Intersection of nuclear structure and high-energy nuclear collisions 2026

Imaging nuclear structure across energy scales: from heavy to light ions

Chunjian Zhang

Fudan University

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Yukawa Institute for Theoretical Physics
Kyoto University

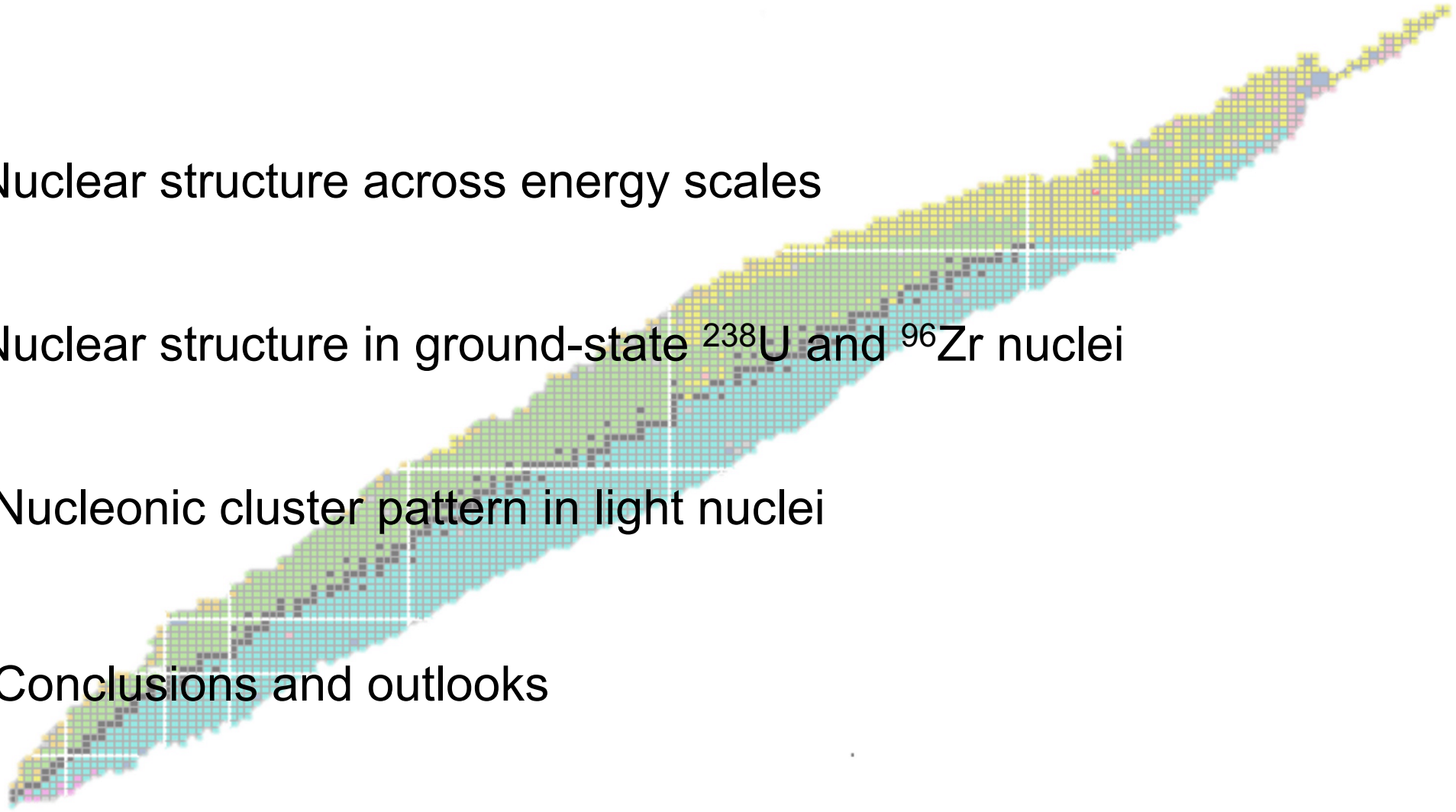
Outline

I. Nuclear structure across energy scales

II. Nuclear structure in ground-state ^{238}U and ^{96}Zr nuclei

III. Nucleonic cluster pattern in light nuclei

IV. Conclusions and outlooks



Collective structure of atomic nuclei

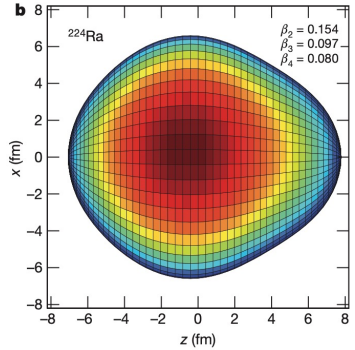
- Emergent phenomena of the many-body quantum system
  - Non-monotonic evolution with N and Z
  - Quadrupole/octupole/hexadecapole deformations
  - Clustering, halo, skin, bubble…

Y. Ye, X. Yang, H. Sakurai, B. Hu, *Nature Review Physics, 7, 21-37 (2025)*

Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022)*

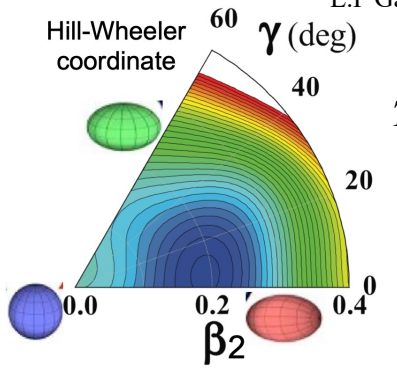
Quadrupole

Octupole



S. Cwiok et al., *Nature 433, 705 (2005)*

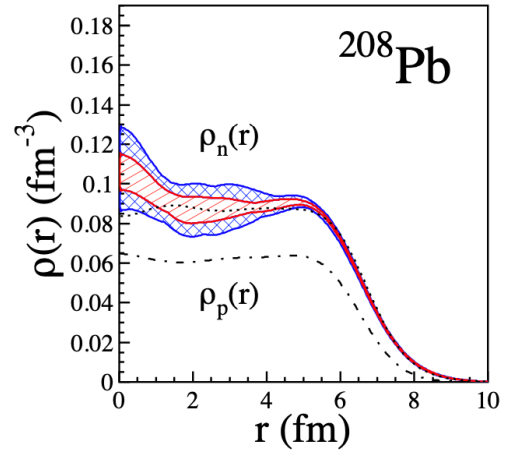
L.P Gaffney et al., *Nature 497, 199 (2013)*

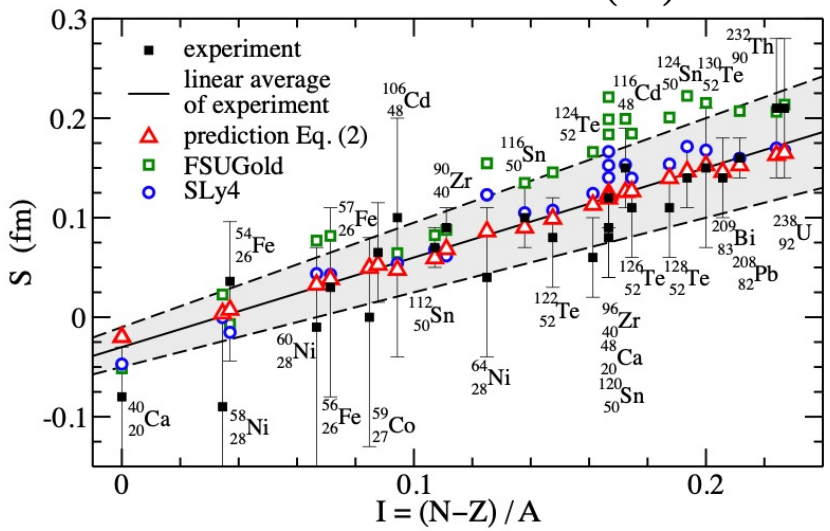


Triaxial spheroid

A. Andreyev et al., *Nature 405, 430 (2000)*

Neutron skin

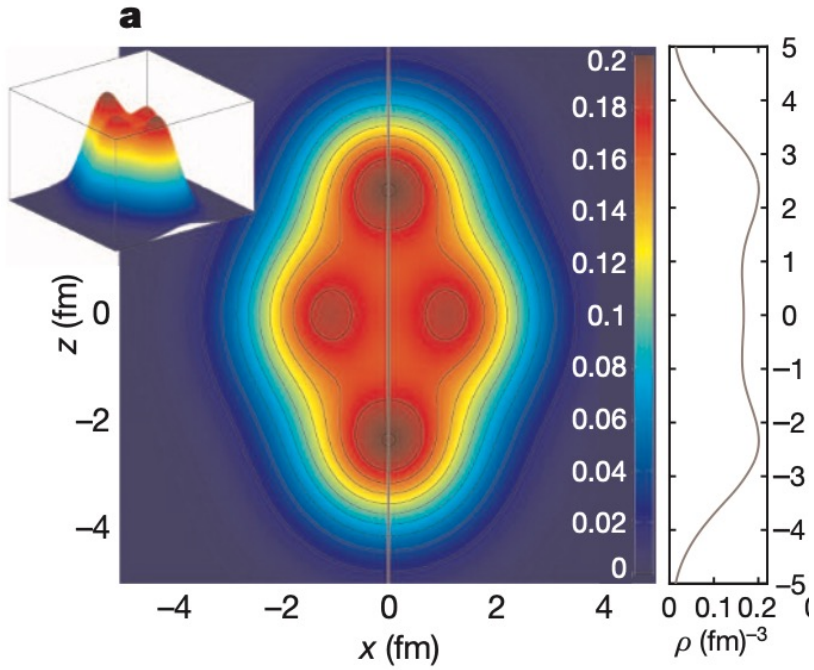




A. Trzcinska et al., *PRL 87, 082501 (2001)*

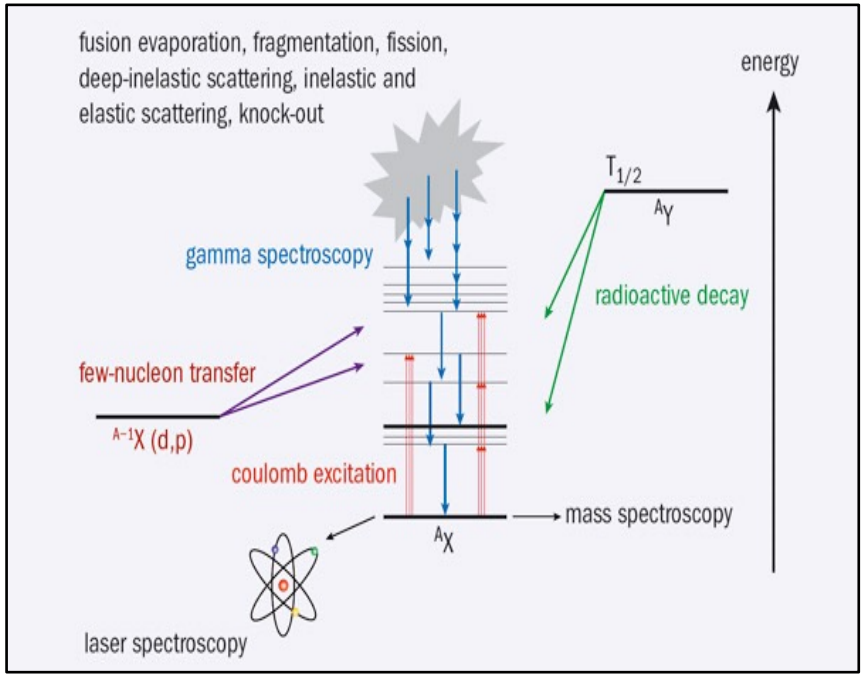
A. M. Centelles et al., *PRL 102, 122502 (2009)*

nucleonic clustering

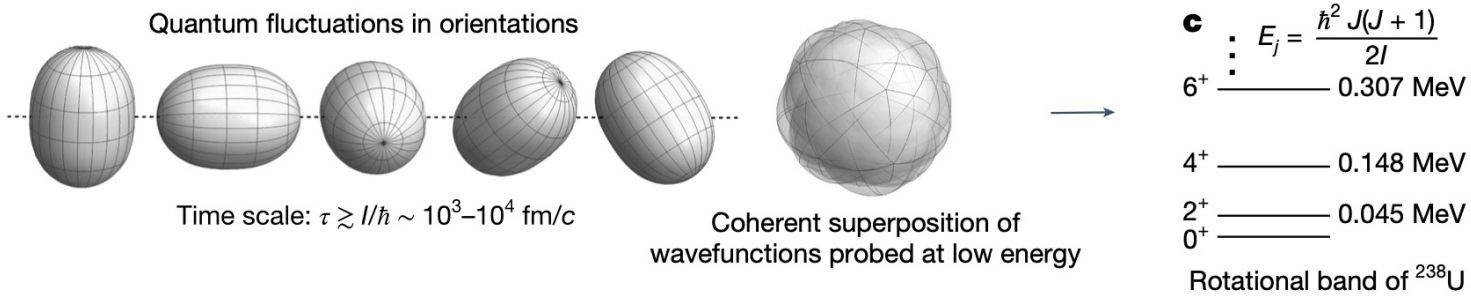


J.P. Ebran et al., *Nature 487, 341 (2012)*

Nuclear shape at low energy: long exposure

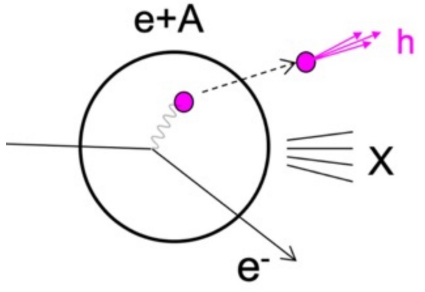


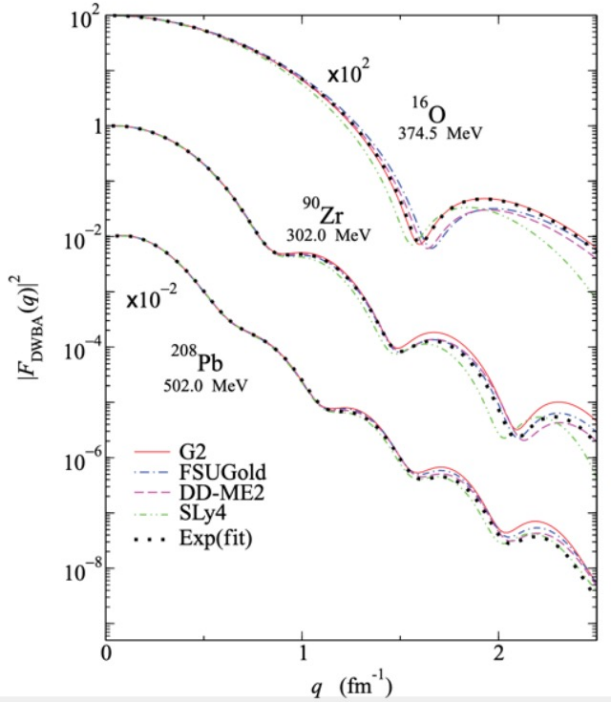
Each DOF has zero-point fluctuations within an intrinsic timescale.

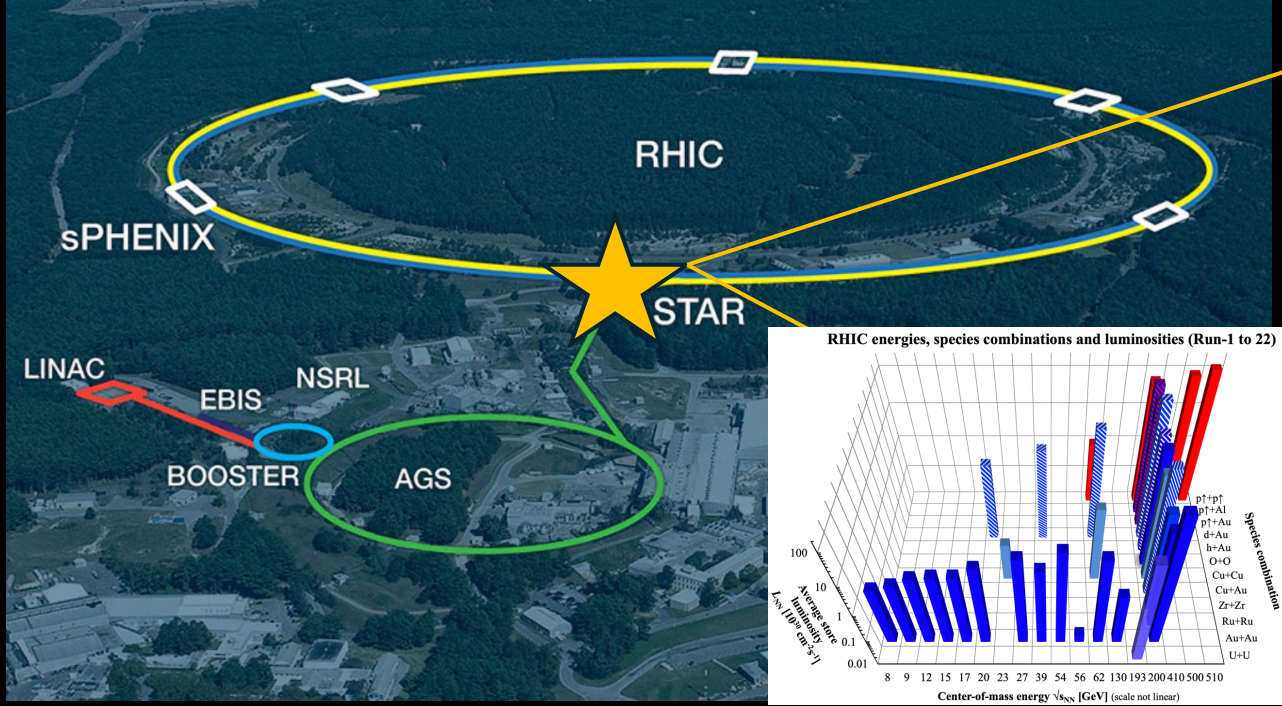


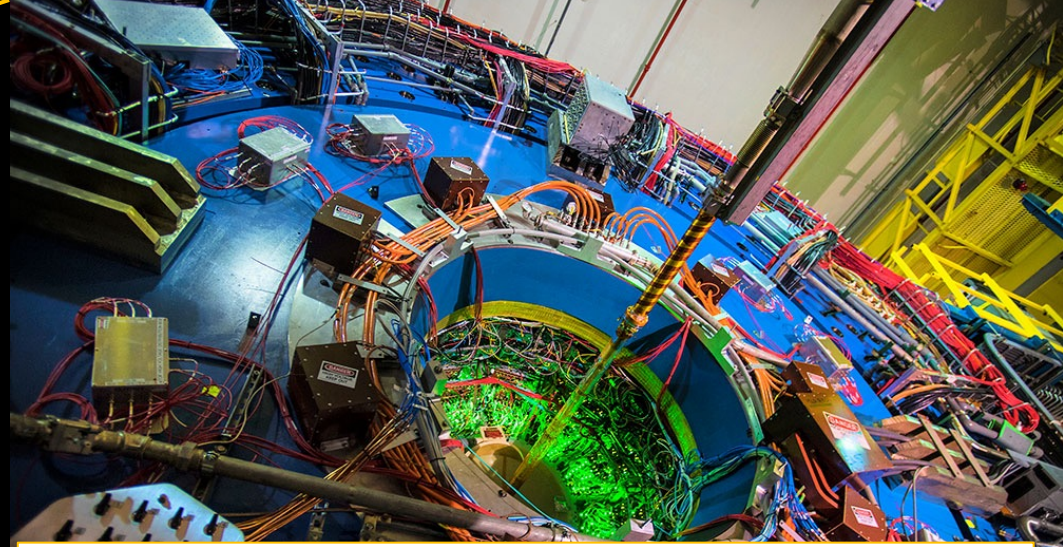
probe a superposition of these fluctuations, instantaneous shapes not directly seen

e+A scattering has very short timescales, but so far mostly imaged the one-body (charge) distribution. The impact of deformation appears as an increase in the radius

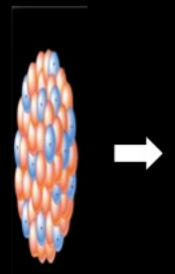


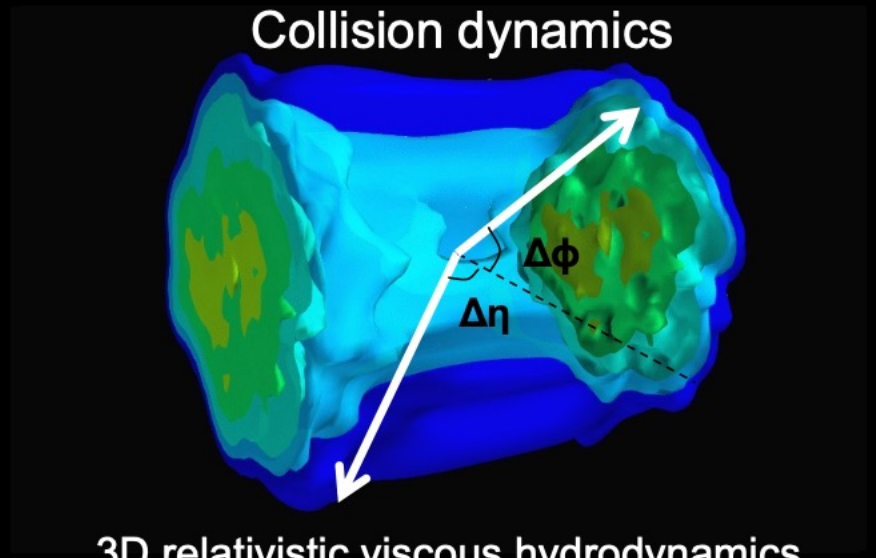


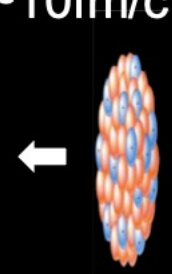




1) large, uniform acceptance at mid-rapidity
2) A vast number of emitted final state hardons
3) capability to access nuclear structures in different collisions…







t~10fm/c =10^{-22} s

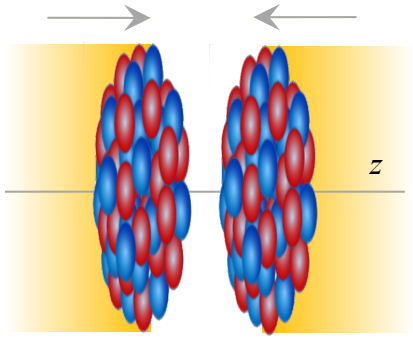
Credit: Bjoern Schenke

Imaging by smashing method

Take a snapshot

Nuclei collisions

$T_{\mu\nu}(\tau = 0)$



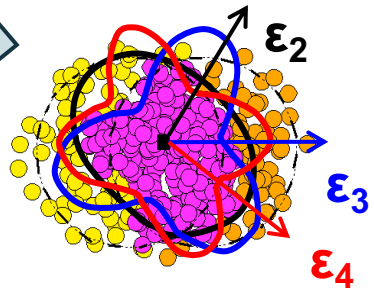
$\tau \sim 2R_0/\Gamma \sim 0.1\mathrm{fm}/c$

exposure

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

- β_2 → quadrupole deformation
- β_3 → octupole deformation
- γ → triaxiality
- a_0 → surface diffuseness
- R_0 → nuclear size

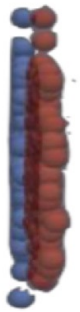
ab initio theory/shell model/DFT



size & shape

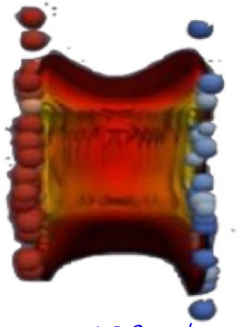
Evolution

$\partial_\mu T^{\mu\nu} = 0$, EOS, viscosity…



Pressure-driven expansion of

Quark-gluon plasma (QGP)



$\tau \sim 10\mathrm{fm}/c$

expansion

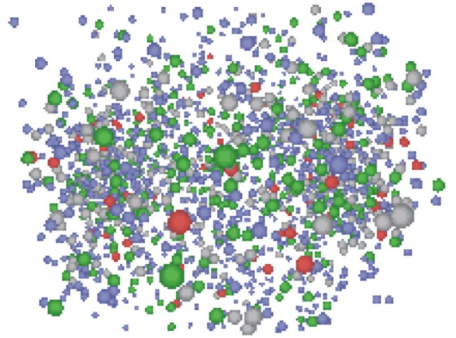
J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024)*

$R_\perp^2 \propto \langle r_\perp^2 \rangle$ $\quad \mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$

R_0 $\quad a_0$ $\quad \beta_n$

Measurement

$T_{\mu\nu}(\tau = \infty)$



free-streaming

$\tau \sim 10^{15}\mathrm{fm}/c$

detection

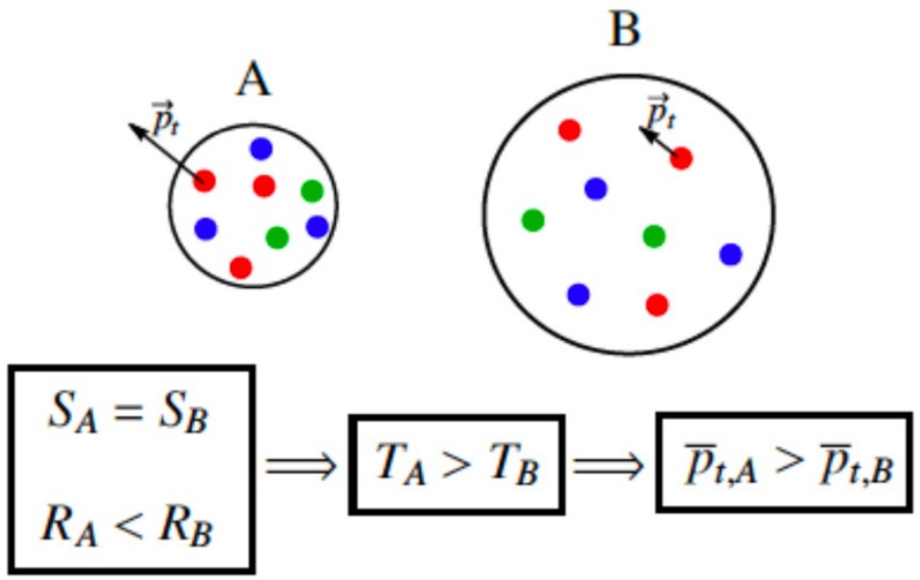
Observables $\dfrac{d^2N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$

Event-by-event linear responses:

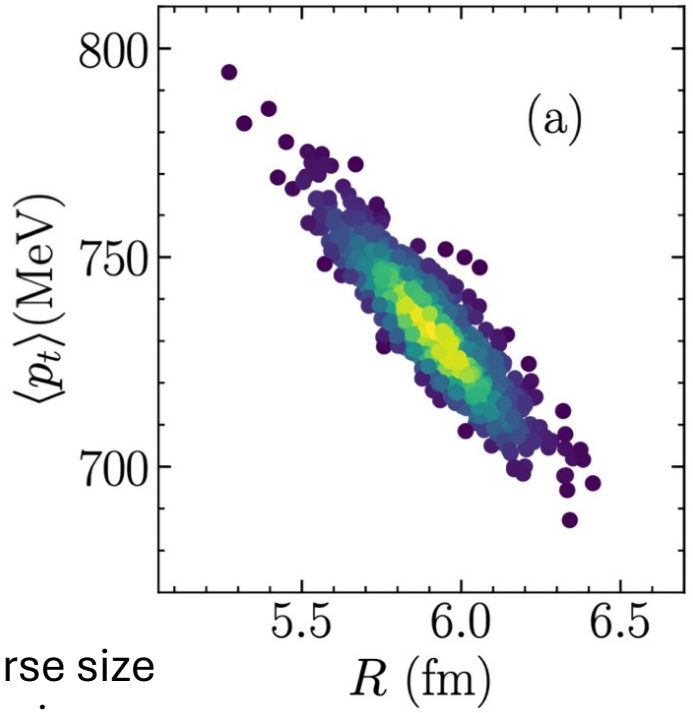
$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

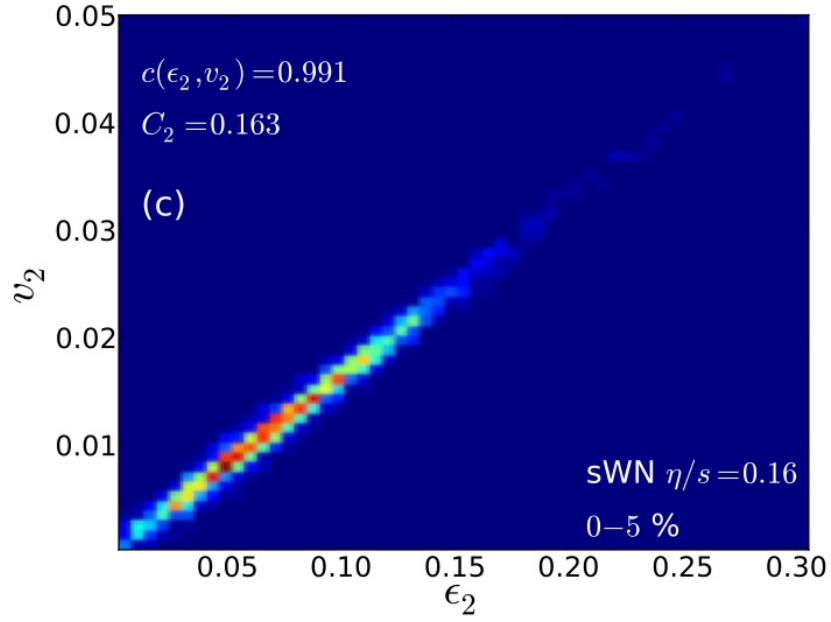
Linear response in ultra-central collisions



G. Giacalone et al., *PRC 103, 024909 (2021)*



H. Niemi et al., *PRC 87, 054901 (2013)*



Same total energy deposition, **smaller** transverse size in the initial state creates **stronger** radial expansion.

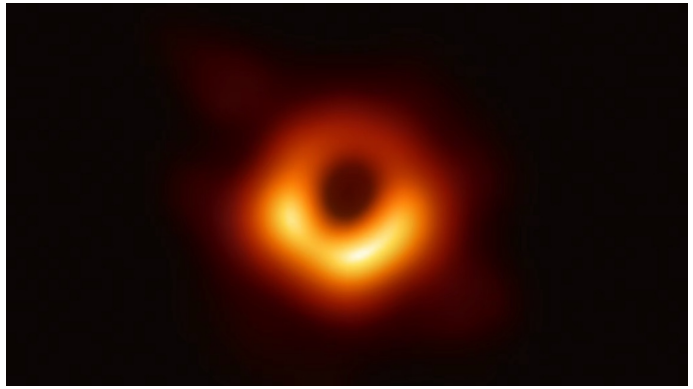
$$\delta[p_{\mathrm{T}}] \propto -\delta R \propto \delta d_{\perp}$$

$$v_n \propto \epsilon_n$$

Linear relations permit us to image colliding nuclear shapes.

Analogy to the snapshot imaging technique

First-ever image of a black hole



MRI CT image

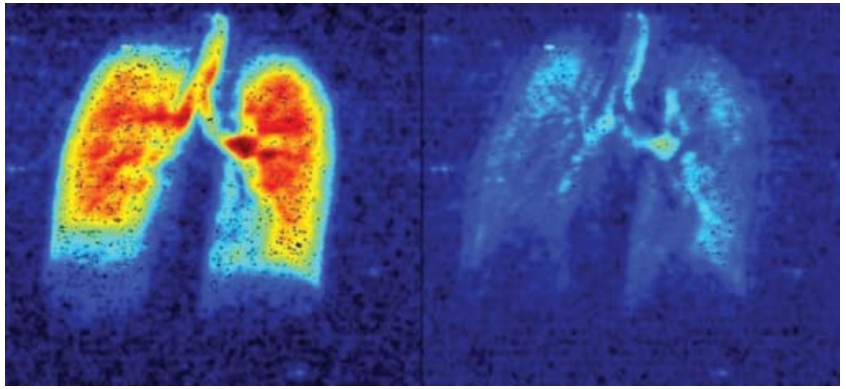
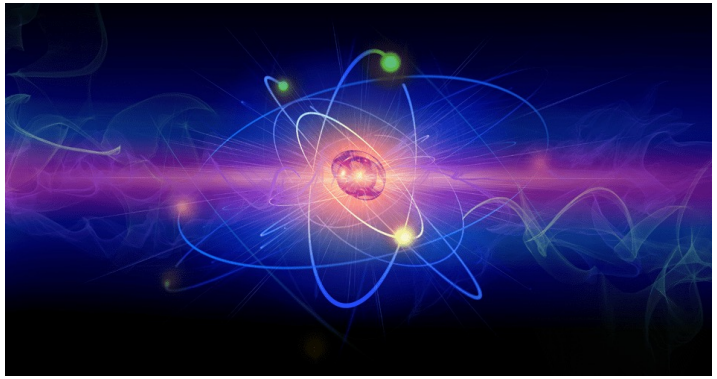


Image of electrons at attosecond

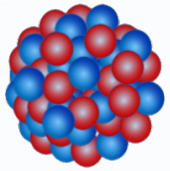


Astronomical scale → **Microscopic scale**

J. Jia et al., *Nucl. Sci. Tech. 35, 220 (2024), G. Giacalone, EPJA 59, 297 (2023), T. Duguet et al., PRL 135, 182301 (2025)* W. Ke, *2509.09549, ...*

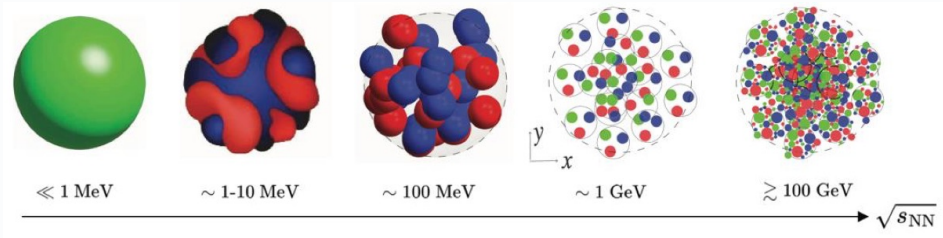
Emergent seeing shape directly require access to instantaneous nucleon distributions

$$\Psi\left(\mathbf{r}_1, \mathbf{r}_2 \ldots\right)$$



Will see all DOFs longer than exposure timescale:

nucleons, hadrons, quark, gluons, gluon saturations



Yoctosecond scale

$1\mathrm{fm}/c = 3 \times 10^{-24}$ seconds
$= 3 \times 10^{-6}$ attoseconds
$= 3$ yoctoseconds

A new, complementary, and independent of low-energy experiments

Analogy to the snapshot imaging technique

Eileen Gu@2022

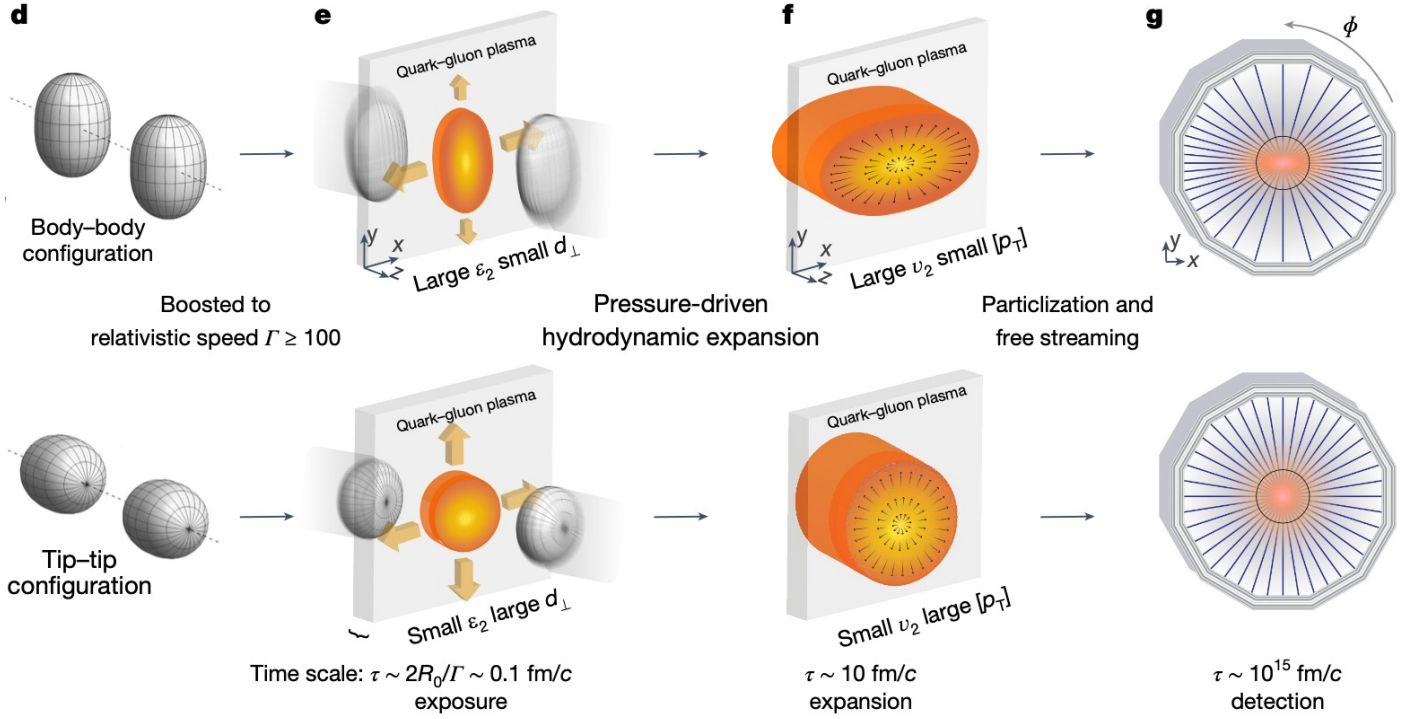
Short-time-scale imaging could reveal detailed shapes.

Imaging nuclear shape in high-energy snapshot

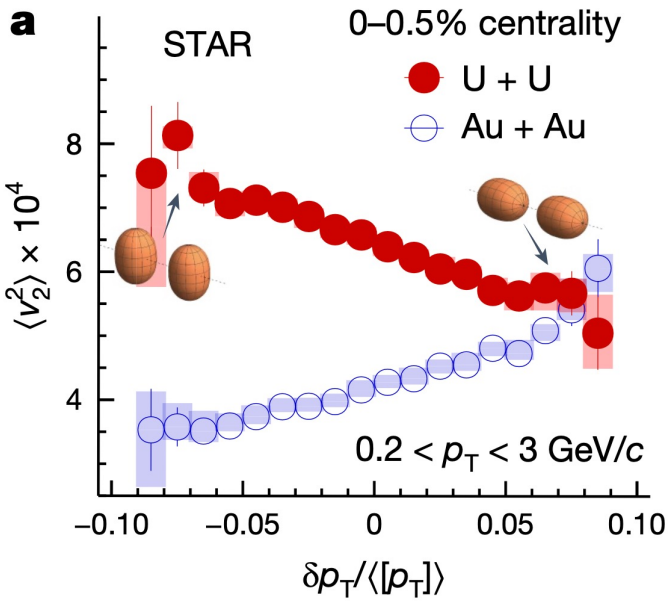
- Nuclear shape in intrinsic (body-fixed) frame not directly visible in the lab frame
  --Mainly inferred from non-invasive spectroscopy methods.

Nuclear deformation across energy scales

STAR, *Nature 635, 67-72 (2024)*
Nature News&Views, News, Podcast



Body-body: $v_2 \nearrow$ $p_T \searrow$



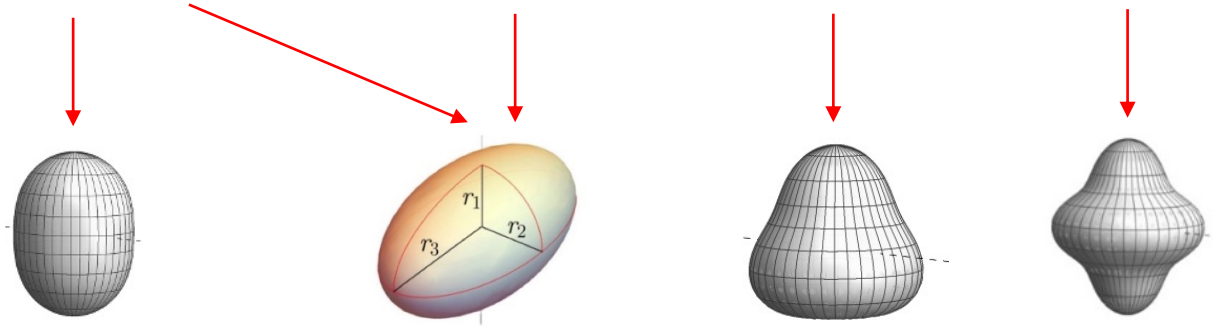
Tip-tip: $v_2 \searrow$ $p_T \nearrow$

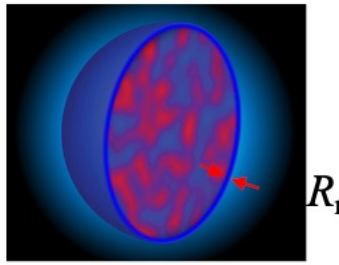
Shape-frozen like a snapshot during nuclear crossing (10^{-25}s << rotational time scale 10^{-21}s)
probe entire mass distribution in the intrinsic frame via multi-point correlations

II. Nuclear structure in ground-state ^{238}U and ^{96}Zr nuclei

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

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





W. Ryssens, G. Giacalone, B. Schenke, C. Shen, *PRL 130, 212302 (2023)*

DFT calculations predict a slightly small WS deformation $\beta_{2U} \approx 0.28 \rightarrow \beta_{2U,WS} \approx 0.25$

corresponding to a larger volume deformation in presence of $\boldsymbol{\beta}_{4U}$~0.1 $\beta_{2,\mathrm{body}} = \frac{4\pi}{3R_0^2 A}\int d^3r\rho(\mathbf{r})r^2Y_{20}$

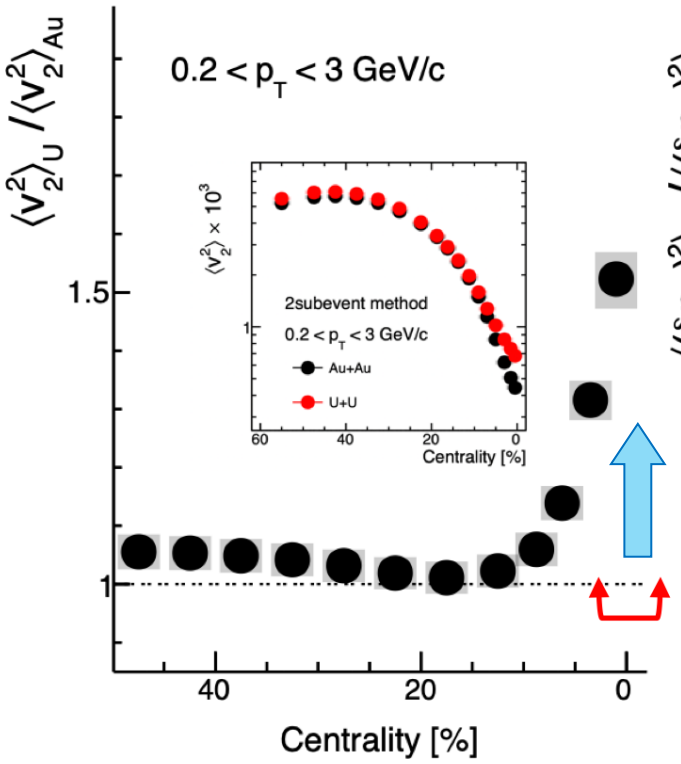
Low-energy estimate with rigid rotor assumption from B(E2) data $\beta_{2,\mathrm{LD}} = \frac{4\pi}{5R_0^2 Z}\sqrt{\frac{B(\mathrm{E2})}{e^2}}$

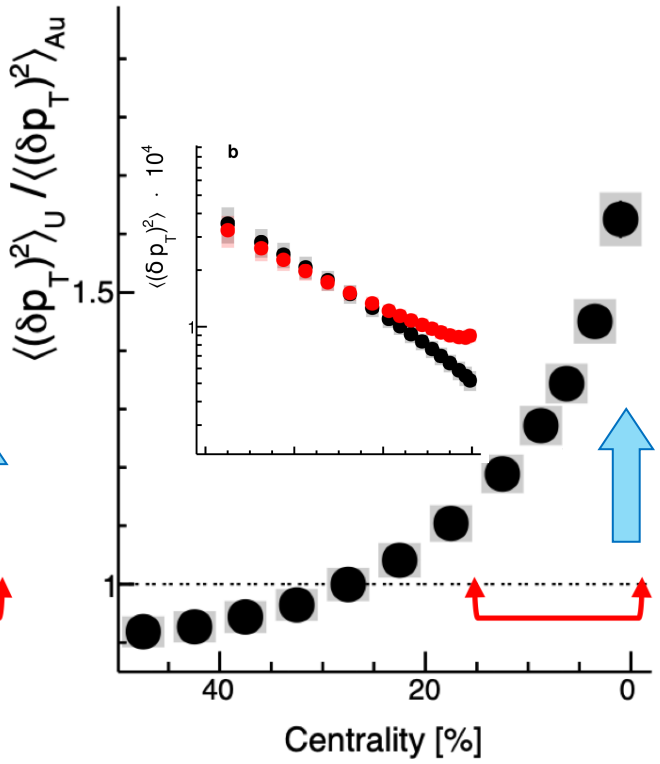
$\beta_{2U,\mathrm{LD}} = 0.287 \pm 0.007 \quad \gamma_{U,\mathrm{LD}} = 6^\circ - 8^\circ$

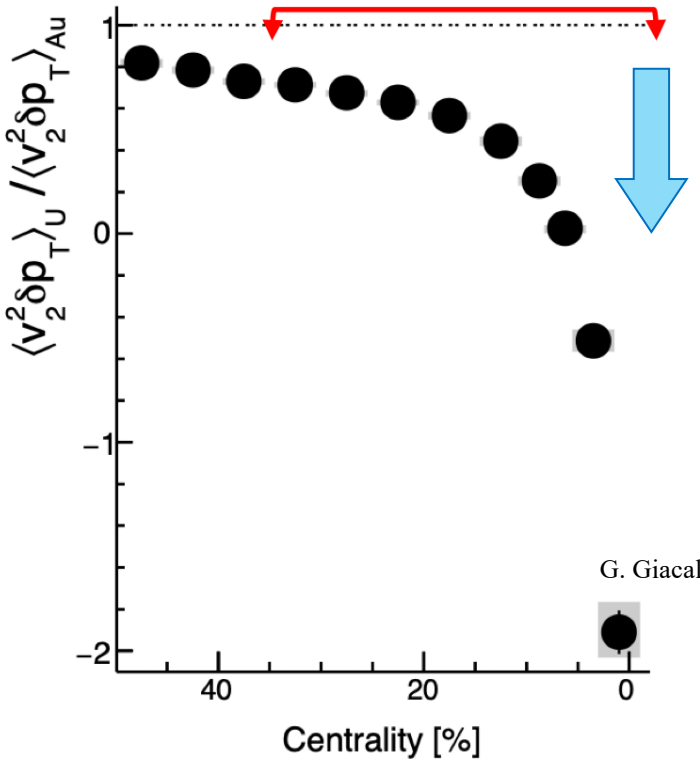
$\boldsymbol{\beta}_{3U} \sim \boldsymbol{\beta}_{4U} \sim 0.1$

B. Pritychenko et al., *J.ADT.107, 1 (2016)*
C. Y. Wu et al., *PRC 54, 2356(1996)*

Ratio of observables







$$R_{(v_2^2)} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$
$$R_{\langle (\delta p_T)^2 \rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$
$$R_{\langle v_2^2 \delta p_T \rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3 \cos(3\gamma)$$

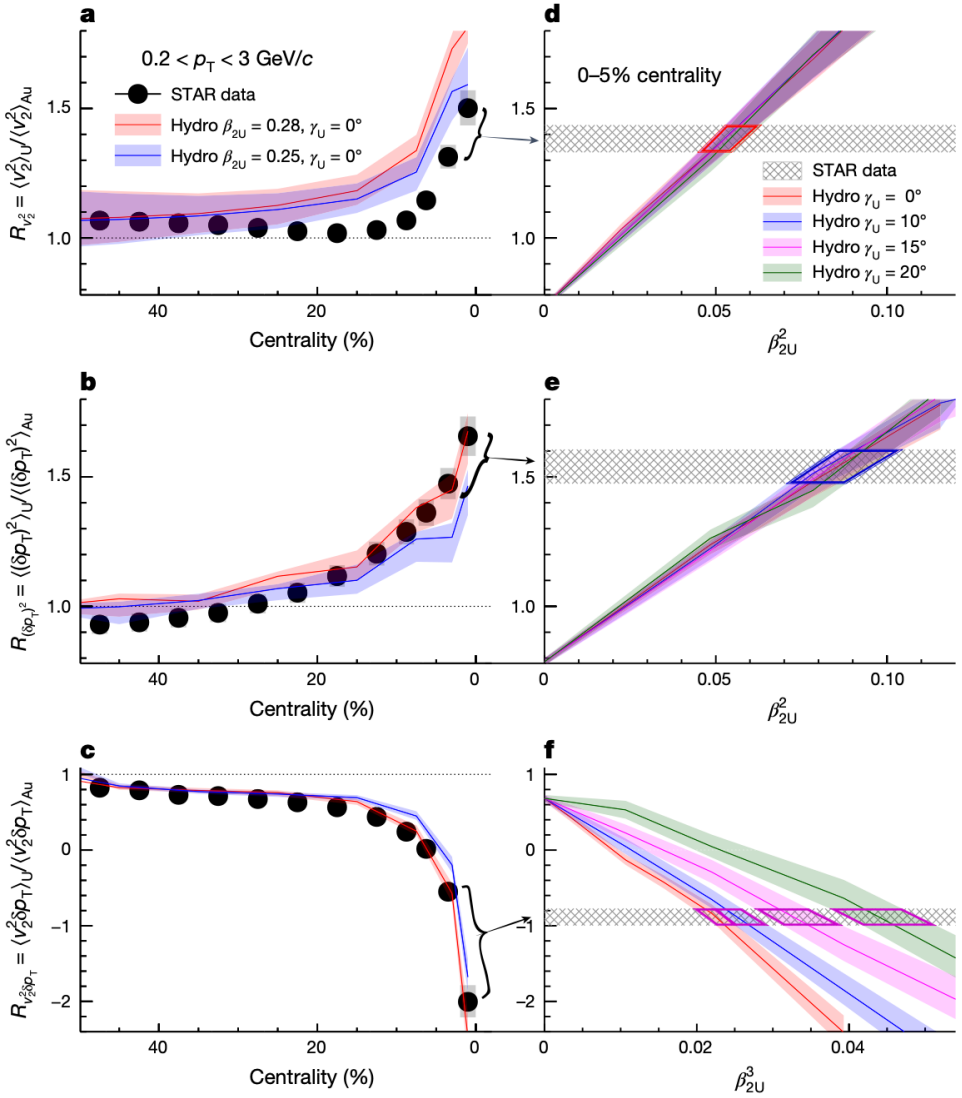
G. Giacalone, J. Jia, C. Zhang, *PRL 127, 242301 (2021)*

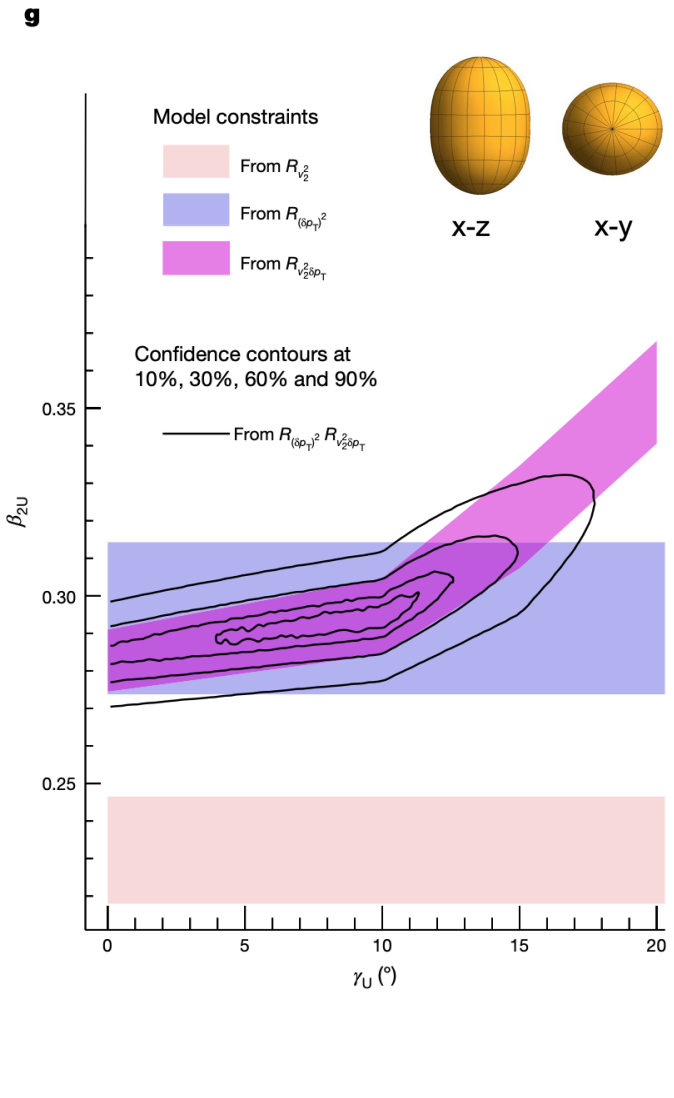
- Elliptic flow and size fluctuation are enhanced by the nuclear deformation effect.

- Ratios cancel final state effects and isolate the effects of initial state/nuclear structures.

→ U deformation dominates the ultra-central collisions (UCC)

Constraining the ground-state ^{238}U: $\beta_{2,U}$ and γ_U





Sufficient precision is achieved from ratios in ultra-central collisions

Relation also confirmed from hydro

$$R_{(v_2^2)} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$
$$R_{\langle (\delta p_T)^2 \rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$
$$R_{\langle v_2^2 \delta p_T \rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3 \cos(3\gamma)$$

High-energy estimate
(*IP-Glasma+MUSIC* and *Trajectum*)

$$\beta_{2U} = 0.286 \pm 0.025$$
$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

low-energy estimate:

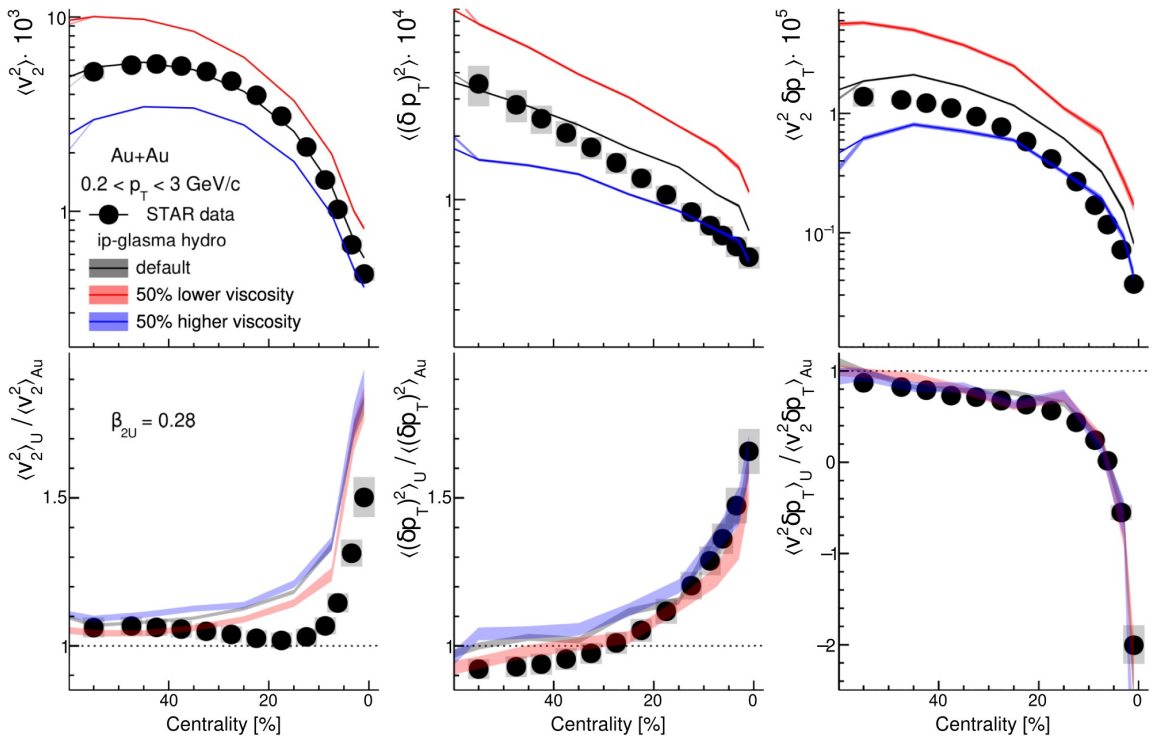
$$\beta_{2U} = 0.287 \pm 0.007$$
$$\gamma_U = 6^\circ - 8^\circ$$

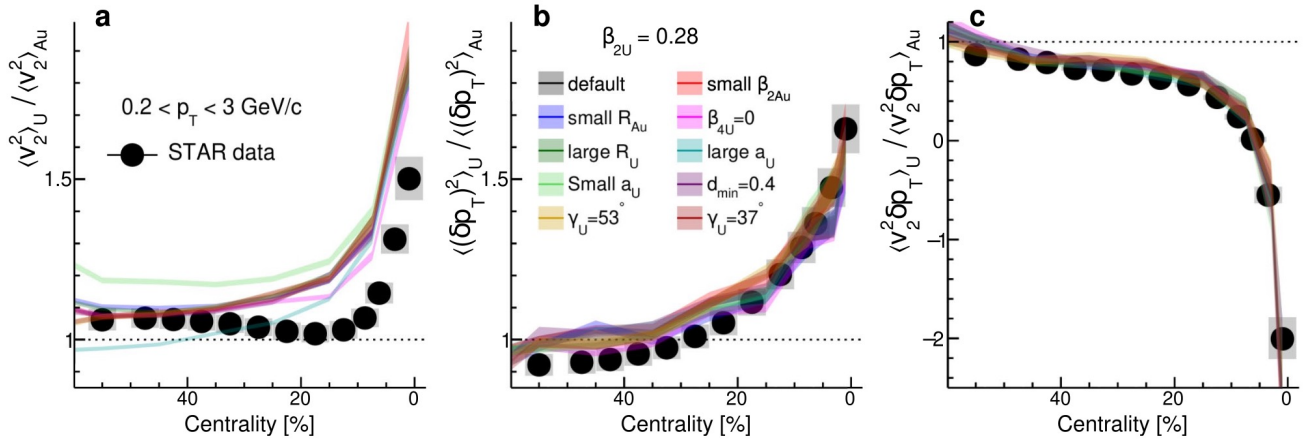
A large deformation with a slight deviation from axial symmetry in the nuclear ground-state

Viscosity, nuclear parameters, and model variations

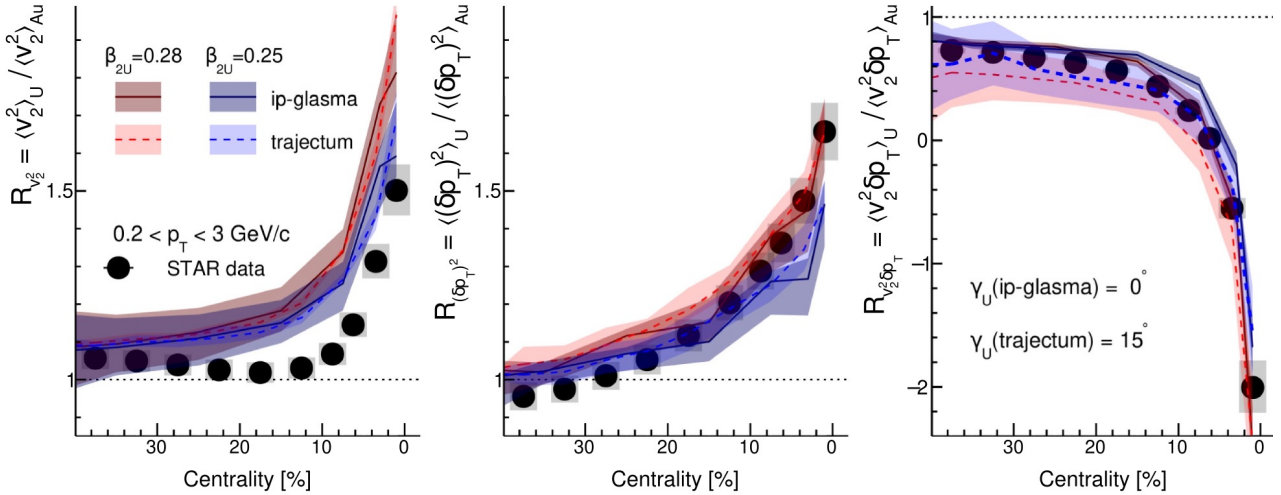
2) Effect from nuclear parameters are small, included as model systematics.

1) Taking the ratios cancels the viscosity effects.



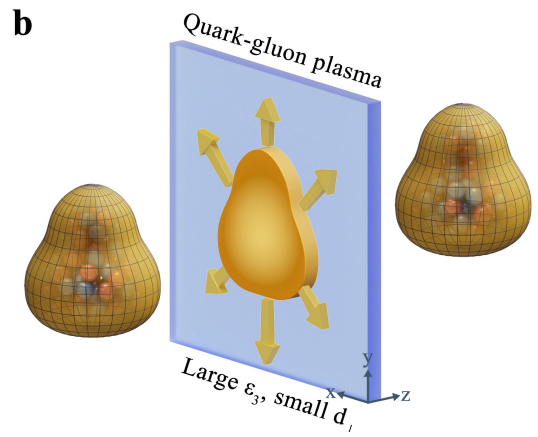


3) Another hydrodynamics model, Trajectum, shows rather consistent extractions even if it was not tuned to RHIC data.



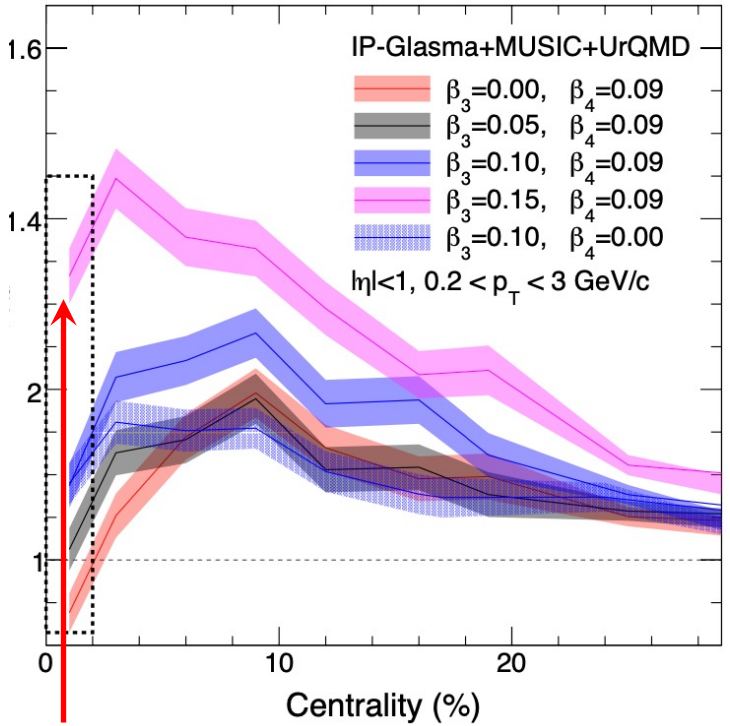
Extracted $\beta_{2,U}$ and γ_U values are robust.

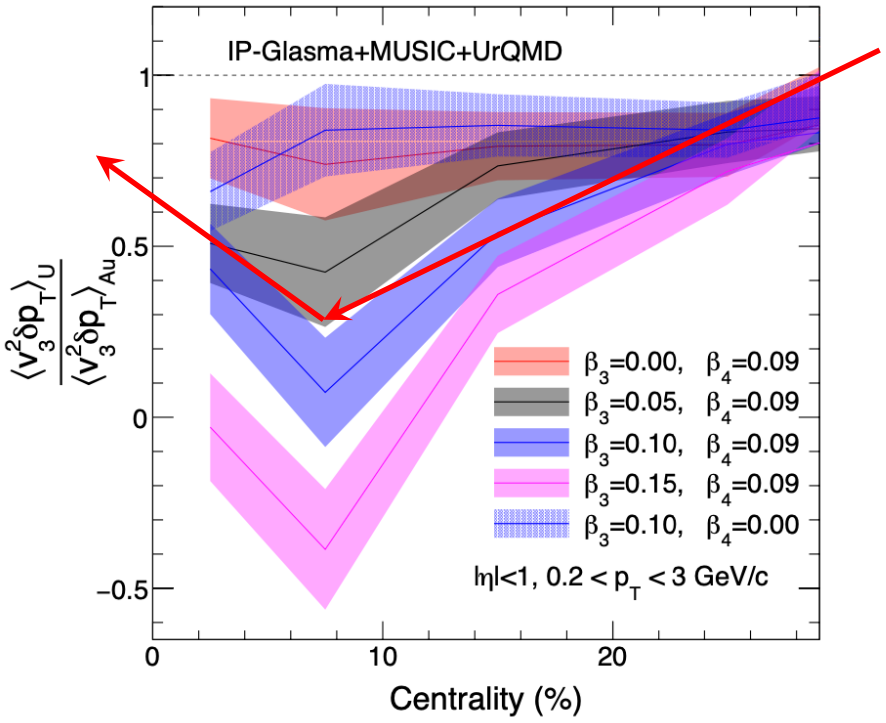
Evidence of octupole deformation $\beta_{3,\mathrm{U}}$



IP-Glasma+MUSIC calculations

C. Zhang, J. Jia, J. Chen, C. Shen, L. Liu, *2504.15245*





However, v_3 is fluctuation driven, expect in central

$$\langle v_3^2 \rangle \propto \langle \varepsilon_3^2 \rangle \sim 1/A$$

mass number

$\langle v_3^2 \rangle$ follows a linear increase with β_3^2,

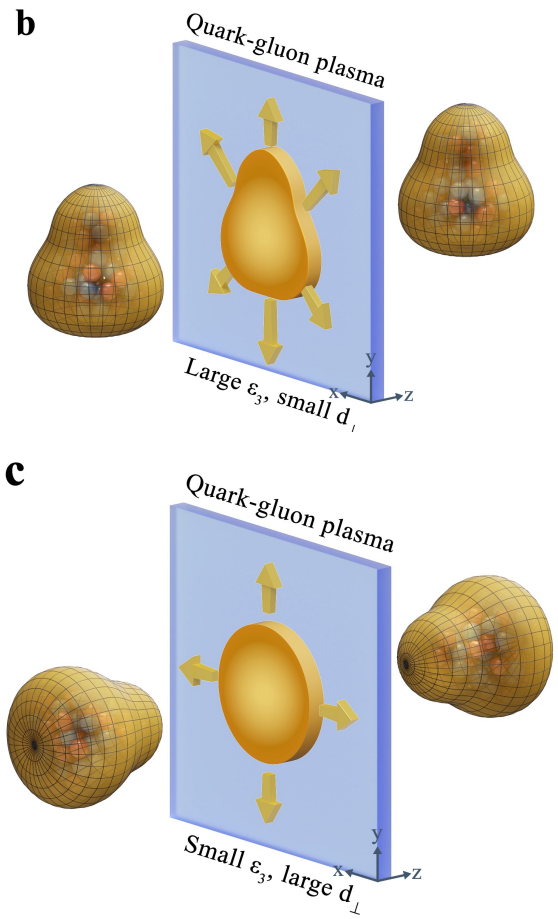
Characteristic anticorrelation in $\langle v_3^2 \delta p_\mathrm{T} \rangle$ shows a pronounced β_3-dependent suppression.

$$R_{v_3^2} = \frac{\langle v_3^2 \rangle_{\mathrm{U+U}}}{\langle v_3^2 \rangle_{\mathrm{Au+Au}}} \approx \frac{a_{3\mathrm{U}}}{a_{3\mathrm{Au}}} + \frac{b_{3,3}}{a_{3\mathrm{Au}}} \beta_3^2 + \frac{b_{3,4}}{a_{3\mathrm{Au}}} \beta_4^2,$$

$$R_{v_3^2 \delta p_\mathrm{T}} = \frac{\langle v_3^2 \delta p_\mathrm{T} \rangle_{\mathrm{U+U}}}{\langle v_3^2 \delta p_\mathrm{T} \rangle_{\mathrm{Au+Au}}} \approx a - b \beta_2 \beta_3^2.$$

B. Alver and G. Roland, *PRC 81, 054905 (2010)*

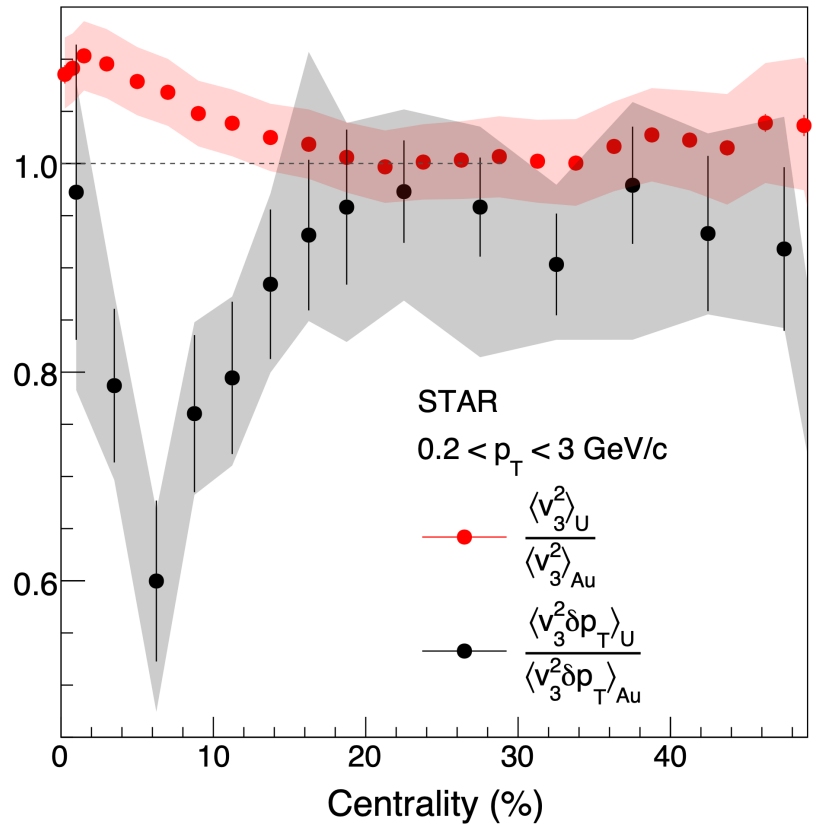
Evidence of octupole deformation $\beta_{3,\mathrm{U}}$



STAR, *Rep. Prog. Phys.* 88, 108601 (2025)
Research Highlight

$$\langle v_3^2 \rangle_{\mathrm{U}} > \langle v_3^2 \rangle_{\mathrm{Au}}$$
$$R_{v_3^2} = a + b\beta_3^2$$

$$\langle v_3^2 \delta p_{\mathrm{T}} \rangle_{\mathrm{U}} < \langle v_3^2 \delta p_{\mathrm{T}} \rangle_{\mathrm{Au}}$$
$$R_{v_3^2 \delta p_{\mathrm{T}}} = a - b\beta_2\beta_3^2$$



However, v_3 is fluctuation driven, expect in central

$$\langle v_3^2 \rangle \propto \langle \varepsilon_3^2 \rangle \sim 1/A$$

mass number

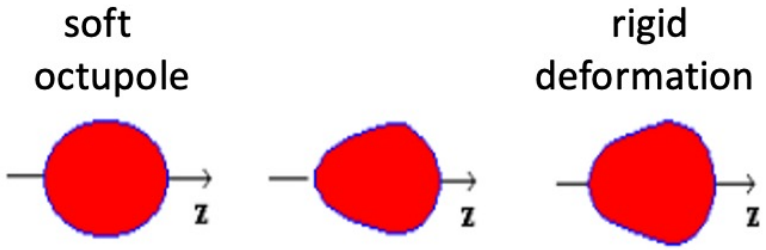
- Order of v_3 and v_3-p_T reversed by considering non-zero $\beta_{3,\mathrm{U}}$, $\beta_{4,\mathrm{U}}$.
- An evidence $\beta_{3,\mathrm{U}}$ and modest $\beta_{3,\mathrm{U}} \sim \beta_{4,\mathrm{U}} \sim 0.08$-$0.10$ are confirmed

B. Alver and G. Roland, *PRC 81, 054905 (2010)*

Probe $\beta_{3,\mathrm{U}}$ and its fluctuation

Octupole "collectivity"

L. Liu, C. Zhang, J. Chen, J. Jia, X. Huang, Y.-G. Ma, *2509.09376*

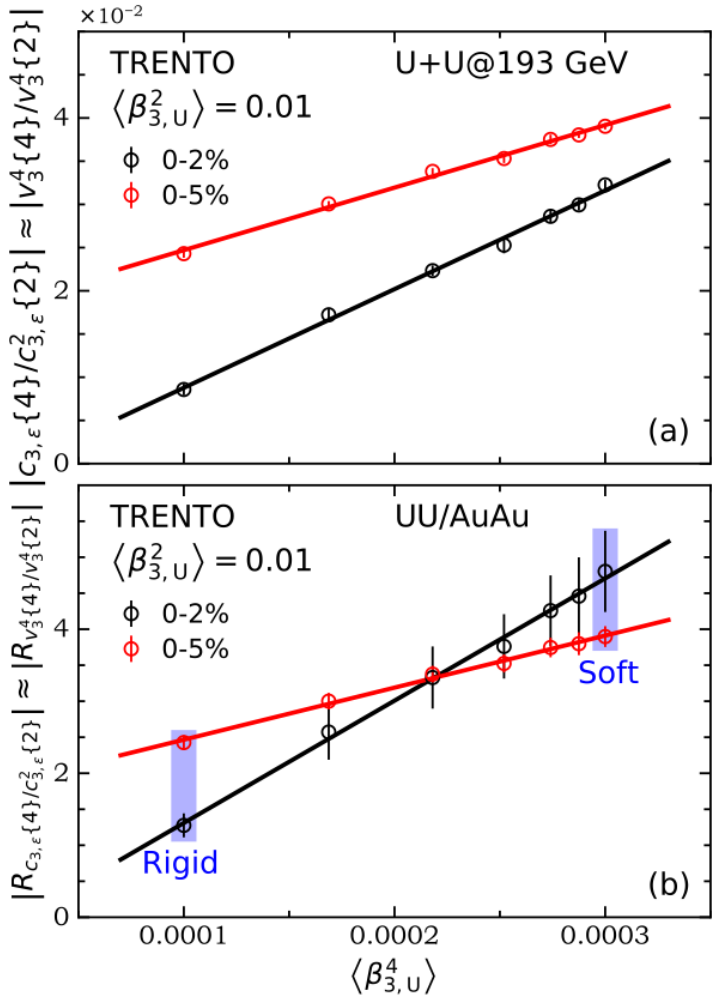


Case	$\bar{\beta}_3$	σ_{β_3}	$\langle\beta_3^2\rangle$	$\langle\beta_3^4\rangle$
$\mathrm{U}_{\mathrm{case0}}$	0.00	0.100	0.01	0.000300
$\mathrm{U}_{\mathrm{case1}}$	0.05	0.087	0.01	0.000288
$\mathrm{U}_{\mathrm{case2}}$	0.06	0.080	0.01	0.000274
$\mathrm{U}_{\mathrm{case3}}$	0.07	0.071	0.01	0.000252
$\mathrm{U}_{\mathrm{case4}}$	0.08	0.060	0.01	0.000218
$\mathrm{U}_{\mathrm{case5}}$	0.09	0.044	0.01	0.000169
$\mathrm{U}_{\mathrm{case6}}$	0.10	0.000	0.01	0.000100

$$\langle\beta_3^2\rangle = \bar{\beta}_3^2 + \sigma_{\beta_3}^2$$

$$c_{n,\varepsilon}\{2\} = \langle\varepsilon_n^2\rangle \approx \langle\varepsilon_{n,0}^2\rangle + \langle p_n p_n^*\rangle \langle\beta_n^2\rangle$$

$$\begin{aligned} c_{n,\varepsilon}\{4\} &= \langle\varepsilon_n^4\rangle - 2\langle\varepsilon_n^2\rangle^2 \\ &\approx \langle\varepsilon_{n,0}^4\rangle - 2\langle\varepsilon_{n,0}^2\rangle^2 + \langle p_n^2 p_n^{2*}\rangle \langle\beta_n^4\rangle - 2\langle p_n p_n^*\rangle^2 \langle\beta_n^2\rangle^2 \end{aligned}$$



Four-particle correlation is linearly scaled to $\langle\beta_{3,\mathrm{U}}^4\rangle$.

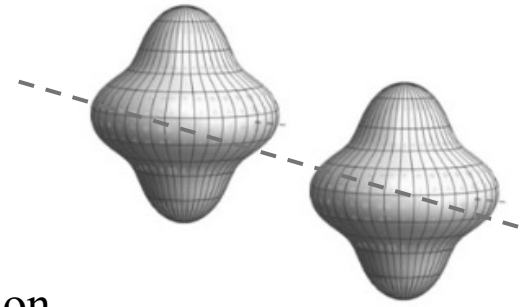
A way to discriminate between static and dynamic collective modes in high-energy nuclear collisions

B. G. Zakharov, *JETP Lett. 112, 393 (2020);* P. Carzon et al., *PRC 102, 054905 (2020);* H. Xu et al., *PRC 112, L051901 (2025); K.* Hagino and M. Kitazawa, *PRC, L041901 (2025)*

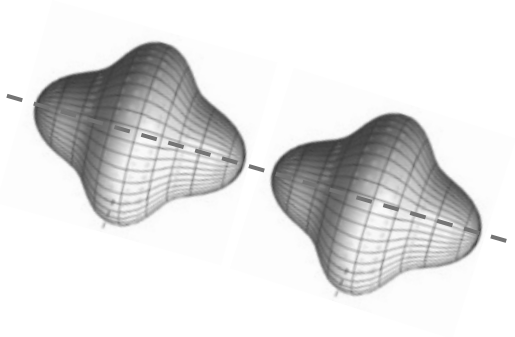
Evidence of hexadecapole deformation $\beta_{4,U}$

$\beta_{4,U}$-induced geometry effect

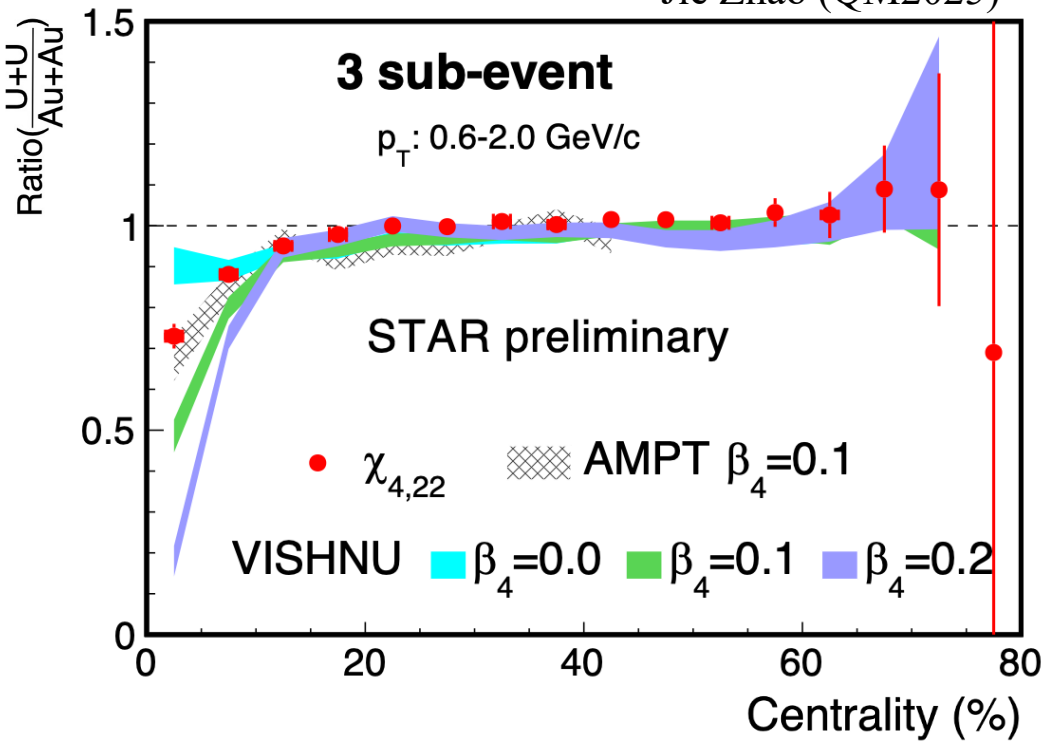
Body-body configuration



Tip-tip configuration



Jie Zhao (QM2025)



Non-linear response coefficient is sensitive to the $\beta_{4,U}$

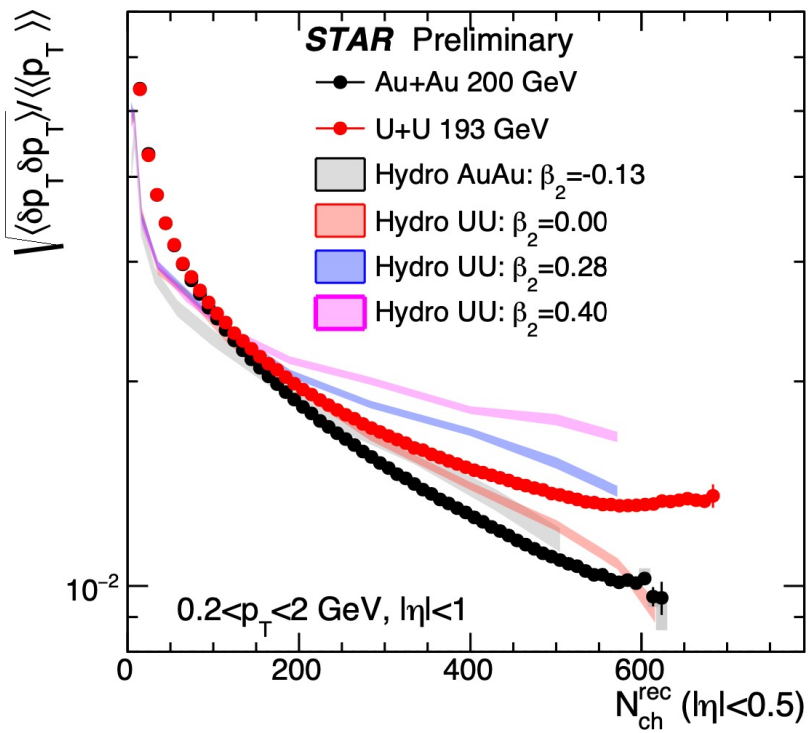
$\beta_{4,U}$ constrained using $\chi_{4,22}$ ratio in the central region

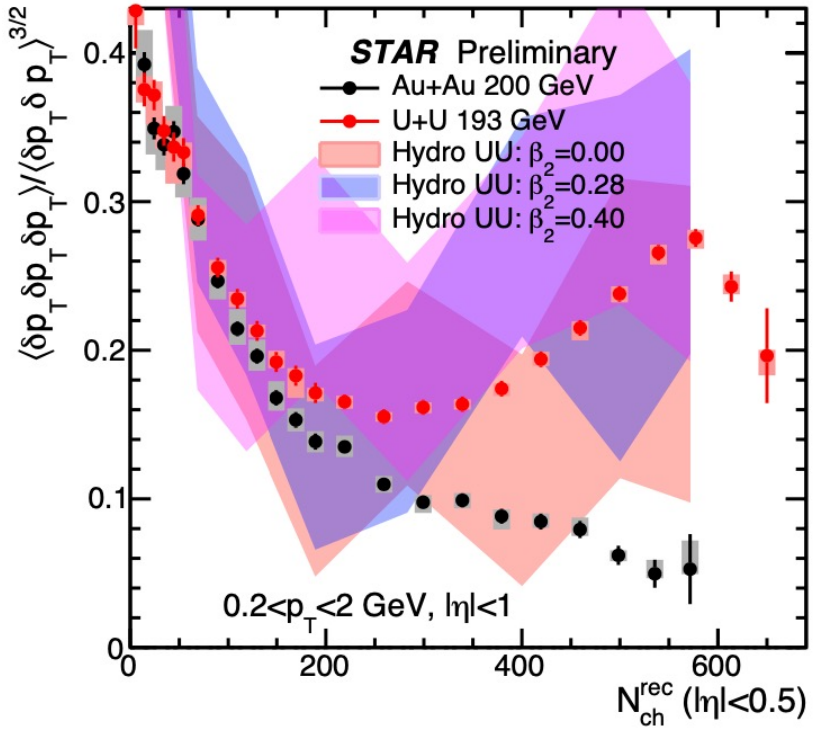
Model tuning is ongoing

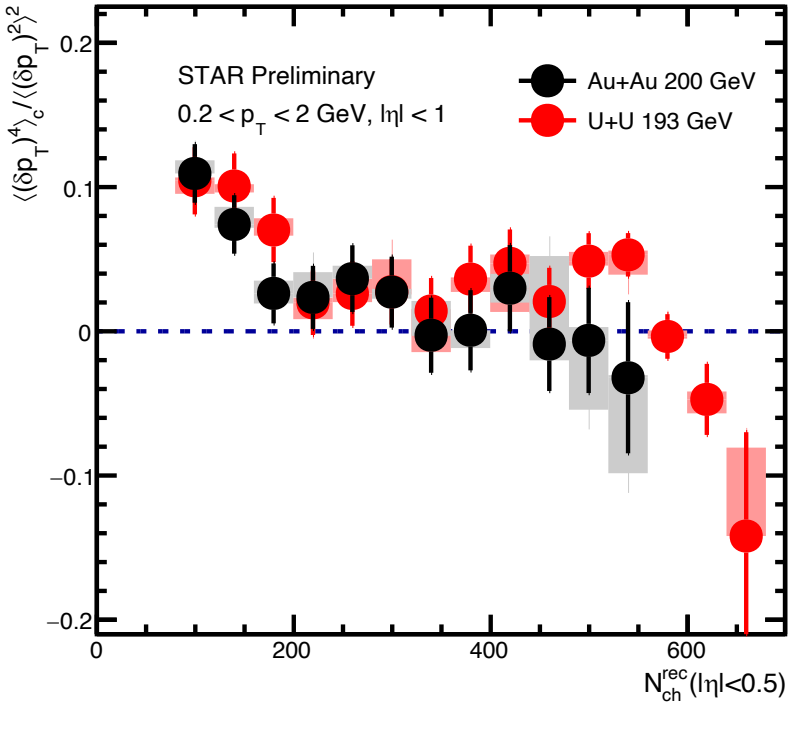
Z. Wang. J. Chen, H. Xu, J. Zhao, *PRC 110, 034907 (2024)*
H. Xu, J. Zhao, F. Wang, *PRL 132, 262301 (2024)*
W. Ryssens, G. Giacalone, B. Schenke, C. Shen, PRL 130, 212302 (2023)

[p_T] fluctuations and comparisons to hydro model

C. Zhang, *INT2023*, *WWND2023*







Au+Au: variance and skewness follow independent source scaling $1/N_s^{n-1}$ within power-law decrease

U+U: large enhancement in normalized variance and skewness and sign-change in normalized kurtosis
⟶ size fluctuations enhanced

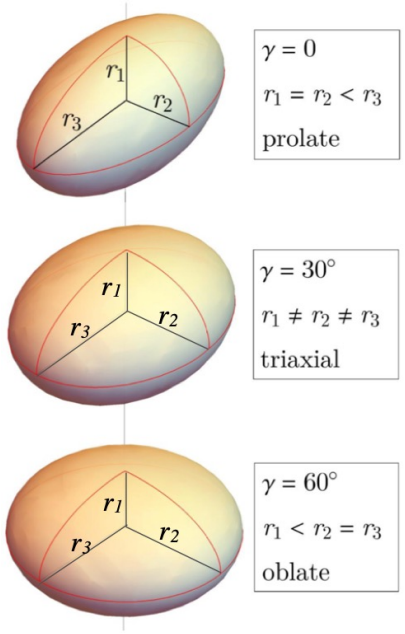
The nuclear deformation role is further confirmed by hydro calculations. But we need more statistics.

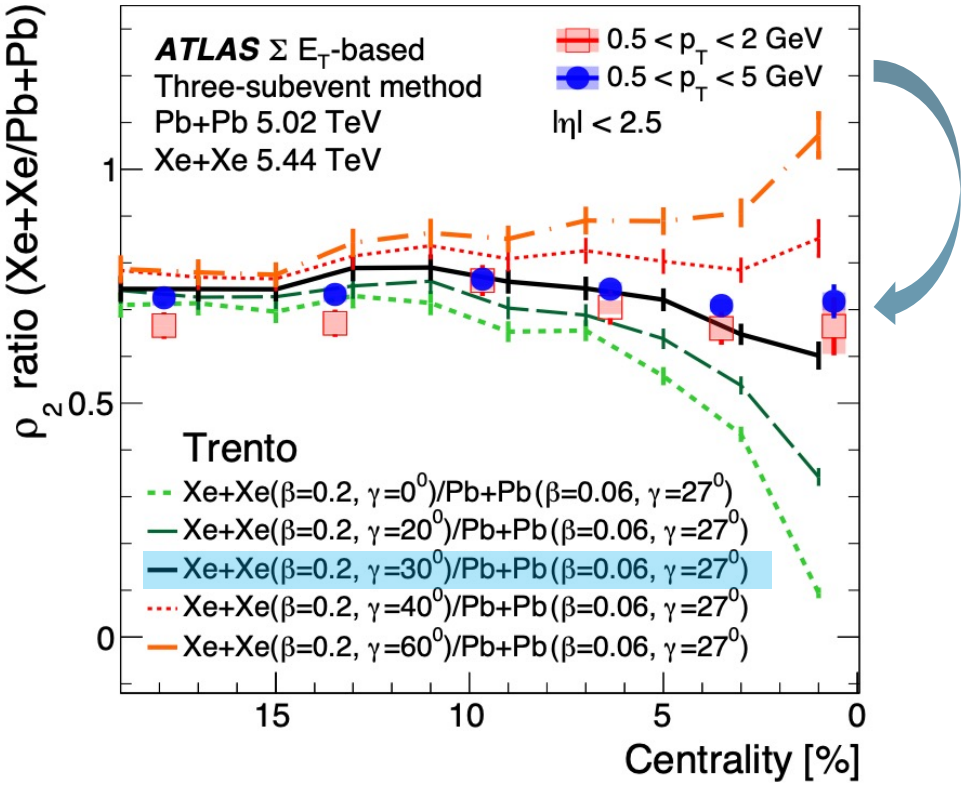
[p_T] fluctuations also serve as a good observable to explore the role of nuclear deformation.

ALICE, *PLB 850, 138541 (2024), PRL 136, 032302 (2026);* **ATLAS**, *PRL 133, 252301 (2024), PRL 136, 032301 (2026);* **STAR**, *2604.06434*

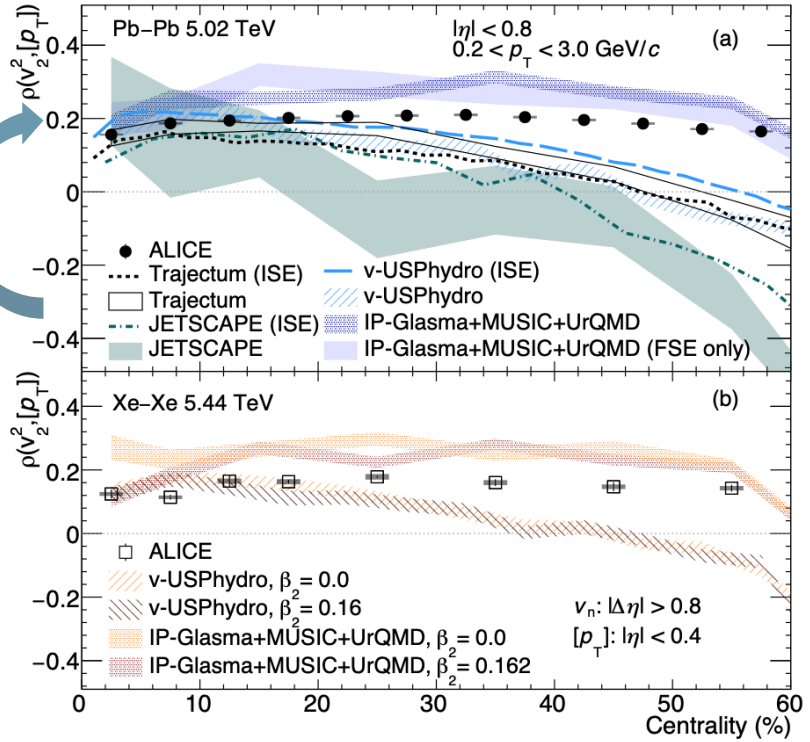
Shape of ground-state ^{129}Xe: $\beta_{2,Xe}$ and γ_{Xe}

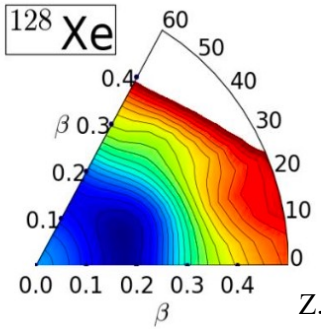
ATLAS, *PRC 107, 054910 (2023)*





ALICE, *PLB 834, 137393 (2022)*





γ-soft (flat distribution in 0≤γ≤60°)

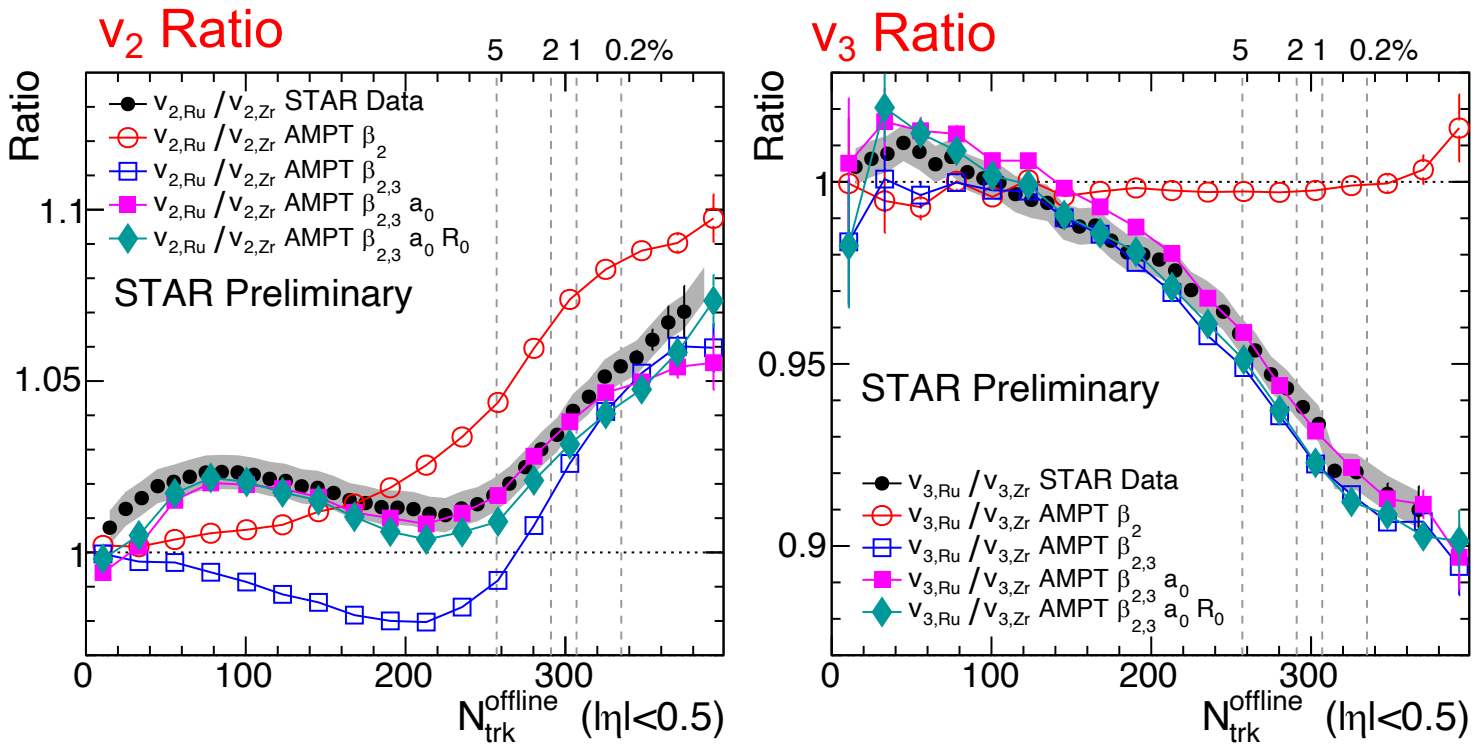
Z.P. Li et al., *PRC 81, 034316 (2010)*

- Pave a novel way to characterize the QGP initial state
- The medium effect was mostly canceled.
- Study the triaxial shape of ^{129}Xe nuclei

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, *PRL 133, 192301 (2024)*

A. Dimri, S. Bhatta, J. Jia, *EPJA59 45(2023)*

Nuclear structure in isobar ^{96}Ru and ^{96}Zr $\frac{\mathcal{O}_{^{96}\mathrm{Ru}} + \mathcal{O}_{^{96}\mathrm{Ru}}}{\mathcal{O}_{^{96}\mathrm{Zr}} + \mathcal{O}_{^{96}\mathrm{Zr}}} \overset{?}{=} 1$



- Direct observation of octupole deformation in ^{96}Zr nucleus
- Imply the neutron skin difference between ^{96}Ru and ^{96}Zr
- Simultaneously constrain parameters using Bayesian analysis

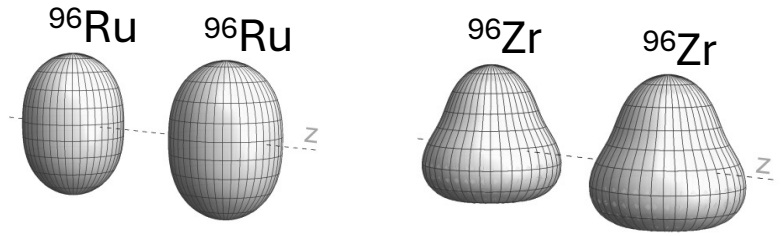
$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a$$

$\beta_{2,\mathrm{Ru}}$ ~ 0.16 increase v_2, no influence on v_3 ratio

$\beta_{3,\mathrm{Zr}}$ ~ 0.2 decrease v_2 in mid-central, decrease v_3 ratio

Δa_0 = -0.06 fm increase v_2 mid-central, small impact on v_3

Radius ΔR_0 = 0.07 fm only slightly affects v_2 and v_3 ratio.



$\beta_{2,\mathrm{Ru}} = 0.16 \pm 0.02$ $\beta_{3,\mathrm{Zr}} = 0.20 \pm 0.02$

difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

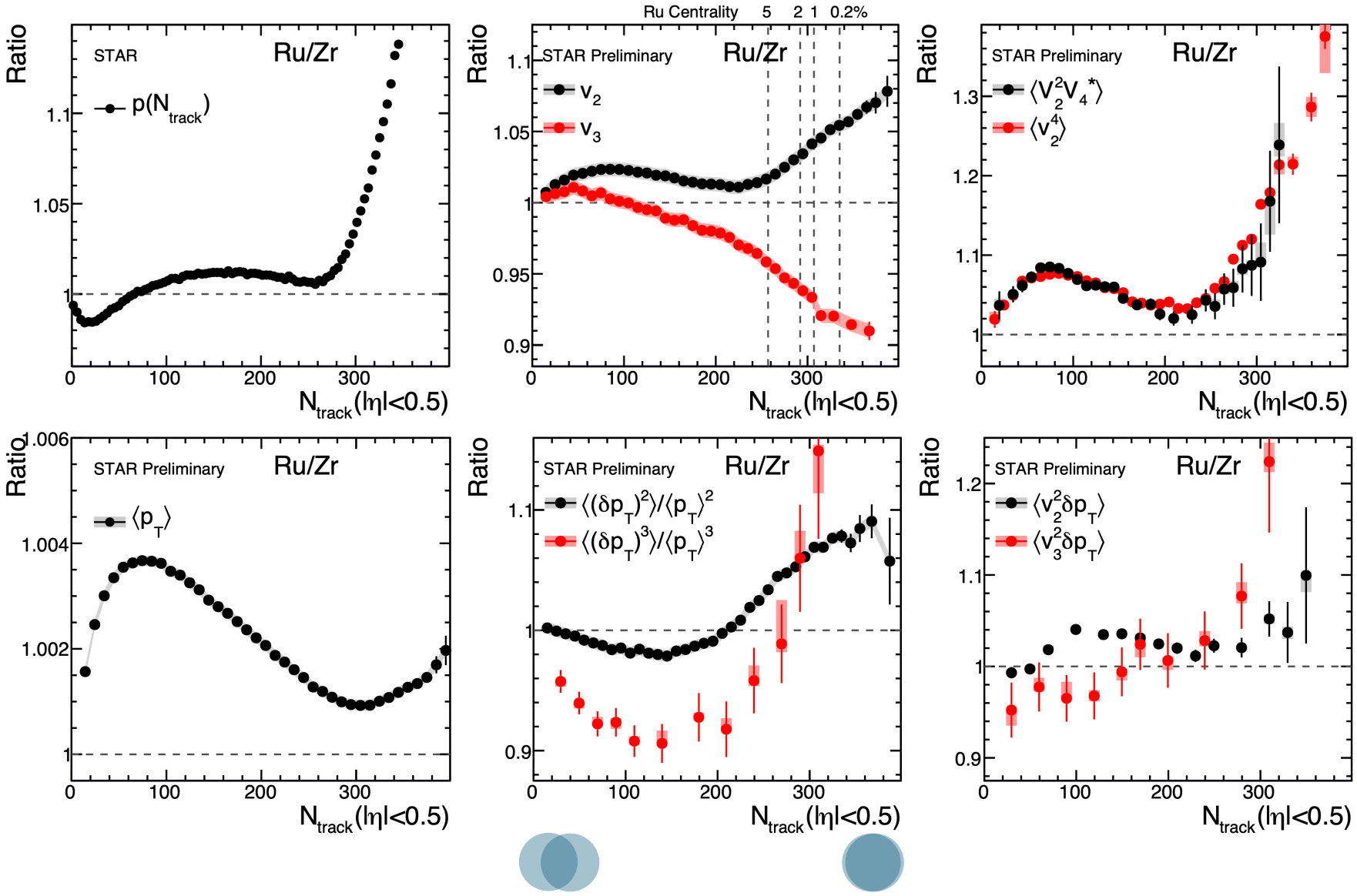
Current estimation is from transport model

C. Zhang, J. Jia, *PRL 128, 022301(2022);* J. Jia, C. Zhang, *PRC 107, L012901 (2023)*

Nuclear structure is inherent of heavy-ion probes

STAR Preliminary

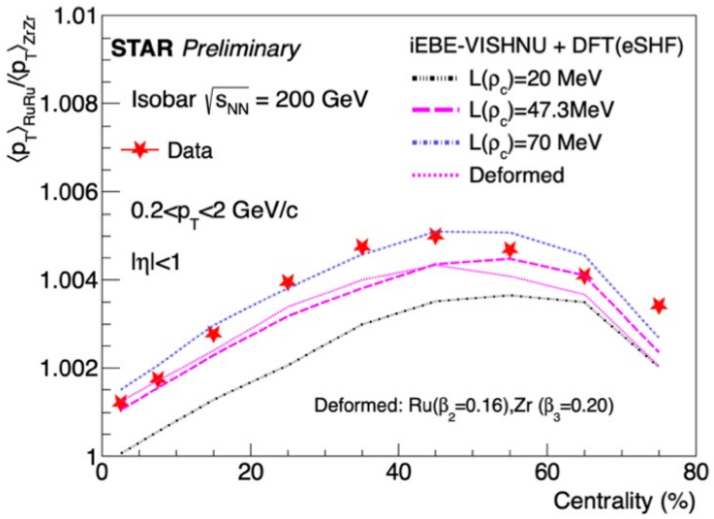
One-body distribution *Two-body correlations* *Three-body correlations*



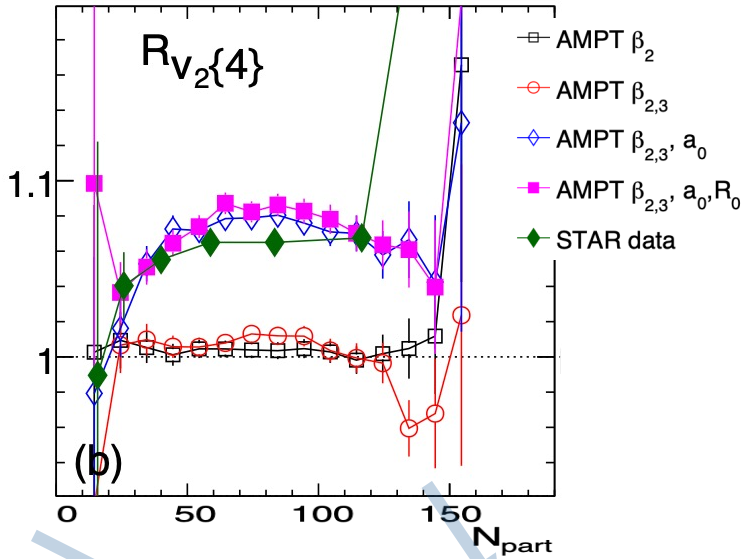
Imaging the radial structures (neutron skin)

Radial parameters R_0, a_0 are properties of one-body distribution → **$\langle p_T \rangle$, $\langle N_{ch} \rangle$, $v_2^{RP} \sim v_2\{4\}$, σ_{tot}, ZDC**

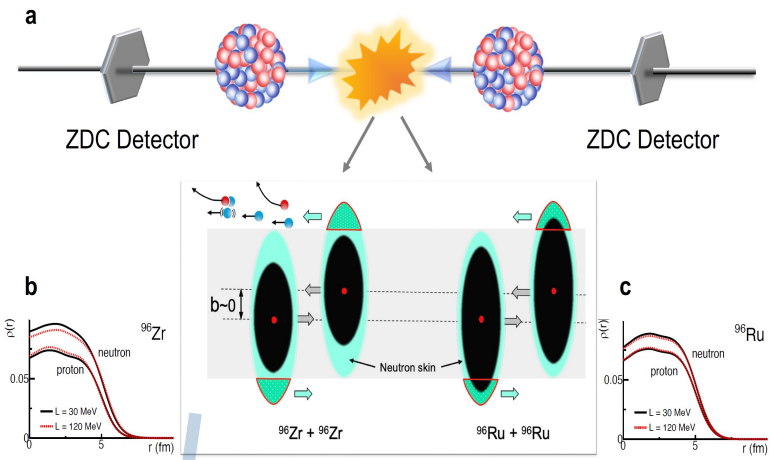
H. Xu, *QM2023*



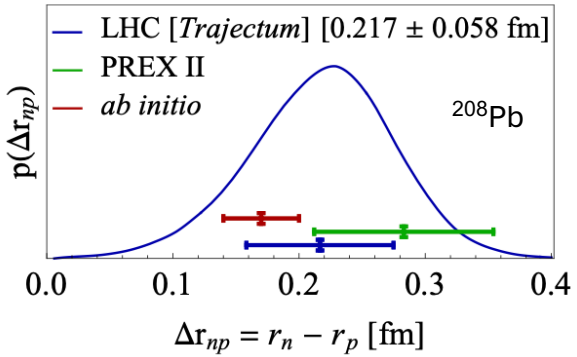
J. Jia, G. Giacalone, C. Zhang, *PRL 131, 022301 (2023)*



L. Liu, J. Xu et al., *PLB 834, 137441 (2022)*
PRC 106, 034913 (2022)

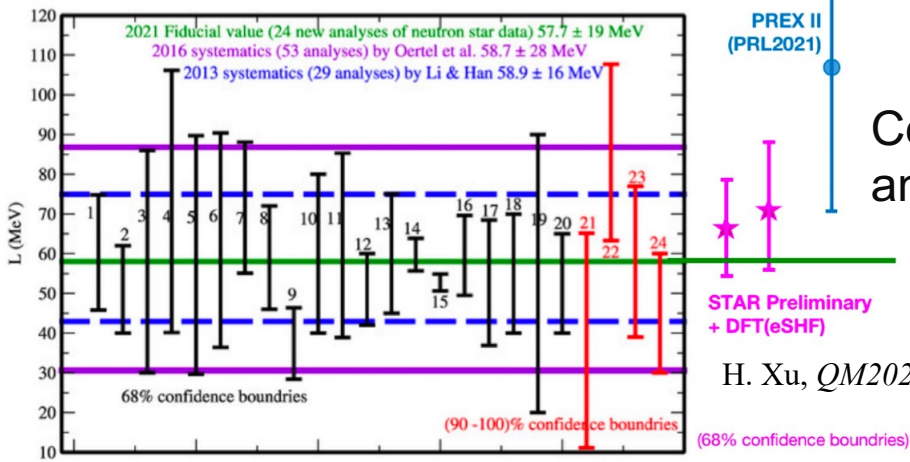


PREX- CREX puzzle in nuclear physics



G. Giacalone, G. Nijs, W. Schee, *PRL 131, 202302 (2023)*

B. Li, et.al Universe 7, 182 (2021)

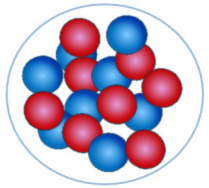


H. Xu, *QM2023*

Constrain neutron skin and symmetry energy

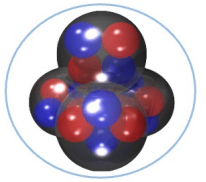
III. Nucleonic cluster pattern in light nuclei

--- from one-body distribution to many-body nucleon correlations



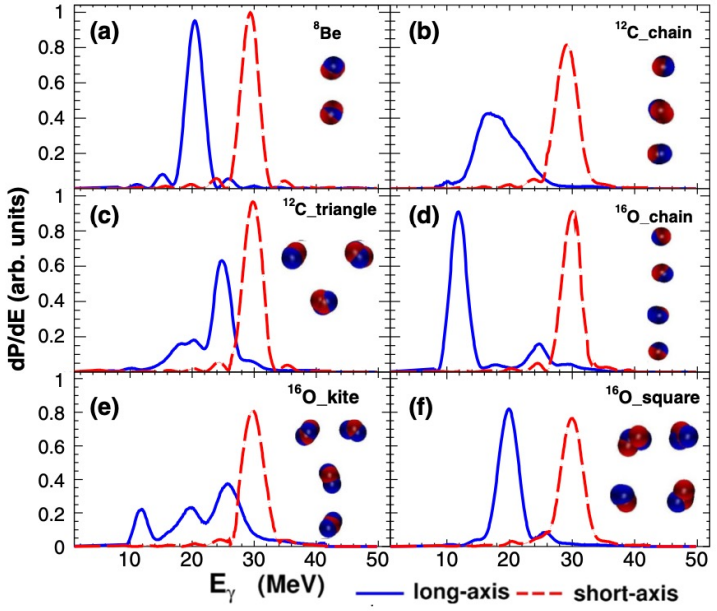
$$\rho(r) \propto \frac{1 + w\left(r^2/R^2\right)}{1 + e^{(r-R)/a_0}} \longrightarrow$$

Modern *ab initio* first-principle calculations

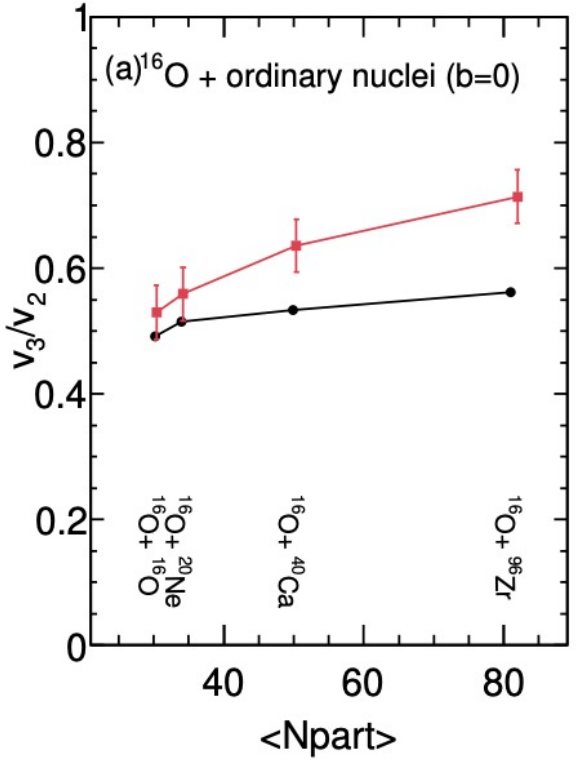


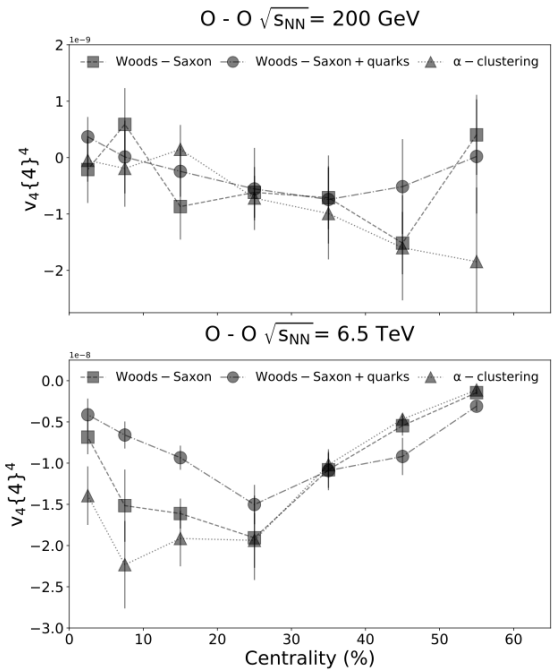
Pioneer theory instructions of the nucleonic clustering

"Double magic number" in $^{16}_{8}O$ nuclei, possible alpha cluster in low-energy studies.

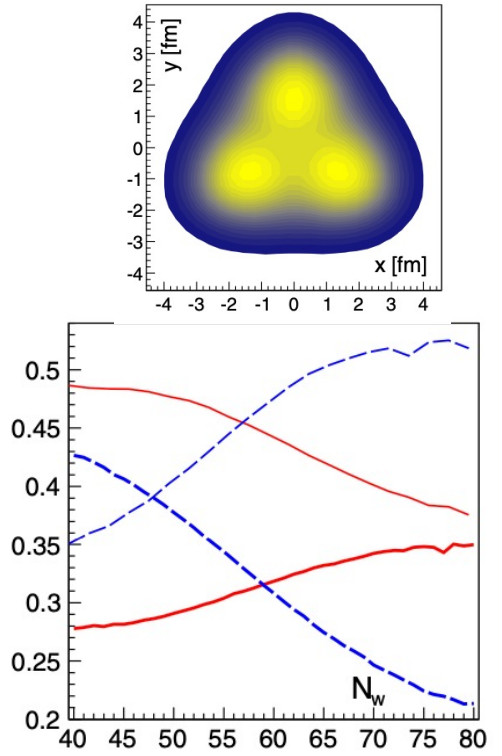


W. He, Y.-G. Ma et al., *PRL 113, 032605 (2014)*





Nicholas et al., *PRC 104, L041901 (2021)*



Y.-G. Ma and S. Zhang, *Handbook of Nuclear Physics,* 2206.08218

- ^{16}O nucleus could have different intrinsic topological structures.
- The initial configurations straightforwardly affect the final state observables in high energies.

W. Broniowski, E. Arriola, *PRL 112, 112501 (2014)*

Nucleon-nucleon correlations in finite quantum many-body systems

Possible cluster in ground-state $^{16}_{8}O$ nuclei in low energy

1) Woods-Saxon: without many-body nuclear correlation

2) Nuclear Lattice Effective Field theory (NLEFT):
model with many-nucleon correlation including α clusters

Lu et al., *PLB 797, 134863 (2019)*
M. Freer et al., *Rev. Mod. Phys. 90, 035004 (2018)*
S. Elhatisari et al., *Nature 630, 59 (2024)*

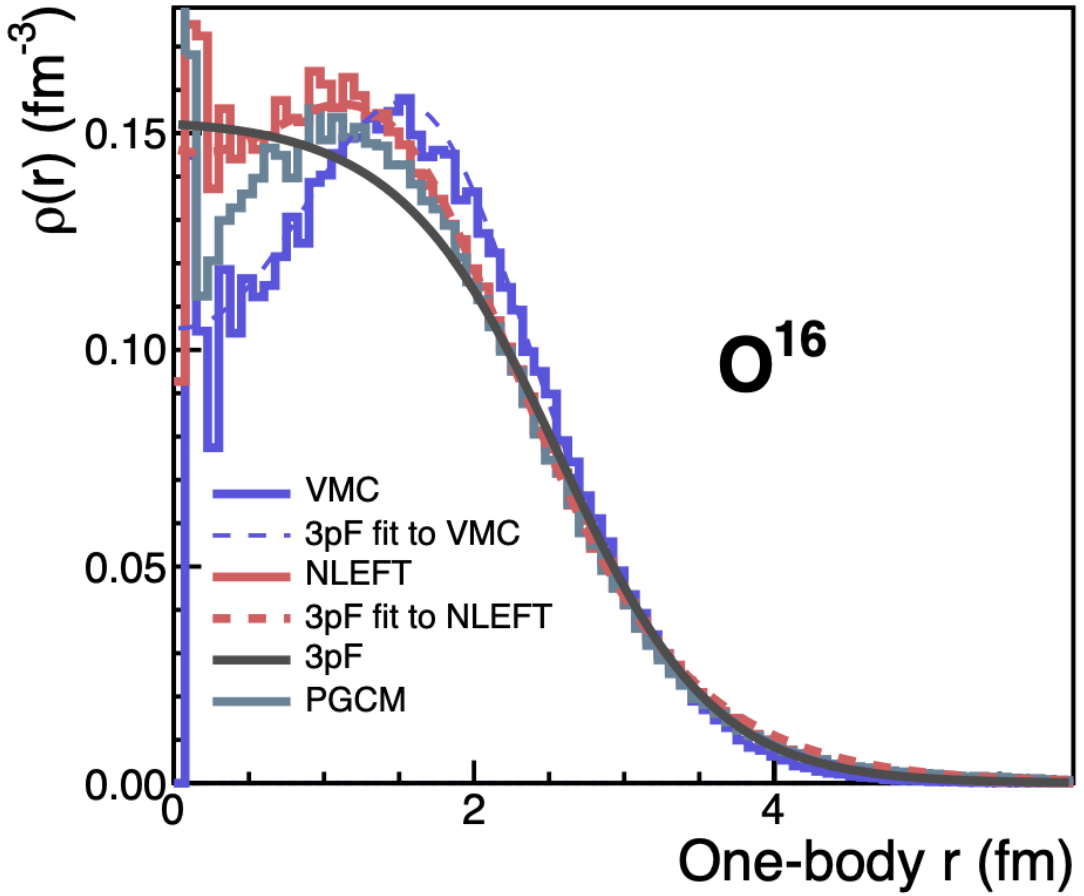
3) Variational auxiliary field diffusion Monte Carlo (VMC):
MC solution of Schrödinger eq. from the time evolution of trial wave function.

A. Lonardoni et al., *PRC 97, 044318 (2018)*
J. Carlson and R. Schiavilla, *Rev. Mod. Phys. 70, 743 (1998)*

4) ab-initio Projected Generator Coordinate Method (PGCM):
Wave function from variational calculation (as in density functional theory)

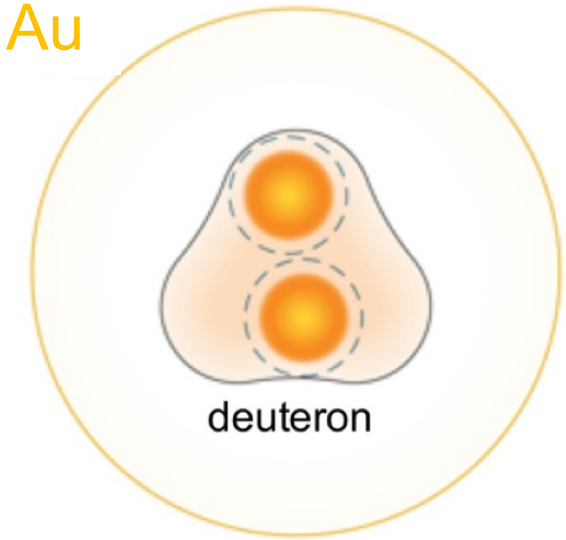
Frosini et al., *EPJA 58, 62 (2022); EPJA 58, 63 (2022); EPJA 58, 64 (2022)*

5) Some other micro models…

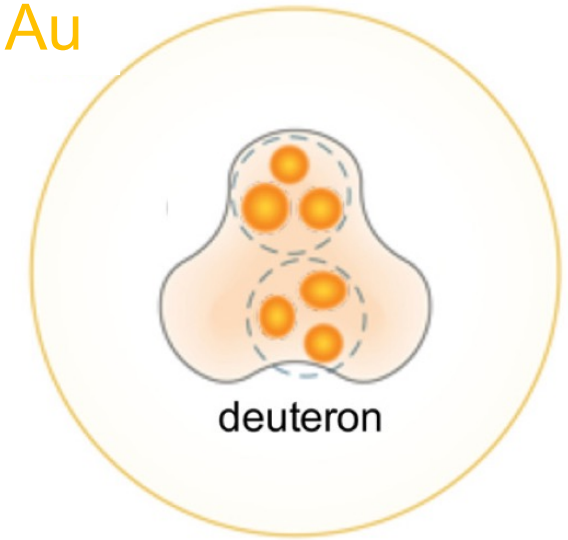


Nucleon/sub-nucleon fluctuation vs. nucleon-nucleon correlations

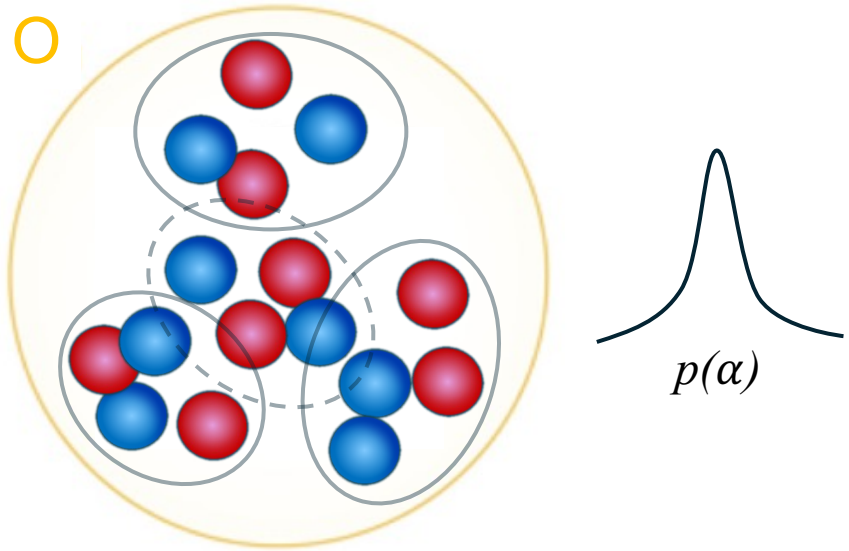
Nucleon fluctuation



subnucleon fluctuation



NN correlation (cluster pattern)



ab initio calculations

STAR, *PRL 130, 242301 (2023)*

STAR, *PRC 110, 064902 (2024)*

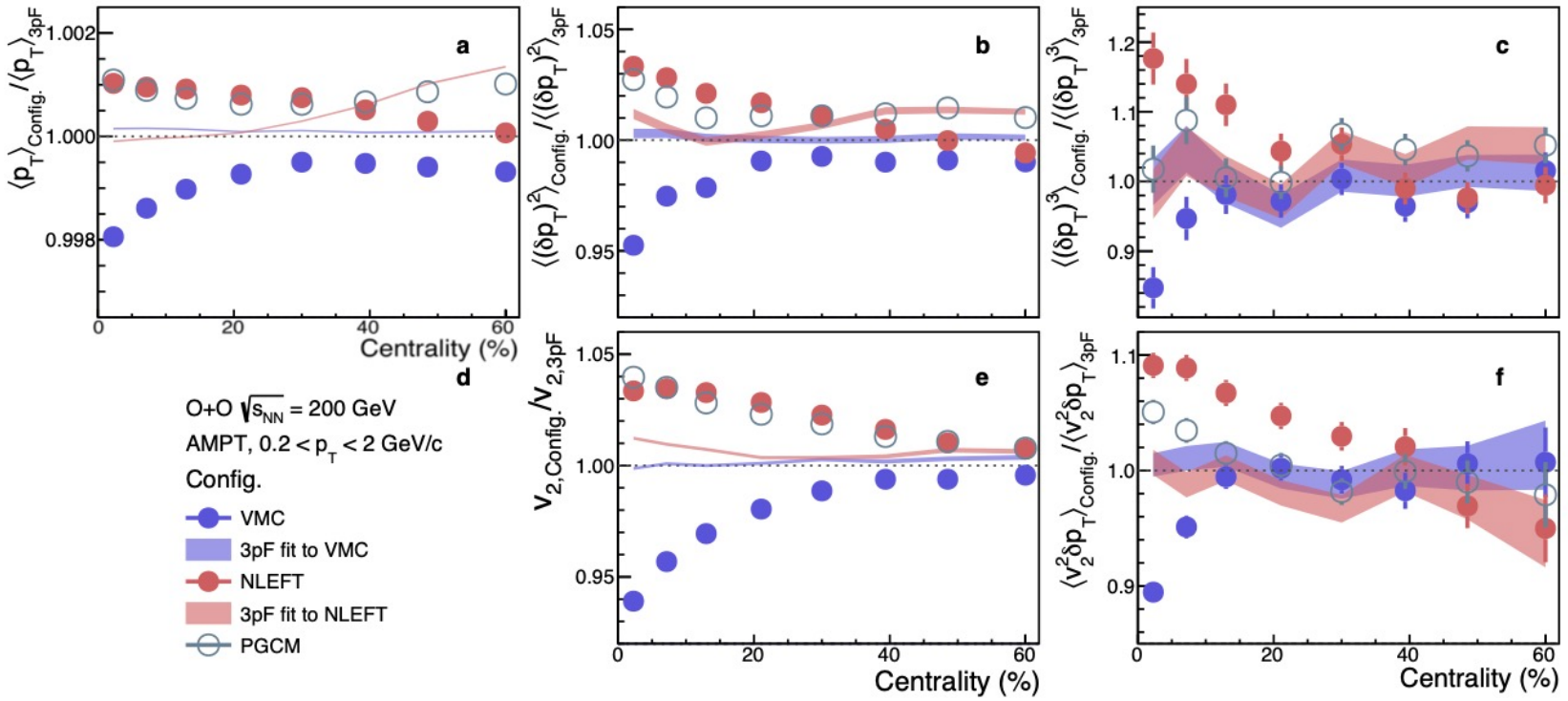
Y.-G. Ma, S. Zhang, *Handbook of Nuclear Physics (2022)*
C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*
S. Huang, J. Jia, C. Zhang, *PLB 870, 139926 (2025)*
X. Zhao, G. Ma. Y. Zhou, Z. Lin and C. Zhang, *PLB 874, 140254 (2026)*
P. Li, B. Zhou, G.-L. Ma, *PRL 136, 082302 (2026)*
S. Jahan, Roch, C. Shen, *PRC 113, 024919 (2026)*
Y. Wang, S. Zhao, B. Cao, H. Xu and H. Song, *PRC 109, L051904 (2024)*
H. Wang, S. Li, J. Xu, Z. Ren, *PLB 866, 139516 (2025)*
J. Hu, H. Xu, X. Wang, S. Pu, *2507.01493*
...

d+Au collision, 200 GeV ⟷ Nearly same N_{ch} ⟷ O+O collision, 200 GeV

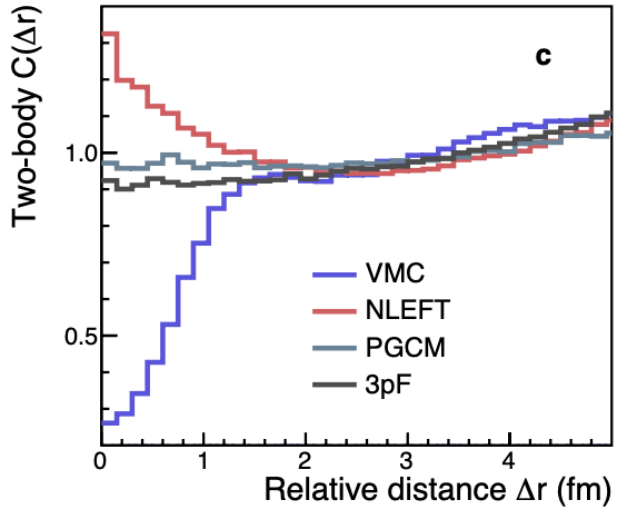
Ab-initio nucleon-nucleon correlations and their impact on high-energy

C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*

Multiple final-state observables



Two-body correlations in coordinate space

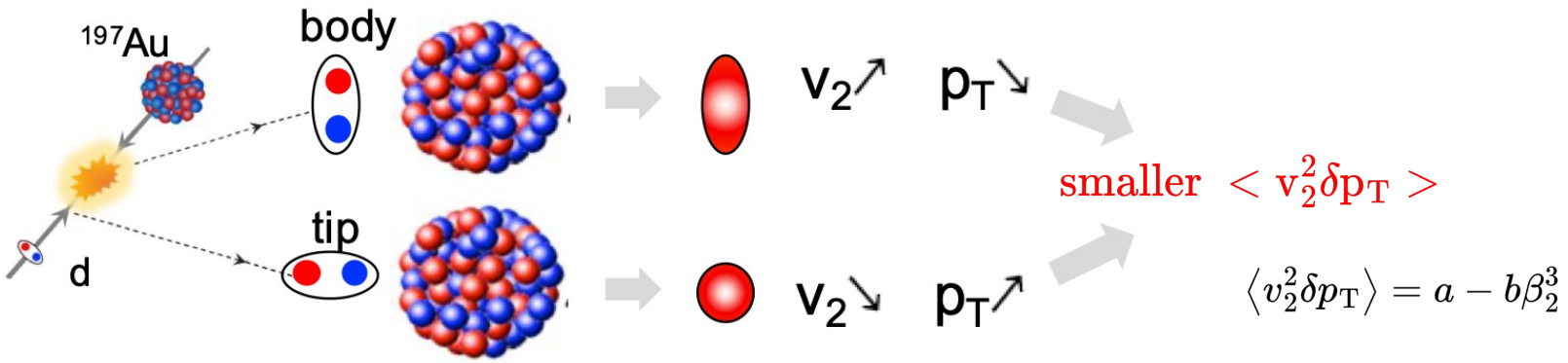


$$C(\Delta r) = \frac{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}, \mathbf{s}-\frac{\mathbf{r}}{2}\right)}{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}\right) f\left(\mathbf{s}-\frac{\mathbf{r}}{2}\right)}$$

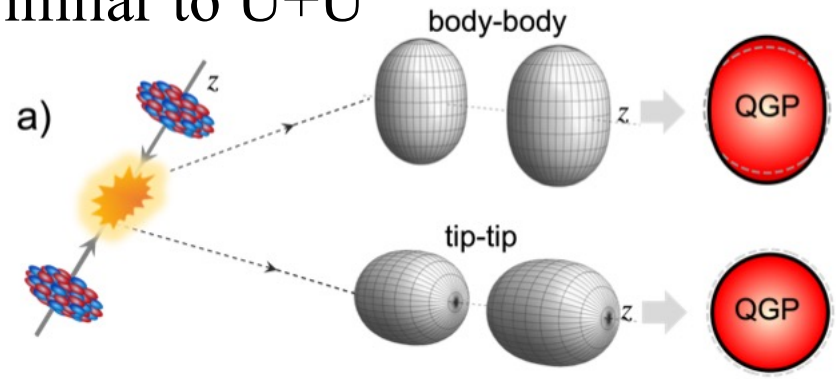
- 3pF as the baseline can NOT capture the NN correlations.
- Distinct differences are observed between VMC and NLEFT/PGCM.
- Central collision is prominent.

Impact of prolate shape of deuteron and the underlying Oxygen structure

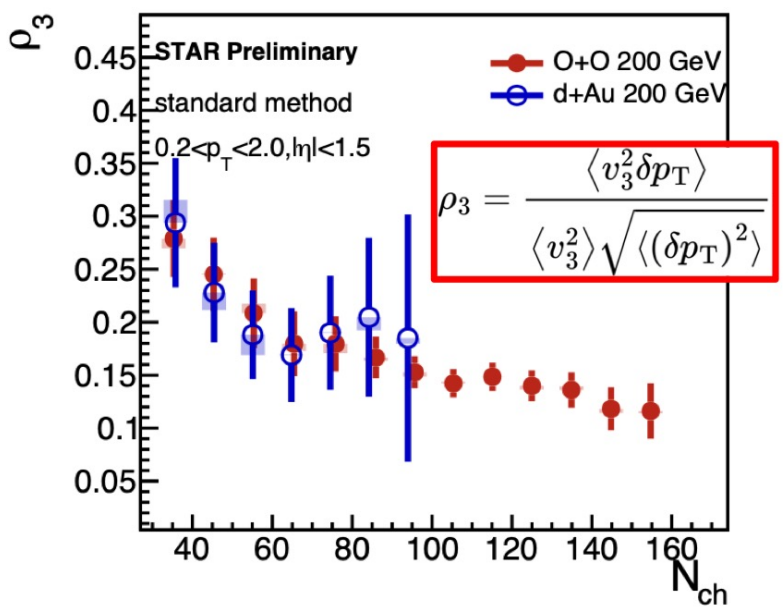
J. Jia, Z. Wang, sQM2026

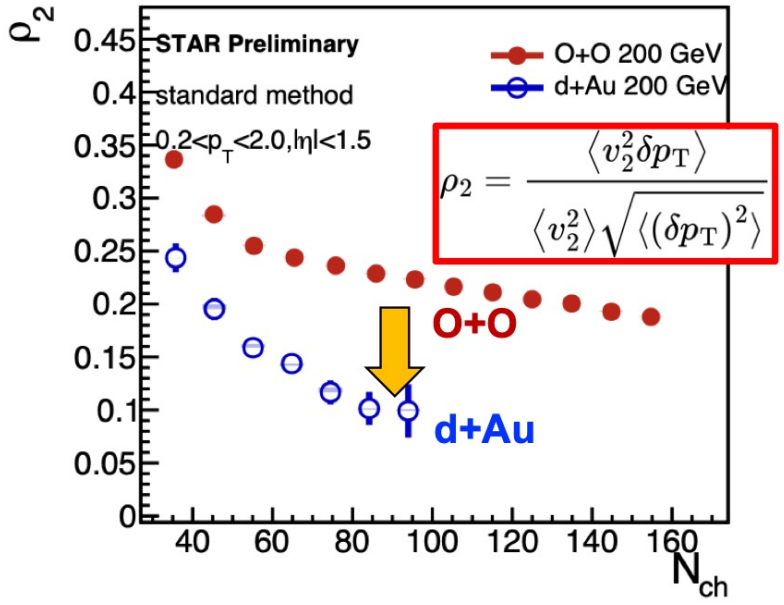


Similar to U+U



STAR, *Rep. Prog. Phys.* 88, 108601 (2025)





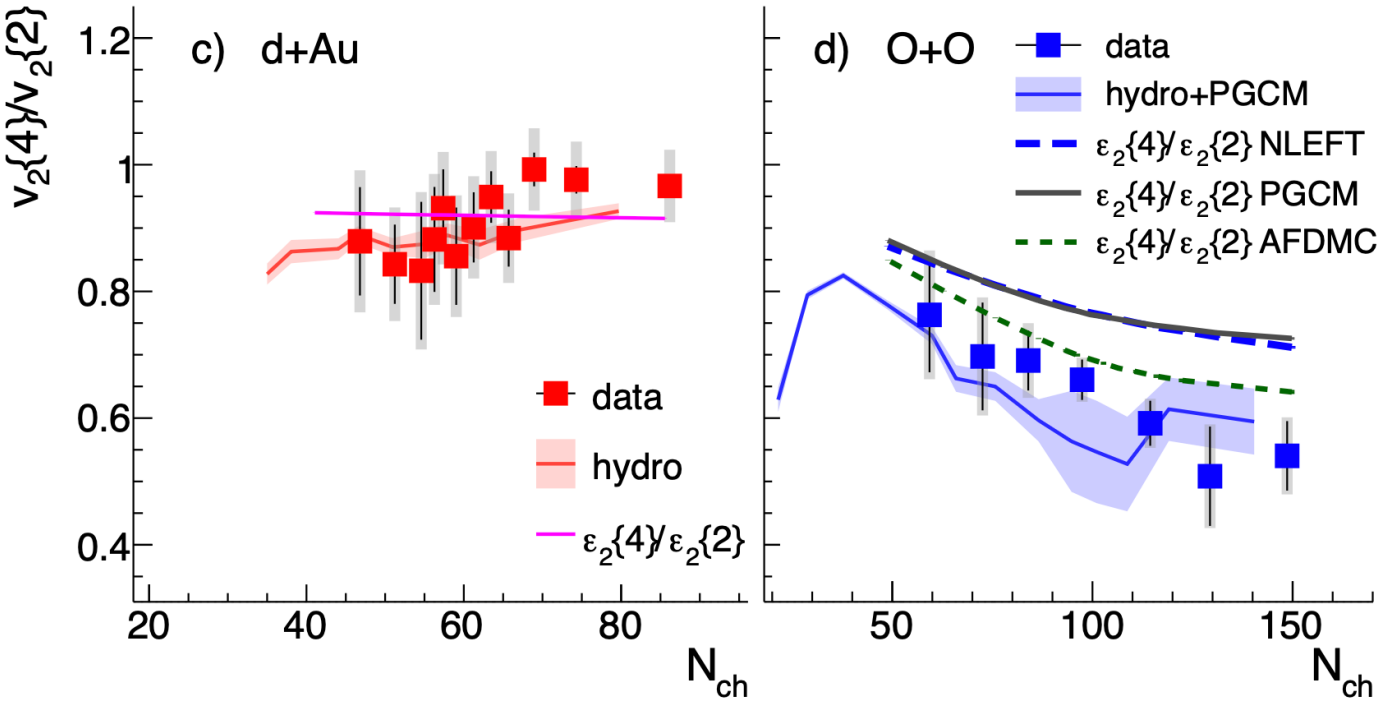
The deuteron wave function is fixed.

^{16}O structure might be important.

Behavior of $\langle v_2^2 \delta p_T \rangle$ consistent with QGP response to the prolate shape of deuteron

Benchmarking geometric tomography of ^{16}O nucleus

STAR, *2510.19645*



S. Jahan, Roch, C. Shen, *PRC 113, 024919 (2026)* *NLEFT from* D. Lee, *PGCM from* B. Bally, T. Duguet

Small fluctuation in d+Au

$$\frac{v_2^{dAu}\{4\}}{v_2^{dAu}\{2\}} \approx \frac{\varepsilon_2^{dAu}\{4\}}{\varepsilon_2^{dAu}\{2\}} \approx 0.9$$

large fluctuation in O+O

$$\frac{v_2^{OO}\{4\}}{v_2^{OO}\{2\}} \approx \frac{\varepsilon_2^{OO}\{4\}}{\varepsilon_2^{OO}\{2\}} \sim 0.6$$

d+Au is flat; Large enhancement in O+O with continuous decrease

$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from three models:

AFDMC vs. EFT/PGCM has a visible difference.

Nucleon-nucleon correlations impact initial-state fluctuations.

C. Zhang et al., *PLB 862, 139322 (2025)*

G. Giacalone, B. Bally, W. Zhao et al., *PRL 135, 012302 (2025), PRL 134, 082301 (2025)*

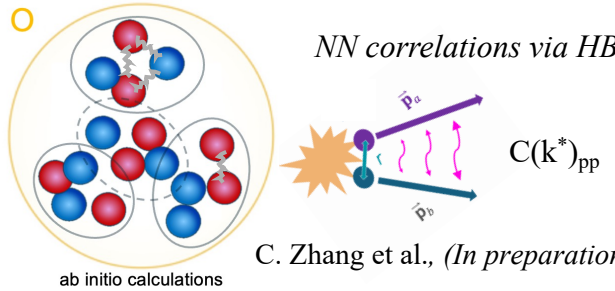
The interplay between nucleon/sub-nucleon fluctuation and many-nucleon correlation.

STAR, *PRL 130, 242301 (2023)*

S. Huang, J. Jia, C. Zhang, *PLB 870, 139926 (2025)*

Geometric scan elucidates nuclear tomography and strong nuclear force?

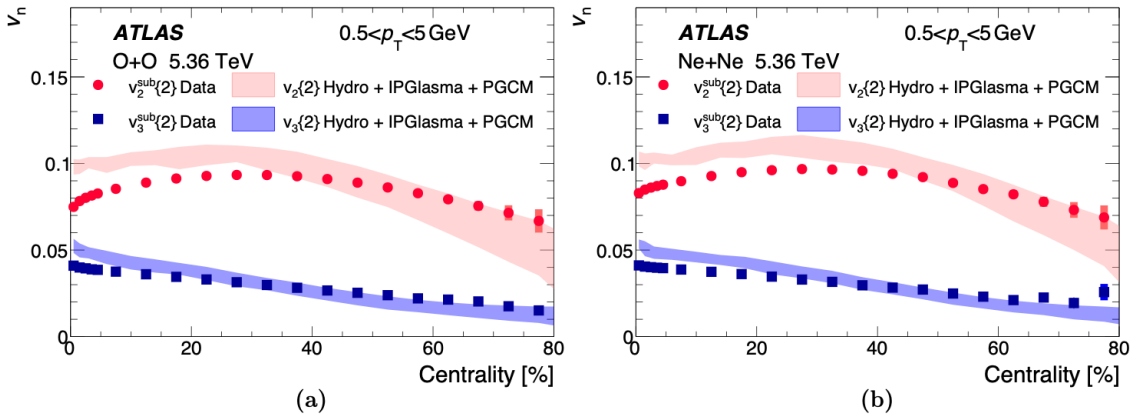
data & high-energy model & low-energy inputs



C. Zhang et al., *(In preparation)*

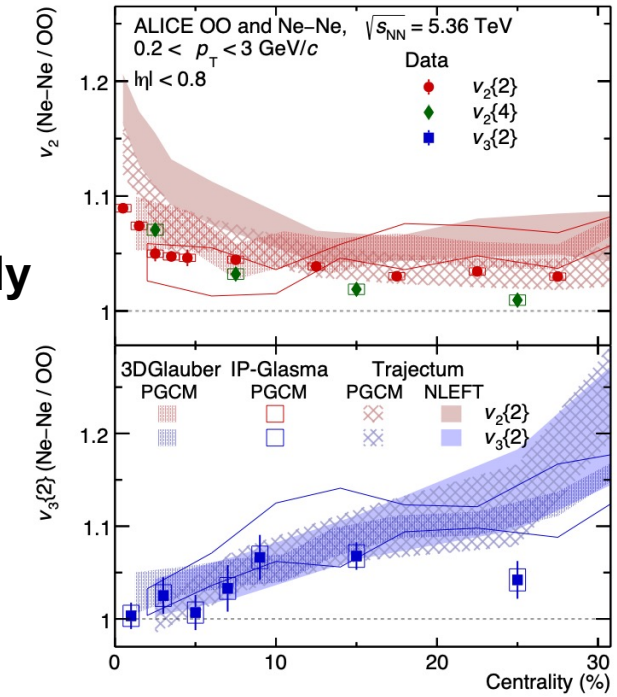
Flow ratios in ATLAS, ALICE, CMS, and LHCb results

ATLAS, *2509.05171*

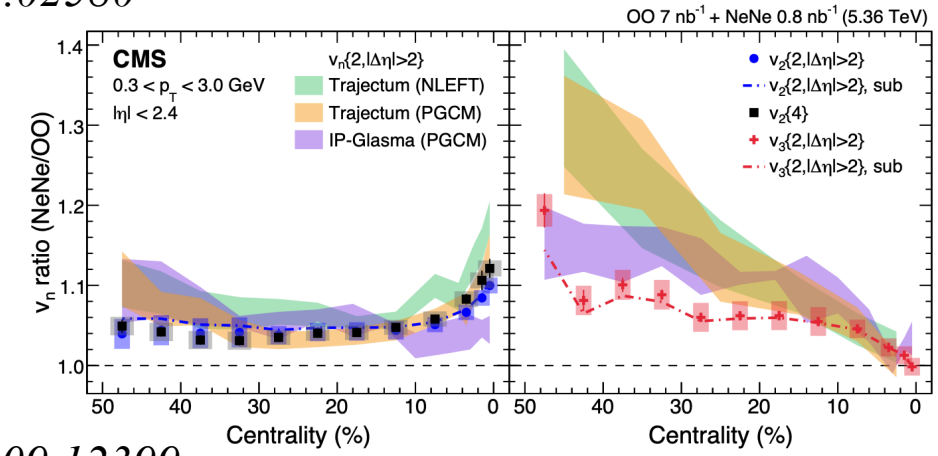


ALICE, *2509.06428*

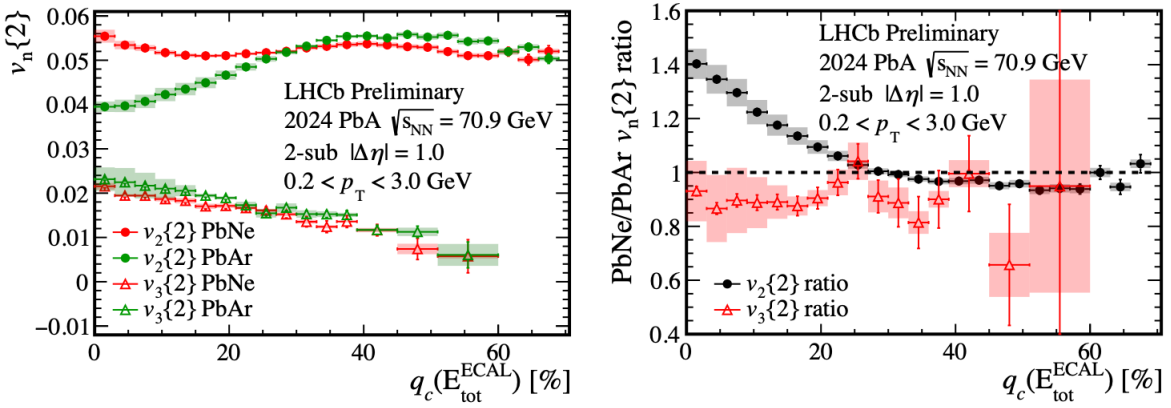
v_2 ratios (Ne/O) are largely enhanced in UCC.



CMS, *2510.02580*



LHCb, *2509.12399*



New avenue: shape imaging method for light ions

G. Giacalone, B. Bally, G. Nijs et al., *PRL 135, 012302 (2025)*

G. Giacalone, W. Zhao, C. Shen et al., *PRL 134, 082301 (2025)*

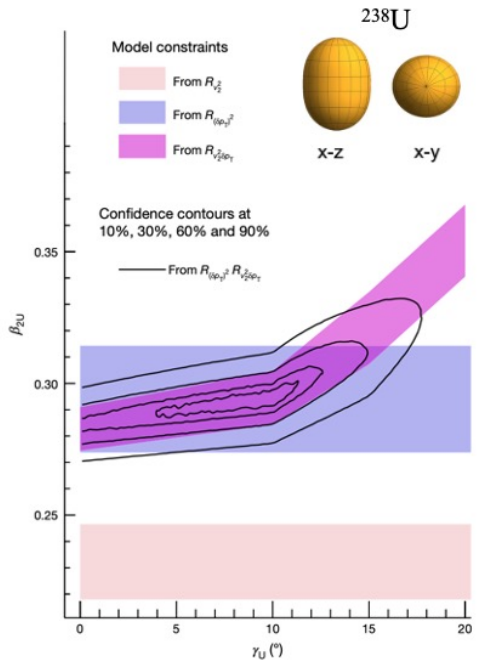
P. Li, B. Zhou, G.-L. Ma, *PRL 136, 082302 (2026)*

…

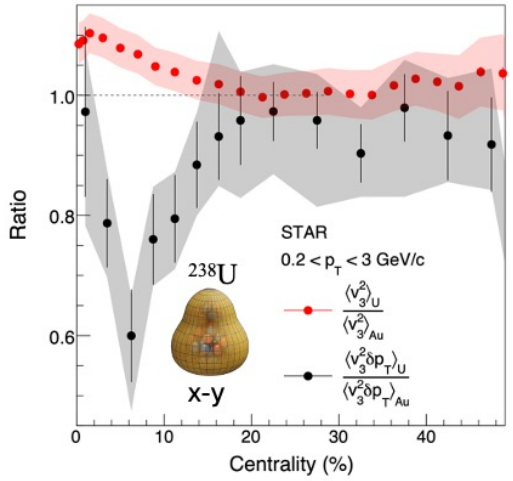
IV. Conclusions and Outlooks

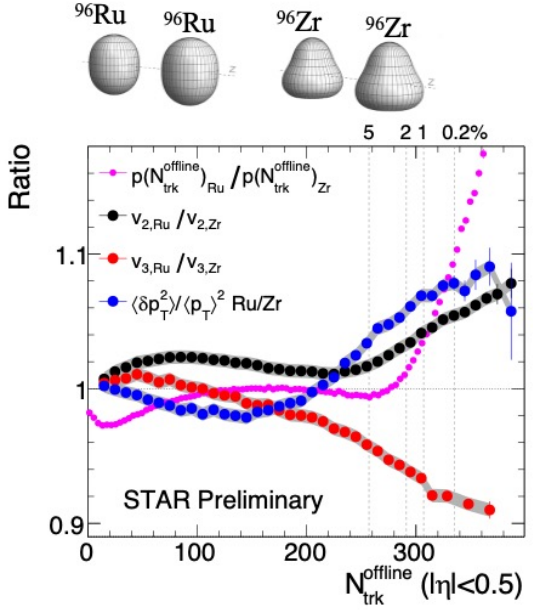
1. The signatures of nuclear structure from large to small nuclear collisions are ubiquitous:

STAR, *Nature 635, 67-72 (2024)*

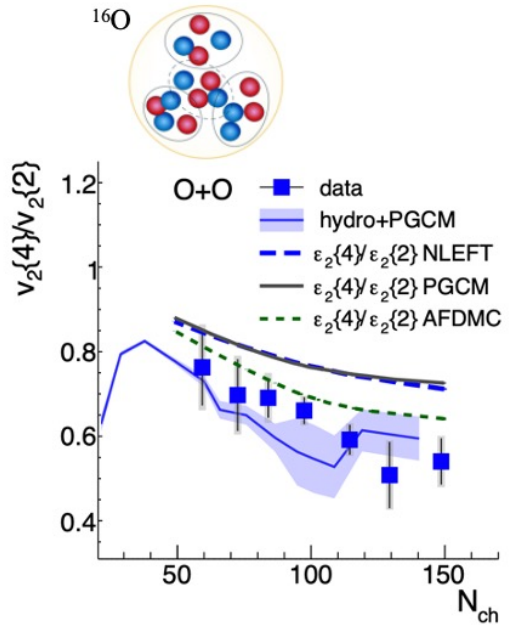


STAR, *Rep. Prog. Phys. 88, 108601 (2025)*





STAR, *2510.19645*



2. Many potential applications :

→ Rigid and soft β_n and γ (shape fluctuations/coexistence)

→ Neutron skin & symmetry energy constraints

→ Confronted with ab initio calculations and more light-ion studies

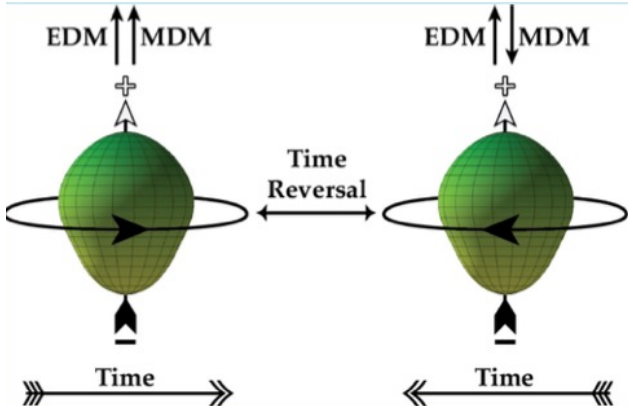
→ Intersection with Nucleosynthesis, nuclear fission, 0νββ

→ Energy evolutions in TeV-GeV facilities, LHC, HIAF, NICA, FAIR, SPS, NA61

→ Other tools, i.e. UPC, AI-assistant work

IV. Conclusions and Outlooks

1) Electric dipole moment (EDM) search



Parity and Time-reversal violating beyond SM physics
(appears in CP-violating coupling constant g).

Higher sensitivity via Schiff nuclear moments in heavy nuclei

$$S = \langle \Psi \hat{S} \Psi \rangle \propto \bar{g} Z A^{2/3} \langle \beta_2 \beta_3^2 \rangle / \Delta E$$

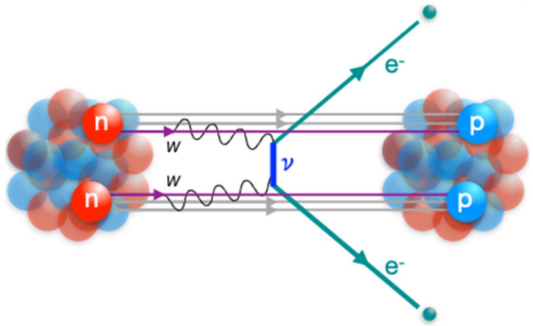
Octupole deformation enable EDM search

J. Jia, *Rep. Prog. Phys. 88, 092301 (2025)*

Heavy-ion collisions: $R_{v_3^2 \delta p_T} = a - b\langle \beta_2 \beta_3^2 \rangle$

Nature 497, 199 (2013); Rev. Mod. Phys. 91, 015001 (2019); Rep. Prog. Phys. 80, 046301 (2017); Ann. Rev. Nucl. Part. Sci. 69, 219 (2019); The 2023 Long-rang plan for nuclear physics

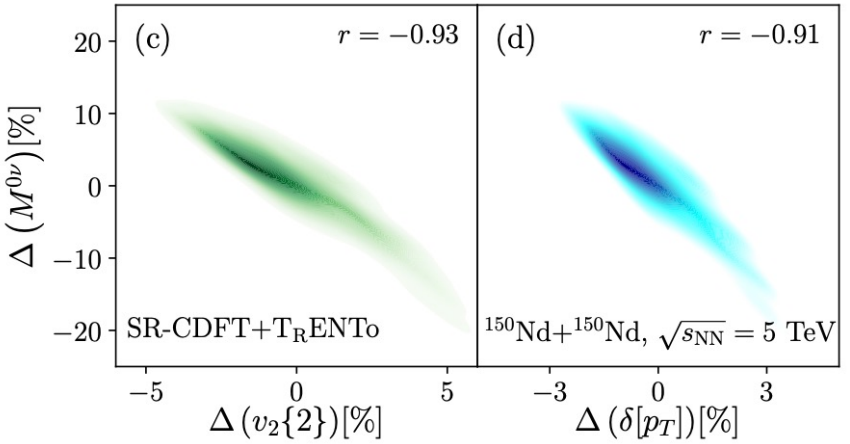
2) Neutrinoless double beta decay



Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA
	> 1.9	$< 0.24 - 0.52$	MAJORANA DEMONSTRATOR
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	NEMO-3
^{96}Zr	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3
^{100}Mo	$> 1.1 \times 10^{-1}$	$< 0.33 - 0.62$	NEMO-3
^{116}Cd	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3
^{128}Te	$> 1.1 \times 10^{-2}$	—	—
^{130}Te	> 1.5	$< 0.11 - 0.52$	CUORE
^{136}Xe	> 10.7	$< 0.061 - 0.165$	KamLAND-Zen
	> 1.8	$< 0.15 - 0.40$	EXO-200
^{150}Nd	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3

Nuclear matrix element

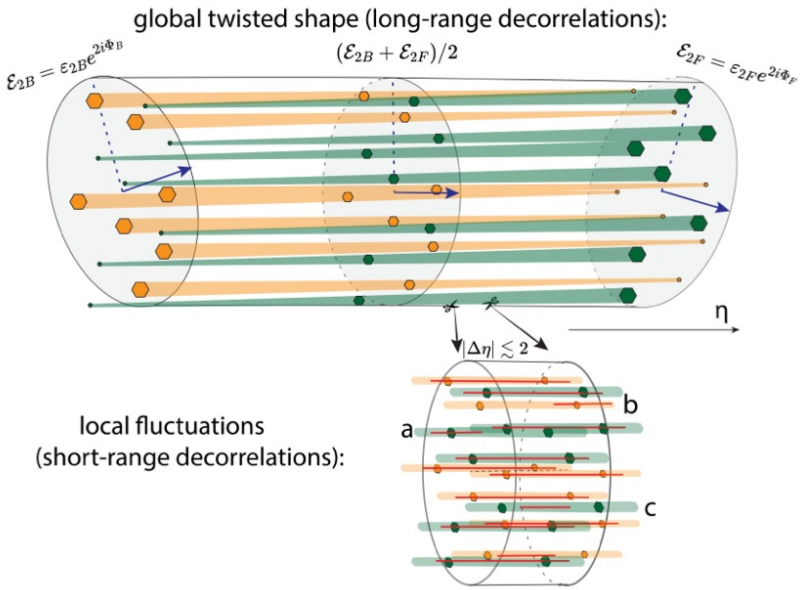
$$T^{0\nu}_{1/2} = \left(G |\mathcal{M}|^2 \langle m_{\beta\beta} \rangle^2 \right)^{-1} \simeq 10^{27-28} \left(\frac{0.01\text{eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \text{y}$$



Y. Li, X. Zhang, G. Giacalone, J. Yao, *PRL 135, 022301 (2025)*

IV. Conclusions and Outlooks

3) 3D structure and precise constraints on QGP initial conditions

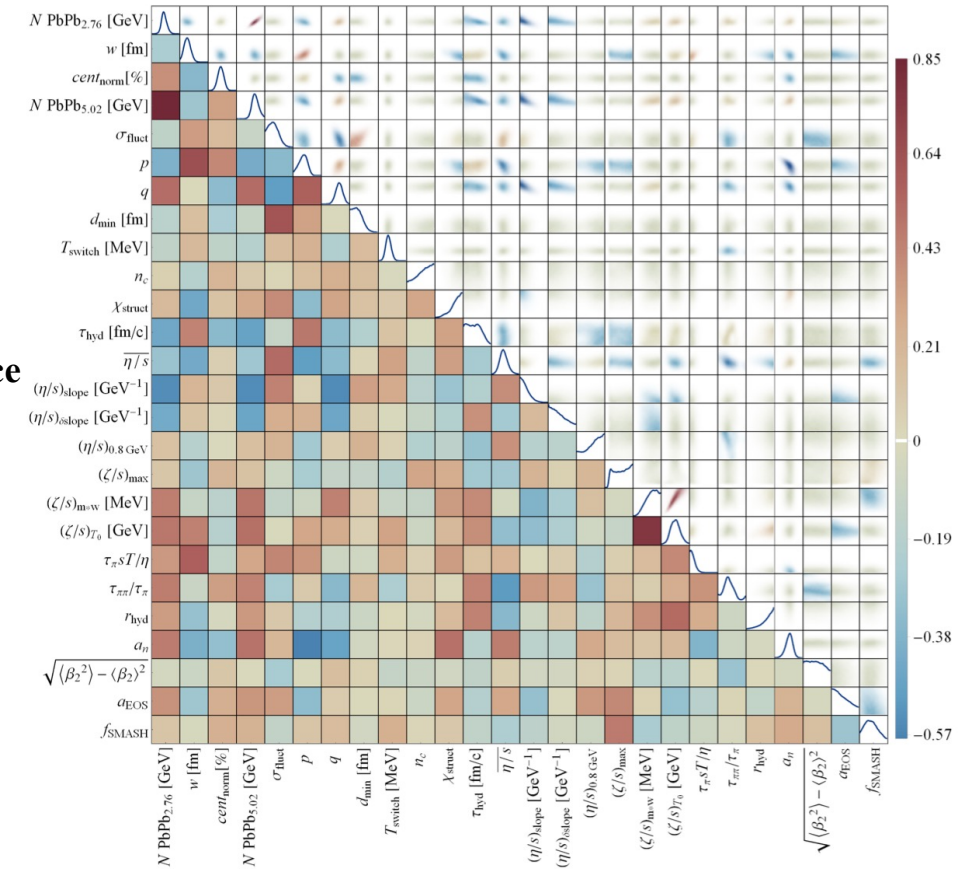


Isolate the decorrelation map of deformation-induced component:

v_n decorrelations:
C. Zhang, S. Huang, J. Jia, *2405.08749*
J. Jia, S. Huang, C. Zhang, S. Bhatta, *2408.15006*

p_T decorrelations:
L. Liu, J. Chen, X.-G. Huang, J. Jia, C. Shen, C. Zhang, *2511.11094*
J. Zhu, X.-Y. Wu, G.-Y. Qin, *2602.04148*
S. Jahan, Roch, C. Shen, *PRC 113, 024919 (2026)*
...

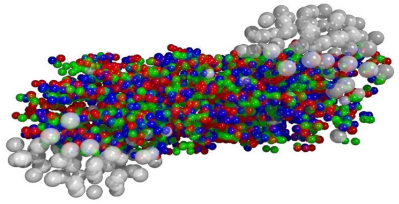
Bayesian Interference

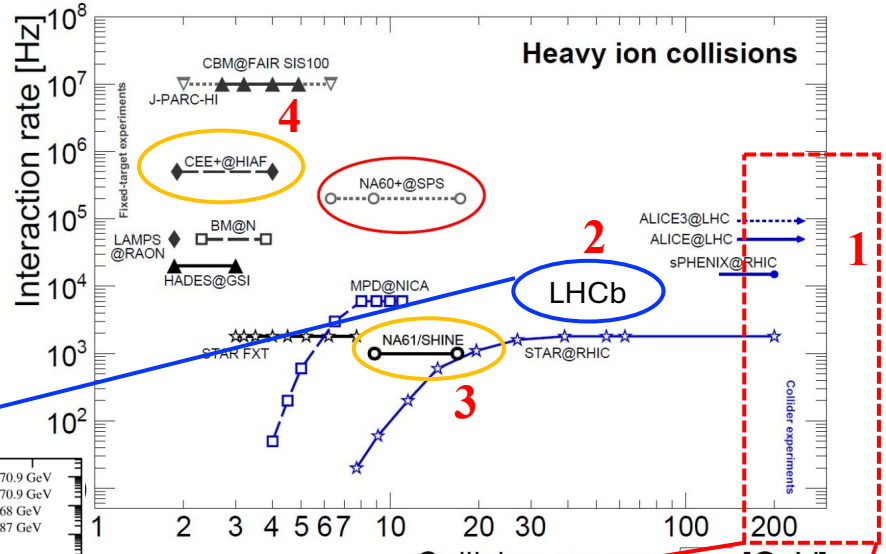


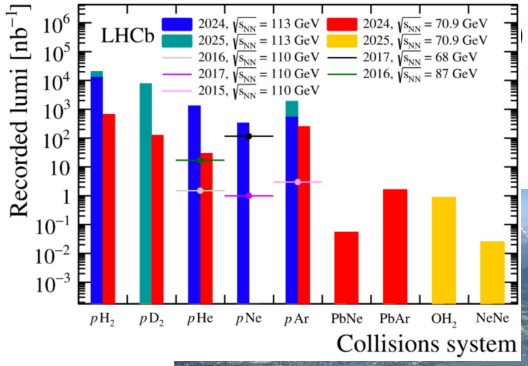
G. Giacalone, G. Nijs, W. Schee, *PRL 131, 202302 (2023)*
S. Jahan, Roch, C. Shen, *PRC 113, 024919 (2026)*
J.E. Bernhard, J.S. Moreland, S.A. Bass, *Nature Physics 15, 1113 (2019)*
D. Everett et al. (JETSCAPE), *PRL 126, 242301 (2021)*
...

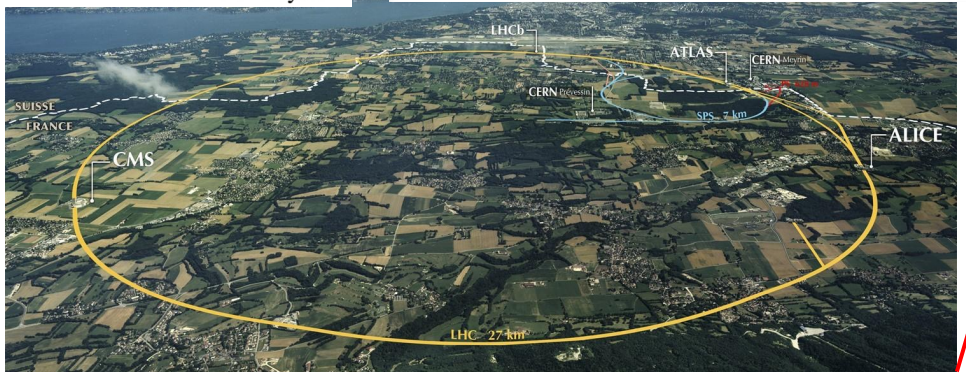
IV. Conclusions and Outlooks

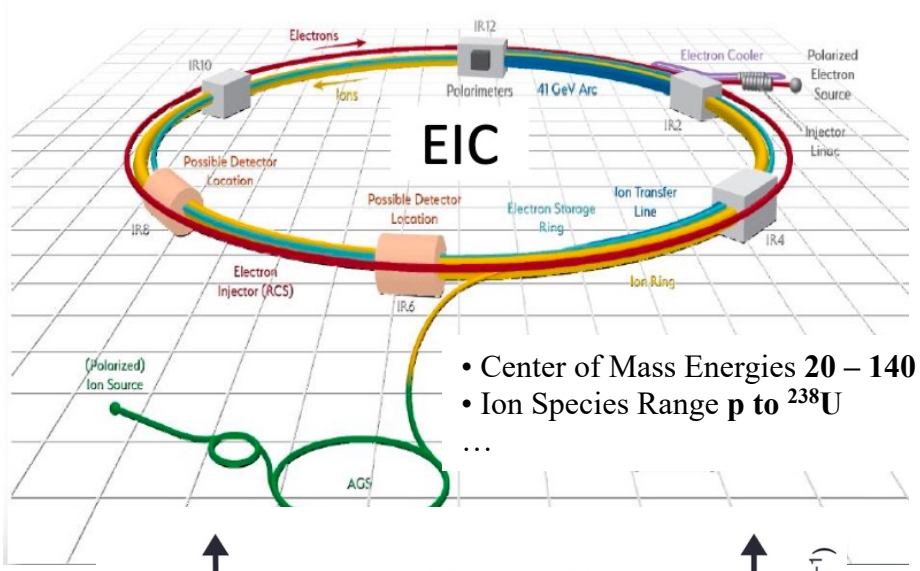
4) Energy evolution of nuclear structure, System scan, and the forward-rapidity DIS



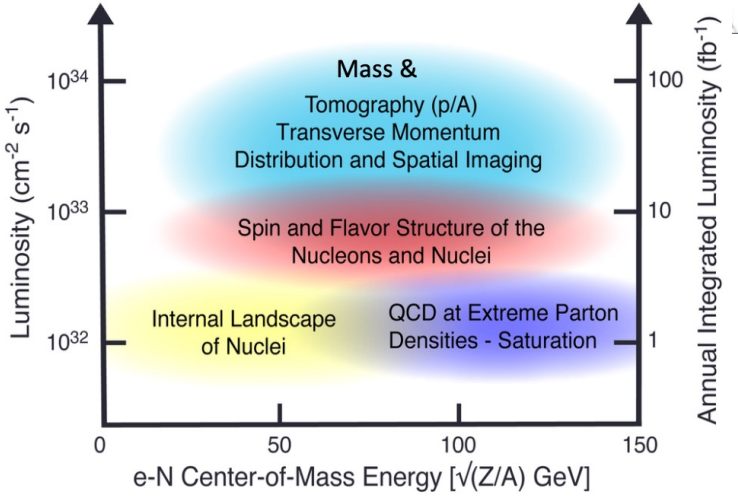








- Center of Mass Energies **20 – 140 GeV**
- Ion Species Range **p to ^{238}U**
- …



H. Mantysaari, B. Schenke, C. Shen, W. Zhao, *PRL 131, 062301 (2023)*
H. Li, L. Liu, J. Chen, Y.-G. Ma, C. Zhang, *CPL (In press)*
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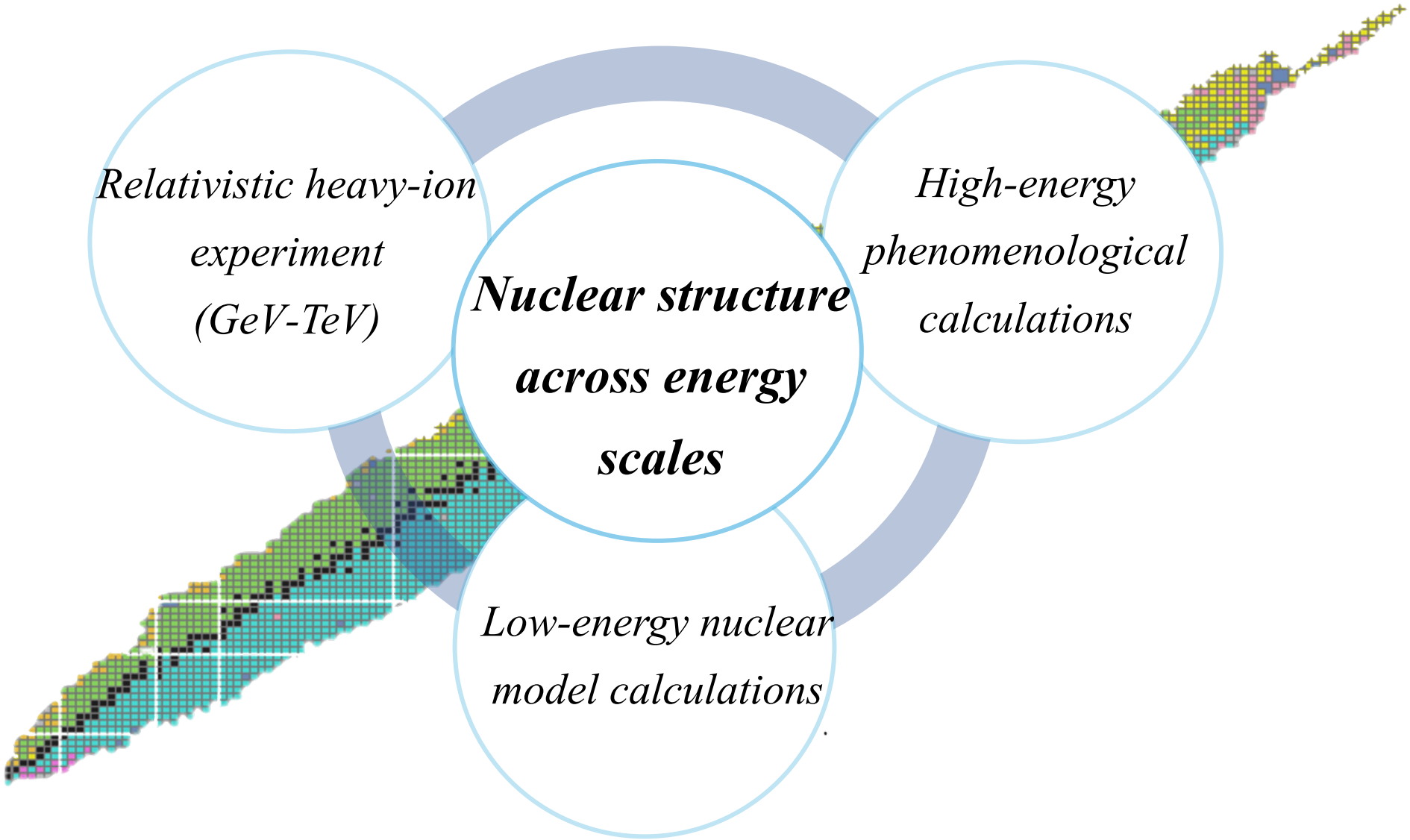
IV. Conclusions and Outlooks



Collaboration with nuclear structure and intermediate energy

Acknowledgement

Thank you