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

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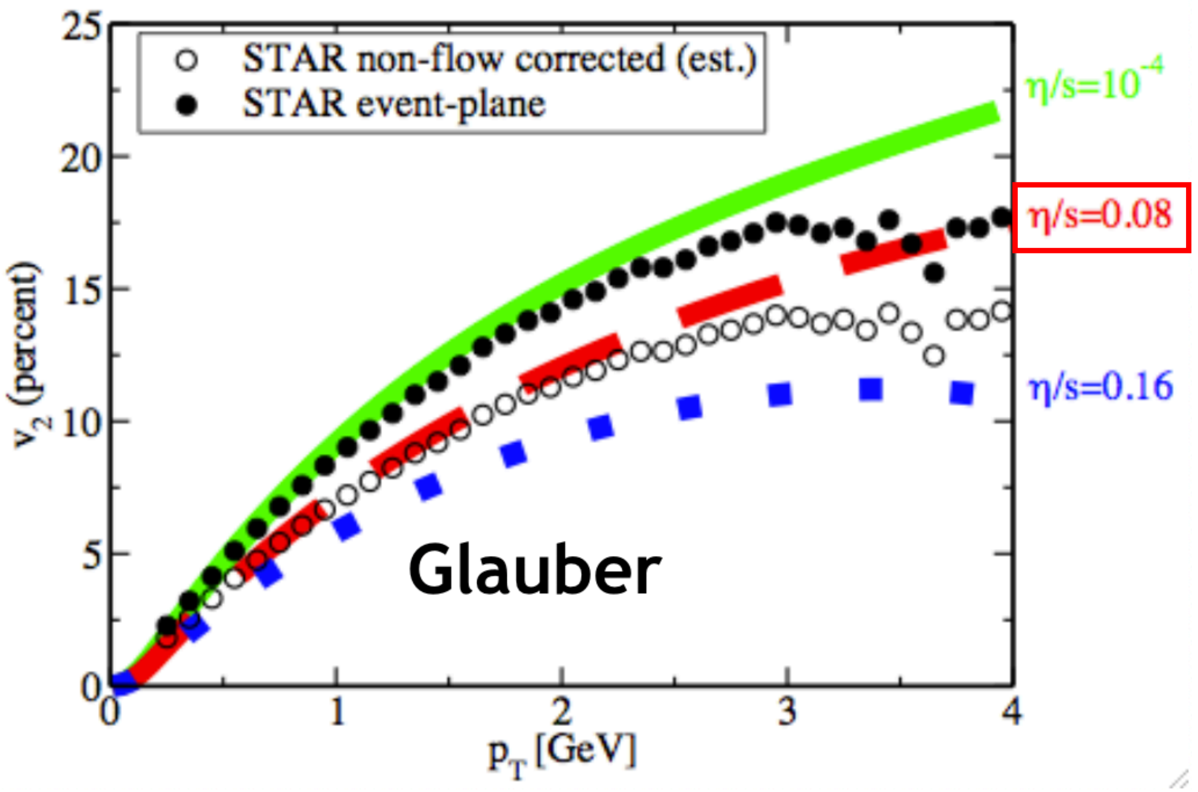
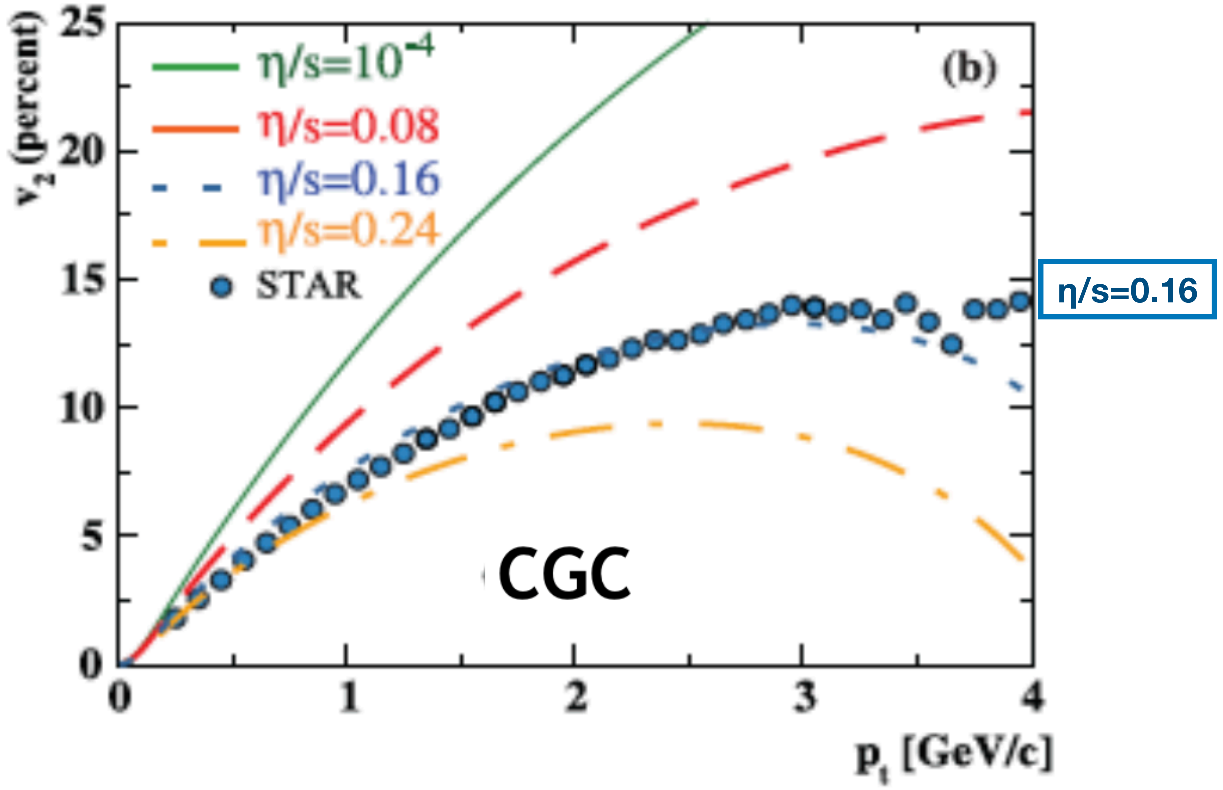
Initial conditions matters for the QGP studies

- The studies of flow in heavy-ion collisions allow to extract transport coefficients (η/s, ζ/s) of QGP
- Very large uncertainties, depending on the applied initial state models
  - i.e. $\eta/s = 0.08$ with Glauber IC, whereas $\eta/s = 0.16$ with CGC IC (with only v_2)





Current status of initial state models

THERE ARE CURRENTLY THREE CATEGORIES OF MODELS.

- **“sharp” models: IP-GLASMA and TRENTo 2016** **(v-USPhydro)**

[Schenke, Shen, Tribedy 2005.14682]

[Bass, Bernhard, Moreland 1605.03954]

Nucleons have a width of ~0.5fm (trento), 3 sub-nucleons with size ~0.3fm (IP-Glasma). Trento is used for the entropy density at the beginning of hydro. IP-Glasma is the only model which incorporates a realistic pre-equilibrium evolution with longitudinal cooling.

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

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

[JETSCAPE Collaboration 2011.01430, 2010.03928]

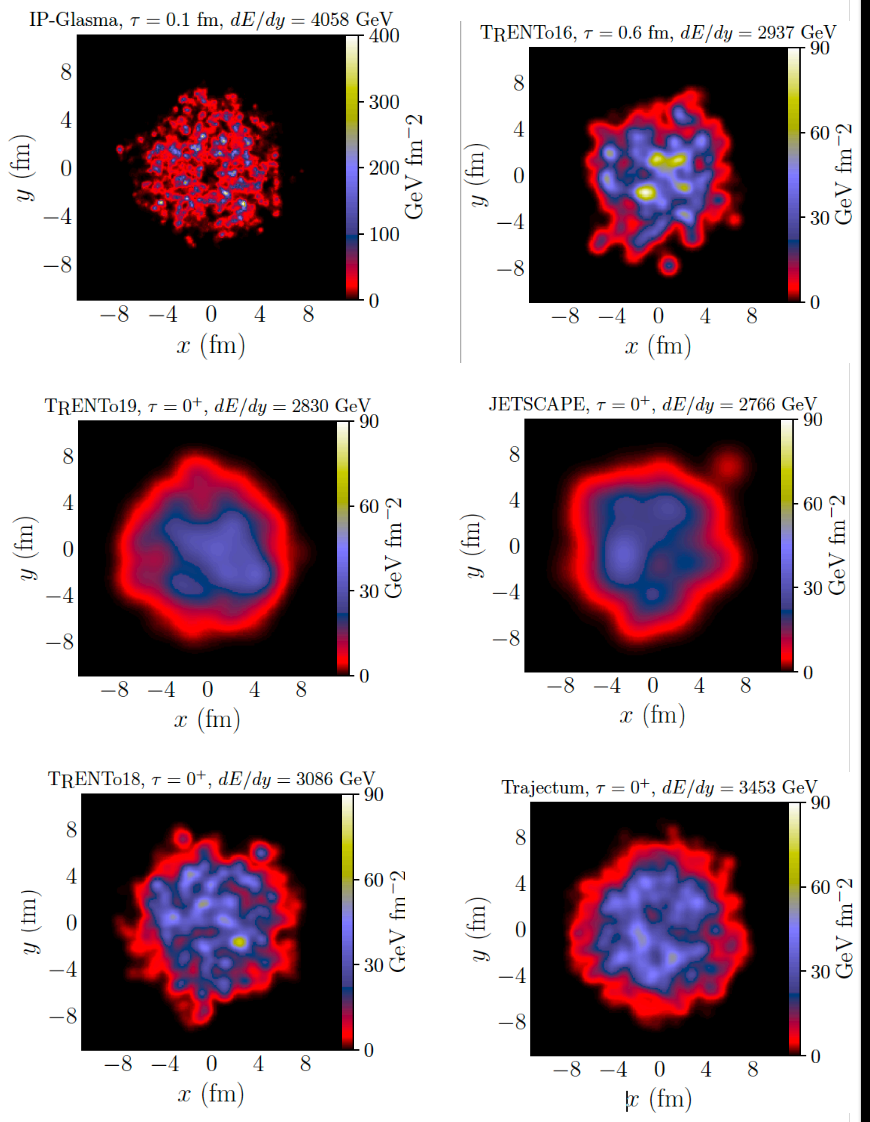
The Trento parametrization is now used for the energy density at tau=0+. There is no substructure. The nucleon width is now ~1fm. Very smooth profiles.

- **“lumpy fat” models: TRENTo 2018 and Trajectum**

[Bass, Bernhard, Moreland 1808.02106]

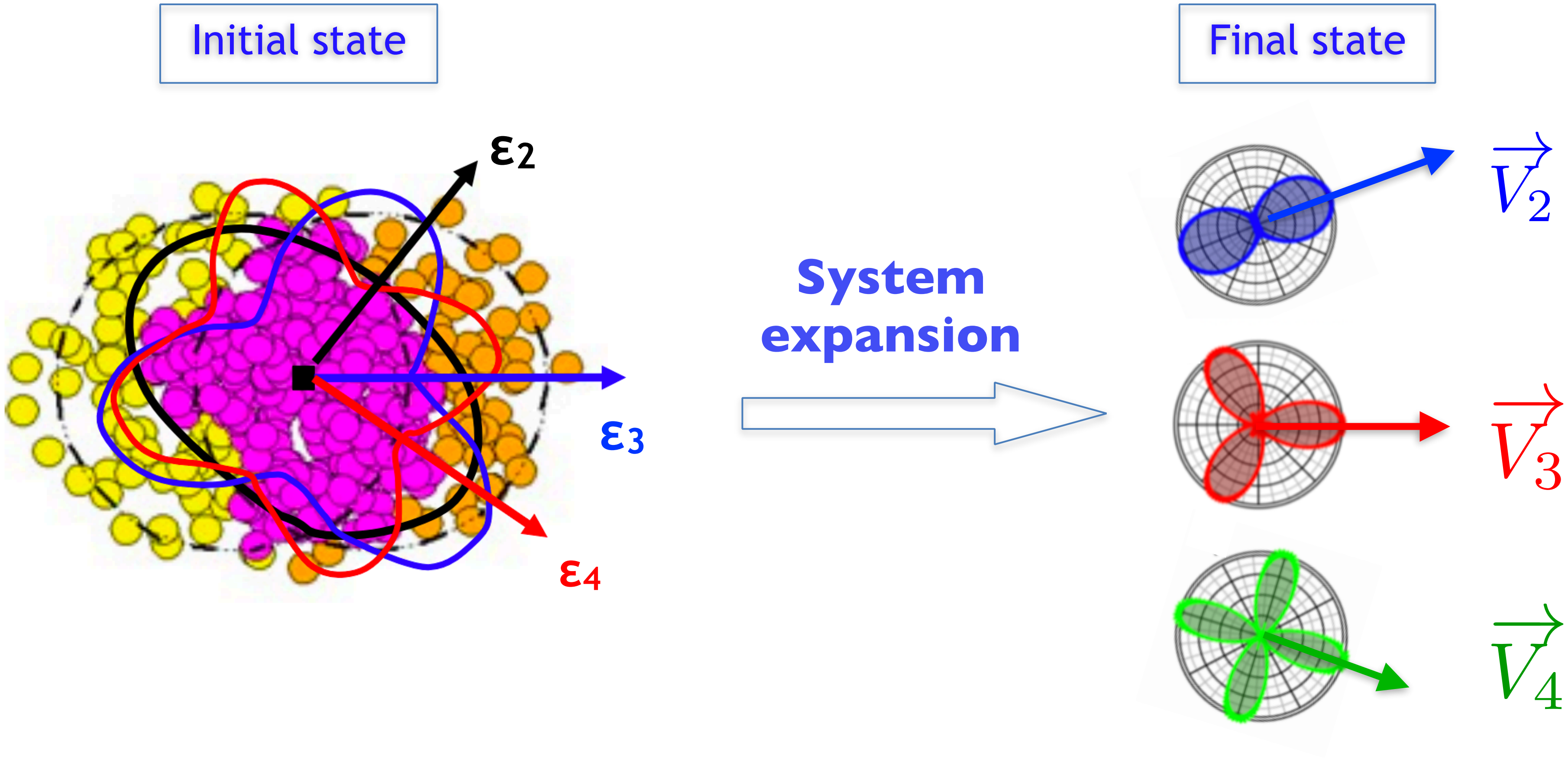
[Nijs, van der Schee, Gürsoy, Snellings 2010.15130, 2010.15134]

The Trento parametrization is the energy density at tau=0+. Substructure is included: 4-6 constituents with width ~0.5fm. Profiles with some ‘old school’ lumpiness.



How can we distinguish different initial state models in EXP ?

From initial anisotropy to anisotropic flow



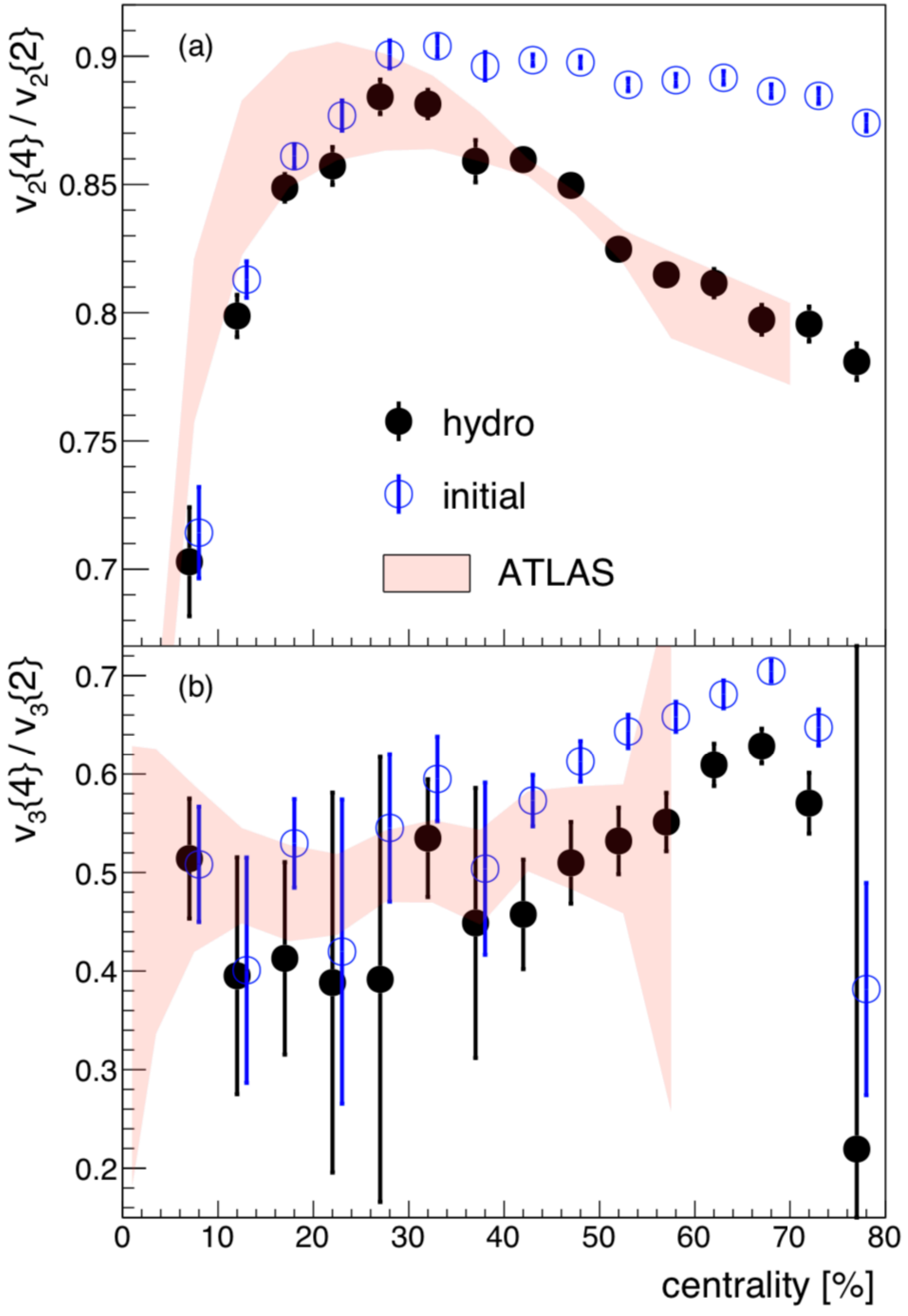
$$\vec{V}_n = v_n \, e^{-in\Psi_n}$$

- v_n :Anisotropic flow
- Ψ_n : Flow symmetry plane

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

Ratio of multi-particle cumulants

G. Giacalone etc, PRC95, 054910 (2017)

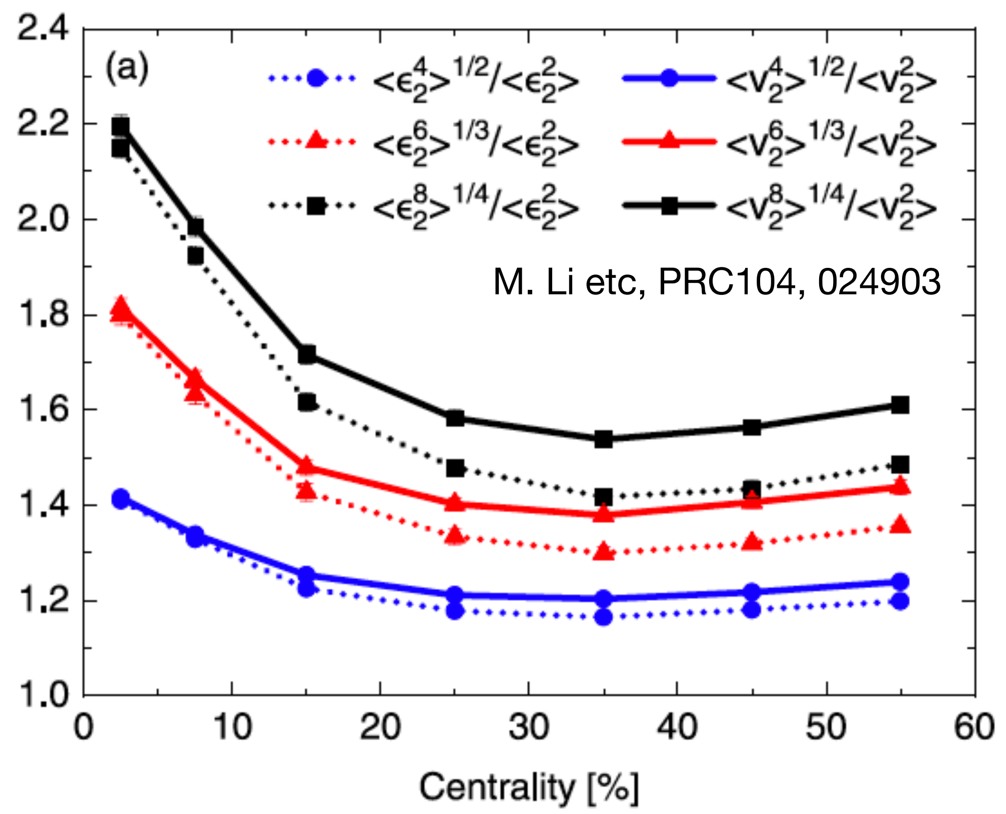


- ❖ if $v_n \propto \varepsilon_n$ or $v_n = \kappa * \varepsilon_n$

  (κ reflects QGP properties)

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

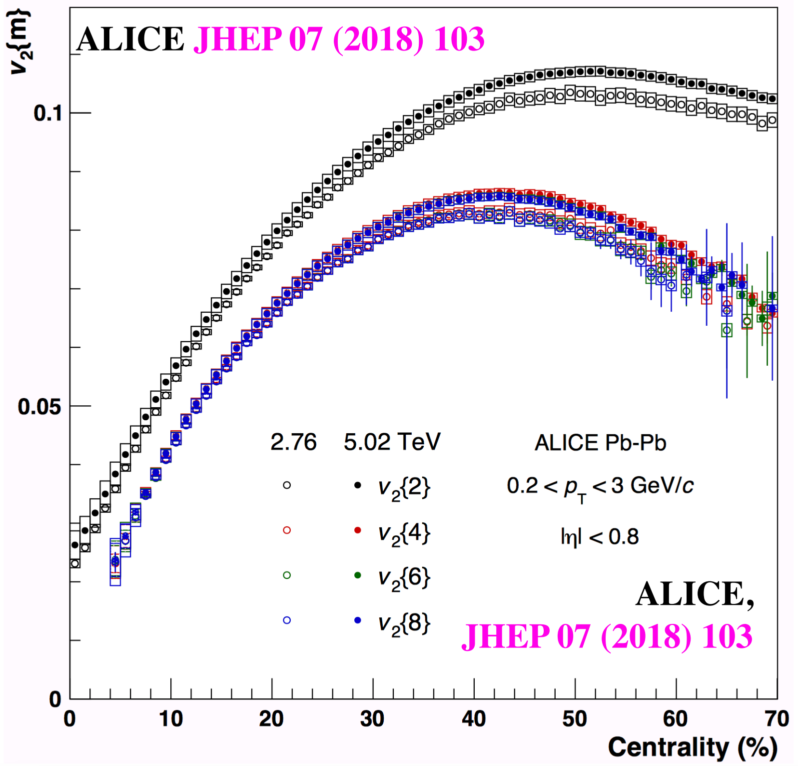
- ❖ Then one can constrain the initial eccentricity via multi-particle cumulants of v_n

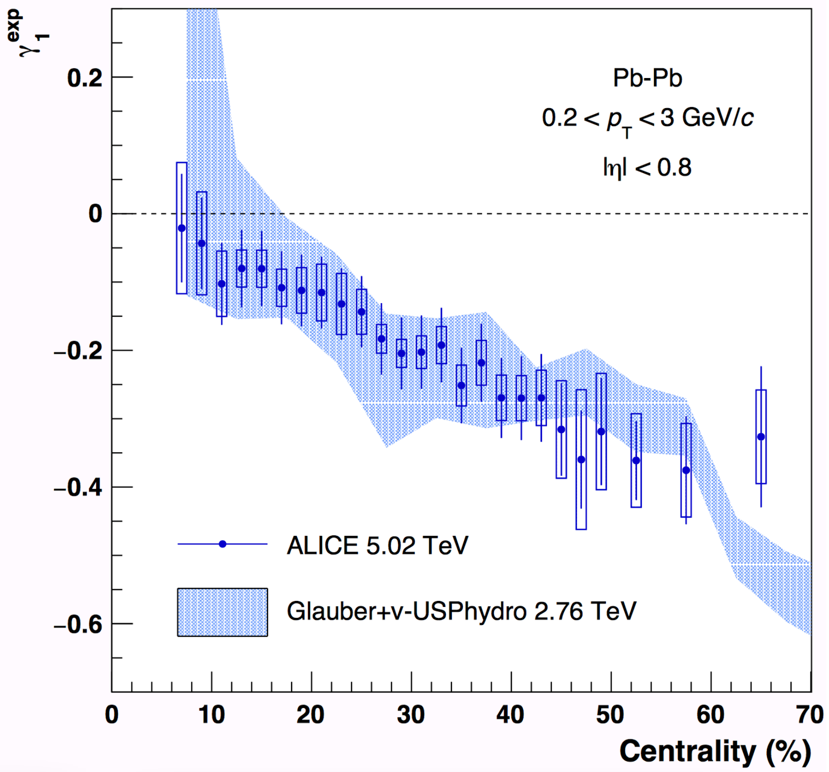


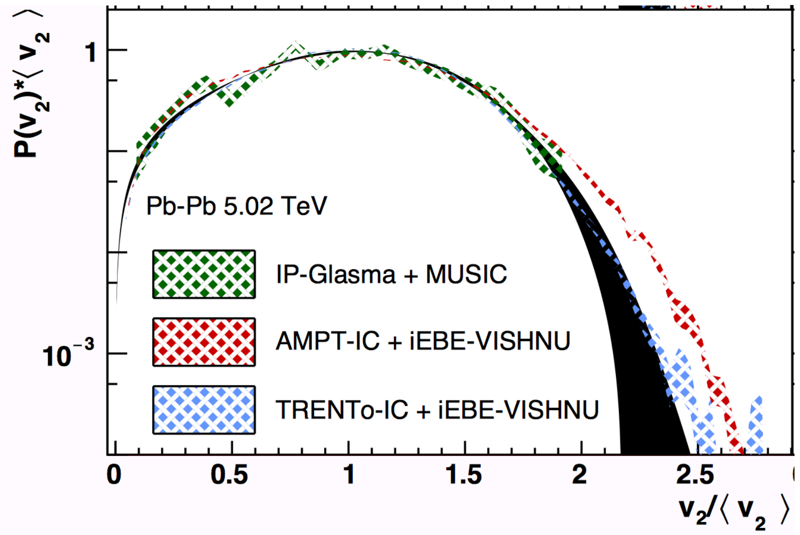
M. Li etc, PRC104, 024903

Probe P(ε_n)

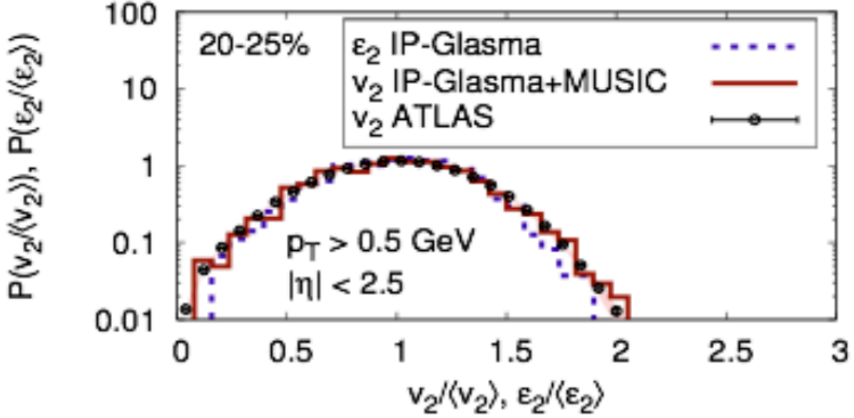
$v_n\{m\}$ → Moments → $p(v_n)$ → $p(\varepsilon_n)$







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



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

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

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

if $v_n \propto \varepsilon_n$ or $v_n = \kappa * \varepsilon_n$

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

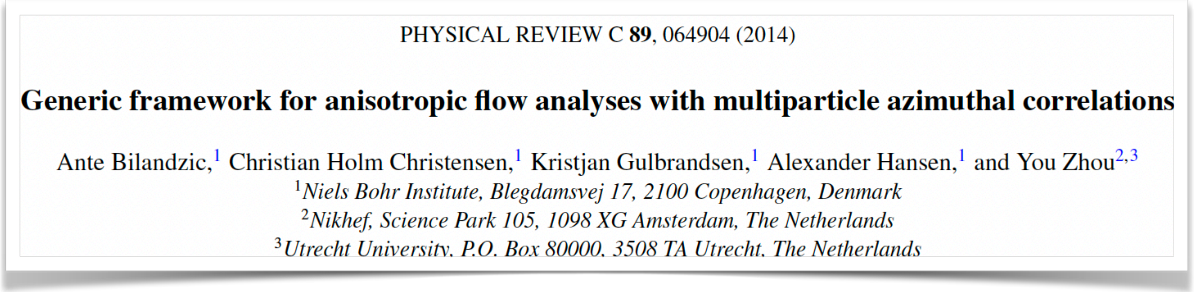
❖ Investigating p(v_2) with multi-particle cumulants

- 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:

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



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

Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations

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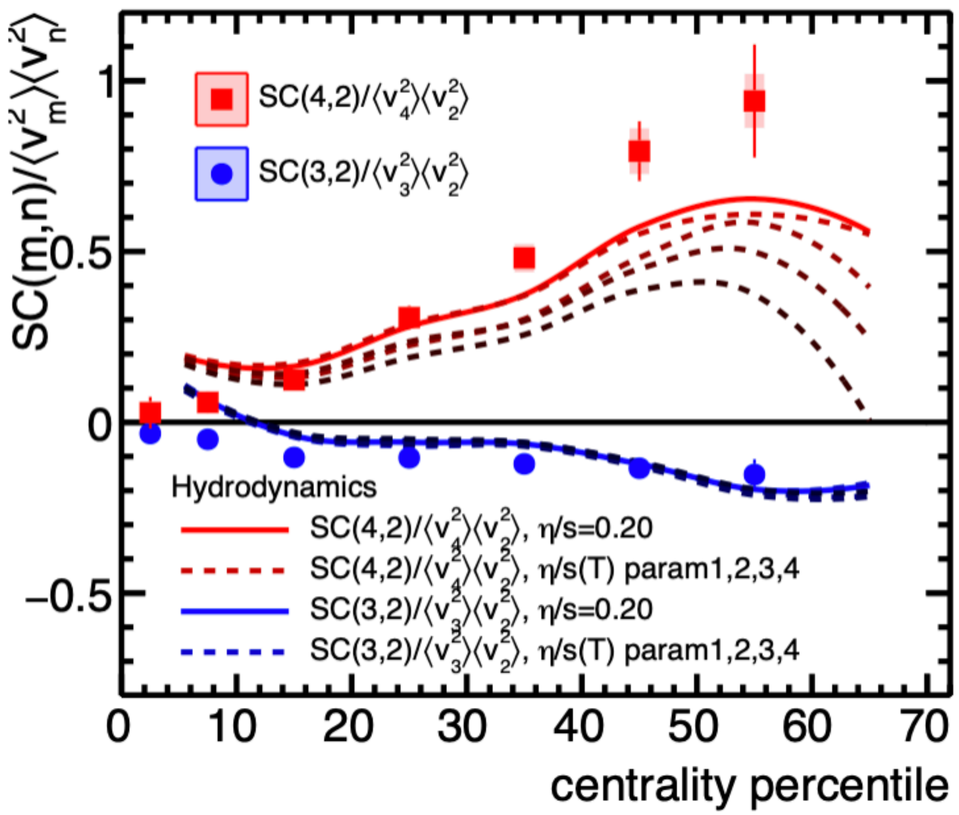
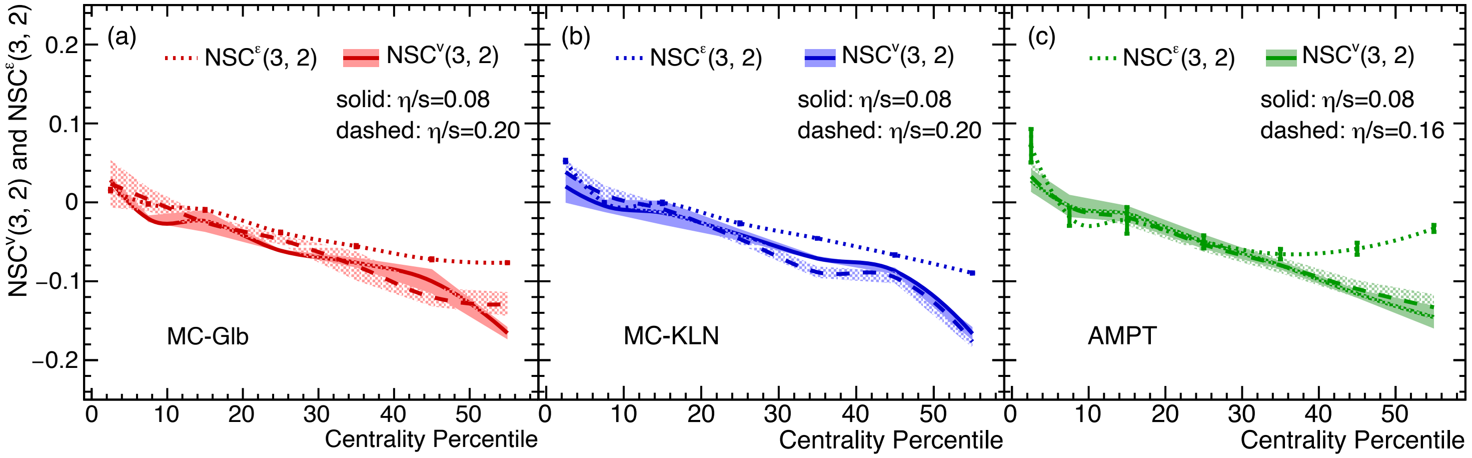
[1] *Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[2] *Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3] *Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

ALICE, PRL117, 182301 (2016)



X. Zhu etc, PRC95, 044902 (2017)



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

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

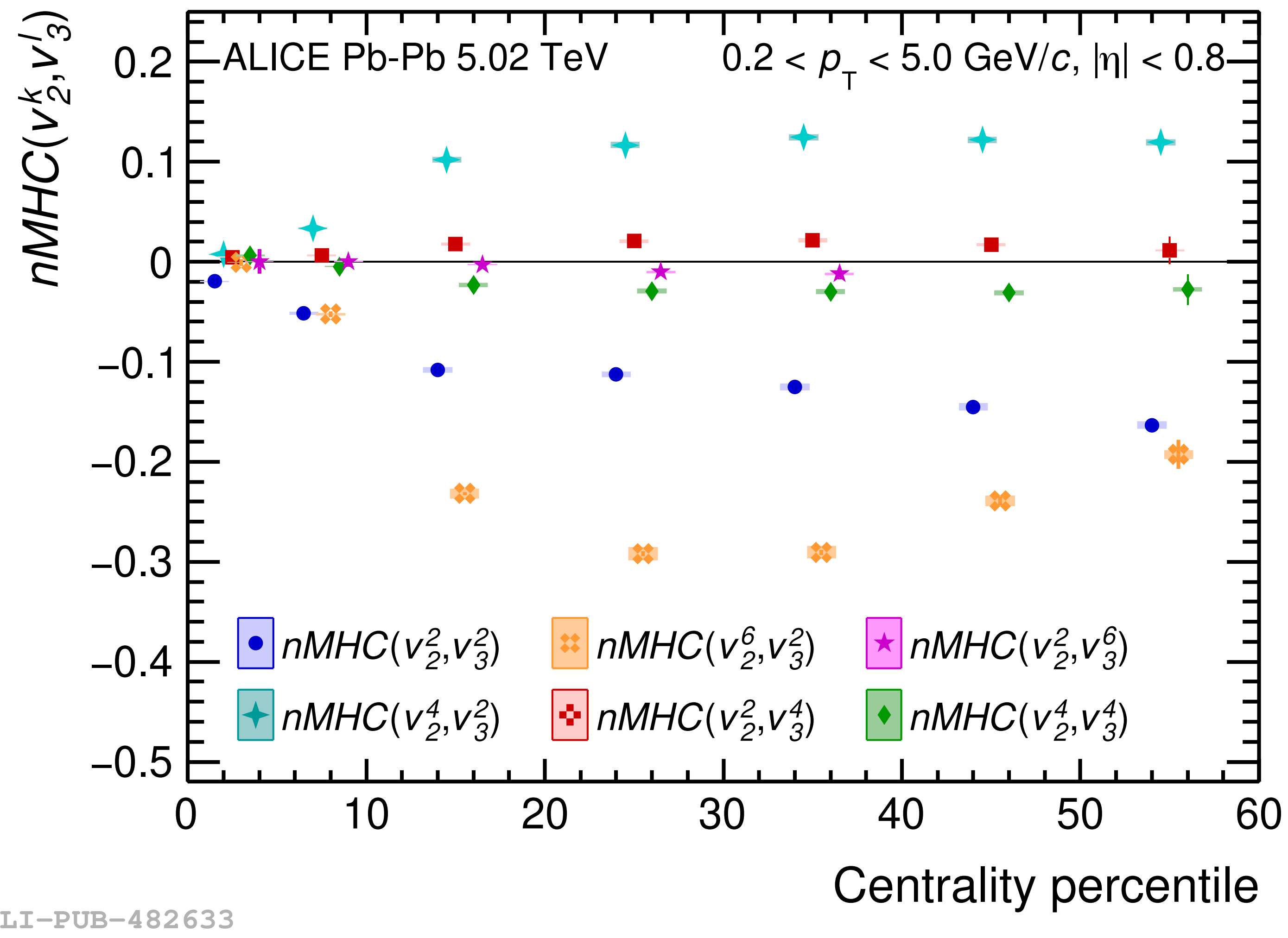
$NSC^{v}(3,2)$ $NSC^{\varepsilon}(3,2)$

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

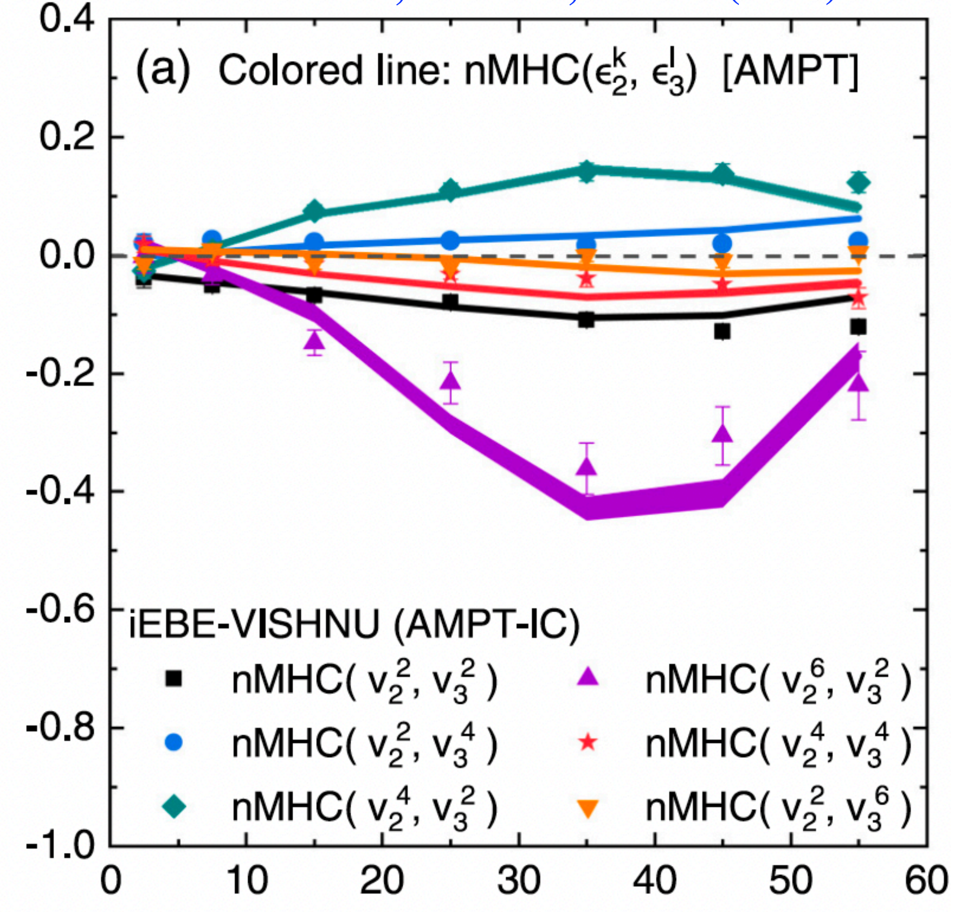
- NSC(3,2) measurements provide direct access into the initial conditions (despite details of systems evolution)
- what is the general correlation between any order of v_n^k and v_m^p and the correlations among multiple flow coefficients

Probe $P(\varepsilon_n^k, \varepsilon_m^p)$

ALICE, PLB818 (2021) 136354



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, $[p_{\rm T}]$
- correlation between v_n and $p_{\rm T}$ -> Initial geometry and fluctuations of shape and size

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

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

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

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

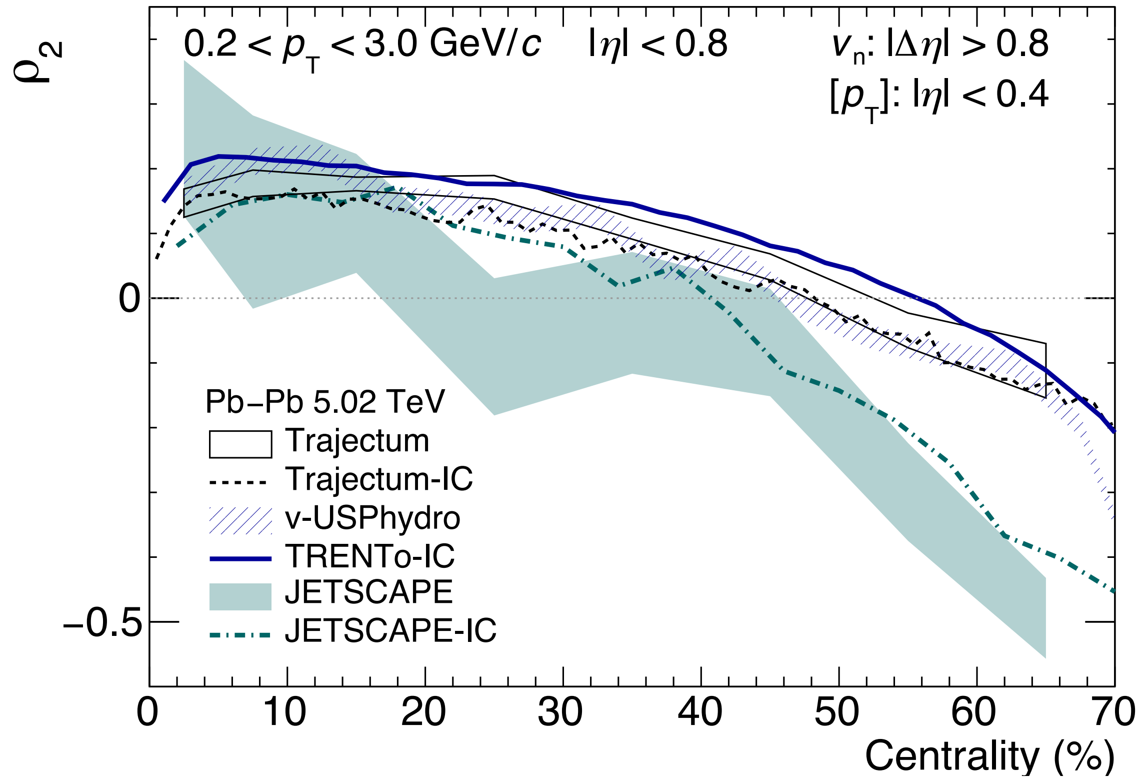
$$= v_n\{2\}^4 - v_n\{4\}^4$$

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

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

JETSCAPE, PRL126, 242301 (2021)
Privation communication

Trajectum, PRL126, 202301 (2021)
Privation communication



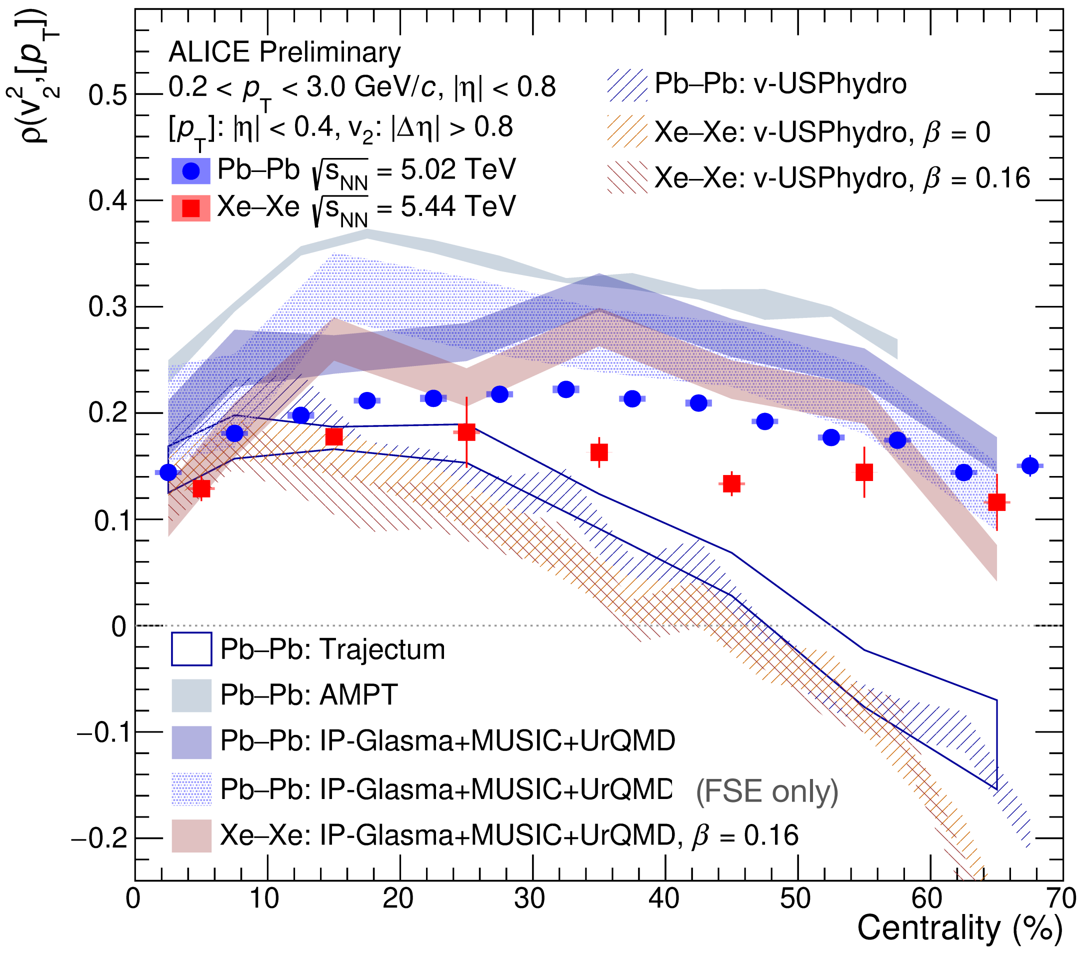
Characterizing the initial conditions

☆ Initial geometric distributions;

☆ Initial momentum anisotropy;

☆ Nuclear structure

ρ_2 in Pb-Pb



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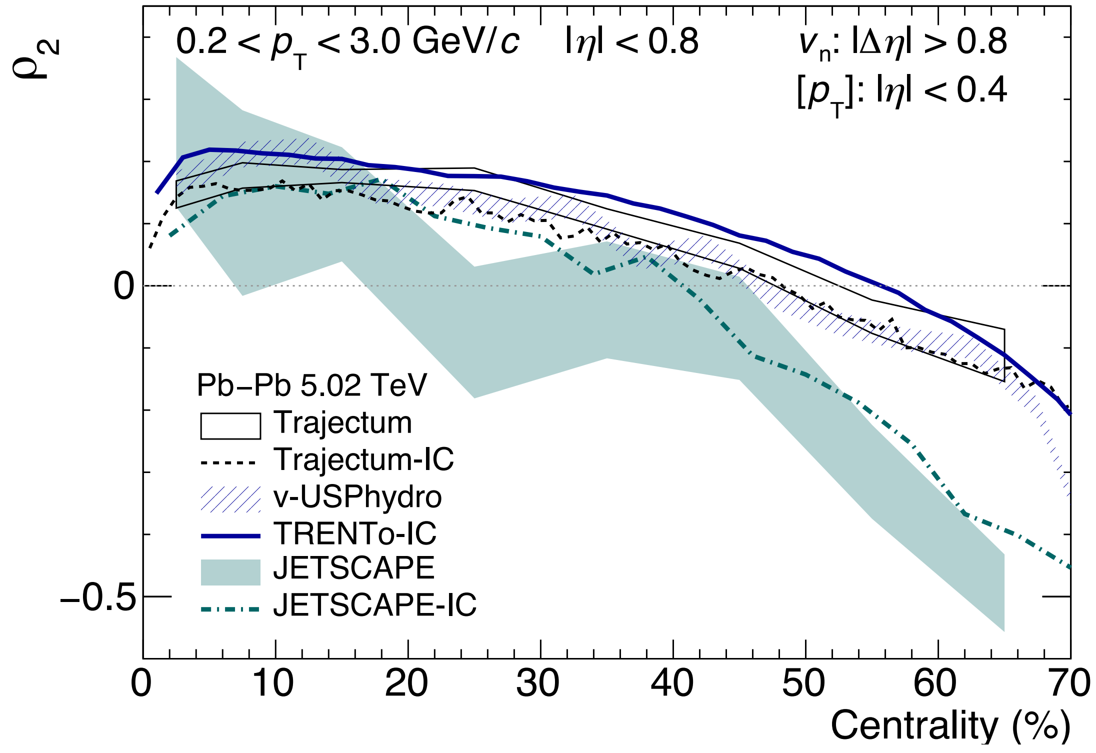


JETSCAPE, PRL126, 242301 (2021)
Privation communication

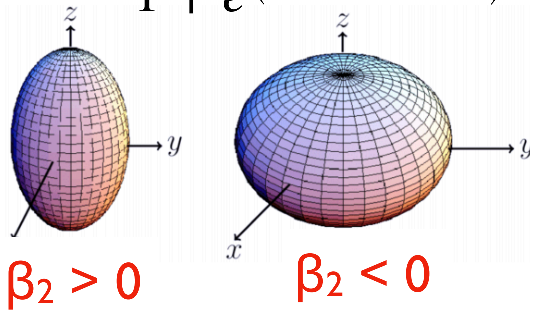
Trajectum, PRL126, 202301 (2021)
Privation communication

v-USPhydro, PRC103 (2021) 2, 024909

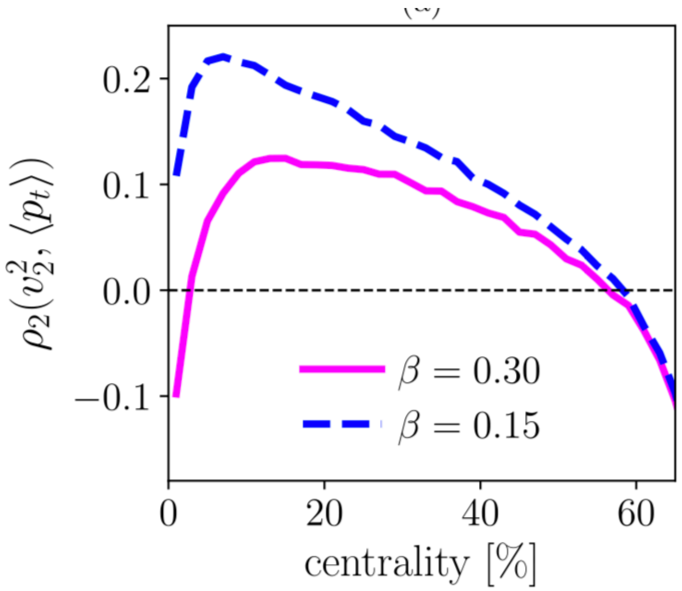
- ❖ IP-Glasma-IC: IP-Glasma+MUSIC+UrQMD slightly overestimate the Pb-Pb data
- ❖ TRENTo-IC based calculations show strong centrality dependence, negative values for centrality >40%
  - v-USPhydro, Trajectum, JETSCAPE
- ❖ The difference is from the initial stage: geometric effects or initial momentum 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

ρ_2 in Xe-Xe

$$D_{WS} = \frac{D_0}{1 + e^{(r - R_0(1+\beta Y_{20}))/a}}$$

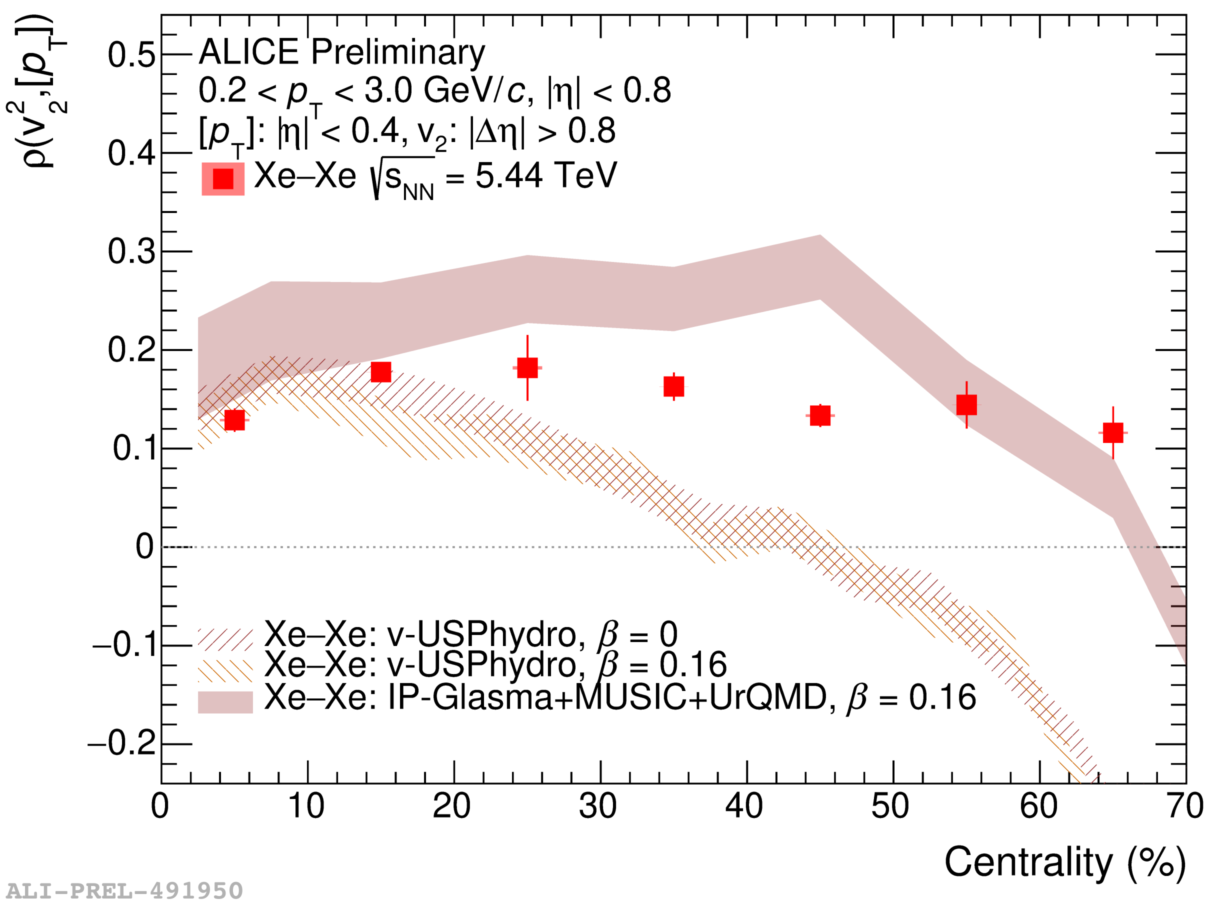


Pb—Pb: $\beta \approx 0$
Xe—Xe: $\beta \approx 0.16$



G.Giacalone, PRC 102 024901 (2020)

v-USPhydro, PRC103 (2021) 2, 024909

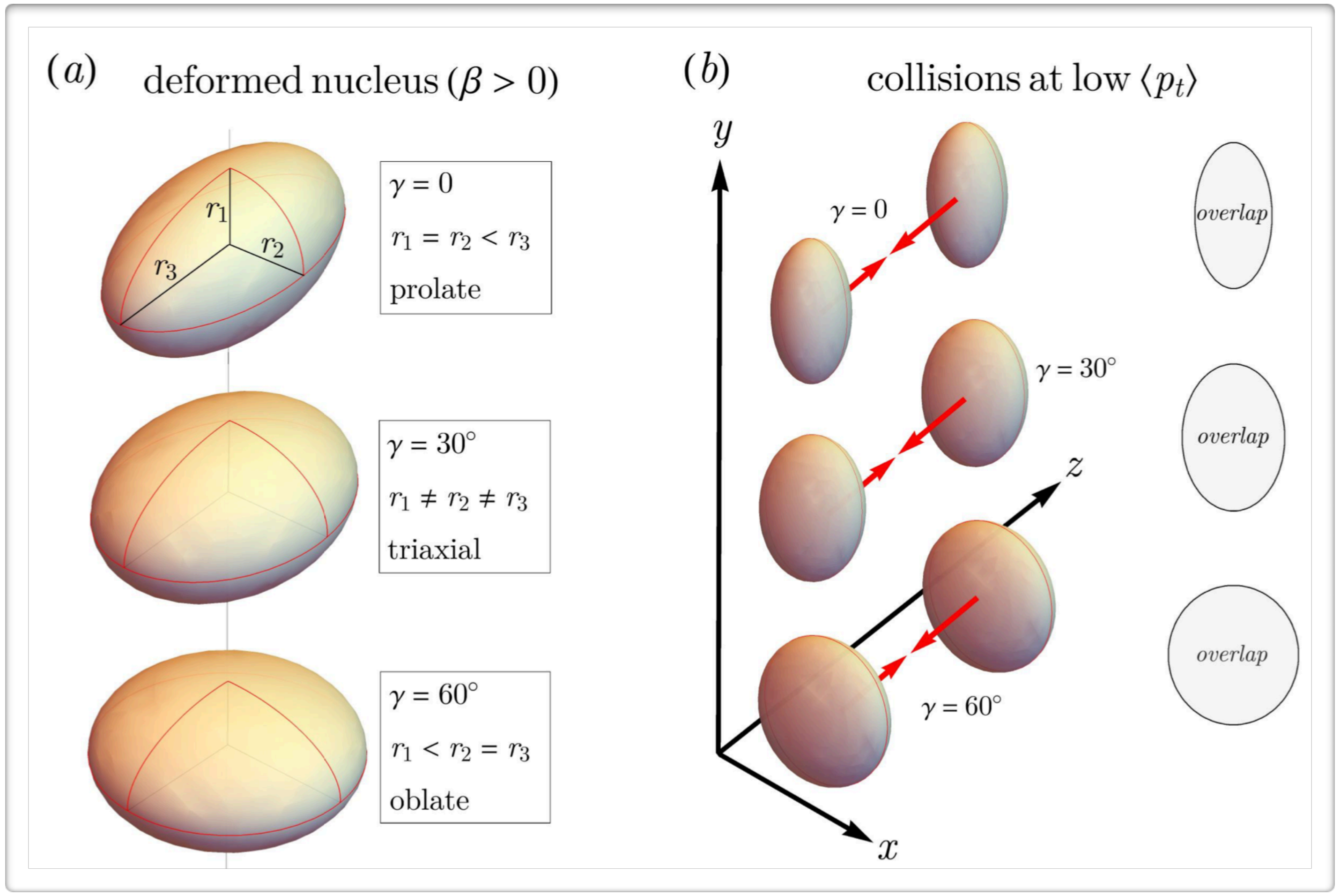


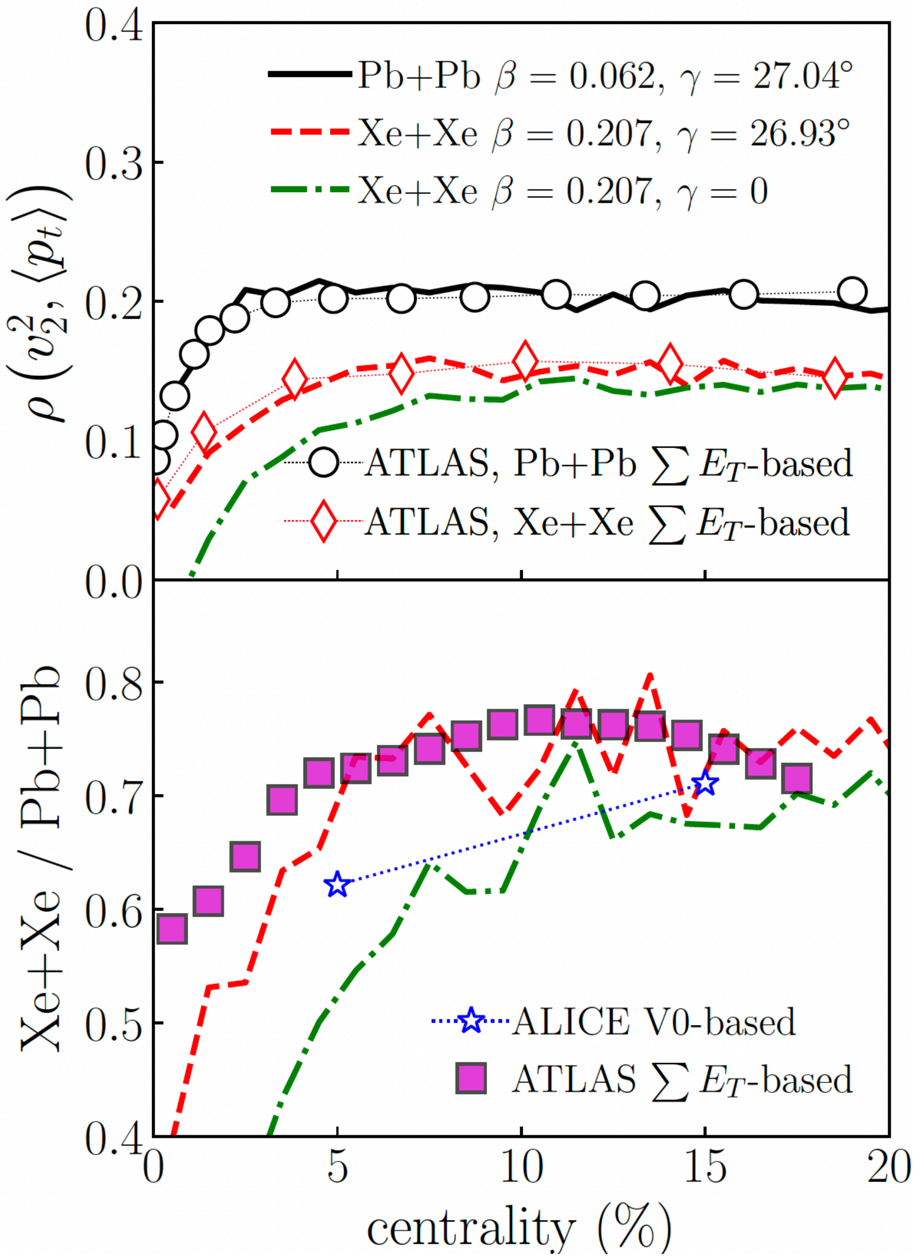
ALI-PREL-491950

- ❖ ρ_2 measurements in Pb-Pb are positive for the presented centrality range
  - Qualitatively reproduced by calculation with IP-Glasma IC
  - TRENTo-IC based calculation (v-USPhydro) has a strong centrality dependence and negative sign for centrality above 50%
- ❖ Significant differences of initial state calculations using different deformation parameter in central Xe-Xe collisions
  - ρ_2 is sensitivties to β_2
  - Better agreement with the calculation using $\beta_2 = 0.16$ (?)

Probe triaxial structure of Xe

B. Bally etc, arXiv:2108.09578



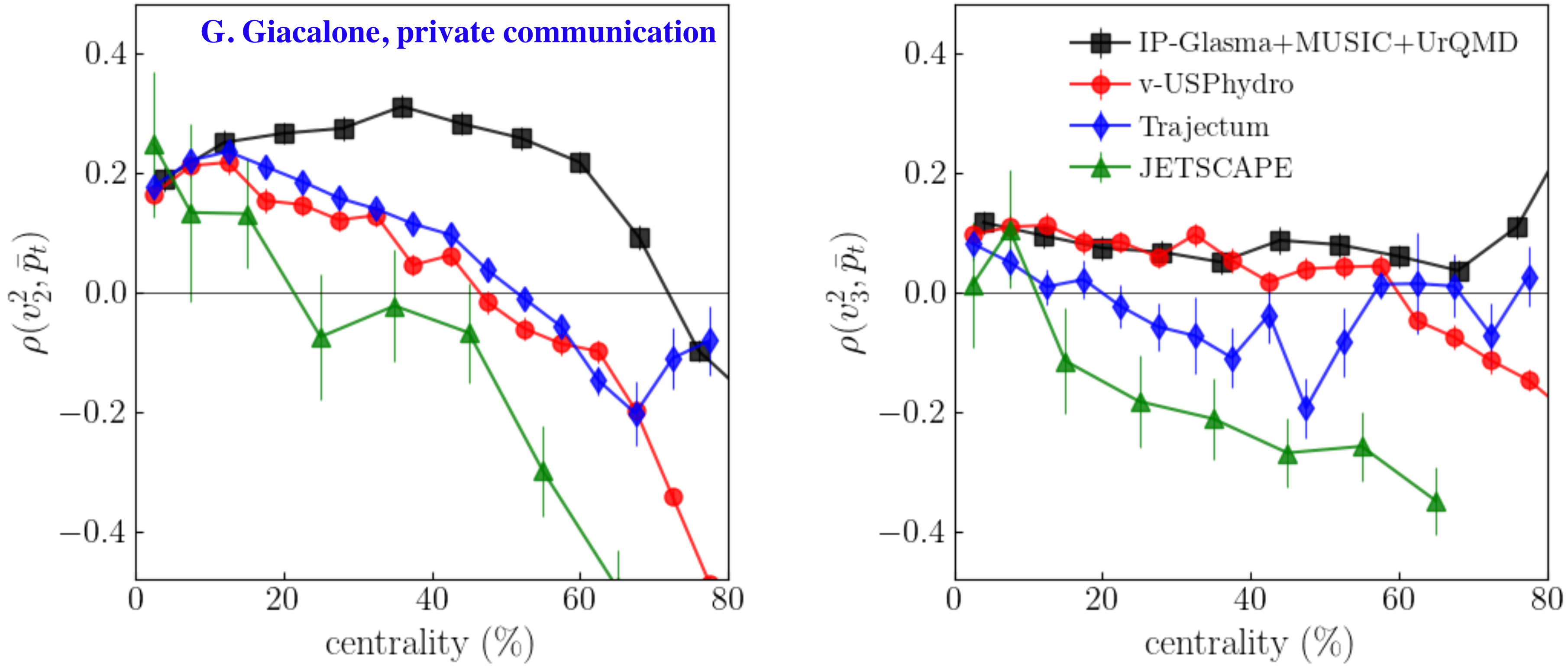


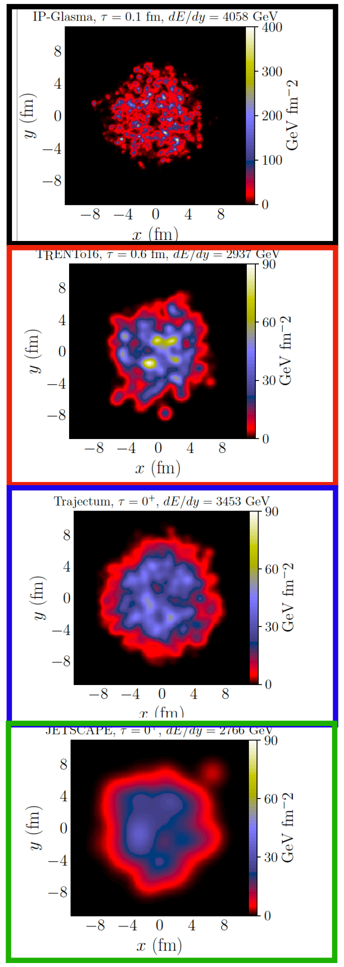
- ❖ Better agreement between ALICE measurements and calculations with γ = 26.93°
  - Indication of triaxial structure of Xe at high energy
  - New connection of high-energy heavy-ion physics to low-energy nuclear (structure) physics

Differences in IP-Glasma and TRENTo: potential explanations

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

- IP-Glasma ~ 0.3; v-USPhydro ~ 0.5; Trajectum~0.7; JETSCAPE (TRENTo) ~ 1.1
- w(IP-Glasma) < w(v-USPhydro)<w(Trajectum) < w(JETSCAPE)





w ~ 0.3

w ~ 0.5

w ~ 0.7

w ~ 1.1

❖ 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

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

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 geometric effects

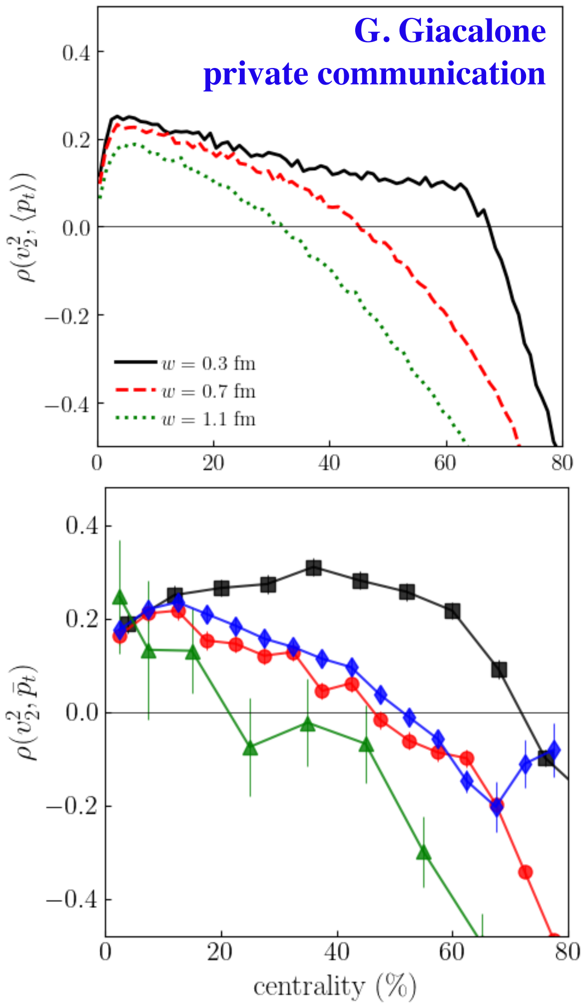
☆ **Initial momentum anisotropy:**

- The observed differences from different models are not originated from initial momentum anisotropy (IMA)
- Potential signal for ρ_3 in peripheral collisions and ρ_n in small systems, not yet conclusive in experiments.

☆ **Nucleon structure**

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

Backup


G. Giacalone
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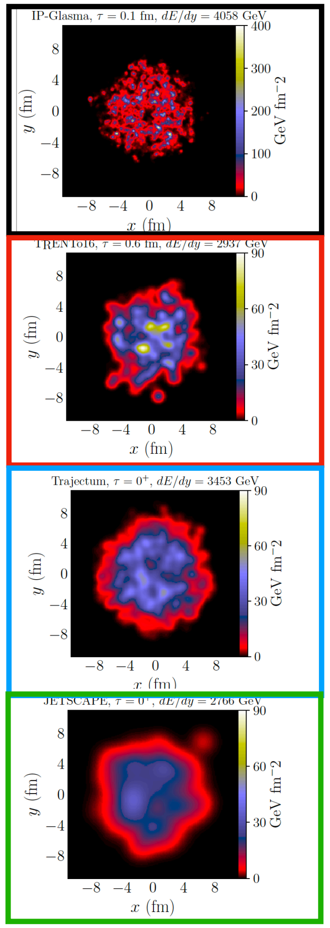
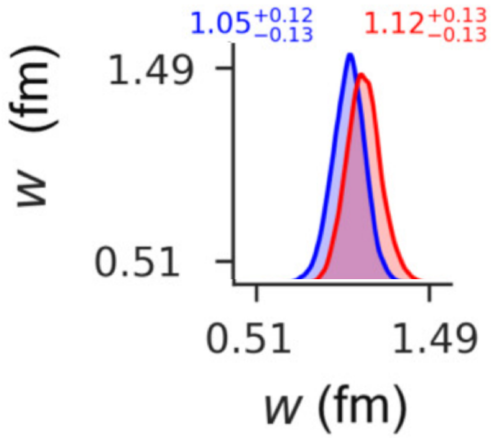
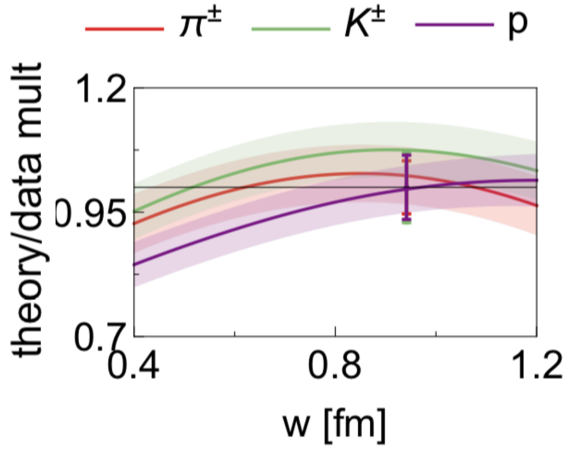


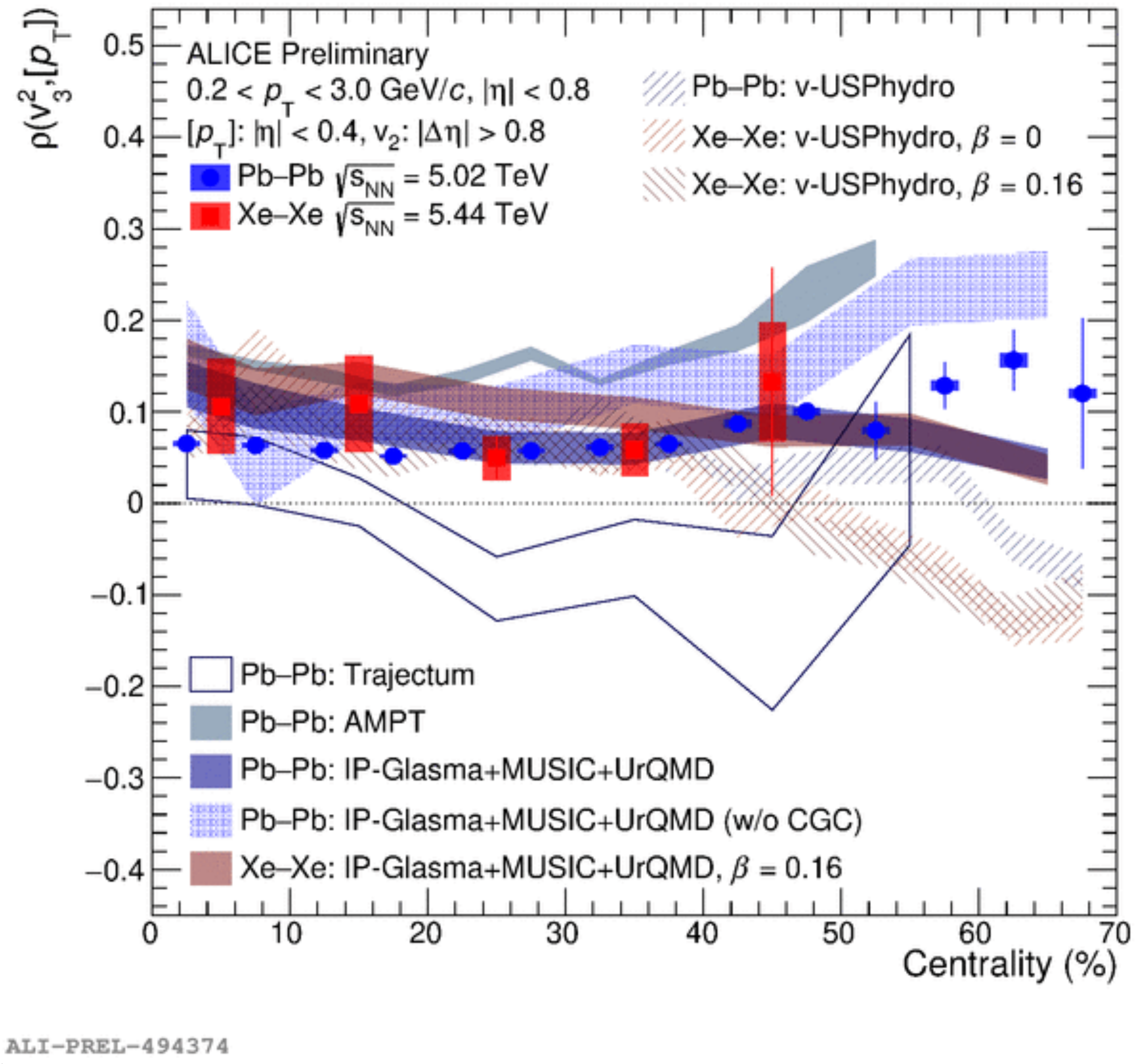
JETSCAPE, PRC103, 054904 (2021)



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?