Estimation of nuclear deformation using Bayesian analysis in the initial state of heavy ion collisions

Eri Miyoshi[1,2], Abdi Cendikia[1], Chiho Nonaka[1,2,4], Azumi Sakai[3]

1 Hiroshima univ. Graduate School of Advanced Science and Engineering 2 Hiroshima Univ. WPI-SKCM[2]
3 Nagasaki Institute of Applied Science Univ. information data science department 4 Nagoya Univ. KMI

1. Abstract

We estimated the nuclear deformation β_2 of ^{129}Xe using v_2 (centrality 0-5%) from Xe + Xe collisions 5.44 TeV (ALICE, LHC).

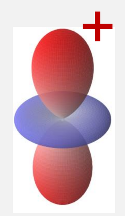
Bayesian analysis shows that κ_2 is constrained, while β_2 remains uncertain.

2. Nuclear Deformation

- Atomic nuclei are quantum many-body systems bound by the strong interaction
- Nuclear shape is a key probe of nuclear structure
- Many nuclei are **deformed**

Deformed nuclear surface

$$R(\theta) = R_0(\;\bullet\; + \beta_2 \times Y_{20} + \cdots)$$



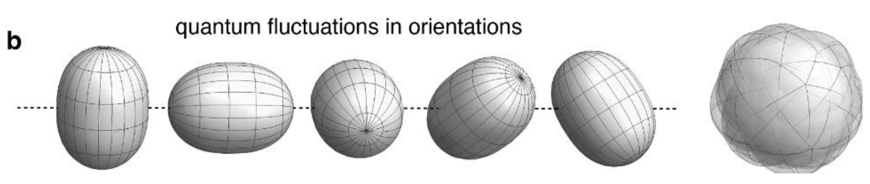
$R(\theta)$: nuclear surface; R_0: radius; Y_{20}: spherical harmonics Y_{20}

β_2 : quadrupole deformation parameter

Goal: **Estimate quadrupole deformation β_2 of ^{129}Xe**

3. Probing Nuclear Deformation

- Early → low-energy method[1]

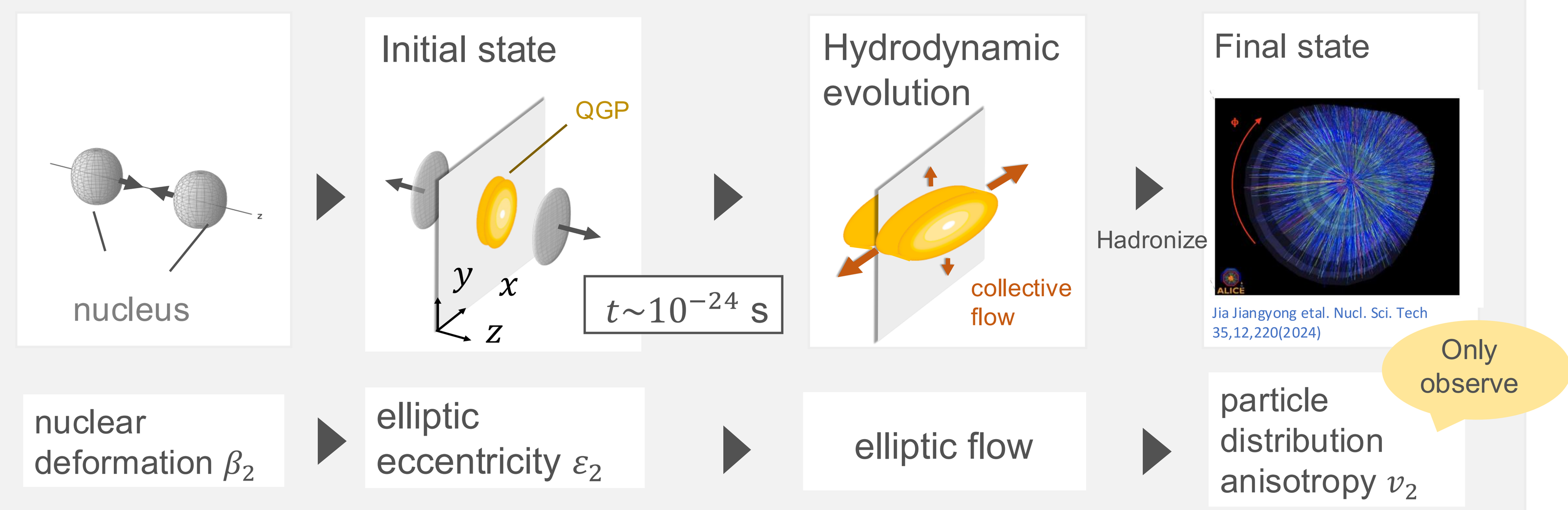


quantum fluctuations obscure the instantaneous nuclear shape

- Recent → **High-energy nuclear collision**[2]

Time scale collision << quantum fluctuations → Capture snapshot

Time space evolution in Xe + Xe collision at the LHC



Estimate β_2 (deformation) from v_2(observable)

4. Model Calculation

Calculate v_2^{model} using Initial state model TRENTo [3]

Initial entropy density $s(r)$ from TRENTo ▶ elliptic eccentricity of initial QGP $\varepsilon_2 = \dfrac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$ ▶ ansatz[4] $v_2 = \kappa_2 \varepsilon_2$ (κ_2: constant)

Initial entropy density $s(r)$

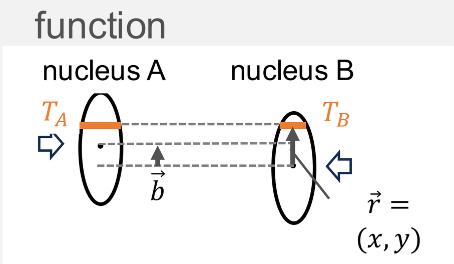
$$\rho(r,\theta) \propto \frac{1}{1 + e^{(r - R(\theta))/a}}$$

Nucleus density

$R(\theta)$:Nuclear surface

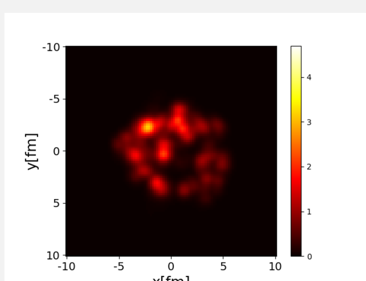
$$T_{A,B}(\vec{r}) = \int \rho_{A,B}(\vec{r}, z)\,dz$$

Thickness function



$$s(\vec{r}) \propto \left(T_A^p + T_B^p\right)^{1/p}$$

fix p=0



5. Bayesian Analysis[5]

Provides probability distributions of parameters (β_2, κ_2) as follows

model calculation $v_2(\beta_2, \kappa_2)$ = Experimental data v_2 ALICE Xe + Xe 5.44 TeV[5]

Bayes' theorem

posterior probability ∝ Likelihood × prior probability

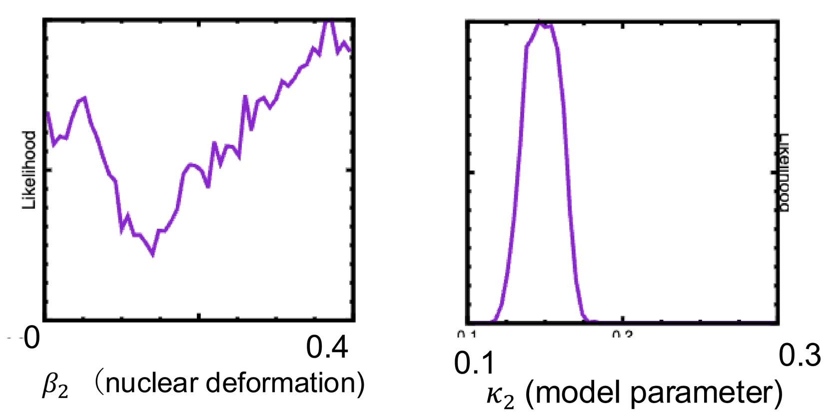
- posterior probability: parameter's probability renewed from data
- Likelihood: How match data and model
- prior probability: parameter's probability from

- Simultaneous fit of multiple observables and parameters
- Fitting is possible even when variables are correlated

6 . Result

- Calculate the probability of parameters using experimental data v_2(centrality 0-5%)

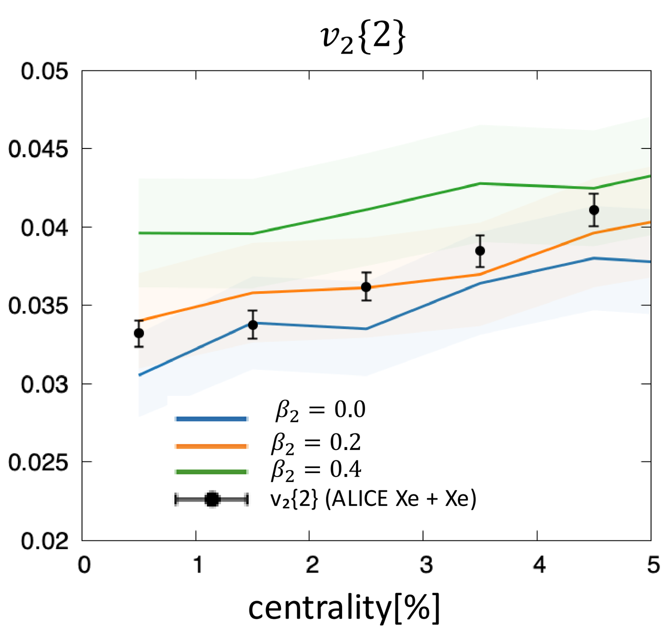
posterior probability



$$\beta_2 = 0.22 \pm 0.12$$
$$\kappa_2 = 0.148 \pm 0.01$$

κ_2 is clearly peaked and constrained
β_2 exhibits a broad distribution and remains poorly constrained

- Comparison between model and data



- Black points: experimental $v_2\{2\}$ (ALICE Xe + Xe)[5]
- Colored lines: model predictions (different β_2)

Limited data points and uncertainties → β_2 not well constrained

7. Discussion and future work

Why β_2 is not well constrained ?

- A more realistic model of space-time evolution is required
- The determination of centrality is crucial, it is unclear whether entropy is an appropriate measure

Next step

- Use simple model for hydrodynamic stage
  - Improve centrality determination to better reproduce experimental conditions
  - Include additional observables (e.g. $v_2\{4\}$, v_3)[5]
  - Perform hydrodynamic calculations [6][7]

[1] S. Raman, C.W. Nestor Jr., P. Tikkanen, *ADNDT* **78**, 1 (2001)
[2] STAR Collaboration, *Nature* **635**, 67–72 (2024)
[3] J. Scott Moreland, Jonah E. Bernhard, and Steffen A. Bass PRC **101**, 024911 (2020)
[4] H. Niemi, G. S. Denicol, H. Holopainen, P. Huovinen PRC **87**, 054901(2013)
[5] ALICE collaboration Phys Letter B, **784**, 82–95 (2018)
[6] ALICE Collaboration, Phys. Lett. B **849** (2024) 138469.
[7] W. van der Schee, QM2025 (Frankfurt), conference talk