Enhancing the CERN LHC small systems program with bowling-pin-shaped neon isotopes

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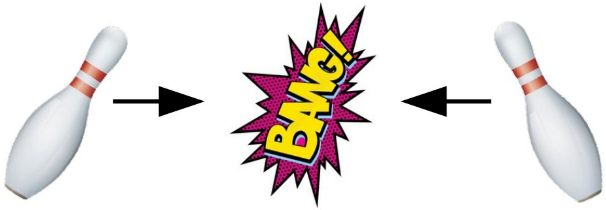


The physical world as an emergent phenomenon.

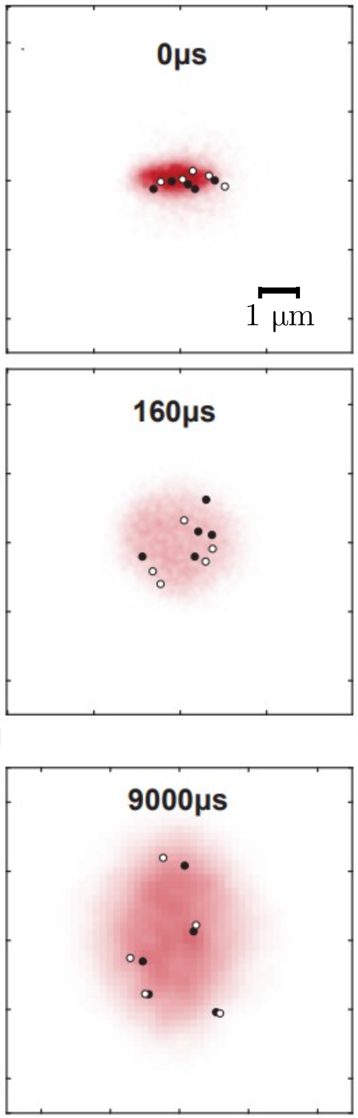
Hydrodynamics: a prime example.

$$F = -\nabla P$$

FRONTIERS:

Mesoscopic regime: small systems and few particles.

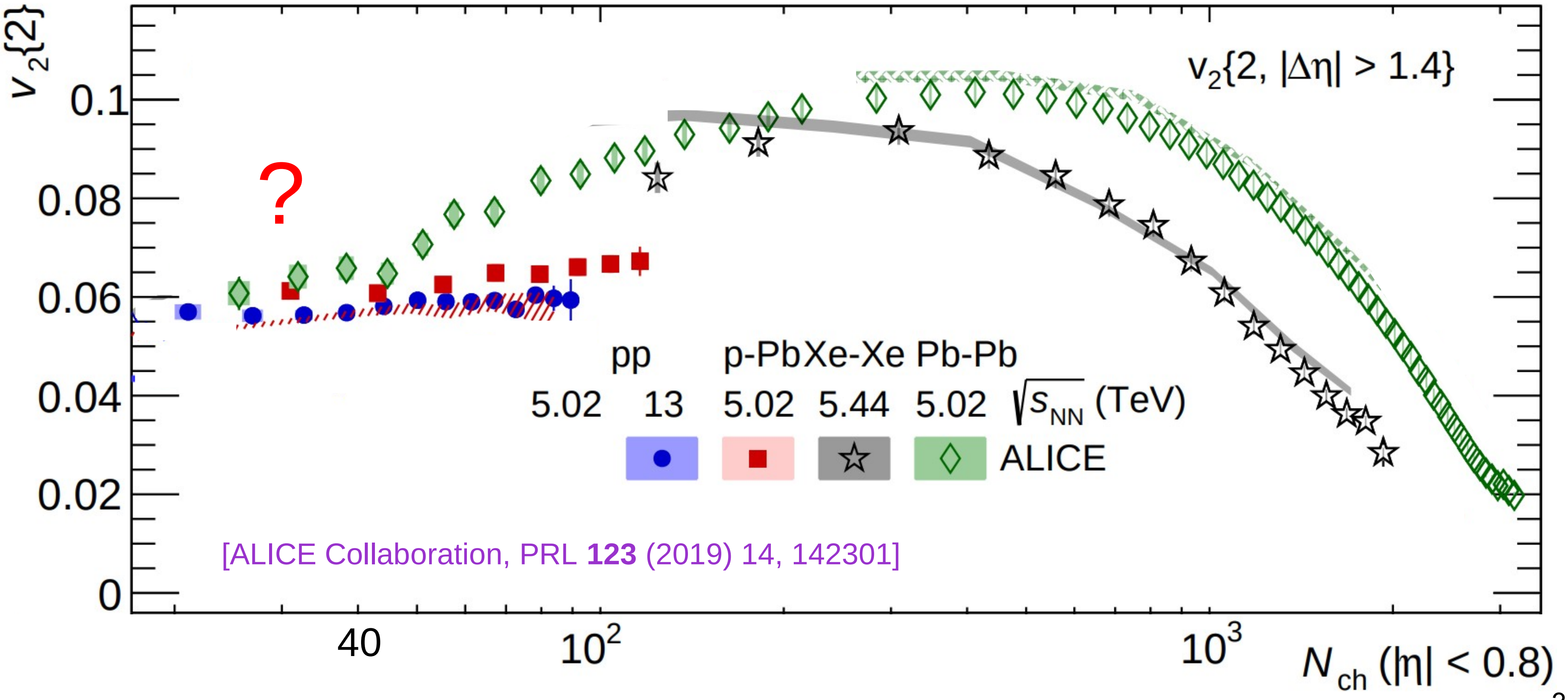
Out-of-equilibrium hydrodynamics.



[Brandstetter et al. (PI Heidelberg),
Emergent fluid behavior with a handful cold atoms]

Small collision systems provide a unique window onto this physics.

Persistent collective phenomena: femtoscale, few hadrons, out of equilibrium.



Understanding small systems: great challenge in strong-interaction physics.

How to make progress?

We need observations that we understand irrespective of model details.

Powerful method:

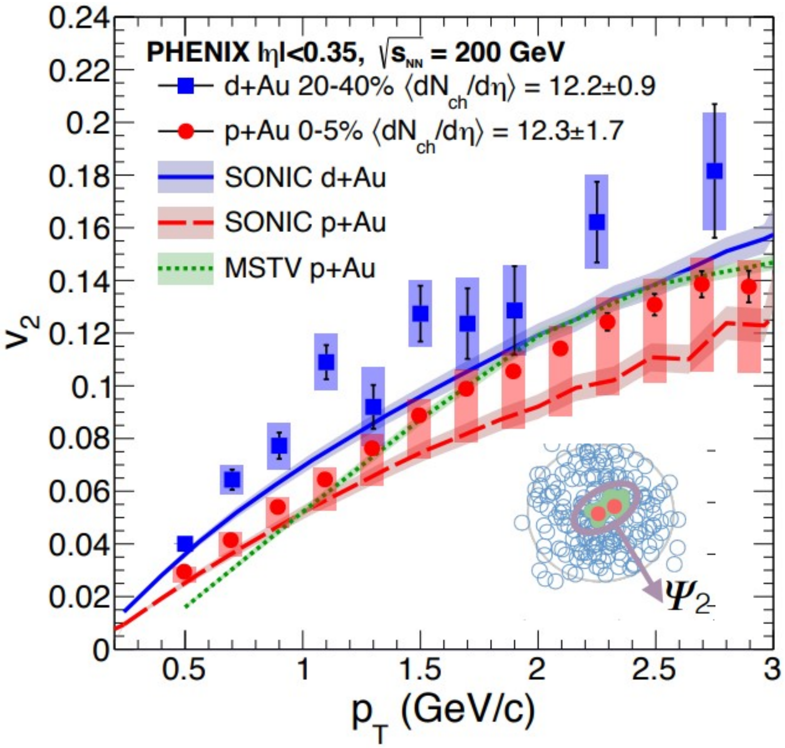
Look for model-independent correlation between final-state anisotropy and initial-state geometry.

PROBING THE GEOMETRIC ORIGIN OF FLOW

Attempt #1 – Use p-A as a baseline. Geometry scan realized at RHIC for this purpose.

[PHENIX Collaboration, Nature Phys. **15** (2019) 3, 214-220]
[STAR collaboration, arXiv:2210.11352]

Clear interpretation from deuteron geometry.



<u>Cons:</u>

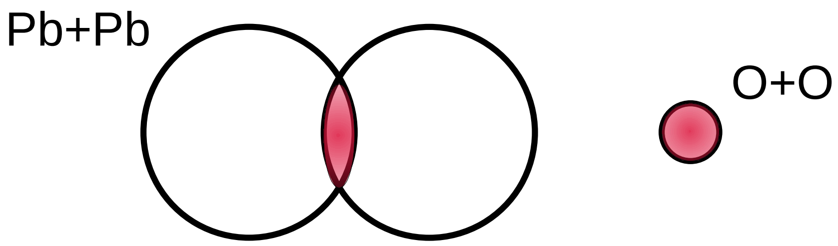
Effects of longitudinal de-correlation.
Not well understood in initial-state models.

The baseline involves protons.
Uncertain proton structure modeling.

PROBING THE GEOMETRIC ORIGIN OF FLOW

Attempt #2 – Use O-O as a baseline. Central O+O vs. peripheral Pb+Pb.

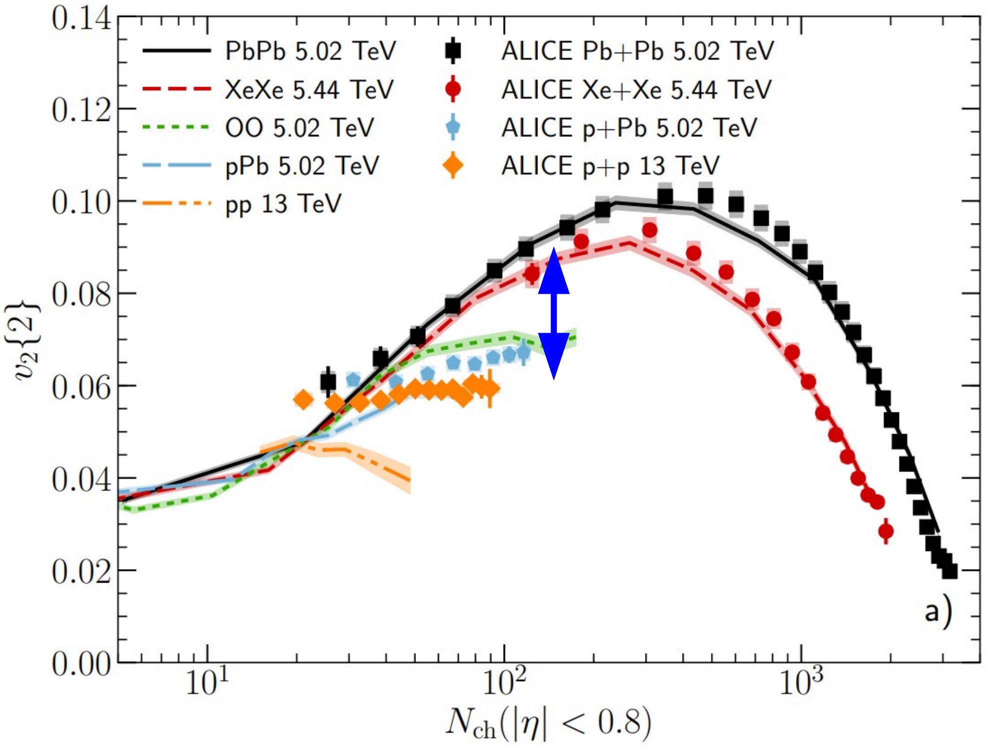
Looks very solid.
No protons in the baseline.



Cons:
Longitudinal structure is different?

$$r_{n|n}(\eta) = \frac{\langle \boldsymbol{q}_n(-\eta)\boldsymbol{q}_n^*(\eta_{\mathrm{ref}})\rangle}{\langle \boldsymbol{q}_n(\eta)\boldsymbol{q}_n^*(\eta_{\mathrm{ref}})\rangle}$$

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

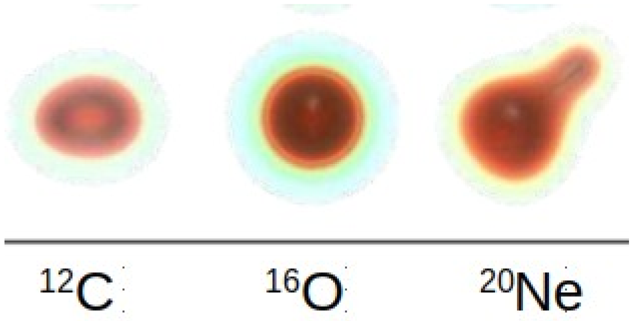


PROBING THE GEOMETRIC ORIGIN OF FLOW

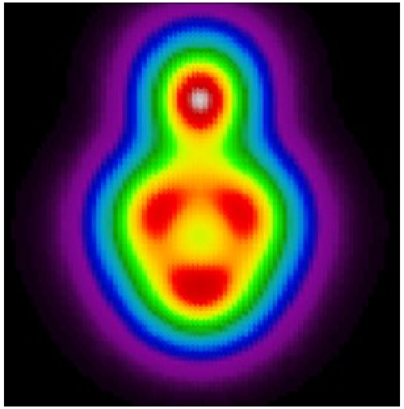
Attempt #3 – Use O-O as a baseline + collisions of an additional light ion.

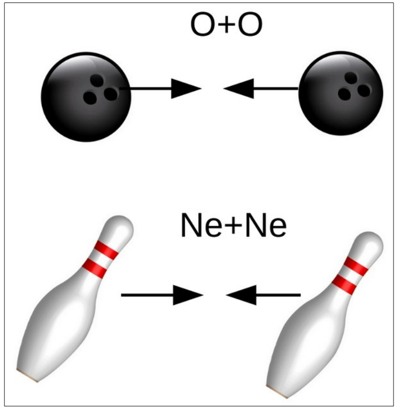
Case enabled by extreme geometry of nucleus ^{20}Ne.

Elongated bowling-pin shape with a well-separated cluster.



[Ebran *et al.*, PRC **90** (2014) 5, 054329]



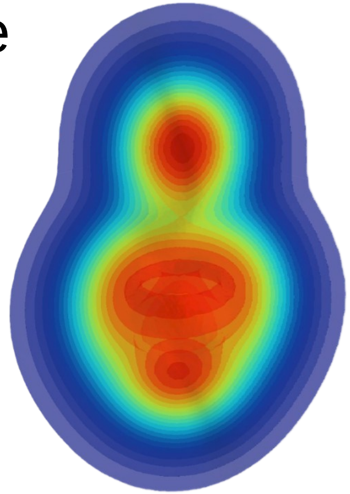


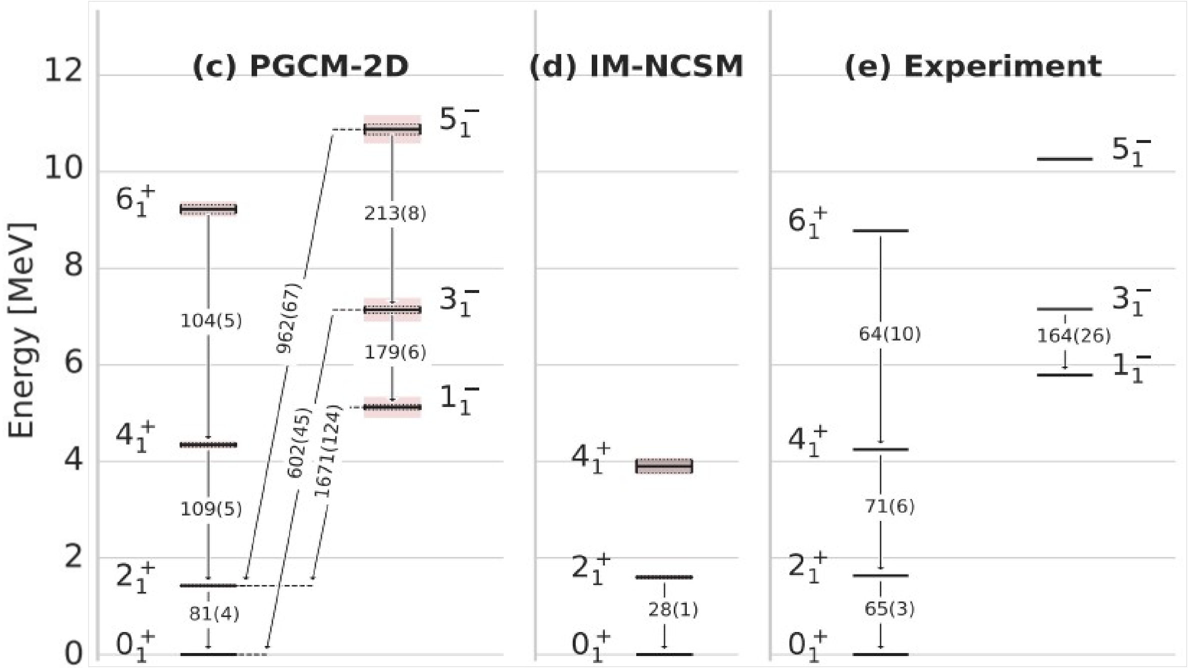
Nucleus has been been subject of extensive study.
Consistent results across nuclear models.

[Marevic *et al.*, PRC **97** (2018) 2, 024334]
[Zhou *et al.*, PLB **753** (2016) 227-231]

[Frosini *et al.*, EPJA **58** (2022) 4, 63]

^{20}Ne





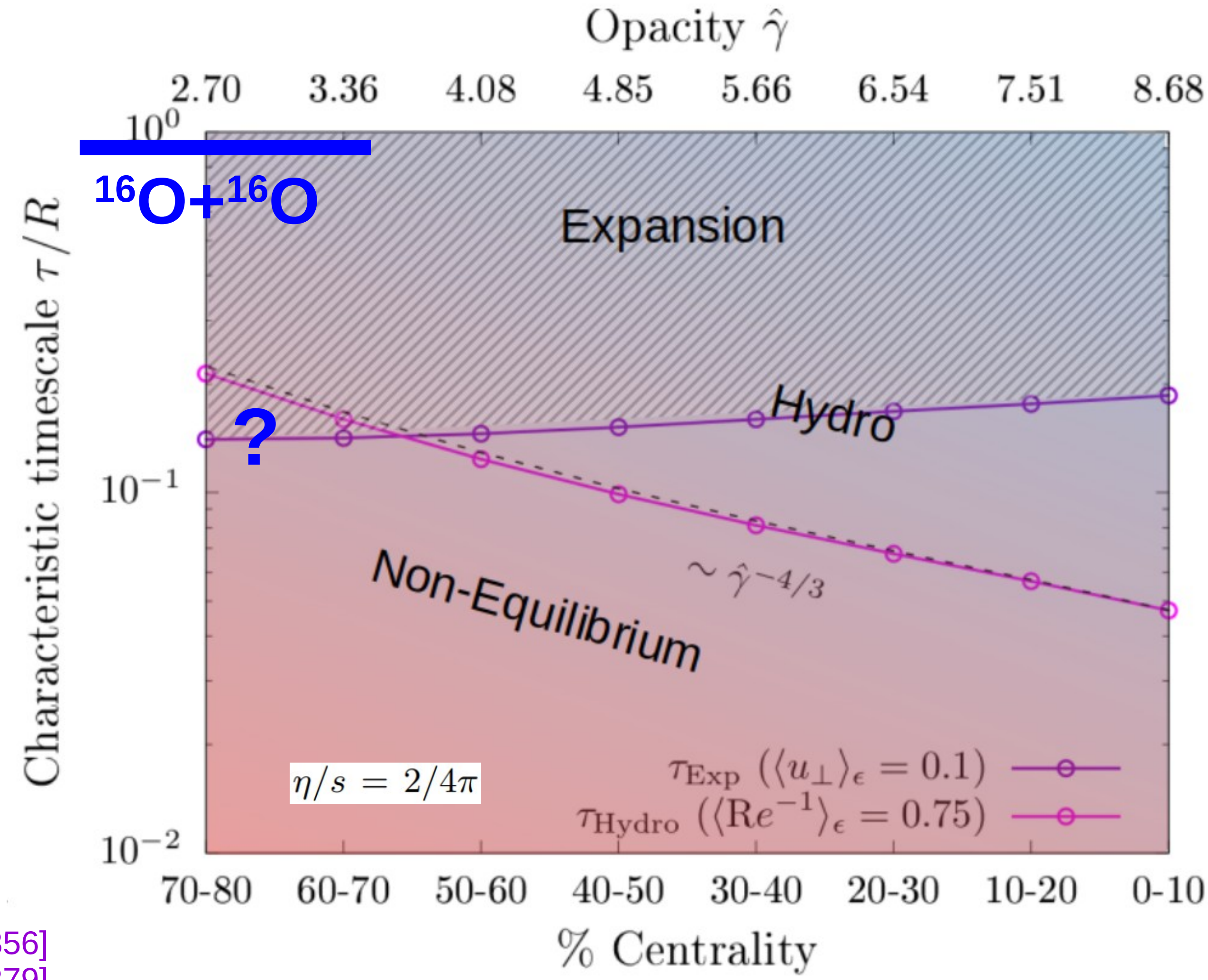
PRECISE INPUTS FROM *AB INITIO* NUCLEAR THEORY = MINIMIZING MODEL UNCERTAINTIES

NEXT SLIDES: CASES UNDER INVESTIGATION

- Robust predictions for flow in hydrodynamics.
- Hard probe energy loss and thermalization.
- Beam energy dependence and longitudinal structure of initial state.
- Initial-state effects in ultra-peripheral collisions.

Hydro or not?

O-O collisions at the crossroads.



This is where we need as much "robust information" as possible.

[Ambrus, Schlichting, Werthmann, arXiv:2211.14356]
[Ambrus, Schlichting, Werthmann, arXiv:2211.14379]

Clear prediction:

v_2 [O+O] = **<u>0.8</u>** v_2 [Ne+Ne]

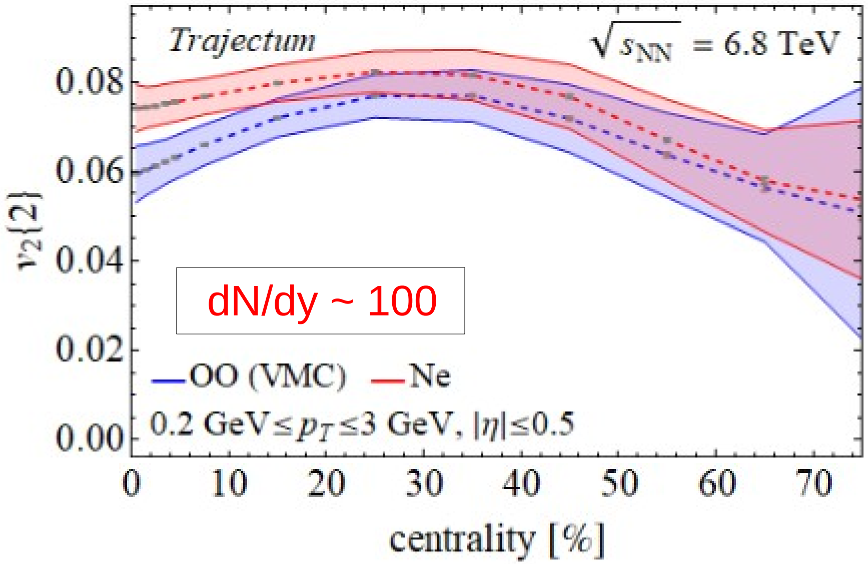
Bands are systematical uncertainties (η/s, ζ/s, …)

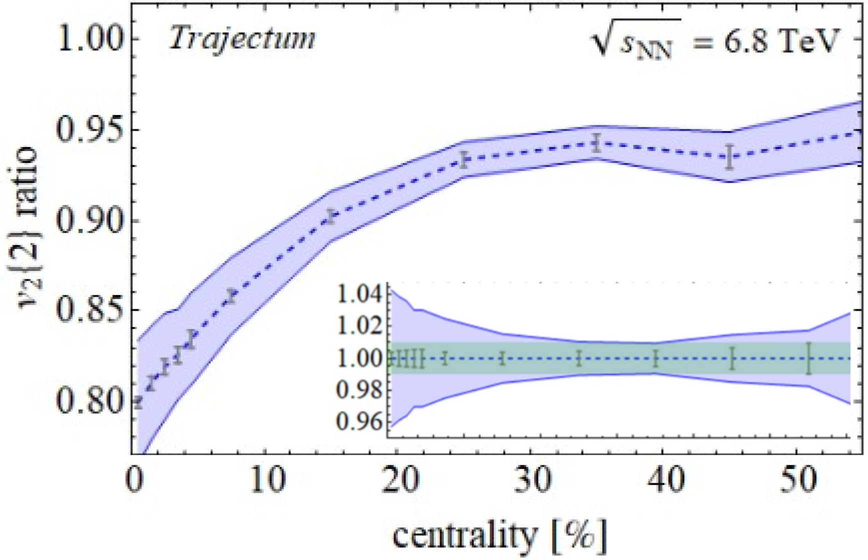
Systematical uncertainty on ratio at % level!

Unambiguous "geometric" interpretation.

Very robust information.

[Bally et al., in preparation]



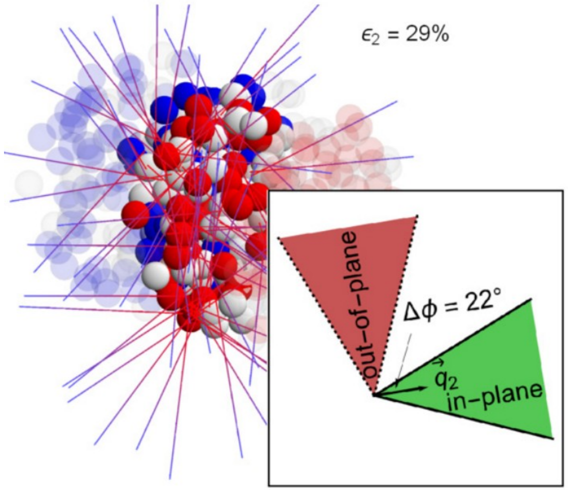


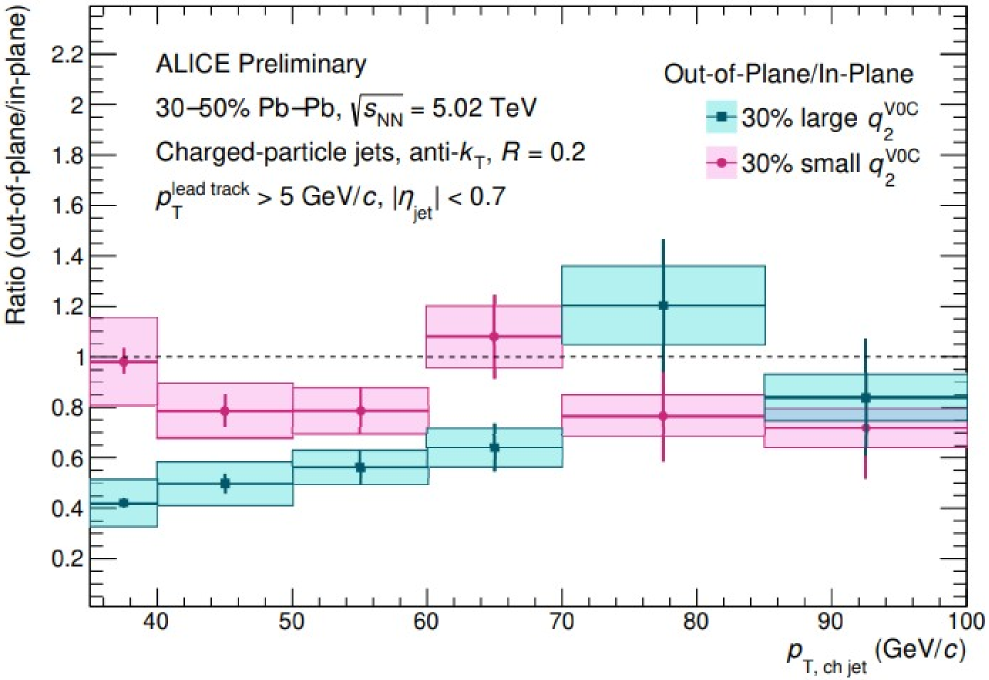
Evidence of jet modification is missing in p-Pb collisions. [e.g. ATLAS Collaboration, arXiv:2206:01138]

O-O as a promising avenue, due to better controlled geometry.

Possibility of observing path-length dependent effects. Ne-Ne vs. O-O ?

[Beattie et al., PLB **836** (2023) 137596]
[Beattie, QM22, arXiv:2210.02937]

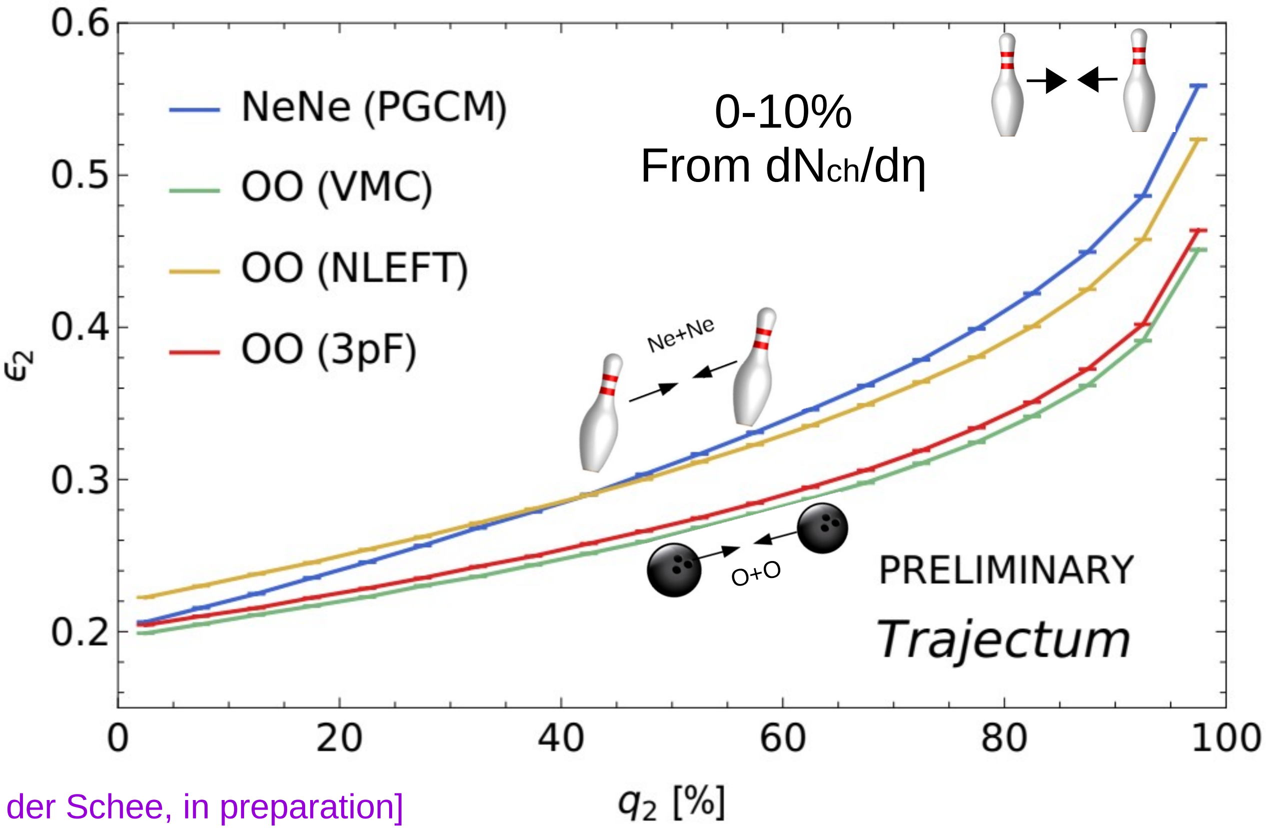




Eccentricity with q_2 selection. Slope is higher for Ne-Ne.

Effective alignment of bowling pins.

Good case for path-length studies. Gives us something we can play with.

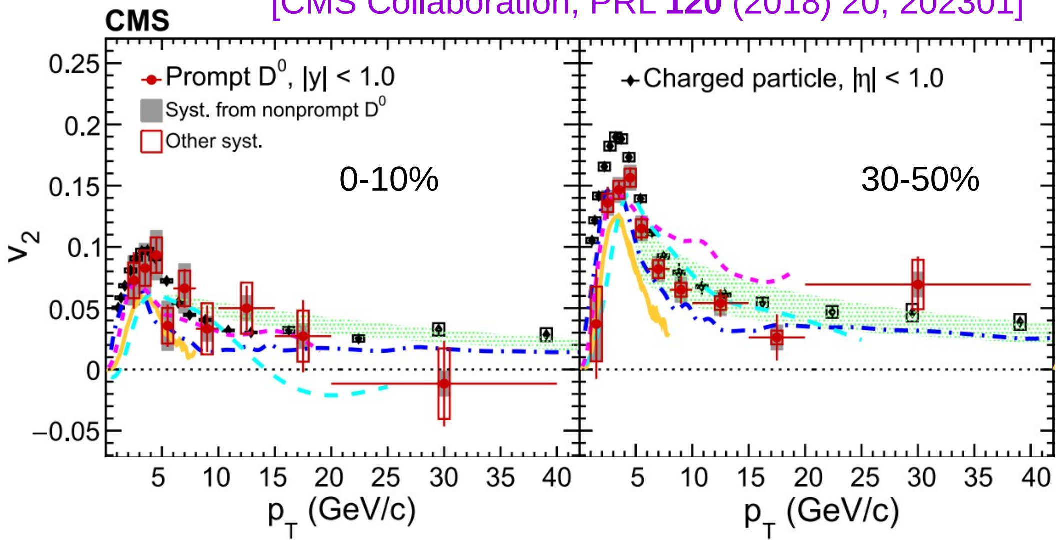


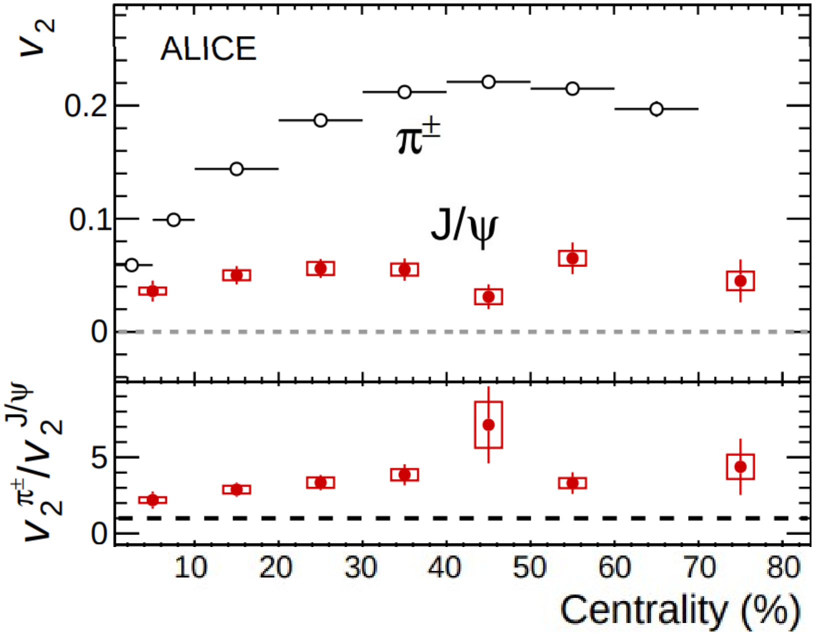
[Giacalone, Nijs, van der Schee, in preparation]

Evidence of “thermalized” charm from elliptic flow.

[ALICE Collaboration, JHEP **10** (2020) 141]

[CMS Collaboration, PRL **120** (2018) 20, 202301]





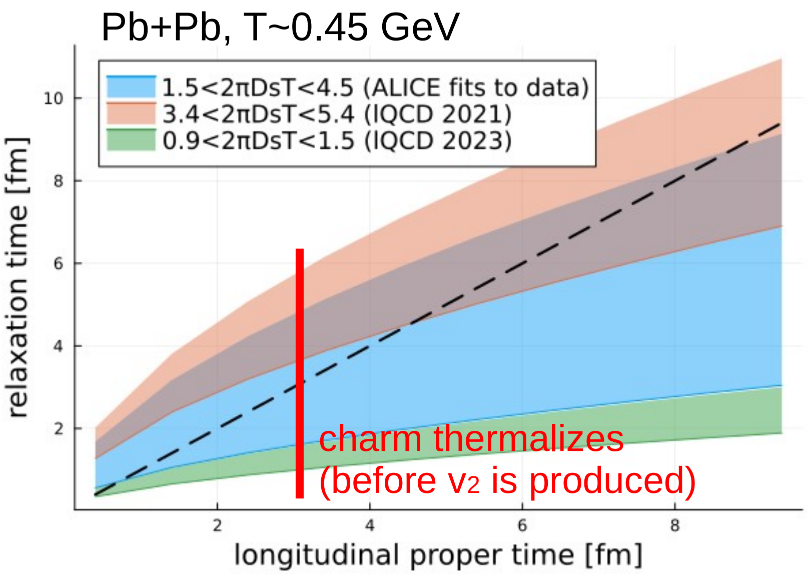
Small systems?

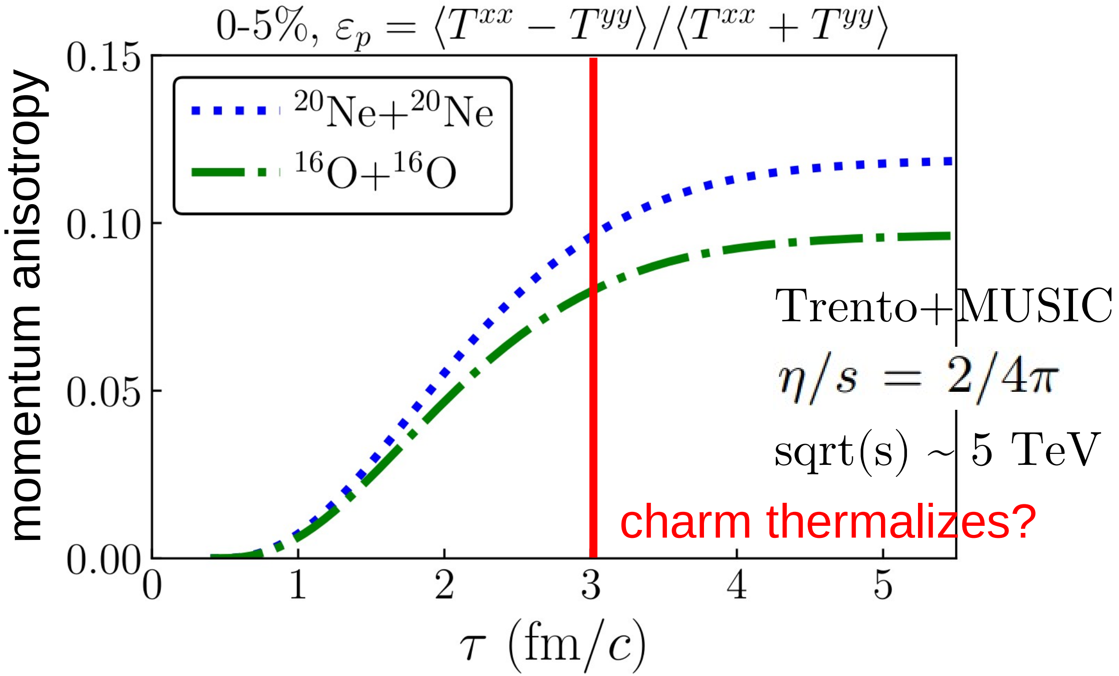
Some observations also in p-Pb. Hard to interpret.

[CMS Collaboration, PLB **791** (2019) 172-194]

Insights from O-O? Introduce a time scale for charm thermalization.

[Capellino *et al.*, PRD **106** (2022) 3, 034021]





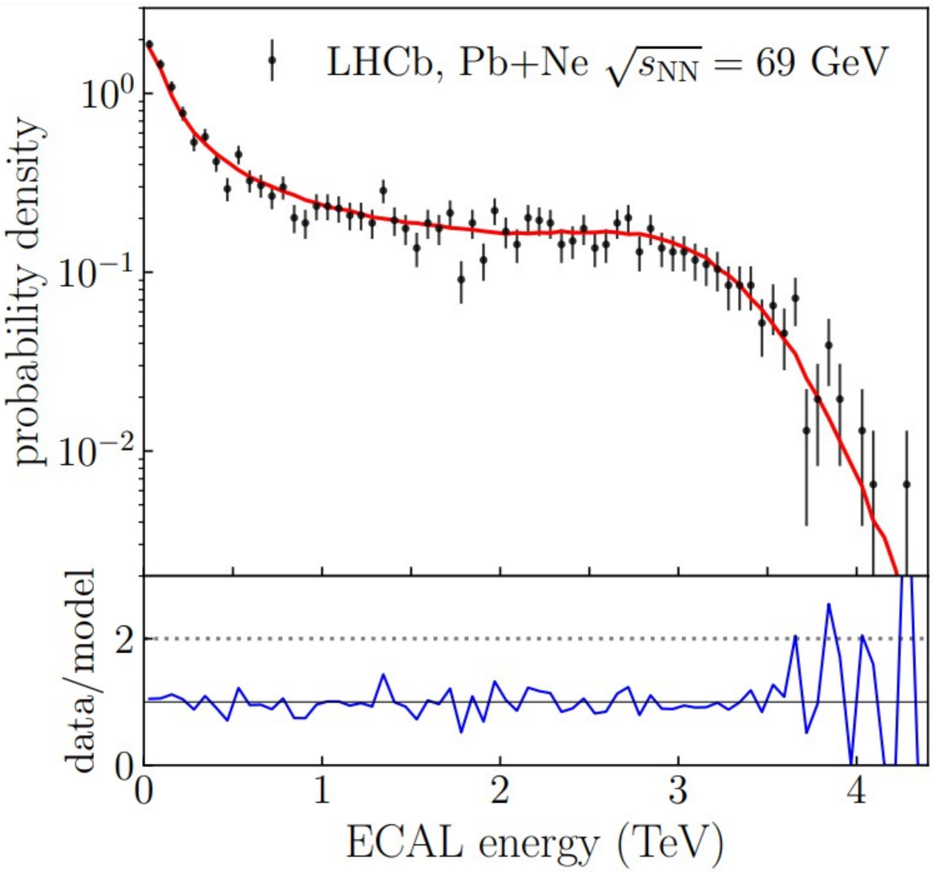
Any observation of v_2 of D or J/ψ in O-O is highly nontrivial.

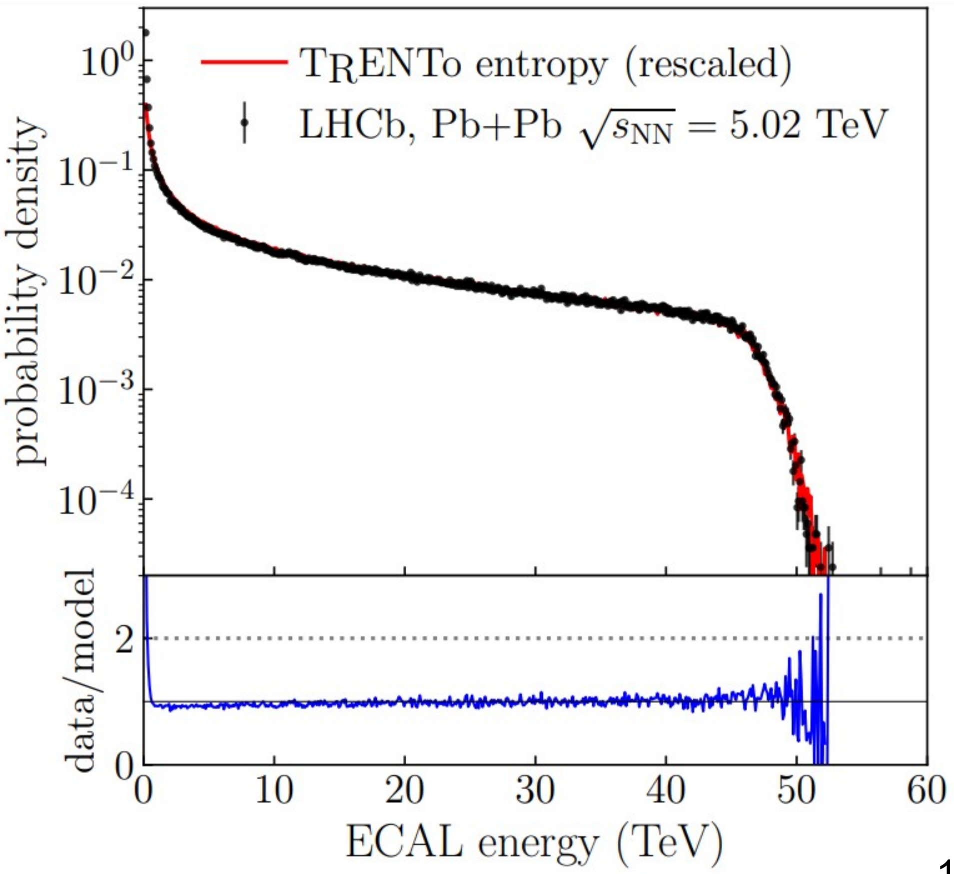
v_2 [O-O] < v_2 [Ne-Ne], hint at potential "thermalized" origin. **Charm attractor?**

[Capellino, Dubla, Giacalone, in preparation]

Synergy with SMOG system @ LHCb detector.

[Giacalone, Mehrabpour, in preparation]
[LHCb Collaboration, JINST **17** (2022) 05, P05009]





All these configurations would become available.

Comprehensive program is possible.

$\sqrt{s}$ = 7 TeV , 0.07 TeV

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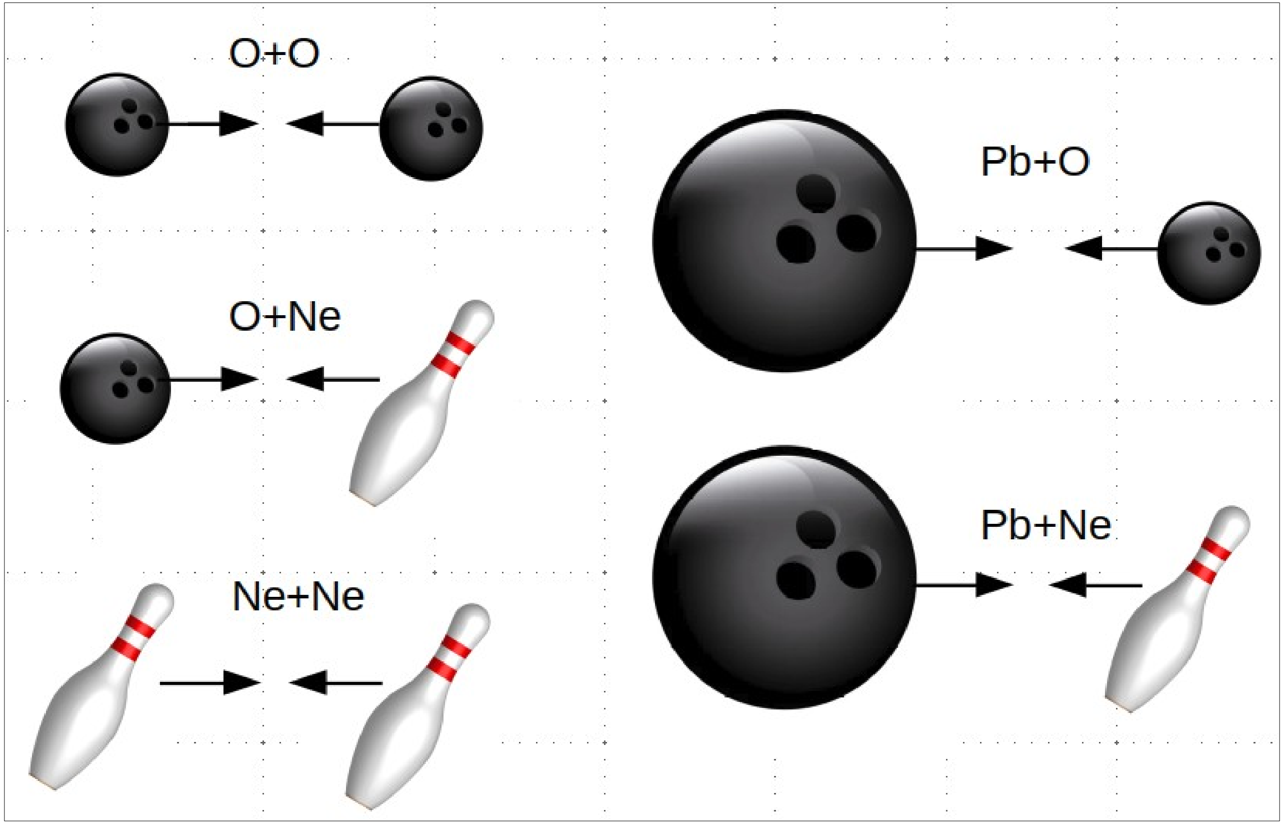

$\sqrt{s}$ = 0.07 TeV

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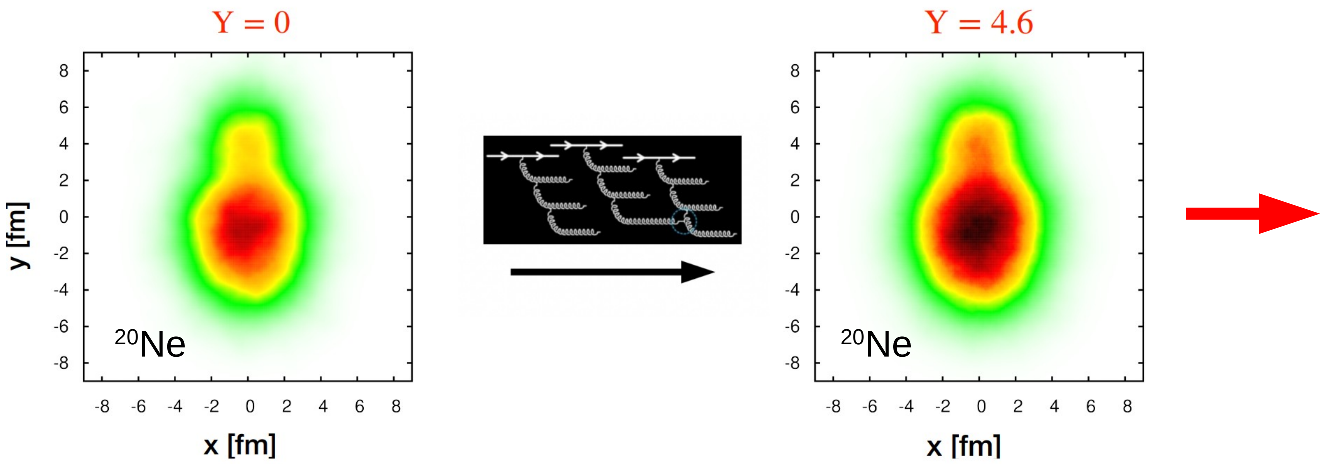
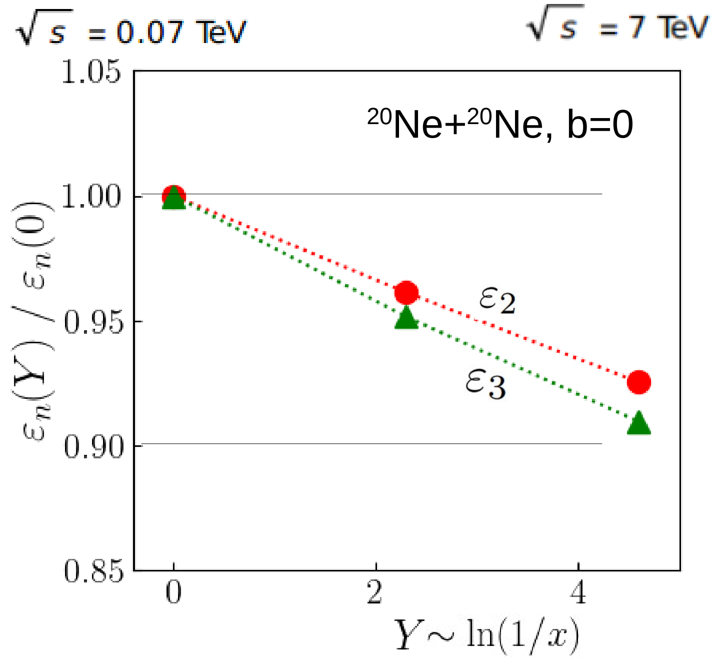
Unique window onto signatures of non-linear QCD evolution.

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

Melting the bowling pin with small-x gluons.





10% reduction of initial anisotropies due to JIMWLK evolution.

Should be visible. Calculation of baseline O-O is ongoing.

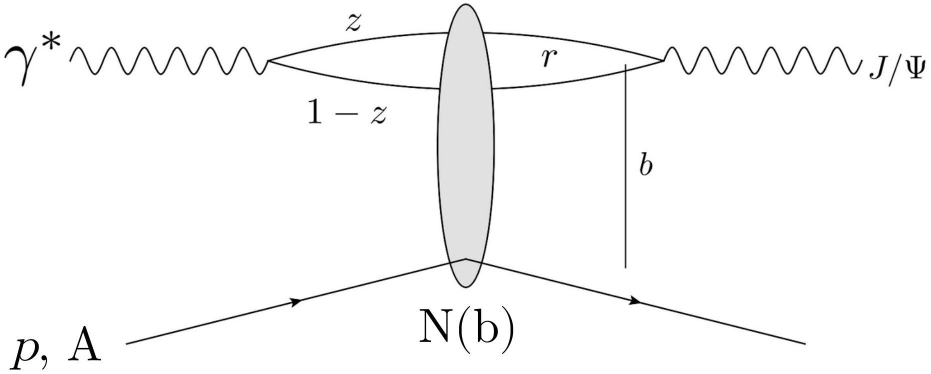
[Singh et al., in preparation]

Multi-scale imaging of nuclei in UPCs.

THE PROCESS:

Diffractive incoherent J/ψ production.

$$\frac{d\sigma^{\gamma^*+A\to V+A^*}}{d|t|} = \frac{1}{16\pi}\left[\left\langle|\mathcal{A}|^2\right\rangle - |\langle\mathcal{A}\rangle|^2\right]$$



In small-*x* framework, scattering amplitude knows about the target gluon density, t(b):

impact parameter

transverse momentum transfer

$$\mathcal{A}^{\gamma^* p\to Vp} \sim \int d^2b\,dz\,d^2r\,\Psi^{\gamma^*}\Psi^{V}(r,z,Q^2)\,e^{-ib\cdot\Delta}\,N(r,x,b) \sim t(b)$$

<|*A*|²> directly probes two-body correlations within the nuclear target.

PHYSICAL REVIEW C **81**, 025203 (2010)

Investigating the gluonic structure of nuclei via *J*/*ψ* scattering

A. Caldwell[1] and H. Kowalski[2,*]

[1]*Max Planck Institute for Physics, München, Germany*

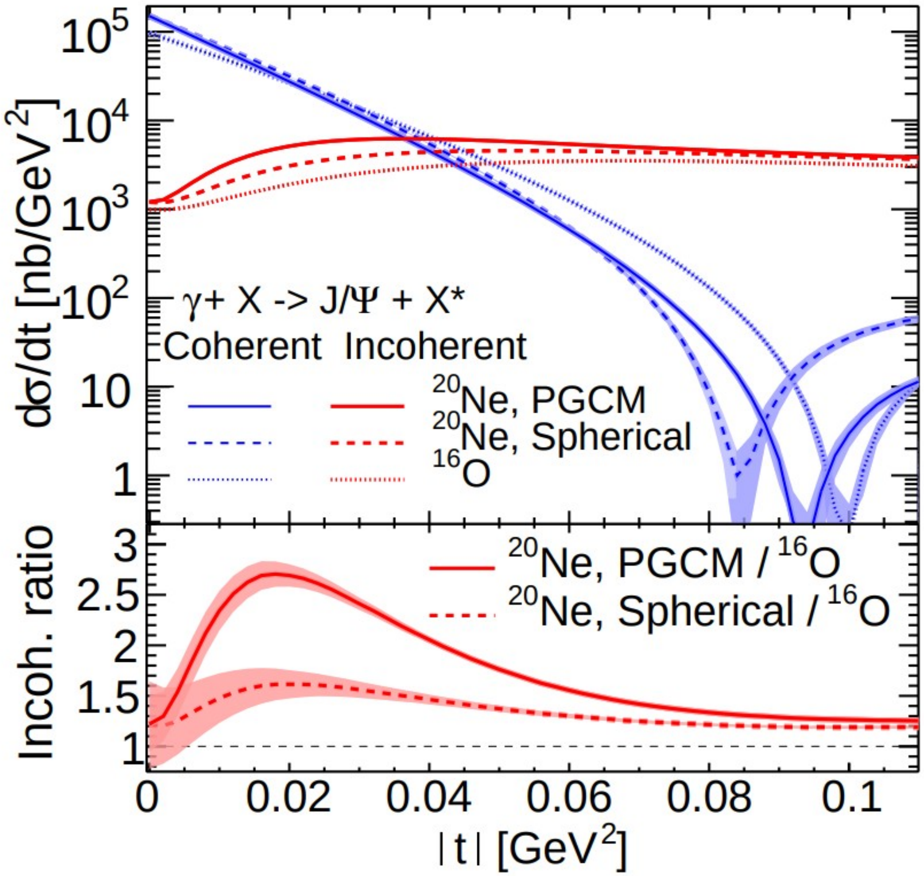
[2]*Deutsches Elektronen-Synchrotron (DESY), D-22607 Hamburg, Germany*

(Received 23 September 2009; published 23 February 2010)

$$\frac{d\sigma^{\gamma A \to VA}}{d|t|} \propto \langle |\mathcal{A}|^2 \rangle - |\langle \mathcal{A} \rangle|^2 \ \propto \int d^2\mathbf{b} \left[\langle t_A(\mathbf{b_1}) t_A(\mathbf{b_2}) \rangle - \langle t_A(\mathbf{b_1}) \rangle \langle t_A(\mathbf{b_2}) \rangle \right] e^{-i\mathbf{\Delta}\cdot(\mathbf{b_1}-\mathbf{b_2})}$$

Sensitive to two-body correlations (i.e. deformation) in target nuclei.

[H. Mäntysaari et al., arXiv:2303.04866]



In fact, same correlation functions driving fluctuations of elliptic flow.

Towards a unified picture.

SUMMARY

- Emergent collective behavior observed at LHC down to femtoscale.
- Exploiting the geometry of ^{20}Ne for robust understanding of phenomena.
- Dramatic extension of science program envisaged via O+O collisions.

PROSPECTS

- Many results are coming. **Further ideas are welcome! Please contribute.**
- Idea brought forward to machine people @ LHC: no difficulties expected from preparation of ^{20}Ne beams.
- For a run in 2025, case to be made this year. **Requires strong endorsement.**