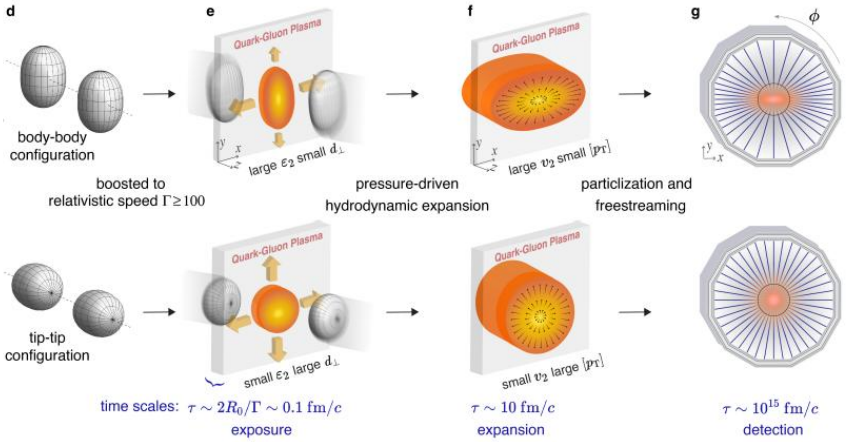


Probe the nuclear shape with relativistic heavy-ion collisions

Shujun Zhao（赵沭钧）

Nuclear physics across energy scales

Wuhan, 2025.09.20

This presentation is supported by Research Fund Program for Early-career Researchers in Sophia University

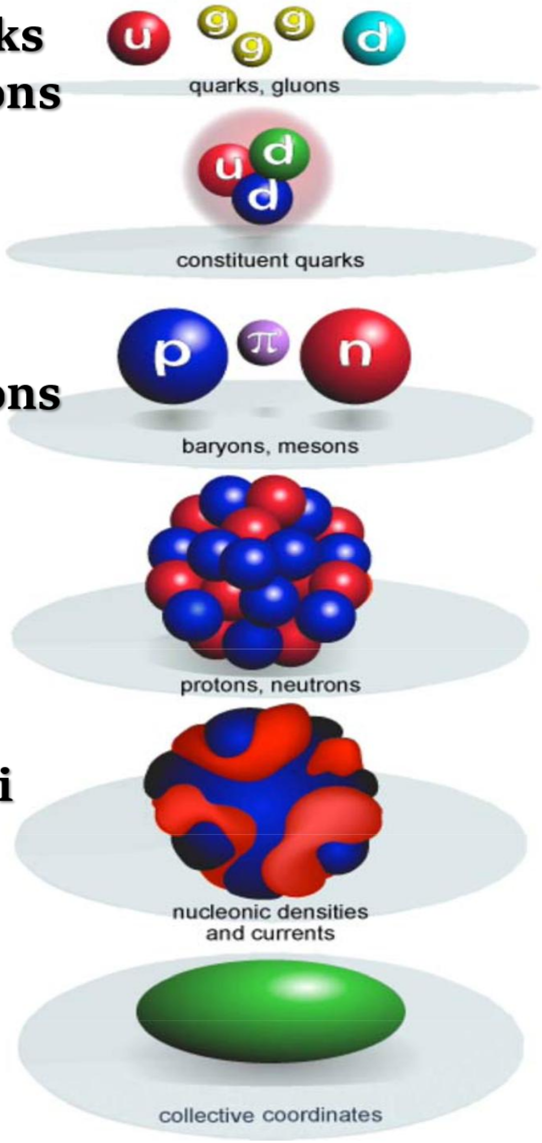
Nuclear Physics in Different Energy Scale

degrees of freedeom

quarks & gluons

hadrons

nuclei



Energy (MeV)

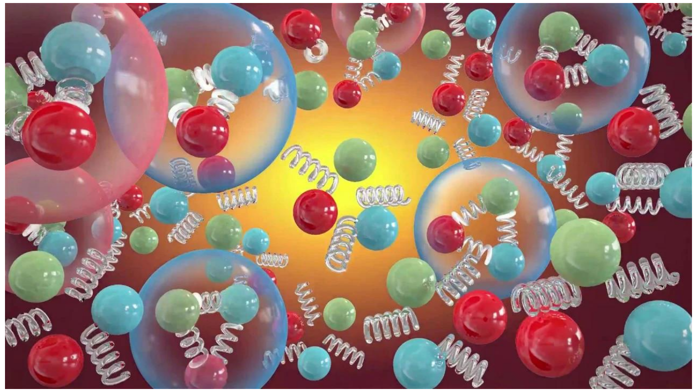
940
neutron mass

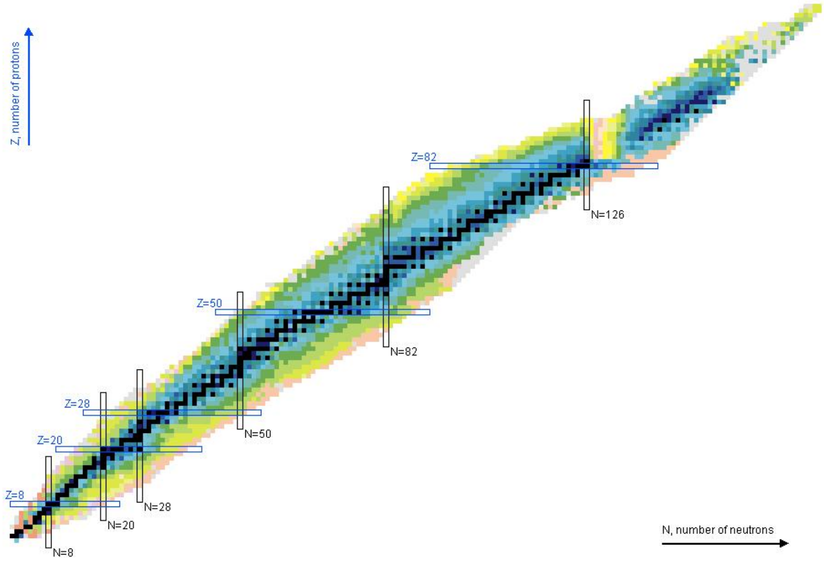
140
pion mass

8
proton separation energy in lead

1.32
vibrational state in tin

0.043
rotational state in uranium





Various Collision Systems in RHIC and LHC

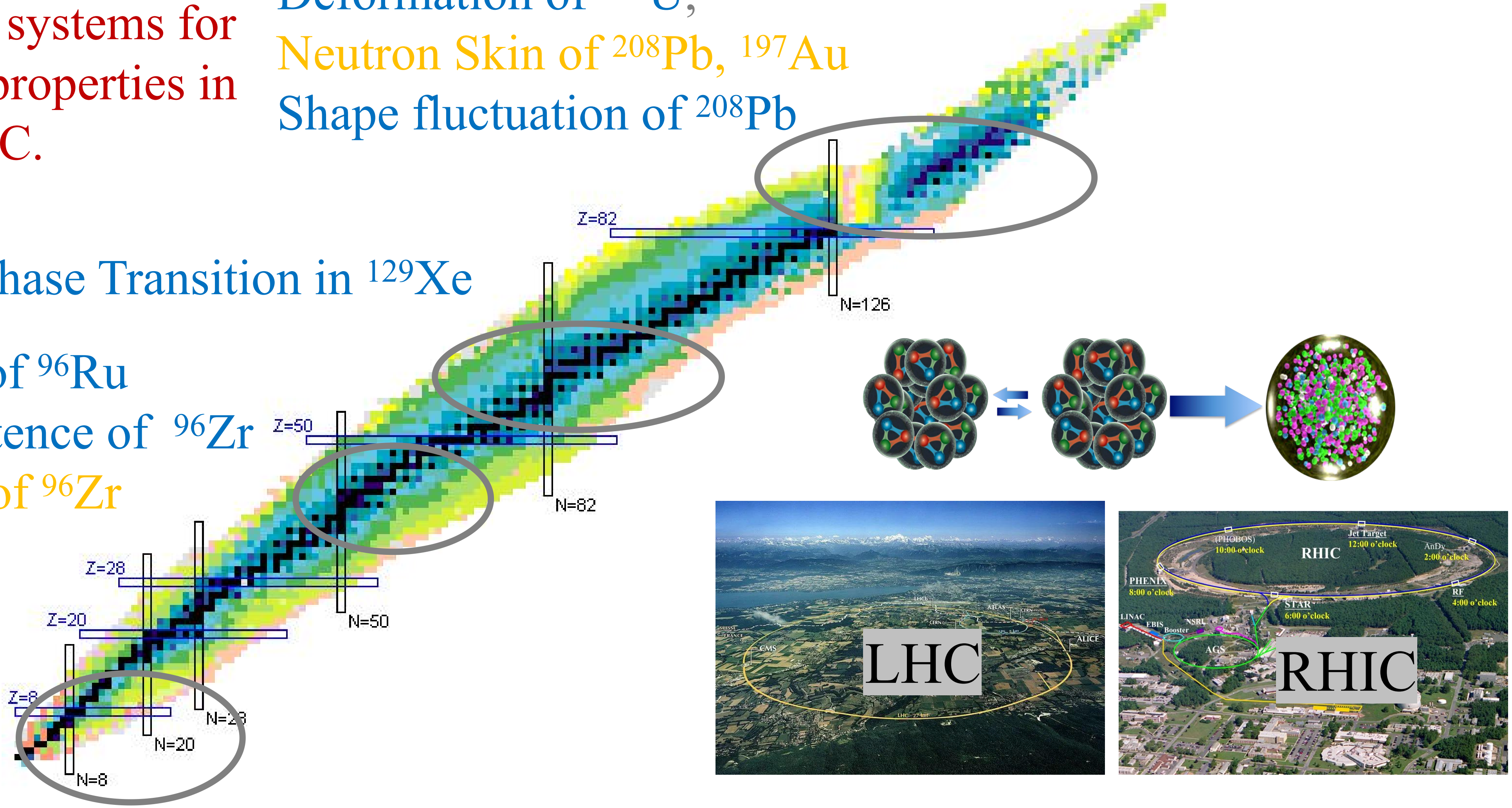
Rich collision systems for studing QGP properties in RHIC and LHC.

Deformation of ^{238}U,
Neutron Skin of ^{208}Pb, ^{197}Au
Shape fluctuation of ^{208}Pb

Shape Phase Transition in ^{129}Xe

Deformation of ^{96}Ru
Shape Coexistence of ^{96}Zr
Neutron skin of ^{96}Zr

Clustering in ^{16}O and ^{20}Ne



—— **intersection studies between relativistic heavy-ion collisions and nuclear structure.** ——

Including Nuclear Structure effects at the Initial Stage

Initial Conditions:

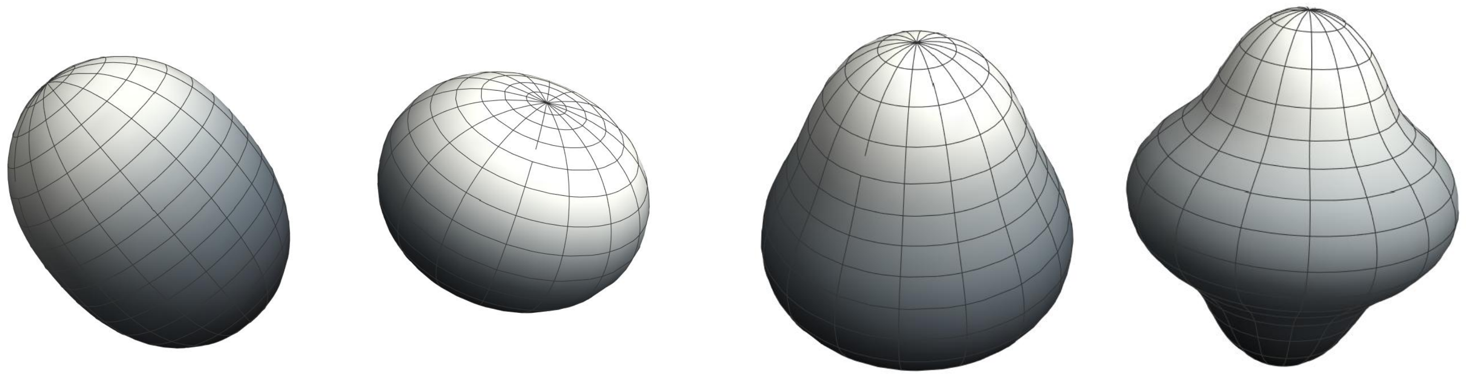
Nucleons are sampled from Woods-Saxon distribution:

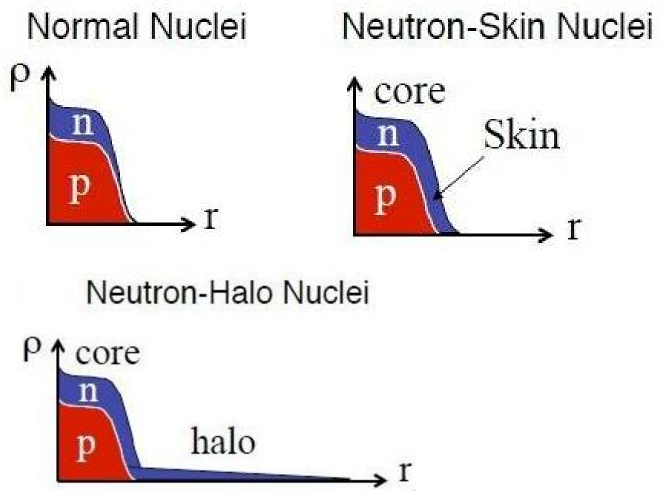
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{(r - R(\theta,\phi))/a_0}}$$

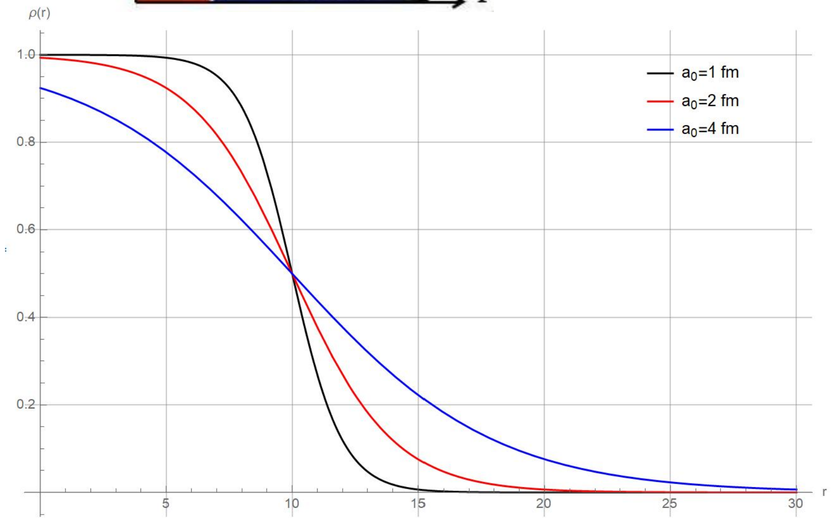
Assumption: Heavy ions with small deformation

$$R(\theta,\phi) = R_0\left(1 + \sum_{lm} \alpha_{lm} Y_{lm}(\theta,\phi)\right)$$

β_2, γ, β_3, β_4, …







More realistic configurations for precise constrain.

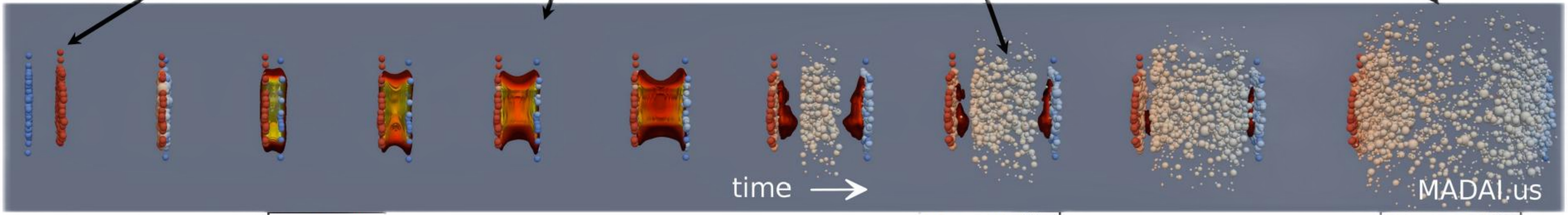
Stages of Relativistic Heavy-Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Measurable Fragments in the detector



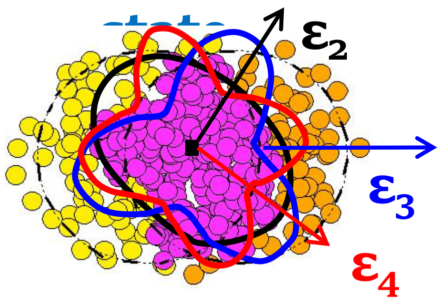
$1\text{x}\ 10^{-23}$ s

10×10^{-23} s

30×10^{-23} s

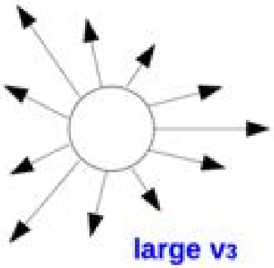
Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

Initial

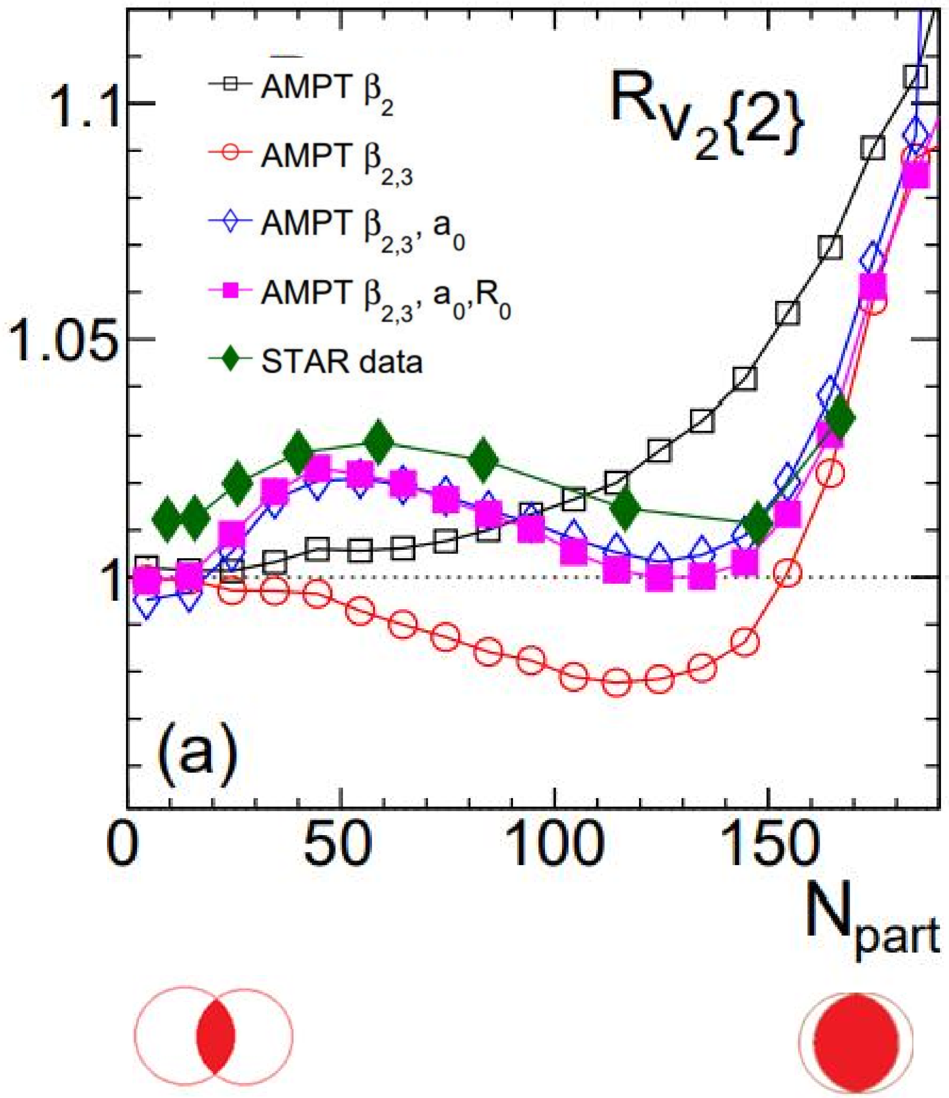


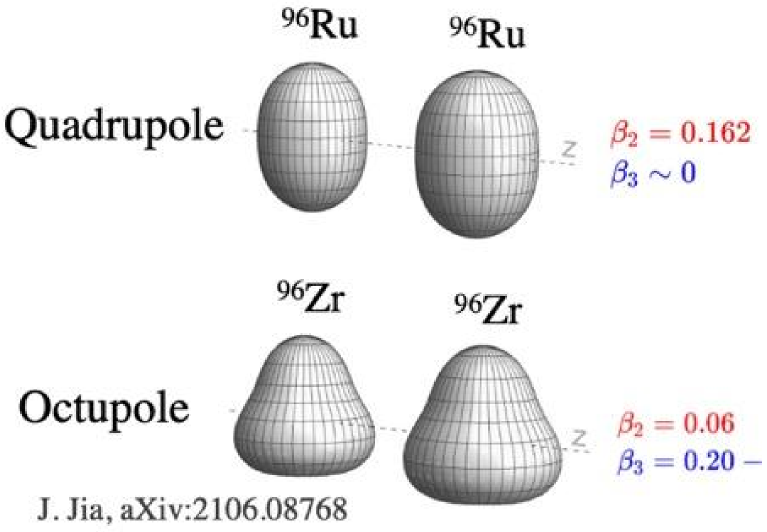
$$\frac{\mathrm{d}^2 S}{r\mathrm{d}r\mathrm{d}\phi_s} \quad \xleftrightarrow[\text{hydro-response}]{F = -\nabla P(\epsilon)} \quad \frac{\mathrm{d}^2 N_{\mathrm{ch}}}{p_T \mathrm{d}p_T \mathrm{d}\phi}$$

Final state



Probing Nuclear Deformation

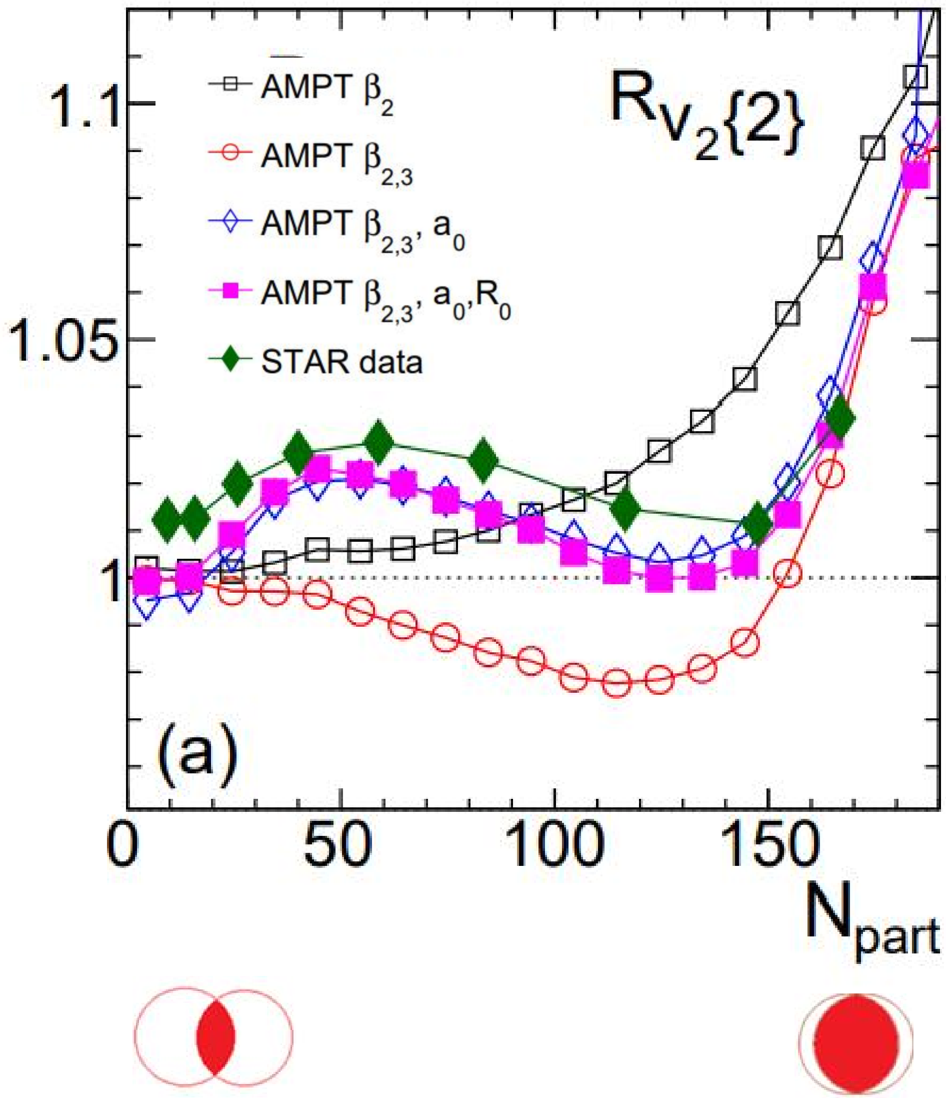




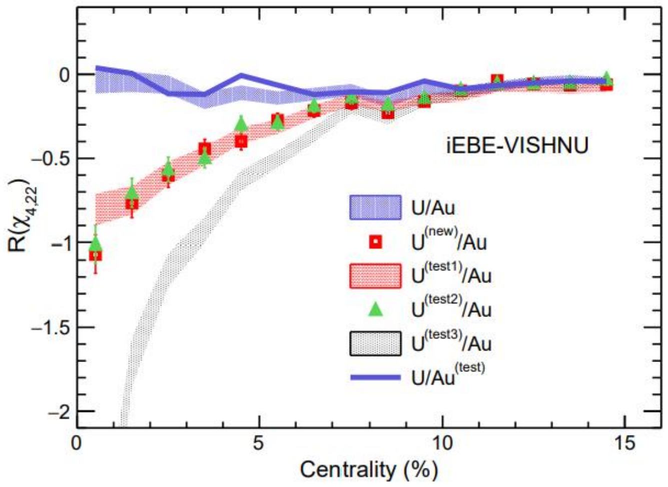
$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$$

Phys.Rev.Lett. 131 (2023) 2, 022301

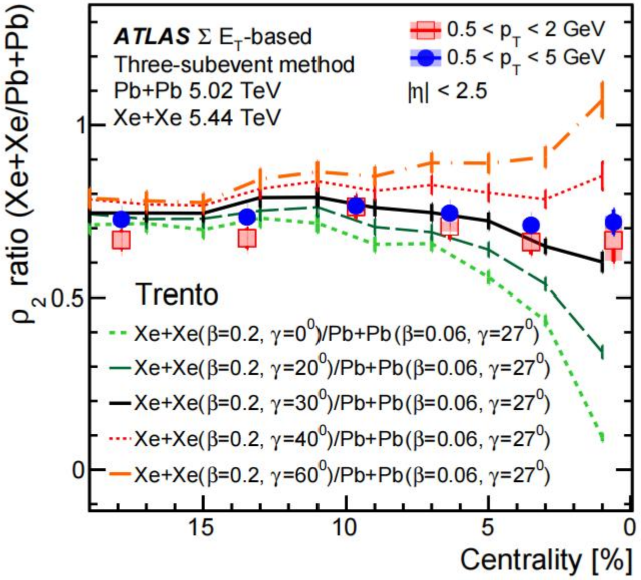
Probing Nuclear Deformation



Phys.Rev.Lett. 131 (2023) 2, 022301

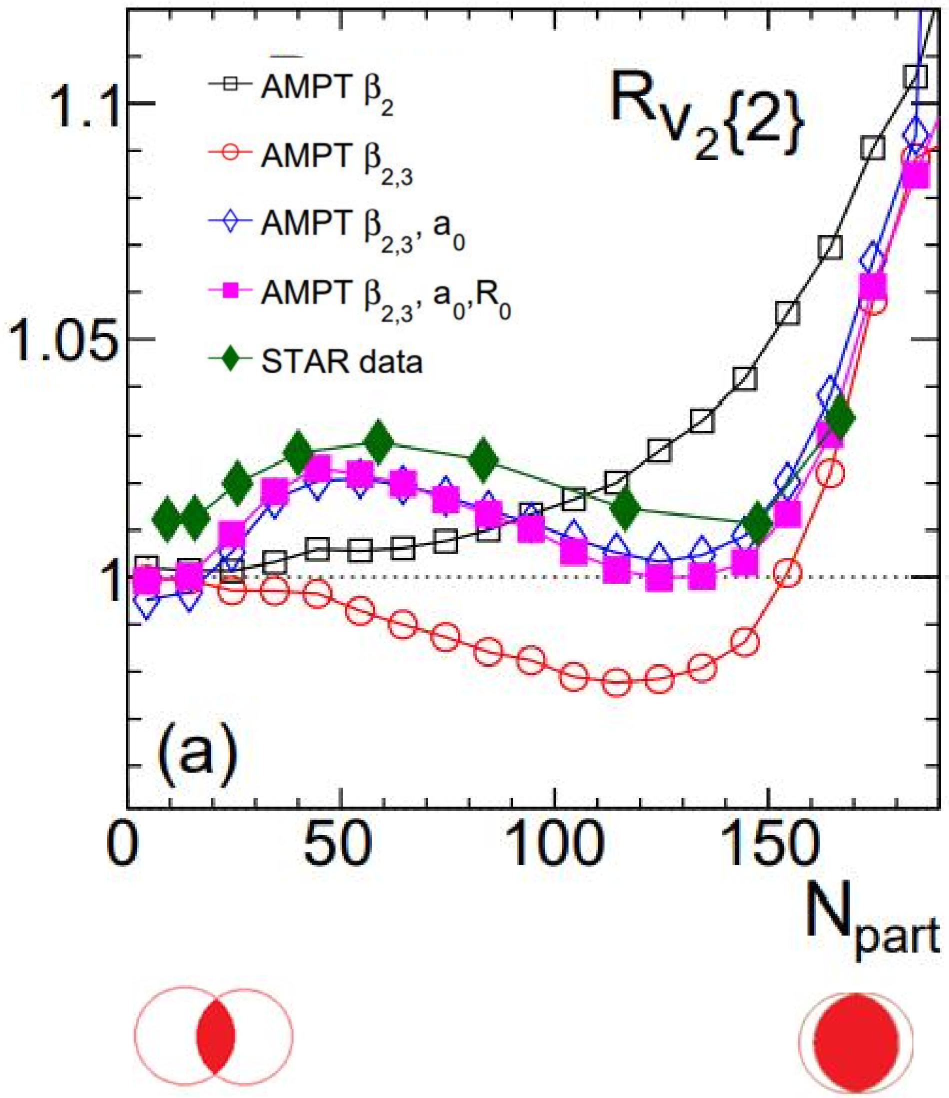


Phys.Rev.Lett. 132 (2024) 26, 262301

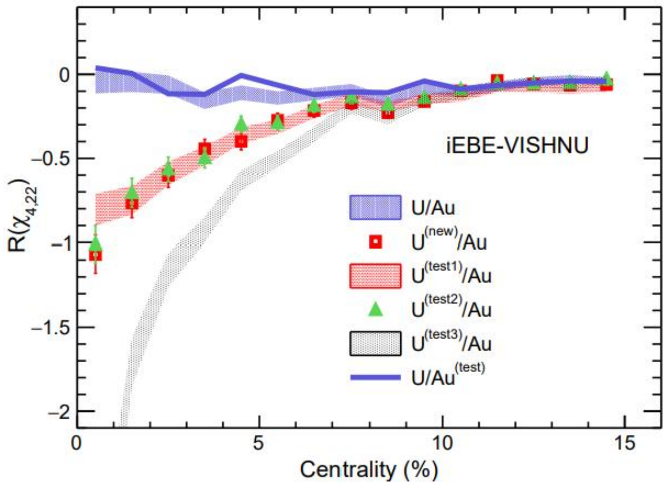


Phys.Rev.Lett. 128 (2022) 8, 082301

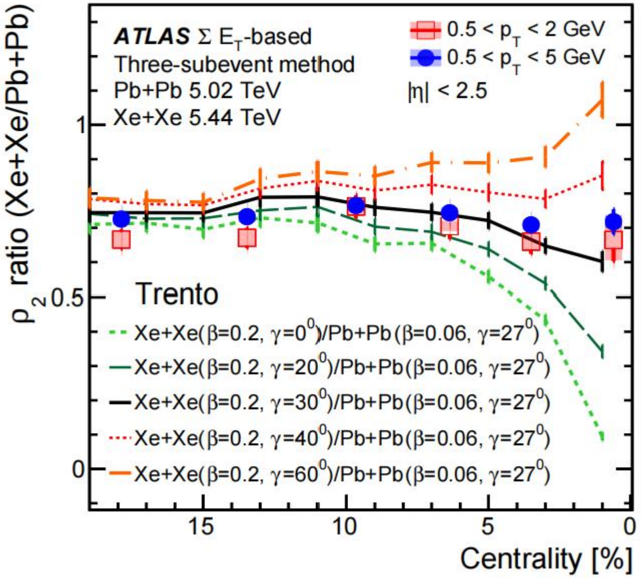
Probing Nuclear Deformation



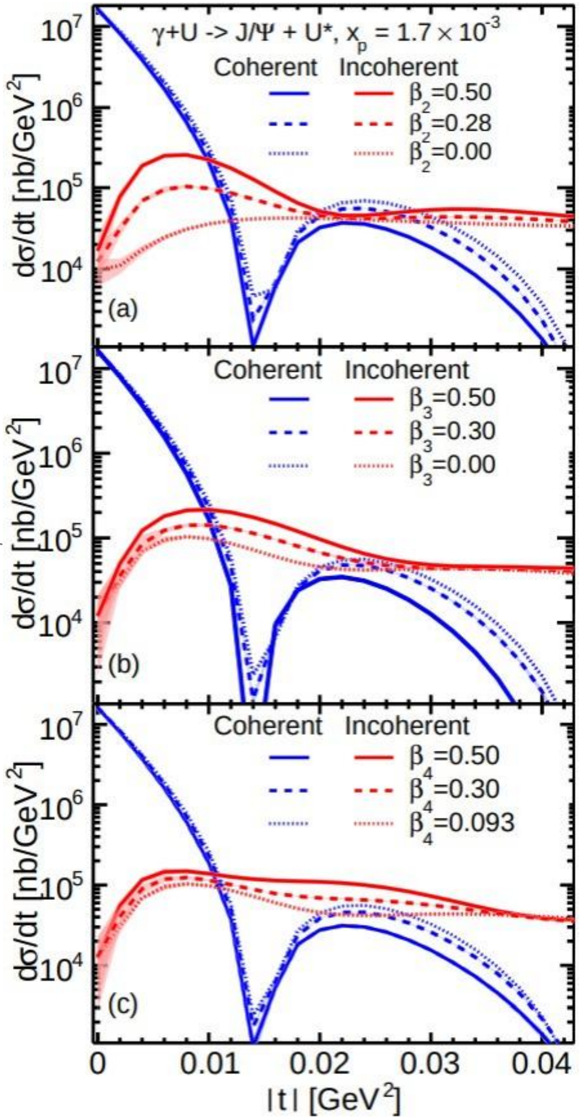
Phys.Rev.Lett. 131 (2023) 2, 022301



Phys.Rev.Lett. 132 (2024) 26, 262301

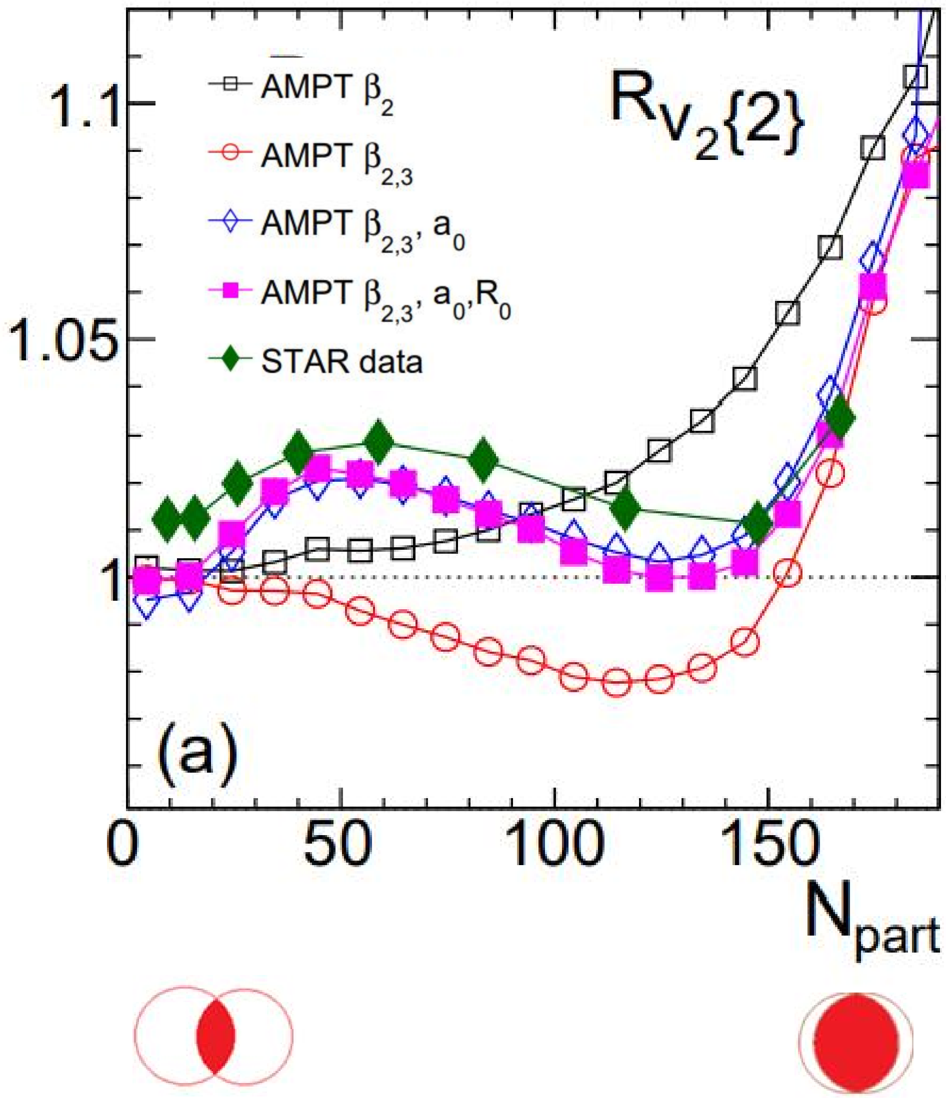


Phys.Rev.Lett. 128 (2022) 8, 082301

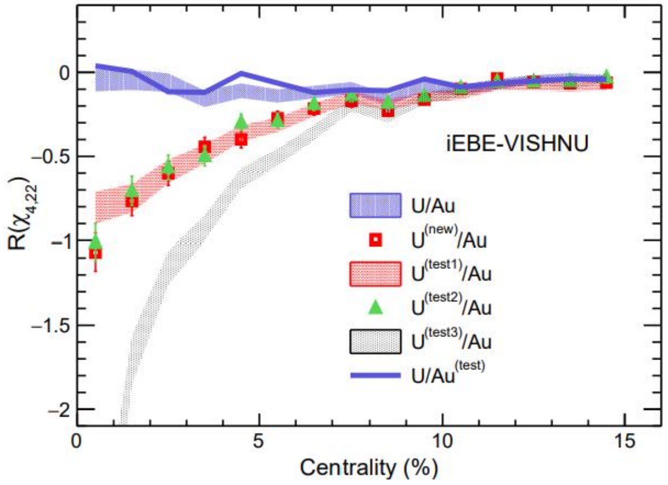


Phys.Rev.Lett. 131 (2023) 6, 062301

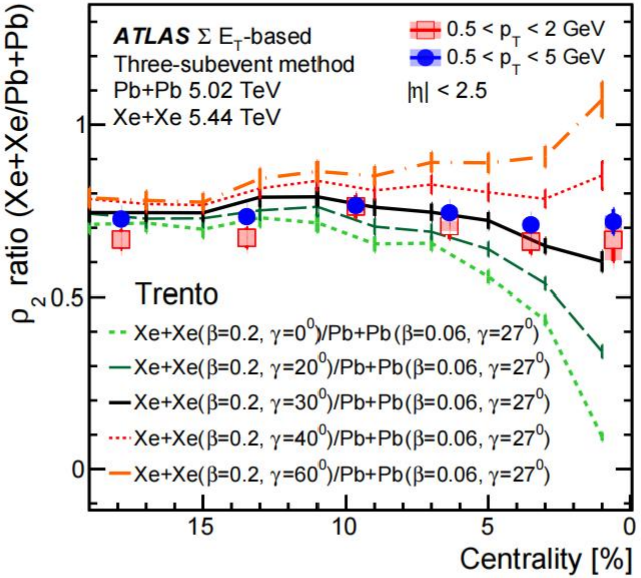
Probing Nuclear Deformation



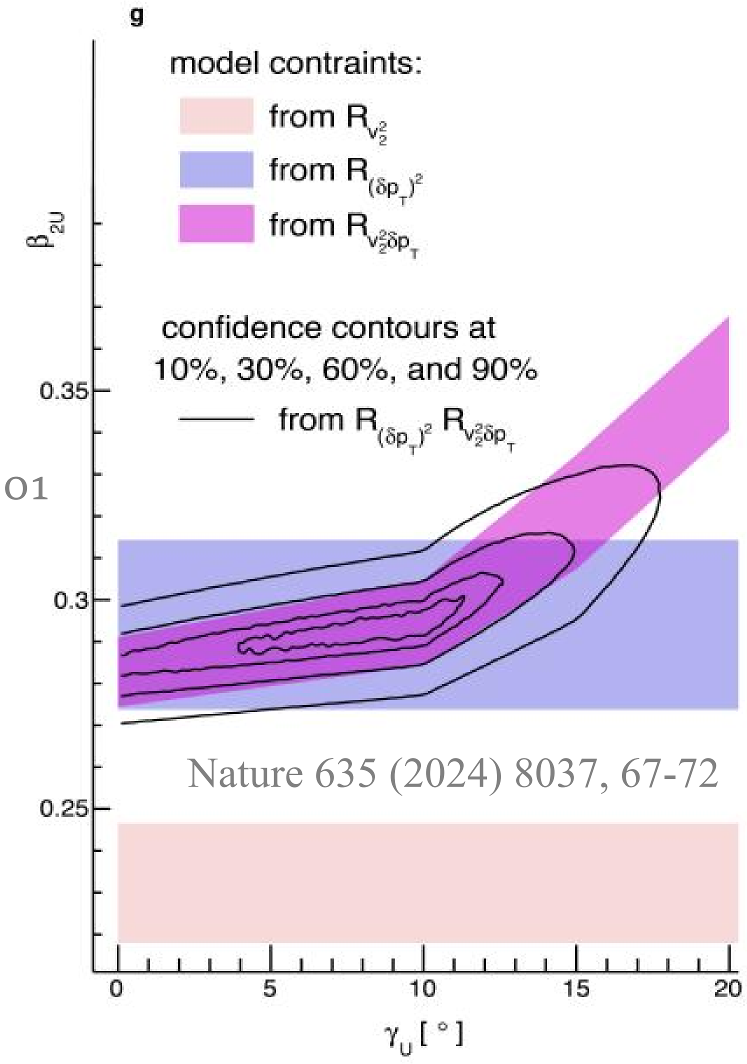
Phys.Rev.Lett. 131 (2023) 2, 022301



Phys.Rev.Lett. 132 (2024) 26, 262301

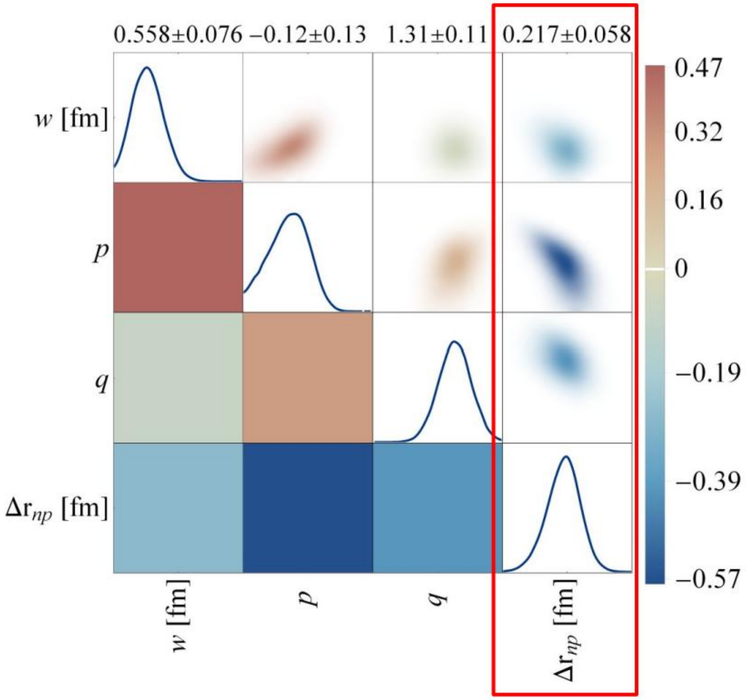


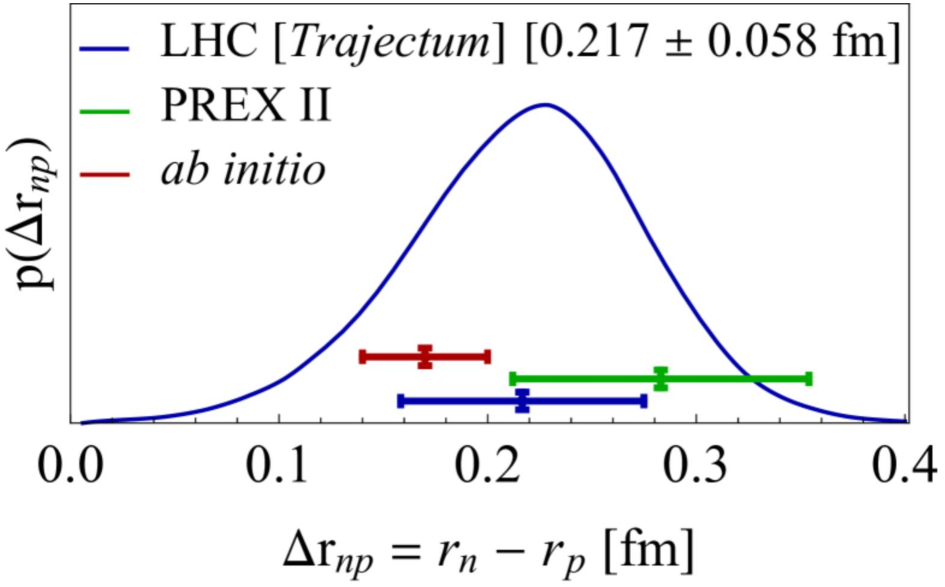
Phys.Rev.Lett. 128 (2022) 8, 082301



Nature 635 (2024) 8037, 67-72

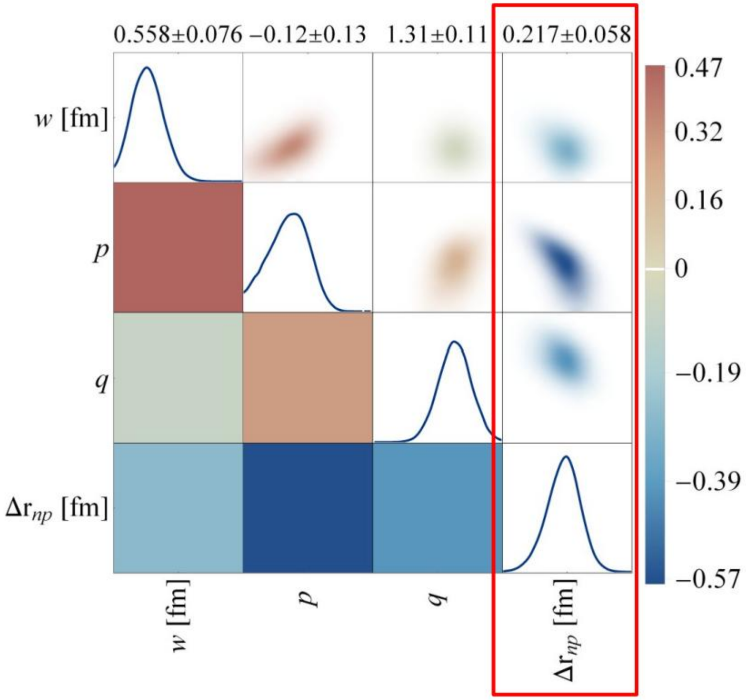
Probing Radial Structure of Nuclei

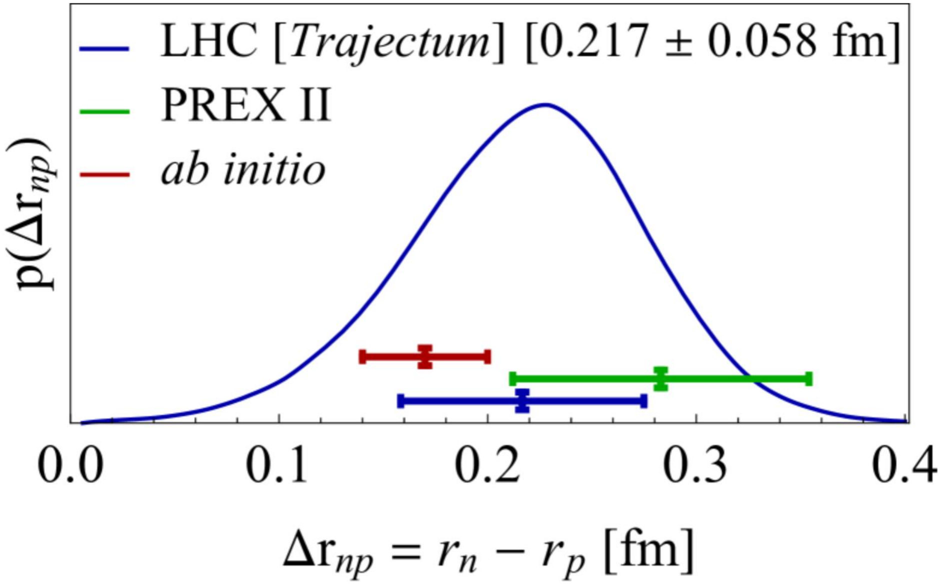




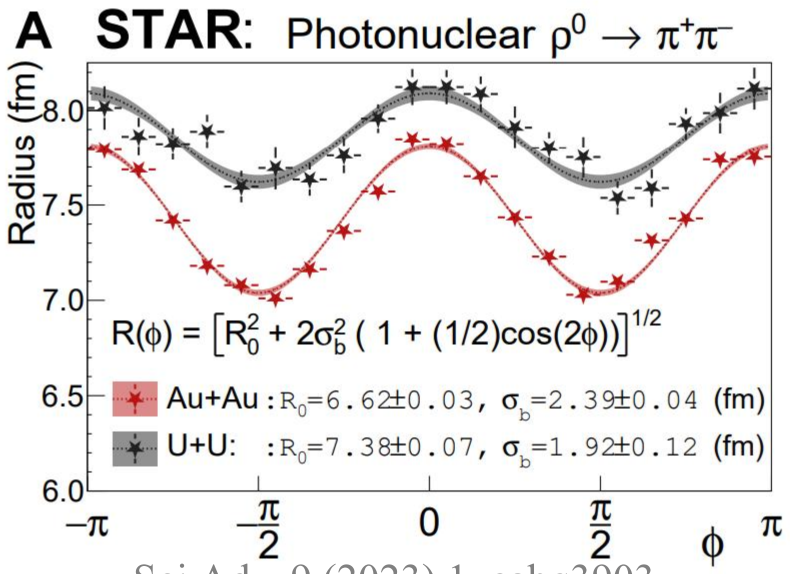
Phys.Rev.Lett. 131 (2023) 20, 20

Probing Radial Structure of Nuclei

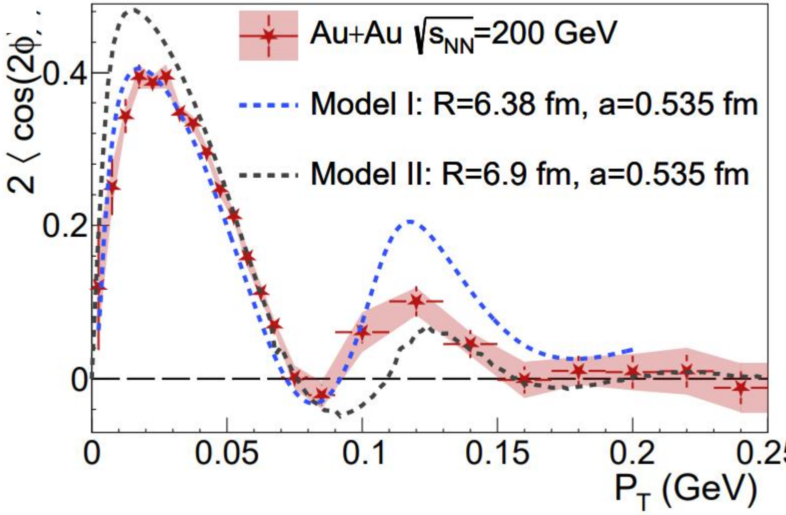




Phys.Rev.Lett. 131 (2023) 20, 20



Sci.Adv. 9 (2023) 1, eabq3903

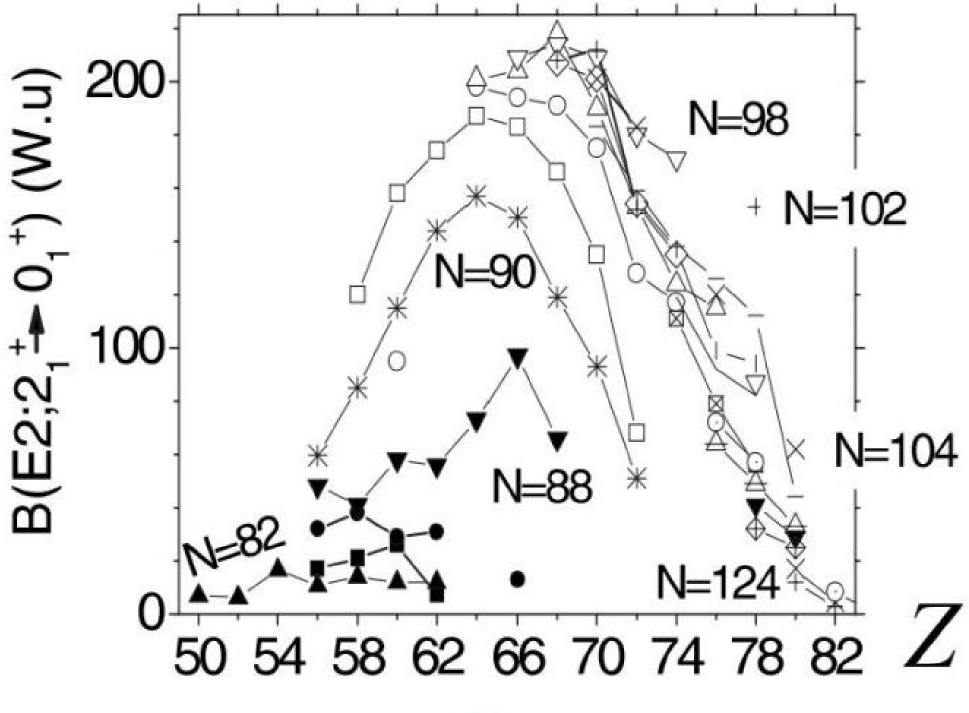


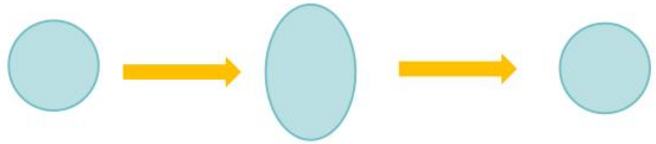
Heavy-Ion Collisions provides a strightforward way for probing the radial structure of ^{197}Au and ^{208}Pb.

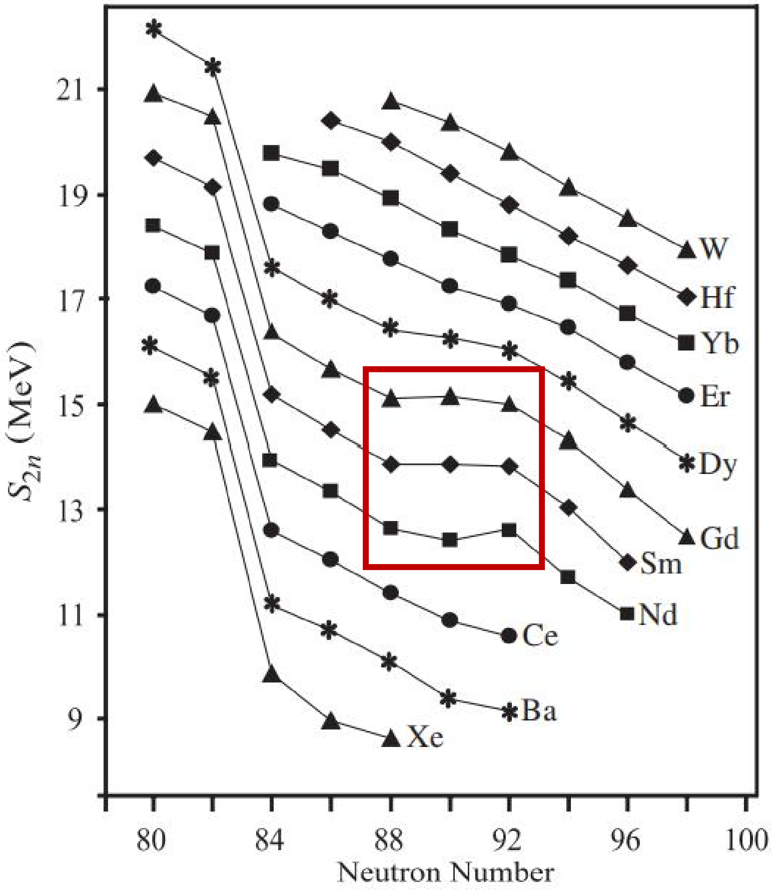
Shape Phase Transition in Nuclear Theory

Shape phase transition: Shape evolution along the isotune/isotope chain.

R. F. Casten, et. al. Rev Mod Phys.82.2155

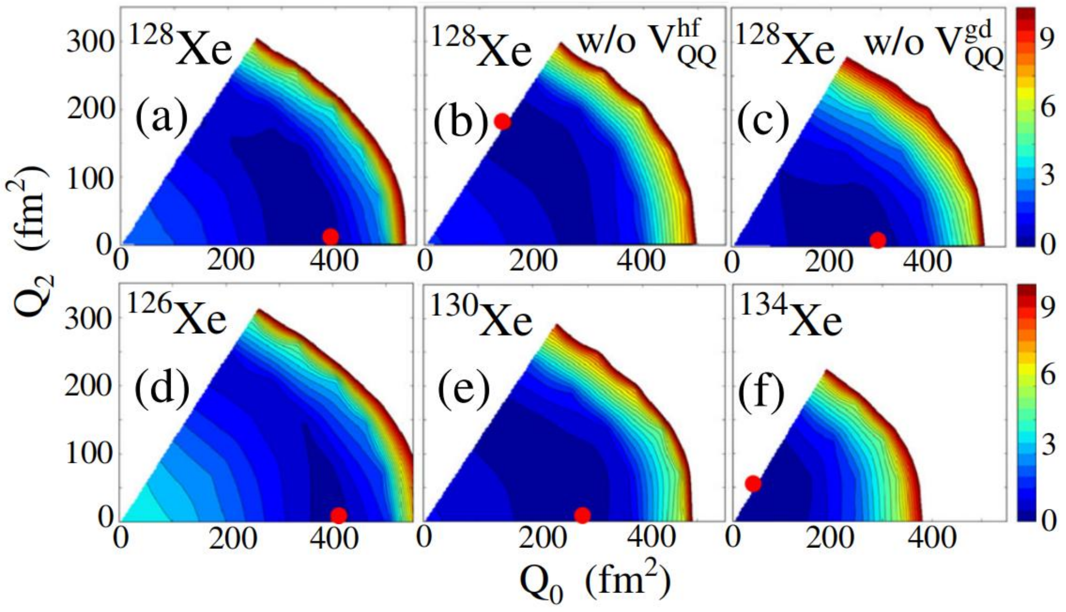






R. F. Casten and E. A. McCutchan, J. Phys. G 34, R285 (2007).

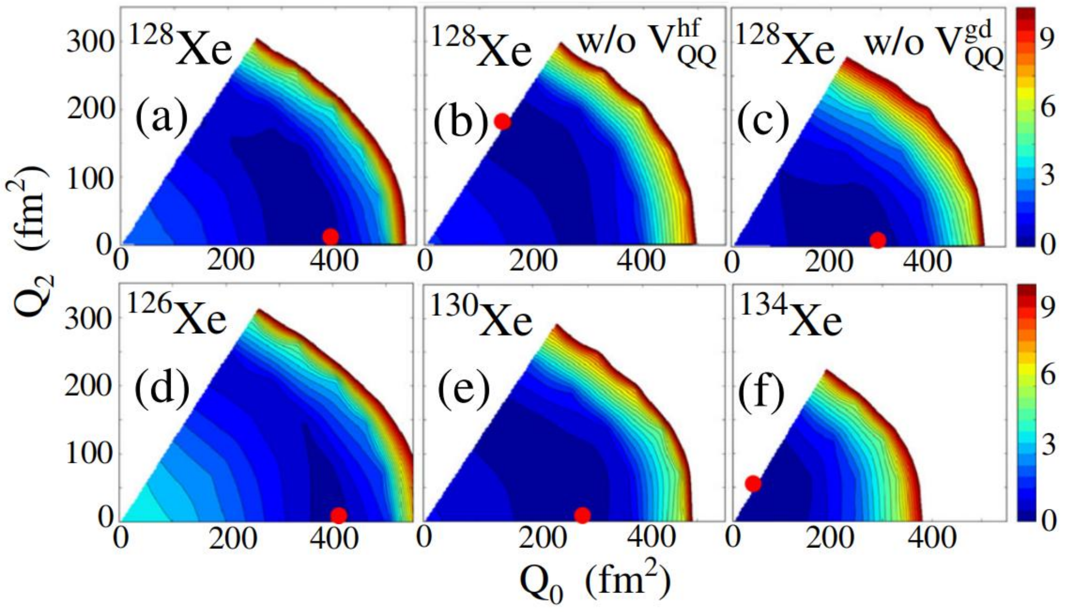
Experimental Evidence for γ-soft Structure in $^{128,130}Xe$



Strong sensitivity to neutron(proton) partner orbits. Reflect the details of proton and neutron interaction inside nuclei.

Y. Sun, et. al.

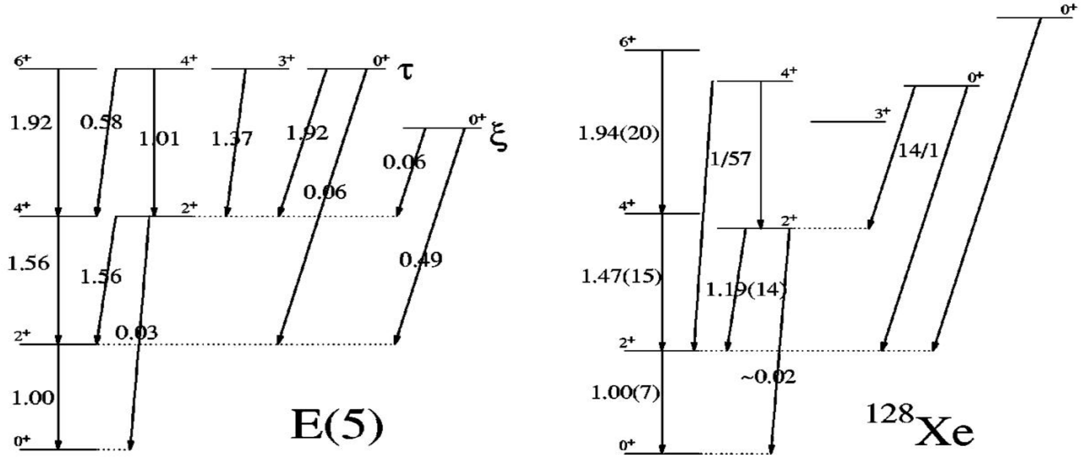
Experimental Evidence for γ-soft Structure in ^{128,130}Xe

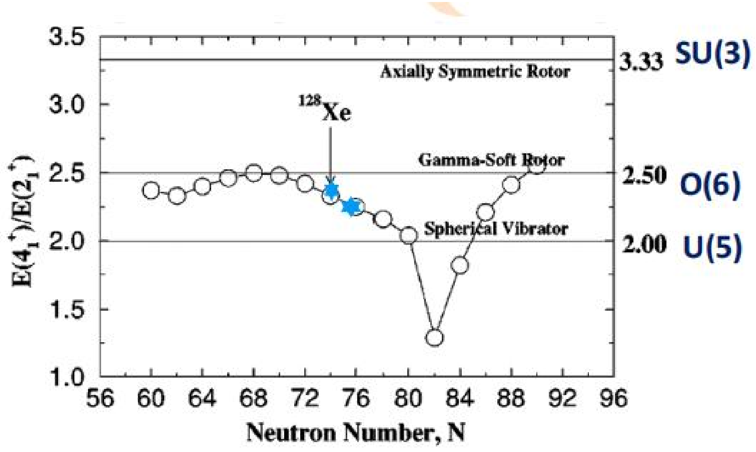


Strong sensitivity to neutron(proton) partner orbits. Reflect the details of proton and neutron interaction inside nuclei.

Y. Sun, et. al.

^{128}Xe lies in between γ-soft rotor and spherical vibrator.





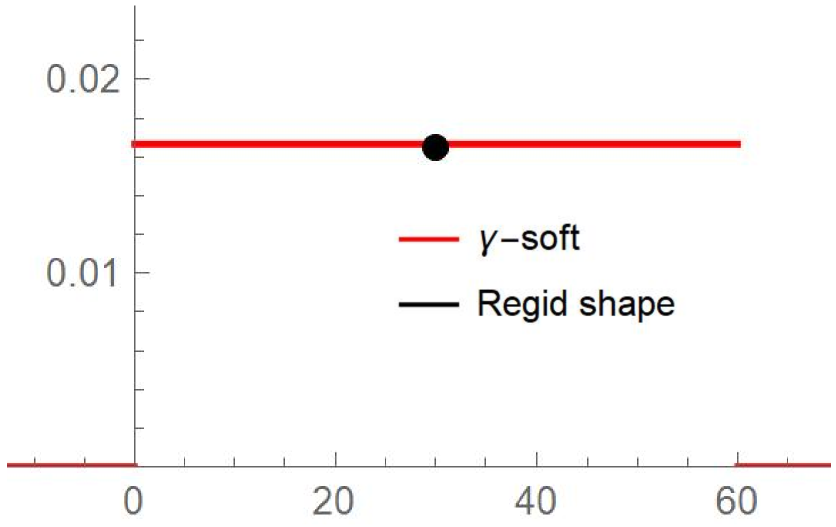
R. M. Clark, et. al. Phys. Rev. C 69, 064322 (2004)

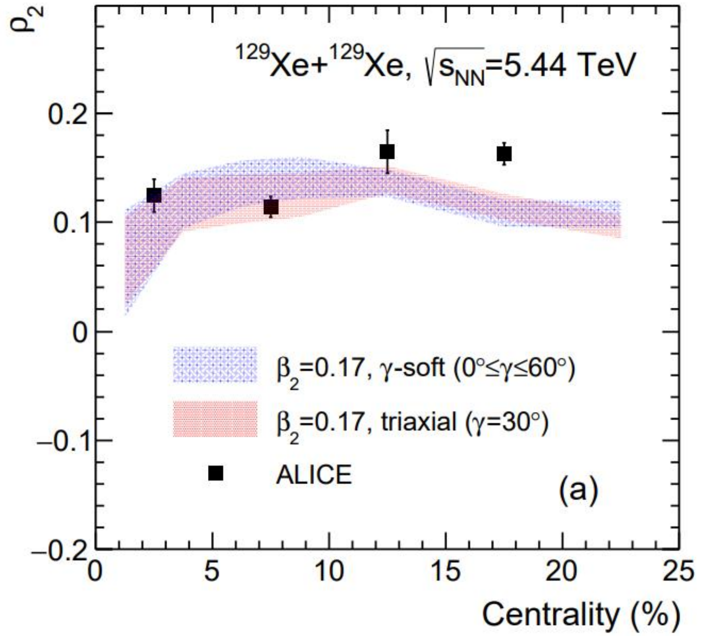
3-Particle Correlations: ρ_2 and Γp_T

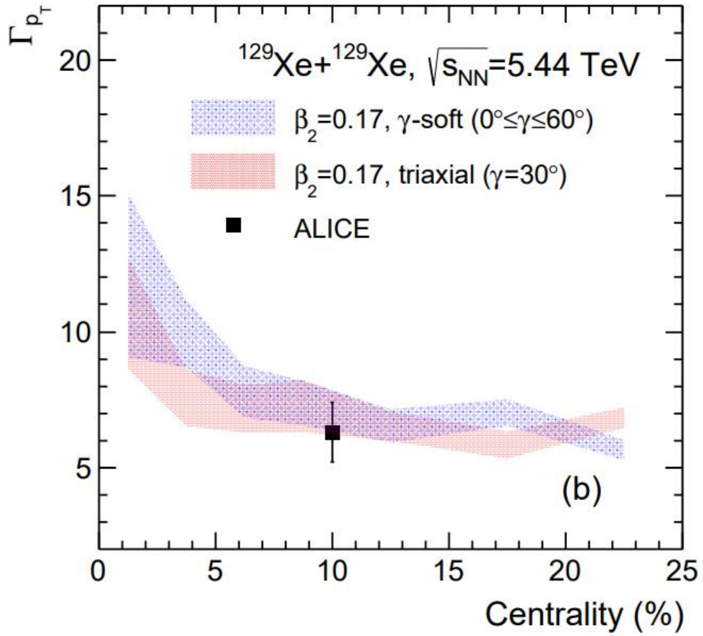
Liquid-drop model prediction:

$$\rho_2, \Gamma_{p_T} \propto \beta_2^3 \cos(3\gamma)$$

$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}. \qquad \Gamma_{p_T} = \frac{\langle \delta p_{T,i}\delta p_{T,j}\delta p_{T,k}\rangle \langle [p_T]\rangle}{\langle \delta p_{T,i}\delta p_{T,j}\rangle^2},$$



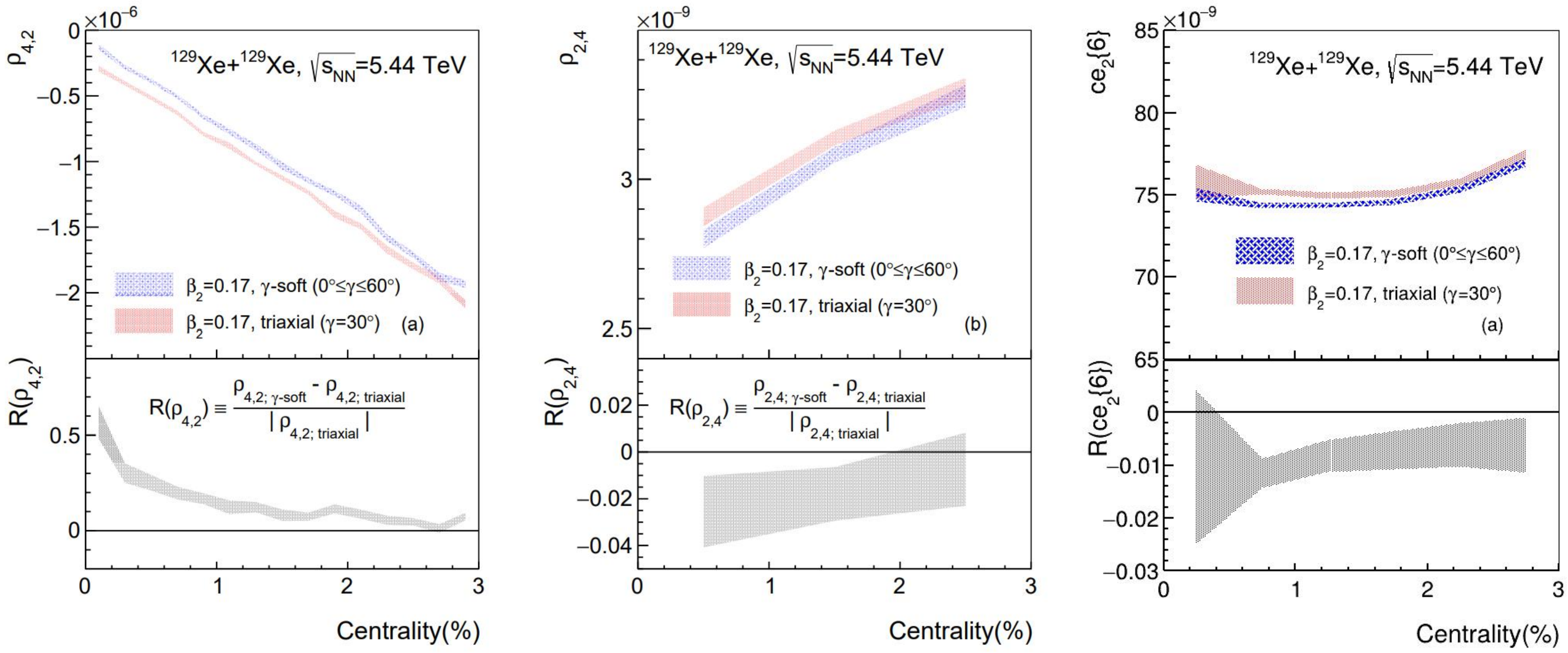




ρ_2 sensitative to the average traxial deformation

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, Phys. Rev. Lett. 133, 192301

6-Particle Correlations: Two New Correlators



Several 6-particle correlations show difference for the two configuration.

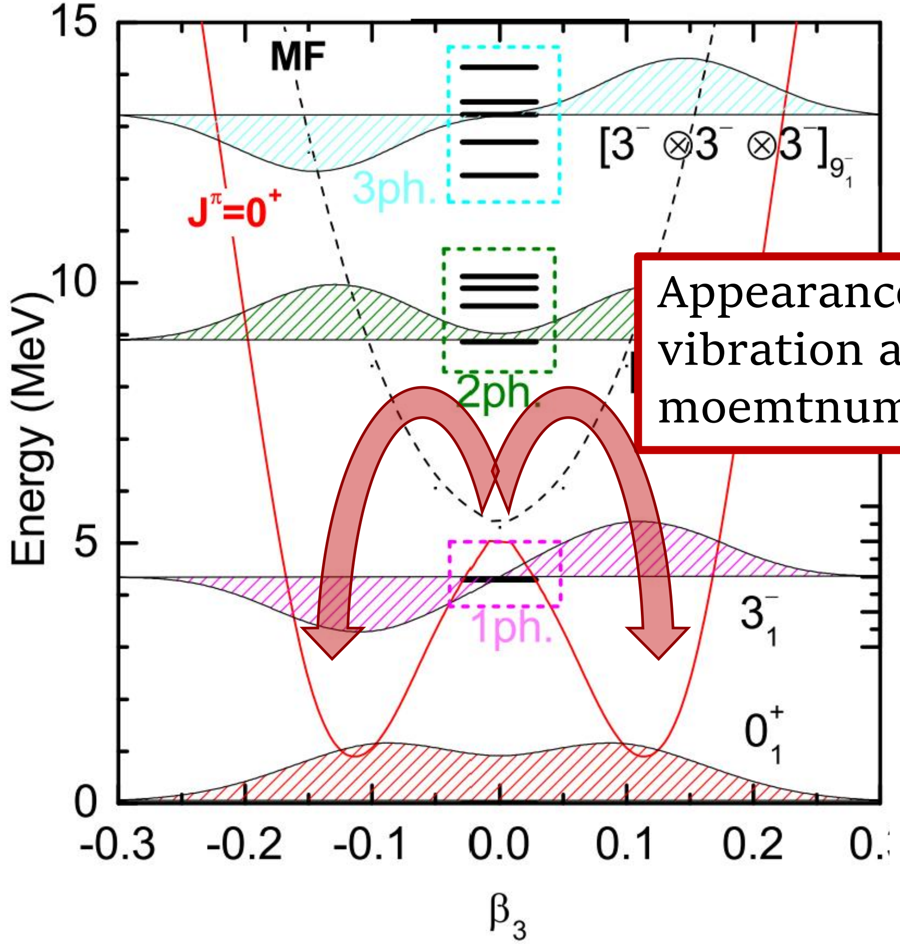
$\rho_{4,2}$ has the most clear signal.

$$R(\rho_{m,n}) = \frac{\rho_{m,n;\,\gamma\text{-soft}} - \rho_{m,n;\,\text{triaxial}}}{|\rho_{m,n;\,\text{triaxial}}|}.$$

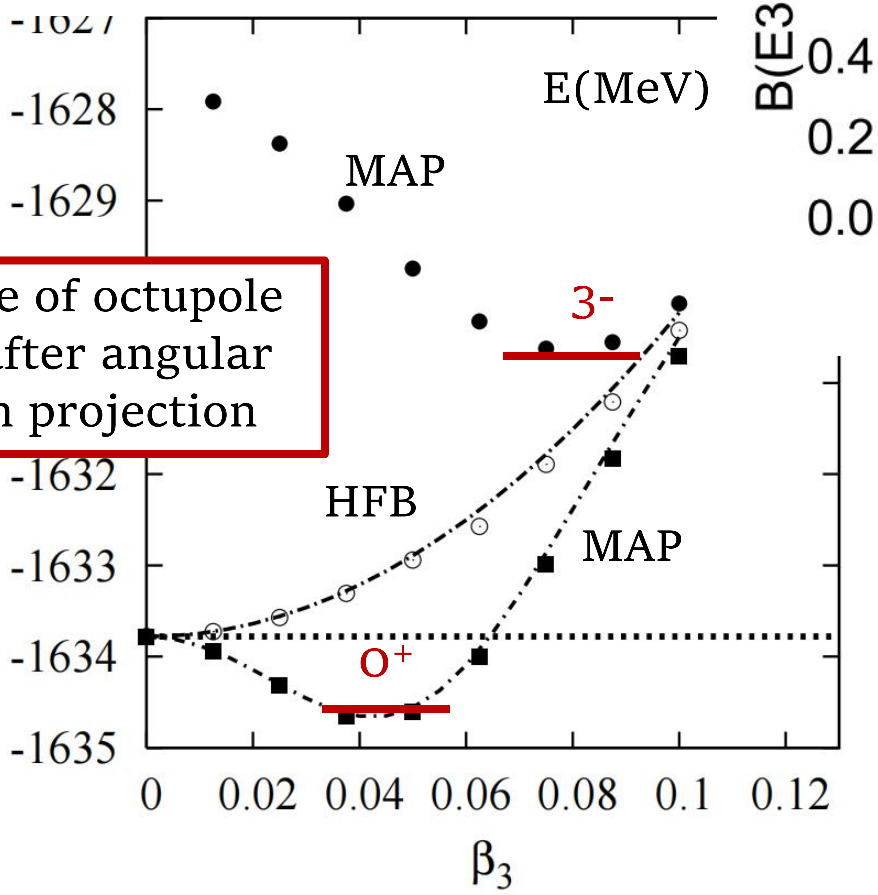
S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, Phys. Rev. Lett. 133, 192301

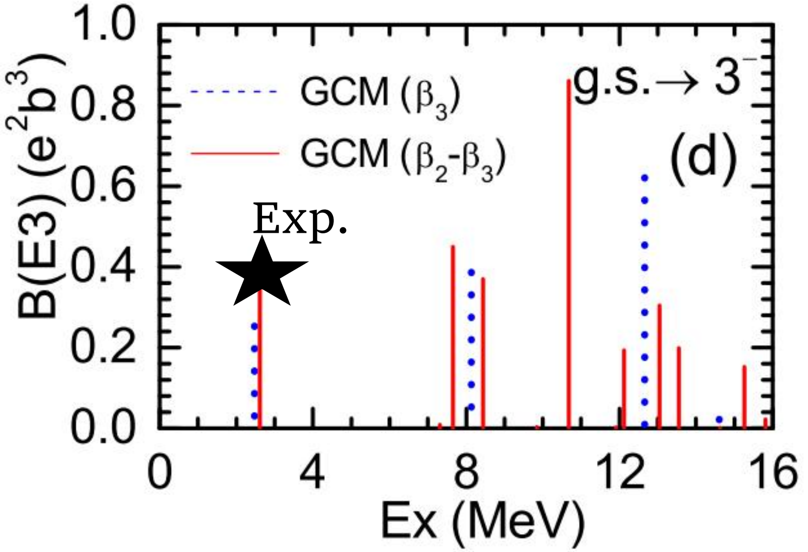
^{208}Pb as a Soft nuclei

$$|JM\pi\rangle = \sum_q f^{J\pi}(q)\hat{P}^J_{M0}\hat{P}^N\hat{P}^Z\hat{P}^\pi|q\rangle,$$



Appearance of octupole vibration after angular moemtnum projection

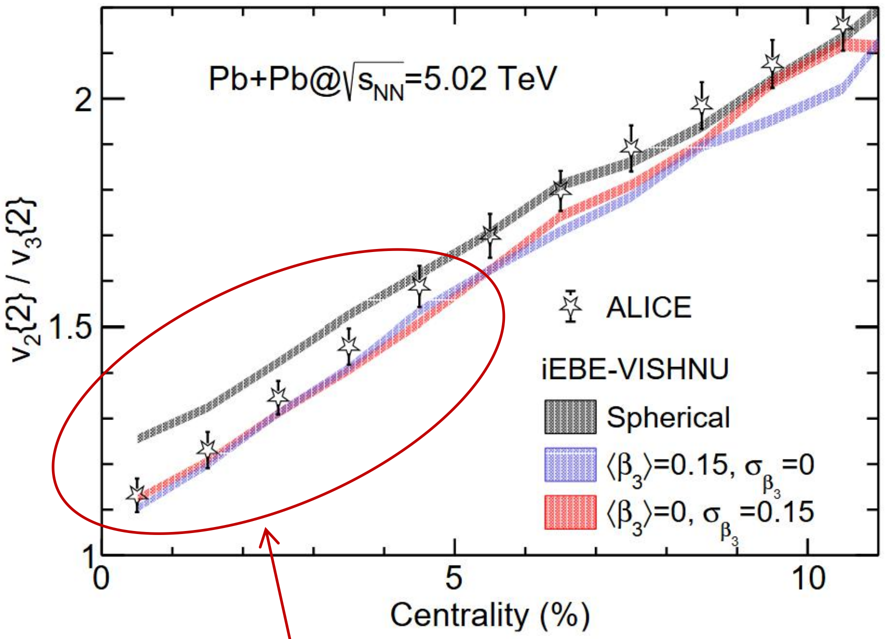




Detect the shape fluctuation mode in relativistic heavy-ion collisions?

J. M. Yao ,K. Hagino. Phys. Rev. C 94, 011303 (2016)
L. M. Robledo, G. F. Bertsch. Phys. Rev. C 84, 054302 (2011).

One way towards solving v_2-v_3 puzzle?

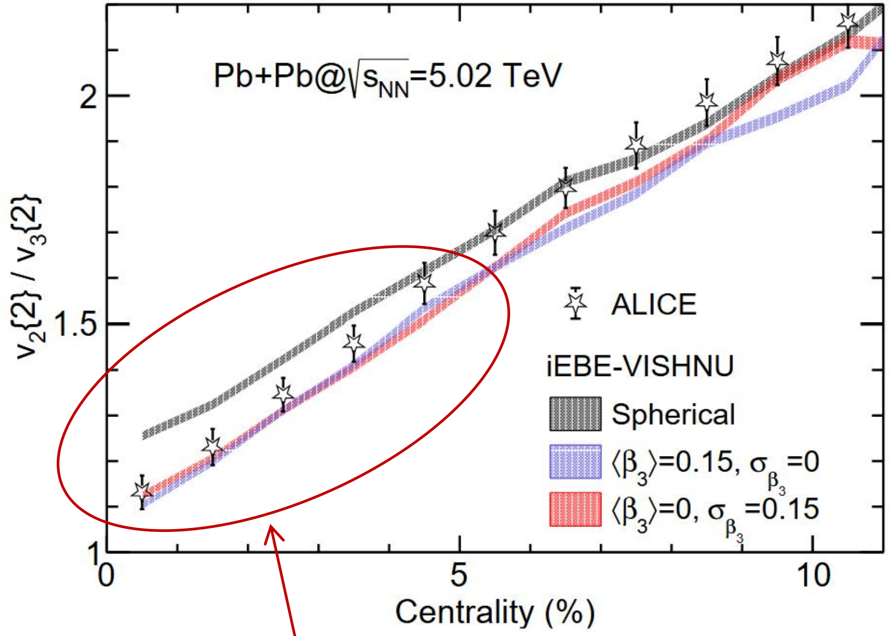


Inproved description of $v_n\{2\}$ ratio by involving octupole deformation / shape fluctuation.

Using ultra-central Pb+Pb collision to perbe dynamical octupole shape fluc. of ^{208}Pb?

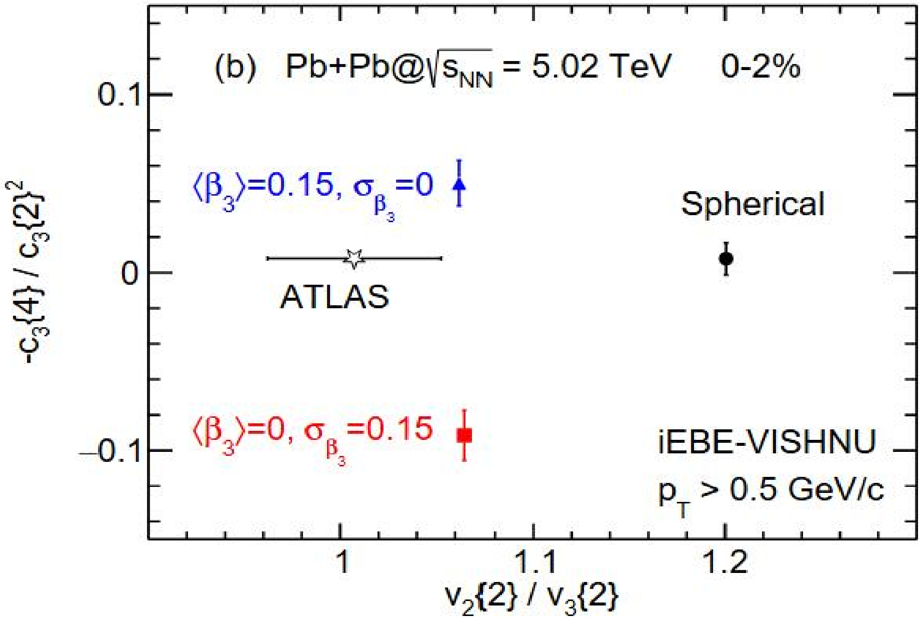
H. Xu, D. Xu, **S. Zhao**, W. Zhao, F. Wang, H. Song. arXiv: 2504.19644

One way towards solving v_2-v_3 puzzle?



Inproved description of $v_n\{2\}$ ratio by involving octupole deformation / shape fluctuation.

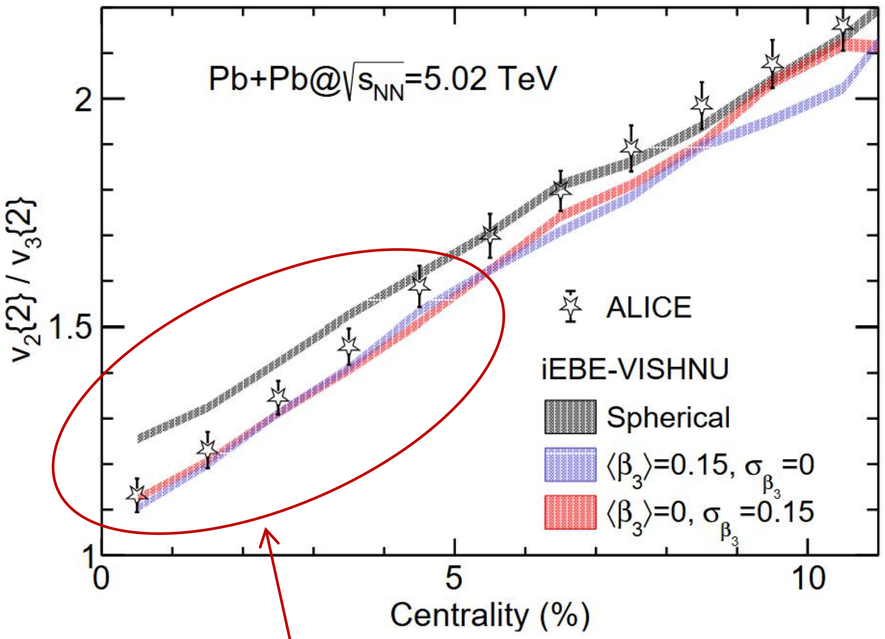
Strong sensitivity of $c_3\{4\}/c_3\{2\}^2$ ratio to octupole fluctuation.



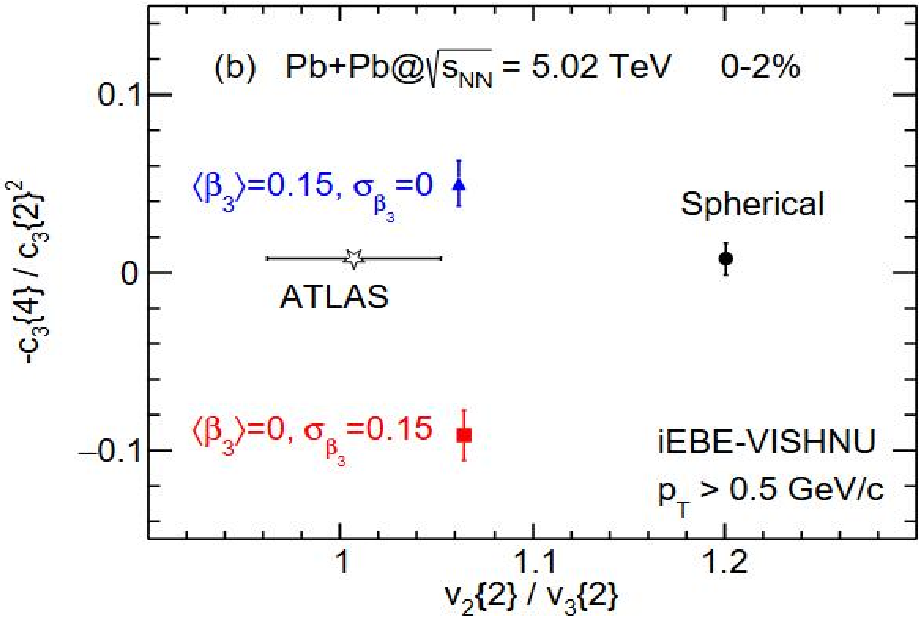
Using ultra-central Pb+Pb collision to perbe dynamical octupole shape fluc. of ^{208}Pb?

H. Xu, D. Xu, **S. Zhao**, W. Zhao, F. Wang, H. Song. arXiv: 2504.19644

One way towards solving v_2-v_3 puzzle?

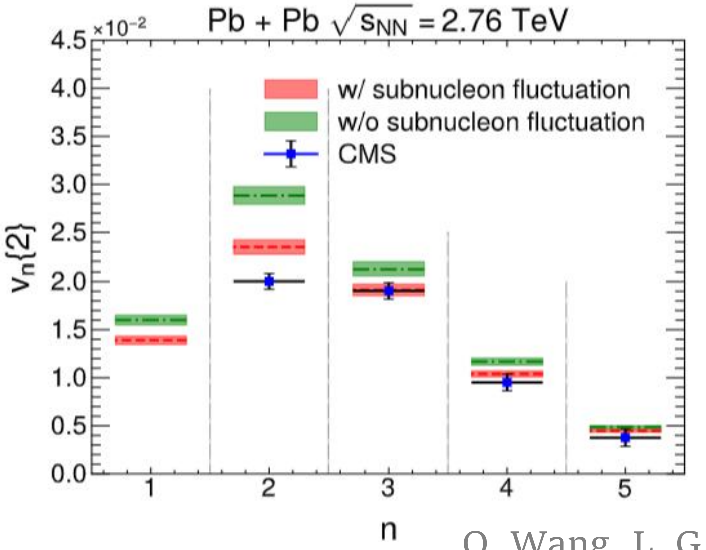


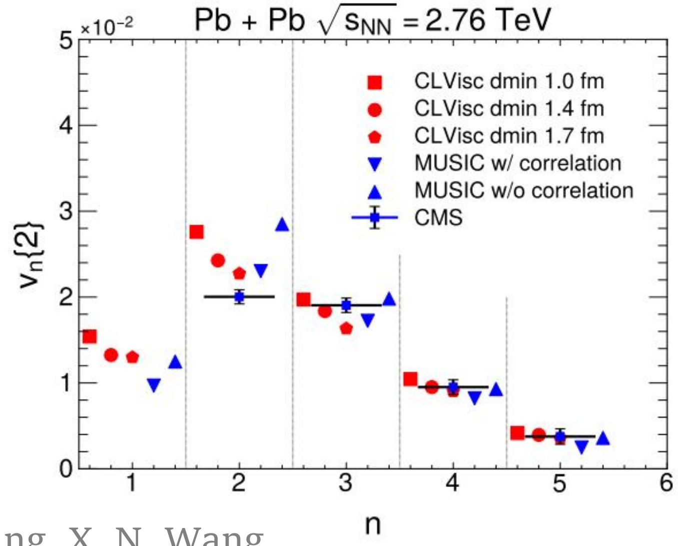
Strong sensitivity of $c_3\{4\}/c_3\{2\}^2$ ratio to octupole fluctuation.



Careful treatments for the initial stage

Inproved description of $v_n\{2\}$ ratio by involving octupole deformation / shape fluctuation.



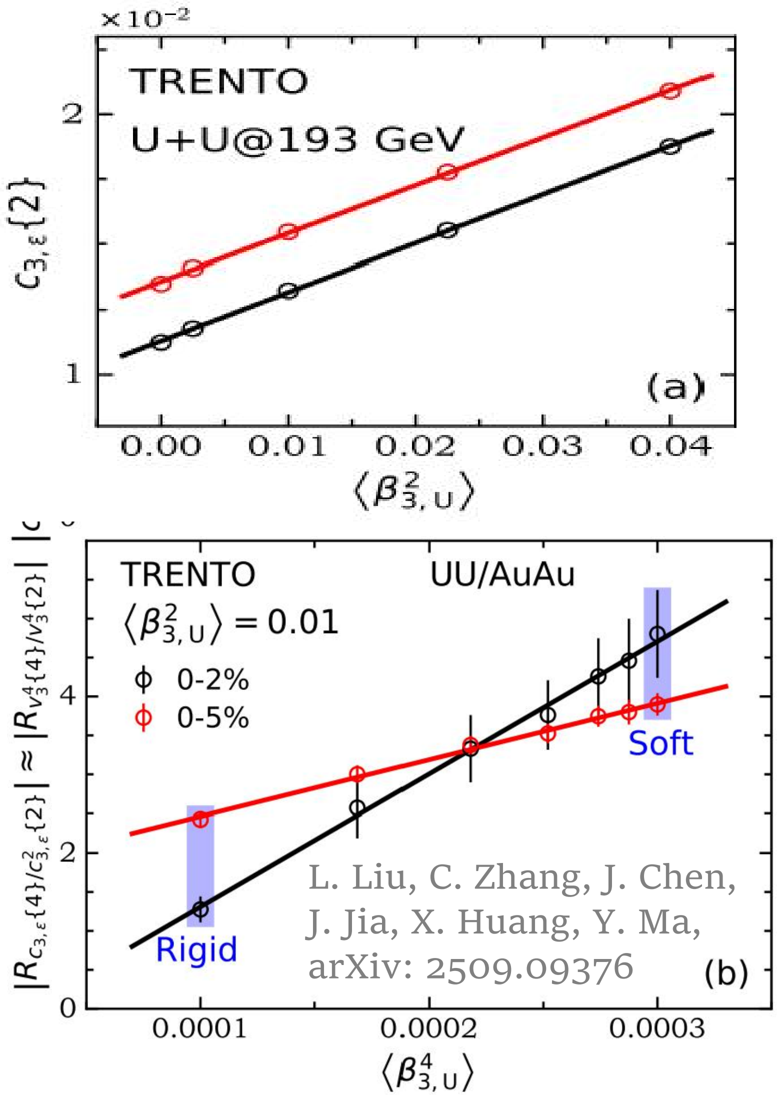


Using ultra-central Pb+Pb collision to perbe dynamical octupole shape fluc. of ^{208}Pb?

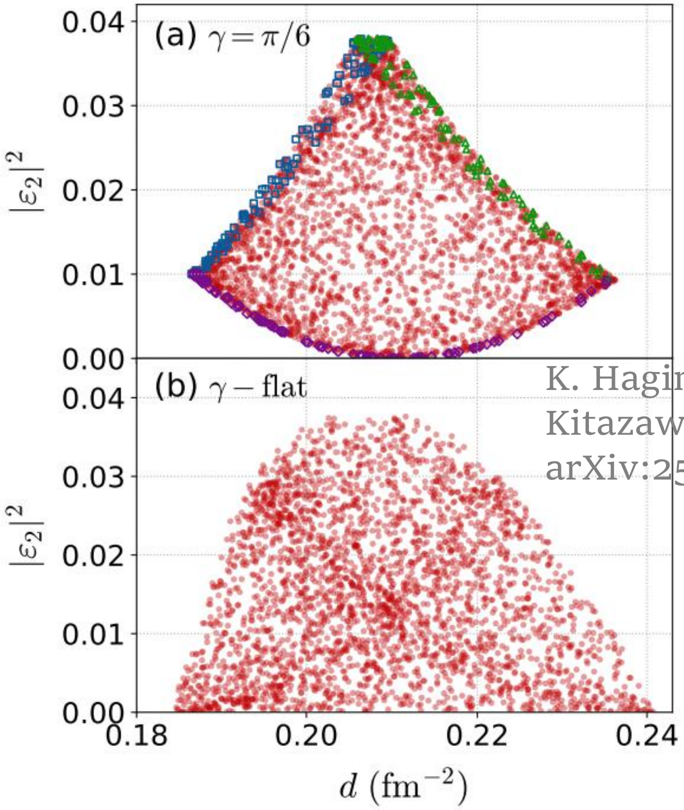
Q. Wang, L. G. Pang, X. N. Wang, arXiv:2504.19208

H. Xu, D. Xu, **S. Zhao**, W. Zhao, F. Wang, H. Song. arXiv: 2504.19644

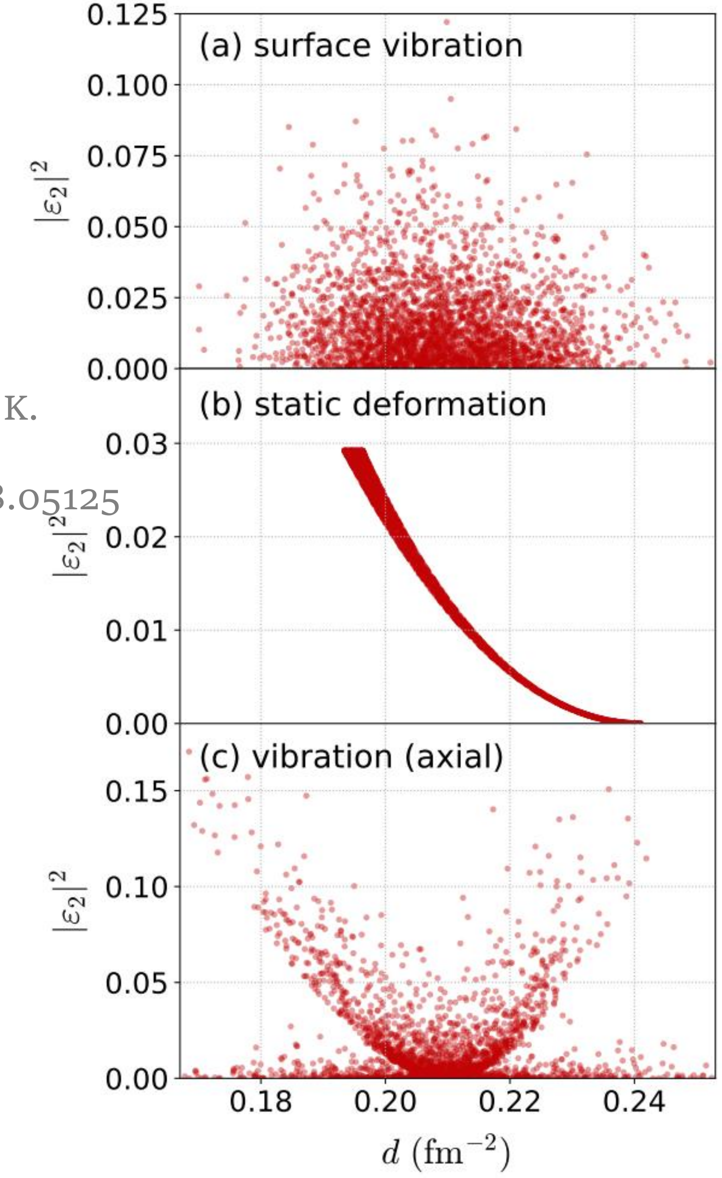
Further studies on Nuclear Shape Fluctuation



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



K. Hagino, K. Kitazawa, arXiv:2508.05125



Probing fluctuations with different cumulants or new methods

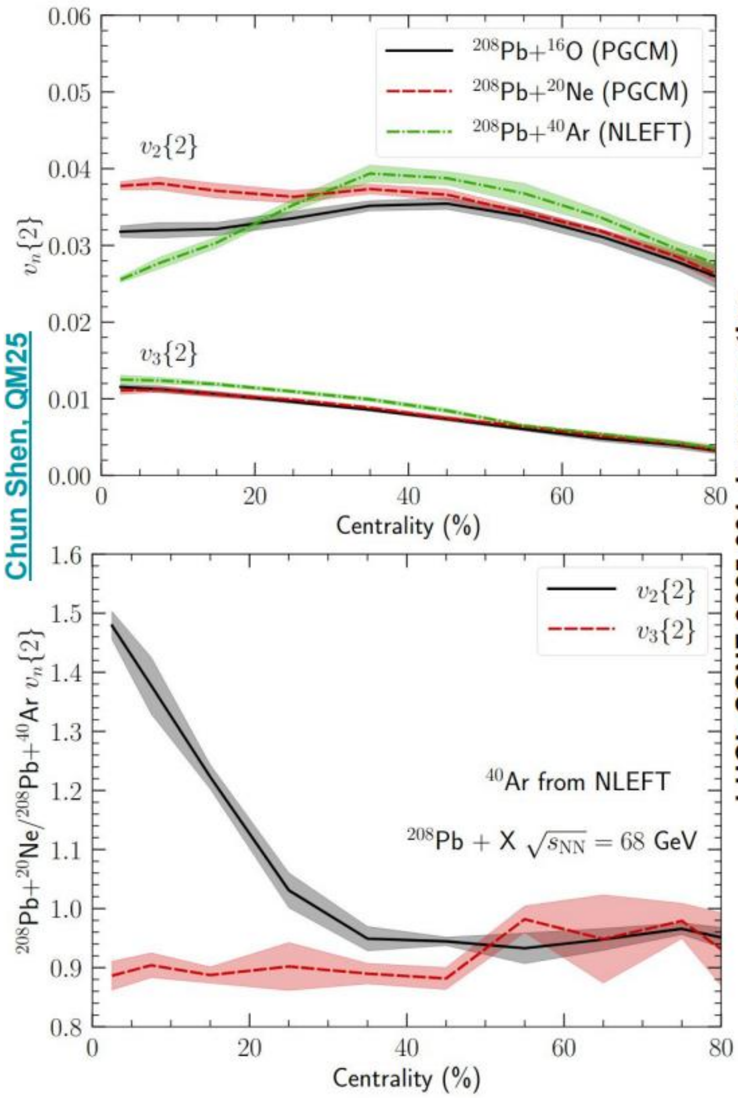
Future perspects: Probing nuclear structure in LHCb

Qualitative consistency between experimental measurements and theoretical calculations.

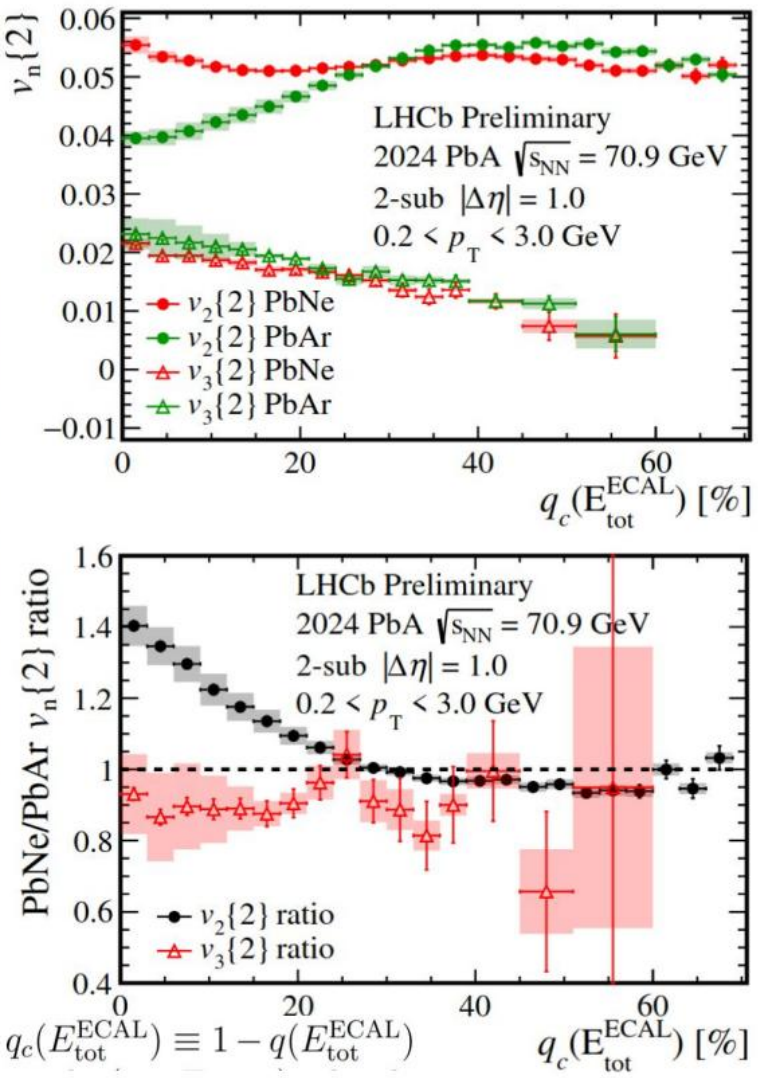
Probing novel nuclear structure with future LHCb runs?

Validity of hydrodynamics in small collision systems at intermediate collision energies?

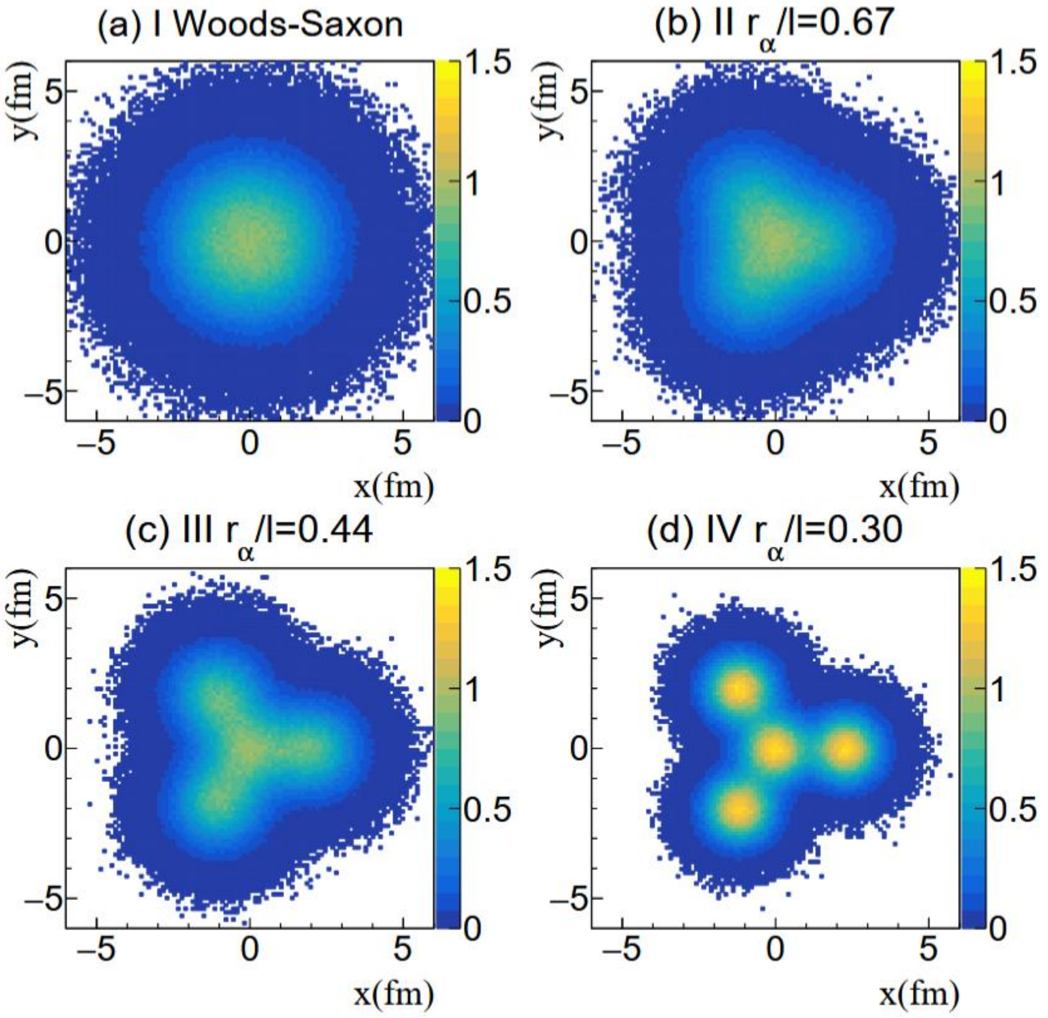
Chun Shen, QM25

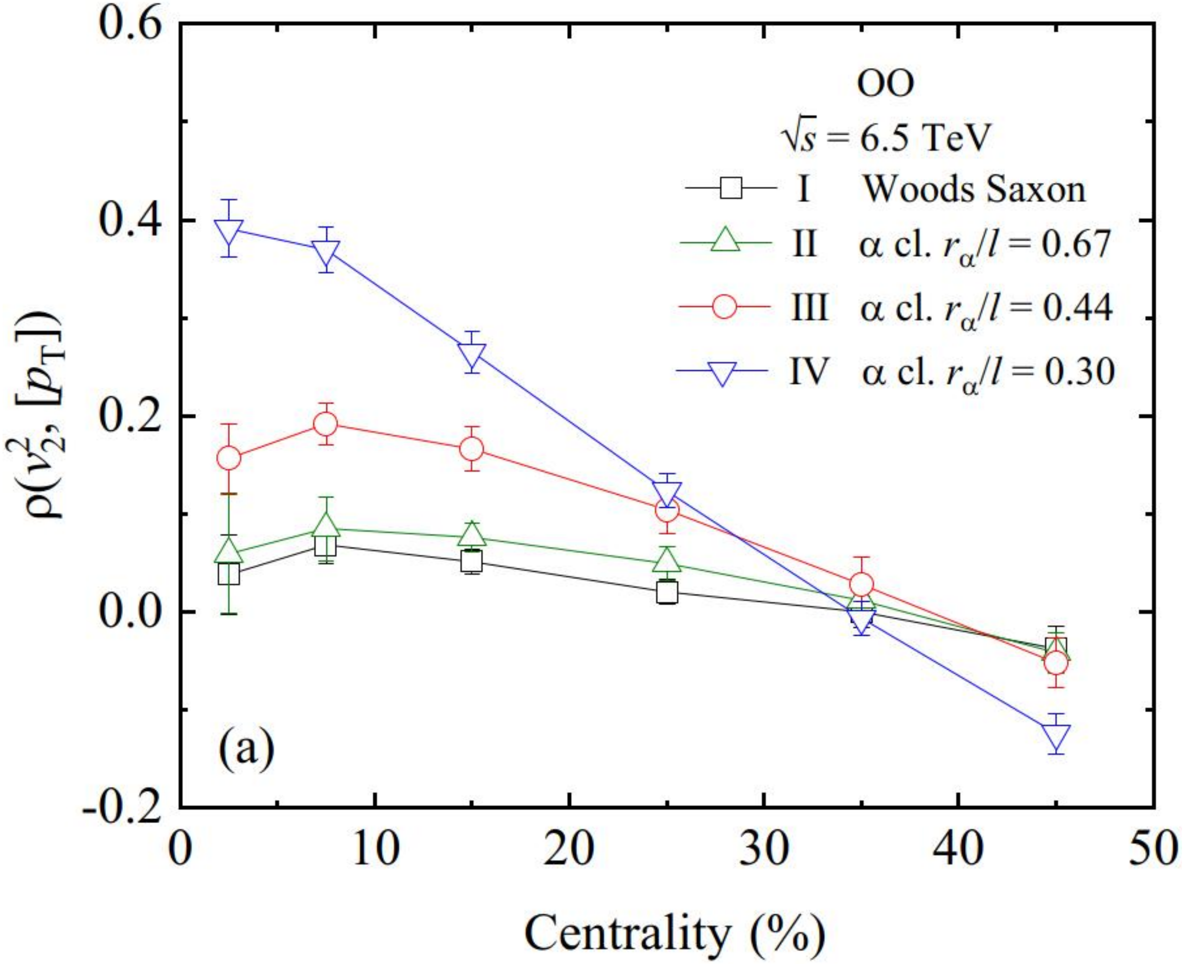


LHCb-CONF-2025-001, in preparation

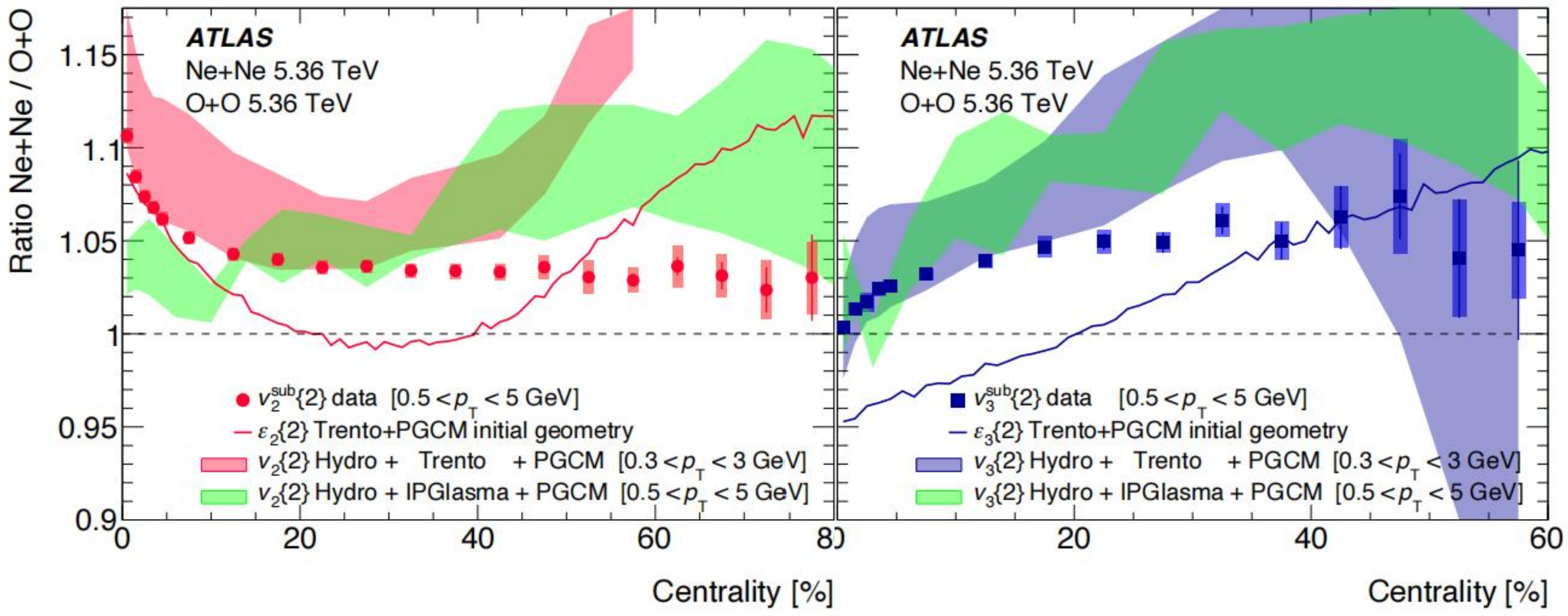


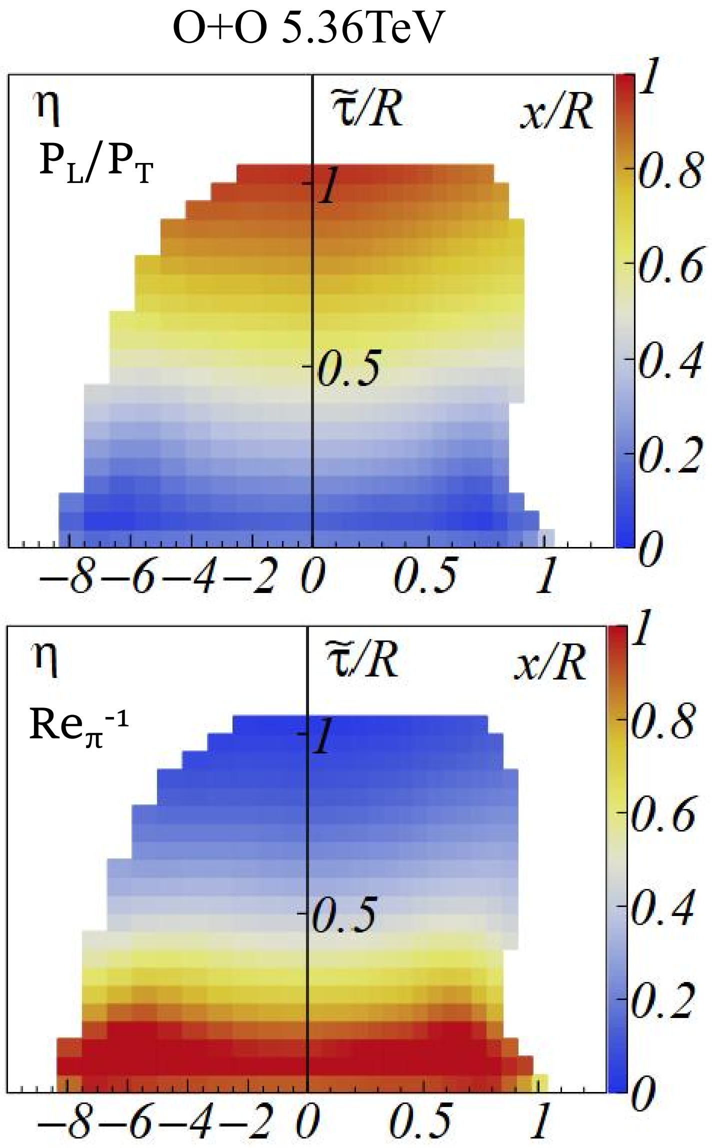
Future perspects: O+O v.s. Ne+Ne





Future perspects: O+O v.s. Ne+Ne





Double ratio is affected by pre-equilibrium modeling.
Anisotropic expansion dominates early-stage evolution.
Realistic modeling of early-stage dynamics is essential for better constraining nuclear shape.

Validity of hydrodynamics

- Including pressure anisotropy

$$T^{\mu\nu} = \mathcal{E}u^\mu u^\nu \boxed{+ \mathcal{P}_L z^\mu z^\nu - \mathcal{P}_T \Xi^{\mu\nu}}$$

$$2W_{\perp z}^{(\mu} z^{\nu)} + \pi_\perp^{\mu\nu}$$

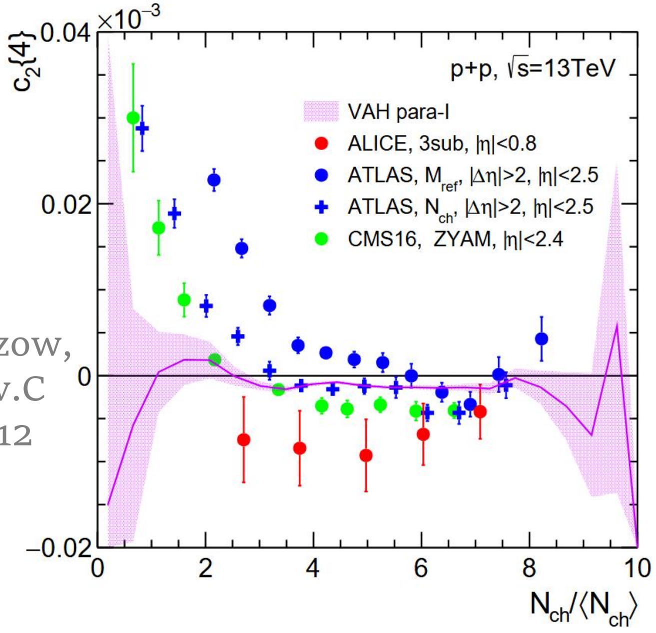
M. McNelis, D. Bazow, U. Heinz, Phys.Rev.C 97 (2018) 5, 054912

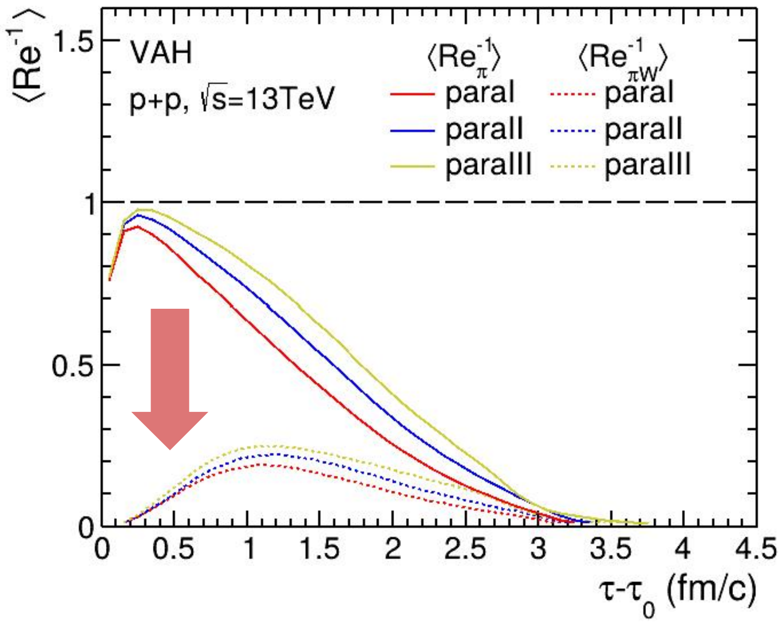
- For pp collisions:

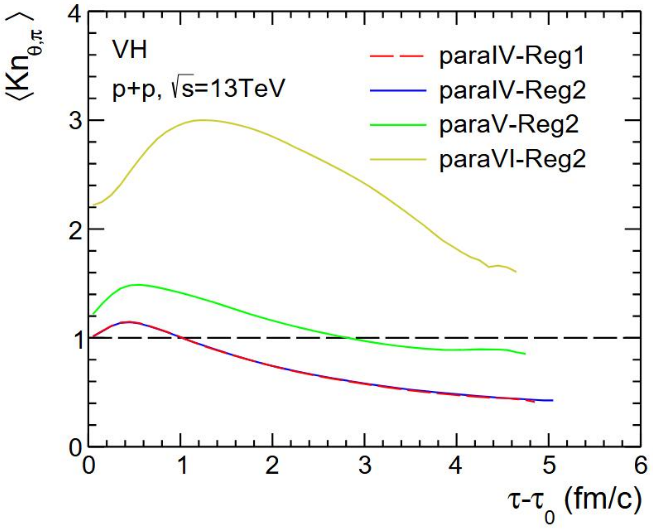
	VAH	VH
Theoretical safty	✔	?
Prediction power	✔	?

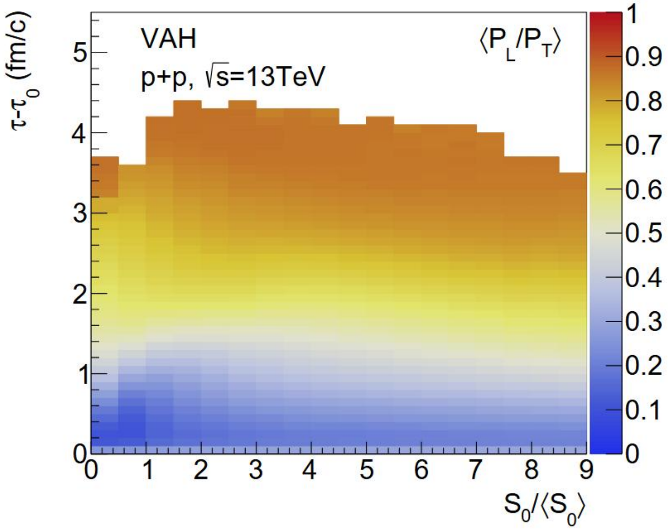
- For O+O/Ne+Ne collisions?

VAH should be safety.
Validity of VH needs more investigations.









S. Zhao, Y. Peng, U. Heinz, H. Song. arXiv:2509.03841

Summary & Outlook

1. Ultra-relativistic heavy-ion collisions offer a unique window to probe intricate nuclear shape phenomena—including deformation, neutron skin, shape phase transitions, shape fluctuations, and further novel features.

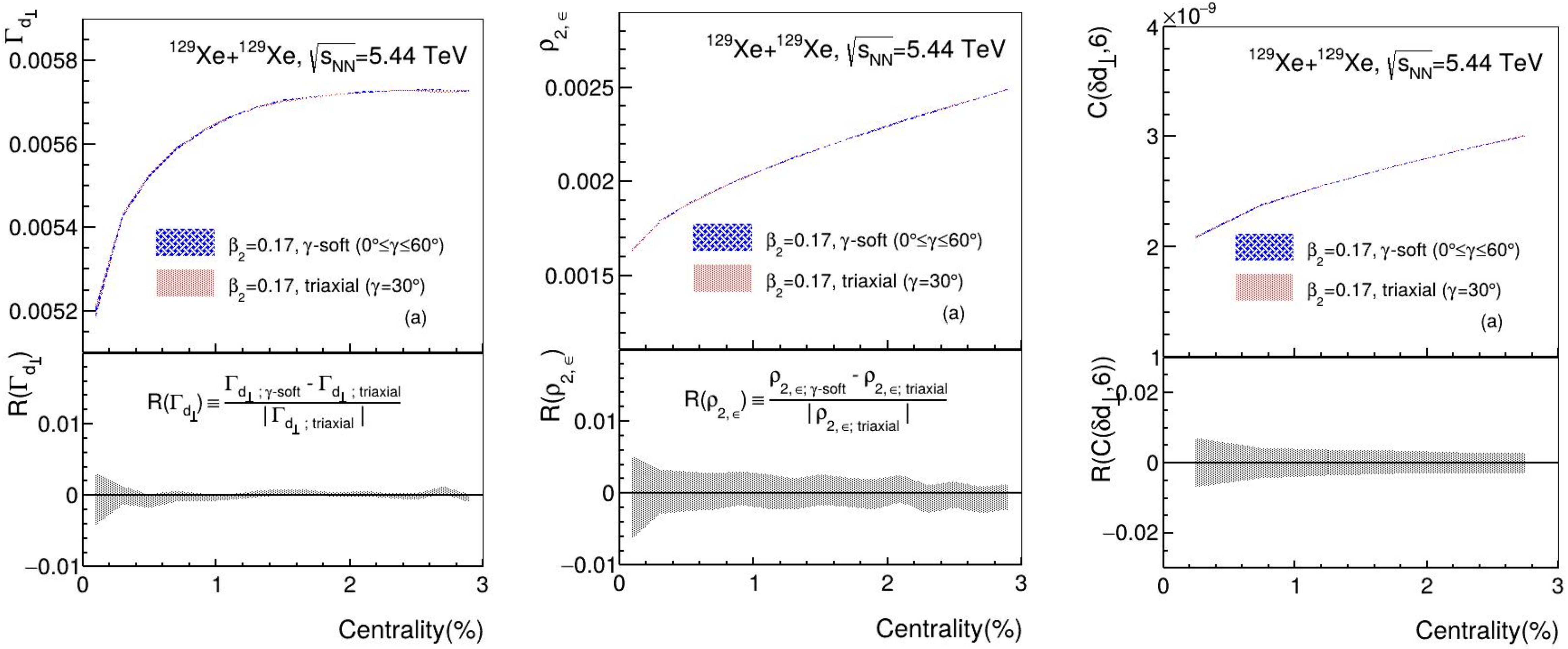
2. O+O /Ne+Ne collisions, as well as Pb+A collisions makes it possible for understanding ligh-nuclei structure and collectivity in small collision systems.

3. Further studying of nuclear structure with high-energy nuclear physics needs more sophisticated model developments and realistic nuclear shape inputs. Discussions for the validity of current model framework.

Relativistic heavy-ion collisions as a cross-disciplinary tool to deepen our understanding of collective behavior and fundamental interactions across different nuclear scales.

Backup

Backup



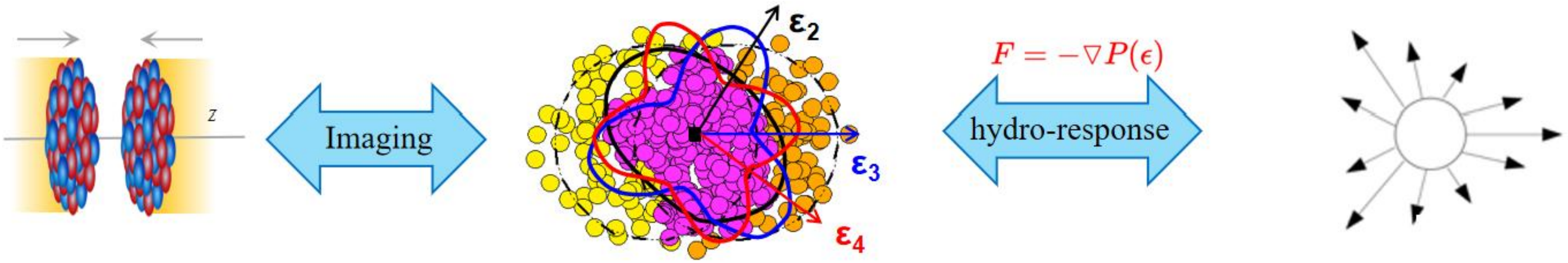
^{129}Xe+^{129}Xe, $\sqrt{s_{NN}}$=5.44 TeV
β_2=0.17, γ-soft (0°≤γ≤60°)
β_2=0.17, triaxial (γ=30°)
(a)
$\Gamma_{d_\perp}$
$R(\Gamma_{d_\perp}) \equiv \frac{\Gamma_{d_\perp;\gamma\text{-soft}} - \Gamma_{d_\perp;\text{triaxial}}}{|\Gamma_{d_\perp;\text{triaxial}}|}$
$\rho_{2,\epsilon}$
$R(\rho_{2,\epsilon}) \equiv \frac{\rho_{2,\epsilon;\gamma\text{-soft}} - \rho_{2,\epsilon;\text{triaxial}}}{|\rho_{2,\epsilon;\text{triaxial}}|}$
$C(\delta d_\perp,6)$
$R(C(\delta d_\perp,6))$
$\times 10^{-9}$
Centrality(%)

What may we learn from ^{129}Xe+^{129}Xe collisions?

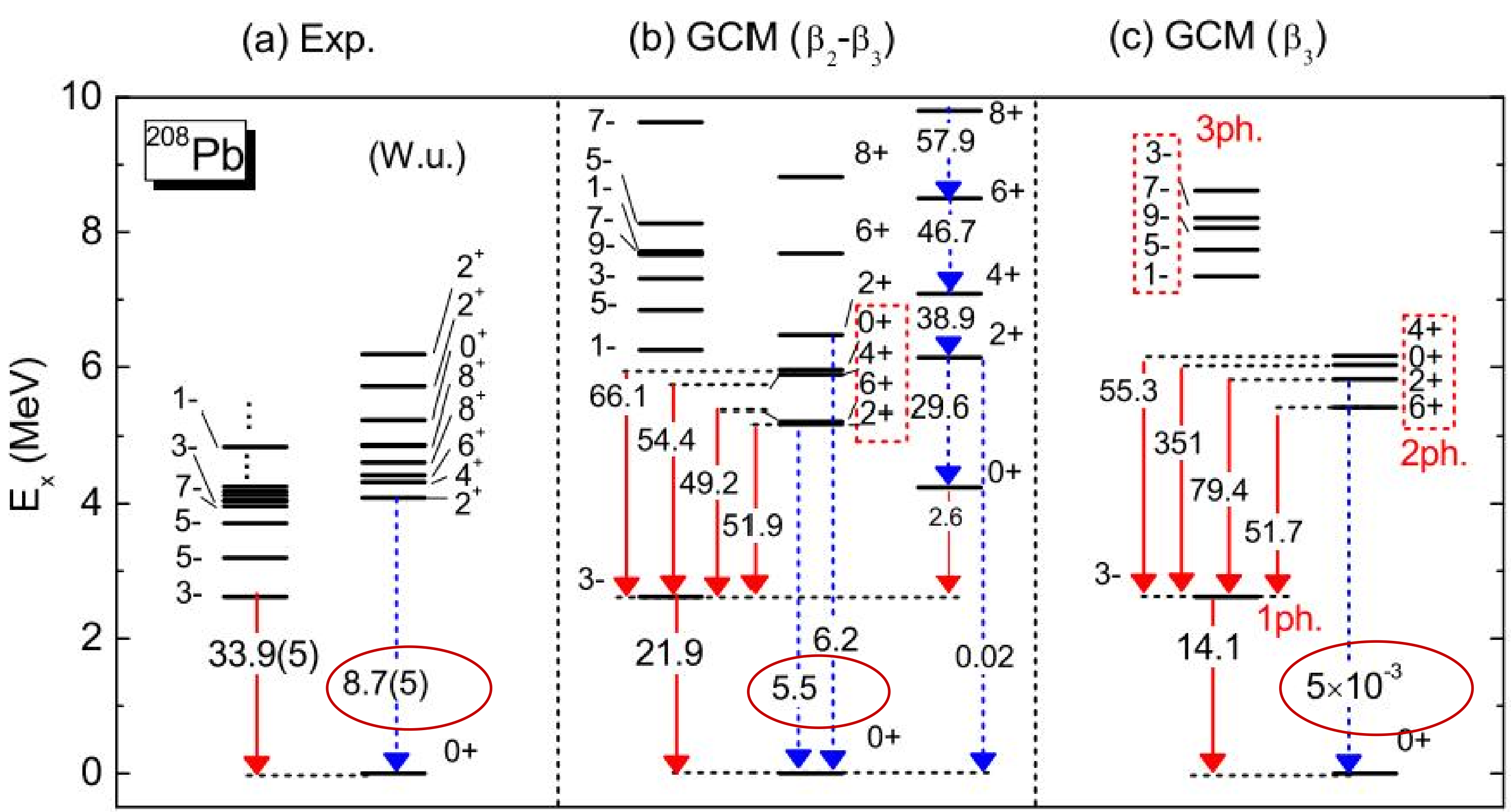
1. Even-A v.s. odd-A system
   Additional valence nucleon (blocking effect)?
   A new way for understanding the odd-A nuclei collectivity?

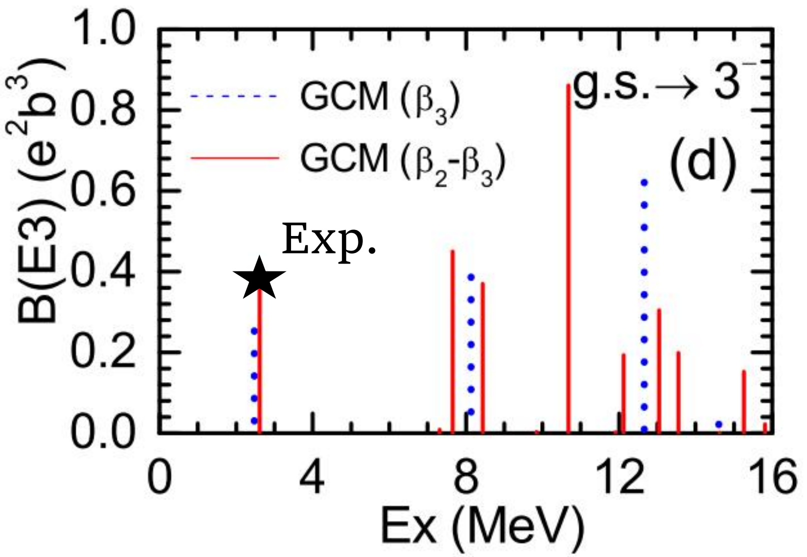
2. ‘measurements’ in high- amd low-energy context
   Capture the same physics for dynamical deformation?

3. Model/observable uncertainty for constraing nuclear shape
   Include nuclear structure effects regorously.
   Different assumption for the nuclear structure probed by different observables.
   New observales directly reflecting the initial geometry?

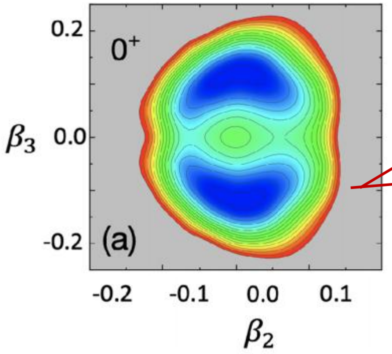


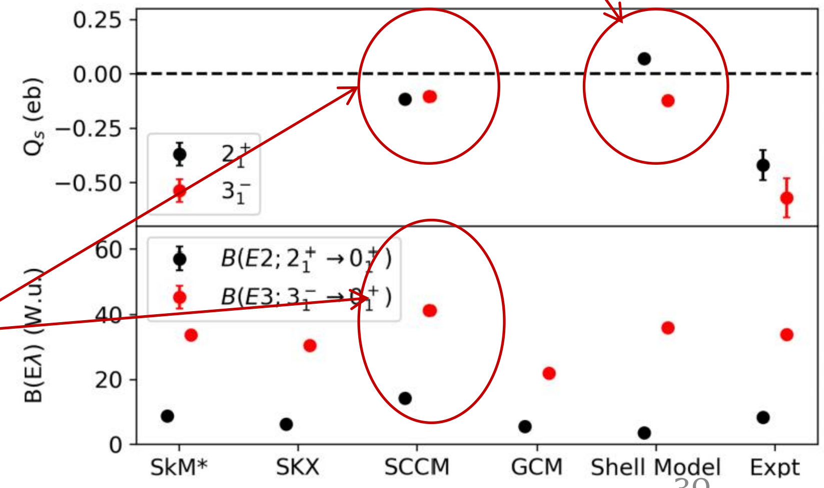
^{208}Pb as a soft nuclei





Positive $Q_s(2_1+)$ from shell model





Improvement of B(E3) and B(E2) description by including β2-β3 coupling.

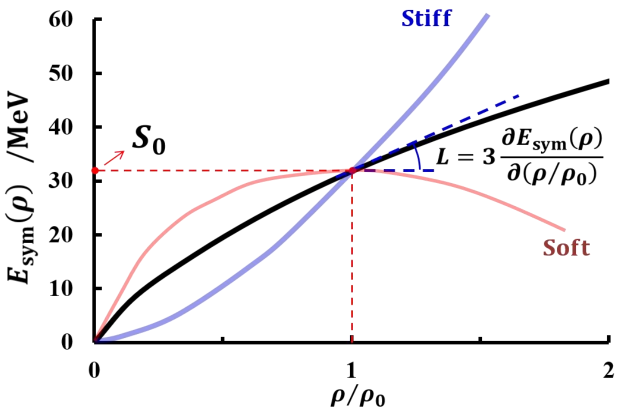
J. Henderson et al. Phys. Rev. Lett. 134, 062502 (2025)
J. M. Yao ,K. Hagino. Phys. Rev. C 94, 011303 (2016)

^{208}Pb as a baseline

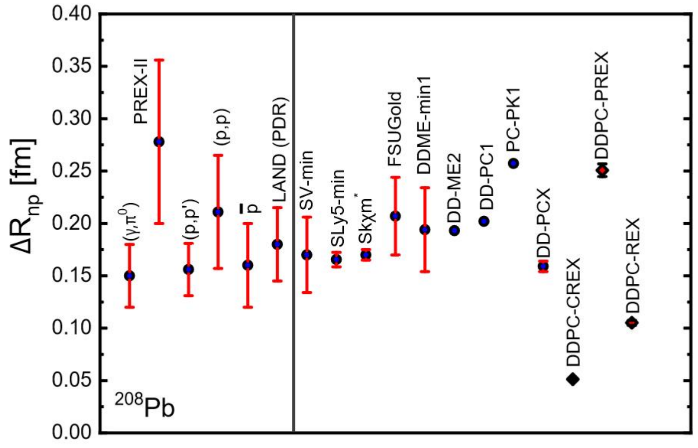
Nuclear EOS: $E(\rho,\delta) = E_0(\rho) + \delta^2 E_{sym}(\rho)\,,\ \ \delta = \frac{\rho_n-\rho_p}{\rho_n+\rho_p}$

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \ldots$$

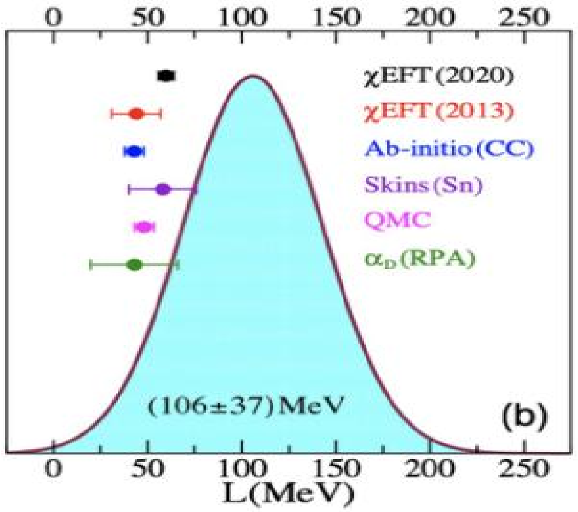
$$\boldsymbol{E_{\mathrm{sym}}(\rho)} = E_{\mathrm{sym}}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\mathrm{sym}}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\mathrm{sym}}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \ldots$$



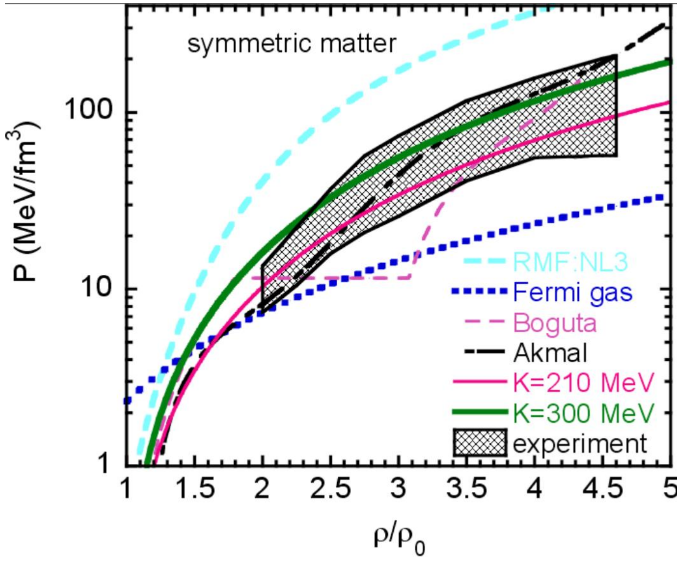
The symmetry energy is crucial to our understanding of the masses and drip lines of neutron-rich nuclei and the equation of state (EOS) of nuclear and neutron star matter.



arXiv:2206.06527 Esra Yüksel and Nils Paar



Phys. Rev. Lett. 126, 172502 D. Adhikari et al



Viscous Anisotropic Hydrodynamics (VAH)

- Traditional hydro: $$T^{\mu\nu} = \mathcal{E}u^\mu u^\nu - (\mathcal{P}+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu},$$
- Including pressure anisotropy in $T^{\mu\nu}$:

$$T^{\mu\nu} = \mathcal{E}u^\mu u^\nu \boxed{+ \mathcal{P}_L z^\mu z^\nu - \mathcal{P}_T \Xi^{\mu\nu}} + 2W_{\perp z}^{(\mu} z^{\nu)} + \pi_\perp^{\mu\nu}$$

- Redecomposition of viscous terms

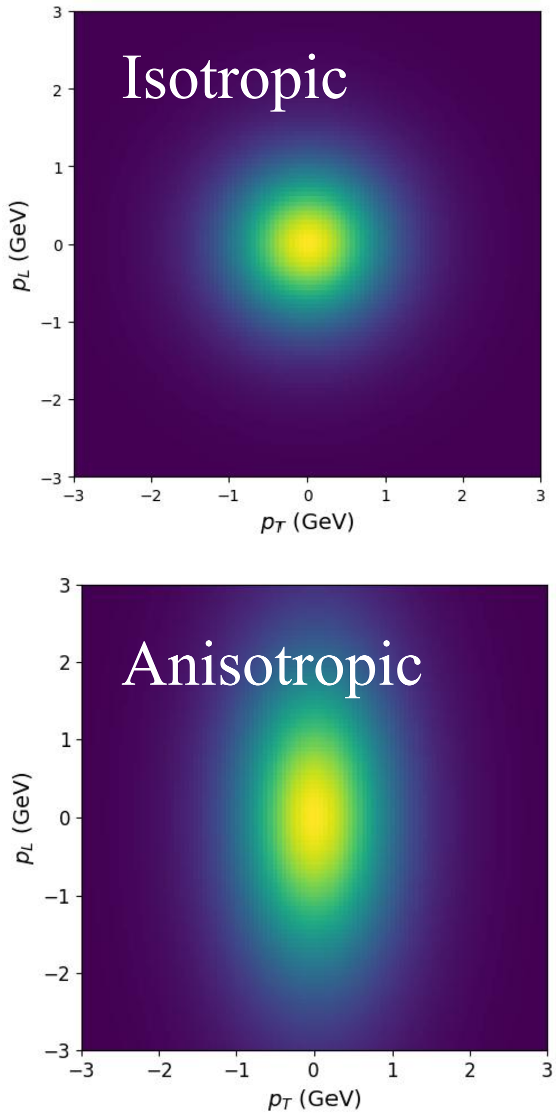
$$\pi^{\mu\nu} = \frac{1}{3}(\mathcal{P}_L - \mathcal{P}_T)(2z^\mu z^\nu + \Xi^{\mu\nu}) \boxed{+ 2W_{\perp z}^{(\mu} z^{\nu)} + \pi_\perp^{\mu\nu}}$$

$$\Pi = \frac{1}{3}(\mathcal{P}_L + 2\mathcal{P}_T) - \mathcal{P}_{\mathrm{eq}}$$

Validity of VAH:
small residual shear stress

- Anisotropic particle distribution:

$$f_a(x,p) = f_{\mathrm{eq}}\left(\frac{\sqrt{\Omega_{\mu\nu}p^\mu p^\nu}}{\Lambda(x)}\right). \qquad \Omega_{\mu\nu}p^\mu p^\nu = m^2 + \frac{p^2_{\perp,\mathrm{LRF}}}{\alpha_\perp^2} + \frac{p^2_{z,\mathrm{LRF}}}{\alpha_L^2}.$$



M. McNelis, D. Bazow, U. Heinz, Phys.Rev.C 97 (2018) 5, 054912