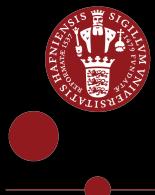
Constraining the initial conditions of heavy-ion collisions at the LHC

QNP2022 - *The 9th International Conference on Quarks and Nuclear Physics*



You Zhou

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UNIVERSITY OF
COPENHAGEN

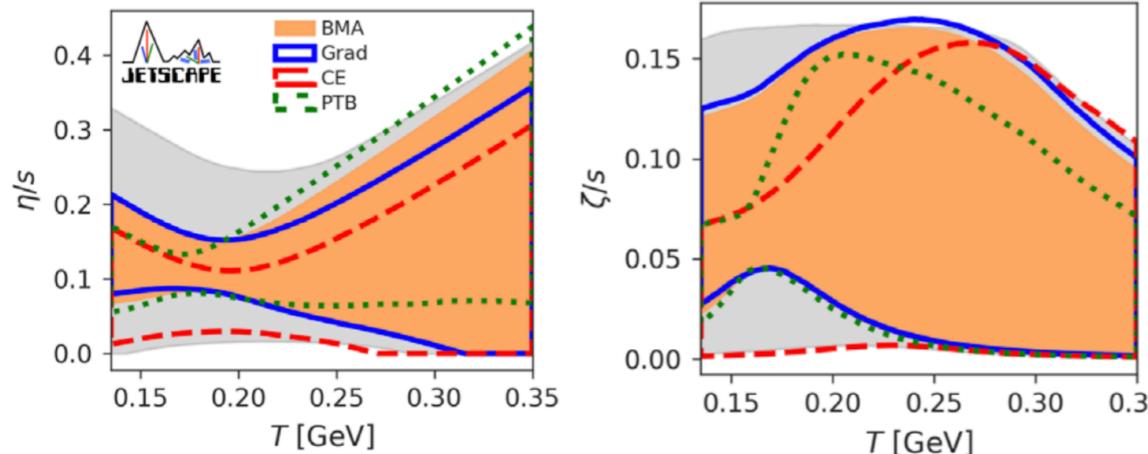
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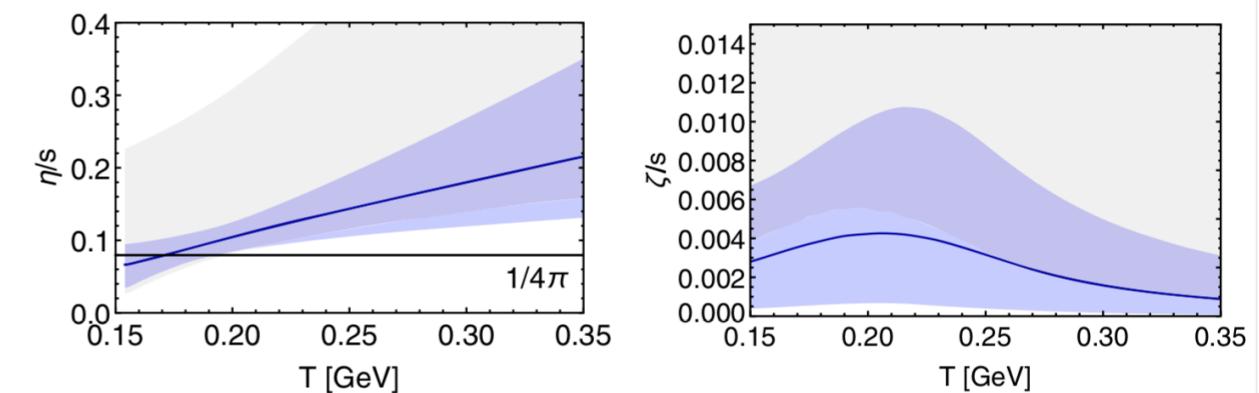
State-of-the-art QGP studies

- ❖ Bayesian analyses represent the state-of-the-art understanding of QGP properties
 - Very large uncertainties (and discrepancies) from various studies

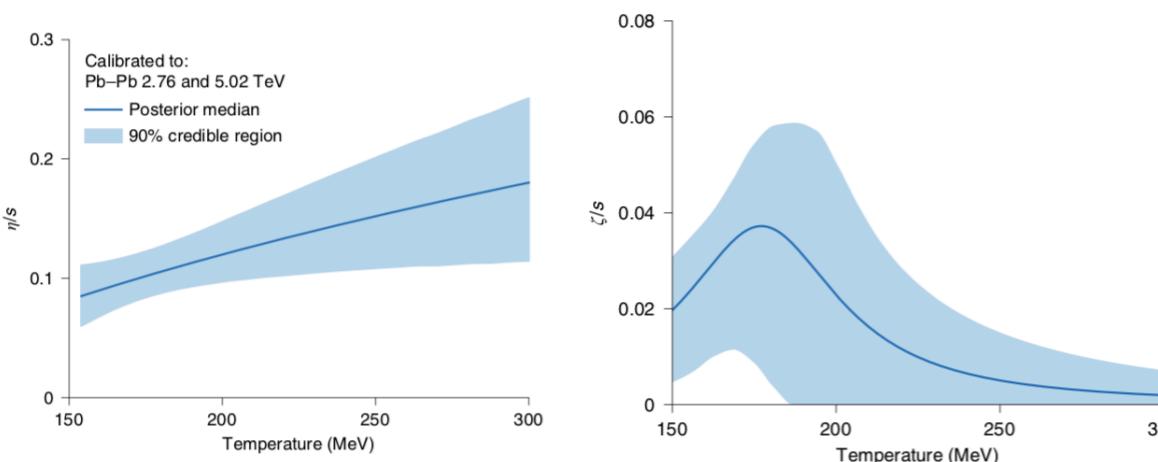
JETSCAPE: *Phys. Rev. Lett.* 126, 242301 (2021)



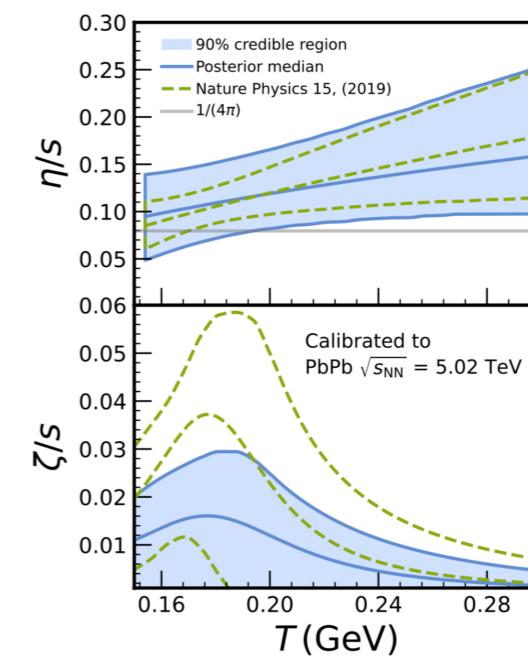
Trajectum: *Phys. Rev. Lett.* 126, 202301 (2021)



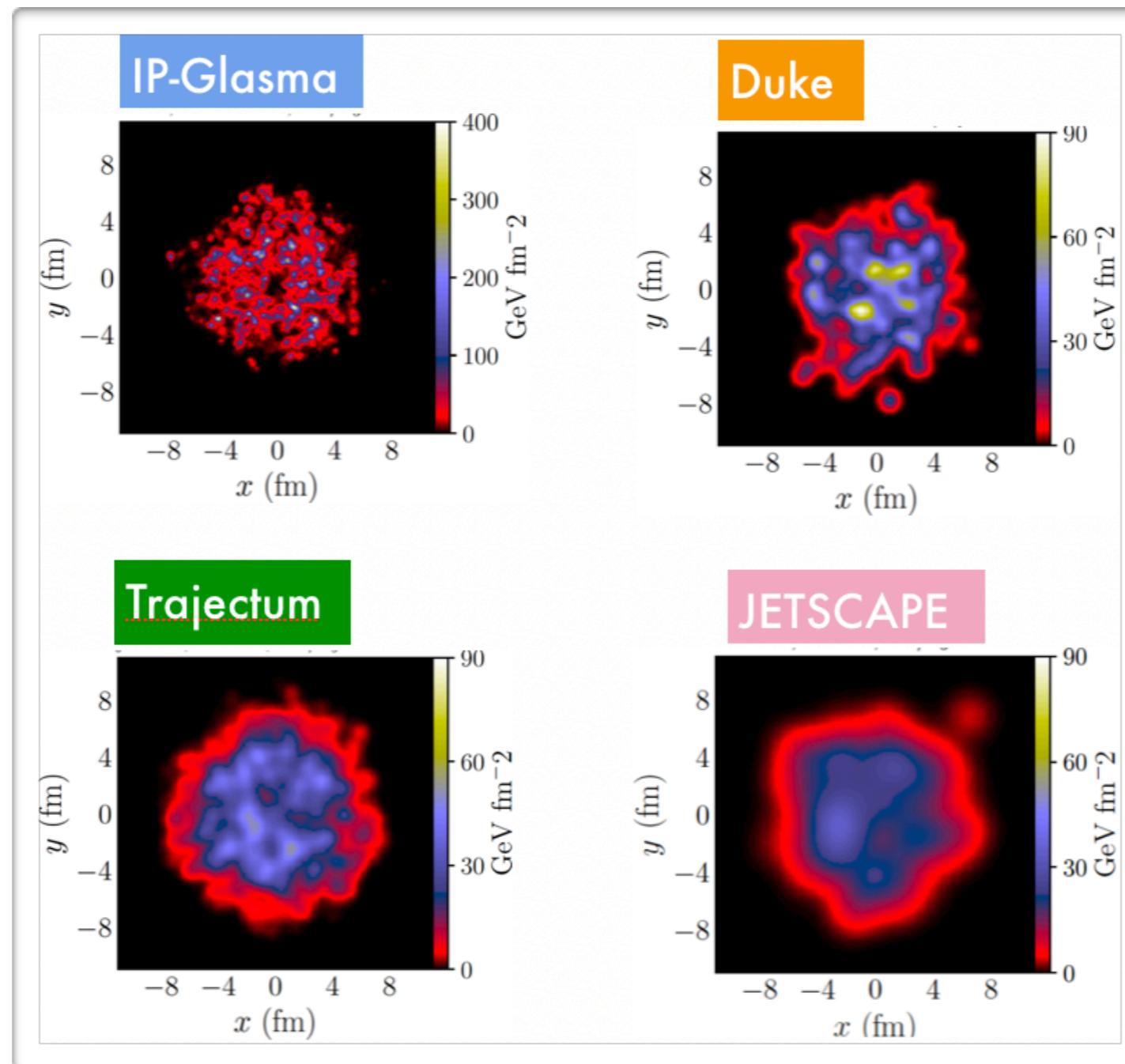
Duke: *Nature Phys.* 15 (2019) 11, 1113



Jyväskylä: *Phys. Rev. C* 104, 054904 (2021)



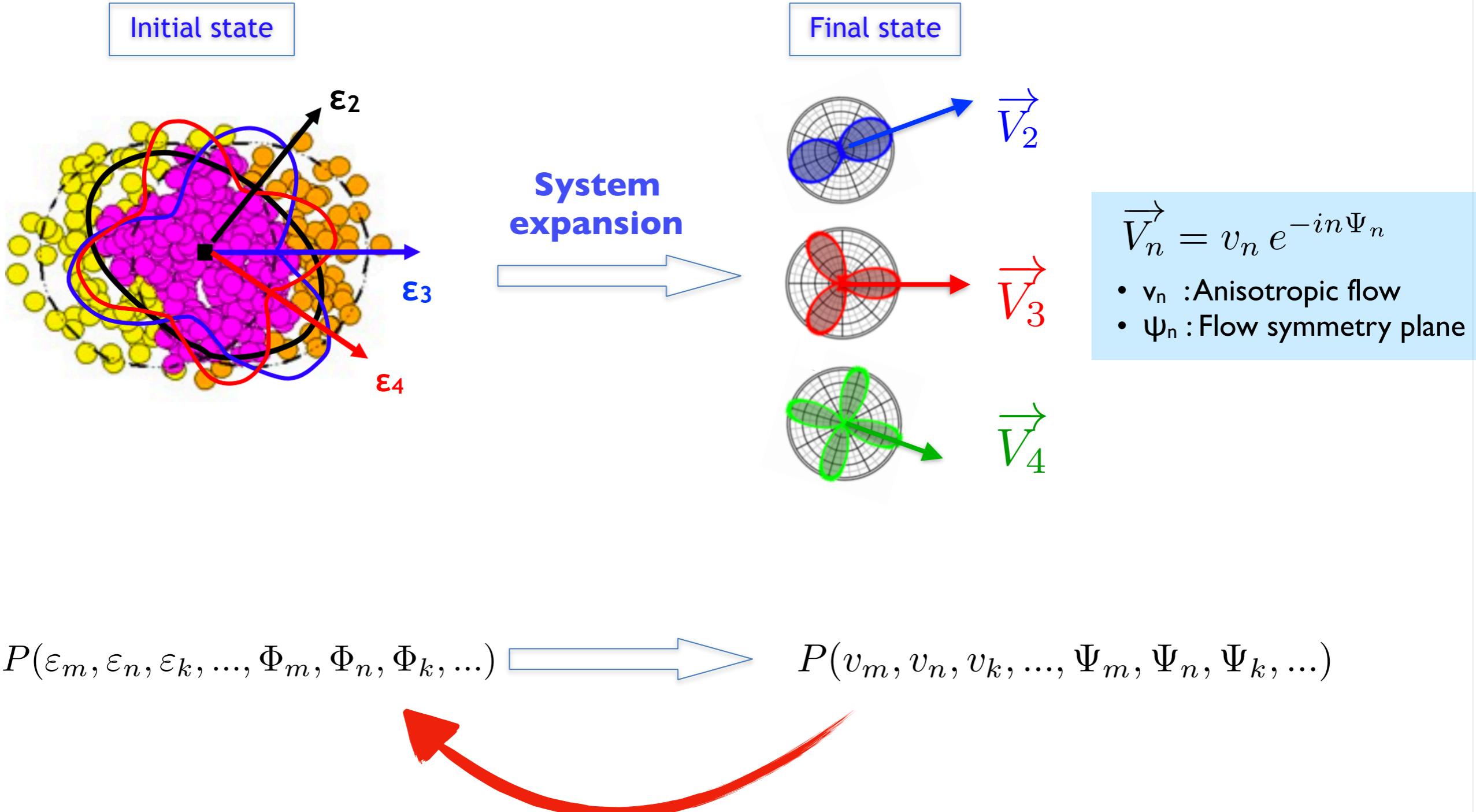
Current status of initial state models



How can we distinguish different initial state models in EXP ?

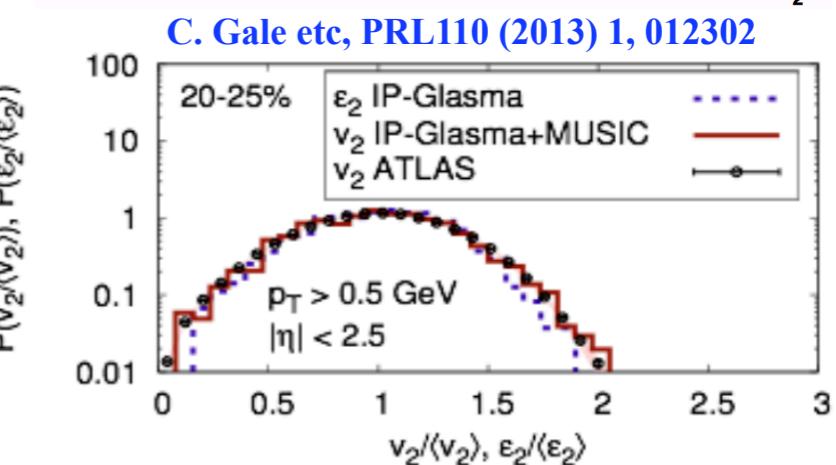
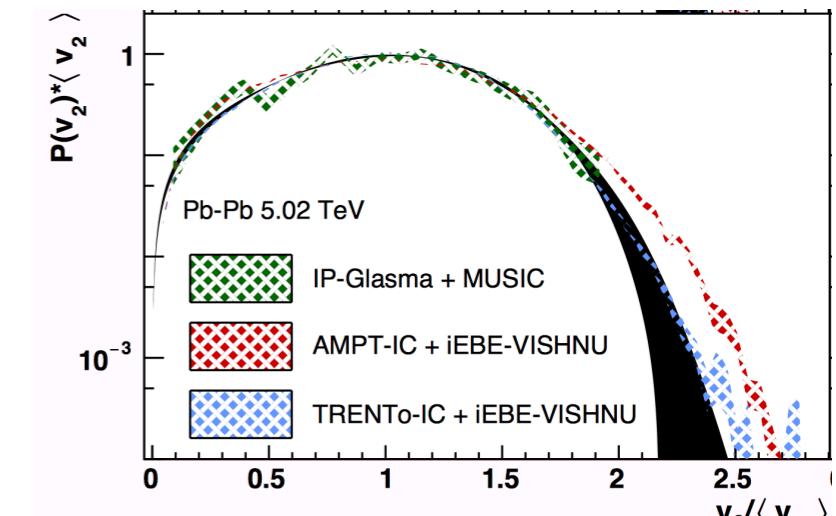
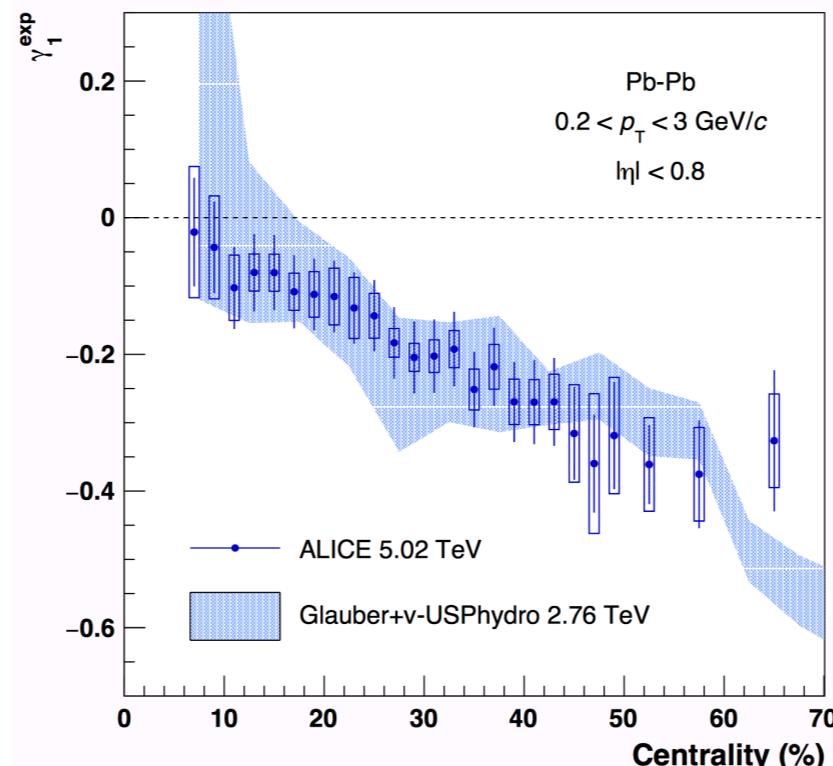
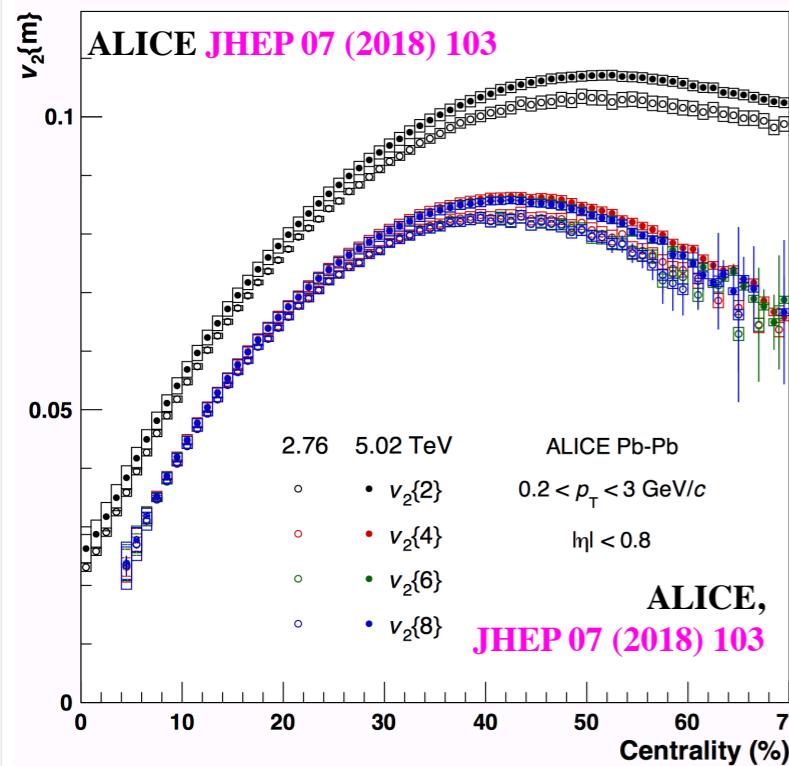


From initial anisotropy to anisotropic flow



Probe $P(\varepsilon_n)$

$v_n\{m\}$ ————— **Moments** ————— $p(v_n) \rightarrow p(\varepsilon_n)$



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

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

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

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

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

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

if $v_n \propto \varepsilon_n$ or $v_n = K * \varepsilon_n$
 $P(v_n / \langle v_n \rangle) \approx P(\varepsilon_n / \langle \varepsilon_n \rangle)$

❖ 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

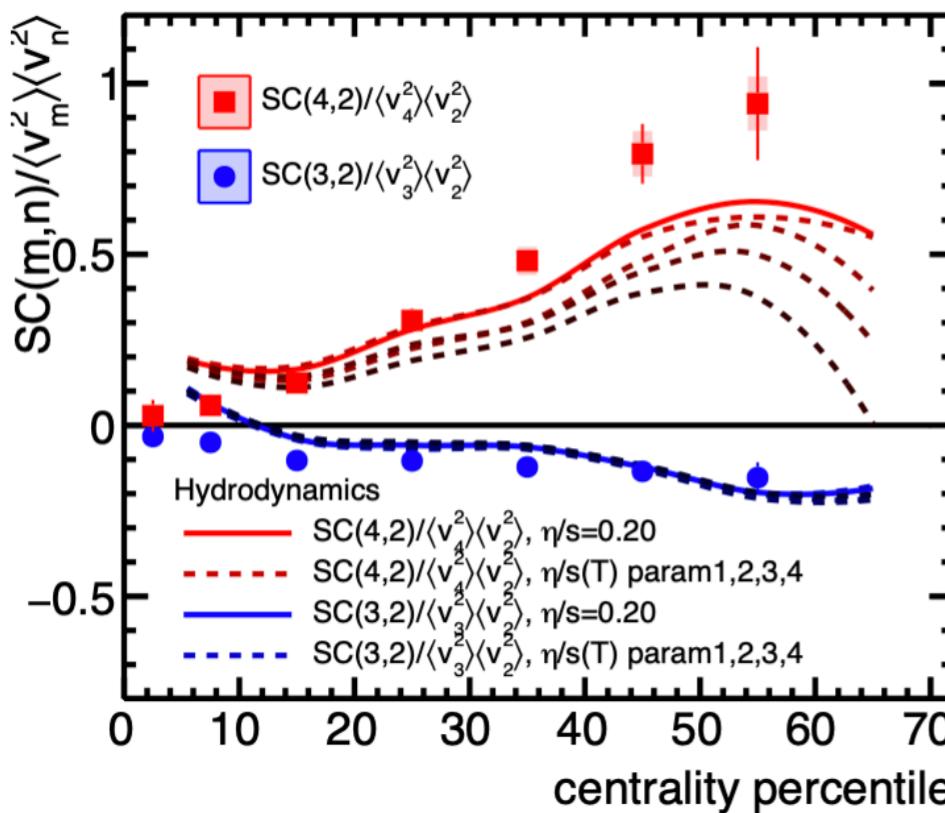


Probe $P(\varepsilon_n^2, \varepsilon_m^2)$

Symmetric cumulants:

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

ALICE, PRL117, 182301 (2016)



PHYSICAL REVIEW C 89, 064904 (2014)

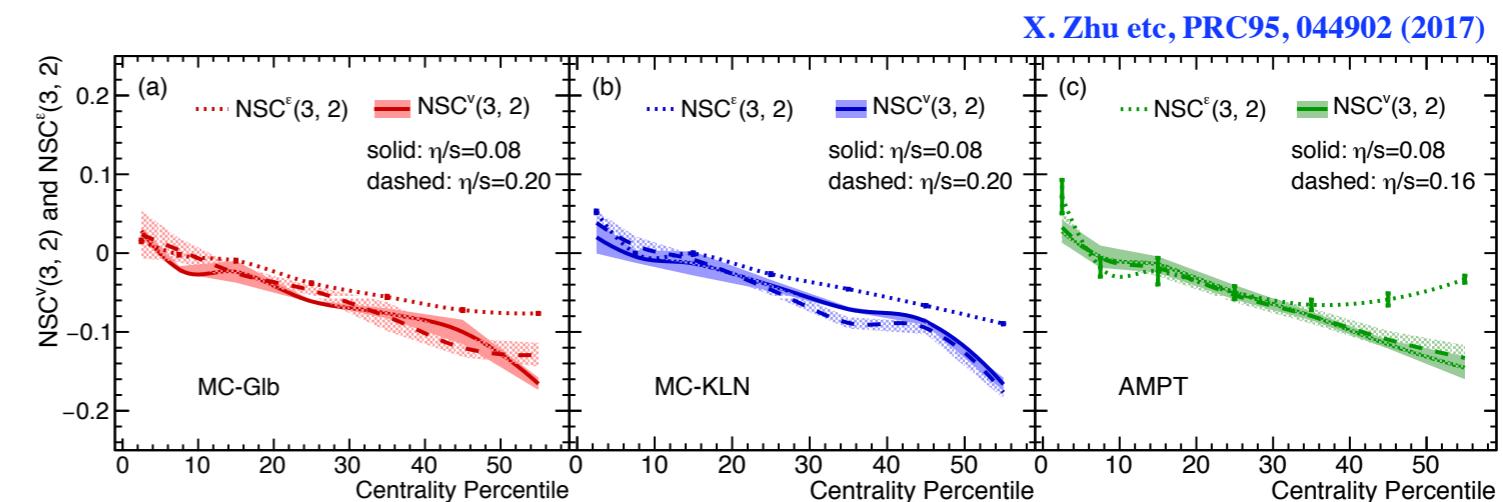
Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations

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$$v_2 \propto \varepsilon_2$$

$$v_3 \propto \varepsilon_3$$



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

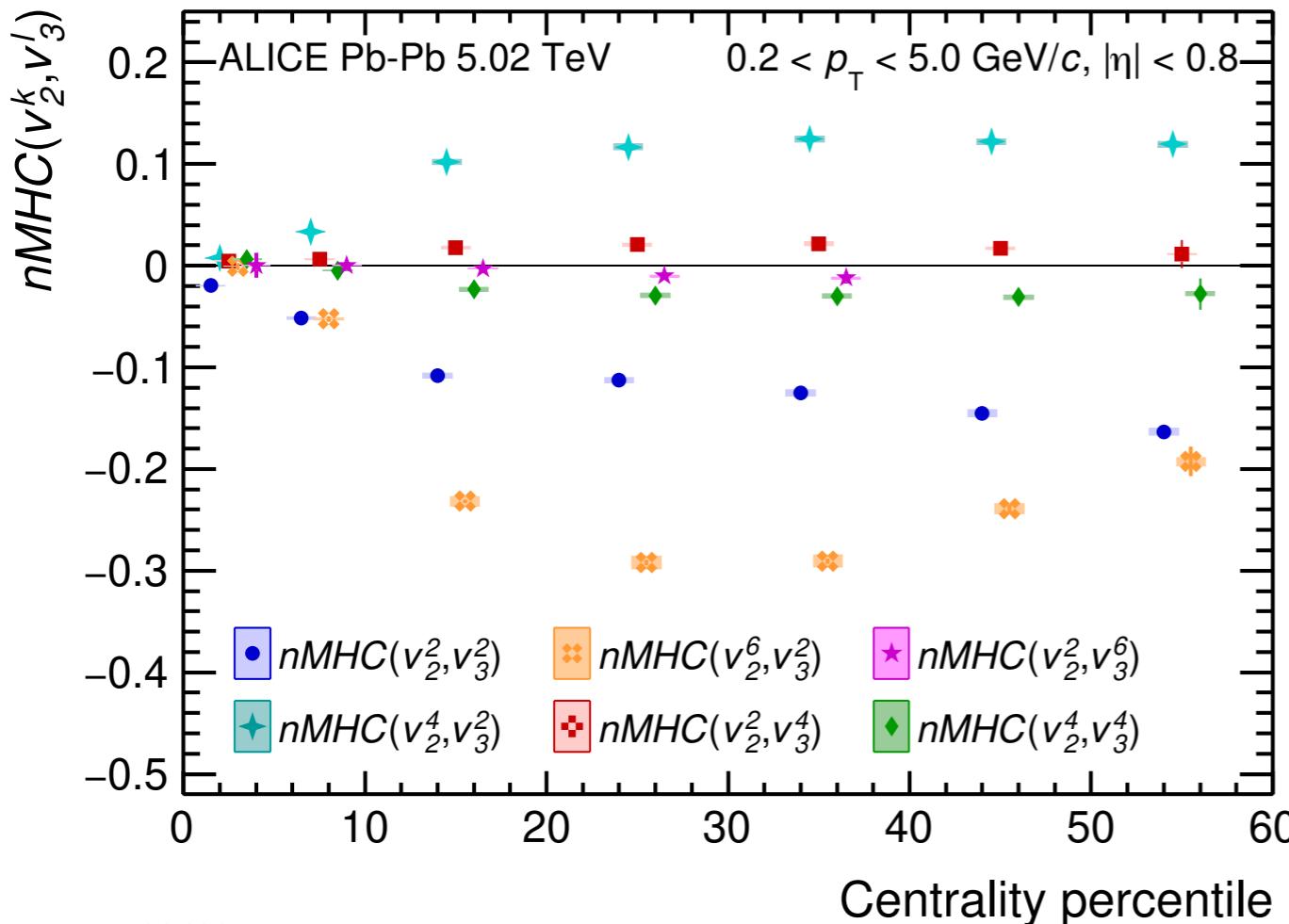
$NSC^v(3,2)$ $NSC^e(3,2)$

- ❖ Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations
 - 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



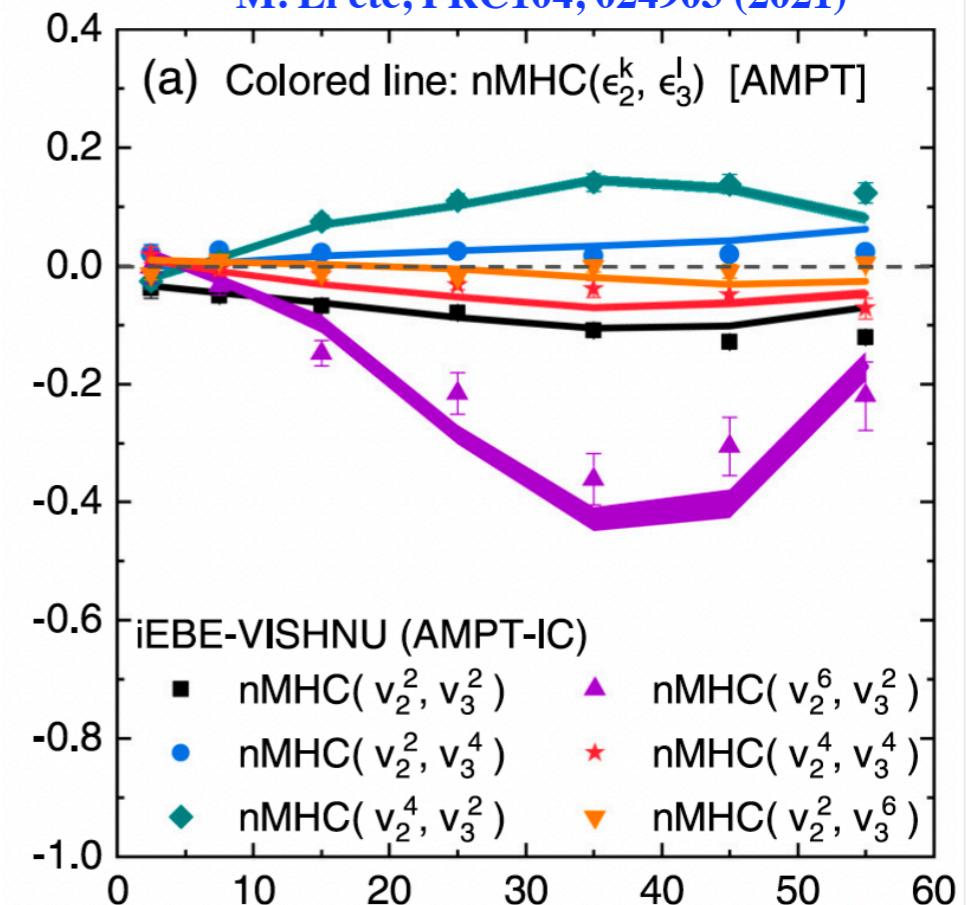
Probe $P(\epsilon_n^k, \epsilon_m^P)$

ALICE, PLB818 (2021) 136354



ALI-PUB-482633

M. Li etc, PRC104, 024903 (2021)



- ❖ First measurement of correlations between v_2^k and v_3^P
 - ▶ characteristic -, +, - signs observed for 4-, 6- and 8-particle cumulants of *mixed harmonic*
 - ▶ Final state results quantitatively reproduced by the initial state correlations using ϵ_2^k and ϵ_3^P
 - ▶ Experimental data provides direct constraints on the correlations of higher order moments of eccentricity coefficients



Size and shape in initial conditions

- ❖ Shape of the fireball: flow v_n
- ❖ Size of the fireball: radial flow, $[p_T]$
- ❖ correlation between v_n and p_T -> Initial geometry and fluctuations of shape and size

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

- ★ $cov(v_n^2, [p_T])$: 3-particle correlation (2 azimuthal, 1 $[p_T]$)

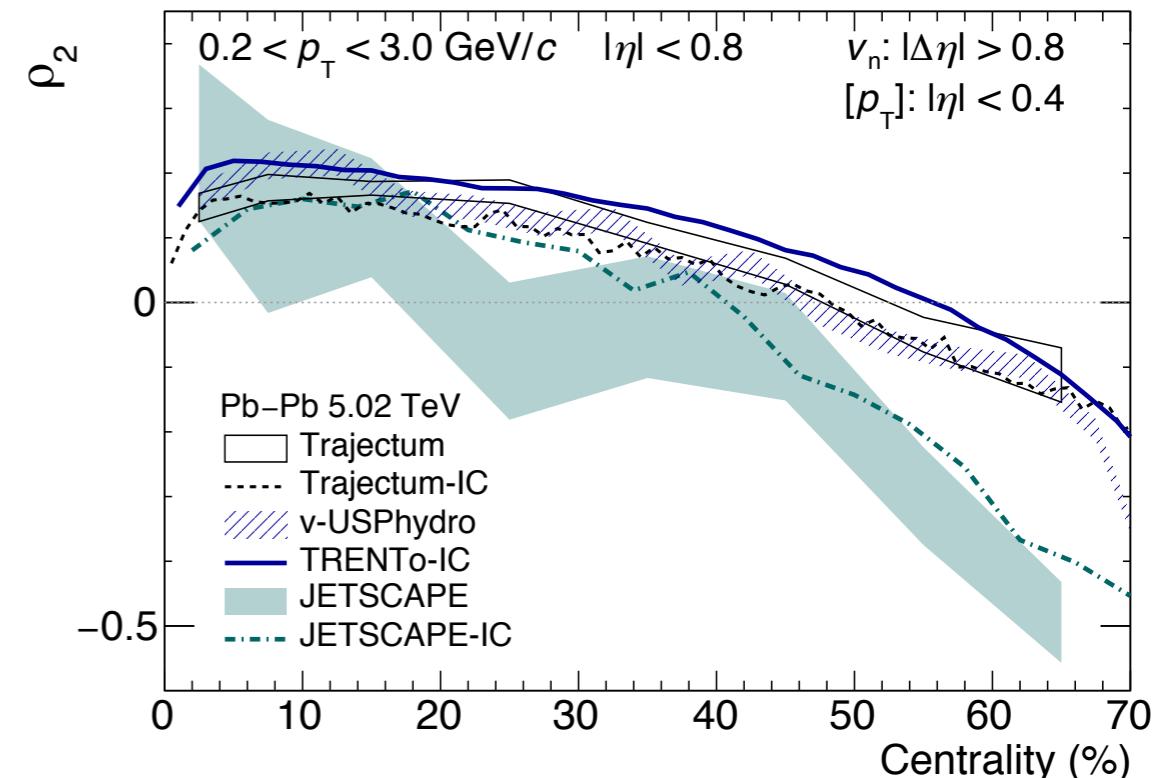
$$\left\langle \frac{\sum_{i \neq j \neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j} (p_{T,k} - \langle \langle p_T \rangle \rangle)}{\sum_{i \neq j \neq k} w_i w_j w_k} \right\rangle_{\text{evt}}$$

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

- ★ $\sqrt{var([p_T])}$: 2-particle $[p_T]$ correlations

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

JETSCAPE, PRL126, 242301 (2021)
 Privation communication
 Trajectum, PRL126, 202301 (2021)
 Privation communication



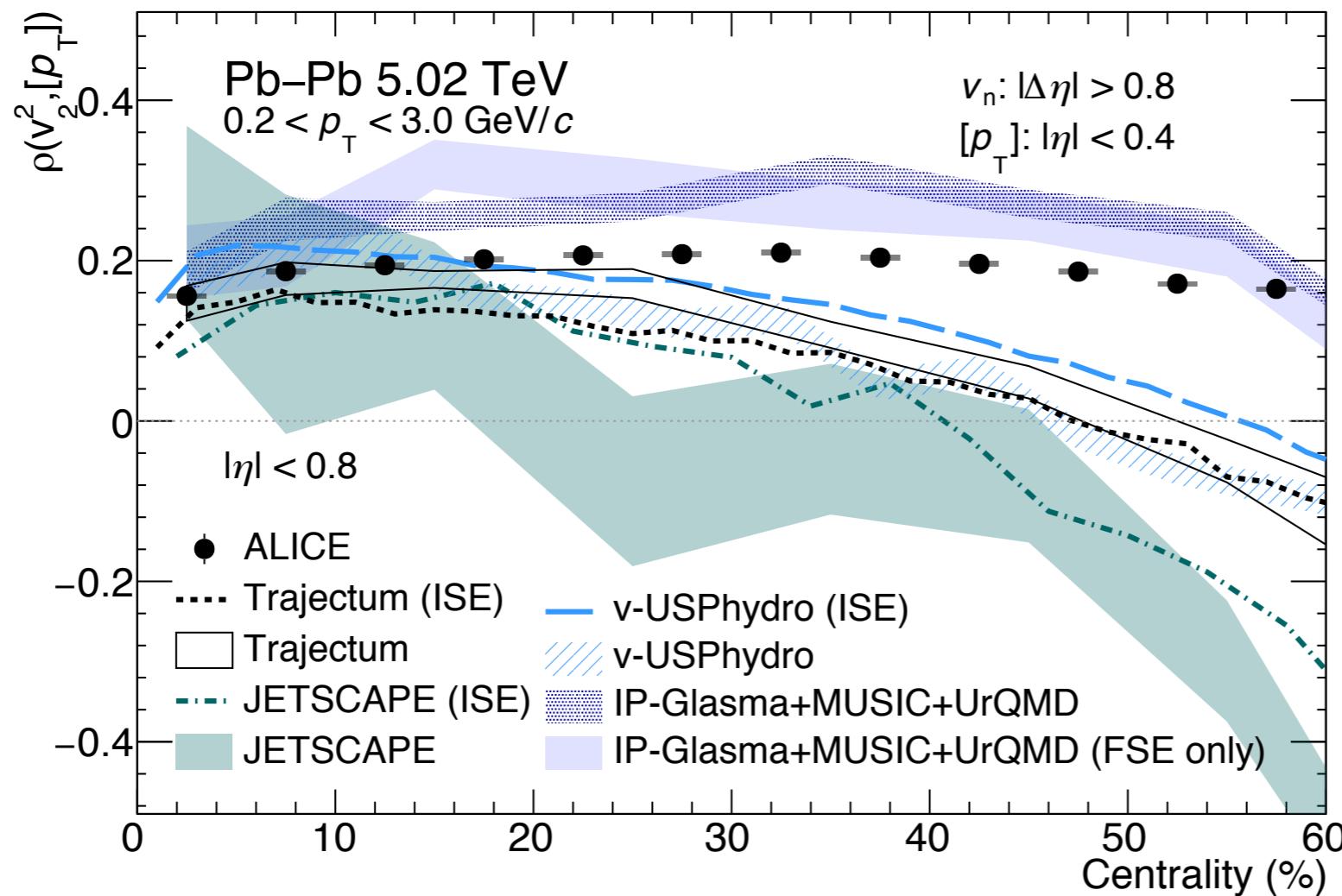
Characterizing the initial conditions



- ★ Initial geometric distributions;
- ★ Initial momentum anisotropy;
- ★ Nuclear structure



ρ_2 in Pb-Pb



ALICE, PLB834 (2022) 137393
v-USPhydro, PRC103 (2021) 2, 024909
IP-Glasma, PRC102, 034905 (2020)
JETSCAPE, PRL126, 242301 (2021)
Trajectum, PRL126, 202301 (2021)
Privation communication
Privation communication

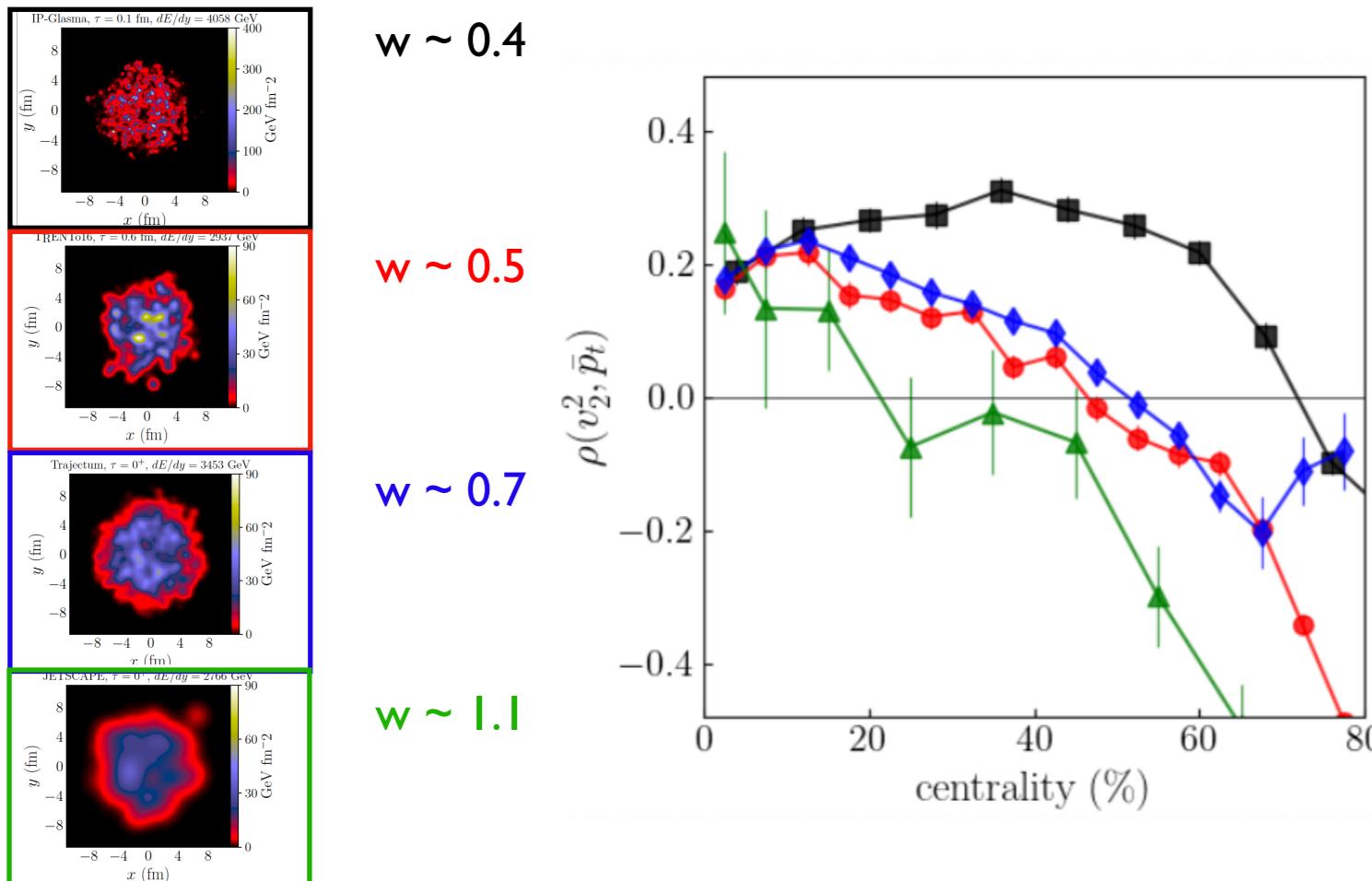
- ❖ Weak centrality dependence of ρ_2 in Pb-Pb collisions,
 - IP-Glasma+MUSIC+UrQMD qualitatively describes the trend, overestimates the data
 - TRENTo-IC based calculations shows a strong centrality dependence and wrong sign in peripheral
- ❖ Why there is such a huge difference between IP-Glasma and TRENTo calculations?



Nucleon width

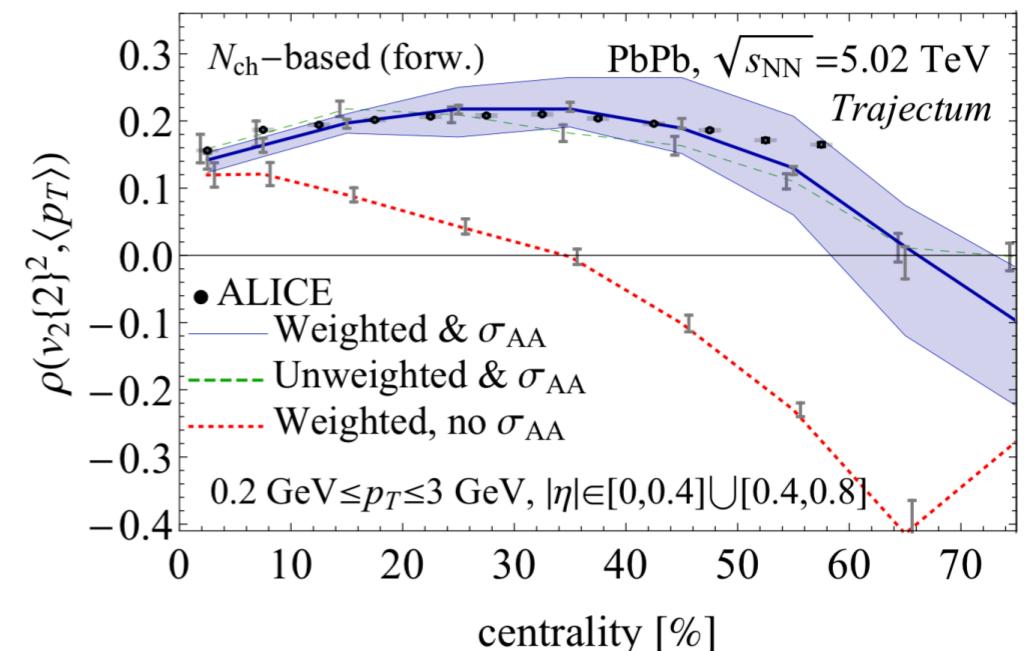
❖ Sensitive to the nucleon width parameter (size of nucleon)

- IP-Glasma ~ 0.4 ; v-USPhydro ~ 0.5 ; Trajectum ~ 0.7 ; JETSCAPE (T_{RENTo}) ~ 1.1
- $w(\text{IP-Glasma}) < w(\text{v-USPhydro}) < w(\text{Trajectum}) < w(\text{JETSCAPE})$
- New constraints on the **nucleon size**, consistent results from cross section measurements



G. Nijs etc, arXiv:2206.13522

$w: 0.4-0.5 \text{ fm}$



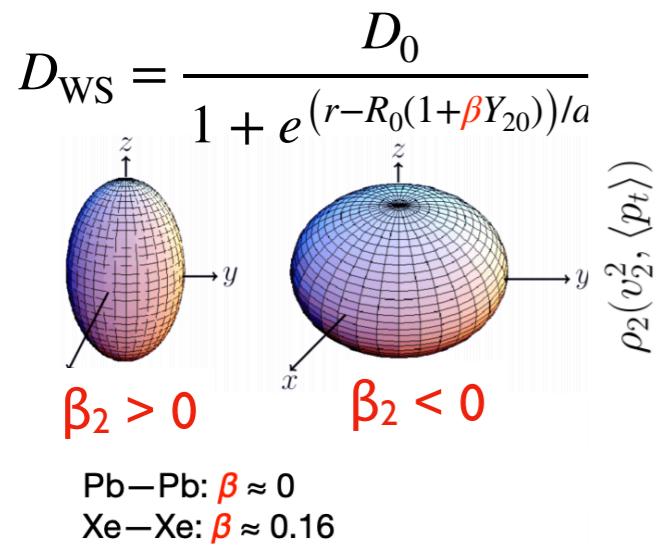
❖ Different types of thickness functions

- $T_{\text{RENTo}} \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p}$ with $p \approx 0 \sqrt{T_A T_B}$, IP-Glasma $T_A T_B$ type

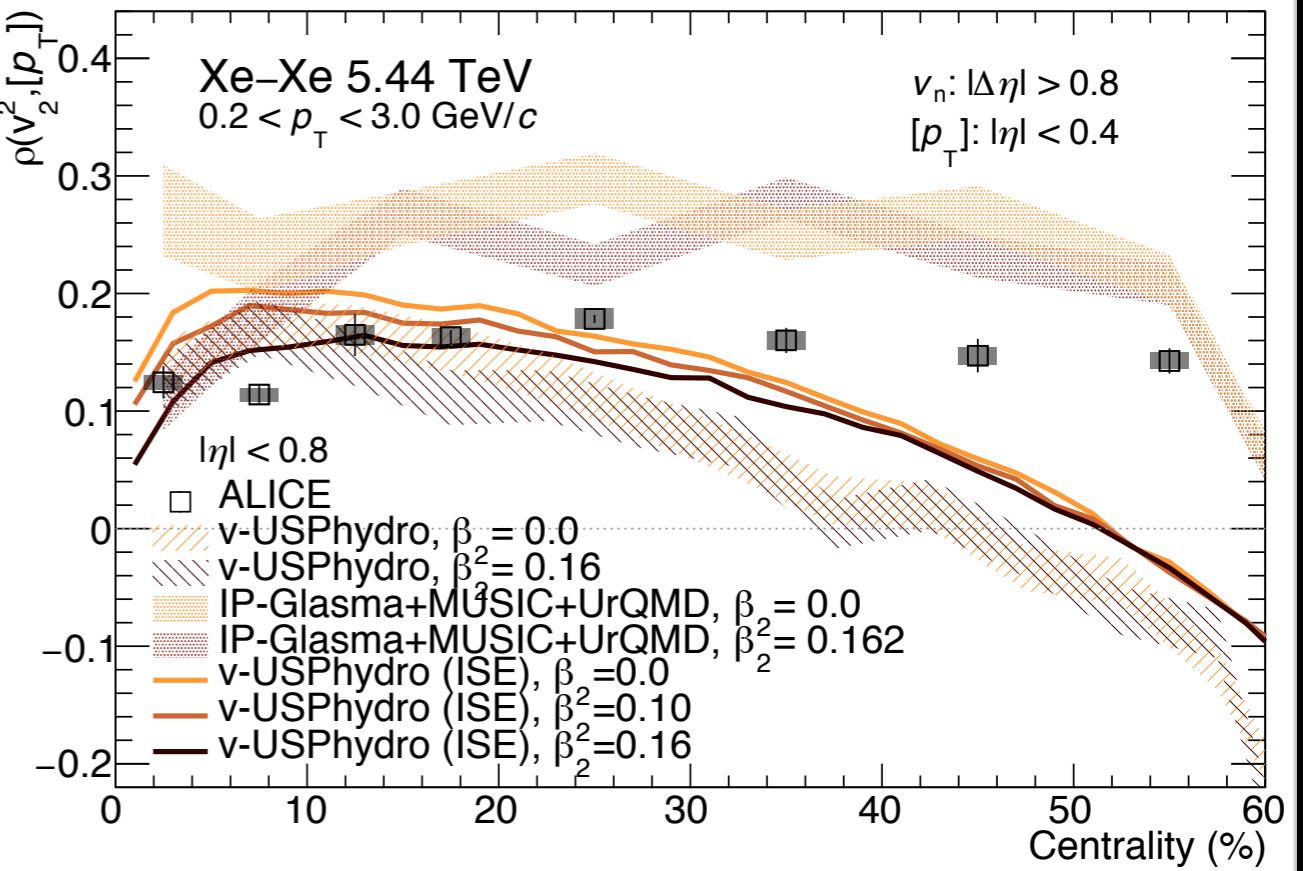
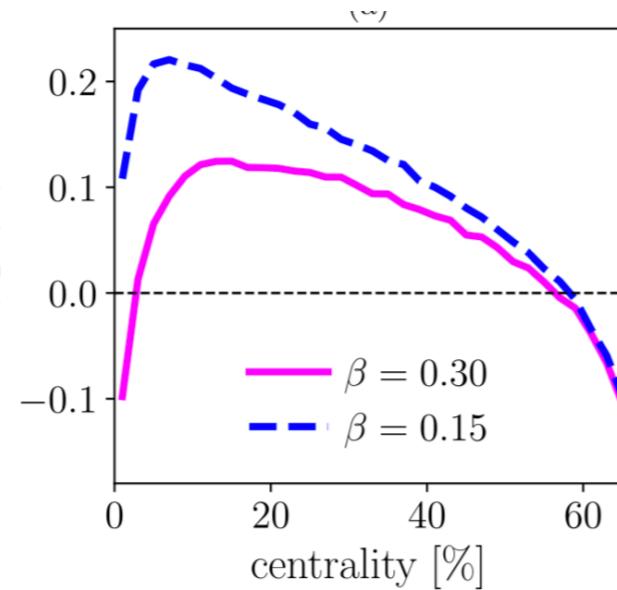
❖ Different contributions from pre-hydrodynamic phase (free streaming) and sub-nucleon structure



ρ_2 in Xe-Xe



G.Giacalone, PRC 102 024901 (2020)



ALICE, PLB834 (2022) 137393

v-USPhydro, PRC103 (2021), 024909

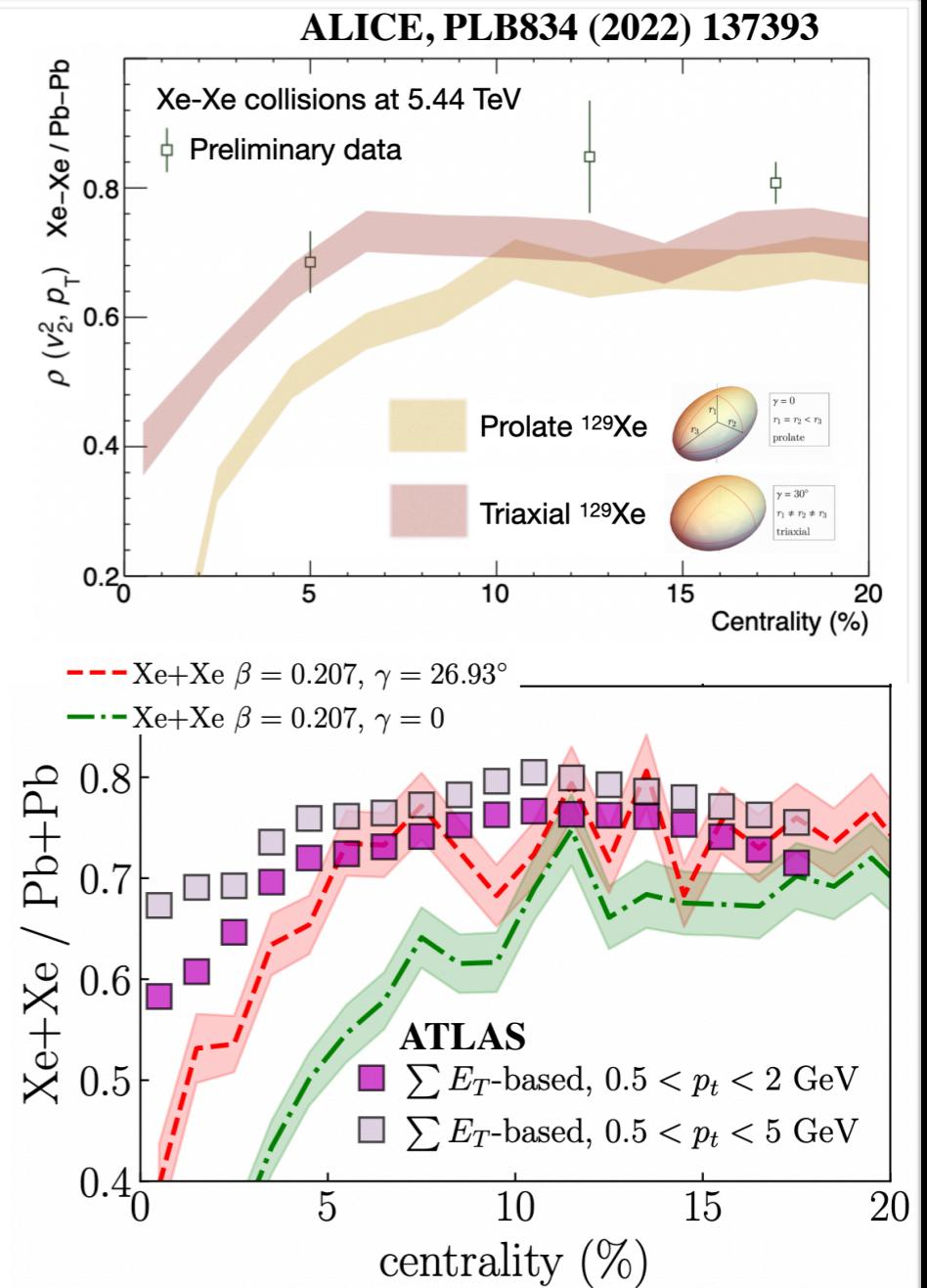
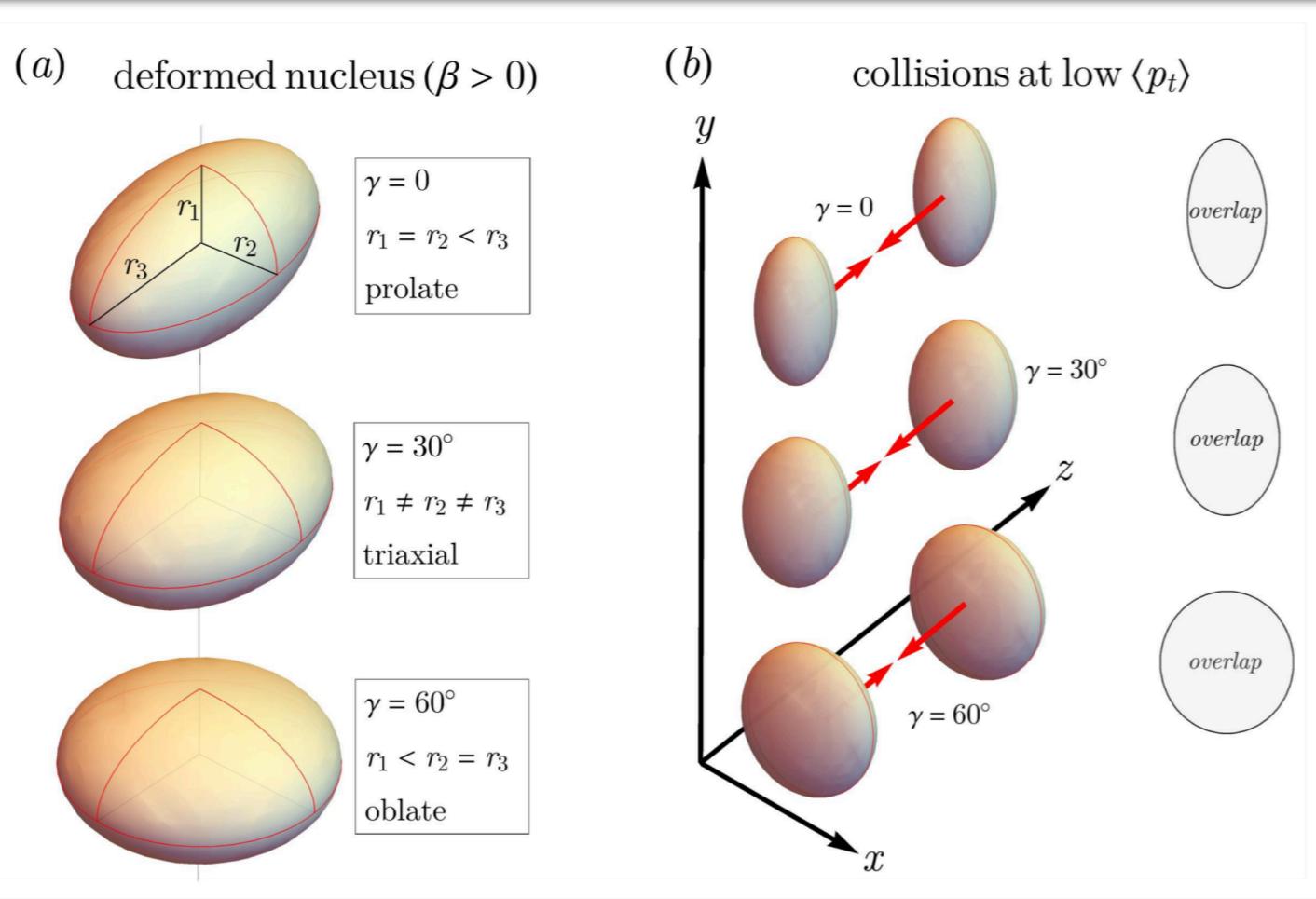
IP-Glasma, PRC102, 034905 (2020)

- ❖ Significant differences of initial state calculations using different deformation parameter in central Xe-Xe collisions
 - ρ_2 is sensitivities to β_2
 - The uncertainty of current v-USPhydro calculations is too large to draw a confirm conclusions
 - Experimental data (in Xe-Xe@LHC and U-U@RHIC) open a new window to study nucleon deformation.



Probe triaxial structure of Xe

B. Bally etc, arXiv:2108.09578



❖ Better agreement between LHC data and calculations with $\gamma = 26.93^\circ$

- 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



Summary

Characterizing the initial conditions in heavy-ion collisions

★ **Initial geometry:**

- For the first time we see completely different flow behaviours using IP-Glasma and TRENTo initial state models, due to the different nucleon width

★ **Nucleon structure**

- ALICE results open a new window to constrain deformation parameter and explore the triaxial structure of ground-state Xenon

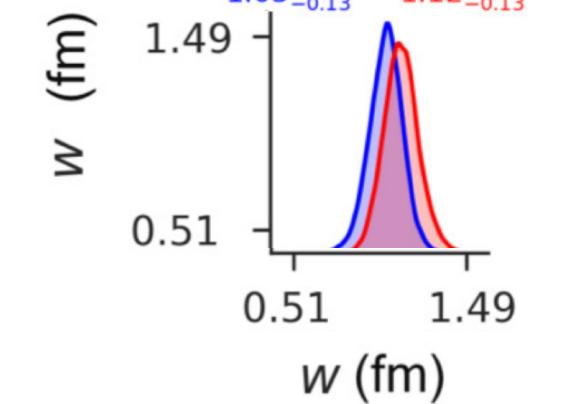
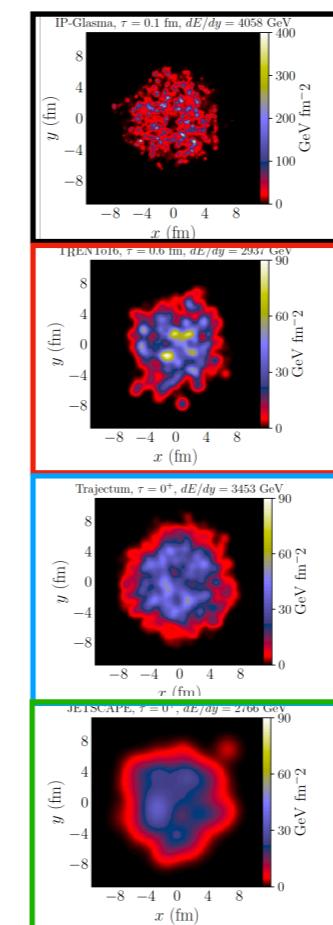
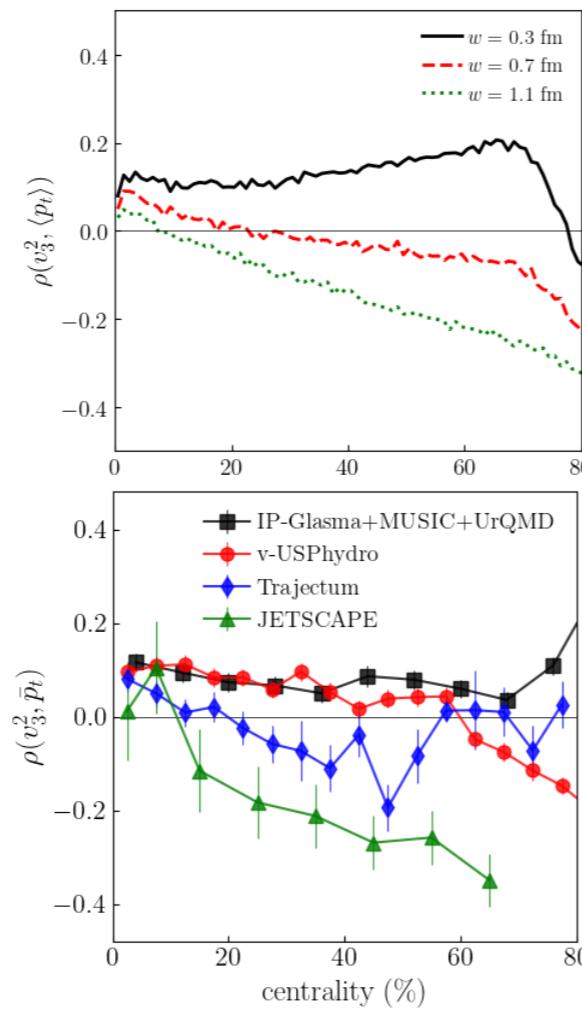
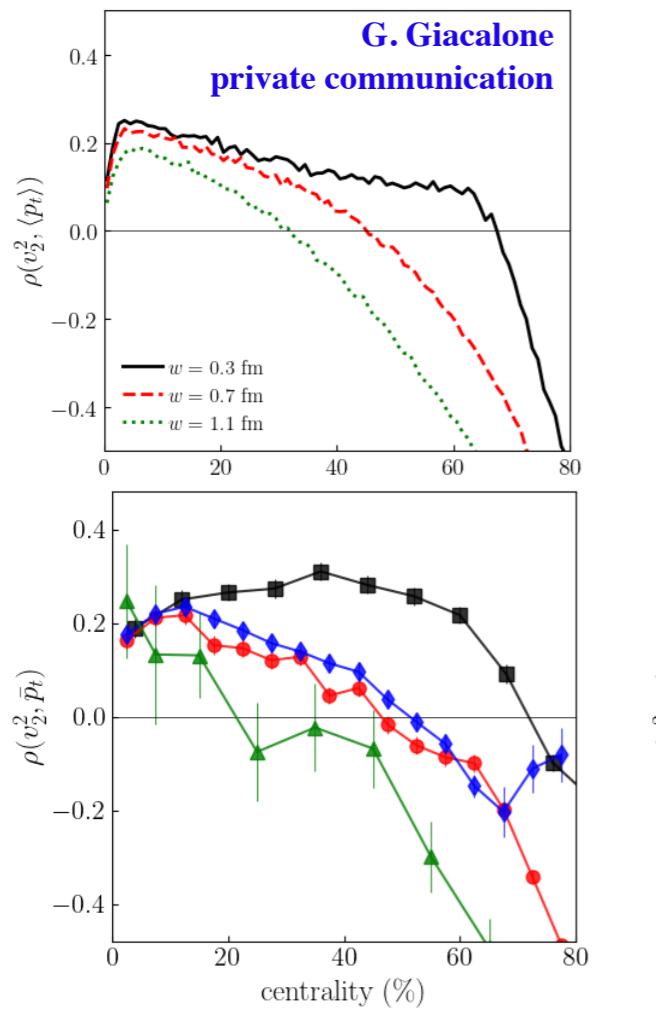
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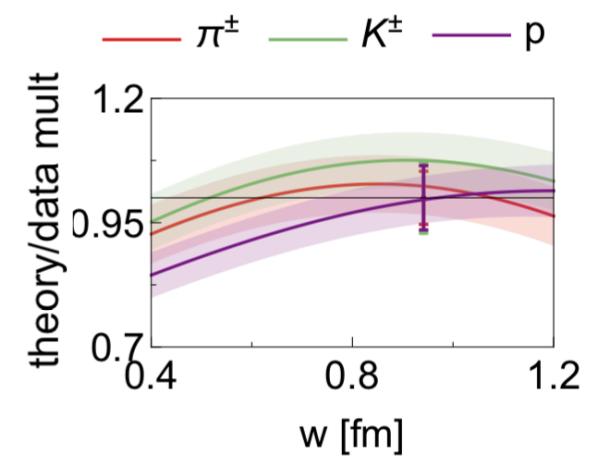
Backup



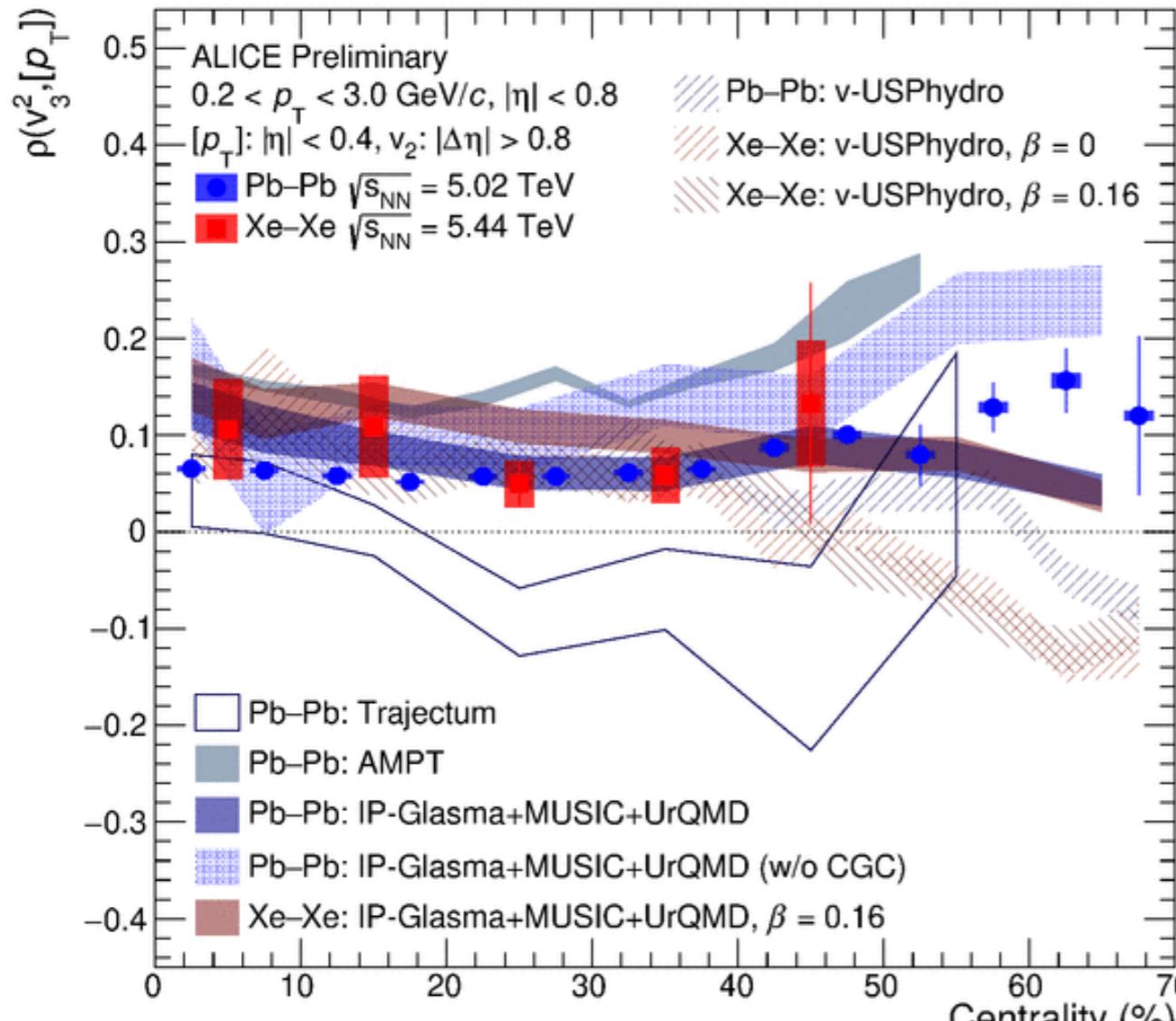
JETSCAPE, PRC103, 054904 (2021)



Trajectum, PRC103 (2021) 5, 054909



ρ_3 in Pb-Pb



ALICE, in preparation

Trajectum, PRL126, 202301 (2021)

Privation communication

v-USPhydro, PRC103 (2021) 2, 024909

JETSCAPE, PRL126, 242301 (2021)

Privation communication

❖ ρ_3 in Pb–Pb is compatible with Xe–Xe for the presented centralities, qualitatively predicted by hydrodynamic calculations

❖ 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

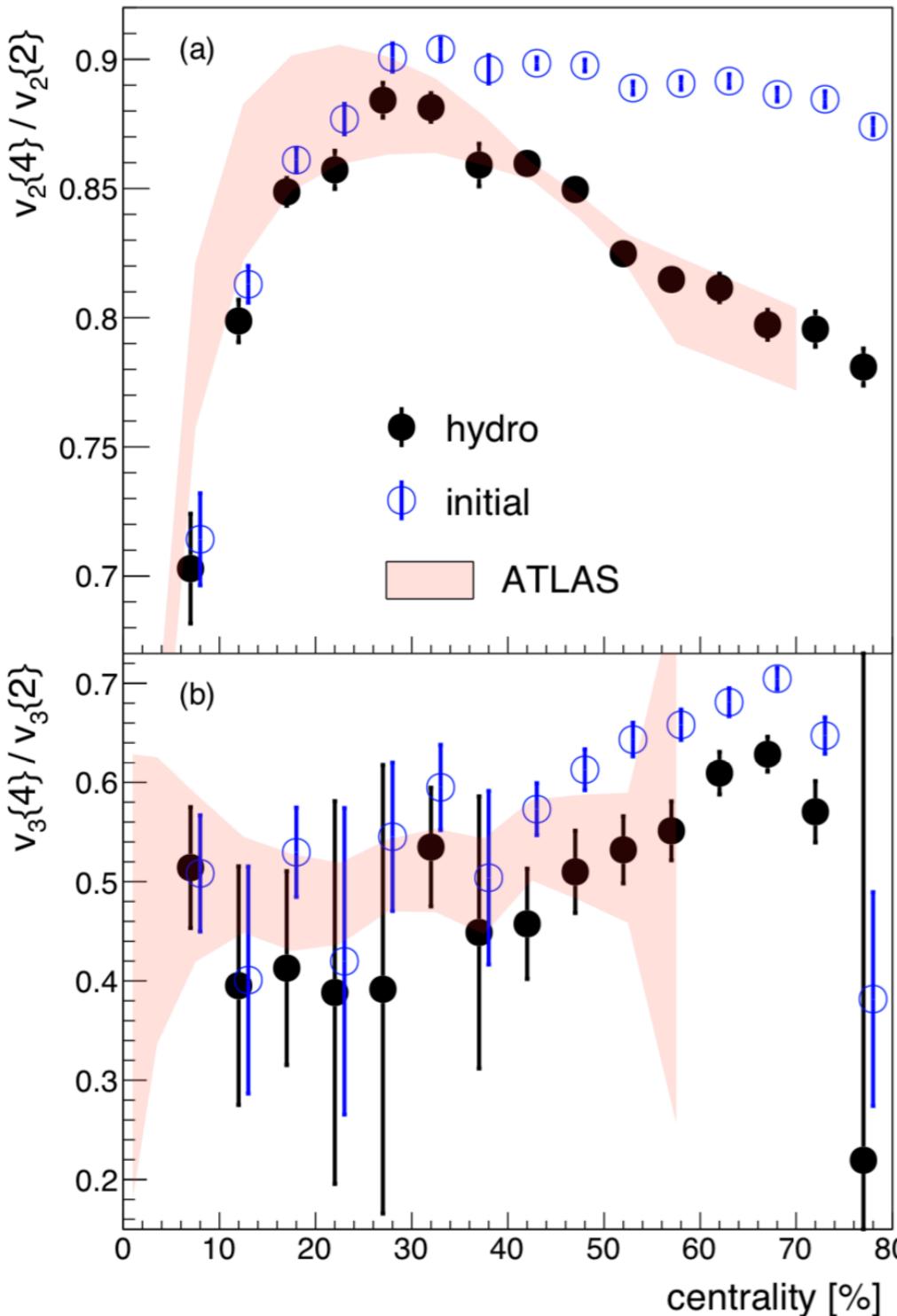
❖ model shows that ρ_3 is not sensitive to β_2

❖ Difference of full IP-Glasma and FSE only, indication of potential contributions from IMA in peripheral?



Ratio of multi-particle cumulants

G. Giacalone etc, PRC95, 054910 (2017)



- ❖ if $v_n \propto \epsilon_n$ or $v_n = K * \epsilon_n$
(K reflects QGP properties)

$$\frac{v_n\{\mu\}}{v_n\nu\} = \frac{\epsilon_n\{\mu\}}{\epsilon_n\nu\}$$

- ❖ Then one can constrain the initial eccentricity via multi-particle cumulants of v_n

