Exploring the Nuclear Shape Phase Transition in Ultra-Relativistic Xe+Xe Collisions at the LHC

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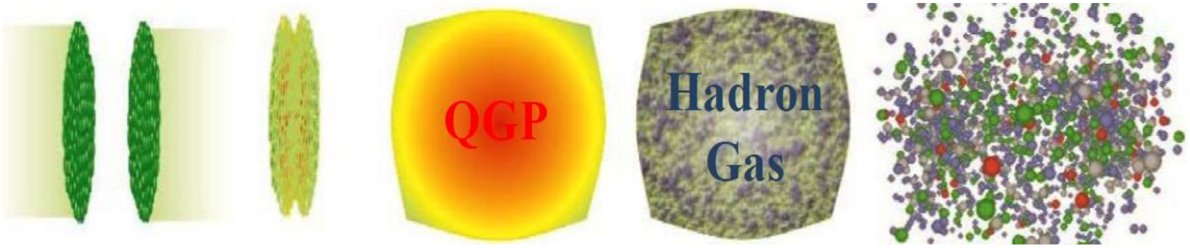
Relativistic Heavy-Ion Collisions

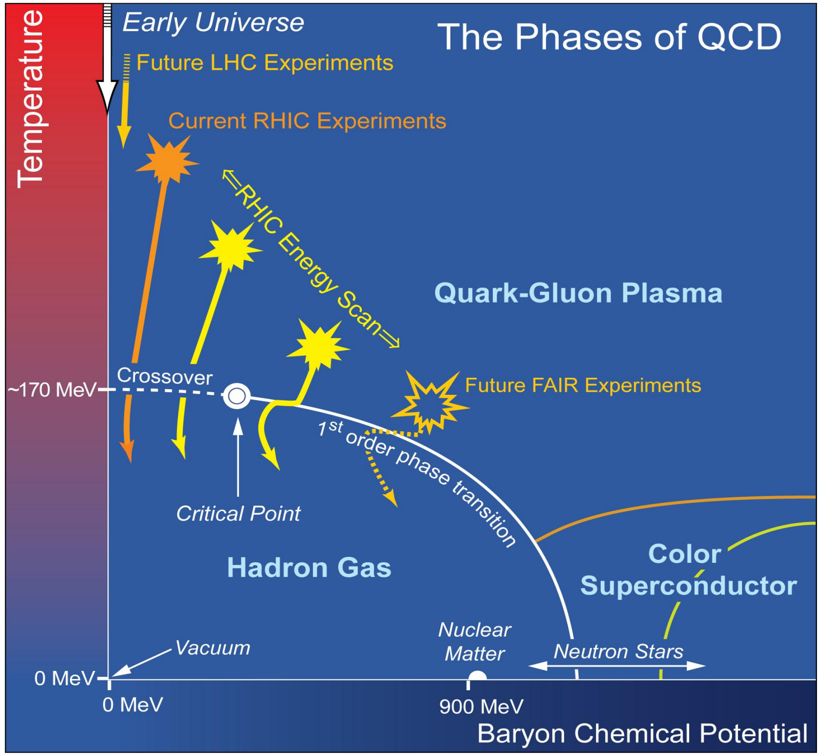


<u>Relativistic heavy ion collisions</u>

- create and study QGP

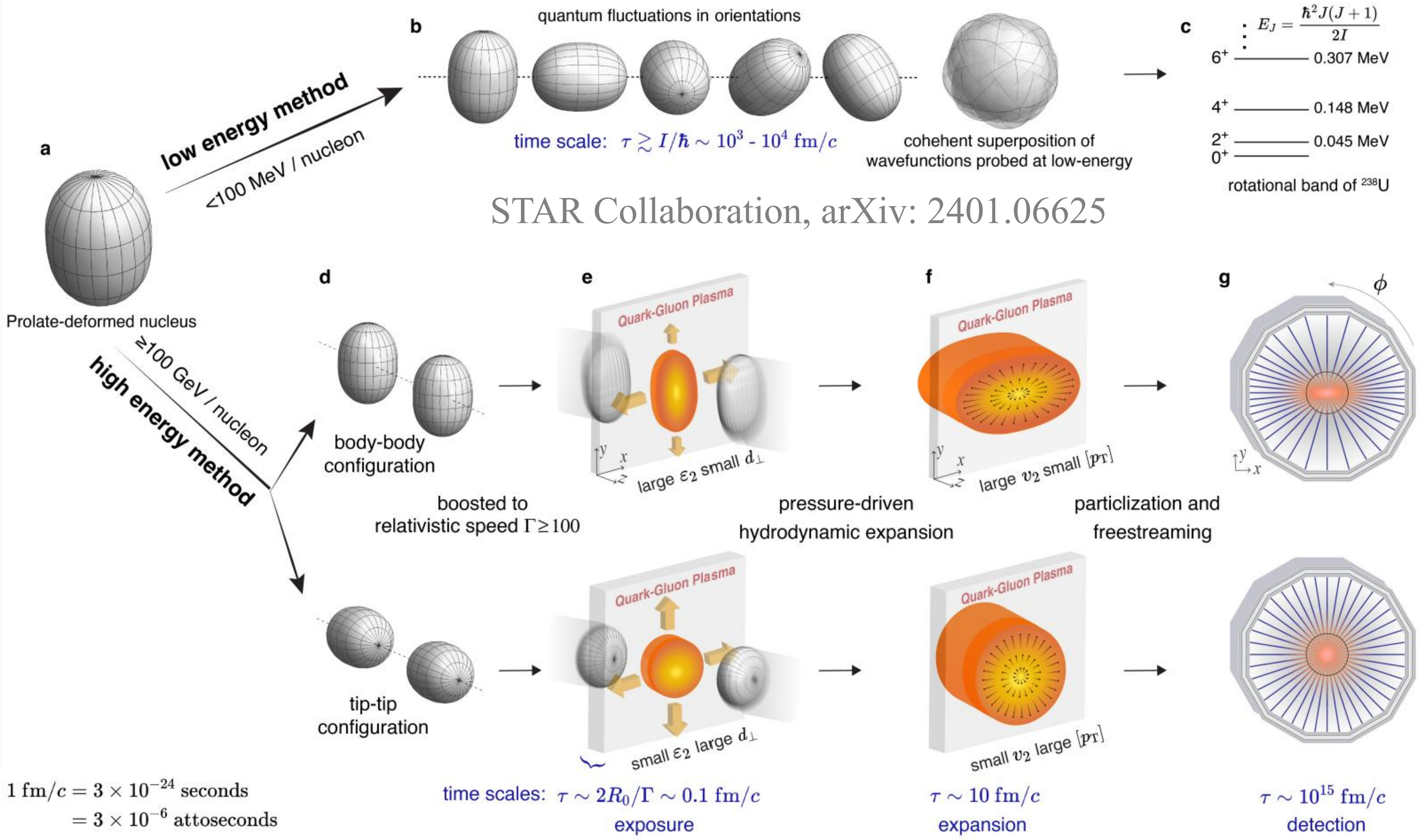
- the QCD phase diagram

- the QCD vacuum



Probing Nuclear Shape in Heavy-Ion Collisions

Relativistic heavy-ion collisions providing a novel way for detecting the intrinsic shape of nuclei.



STAR Collaboration, arXiv: 2401.06625

Event-by-event linear responses:

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

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

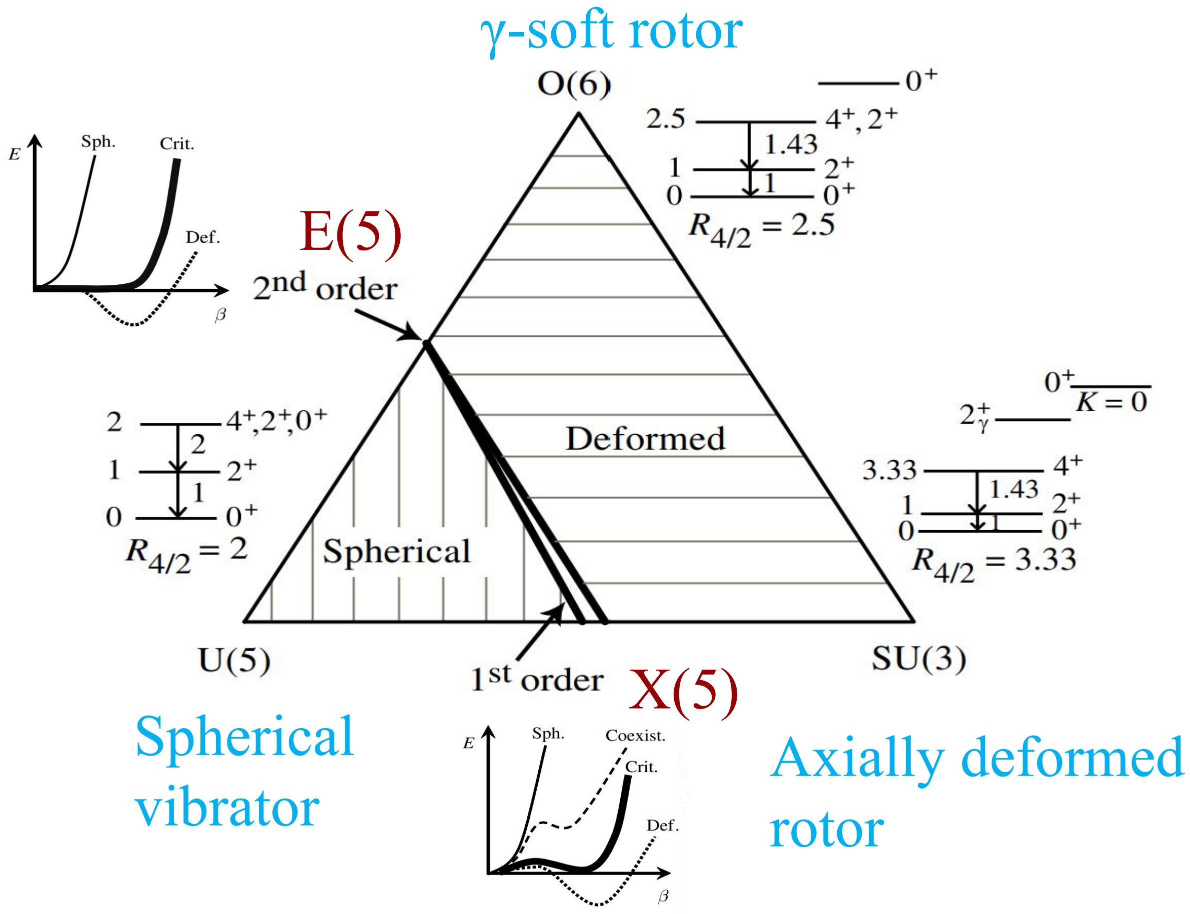
Shape Phase Transition

Critical Point Symmetry capture different times of SPT.

IBM framework: the Xe isotopes undergo a shape phase transition from a γ-soft rotor to a spherical vibrator

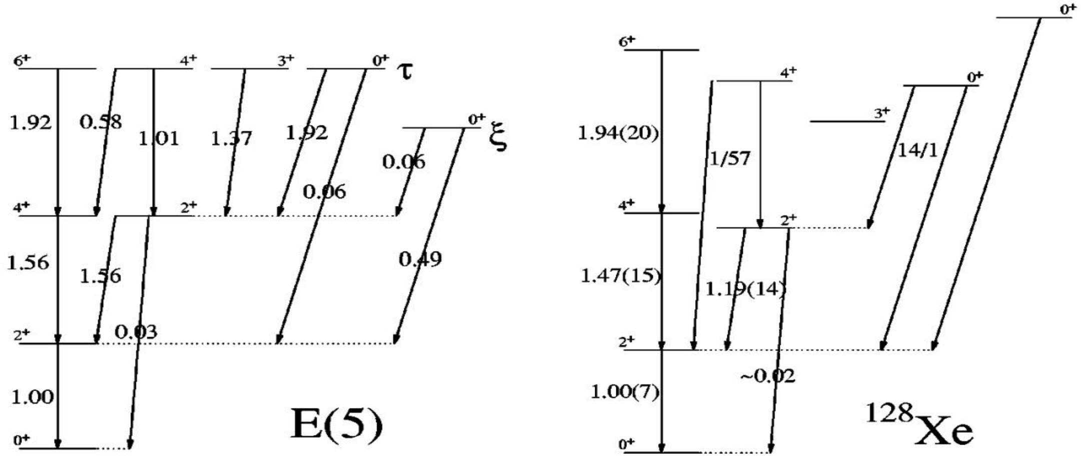
R. F. Casten, Nucl. Phys. A 439, 289 (1985). G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. A 348, 109 (1980). R. F. Casten and P. Von Brentano, Phys. Lett. B 152, 22 (1985).

The critical point is described by the $E(5)$ symmetry, associated with a 2[nd] order phase transition



F. Iachello, Phys. Rev. Lett. 87, 052502 (2001).
F. Iachello, Phys. Rev. Lett. 85, 3580 (2000).

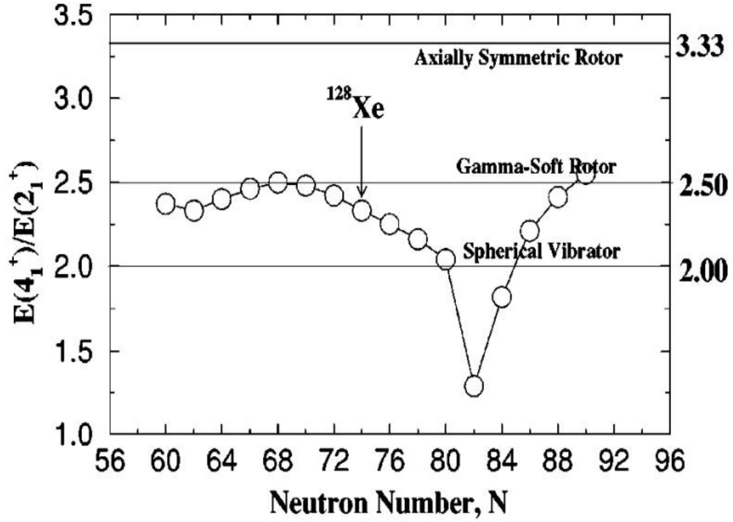
Exp evidence of E(5) symmetry for ^{128}Xe



Energy spectroscopy: good agreement with E(5) prediction

Nucleus	$E(4_1^+)/E(2_1^+)$	$E(0_2^+)/E(2_1^+)$	$E(0_3^+)/E(2_1^+)$
^{128}Xe	2.33	3.57	4.24
^{130}Xe	2.25	(3.35)	(3.76)
^{132}Xe	2.16		
^{134}Xe	2.04		

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



Evolution of $E(4_1^+)/E(2_1^+)$ ratio close to 2.2

Existence of two 0^+ states with $3<E(0_n^+)/E(2_1^+)<4$

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

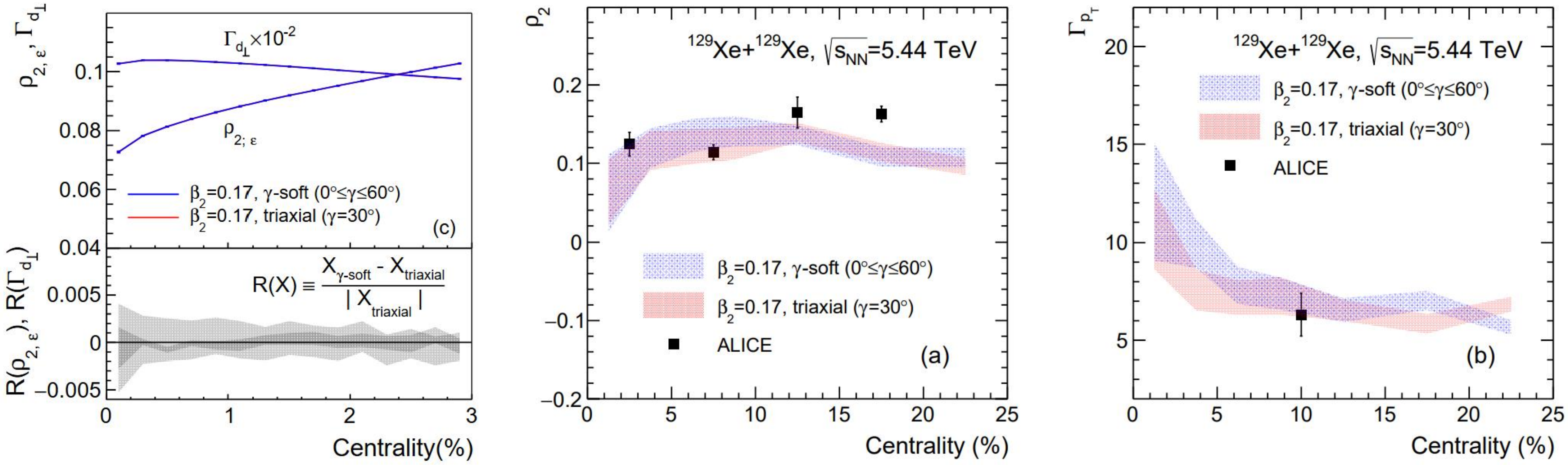
Results: 3-particle correlations

Liquid-drop model prediction:

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

$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}.$$

$$\Gamma_{p_T} = \frac{\langle \delta p_{T,i} \delta p_{T,j} \delta p_{T,k} \rangle \langle [p_T] \rangle}{\langle \delta p_{T,i} \delta p_{T,j} \rangle^2},$$



No effects both from initial and final stage.

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th], Phys. Rev. Lett. Accepted

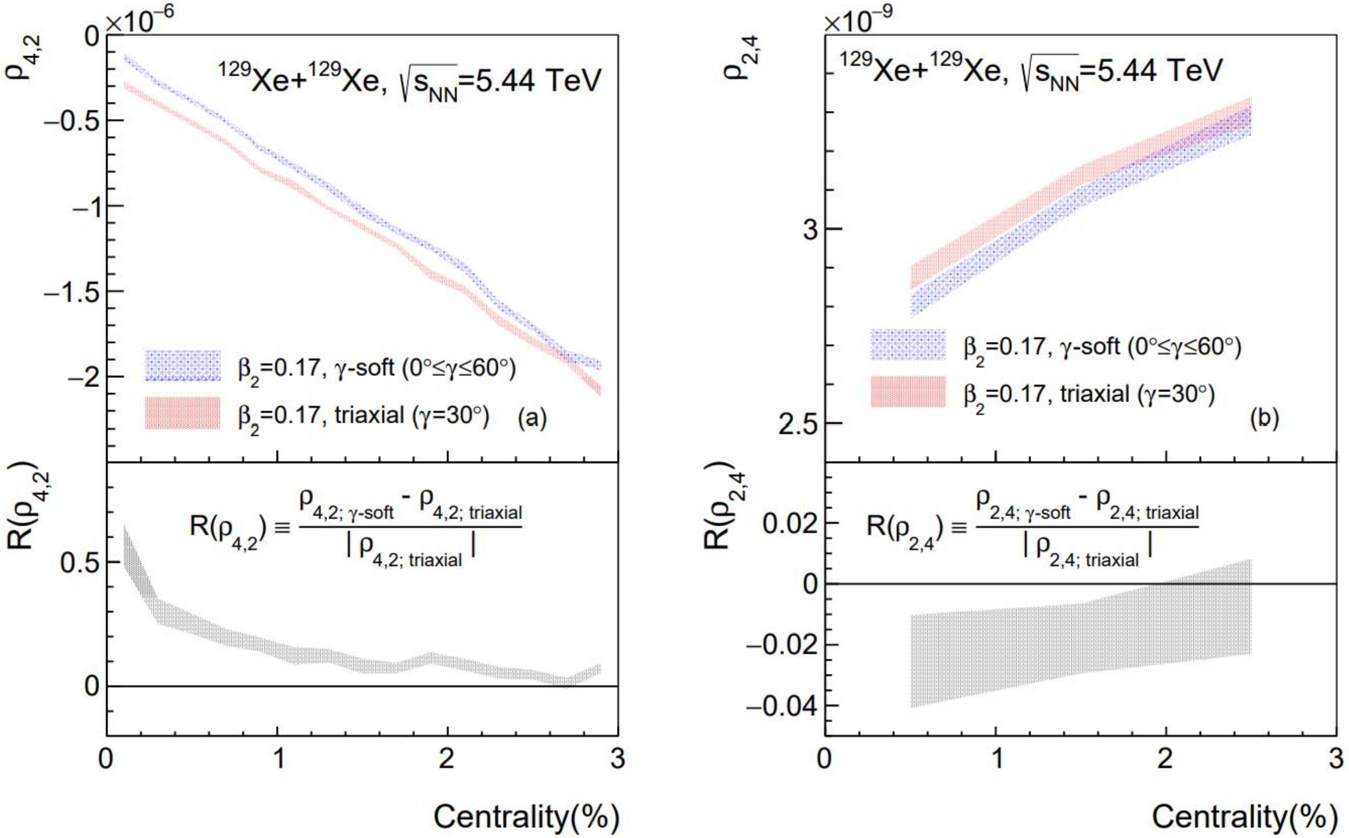
Results: 6-particle correlations

Clear enhencement (suppression) for the γ-soft (regid triaxial) shape, consistent with liquid drop calculations.

Effects on $\rho_{4,2}$ are one magnitude larger than $\rho_{2,4}$.

By constraining 3- and 6-particle correlations simultaneously, it would be possible to determine the details of traxial shape of ^{129}Xe.

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



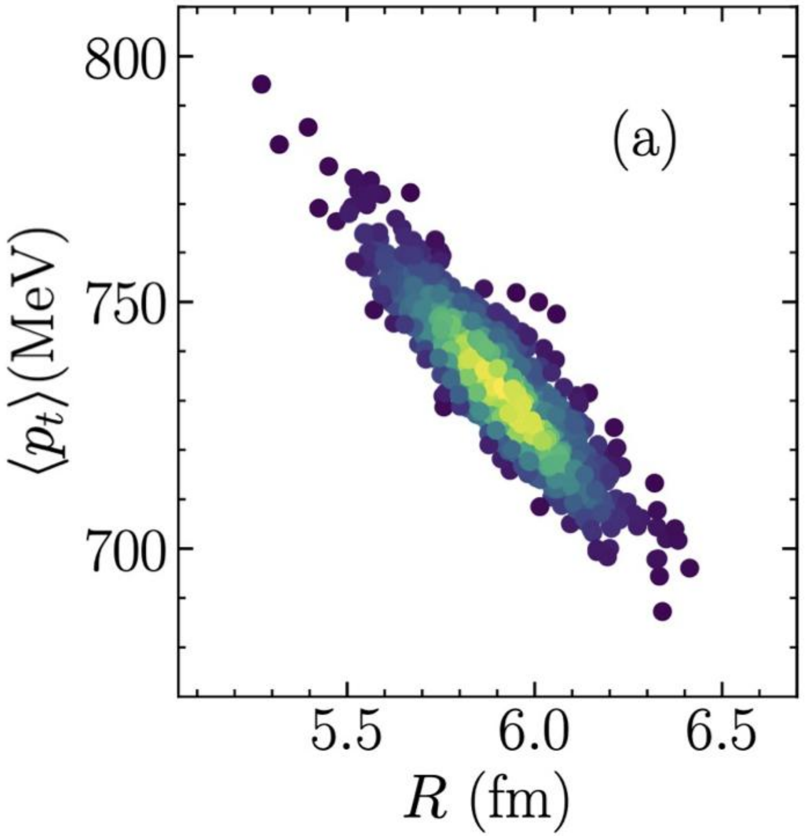
S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th], Phys. Rev. Lett. Accepted

Summary

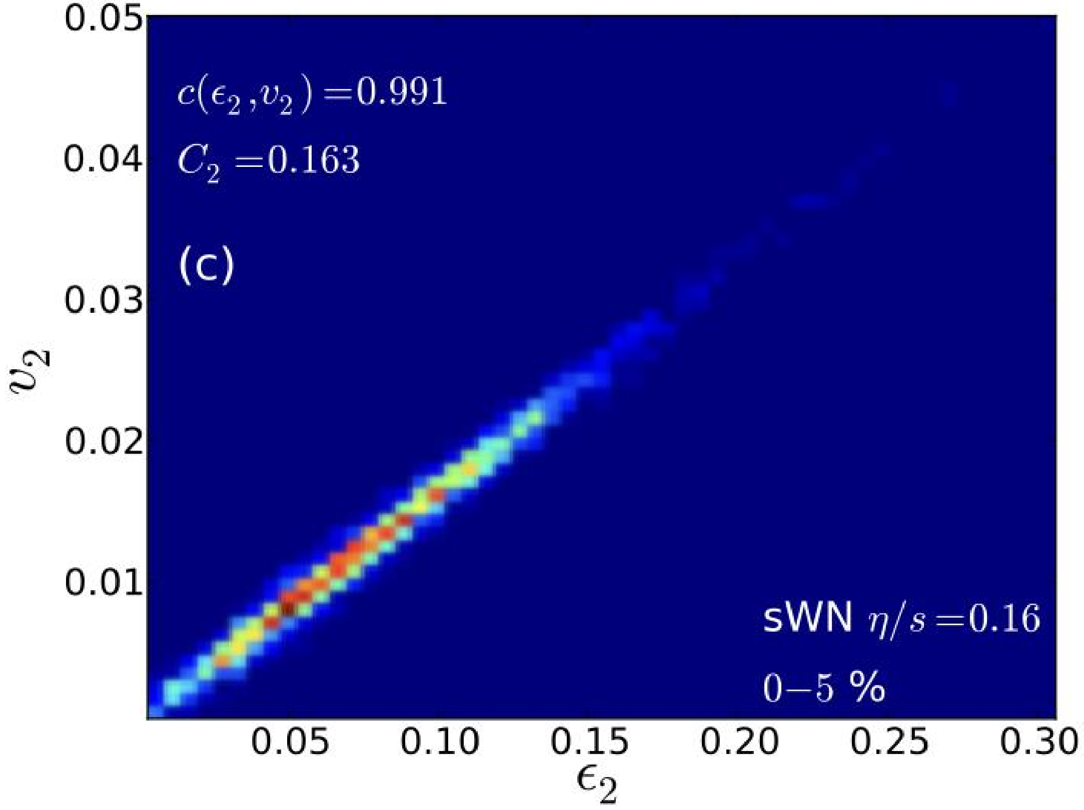
- ^{129}Xe may lay in the critical region of the second order shape phase transition along the Xe isotropes. Studing the traxial structure in ^{129}Xe may help for a better understanding the shape phase transition.
- 3-particle correlations cannot distinguish the traxial and γ-soft configurations of ^{129}Xe.
- By measuring the 3- and 6-particle correlations simultaneously, it would be possible to impose a constraint on the γ configuration of ^{129}Xe.
- This work suggest the possibility for studing the nuclear shape phase transition using relativistic heavy-ion collisions.

Backup

Linear response between ini. & fin. stage

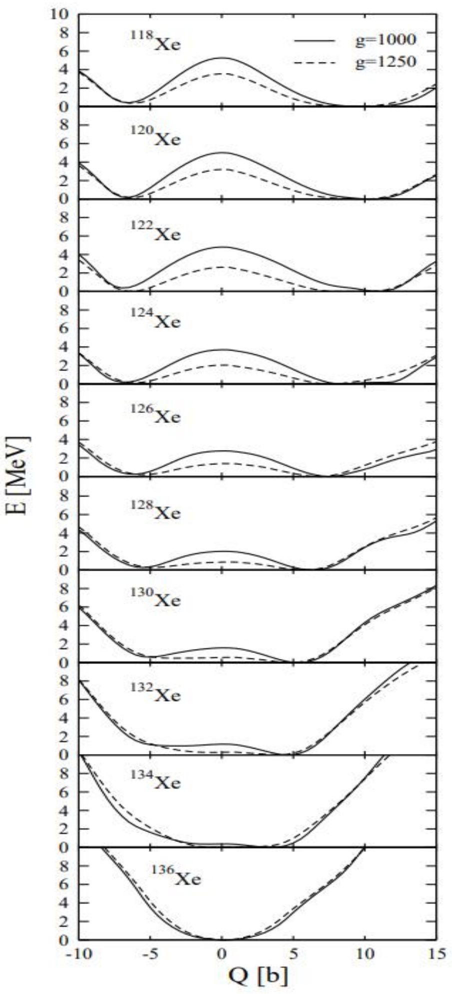


$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$$

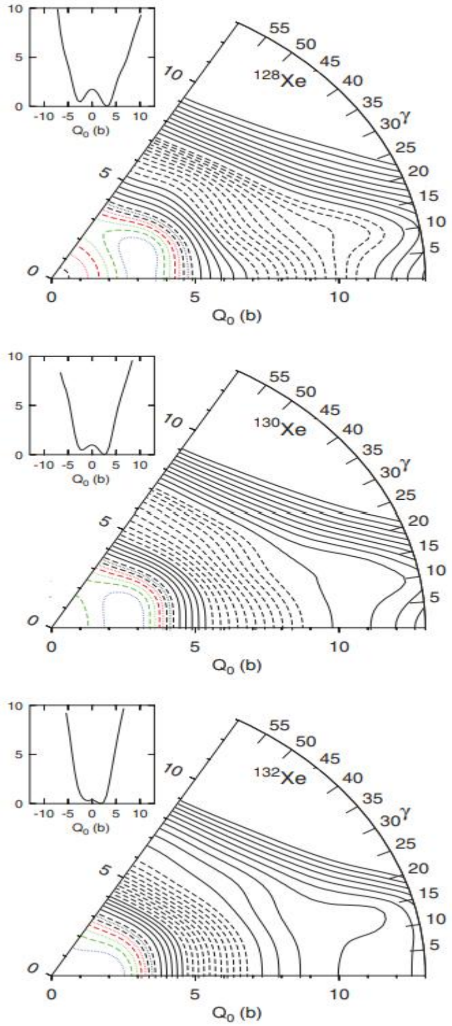


$$V_n \propto \mathcal{E}_n$$

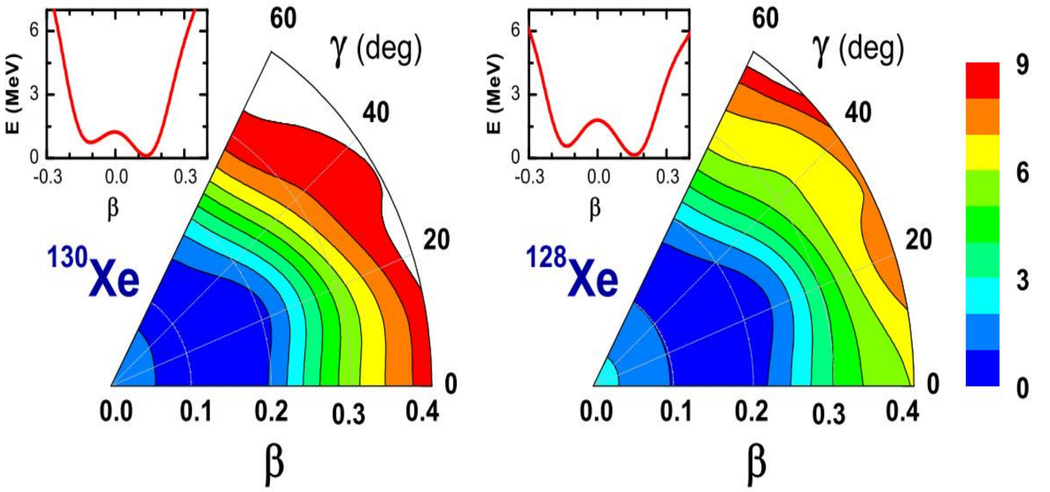
Th. predictions on E(5) symmetry near $^{128\text{-}130}$Xe



R. Rodriguez-Guzman, et. al.
Phys. Rev. C 76, 064303 (2007)



L.M.Robledo, et. al. Phys. Rev.C 78 (2008) 034314



Z. P. Li, T. Niksic, D. Vretenar, and J. Meng (2010)

Various theoretical calculations indicate a critical point of the second-order shape phase transition (E(5) symmetry) lies in the vicinity of $^{128-130}$Xe, associated with a γ-soft deformation

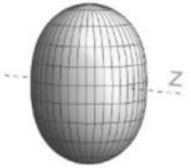
Involving γ fluctuation at initial stage

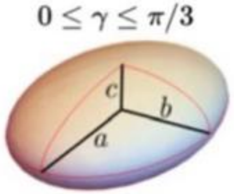
Initial Conditions (TRENTO)

Nucleons are sampled from Woods-Saxon distribution:

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

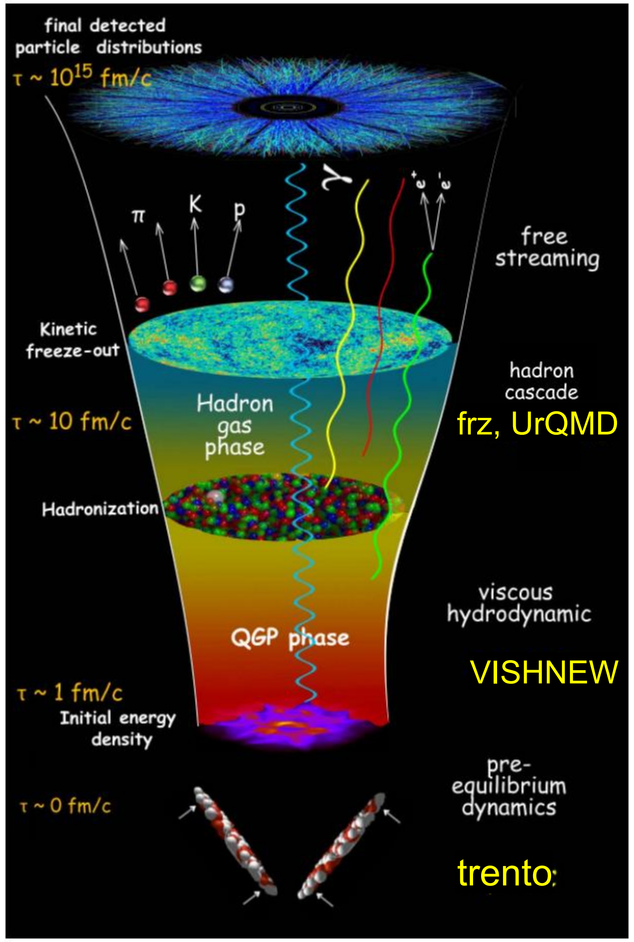
$$R(\theta,\phi) = R_0(1 + \beta_2[\cos\gamma Y_{2,0}(\theta,\phi) + \sin\gamma Y_{2,2}(\theta,\phi)]).$$





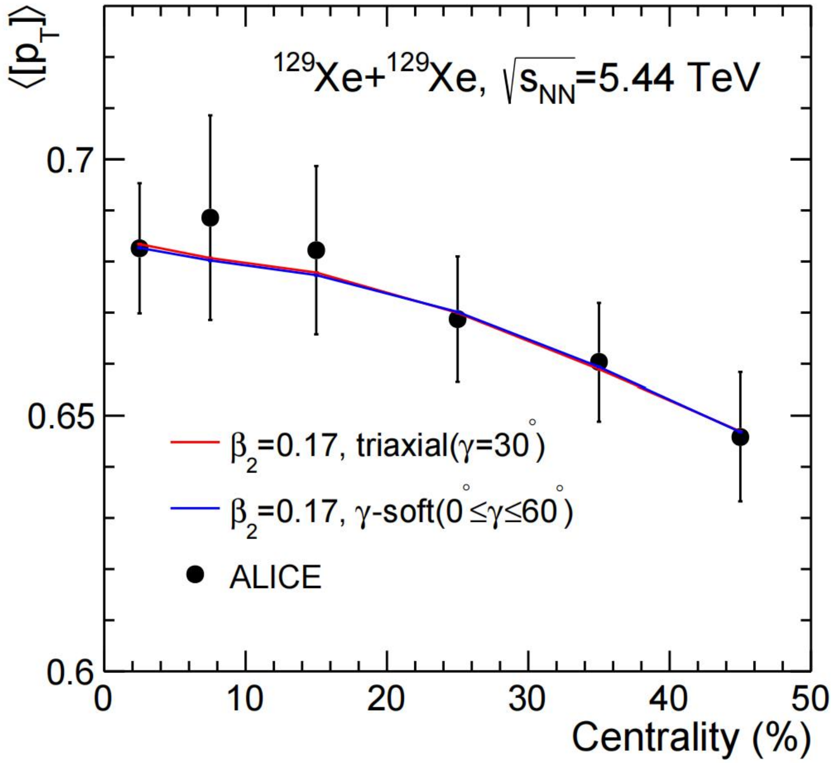
Sample the triaxial parameter gamm with different distribution:

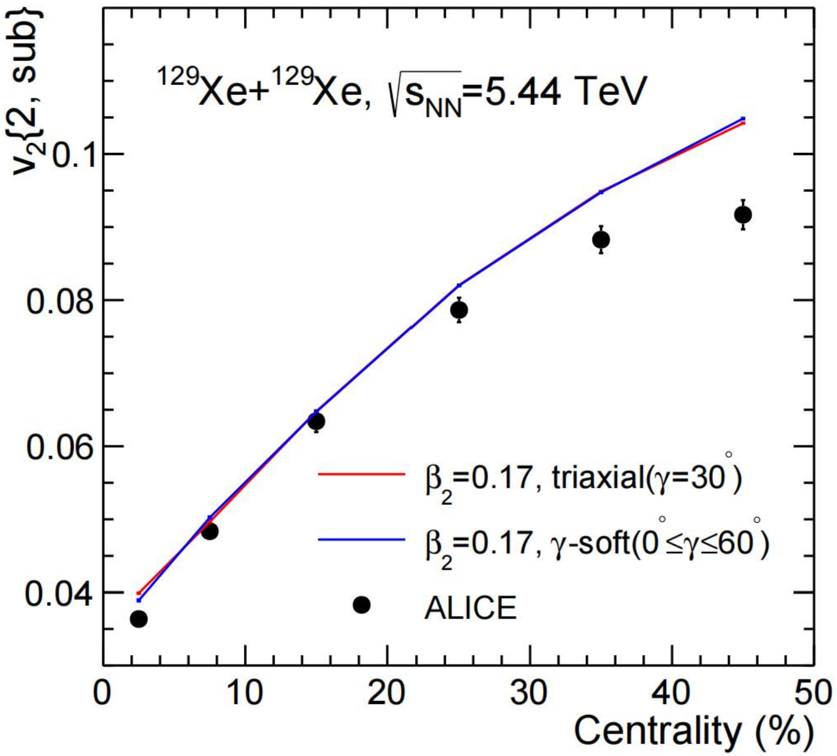
- Rigid triaxial deformation (γ=30º)
- γ-soft (flat distribution in 0≤γ≤60º)



S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th], Phys. Rev. Lett. Accepted

Parameter Validation





With the parameters obtained from previous Bayesian analysis (Pb+Pb coll), our iEBE-VISHNU, with rigid triaxial or γ-soft deformation of ^{129}Xe, can describe most of the bulk observables in Xe+Xe collisions

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th], Phys. Rev. Lett. Accepted

Results: 6-particle correlations

Here we propose the following two 6-particle correlations at the initial stage:

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

$$\rho_{2,4} \equiv \left(\frac{\langle \varepsilon_2^2 \delta d_\perp^4 \rangle}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4}\right)_c \equiv \frac{1}{\langle \varepsilon_2^2 \rangle \langle d_\perp \rangle^4} \left[\langle \varepsilon_2^2 \delta d_\perp^4 \rangle - 6\langle \varepsilon_2^2 \delta d_\perp^2 \rangle \langle \delta d_\perp^2 \rangle - 4\langle \varepsilon_2^2 \delta d_\perp \rangle \langle \delta d_\perp^3 \rangle - \langle \varepsilon_2^2 \rangle \langle \delta d_\perp^4 \rangle + 6\langle \varepsilon_2^2 \rangle \left(\langle \delta d_\perp^2 \rangle\right)\right].$$

The calculations based on the liquid-drop model suggest that

$$\langle \varepsilon_2^4 \rangle \rho_{4,2} = A\beta_2^6 (53 + 16\langle \cos(6\gamma) \rangle) + f_{4,2}(\beta_2^6, \langle \cos(3\gamma) \rangle),$$

$$\langle \varepsilon_2^2 \rangle \rho_{2,4} = \frac{A}{16}\beta_2^6 (43 - 14\langle \cos(6\gamma) \rangle) + f_{2,4}(\beta_2^6, \langle \cos(3\gamma) \rangle),$$

Thus it would be possible for distinguish the two cases (traixial shape with $\gamma=30^o$ and γ-soft in $0\leq\gamma\leq60^o$) using the two 6-particle correlations.

S. Zhao, H. Xu, Y. Zhou, Y. Liu, H. Song, arXiv: 2403.07441 [nucl-th], Phys. Rev. Lett. Accepted