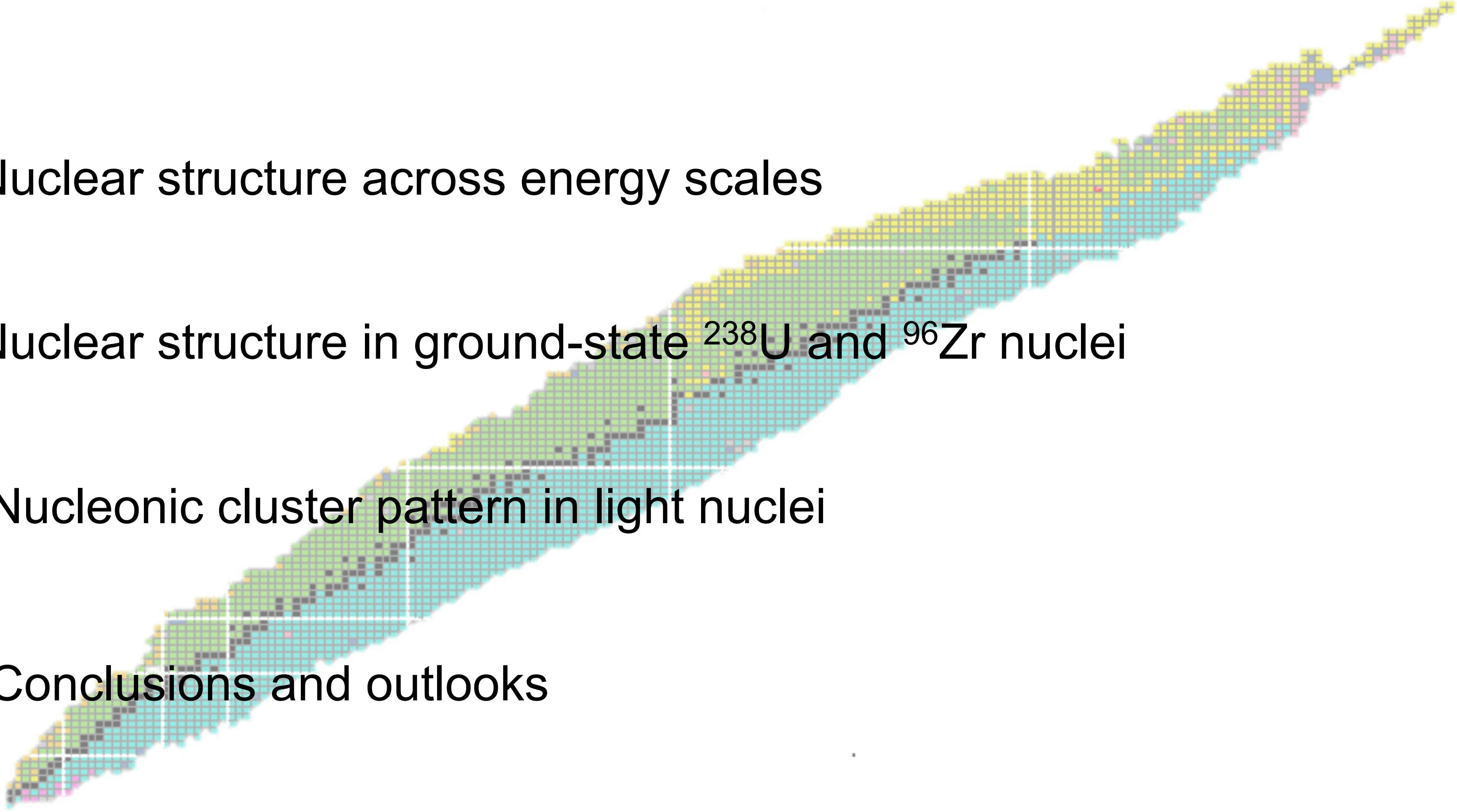
Imaging nuclear structure across energy scales: from heavy to light ions

Chunjian Zhang

Fudan University

July 17, 2026, Guangzhou

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…

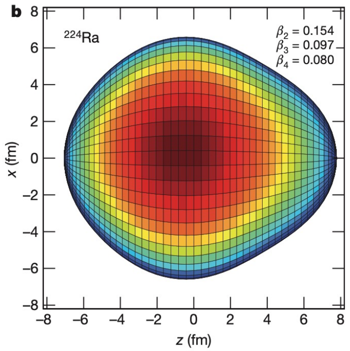
Y. Ye, X. Yang, H. Sakurai, B. Hu, *Nature Review Physics, 7, 21-37 (2025)*

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

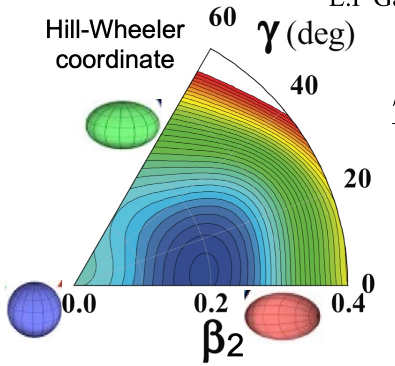
Quadrupole

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

Octupole

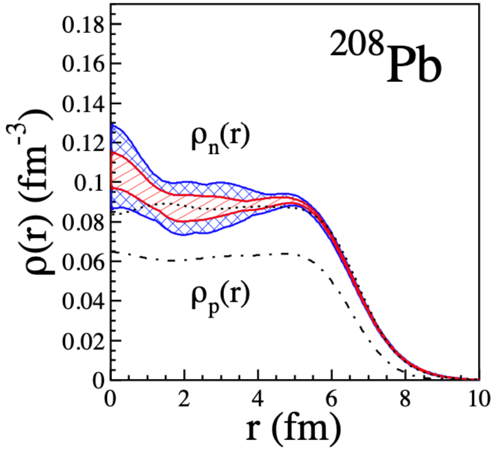


L.P Gaffney et al., *Nature 497, 199 (2013)*

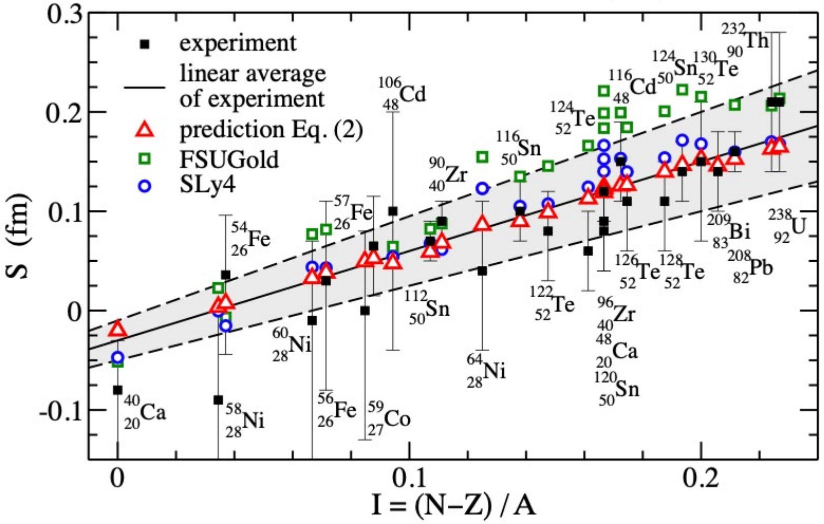


Triaxial spheroid

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



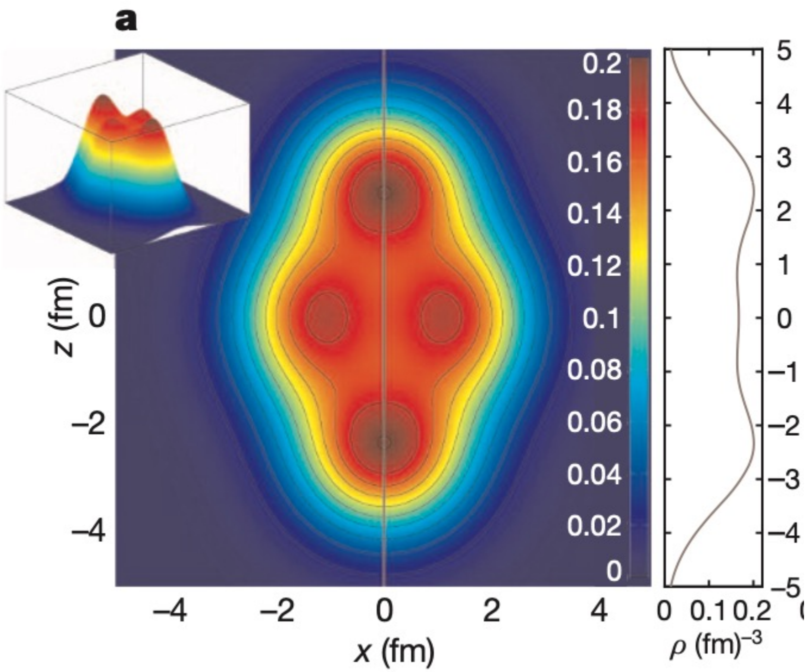
Neutron skin



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

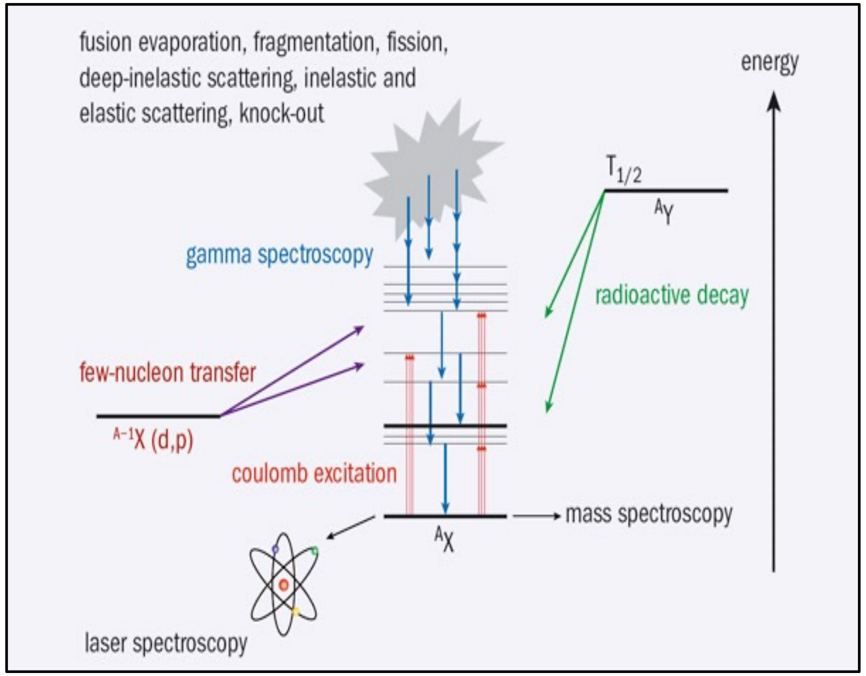
A. M. Centelles et al., *PRL 102, 122502 (2009)*

nucleonic clustering

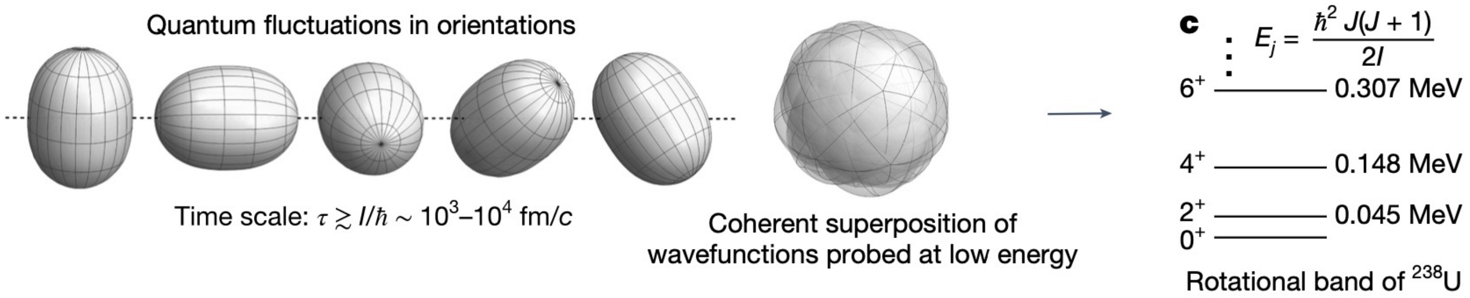


J.P. Ebran et al., *Nature 487, 341 (2012)*

Nuclear shape at low energy: long exposure

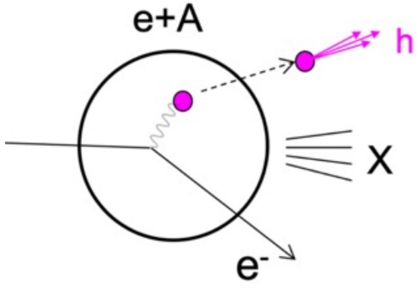


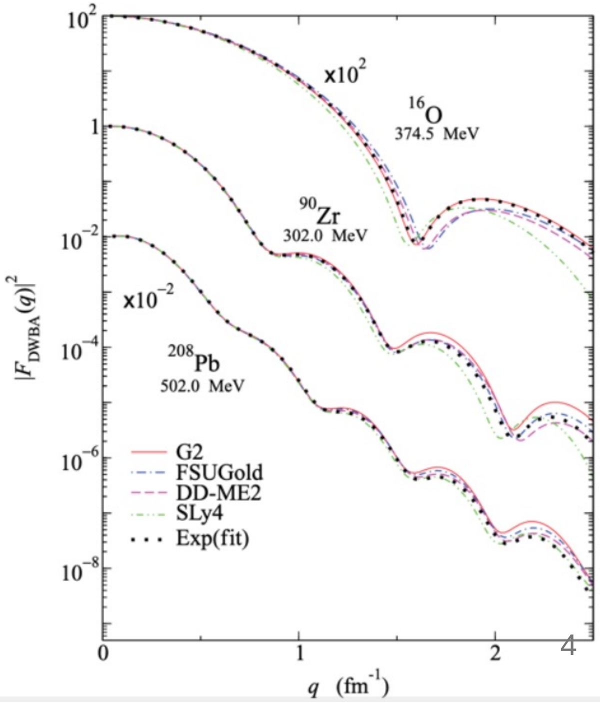
Each DOF has zero-point fluctuations within an intrinsic timescale.

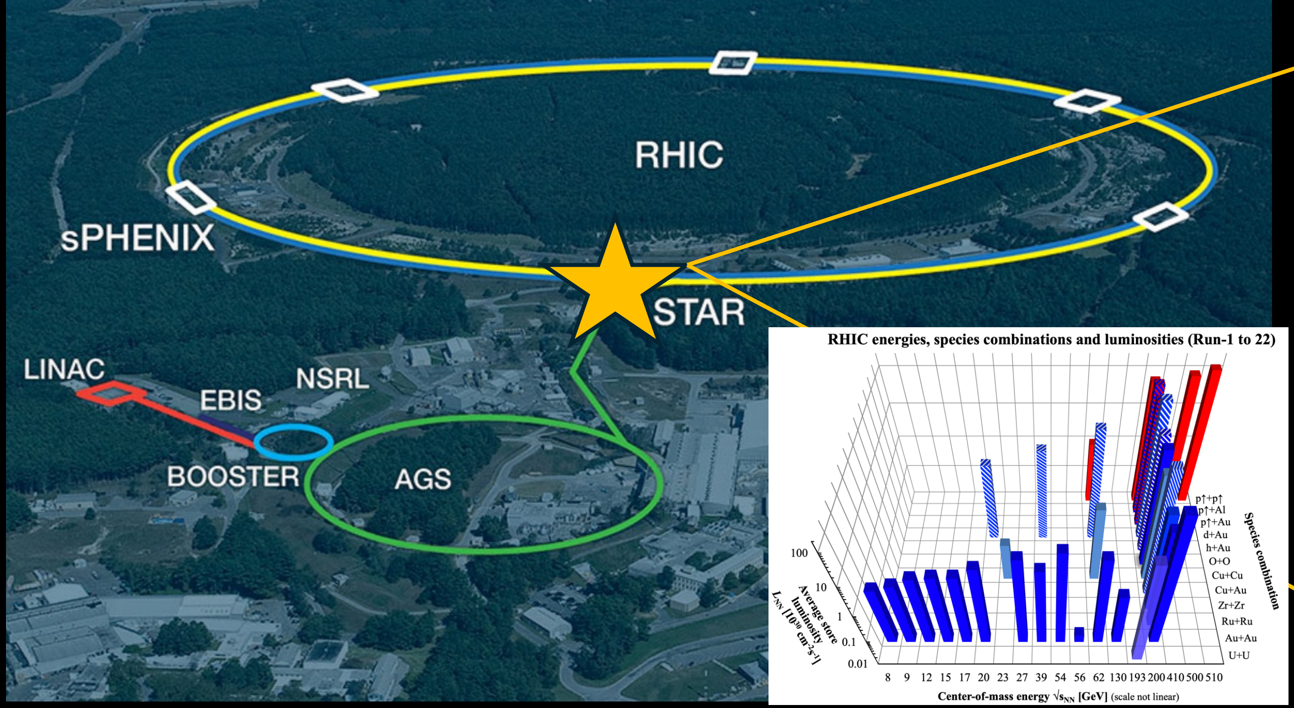


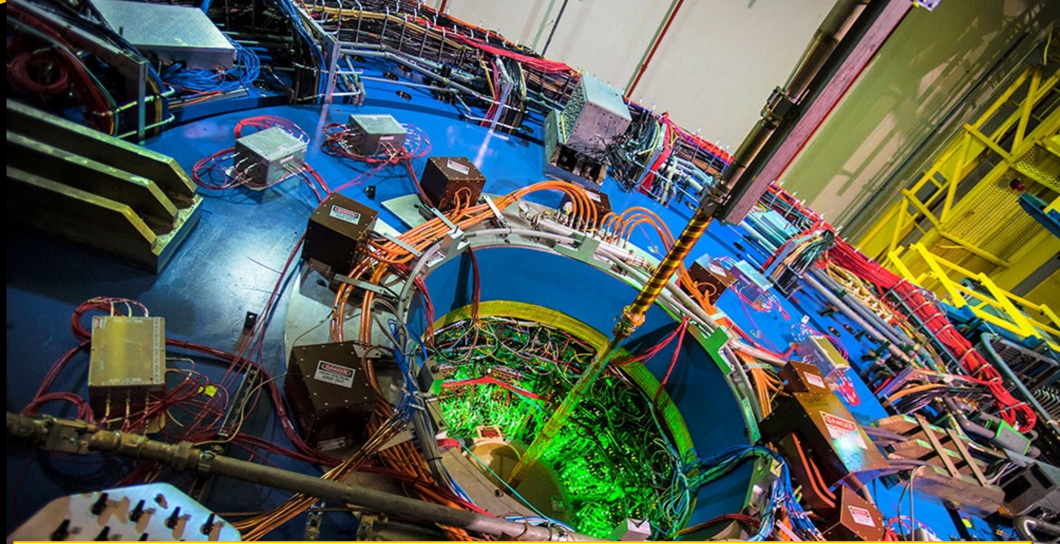
probe a superposition of these fluctuations, instantaneous shapes not directly seen

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

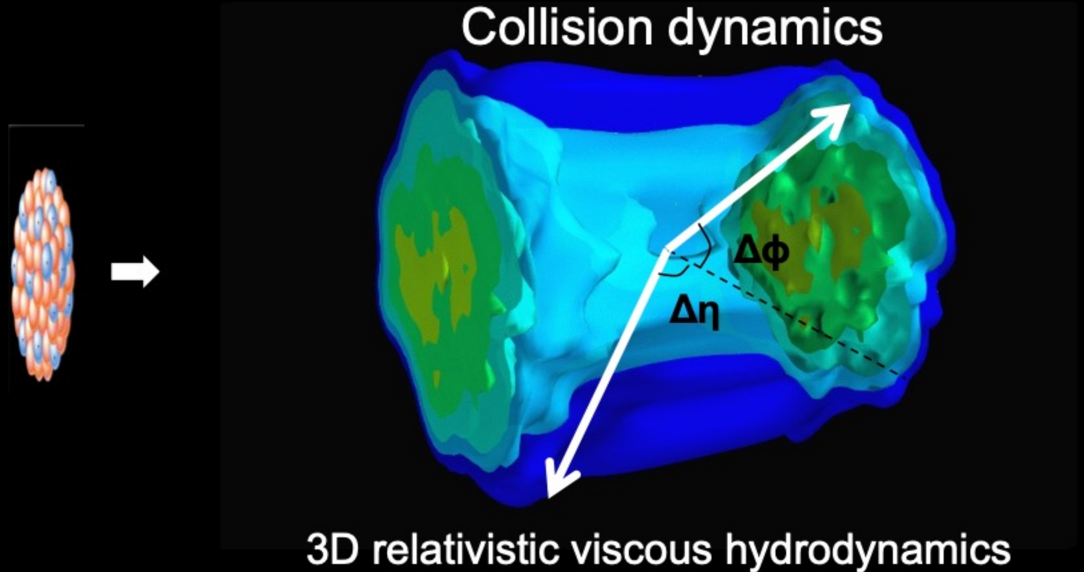








1) large, uniform acceptance at mid-rapidity
2) A vast number of emitted final state hardons
3) capability to access nuclear structures in different collisions…



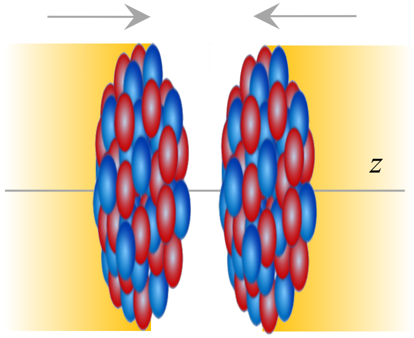
$t \sim 10 fm/c = 10^{-22}$ s

Credit: Bjoern Schenke

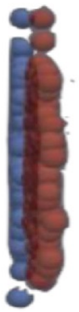
Imaging by smashing method

Take a snapshot | Evolution | Measurement

Nuclei collisions



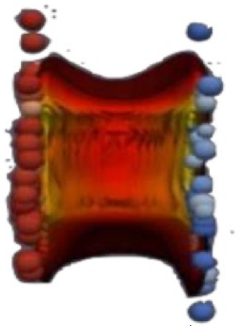
$T_{\mu\nu}(\tau = 0)$



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

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

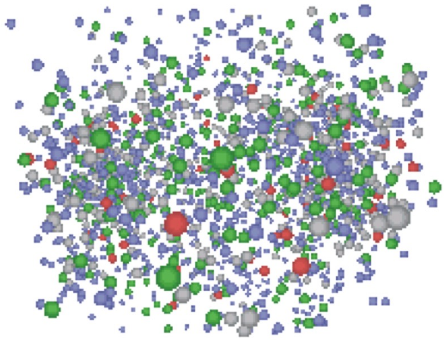
Pressure-driven expansion of
Quark-gluon plasma (QGP)



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

free-streaming

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



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

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

- $\beta_2 \longrightarrow$ quadrupole deformation
- $\beta_3 \longrightarrow$ octupole deformation
- $\gamma \longrightarrow$ triaxiality
- $a_0 \longrightarrow$ surface diffuseness
- $R_0 \longrightarrow$ nuclear size

ab initio theory/shell model/DFT

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

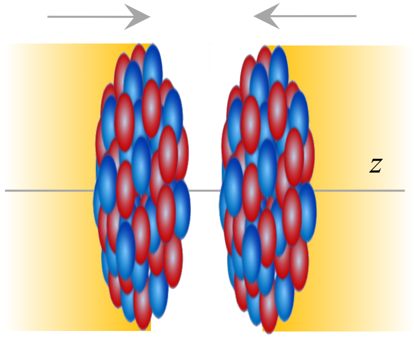
Imaging by smashing method

Take a snapshot

Evolution

Measurement

Nuclei collisions



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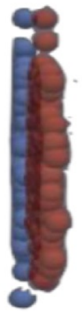

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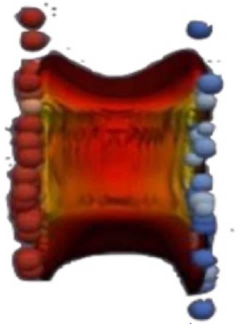

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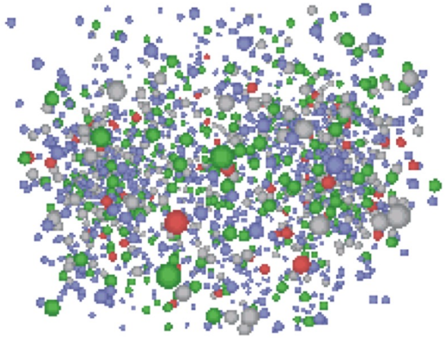

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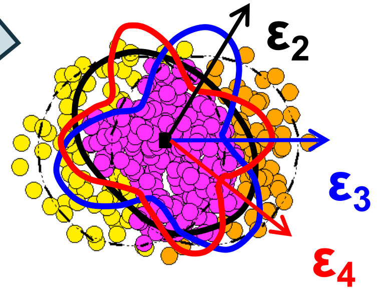


size & shape

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 $\quad$ β_n

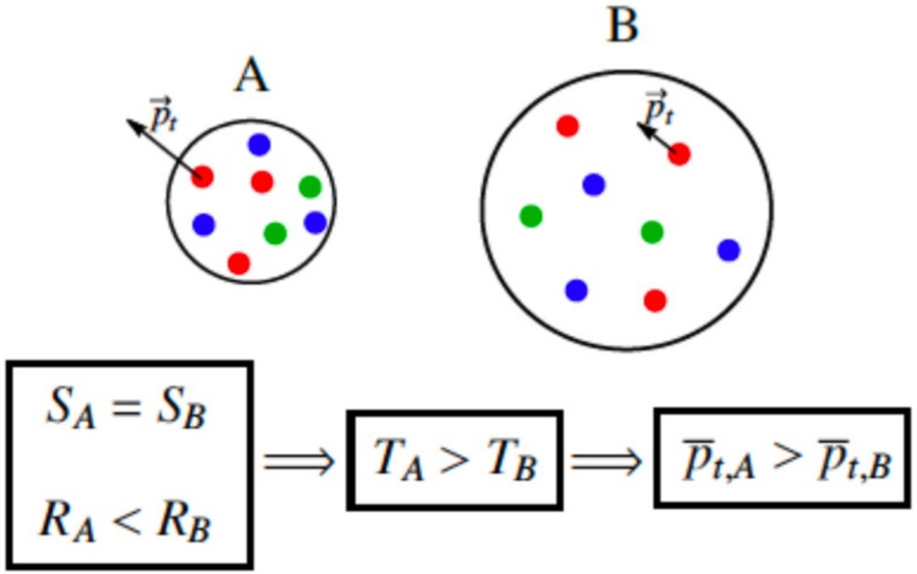
Observables $\dfrac{d^2 N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$

Event-by-event linear responses:

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

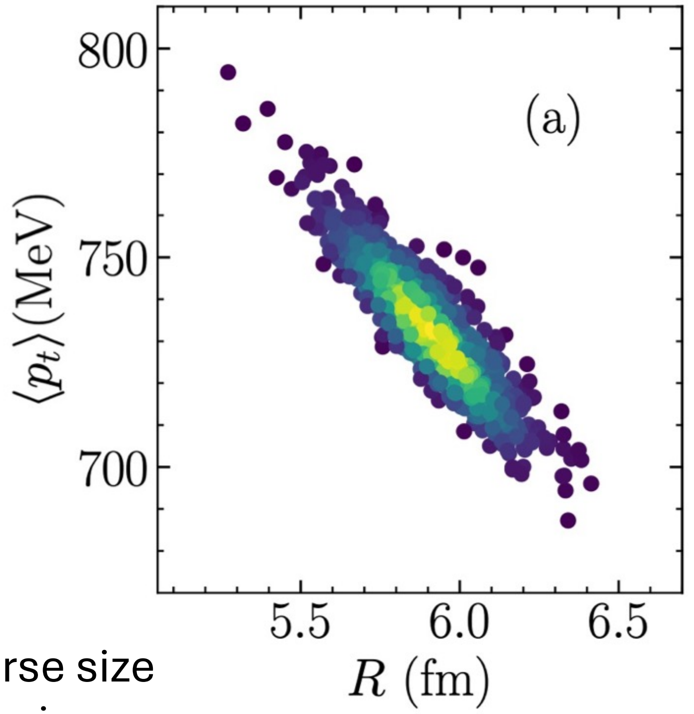
Key: 1) fast snapshot, 2) linear response, 3) large multiplicity for many-body correlation

Linear response in ultra-central collisions



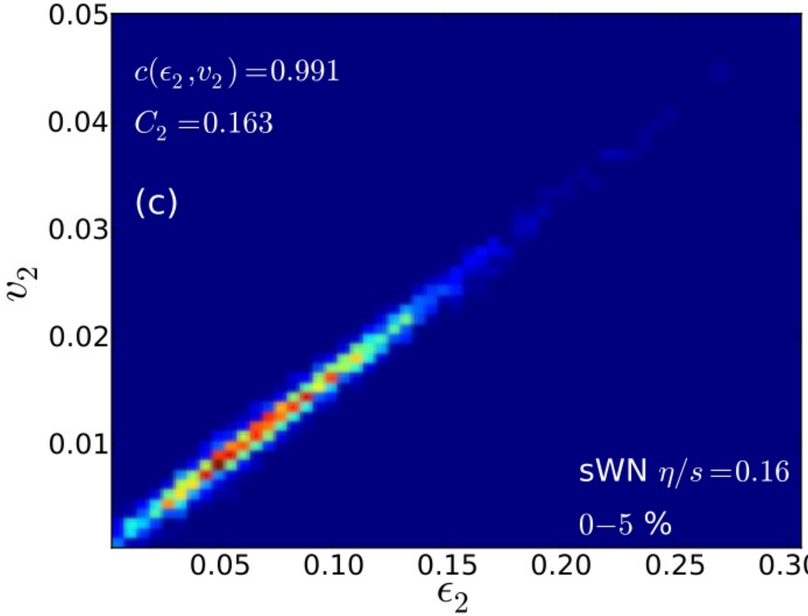
Same total energy deposition, **smaller** transverse size in the initial state creates **stronger** radial expansion.

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



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

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



$$v_n \propto \epsilon_n$$

Linear relations permit us to image colliding nuclear shapes.

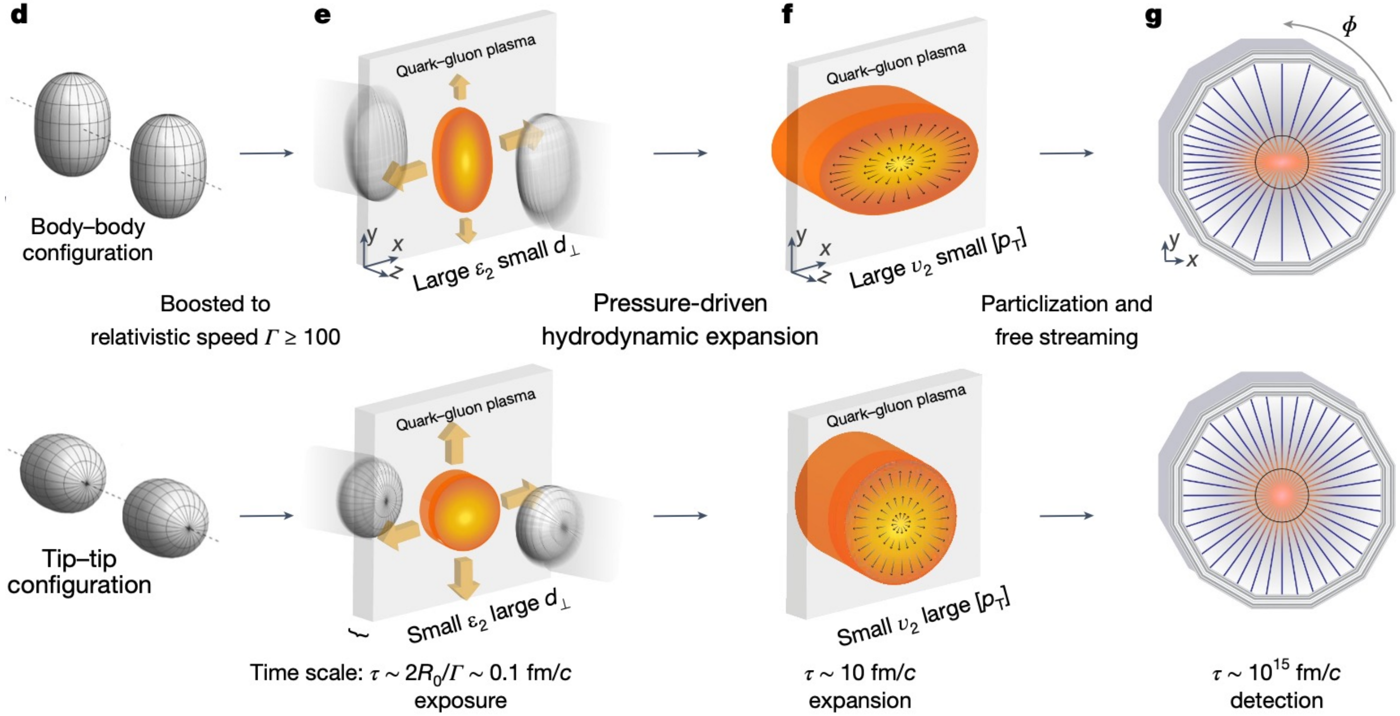
Imaging nuclear shape in high-energy snapshot

- 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

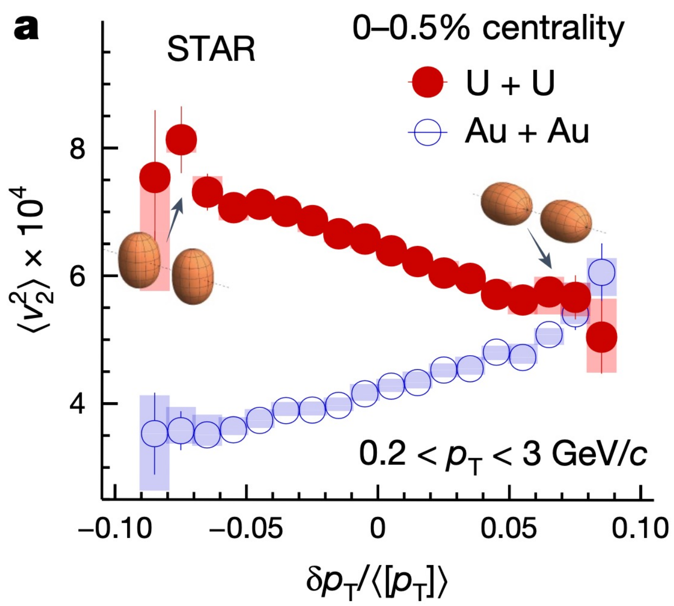
STAR, *Nature 635, 67-72 (2024)*
Nature News&Views, News, Podcast

Yoctosecond scale



$$1\text{fm}/c = 3\times10^{-24}\text{ seconds} = 3\times10^{-6}\text{ attoseconds} = 3\text{ yoctoseconds}$$

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)

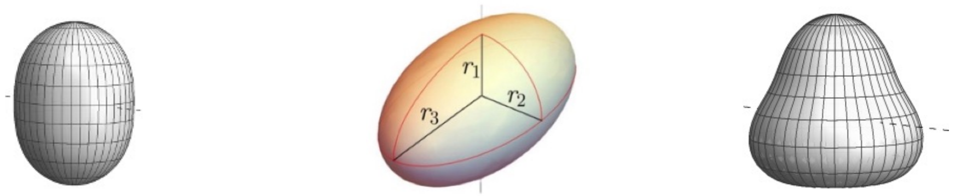
probe the entire mass distribution in the intrinsic frame via multi-point correlations

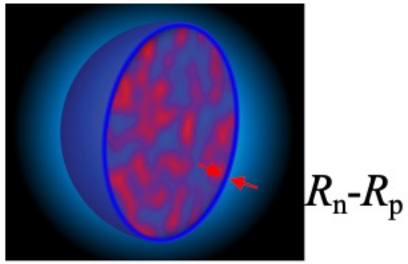
A new, complementary, and independent of low-energy experiments

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 $\boxed{\beta_{2\mathrm{U}} \approx 0.28 \rightarrow \beta_{2\mathrm{U,WS}} \approx 0.25}$

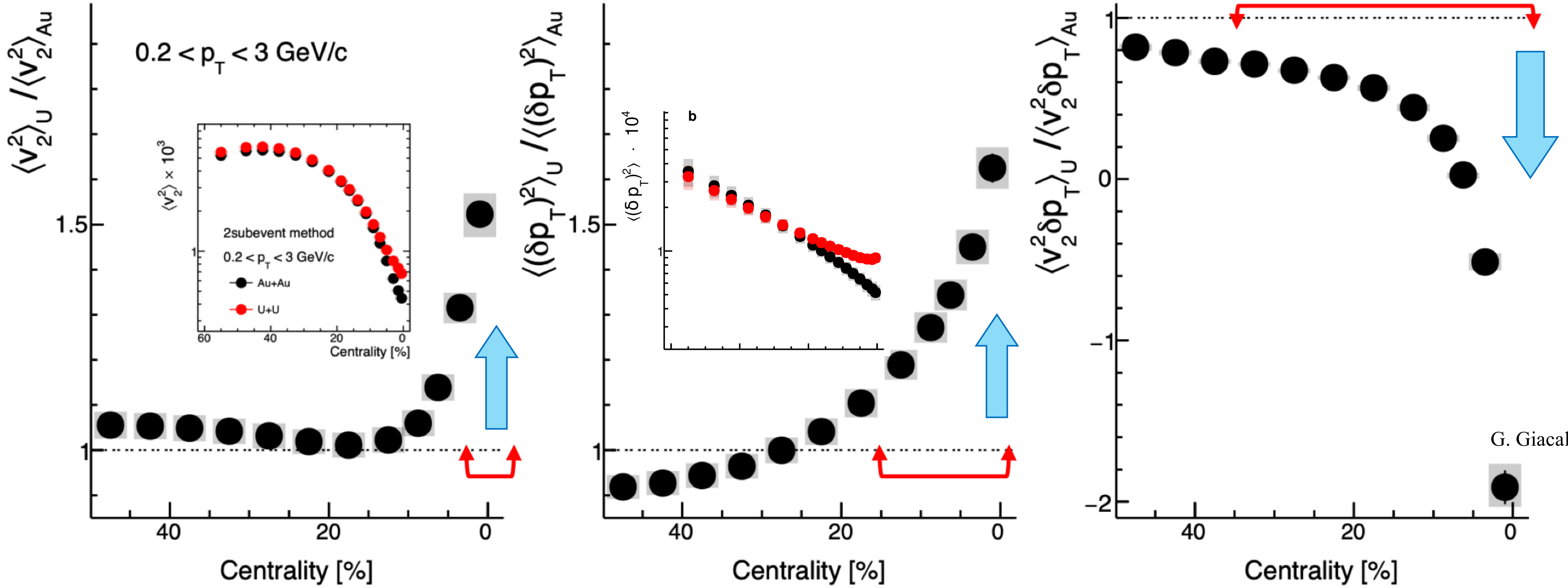
corresponding to a larger volume deformation in presence of $\boldsymbol{\beta}_{4\mathrm{U}}$~0.1 $\beta_{2,\mathrm{body}} = \frac{4\pi}{3R_0^2 A}\int d^3r\rho(\mathbf{r})r^2 Y_{20}$

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

$$\boxed{\begin{array}{c} \beta_{2\mathrm{U,LD}} = 0.287 \pm 0.007 \quad \gamma_{\mathrm{U,LD}} = 6^\circ - 8^\circ \\ \boldsymbol{\beta}_{3\mathrm{U}} \sim \boldsymbol{\beta}_{4\mathrm{U}} \sim 0.1 \end{array}}$$

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

Ratio of multipole observables



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

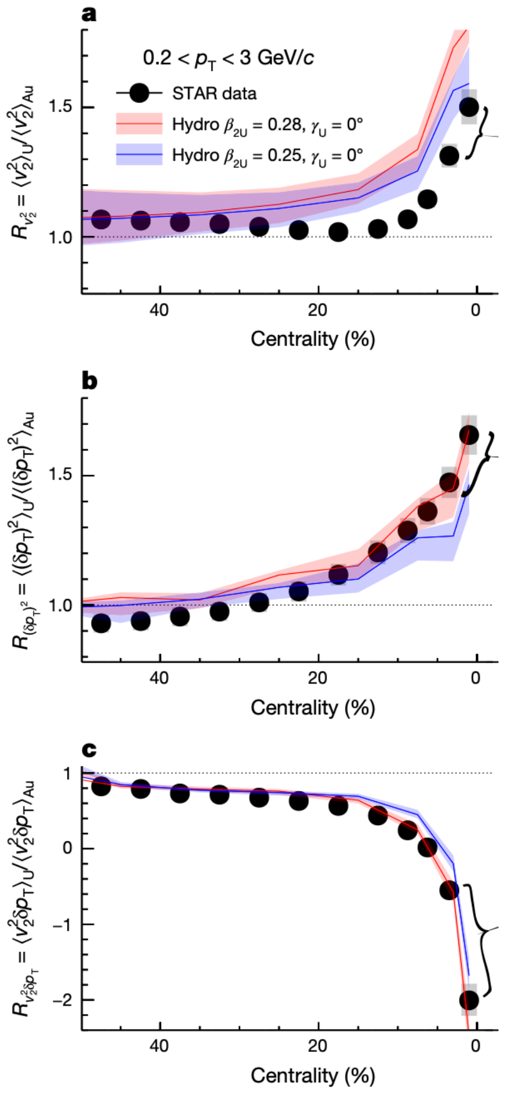
G. Giacalone, J. Jia, C. Zhang, *PRL 127, 242301 (2021)*

- 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



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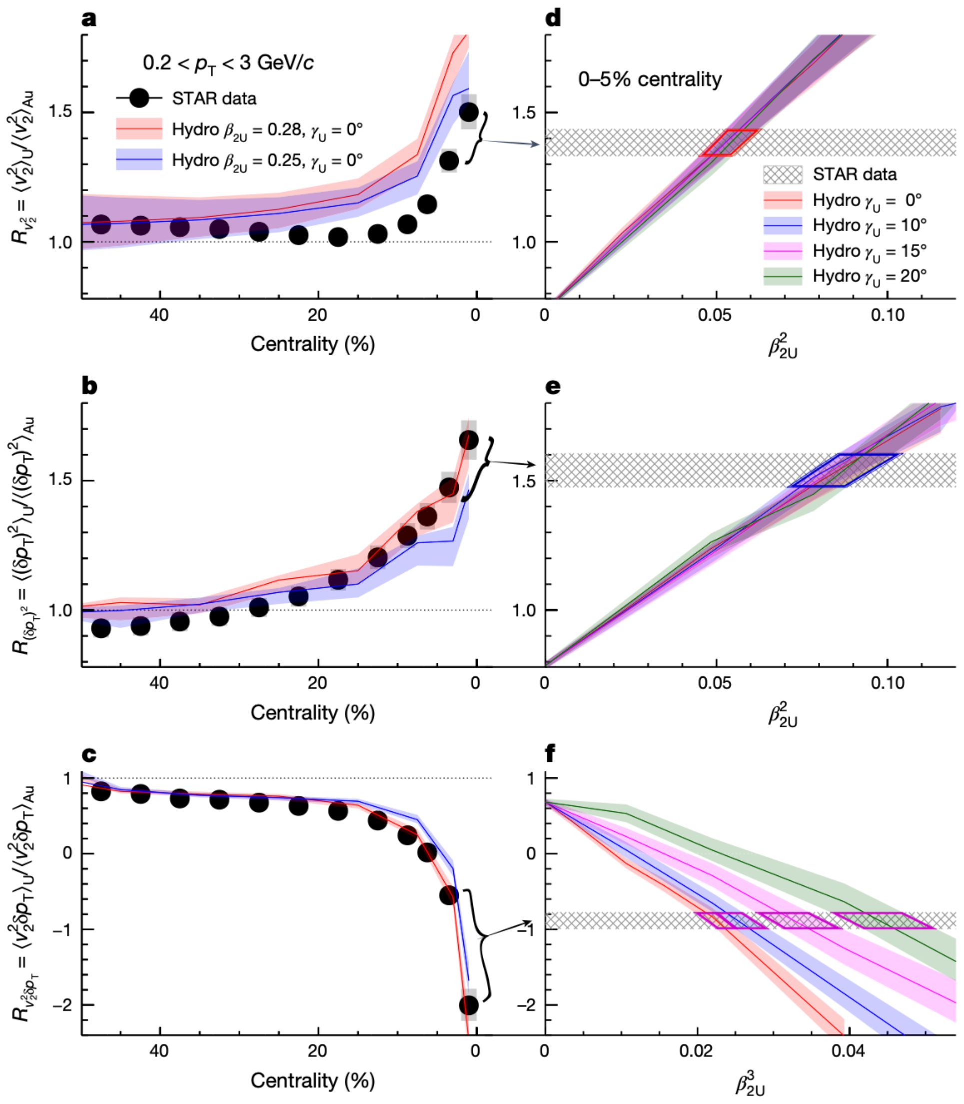

Sufficient precision is achieved from ratios in ultra-central collisions

Relation also confirmed from hydro

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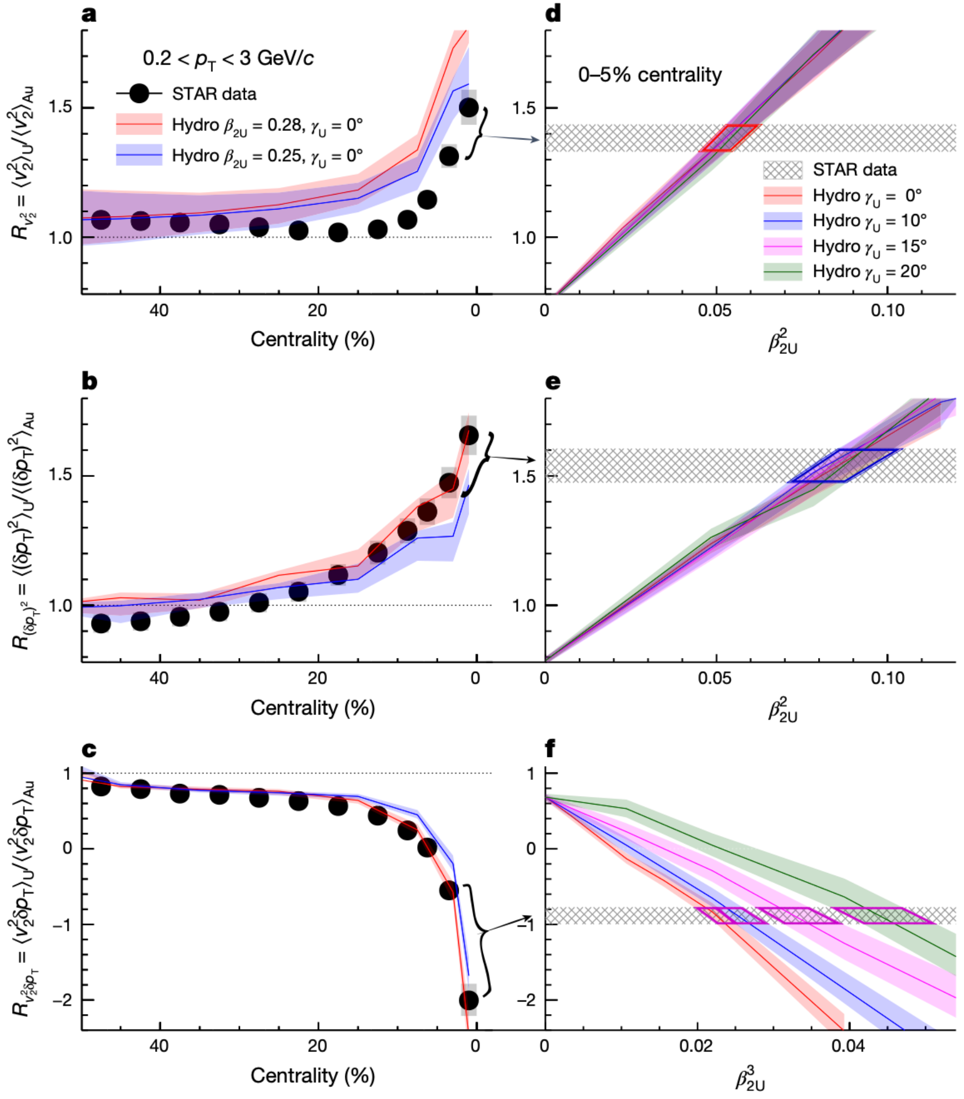
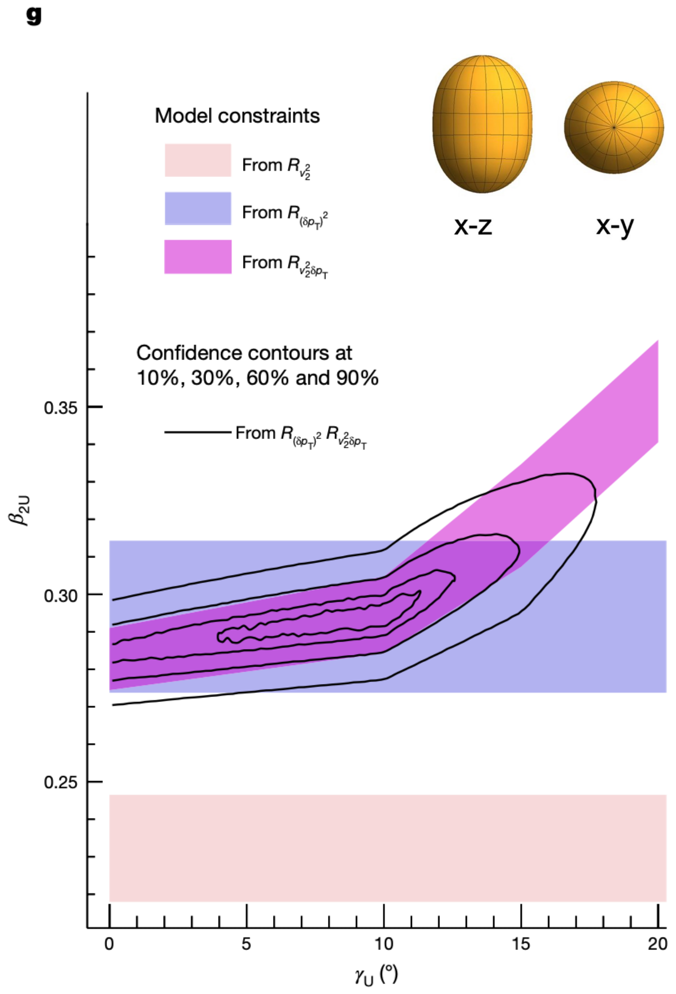
Constraining the ground-state ^{238}U: $\beta_{2,\mathrm{U}}$ and γ_{U}





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High-energy estimate

(*IP-Glasma+MUSIC* and *Trajectum*)

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

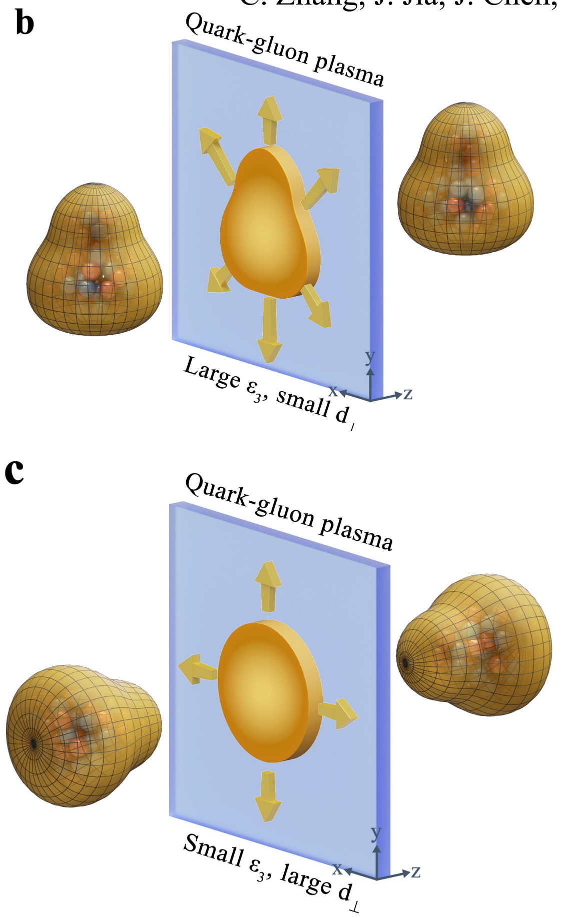
low-energy estimate:

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

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

Evidence of octupole deformation $\boldsymbol{\beta}_{3,\mathrm{U}}$

C. Zhang, J. Jia, J. Chen, C. Shen, L. Liu, *Phys. Rev. Research 8, 033018 (2026)*



However, v_3 is fluctuation driven, expect in central

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

mass number

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

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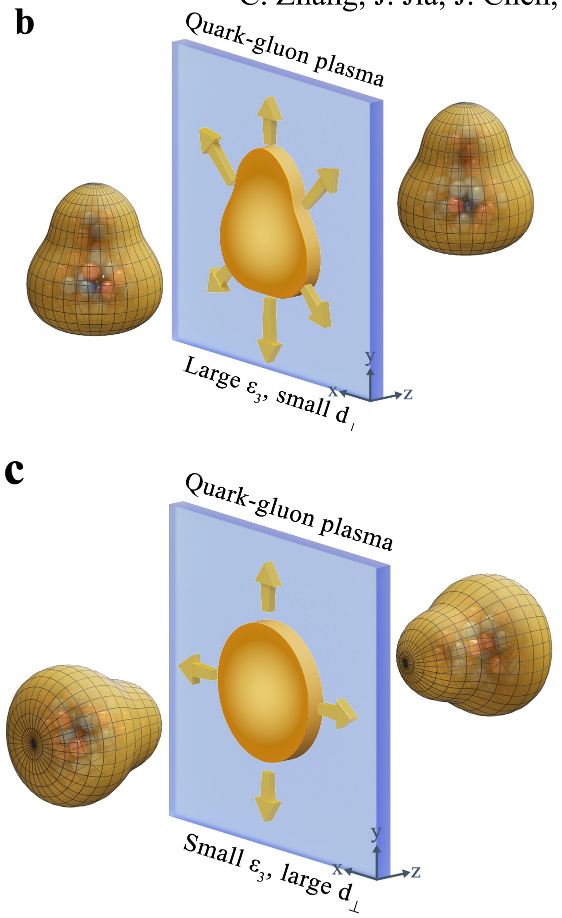
C. Zhang, J. Jia, J. Chen, C. Shen, L. Liu, *Phys. Rev. Research 8, 033018 (2026)*

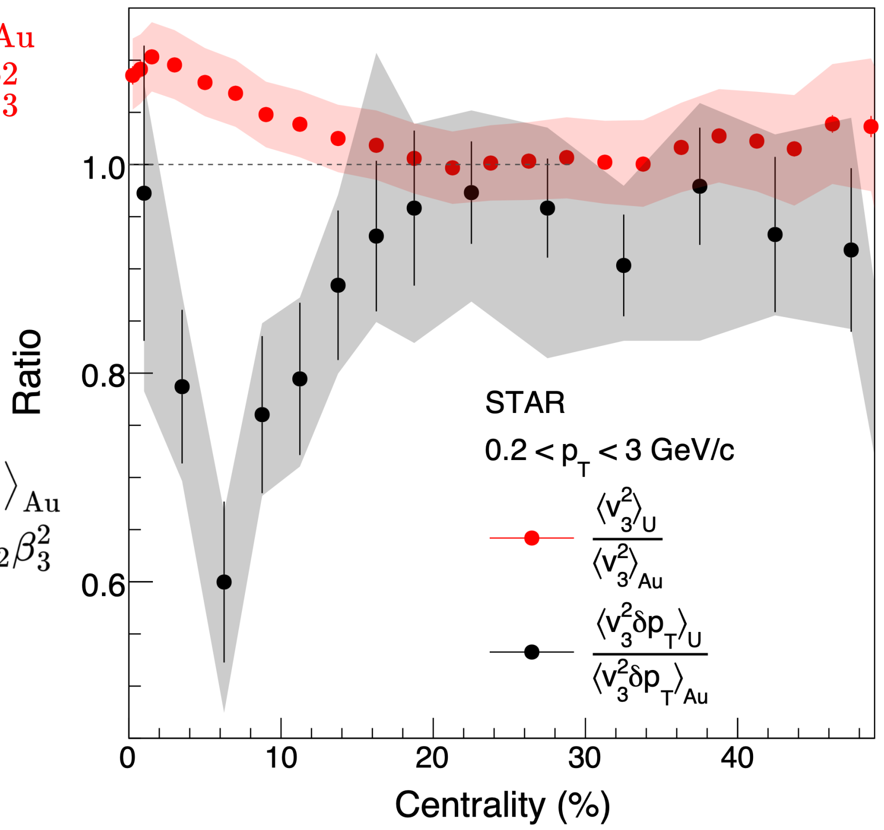


$$\langle v_3^2\rangle_{\mathrm{U}} > \langle v_3^2\rangle_{\mathrm{Au}}$$
$$R_{v_3^2} = a + b\beta_3^2$$

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

$$R_{v_3^2} = \frac{\langle v_3^2\rangle_{\mathrm{U+U}}}{\langle v_3^2\rangle_{\mathrm{Au+Au}}} \approx \frac{a_{3\mathrm{U}}}{a_{3\mathrm{Au}}} + \frac{b_{3,3}}{a_{3\mathrm{Au}}}\beta_3^2 + \frac{b_{3,4}}{a_{3\mathrm{Au}}}\beta_4^2,$$
$$R_{v_3^2\delta p_{\mathrm{T}}} = \frac{\langle v_3^2\delta p_{\mathrm{T}}\rangle_{\mathrm{U+U}}}{\langle v_3^2\delta p_{\mathrm{T}}\rangle_{\mathrm{Au+Au}}} \approx a - b\beta_2\beta_3^2.$$

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



However, v_3 is fluctuation driven, expect in central

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

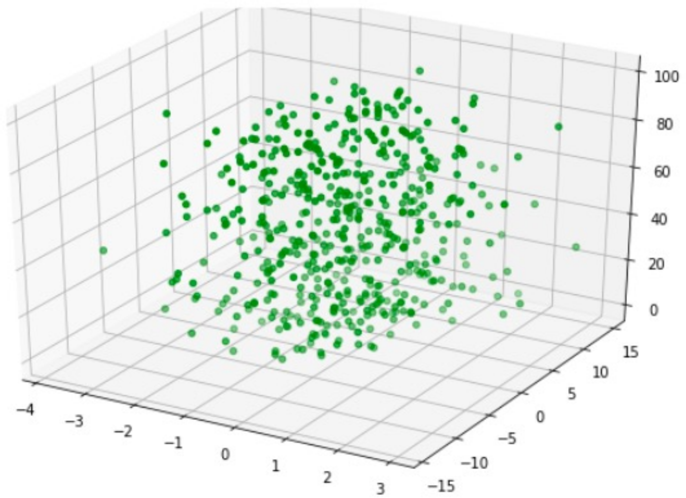
mass number

- 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)*

Mean transverse momentum ($[p_T]$) fluctuations

$$f\left(p_{x1}, p_{y1}, p_{z1}, p_{x2}, p_{y2}, p_{z2}\ldots\right)$$



Event-by-event temperature fluctuations

J. Jia, S. Huang, C. Zhang, *PRC 105 , 014906 (2022)*
S. Bhatta, C. Zhang, J. Jia, *PRC106, L031901 (2022)*
C. Zhang, A. Behera, S. Bhatta, J. Jia, *PLB 822, 136702 (2021)*

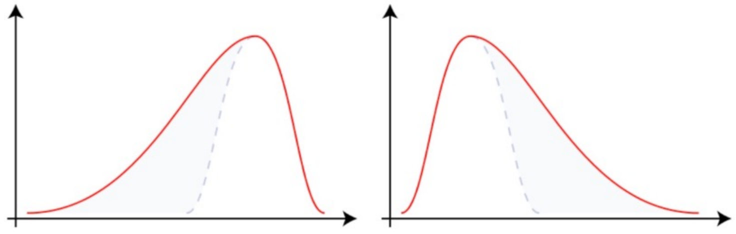
Mean: $$\langle\langle p_{\mathrm{t}}\rangle\rangle=\frac{\sum_{k=1}^{N_{\text{events}}}\langle p_{\mathrm{t}}\rangle_k}{N_{\text{events}}}$$ where $$\langle p_{\mathrm{t}}\rangle_k=\frac{\sum_{i=1}^{N_k} p_{\mathrm{t},i}}{N_k}$$

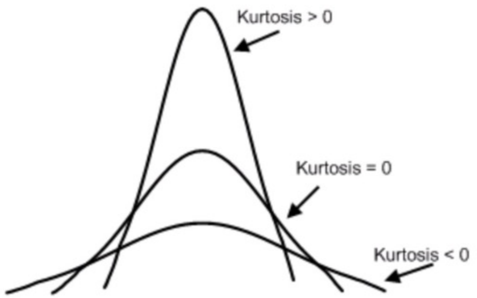
Variance: $$\left\langle\left(\delta p_T\right)^2\right\rangle=\frac{\sum_i\sum_{j\neq i}\omega_i\omega_j\left(p_{T,i}-\langle[p_T]\rangle\right)\left(p_{T,j}-\langle[p_T]\rangle\right)}{\sum_i\sum_{j\neq i}\omega_i\omega_j},$$

Skewness: $$\left\langle\left(\delta p_T\right)^3\right\rangle=\frac{\sum_{i,j\neq i,k\neq j\neq i}\omega_i\omega_j\omega_k\left(p_{T,i}-\langle[p_T]\rangle\right)\left(p_{T,j}-\langle[p_T]\rangle\right)\left(\left(p_{T,k}-\langle[p_T]\rangle\right)\right.}{\sum_{i,j\neq i,k\neq j\neq i}\omega_i\omega_j\omega_k},$$

Kurtosis: $$\left\langle\left(\delta p_T\right)^4\right\rangle=\frac{\sum_{i,j\neq i,k\neq j\neq i,l\neq k\neq j\neq i}\omega_i\omega_j\omega_k\omega_l\left(p_{T,i}-\langle[p_T]\rangle\right)\left(p_{T,j}-\langle[p_T]\rangle\right)\left(\left(p_{T,k}-\langle[p_T]\rangle\right)\right)\left(p_{T,l}-\langle[p_T]\rangle\right)}{\sum_{i,j\neq i,k\neq j\neq i,l\neq k\neq j\neq i}\omega_i\omega_j\omega_k\omega_l}$$

Related to the entropy of the initial source presumably deposited early
in the collision before thermalization and interactions with QGP

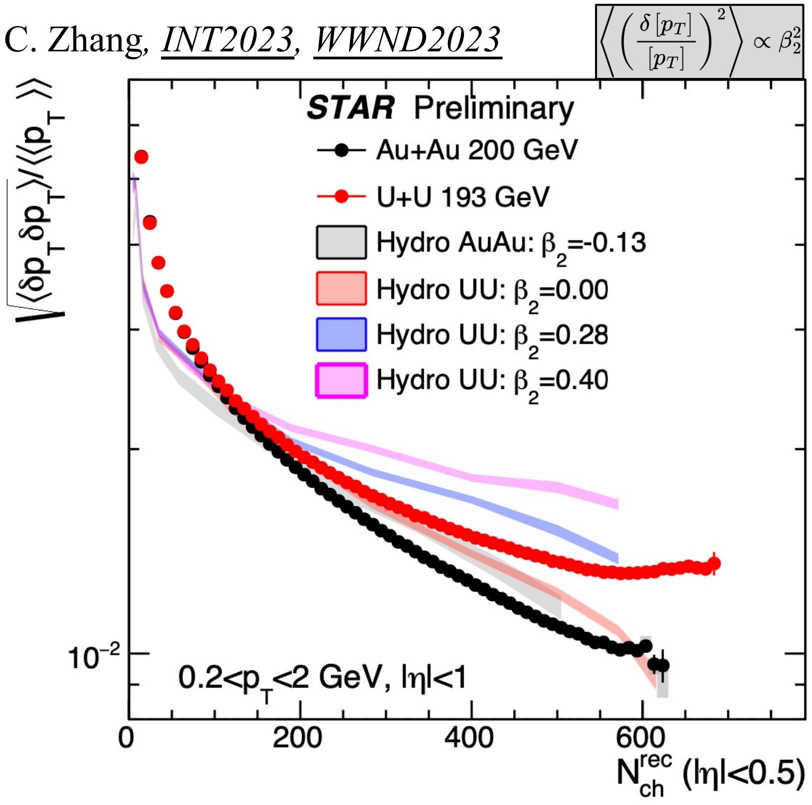


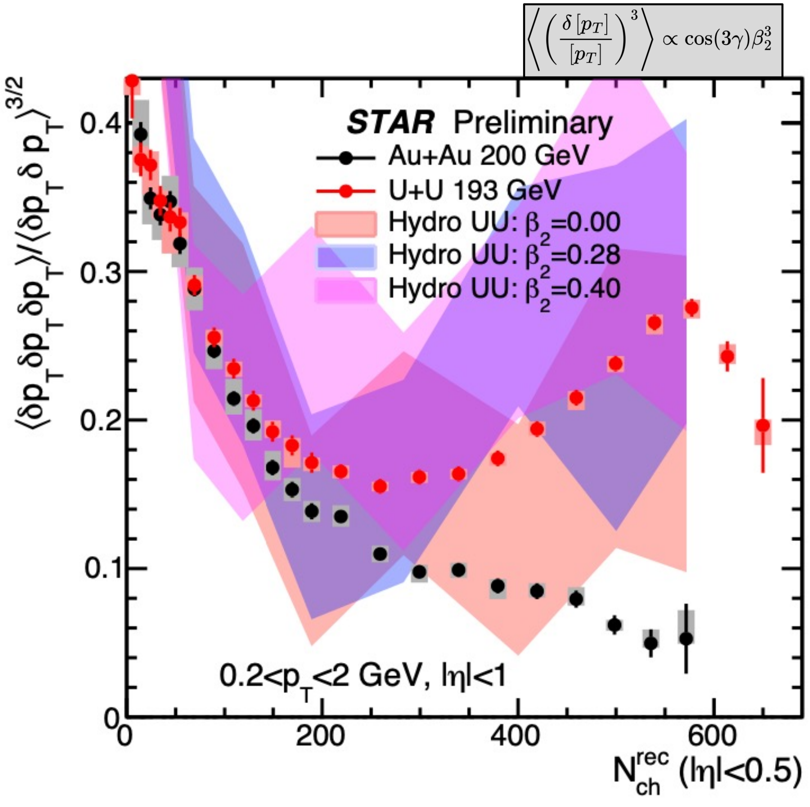


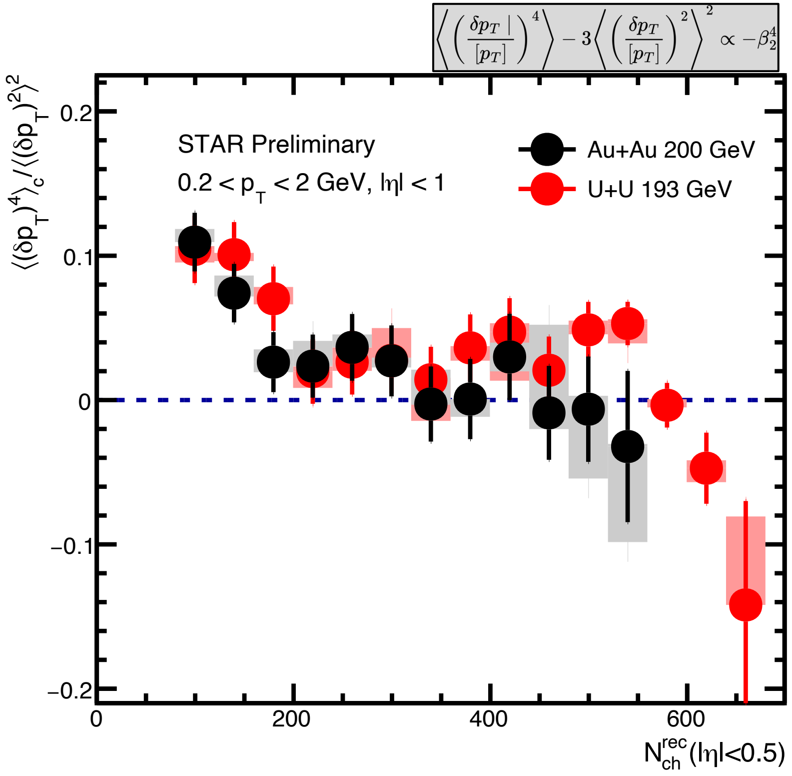
S. Gavin, *PRL 92, 162301 (2004)*

$[p_T]$ fluctuations (size fluctuation) vs. collision system

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

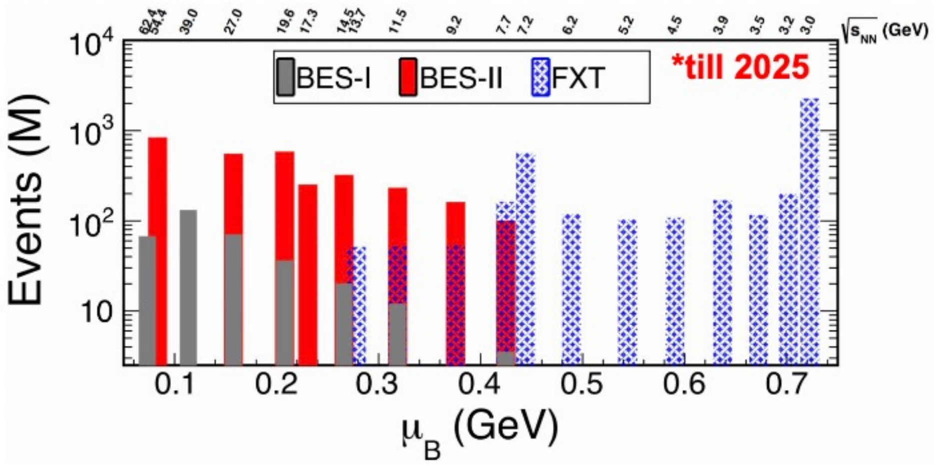
The nuclear deformation role is further confirmed by hydro calculations. But we need more statistics.

$[p_T]$ 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, PRL accepted*

[p_T] variance vs. collision energy in FXT mode

Large datasets with iTPC upgrade ~10 x BES-I



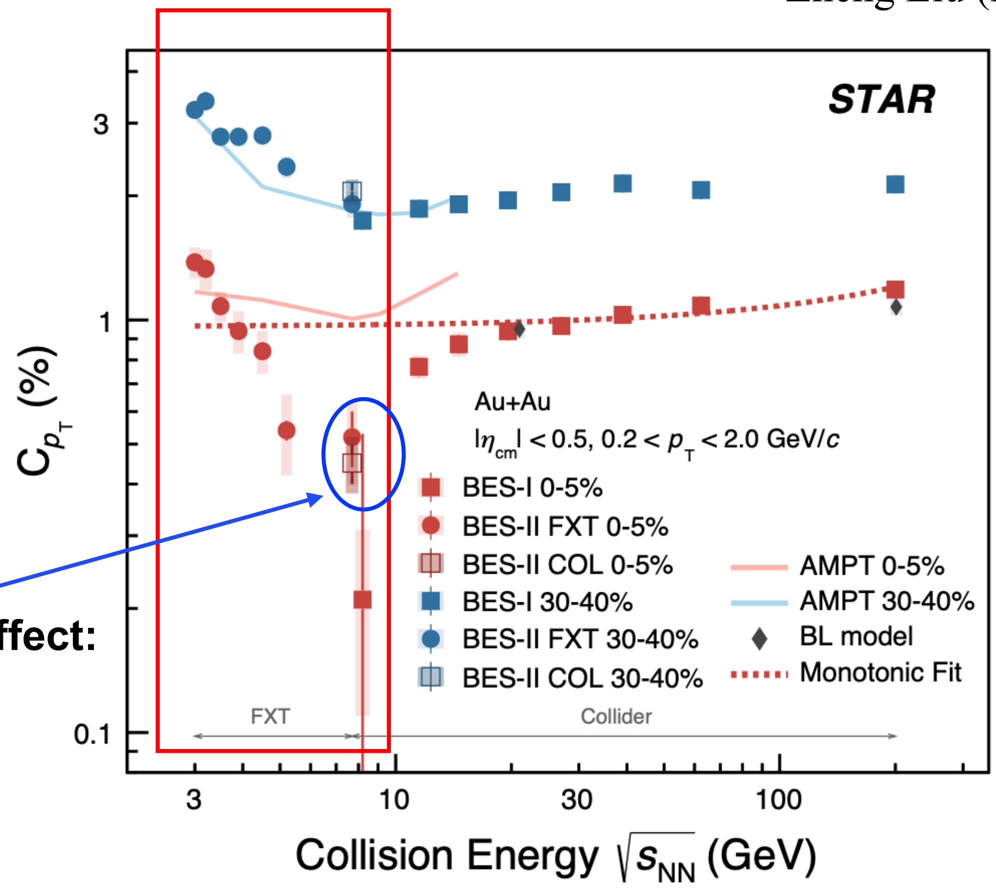
BES-II results show a **significant non-monotonic behavior** in 0–5% central collisions, but not in 30–40%.

STAR 0-5 %	~5.5 σ
AMPT 0-5 %	~1.4 σ
STAR 30-40 %	~2 σ

No clear acceptance effect: at 7.7 GeV, BES-II is consistent with BES-I.

STAR, *arXiv: 2604.06434, PRL accepted*

Zheng Liu (Fudan)



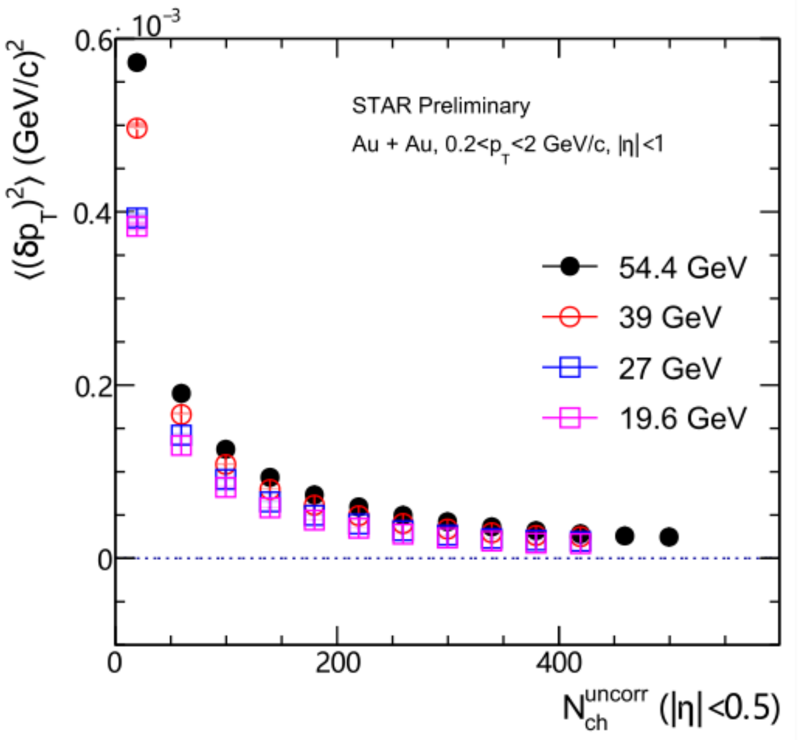
Useful for constraining EoS and understanding the phase diagram.

Li Yan (Fudan), Theoretical details
16:10-16:35, 7月16日, 分会场III

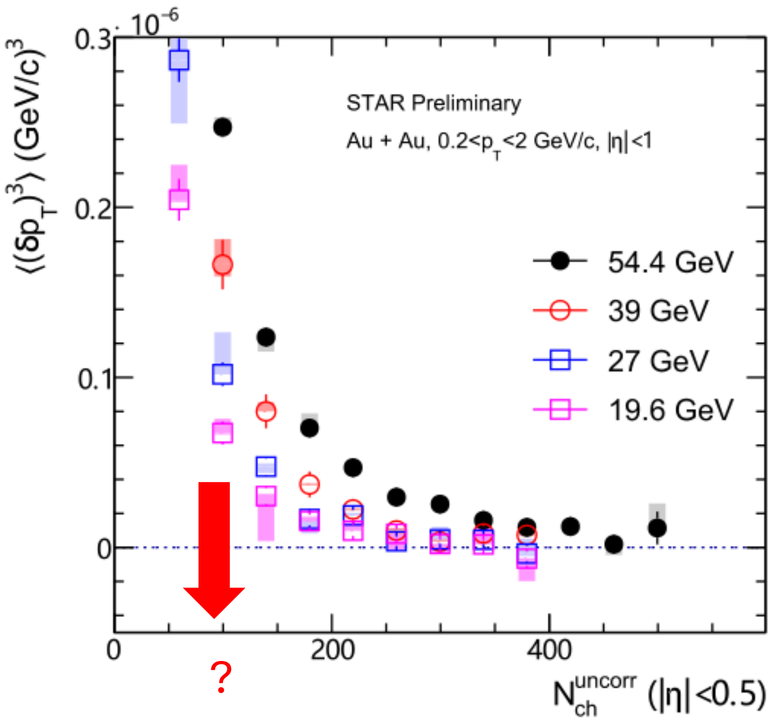
L. Zhang, J. Chen, C. Zhang, *PRC 111, 024911 (2025)*
J. Chen, W. Fu, S. Yin, C. Zhang, *arXiv:2504.0688, PRD accepted*

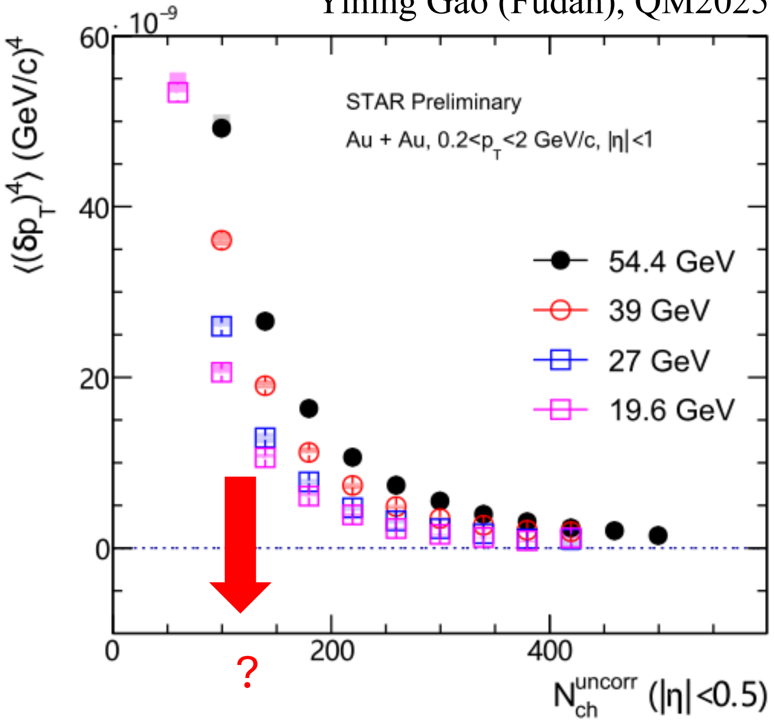
[p_T] fluctuations vs. collision energy in collider mode

Yining Gao (Fudan), QM2025



Efficiency-uncorrected N_{ch}





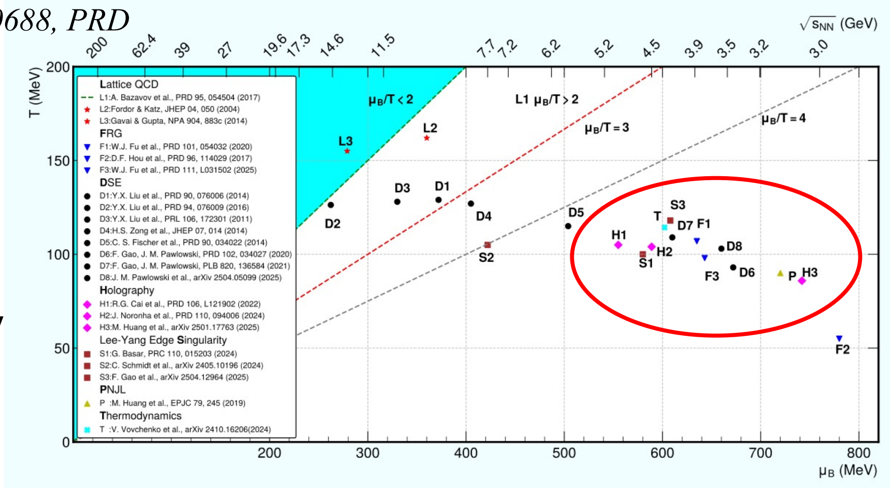
J. Chen, W. Fu, S. Yin, C. Zhang, *arXiv:2504.0688, PRD*

- Values of correlators of variance, skewness and kurtosis increase towards peripheral collisions.
- Slight energy dependence is observed.

Weijie Fu (DUT), Theoretical details
16:10-16:35, 7月15日, 分会场III

Interesting to do:

1) scan collision energy
2) EbE [p_T] fluc. vs. energy in the central regime



Y. Zhang, Z. Wang, X. Luo, N. Xu, *Eur. Phys. J. Spec. Top. (2026)*

$[p_T]$ fluctuations vs. collision system and PID

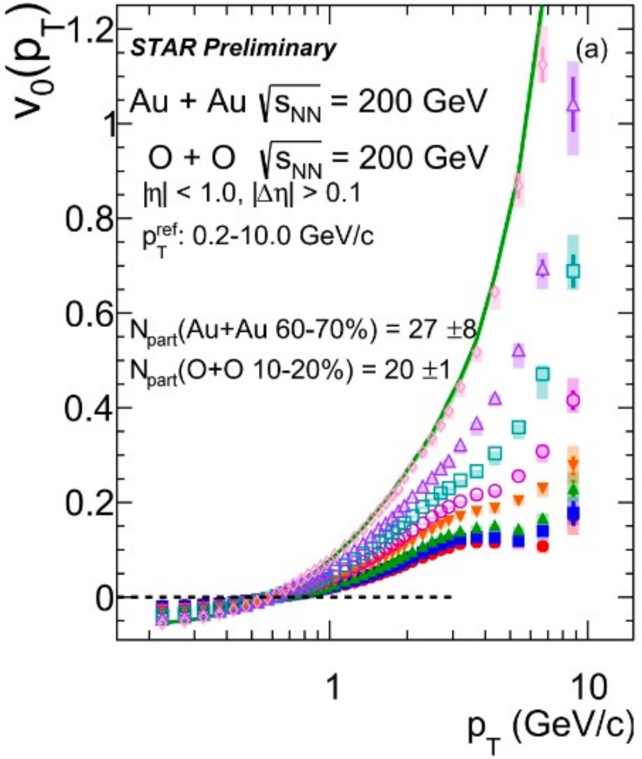
Zaining (Fudan), sQM2026

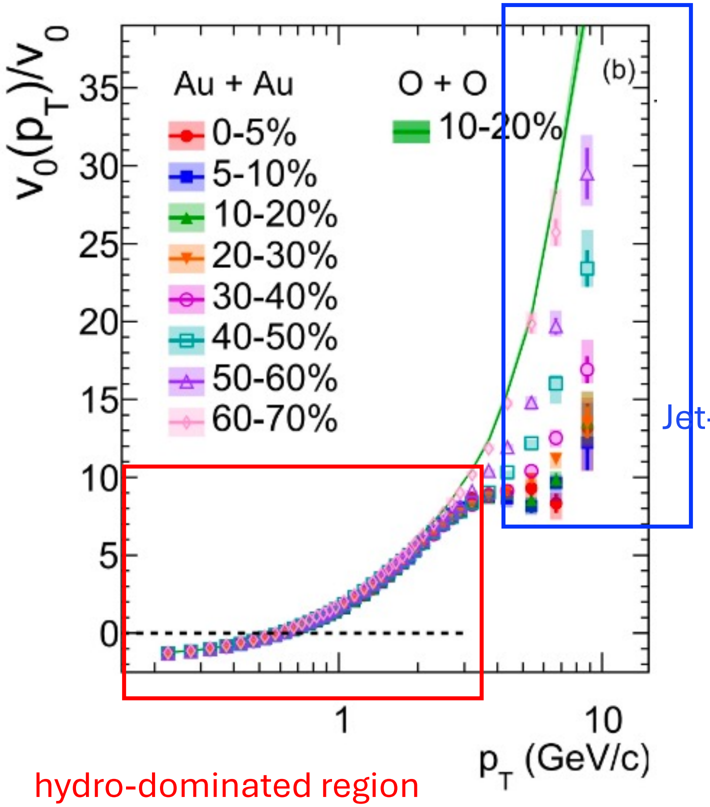
- First measurement for charged hadrons, protons, kaons and pions in O+O to Au+Au.
- larger fluctuation signals for heavier particles.
- v_0 follows an approximate power scaling $v_0 \sim 1/\sqrt{N_{ch}}$

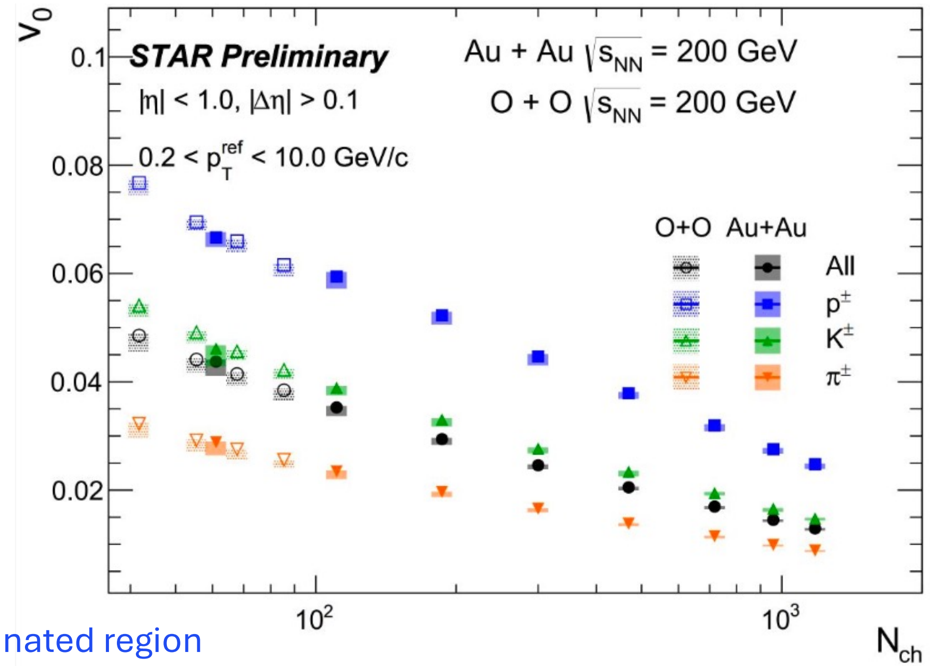
$$v_0 = C_{p_T} = \frac{\sqrt{\langle(\delta p_T)^2\rangle}}{\langle\langle p_T\rangle\rangle}$$

$$\boxed{v_{0,\mathrm{PID}} = \frac{\langle \delta[p_T]_{\mathrm{PID}}\delta[p_T]_h\rangle}{\langle[p_T]\rangle_h}}$$

$$\boxed{v_0(p_T) = \frac{\langle \delta n(p_T)\delta[p_T]\rangle}{\langle n(p_T)\rangle\langle[p_T]\rangle} \times \frac{1}{v_{0,\mathrm{int}}}}$$







$$\frac{v_0(p_T)}{v_0} = \frac{\kappa_0(p_T)}{\kappa_0}$$

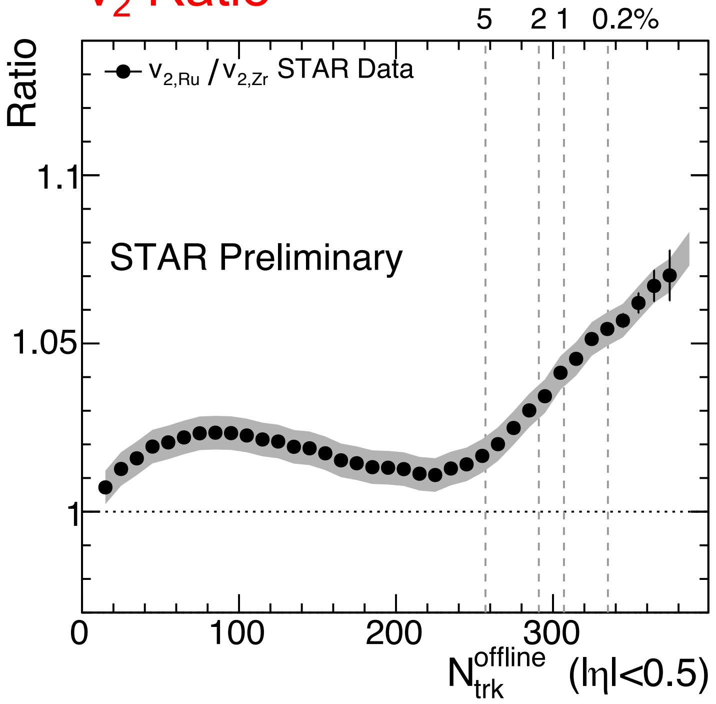
Universal shape scaling across Centrality and systems, except at high p_T

Guoping Wang (CCNU), Strange hadrons
17:45-18:00, 7月16日, 分会场III

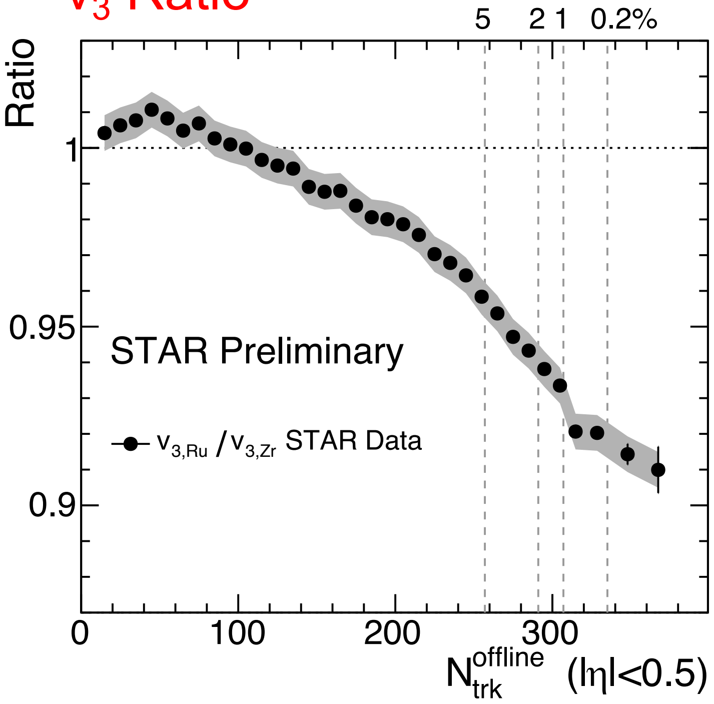
ATLAS, *PRL 136, 032301 (2026),* ALICE, *PRL 136, 032302 (2026)* J. Zhu, X.-Y. Wu, G.-Y. Qin, *2602.04148*

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

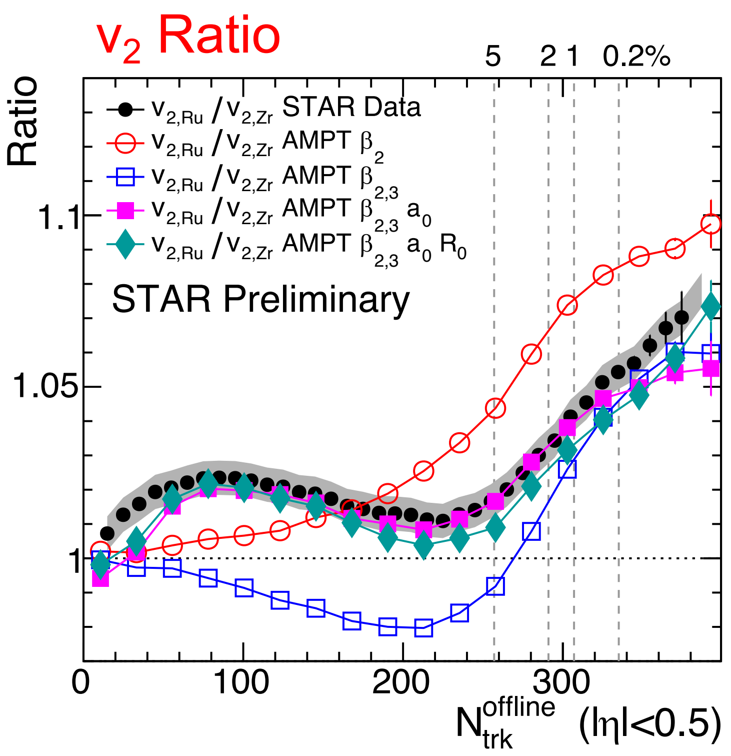
v_2 Ratio

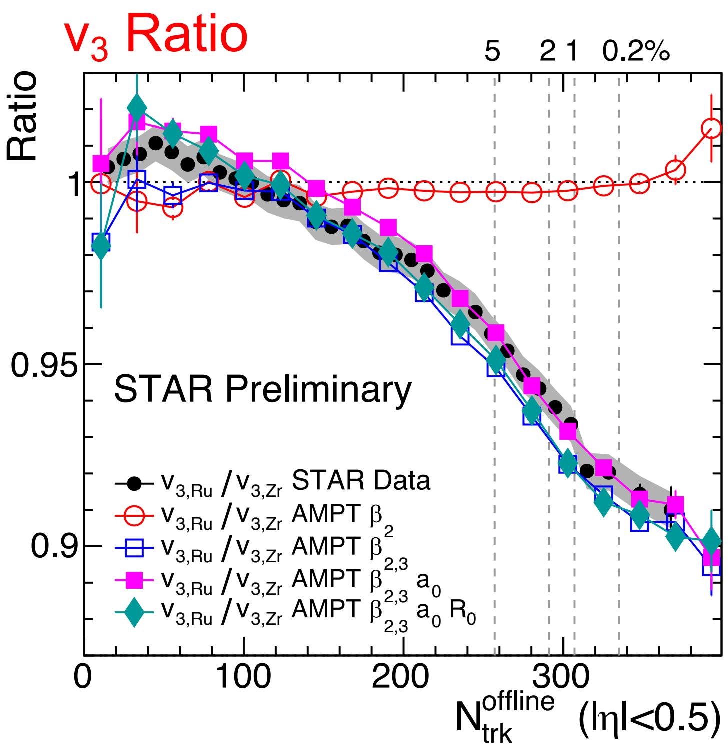


v_3 Ratio



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



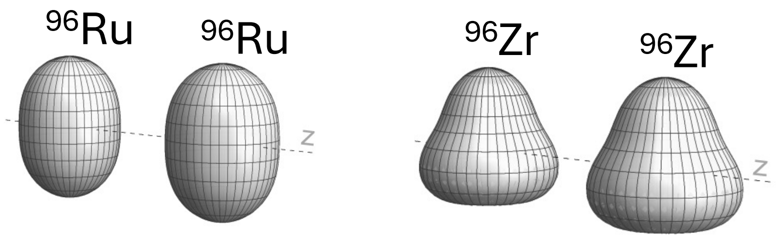


$\beta_{2,Ru} \sim 0.16$ increase v_2, no influence on v_3 ratio

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

$\Delta a_0 = -0.06$ fm increase v_2 mid-central, small impact on v_3

Radius $\Delta R_0 = 0.07$ fm only slightly affects v_2 and v_3 ratio.



- 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

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

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

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

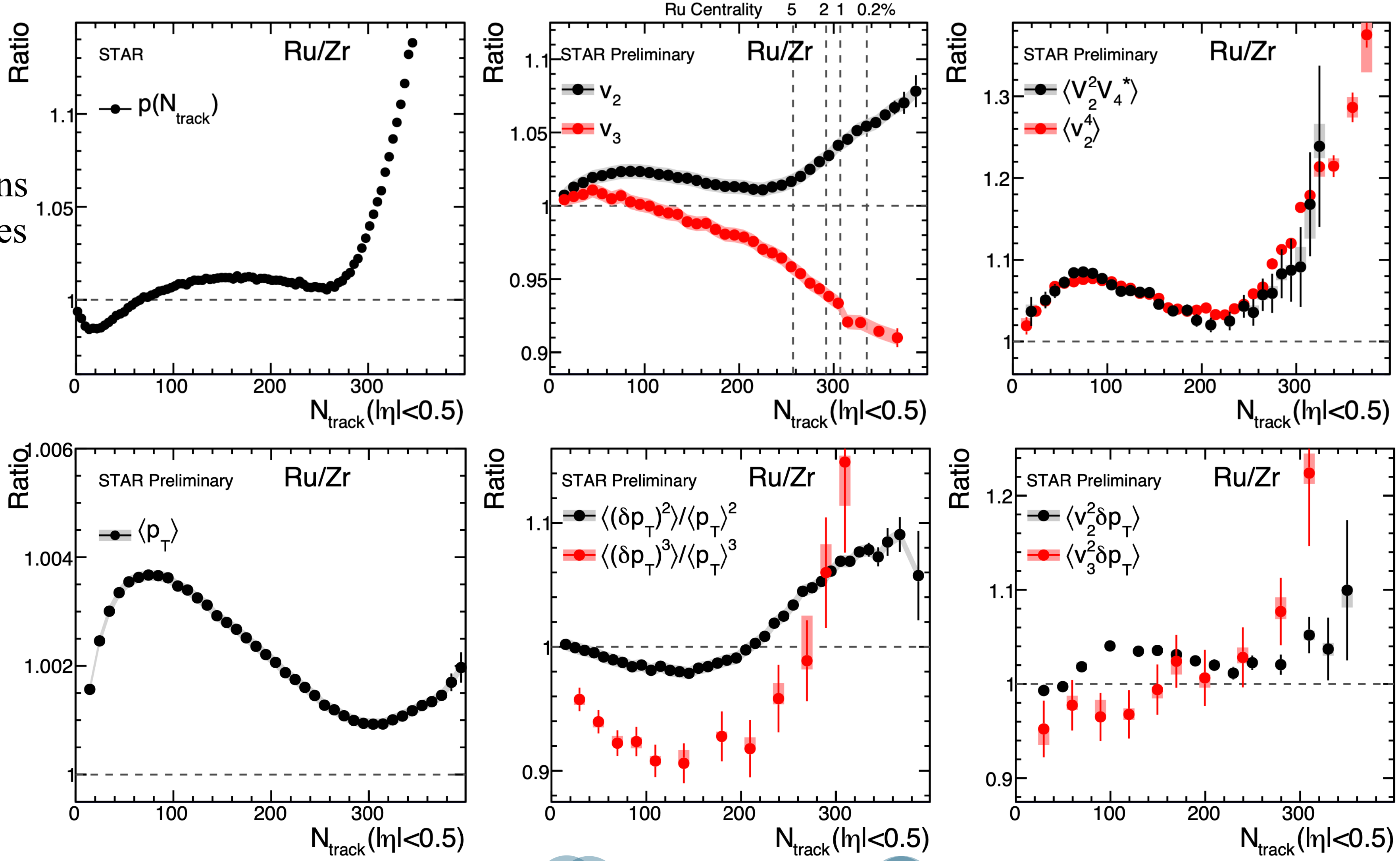
C. Zhang, J. Jia, *PRL 128, 022301(2022)*; J. Jia, C. Zhang, *PRC 107, L012901 (2023)*

Nuclear structure is inherent of heavy-ion probes

Many-body correlations probe nuclear structures

STAR Preliminary

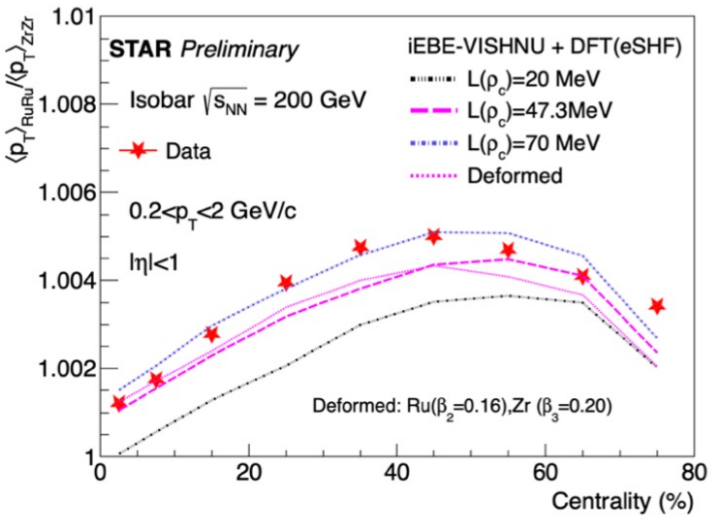
One-body distribution | *Two-body correlations* | *Three-body correlations*



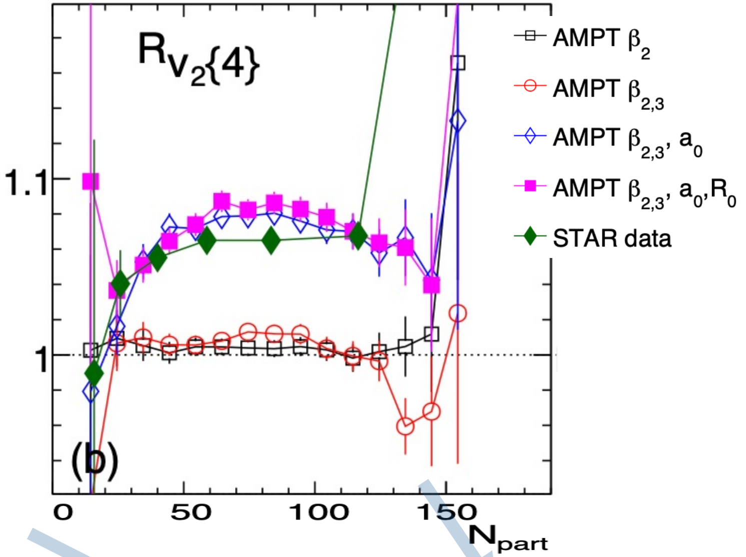
Imaging the radial structures (neutron skin)

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

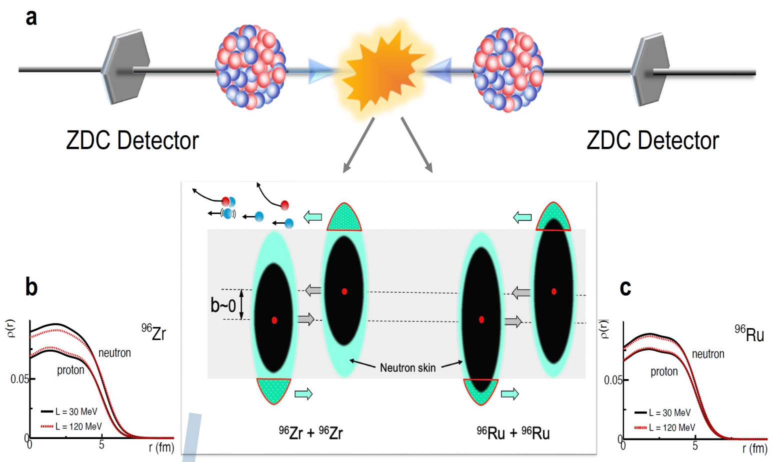
H. Xu, *QM2023*



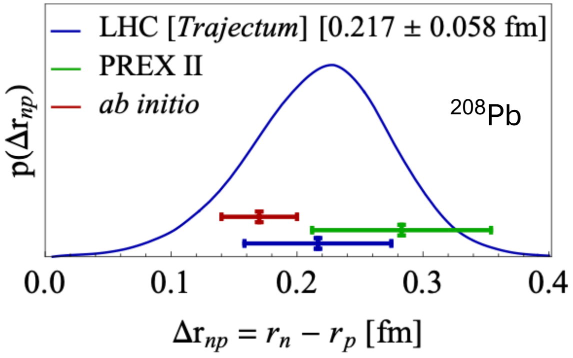
J. Jia, G. Giacalone, C. Zhang, *PRL 131, 022301 (2023)*



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

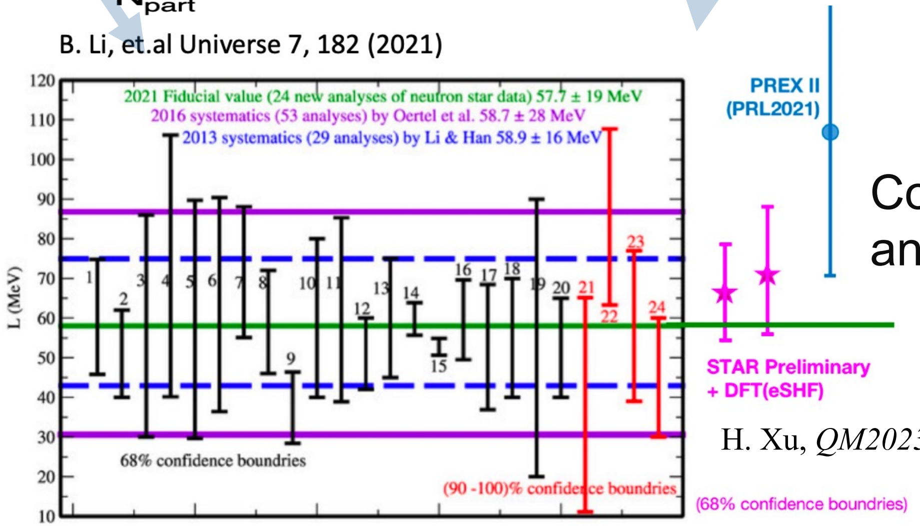


PREX- CREX puzzle in nuclear physics



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

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

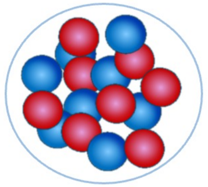


H. Xu, *QM2023*

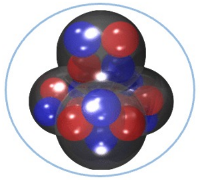
Constrain neutron skin and symmetry energy

III. Nucleonic cluster pattern in light nuclei

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

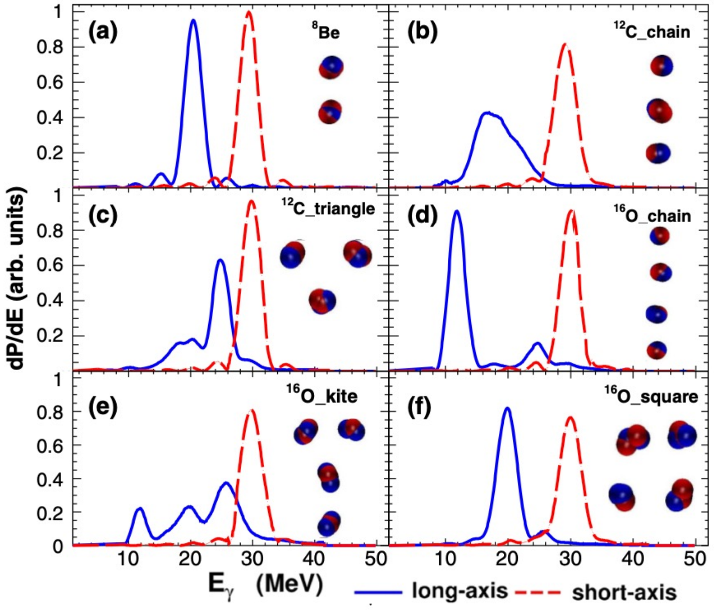


$$\rho(r) \propto \frac{1 + w\left(r^2/R^2\right)}{1 + e^{(r-R)/a_0}} \longrightarrow \text{Modern } \textit{ab initio} \text{ first-principle calculations}$$

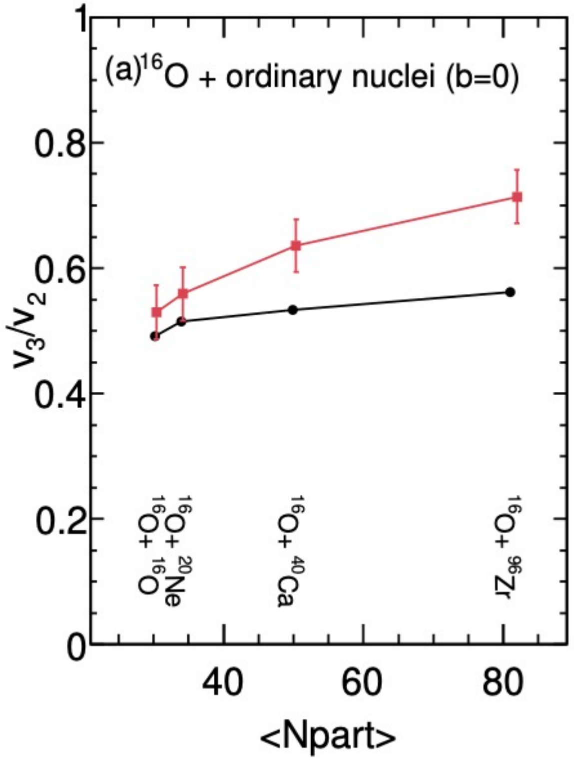


Pioneer theory instructions of the nucleonic clustering

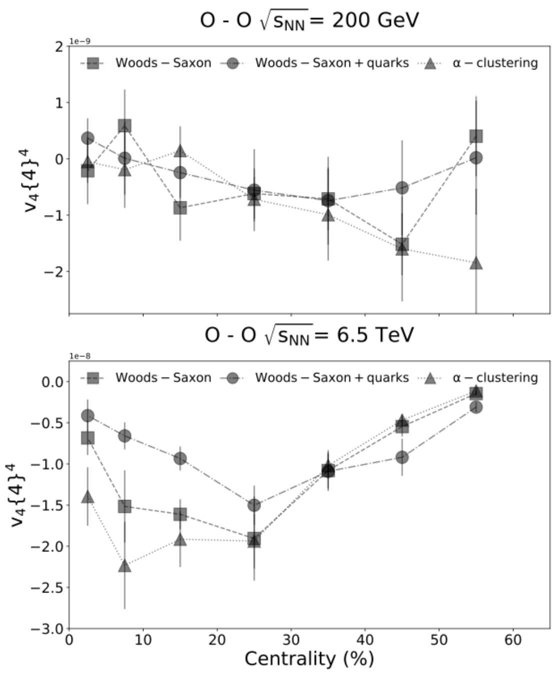
“Double magic number” in ${}^{16}_{8}\mathrm{O}$ nuclei, possible alpha cluster in low-energy studies.



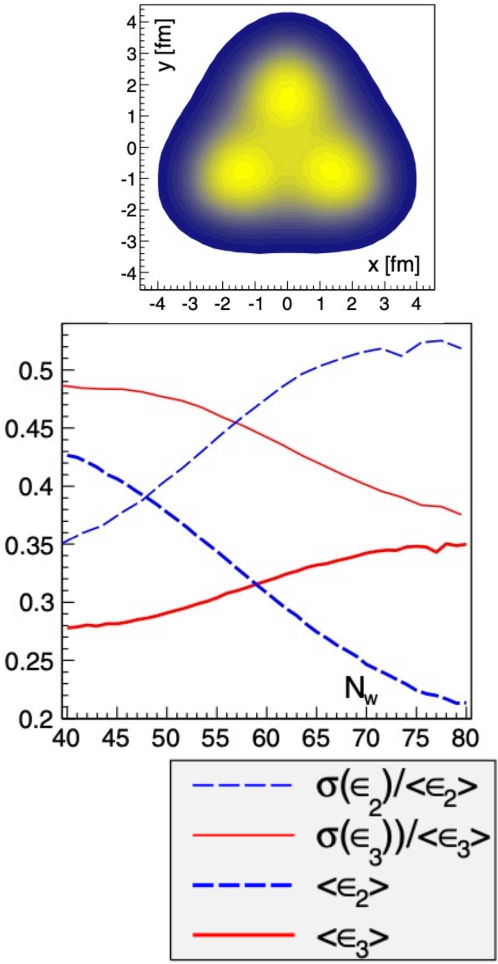
W. He, Y.-G. Ma et al., *PRL 113, 032605 (2014)*



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



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



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

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

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)*

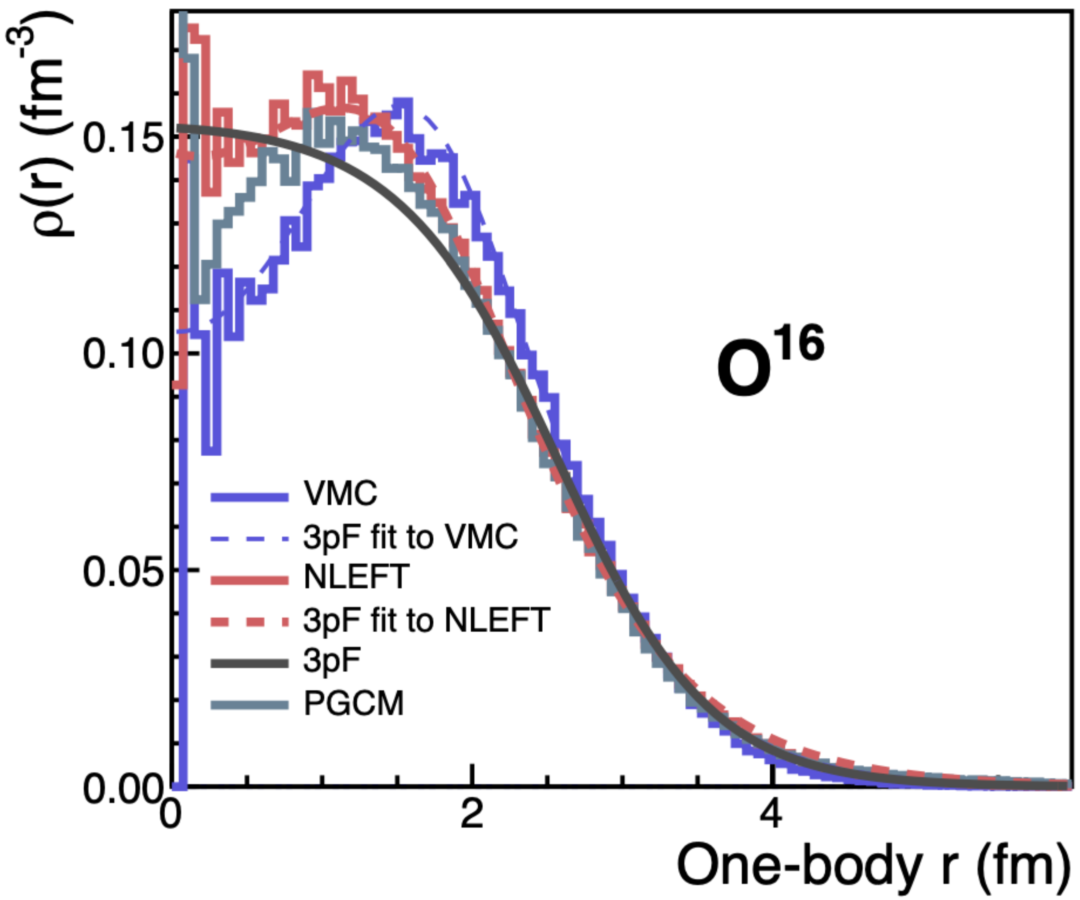
3) Variational auxiliary field diffusion Monte Carlo (VMC):
MC solution of Schrödinger eq. from the time evolution of trial wave function.

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)

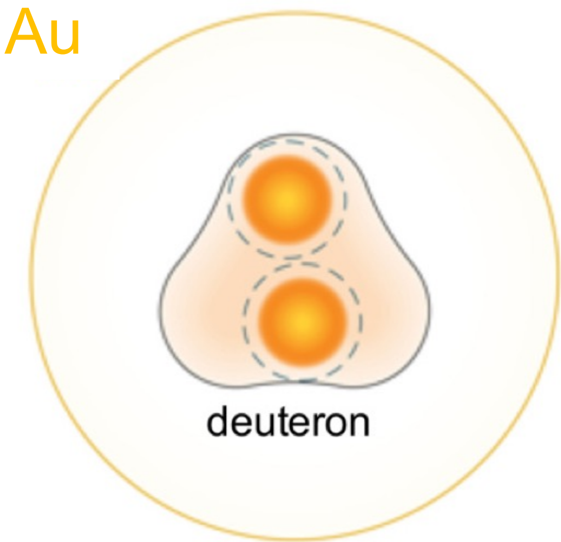
Frosini et al., *EPJA 58, 62 (2022); EPJA 58, 63 (2022); EPJA 58, 64 (2022)*

5) Some other micro models…

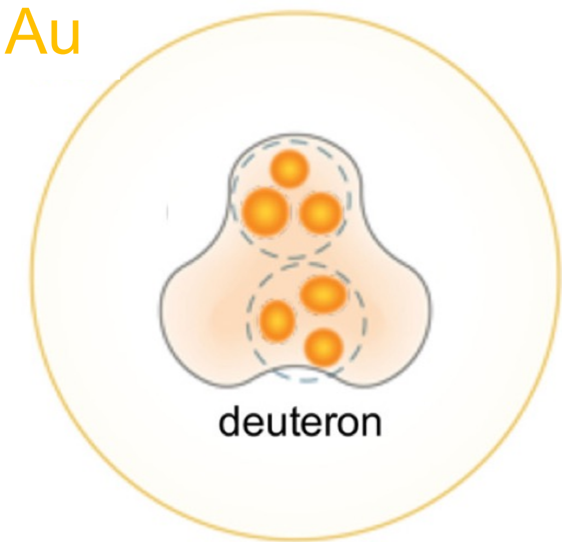


Nucleon/sub-nucleon fluctuation vs. nucleon-nucleon correlations

Nucleon fluctuation



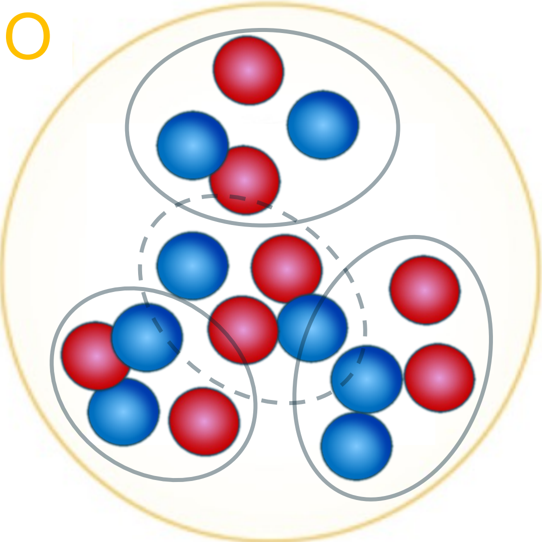
subnucleon fluctuation

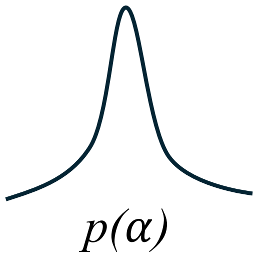


STAR, *PRL 130, 242301 (2023)*

STAR, *PRC 110, 064902 (2024)*

NN correlation (cluster pattern)





ab initio calculations

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*

...

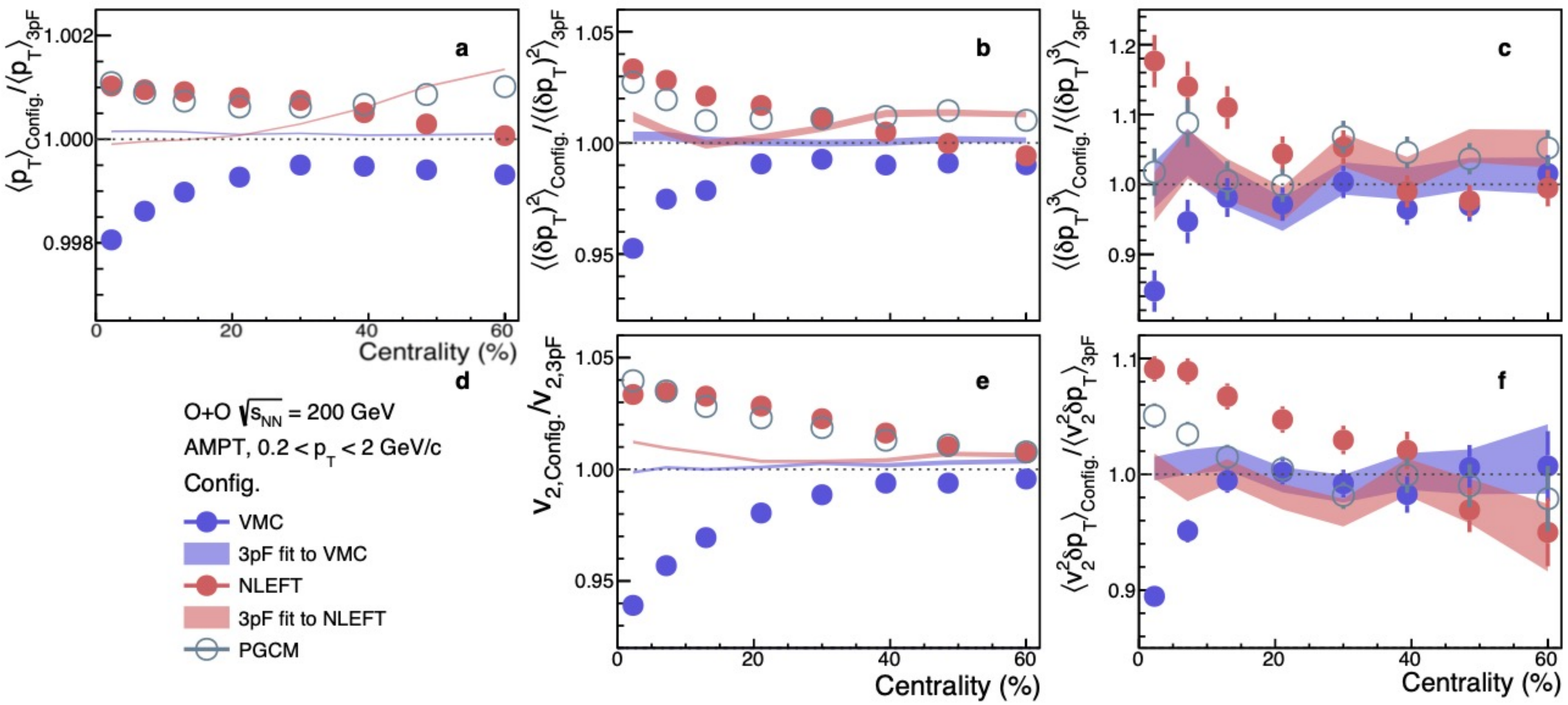
d+Au collision, 200 GeV ⟷ Nearly same N_{ch} ⟷ O+O collision, 200 GeV

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

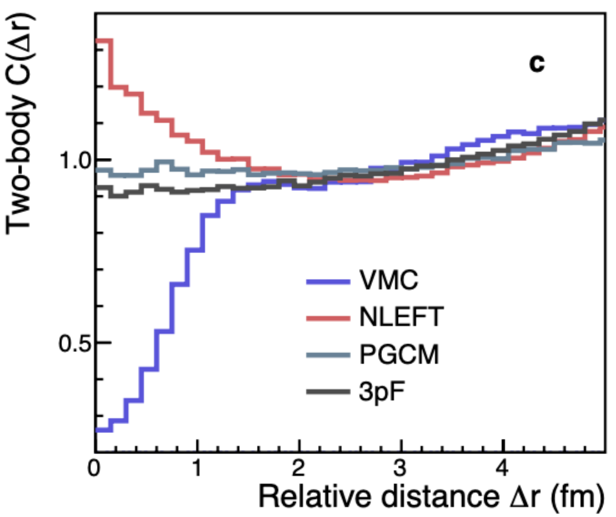
C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *PLB 862, 139322 (2025)*

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

Multiple final-state observables



Two-body correlations in coordinate space

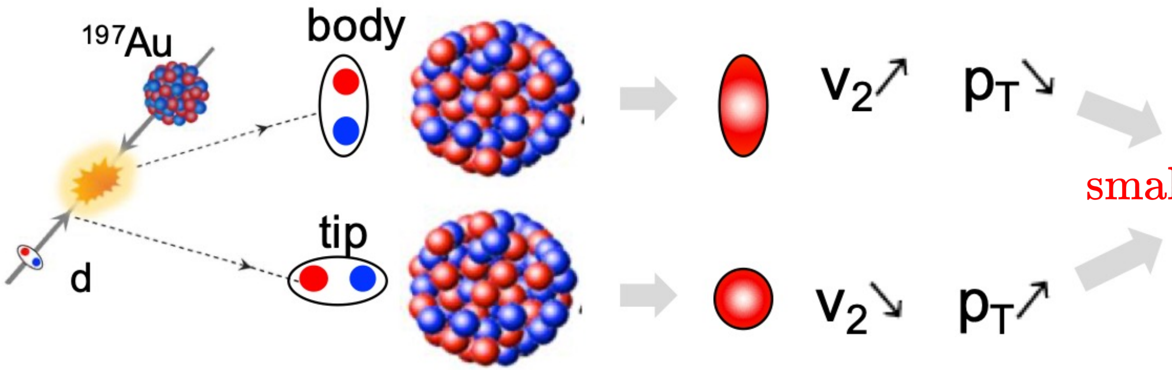


$$C(\Delta r) = \frac{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}, \mathbf{s}-\frac{\mathbf{r}}{2}\right)}{\int d^3\mathbf{s} f\left(\mathbf{s}+\frac{\mathbf{r}}{2}\right) f\left(\mathbf{s}-\frac{\mathbf{r}}{2}\right)}$$

- 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

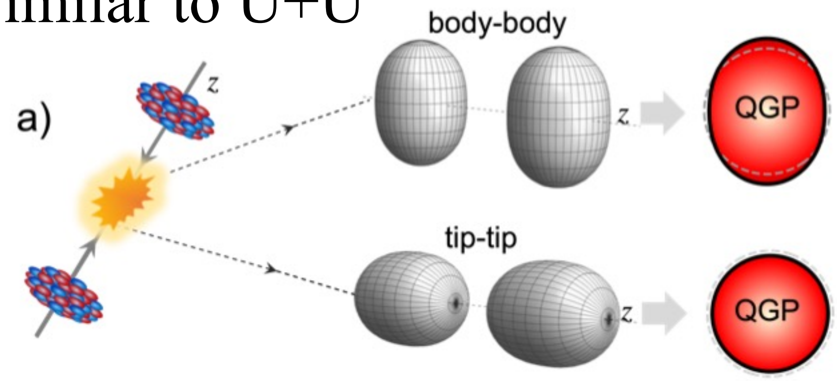
Zaining Wang (Fudan), sQM2026



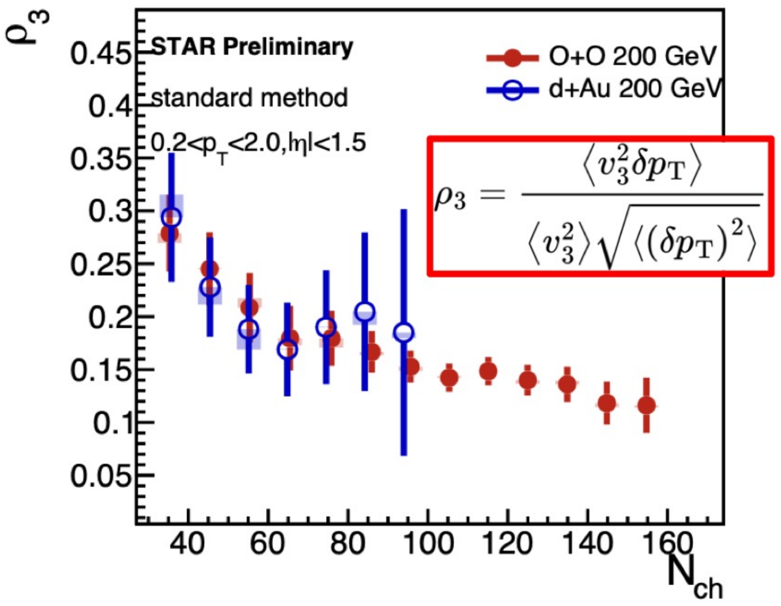
smaller $< v_2^2\delta p_T >$

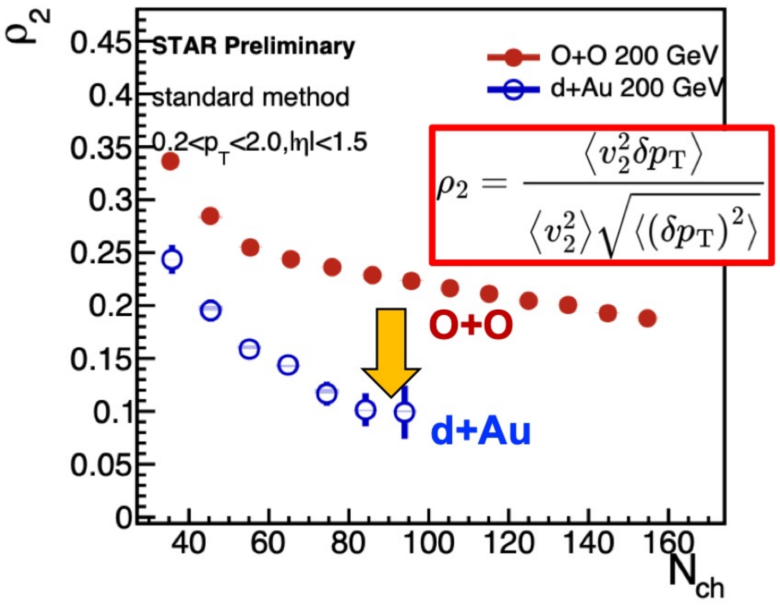
$$\langle v_2^2 \delta p_T \rangle = a - b\beta_2^3$$

Similar to U+U



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





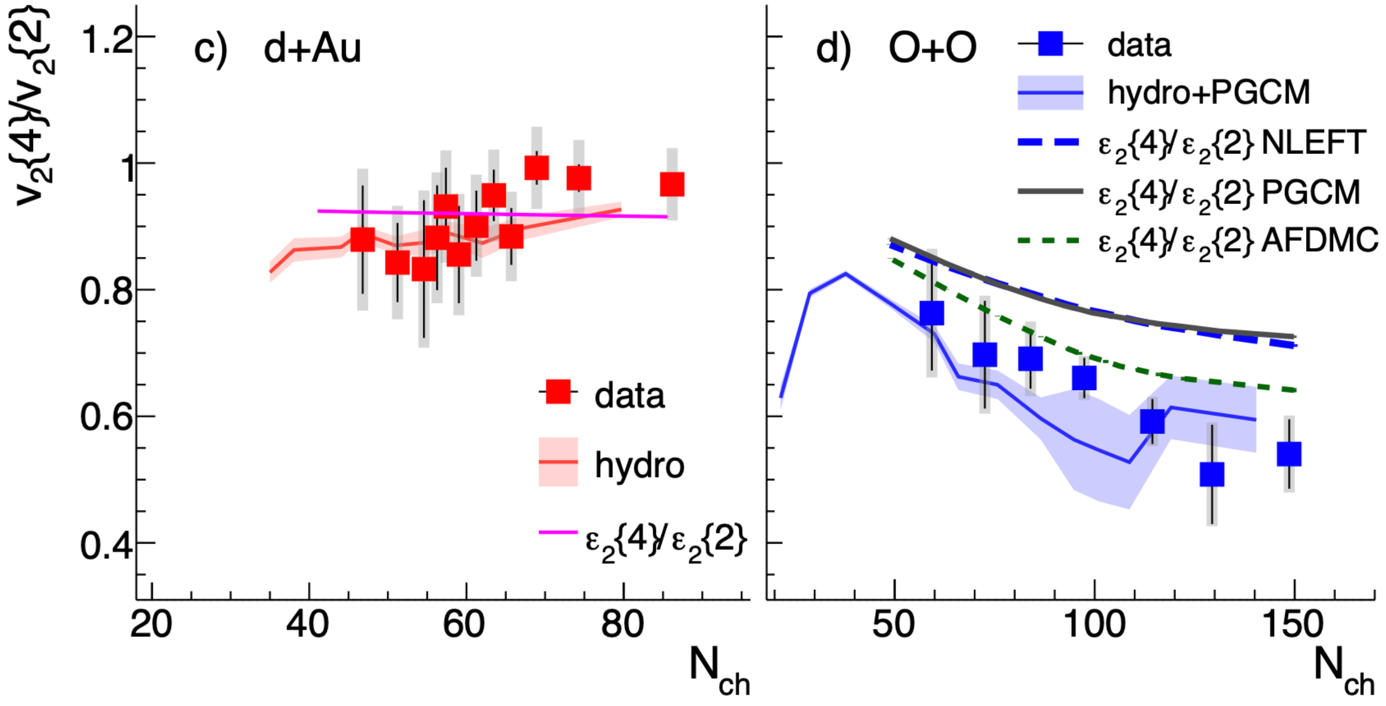
The deuteron wave function is fixed.

^{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

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

AFDMC vs. EFT/PGCM has a visible difference.

Nucleon-nucleon correlations impact initial-state fluctuations.

C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *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)*

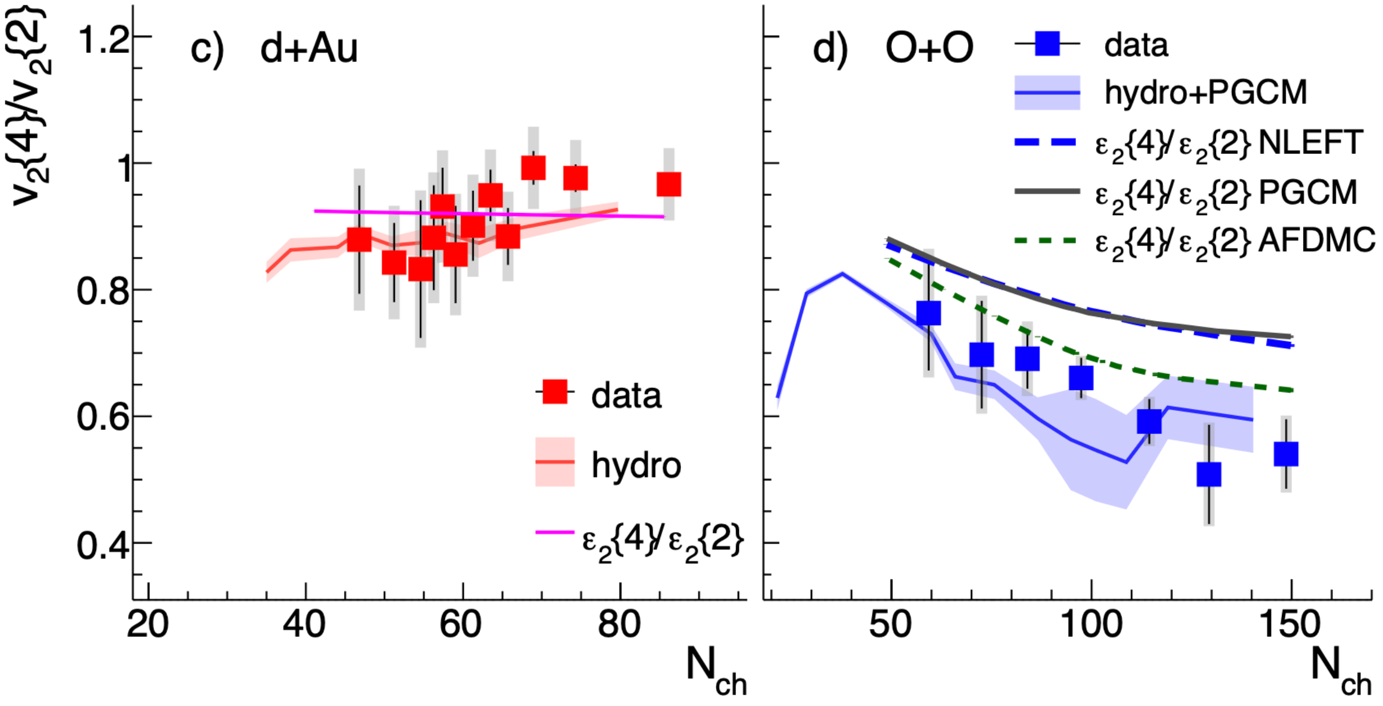
Small fluctuation in d+Au **large fluctuation in O+O**

$$\frac{v_2^{dAu}\{4\}}{v_2^{dAu}\{2\}} \approx \frac{\varepsilon_2^{dAu}\{4\}}{\varepsilon_2^{dAu}\{2\}} \approx 0.9 \qquad \frac{v_2^{\rm OO}\{4\}}{v_2^{\rm OO}\{2\}} \approx \frac{\varepsilon_2^{\rm OO}\{4\}}{\varepsilon_2^{\rm OO}\{2\}} \sim 0.6$$

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

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 **large fluctuation in O+O**

$$\frac{v_2^{dAu}\{4\}}{v_2^{dAu}\{2\}} \approx \frac{\varepsilon_2^{dAu}\{4\}}{\varepsilon_2^{dAu}\{2\}} \approx 0.9 \qquad \frac{v_2^{OO}\{4\}}{v_2^{OO}\{2\}} \approx \frac{\varepsilon_2^{OO}\{4\}}{\varepsilon_2^{OO}\{2\}} \sim 0.6$$

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, J. Chen, G. Giacalone, S. Huang, J. Jia, Y.-G. Ma, *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)*

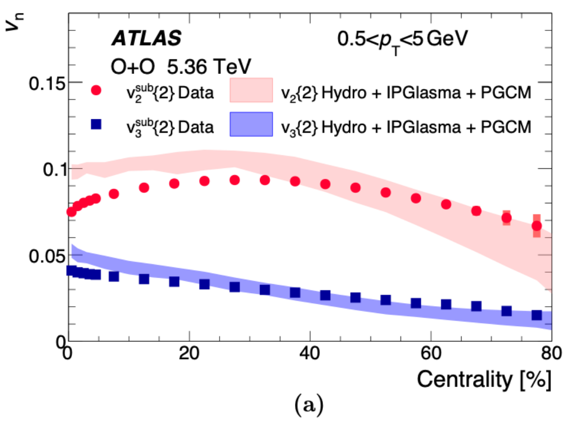
Geometric scan elucidates nuclear tomography and strong nuclear force?

data & high-energy model & low-energy inputs

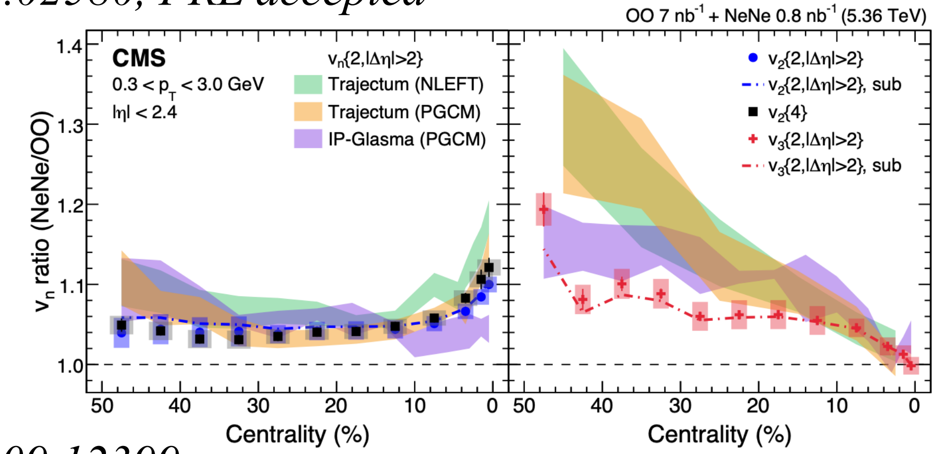
New 2025-2026 dataset: ~10 x High multiplicity

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

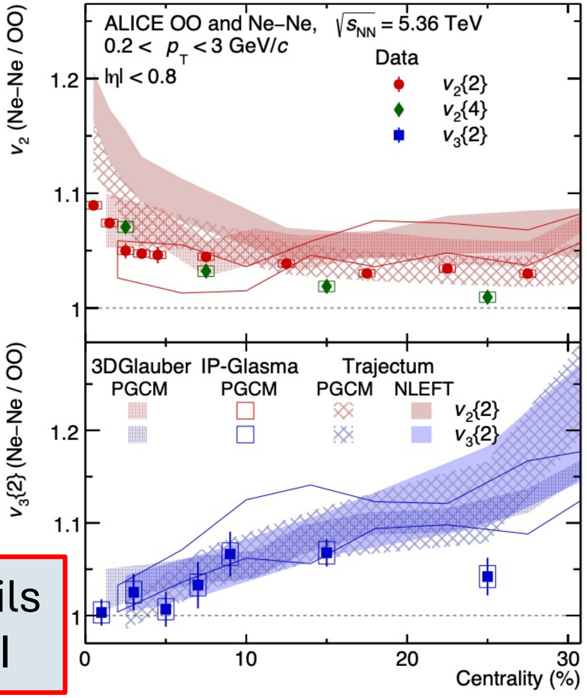
ATLAS, *2509.05171, PRC*



CMS, *2510.02580, PRL accepted*



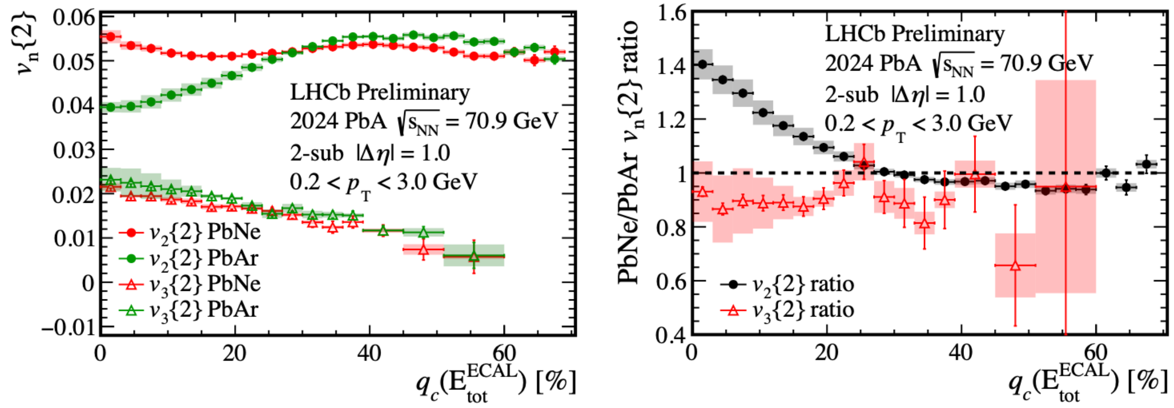
ALICE, *2509.06428, PRL accepted*



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

Pei Li (Fudan), Theoretical details
17:30-17:45, 7月16日, 分会场III

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)*

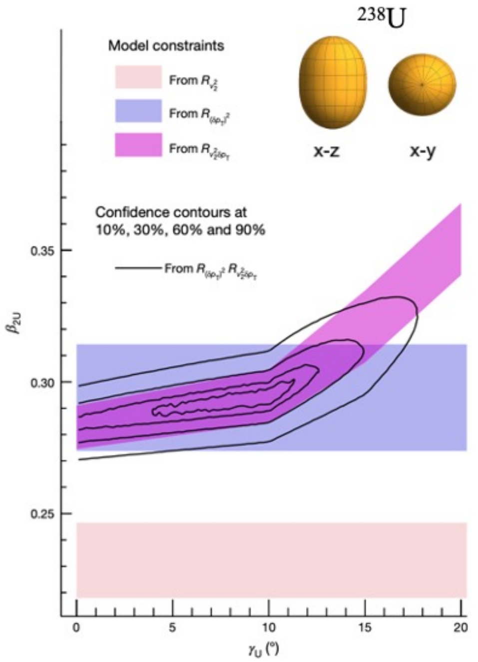
P. Li, B. Zhou, G.-L. Ma, *PRL 136, 082302 (2026)*

…

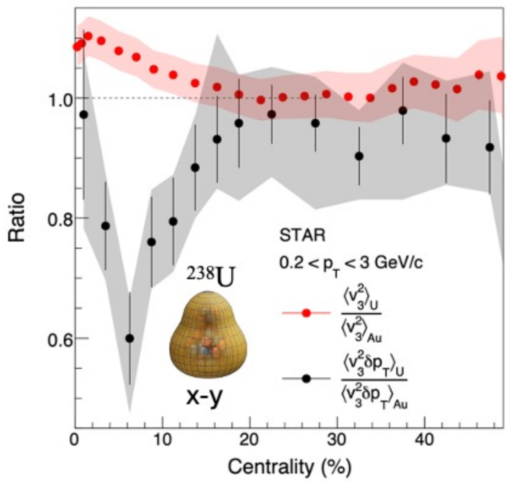
IV. Conclusions and Outlooks

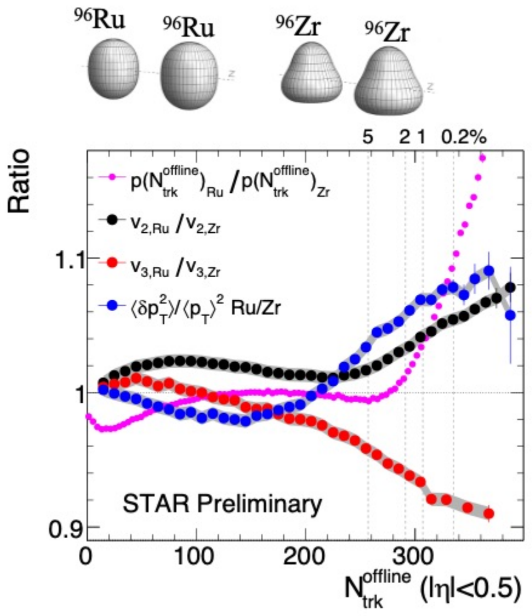
1. The signatures of nuclear structure from large to small nuclear collisions are ubiquitous:

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

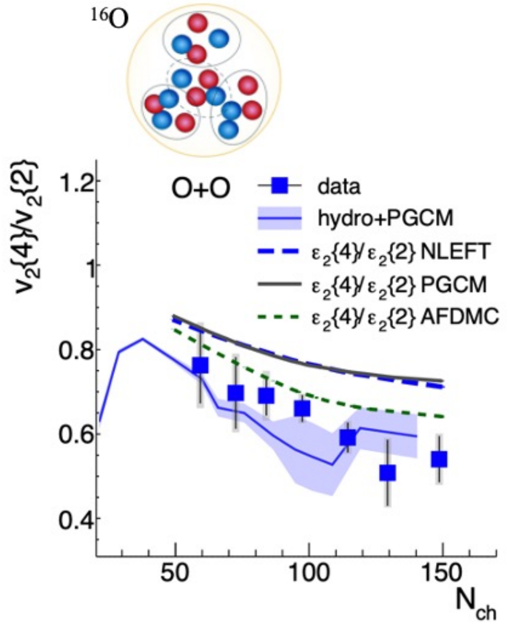


STAR, *Rep. Prog. Phys. 88, 108601 (2025)*





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

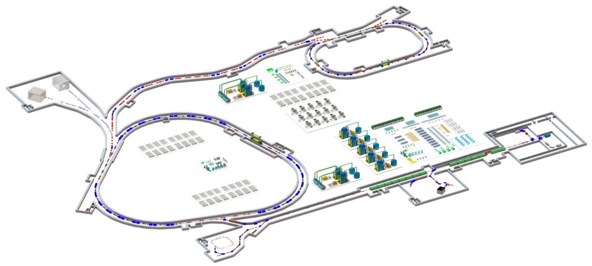
→ Intersection with Nucleosynthesis, nuclear fission, 0νββ, EDM

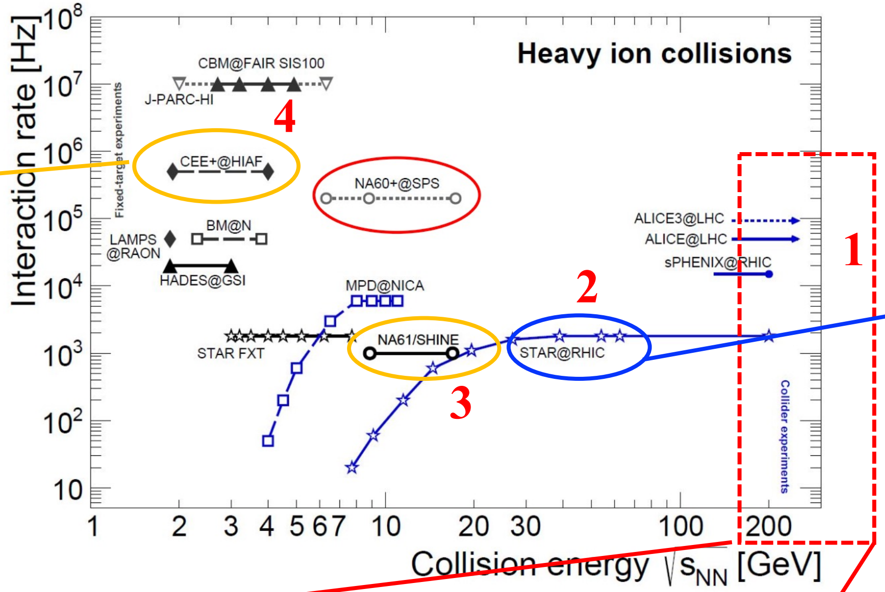
→ Energy evolutions in TeV-GeV facilities, LHC, HIAF, NICA, FAIR, SPS, NA61

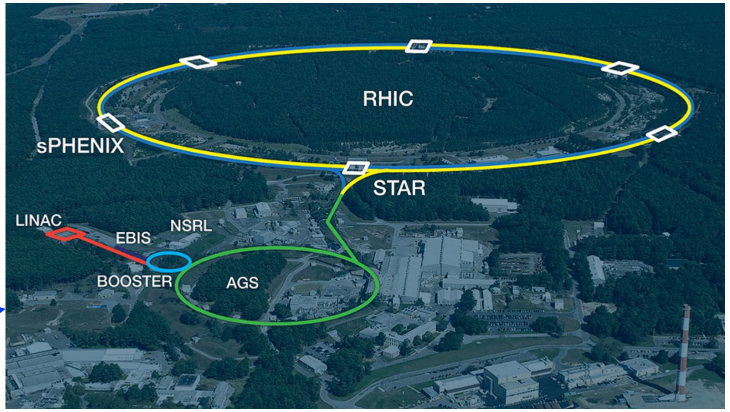
→ Other tools, i.e. UPC, AI-assistant work

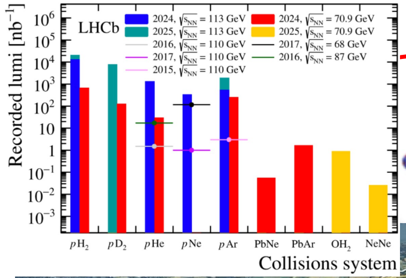
IV. Conclusions and Outlooks

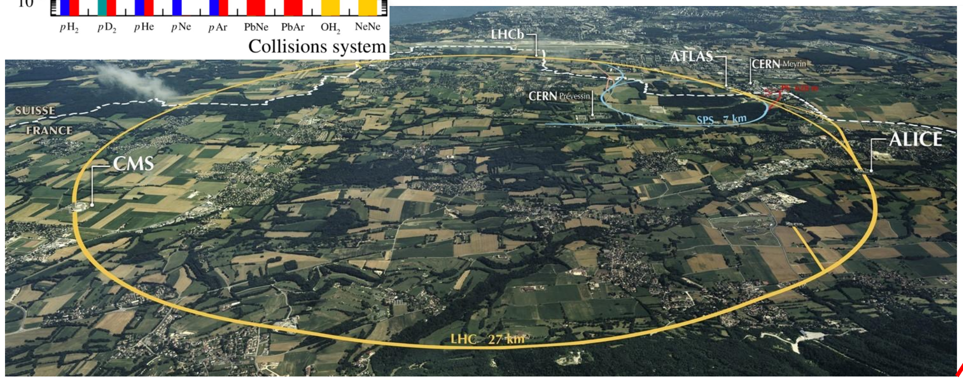
Energy evolution of nuclear structure, System scan, and the forward-rapidity DIS

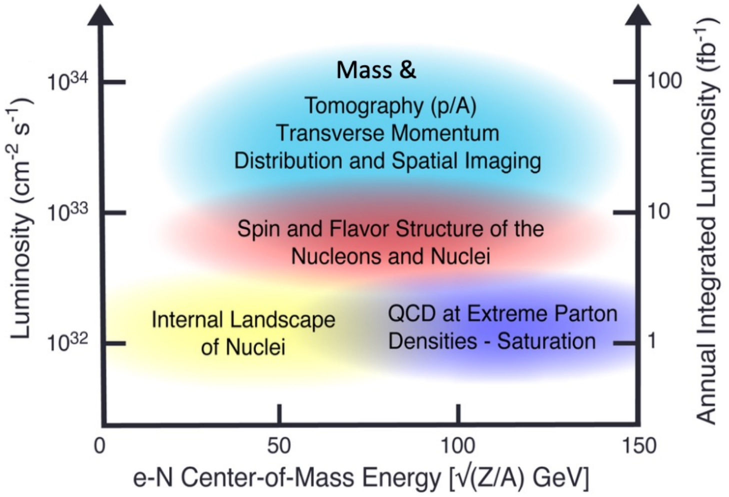






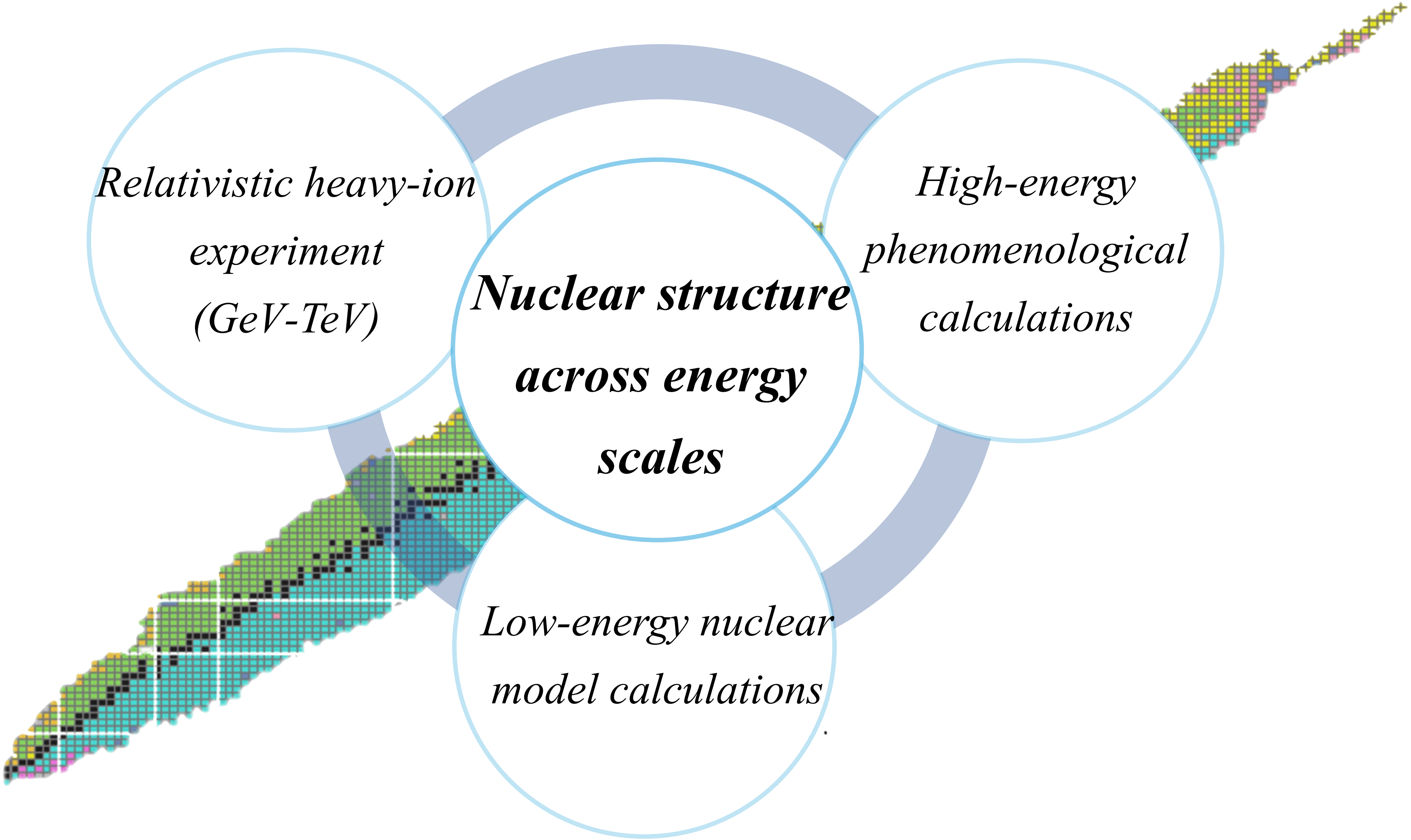






H. Mantysaari, B. Schenke, C. Shen, W. Zhao, *PRL 131, 062301 (2023)*
H. Li, L. Liu, J. Chen, Y.-G. Ma, C. Zhang, *Chinese Phys. Lett. 43, 050101 (2026)*
J.Z. Zhang, W.M. Zha, Li.X. Wang, G.-L. Ma, arXiv:2606.23353
...

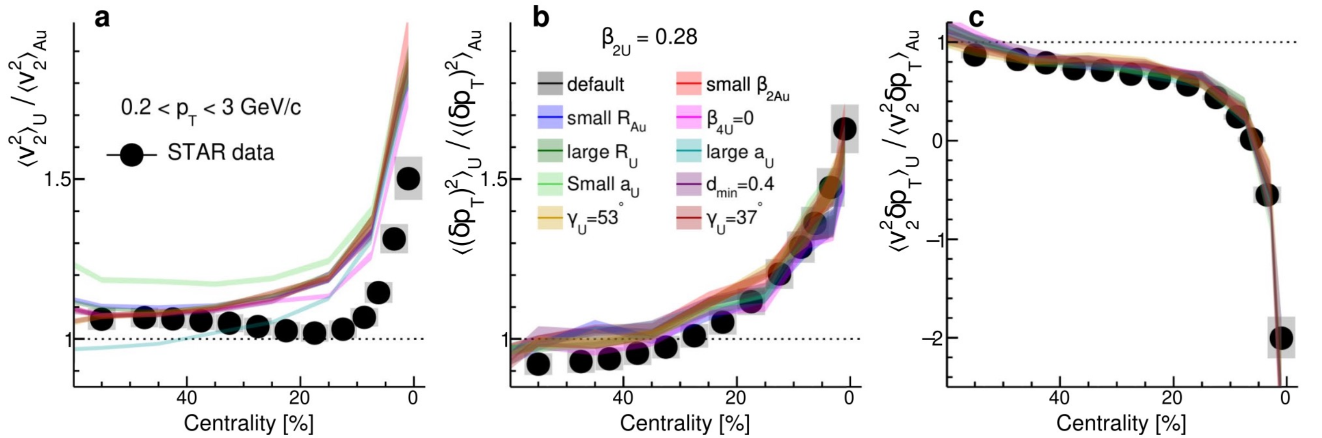
IV. Conclusions and Outlooks



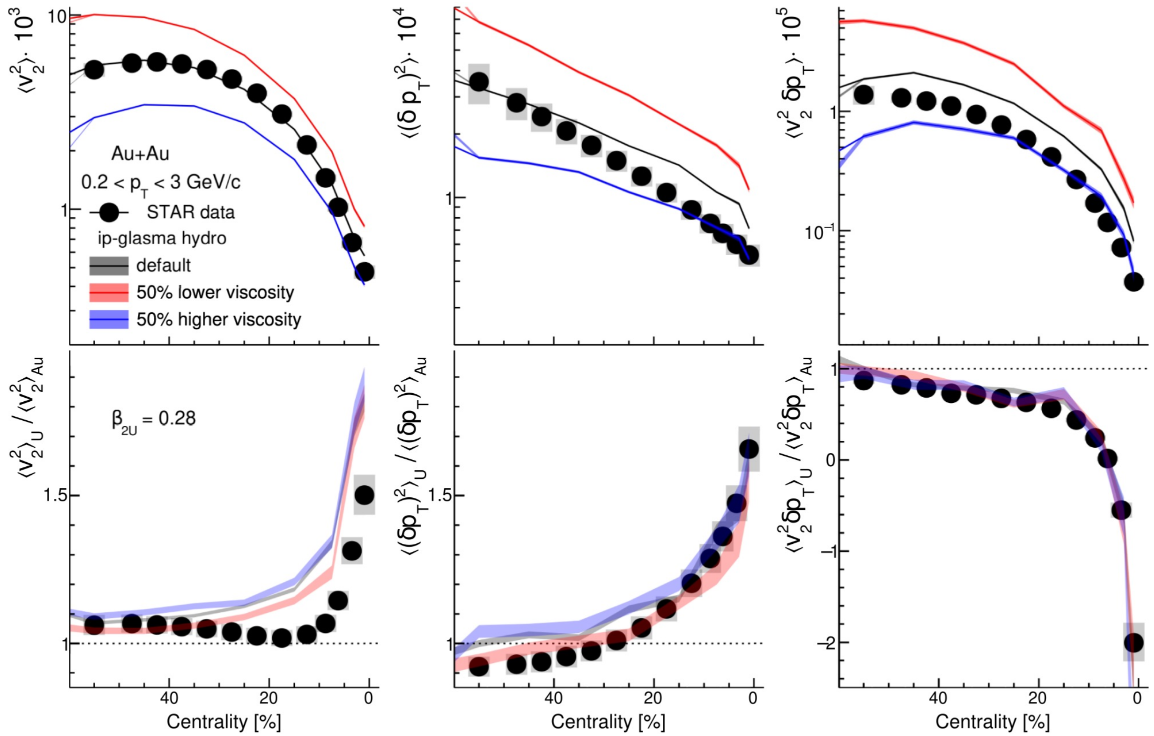
Collaboration with nuclear structure and intermediate energy

Viscosity, nuclear parameters, and model variations

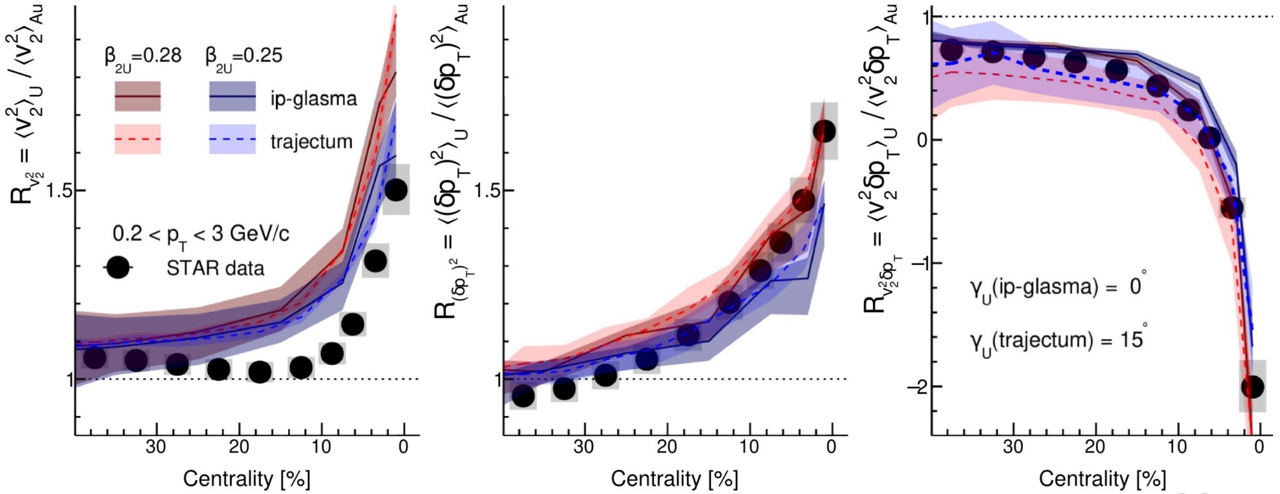
2) Effect from nuclear parameters are small, included as model systematics.



1) Taking the ratios cancels the viscosity effects.



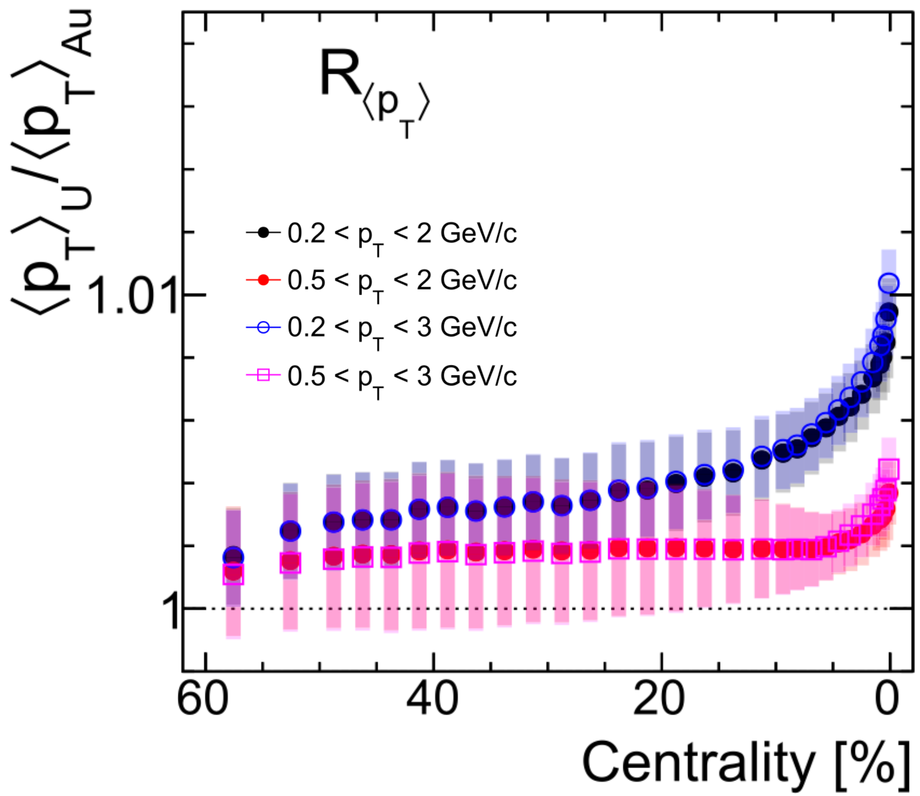
3) Another hydrodynamics model, Trajectum, shows rather consistent extractions even if it was not tuned to RHIC data.

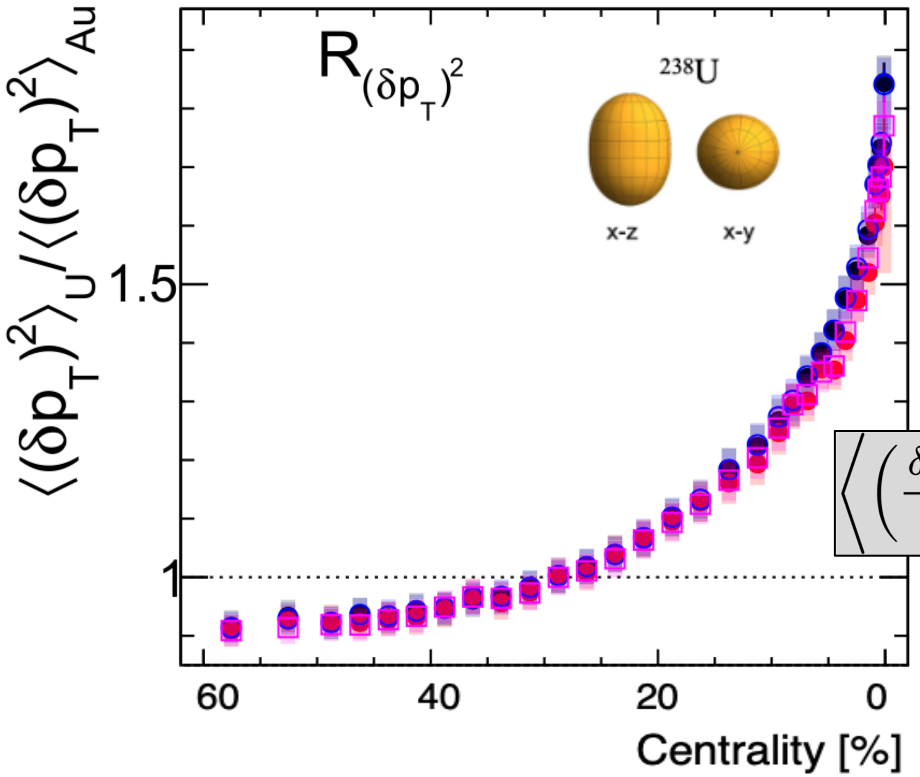


Extracted $\boldsymbol{\beta}_{2,\mathrm{U}}$ and $\boldsymbol{\gamma}_{\mathrm{U}}$ values are robust.

Size fluctuation sensitive to nuclear deformation

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





$$\left\langle \left(\frac{\delta [p_T]}{[p_T]} \right)^2 \right\rangle \propto \beta_2^2$$

large enhancement in mean and variance ⟶ size fluctuations enhanced

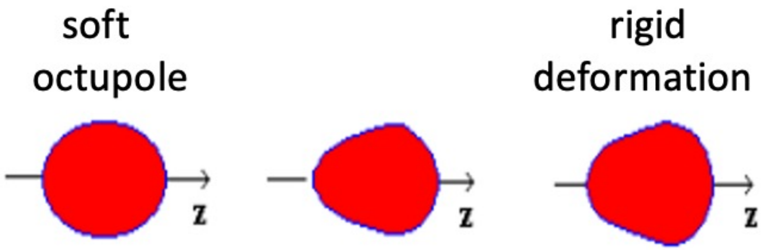
A good probe to image nuclear deformation.

ALICE, *PLB 850, 138541 (2024);* ATLAS, *PRL 133, 252301 (2024);* G. Giacalone, J. Jia, C. Zhang, *PRL 127, 242301 (2021)*

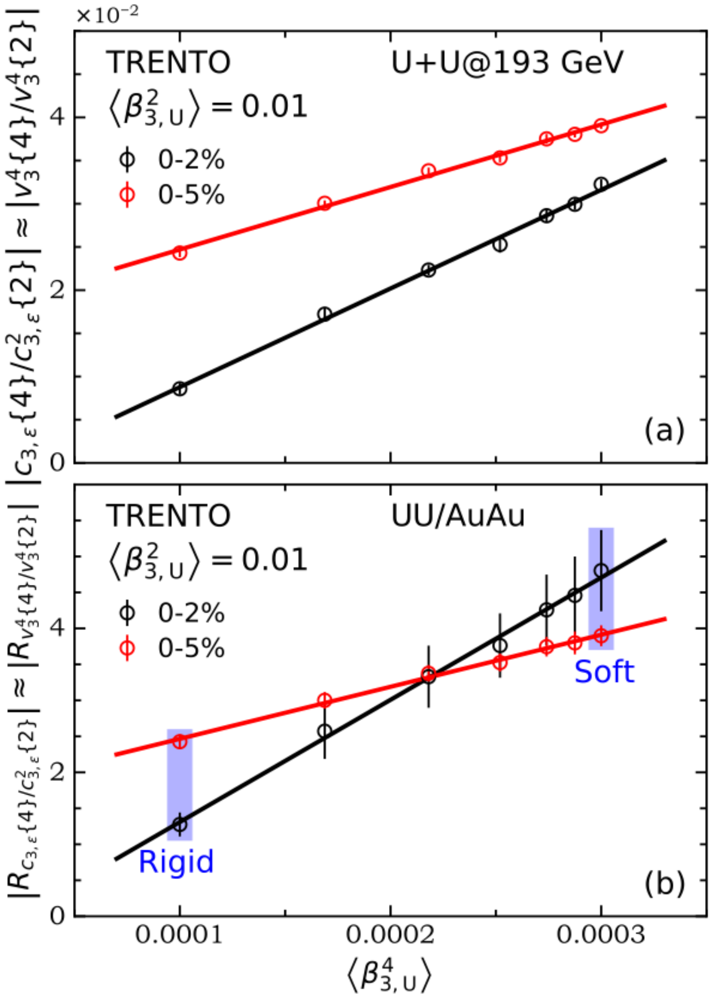
Probe $\beta_{3,\mathrm{U}}$ and its fluctuation

Octupole "collectivity"

L. Liu, C. Zhang, J. Chen, J. Jia, X. Huang, Y.-G. Ma, *Phys. Lett. B 879, 140636 (2026)*



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



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

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

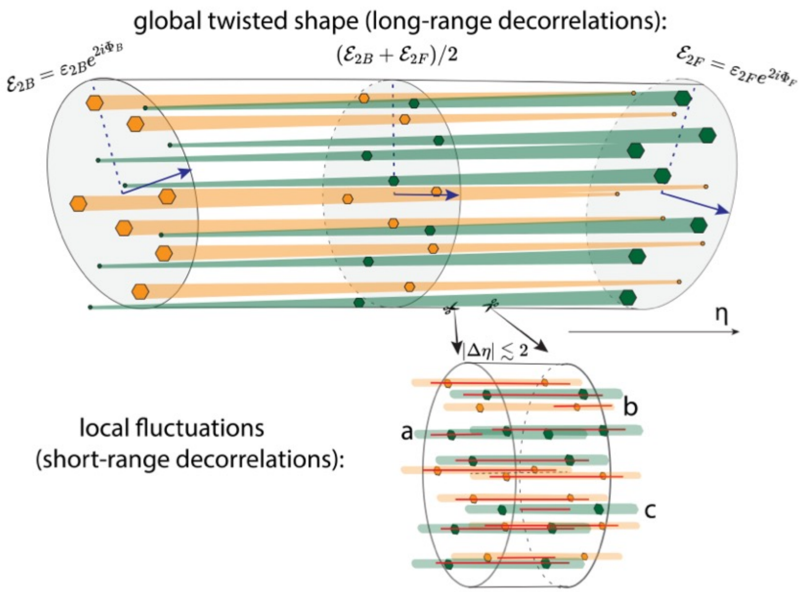
$$c_{n,\varepsilon}\{4\} = \langle\varepsilon_n^4\rangle - 2\langle\varepsilon_n^2\rangle^2$$
$$\approx \langle\varepsilon_{n,0}^4\rangle - 2\langle\varepsilon_{n,0}^2\rangle^2 + \langle p_n^2 p_n^{2*}\rangle \underline{\langle\beta_n^4\rangle} - 2\langle p_n p_n^*\rangle^2 \underline{\langle\beta_n^2\rangle^2}$$

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)*

3D structure and precise constraints on QGP initial conditions



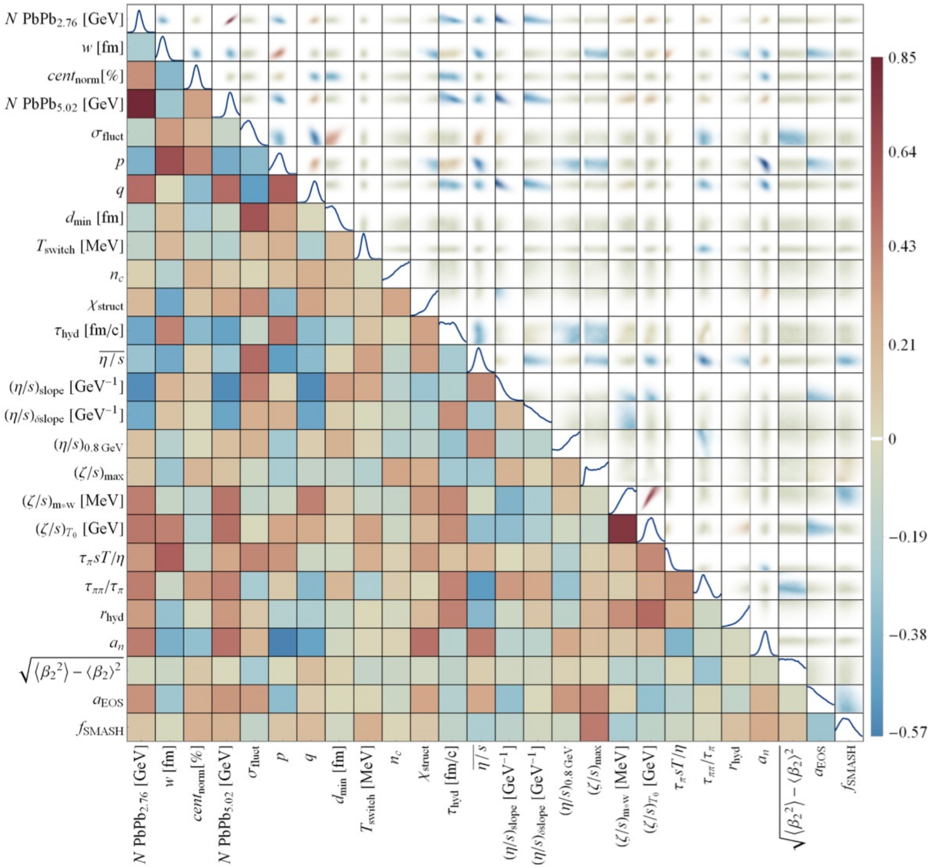
Isolate the decorrelation map of deformation-induced component:

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)*
…

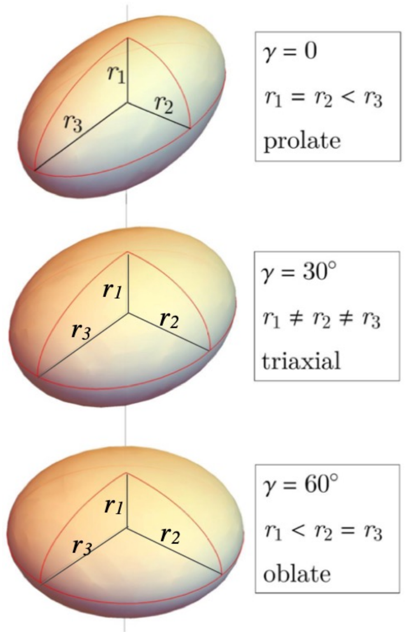
Bayesian Interference

$\otimes$

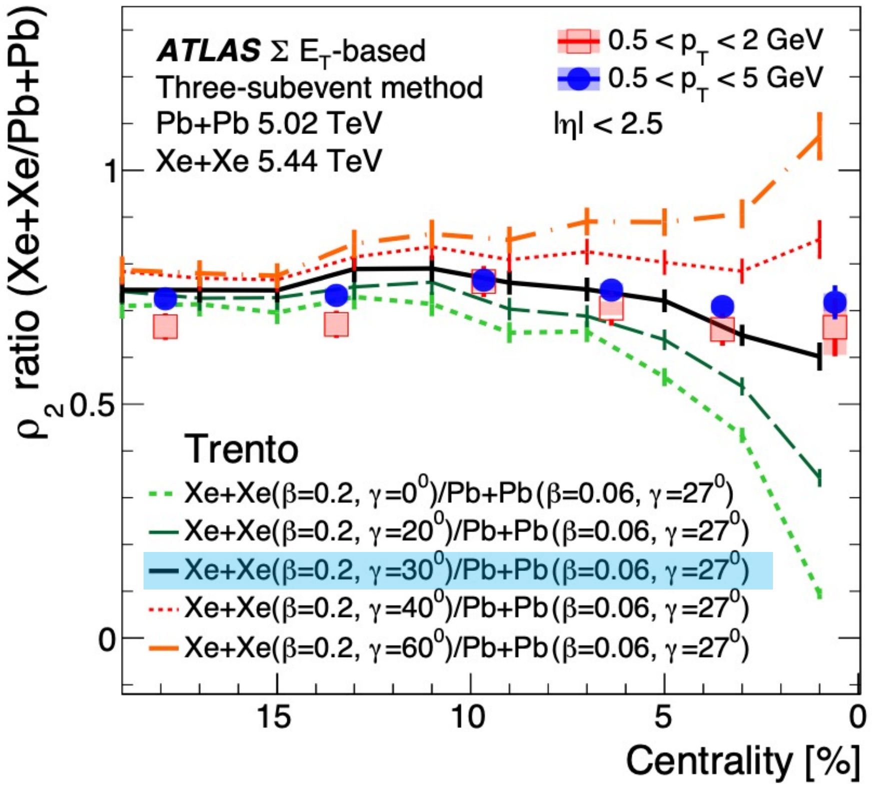


G. Giacalone, G. Nijs, W. Schee, *PRL 131, 202302 (2023)*
S. Jahan, Roch, C. Shen, *PRC 113, 024919 (2026)*
J.E. Bernhard, J.S. Moreland, S.A. Bass, *Nature Physics 15, 1113 (2019)*
D. Everett et al. (JETSCAPE), *PRL 126, 242301 (2021)*
…

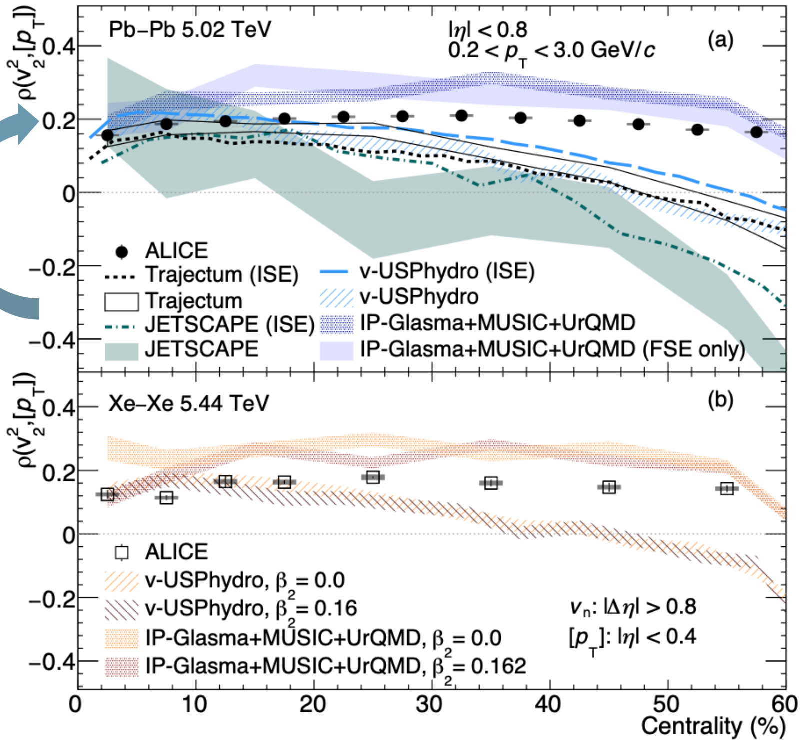
Shape of ground-state ^{129}Xe: $\beta_{2,Xe}$ and γ_{Xe}

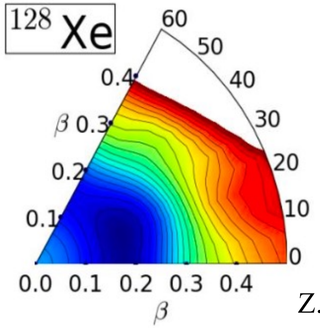


ATLAS, *PRC 107, 054910 (2023)*



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)*