Intersection of nuclear structure and heavy-ion collisions: perspectives from high-energy heavy-ion theory

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OUTLINE

1 – Nuclear structure in AA collisions.

2 – Nuclear structure and nuclear interactions with colliders.

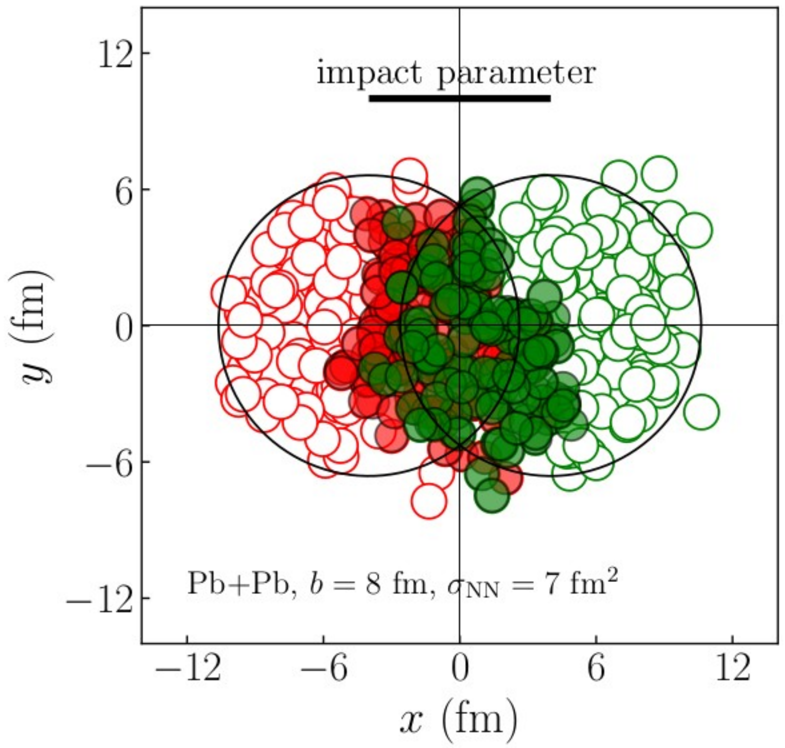
3 – Connecting low- and high-energy QCD in γA collisions.

4 – Physics opportunities with Neon-20.

1 – Nuclear structure in AA collisions

“Glauber Monte Carlo” approach.

[Miller *et al.*, Ann.Rev.Nucl.Part.Sci. **57** (2007) 205-243]



“quantum measurement” of the nucleon positions

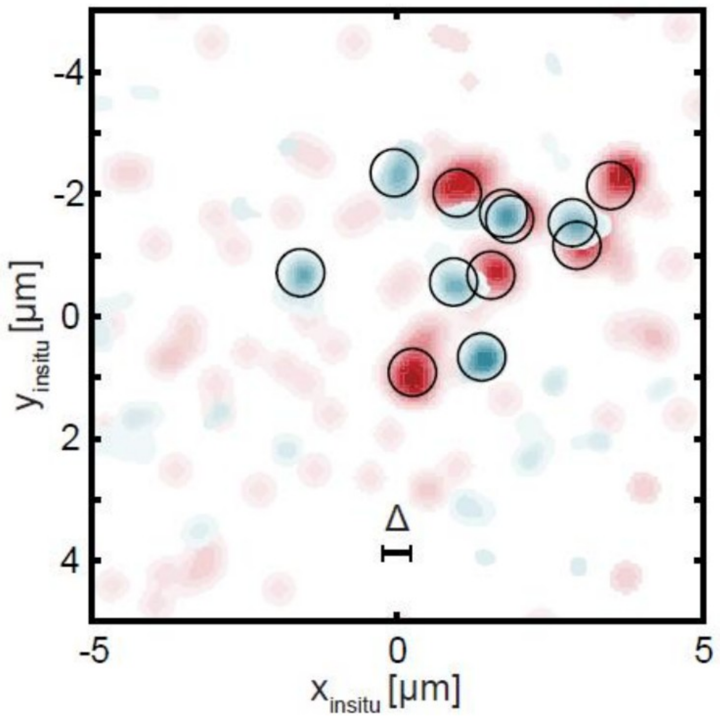


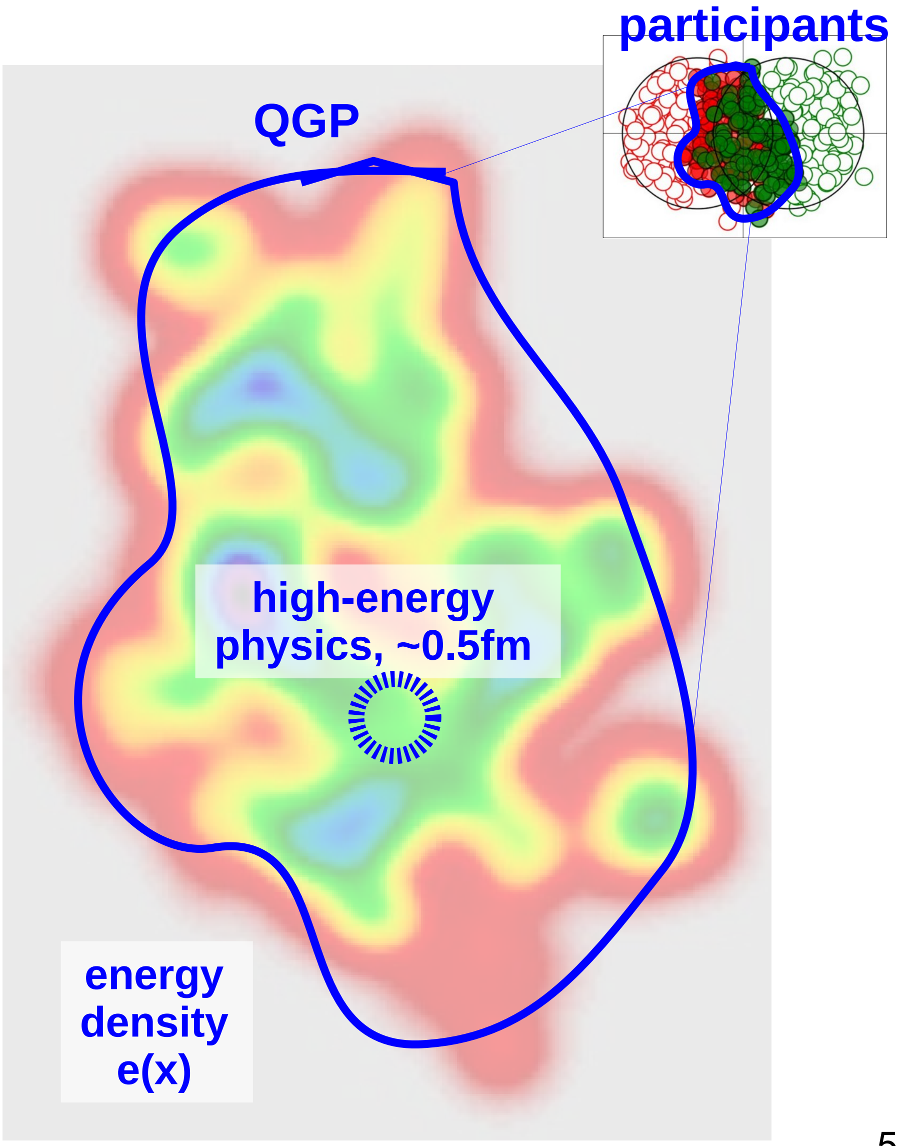
Image of collapsed wave function of 10 Li atoms
[from S. Brandstetter (PI Heidelberg)]

Density fluctuations and correlations due to **mesoscopic** nature of nuclei.

[PHOBOS Collaboration, PRL **98** (2007) 242302]
[Alver, Roland, PRC **81** (2010) 054905]

Energy deposition (high-energy physics) creates structures on short scales (1/Q).

Nuclear structure (+ non-zero impact parameter) govern the global geometry.



Simple collision model ("dense-dense scaling").

$$Q_A^2 = \sum_i^A Q_{p,i}^2 \quad Q_B^2 = \sum_i^A Q_{p,i}^2 \longrightarrow \boxed{e(\mathbf{x}) \propto Q_A^2 \; Q_B^2}$$

Energy-density correlations:

$$\langle e(\mathbf{x}) \rangle \longrightarrow P_1(\mathbf{r}_1)$$

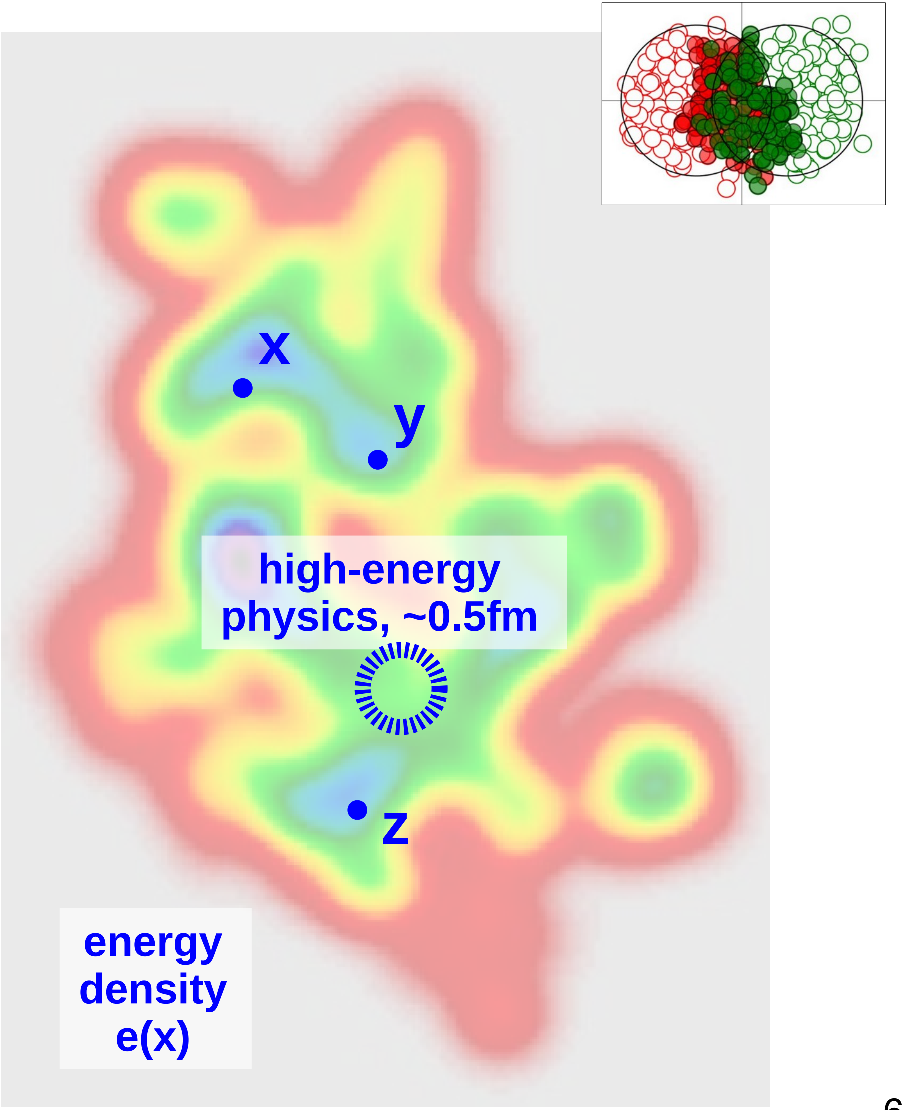
$$\langle e(\mathbf{x}) e(\mathbf{y}) \rangle \longrightarrow P_2(\mathbf{r}_1, \mathbf{r}_2)$$

$$\langle e(\mathbf{x}) e(\mathbf{y}) e(\mathbf{z}) \rangle \longrightarrow P_3(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$$

[Giacalone, arXiv:2305.19843]

For any nuclear *n*-body density:

$$P_n(\mathbf{r}_1, \ldots, \mathbf{r}_n) = \sum_{s,t} \int d\mathbf{r}_{n+1} \ldots d\mathbf{r}_A |\Psi_A|^2$$



Energy density correlations determine multi-particle correlations (e.g. elliptic and higher-order flows).

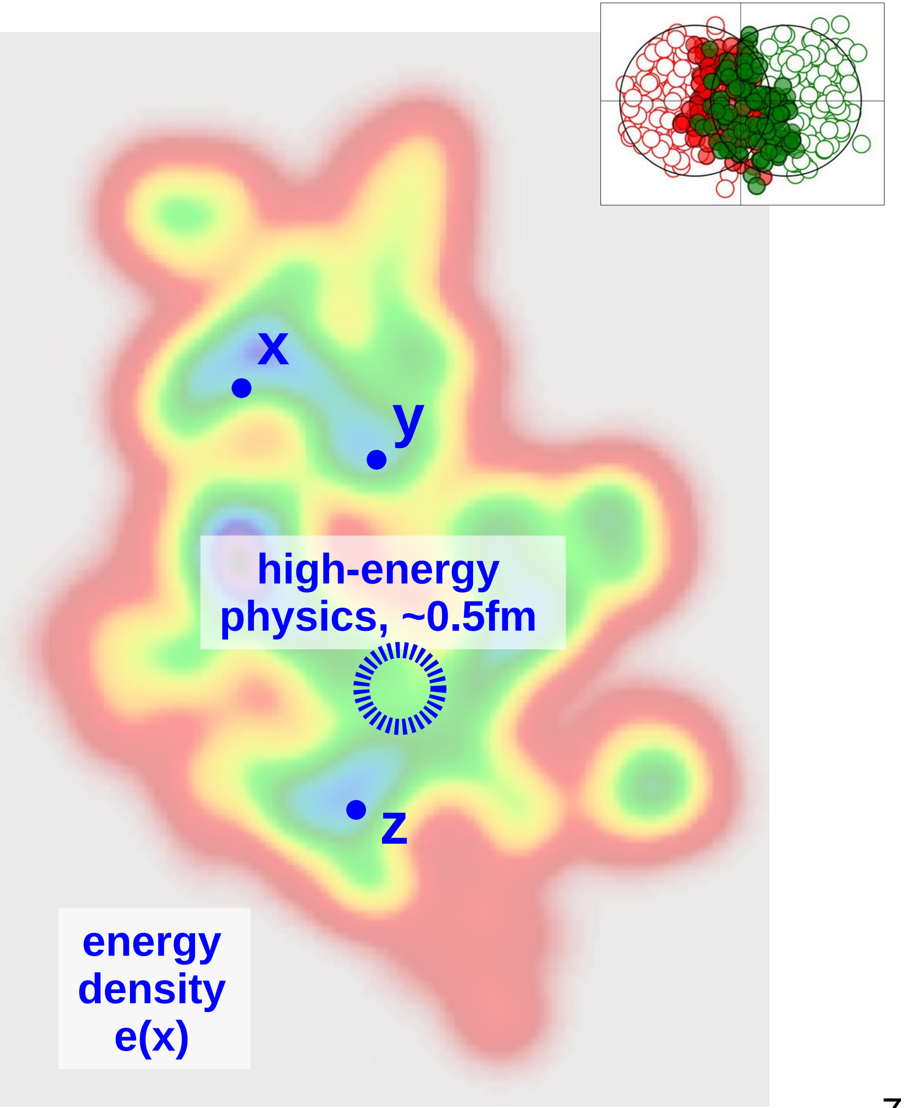
[Blaizot, Broniowski, Ollitrault, PLB **738** (2014) 166-171]

N-particle correlations from N-body densities.

$$\left\langle e^{in(\phi_1-\phi_2)}\right\rangle \propto \int_{\mathbf{r}_1,\mathbf{r}_2} P_2(\mathbf{r}_1,\mathbf{r}_2)\ \ldots$$

$$\left\langle (p_{t,1}-\langle p_t\rangle)e^{in(\phi_2-\phi_3)}\right\rangle \propto \int_{\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3} P_3(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\ \ldots$$

Bottom line:
Spatial correlations in the nuclear wave functions will affect multi-particle correlation measurements.

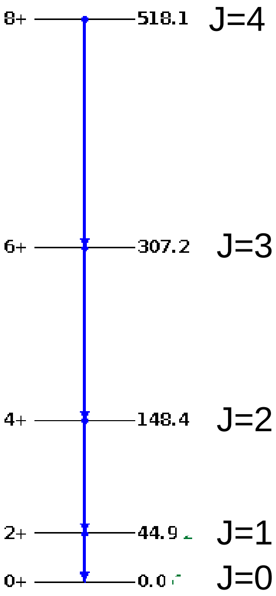


Extremely rich phenomenology of atomic nuclei driven by the strong nuclear force.

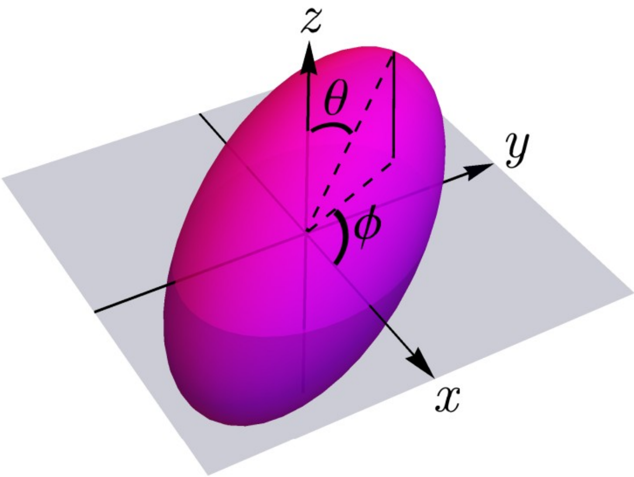
Many-body correlations are central to the study of nuclear structure.

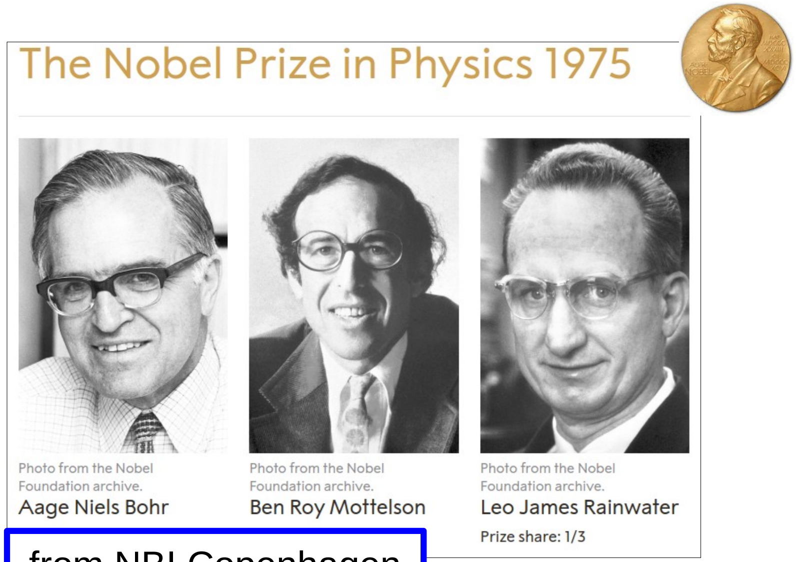
[next talk by Elena Litvinova]

Capturing spatial correlations: Nuclear shapes as emergent collective phenomena.



$^{238}_{92}\mathrm{U}$ **E = B J(J+1)**

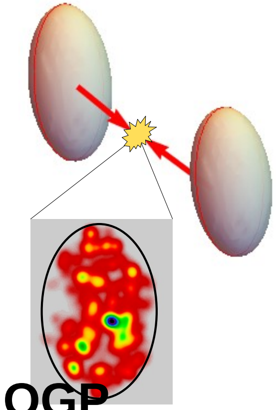




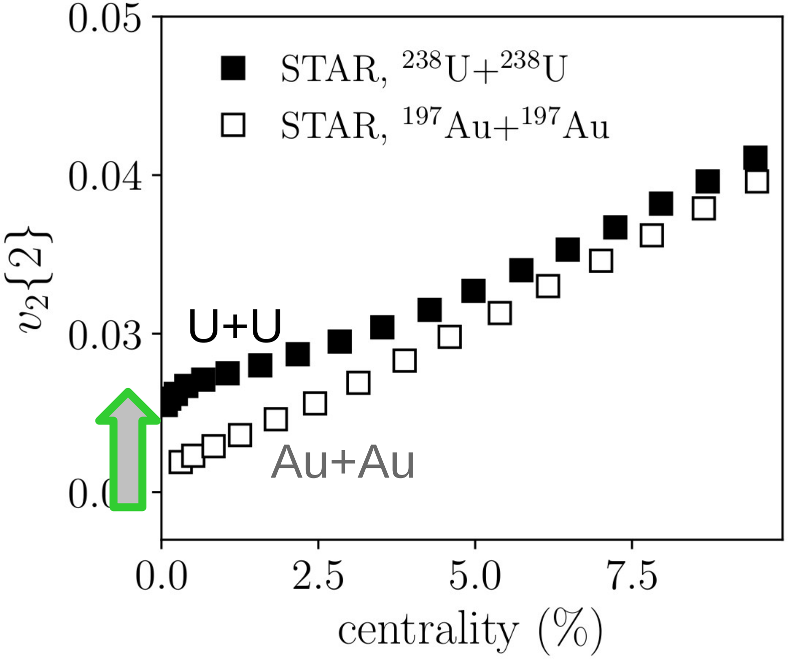
from NBI Copenhagen

Consistency of the paradigm: Intrinsic shape effects in high-energy collisions?

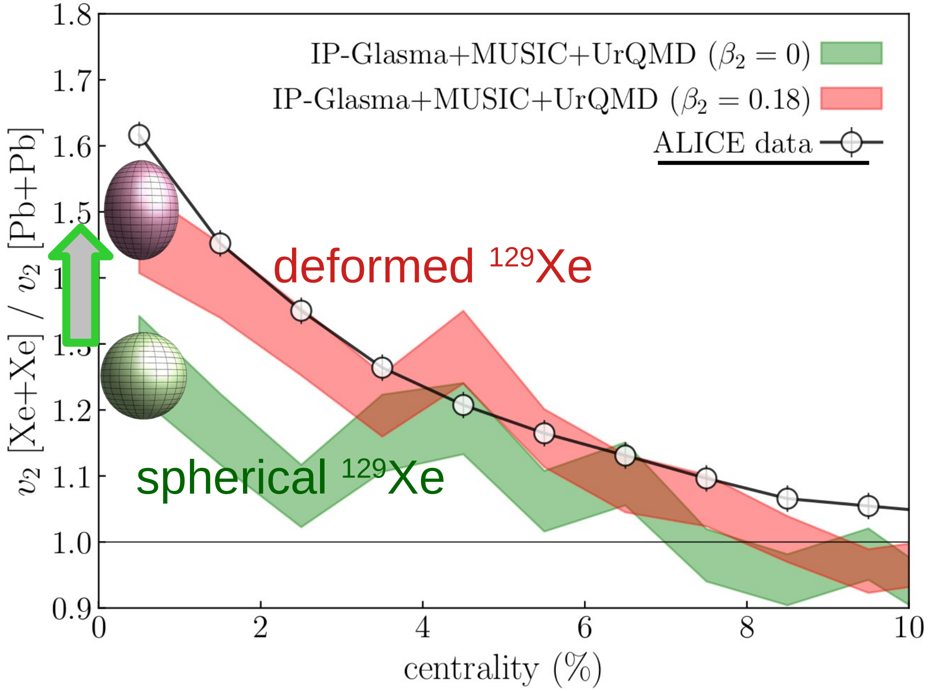
[previous talk by C. Zhang / J. Jia]



Shape-enabled elliptical geometry for the QGP.

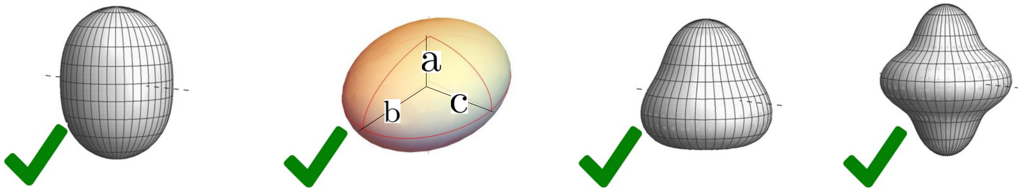


[STAR Collaboration, PRL **115** (2015) 22, 222301]



[ALICE Collaboration, PLB **784** (2018) 82-95]

$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma} Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3}Y_{30}(\Theta)+\underline{\beta_4}Y_{40}(\Theta)\right]$$



LANDMARKS

– ^{238}**U**, Signatures of quadrupole (β_2) and hexadecapole (β_4) deformations.

– ^{129}**Xe**, Evidence of the full triaxial shape ($\beta_2 + \gamma$).

[see previous talk by C. Zhang / J. Jia]

– ^{96}**Zr**, Evidence of the octupole deformation (β_3).

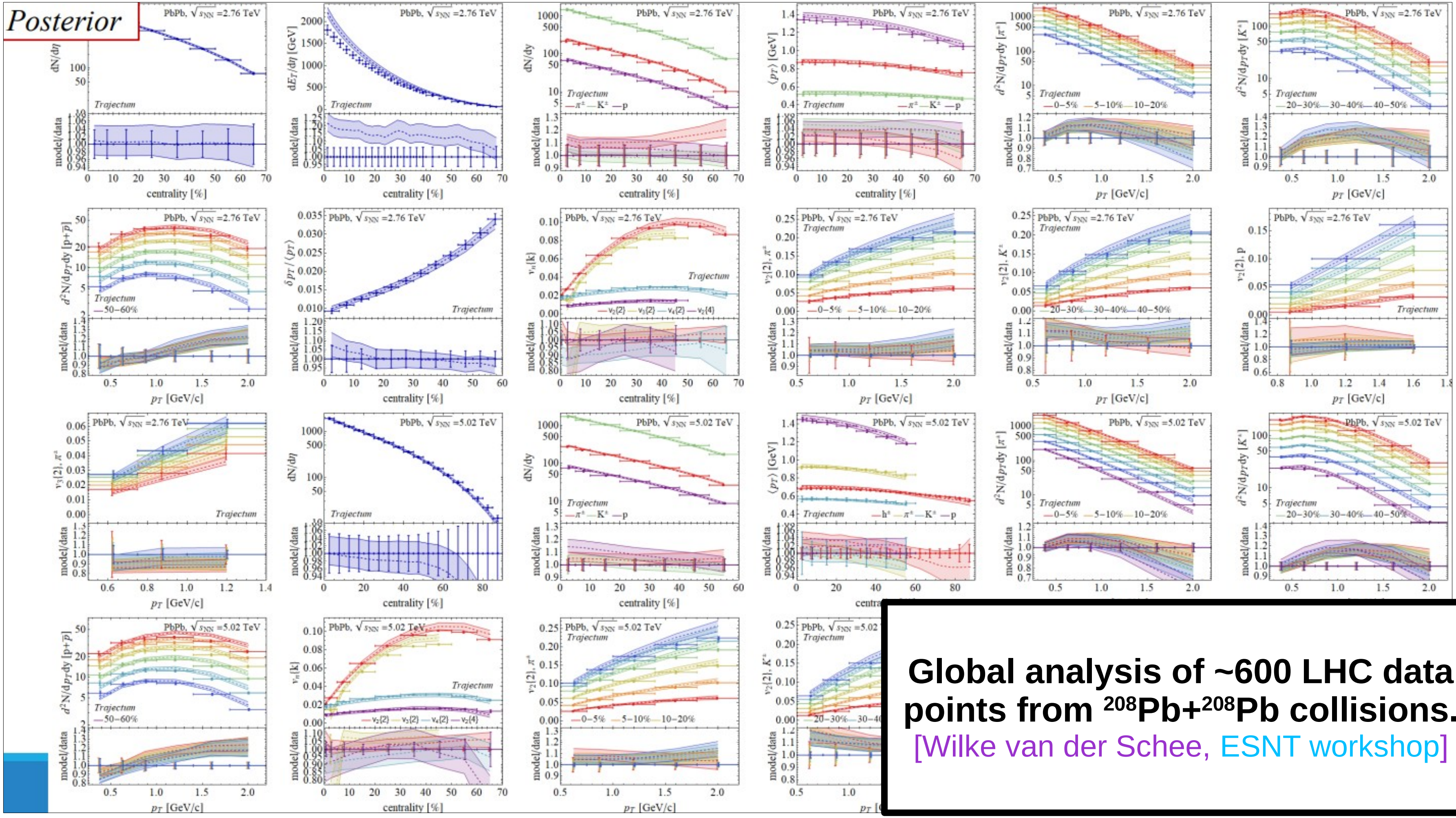
– ^{96}**Zr & ^{96}Ru**, Evidence of the larger skin (a) of ^{96}Zr due to neutron excess.

– About 40 theory papers on the subject in the last two years.

All expected signatures are confirmed. Nuclear structure is part of the problem.

2 – Nuclear structure and nuclear interactions with colliders.

20 years later: hydrodynamic model constrained via global statistical analyses.



Global analysis of ~600 LHC data points from ^{208}Pb+^{208}Pb collisions.
[Wilke van der Schee, ESNT workshop]

Idea: Extract nuclear structure from global analysis. Check consistency with low-energy input.

First attempt with ^{208}Pb+^{208}Pb data. [Giacalone, Nijs, van der Schee, arXiv:2305.00015]

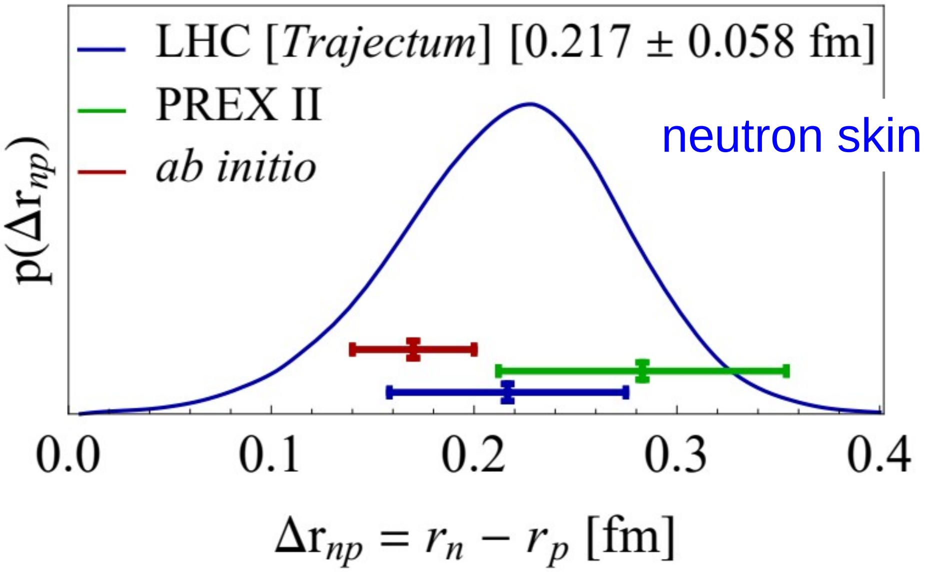
[see also talk by G. Nijs]

Extracting the radial profile. Matter radius:

$$R_{\rm Pb}({\rm LHC}) = 5.568 \pm 0.058 \text{ fm}$$

$$R_{\rm Pb}(ab\ initio) = 5.534 \pm 0.030 \text{ fm}$$

[Hu *et al.*, Nature Phys. 18 (2022) 10, 1196-1200]



Model uncertainty on skin competes with best low-energy experiment estimate.

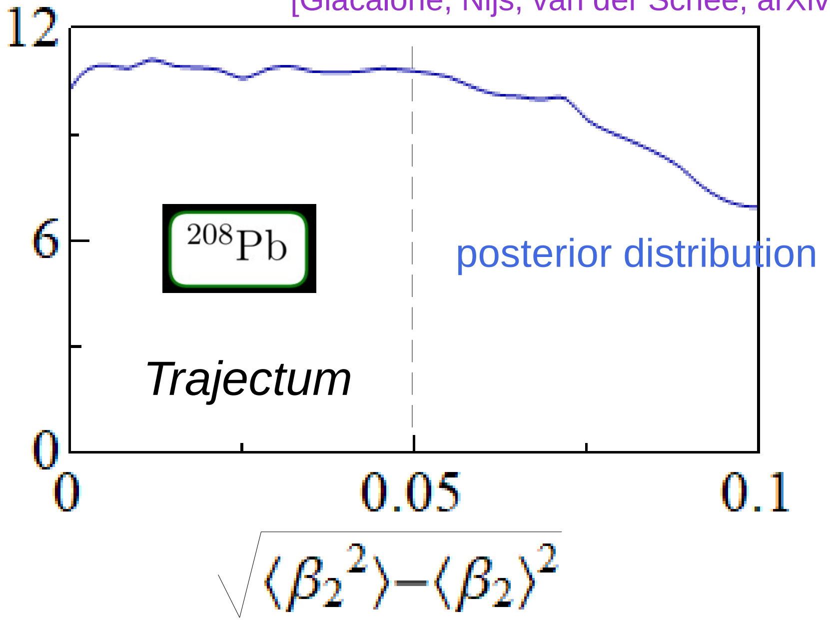
PREX II	$0.278 \pm 0.078 \ (\text{exp.}) \pm 0.012 \ (\text{theo.}) \text{ fm}$
LHC	$0.217 \pm 0.058 (\text{theo.}) \text{ fm}$

[PREX Collaboration, PRL **126** (2021) 17, 172502]

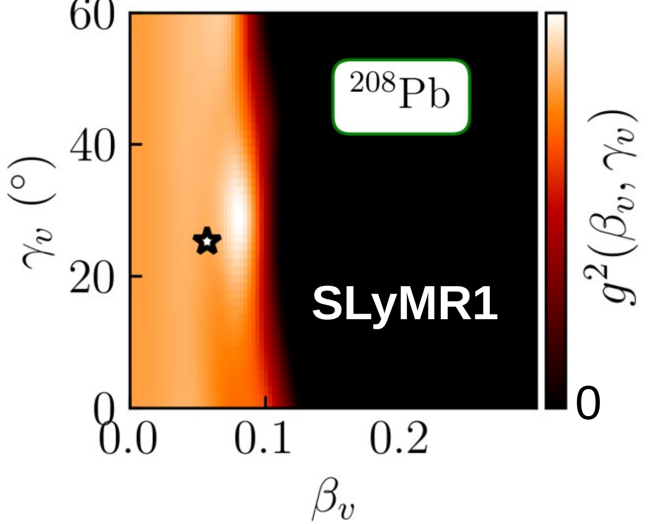
Extracting the deformed shape (β_2 only).

Shapes 'equiprobable' up to β_2~0.05. Sort of in line with density-functional results.

[Giacalone, Nijs, van der Schee, arXiv:2305.00015]



"Distribution" of deformations in density functional theory



[Bally et al., PRL **128** (2022) 8, 082301]

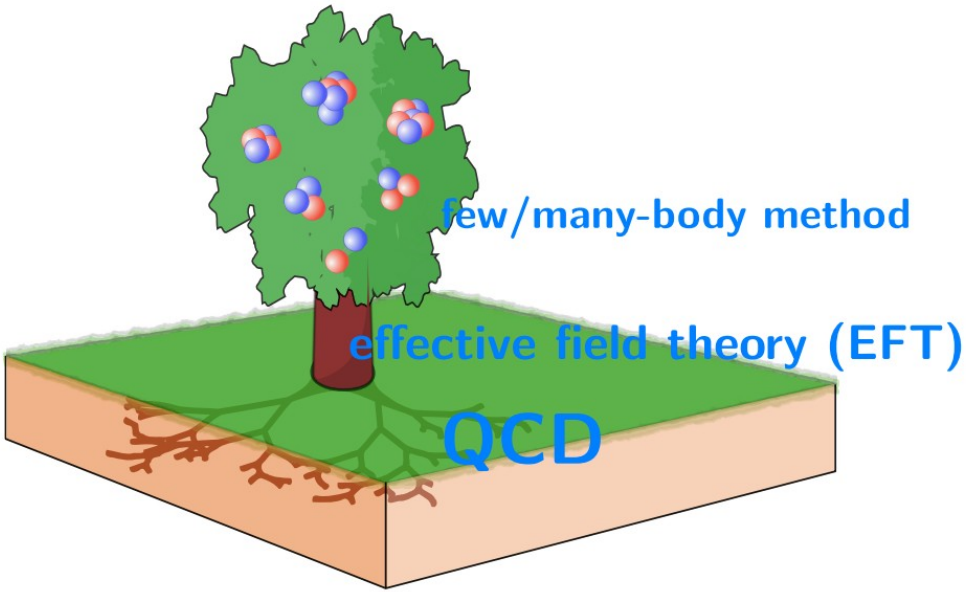
Extraction of intrinsic shape of ^{96}Ru, ^{96}Zr, ^{129}Xe, ^{238}U seems possible.

Assess consistency.

Reverse-engineering: Gauging the nuclear interaction with high-energy experiments?

Modern nuclear interactions: Effective field theory of low-energy QCD.

1. Systematic expansion of hadron-hadron interactions based on symmetries of QCD.
2. Power counting enabled by separation of scales. $m_\pi / m_{\rm QCD} \ll 1$
3. Coupling constants from lattice QCD or experiments.



[from S. König (NCSU)]

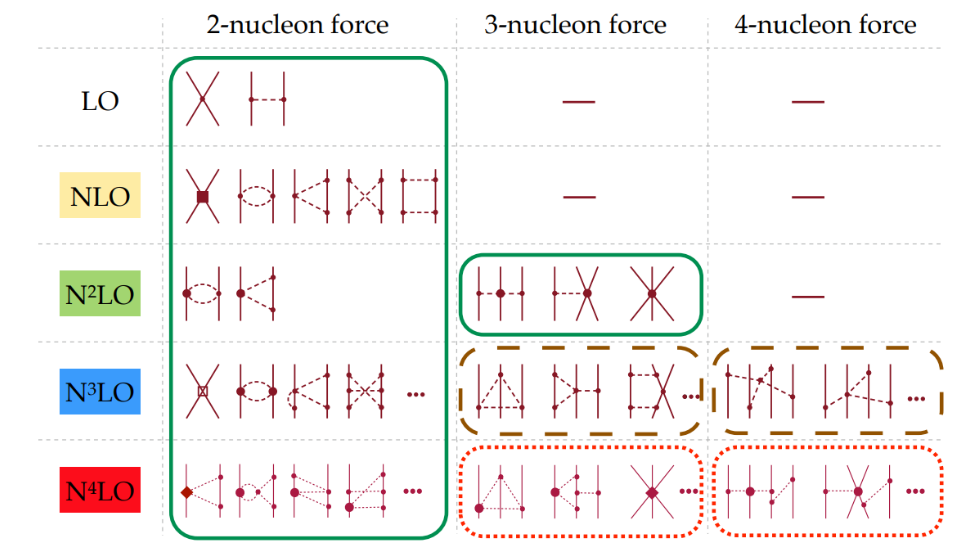


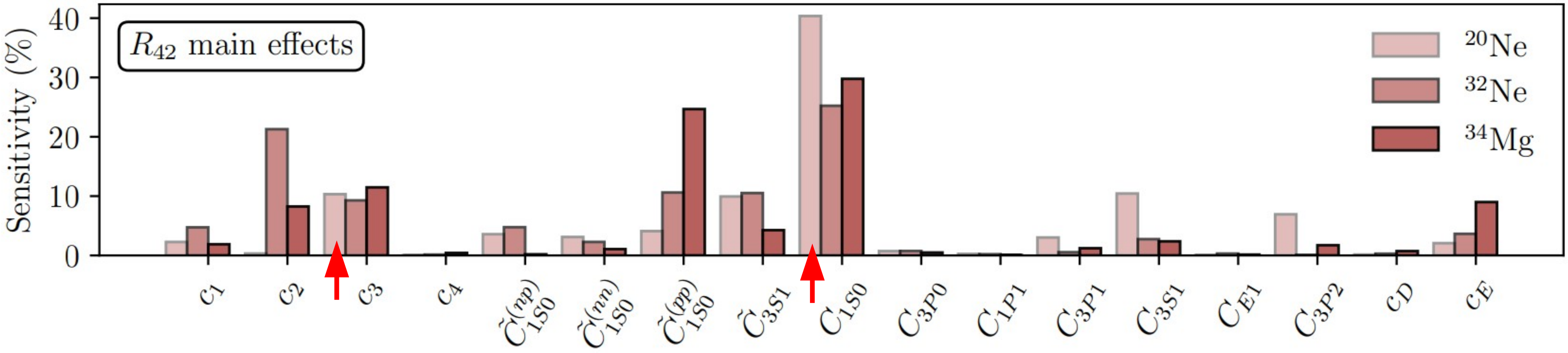
Fig. 19. Diagrams appearing in the first five orders of chiral EFT derived within Weinberg power counting.

[Somà, EPJ Plus 133 (2018) 10, 434]

What drives deformation in chiral EFT? Going beyond shapes.

Measure of rigid-rotor-like behavior: $R_{42} \equiv E(4^+)/E(2^+)$

Δ-full chiral EFT with 17 low-energy constants. **Global sensitivity analysis.**



A global sensitivity analysis shows that the subleading singlet S-wave contact and a pion-nucleon coupling strongly impact deformation in chiral EFT.

[Ekström *et al.*, arXiv:2305.06955]

Repeat the analysis with high-energy observables?

$$\left\langle e^{in(\phi_1-\phi_2)} \right\rangle \propto \int_{\mathbf{r}_1,\mathbf{r}_2} P_2(\mathbf{r}_1,\mathbf{r}_2) \ldots$$

mean squared anisotropic flow

nuclear two-body density

Systematic calculations of $P_2\,(\mathbf{r}_1, \mathbf{r}_2)$ for different nuclear interactions?

High-energy observables may present novel sensitivities.

Complementarity of nuclear experiments?

3 – Connecting low- and high-energy QCD in γA collisions

BREAKING BARRIERS

Flow fluctuations in AA collisions
due to energy density fluctuations.

$$\langle e(\mathbf{x})e(\mathbf{y})\rangle \quad \langle e(\mathbf{x})e(\mathbf{y})e(\mathbf{z})\rangle$$

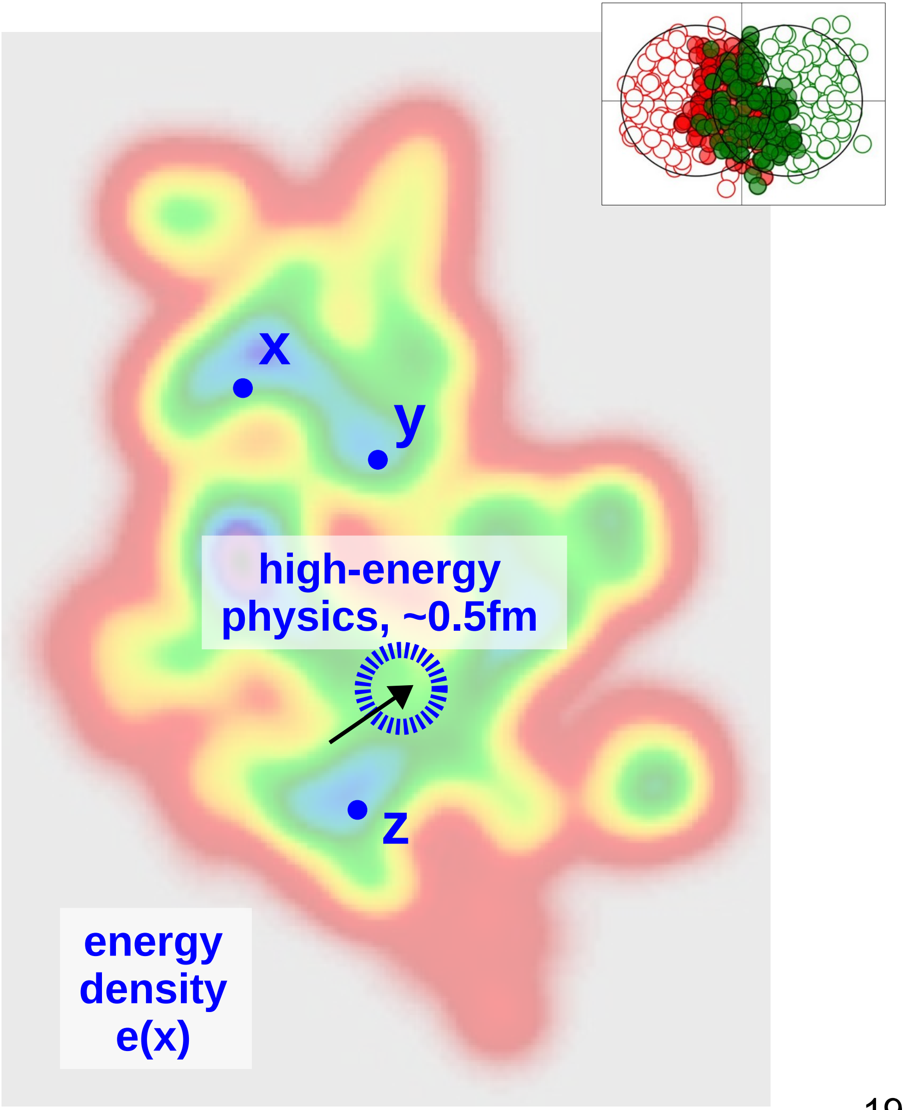
Large scales: nuclear structure, $P_2(\mathbf{r}_1, \mathbf{r}_2)$.

LOW ENERGY PHYSICS

Small scales: modifications of $P_2(\mathbf{r}_1, \mathbf{r}_2)$ from boost, nuclear modification (nPDF, saturation), nucleon geometry.

HIGH ENERGY PHYSICS

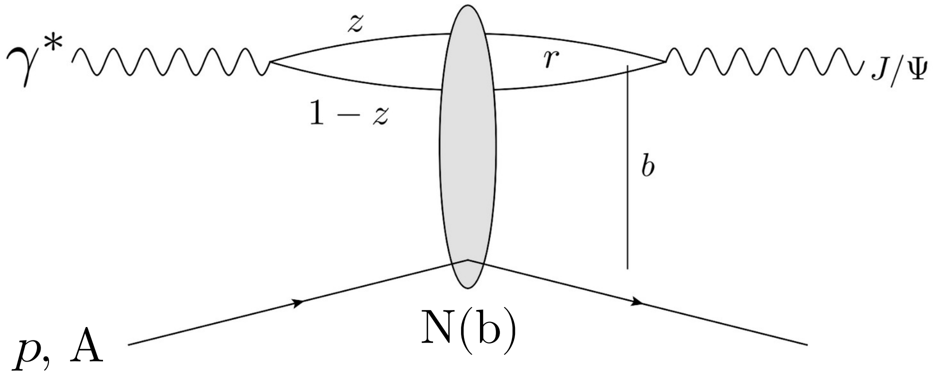
Better handle on their connection?



THE PROCESS:

Diffractive incoherent J/ψ production.

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



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

impact parameter

transverse momentum transfer

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

thickness function

Incoherent cross section gives access to the two-body nuclear density (t = - Δ²):

$$\left\langle\, |\mathcal{A}|^2(|t|)\,\right\rangle \longrightarrow \int_{\mathbf{r}_1,\mathbf{r}_2} P(\mathbf{r}_1,\mathbf{r}_2;|t|)\ldots$$

[Caldwell, Kowalski, PRC **81** (2010) 025203]

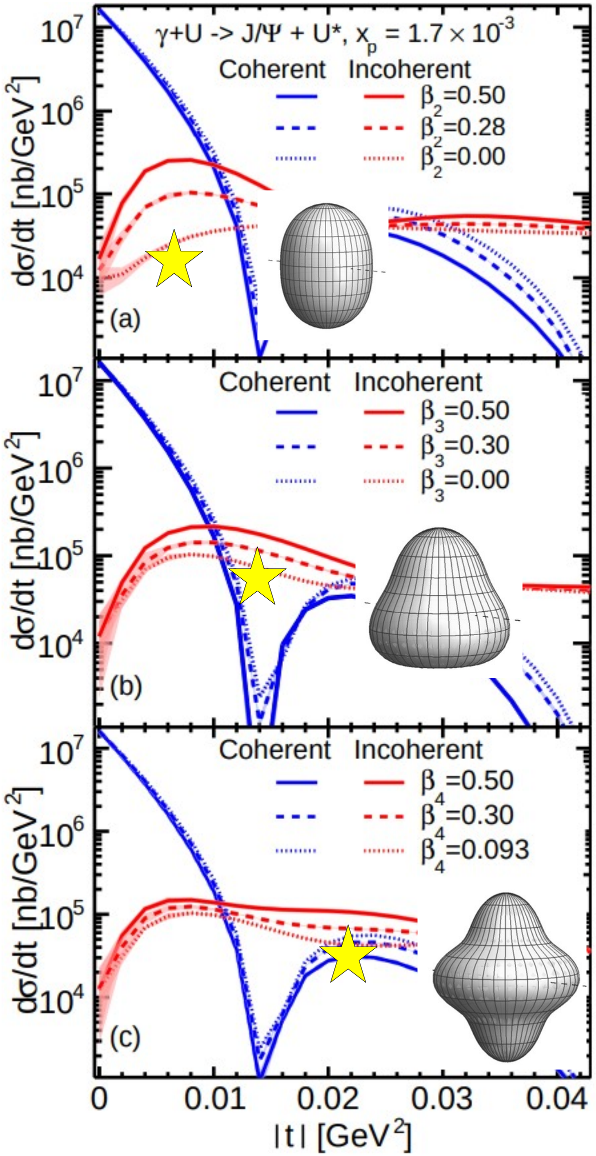
First calculation with a deformed target.

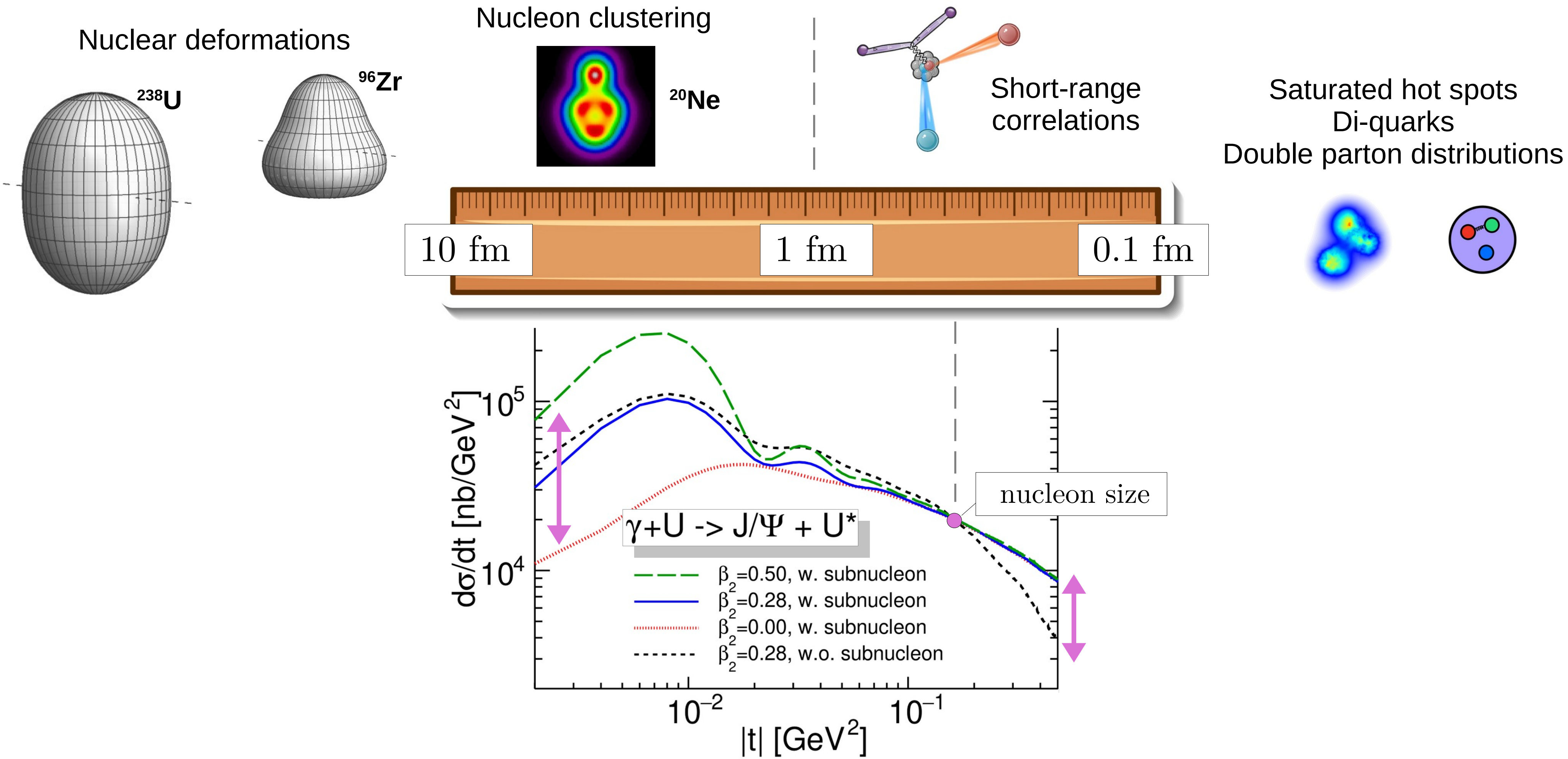
[Mäntysaari *et al.*, arXiv:2303.04866]

Prominent signatures of long-range two-body correlations.

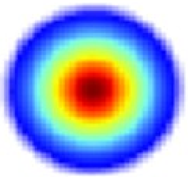
Different deformations impact different scales.

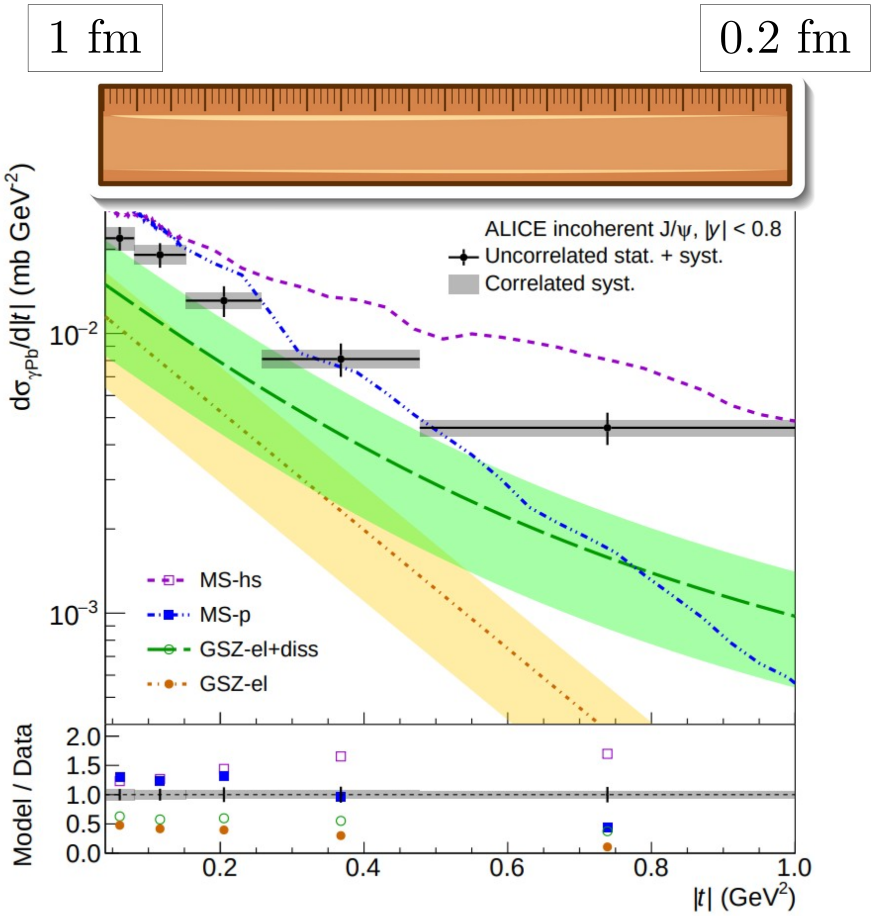
[see also talk by Chun Shen]

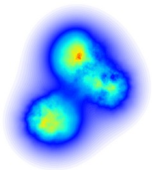




Chiral effective field theory (low-energy QCD) ← ? → **CGC effective field theory (high-energy QCD)**







Resolving two-body correlations.

$$P_2(\mathbf{r}_1, \mathbf{r}_2, |t|)$$

Typically, nucleons in nuclei do not behave like free nucleons.

Lower values of |t|?

EIC?

[ALICE collaboration, arXiv:2305.06169]

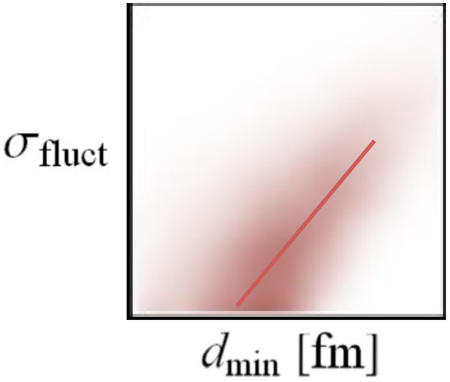
Assisting AA collisions with γA collisions. Two important cases.

[e.g. Nijs, van der Schee, arXiv:2304.06191]

1) Interplay of short-range correlations and high-energy physics.
"d_{min}" and "Q_s fluctuations" are degenerate in Bayesian analyses.

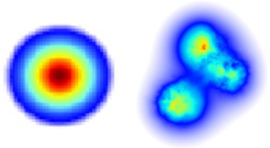
$P_2(\mathbf{r}_1, \mathbf{r}_2)$ modification at high energy?

Fundamental understanding?



2) Major role played by the nucleon size for some observables in AA collisions.

[Giacalone, Schenke, Shen, PRL **128** (2022) 4, 042301]
[Nijs, van der Schee, PRL **129** (2022) 23, 232301]



Nucleon size parameter of Trento: same nucleon size extracted from e-p data?

Can we extract a nucleon size from γA data?

4 – Physics opportunities with Neon-20

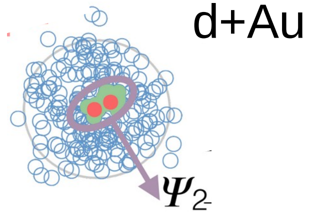
Main purpose: Deciphering small system collectivity.

Find “model-independent” correlation between final-state anisotropy and initial-state geometry.

Achievements so far:

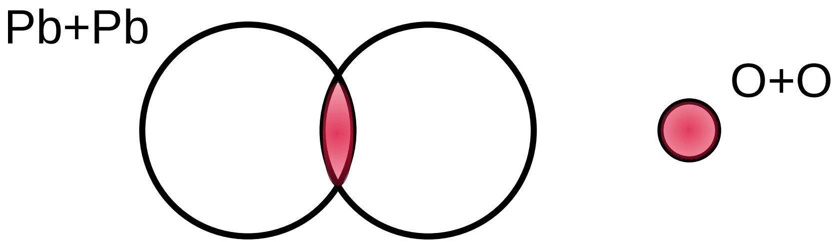
[PHENIX Collaboration, Nature Phys. **15** (2019) 3, 214-220]
[STAR collaboration, PRL **130** (2023) 242301]

- $v_2\{2\}_{d+{}^{197}\mathrm{Au}} > v_2\{2\}_{p+{}^{197}\mathrm{Au}}$
- $v_2\{2\}_{{}^{208}\mathrm{Pb}+{}^{208}\mathrm{Pb}} > v_2\{2\}_{p+{}^{208}\mathrm{Pb}}$
- $v_3\{2\}_{{}^{208}\mathrm{Pb}+{}^{208}\mathrm{Pb}} \approx v_3\{2\}_{p+{}^{208}\mathrm{Pb}}$



Upcoming:

- $v_2\{2\}_{{}^{208}\mathrm{Pb}+{}^{208}\mathrm{Pb}} > v_2\{2\}_{{}^{16}\mathrm{O}+{}^{16}\mathrm{O}}$



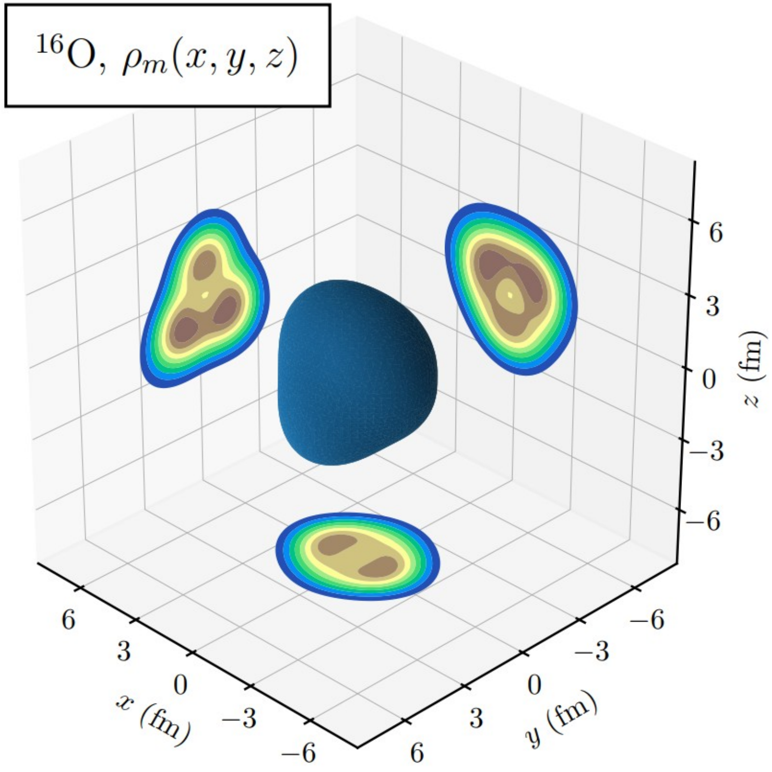
But can one make solid predictions for these effects?
(issues: proton structure at low x, longitudinal de-correlations, large dependence on parameters … **)**

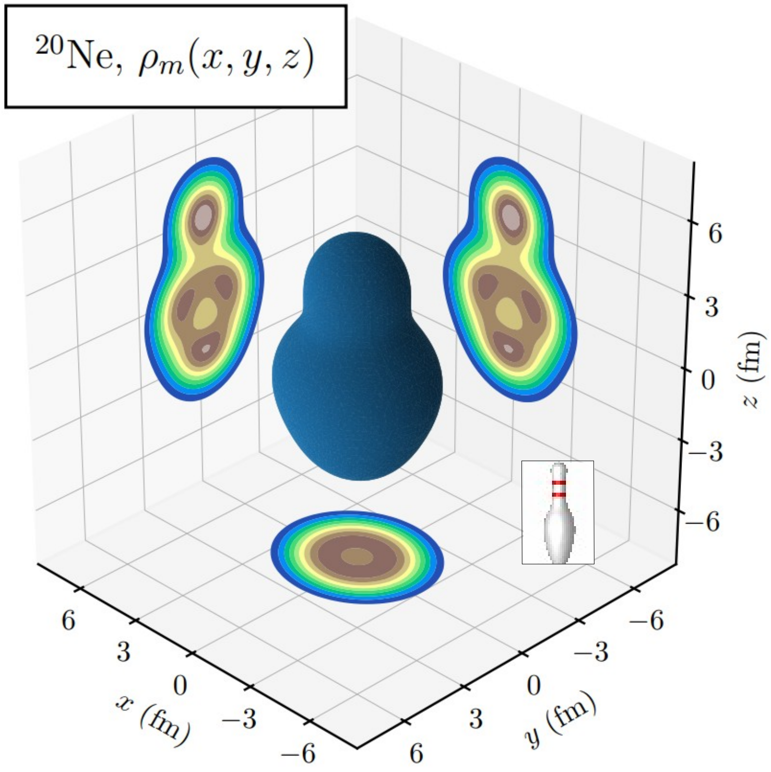
IDEA → **Employ two light ions to obtain substantially more robust information.**

Exploiting O+O collisions. The candidates: Bowling pin and Tetrahedron.

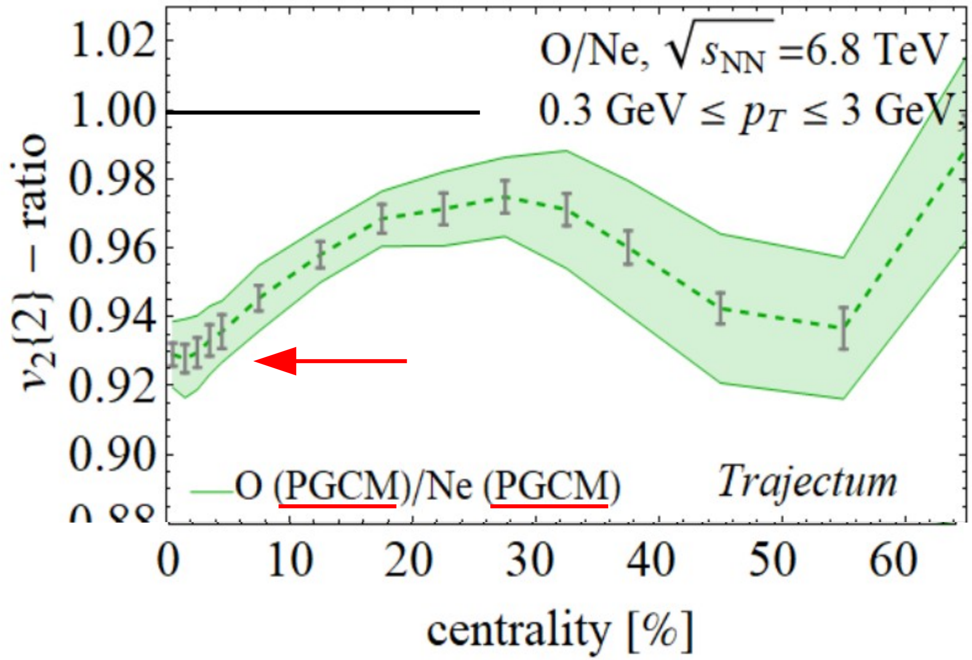
From *ab initio* Projected Generator Coordinate Method approach.

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





A quantitative prediction.



dN / dy ~ 100

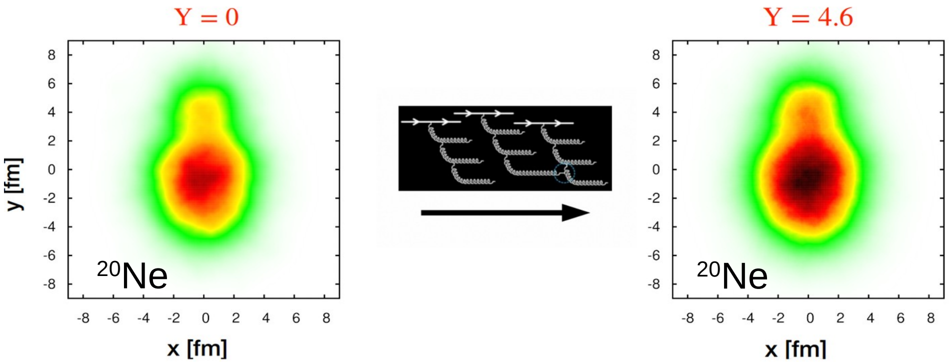
$$\frac{v_2\ [\mathrm{O+O}]}{v_2\ [\mathrm{Ne+Ne}]} = 0.93 \pm 0.01$$

[Bally *et al*. in preparation]

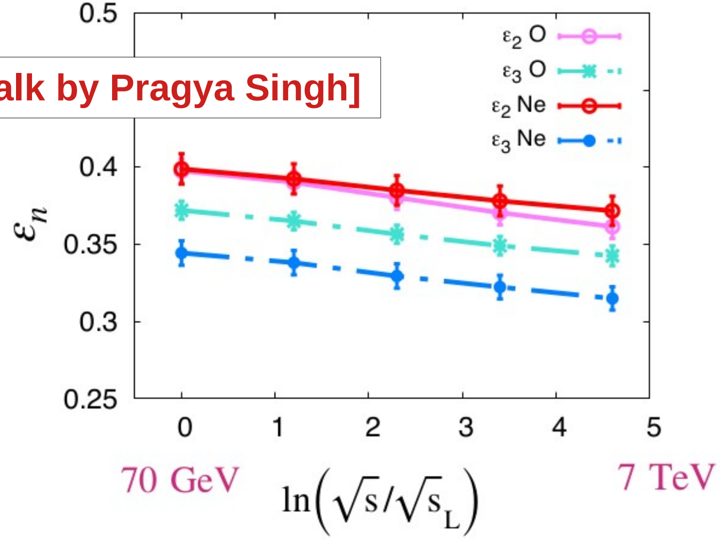
- **Uncertainty contains large systematic scan of hydro model parameters.**
- **Nuclear shapes consistently taken from *ab initio* theory.**

Connection with LHCb SMOG program and small-x evolution.

Smearing the bowling pin with small-x gluons.

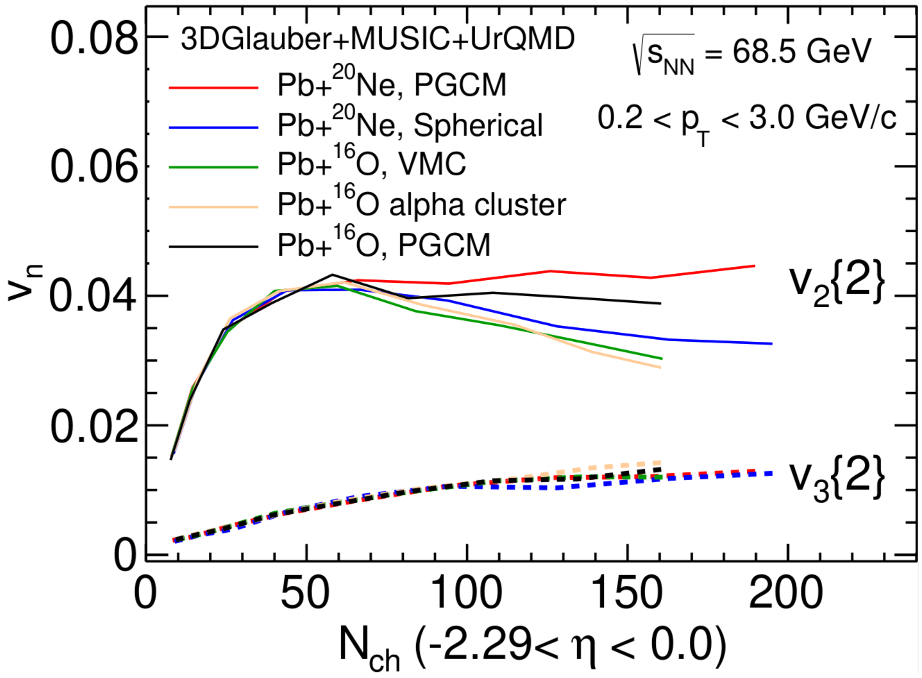


[talk by Pragya Singh]



Hydro predictions for LHCb.

[W. Zhao *et al.*, in preparation]



[talk by Chun Shen]

Seeing the bowling pin in γA collisions.

$$\left\langle\, |\mathcal{A}|^2(|t|) \,\right\rangle \longrightarrow \int_{\mathbf{r}_1,\mathbf{r}_2} P(\mathbf{r}_1,\mathbf{r}_2;|t|)\ldots$$

Important:

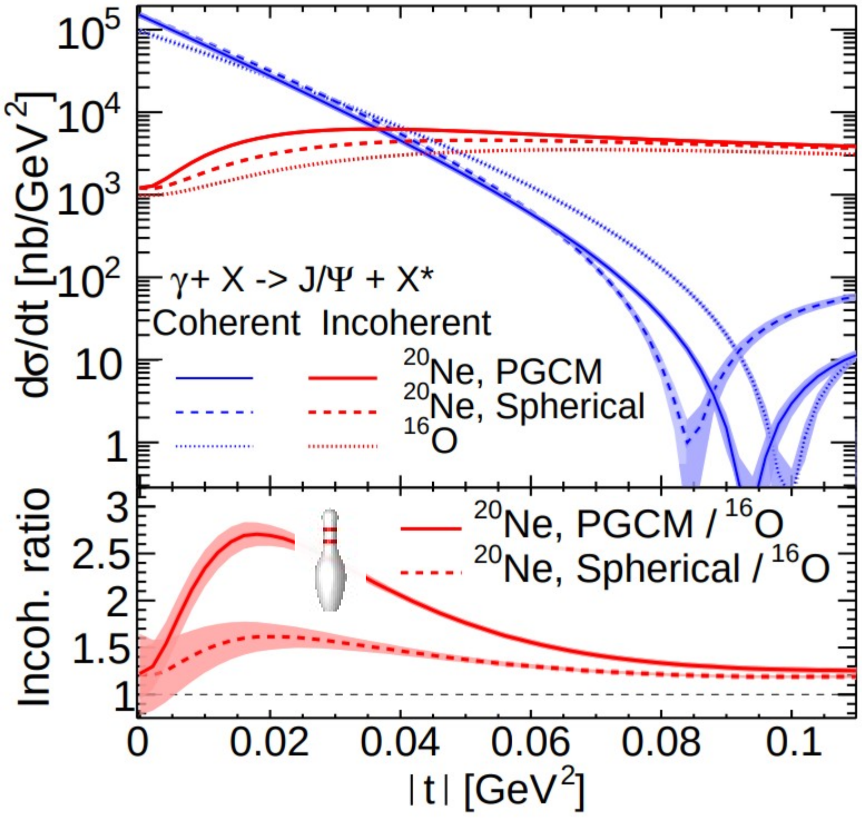
Direct access to initial-state effects with nuclei.

No bias from final-state effects.

Fully complementary to flow fluctuations.

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

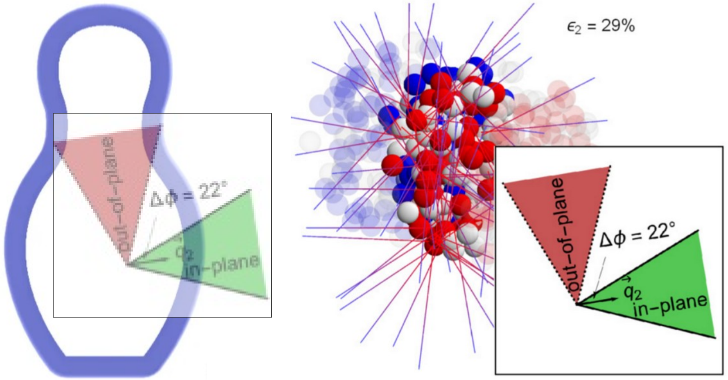
Cancellation of uncertainties in ratio?



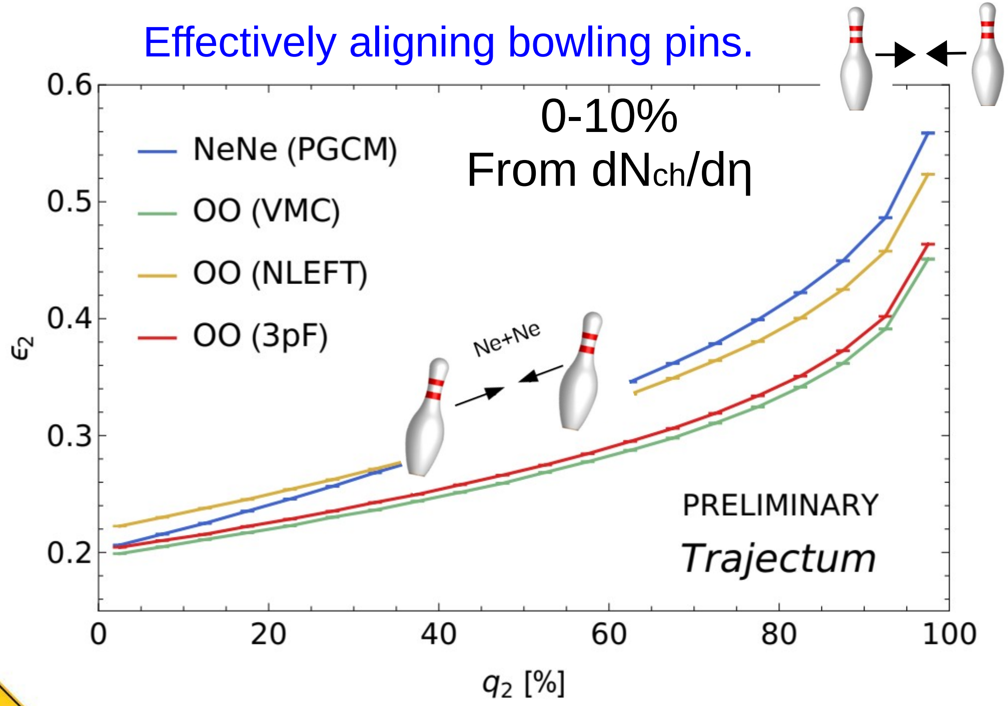
Elongated shape to investigate hard probe modification in a small system.

Observation of path-length dependent energy loss reported in Pb+Pb collisions.

[Beattie, QM22, arXiv:2210.02937]

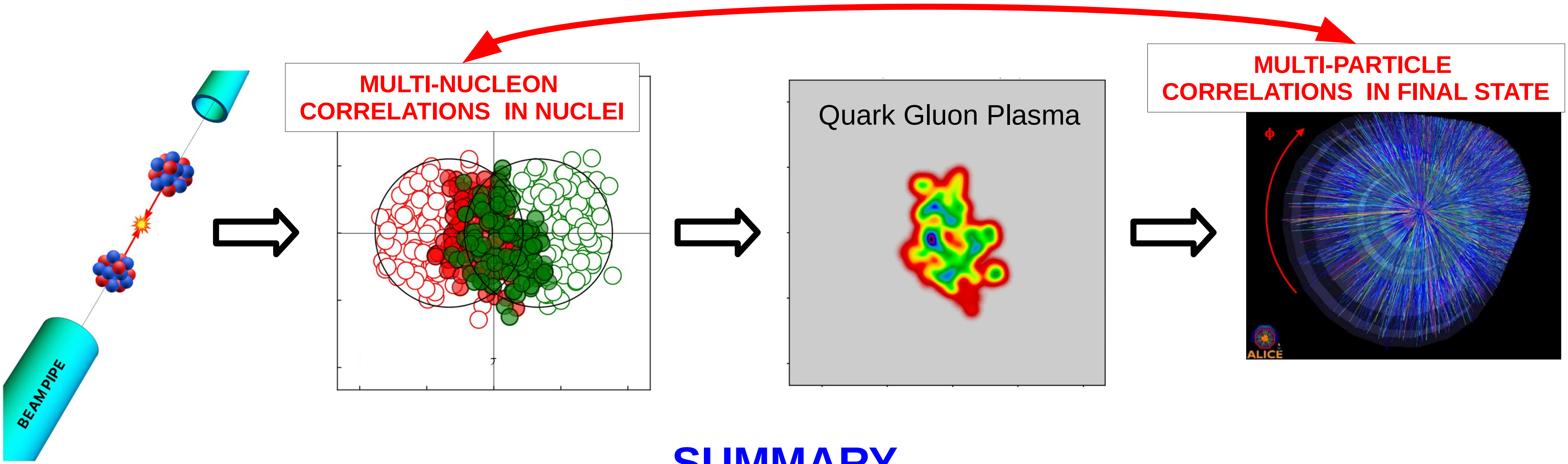


Effectively aligning bowling pins.



Studies of path lengths are underway.

[Beattie et al., PLB **836** (2023) 137596]



SUMMARY

- **Precision study of AA collisions + multiple species: nuclear structure is part of the problem.**
- **So far, all expected signatures of spatial correlations are observed at high energy.**
- **Reconstruction of nuclear properties from global sensitivity analyses in near future.**
- **Mapping transition from low-energy to high-energy nuclear structure in γA collisions.**
- **^{20}Ne ions to complement O+O collisions.**

CHECK OUR ACTIVITIES (2022-23)

→ RBRC workshop on isobar collisions (Jan 2022, link, J. Jia, C. Shen. D. Teaney, Z. Xu)

→ EMMI Task Force (May link & Oct link 2022, with J. Jia, V. Somà, Y. Zhou)

→ ESNT Workshop (Sep 2022, link, with J-Y. Ollitrault, Y. Zhou)

→ INT Program (Jan-Feb 2023, link, with J. Jia, D. Lee, M. Luzum, J. Noronha-Hostler, F. Wang)

→ More to come! (Beijing, Aug 2023? workshops in 2024? any suggestions?)

→ Input to Nuclear Physics LRP in the US, both hot QCD (e.g. arXiv link) and nuclear theory.

→ Contributed input to NUPECC LRP 2024 [link with Y. Zhou (NBI Copenhagen)]

→ Topical Issue on EPJA on the intersection of the two areas (link ~20 papers in 2023)
[T. Duguet, G. Giacalone, V. Somà, Y. Zhou]