Collectivity in small systems: status, prospects, interdisciplinary connections

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November 17th 2022

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

isoQuant SFB1225

13th International workshop on Multiple Partonic Interactions at the LHC

OUTLINE

1 – Small system collectivity.

2 – Dynamics.

3 – Initial conditions.

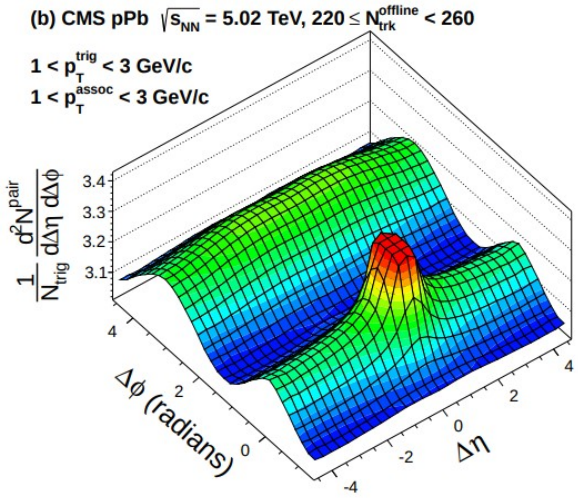
4 – Prospects with light ions.

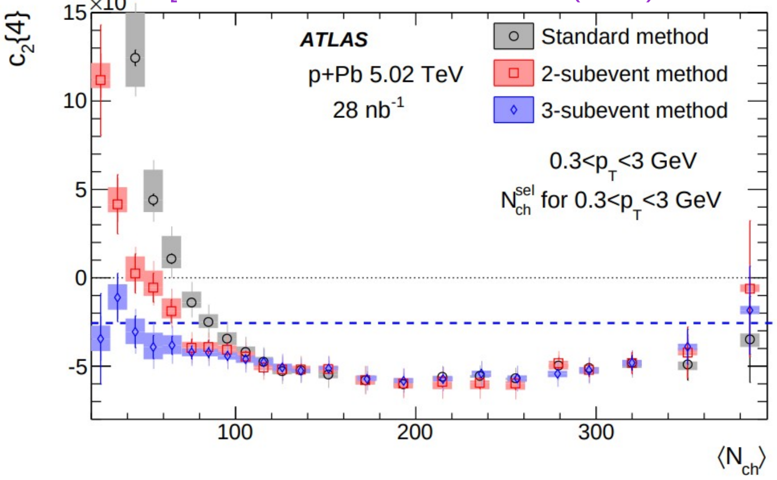
Conclusion

1 – Small system collectivity.

Robust signals of collectivity in small systems

p+Pb

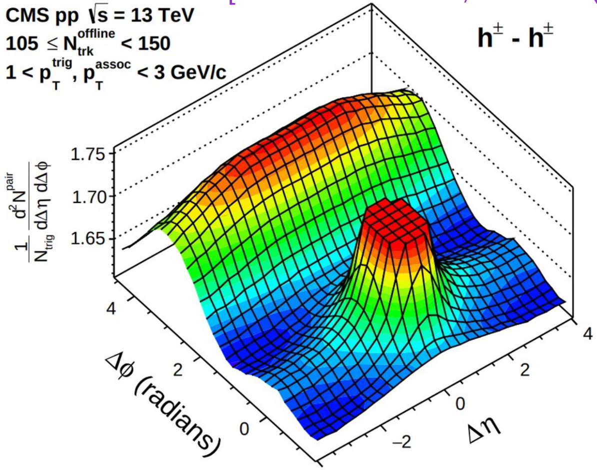


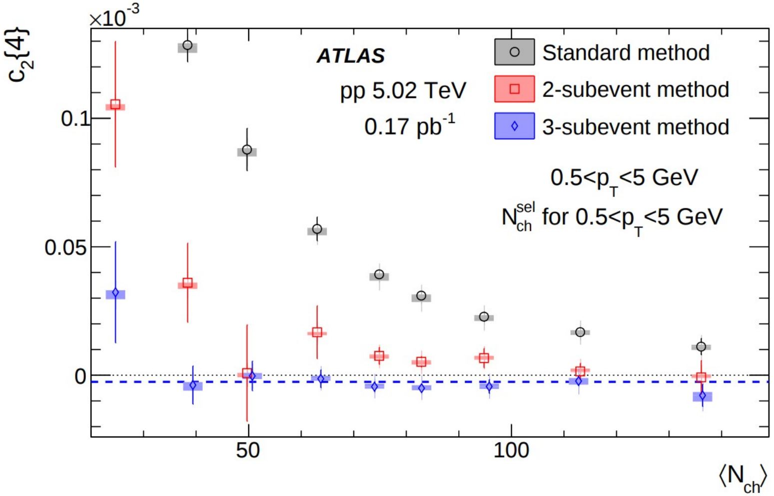


[ATLAS collaboration, PRC **97** (2018) 2, 024904]

[CMS collaboration, PLB **724** (2013) 213-240]
[CMS collaboration, PLB **765** (2017) 193-220]

p+p





In a "small system", hydro description is hard to justify.
Fluid dynamics applicable if:

$$\frac{\eta}{e+\mathcal{P}}\frac{1}{\tau} \ll 1$$

D. Teaney, QGP4 [arXiv:0905.2433]

In practice:

$$\underbrace{\frac{\eta}{s}}_{\text{medium parameter}} \times \underbrace{\frac{1}{\tau T}}_{\text{experimental parameter}} \ll 1$$

Phenomenological values:

$$\rightarrow \underline{0.2}\left(\frac{\eta/s}{0.3}\right)\left(\frac{1\,\mathrm{fm}}{\tau_o}\right)\left(\frac{300\,\mathrm{MeV}}{T_o}\right) \ll 1$$

Borderline already for 'optimal' A-A scenario.

Small system: time scale of the interaction (equilibration) as large as the system size.

Small systems allow us to assess the origin of emergent hydrodynamic behavior

AMAZING EXPERIMENTAL PROGRAM
(“simple” integrated quantities)

- Cumulants of anisotropic flow $\qquad v_2\{2,4,6,8\} \quad v_3\{2,4\} \quad v_4\{2\}$

- Flow magnitude correlations $\qquad \langle v_2^2 v_3^2 \rangle \quad \langle v_2^2 v_4^2 \rangle$

- Event-plane correlations $\qquad \langle V_2^2 V_4^* \rangle$

- Flow-mean p_t correlations $\qquad \langle v_2^2 \langle p_t \rangle \rangle \quad \langle v_3^2 \langle p_t \rangle \rangle$

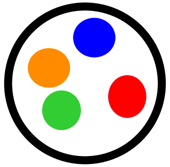
All the information is there. Theory?

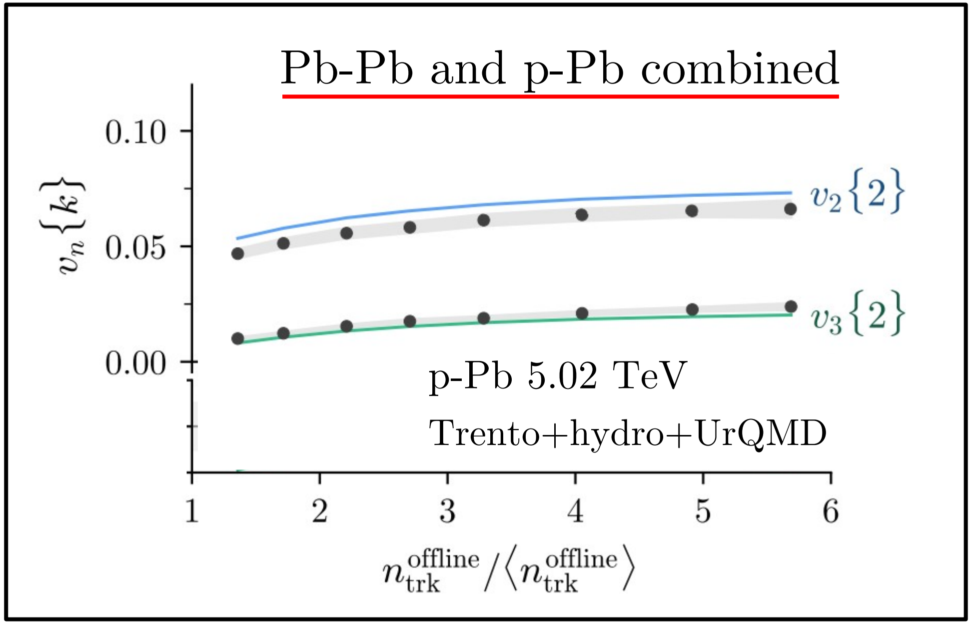
Theory? data-driven consistency between p-Pb and Pb-Pb (Bayesian analyses).

energy deposition

$$dE/dy(\tau = 0^+) \propto (T_A T_B)^{1/2}$$

nucleon structure





[Bass, Bernhard, Moreland, PRC **101** (2020) 2, 024911]
[Nijs, van der Schee, Gürsoy, Snellings, PRL **126** (2021) 20, 202301]

SEEMINGLY SUCCESSFUL PARADIGM FOR BASIC OBSERVABLES:

Nuclei with sub-nucleonic structure + CGC-like energy deposition / early phase + hydrodynamics

Good baseline. Understanding the details?

2 – Dynamics.

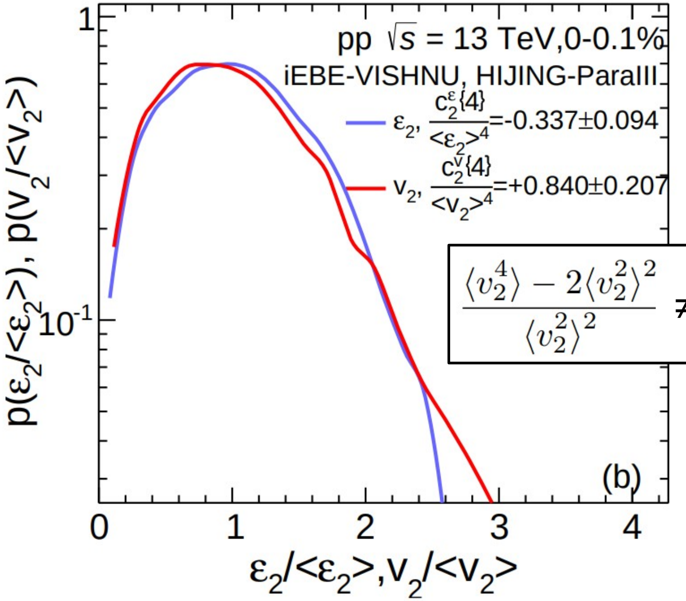
Dynamical evolution more important in a small system.

$$V_n = \sum_{m=n}^{\infty} \kappa_{n,m} \mathcal{E}_{n,m} \quad + \quad \text{higher orders}$$

$$(1/\text{system size})^{\text{m}}$$

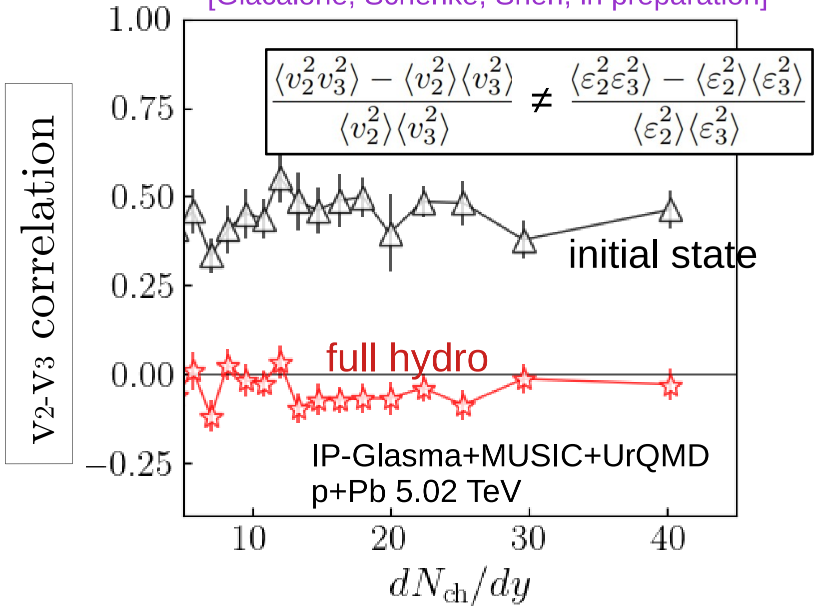
Linear response to eccentricity not enough.

[Zhao *et al.*, EPJC **80** (2020) 9, 846]



$$\frac{\langle v_2^4\rangle - 2\langle v_2^2\rangle^2}{\langle v_2^2\rangle^2} \neq \frac{\langle \varepsilon_2^4\rangle - 2\langle \varepsilon_2^2\rangle^2}{\langle \varepsilon_2^2\rangle^2}$$

[Giacalone, Schenke, Shen, in preparation]



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

Elucidating the dynamics: medium response as a function of system size.

$$v_2/\varepsilon_2$$

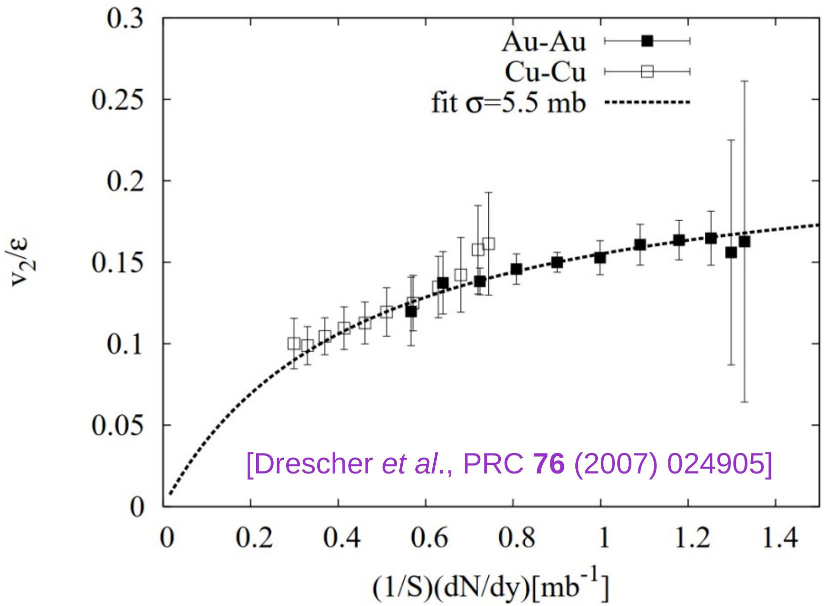
[Voloshin, Poskanzer, PLB **474** (2000) 27-32]

New opacity variable.

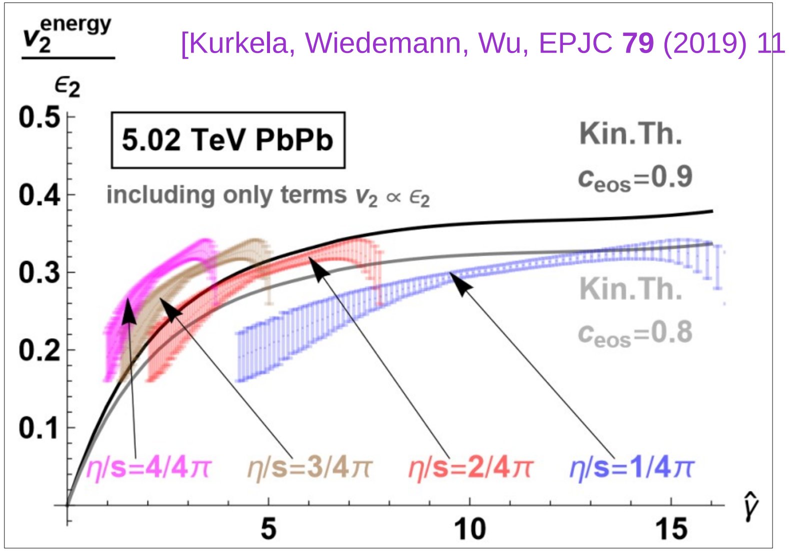
$$\hat{\gamma} = R^{3/4}\gamma(\,\varepsilon_0\tau_0)^{1/4}$$

[Kurkela, Wiedemann, Wu, PLB **783** (2018) 274-279]

- min. bias pp: $\hat{\gamma} \approx 0.88 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.4\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{5\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{40}\right)^{-1/4}$
- central PbPb: $\hat{\gamma} \approx 9.2 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{6\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{4000\,\mathrm{GeV}}\right)^{1/4} \left(\frac{\nu_{\mathrm{eff}}}{40}\right)^{-1/4}$



[Drescher *et al.*, PRC **76** (2007) 024905]

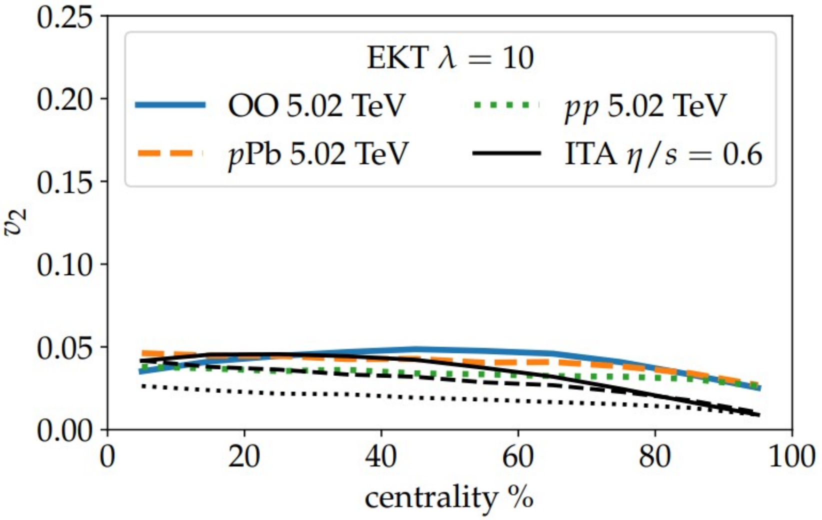


[Kurkela, Wiedemann, Wu, EPJC **79** (2019) 11, 965]

Progress with kinetic theory simulations.

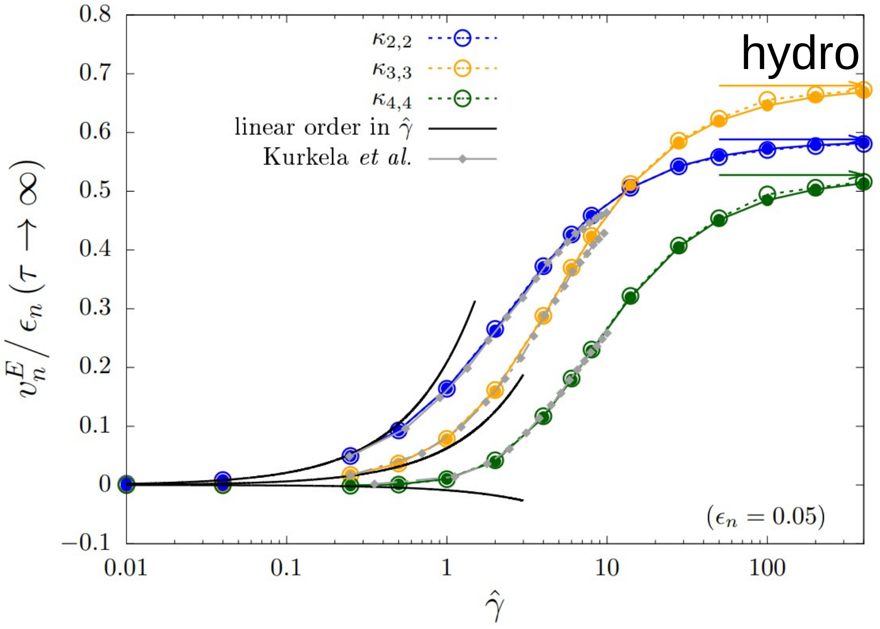
Implementations of QCD effective kinetic theory kernel (single hit).

[Kurkela, Mazeliauskas, Törnkvist, JHEP 11 (2021) 216]



Methods for full solution of kinetic theory (RTA) with detailed transverse profiles.

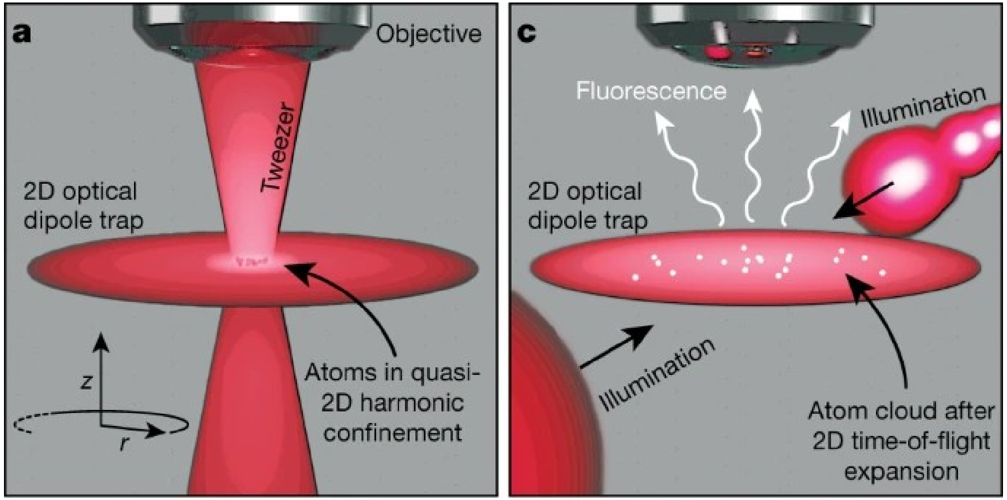
[Kurkela *et al.*, PLB **811** (2020) 135901]
[Ambrus, Schlichting, Werthmann, PRD **105** (2022) 1, 014031]



New Monte Carlo and analytical methods for billiard ball calculations.

[Borghini,Roch, EPJC **81** (2021) 5, 380]
[Borrell, Borghini, EPJC **82** (2022) 6, 525]
[Borghini, Borrell, Roch, EPJC **82** (2022) 10, 961]

[from Holten et al., Nature **606**, 287-291 (2022)]

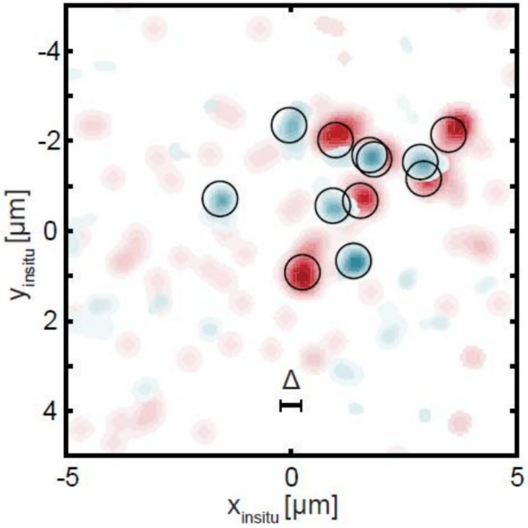


Addressing collectivity with controllable quantum systems.

@Heidelberg University

We use an ultracold gas of ^{6}Li atoms with tunable:

– Geometry
– Particle number
– Inter-atom interaction

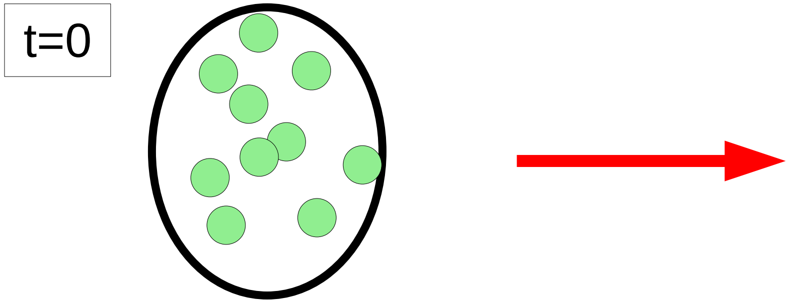


Emergent hydrodynamics in few-body systems?

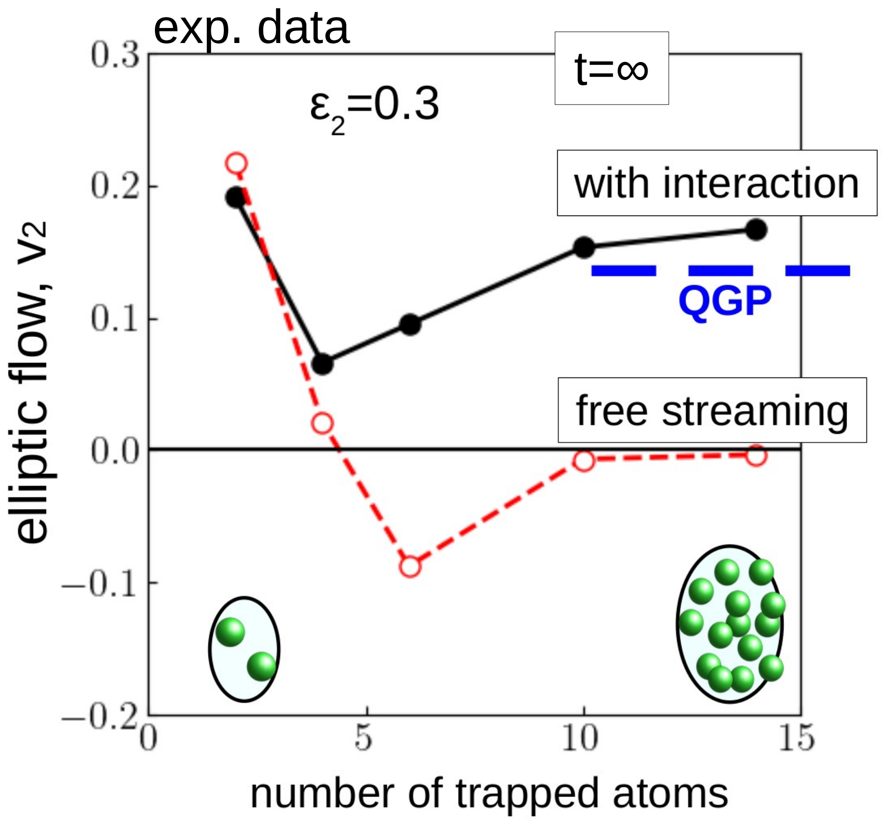
[Floerchinger, Giacalone, Heyen, Tharwat, PRC **105**, 044908 (2022)]

Strongly-interacting atoms in an elliptical trap.

Measure elliptic flow after time of flight.



[Brandstetter et al., **in preparation**]



Robust conclusion:
Emergent hydrodynamic behavior can happen with just 10 (strongly-interacting) particles.

Looking forward: Out-of-equilibrium dynamics. Hydrodynamization? Attractors?

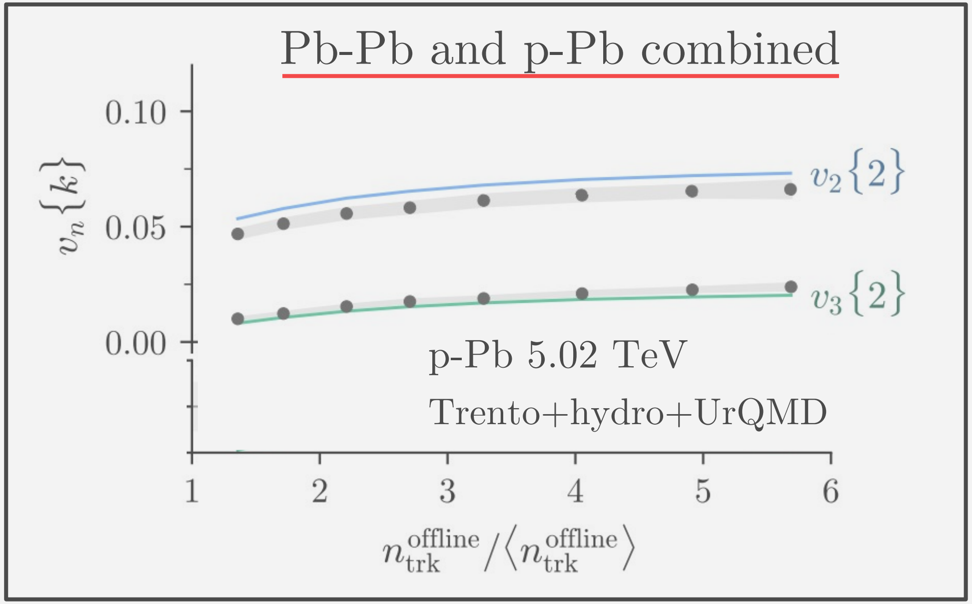
3 – Initial conditions.

Theory? data-driven consistency between p-Pb and Pb-Pb (Bayesian analyses).

energy deposition

$$dE/dy(\tau = 0^+) \propto (T_A T_B)^{1/2}$$

nucleon structure



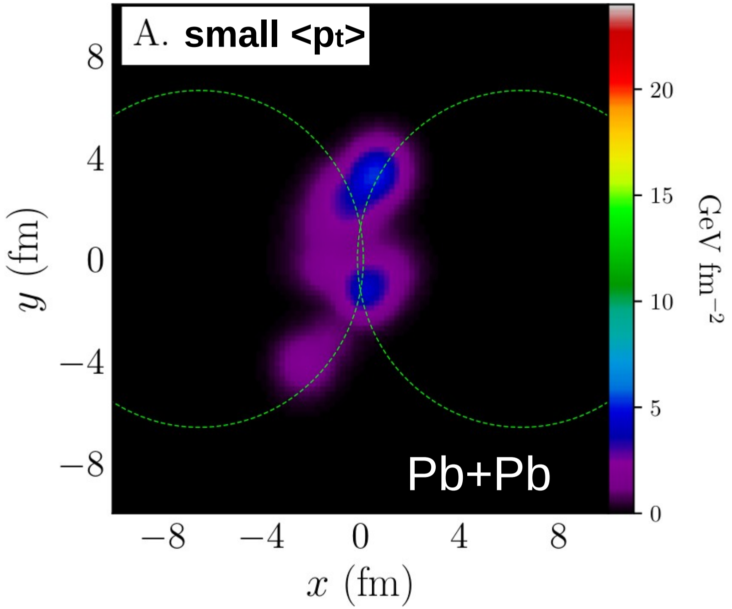
nuclei with sub-nucleonic structure + CGC-like energy deposition / early phase

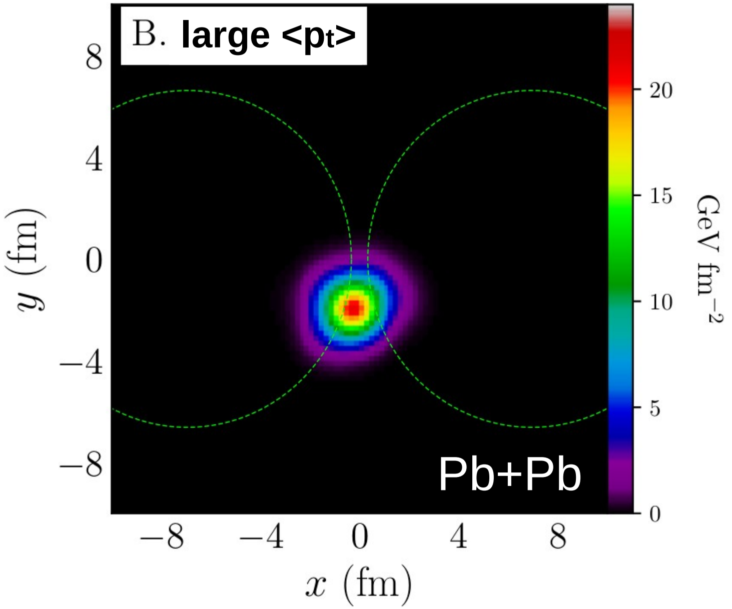
Can we validate this in small systems alone (without A-A)?

Manipulating the collision geometry in small systems.

At large mean pt, hot spots are clustered around one point.

[Schenke, Shen, Teaney, PRC **102** (2020) 3, 034905]





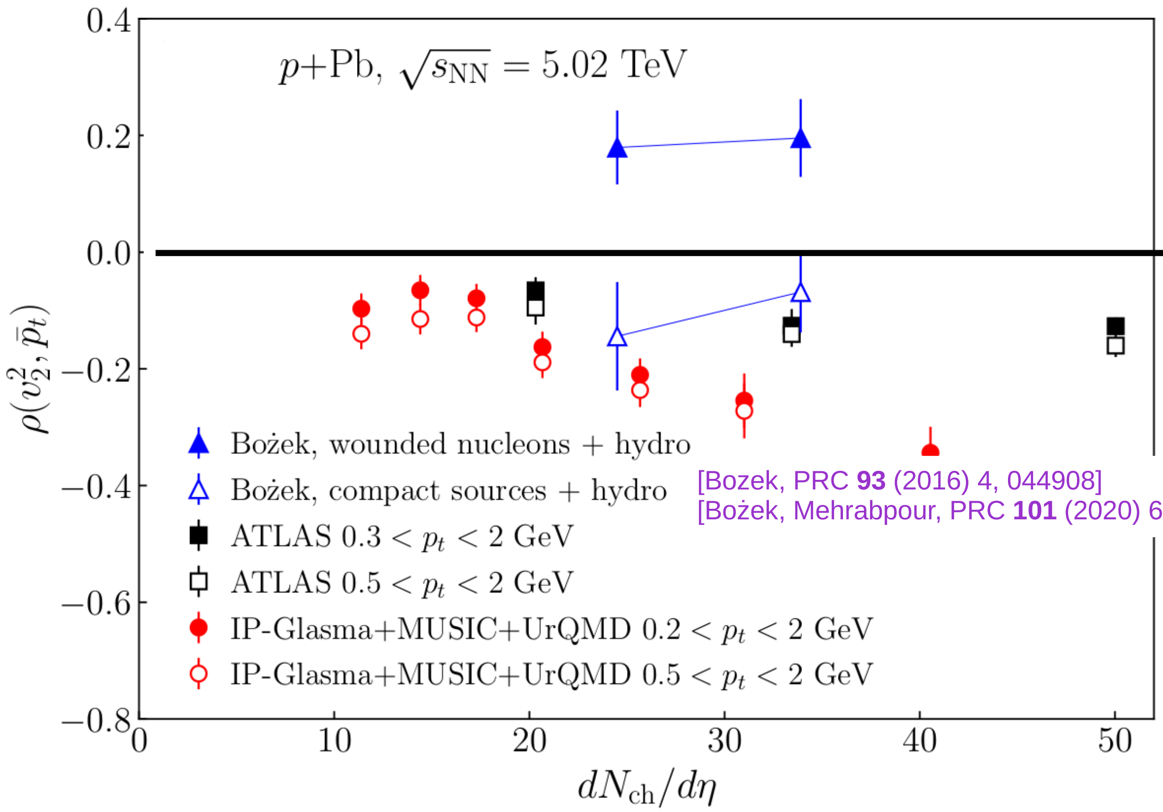
event	A	B
N_{ch}	134	134
b (fm)	13.0	13.9
$[p_t]/\langle[p_t]\rangle$	0.907	1.143
R (fm)	2.97	1.34
ε_2	0.675	0.133
ε_3	0.229	0.067

Predicts negative correlation between anisotropy and mean momentum.

$$\rho(v_n^2, [p_t]) < 0$$

Data confirms the generic prediction. $\rho(v_n^2, [p_t]) < 0$

[ATLAS collaboration, EPJC **79** (2019) 12, 985]



[Bozek, PRC **93** (2016) 4, 044908]
[Bożek, Mehrabpour, PRC **101** (2020) 6, 064902]

wounded nucleons

$$(T_A + T_B)$$

CGC- or TRENTo-like

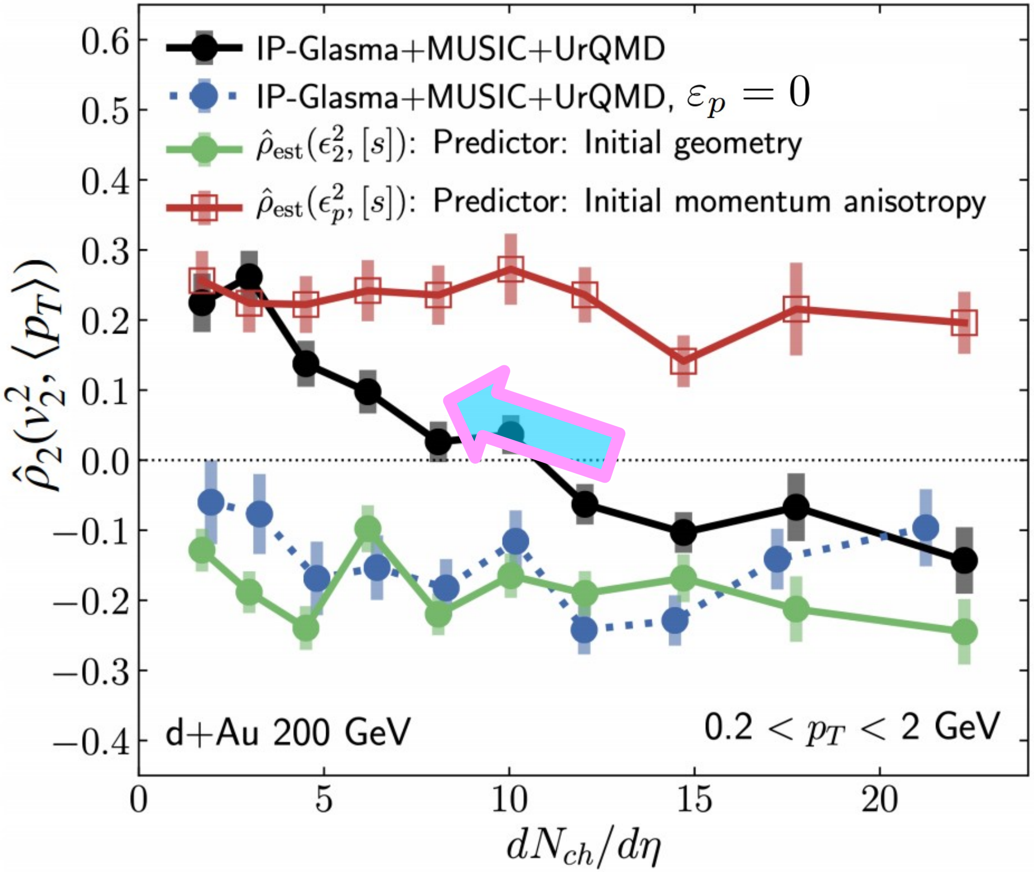
$$\left(T_A(\mathbf{x})T_B(\mathbf{x})\right)^q$$

Constrains the energy deposition in pA collisions (independent of AA)!

Paradigm with active sub-nucleonic structure is favored.

Lower multiplicities: Potential window onto primordial momentum anisotropy.

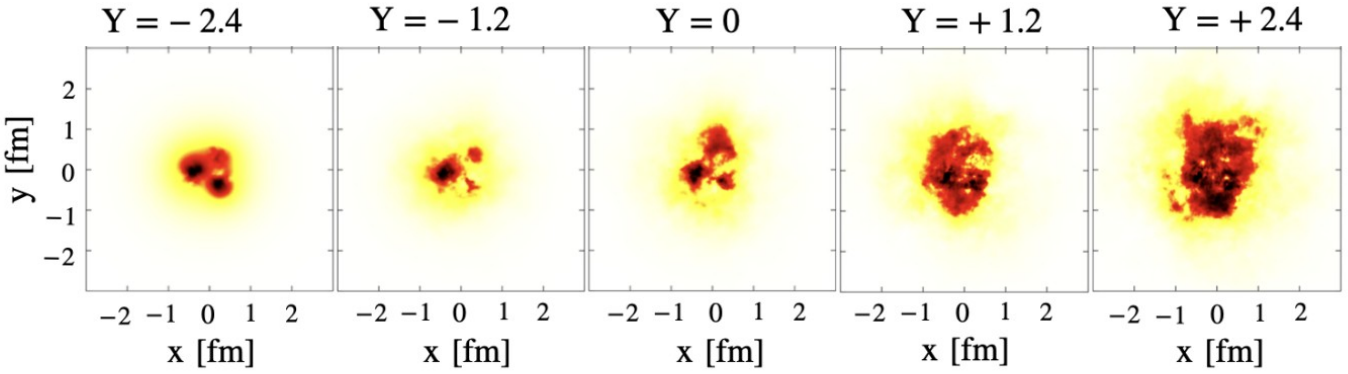
[Giacalone, Schenke, Shen, PRL. **125** (2020) 19, 192301]



Competing effects from non-flow models.

[Zhang *et al.*, PLB **822** (2021) 136702]
[Lim, Nagle, PRC **103** (2021) 6, 064906]

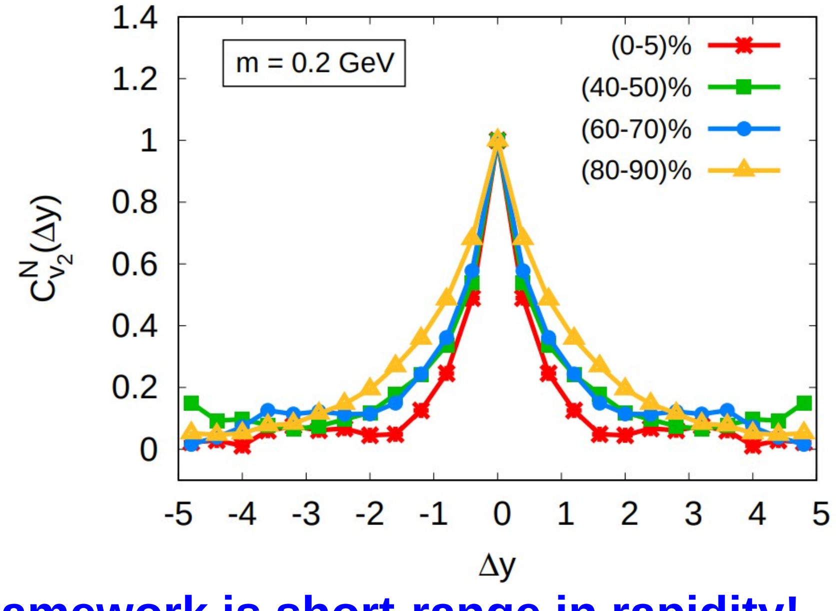
Assessing robustness of prediction. Role of longitudinal structure.



Anisotropy of gluon spectrum in
3+1D IP-Glasma implementation:

$$v_2^g(y) = \frac{\int d^2\mathbf{k}_\perp |\mathbf{k}_\perp| \frac{dN_g}{dyd^2\mathbf{k}_\perp}(y) e^{2i\phi_{\mathbf{k}_\perp}}}{\int d^2\mathbf{k}_\perp |\mathbf{k}_\perp| \frac{dN}{dyd^2\mathbf{k}_\perp}(y)}$$

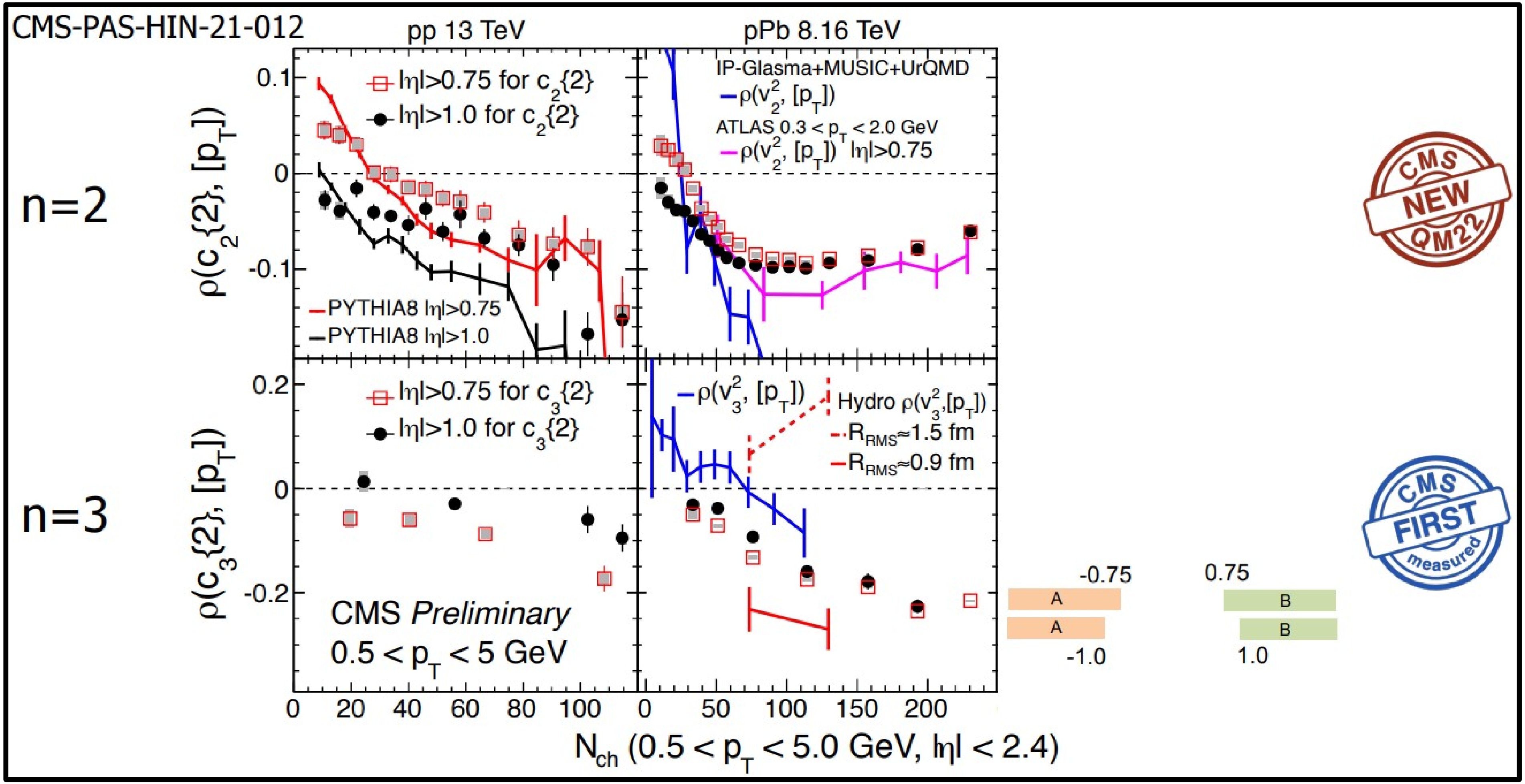
[Schenke, Schlichting, Singh, PRD **105** (2022) 9, 094023]



Primordial momentum anisotropy in CGC framework is short-range in rapidity!

Signal goes down with larger η gap. We need a three-dimensional model.

[Shengquan Tuo, Quark Matter 22]



More on longitudinal structure.

$v_3[^3He+Au] > v_3\,[d+Au], v_3[p+Au]$

[PHENIX collaboration, Nature Phys. **15** (2019) 3, 214-220]

$v_3[^3He+Au] = v_3\,[d+Au], v_3[p+Au]$

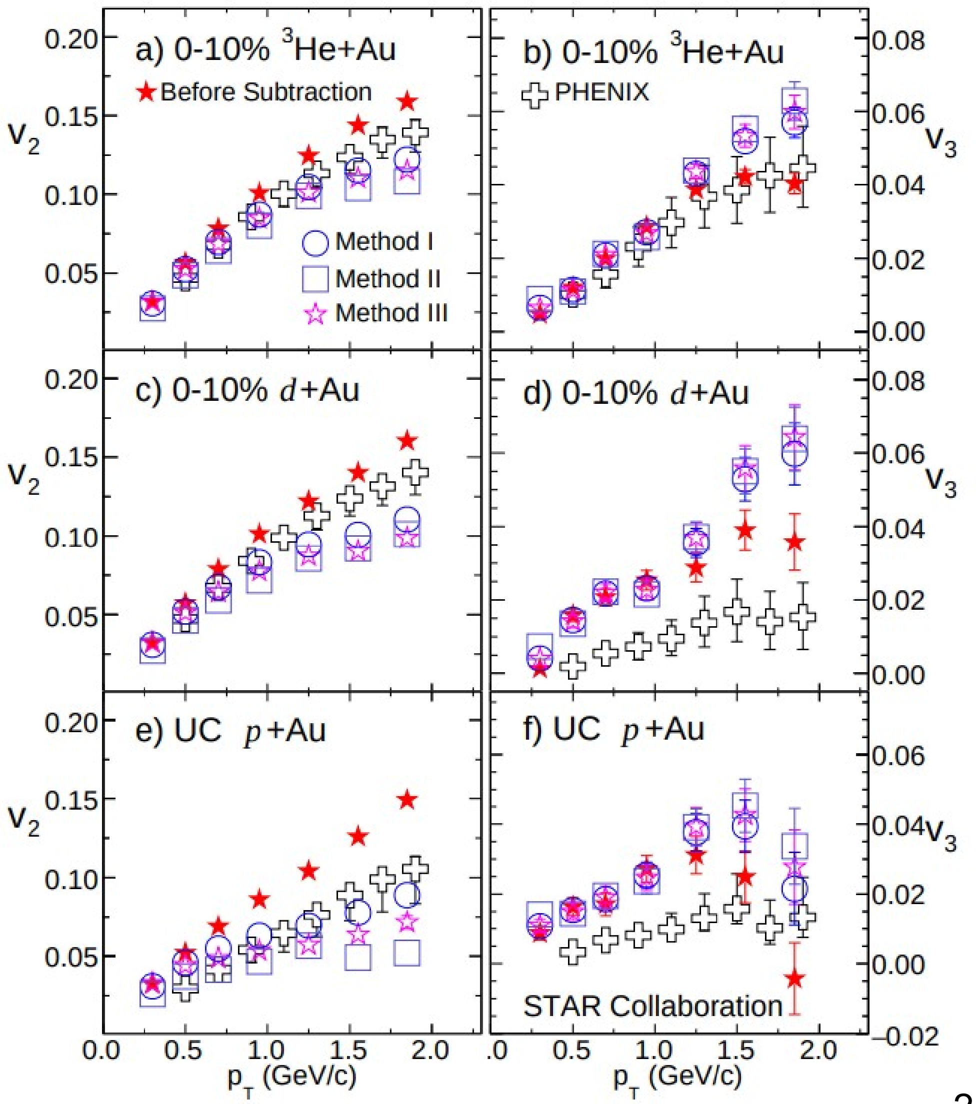
[STAR collaboration, arXiv:2210.11352]

Measurements performed with different η cuts.

$\langle N_{ch}\rangle \approx 20\text{-}30$

Hydro calculations?

Current hydro calculations neglect rapidity de-correlation effects.

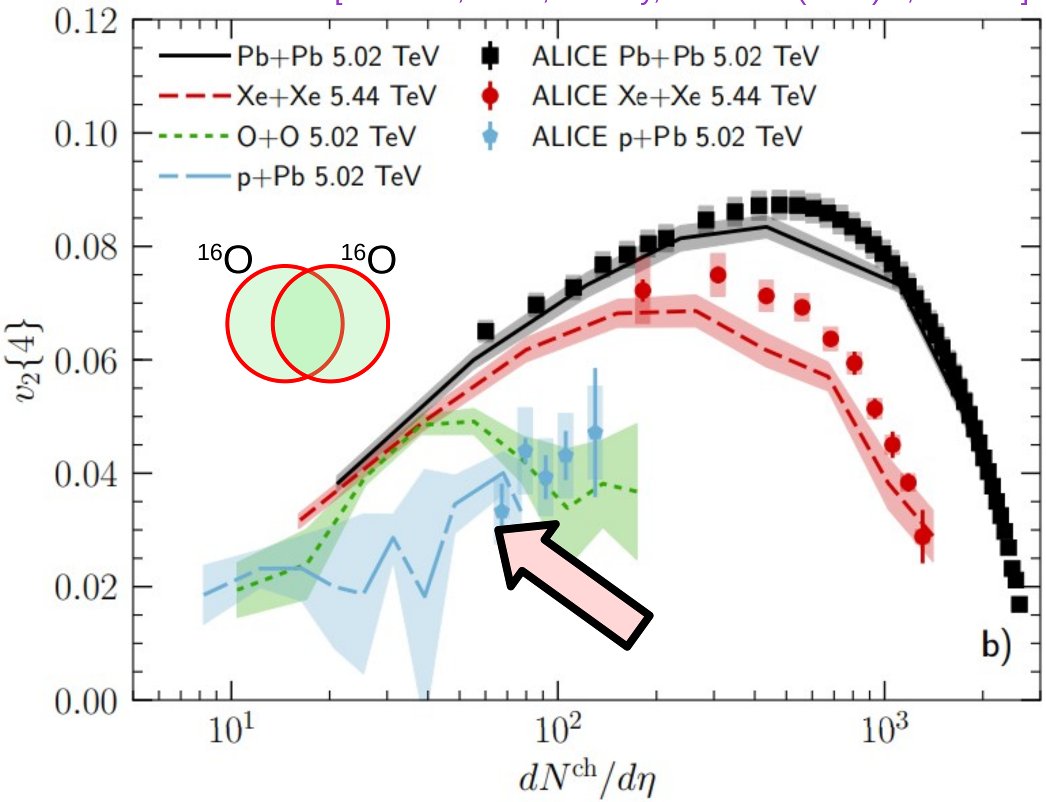


4 – Prospects with light ions.

Better control on initial conditions with light ions

[Schenke, Shen, Tribedy, PRC **102** (2020) 4, 044905]

Oxygen-oxygen data from RHIC and LHC.



Intrinsic shape of overlap area should become manifest.

Same multiplicity as pA collisions.

[see also Nijs, van der Schee, PRC **106** (2022) 4, 044903]

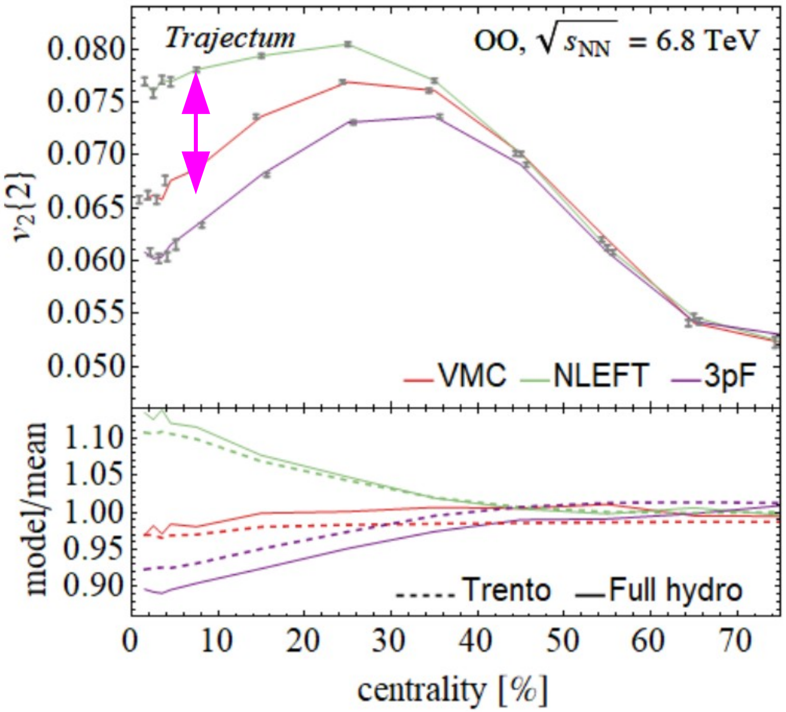
Input from nuclear structure community for uncertainty quantification

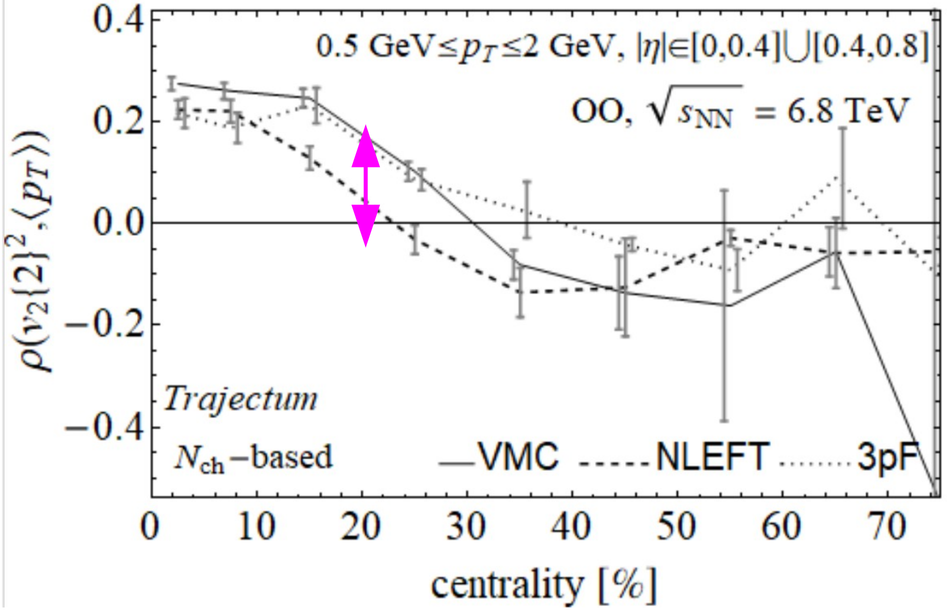
- 6000 configurations from cluster **Variational Monte Carlo (VMC)** simulations.

[Lonardoni *et al.*, PRC **96** (2017) 2, 024326] [Rybczyński, Broniowski., PRC **100** (2019) 6, 064912]

- 15359 configurations from **Nuclear Lattice Effective Field Theory (NLEFT)**.

[Summerfield *et al.*, PRC **104** (2021) 4, L041901]

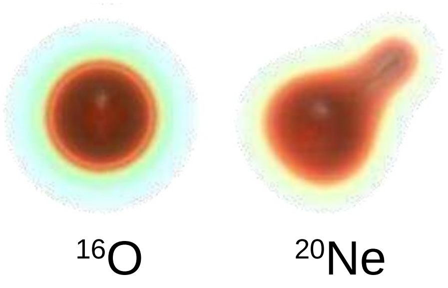




[Giacalone, Lee, Nijs, van der Schee, in preparation]

A new tool to exploit / test effective theories of QCD for nuclei.

Case study: Impact of neon-neon collisions on small system program at LHC?



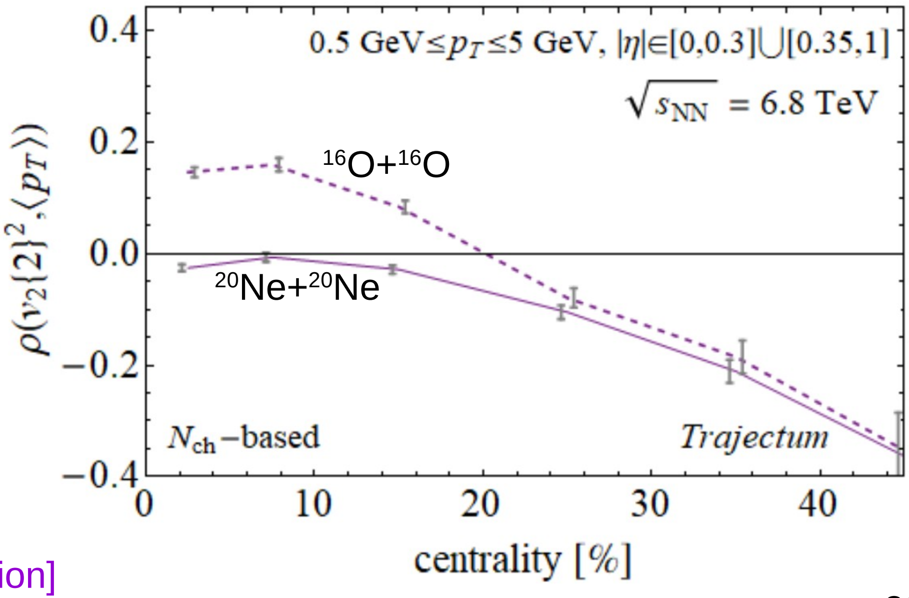
Strong geometry effects in a small system.
As dramatic as observed in large systems.

dN/dy ~ 100

Extreme structure to test “hydro” response.

Nucleus amenable to *ab-initio* description.

Trajectum preliminary, MAP values



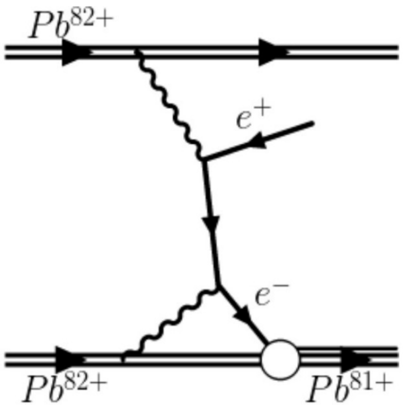
[Saclay nucl-th group + Giacalone, Nijs, van der Schee, in preparation]

Possibility of collisions of additional species @ LHC Run 5 and Run 6?

Light species to improve understanding of initial states.

Input from nuclear structure community will be essential.

[from Alexander Kalweit, ESNT workshop]



[https://indico.cern.ch/event/1078695/]

Nucleon-nucleon luminosity: $\mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA}$

optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5\cdot10^{29}$	$2.0\cdot10^{29}$	$1.9\cdot10^{29}$	$5.0\cdot10^{28}$	$2.3\cdot10^{28}$	$1.6\cdot10^{28}$	$3.3\cdot10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4\cdot10^{32}$	$3.3\cdot10^{32}$	$3.0\cdot10^{32}$	$3.0\cdot10^{32}$	$3.0\cdot10^{32}$	$2.6\cdot10^{32}$	$1.4\cdot10^{32}$
$\mathcal{L}_{AA}$ (nb^{-1} / month)	$1.6\cdot10^{3}$	$3.4\cdot10^{2}$	$3.1\cdot10^{2}$	$8.4\cdot10^{1}$	$3.9\cdot10^{1}$	$2.6\cdot10^{1}$	$5.6\cdot10^{0}$
$\mathcal{L}_{NN}$ (pb^{-1} / month)	409	550	500	510	512	434	242

CONCLUSION

- Small system collectivity to understand emergent hydrodynamic behavior.

- Precision measurements of relevant observables are available.

- **Dynamics:** Progress with hydrodynamic/kinetic theory simulations.
  Fertile ground for connections with quantum physics experiments.

- **Initial condition:** Robust evidence of nucleon structure. Longitudinal structure?
  Prospects with ^{16}O **[and ^{20}Ne!]** + *ab initio* nuclear structure theory.

THANK YOU!

Intersection of nuclear structure and high-energy nuclear collisions

https://www.int.washington.edu/programs-and-workshops/23-1a

Jan 23rd - Feb 24th 2023

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