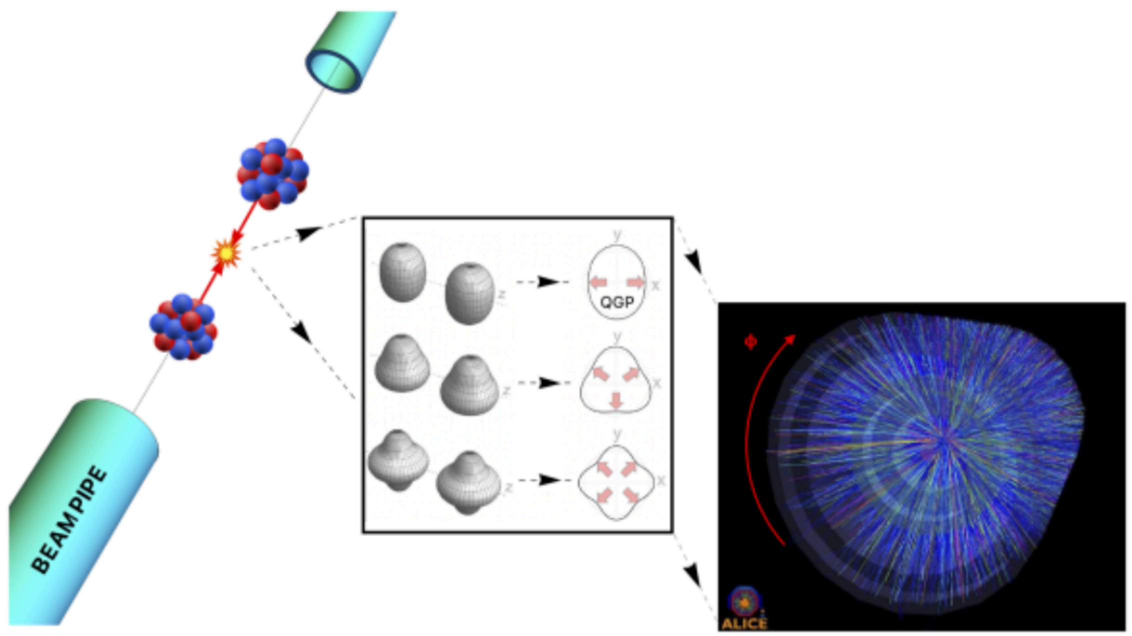
Accessing the initial conditions with multi-particle correlations

INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023



High-energy heavy-ion collisions producing a quark gluon plasma whose energy density profile reflects the collective structure of the colliding ions

You Zhou (周铀)

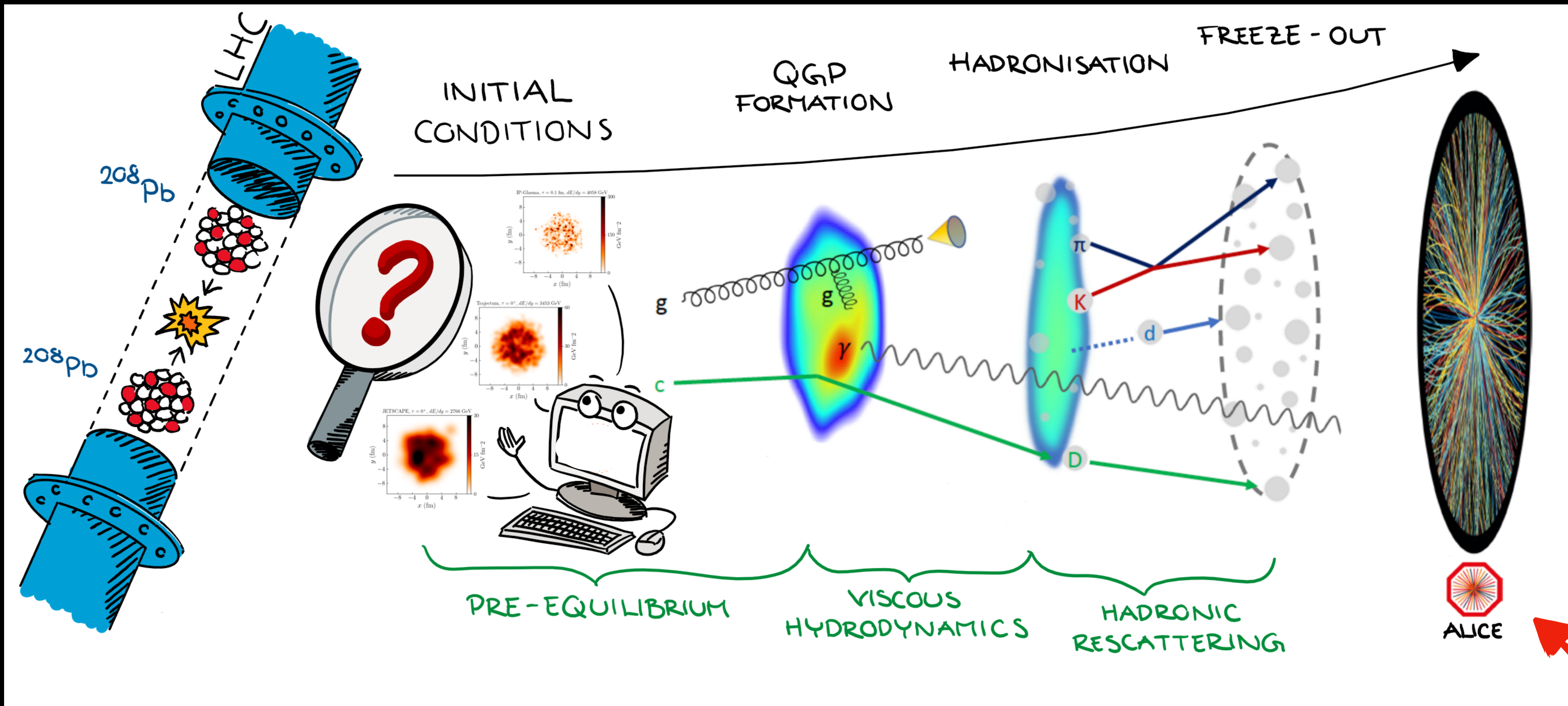
Niels Bohr Institute

UNIVERSITY OF COPENHAGEN

INDEPENDENT RESEARCH FUND DENMARK

THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

Evolution in the *Little Bang*



TH

IC → Hydro → Rescattering → Final

IC → Partonic/hadronic transport → Final

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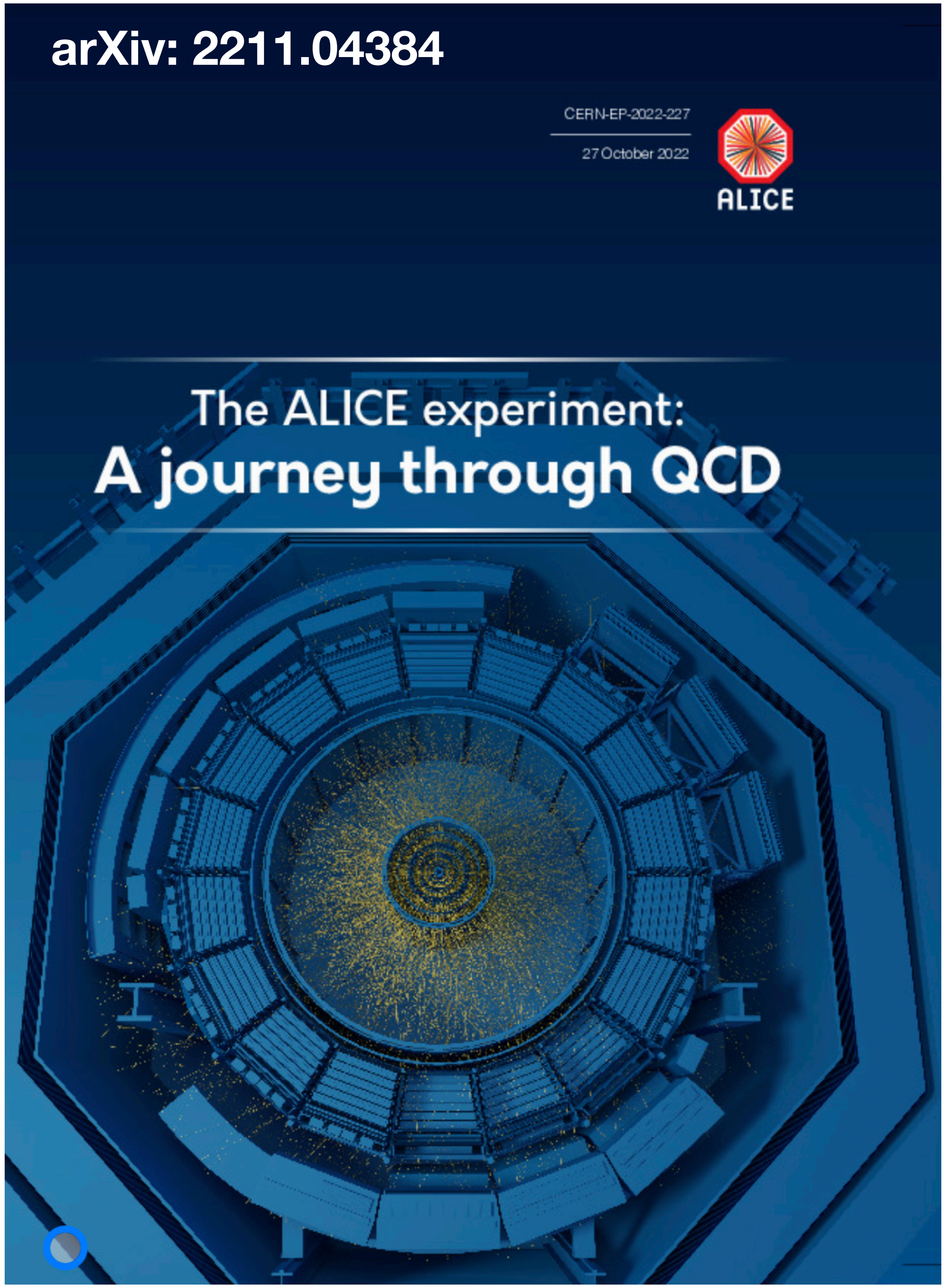
You Zhou (NBI) @ INT, Seattle

ALICE
the dedicated heavy-ion
experiments at the LHC



Current status of 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]

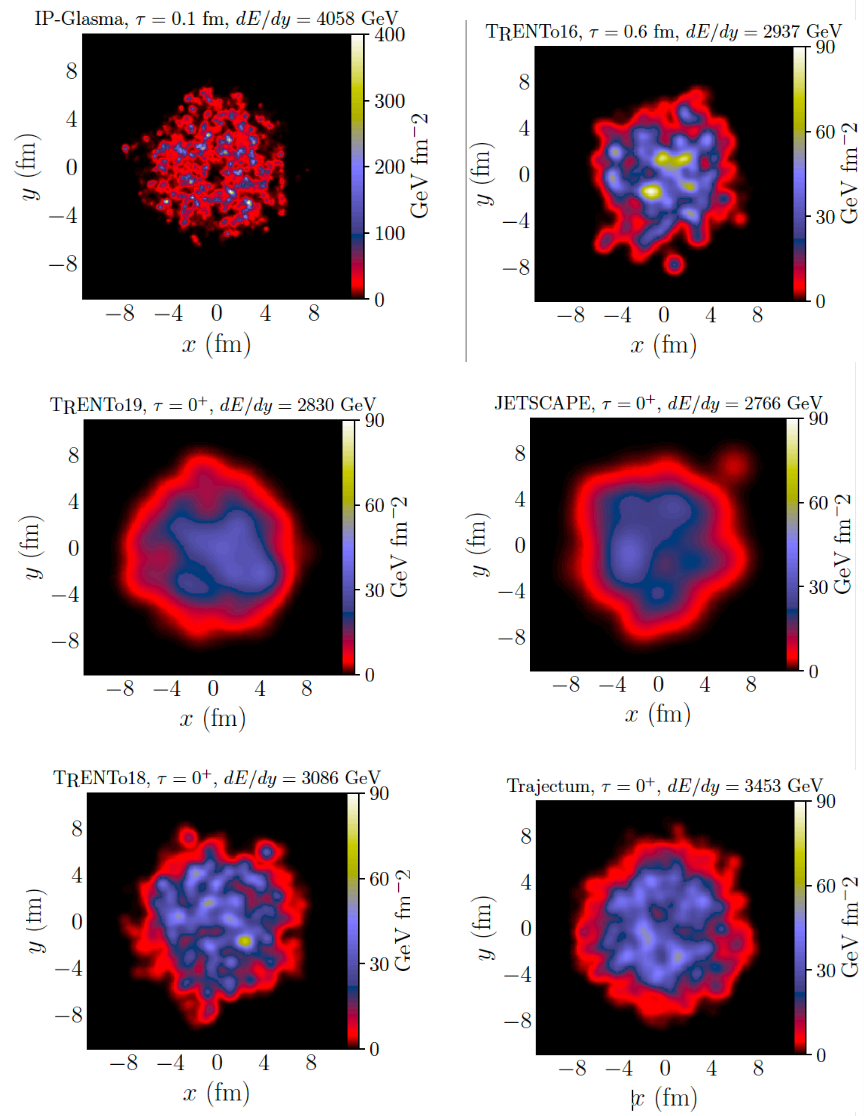
The Trento parametrization is now used for the energy density at tau=0+. There is no substructure. The nucleon width is now ~1fm. Very smooth profiles.

– **"bumpy" models: TRENTo 2018 and Trajectum**

[Bass, Bernhard, Moreland 1808.02106]

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

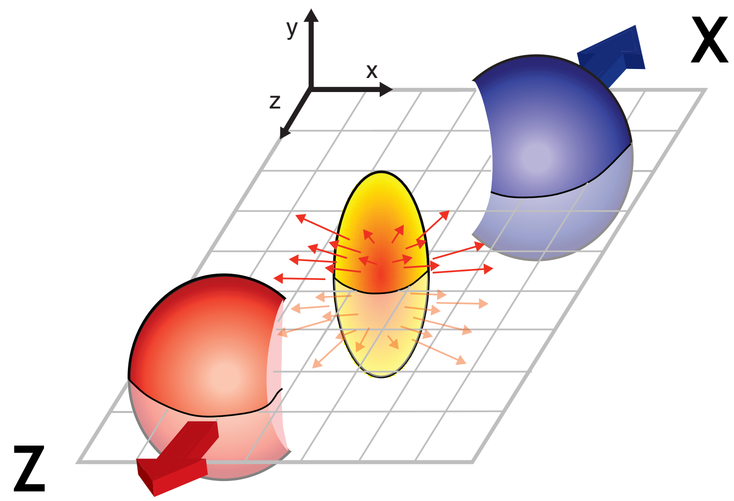
The Trento parametrization is the energy density at tau=0+. Substructure is included: 4-6 constituents with width ~0.4fm. Profiles with some lumpiness.



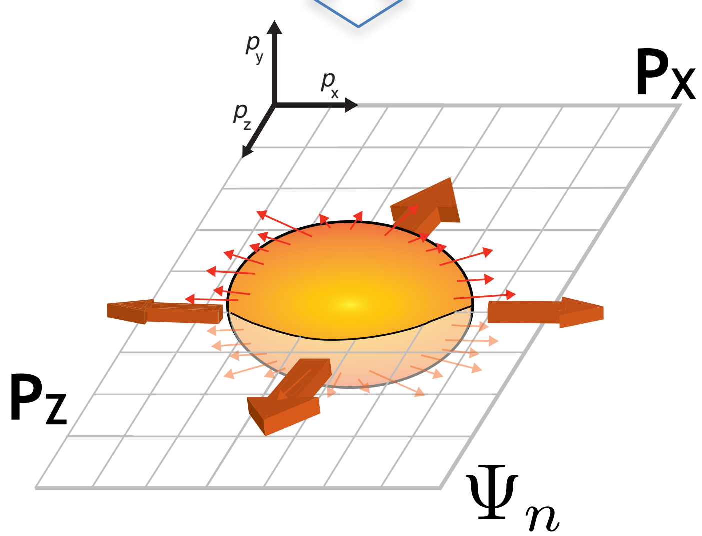
How can we access the initial conditions in EXP ?

Anisotropic flow

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



system expansion



Initial state

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

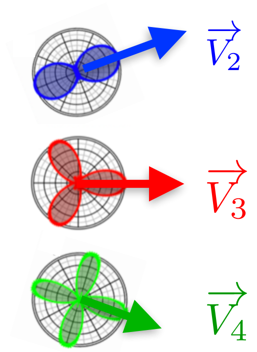
Initial spatial Anisotropy

Final state

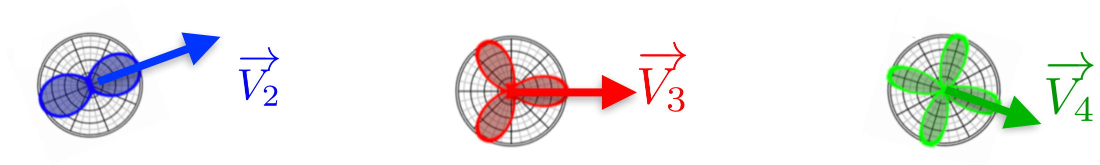
$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

momentum space Anisotropic Flow

$$\overrightarrow{V_n} = v_n \, e^{in\Psi_n}$$



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

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

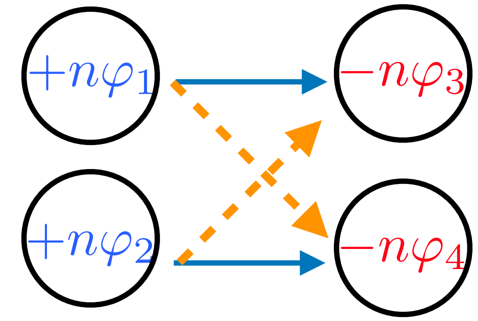
→ *Nonflow (resonance decay, jets etc)*

$$\delta_2 \sim 1/M$$

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

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

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

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

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

$$v_n\{2\} = \langle v_n^2\rangle^{1/2},$$

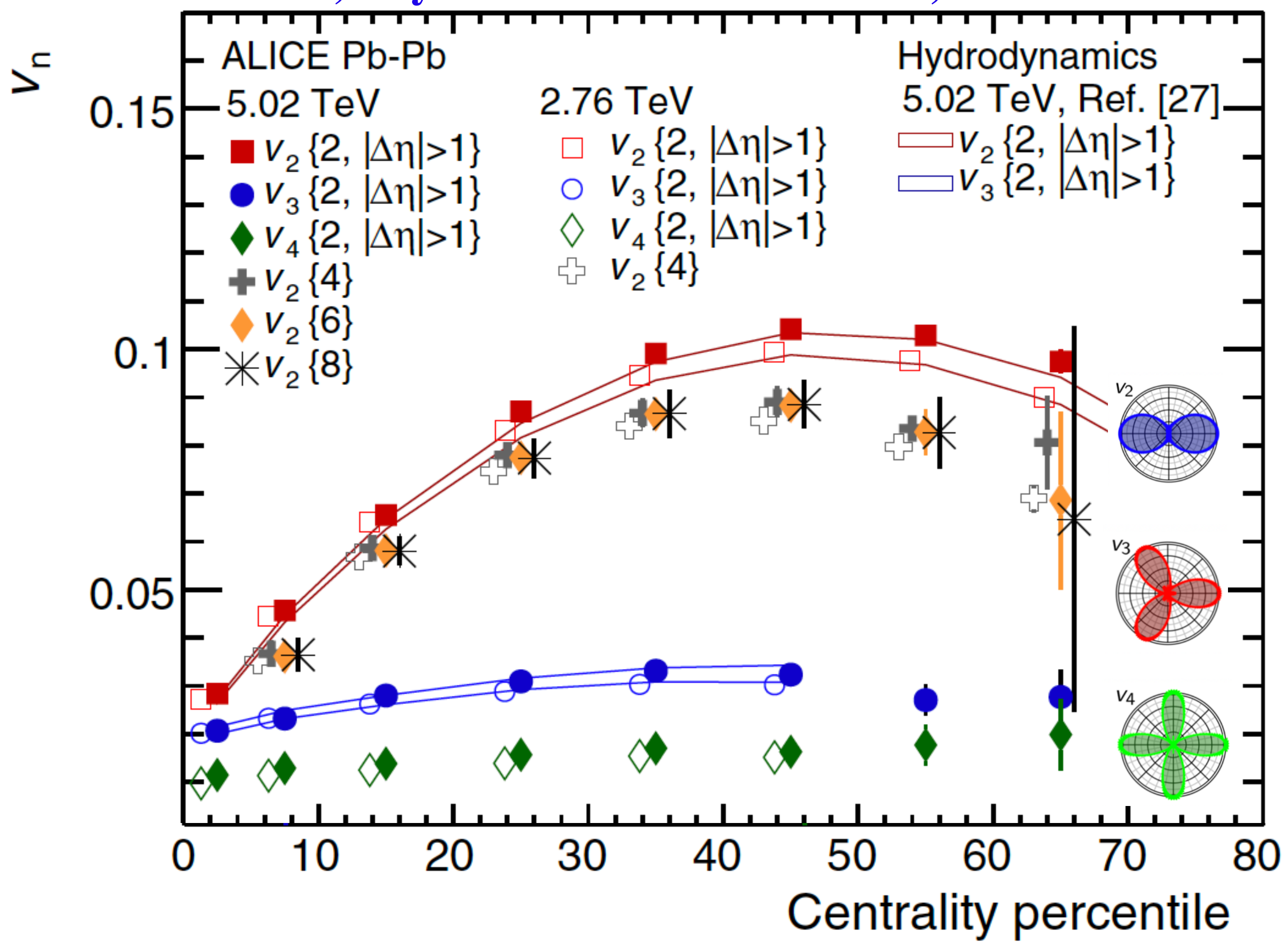
$$v_n\{4\} = \left[2\langle v_n^2\rangle^2 - \langle v_n^4\rangle\right]^{1/4},$$

$$v_n\{6\} = \left[(1/4)\cdot\left(\langle v_n^6\rangle - 9\langle v_n^4\rangle\langle v_n^2\rangle + 12\langle v_n^2\rangle^3\right)\right]^{1/6},$$

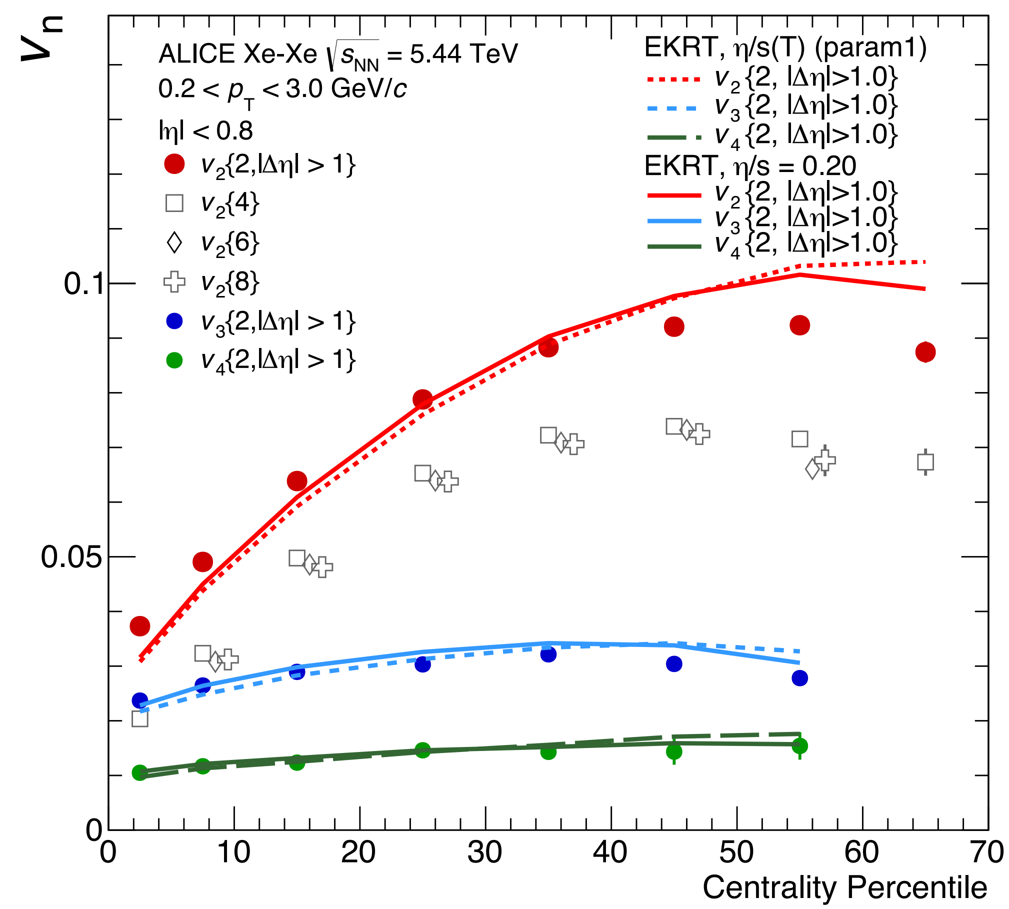
$$v_n\{8\} = \left[-(1/33)\cdot\left(\langle v_n^8\rangle - 16\langle v_n^6\rangle\langle v_n^2\rangle - 18\langle v_n^4\rangle^2 + 144\langle v_n^4\rangle\langle v_n^2\rangle^2 - 144\langle v_n^2\rangle^4\right)\right]^{1/8},$$

Anisotropic flow in Pb-Pb and Xe-Xe collisions

ALICE, Physical Review Letters 116, 132302



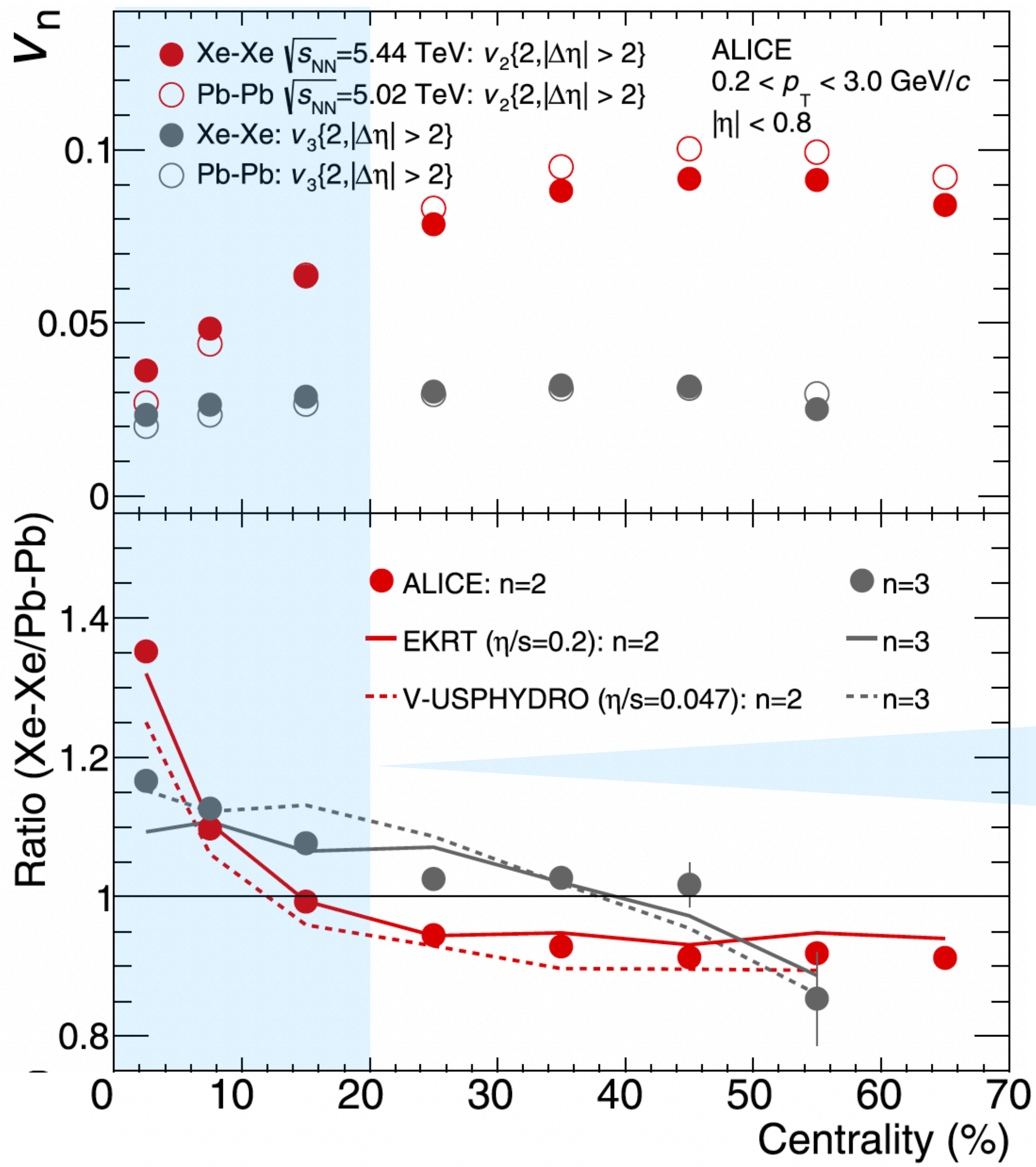
ALICE, Physics Letters B784 (2018) 82



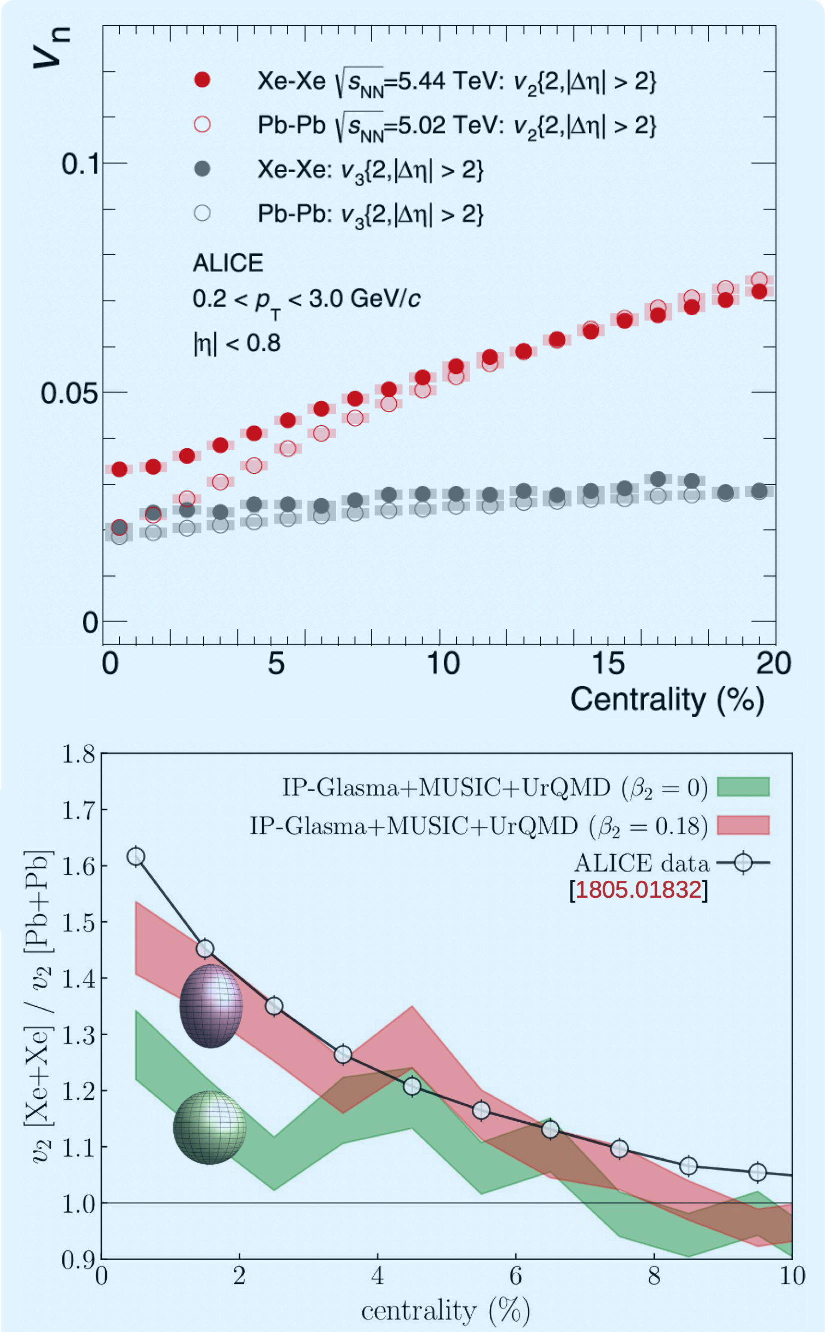
- Flow measurements at the top LHC energies agree with hydrodynamic predictions
  - **The Quark-Gluon Plasma behaves like a perfect fluid**

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



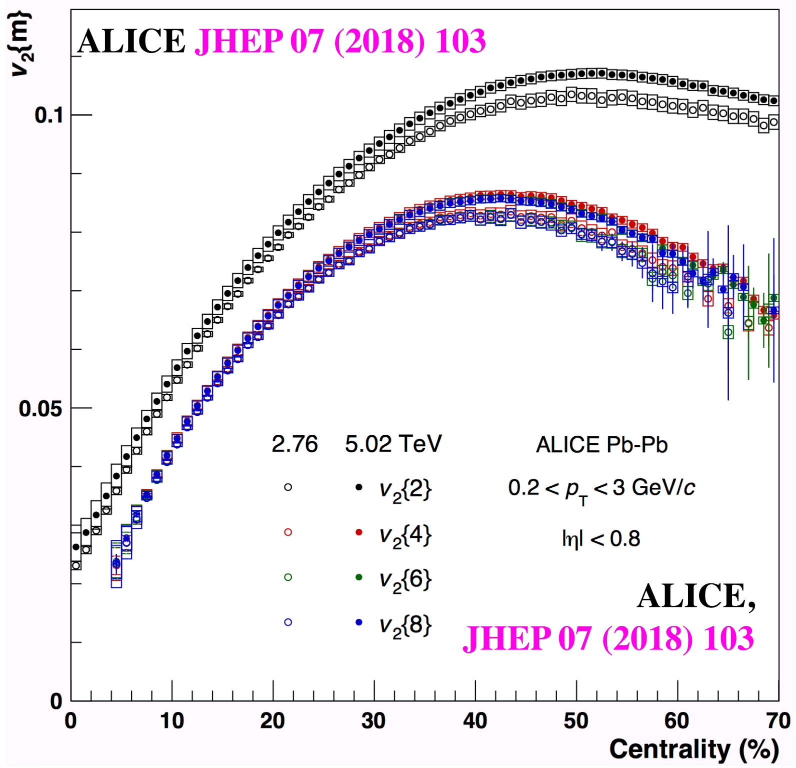
Zoom-in

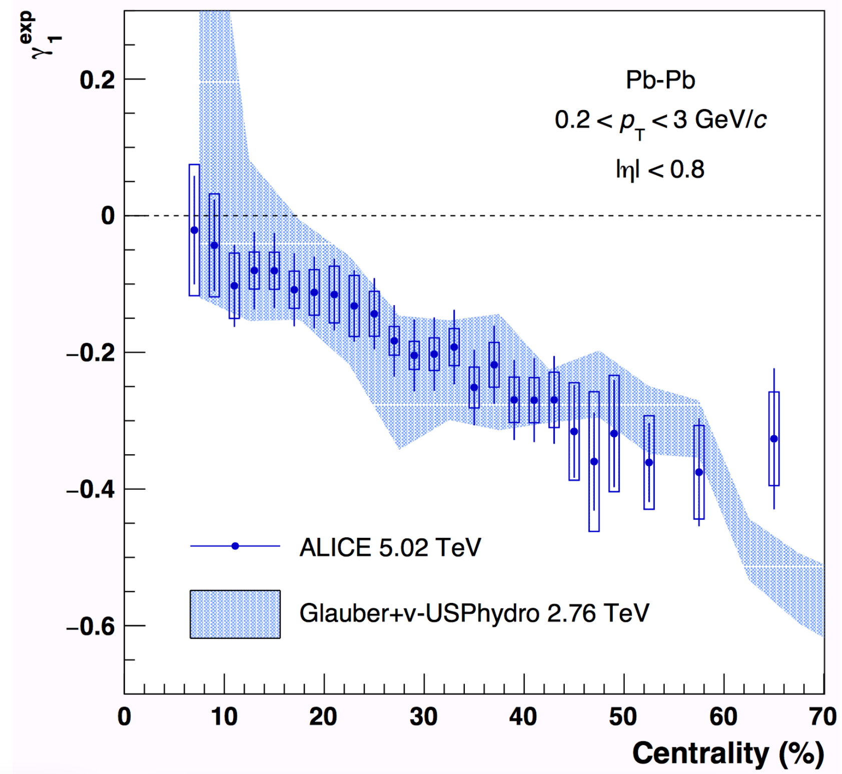


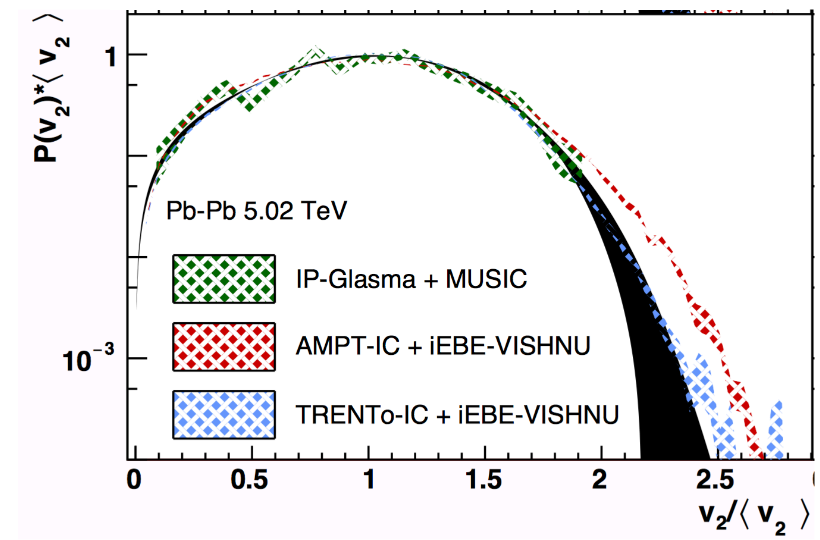
- Significant v_2 enhancement in central Xe-Xe collisions, originated from large deformation
- Help to constrain β_2

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

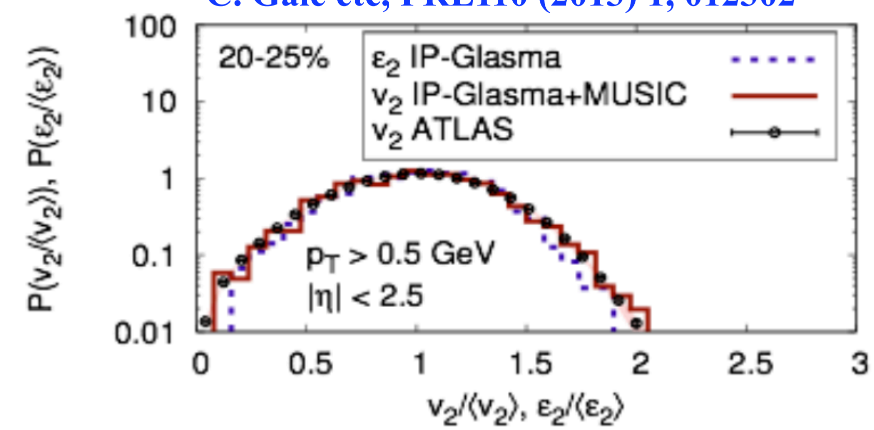
$v_n\{m\}$ → *Moments* → $p(v_n)$ → $p(\varepsilon_n)$







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



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

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

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

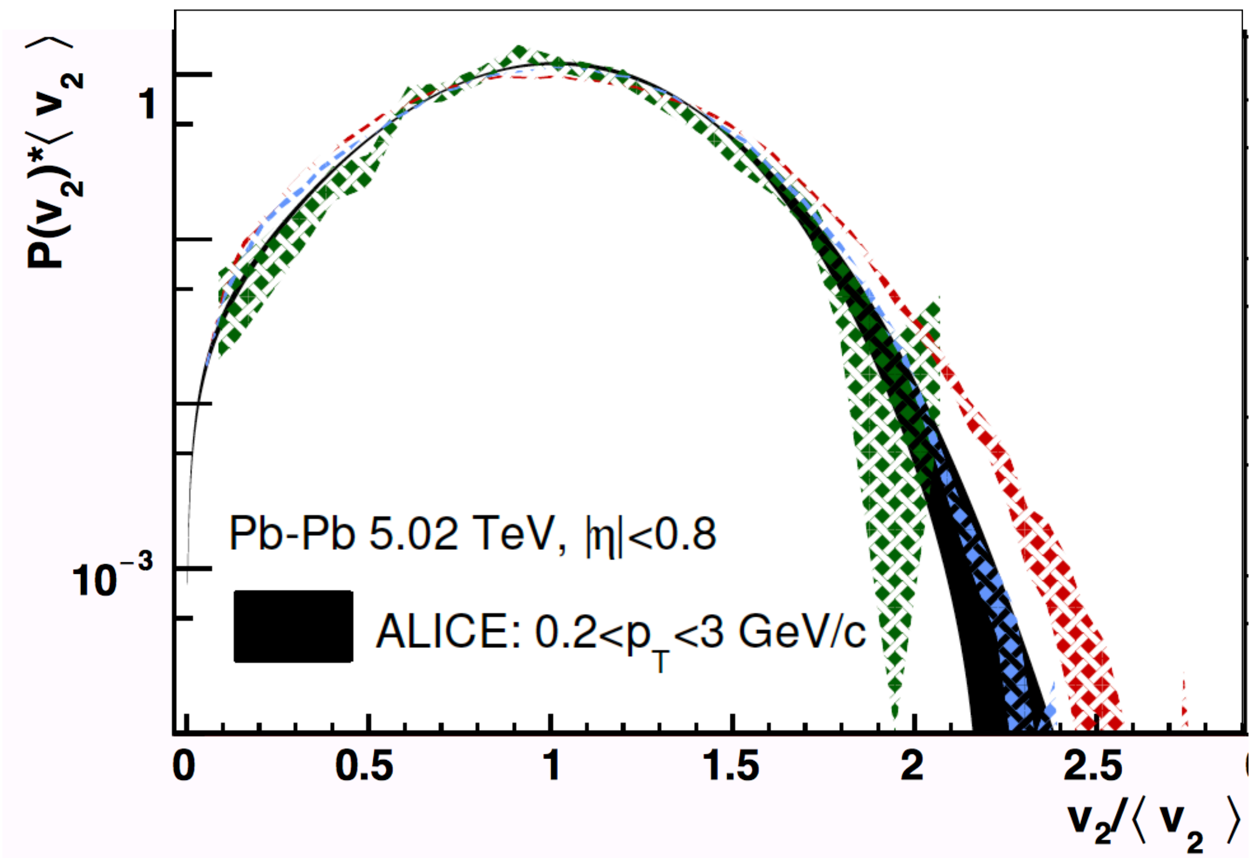
$$v_n \propto \varepsilon_n$$
$$P(v_n/\langle v_n\rangle) \approx P(\varepsilon_n/\langle\varepsilon_n\rangle)$$

❖ 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

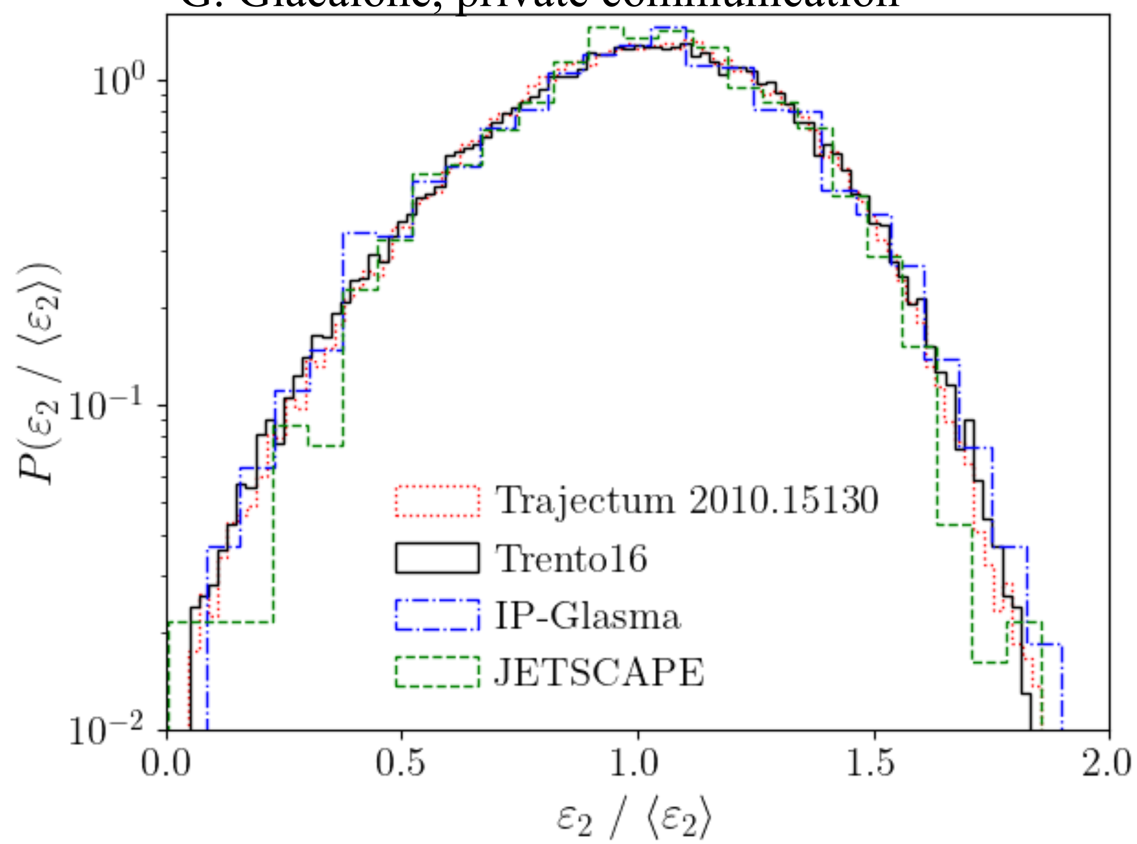
P(v_n) and P(ε_n), HOWEVER

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

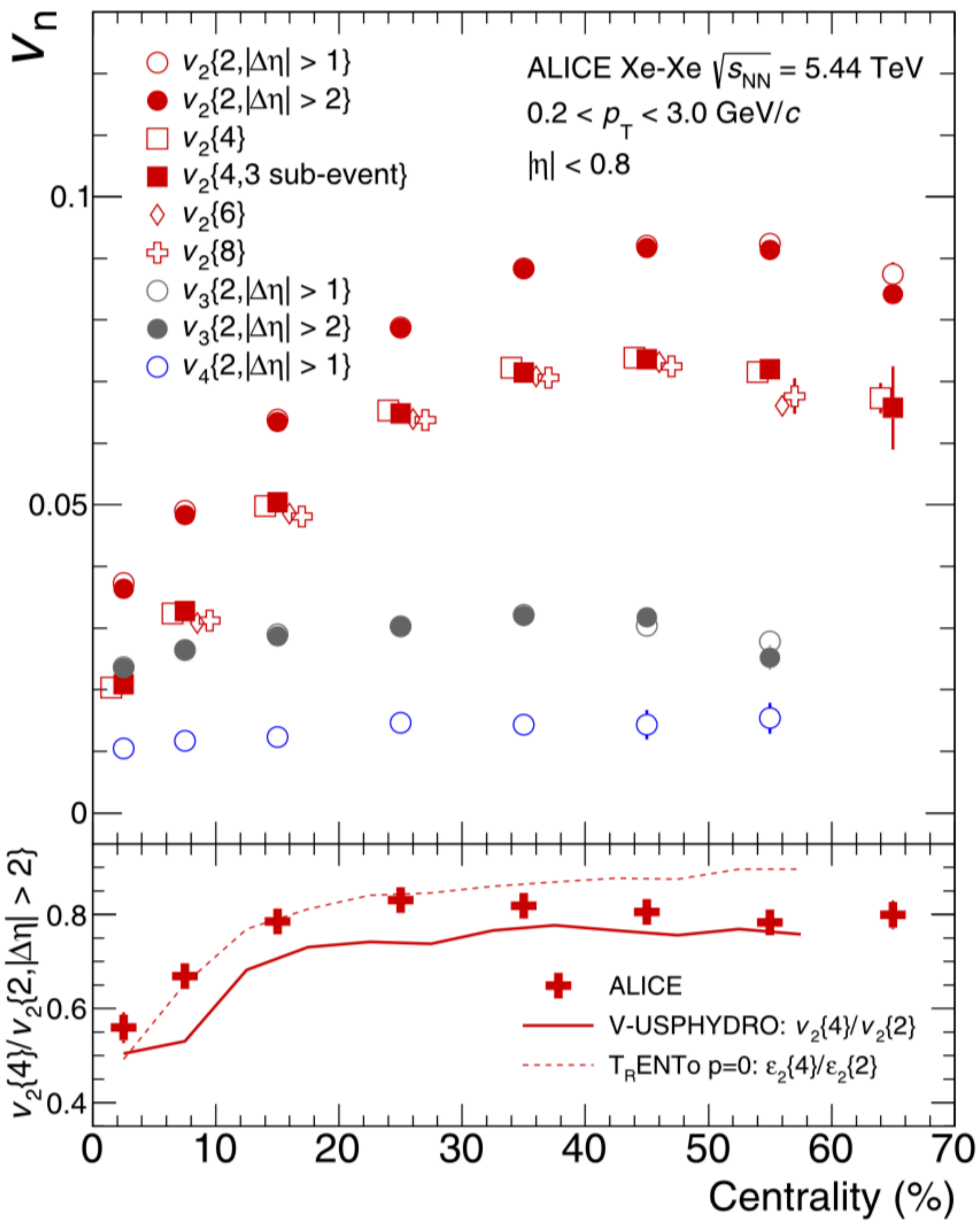


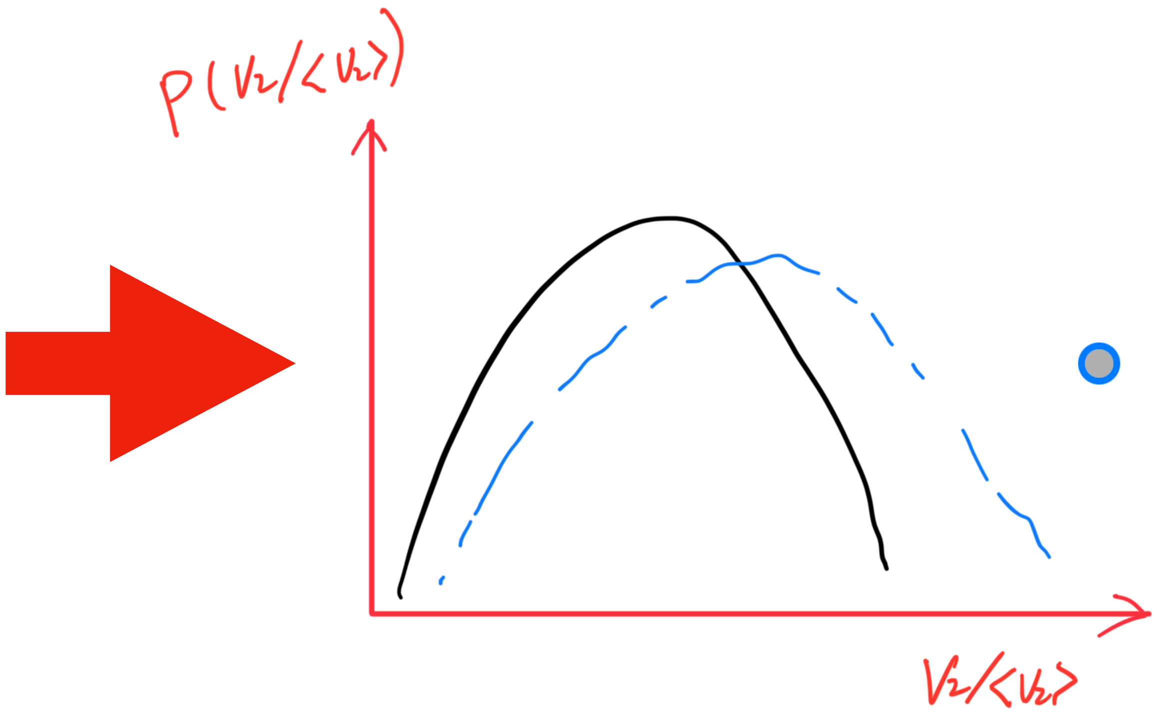
Minor difference from IC

G. Giacalone, private communication



❖ Despite the precision of experimental data (ALICE, ATLAS, CMS), the differences of P(ε_n) from various initial state models are minor

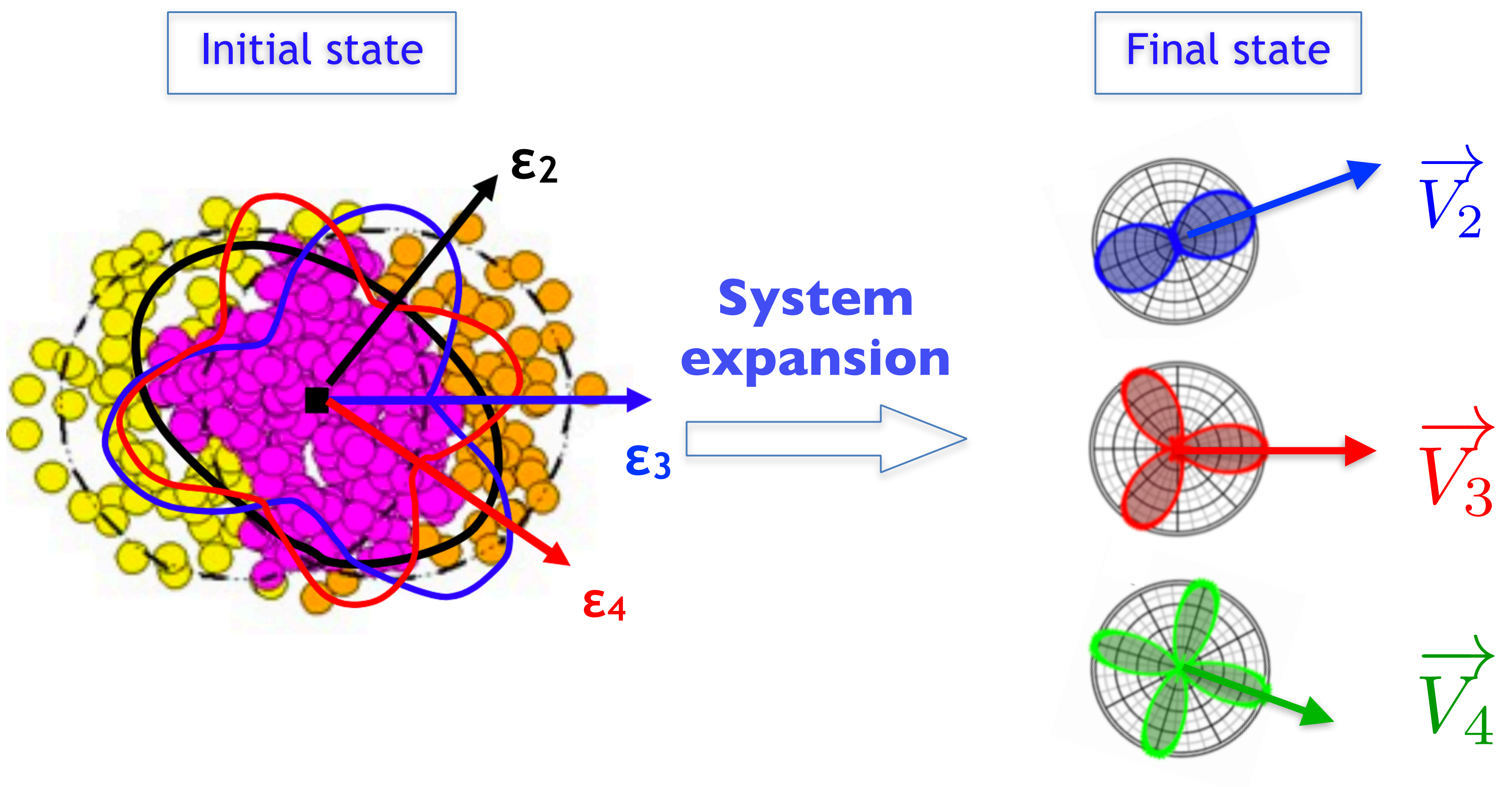




Question: do we see a difference in $p(e_2/\langle e_2\rangle)$ with different NS?

Question: it is argued that 3-particle correlations will be sensitive to the triaxial structure, then should we see a significant difference in $v_2\{6\}$ with and w/o triaxial structure?

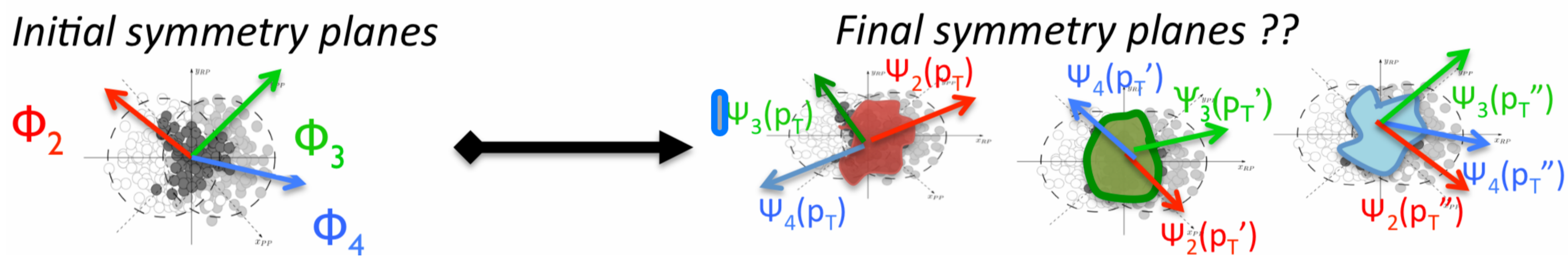
From initial anisotropy to anisotropic flow



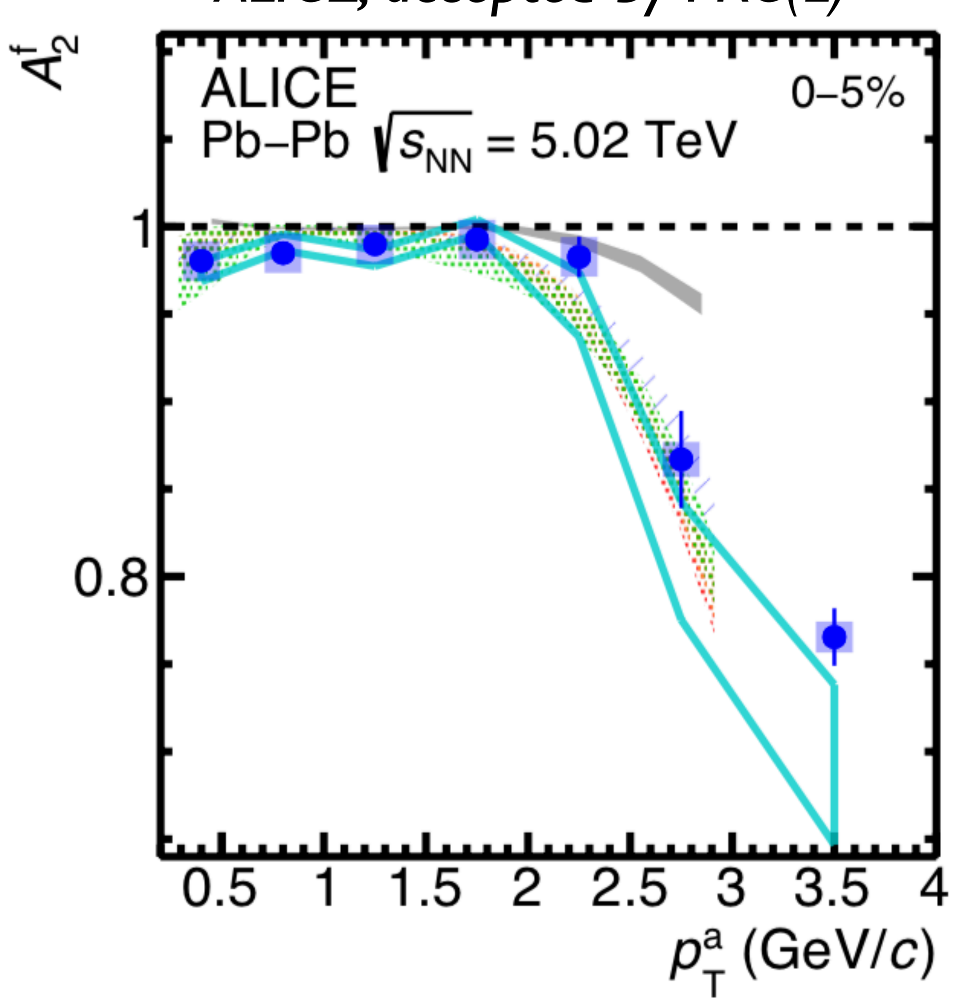
$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, ..., \Phi_m, \Phi_n, \Phi_k, ...)$ ⇒ $P(v_m, v_n, v_k, ..., \Psi_m, \Psi_n, \Psi_k, ...)$

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
$P(v_n)$	$P(\Psi_n)$	$P(v_m, v_n, v_k, ...)$	$P(\Psi_m, \Psi_n, \Psi_k, ...)$

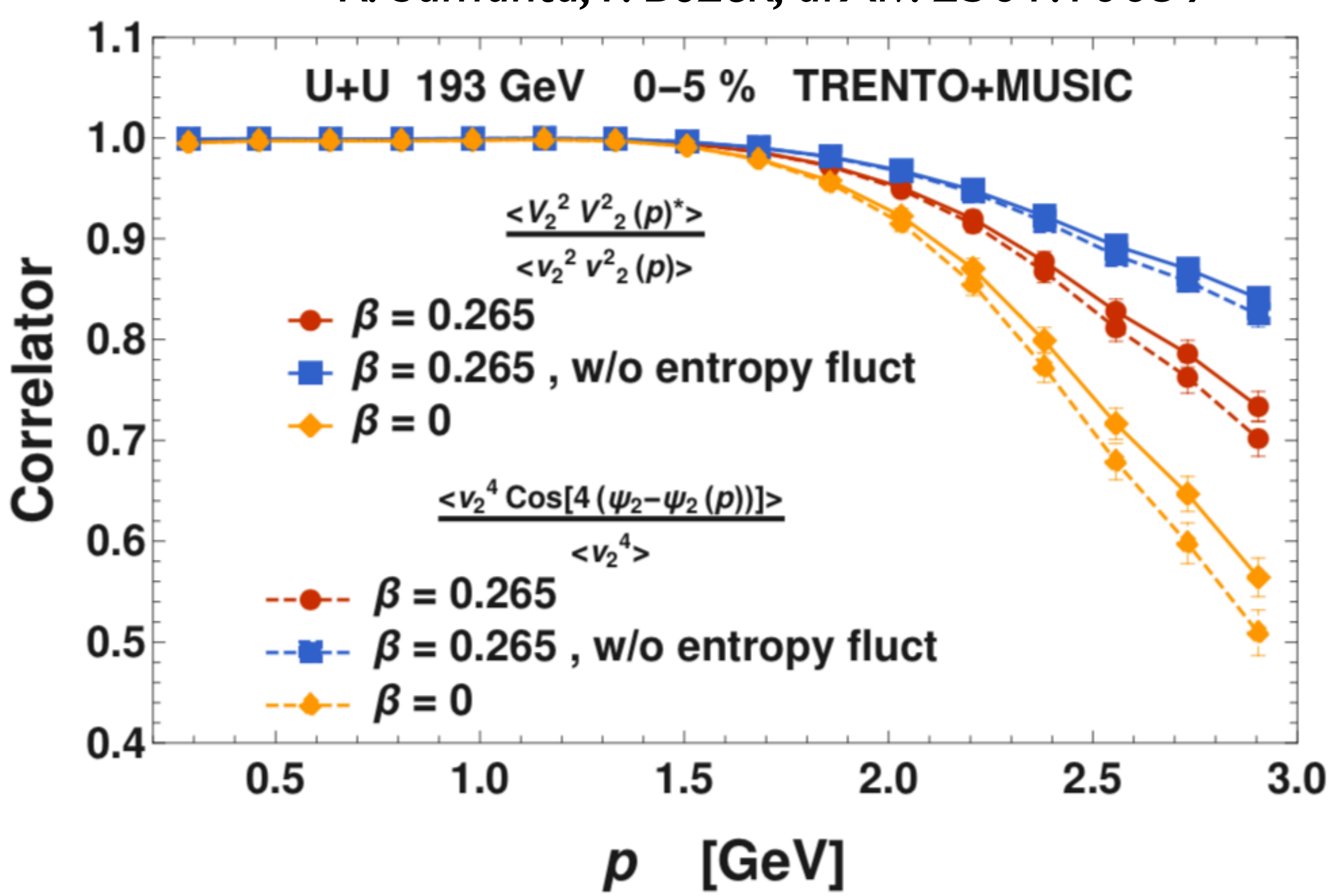
Flow decorrelation



ALICE, accepted by PRC(L)



R. Samanta, P. Bozek, arXiv: 2301.10659



(Normalized) Symmetric Cumulant

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) — 309 citations

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]
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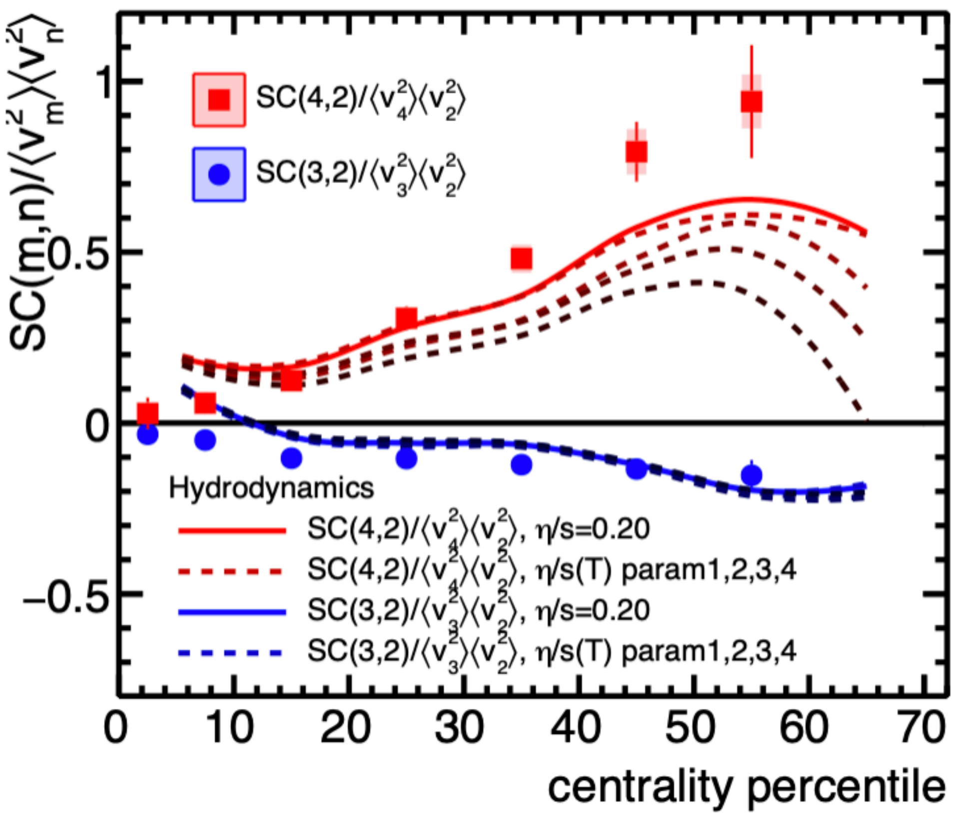
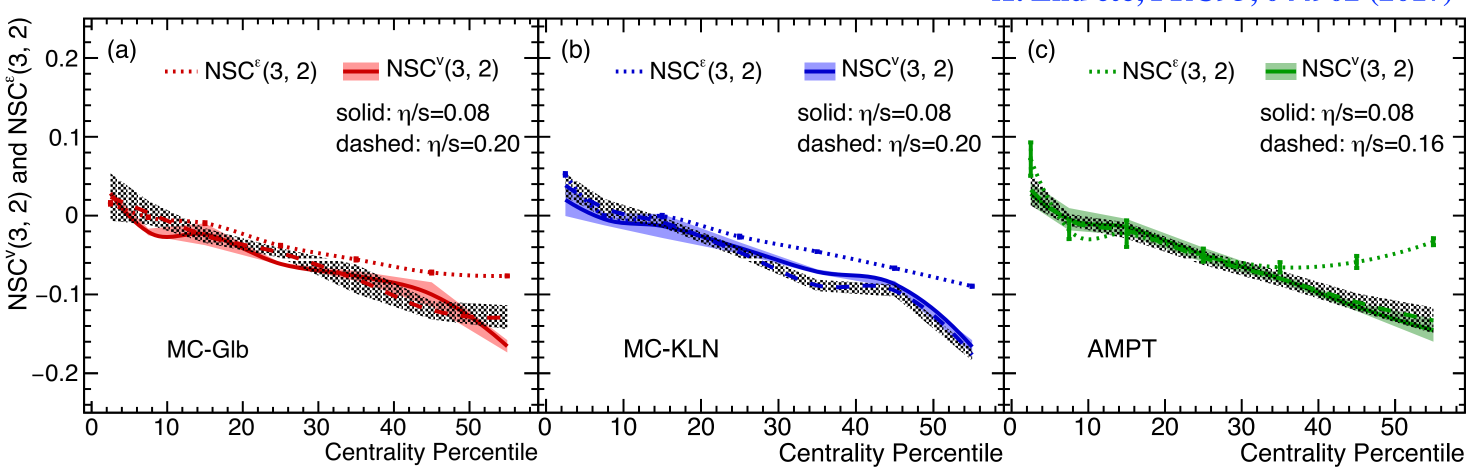
[2]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3]*Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

ALICE, PRL117, 182301 (2016)



X. Zhu etc, PRC95, 044902 (2017)



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

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

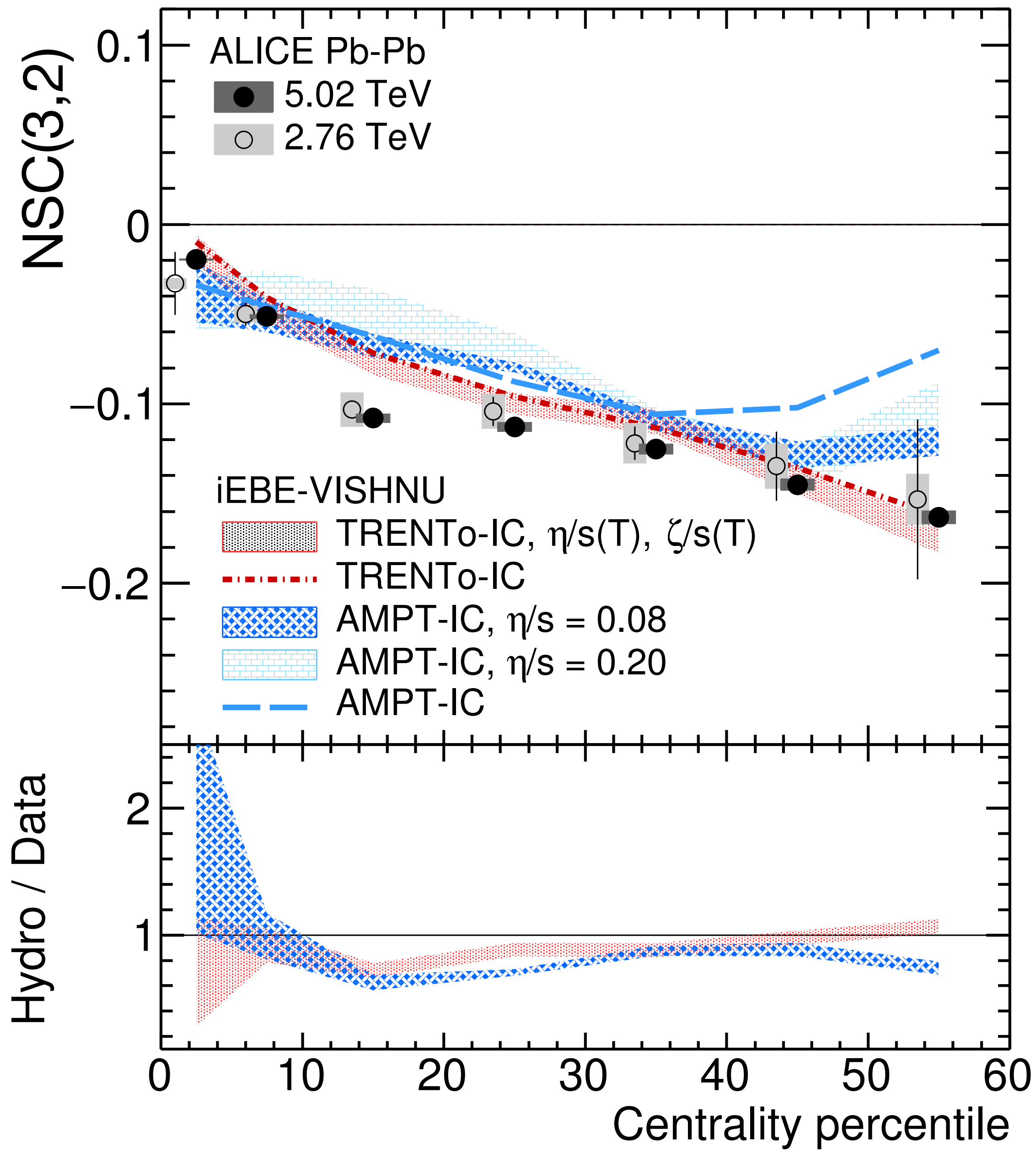
Or: $NSC^v(3,2) = NSC^\varepsilon(3,2)$

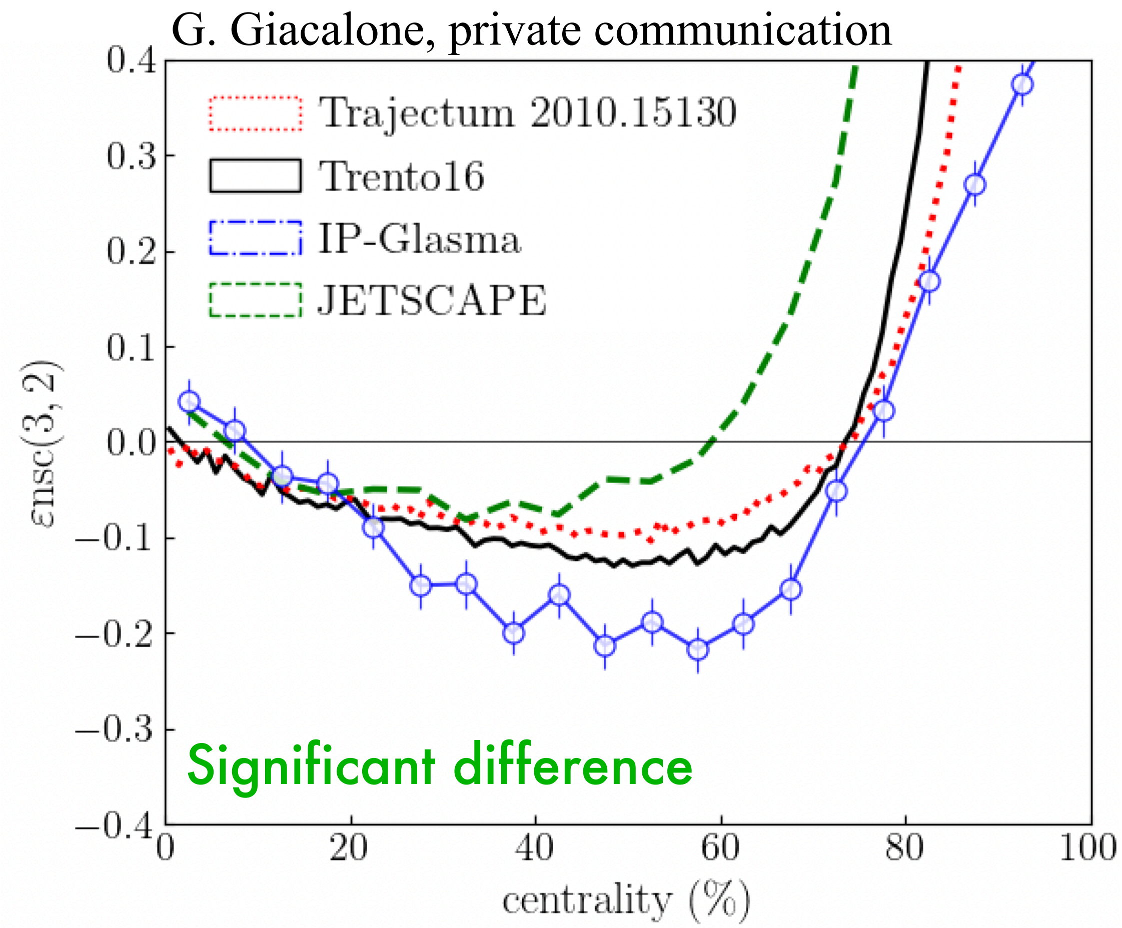
- The very first direct measurement of correlations between v_n and v_m
  - NSC(3,2) is insensitive to η/s
  - NSC(3,2) measurements provide a direct access into the initial conditions (despite details of systems evolution)

Probe IC with NSC(3,2)

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

ALICE, PLB818 (2021) 136354

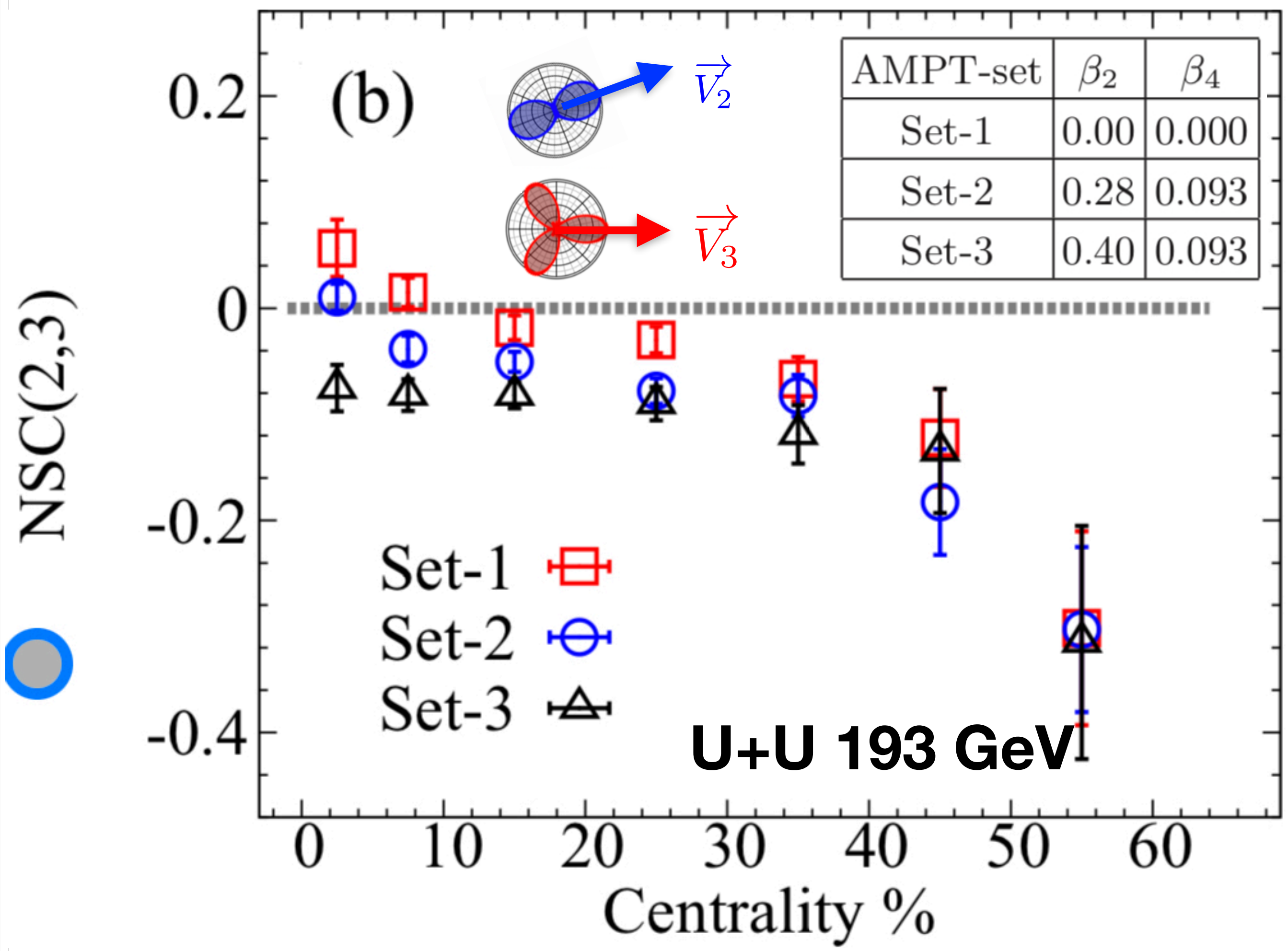




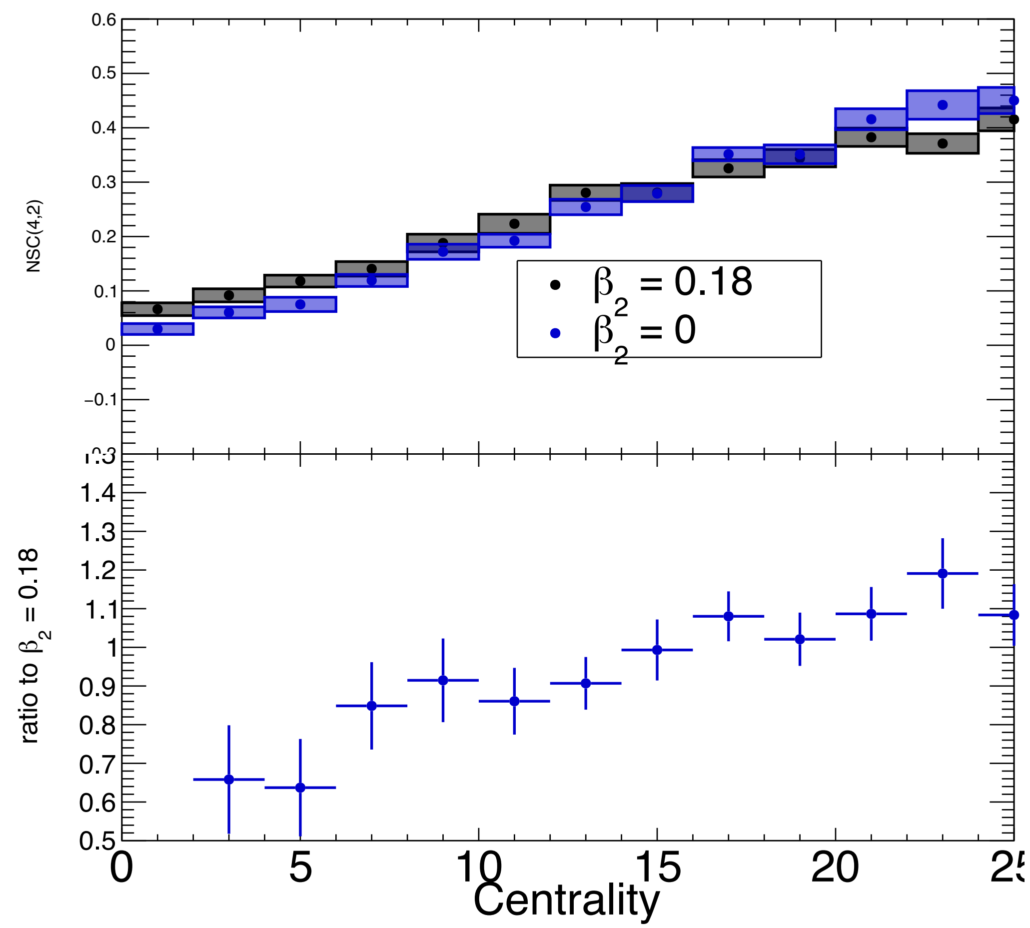
- ❖ Precision NSC(3,2) data provides tight constraints on the initial state models
- ❖ what is the general correlation between any order of v_n^k and v_m^p and the correlations among multiple flow coefficients

Probe Nuclear structure with NSC

N. Magdy, arXiv: 2206.05332



M. Zhao, L. Zhi, YZ, in preparation



- ❖ Significant differences seen in NSC(3,2) and NSC(4,2)
- ❖ Coming measurements should allow the constrain the β_2 parameter

P(v_m, v_n, v_k,...)

A reminder

J. Jia, JPG41 (2014) 124003

	pdfs	cumulants
Flow-amplitudes	$p(v_n)$	$v_n\{2k\}$, $k = 1,2,...$
	$p(v_n, v_m)$	$\langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$, $n \neq m$ ...
	$p(v_n, v_m, v_l)$	$\langle v_n^2 v_m^2 v_l^2\rangle + 2\langle v_n^2\rangle\langle v_m^2\rangle\langle v_l^2\rangle - \langle v_n^2 v_m^2\rangle\langle v_l^2\rangle - \langle v_m^2 v_l^2\rangle\langle v_n^2\rangle - \langle v_l^2 v_n^2\rangle\langle v_m^2\rangle$ $n \neq m \neq l$ ...
	...	Obtained recursively as above
EP-correlation	$p(\Phi_n, \Phi_m, ...)$	$\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$
Mixed-correlation	$p(v_l, \Phi_n, \Phi_m, ...)$	$\langle v_l^2 v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle - \langle v_l^2\rangle\langle v_n^{\lvert c_n\rvert} v_m^{\lvert c_m\rvert} ... \cos(c_n n\Phi_n + c_m m\Phi_m + ...)\rangle$ $\sum_k kc_k = 0$, $n \neq m \neq l ...$

- ❖ One algorithm for any particle cumulant
  - 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
  - No need of any package !

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

m-particle cumulant

```
complex Cumulant(int* harmonic, int n, bool remove_zeros=true, int negsplit=-1,
    int mult = 1, int skip = 0)
  {
   bool remove_term = false;
   if (remove_zeros)
   {
    int har_sum = 0;
    for (int i = 0; i<mult; ++i) har_sum += harmonic[n-1+i];
    if (har_sum != 0) remove_term = true;
   }
   complex c = 0;
   if (!remove_term)
   {
    c = Corr(harmonic+(n-1), mult);
    if (n == 1) return c;
    c *= negsplit*Cumulant(harmonic, n-1, remove_zeros, negsplit-1);
   }

   int h_hold = harmonic[n-2];
   for (int counter = 0; counter <= n-2-skip; ++counter)
   {
    harmonic[n-2] = harmonic[counter];
    harmonic[counter] = h_hold;
    c += Cumulant(harmonic, n-1, remove_zeros, negsplit, mult+1, n-2-counter);
    harmonic[counter] = harmonic[n-2];
   }
   harmonic[n-2] = h_hold;
   return c;
  }
```

m-particle correlation

```
complex Correlator(int* harmonic, int n, int mult = 1, int skip = 0)
 {
  int har_sum = 0;
  for (int i = 0; i<mult; ++i) har_sum += harmonic[n-1+i];
  complex c(Q(har_sum, mult));
  if (n == 1) return c;
  c *= Correlator(harmonic, n-1);
  if (n == 1+skip) return c;

  complex c2 = 0;
  int h_hold = harmonic[n-2];
  for (int counter = 0; counter <= n-2-skip; ++counter)
  {
   harmonic[n-2] = harmonic[counter];
   harmonic[counter] = h_hold;
   c2 += Correlator(harmonic, n-1, mult+1, n-2-counter);
   harmonic[counter] = harmonic[n-2];
  }
  harmonic[n-2] = h_hold;
  return c-mult*c2;
 }
```

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

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

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

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

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

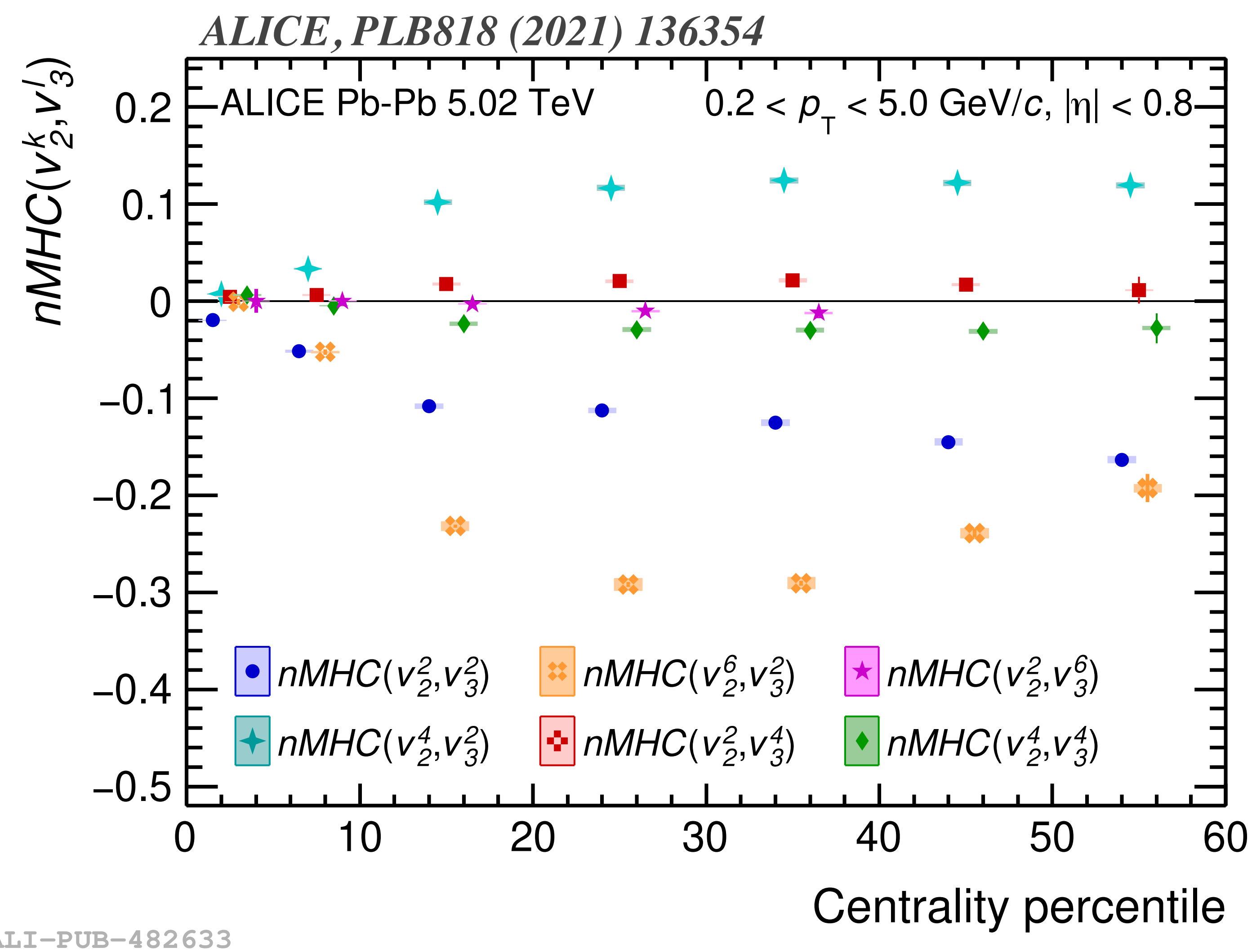
Mixed harmonic cumulants with 8-particles

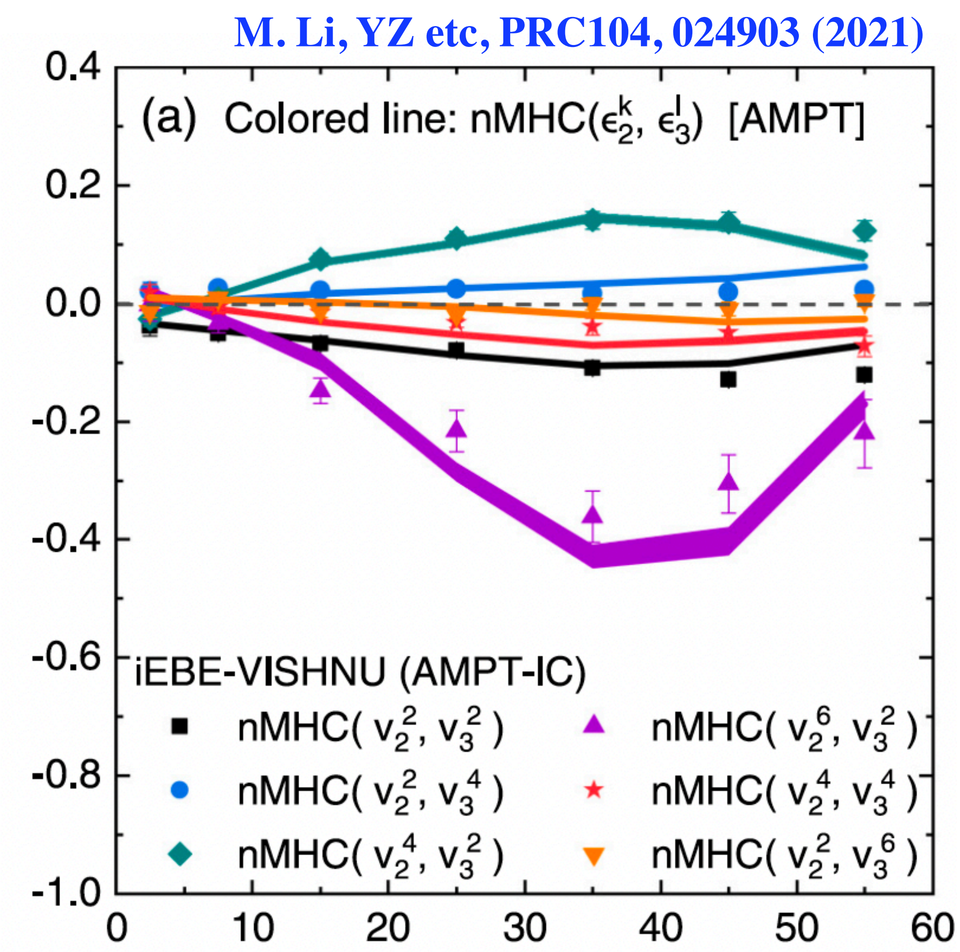
$$\begin{aligned}\mathrm{MHC}(v_2^6, v_3^2) &= \langle\langle e^{i\,(2\varphi_1+2\varphi_2+2\varphi_3+3\varphi_4-2\varphi_5-2\varphi_6-2\varphi_7-3\varphi_8)}\rangle\rangle_c \\ &= \langle v_2^6\, v_3^2\rangle - 9\langle v_2^4\, v_3^2\rangle\langle v_2^2\rangle - \langle v_2^6\rangle\langle v_3^2\rangle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

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

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

Correlations between v_2^k and v_3^L





- 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 from initial state models

Questions:

EXP: can one perform the measurements of 6-particle cumulants of mixed harmonics in Xe-Xe collisions (ATLAS? CMS?)

TH: can we quickly check the initial state e_2^4 and e_3^2 correlations, with different nuclear structure?

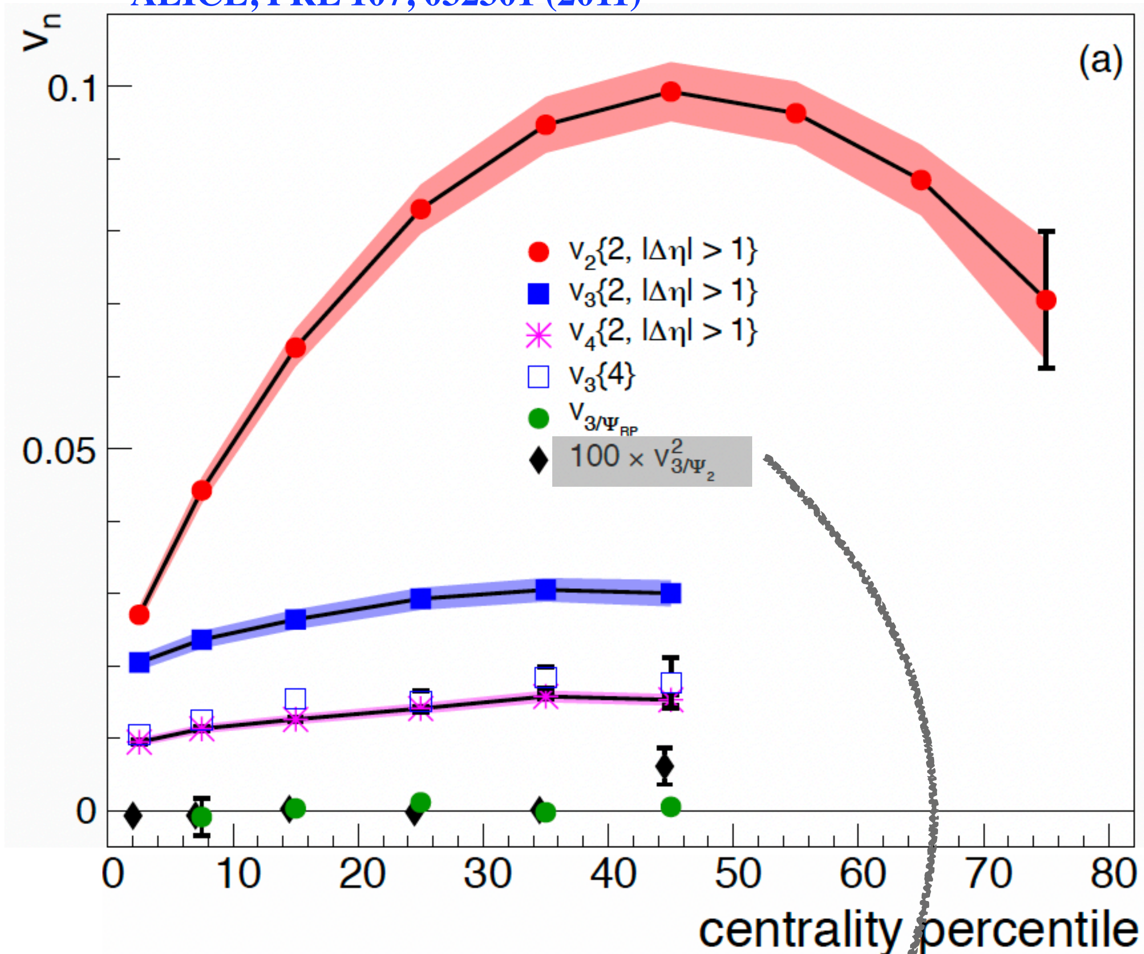
$$\begin{aligned}
\mathrm{MHC}(v_2^4, v_3^2) &= \langle\langle e^{i\,(2\varphi_1+2\varphi_2+3\varphi_3-2\varphi_4-2\varphi_5-3\varphi_6)}\rangle\rangle_c \\
&= \langle v_2^4\, v_3^2\rangle - 4\langle v_2^2\, v_3^2\rangle\langle v_2^2\rangle - \langle v_2^4\rangle\langle v_3^2\rangle \\
&\quad + 4\langle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

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

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

ψn correlations: P(ψm, ψn, ψk)

ALICE, PRL 107, 032301 (2011)



$$v^2_{3/\Psi_2} = \frac{\langle v_2^3 v_3^2 \cos 5(\Psi_2 - \Psi_3)\rangle}{v_2^2}$$

- First flow symmetry plane correlations at the LHC in 2011
- More complicated higher order and multiple plane correlations -> indirect constraints on IC

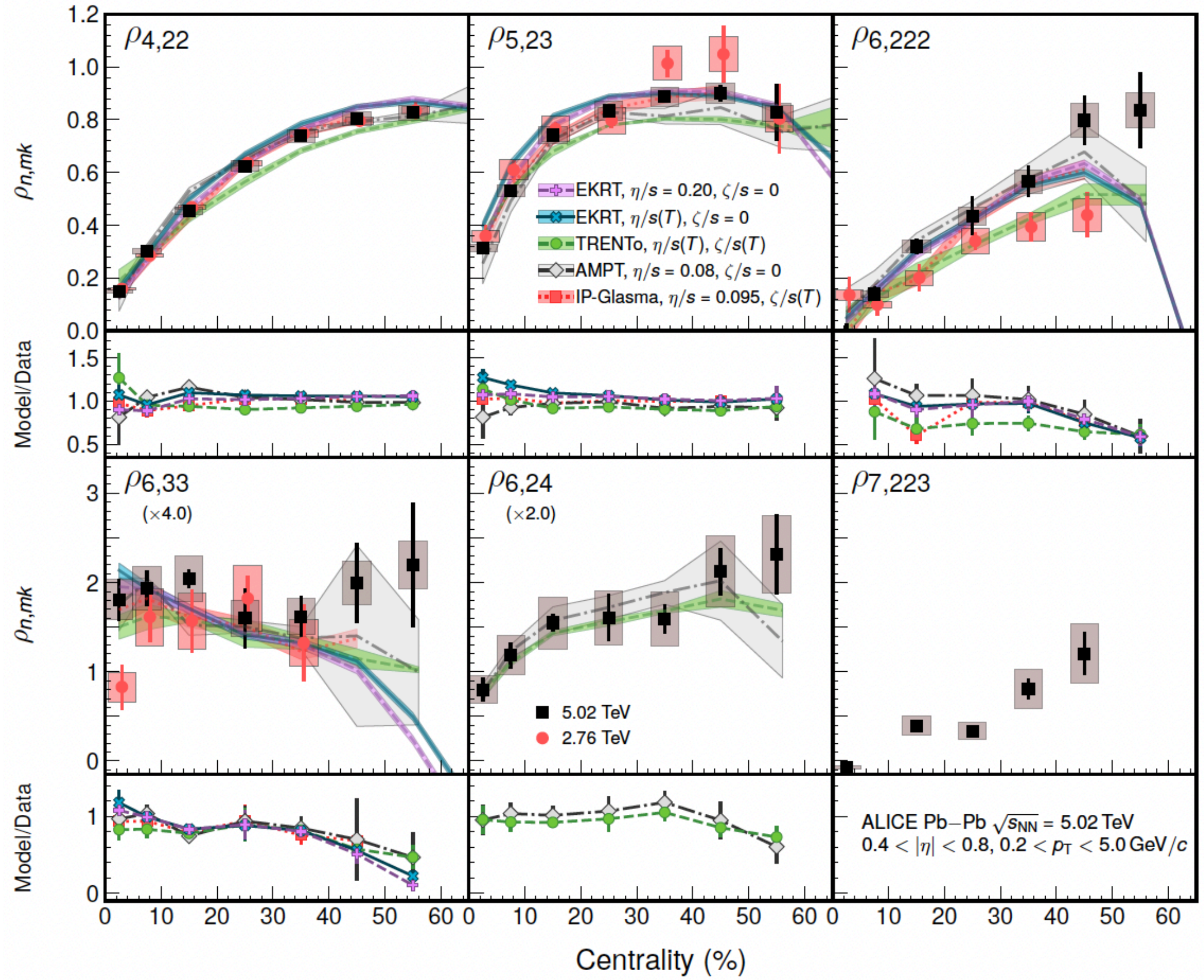
$\rho_{422} \approx \langle\cos(4\Psi_4 - 4\Psi_2)\rangle$

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

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

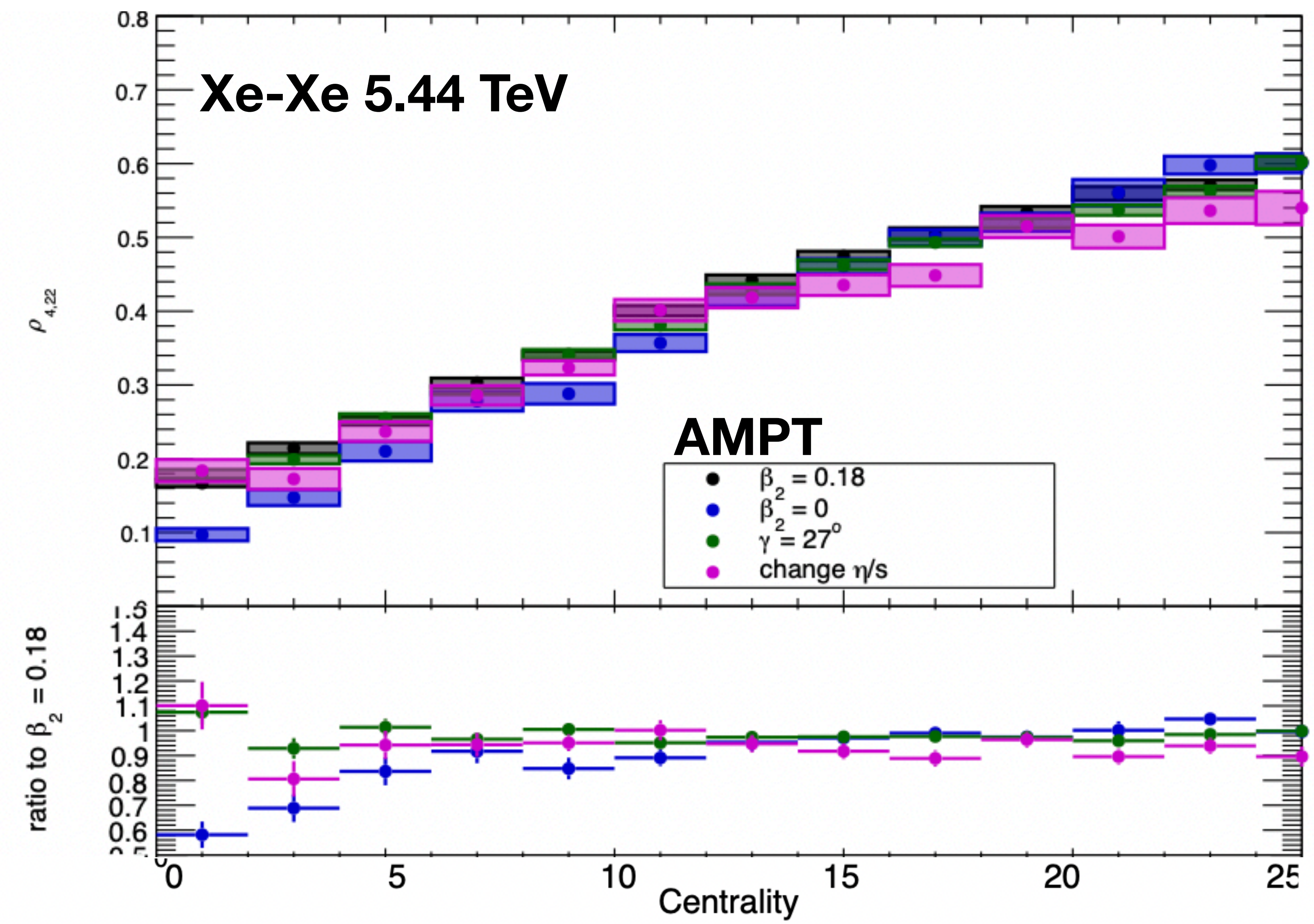
$\rho_{633} \approx \langle\cos(6\Psi_6 - 6\Psi_3)\rangle$

ALICE, PLB773 (2017) 68, JHEP05 (2020) 085
EKRT, PRC93, 024907 (2016)
TRENTo, EPJC77 (2017) 645
AMPT, EPJC77 (2017) 645
IP-Glasma, PRC95, 064913 (2017)



Enhanced ψ_n correlations

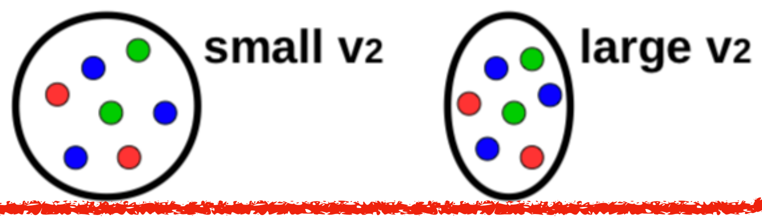
A Stronger correlation can be found with the deformed ^{129}Xe



$[p_T]$ correlations

❖Shape of the fireball: Anisotropic flow

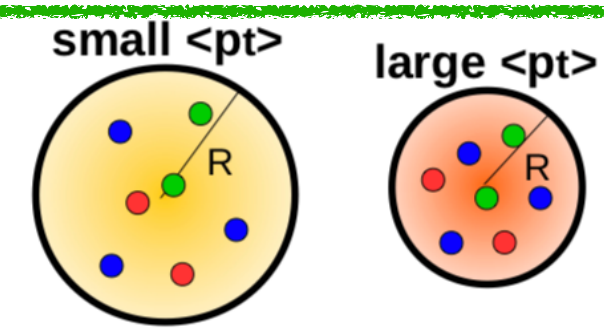
$$V_n \propto \mathcal{E}_n$$



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

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

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



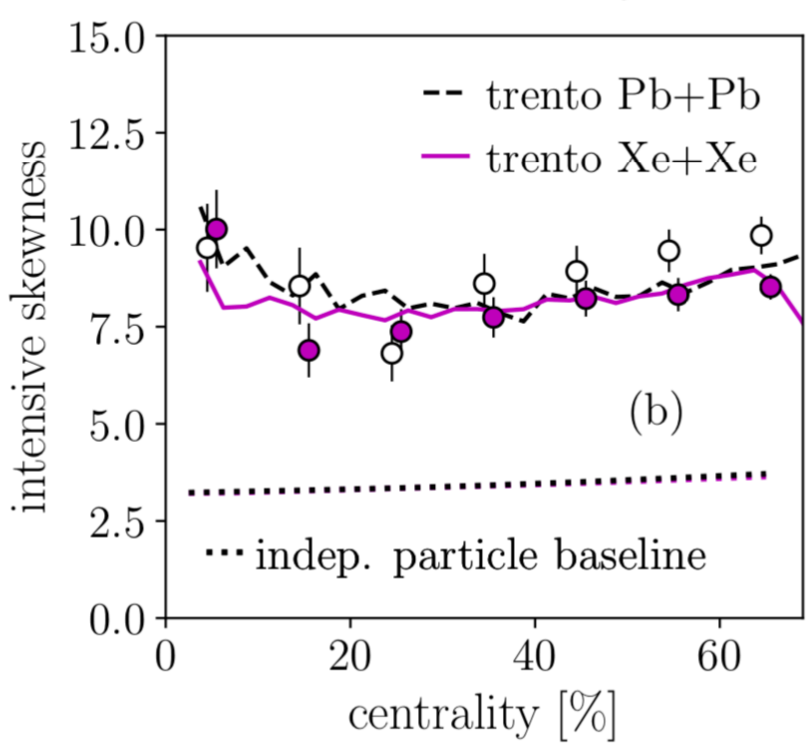
Multi-particle p_T correlations

PHYSICAL REVIEW C **103**, 024910 (2021)

Skewness of mean transverse momentum fluctuations in heavy-ion collisions

Giuliano Giacalone[1,2] Fernando G. Gardim,[3] Jacquelyn Noronha-Hostler,[4] and Jean-Yves Ollitrault[1]
[1]Université Paris Saclay, CNRS, CEA, Institut de physique théorique, 91191 Gif-sur-Yvette, France
[2]Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
[3]Instituto de Ciência e Tecnologia, Universidade Federal de Alfenas, 37715-400 Poços de Caldas, Minas Gerais, Brazil
[4]Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

$$\Gamma_{p_t} \equiv \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle \langle\langle p_t \rangle\rangle}{\langle \Delta p_i \Delta p_j \rangle^2}$$



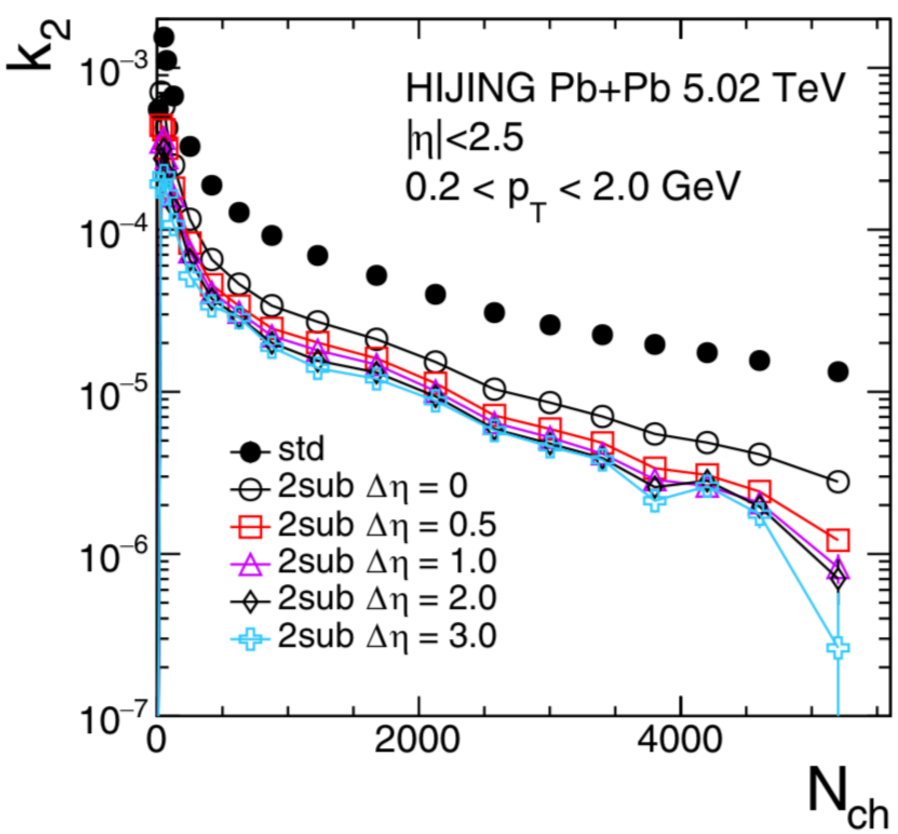
PHYSICAL REVIEW C **105**, 024904 (2022)

Higher-order transverse momentum fluctuations in heavy-ion collisions

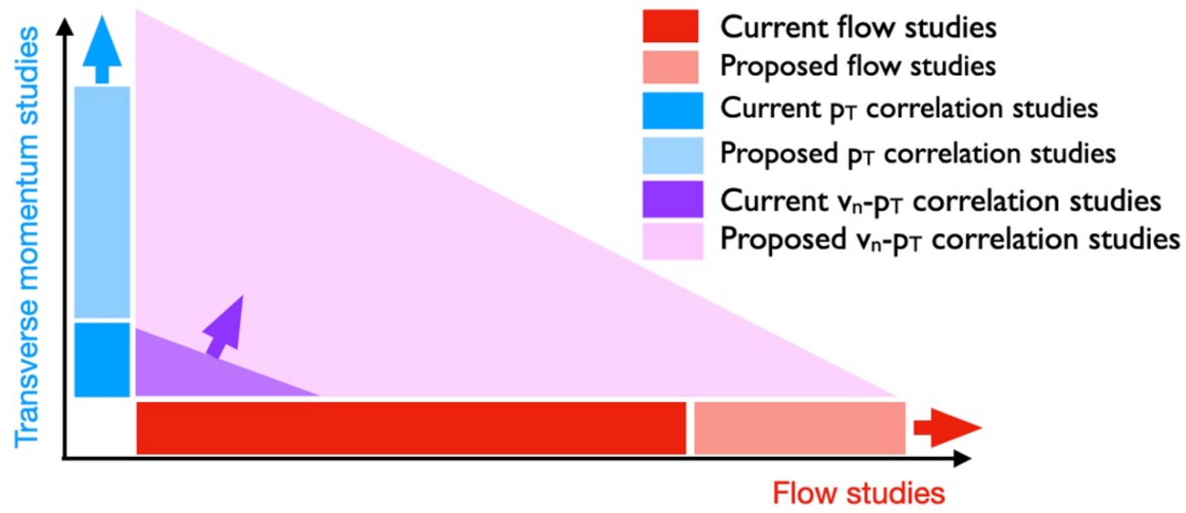
Somadutta Bhatta,[1] Chunjian Zhang,[1] and Jiangyong Jia[1,2,*]
[1]Department of Chemistry, Stony Brook University, Stony Brook, New York 11794, USA
[2]Physics Department, Brookhaven National Laboratory, Upton, New York 11976, USA

$$k_2 = \frac{\langle c_2 \rangle}{\langle\langle p_T \rangle\rangle^2}, \quad k_3 = \frac{\langle c_3 \rangle}{\langle\langle p_T \rangle\rangle^3},$$

$$k_4 = \frac{\langle c_4 \rangle - 3\langle c_2 \rangle^2}{\langle\langle p_T \rangle\rangle^4}, \quad k_{2,2\mathrm{sub}} = \frac{\langle c_{2,2\mathrm{sub}} \rangle}{\langle\langle p_T \rangle\rangle_a \langle\langle p_T \rangle\rangle_c},$$



Generic formula for pt-correlations



Generic multi-particle **cumulant** using recursive formula (example)

$$c\{m\} = \langle\langle m \rangle\rangle - \sum_{k=1}^{m-1} \binom{m-1}{k-1} c\{k\} \langle\langle m-k \rangle\rangle$$

Generic multi-particle **correlation** using recursive formula (example for p_T correlations)

$$\langle m \rangle = \frac{\sum\limits_{\substack{i_1,i_2,\dots,i_m=1 \\ i_1 \neq i_2 \neq \dots \neq i_m}}^{M} w_{i_1} w_{i_2} \cdots w_{i_m} p_T^{(i_1)} p_T^{(i_2)} \cdots p_T^{(i_m)}}{\sum\limits_{\substack{i_1,i_2,\dots,i_m=1 \\ i_1 \neq i_2 \neq \dots \neq i_m}}^{M} w_{i_1} w_{i_2} \cdots w_{i_m}}$$

Multi-particle Correlations

❖ First few correlations

$$\langle 1 \rangle = \frac{\sum w p_T}{\sum w} \qquad \langle 2 \rangle = \frac{\left(\sum w p_T\right)^2 - \sum w^2 p_T^2}{\left(\sum w\right)^2 - \sum w^2} \qquad \langle 3 \rangle = \frac{\left(\sum w p_T\right)^3 - 3\sum w^2 p_T^2 \sum w + 2\sum w^3 p_T^3}{\left(\sum w\right)^3 - 3\sum w^2 \sum w + 2\sum w^3}$$

$$\langle 4 \rangle = \frac{\left(\sum w p_T\right)^4 - 6\sum w^2 p_T^2 \left(\sum w p_T\right)^2 + 3\left(\sum w^2 p_T^2\right)^2 + 8\sum w^3 p_T^3 \sum w p_T - 6\sum w^4 p_T^4}{\left(\sum w\right)^4 - 6\sum w^2 \left(\sum w\right)^2 + 3\left(\sum w^2\right)^2 + 8\sum w^3 \sum w - 6\sum w^4}$$

$$\langle 5 \rangle = \frac{\left(\sum w p_T\right)^5 - 10\sum w^2 p_T^2 \left(\sum w p_T\right)^3 - 4\sum w^2 p_T^2 \sum w^3 p_T^3 - 4\left(\sum w p_T\right)^2 \sum w^3 p_T^3 + 15\left(\sum w^2 p_T^2\right)^2 \sum w p_T - 30\sum w^4 p_T^4 \sum w p_T + 24\sum w^5 p_T^5}{\left(\sum w\right)^5 - 10\sum w^2 \left(\sum w\right)^3 - 4\sum w^2 \sum w^3 - 4\left(\sum w\right)^2 \sum w^3 + 15\left(\sum w^2\right)^2 \sum w - 30\sum w^4 \sum w p_T + 24\sum w^5}$$

Multi-particle Cumulants

$$\kappa_1 = \langle\langle 1 \rangle\rangle$$

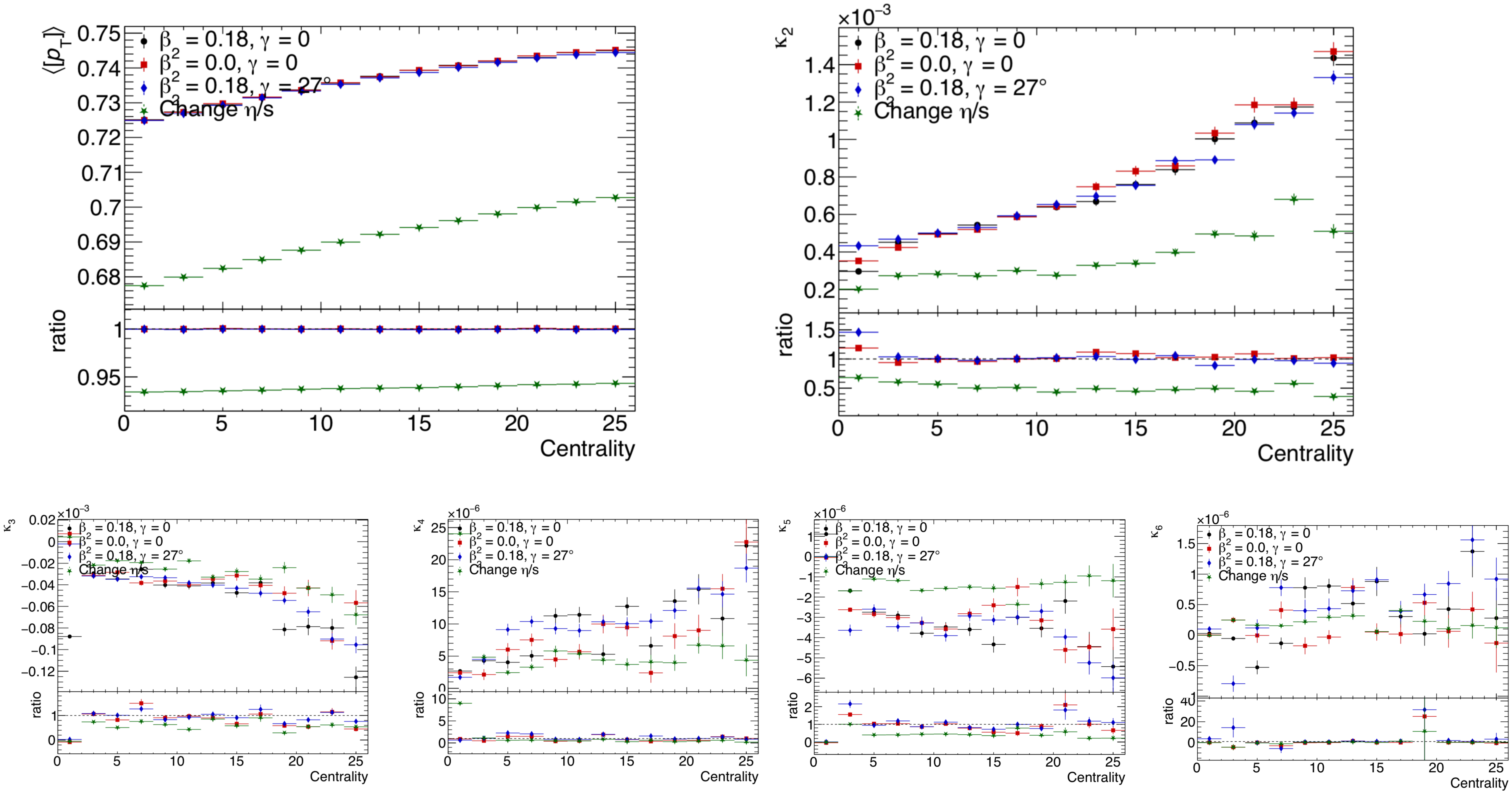
$$\kappa_2 = \langle\langle 2 \rangle\rangle - \langle\langle 1 \rangle\rangle^2$$

$$\kappa_3 = \langle\langle 3 \rangle\rangle - 3\langle\langle 2 \rangle\rangle\langle\langle 1 \rangle\rangle + 2\langle\langle 1 \rangle\rangle^3$$

$$\kappa_4 = \langle\langle 4 \rangle\rangle - 4\langle\langle 3 \rangle\rangle\langle\langle 1 \rangle\rangle - 3\langle\langle 2 \rangle\rangle^2 + 12\langle\langle 2 \rangle\rangle\langle\langle 1 \rangle\rangle^2 - 6\langle\langle 1 \rangle\rangle^4$$

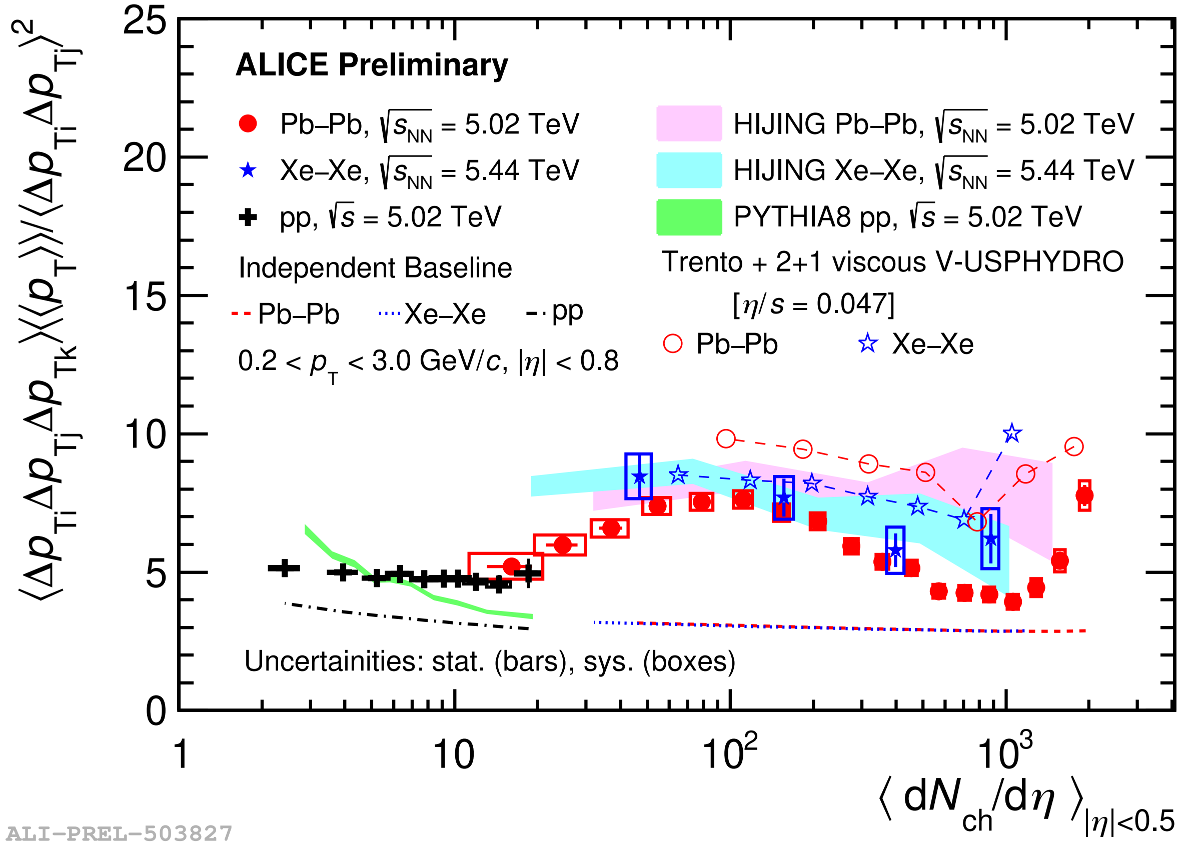
$$\kappa_5 = \langle\langle 5 \rangle\rangle - 5\langle\langle 4 \rangle\rangle\langle\langle 1 \rangle\rangle - 10\langle\langle 3 \rangle\rangle\langle\langle 2 \rangle\rangle + 20\langle\langle 3 \rangle\rangle\langle\langle 1 \rangle\rangle^2 + 30\langle\langle 2 \rangle\rangle^2\langle\langle 1 \rangle\rangle - 60\langle\langle 2 \rangle\rangle\langle\langle 1 \rangle\rangle^3 + 24\langle\langle 1 \rangle\rangle^5$$

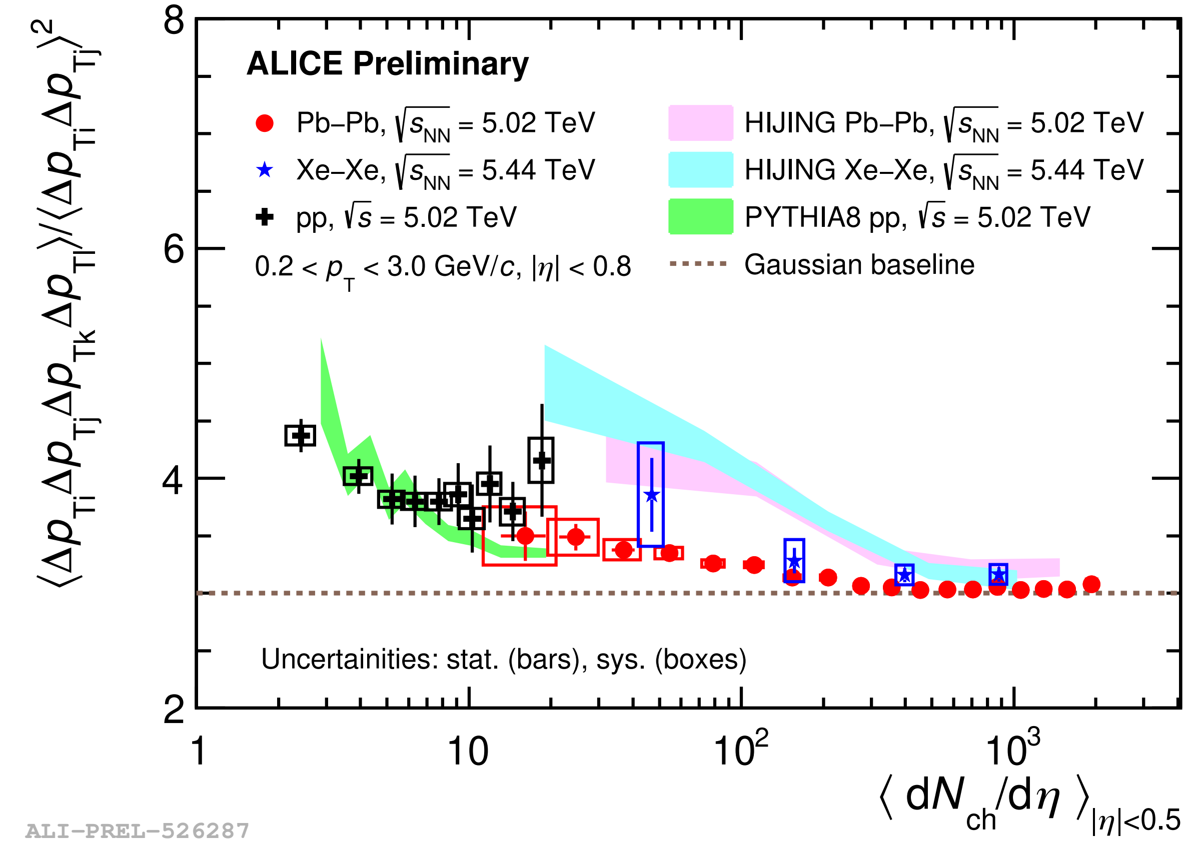
Results from AMPT



- **Precision calculations are needed to confirm the sensitivities (will be updated very soon with the new AMPT production at NBI).**

ALICE preliminary results

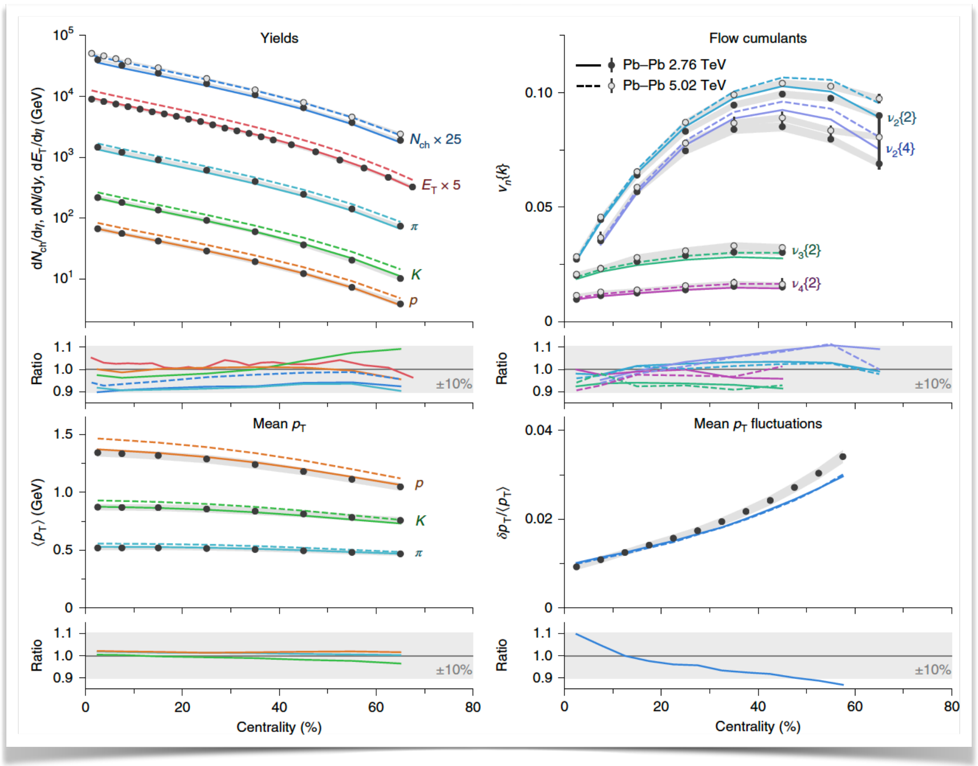


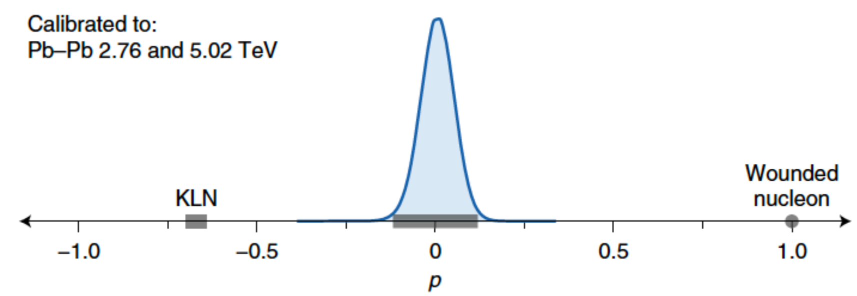


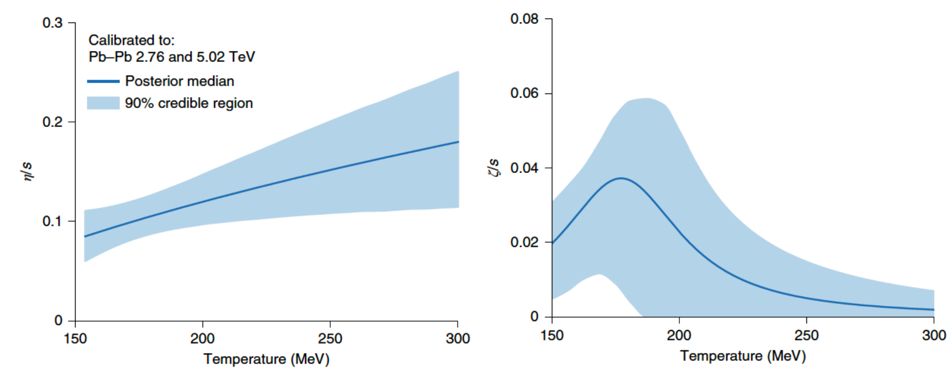
- The Skewness is expected to be sensitive to the triaxial structure
  - Any dedicated calculations for Xe-Xe collisions?

Bayesian analyses with simple v_n and $[p_T]$

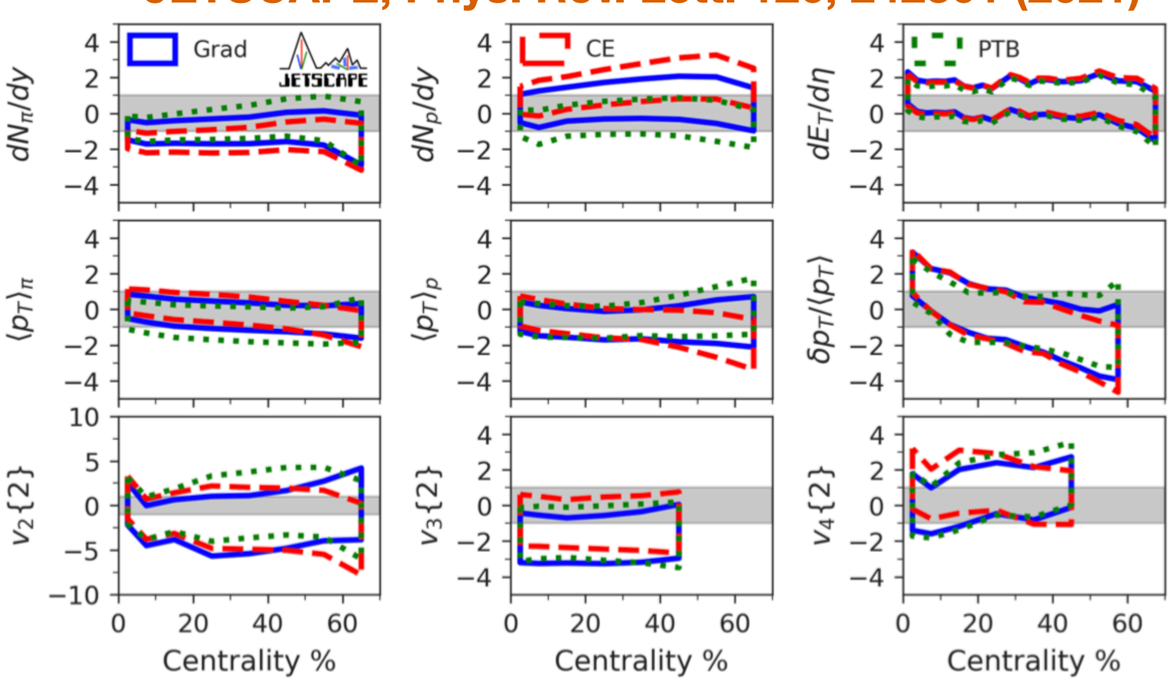
J.E. Bernhard etc, Nature Physics,15, 1113 (2019)

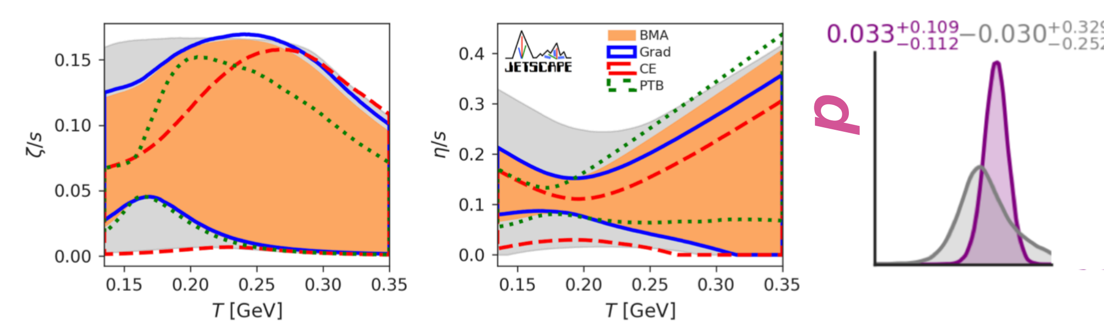






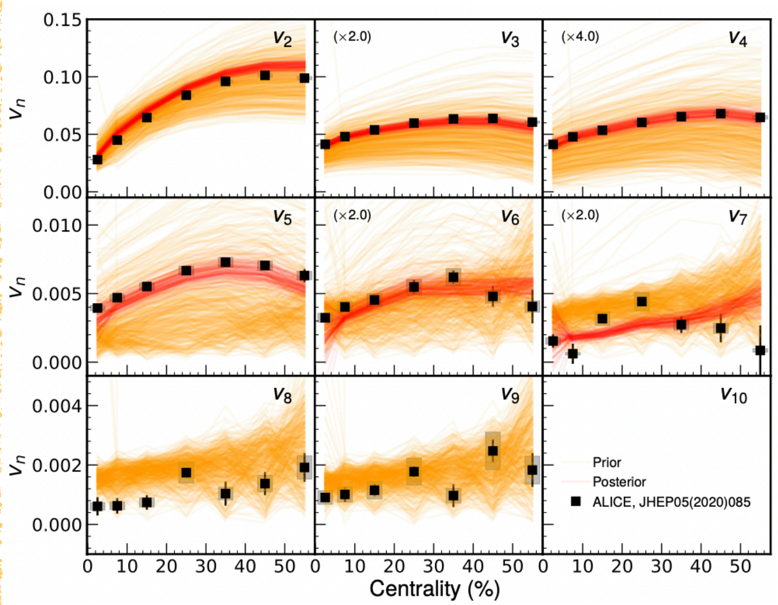
JETSCAPE, Phys. Rev. Lett. 126, 242301 (2021)



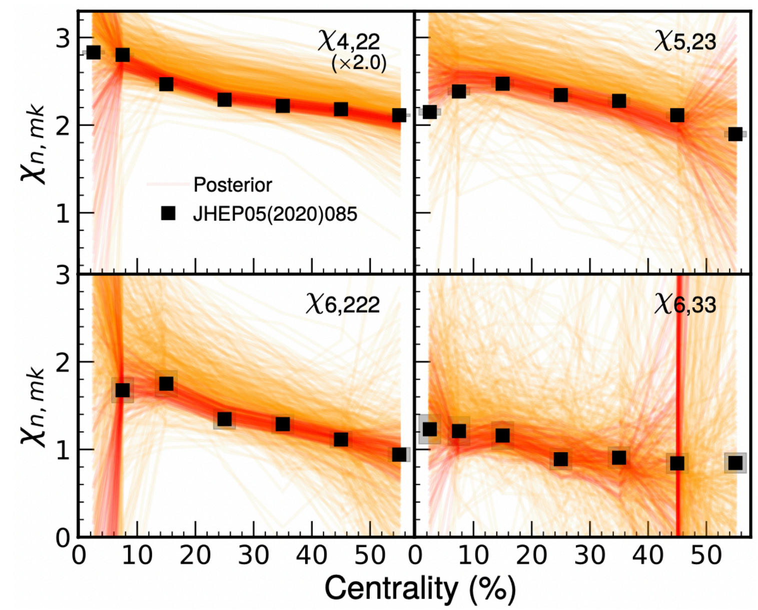


Bayesian analysis with more flow observables

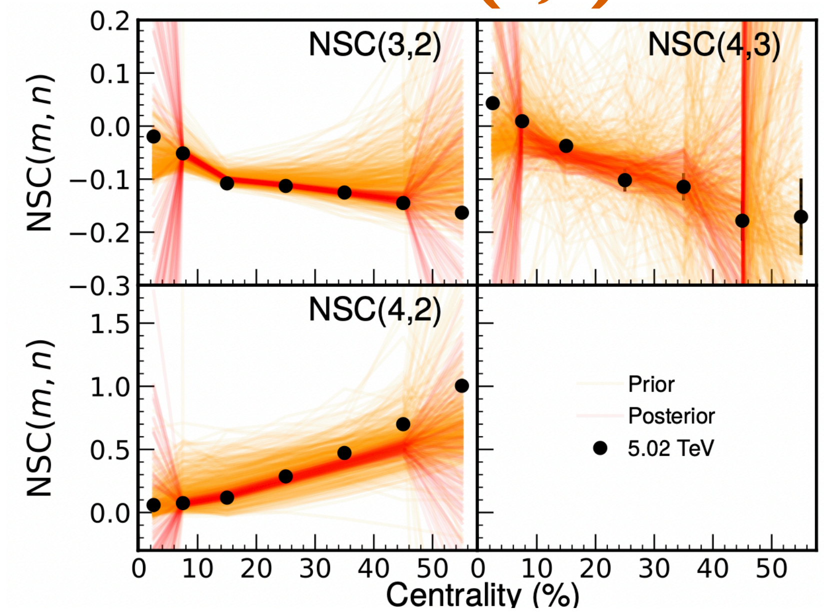
v_n

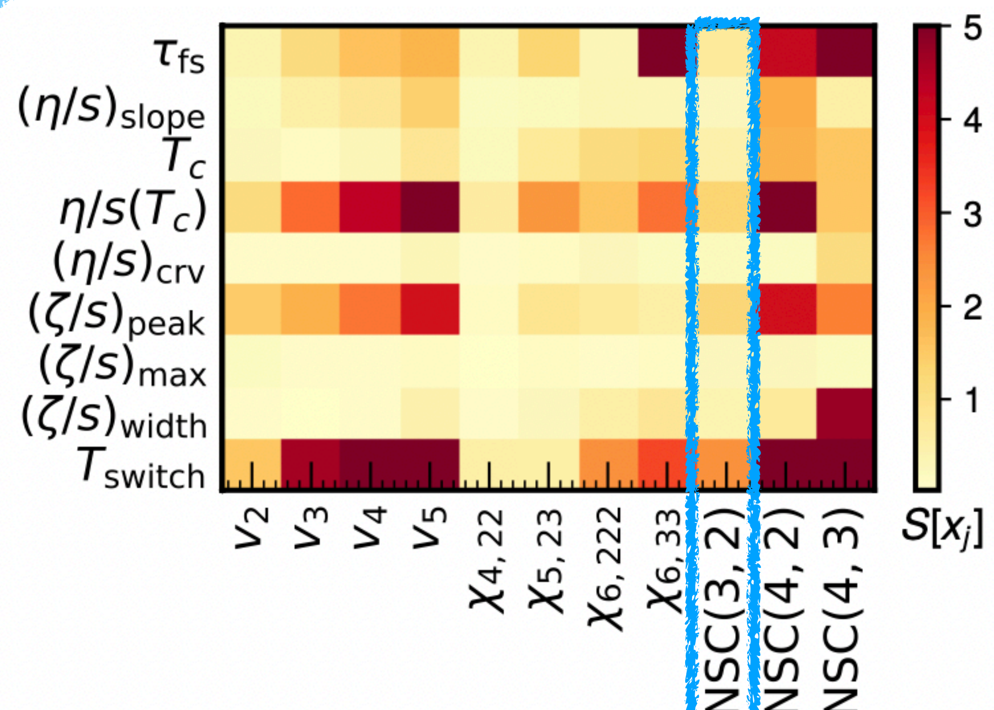


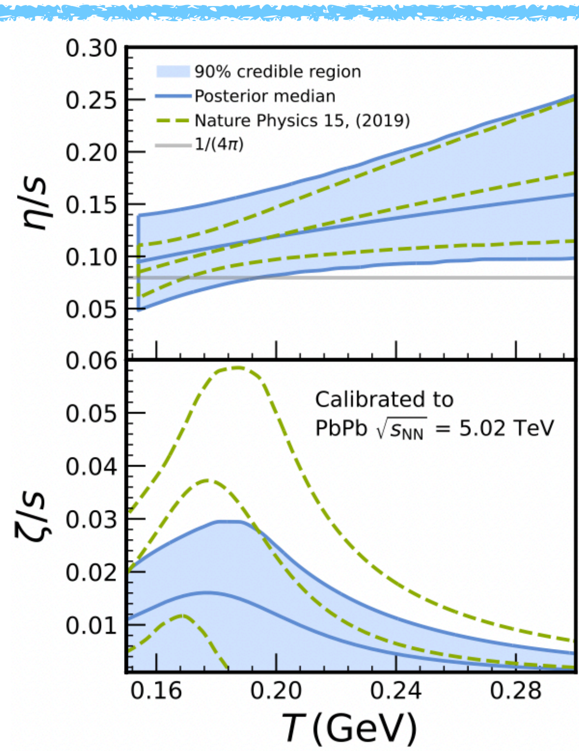
$\chi_{n,mk}$



NSC(3,2)





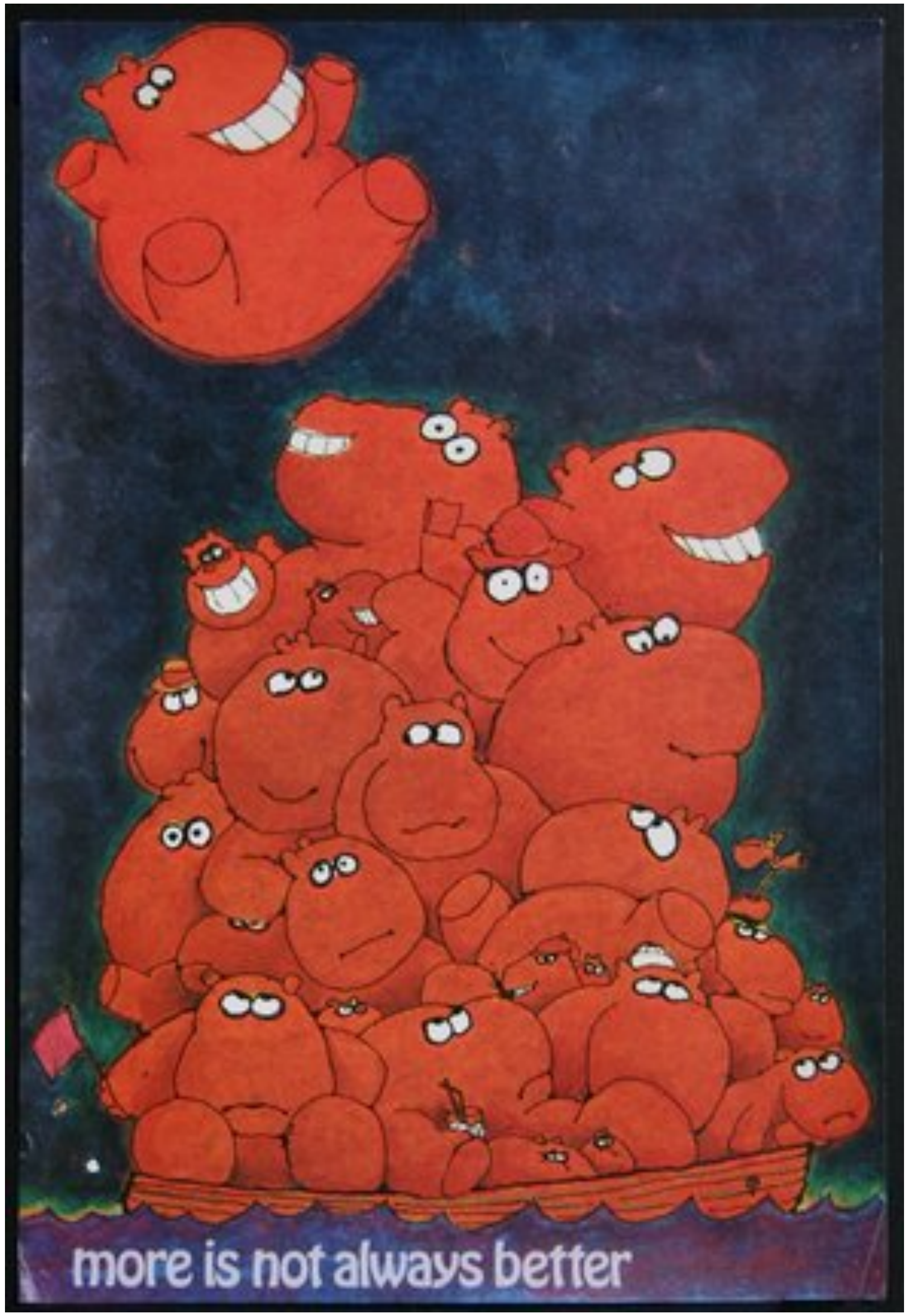


Initial conditions	
Parameter	MAP value
Norm	21.06
p	0.0077
σ_k	0.881
d^3_{min}	0.975
τ_{fs}	0.901
T_c	0.147
T_{switch}	0.160

J.E. Parkkila etc, Phys.Rev.C 104 (2021) 5, 054904

Also see:
G. Nijs, W. Van der Schee, arXiv: 2110.13153

More is not always better



Personal comment:

Many observables are correlated and thus should not be used as independent experimental inputs

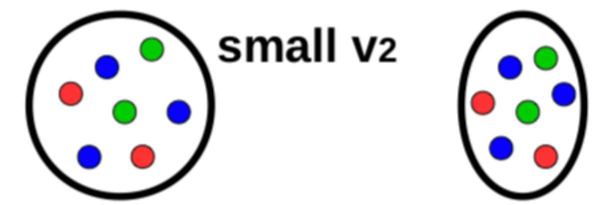
$[p_T]$ - v_n correlations

- Shape of the fireball: Anisotropic flow
- Size of the fireball: radial flow, $[p_{\mathrm{T}}]$
- Initial geometry and fluctuations of shape and size
- Final state: correlation between v_n and p_{T}

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

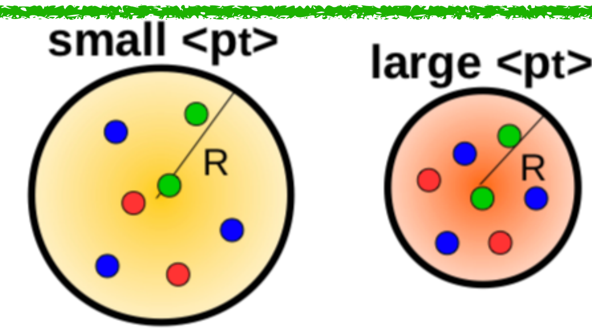
P. Bozek etc, PRC96 (2017) 014904

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



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

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



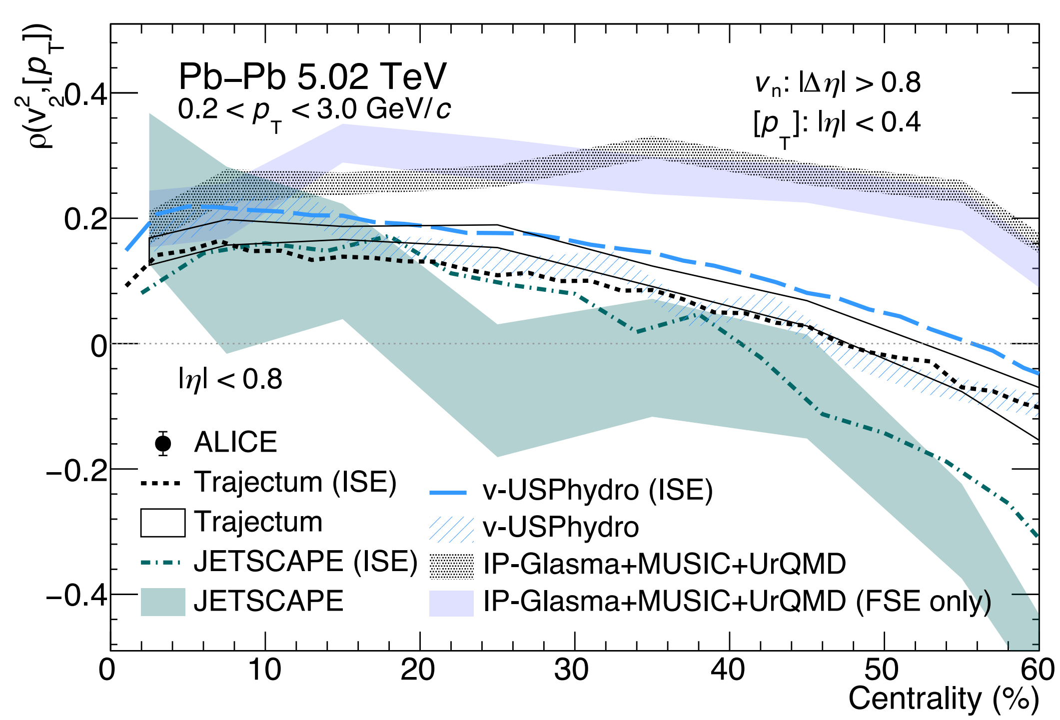
- Assuming $v_n \propto \varepsilon_n$, $[p_T] \propto E_0$

$$\rho(v_n^2, [p_{\mathrm{T}}]) = \rho(\varepsilon_n^2, [E_0])$$

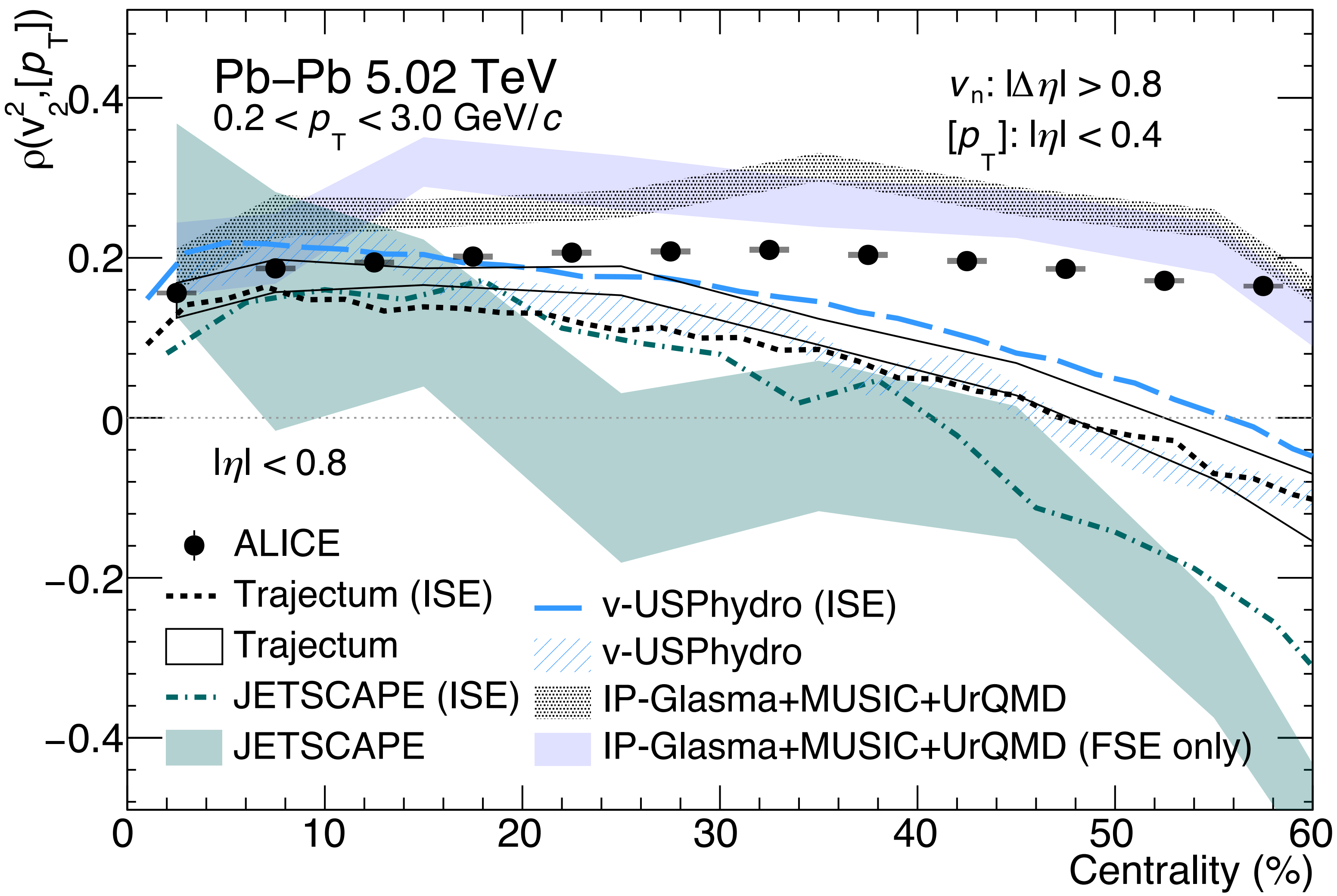
final-state model calculation

Initial-state model estimation

- One can compare $\rho(v_n^2, [p_{\mathrm{T}}])$ measurements to $\rho(\varepsilon_n^2, [E_0])$ calculations, to constrain the initial state model



ρ_2 in Pb-Pb



ALICE, arXiv: 2111.06106

v-USPhydro, PRC103 (2021) 2, 024909

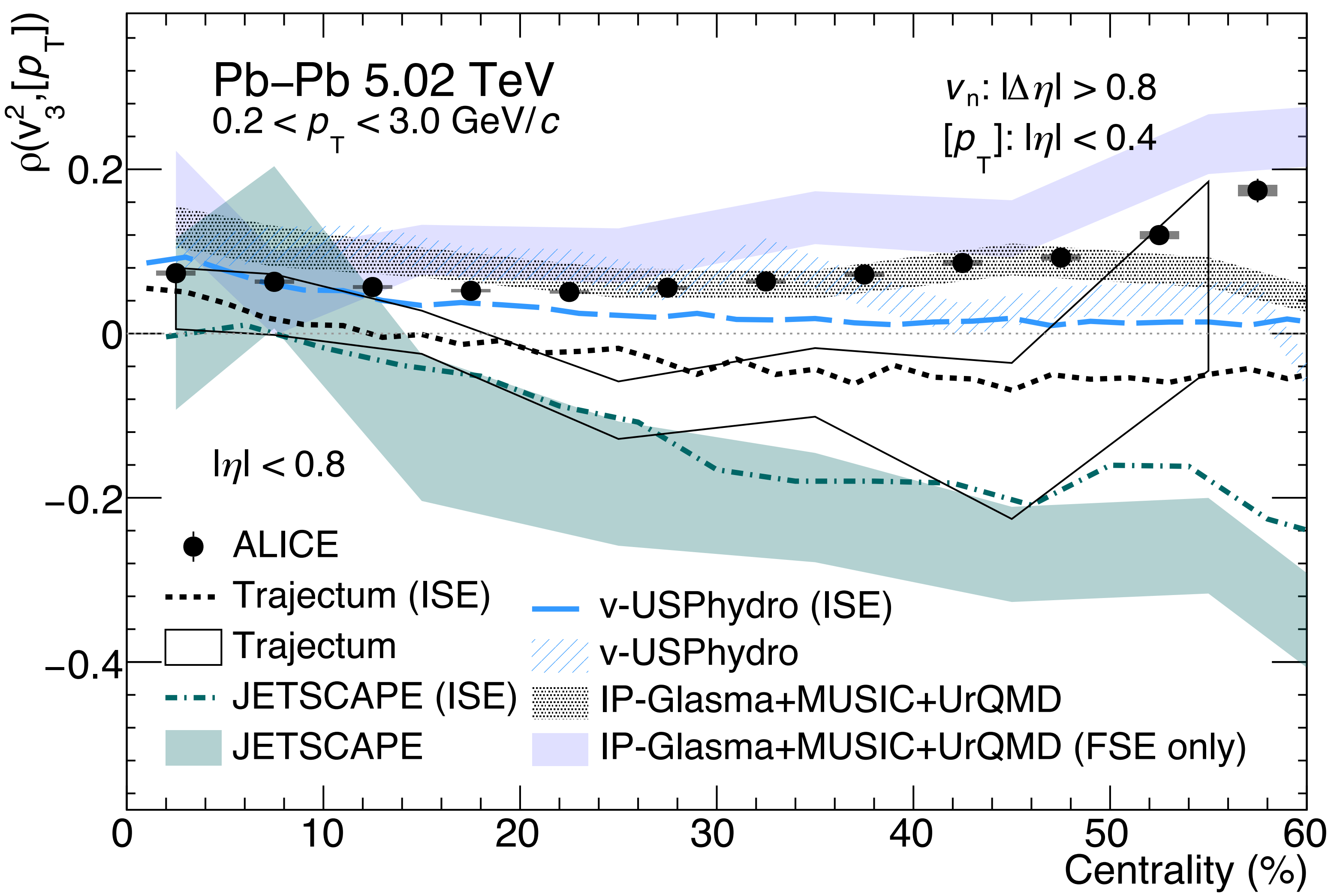
IP-Glasma, PRC102, 034905 (2020)

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

ρ3 in Pb-Pb



ALICE, arXiv: 2111.06106

v-USPhydro, PRC103 (2021) 2, 024909

IP-Glasma, PRC102, 034905 (2020)

JETSCAPE, PRL126, 242301 (2021)
Privation communication

Trajectum, PRL126, 202301 (2021)
Privation communication

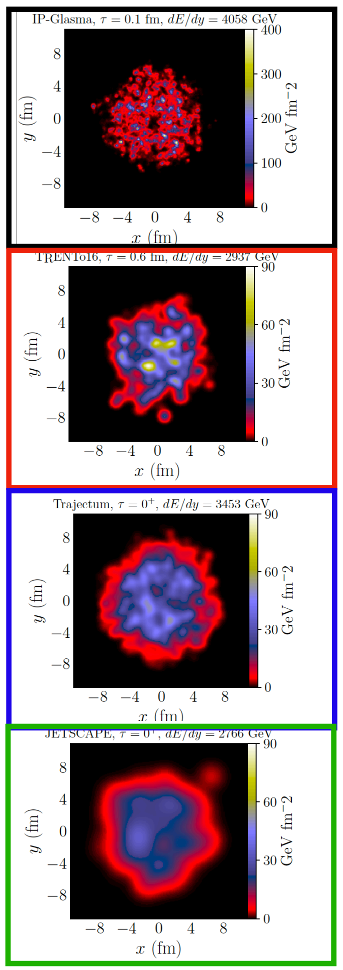
- ρ3 values:
  - positive
  - have a modest centrality dependence for the presented centralities,
  - better described by IP-Glasma,
  - TRENTo predicts negative ρ3 , getting worse for Trajectum and JETSCAPE calculations
- model shows that ρ3 is not sensitive to β2
- Difference of full IP-Glasma and FSE only, indication of potential contributions from IMA in peripheral?

Questions: kinematic cuts and centrality determinations

- How to understand the strong dependence on pt cuts (both low and high pt cut)
  - If the final state is entirely driven by the initial state, then the results in the final state should be independent on the kinematic cut and reflect the initial state information only

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***

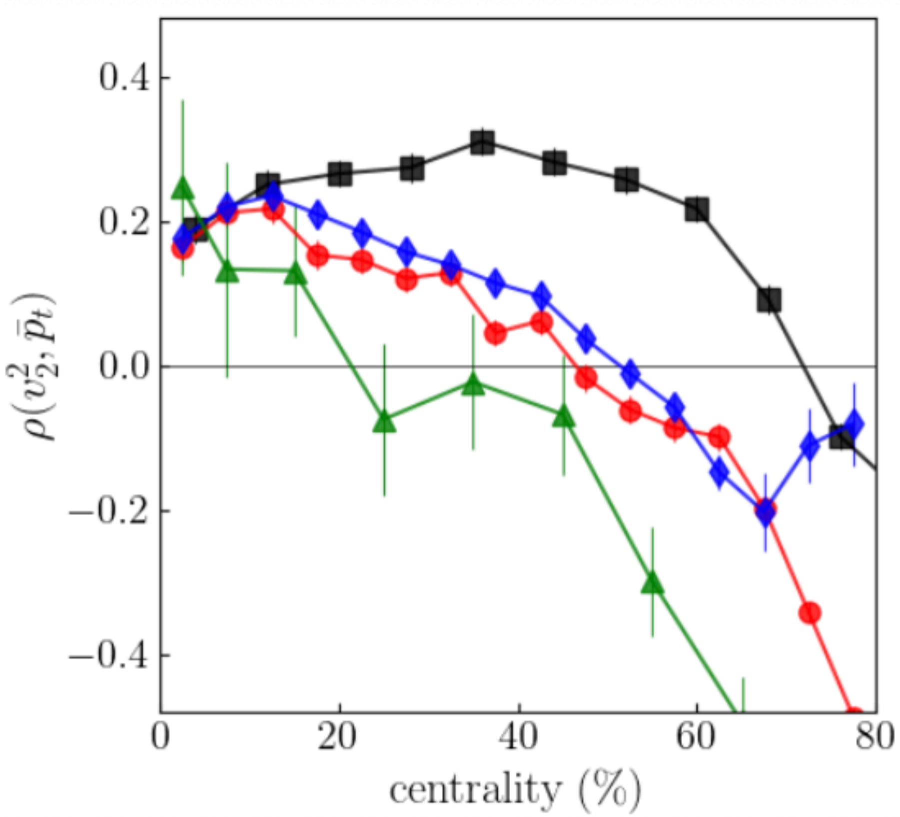


w ~ 0.4

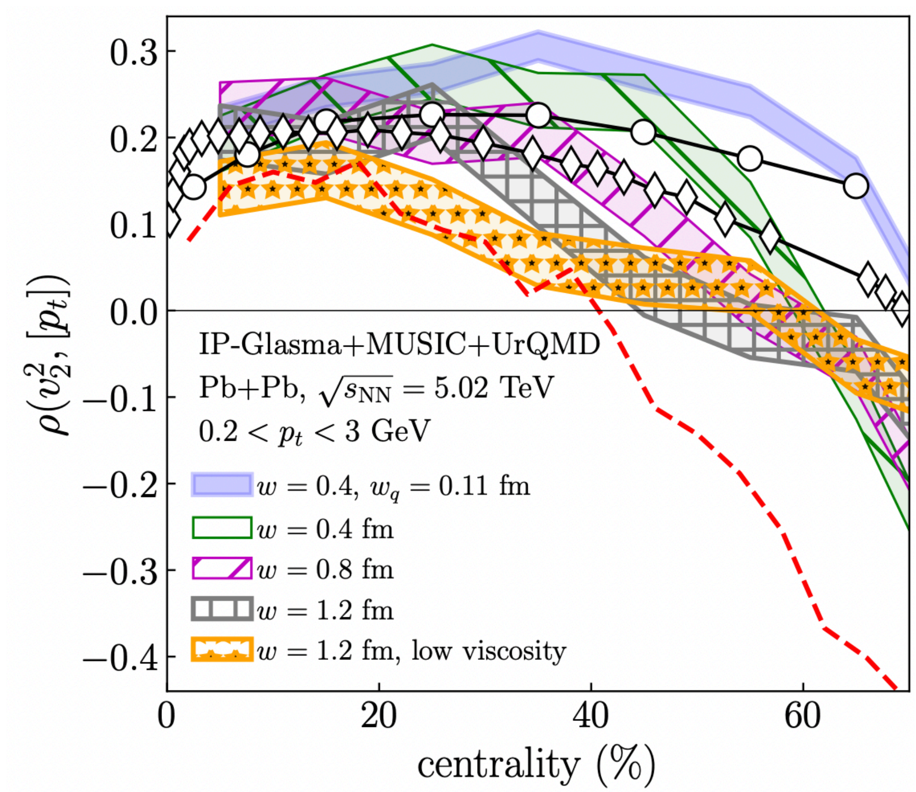
w ~ 0.5

w ~ 0.7

w ~ 1.1

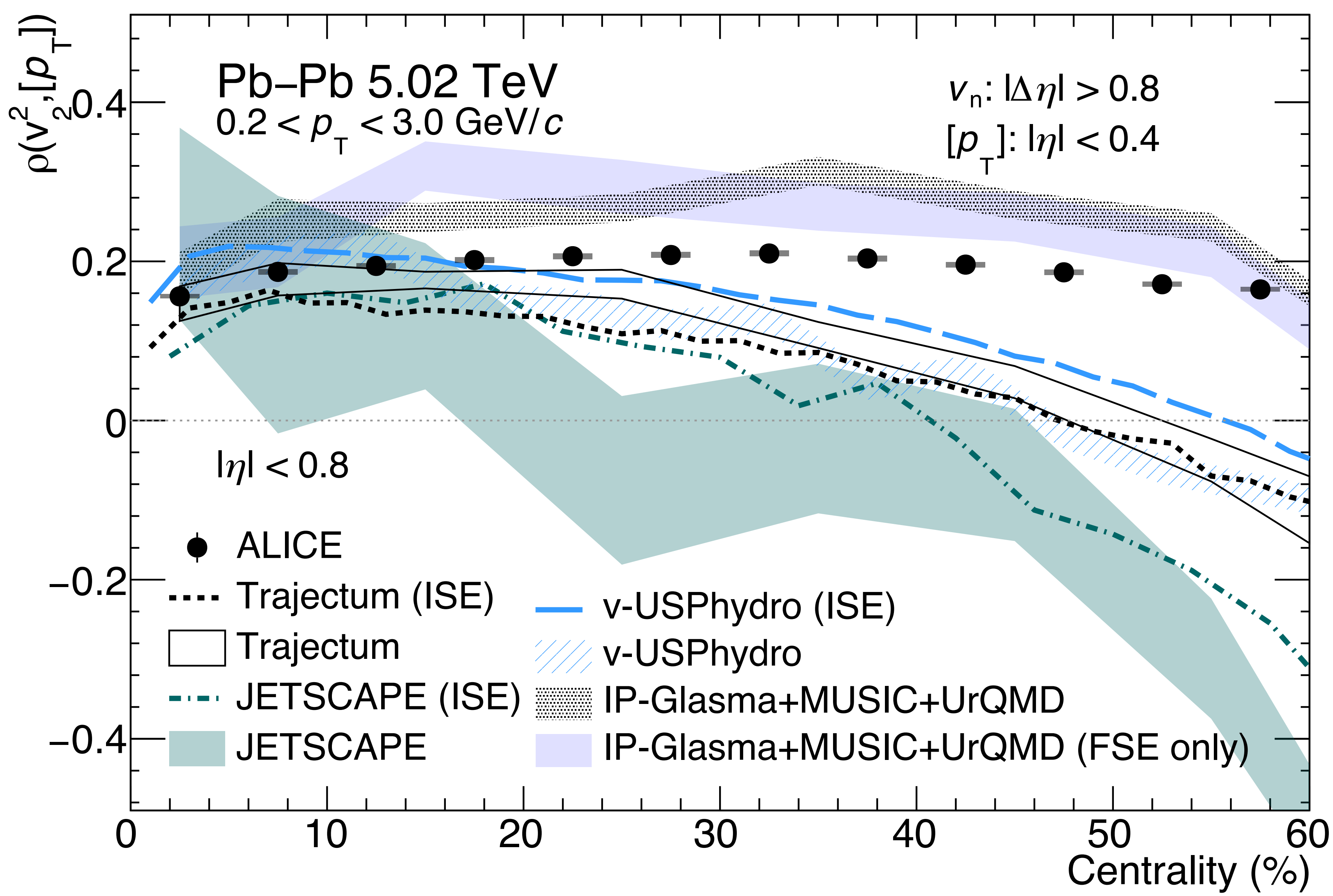


Giacalone, Schenke, Shen, arXiv: 2111.02908



- 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

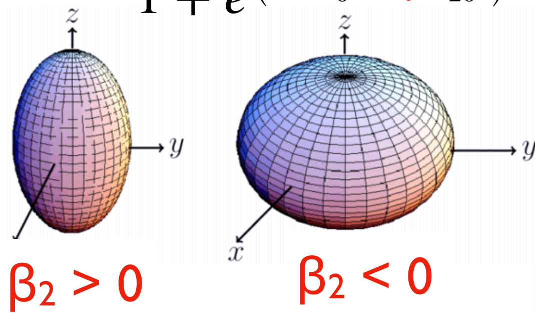
Differences in models or differences in parameters?



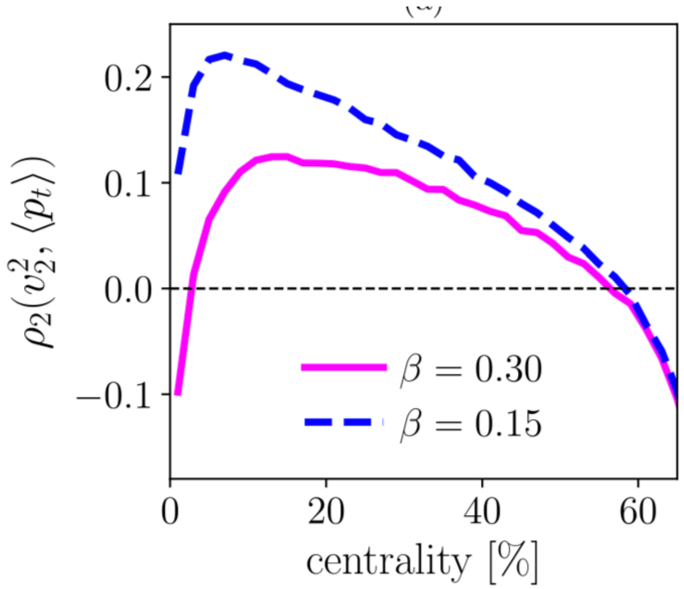
Questions: are the differences **ONLY** due to the values of width used in different models?
Example: can we compare the rho2 results from different models using the same width? Should we expect consistent results?

ρ_2 in Xe-Xe

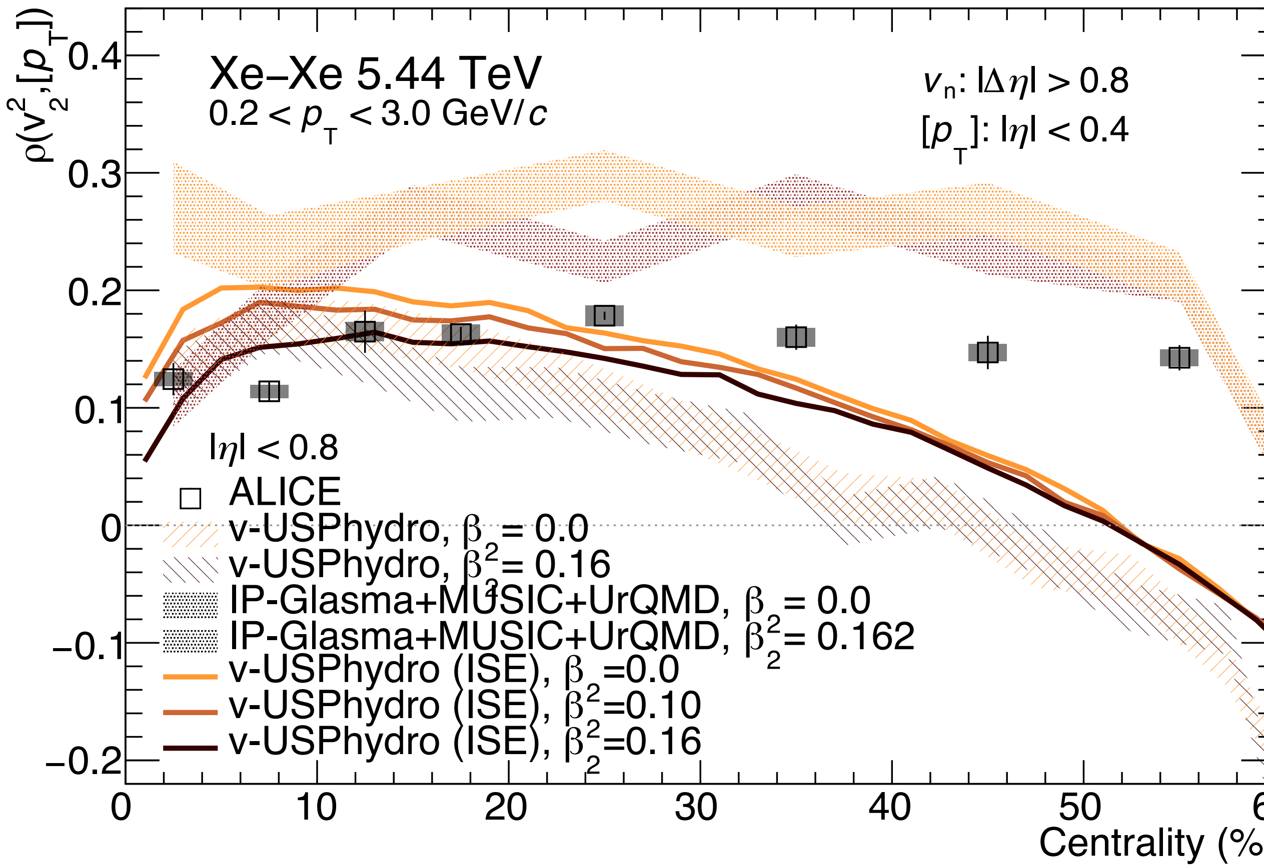
$$D_{WS} = \frac{D_0}{1 + e^{(r - R_0(1+\beta Y_{20}))/a}}$$



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



G.Giacalone, PRC 102 024901 (2020)

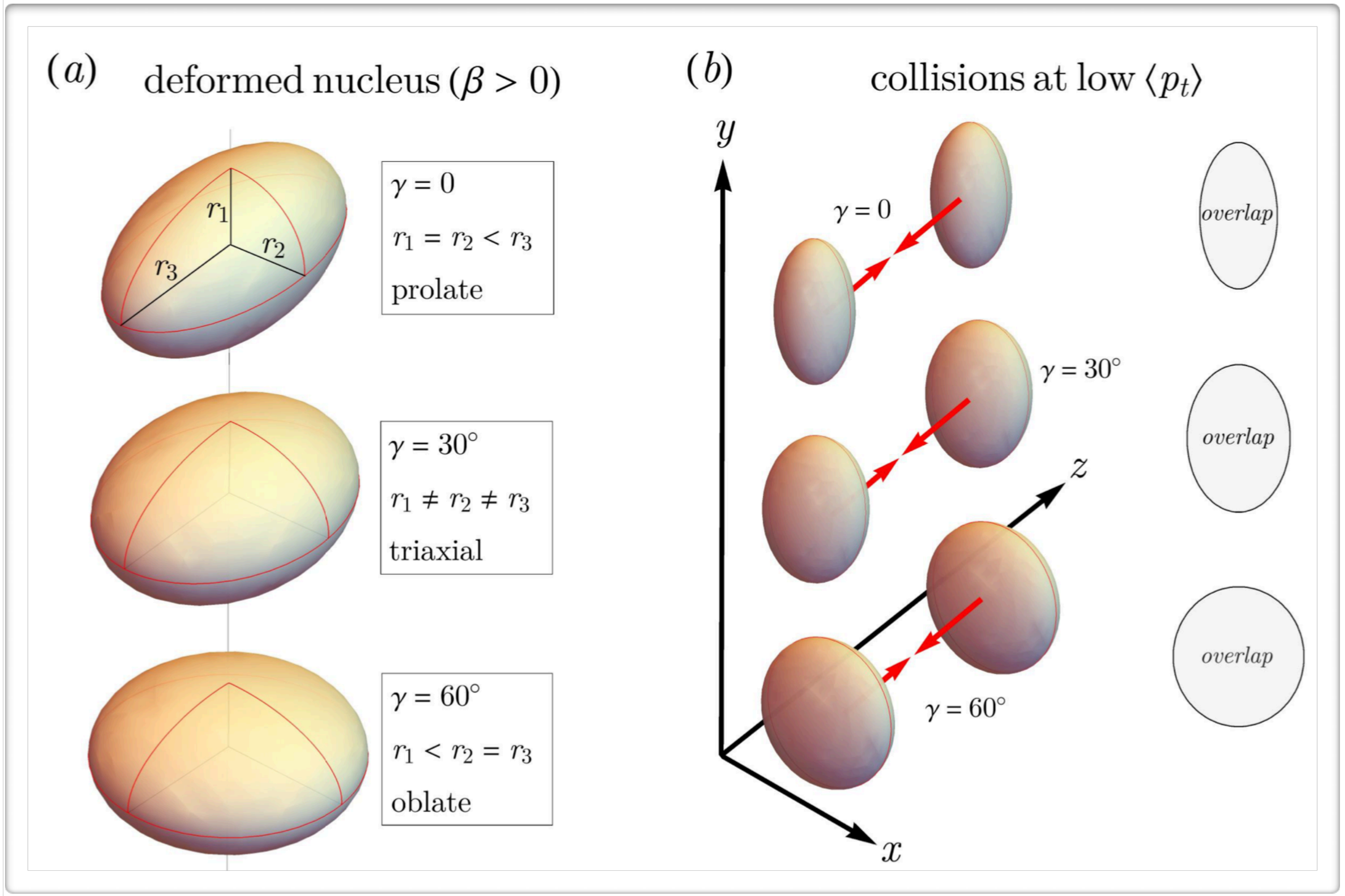


ALICE, arXiv: 2111.06106
v-USPhydro, PRC103 (2021), 024909
IP-Glasma, PRC102, 034905 (2020)

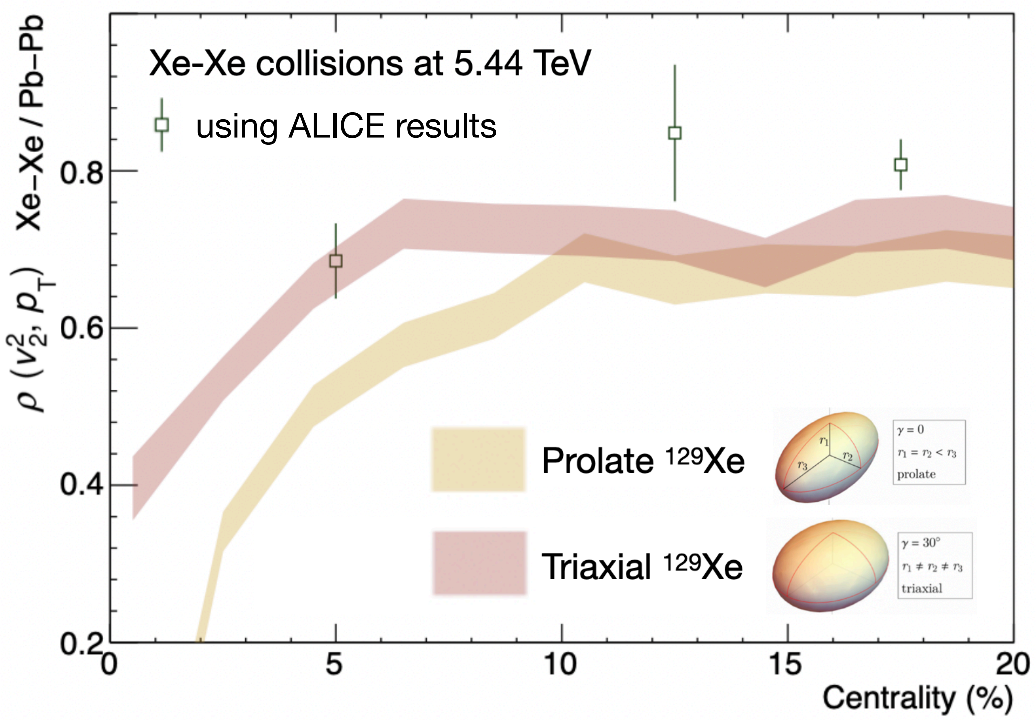
- Significant differences of initial state calculations using different deformation parameter in central Xe-Xe collisions
  - ρ_2 is sensitivties to β_2
  - The uncertainty of current v-USPhydro calculations is too large to draw a confirm conclusions
  - Experimental data (in Xe-Xe@LHC and U-U@RHIC)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

Probe triaxial structure of Xe

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

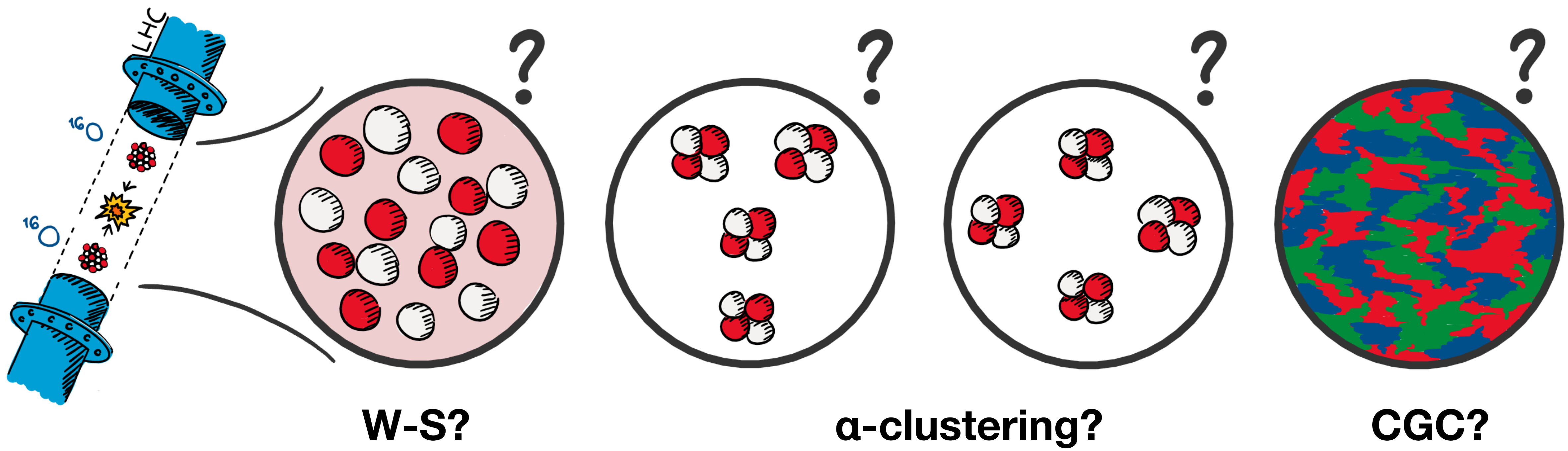


ALICE, Phys. Lett. B 834 (2022) 137393

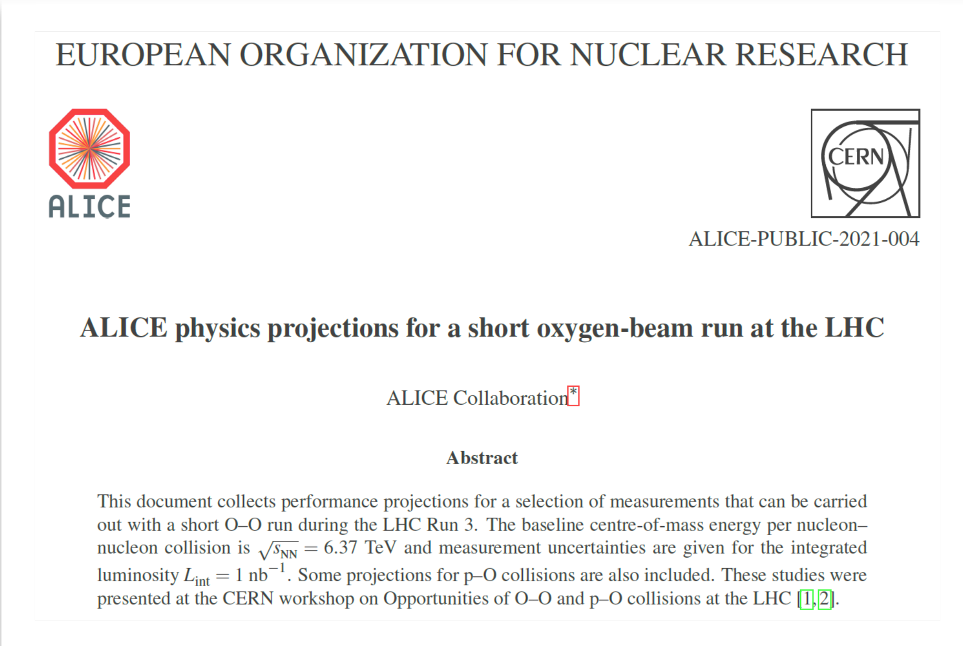


- Better agreement between LHC data and calculations with $\gamma = 26.93°$
  - Indication of triaxial structure of ^{129}Xe at high energy collisions at the LHC
  - New connection of high-energy heavy-ion physics to low-energy nuclear (structure) physics

O-O collisions at LHC Run 3



O-O projection studies


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

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ALICE-PUBLIC-2021-004

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

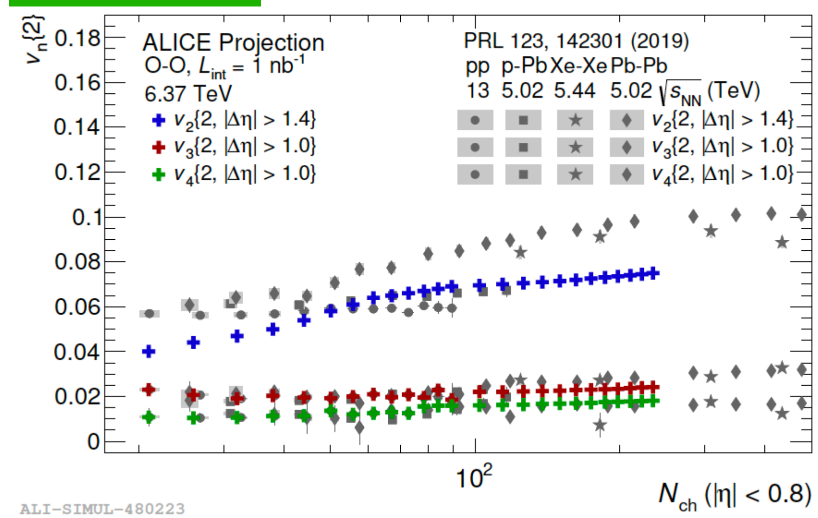
ALICE Collaboration

Abstract

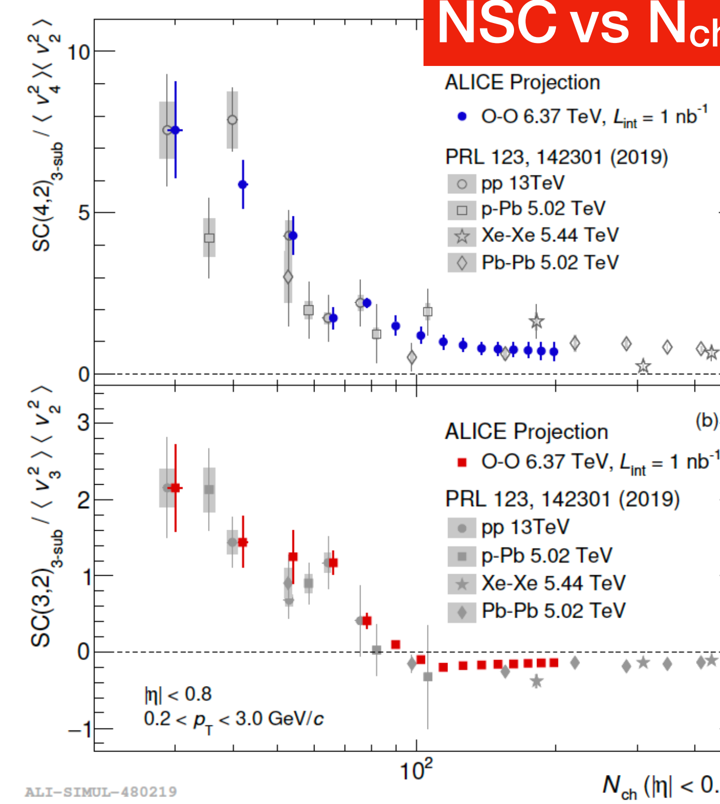
This document collects performance projections for a selection of measurements that can be carried out with a short O–O run during the LHC Run 3. The baseline centre-of-mass energy per nucleon–nucleon collision is $\sqrt{s_{NN}} = 6.37$ TeV and measurement uncertainties are given for the integrated luminosity $L_{int} = 1\ nb^{-1}$. 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)

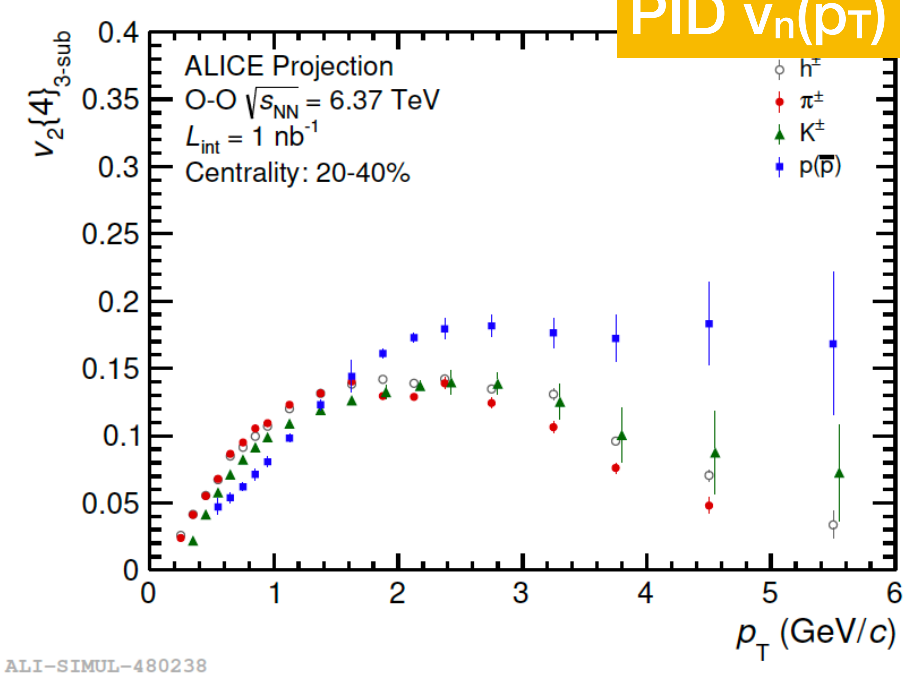
v_n vs N_{ch}



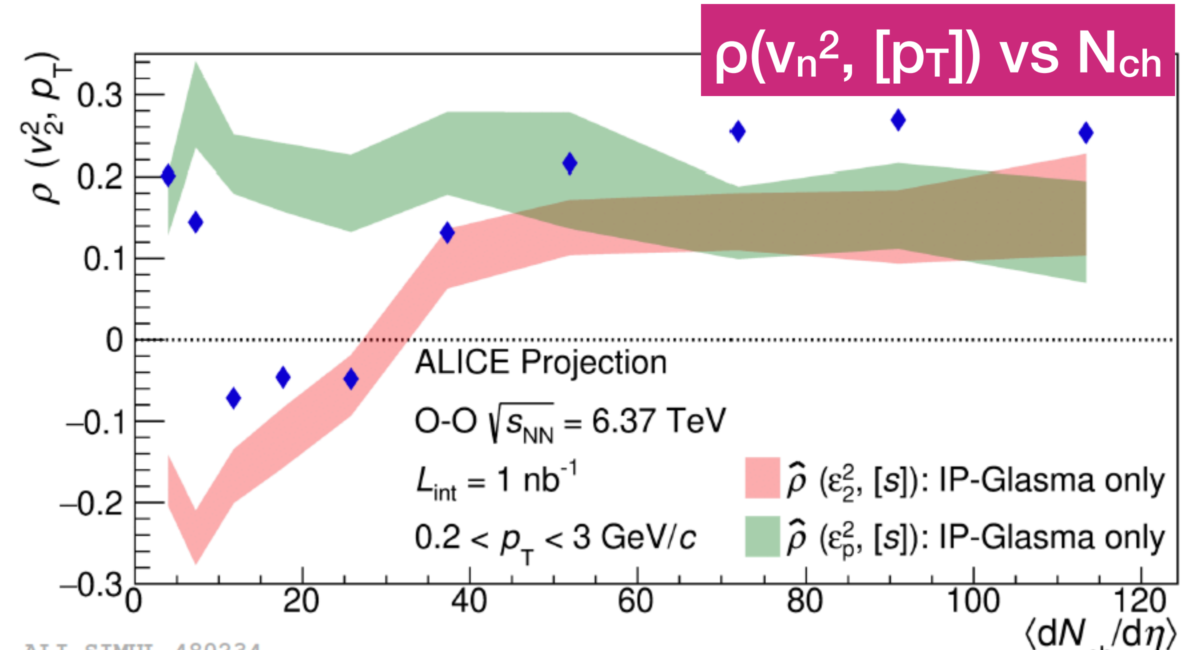
NSC vs N_{ch}



PID $v_n(p_T)$



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



Future possibilities at the LHC

Proposal for NuPECC Long-range plan

Imaging nuclear structure and quark-gluon plasma
at the Large Hadron Collider

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Abstract:

It has been established recently that nuclear collision experiments performed in high-energy collider machines, such as the CERN Large Hadron Collider (LHC), provide a novel tool to observe signatures of the shape and the radial structure of atomic nuclei. By taking *snaphots* of the state of the colliding ions at the interaction point, such experiments open an access route to a range of phenomena shaped by the collective behavior of nucleons that emerge from the strong nuclear force, such as nuclear deformations and neutron skins. The European nuclear community should explore the potential of a program of high-energy collisions across the Segrè chart to be pursued beyond LHC Run 3 to exploit the synergy between two areas of nuclear science. This will permit us, on the one hand, to advance our knowledge of the conditions that set the stage for the formation of quark-gluon plasma (QGP) in heavy-ion collisions and better constrain key physical parameters associated with the Hubble-like expansion of this medium. On the other hand, full exploitation of the LHC as an imaging tool will advance our understanding of strongly-correlated nuclear systems via probes and techniques complementary to those utilized in low-energy applications. Such studies will ultimately yield unique insight into the behavior of quantum chromodynamics (QCD) across systems and energy scales.

Proposal for US Long-range plan

arXiv > nucl-ex > arXiv:2209.11042

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Nuclear Experiment

[Submitted on 22 Sep 2022]

Imaging the initial condition of heavy-ion collisions and nuclear structure across the nuclide chart

Benjamin Bally, James Daniel Brandenburg, Giuliano Giacalone, Ulrich Heinz, Shengli Huang, Jiangyong Jia, Dean Lee, Yen-Jie Lee, Wei Li, Constantin Loizides, Matthew Luzum, Govert Nijs, Jacquelyn Noronha-Hostler, Mateusz Ploskon, Wilke van der Schee, Bjoern Schenke, Chun Shen, Vittorio Somà, Anthony Timmins, Zhangbu Xu, You Zhou

A major goal of the hot QCD program, the extraction of the properties of the quark gluon plasma (QGP), is currently limited by our poor knowledge of the initial condition of the QGP, in particular how it is shaped from the colliding nuclei. To attack this limitation, we propose to exploit collisions of selected species to precisely assess how the initial condition changes under variations of the structure of the colliding ions. This knowledge, combined with event-by-event measures of particle correlations in the final state of heavy-ion collisions, will provide in turn a new way to probe the collective structure of nuclei, and to confront and exploit the predictions of state-of-the-art ab initio nuclear structure theories. The US nuclear community should capitalize on this interdisciplinary connection by pursuing collisions of well-motivated species at high-energy colliders.

Comments: 23 pages, 6 figures
Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)
Cite as: arXiv:2209.11042 **[nucl-ex]**
(or arXiv:2209.11042v1 **[nucl-ex]** for this version)
https://doi.org/10.48550/arXiv.2209.11042

^{40}Ca, ^{48}Ca
^{20}Ne

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

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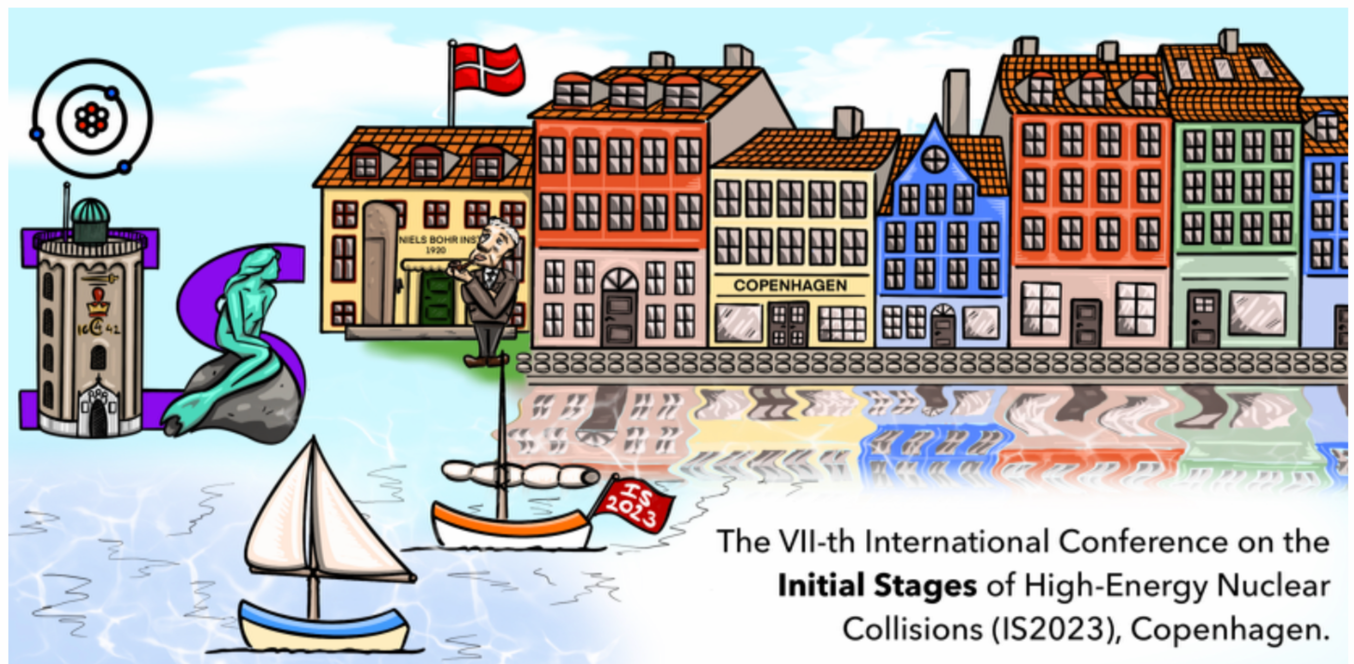


- Partonic structure of protons and nuclei PDF
- Physics at low-x and gluon saturation CGC
- The initial stages and nuclear structure in heavy-ion collisions IS
- Collective dynamics from small to large systems CD
- New theoretical techniques at large and small coupling NT
- New facilities: DIS and hadronic experiments FE

Initial Stages 2023

Banquet

Reception

IAC dinner

Boat tour

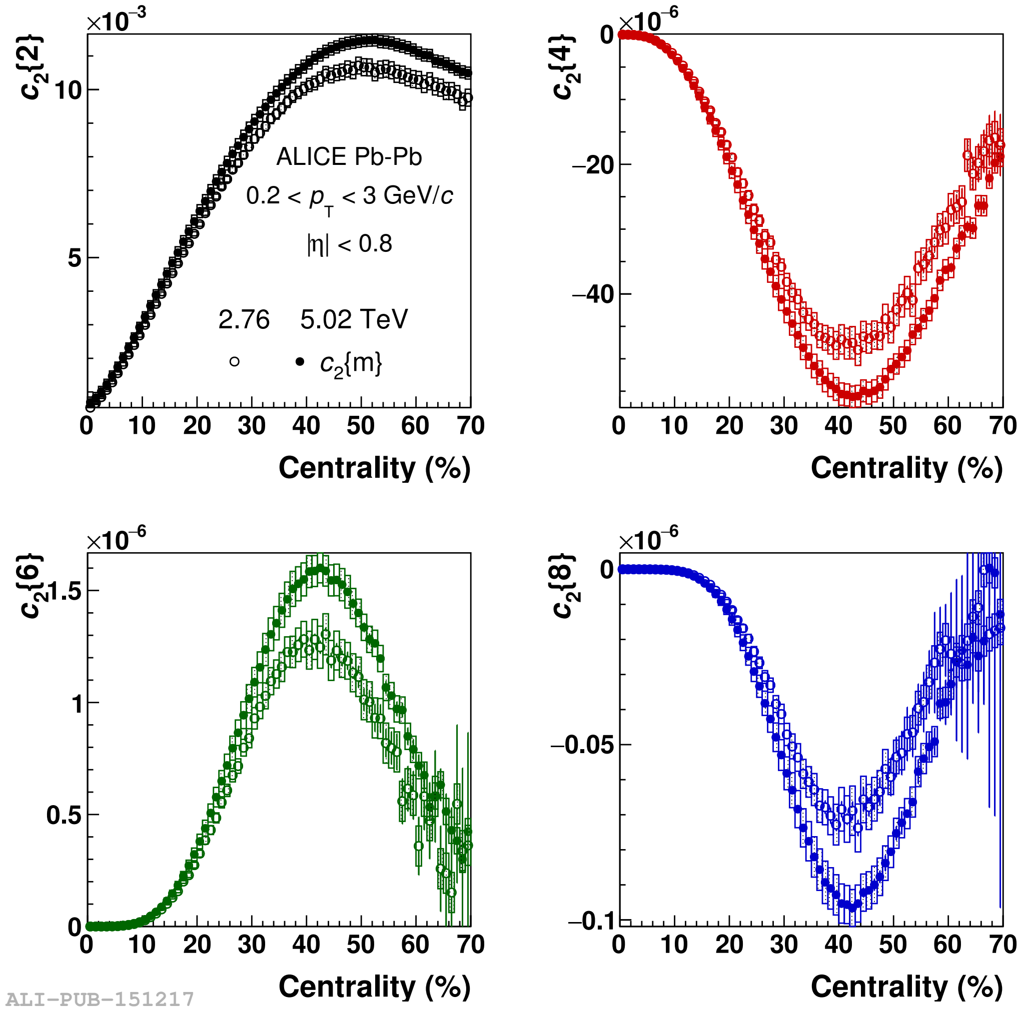
50+ junior supports (encourage all students and young postdocs to attend)

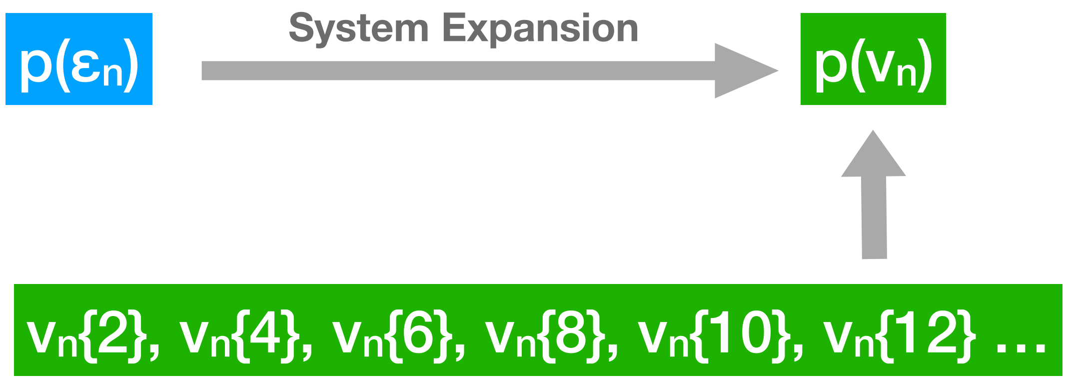
- **Hotels in Copenhagen during the entire conference for FREE**
- **Reduced conference fee**

Backup

P(v_n) from multi-particle cumulants of v_n

ALICE, JHEP 07 (2018) 103





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

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

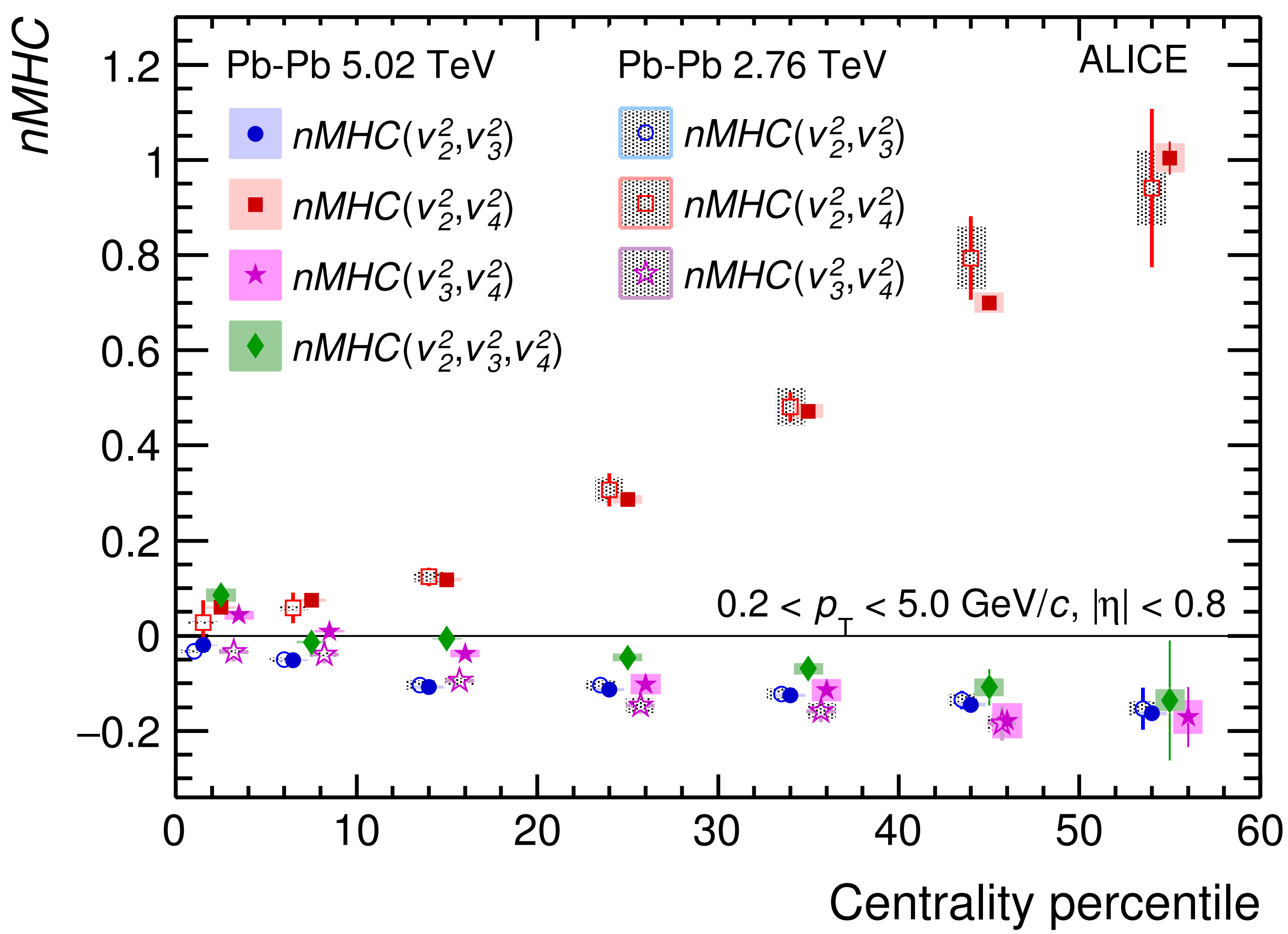
Multi-particle ***cumulants*** of single harmonic v_n

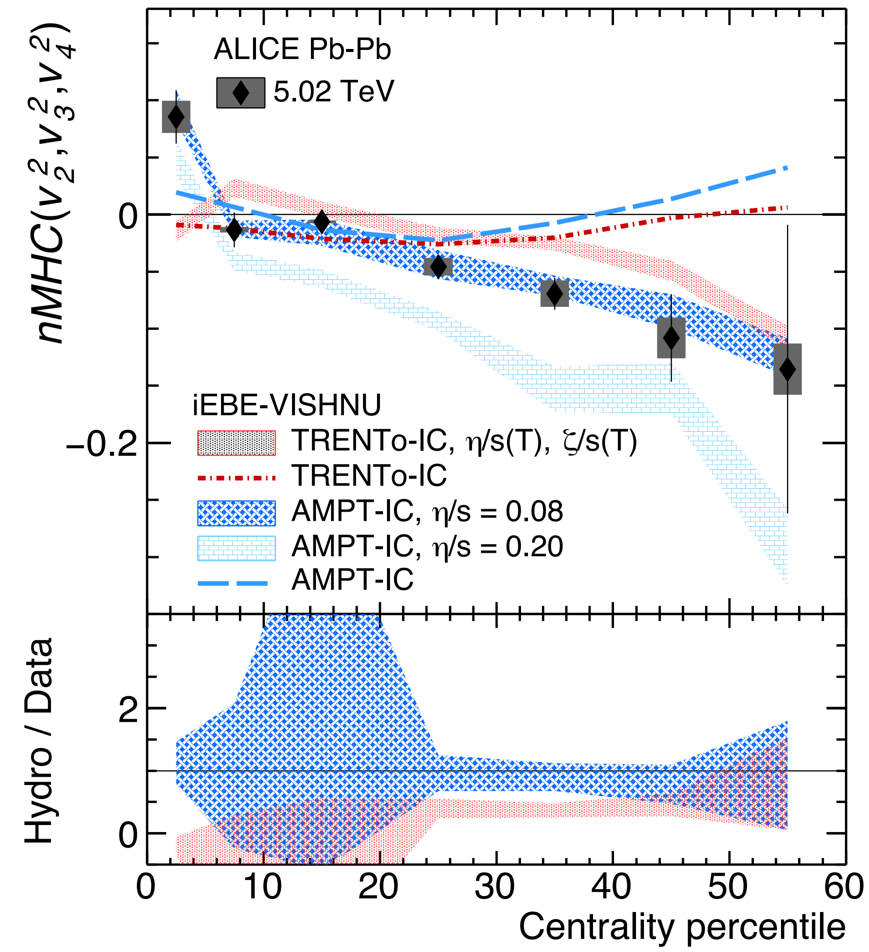
$$\langle\langle \cos(n\phi_1 - n\phi_2 + n\phi_3 - n\phi_4)\rangle\rangle_c = \langle \cos(n\phi_1 - n\phi_2 + n\phi_3 - n\phi_4)\rangle$$
$$- \langle\langle \cos(n\phi_1 - n\phi_2)\rangle\rangle \langle\langle \cos(n\phi_3 - n\phi_4)\rangle\rangle$$
$$- \langle\langle \cos(n\phi_1 - n\phi_4)\rangle\rangle \langle\langle \cos(n\phi_2 - n\phi_3)\rangle\rangle$$
$$= \left\langle v_n^4 \right\rangle - 2\left\langle v_n^2 \right\rangle^2$$

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

Correlations between v_m^2, v_n^2, v_k^2,…

ALICE, PLB818 (2021) 136354



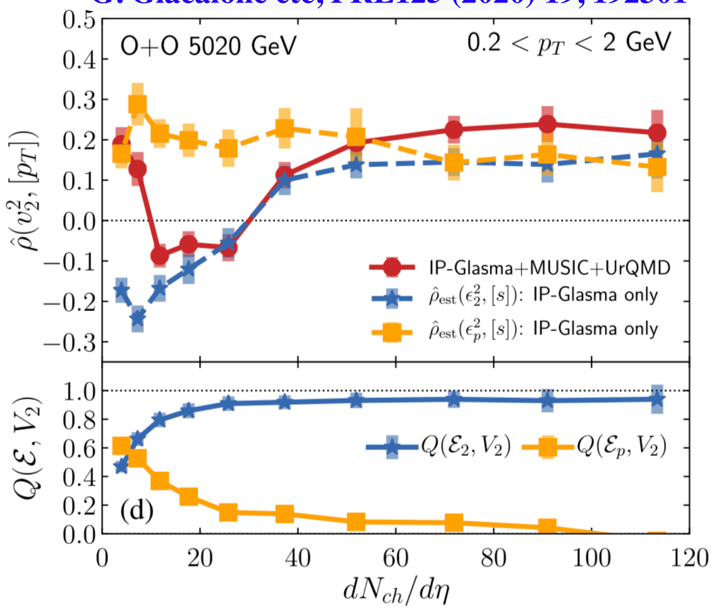


$$\mathrm{MHC}(v_2^2, v_3^2, v_4^2) = \langle\langle e^{i(2\varphi_1+3\varphi_2+4\varphi_3-2\varphi_4-3\varphi_5-4\varphi_6)}\rangle\rangle_c$$
$$= \langle v_2^2\, v_3^2\, v_4^2\rangle - \langle v_2^2\, v_3^2\rangle\langle v_4^2\rangle - \langle v_2^2\, v_4^2\rangle\langle v_3^2\rangle$$
$$-\langle v_3^2\,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

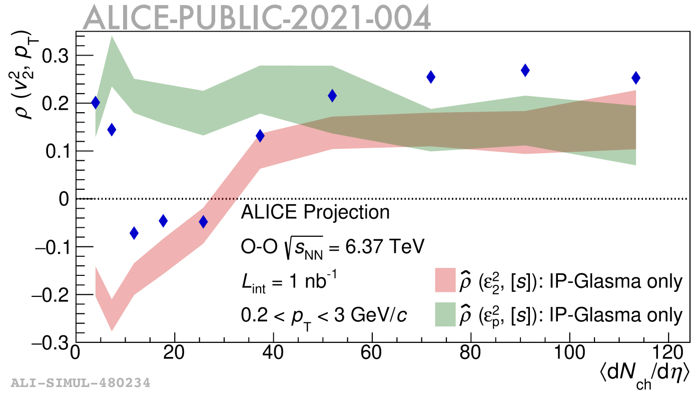
- ❖ Non-zero value of *nMHC*(v_2^2, v_3^2, v_4^2) in Pb-Pb collisions
  - Highly non-trivial correlations among three flow coefficients

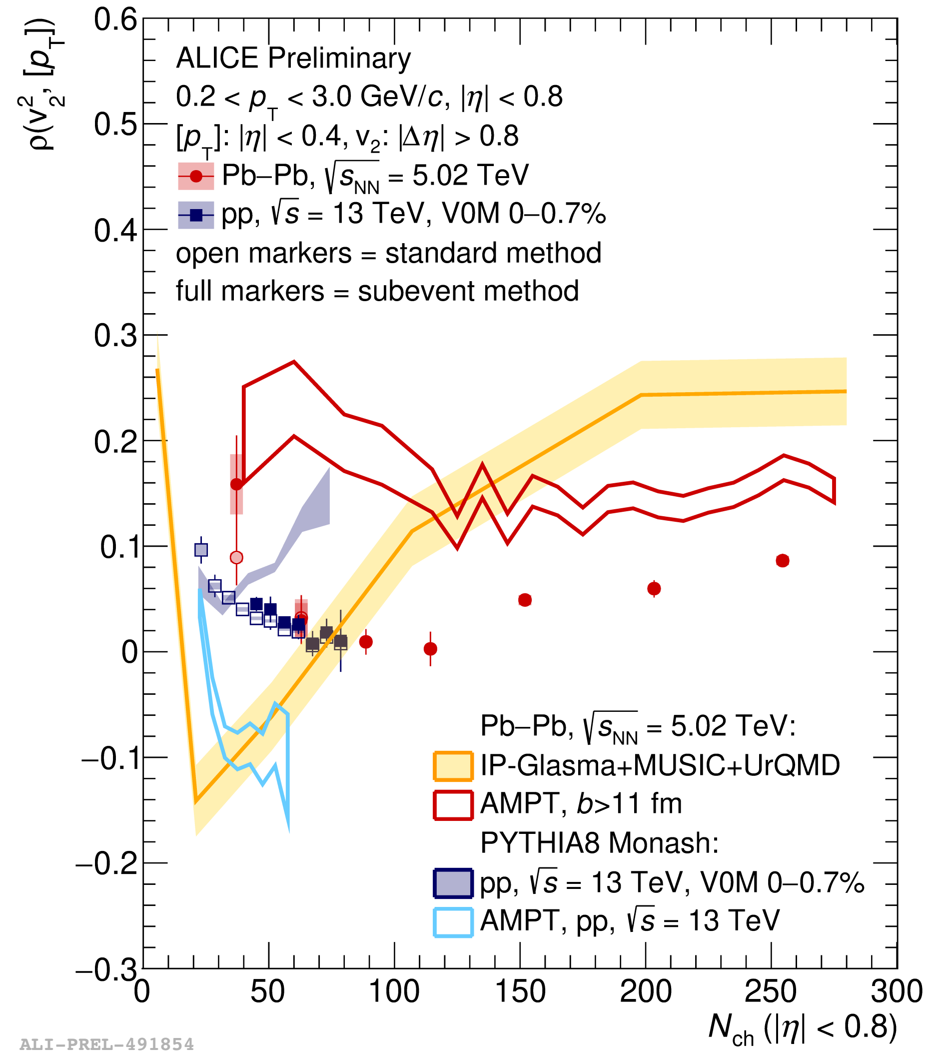
More results in smaller colliding systems

G. Giacalone etc, PRL125 (2020) 19, 192301



ALICE-PUBLIC-2021-004





- 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

Higher-order correlations

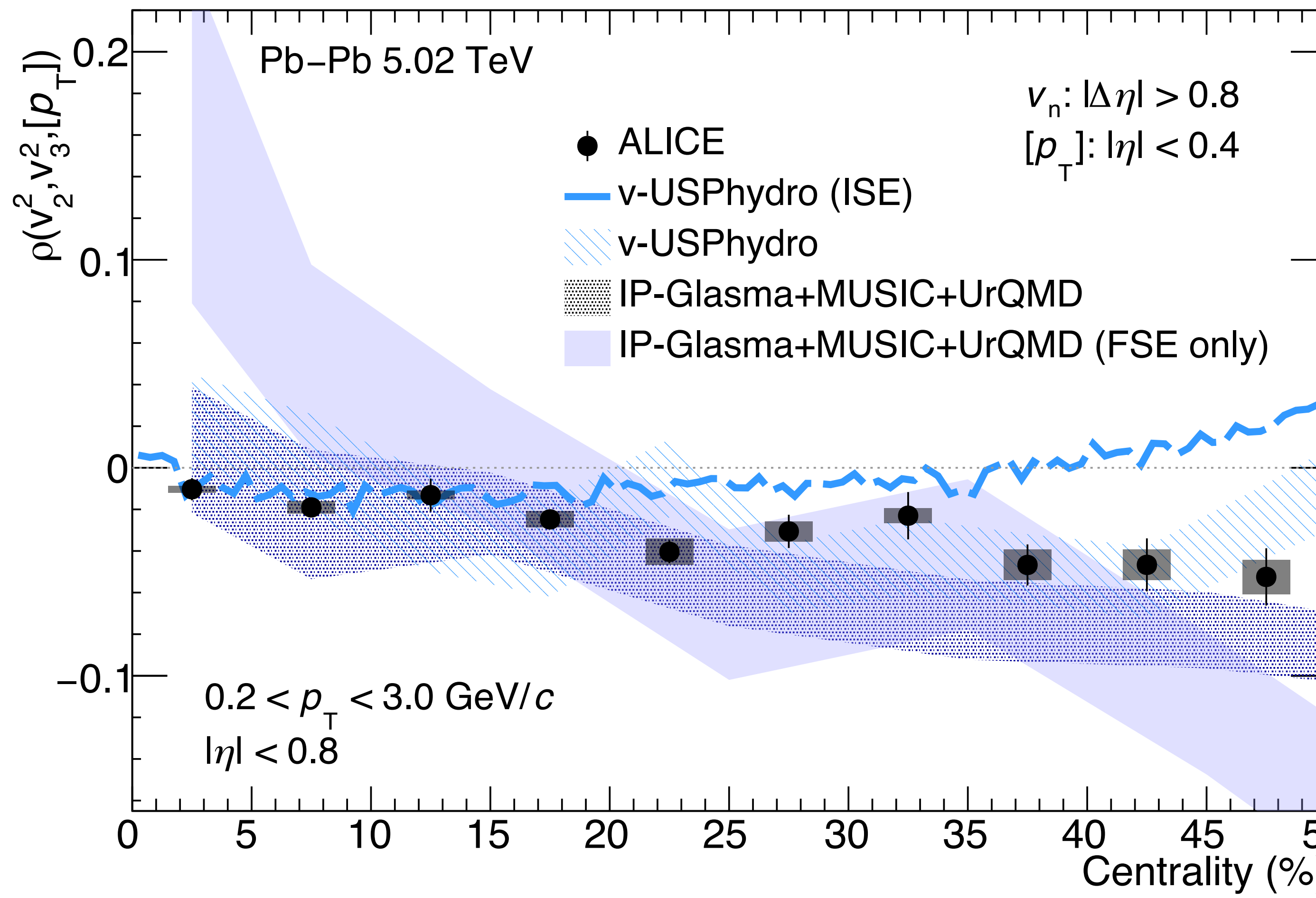
❖ The **first** measurement of higher-order $[p_T]$, v_2 and v_3 correlations P. Bozek etc, PRC104 (2021) 1, 014905

$$\rho(v_m^2, v_n^2, [p_T]) = \frac{C(v_m^2, v_n^2, [p_T])}{\sqrt{\mathrm{Var}(v_m^2)}\sqrt{\mathrm{Var}(v_n^2)}\sqrt{c_k}} - \frac{\langle v_m^2\rangle}{\sqrt{\mathrm{Var}(v_m^2)}} \cdot \rho_n - \frac{\langle v_n^2\rangle}{\sqrt{\mathrm{Var}(v_n^2)}} \cdot \rho_m - \frac{\langle [p_T]\rangle}{\sqrt{c_k}} \cdot \frac{SC(m,n)}{\sqrt{\mathrm{Var}(v_m^2)}\sqrt{\mathrm{Var}(v_n^2)}},$$

❖ 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

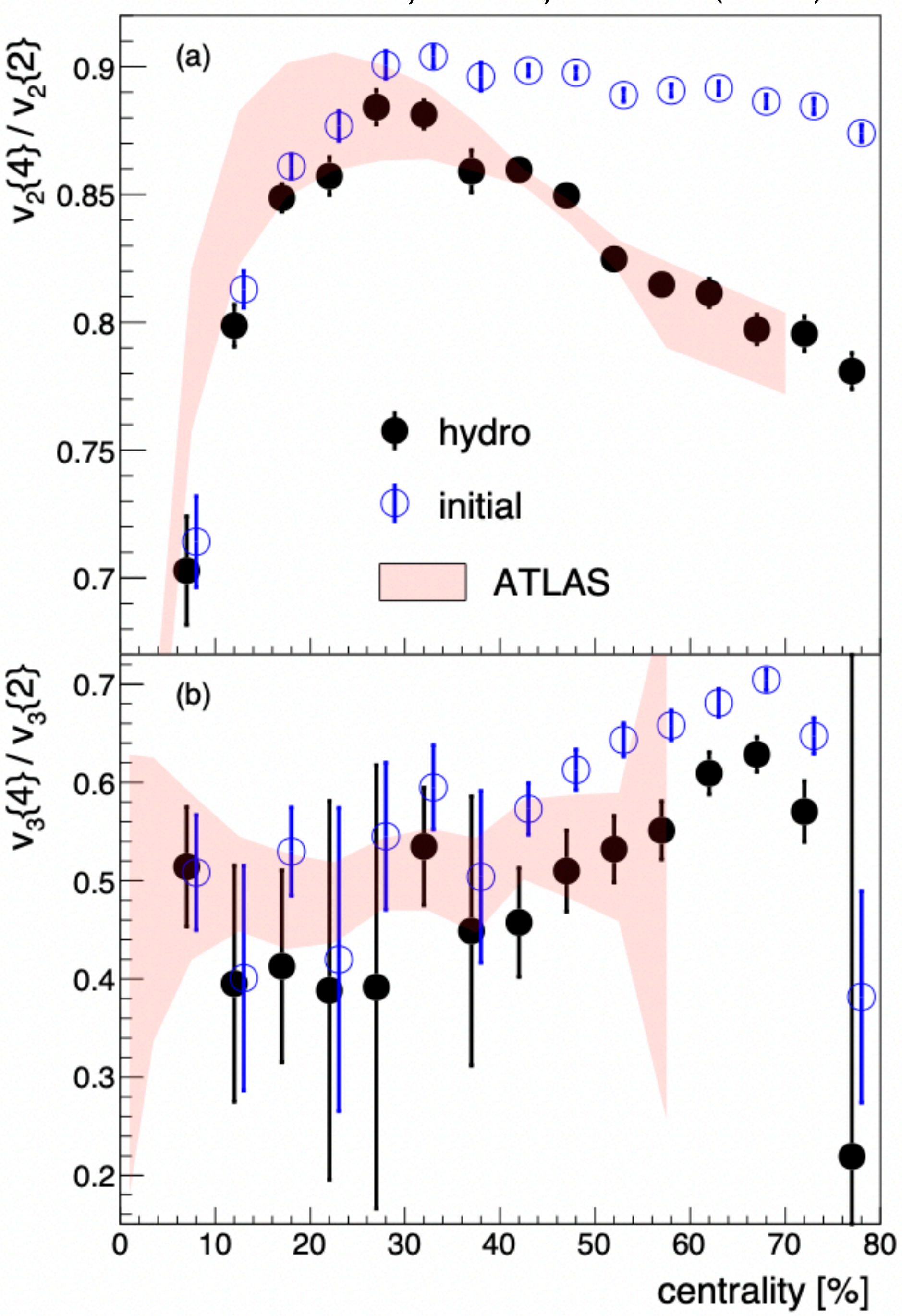
❖ Not conclusive on which model works better due to sizeable uncertainties from model calculations

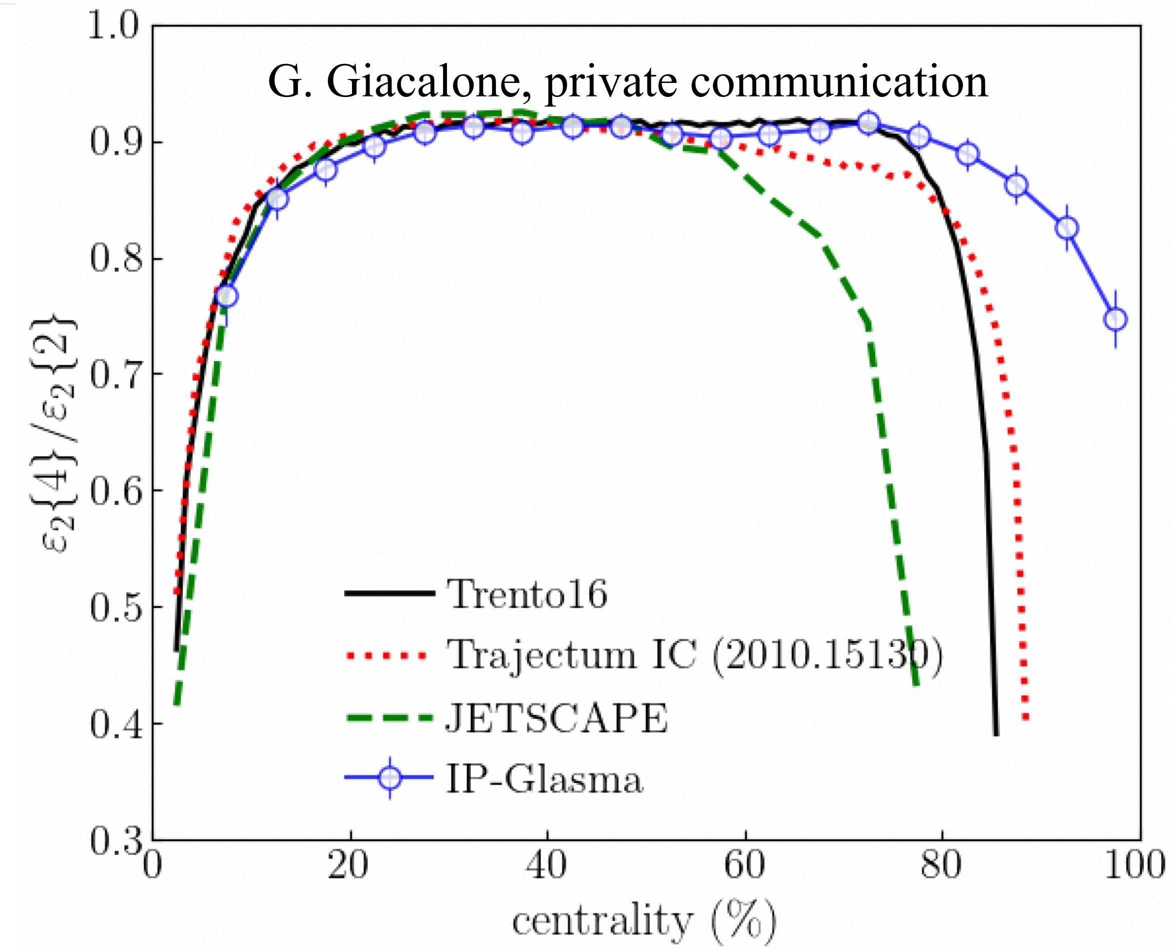


Event-by-event v_n fluctuations

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

G. Giacalone etc, PRC95, 054910 (2017)





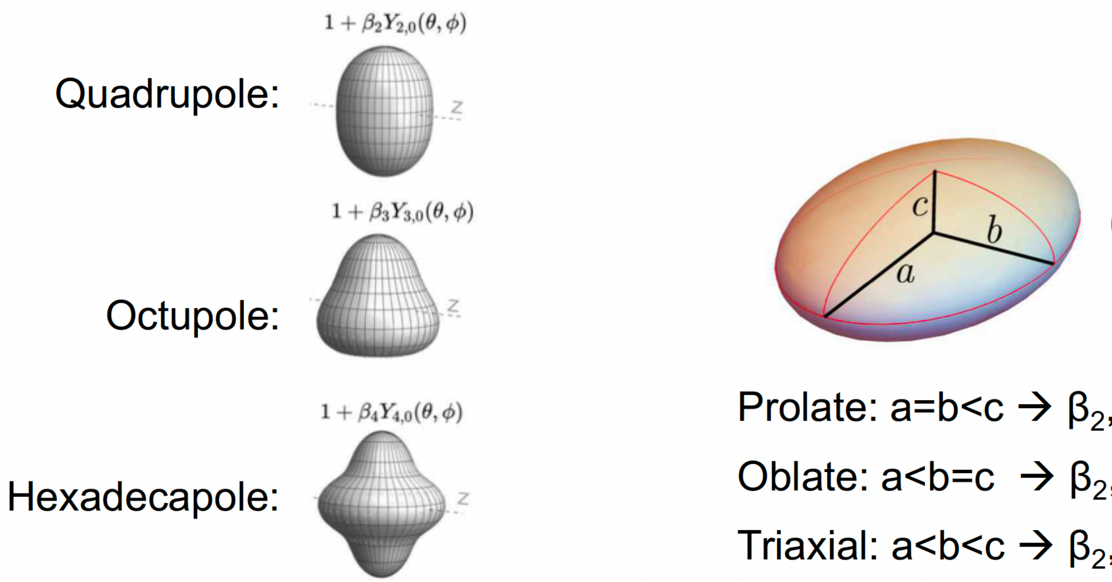
Minor difference from IS models

- 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

Explore nuclear structure with AMPT

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r - R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0\left(1 + \beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}] + \beta_3 \sum_{m=-3}^{3} \alpha_{3,m} Y_{3,m} + \beta_4 \sum_{m=-4}^{4} \alpha_{4,m} Y_{4,m}\right)$$



$0 \le \gamma \le \pi/3$

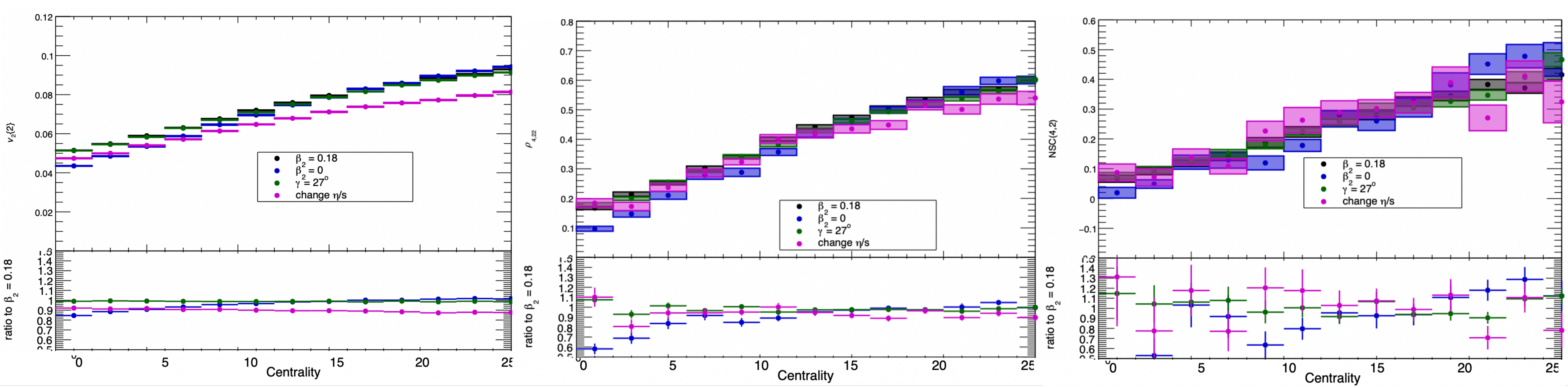
Prolate: a=b<c → β_2, γ=0

Oblate: a<b=c → β_2, γ=π/3

Triaxial: a<b<c → β_2, γ=π/6

- ● $\beta_2 = 0.18$
- ● $\beta_2 = 0$
- ● $\gamma = 27^o$
- ● change η/s

- Current findings: all "flow" observables with only azimuthal angle correlation -> β_2 but not γ



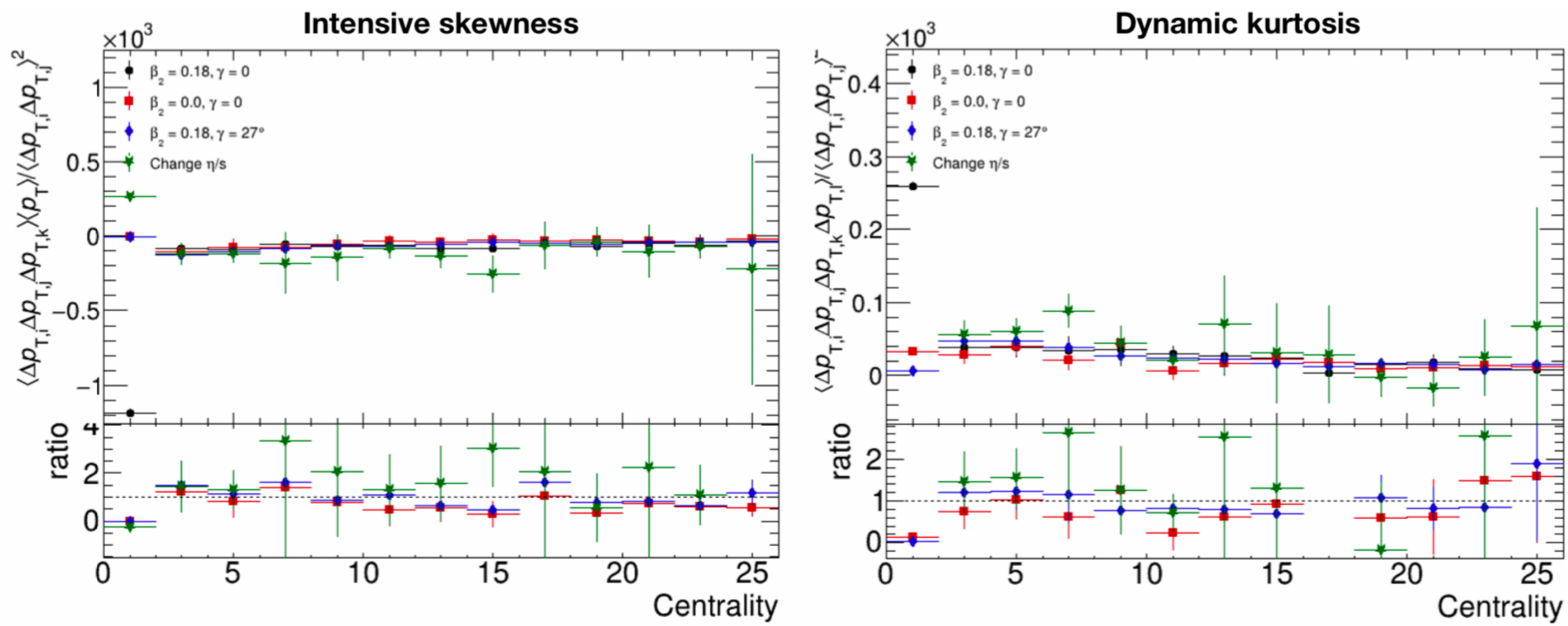
Study from isobar runs for v2{2}, v2{4}, delta_2 which was used to probe nuclear structure R, a_0.

What will be the possibility to study ^{129}Xe?

My guess is that different from Pb-Pb collisions, where e_RP ~ 0 in the most central collisions, the e_RP has a finite value in the most central Xe-Xe collisions

Bread & butter measurements, some of which to be available this summer

Results from AMPT



- Currently too large uncertainties