WPCF 2024

welcomes you in Toulouse
France

XVIIth edition of the Workshop
on Particle Correlations
and Femtoscopy

4th to 8th November 2024

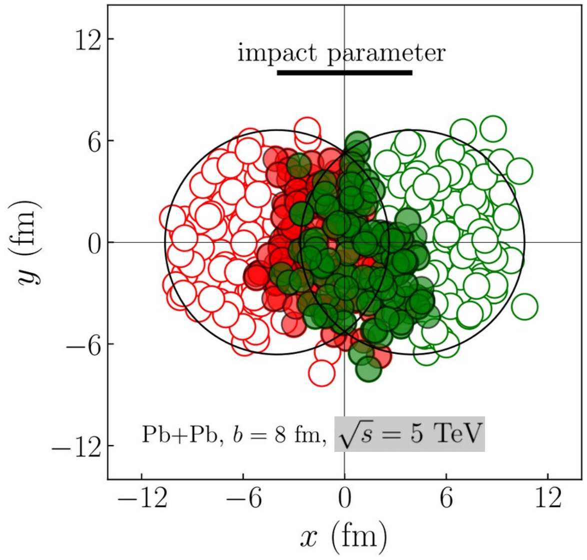
Giuliano Giacalone

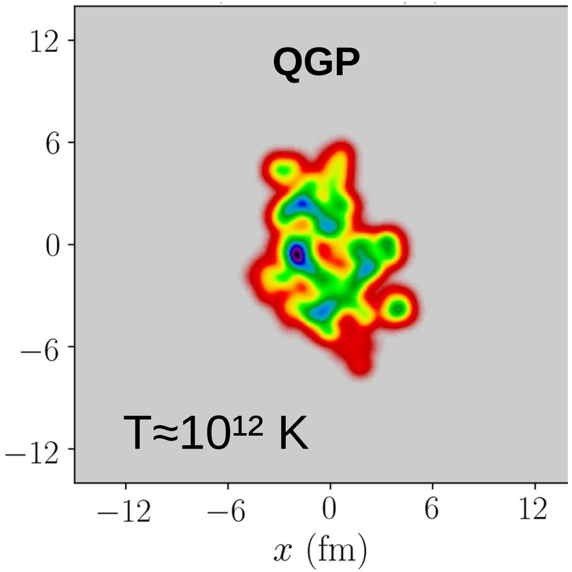
CERN

November 4, 2024

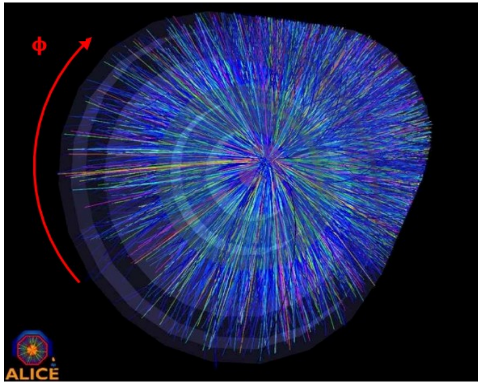
Imaging nuclei with relativistic ion collisions

RHIC program started in 2000 – Two decades later …





hydro



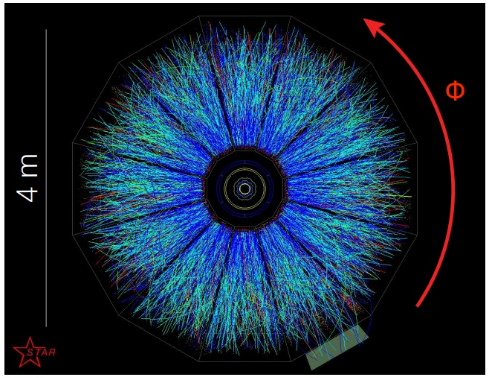
Relativistic fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$

Equation of state from lattice QCD

[HoTQCD collaboration, PRD **90** (2014) 094503]

[Romatschke & Romatschke, arXiv:1712.05815]

Fluid is viscous (η/s **,** ζ/s **, …)**



The art of event-by-event analysis

SPECTRUM

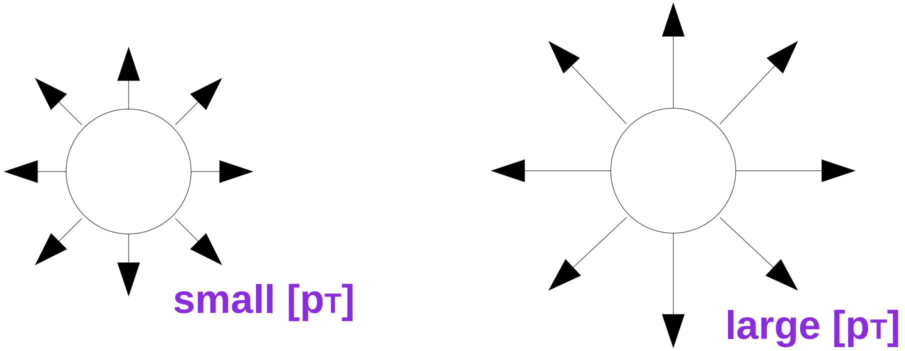
$$\frac{dN_{\rm ch}}{d\phi p_t dp_t}$$

CHARGED MULTIPLICITY

$$N_{\rm ch} = \int d\phi p_t dp_t \; \frac{dN_{\rm ch}}{d\phi p_t dp_t}$$

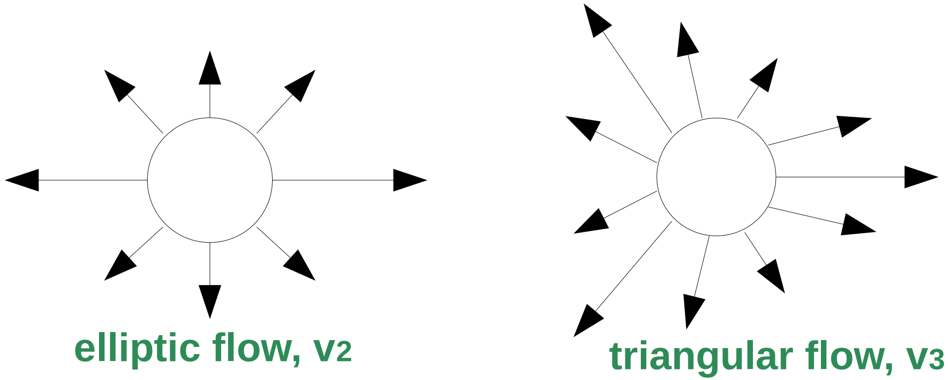
MEAN MOMENTUM

$$[p_t] = \frac{1}{N_{\rm ch}} \sum_{i=1}^{N_{\rm ch}} p_{t,i}$$



FOURIER HARMONICS

$$V_n = \frac{1}{N_{\rm ch}} \sum_{i=1}^{N_{\rm ch}} e^{-in\phi_i}$$



- $$\mathrm{var}([p_t]) = \left\langle \frac{\sum_{i\neq j}(p_i - \langle [p_t]_{\mathrm{ev}}\rangle)(p_j - \langle [p_t]_{\mathrm{ev}}\rangle)}{N_{\mathrm{ch,ev}}(N_{\mathrm{ch,ev}}-1)} \right\rangle_{\mathrm{ev}}$$
  2 particles

- $$v_n\{2\}^2 \equiv \langle V_n V_n^* \rangle_{\mathrm{ev}} = \left\langle \frac{\sum_{i\neq j} e^{in(\phi_i-\phi_j)}}{N_{\mathrm{ch,ev}}(N_{\mathrm{ch,ev}}-1)} \right\rangle_{\mathrm{ev}}$$
  2 particles

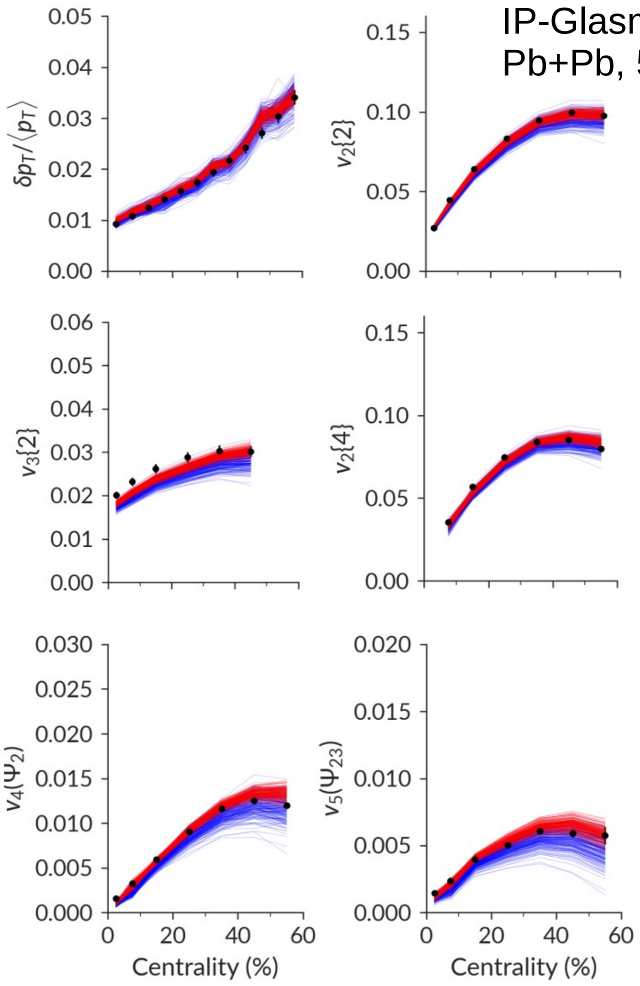
  $$\langle v_n^4 \rangle = \langle e^{n(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle_{\mathrm{ev}}$$
  4 particles

- $$\langle V_2^2 V_4^* \rangle = \langle e^{2(\phi_1+\phi_2)-4\phi_3} \rangle_{\mathrm{ev}}$$
  3 particles

  $$\langle V_2 V_3 V_5^* \rangle = \langle e^{2\phi_1+3\phi_2-5\phi_3} \rangle_{\mathrm{ev}}$$
  3 particles

- $$\mathrm{cov}([p_t], v_n^2) = \left\langle \frac{\sum_{i\neq j\neq k}(p_i - \langle [p_t]_{\mathrm{ev}}\rangle) e^{in(\phi_j-\phi_k)}}{N_{\mathrm{ch,ev}}(N_{\mathrm{ch,ev}}-1)(N_{\mathrm{ch,ev}}-2)} \right\rangle_{\mathrm{ev}}$$
  3 particles

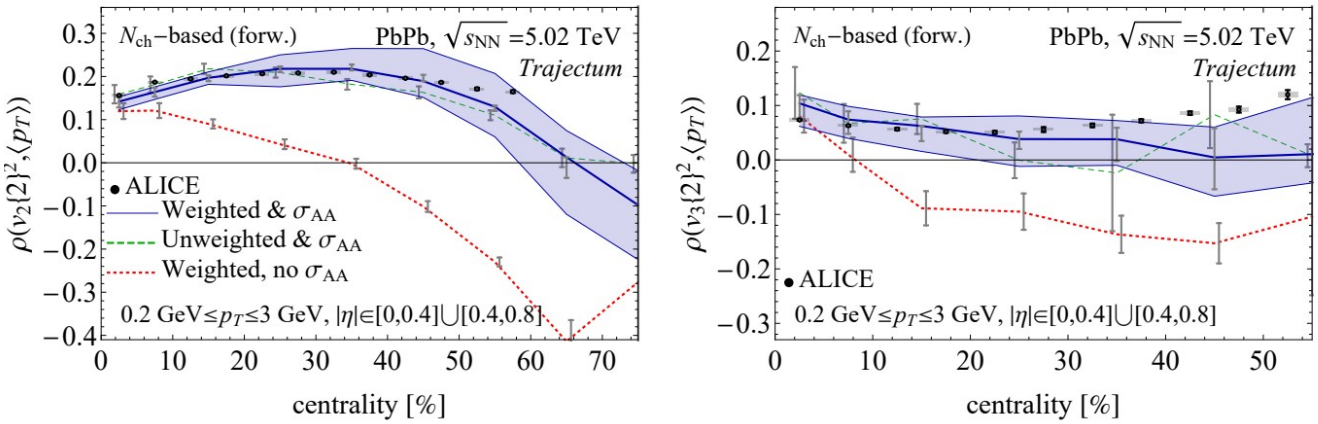
2-3-4 particle correlations … Bayesian analyses for quantitative studies

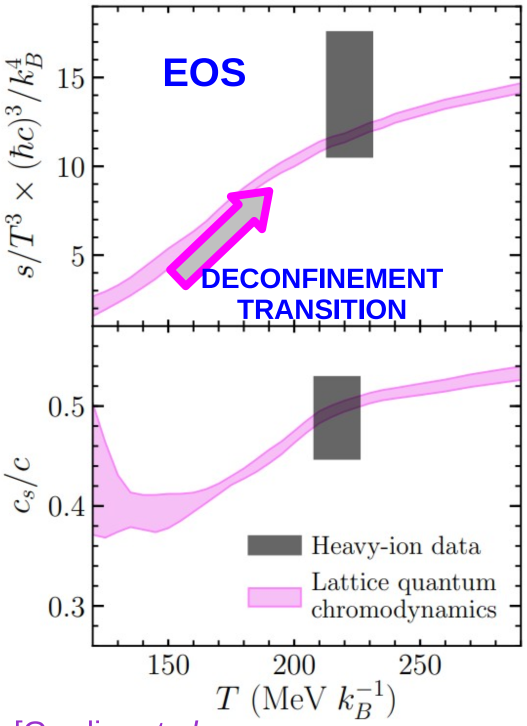


IP-Glasma+MUSIC+UrQMD
Pb+Pb, 5020 GeV

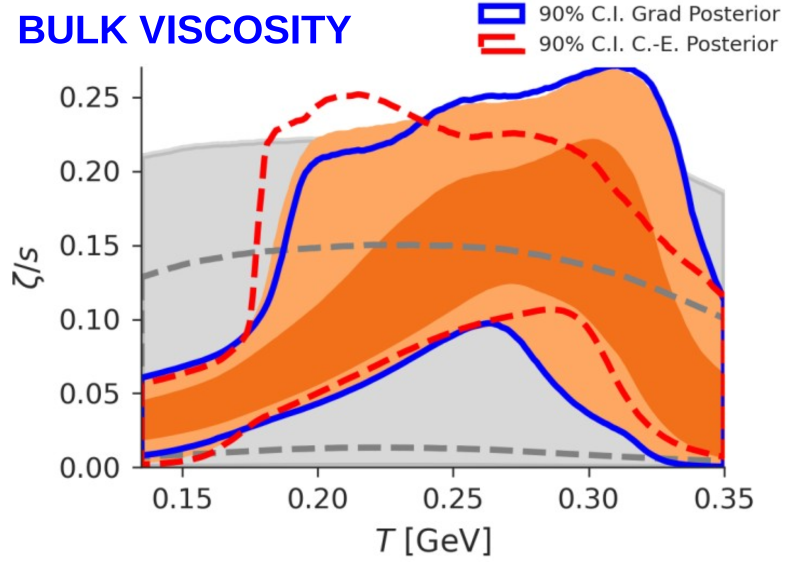
[Heffernan *et al.*, PRC **109** (2024) 6, 065207]

[Nijs, van der Schee, PRL **129** (2022) 23, 232301]

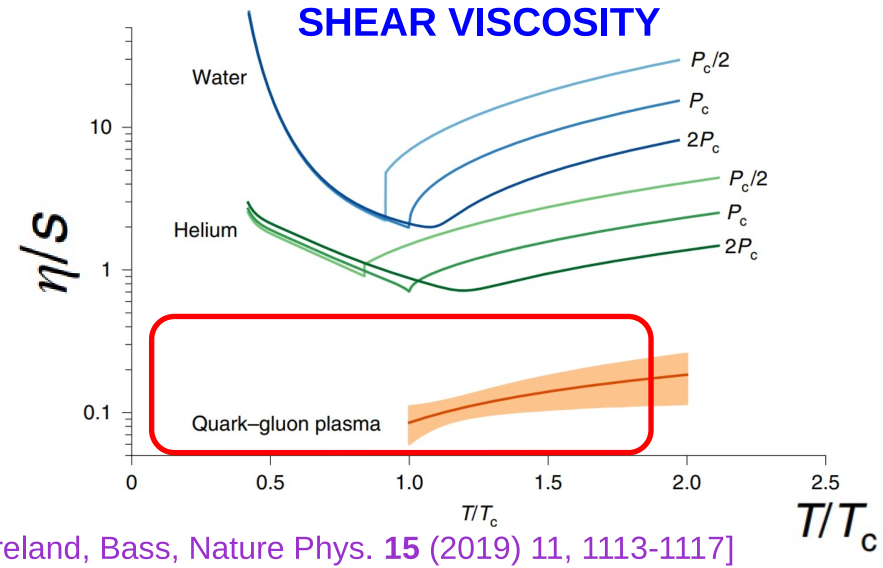




[Gardim *et al.*,
Nature Phys. **16** (2020) 6, 615-619]



[Heffernan *et al.*,
PRL **132** (2024) 25, 252301]

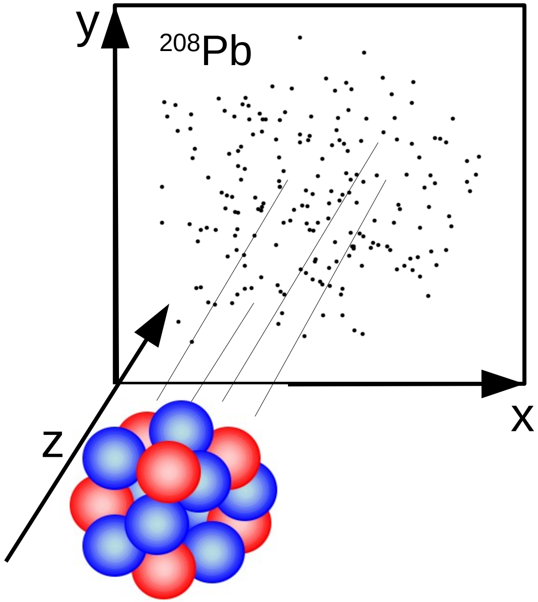


[Bernhard, Moreland, Bass, Nature Phys. **15** (2019) 11, 1113-1117]

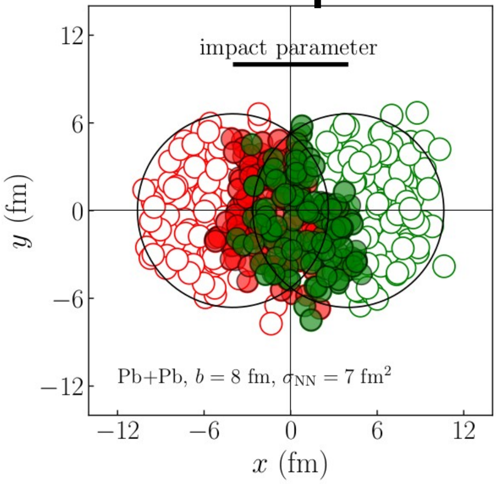
Origin of multi-particle correlations?

$$|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})|^2$$

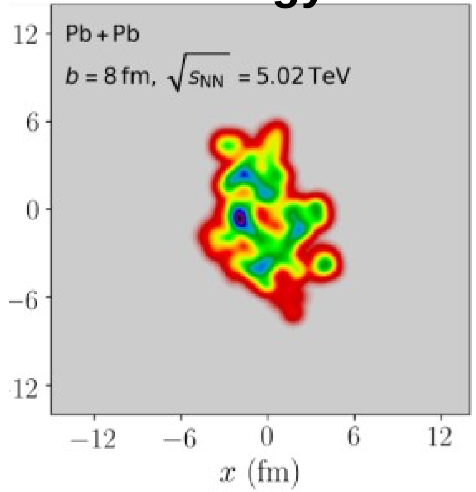
nucleon centers



overlap two nuclei



energy density



Initial-state fluctuations and correlations due to the random nucleon positions

[Alver, Roland, PRC **81** (2010) 054905]

Imaging finite quantum systems

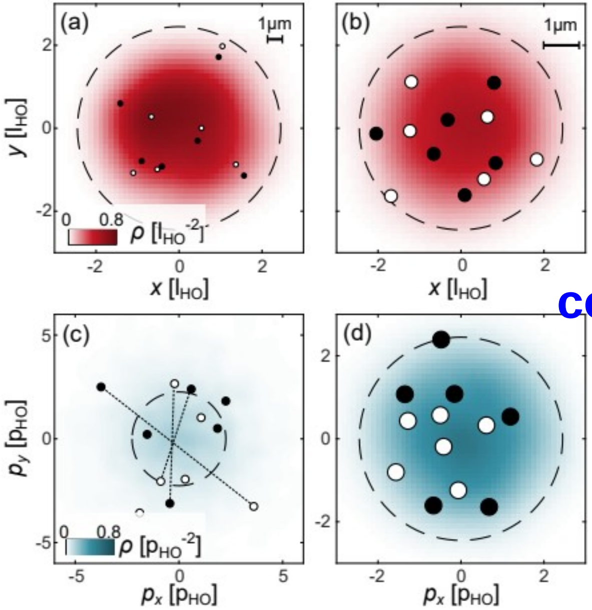


FIG. 3. **Fermionic systems in real and momentum space.** We image a system of 6 spin up and 6 spin down atoms (black/white dots) in real (a,b) and momentum (c,d) space, both in the strongly interacting (a,c) and the non-interacting regime (b,d). The two dimensional histograms show the density distribution, obtained from averaging over many experimental realizations of the same quantum state. The black and white dots show a single, randomly chosen snapshot of the wave-function. The size of the dots represents the resolution. The dashed circles show the Thomas Fermi radius (a,b) and the Fermi momentum (c,d) calculated from the non-interacting system. The lines connecting atoms of opposite spin and momentum in c) serve as a guide to the eye to highlight the opposite momentum correlations.

cold atoms

[Brandstetter *et al.*, arXiv:2308.09699 arXiv:2409.18954]

Resolution ≈ 300 nm

nuclear physics

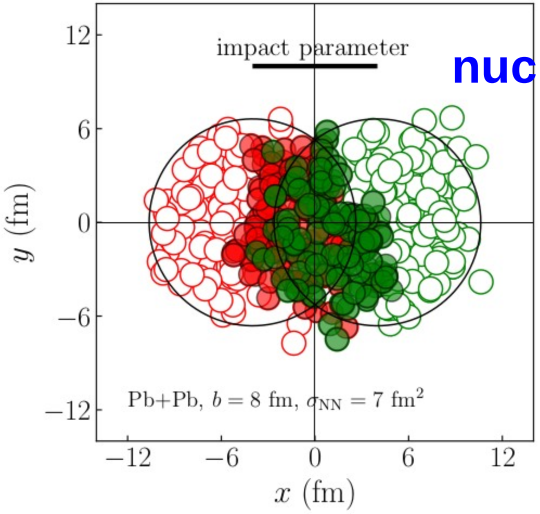
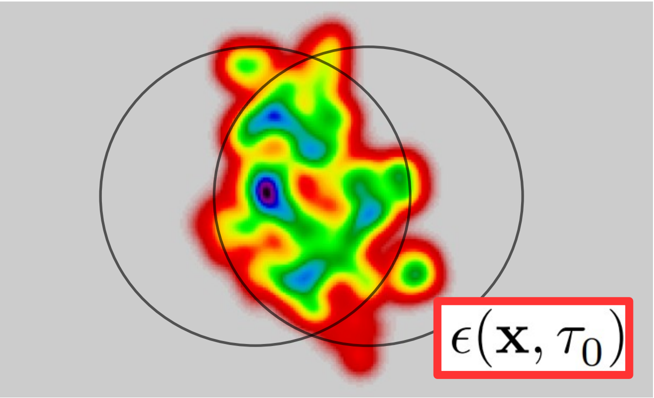
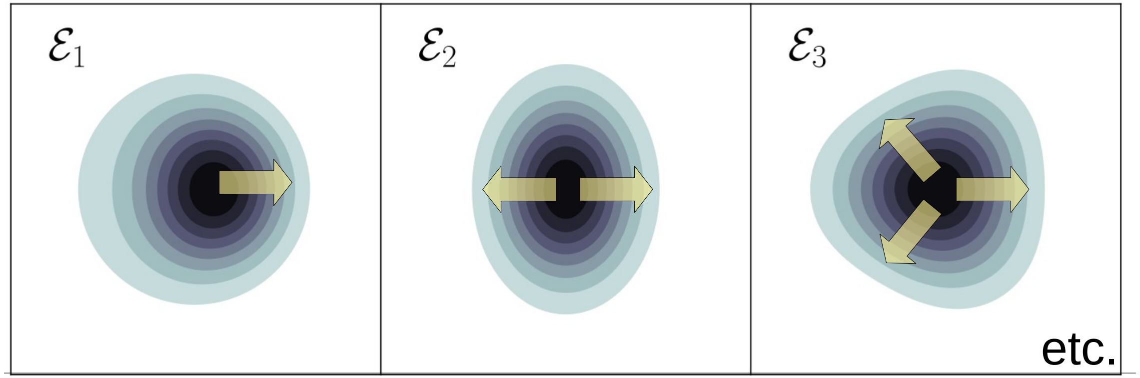


Figure 2.3: Transverse plane projection of a collision between ^{208}Pb nuclei in the Glauber Monte Carlo model. The two nuclei are shown as circles of radius $R_A = 6.62$ fm, and are shifted by $\pm b/2$, with $b = 8$ fm, along the x direction. There is a total of 416 nucleons, depicted as circles, and colored respectively in green or in red depending of their parent nucleus. The nuclei collide at $\sqrt{s_{\rm NN}} = 5.02$ TeV, corresponding to $\sigma_{\rm NN} = 7$ fm^2. Therefore, a green(red) nucleon is tagged as a participant nucleon whenever its distance from at least one red(green) nucleon is lower than $D = 1.5$ fm, which corresponds in fact to the diameters of the small circles in the figure. Participant nucleons are highlighted as full symbols.

“Resolution” in the transverse plane is the inverse typical momentum transfer, ≈ Gev ≈ 0.1 fm

Initial-state properties seen through final-state observables

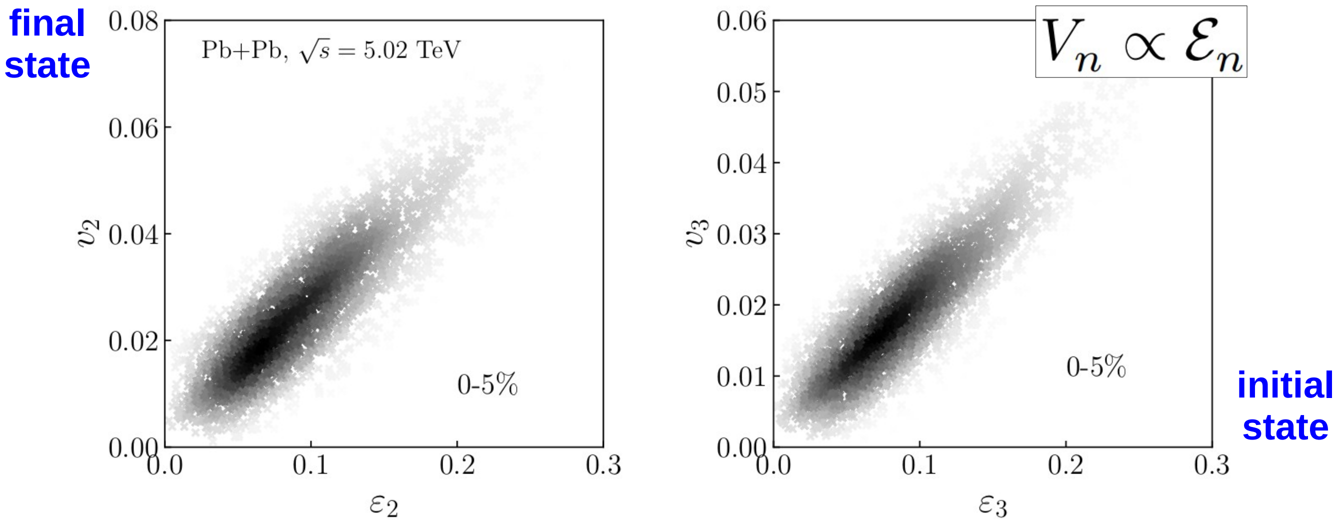




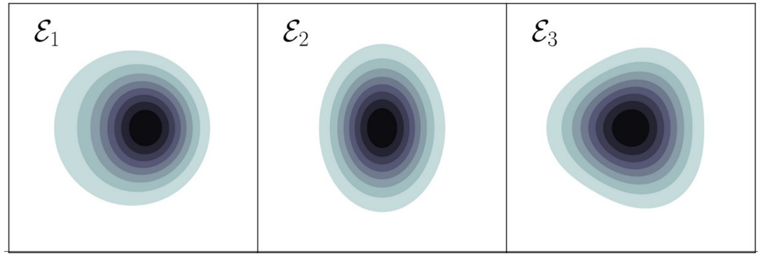
$$F = -\nabla P$$

1/R

[Teaney, Yan, PRC **83** (2011) 064904]

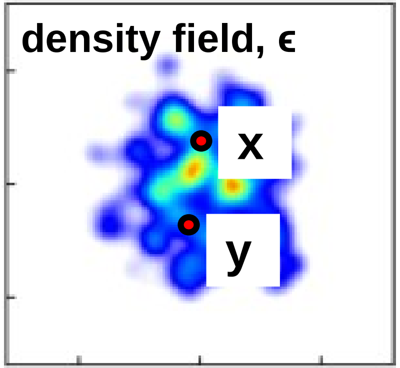


Analytical insights



– **Initial spatial anisotropy:**

$$\mathcal{E}_n = -\frac{\int_{\mathbf{x}} \epsilon(\mathbf{x})\ |\mathbf{x}|^n e^{in\phi_x}}{\int_{\mathbf{x}} \epsilon(\mathbf{x})\ |\mathbf{x}|^n}$$



– **Perturbative expansion:**

$$\epsilon(\mathbf{x}) = \langle \epsilon(\mathbf{x}) \rangle + \delta\epsilon(\mathbf{x})$$

– **Mean squared anisotropy:**

INITIAL STATE

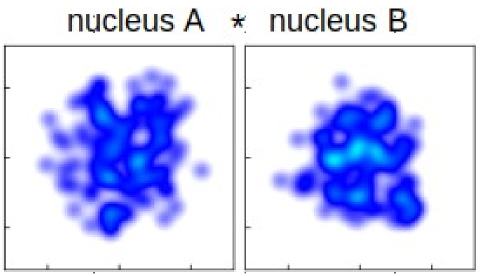
two-point correlation

FINAL STATE

$$\underset{\varepsilon_n^2}{\langle \mathcal{E}_n \mathcal{E}_n^* \rangle} = \frac{\int_{\mathbf{x},\mathbf{y}} |\mathbf{x}|^n |\mathbf{y}|^n e^{in(\phi_x - \phi_y)} \langle \epsilon(\mathbf{x}) \epsilon(\mathbf{y}) \rangle}{\left(\int_{\mathbf{x}} \langle \epsilon(\mathbf{x}) \rangle |\mathbf{x}|^n \right)^2} \propto \underset{v_n^2}{\langle V_n V_n^* \rangle}$$

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

Analytical insights

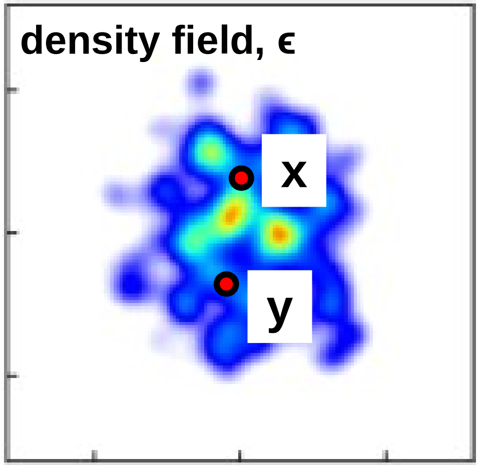


With:

$$\epsilon(\mathbf{x}, \tau = 0^{+}) \propto t_A(\mathbf{x}) t_B(\mathbf{x}) \qquad t(\mathbf{x}) = \sum_{i=1}^{A} \underline{g(\mathbf{x}; \mathbf{x}_i, w)}$$

NUCLEON STRUCTURE

Correlation functions:



[Giacalone, EPJA **59** (2023) 12, 297]

$$\langle \epsilon(\mathbf{x}) \rangle_{\rm ev} = A^2 \left(\int_{\mathbf{r}_1} \rho^{(1)}(\mathbf{r}_1) g(\mathbf{x} - \mathbf{r}_{1\perp}) \right)^2$$

$$\underline{\langle \epsilon(\mathbf{x}) \epsilon(\mathbf{y}) \rangle}_{\rm ev} = \Bigg(A \int_{\mathbf{r}_1} \rho^{(1)}(\mathbf{r}_1) \; g(\mathbf{x} - \mathbf{r}_{1\perp}) g(\mathbf{y} - \mathbf{r}_{1\perp})$$

ENERGY DENSITY

$$+ (A^2 - A) \int_{\mathbf{r}_1, \mathbf{r}_2} \underline{\rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2)} g(\mathbf{x} - \mathbf{r}_{1\perp}) g(\mathbf{y} - \mathbf{r}_{2\perp}) \Bigg)^2$$

NUCLEAR STRUCTURE

nuclear *n*-body density: $\rho^{(n)}(\mathbf{r}_1, \ldots, \mathbf{r}_n) = \sum_{s,t} \int_{\mathbf{r}_{n+1}, \ldots, \mathbf{r}_A} |\Psi_A|^2$

GROUND STATE

Origin of multi-particle correlations?

MEAN SQUARED ELLIPTIC FLOW

2P CORRELATOR FINAL STATE

$$v_n\{2\}^2 \equiv \langle V_n V_n^* \rangle_{\rm ev} = \left\langle \frac{\sum_{i\neq j} e^{in(\phi_i - \phi_j)}}{N_{\rm ch,ev}(N_{\rm ch,ev}-1)} \right\rangle_{\rm ev}$$

MEAN SQUARED ECCENTRICITY

$$\langle \mathcal{E}_n \mathcal{E}_n^* \rangle_{\rm ev} = \frac{\int_{\mathbf{x},\mathbf{y}} |\mathbf{x}|^n |\mathbf{y}|^n e^{in(\phi_x - \phi_y)} \langle \epsilon(\mathbf{x})\epsilon(\mathbf{y})\rangle_{\rm ev}}{\left(\int_{\mathbf{x}} \langle \epsilon(\mathbf{x})\rangle |\mathbf{x}|^n\right)^2}$$

$$\langle \epsilon(\mathbf{x})\epsilon(\mathbf{y})\rangle_{\rm ev} = \Bigg(A\int_{\mathbf{r}_1} \rho^{(1)}(\mathbf{r}_1)\; g(\mathbf{x}-\mathbf{r}_{1\perp})g(\mathbf{y}-\mathbf{r}_{1\perp}) + (A^2 - A)\int_{\mathbf{r}_1,\mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1,\mathbf{r}_2) g(\mathbf{x}-\mathbf{r}_{1\perp})g(\mathbf{y}-\mathbf{r}_{2\perp})\Bigg)^2$$

ENERGY DENSITY 2P CORRELATOR

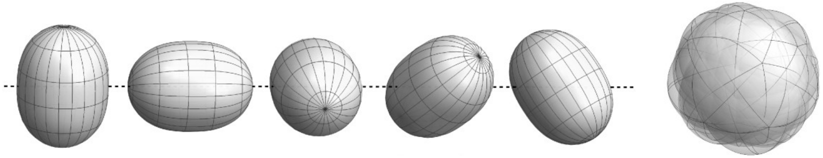
NUCLEAR STRUCTURE 2-BODY DENSITY

Atomic nuclei – Collective spatial correlations of nucleons

Random rotation of an intrinsic deformed object

[STAR collaboration, arXiv:2401.06625, to appear in Nature (2024)]

$$\rho^{(1)}(\mathbf{r}_1) = \int_\Omega \rho_\Omega(\mathbf{r}_1)$$



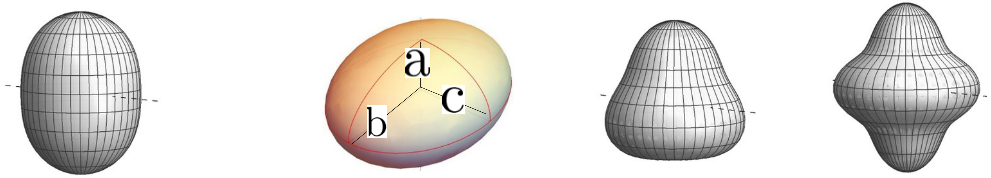
EULER ANGLES

$$\rho^{(2)}(\mathbf{r}_1, \mathbf{r}_2) = \int_\Omega \rho_\Omega(\mathbf{r}_1)\rho_\Omega(\mathbf{r}_2) \neq \rho^{(1)}(\mathbf{r}_1)\rho^{(1)}(\mathbf{r}_2)$$

DEFORMATION

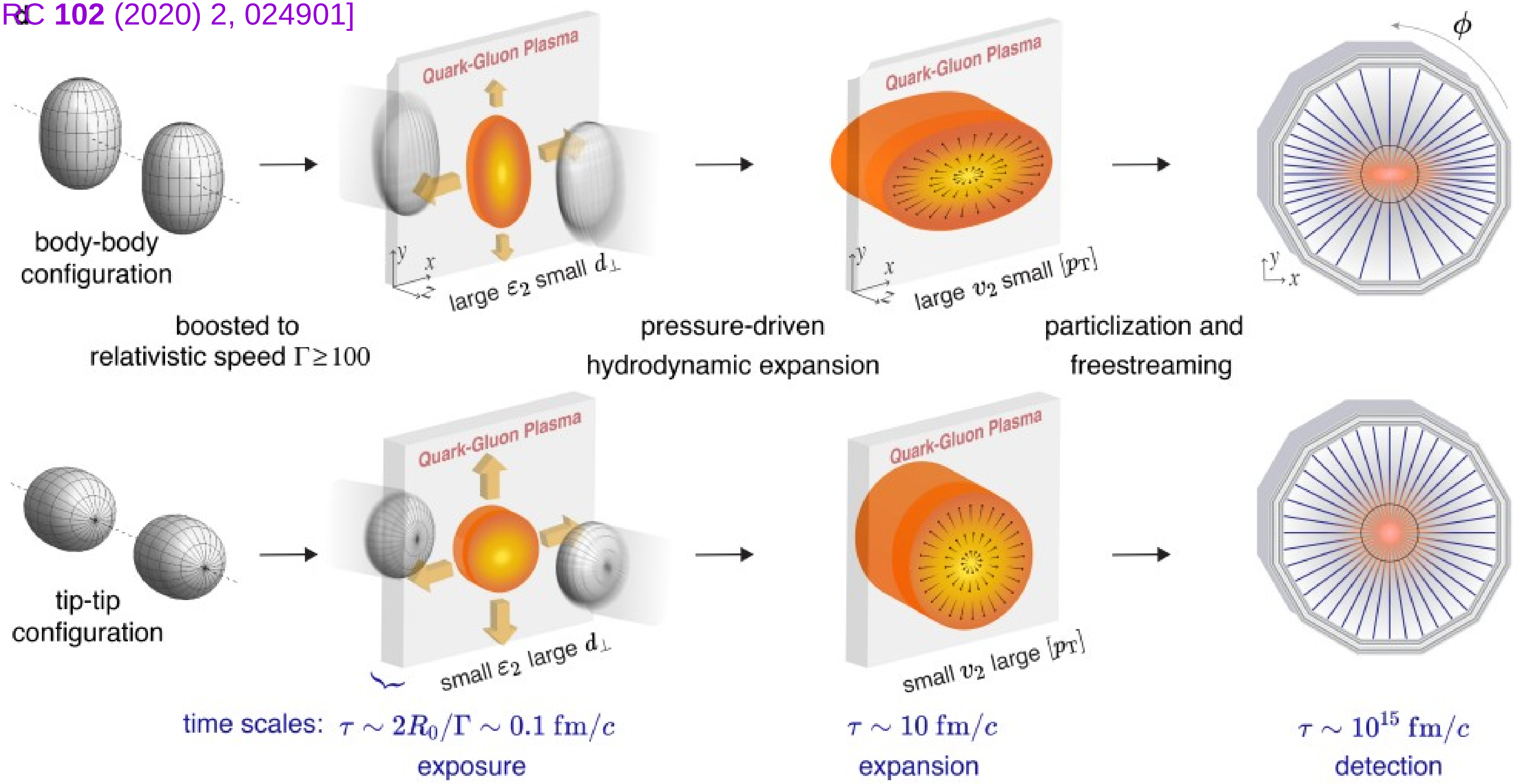
$$\rho(r,\theta,\phi) \propto \frac{1}{1+\exp\left(\left[r - R(\theta,\phi)\right]/a\right)} \quad , \quad R(\theta,\phi) = R_0\left[1 + \underline{\beta_2}\left(\cos\gamma Y_{20}(\theta) + \sin\underline{\gamma} Y_{22}(\theta,\phi)\right) + \underline{\beta_3} Y_{30}(\theta) + \underline{\beta_4} Y_{40}(\theta)\right]$$

e.g. Woods-Saxon



Best example – New “classical” phenomenon in nuclear physics

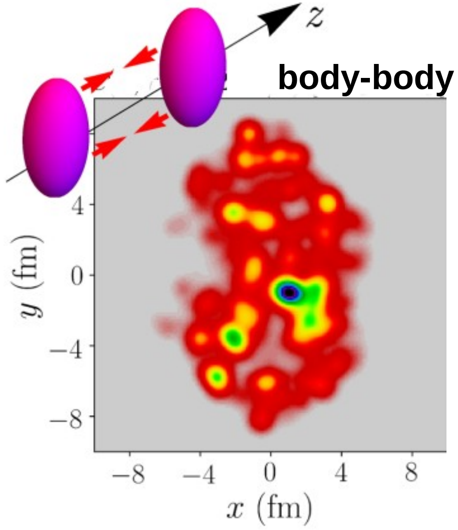
[Giacalone, PRL **124** (2020) 20, 202301]
[Giacalone, PRC **102** (2020) 2, 024901]

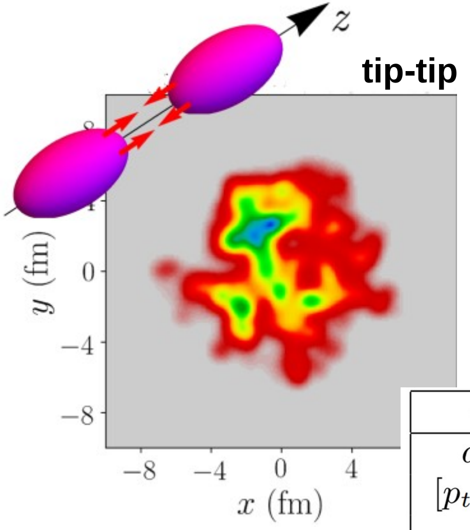


[STAR collaboration, arXiv:2401.06625, to appear in Nature (2024)]

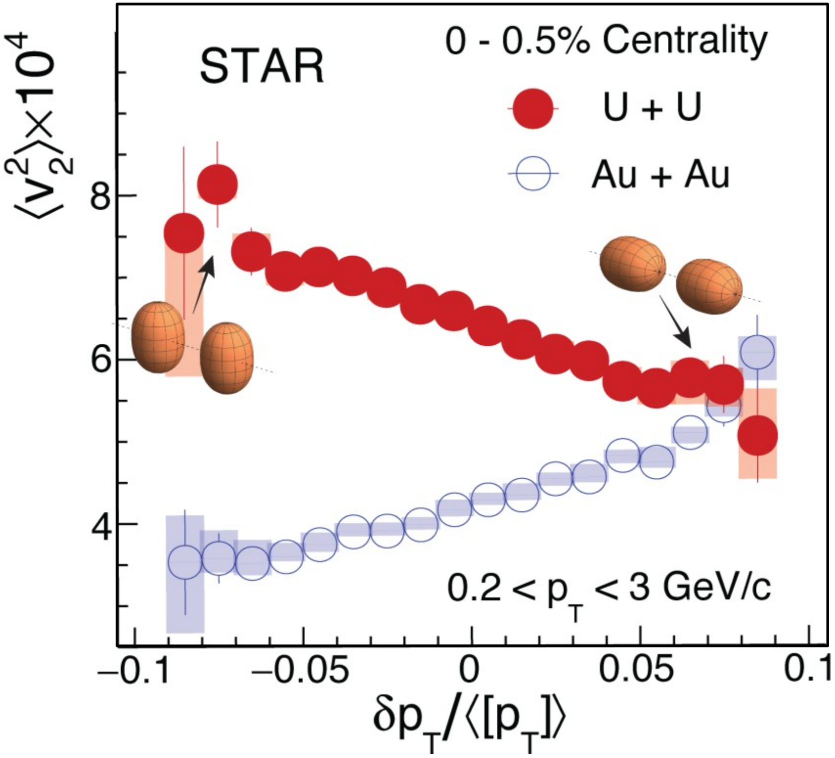
If elliptic flow increases … then average pT decreases!

"Seeing" the deformation of ^{238}U





event	body-body	tip-tip
$dN/d\eta$	1296	1280
$[p_t]$ (GeV)	0.587	0.651
v_2	0.083	0.027



How do we extract quantitative information on the nuclei?

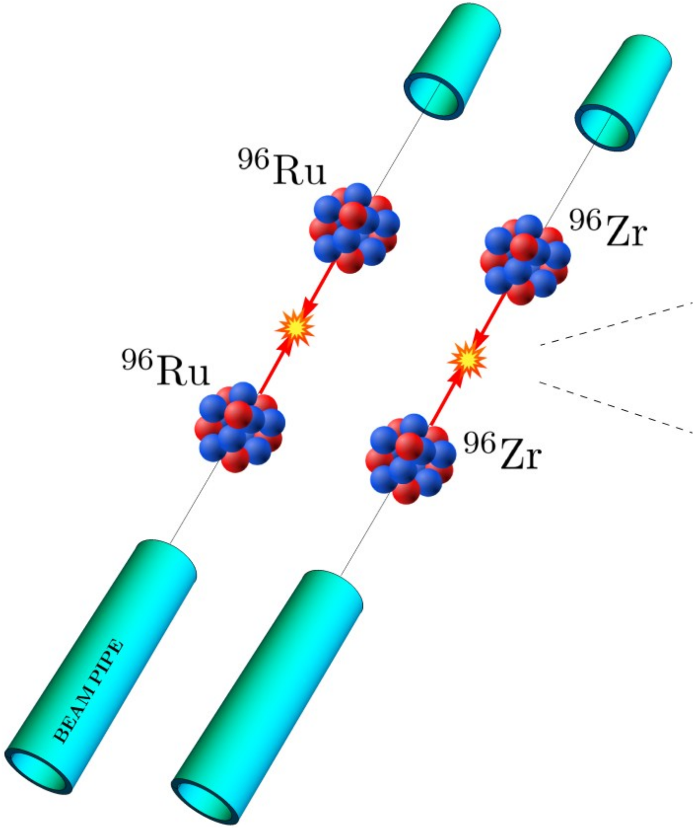
The “isobar” strategy – Ratio observables to cancel uncertainties

The idea. We exploit the seemingly uninteresting fact that a large number of stable nuclides belong to pairs of isobars, i.e., that for a given nuclide X one can often find a different nuclide Y that contains the same number of nucleons. This feature has an important implication for high-energy collisions. If X and Y are isobars, then X+X collisions produce a system which has the same properties (volume, density) as that produced in Y+Y collisions. As a consequence, X+X and Y+Y systems present the same geometry, the same dynamical evolution, and thus the same elliptic flow in the final state.

This leads us to our main point. Given two isobars, X and Y, we ask the following:

$$\frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \stackrel{?}{=} 1$$

[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]

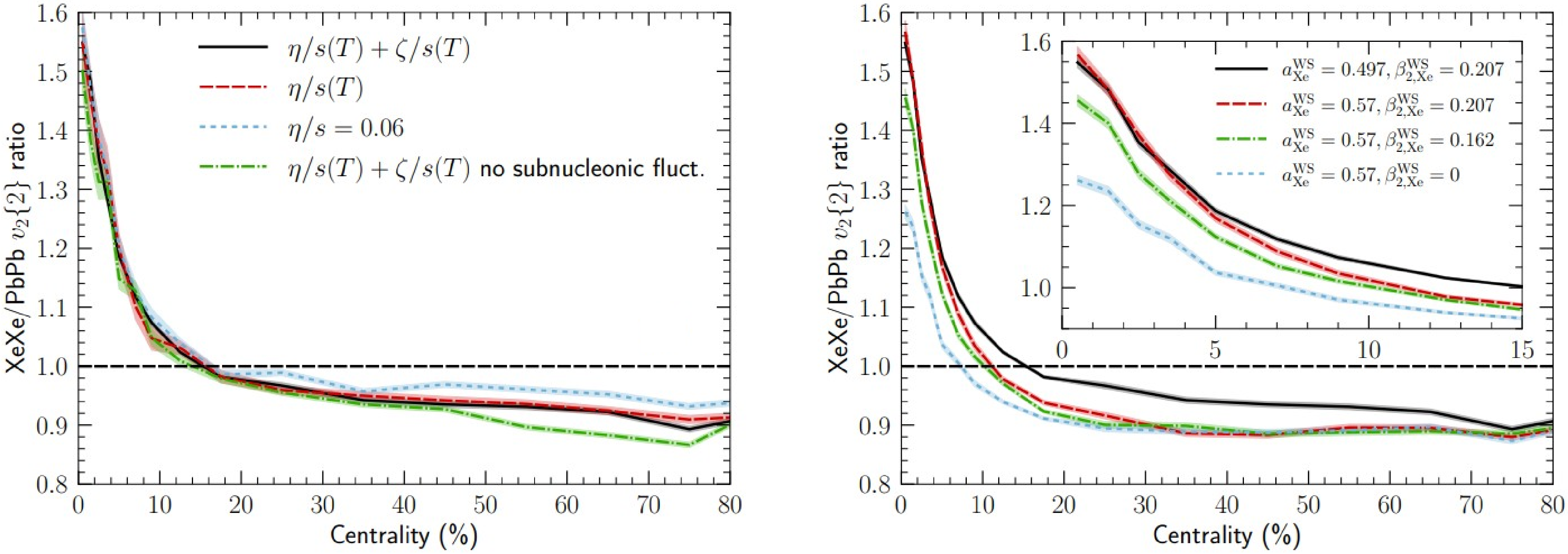


Cancellation of systematics is highly effective … even without isobars!

Neat probes of nuclear geometry (^{129}Xe vs ^{208}Pb)

$$\langle v_2^2 \rangle = a + b\beta^2$$

[Mäntysaari, Schenke, Shen, Zhao, arXiv:2409.19064]



Actual isobar collisions (^{96}Ru+^{96}Ru vs ^{96}Zr+^{96}Zr)

$$\langle v_n^2 \rangle = a + b\beta_n^2$$

spherical baseline → a

QGP response → b

deformation → β_n^2

[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]
[Jia, PRC **105** (2022) 1, 014905]

Isobar ratio and Taylor expand around unity:

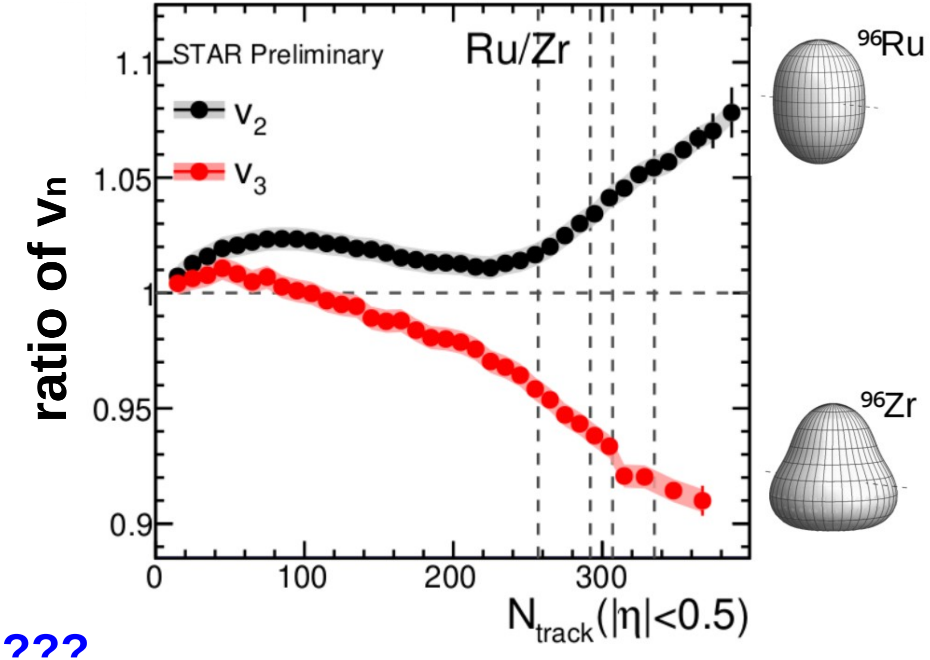
$$\frac{\langle v_n^2 \rangle_{\mathrm{Ru+Ru}}}{\langle v_n^2 \rangle_{\mathrm{Zr+Zr}}} = 1 + c\left(\beta_{n,\mathrm{Ru}}^2 - \beta_{n,\mathrm{Zr}}^2\right)$$

positive coeff → c

Low-energy nuclear physics: $\beta_{2,\mathrm{Ru}}^2 \gg \beta_{2,\mathrm{Zr}}^2$

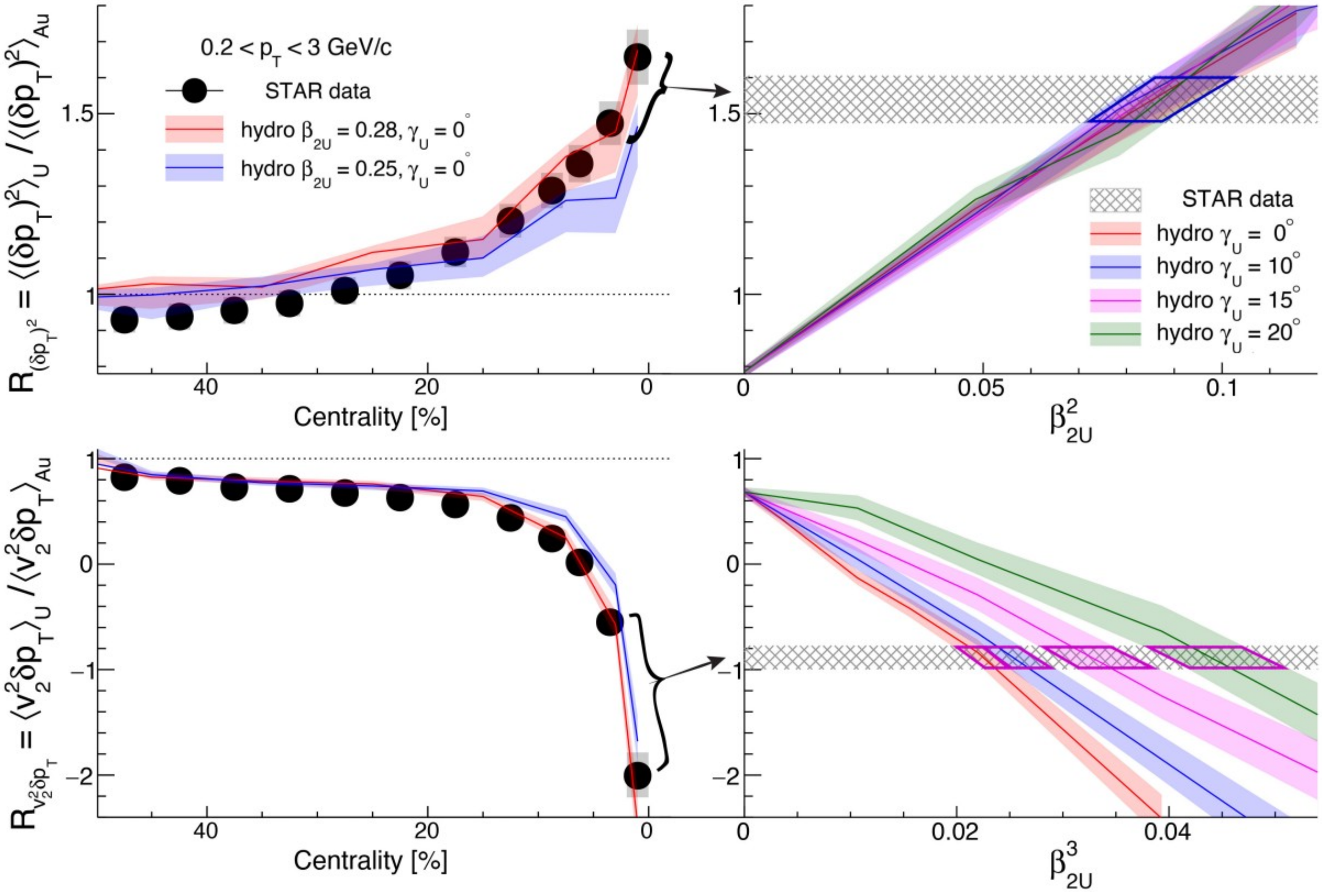
RHIC data: $\beta_{2,\mathrm{Ru}}^2 \gg \beta_{2,\mathrm{Zr}}^2$ $\beta_{3,\mathrm{Zr}}^2 \gg \beta_{3,\mathrm{Ru}}^2$ **???**

[STAR collaboration, PRC **105** (2022) 1, 014901]
[Courtesy of Chunjian Zhang]



Different observables access different features of the incoming shapes

[STAR collaboration, arXiv:2401.06625, to appear in Nature (2024)]



$$\left\langle (\delta p_T)^2 \right\rangle = a_0 + a_1 \beta_2^2,$$

$$\left\langle v_2^2 \delta p_T \right\rangle = a_0' - a_1' \beta_2^3 \cos(3\gamma)$$

[Jia, PRC **105** (2022) 4, 044905]

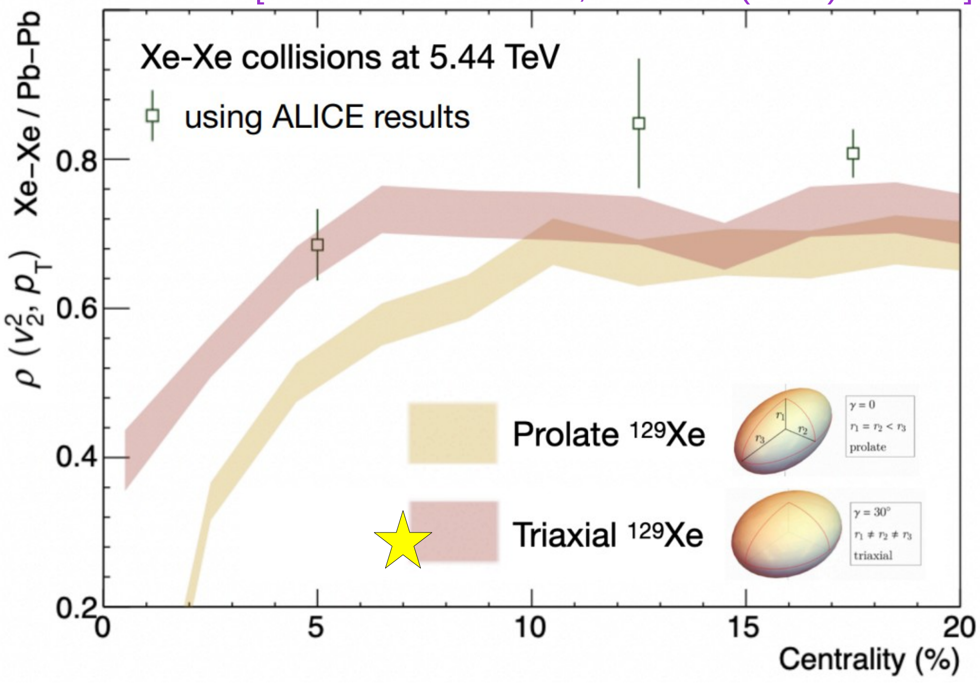
$$\gamma_U \approx 8^o$$

Energy density functional theory: ^{129}Xe is triaxial in the ground state

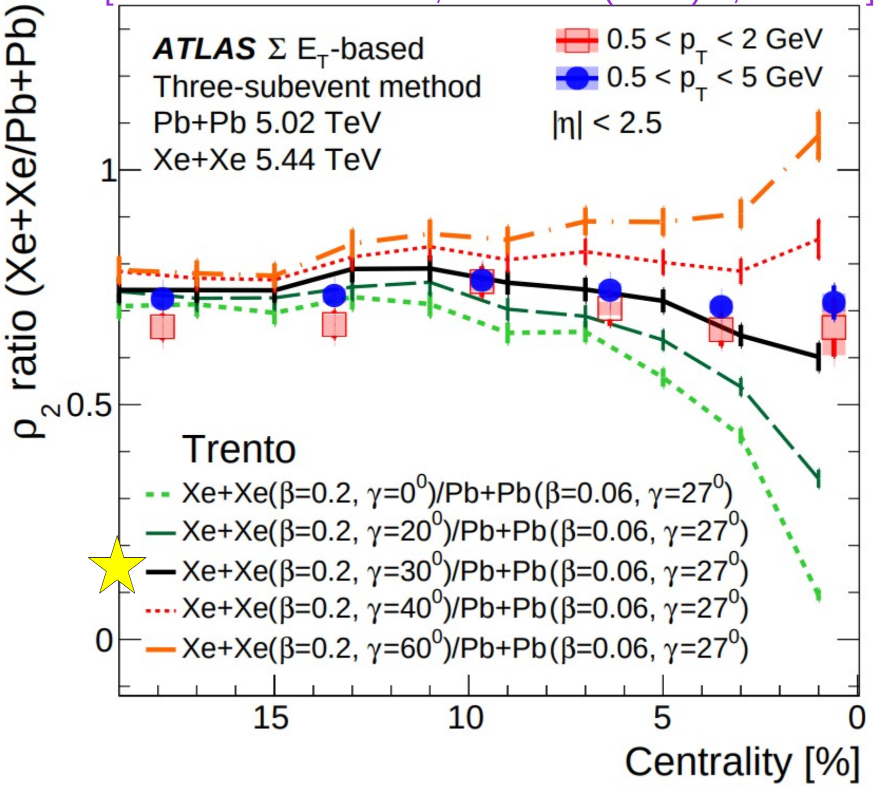
[Bally *et al.*, PRL **128** (2022) 8, 082301]
[Bally, Giacalone, Bender, EPJA **58** (2022) 9, 187]

Consistent with high-energy observations

[ALICE Collaboration, PLB **834** (2022) 137393]



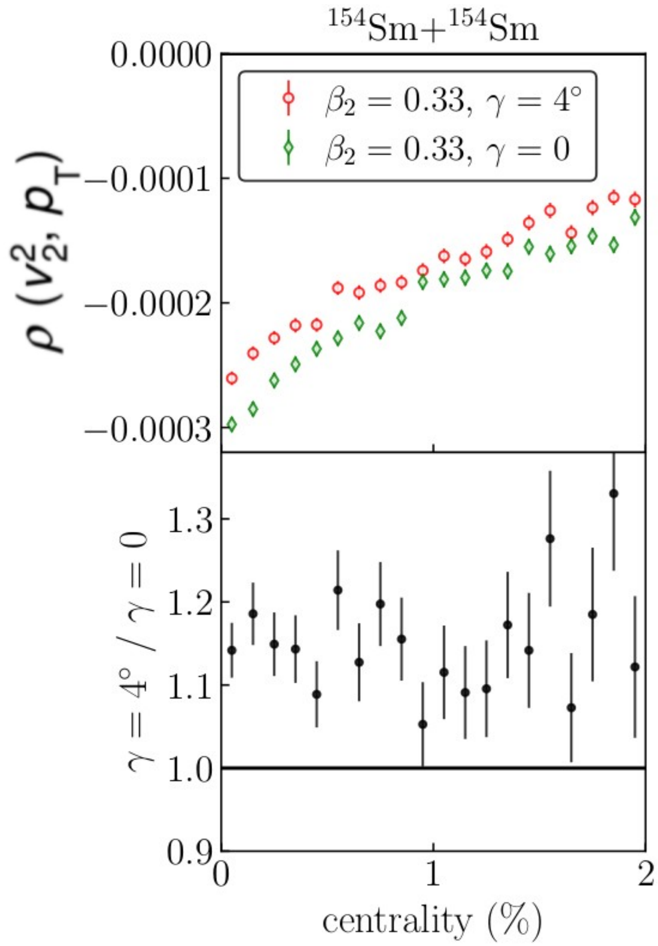
[ATLAS Collaboration, PRC **107** (2023) 5, 054910]



In summary, we image atomic nuclei in their ground states

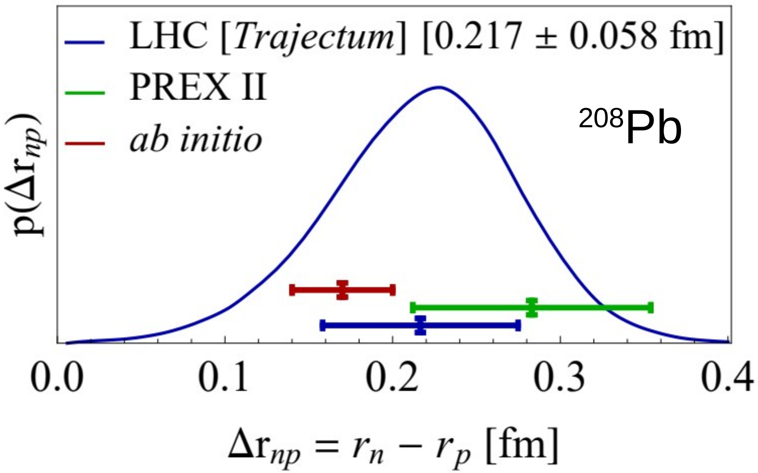
Some implications:

- Triaxiality of well-deformed nuclei



[Otsuka *et al.*, arXiv:2303.11299]
[Work in progress]

- Skin of nuclei



[Giacalone, Nijs, van der Schee, PRL **131** (2023) 20, 20]

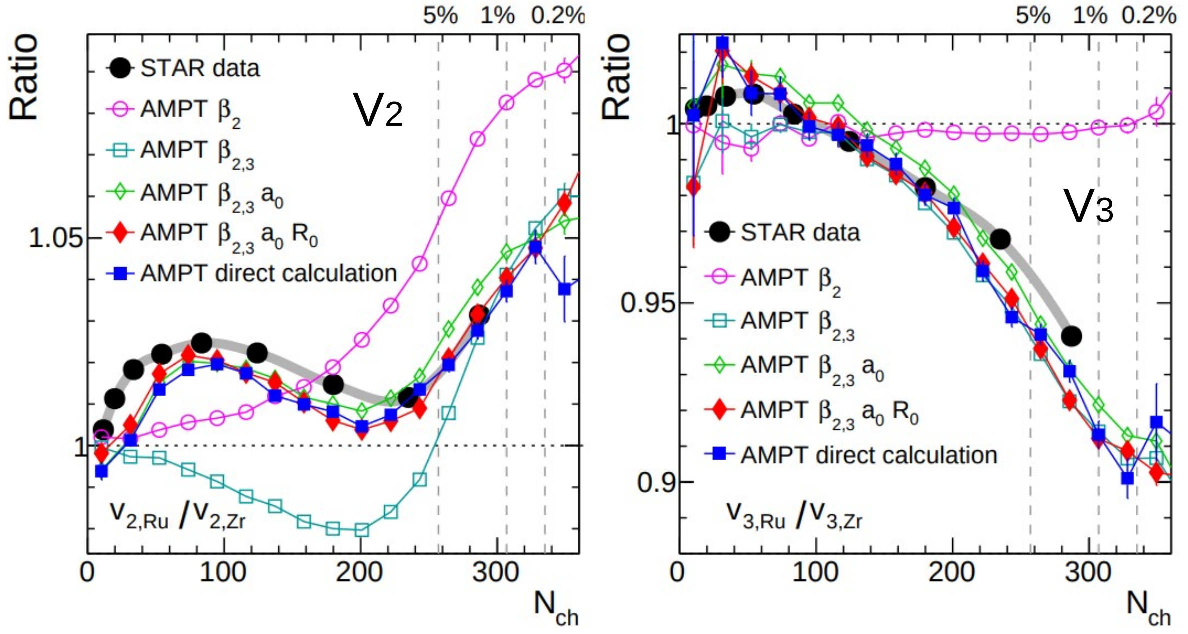
What else?

Recall: we access structure differences of isobars directly in ground states

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

$$\frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a$$

[Zhang, Jia, PRL **128** (2022) 2, 022301]
[Zhang, Jia, PRC **107** (2023) 2, L021901]



$$\Delta\beta_n^2 = \beta_{n,\mathrm{Ru}}^2 - \beta_{n,\mathrm{Zr}}^2$$

$$\Delta a = a_{\mathrm{Ru}} - a_{\mathrm{Zr}}$$

Natural application – Search for neutrinoless double beta decay

[Engel, Menéndez, Rept.Prog.Phys. **80** (2017) 4, 046301]

$$(A, Z) \to (A, Z+2) + 2\,e^- \qquad (0\nu\beta\beta)$$

Rate involves nuclear matrix element – Structure of initial and final nuclei

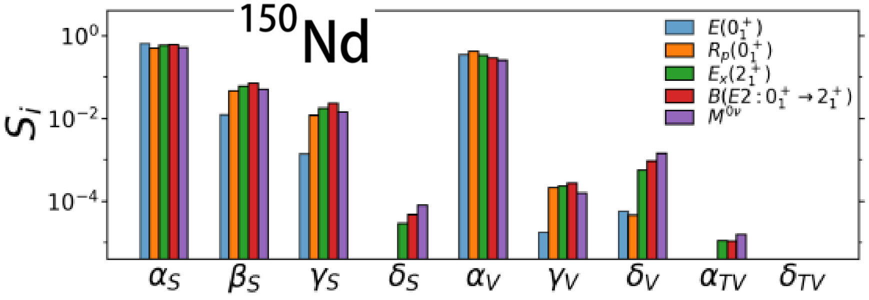
$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q, Z)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

measured — known — ??? — to determine

Issue for interpretation of rate data is knowledge of the NME

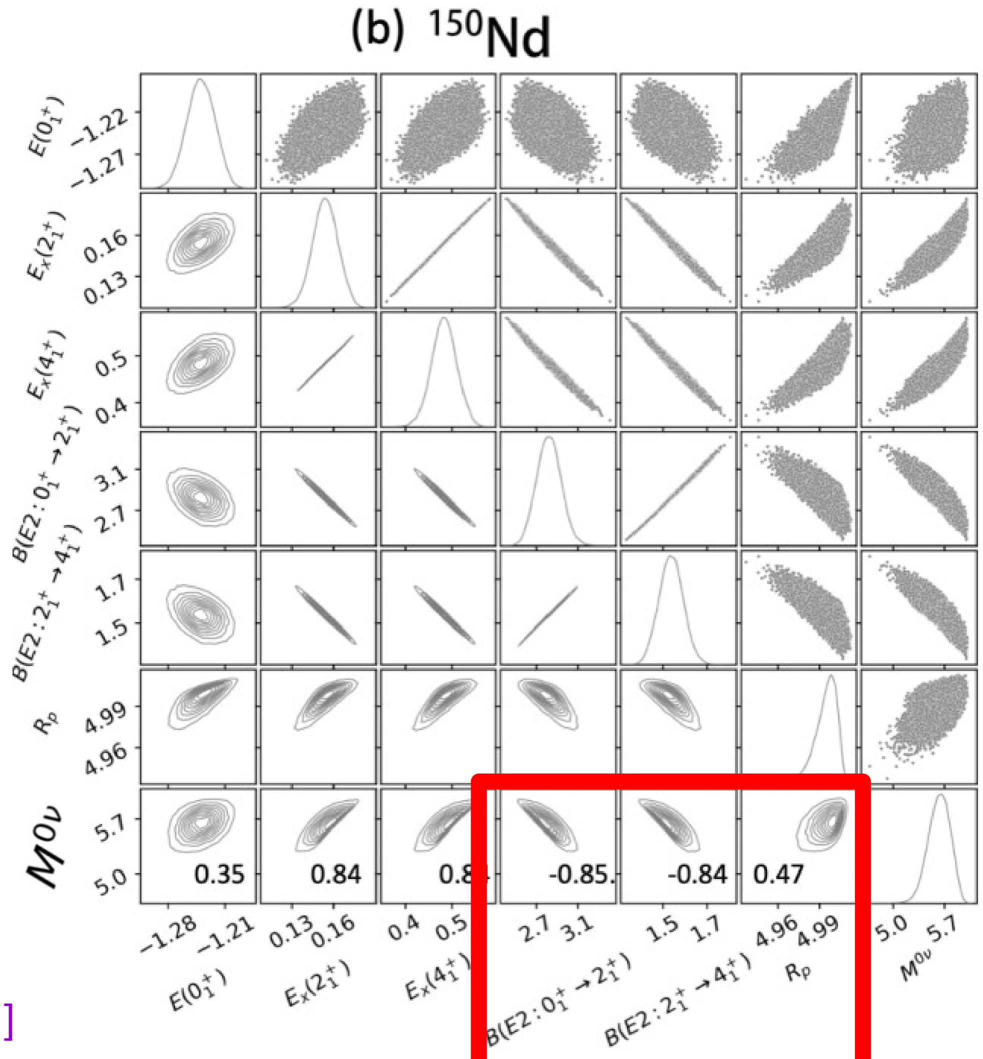
New experiments to benchmark theoretical models? High-energy collisions?

Bayesian analysis and emulators in energy density functional theory



NME strongly correlated with nuclear size and the "deformation" [B(E2) values]

[Zhang *et al.*, arXiv:2408.13209]



Eccentricities of the QGP and related observables are correlated with the NME

[Work in progress with Jiangming Yao *et al.*]

Similar result in *ab initio* theory

Delta-full EFT with 17 LECs

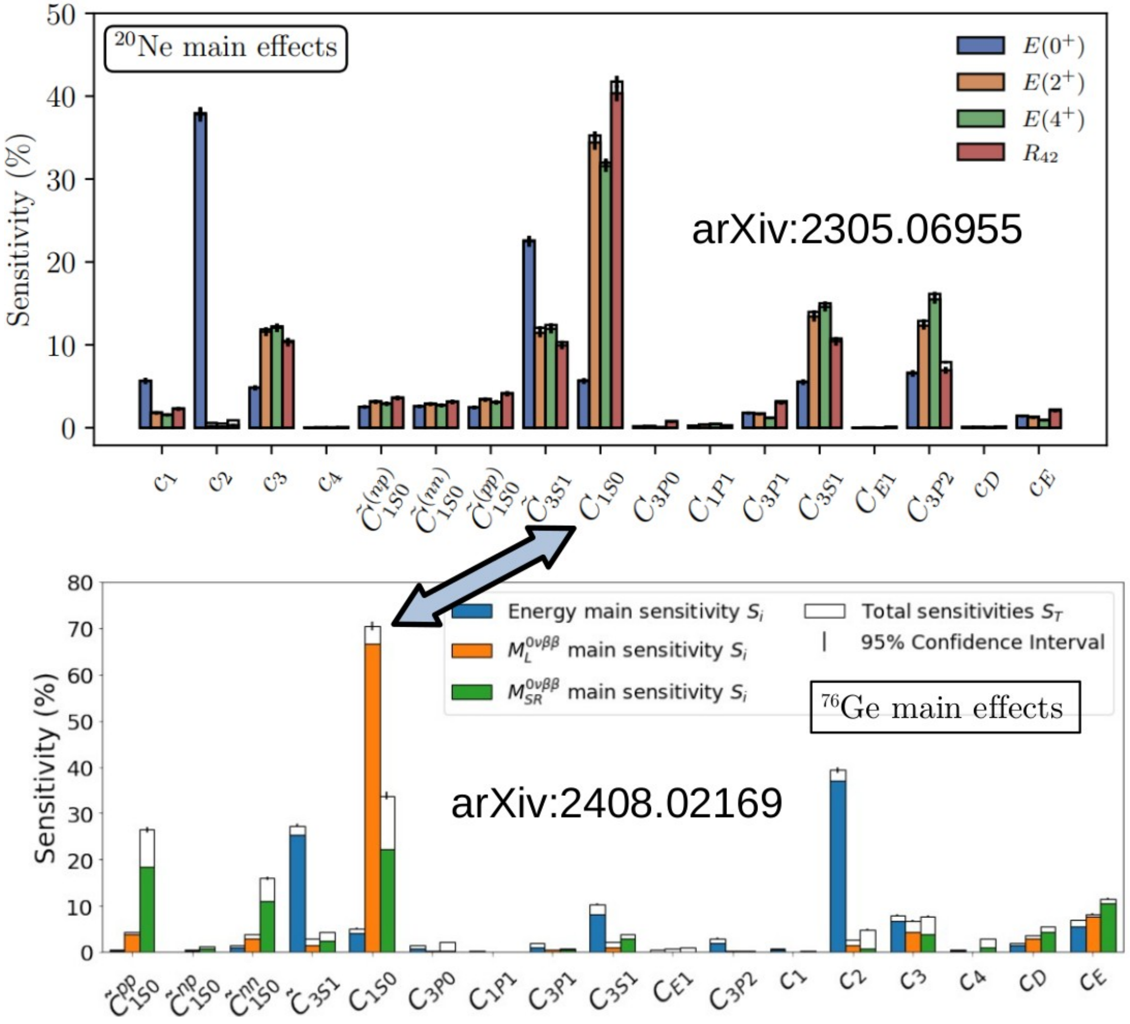
Deformation (R_{42}~3.33) has strong sensitivity to C_{1S0} constant

[Ekström *et al.*, arXiv:2305.06955]

NME strongly sensitive to C_{1S0}

[Belley *et al.*, arXiv:2408.02169]

Heavy-ion observables will be strongly correlated with the NME



[Work in progress with Charles Gale, Sangyong Jeon, *et al.*]

How about small nuclei? Big LHC discovery: Small system collectivity

[Wiedemann, Grosse-Oetringhaus, arXiv:2407.7484]

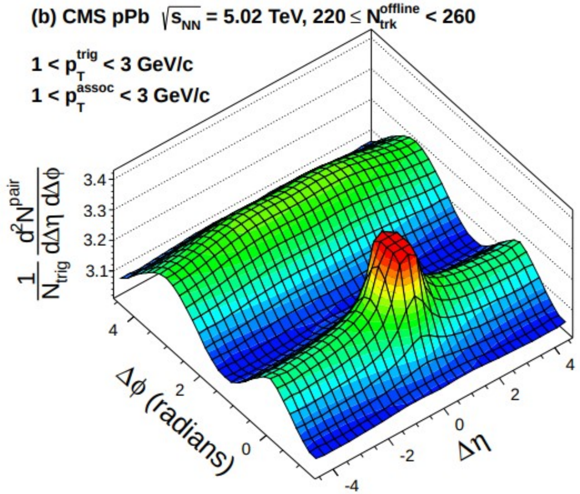
A hydrodynamic description is not justified based on “standard criteria”

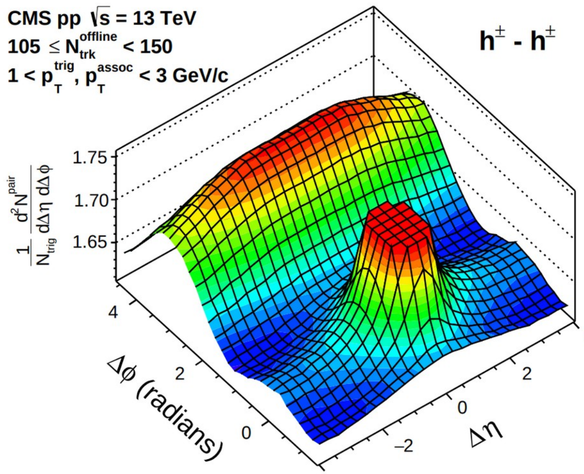
[Ambrus, Schlichting, Werthmann, PRL **130** (2023) 15, 152301]
[Kurkela, Wiedemann, Wu, EPJC **79** (2019) 11, 965]

Triggered vast program on thermalization and out-of-equilibrium dynamics

[Berges, Heller, Mazeliauskas, Venugopalan, RMP **93** (2021) 3, 035003]

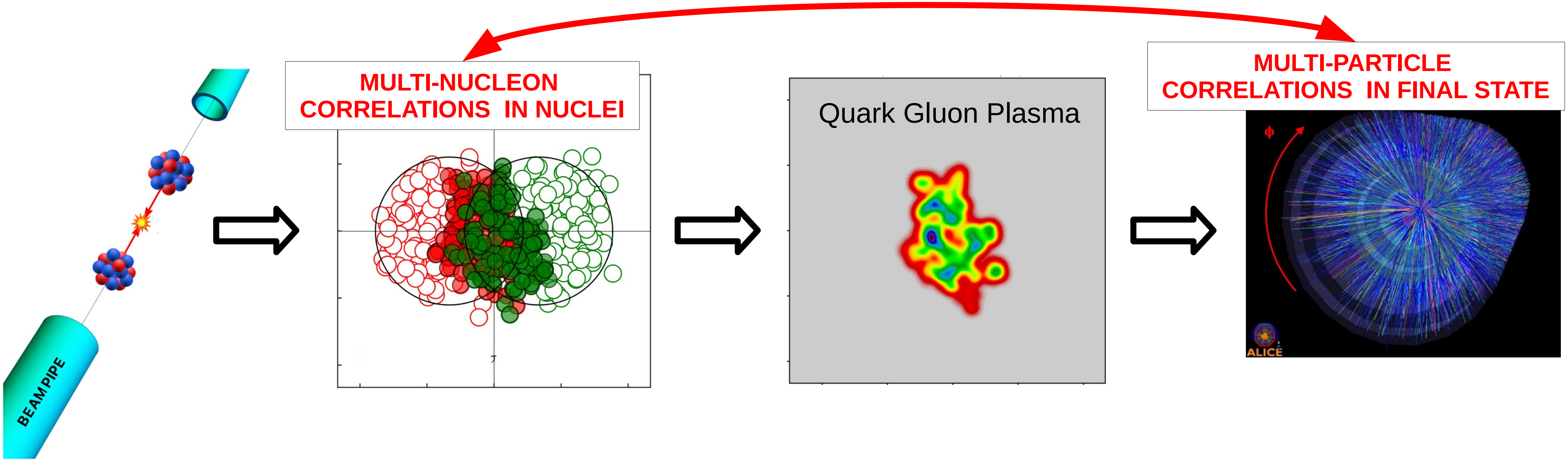
[CMS collaboration, PLB **724** (2013) 213-240]
[CMS collaboration, PLB **765** (2017) 193-220]





[can be followed on zoom, registration is open]

Conclusion



A new method for precision imaging of nuclear ground states via high-energy collisions

New constraints on 0νββ decay NMEs for potentially all candidate isotopes?

Collisions of light ions to shed light on small system collectivity