第二十届全国中高能核物理大会暨第十四届全国中高能核物理专题研讨会

Nuclear structure through heavy-ion collisions

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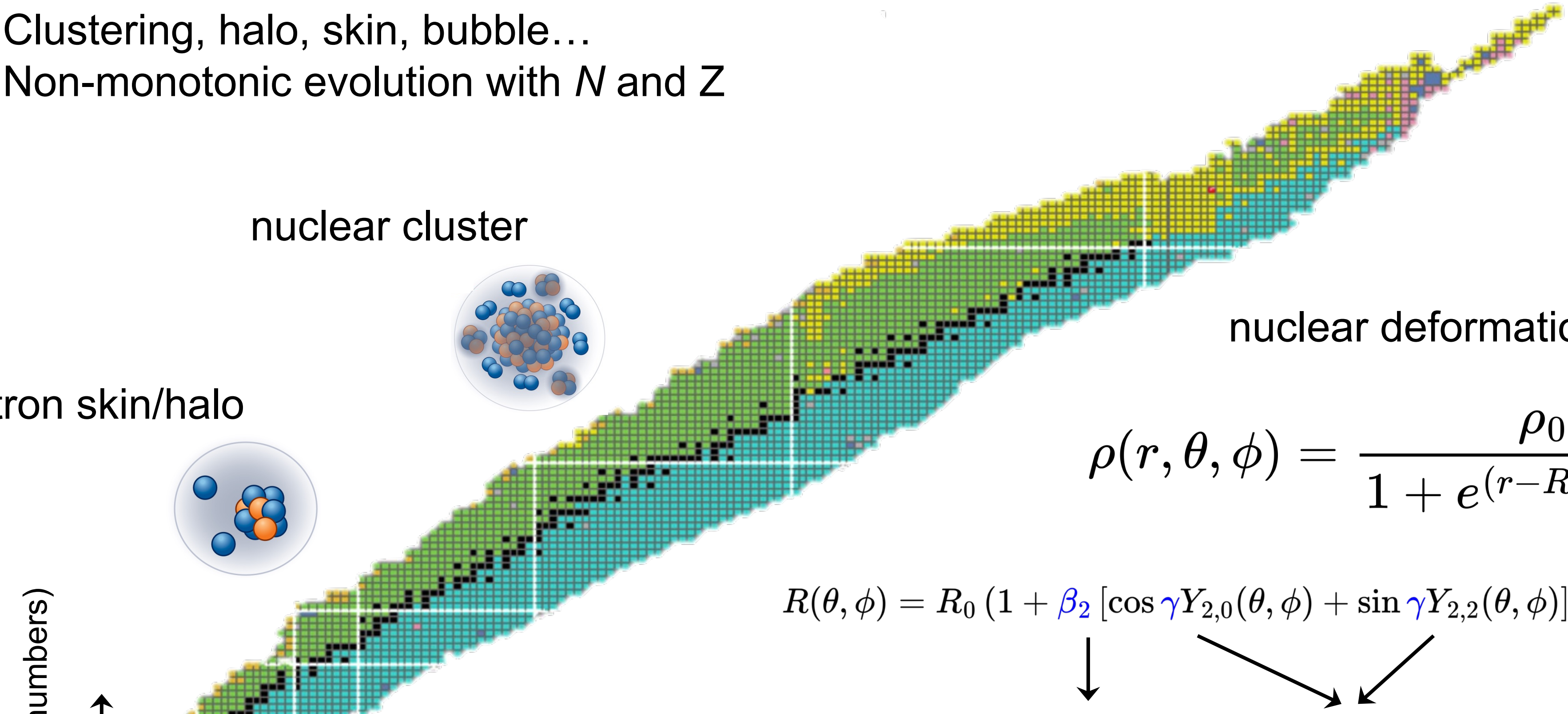
2025年4月25日，上海

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*



nuclear deformation

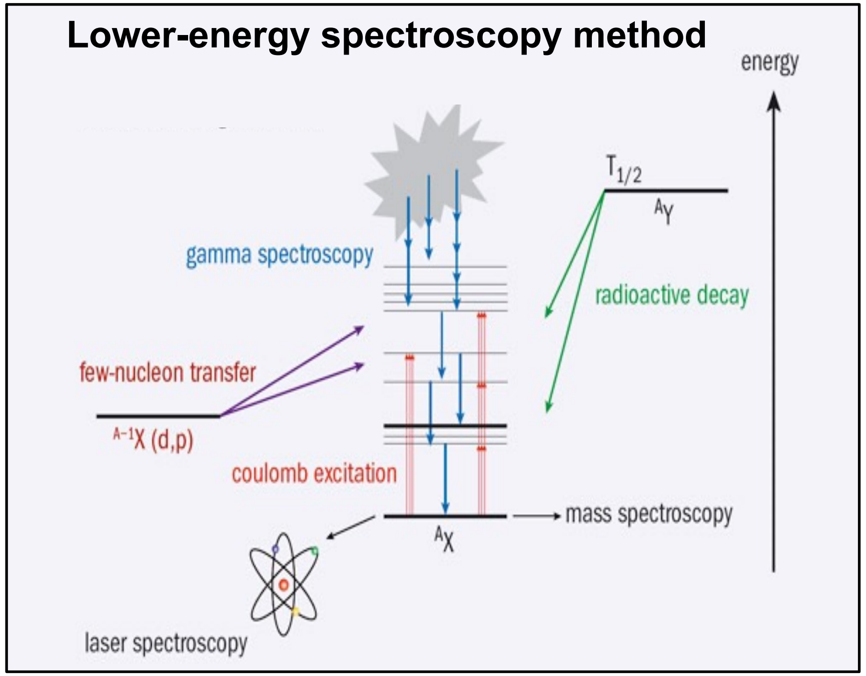
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

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

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

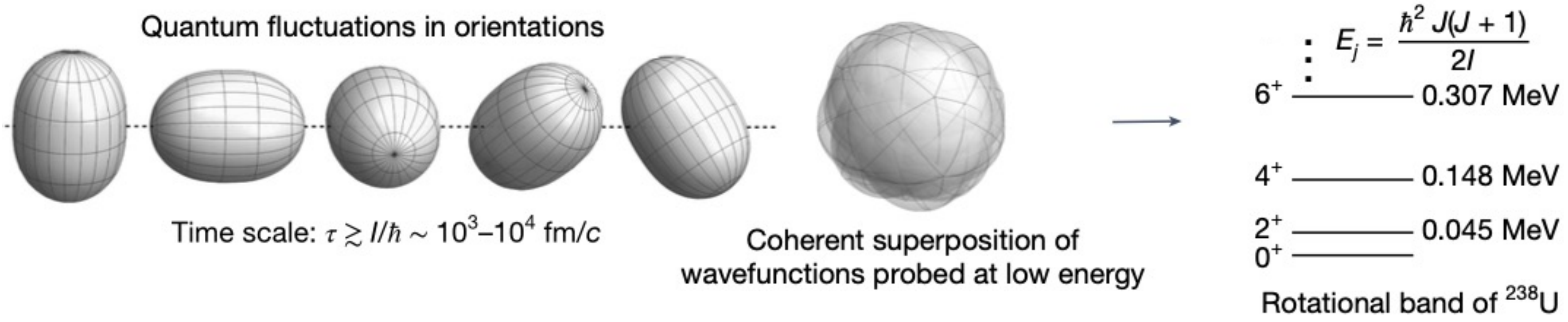


Traditional imaging method taken before destruction

→ Low energy spectroscopic methods probe a superposition of these fluctuations.

→ Instantaneous shapes not directly seen, but inferred from model comparison.

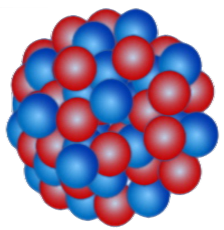
Each DOF has zero-point fluctuations within certain timescales.



Nuclear shape at high-energy: short exposure

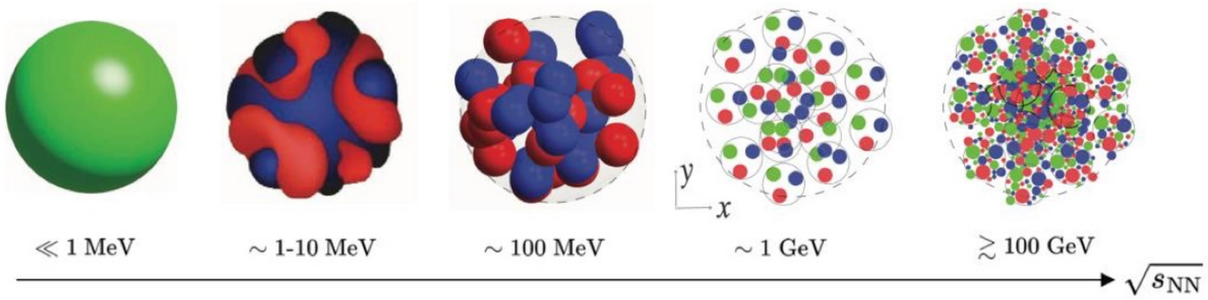
Emergent seeing shape directly require access to instantaneous nucleon distributions

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



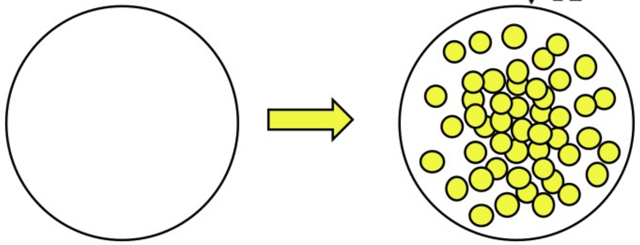
Will see all DOFs longer than exposure timescale: $\tau > \tau_{\rm expo}$

nucleons, hadrons, quark, gluons, gluon saturations



Hence concept of shape is collision energy dependent

$\epsilon_2 = 0$ $\qquad$ $\epsilon_2 \sim \frac{1}{\sqrt{A}}$

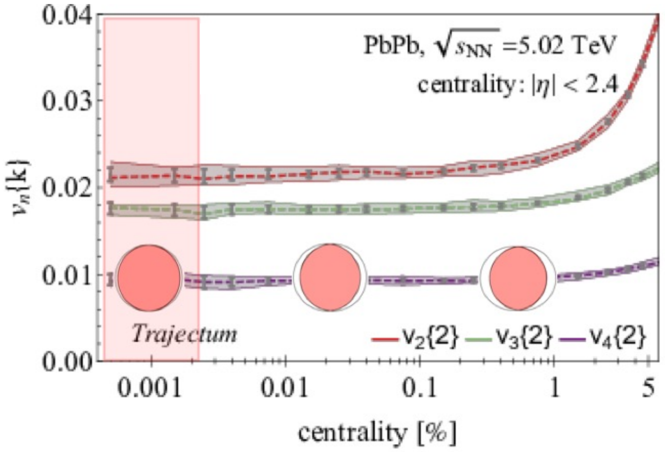


Spherical Woods-saxon $\qquad$ Sampled with A nucleons

$$\boldsymbol{\epsilon}_2 = \underbrace{\boldsymbol{\epsilon}_0} + \underbrace{\boldsymbol{p}(\Omega)\beta_2} + \mathcal{O}\left(\beta_2^2\right)$$

$\sqrt{s}$-dependent quantum fluctuation induced shape

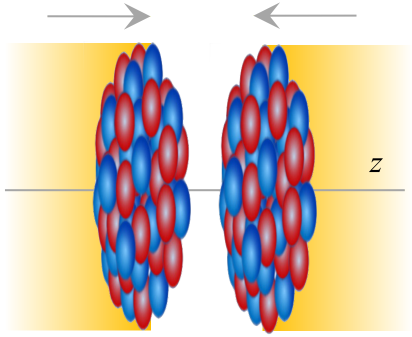
Global shape rotational vibrational



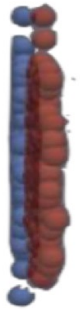
Imaging by smashing method

Take a snapshot | Evolution | Measurement

Nuclei collisions



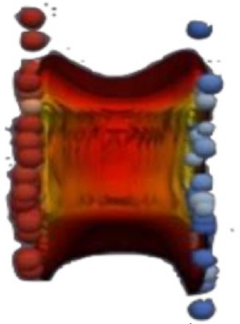
$T_{\mu\nu}(\tau = 0)$



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

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

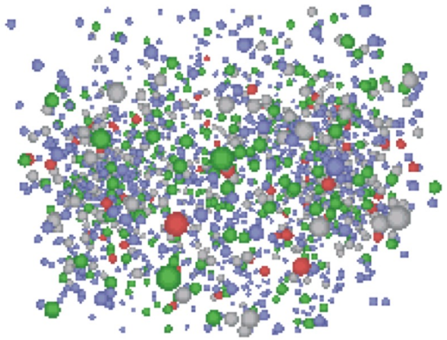
$\partial_\mu T^{\mu\nu} = 0$, EOS, viscosity…



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

free-streaming

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



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

$T_{\mu\nu}(\tau = 0)$ snapshot ⟶ $\partial_\mu T^{\mu\nu} = 0$ evolution ⟶ $T_{\mu\nu}(\tau = \infty)$ measurement

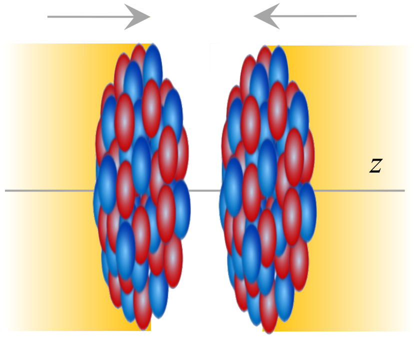
J. Jia et al., Nucl. Sci. Tech 35, 220 (2024)

Image inferred after destruction

Imaging by smashing method

Take a snapshot — Evolution — Measurement

Nuclei collisions



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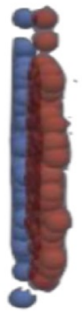

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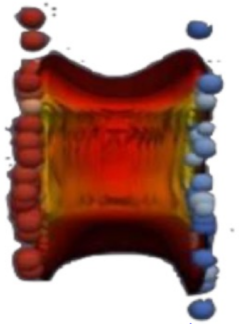

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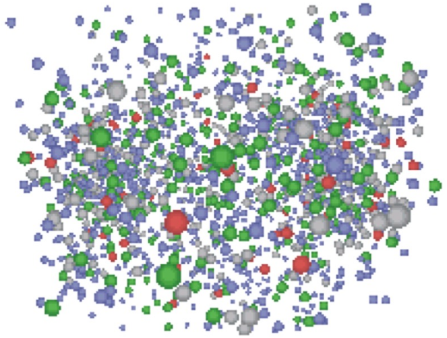


$\tau \sim 10^{15}\text{fm}/c$
detection

Large entropy production enable a semi-classical description

- Initial condition is a fast snapshot of nuclear structure (<0.1fm/c)
- Transformed to the final state via hydrodynamic expansion
- Reverse-engineer to infer the snapshot, aided by large information output

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

Ability to image ⟷ Understanding of the QGP

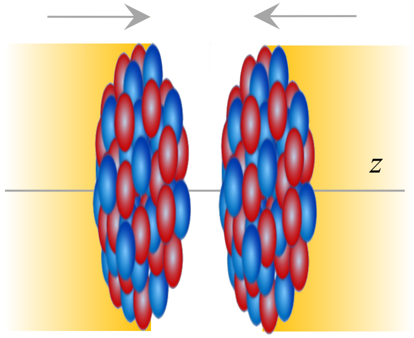
Imaging by smashing method

Take a snapshot

Evolution

Measurement

Nuclei collisions



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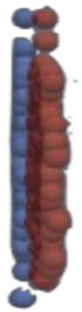

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exposure

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Pressure-driven expansion of
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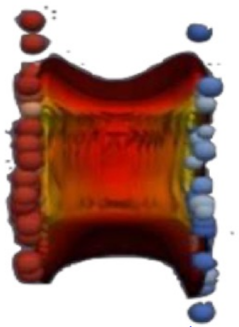

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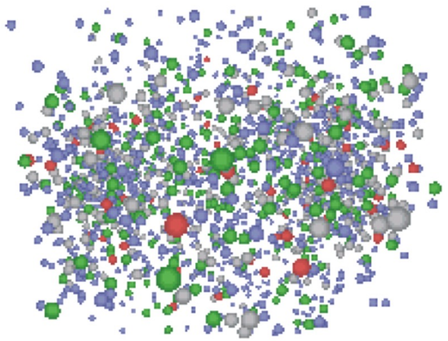
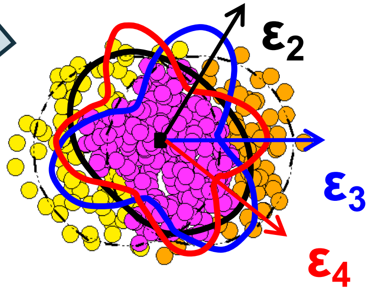


$\tau \sim 10^{15}\mathrm{fm}/c$
detection

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

- $\beta_2 \longrightarrow$ 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



size & shape

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

$R_0 \qquad a_0 \qquad \beta_n$

observables

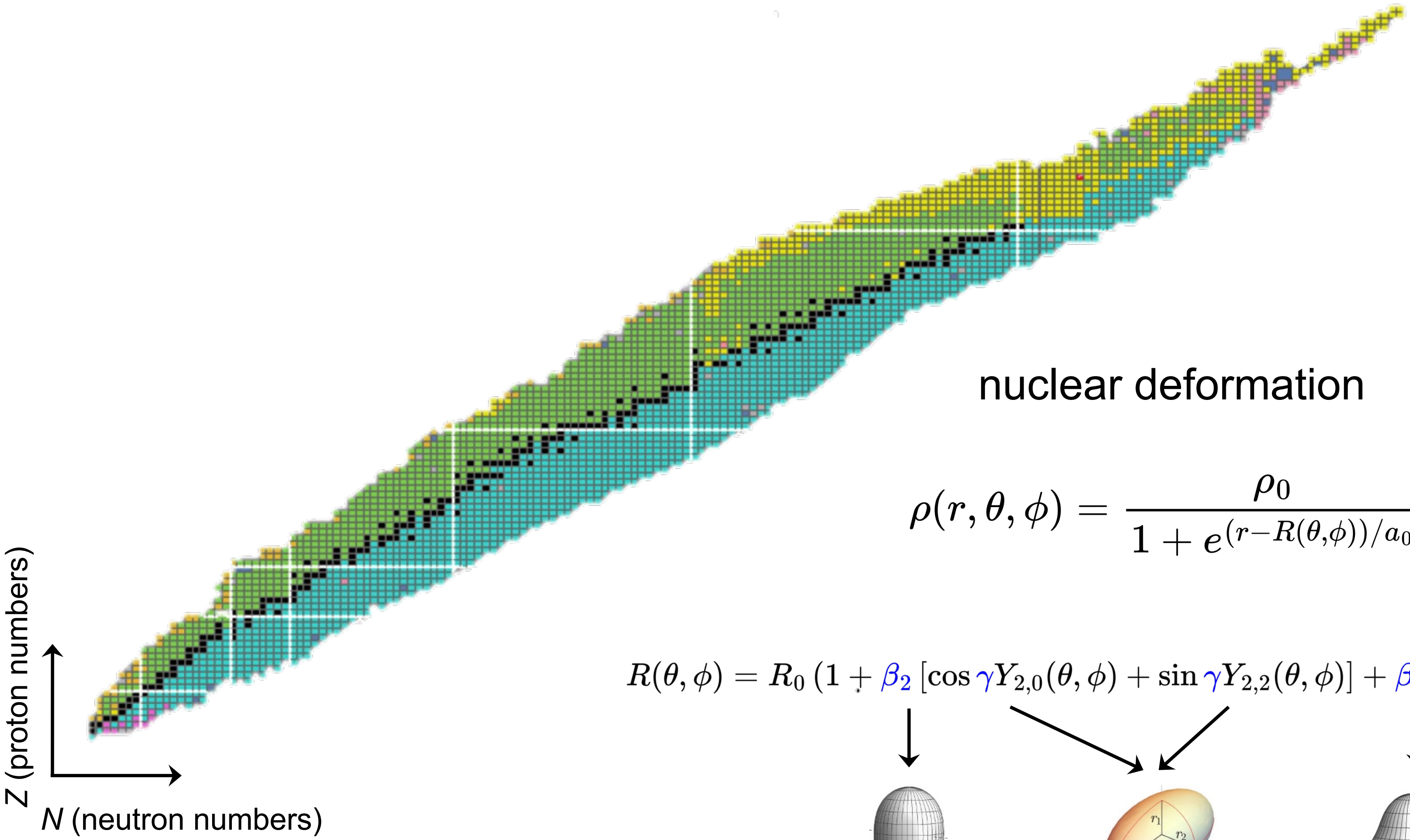
$$\frac{d^2N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$$

Event-by-event linear responses:

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

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

Nuclear deformation in ^{238}U and ^{129}Xe



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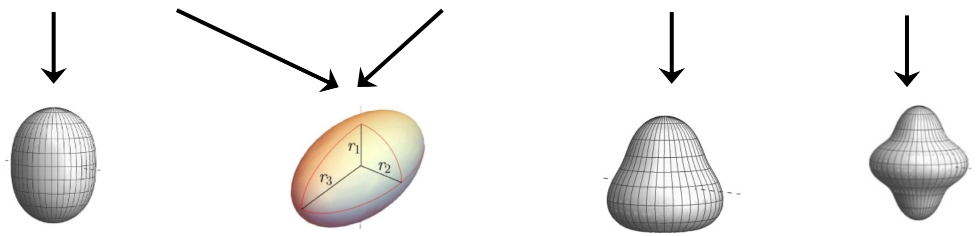
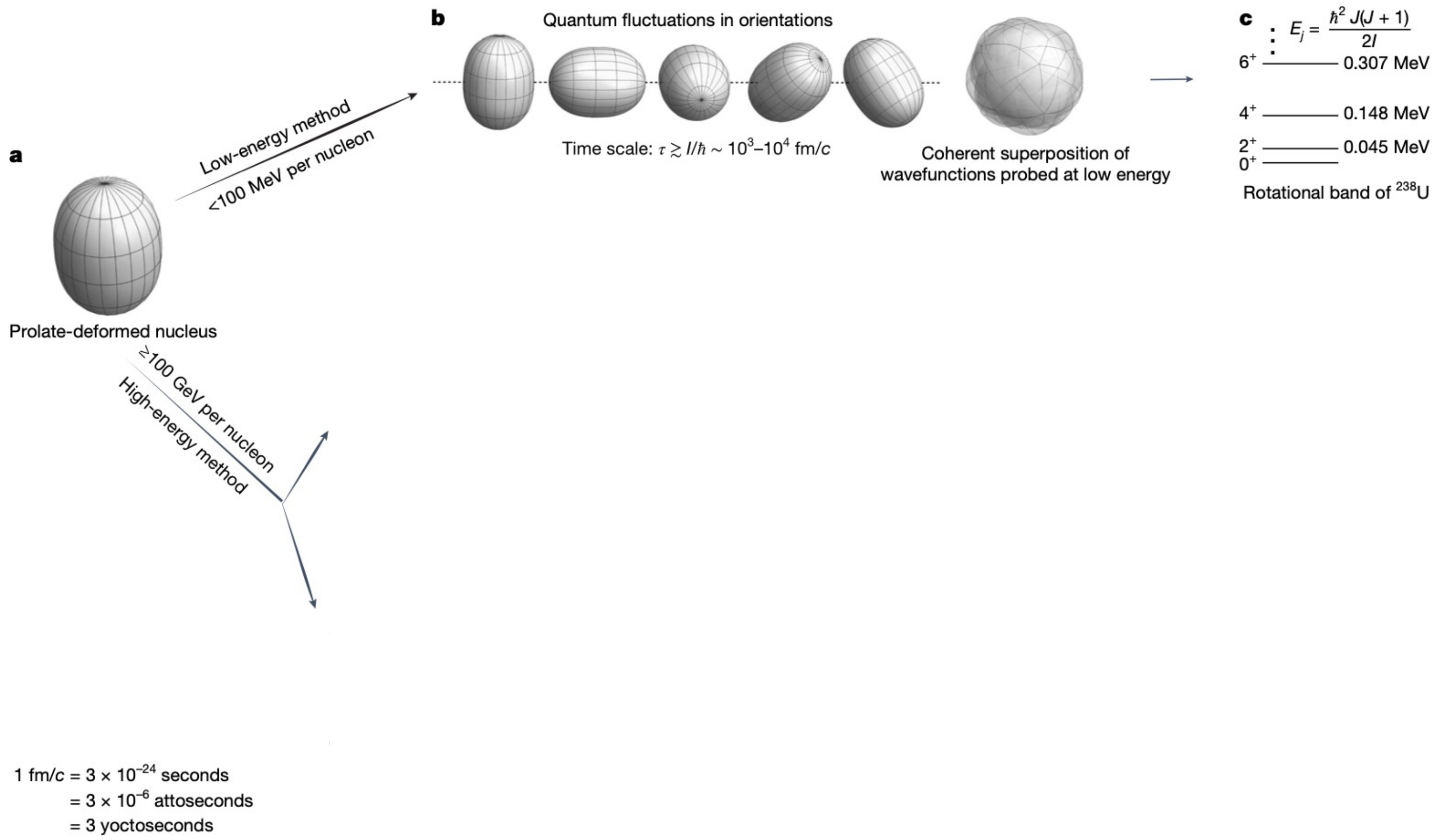


Imaging nuclear shape in high-energy snapshot as a novel way

- Nuclear shape in intrinsic (body-fixed) frame not directly visible in the lab frame

  --Mainly inferred from non-invasive spectroscopy methods.



Impact of deformation: head-on collisions

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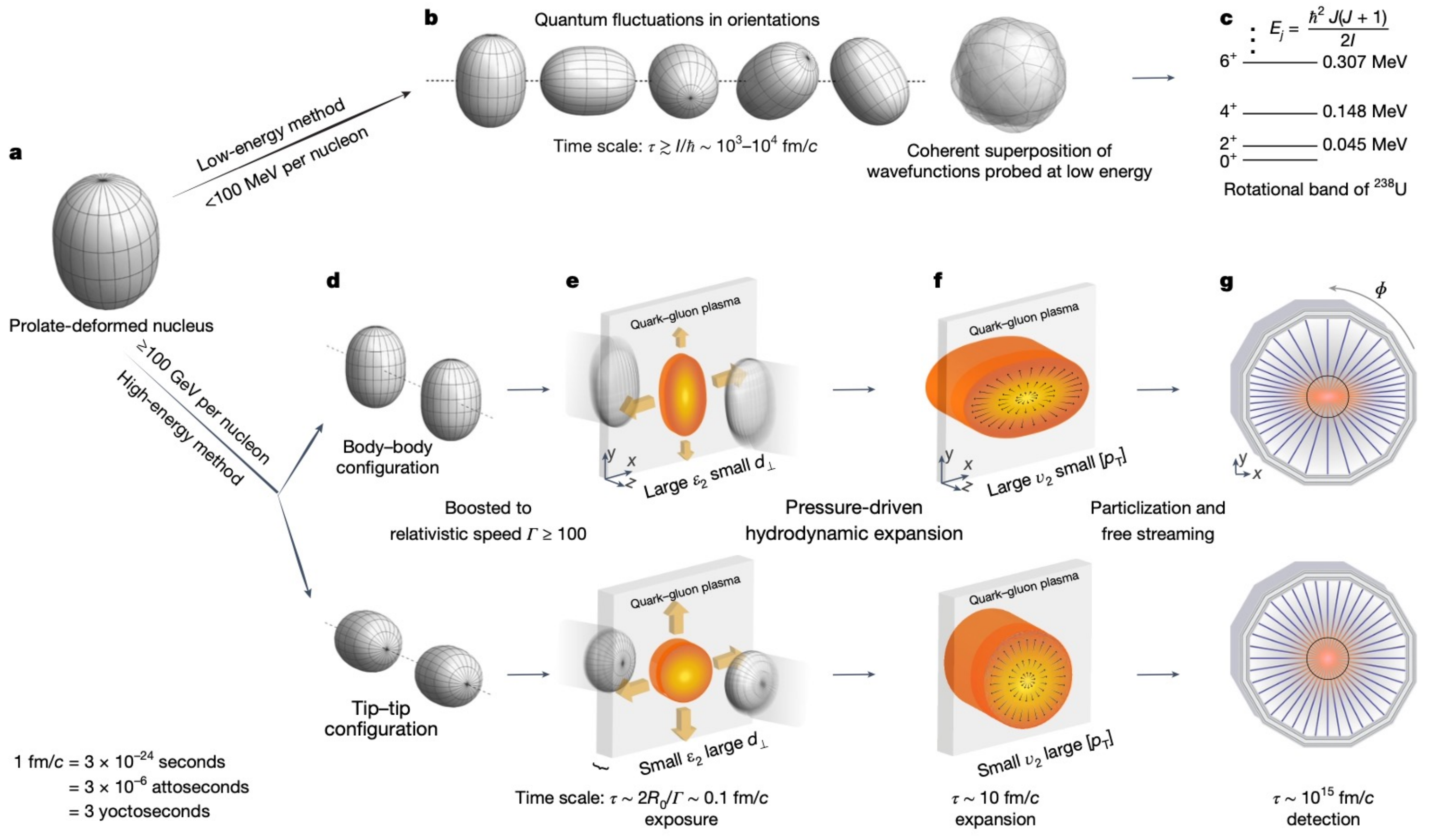


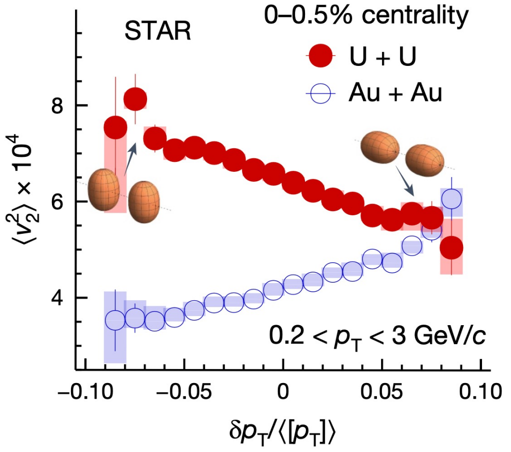
STAR, Nature 635, 67-72 (2024)
https://www.nature.com/articles/s41586-024-08097-2

Body-body: large-eccentricity large-size

v_2↗ p_T↘

Tip-tip : small-eccentricity small-size

v_2↘ p_T↗



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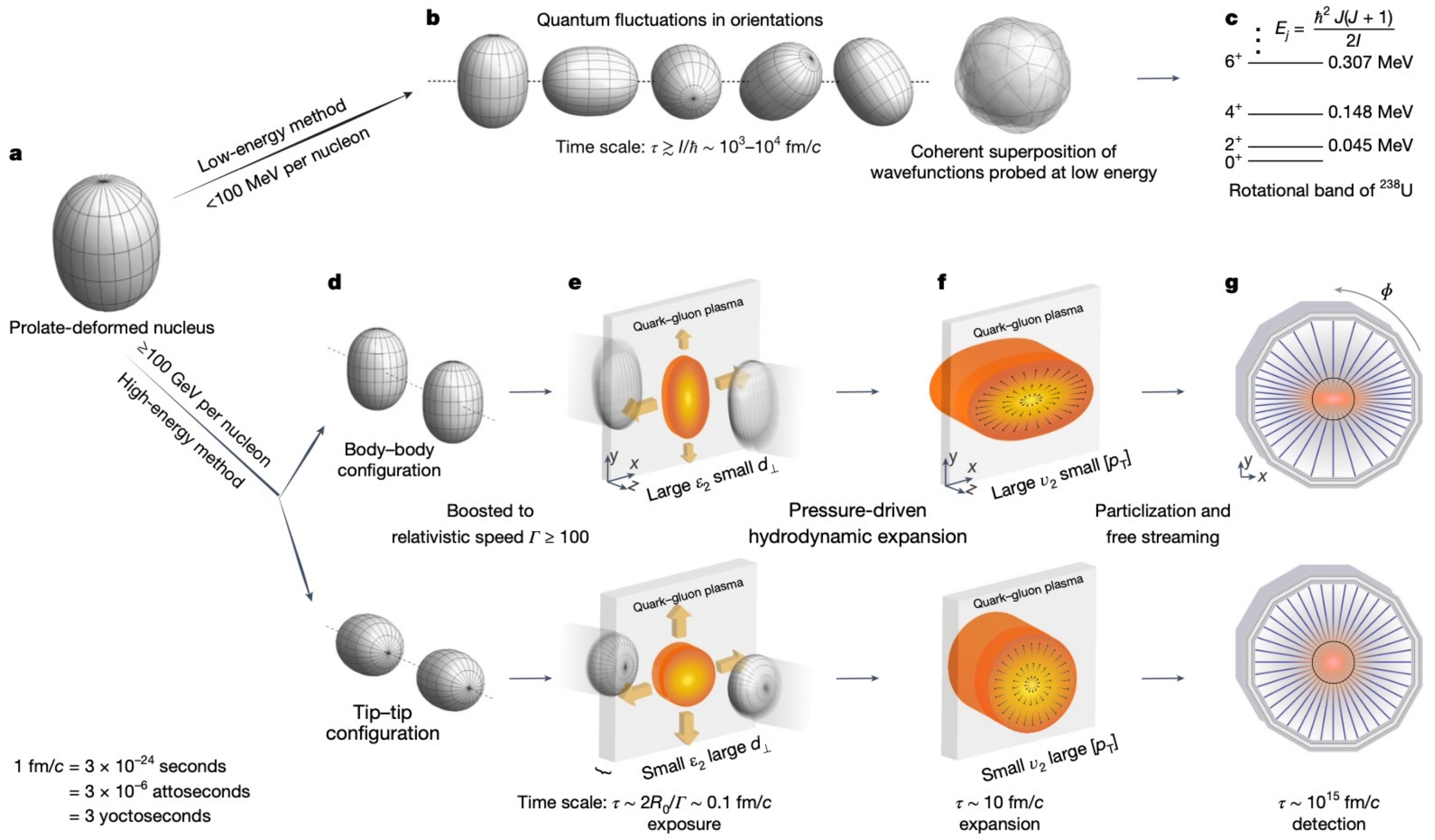


STAR, Nature 635, 67-72 (2024)

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

$v_2 \searrow$ $p_T \nearrow$

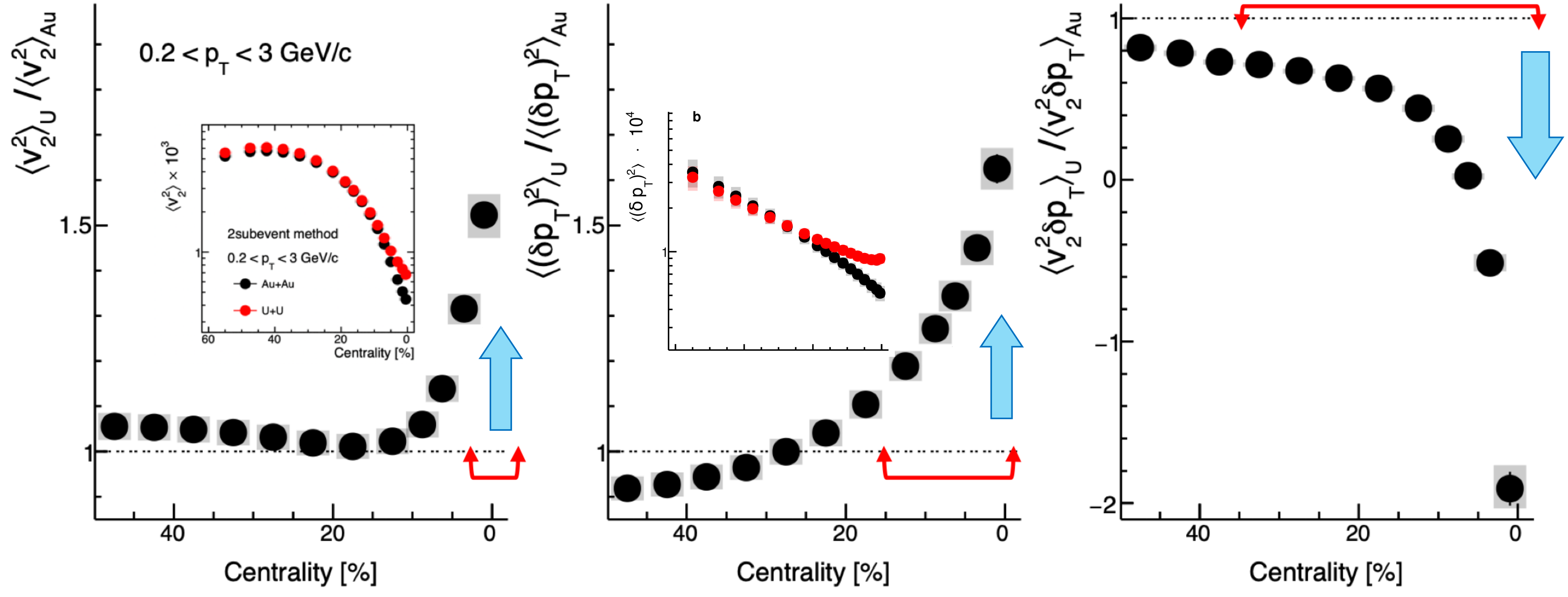
$$\langle v_2^2 \rangle = a_1 + b_1 \beta_2^2,$$
$$\langle (\delta p_T)^2 \rangle = a_2 + b_2 \beta_2^2,$$
$$\langle v_2^2 \delta p_T \rangle = a_3 - b_3 \beta_2^3 \cos(3\gamma).$$

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

Ratio of observables



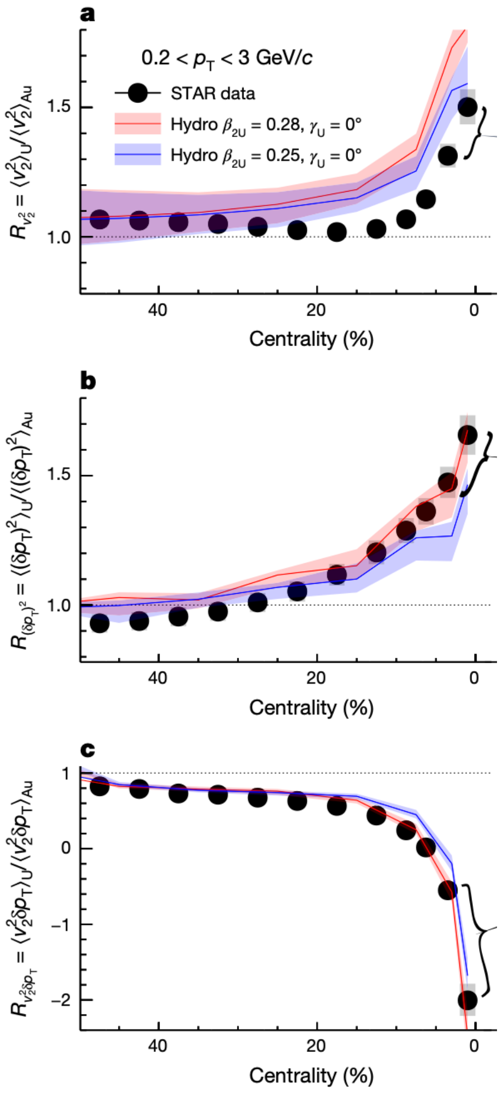
$$R_{\langle v_2^2\rangle} \approx 1 + \frac{b_1}{a_1}\beta_2^2,$$
$$R_{\langle(\delta p_T)^2\rangle} \approx 1 + \frac{b_2}{a_2}\beta_2^2,$$
$$R_{\langle v_2^2 \delta p_T\rangle} \approx 1 - \frac{b_3}{a_3}\beta_2^3\cos(3\gamma)$$

- 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: β_2 and γ



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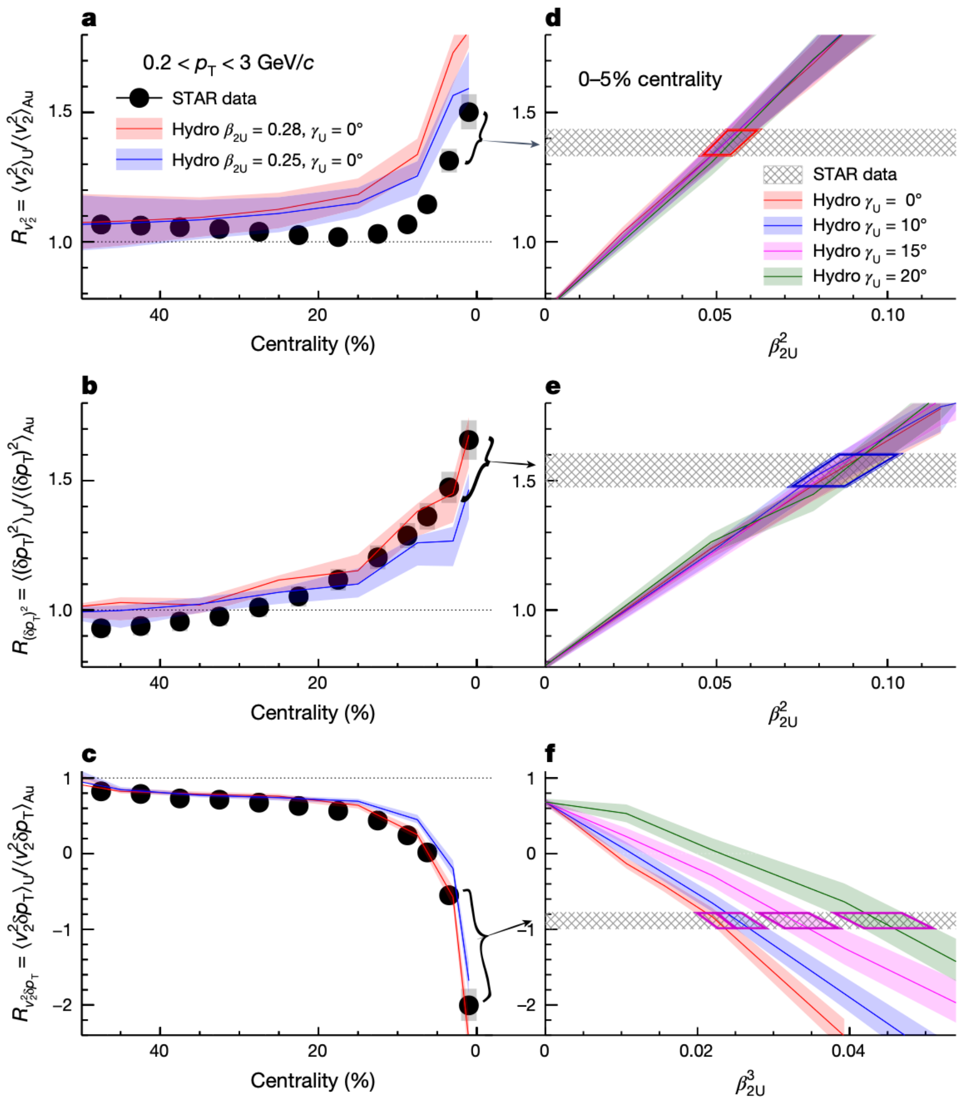

Sufficient precision is achieved from ratios in ultra-central collisions

Relation confirmed from hydro

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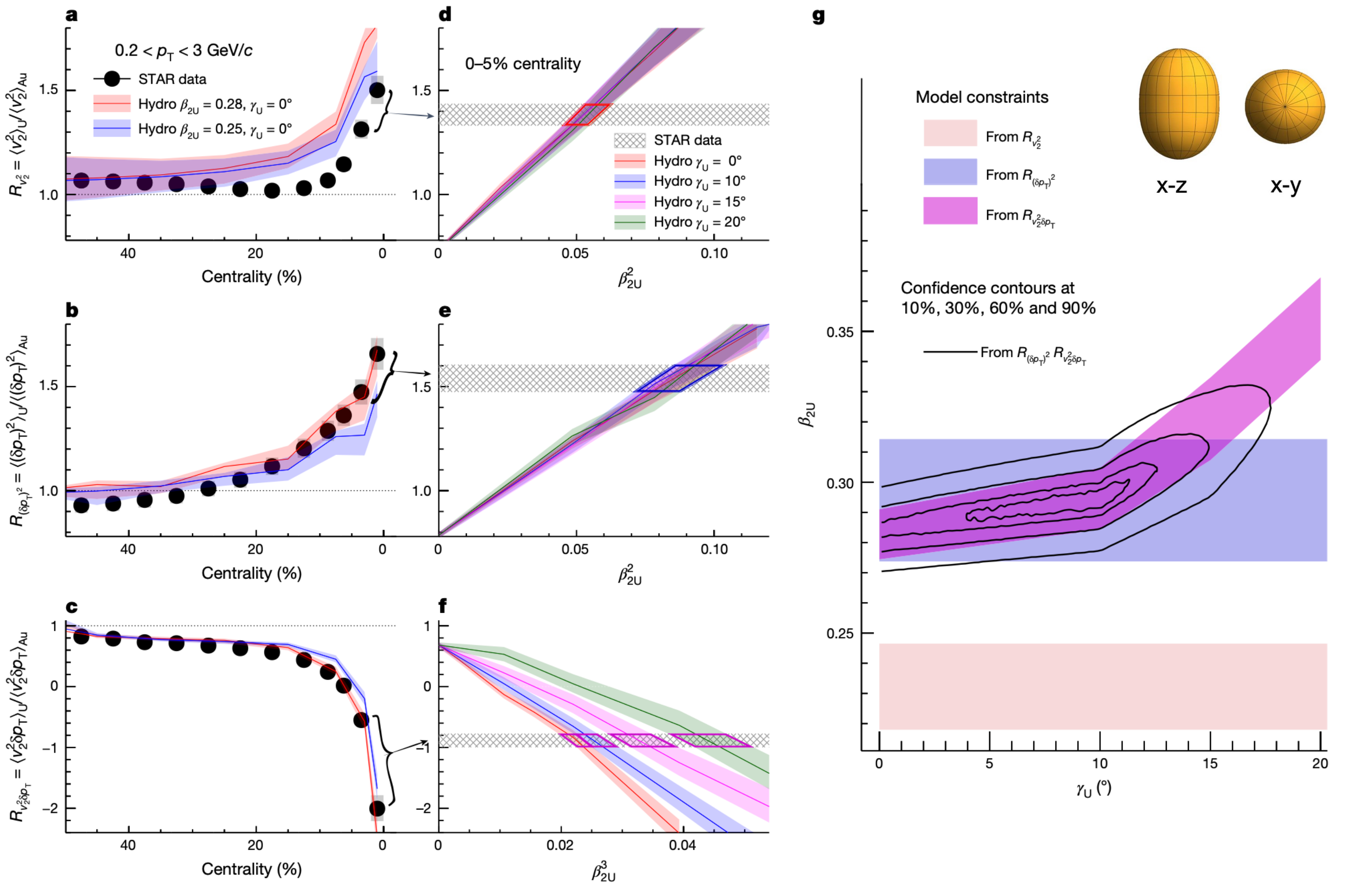

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$$R_{\langle v_2^2 \delta p_T \rangle} \approx 1 - \frac{b_3}{a_3} \beta_2^3 \cos(3\gamma)$$

High-energy estimate:

$$\beta_{2\mathrm{U}} = 0.286 \pm 0.025$$

$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

low-energy estimate:

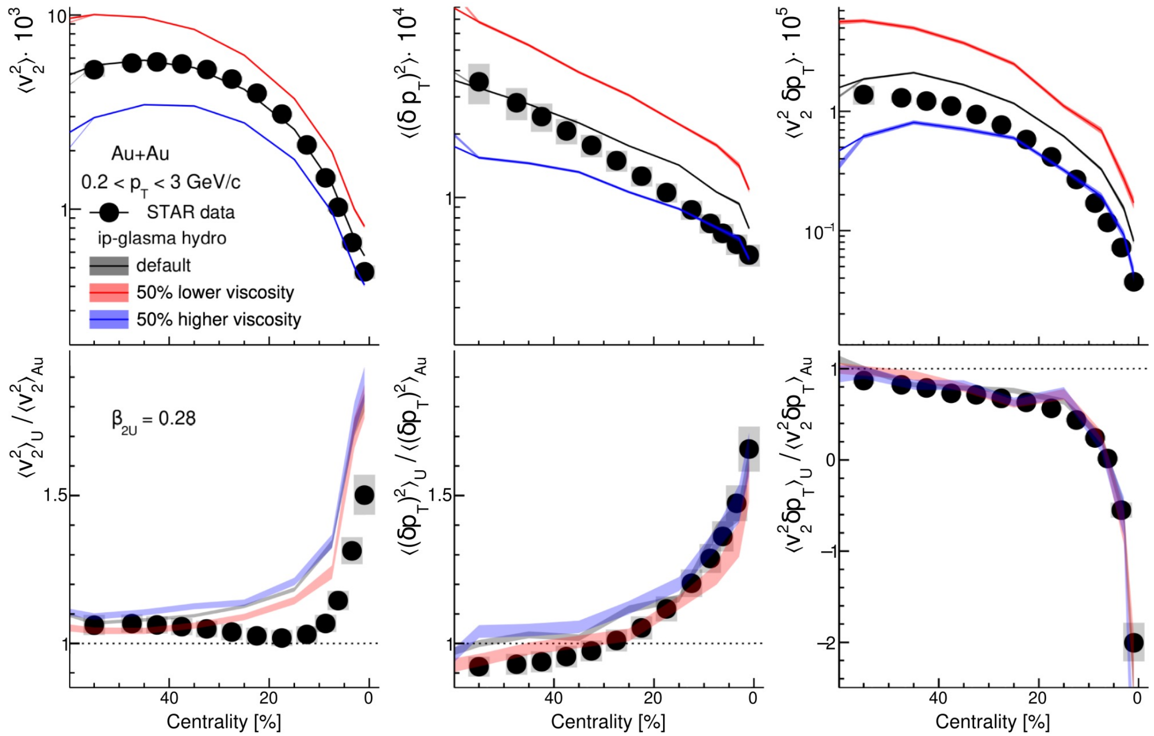
$$\beta_{2\mathrm{U}} = 0.287 \pm 0.007$$

$$\gamma_U = 6^\circ - 8^\circ$$

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

Viscosity, nuclear parameters, and model variations

1) Taking the ratios cancels the viscosity effects.



Viscosity, nuclear parameters, and model variations

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

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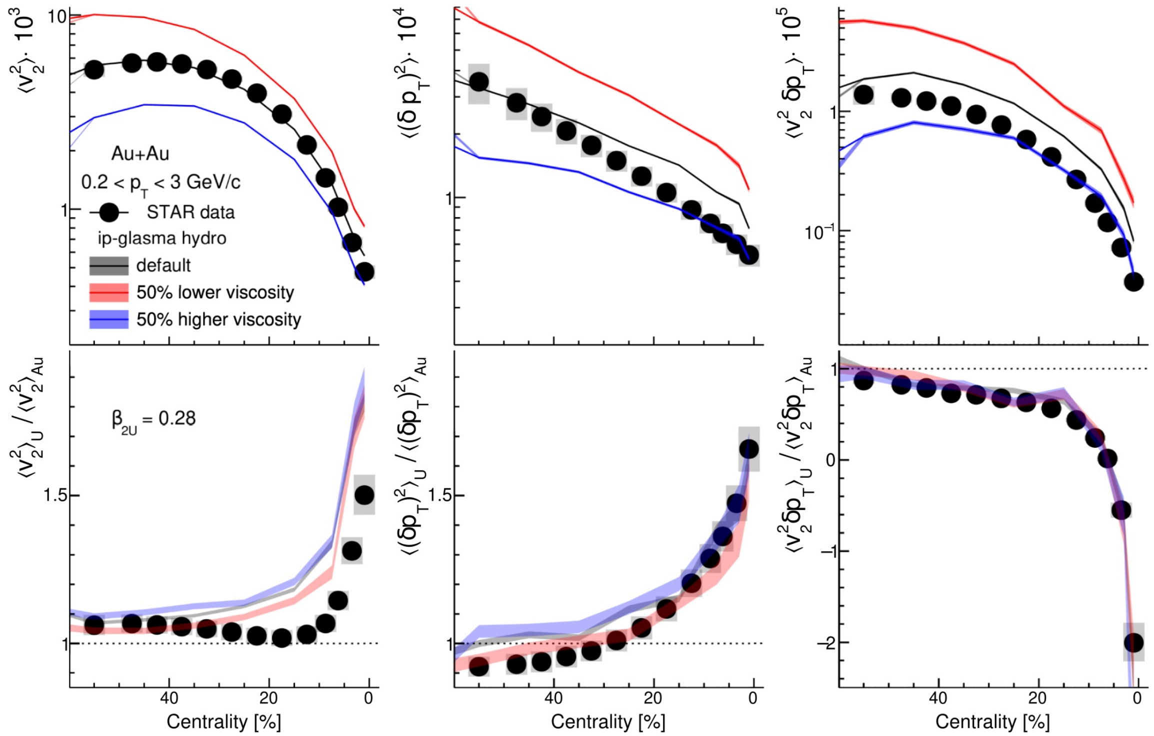

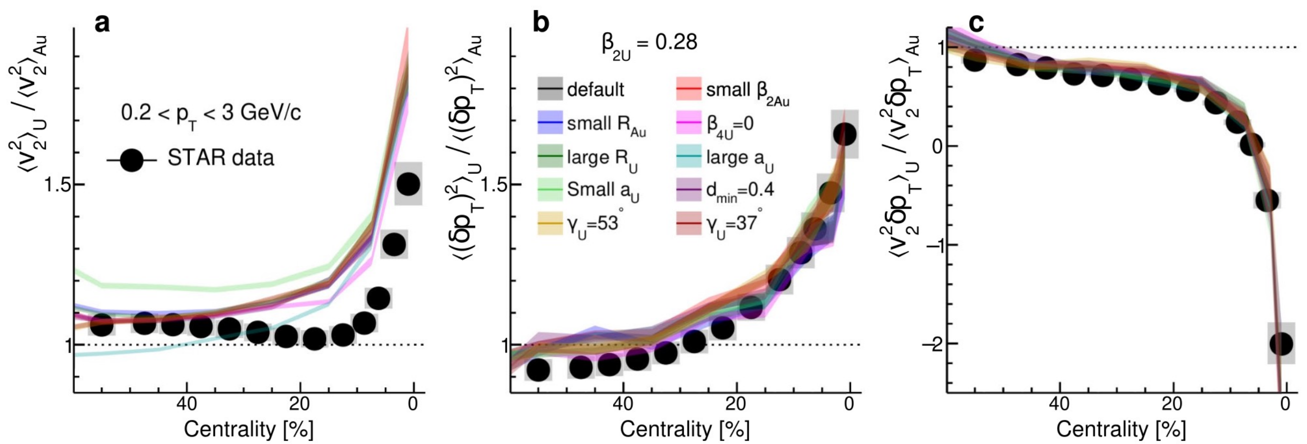

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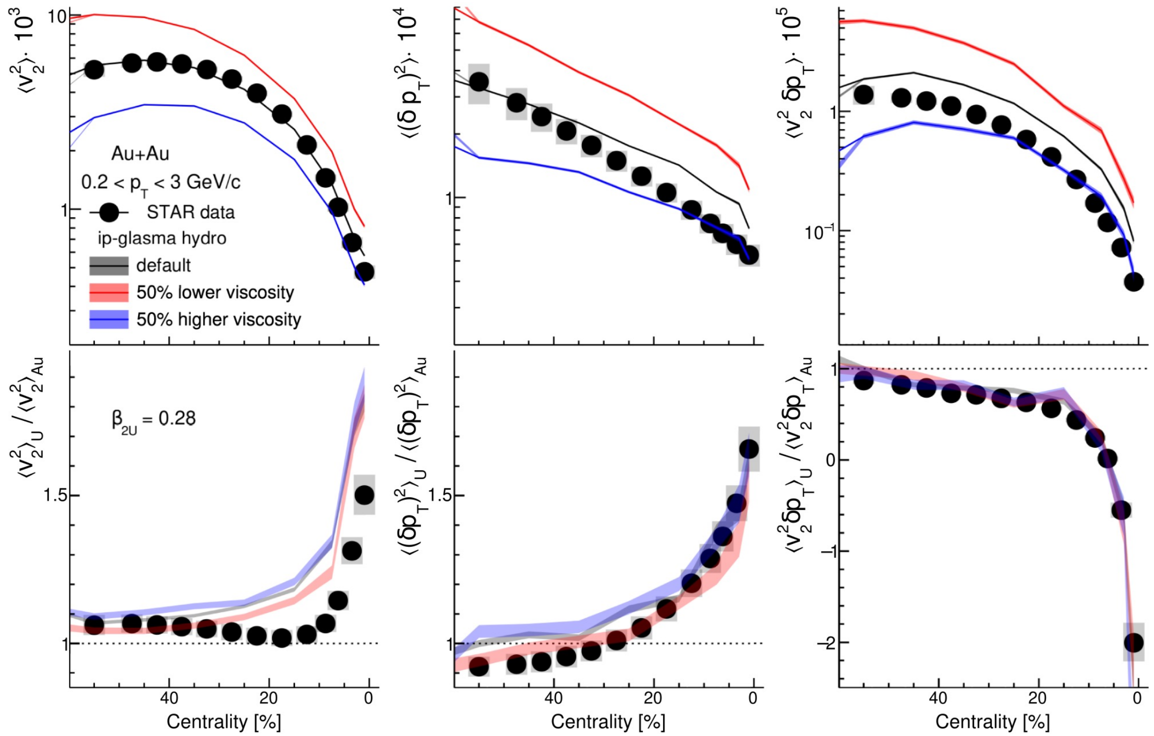

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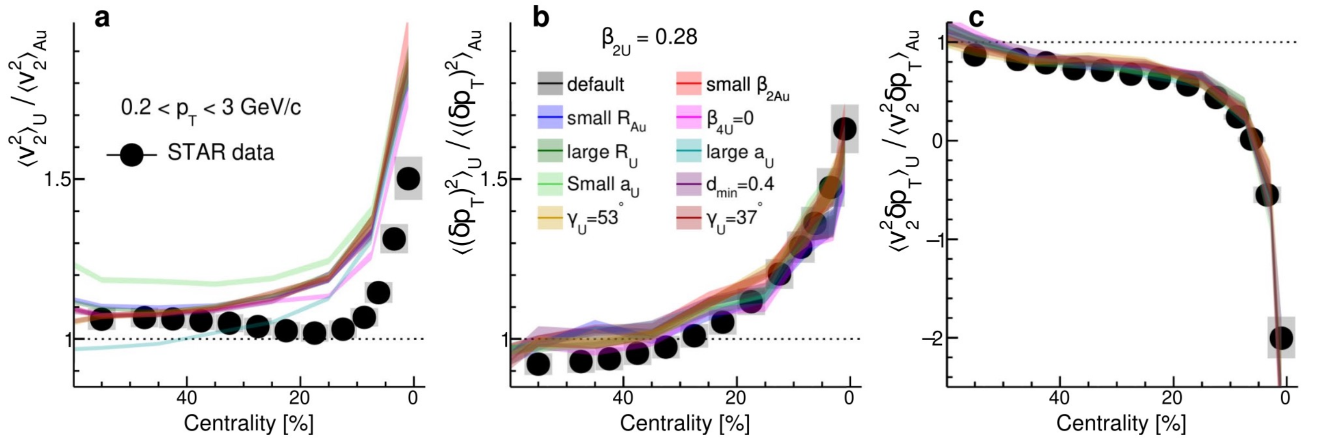
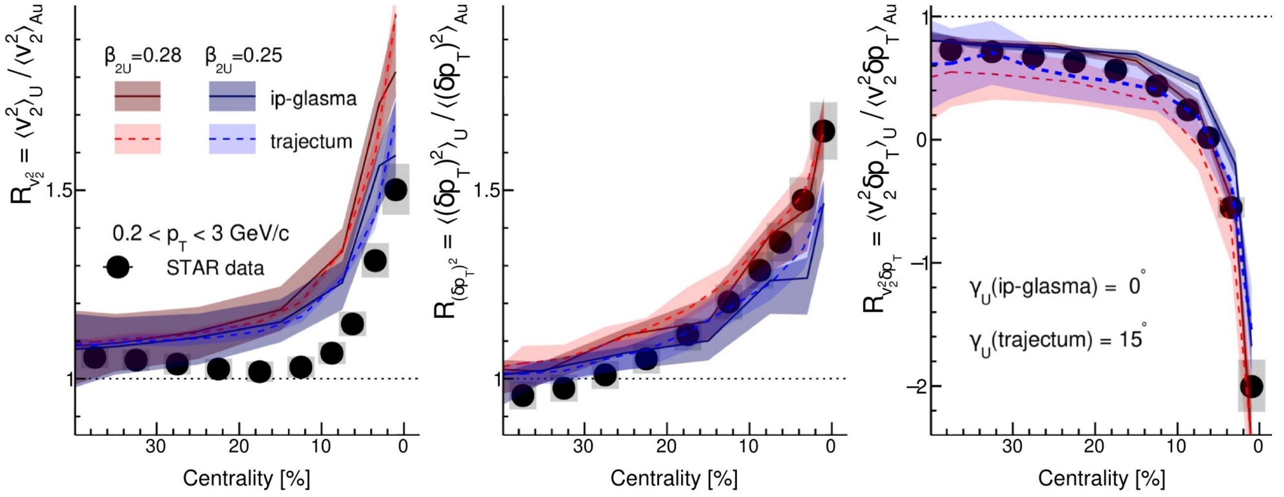


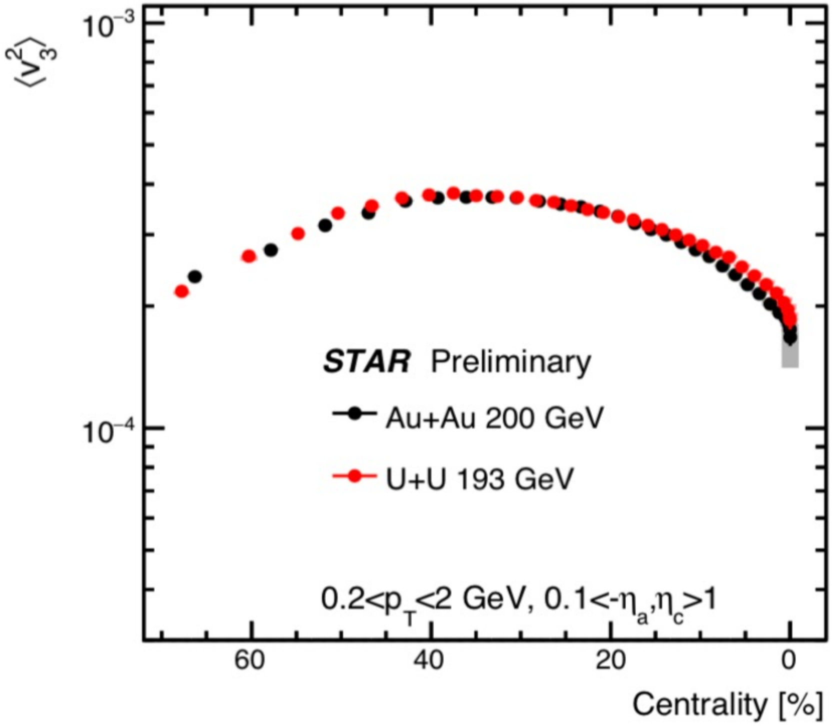
3) Another hydrodynamics model, Trajectum, shows rather consistent extractions even if it was not tuned to RHIC data.



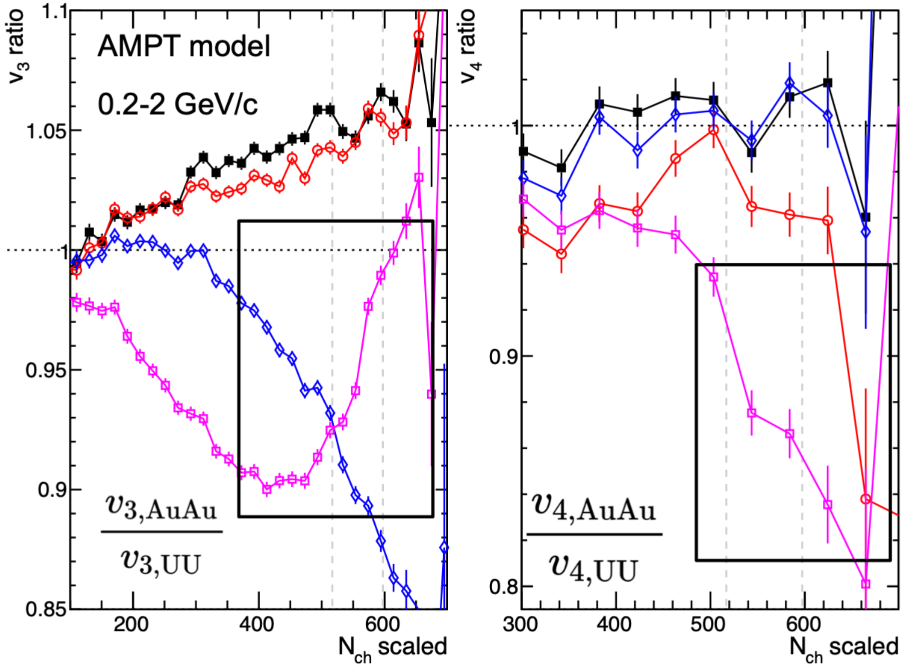
Extracted β_2 and γ values are robust.

Possible octupole deformation?

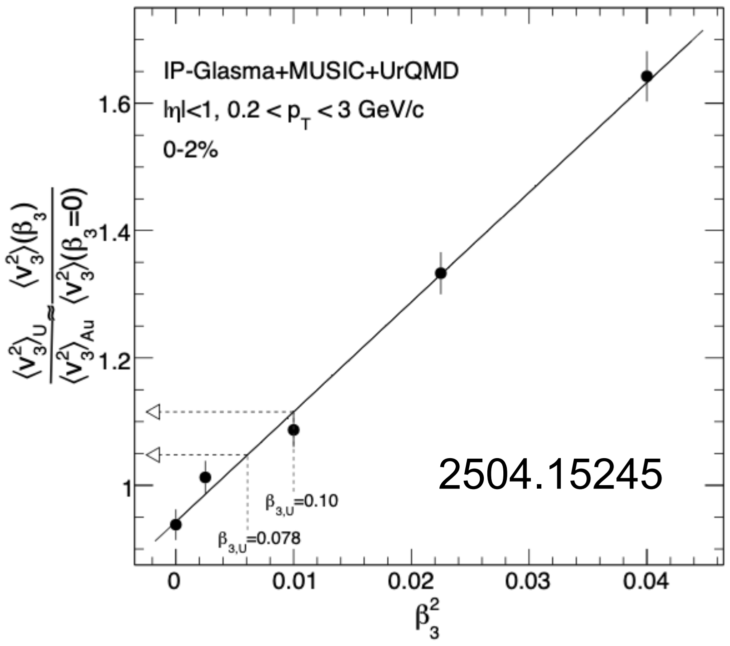
Presented in workshops in INT2023, Seattle and WWND2023, Mexico



AMPT



IP-Glasma+MUSIC



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 reversed by considering non-zero $\beta_{3,U}$, $\beta_{4,U}$ which can be constrained in the central region.

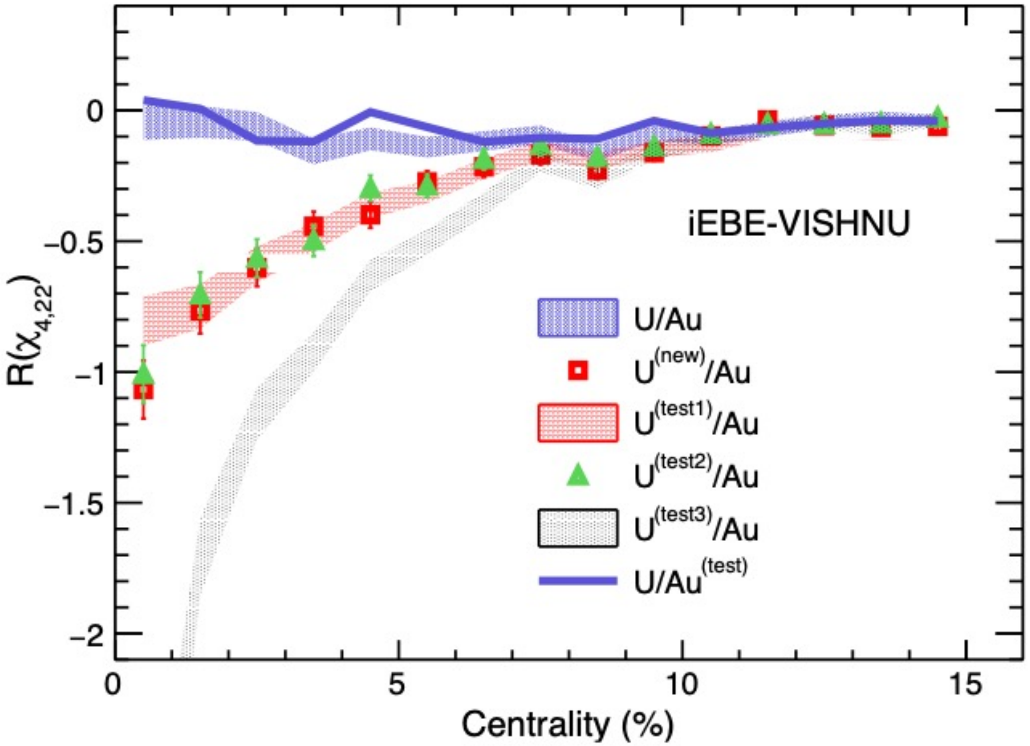
$\beta_{4,U}$ constrained using v_4 ratio in the central region

STAR manuscript including more results is under preparation.

More model: Yuan Li (Fudan), poster #184

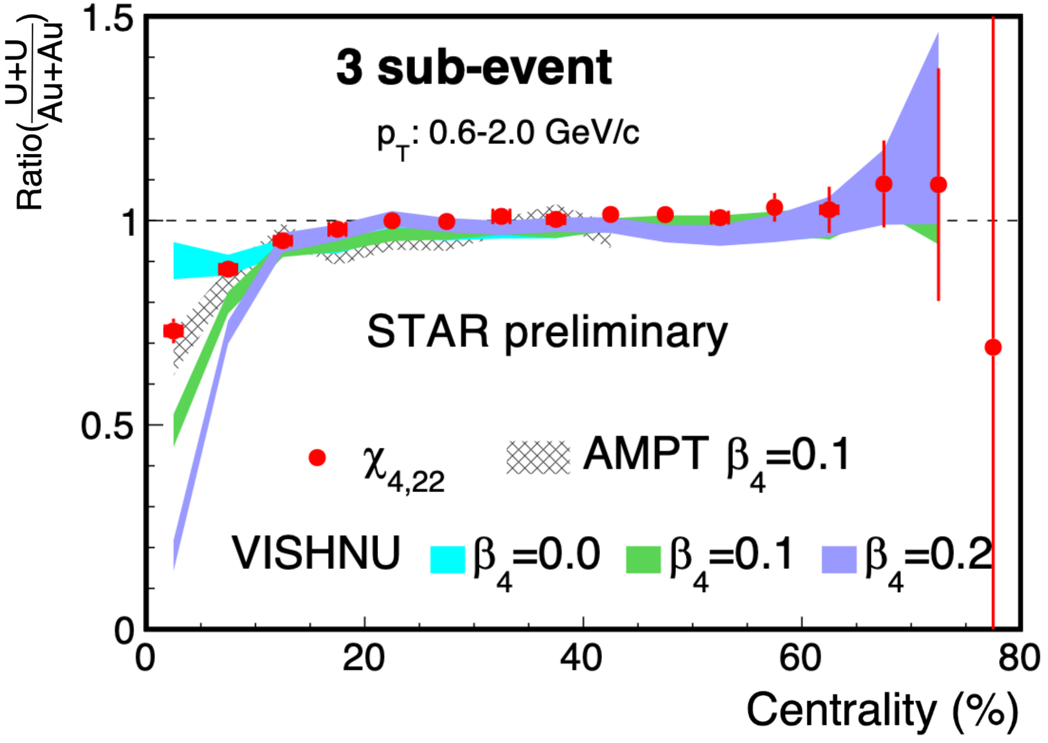
Hexadecapole deformation

H. Xu, J. Zhao, F. Wang, PRL132, 262301 (2024)
Z. Wang. J. Chen, H. Xu, J. Zhao, PRC 110, 034907 (2024)



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

Jie Zhao (QM2025)



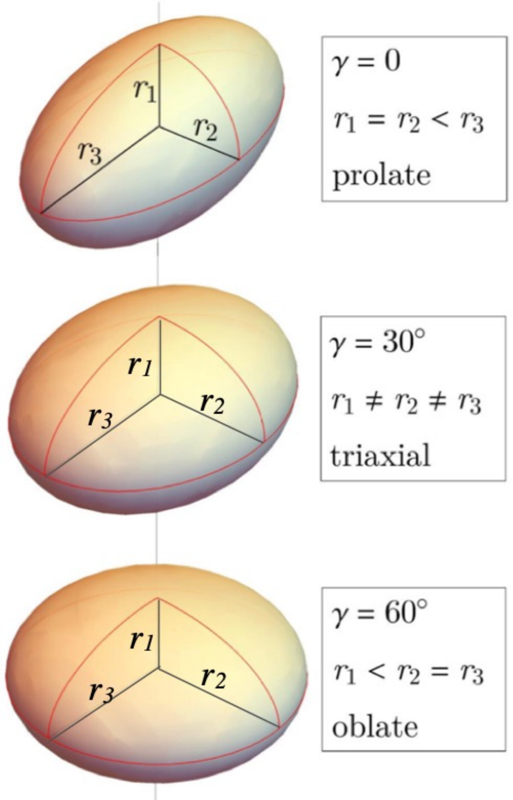
$\beta_{4,\mathrm{U}}$ constrained using $\chi_{4,22}$ ratio in the central region

VISHNU overpredicts the data but AMPT prediction is well

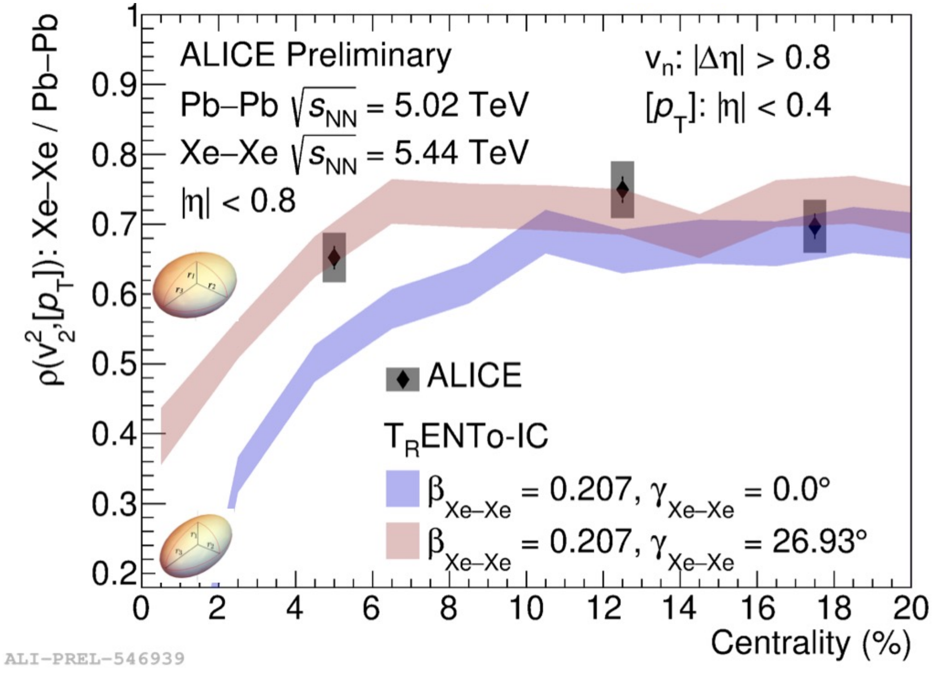
More $\beta_{4,\mathrm{U}}$ work: W. Ryssens, G. Giacalone, B. Schenke, C. Shen, PRL130, 212302 (2023)

Model: Zhijie Yang (HuZhou), Poster #140

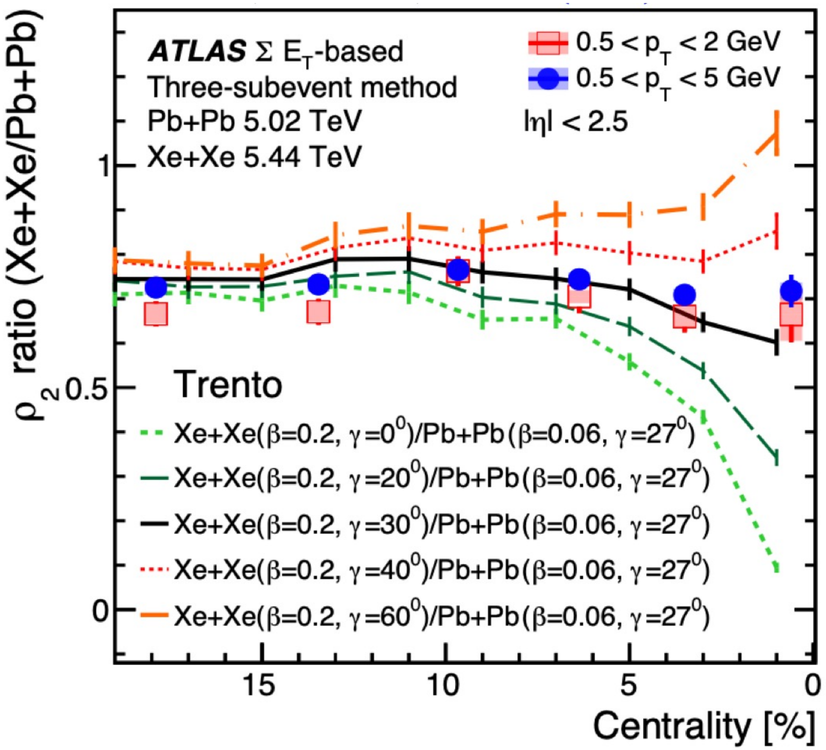
Explore triaxial structure of ^{129}Xe at LHC



ALICE, PLB 834, 137393 (2022)



ATLAS, PRC 107, 054910 (2023)

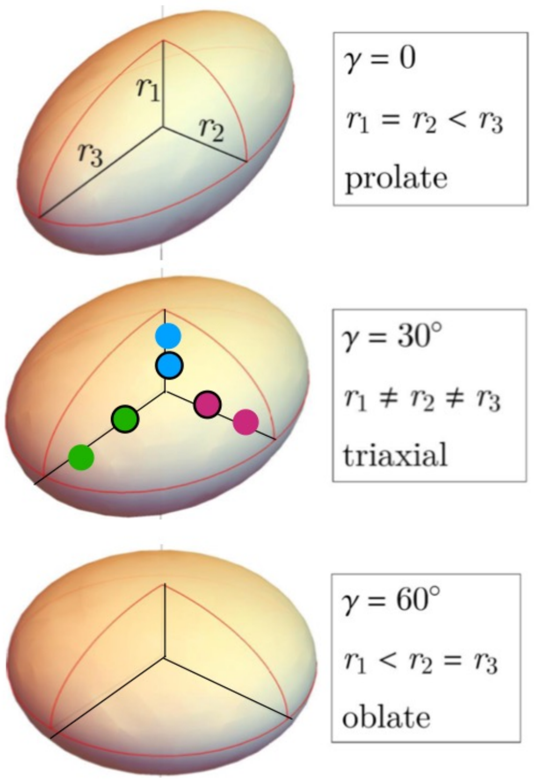


Better agreement between LHC data and calculations with γ = 27°-30° (triaxial)
→ First study of triaxial structure of ^{129}Xe at high energy collisions at the LHC
→ Evidence of triaxial structure of ^{129}Xe?

More γ work: B. Bally etc, PRL128, 082301 (2022); E. Nielsen (ALICE), A. Dattamunsi (CMS), QM2025.

Nuclear shape transition (γ fluctuation)

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



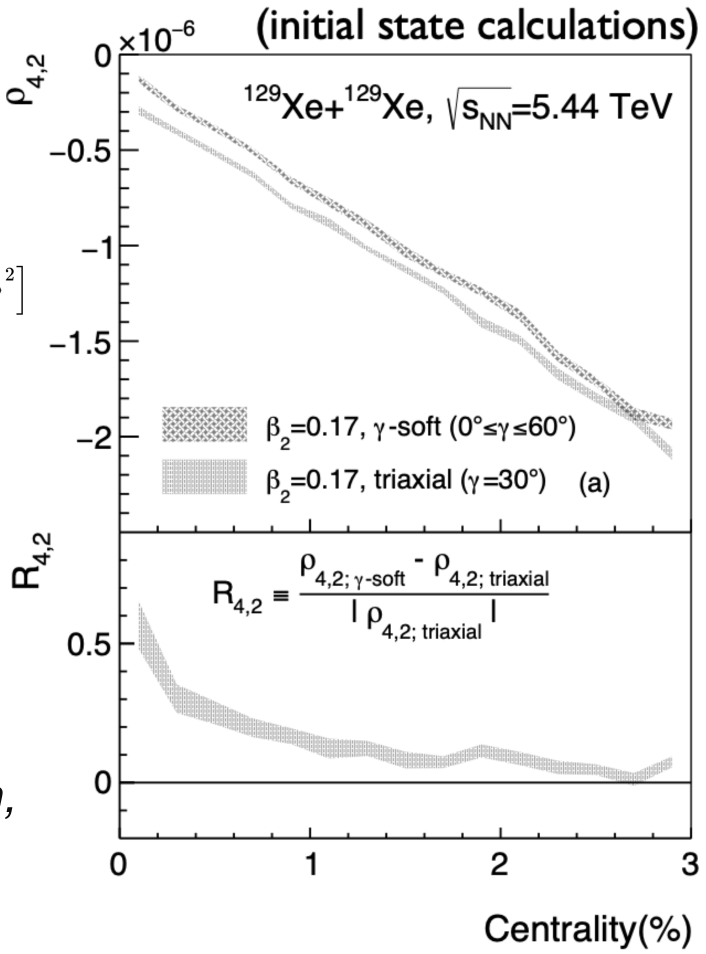
To probe the relation of r_1, r_2 and r_3, we need 3-particle correlations

To probe the γ fluctuations, we need 6-particle correlations

New proposal:

$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \right)_c \equiv \frac{1}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2} \left[\langle \varepsilon_2^4 \delta d_\perp^2 \rangle + 4 \langle \varepsilon_2^2 \rangle^2 \langle \delta d_\perp^2 \rangle - \langle \varepsilon_2^4 \rangle \langle \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \rangle \langle \varepsilon_2^2 \delta d_\perp^2 \rangle - 4 \langle \varepsilon_2^2 \delta d_\perp \rangle^2 \right]$$

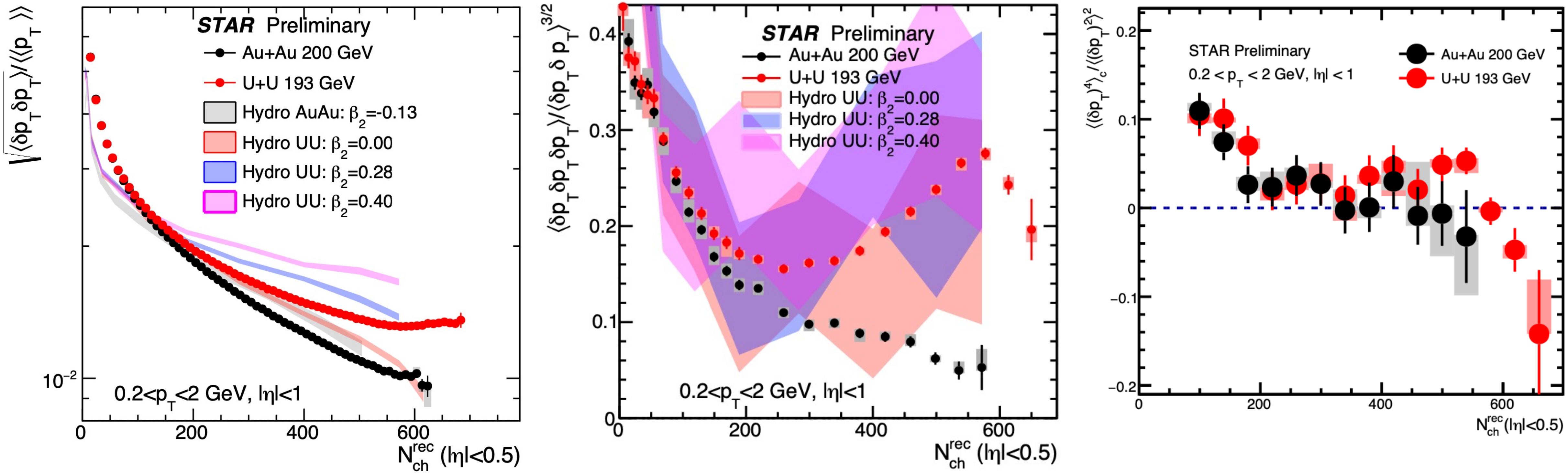
The six-particle correlations allow to differentiate **γ-rigid and γ-soft** (fluctuating γ) structures.



Higher-order v_n and p_T correlations allows to probe nuclear shape phase transition, but their implementations are highly non-trivial!

$[p_T]$ fluctuations as other novel tool

Presented in workshops in INT2023, Seattle and WWND2023, Mexico



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

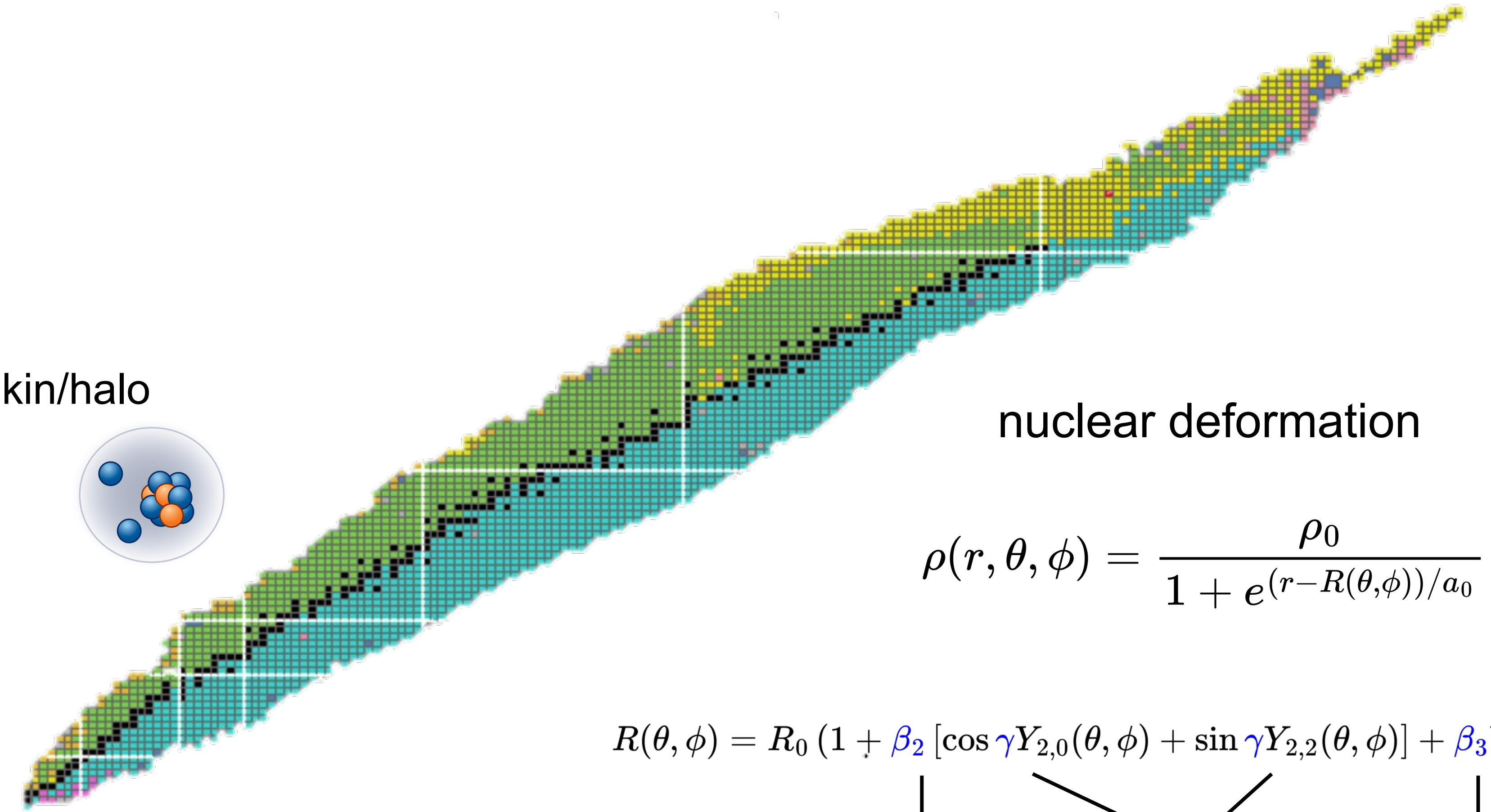
The nuclear deformation role is further confirmed by hydro calculations. But we need more statistics.

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

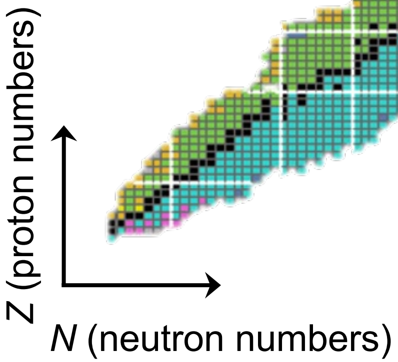
ALICE, PLB 850, 138541 (2024); ATLAS, PRL 133, 252301 (2024)

Model: Chao Zhang (WUT), 4.26, 17:20-17:40; Liuyao Zhang (Henan-CAS), 4.27, 11:55-12:15

Nuclear deformation and neutron skin in ^{96}Ru and ^{96}Zr



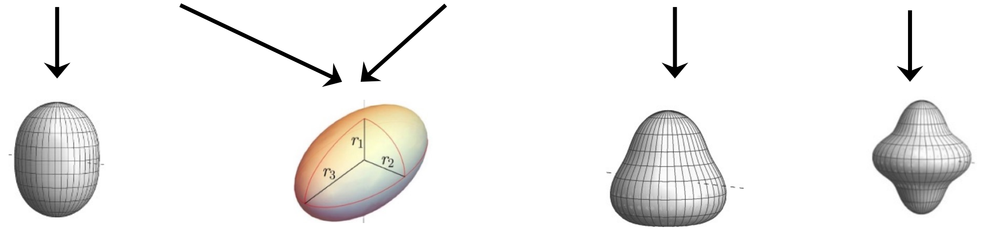
neutron skin/halo



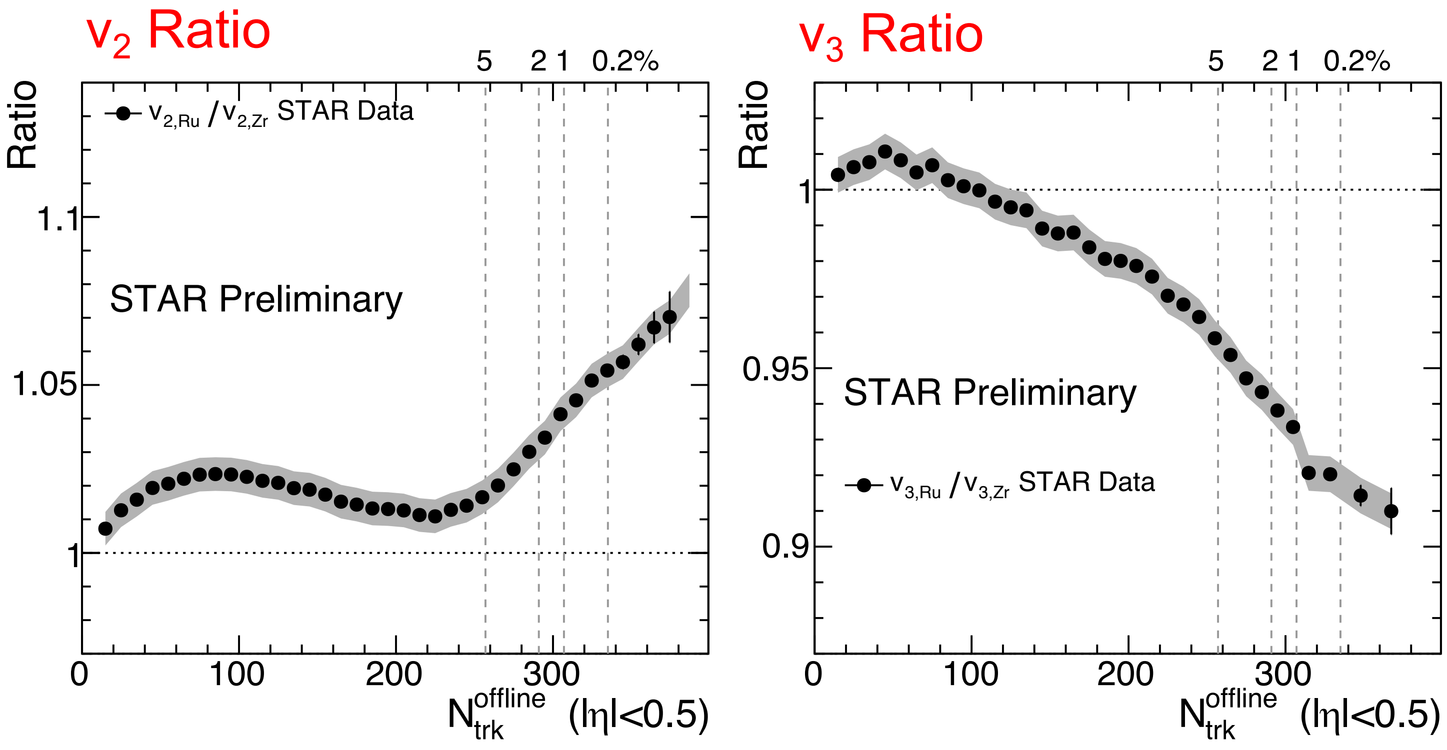
nuclear deformation

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

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

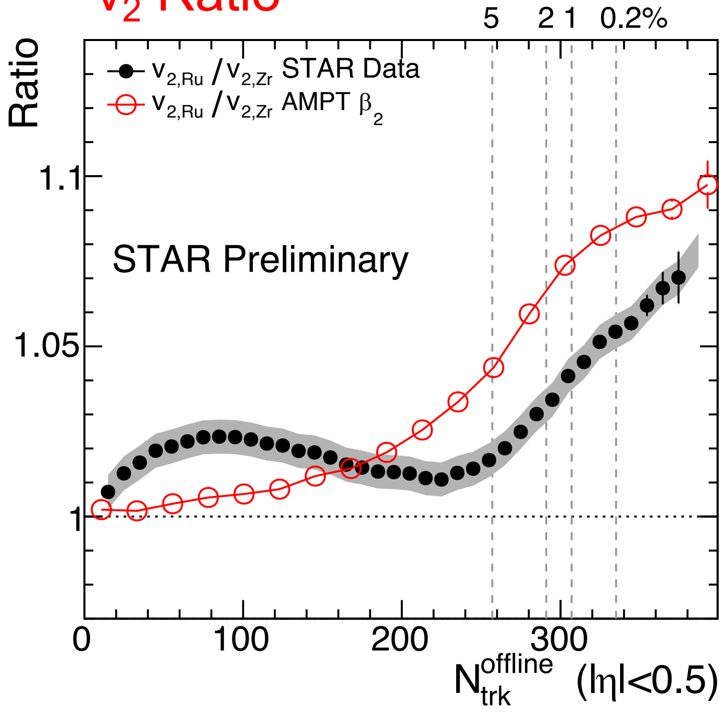


Nuclear structure via collectivity v_n ratio

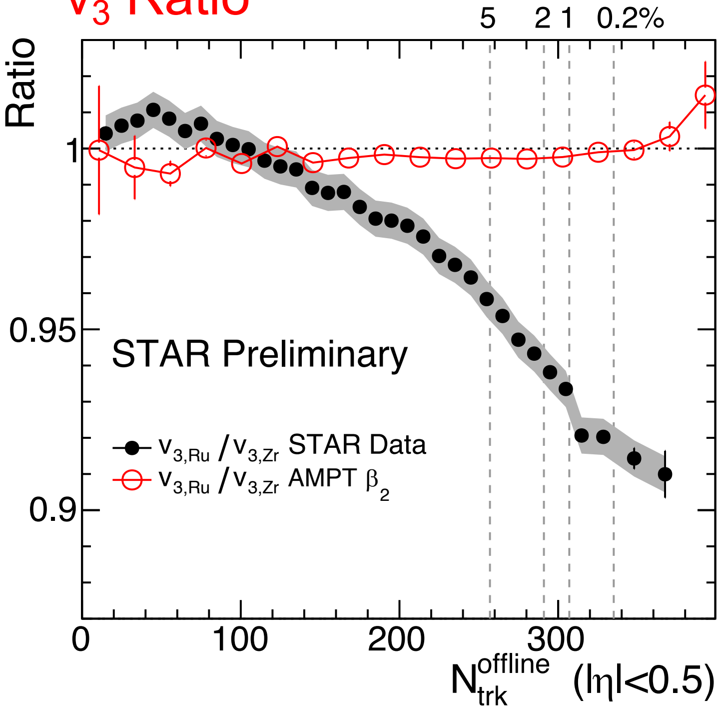


Nuclear structure via collectivity v_n ratio

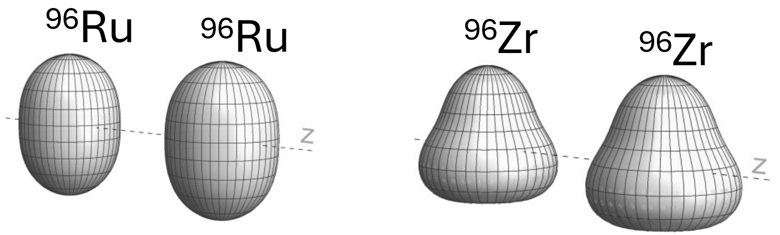
v_2 Ratio



v_3 Ratio



β_{2Ru} ~ 0.16 increase v_2, no influence on v_3 ratio



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

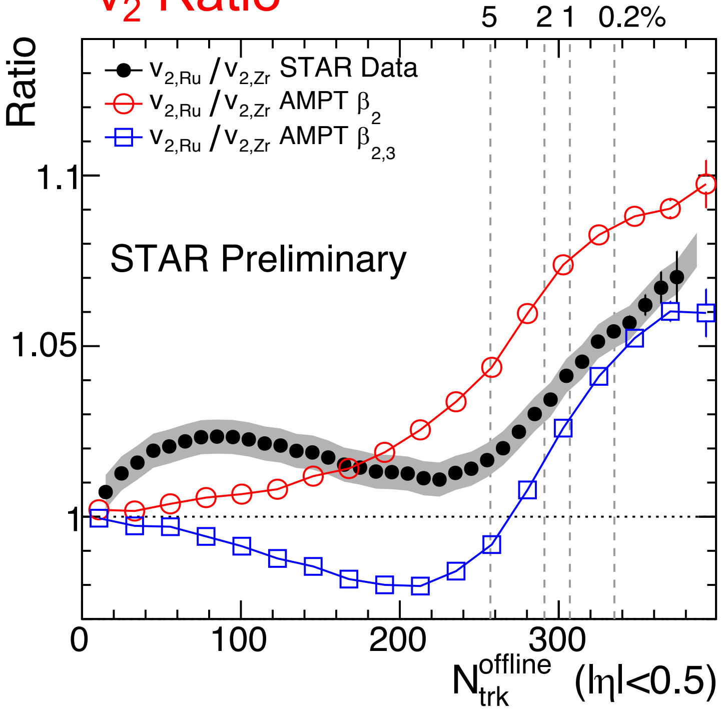
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

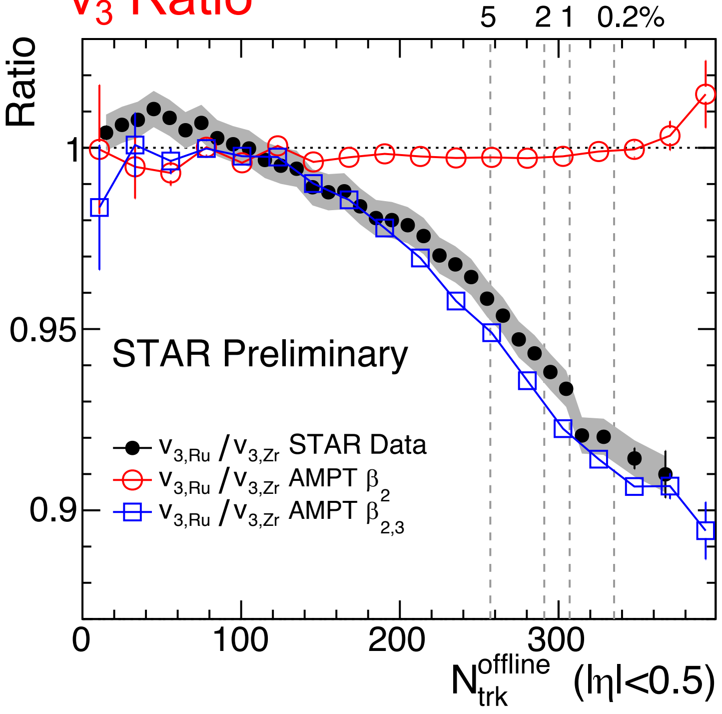
C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, C. Zhang, PRC 107, L012901(2023)

Nuclear structure via collectivity v_n ratio

v_2 Ratio



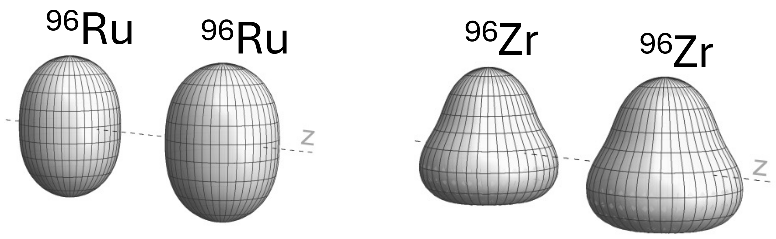
v_3 Ratio



β_{2Ru} ~ 0.16 increase v_2, no influence on v_3 ratio

β_{3Zr} ~ 0.2 decrease v_2 in mid-central, decrease v_3 ratio

- Direct observation of octupole deformation in ^{96}Zr nucleus



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

difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
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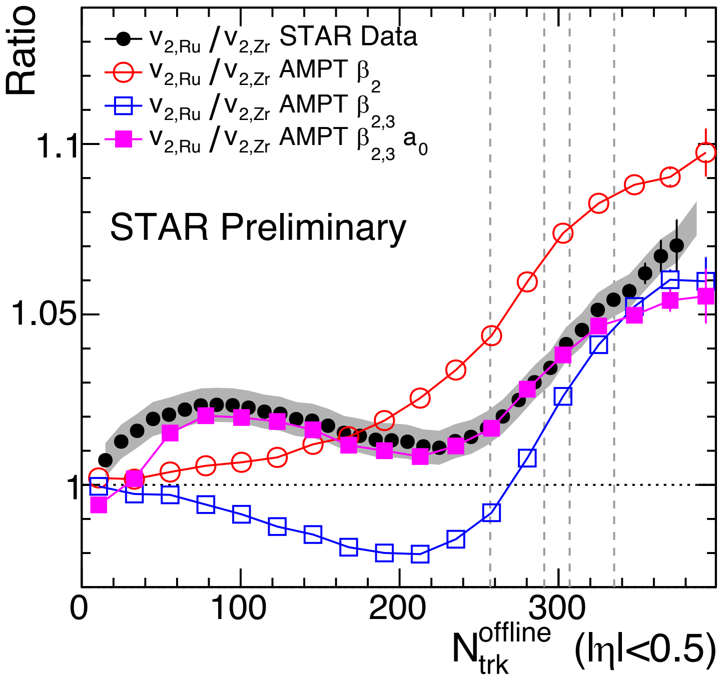
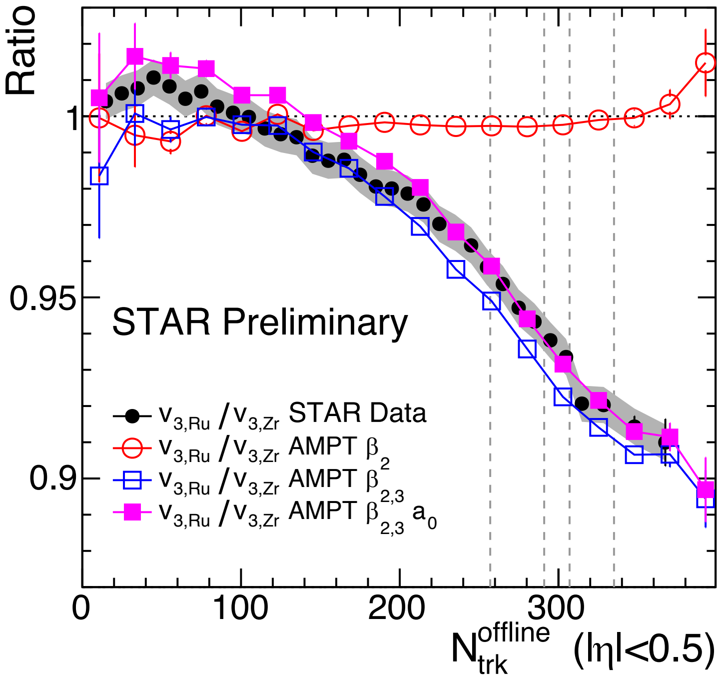
Nuclear structure via collectivity v_n ratio

v_2 Ratio



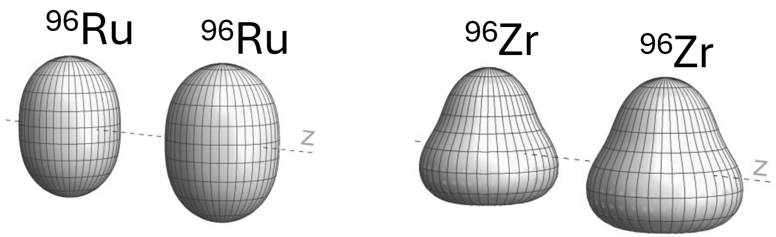
v_3 Ratio



β_{2Ru} ~ 0.16 increase v_2, no influence on v_3 ratio

β_{3Zr} ~ 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



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

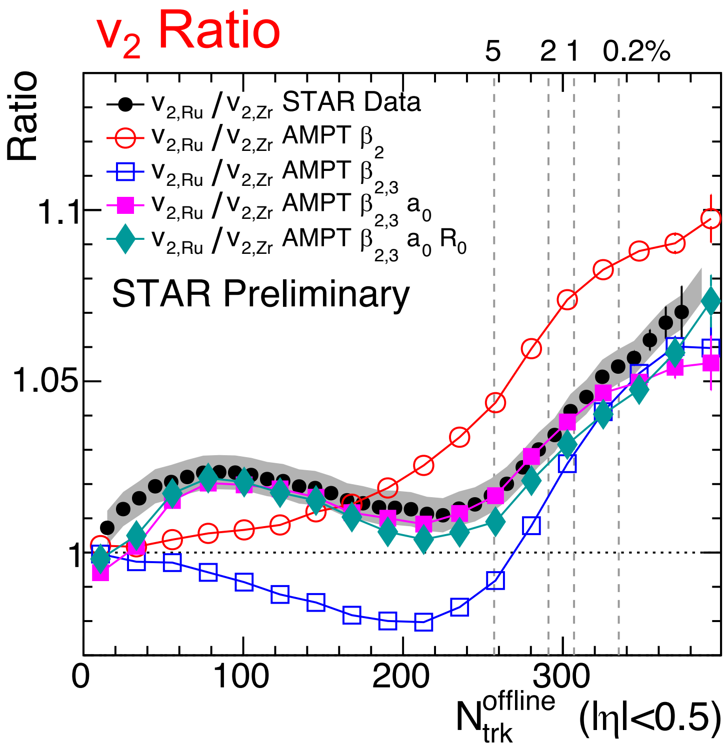
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

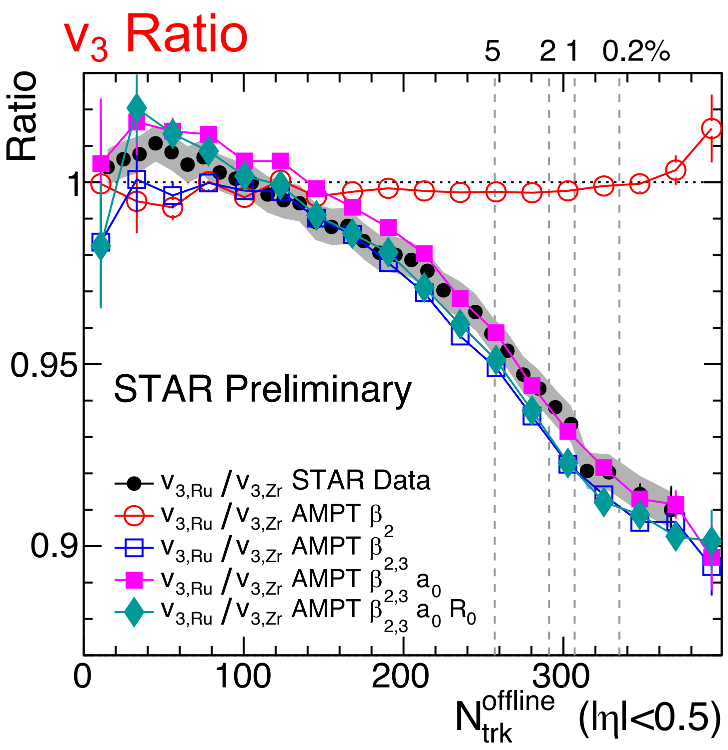
Current estimation is from transport model

- Direct observation of octupole deformation in ^{96}Zr nucleus
- Imply the neutron skin difference between ^{96}Ru and ^{96}Zr

C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, C. Zhang, PRC 107, L012901(2023)

Nuclear structure via collectivity v_n ratio



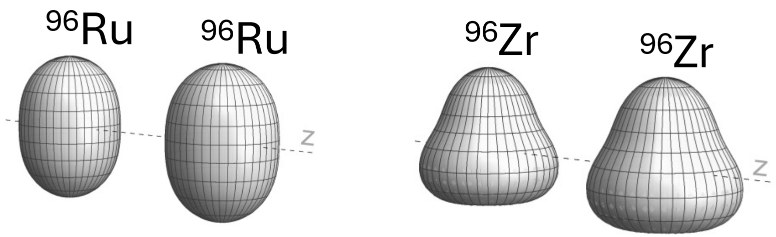


$\beta_{2Ru} \sim 0.16$ increase v_2, no influence on v_3 ratio

$\beta_{3Zr} \sim 0.2$ 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

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

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

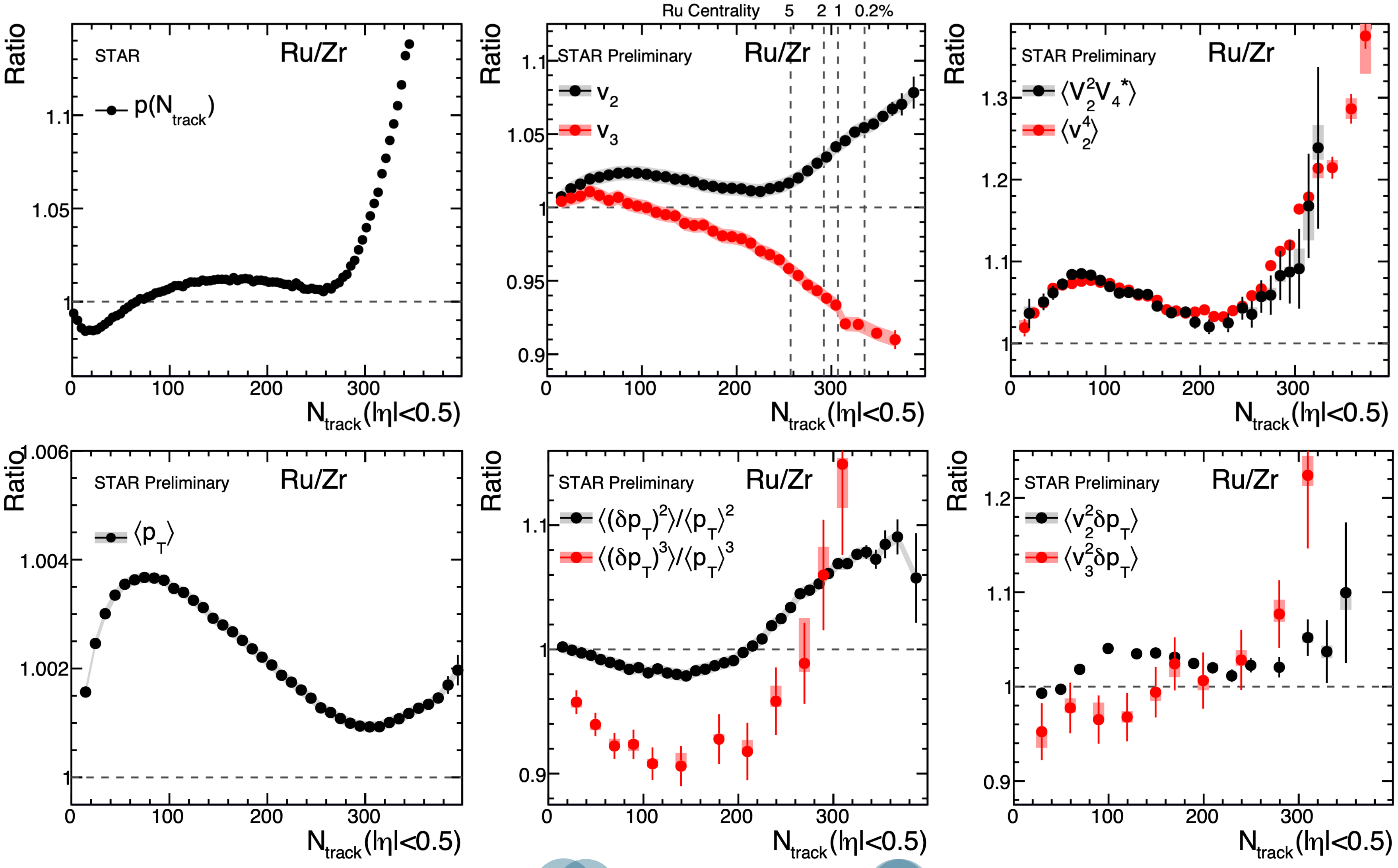
	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
difference	0.0226	-0.04	-0.06 fm	0.07 fm

Current estimation is from transport model

C. Zhang and J. Jia, PRL128, 022301(2022); J. Jia, C. Zhang, PRC 107, L012901(2023)

Nuclear structure is inherent of heavy-ion probes

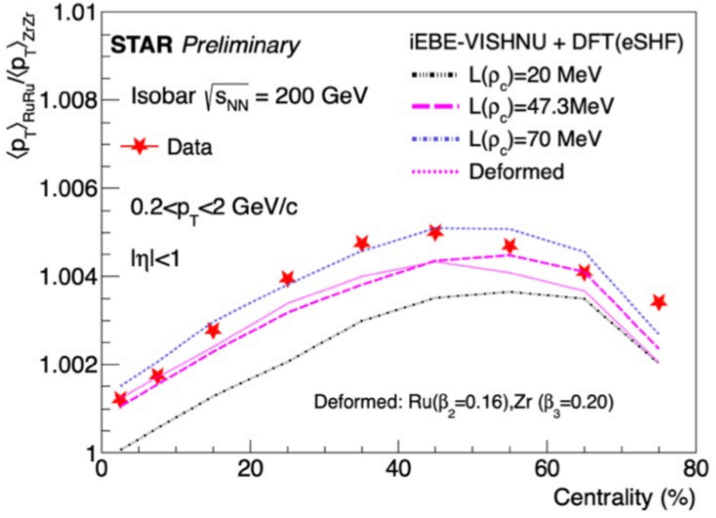
one-body distribution | two-body correlations | three-body correlations



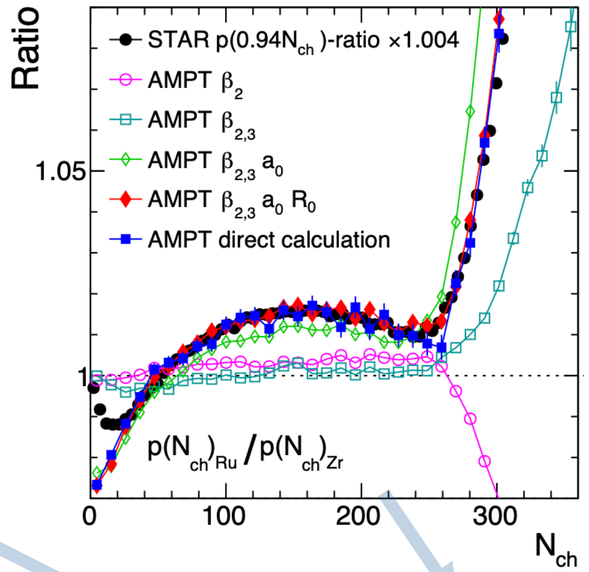
Imaging the radial structures (neutron skin)

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},**

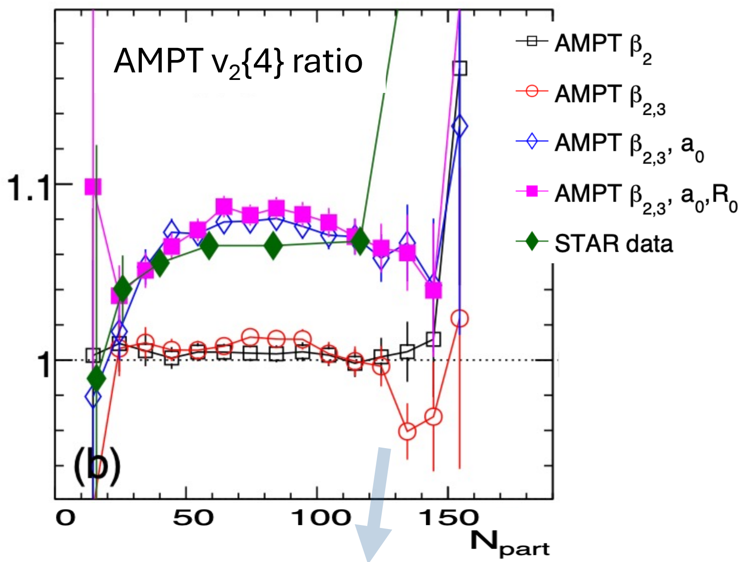
H. Xu, QM2023



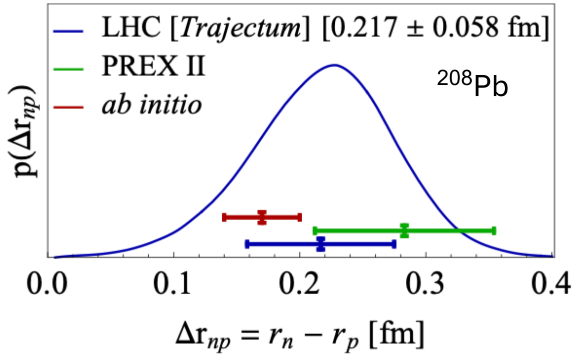
J. Jia, C. Zhang, PRC 107, L02901 (2023)



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

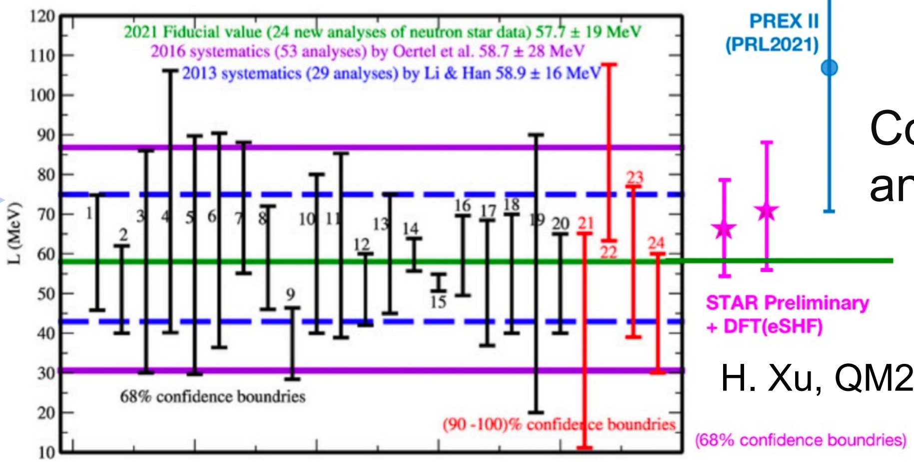


Current puzzle in low-energy nuclear physics



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

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

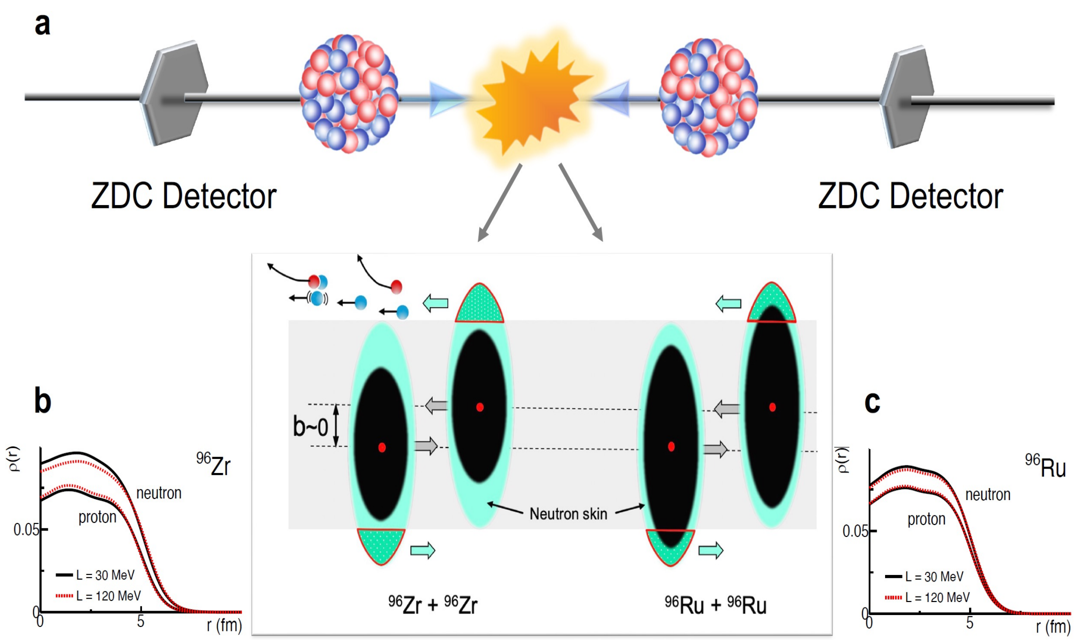


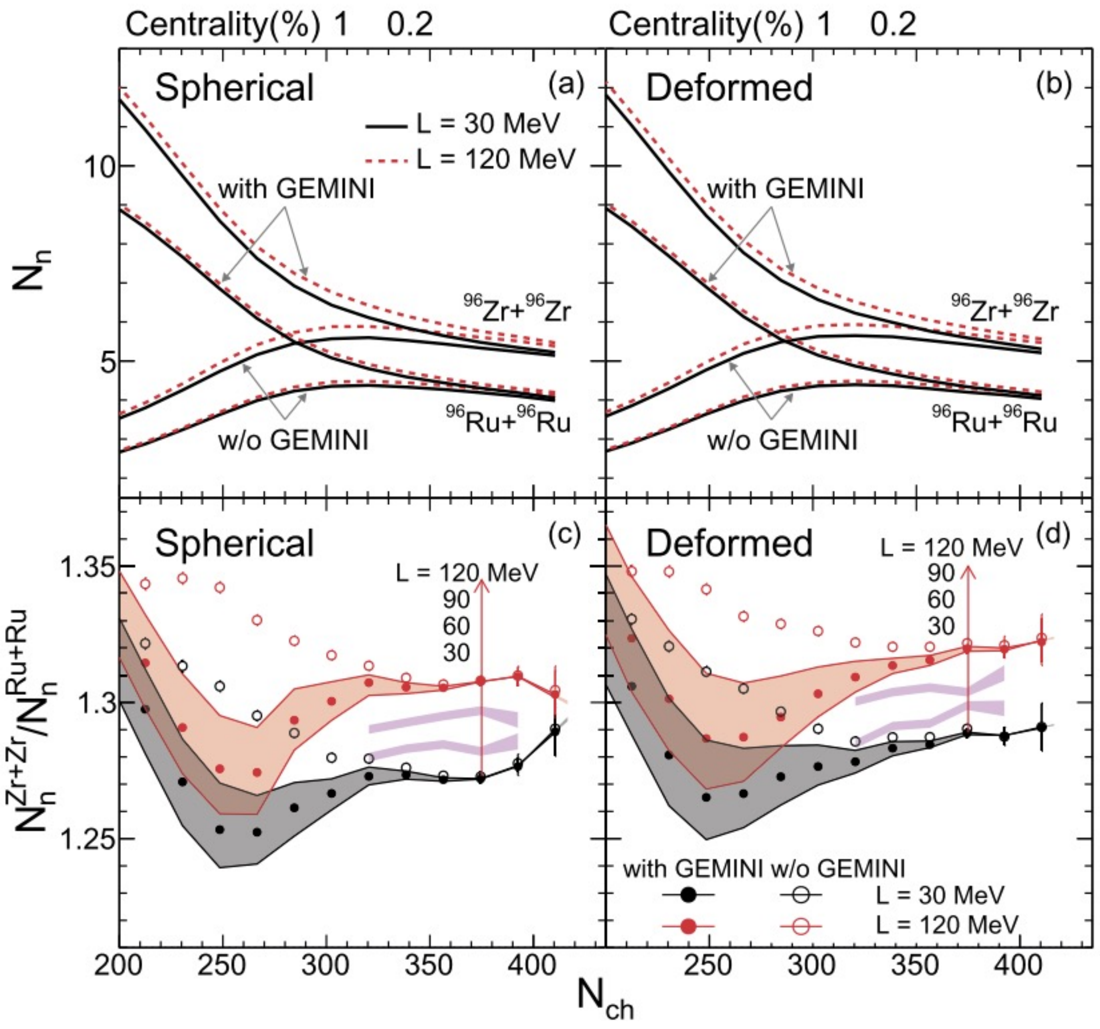
H. Xu, QM2023

Constrain neutron skin and symmetry energy

Haojie Xu (Huzhou), 4.26, 16:10-16:35; Pengcheng Li (Huzhou), Poster #169; Guojun Wei (Huzhou), Poster #181, Shanliang Zhang (Hubei), Poster #194

Imaging the radial structures (neutron skin): spectator nucleons





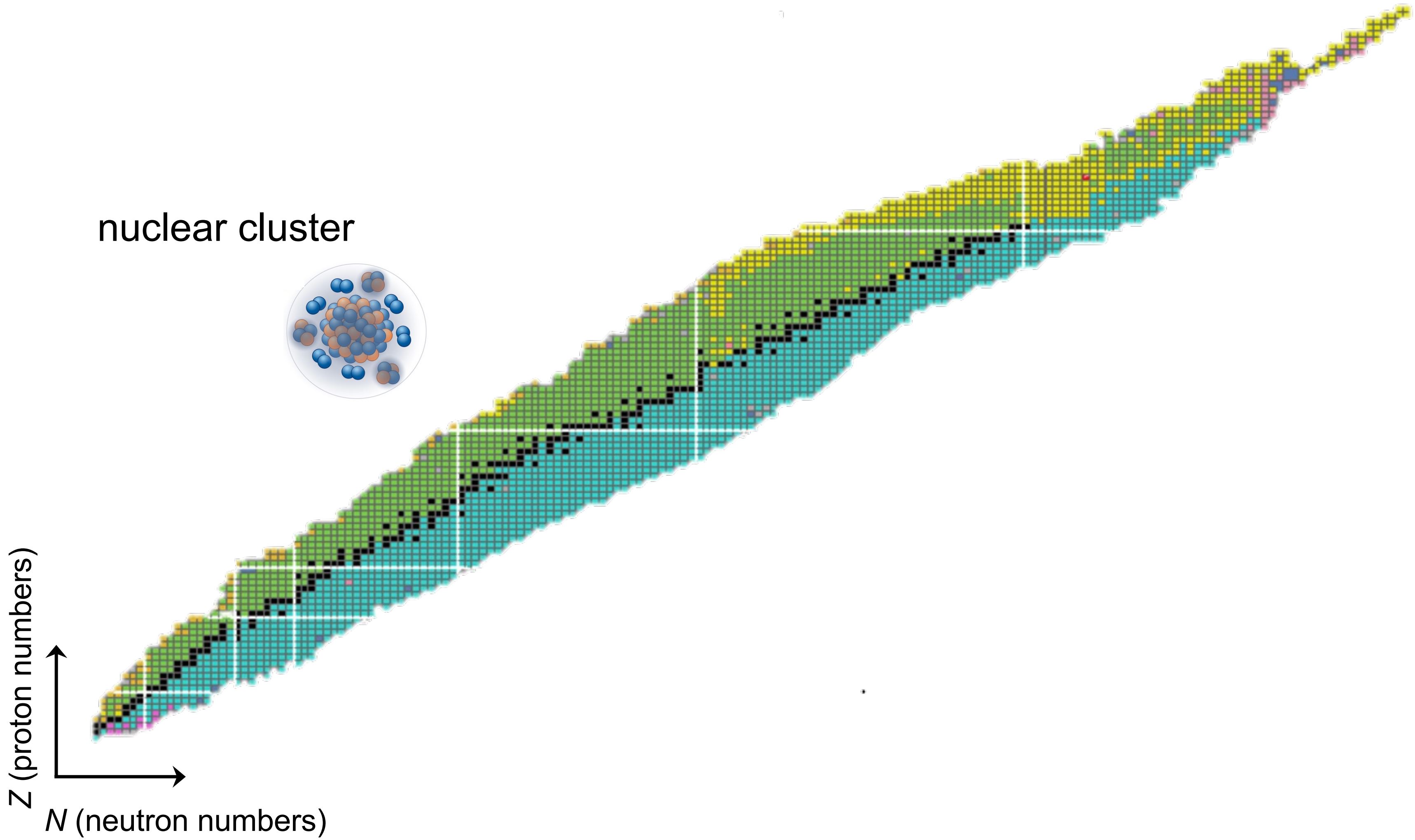
In UCC region, most spectator nucleons originate from the surface.

Initial state: DFT+MC Glauber → Clusterization: Winger function → Deexicitaiton: GEMINI → detection of N_n and N_p

More neutron-rich spectator matter with a larger L or a thicker neutron skin Δr_{np} in UCC.

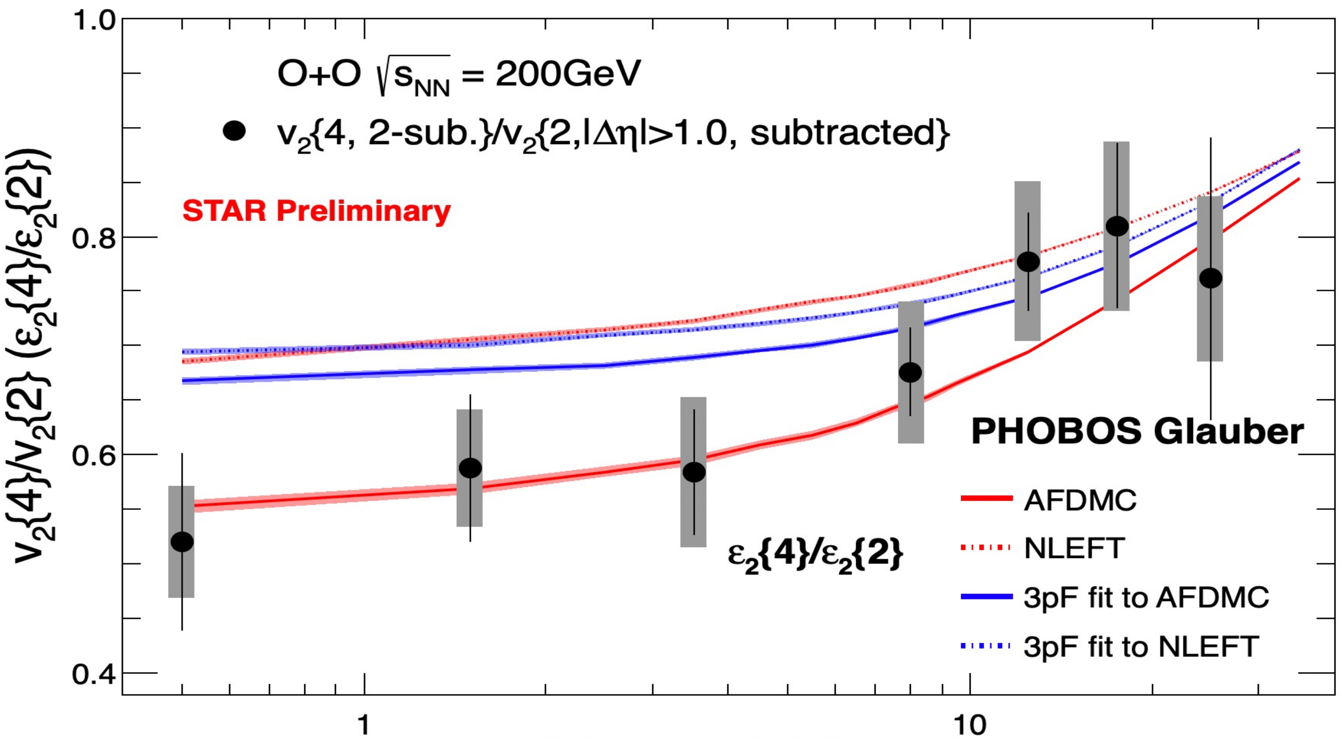
Jun Xu (Tongji), 4.26, 17:40-18:00

Nucleonic clustering in ^{16}O



Geometric tomography of ^{16}O nucleus

O+O run2021: 600M MB and 250M HM events



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

$$\varepsilon_2\{2\}^2 = \langle \varepsilon_2^2 \rangle$$
$$\varepsilon_2\{4\}^4 = 2\langle \varepsilon_2^2 \rangle^2 - \langle \varepsilon_2^4 \rangle$$

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

1. WS is away from STAR data.

2. VMC and EFT have a visible difference.

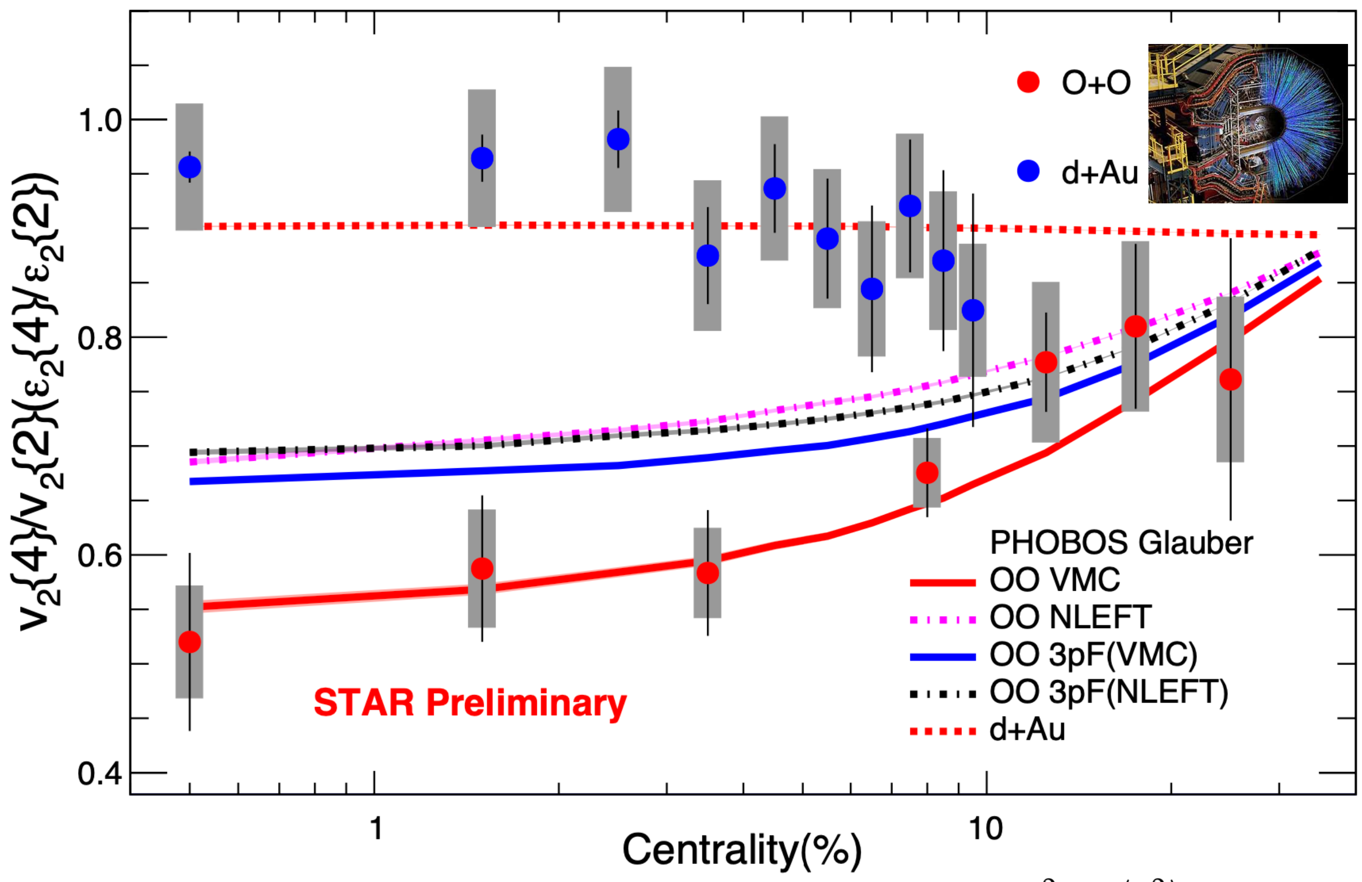
Can many-nucleon correlations significantly impact the eccentricity fluctuations? YES!

VMC and EFT theory have visible differences describing the $v_2\{4\}/v_2\{2\}$. The interplay between sub-nucleon fluctuation and many-nucleon correlation.

STAR, PRL130, 242301(2023)

Geometric tomography of ^{16}O nucleus

O+O run2021: 600M MB and 250M HM events; dAu: 70M MB



$$(v_n\{2\})^2 = c_n\{2\} = \langle v_n^2 \rangle$$
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Can many-nucleon correlations significantly impact the eccentricity fluctuations? YES!

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STAR, PRL130, 242301(2023)

O+O and p+O at LHC Run2025 possible Ne+Ne collisions?

Geometric scan elucidates nuclear tomography and **strong nuclear force?**

Need more macroscopic model inputs.

STAR: Zaining Wang (Fudan), Poster #119

Model: Xinli Zhao (USST), 4.26, 17:20-17:40; Pei Li (Fudan), Poster #117

Conclusions and Outlooks

1. Intersection of nuclear structure and hot QCD across energy scales:

→ better control variation of the QGP initial conditions

→ a novel way to unveil nuclear structure across energy scales

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

→ constrain β_2 and observe γ shape in ground-state ^{238}U:

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

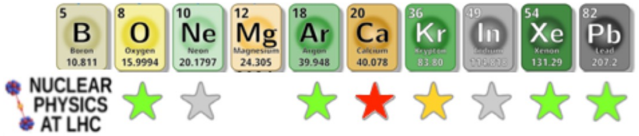
→ observe large β_3 in ^{96}Zr, a_0 difference between isobaric ^{96}Zr and ^{96}Ru

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

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

3. Many potential applications from large to small heavy-ion collision systems :

→ high-order β_3 and β_4 nuclear deformations
→ rigid and soft γ (shape fluctuations/coexistence)
→ neutron skin
→ nuclear cluster in light nuclei (^{16}O) at RHIC , collider mode (^{16}O and ^{20}Ne) at LHC and FXT mode in LHCb
→ nucleosyntheis, nuclear fission, neutrinoless double-beta decay
→ UPC- and AI-assisted nuclear shape imaging

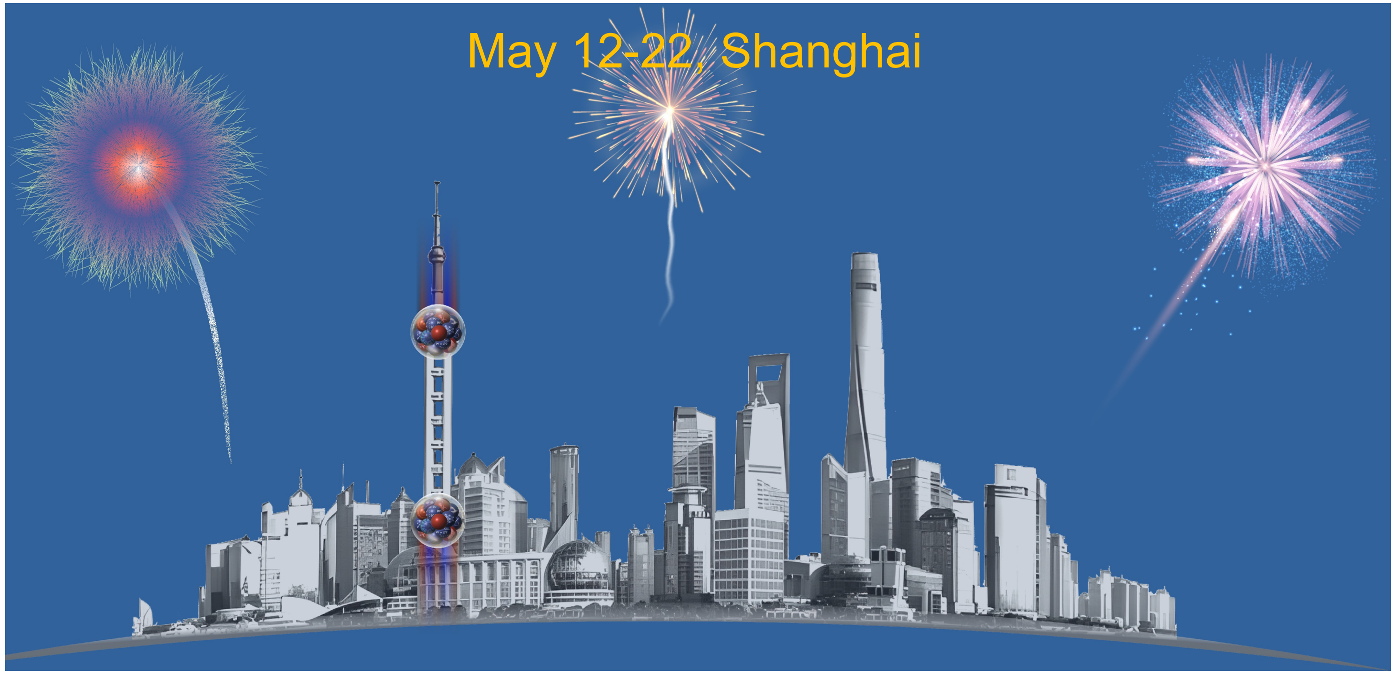


The past activities and nearest workshop

Recently organized activities from 2022:

- RBRC workshop Jan 2022, link
- EMMI Taskforce May&Oct 2022, link
- ESNT workshop Sep 2022, link
- INT program Jan-Feb 2023, link
- Dalian workshop Aug 2023, link
- Beijing workshop April 2024, link
- CERN workshop Nov 2024, link

Nuclear structure physics across the energy spectrum 2025, link



And more Nuclear structure-high-energy workshops in Sep.

Continue the efforts to further constrain QGP initial conditions and nuclear structure across energy scales.

恳请批评指正！

Backup

Some references for this article

nature › article metrics

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

Article metrics | Last updated: Tue, 8 Apr 2025 7:19:52 Z

Imaging shapes of atomic nuclei in high-energy nuclear collisions

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Scientists use high-energy heavy ion collisions as a new tool to reveal subtleties of nuclear structure with implications for many areas of physics

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By Magda Zielińska & Paul E. Garrett

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By Benjamin Thompson & Emily Bates

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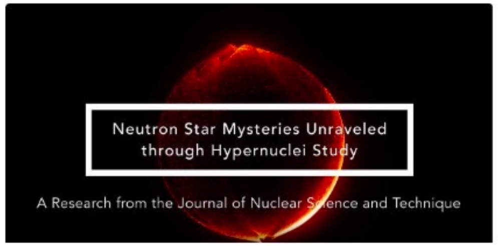

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