QPT 2025

Guilin, China

A new pathway to probe the structure of nuclei from heavy to light

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Fudan University

24-28, October

Outline

I. Nuclear structure across energy scales

II. Octupole deformation in ground-state ^{238}U nucleus

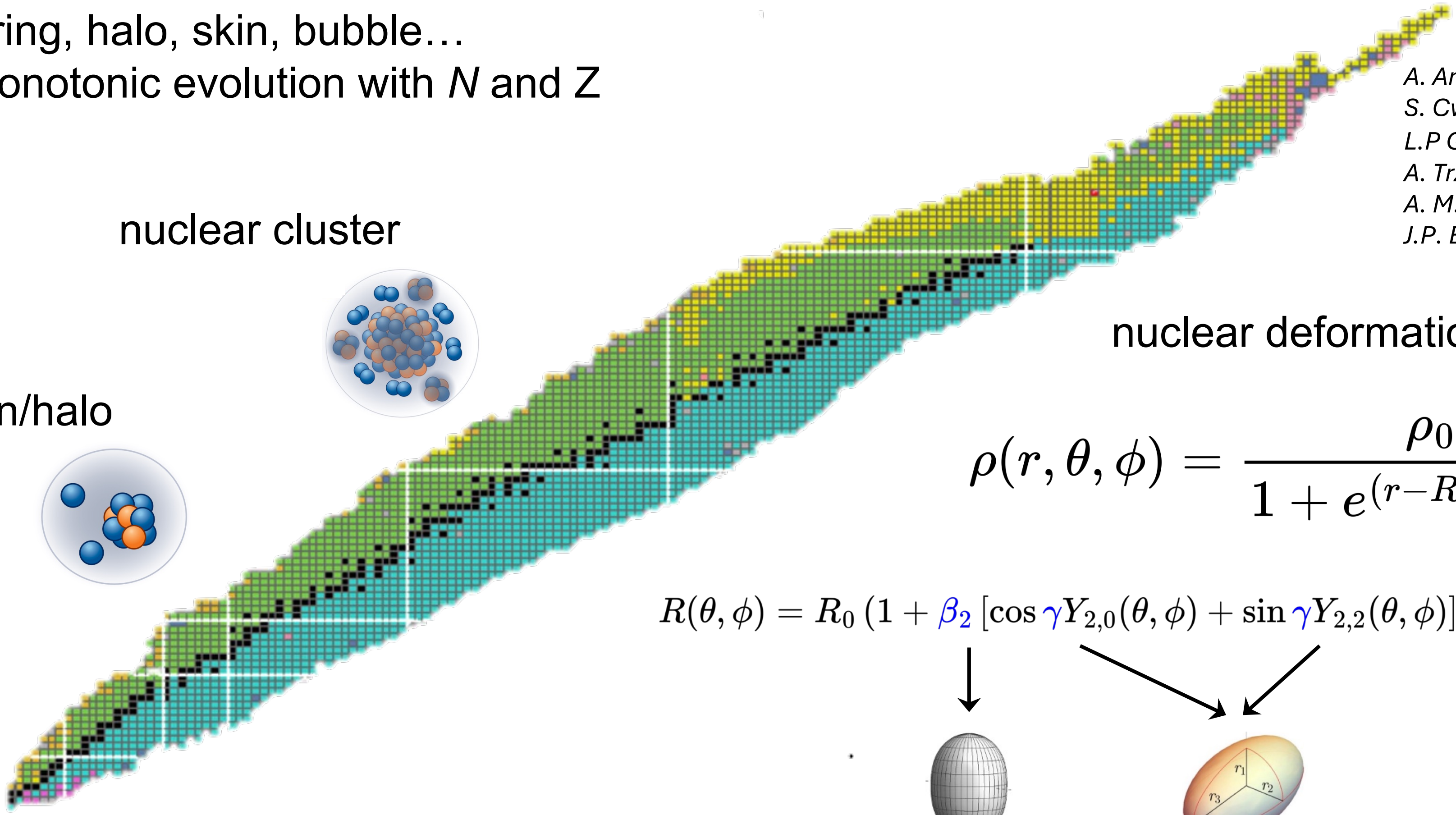
III. Nucleonic clustering in light ^{16}O nucleus

IV. Conclusions and outlooks

Shape of atomic nuclei

Emergent phenomena of the many-body quantum system, govern by short-range strong nuclear force

- Quadrupole/octupole/hexadecapole deformations
- Clustering, halo, skin, bubble…
- Non-monotonic evolution with *N* and *Z*



A. Andreyev et al., Nature 405, 430 (2000)
S. Cwiok et al.,Nature 433, 705 (2005)
L.P Gaffney P. Butler et al., Nature 497, 199 (2013)
A. Trzcinska et al., PRL 87, 082501 (2001)
A. M. Centelles et al., PRL 102, 122502 (2009)
J.P. Ebran et al. Nature 487, 341 (2012)

nuclear cluster

neutron skin/halo

Z (proton numbers)

N (neutron numbers)

nuclear deformation

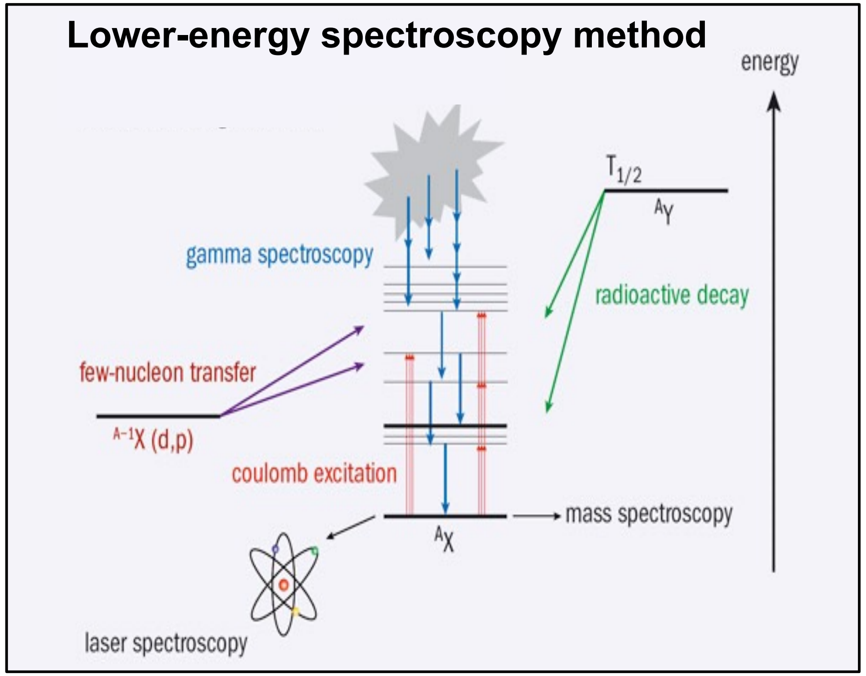
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

Very rich landscape of shapes and other structures

Y. Ye, X. Yang, H. Sakurai, B. Hu, Nature Review Physics, 7, 21-37 (2025); Y. Ma, S. Zhang, Handbook of Nuclear Physics (2022)

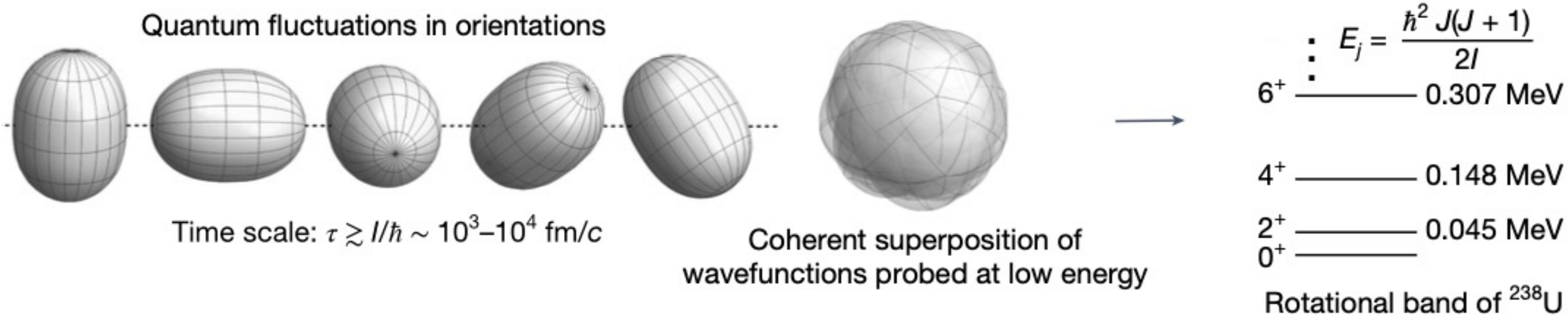
Nuclear shape at low energy: long exposure



Traditional imaging method taken before destruction

→ Low energy spectroscopic methods probe a superposition of these fluctuations.
→ Instantaneous shapes not directly seen, but inferred from model comparison.

Each DOF has zero-point fluctuations within certain timescales.



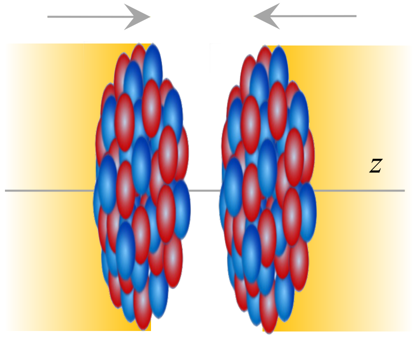
Imaging by smashing method

Take a snapshot

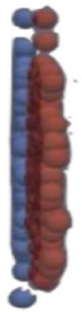
Evolution

Measurement

Nuclei collisions



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



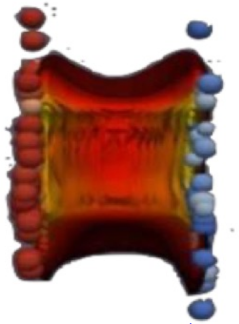
$\tau \sim 2R_0/\Gamma \sim 0.1\mathrm{fm}/c$

exposure

Pressure-driven expansion of

Quark-gluon plasma (QGP)

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

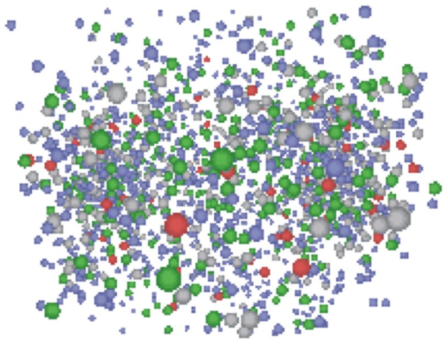


$\tau \sim 10\mathrm{fm}/c$

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

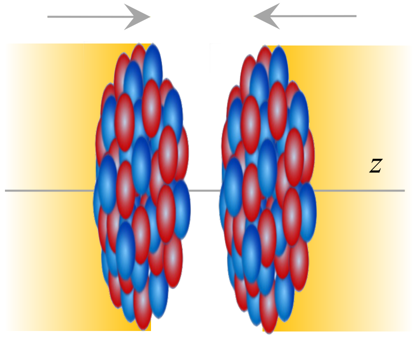
ab initio theory/shell model/DFT

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

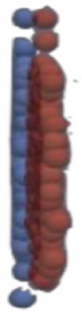
Imaging by smashing method

Take a snapshot | Evolution | Measurement

Nuclei collisions



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



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

Pressure-driven expansion of

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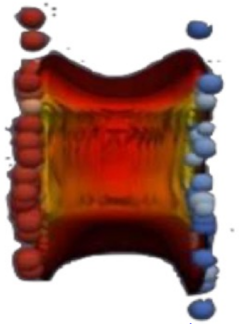

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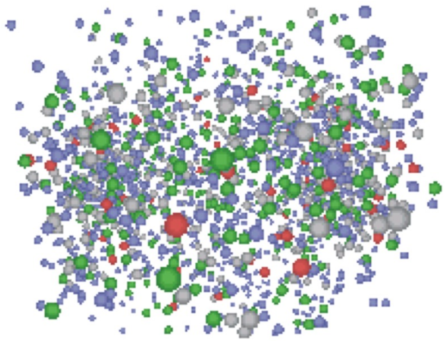
$T_{\mu\nu}(\tau=\infty)$



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

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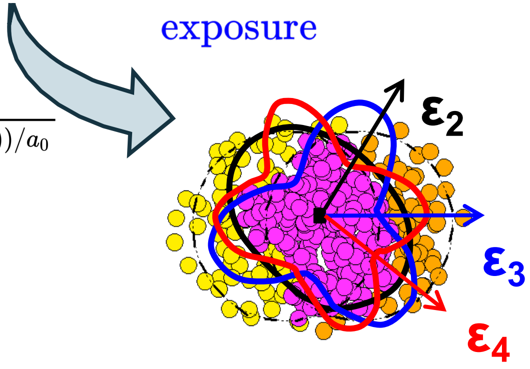
- β_3 → octupole deformation
- γ → triaxiality
- a_0 → surface diffuseness
- R_0 → nuclear size

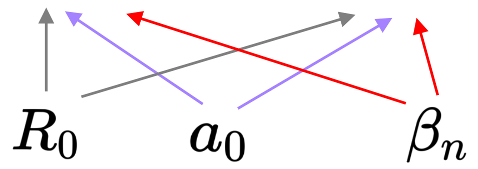
ab initio theory/shell model/DFT



size & shape

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

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



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

Event-by-event linear responses:

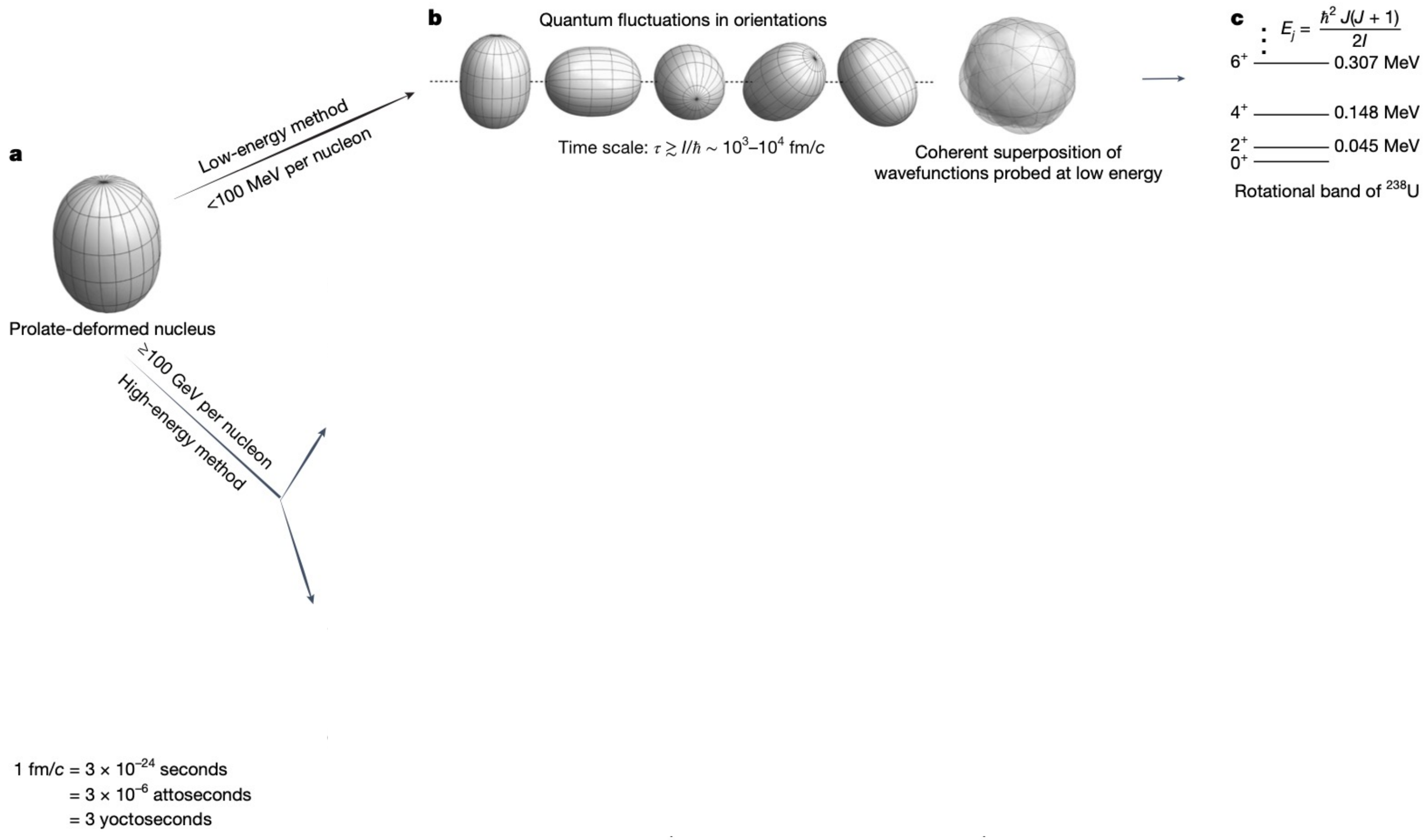
$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

G. Giacalone et al., PRC 103, 024909 (2021); H. Niemi et al., PRC 87, 054901 (2013)

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

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.



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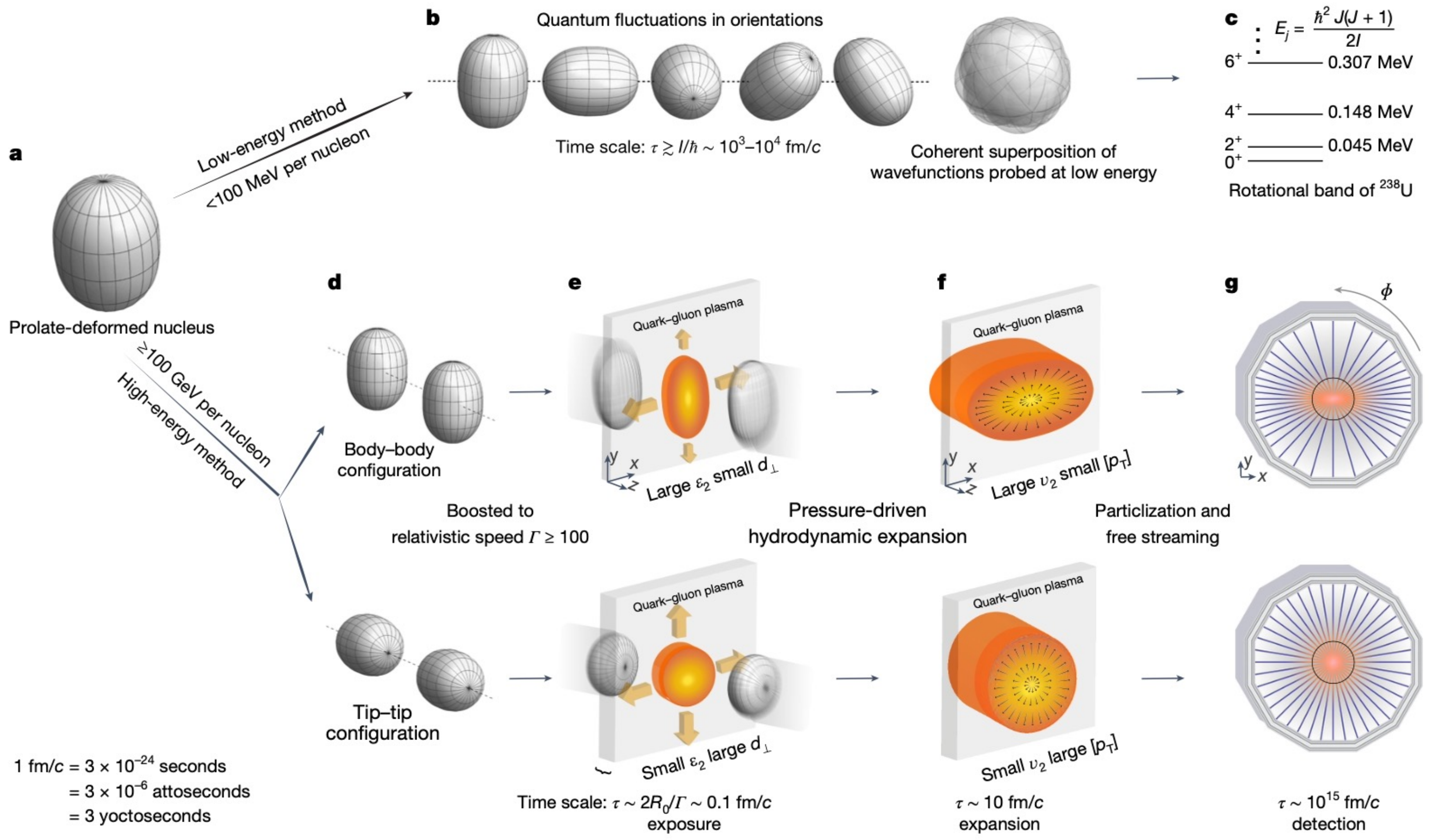


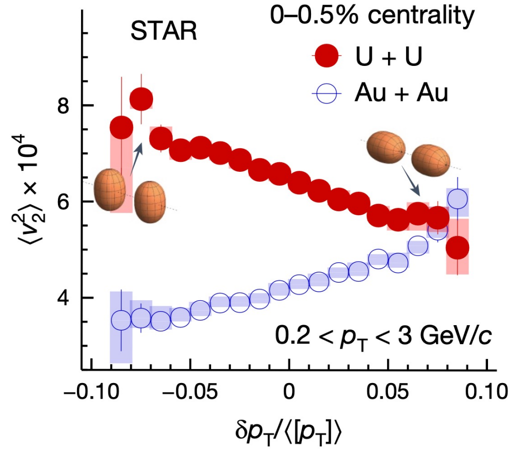
STAR, Nature 635, 67-72 (2024)
https://www.nature.com/articles/s41586-024-08097-2

Body-body: large-eccentricity large-size

$v_2\nearrow$ $p_T\searrow$

Tip-tip : small-eccentricity small-size

$v_2\searrow$ $p_T\nearrow$



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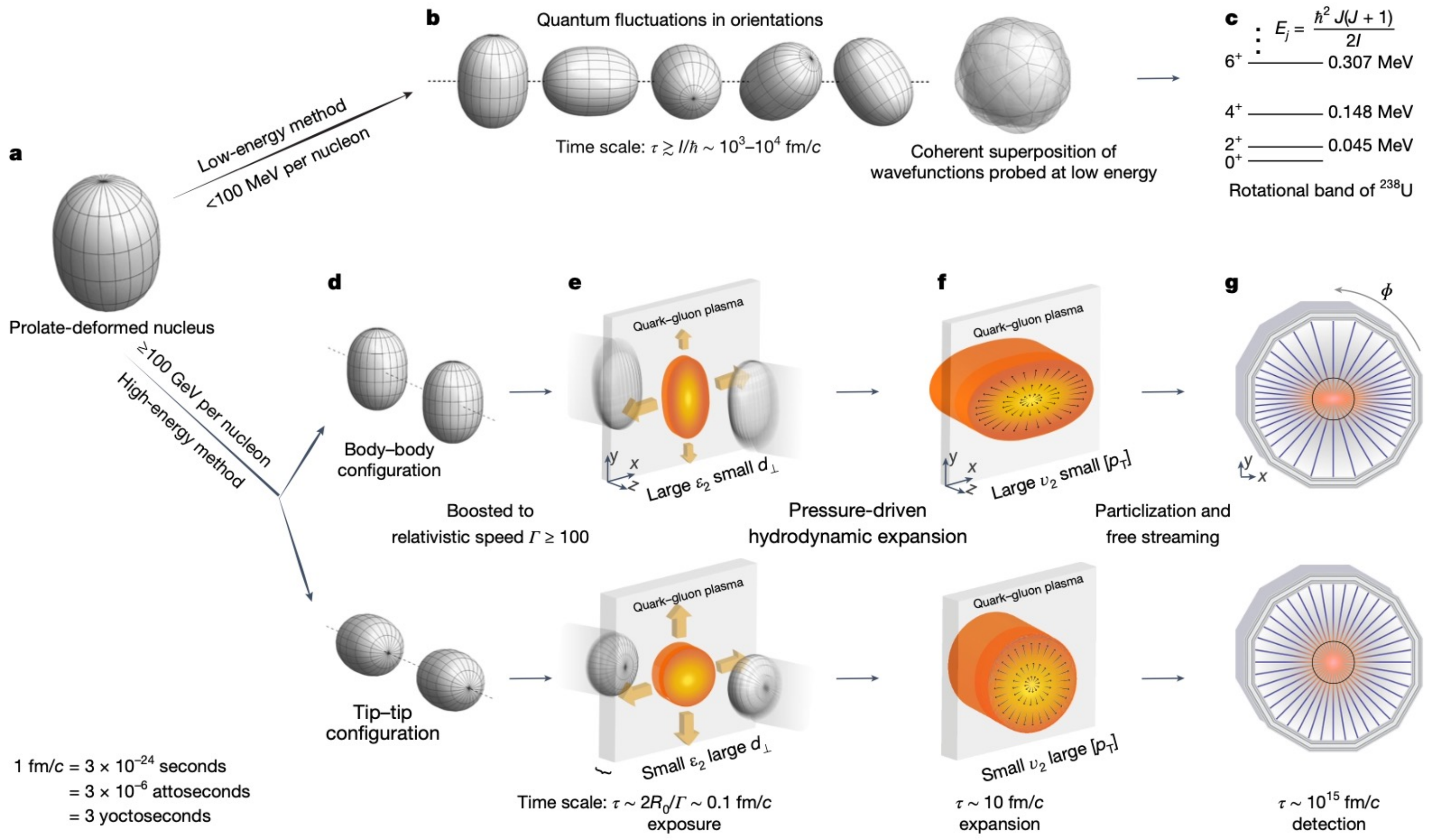


STAR, Nature 635, 67-72 (2024)

https://www.nature.com/articles/s41586-024-08097-2

across energy scales

Body-body: large-eccentricity large-size

$v_2 \nearrow$ $p_T \searrow$

Tip-tip : small-eccentricity small-size

$v_2 \searrow$ $p_T \nearrow$

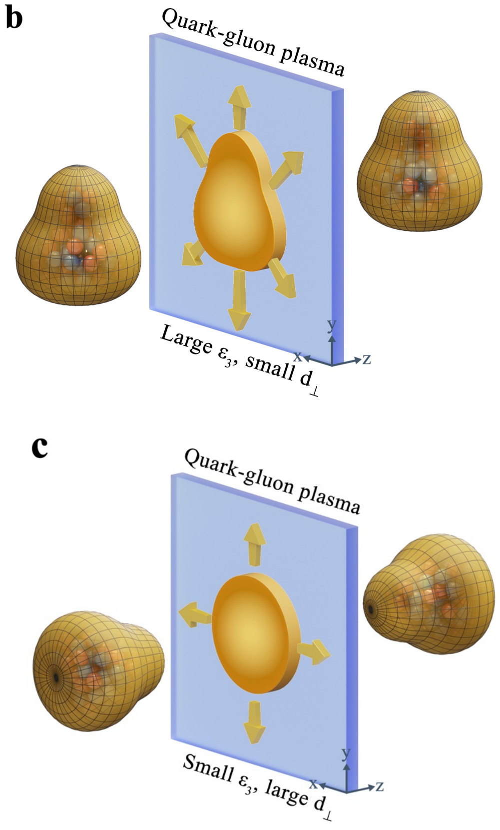
$$\langle v_2^2 \rangle = a_1 + b_1 \beta_2^2,$$
$$\langle (\delta p_T)^2 \rangle = a_2 + b_2 \beta_2^2,$$
$$\langle v_2^2 \delta p_T \rangle = a_3 - b_3 \beta_2^3 \cos(3\gamma).$$

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

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

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



However, v_3 is fluctuation driven, expect in central

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

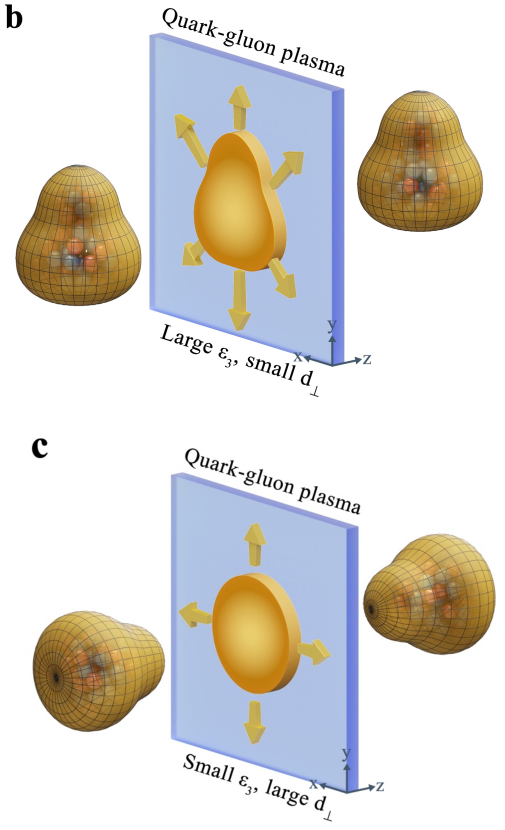
mass number

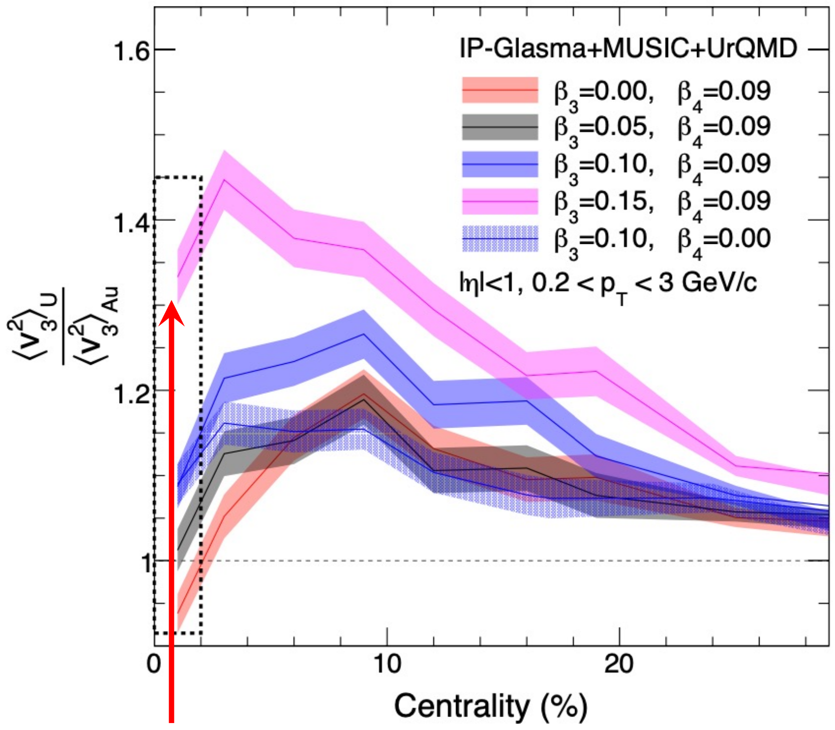
B. Alver and G. Roland, PRC 81, 054905 (2010)

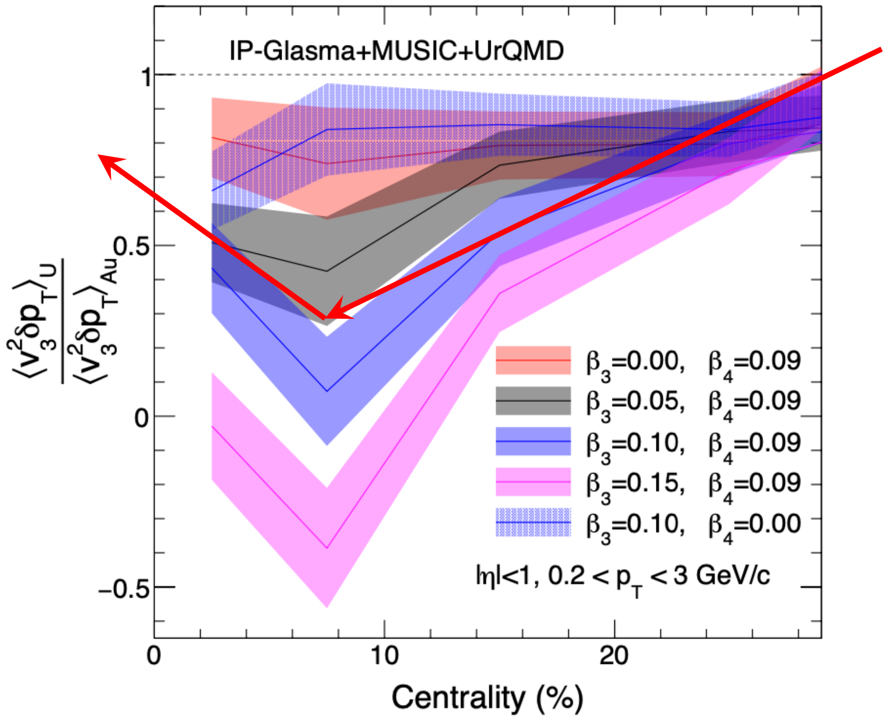
Evidence of octupole deformation $\beta_{3,\mathrm{U}}$

IP-Glasma+MUSIC calculations

C. Zhang, J. Jia, J. Chen, C. Shen, L. Liu, arXiv: 2504.15245







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

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

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,

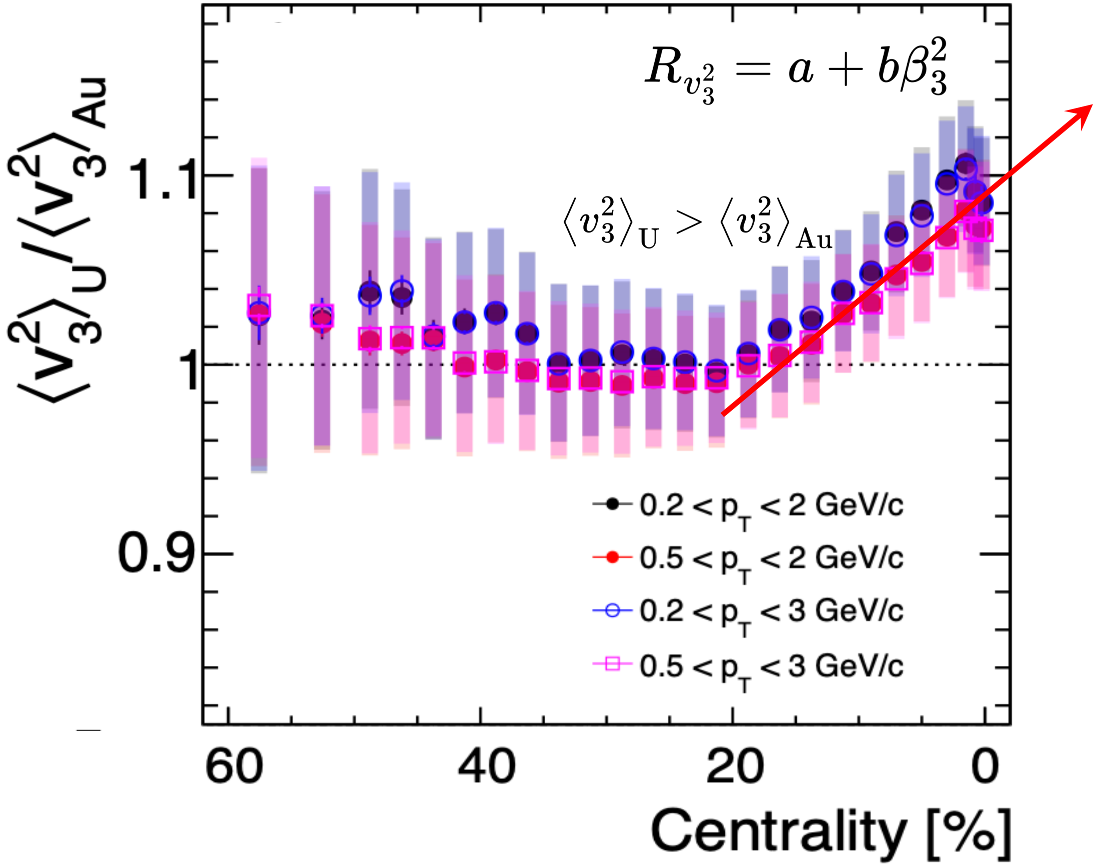
Characteristic anticorrelation in $\langle v_3^2\delta p_{\mathrm{T}}\rangle$ shows a pronounced β_3-dependent suppression.

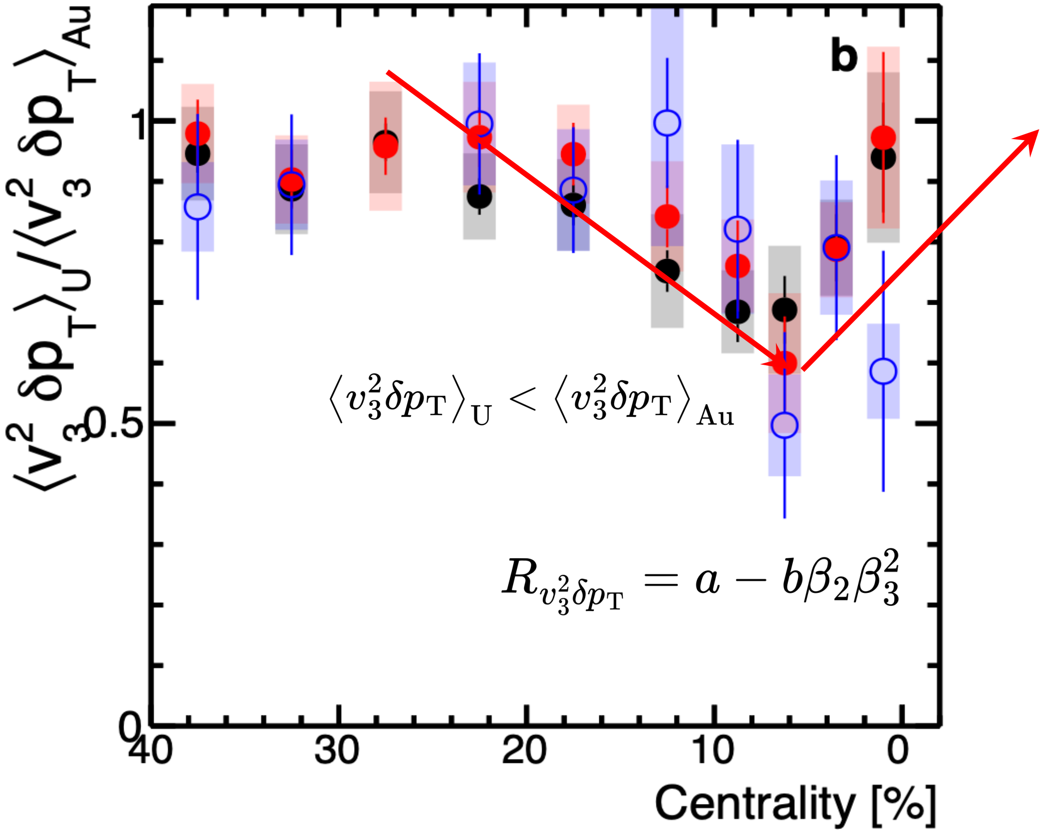
B. Alver and G. Roland, PRC 81, 054905 (2010)

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

New

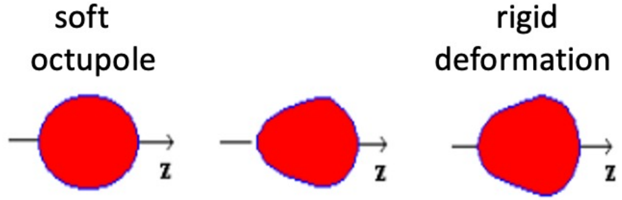
STAR, Rep. Prog. Phys. **88,** 108601 (2025)





Order of v_3 and v_3-p_T reversed by considering non-zero $\beta_{3,\mathrm{U}}$, $\beta_{4,\mathrm{U}}$.

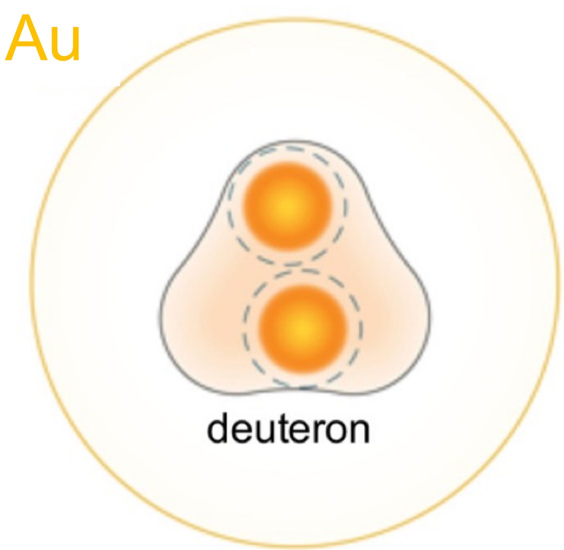
An evidence and modest $\beta_{3,\mathrm{U}} \sim 0.08$-$0.10$ are confirmed.



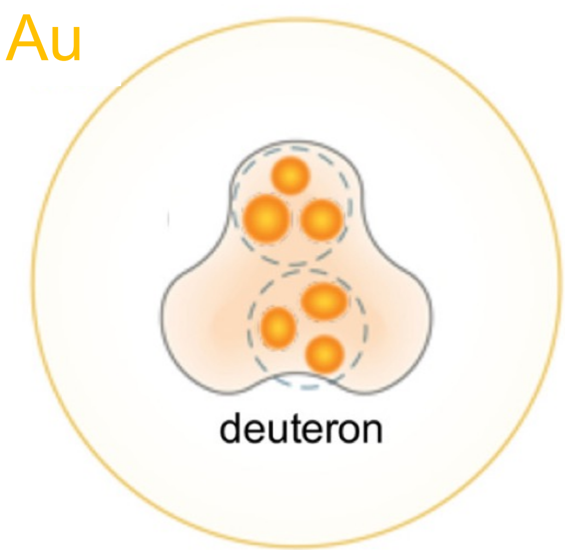
H. Xu, D. Xu, S. Zhao, W. Zhao, H. Song, F. Wang, 2504.19644; K. Hagino and M. Kitazawa, 2508.05125; *L. Liu, C. Zhang, J. Chen, J. Jia, X. Huang, Y. Ma, 2509.09376*

Light nuclear geometry and nucleon nucleon correlations

Nucleon fluctuation



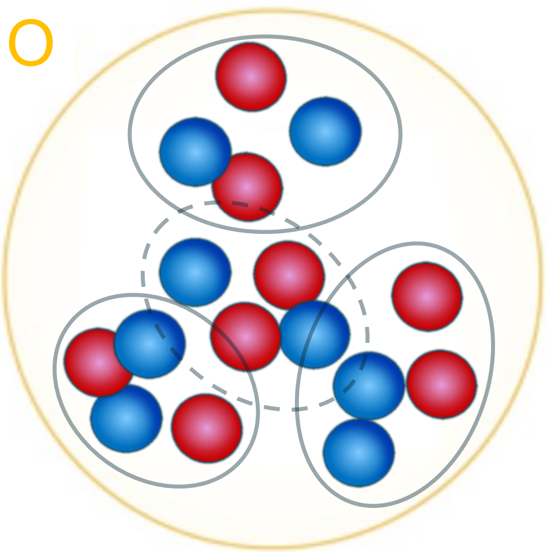
Nucleon & subnucleon fluctuation

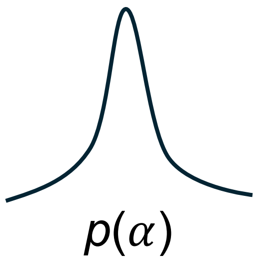


STAR, *PRL 130, 242301 (2023)*

STAR, *PRC 110, 064902 (2024)*

Nucleon-nucleon correlation





ab initio calculations

W. He, Y. Ma et al., *PRL 113, 032506 (2014);…*

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

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

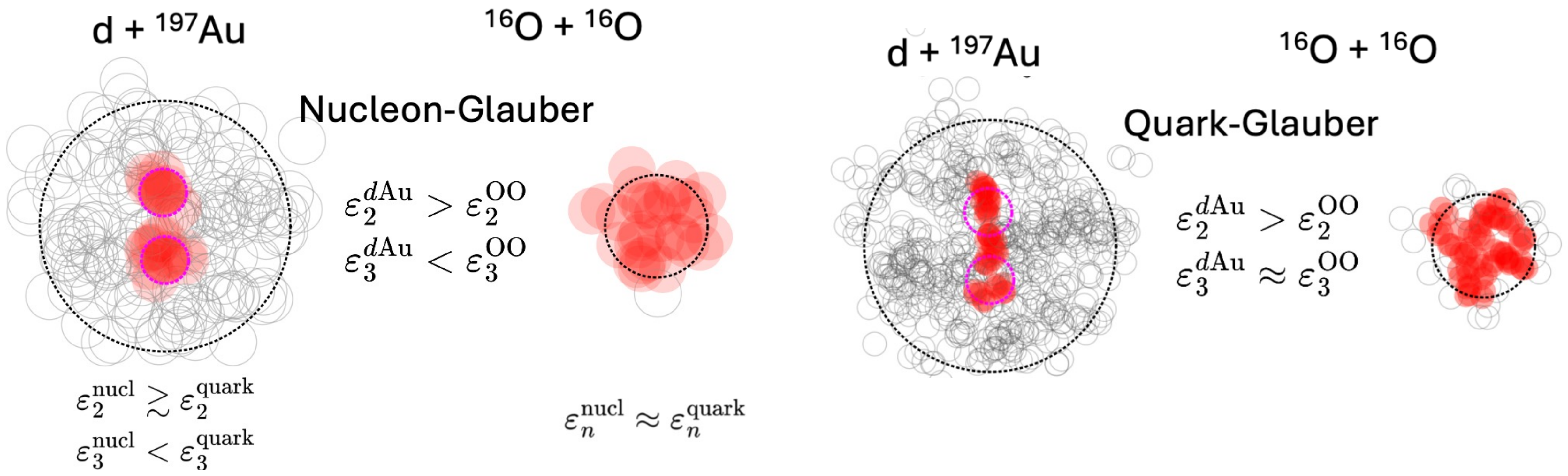
…

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

Benchmarking geometric tomography of ^{16}O nucleus

New

STAR, *2510.19645*

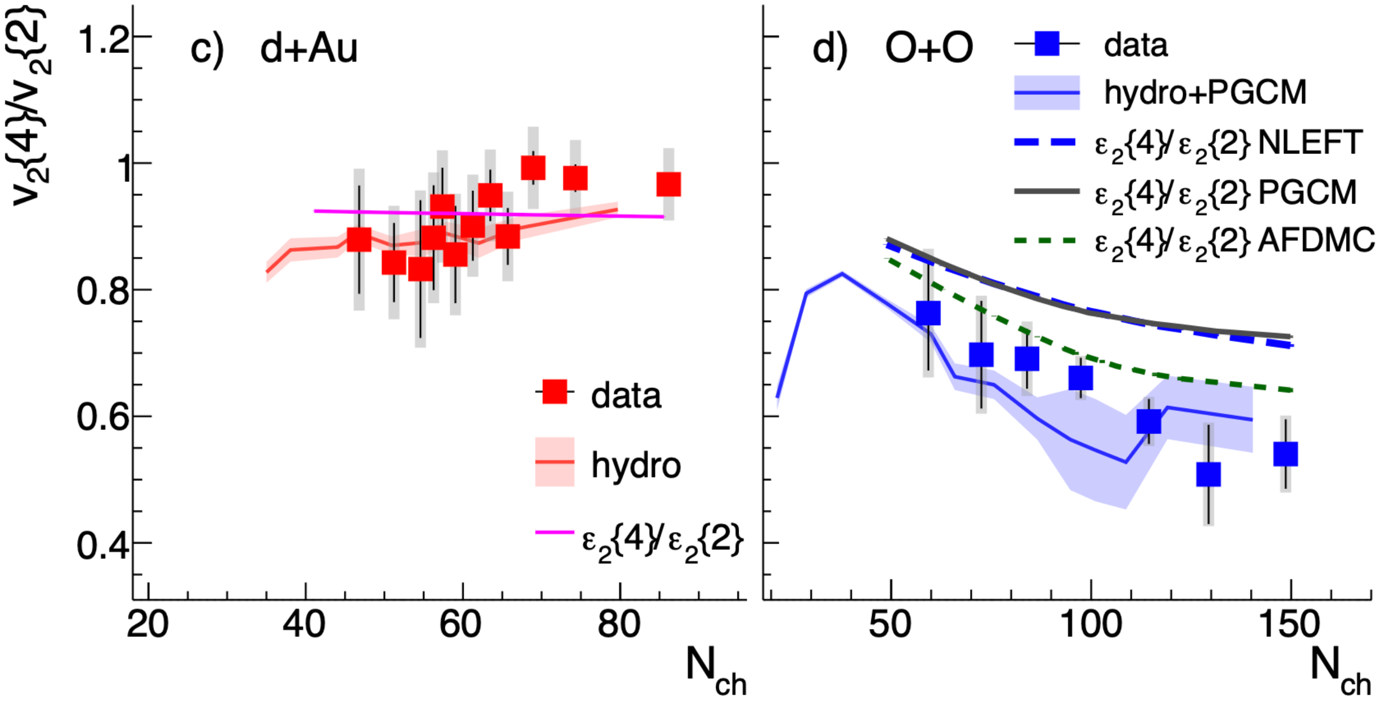


Nucleon-Glauber and quark-Glauber yield different triangular v_3

Benchmarking geometric tomography of ^{16}O nucleus

New

STAR, *2510.19645*



$\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from three models:
AFDMC vs. EFT/PGCM have a visible difference.

Can many-nucleon correlations significantly impact the eccentricity fluctuations? YES!

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

STAR, PRL 130, 242301 (2023)

$$(v_n\{2\})^2 = c_n\{2\} = \langle v_n^2 \rangle \qquad \varepsilon_2\{2\}^2 = \langle \varepsilon_2^2 \rangle$$

$$(v_n\{4\})^4 = -c_n\{4\} = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle \qquad \varepsilon_2\{4\}^4 = 2\langle \varepsilon_2^2 \rangle^2 - \langle \varepsilon_2^4 \rangle$$

Y. Ma, S. Zhang, Handbook of Nuclear Physics (2022); W. He, Y. Ma et al, PRL 113, 032506 (2014)

G. Giacalone, G. Nijs et al., PRL135, 012302 (2025), G. Giacalone, W. Zhao et al., PRL134, 082301 (2025); *C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y. Ma, PLB 862, 139322 (2025)*

Y. Wang, S. Zhao, B. Cao, H. Xu, H. Song, PRC 109, L051904 (2024); X. Zhao, G. Ma. Y. Zhou, Z. Lin, C. Zhang, 2404.09780; S. Jahan, Roch, C. Shen, 2507. 11394

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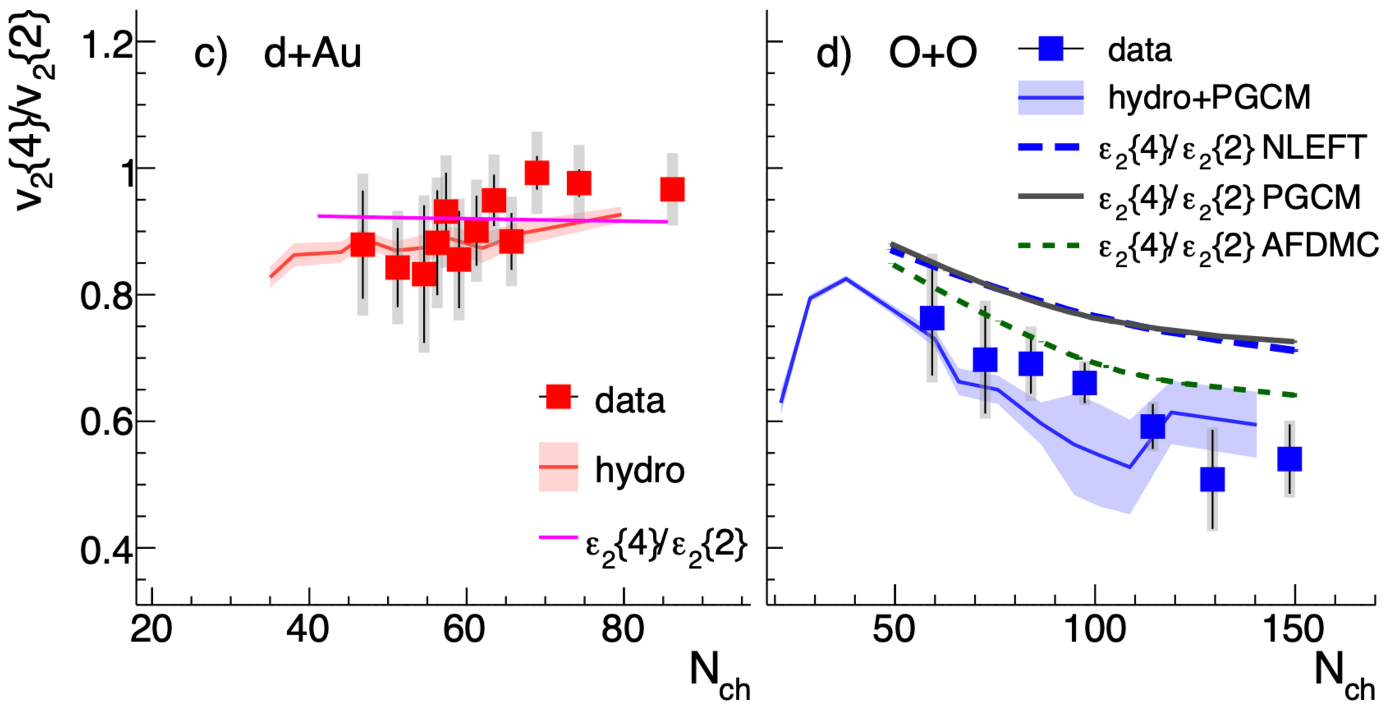

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STAR, PRL 130, 242301 (2023)

Geometric scan elucidates nuclear tomography and strong nuclear force?

Need more low-energy model inputs.

$$(v_n\{2\})^2 = c_n\{2\} = \langle v_n^2 \rangle \qquad \varepsilon_2\{2\}^2 = \langle \varepsilon_2^2 \rangle$$

$$(v_n\{4\})^4 = -c_n\{4\} = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle \qquad \varepsilon_2\{4\}^4 = 2\langle \varepsilon_2^2 \rangle^2 - \langle \varepsilon_2^4 \rangle$$

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Benchmarking geometric tomography of ^{16}O nucleus

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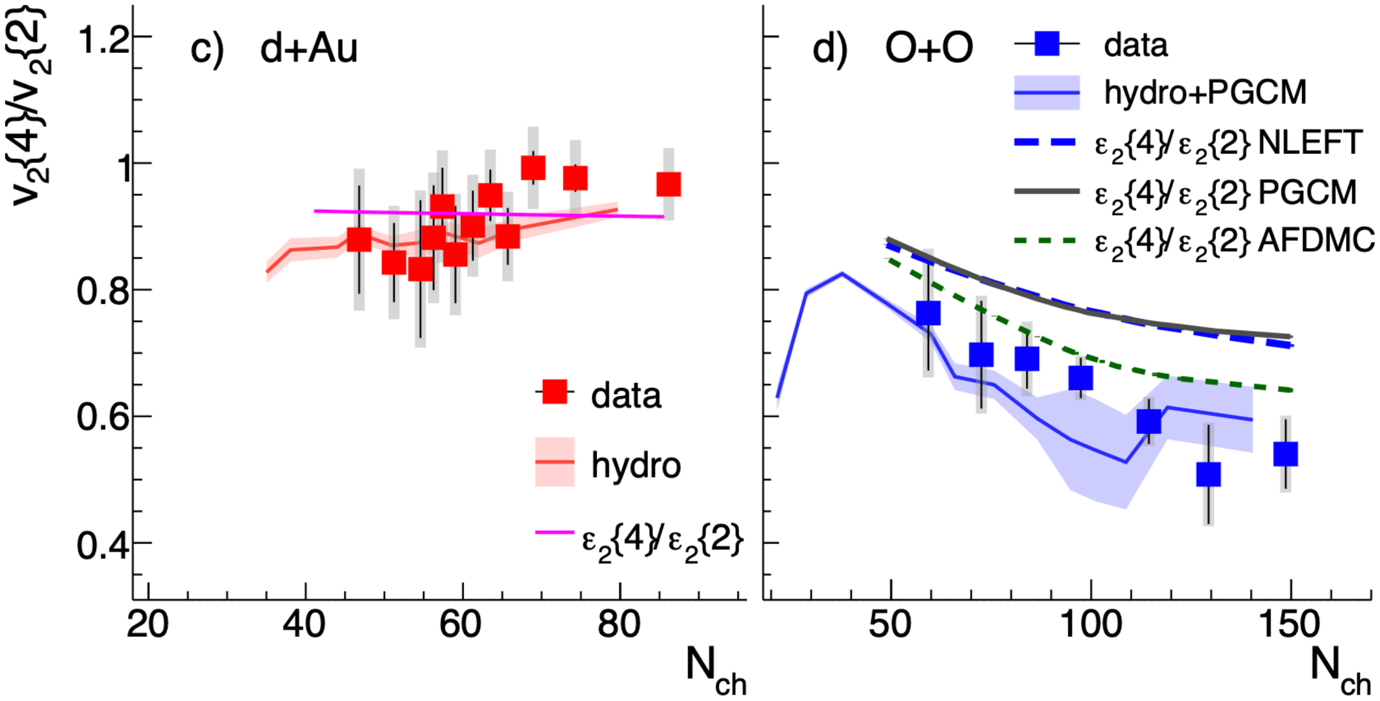
STAR, *2510.19645*



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STAR, *PRL 130, 242301 (2023)*

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LHC (ALICE, ATLAS, CMS, LHCb) also released the O+O/Ne+Ne!!
Shape imaging method for light ions (New avenue)

Y. Ma, S. Zhang, Handbook of Nuclear Physics (2022); W. He, Y. Ma et al, PRL 113, 032506 (2014)
G. Giacalone, G. Nijs et al., PRL135, 012302 (2025), G. Giacalone, W. Zhao et al., PRL134, 082301 (2025); *C. Zhang, J. Chen, G. Giacalone, S. Huang, J. Jia, Y. Ma, PLB 862, 139322 (2025)*
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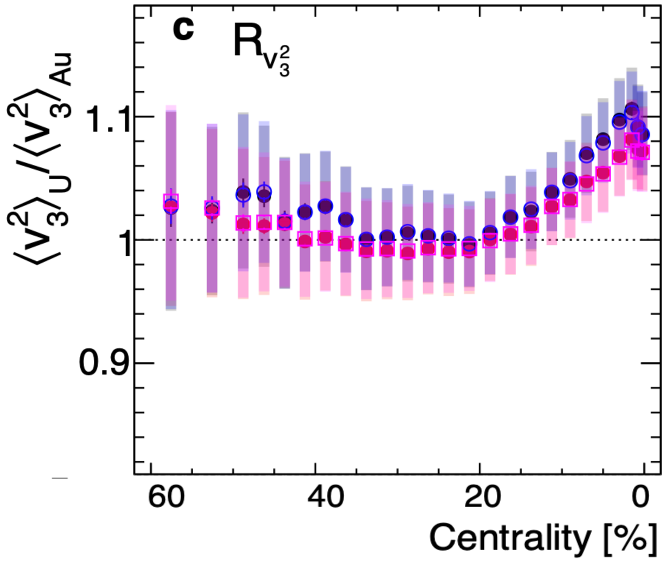
IV. Conclusions and Outlooks

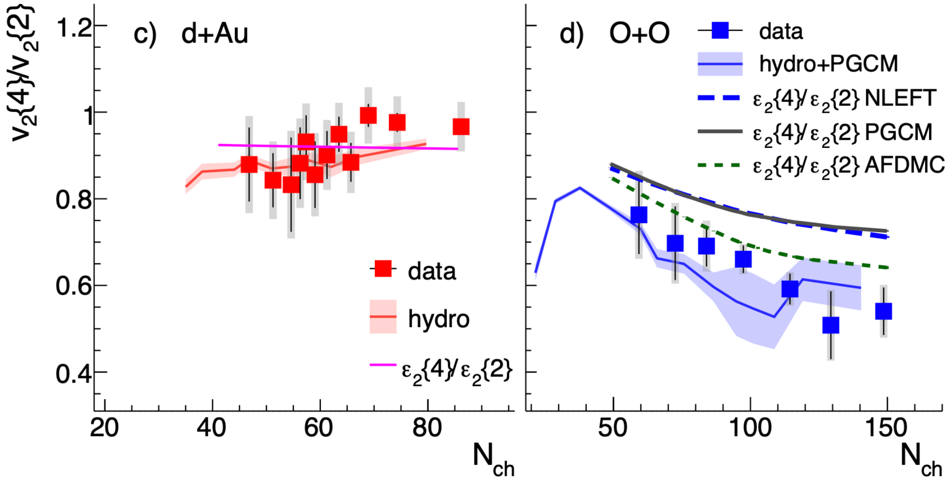
1. The signatures of nuclear structure in nuclear collisions are ubiquitous:

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



$\beta_{3U} = 0.08 - 0.1; \quad \beta_{3U} \sim \beta_{4U}$

STAR, *2510.19645*



Nucleon-nucleon correlation is remarkable

Nuclear mass number (A)

2. Many potential applications from large to small collision systems :

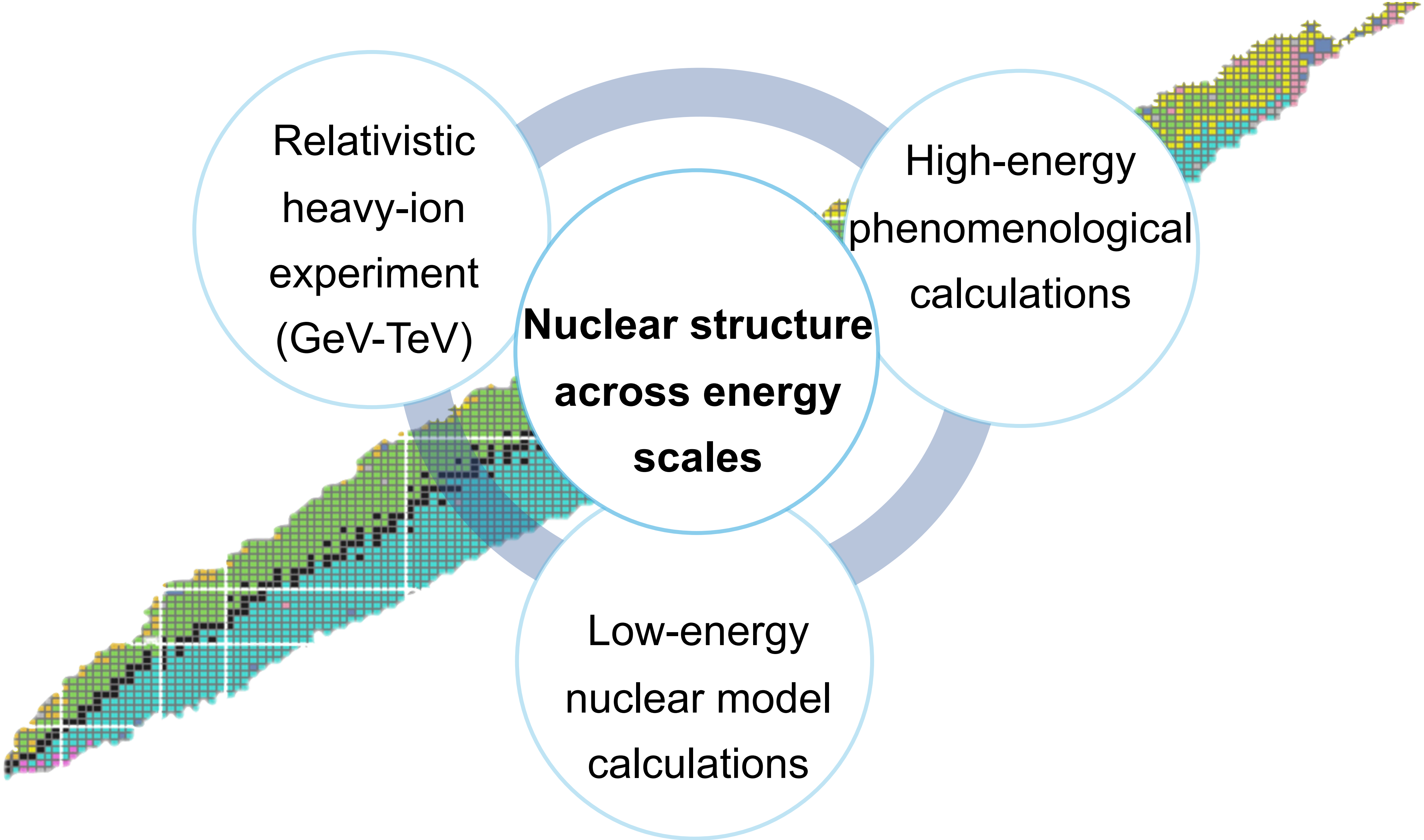
→ Nucleosynthesis, nuclear fission, $0\nu\beta\beta$

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

→ Neutron skin

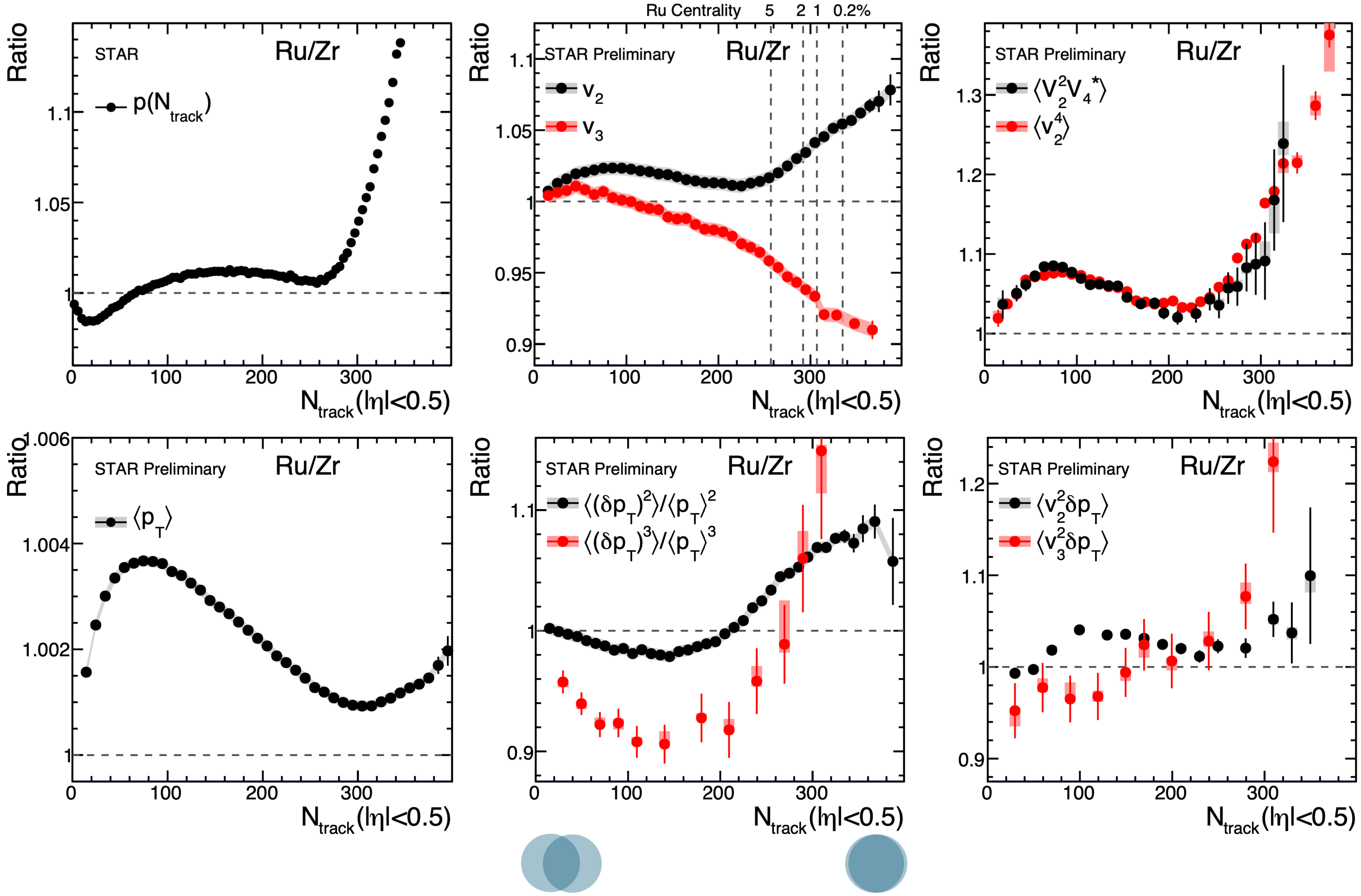
→ Energy evolution between GeV/TeV and MeV in even-and odd-A nuclei

IV. Conclusions and Outlooks



Nuclear structure is inherent of heavy-ion probes

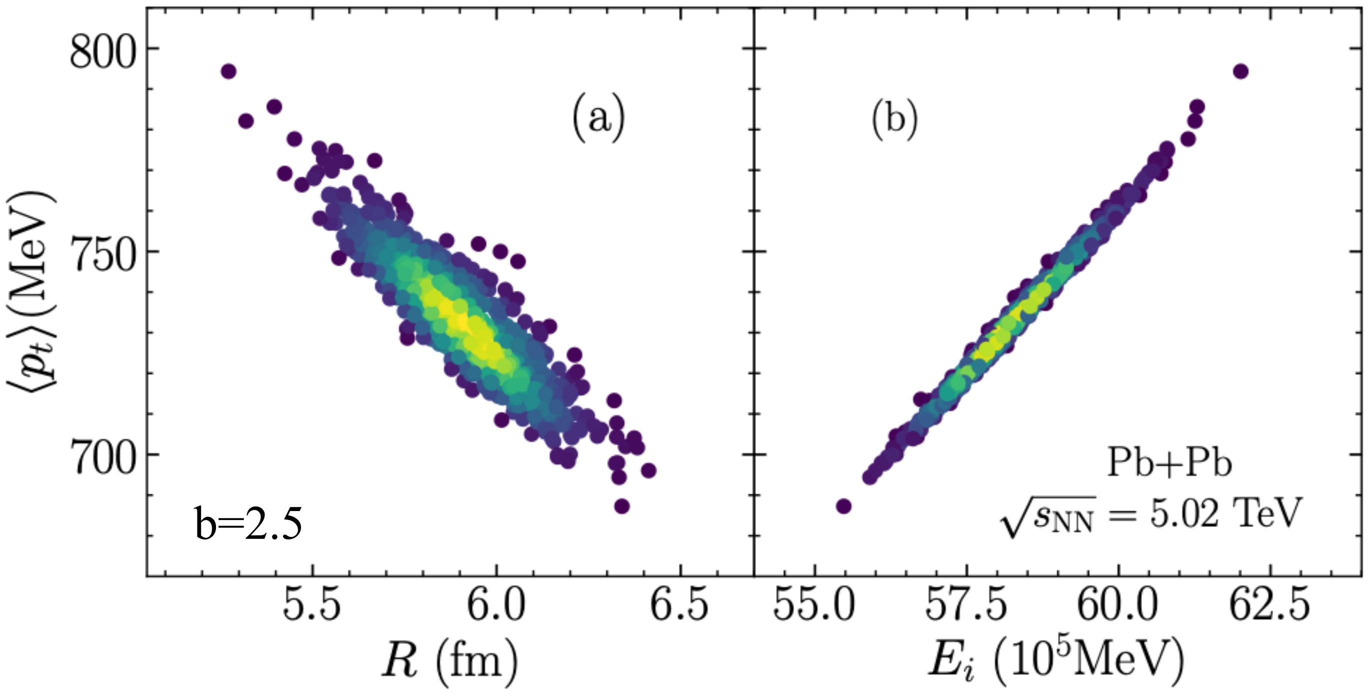
one-body distribution | two-body correlations | three-body correlations

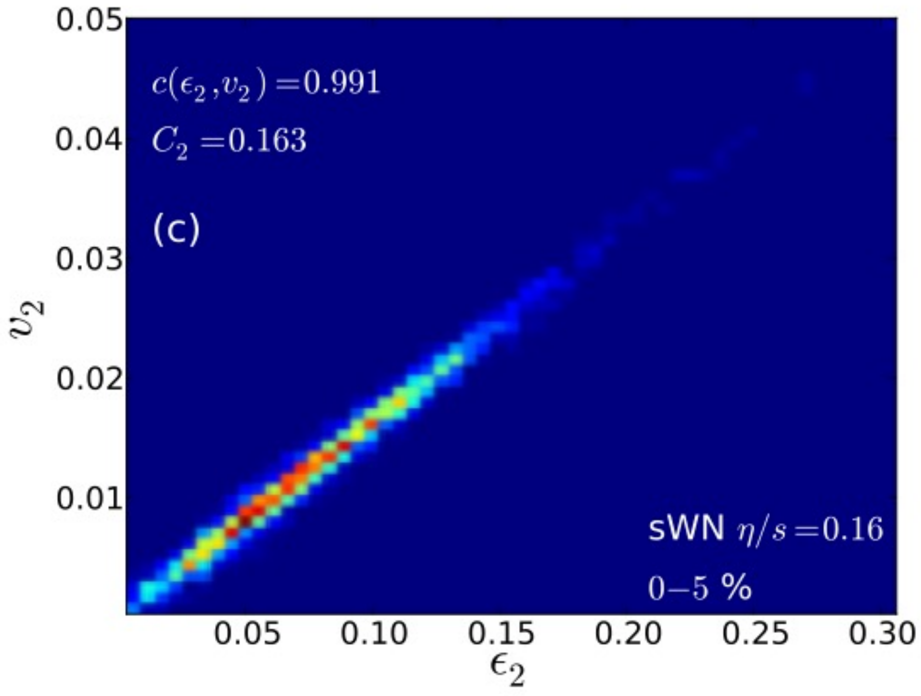


Linear response in ultra-central collisions

$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$$

$$V_n \propto \mathcal{E}_n$$





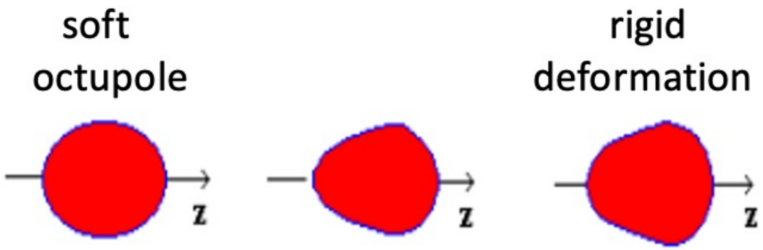
G. Giacalone, F. Gardim, J. Hostler, J. Ollitrault, et al, PRC 103, 024909 (2021)

H. Niemi, G. Denicol, H. Holopainen, P. Huovinen, PRC 87, 054901 (2013)

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

Octupole collectivity

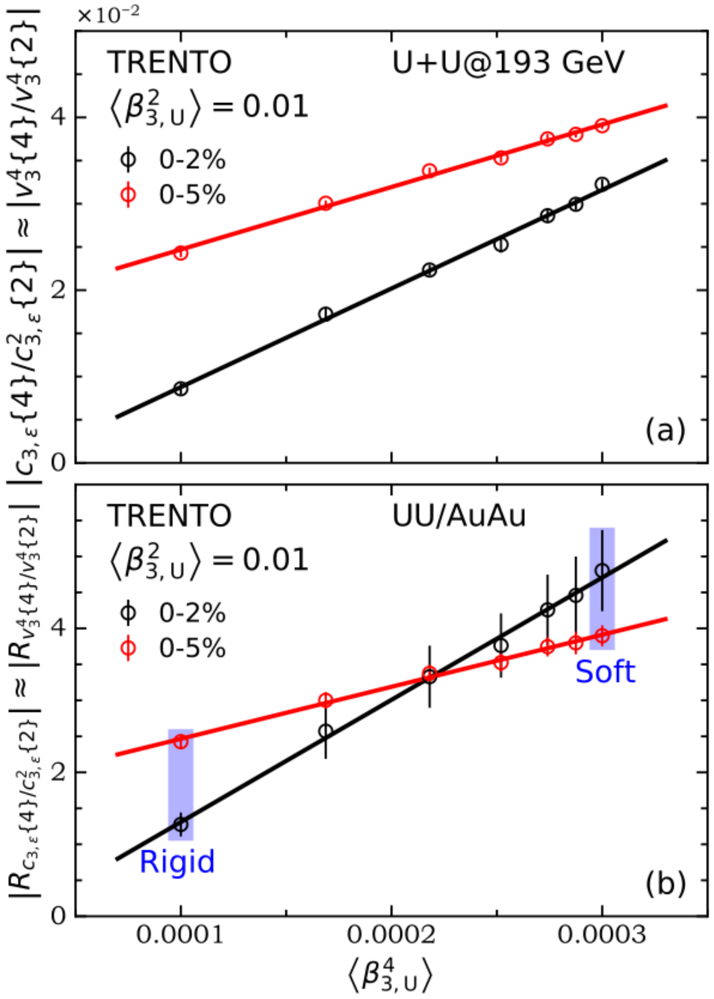
L. Liu, C. Zhang, J. Chen, J. Jia, X. Huang, Y. Ma, 2509.09376



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

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

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



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