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

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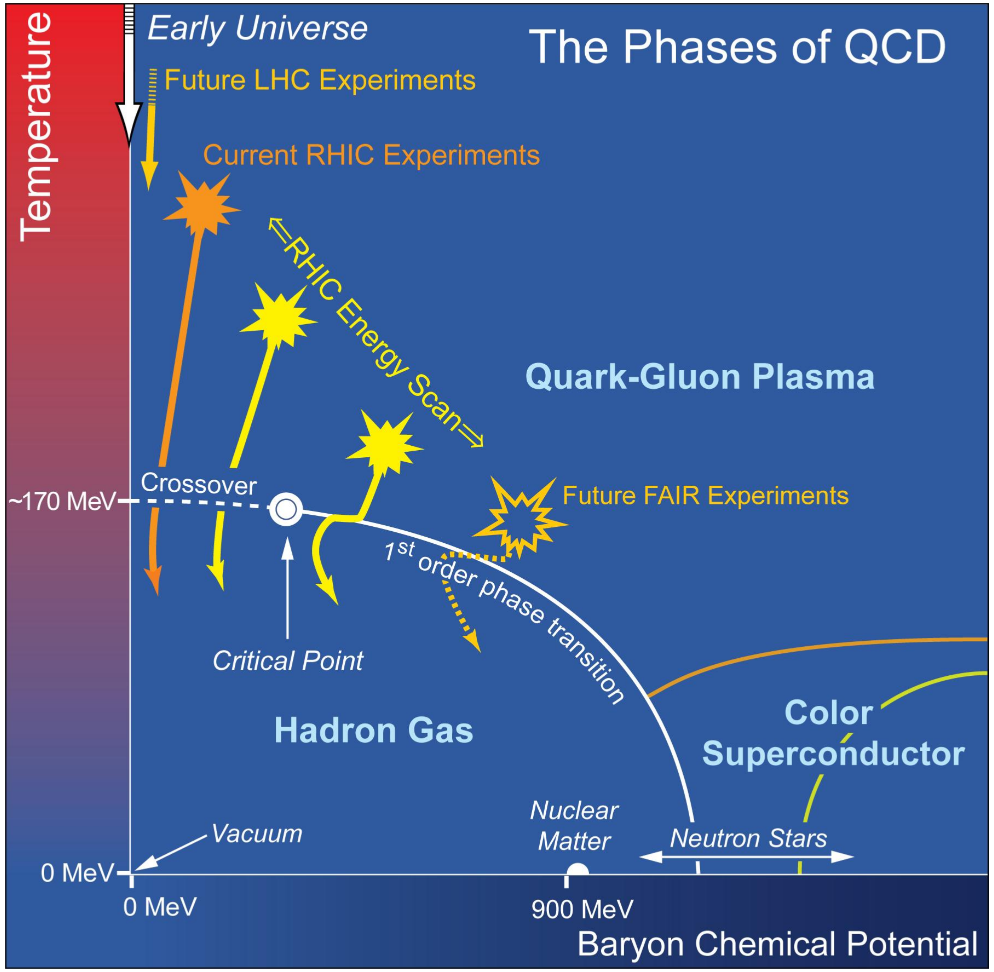
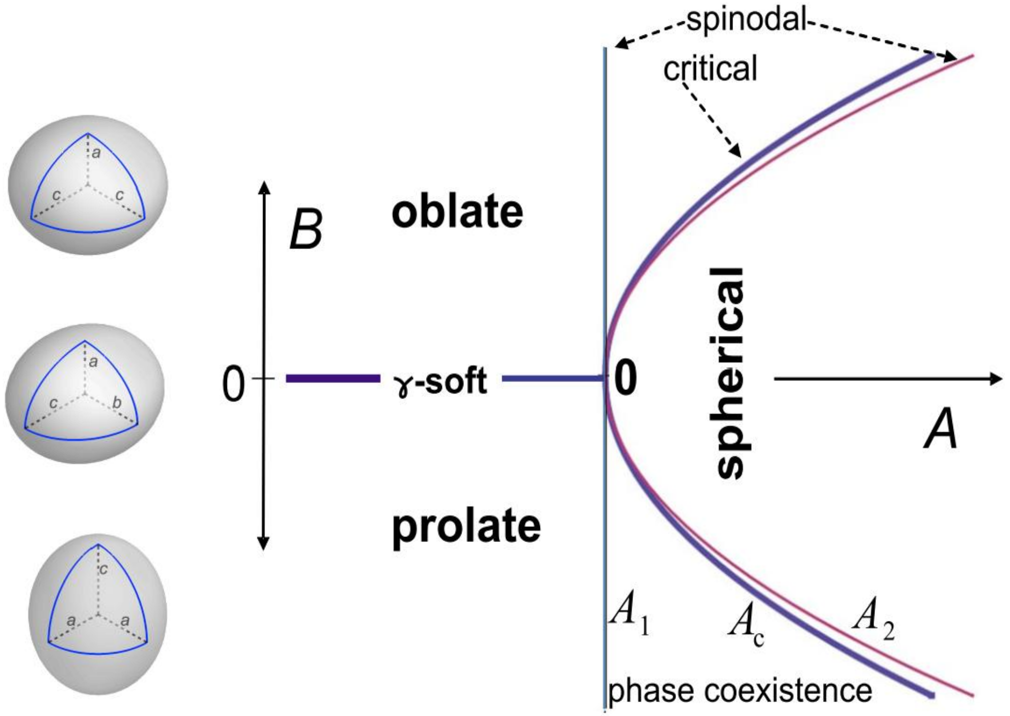
In collaboration with Haojie Xu, You Zhou, Yu-Xin Liu and Huichao Song

中国物理学会高能物理分会第十四届全国粒子物理学术会议， 15/08/2024， 山东 青岛

Phase Transition: Thermal v.s. Quantum

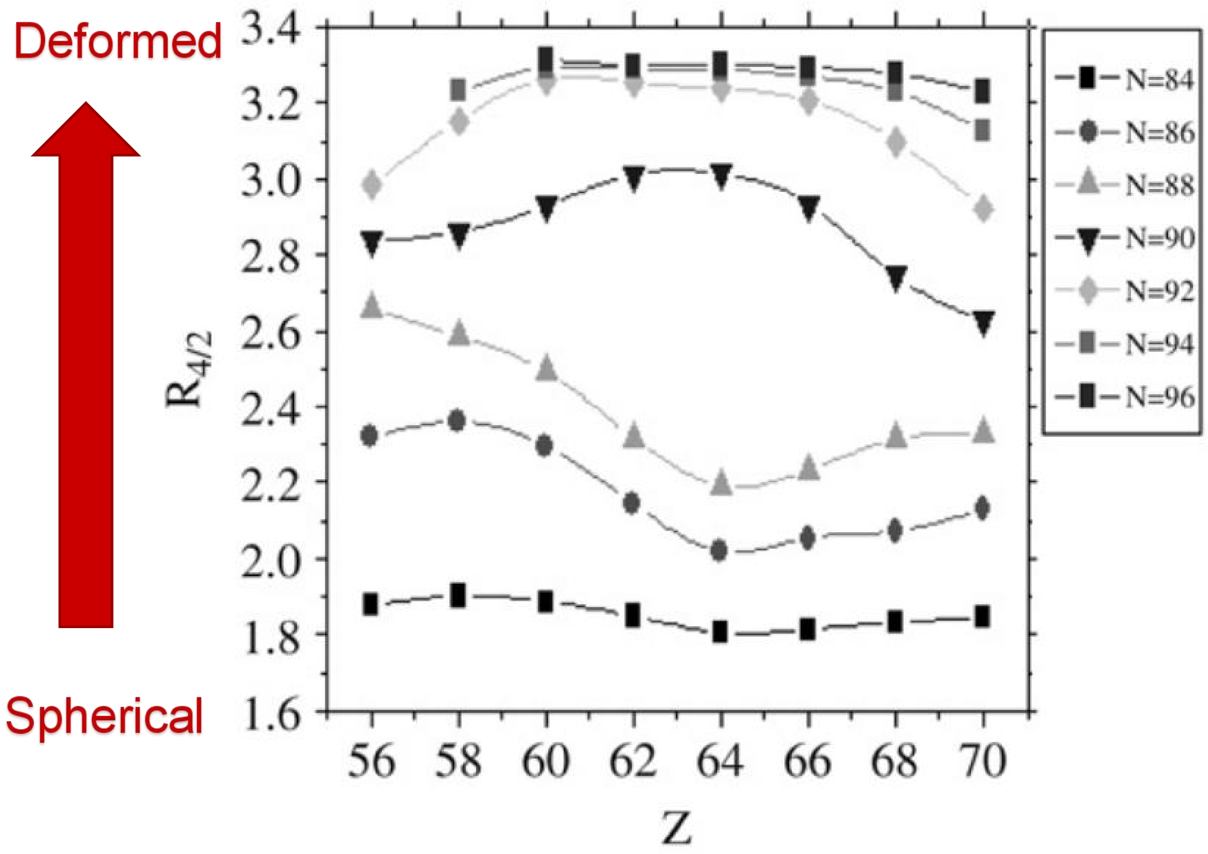


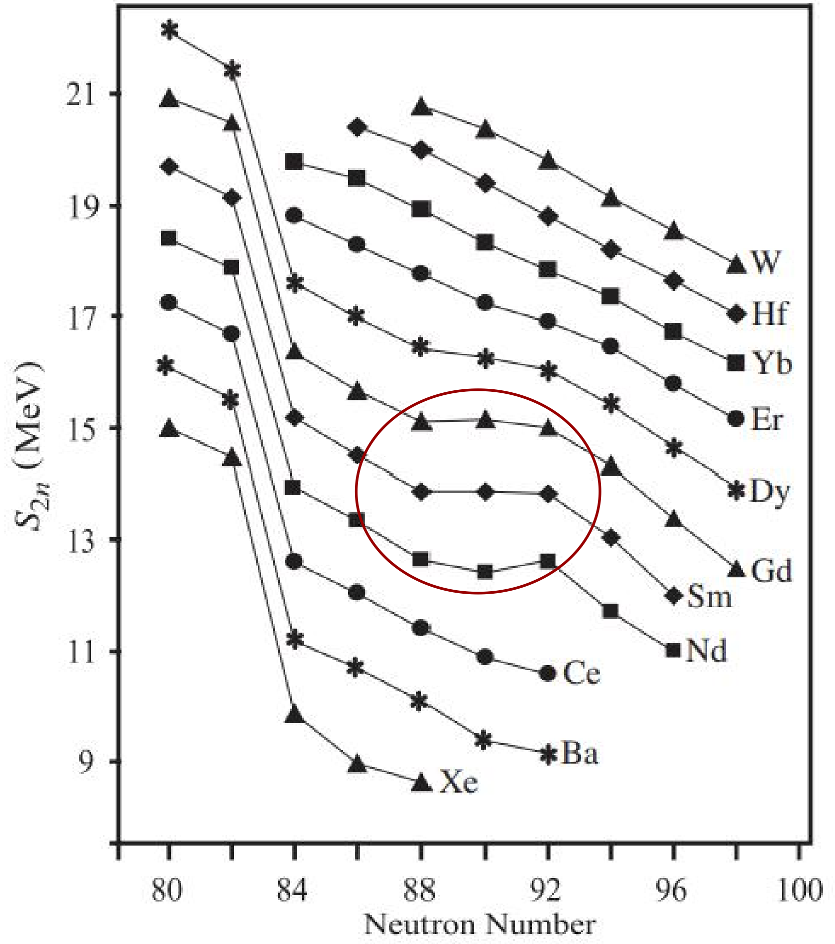


Driven by thermal fluctuation occurs at T≠0 K

Driven by quantum fluctuation occurs at T≈0 K

Shape Phase Transition in Nuclear Theory





The Shape Phase Transition:
Evolution of nuclear shape along certain isotope/isotone chain.

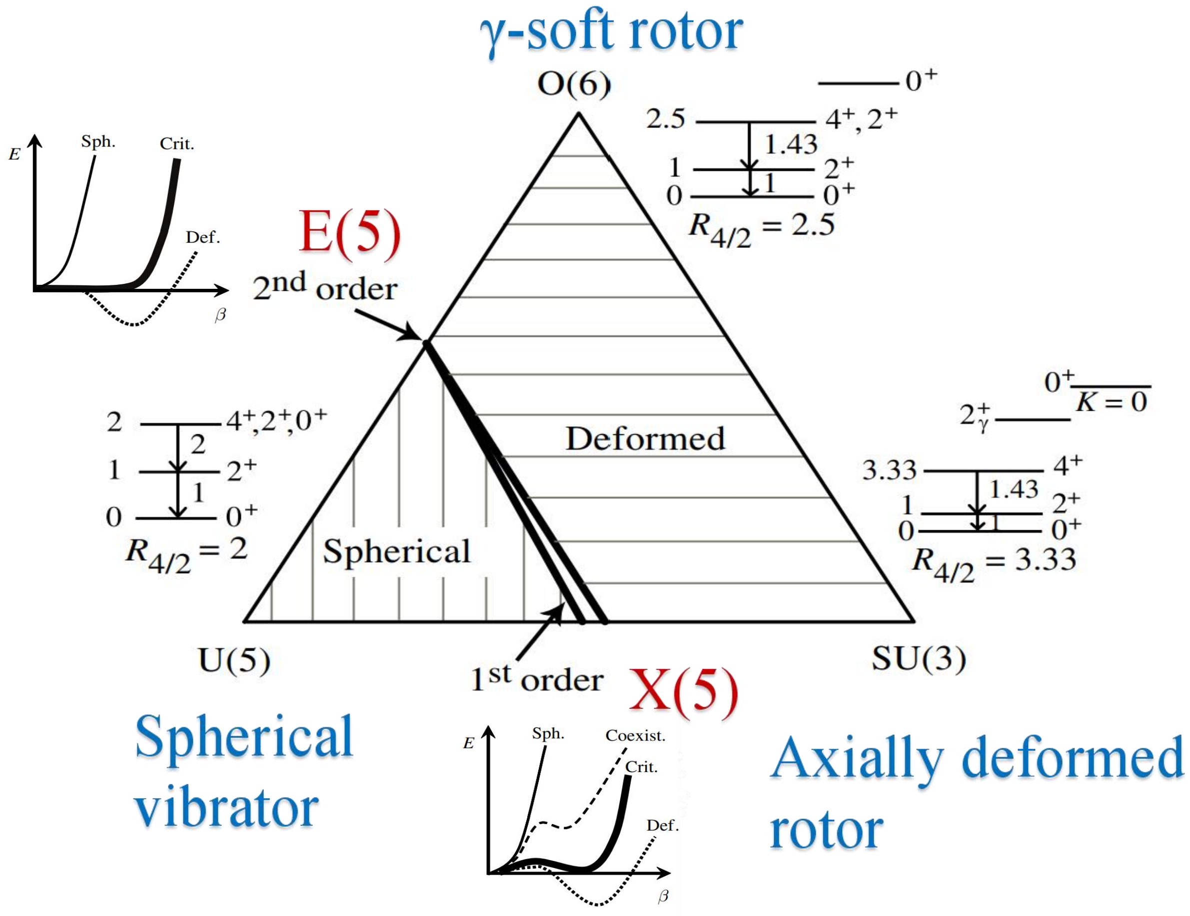
R.F. Casten / Progress in Particle and Nuclear Physics 62 (2009) 183–209

Critical Point Symmetry (CPS)

$$H(\zeta,\chi) = a\left[(1-\zeta)\hat{n}_d - \frac{\zeta}{4N_B}\hat{Q}^{\chi}\cdot\hat{Q}^{\chi}\right]$$

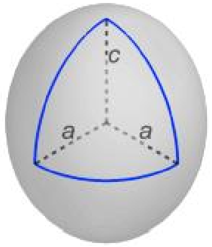
1^{st} order SPT: X(5) symmetry
2^{nd} order SPT: E(5) symmetry

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).



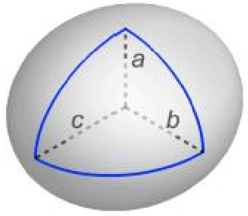
Prolate

$\beta_2 = 0.25, \cos(3\gamma) = 1$



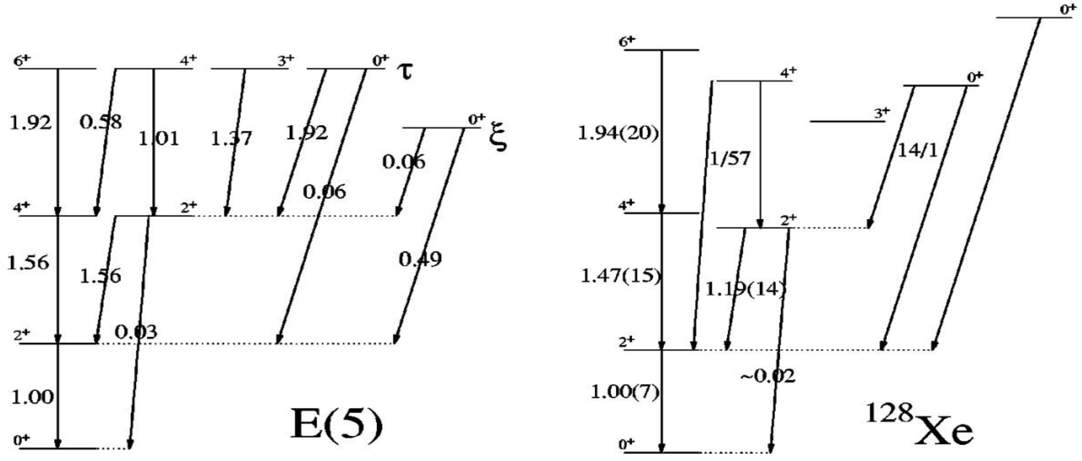
Triaxial

$\beta_2 = 0.25, \cos(3\gamma) = 0$

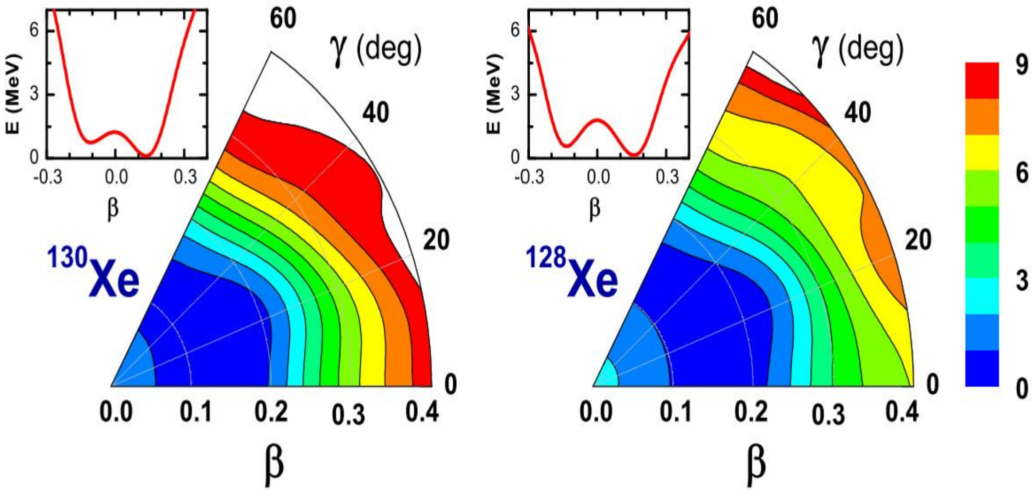


F. Iachello, Phys. Rev. Lett. 87, 052502 (2001).
F. Iachello, Phys. Rev. Lett. 85, 3580 (2000).

Evidence of E(5) symmetry for ^{129}Xe

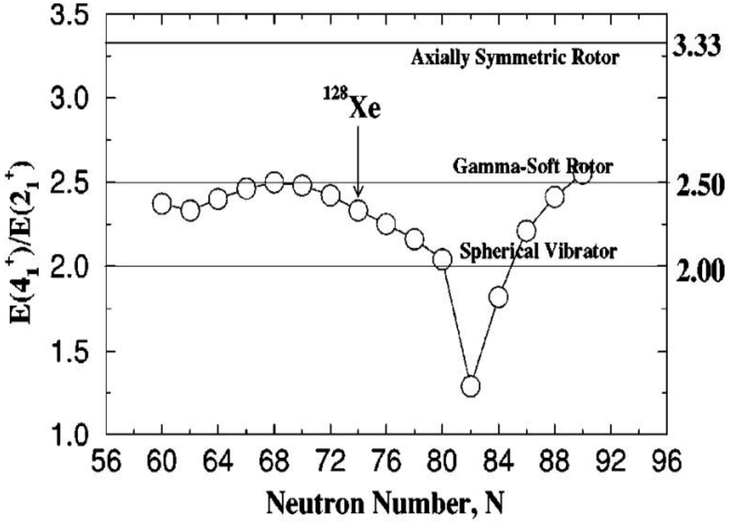


R. M. Clark, et. al. Phys. Rev. C 69, 064322 (2004)



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

^{129}Xe lies in between γ-soft rotor and spherical vibrator.



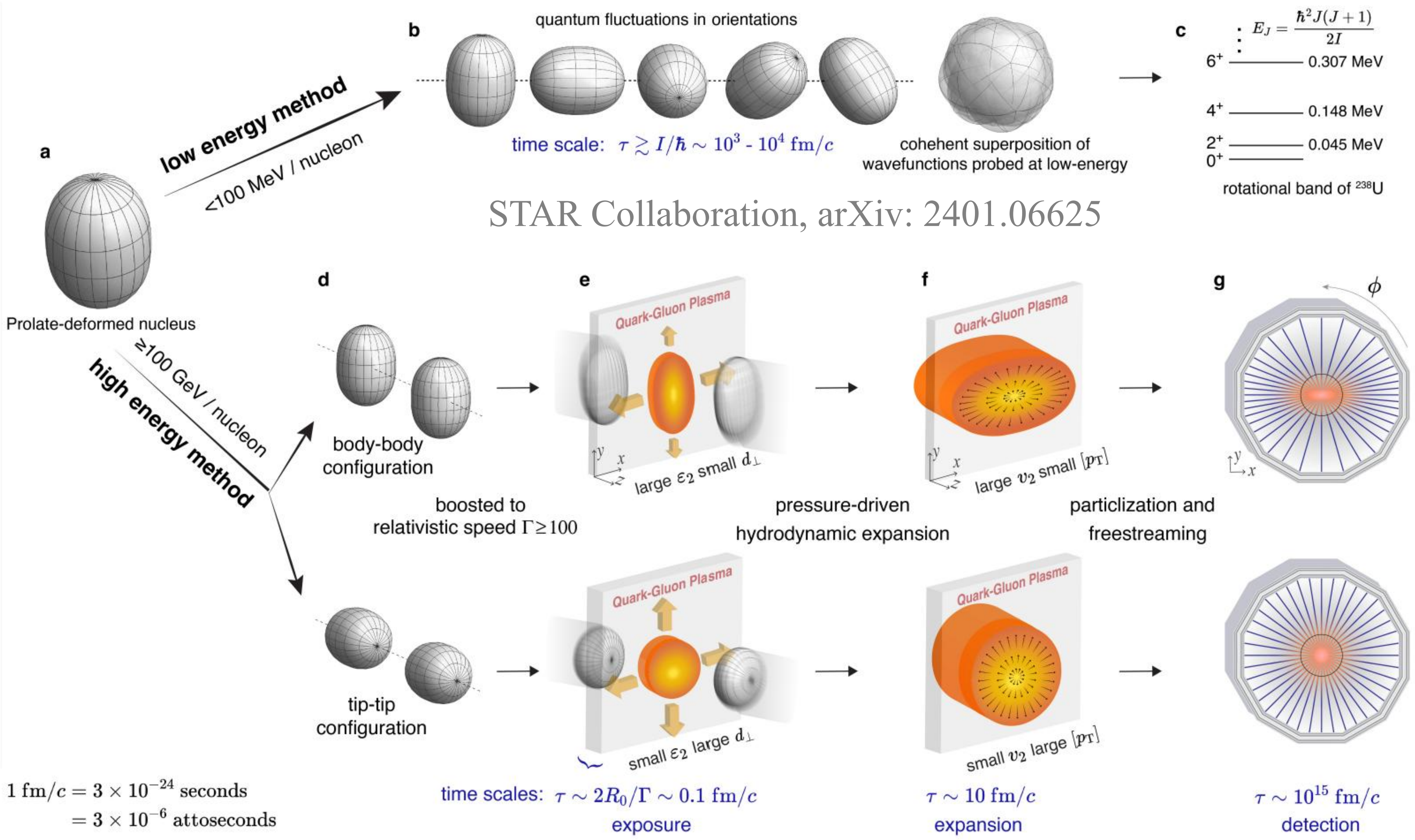
Probing Nuclear Shape in Heavy-Ion Collisions

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

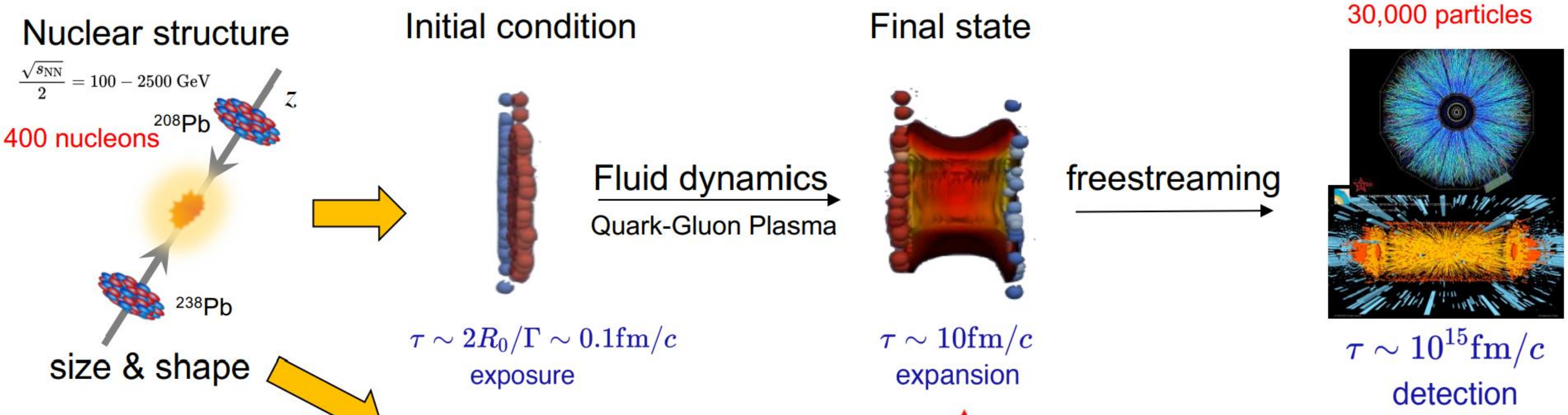
Event-by-event linear responses:

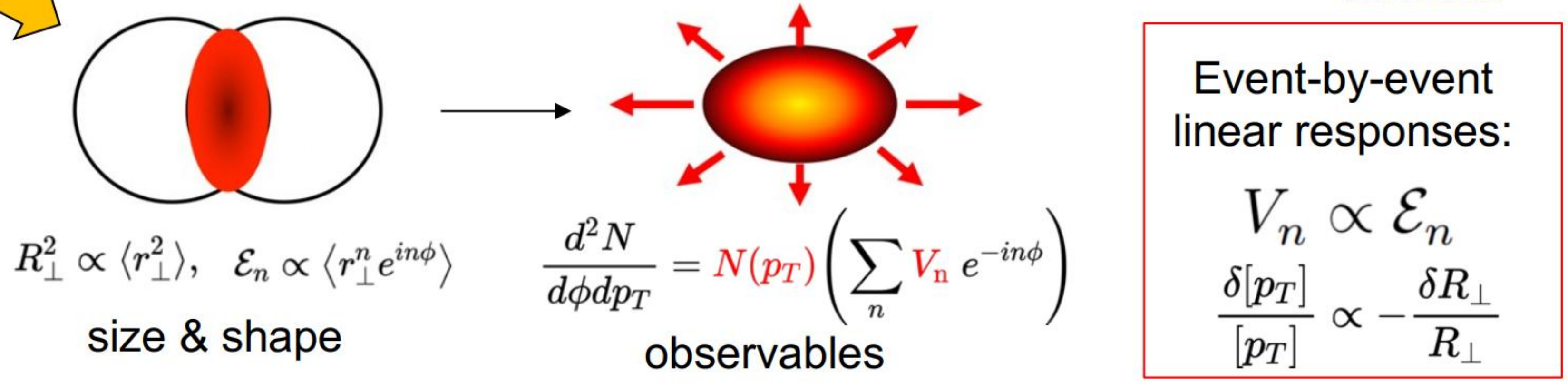
$$V_n \propto \mathcal{E}_n$$

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



Relativistic Heavy-Ion Collisions

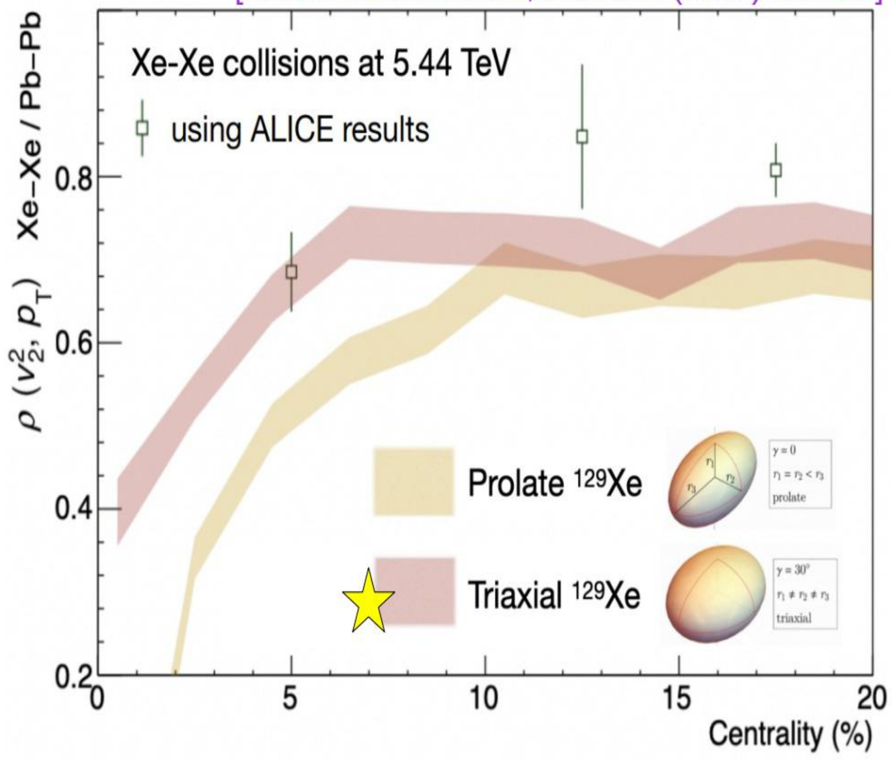




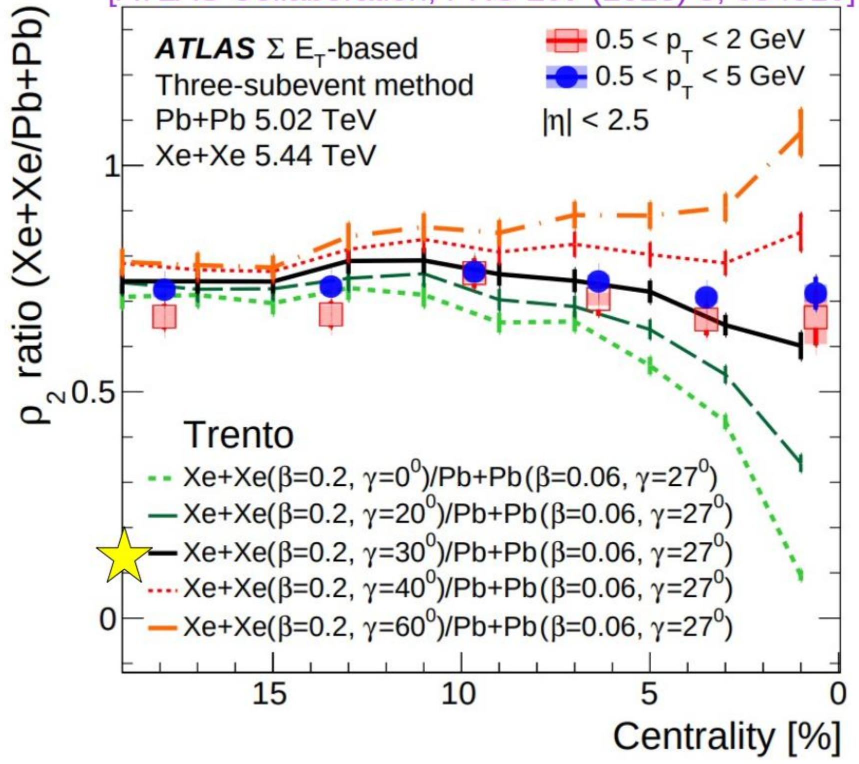
Probing initial stage geometry from final stage observables.

Probing triaxial deformation in Xe+Xe collisions

[ALICE Collaboration, PLB **834** (2022) 137393]



[ATLAS Collaboration, PRC **107** (2023) 5, 054910]



Distinguish rigid triaxial and γ-soft configuration in heavy-ion collisions.
Explore the possible 2nd order shape phase transition of Xe isotopes.

B. Bally, M. Bender, G. Giacalone, V. Somà, Phys. Rev. Lett. 128 (8) (2022) 082301

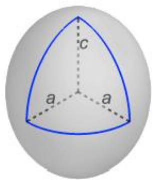
Involving γ fluctuation at initial stage

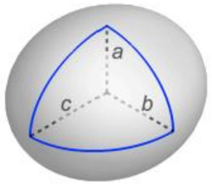
Initial Conditions (TRENTo)

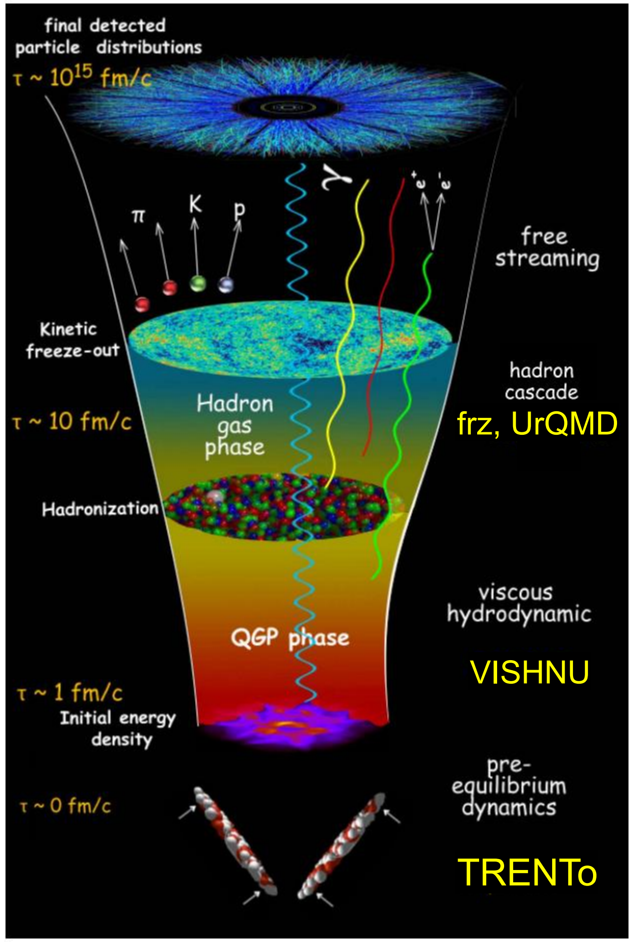
Nucleons are sampled from Woods-Saxon distribution:

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

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





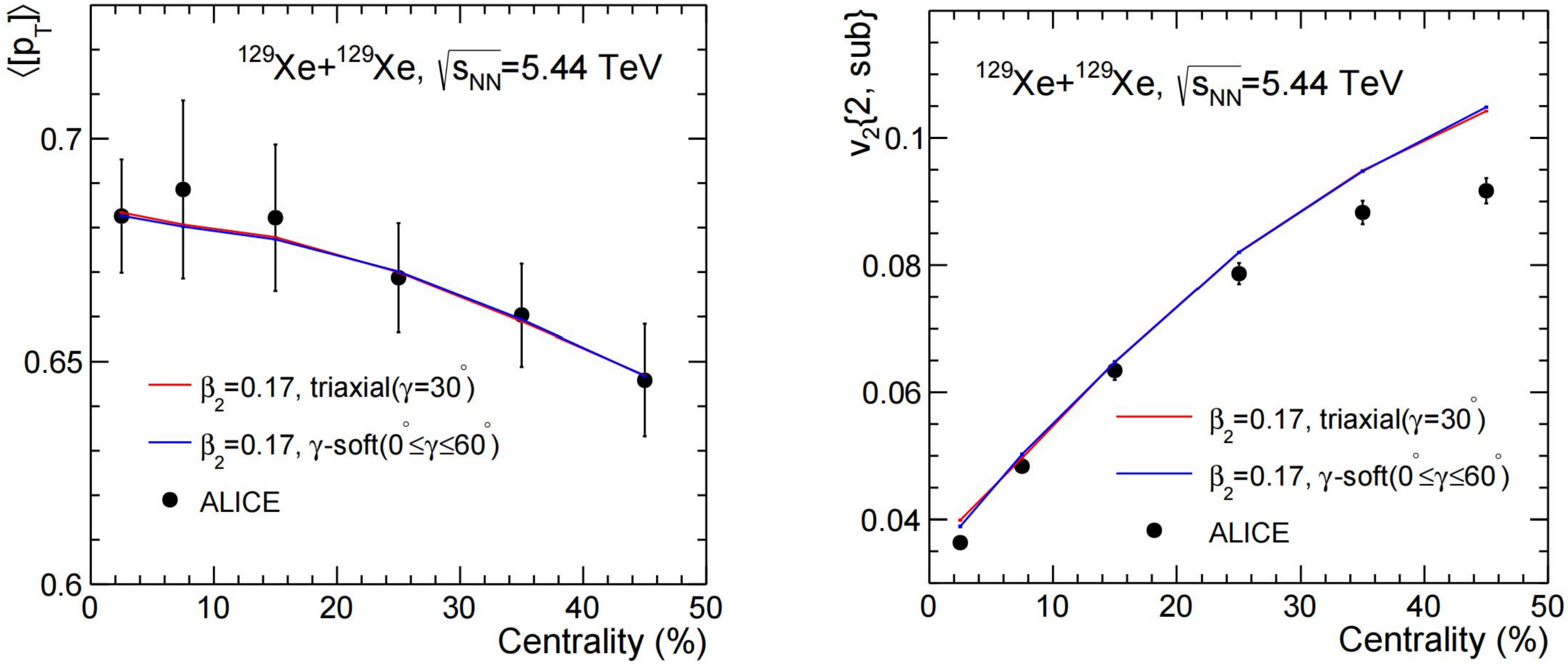


Sample the triaxial parameter γ with different distribution:

- 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]

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]

Results: 3-particle correlations

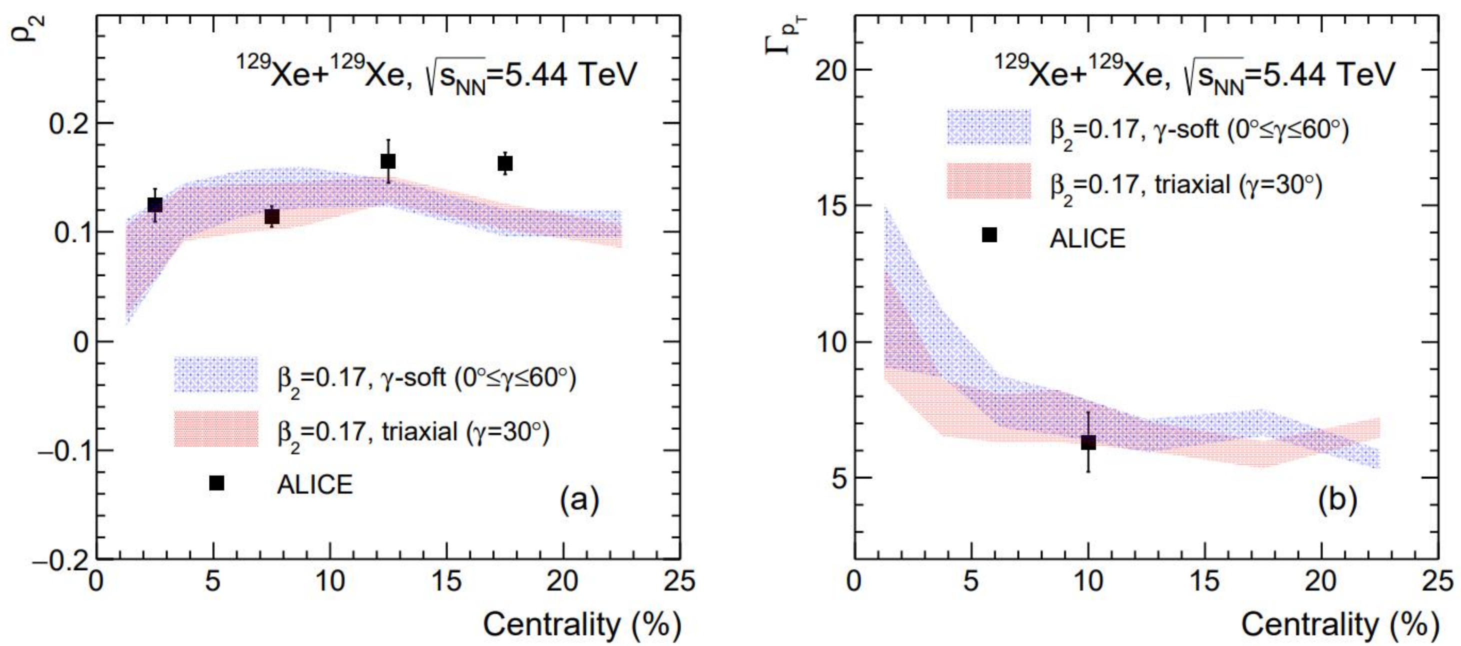
Liquid-drop model prediction:

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

3-particle correlation can also be explained by the γ-soft ^{129}Xe.

higher order correlations between v_2 and $[p_T]$ is crucial for distinguish the two different γ configuration.

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



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

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 γ=30º and γ-soft in 0≤γ≤60º) using the two 6-particle correlations.

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

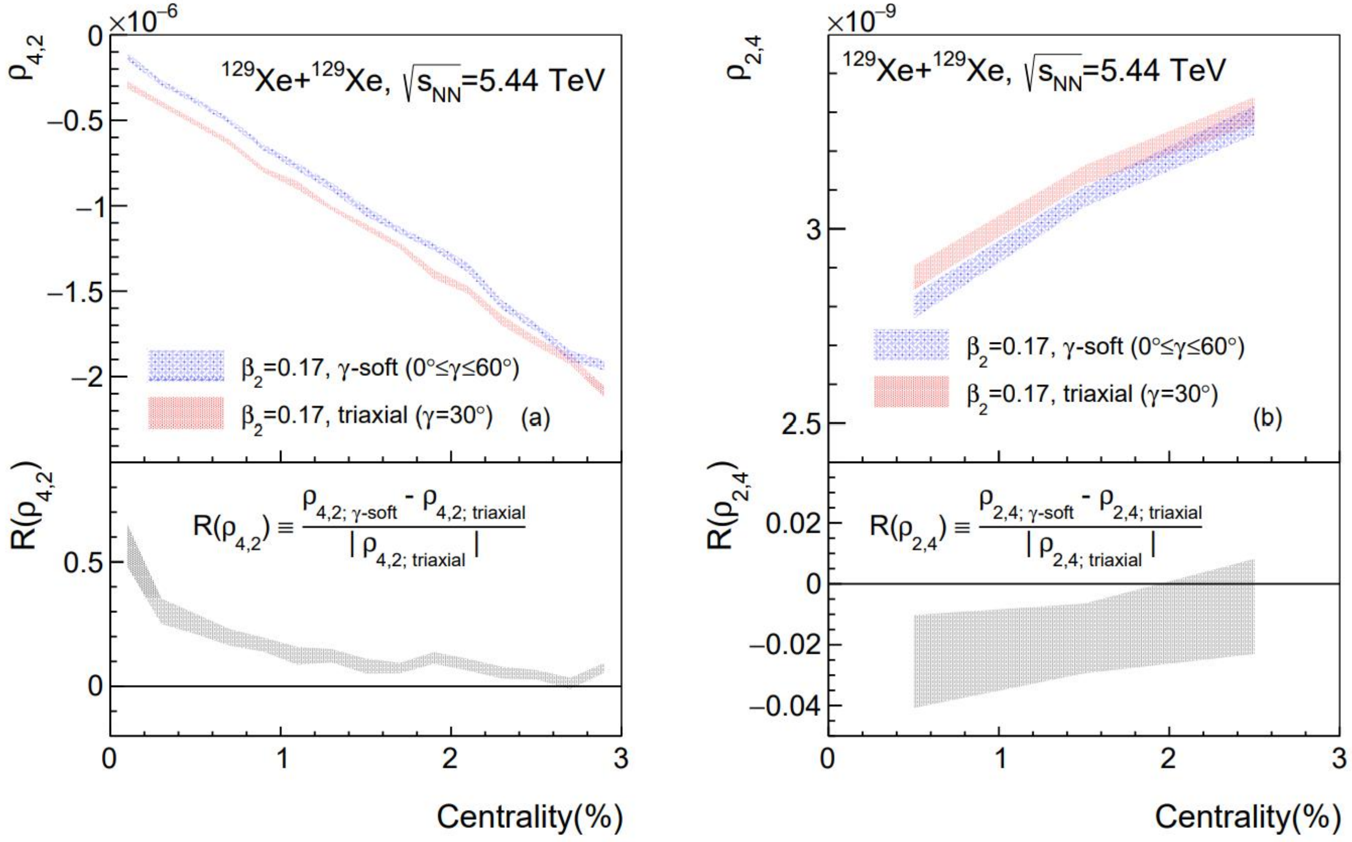
Results: 6-particle correlations

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]

Summary & Outlook

➢Summary:

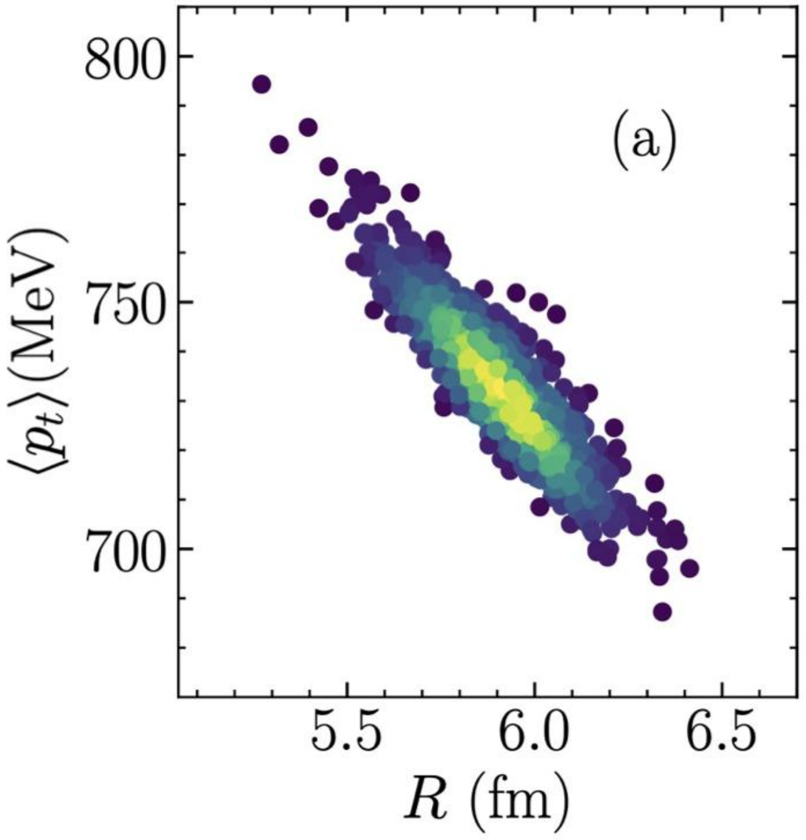
- Possible 2nd order SPT for Xe isotope
- Constraint the shape of Xe with 3- and 6-particle correlations
- Studing the nuclear shape phase transition using relativistic heavy-ion collisions.

➢Outlook:

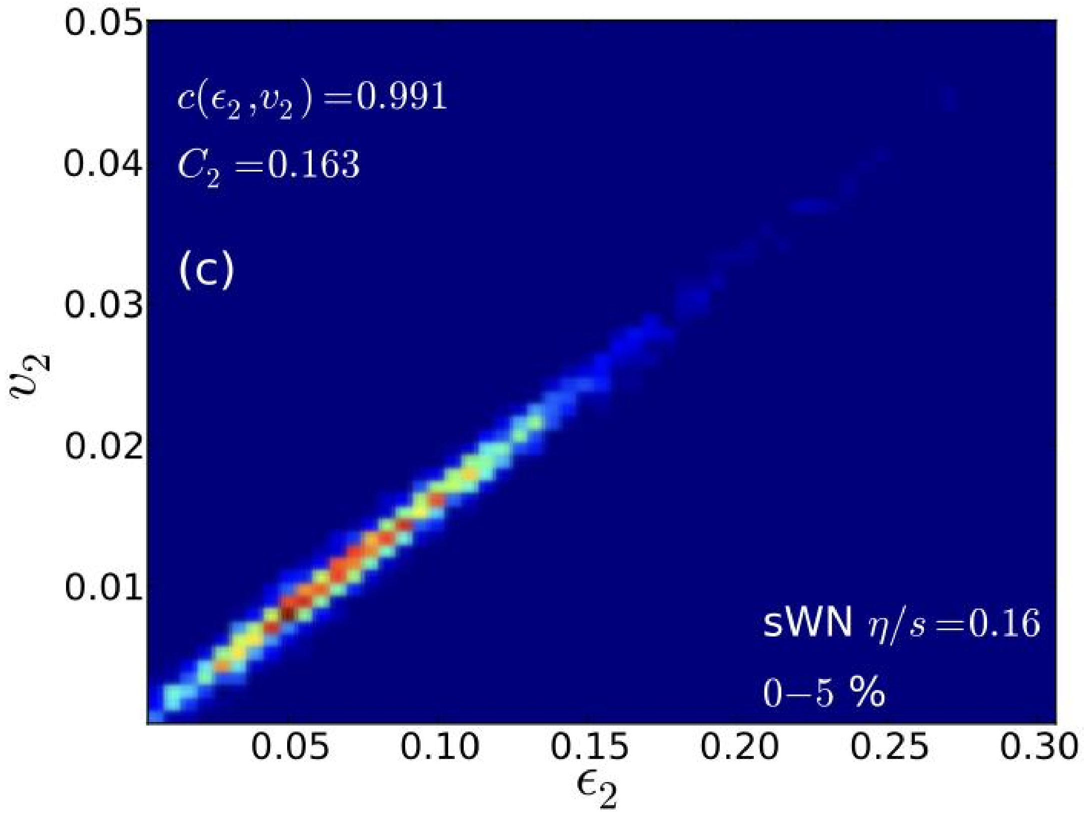
- More typical nuclei going through SPT?
  - ✓ ^{152}Sm, ^{150}Nd, ^{154}Gd, ^{156}Dy
  - ✓ ^{134}Ba, ^{102}Pd, ^{104}Ru, ^{106}Cd

Backup

Linear response between ini. & fin. stage

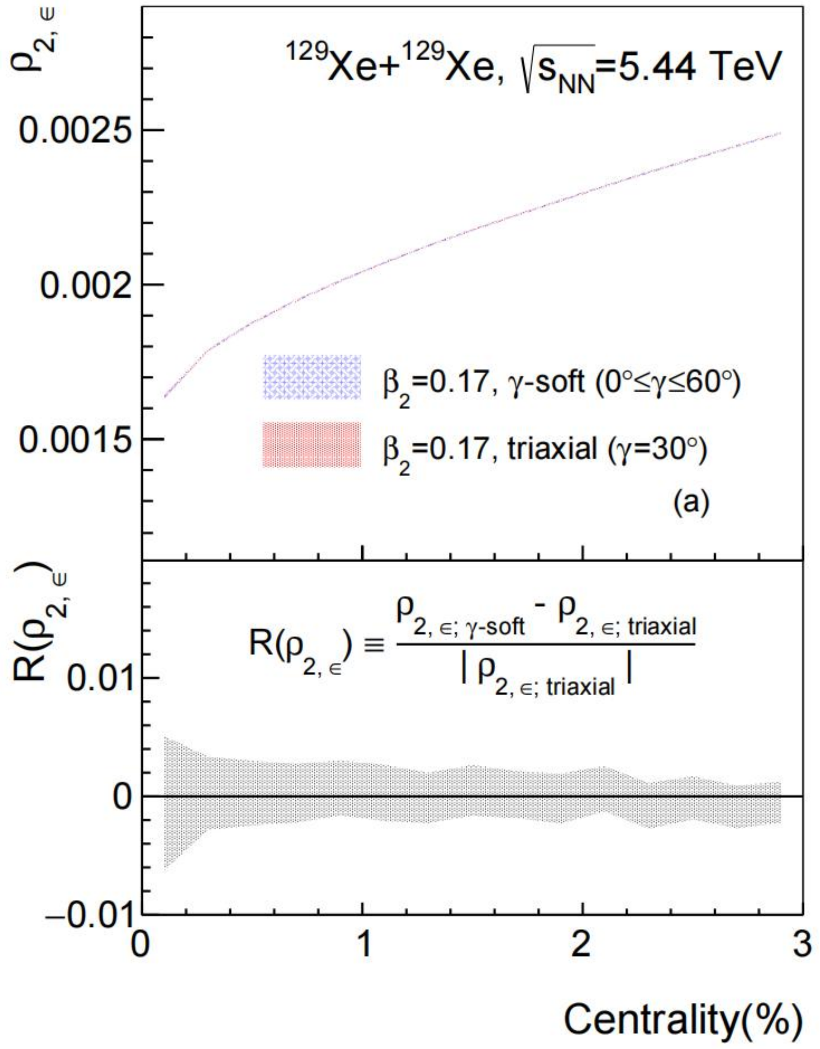


$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp}$$

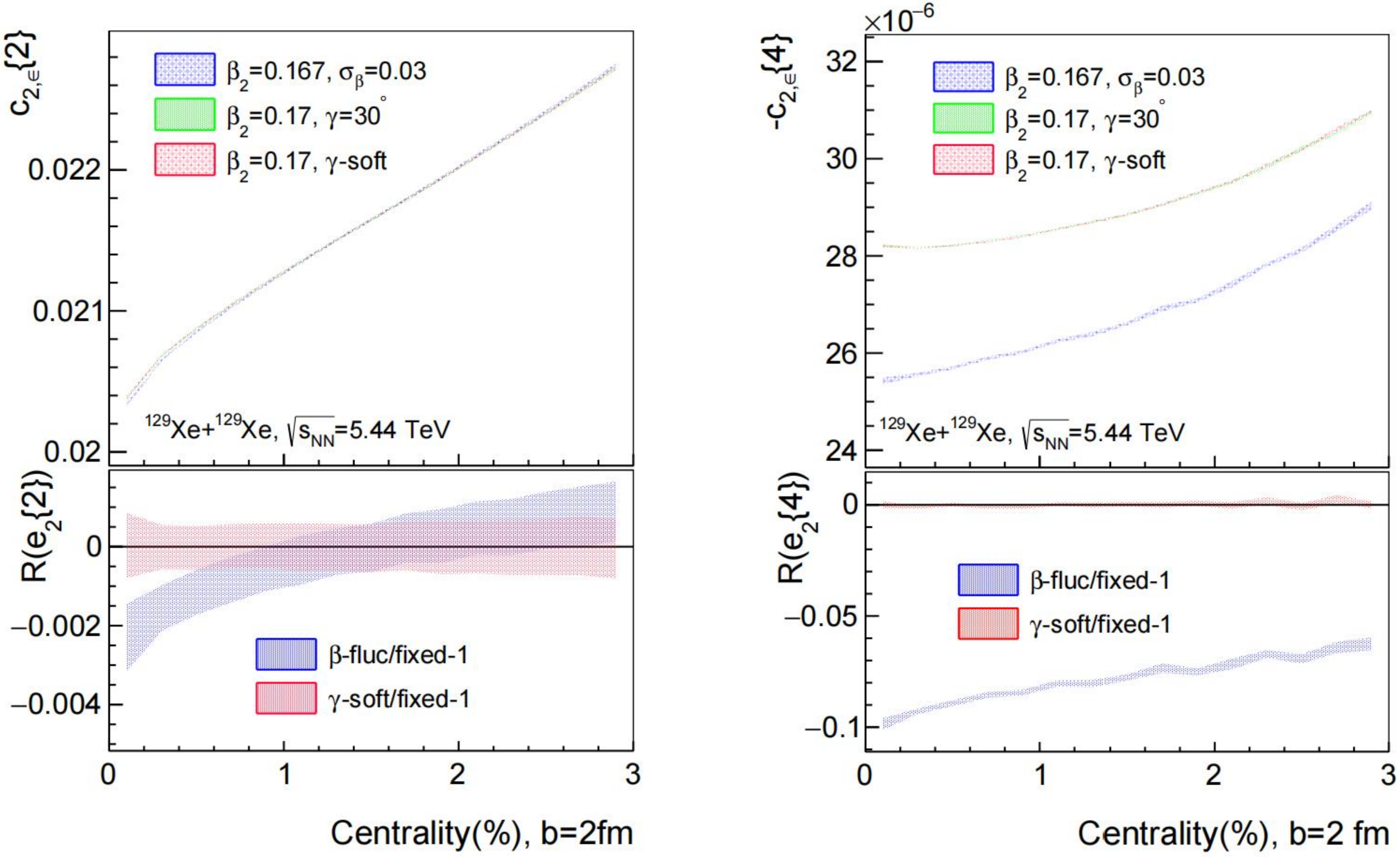


$$V_n \propto \mathcal{E}_n$$

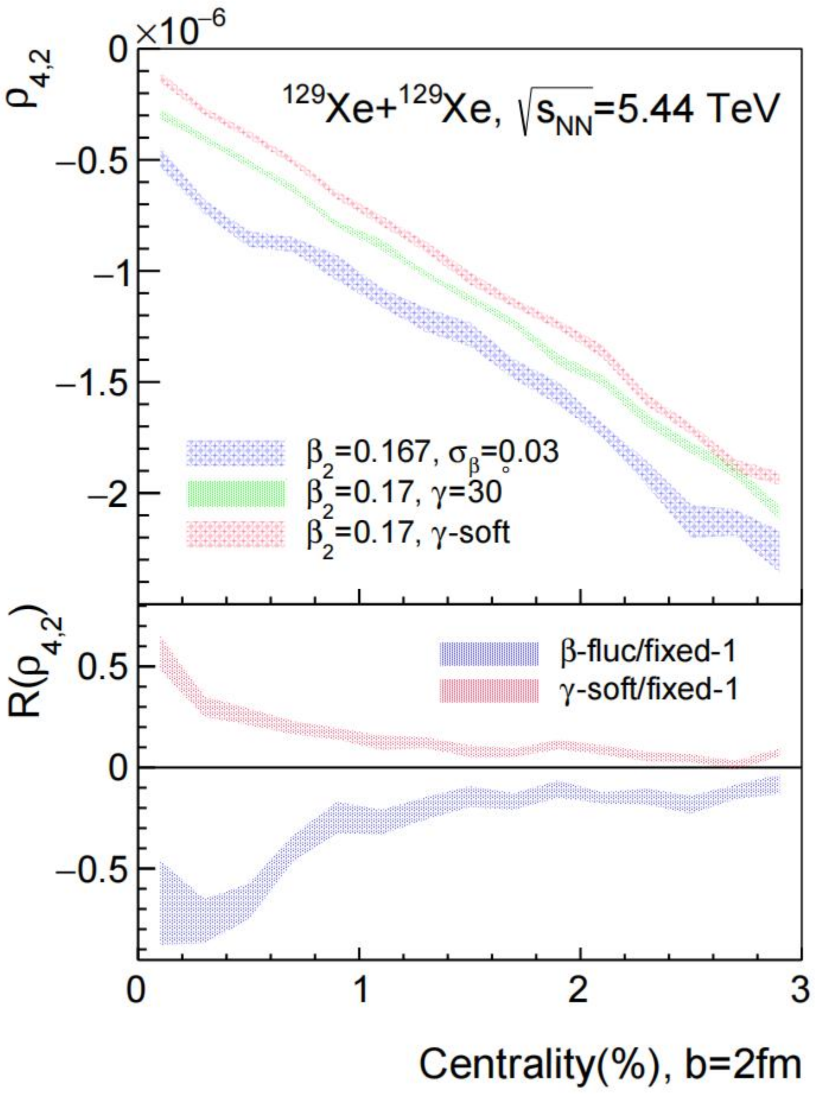
e_2^2-δd_T correlation in the initial stage

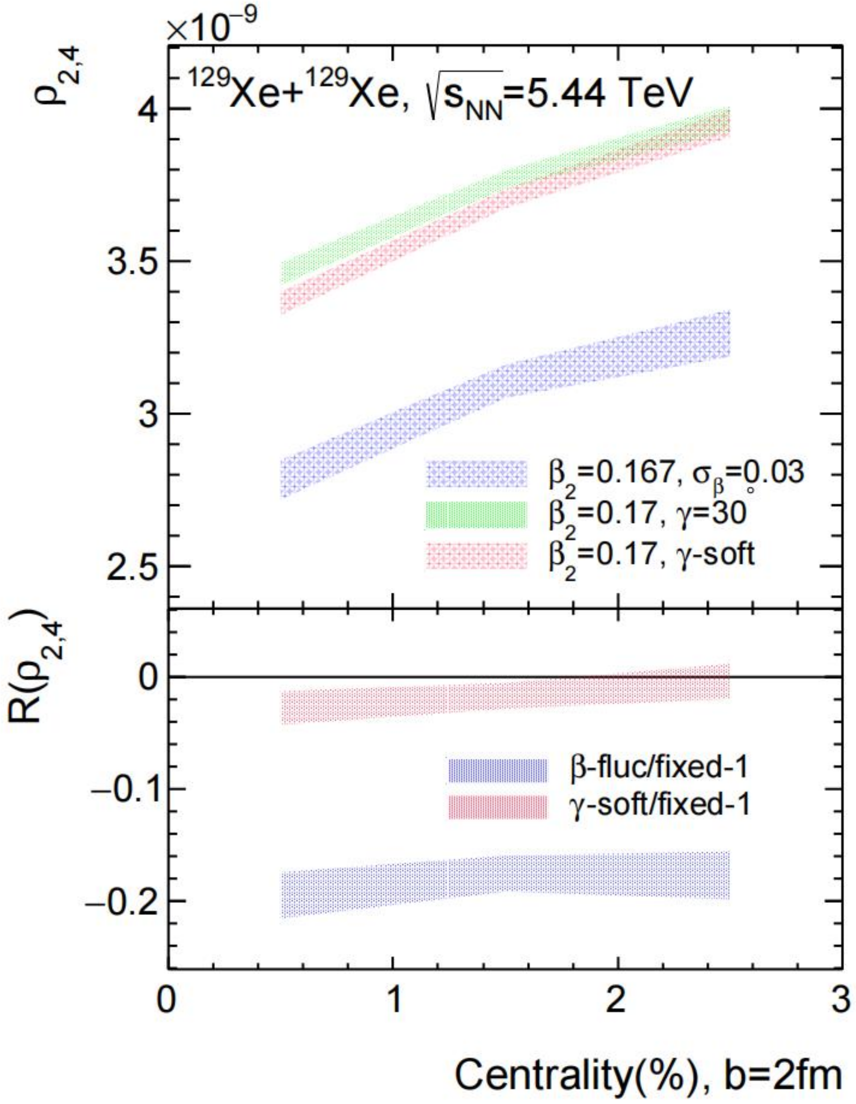


β_2-fluctuation in the initial stage

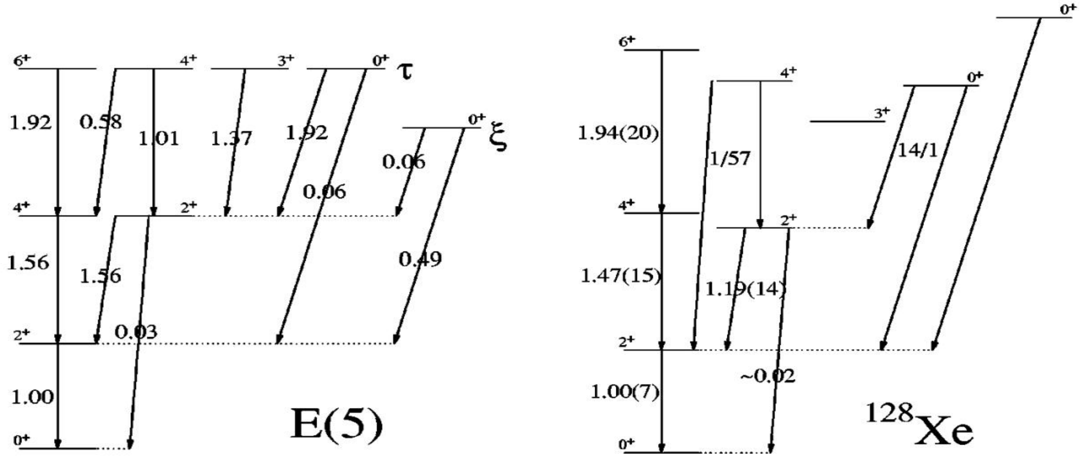


β_2-fluctuation in the initial stage





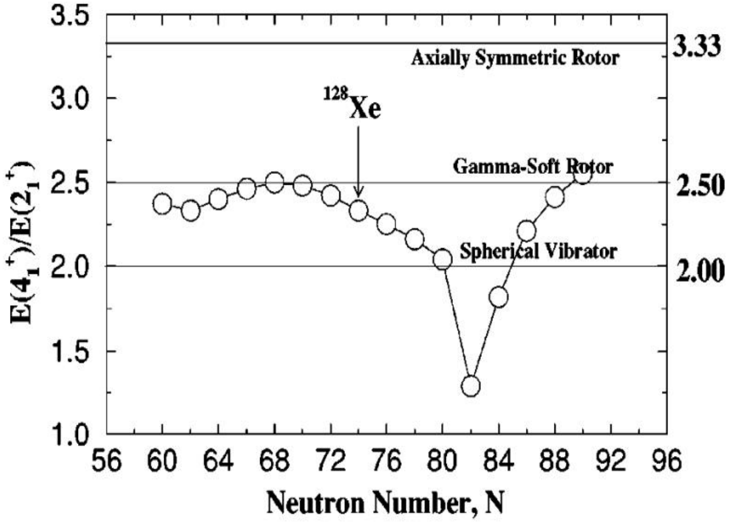
Exp evidence of E(5) symmetry for ^{128}Xe



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.

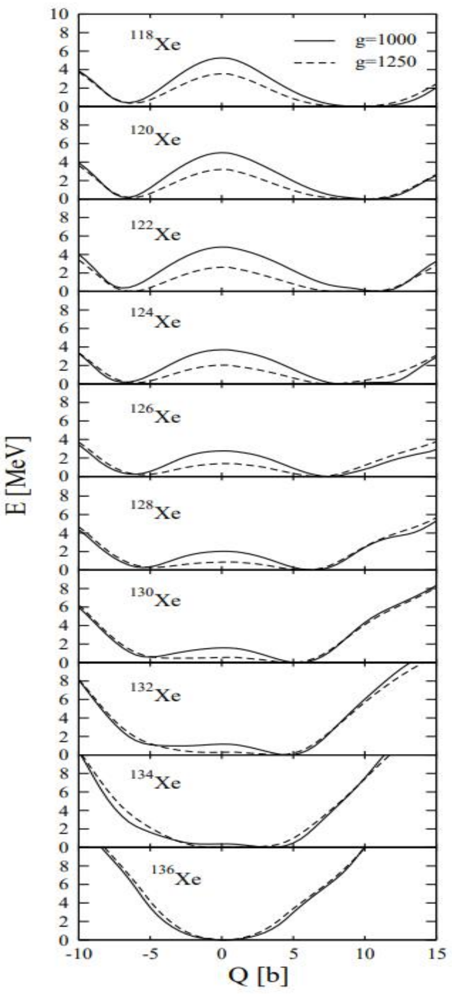


Evolution of $E(4_1^+)/E(2_1^+)$ ratio close to 2.2

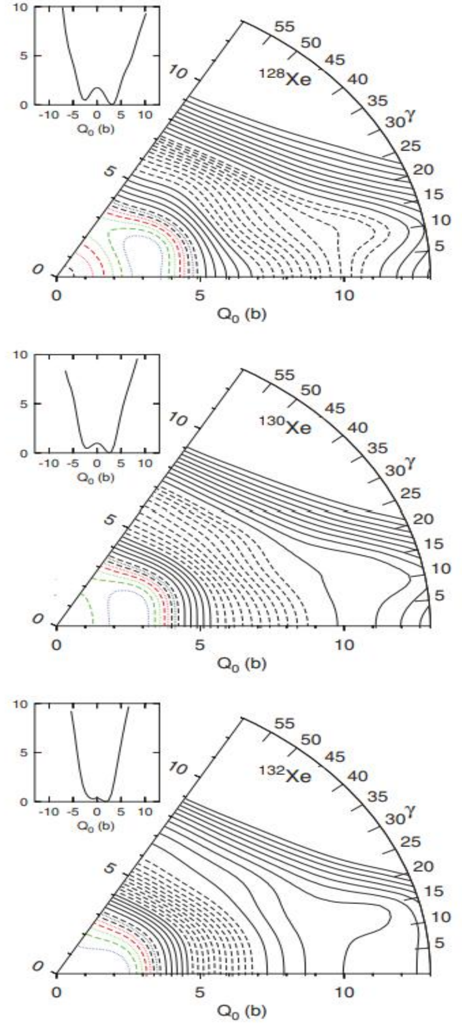
Existence of two 0^+ states with $3<E(0_n^+)/E(2_1^+)<4$

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

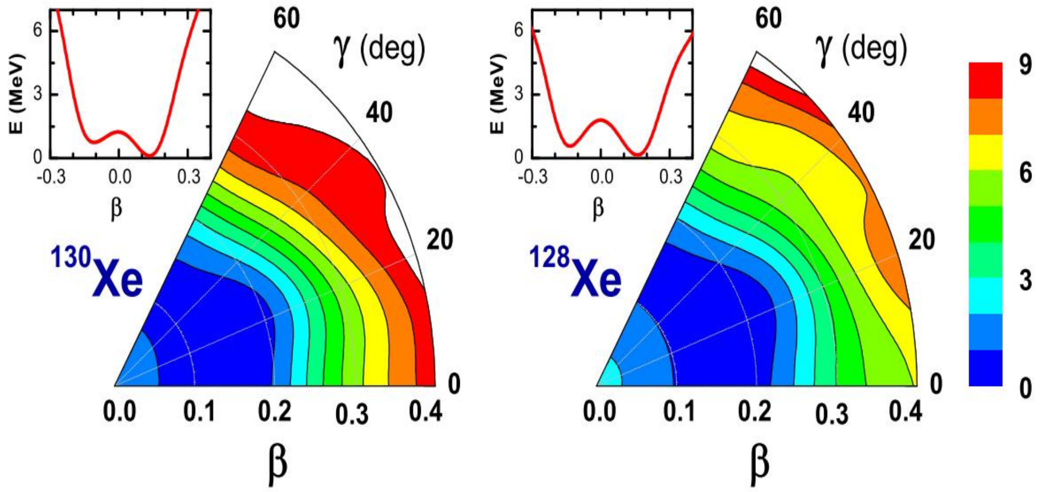
Th. predictions on E(5) symmetry near $^{128\text{-}130}$Xe



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



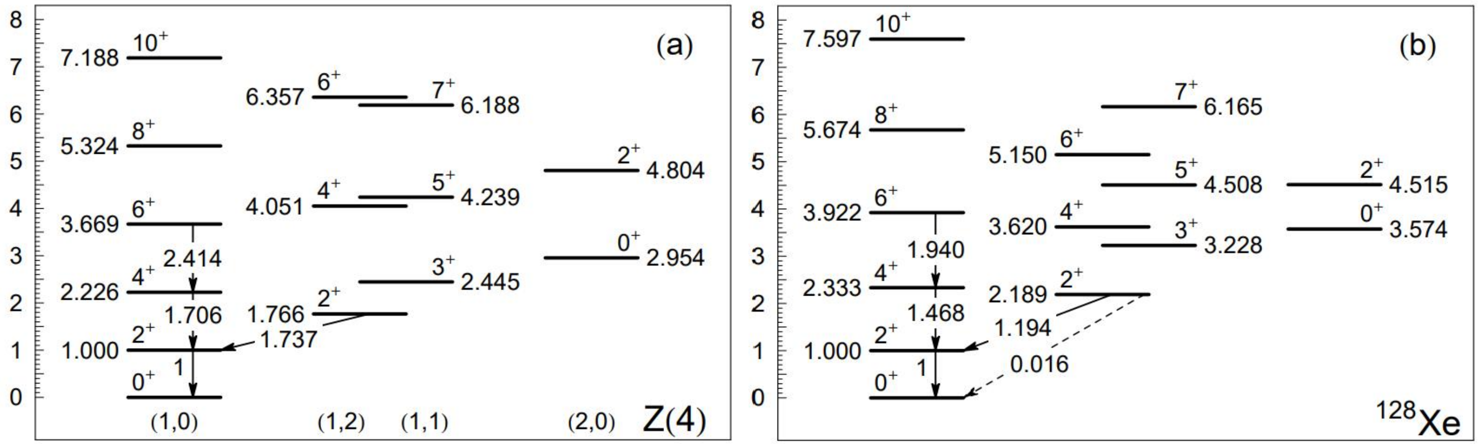
L.M.Robledo, et. al. Phys. Rev.C 78 (2008) 034314



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

E(5) v.s. Z(4) ?



Z(4) symmetry with a frozen γ at 30º can also describe the spectra and $B(E2)$ rates for ^{128,130,132}Xe

D. Bonatsos, D. Lenis, D. Petrellis, P. A. Terziev, and I. Yigitoglu, Phys. Lett. B 621, 102 (2005),

The mean difference between E(5) and Z(4) is the pair order of energy levels in the γ band.

However, It's hard to dintinguish the E(5) and Z(4) nuclei in low energy nuclear physics.