Exploring nuclear structure with multiparticle azimuthal correlations at the LHC

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Nuclear structure at low energies

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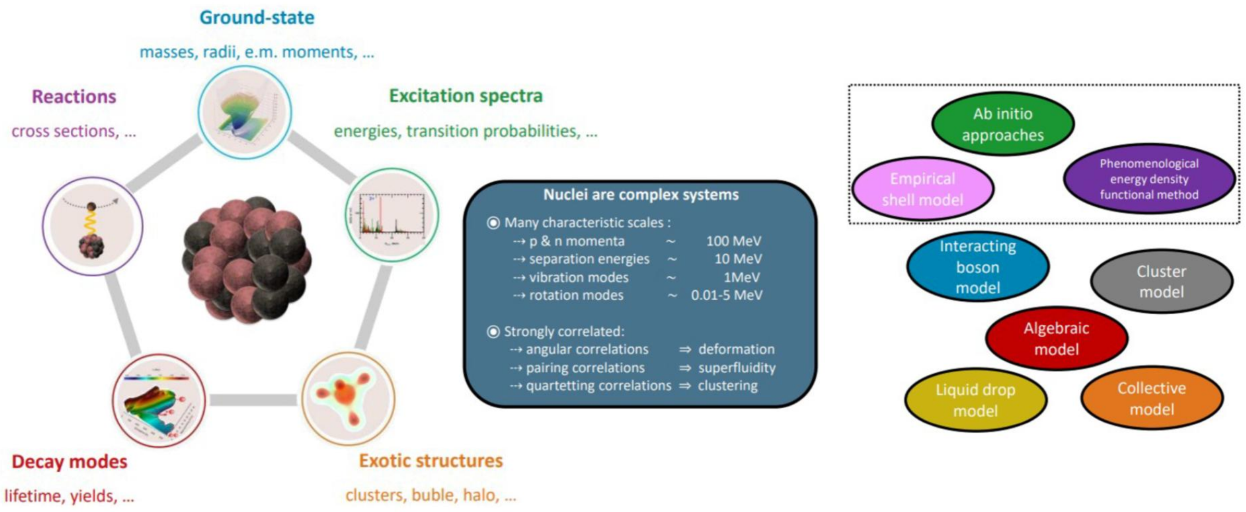
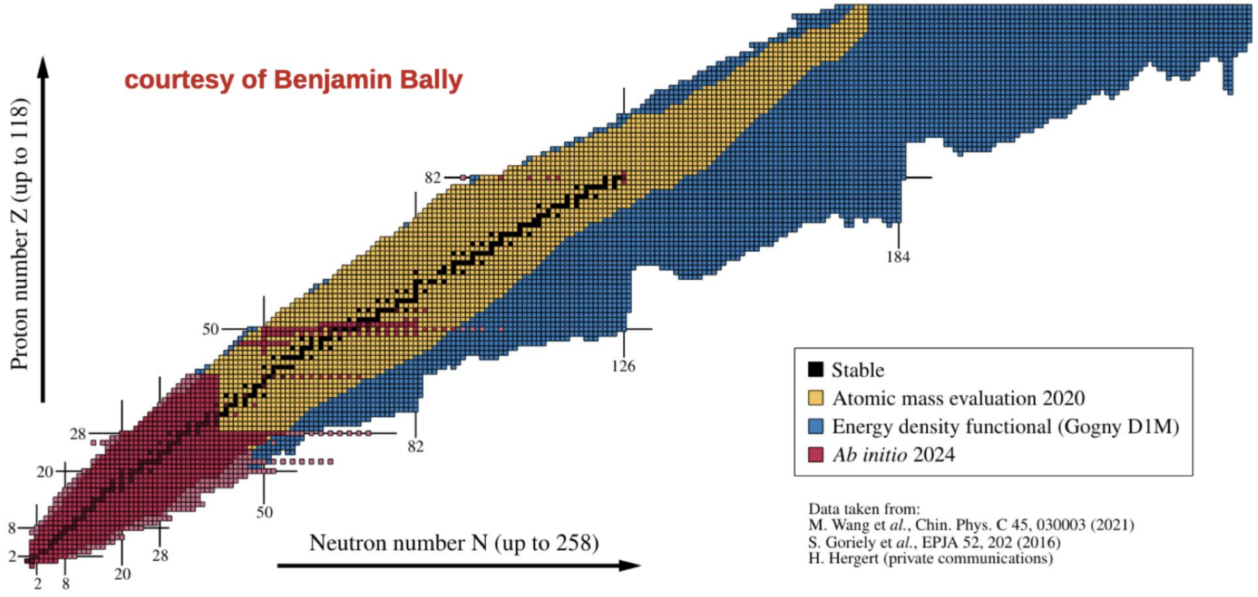
Atomic nuclei have rich phenomenology. Rooted in the strong nuclear force.
Nuclear structure is a very old field. Many different approaches.

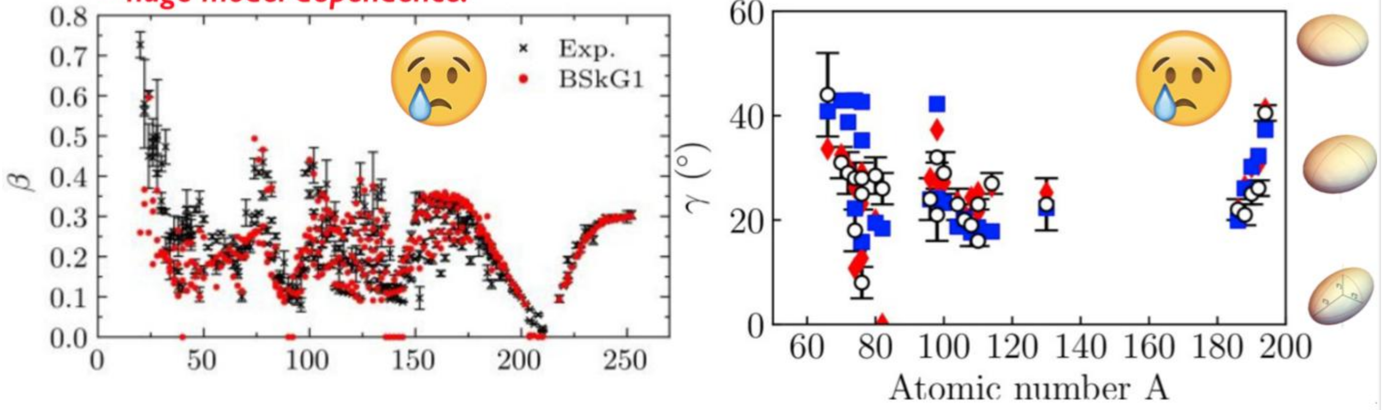




Modern ab-initio methods have successfully described light nuclei with A ≤ 50

- *there are no real probes of multi-nucleon correlations*
- *huge model dependence.*

For heavy nuclei, computational complexity rapidly arises due to the increasing number of nucleons



Nuclear structure at high energies

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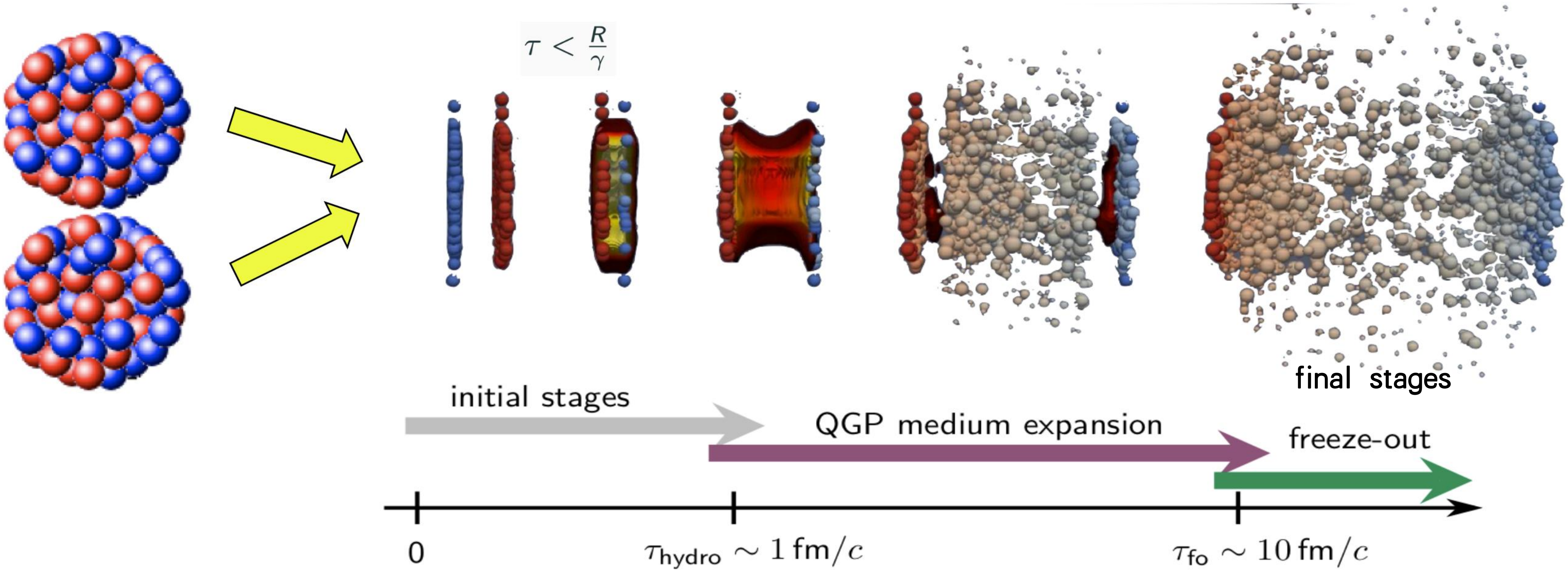

nuclear structure ⟷ **inital conditions** ⇄ **azimuthal distribution of final-state particles**

hydro evolution

probe

Nuclear structure parameter

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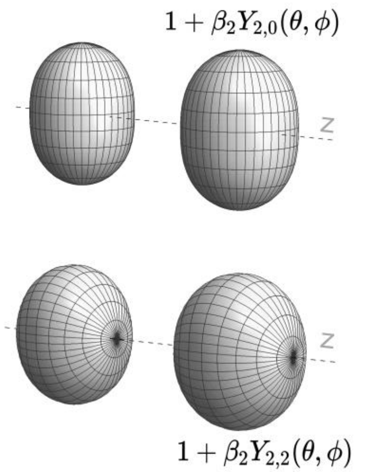
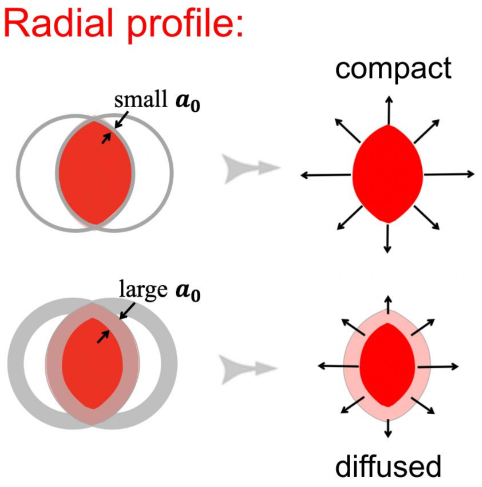
nucleon density described by **Woods-Saxon profile**

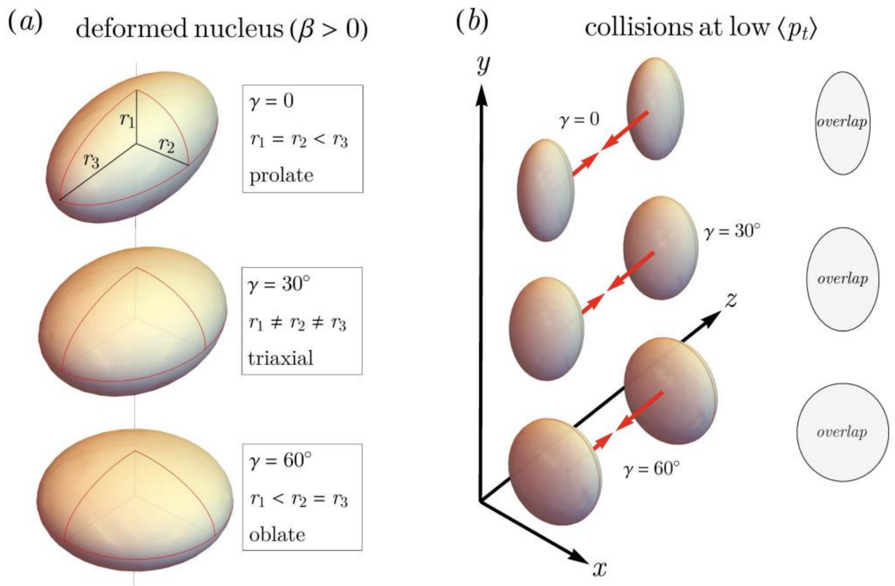
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{[r-R(\theta,\phi)]/a_0}},$$

$$R(\theta,\phi) = R_0(1+\beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}] + \beta_3 \sum_{m=-3}^{3} \alpha_{3,m} Y_{3,m} + \beta_4 \sum_{m=-4}^{4} \alpha_{4,m} Y_{4,m})$$

β_2: quadrupole deformation parameter
a_0: nuclear diffuseness parameter
γ: triaxiality parameter







Experimental tool: anisotropic flow

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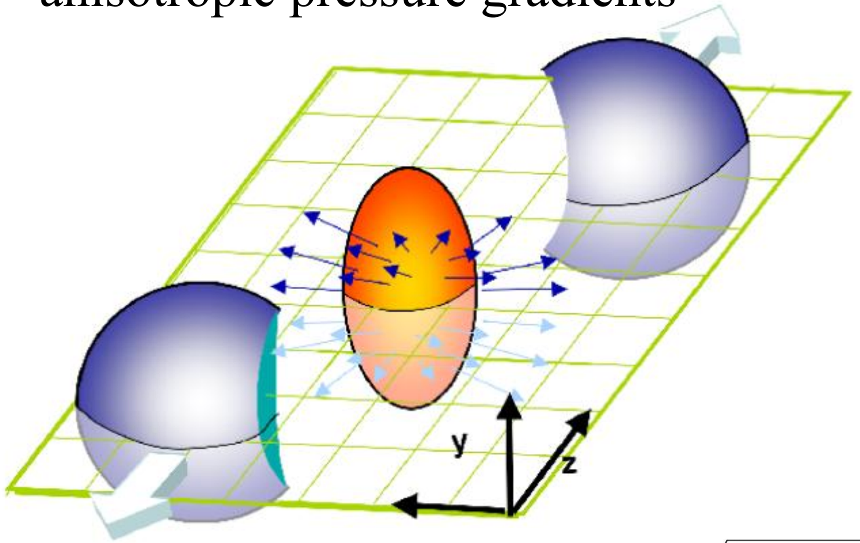
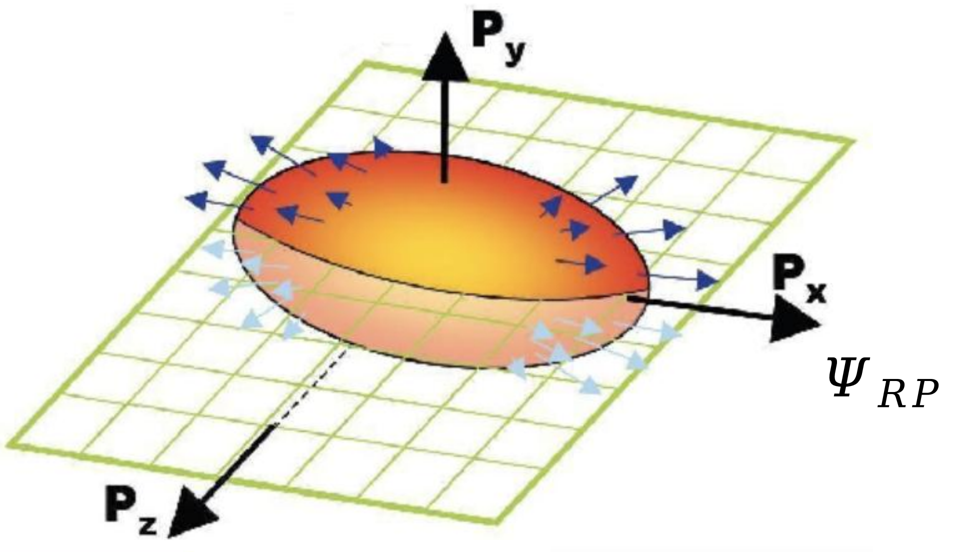
anisotropic pressure gradients



system expansion

anisotropic momentum distributions

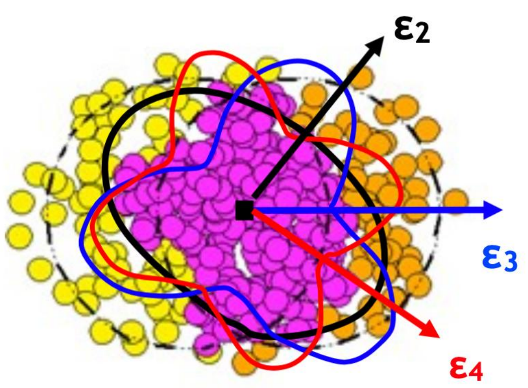


Initial state

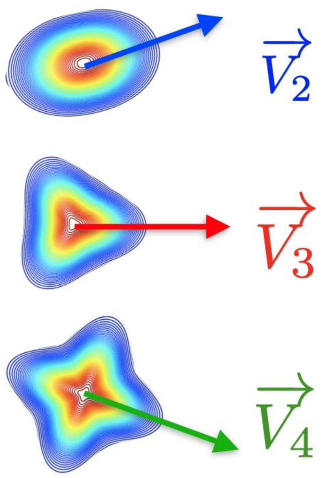
$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

Final state

$$\vec{V_n} = v_n\, e^{in\Psi_n}$$



System expansion



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$

Fourier expansions

Carry unique information from initial state and nuclear structure

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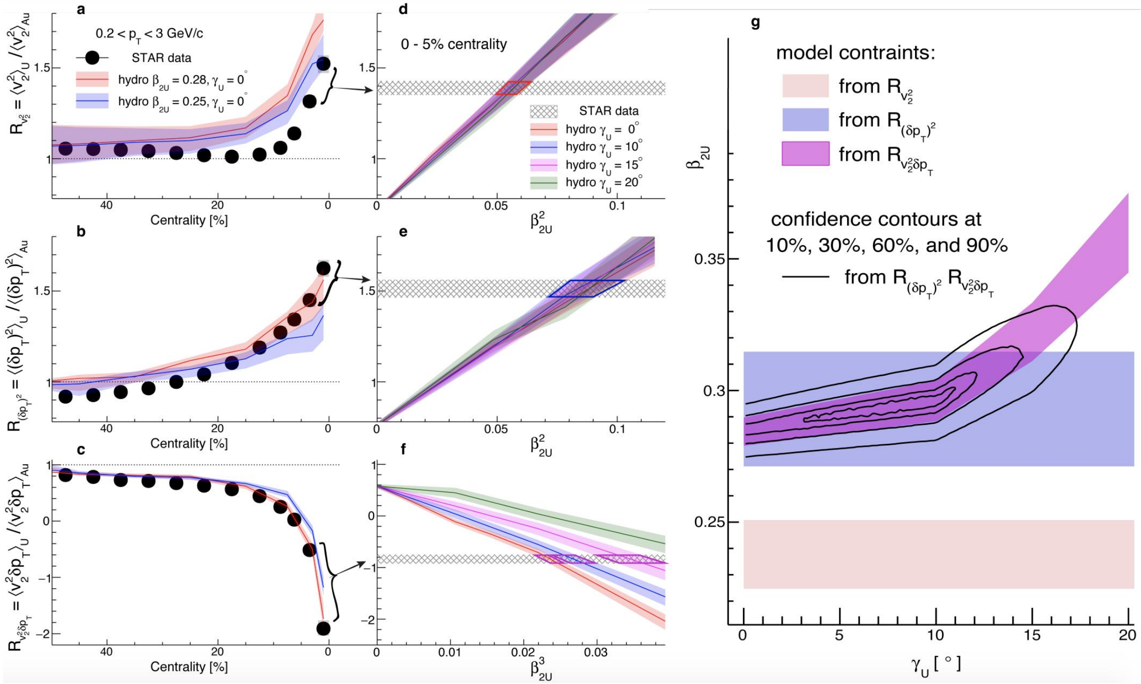
Nuclear structure at HIC

Many nuclear structure studies on GeV energies have been inplemented in RHIC-STAR

J. Jia, Phys. Rev. Lett. 131 no. 2, (2023) 022301
J. Jia, Chin. Phys. Lett. 40 no. 4, (2023) 042501
S. Zhao, Phys. Lett. B 839 (2023) 137838
etc...

STAR, arxiv: 2401.06625 (accepted by nature)
talked by Chunjian, Wednesday afternoon



The intersections between STAR data and the state-of-art IPGlasma+MUSIC hydrodynamic model constrain the ^{238}U nucleus as: $\beta_2 = 0.297 \pm 0.013$, $\gamma = 8.6^\circ \pm 4.8^\circ$

Nuclear structure at HIC

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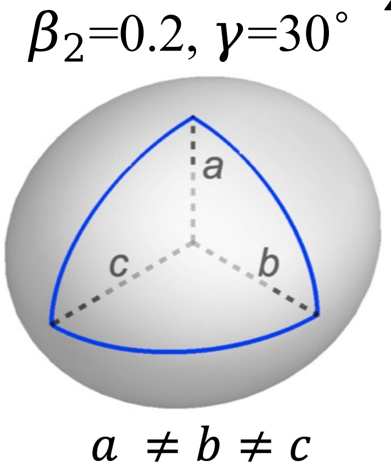
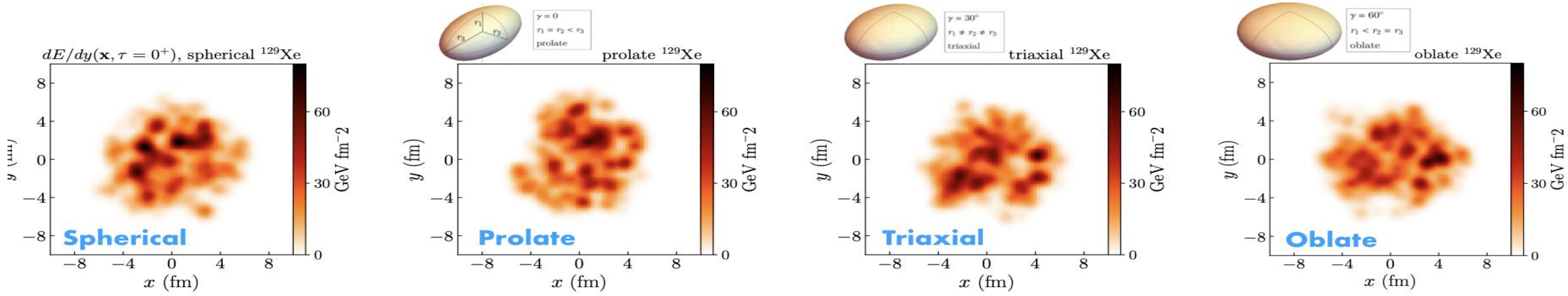
At the LHC, B. Bally et al., Phys.Rev.Lett. 128 (2022) 8, 082301

^{129}Xe is predicted to have deformed and triaxial structure ($r_1 \neq r_2 \neq r_3$).



J. Jia, Phys.Rev.C 105 (2022) 4, 044905



Study the effect of nuclear structure on azimuthal distribution of final-state particles in ^{129}Xe–^{129}Xe, compared to ^{209}Pb–^{209}Pb (no deformation)

X-axis: centrality

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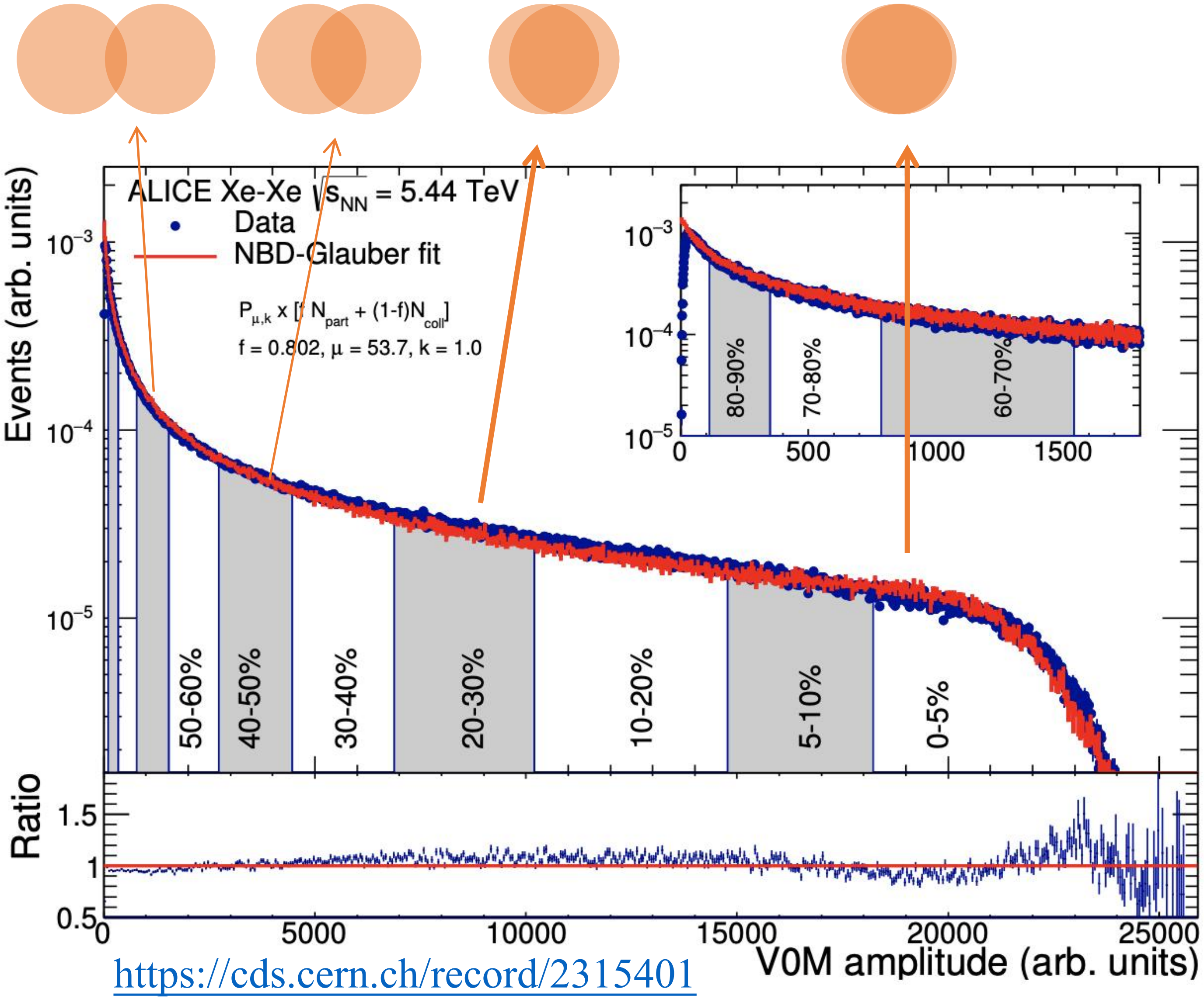
Centrality: a percentage of the hadronic cross section corresponding to a particle multiplicity, directly related to the impact parameter

0% centrality: almost fully overlap
90% centrality: peripheral collisions

Initial shape is strongly related to centrality
The most central collisions can project the shape of colliding nucleus



https://cds.cern.ch/record/2315401

Sensitivity in model

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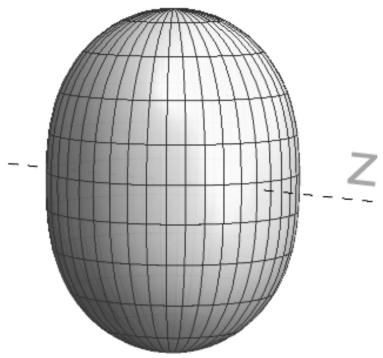
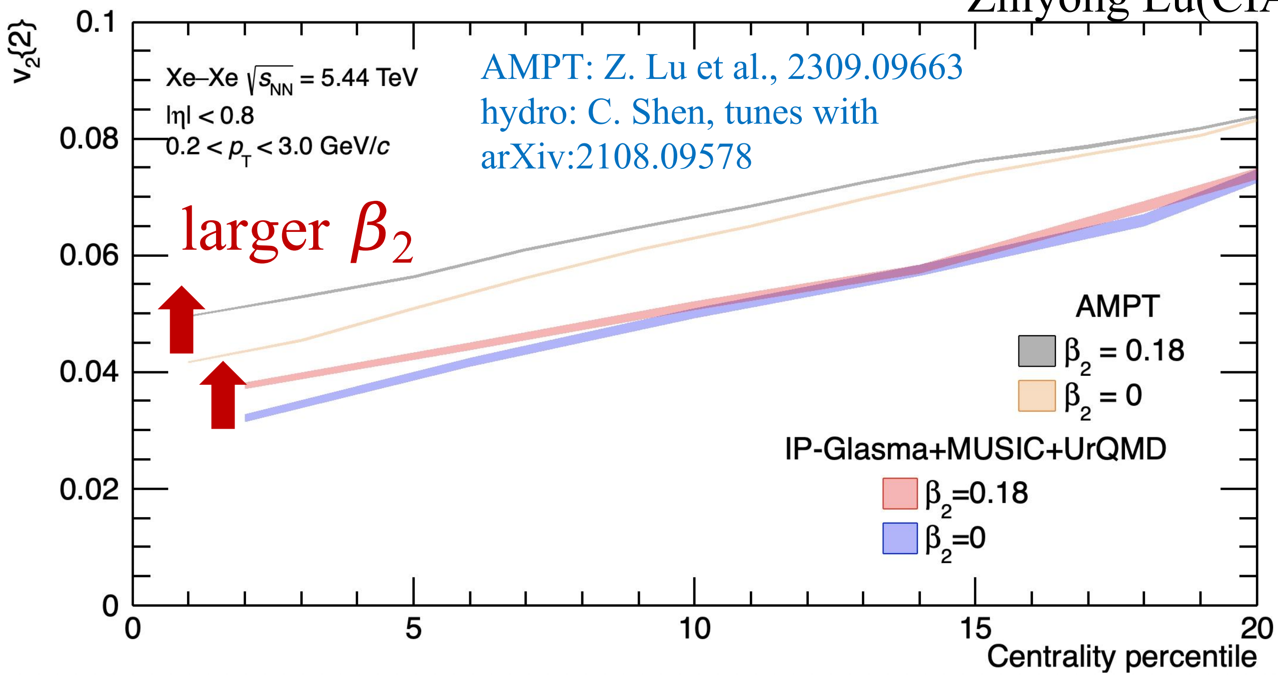
larger quadrupole deformation β_2

↓

increase initial geometric anisotropy (more elliptical)

$1 + \beta_2 Y_{2,0}(\theta, \phi)$



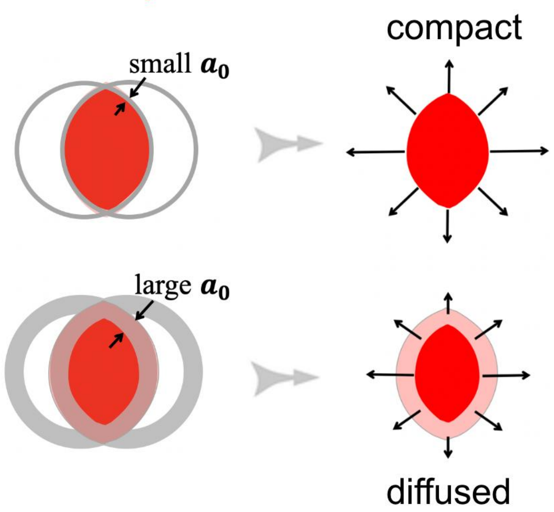


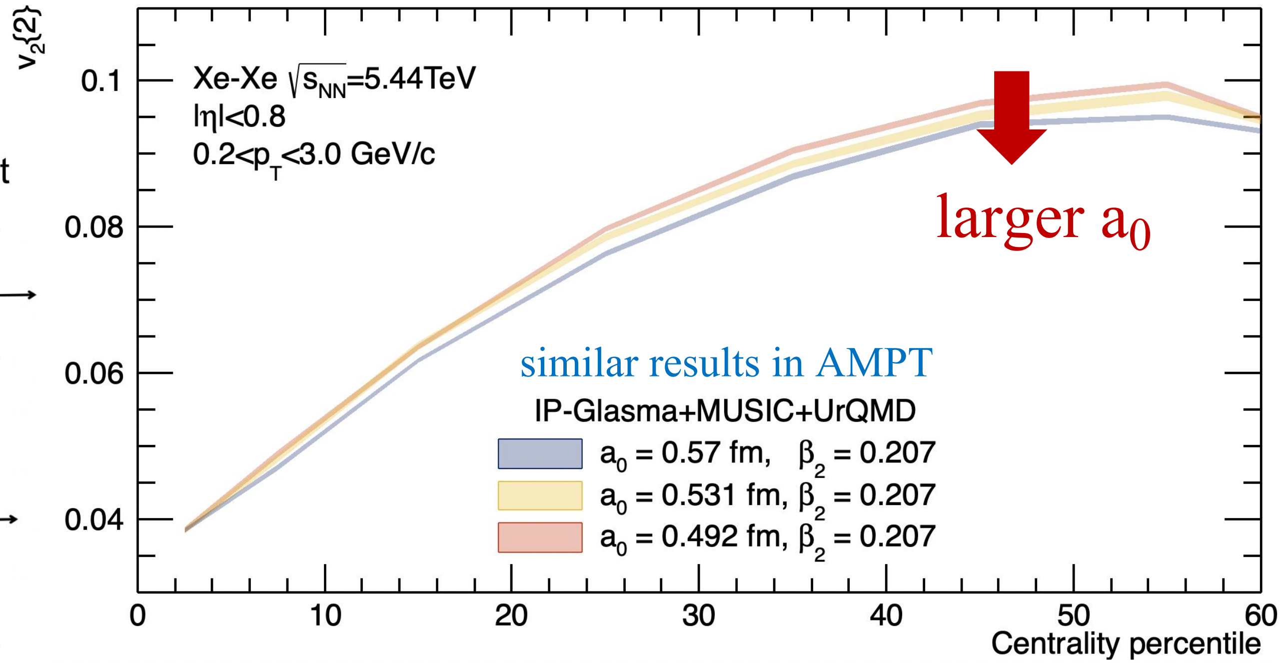
larger nuclear diffuseness a_0

↓

more diffuse and less elliptical

Radial profile:





Results: v_2

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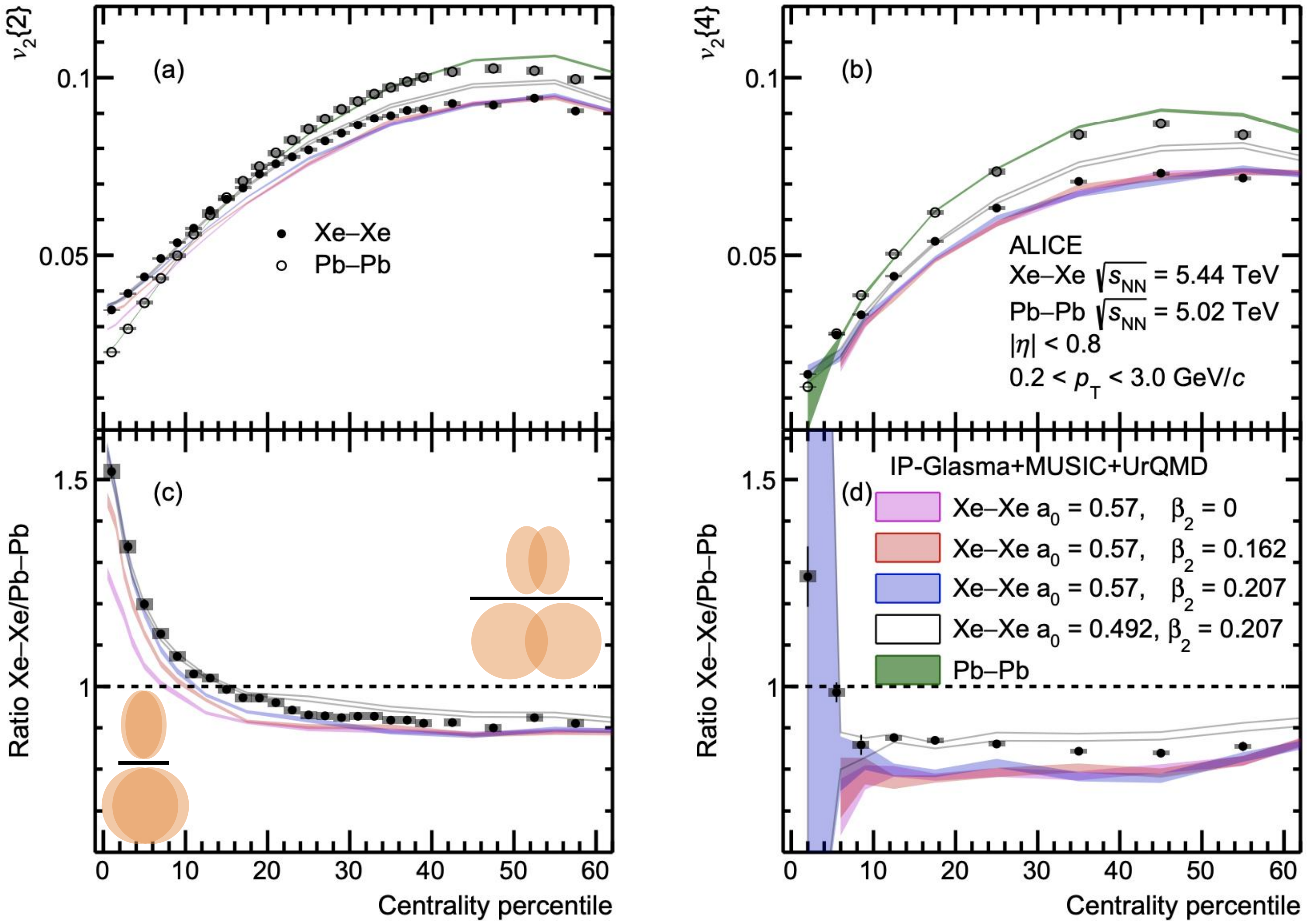
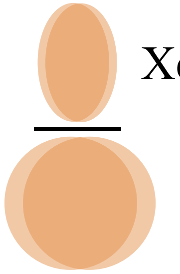
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$ n=2 with two or four-particle correlations



ALICE, arxiv: 2409.04343

- $v_2\{2\}$(Xe–Xe/Pb–Pb) starts from 1.5 in the most central collisions, then goes near 0.9 in midcentral collisions
- Central: deformation effect dominates

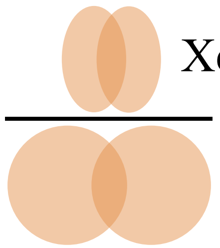


Xe–Xe

Pb–Pb

significantly different initial shape

- Midcentral: viscous effects (medium) dominates



Xe–Xe

Pb–Pb

- Suppressed by larger nuclear diffuseness a_0 in midcentral collisions

Results: v_2 mean and flucutations

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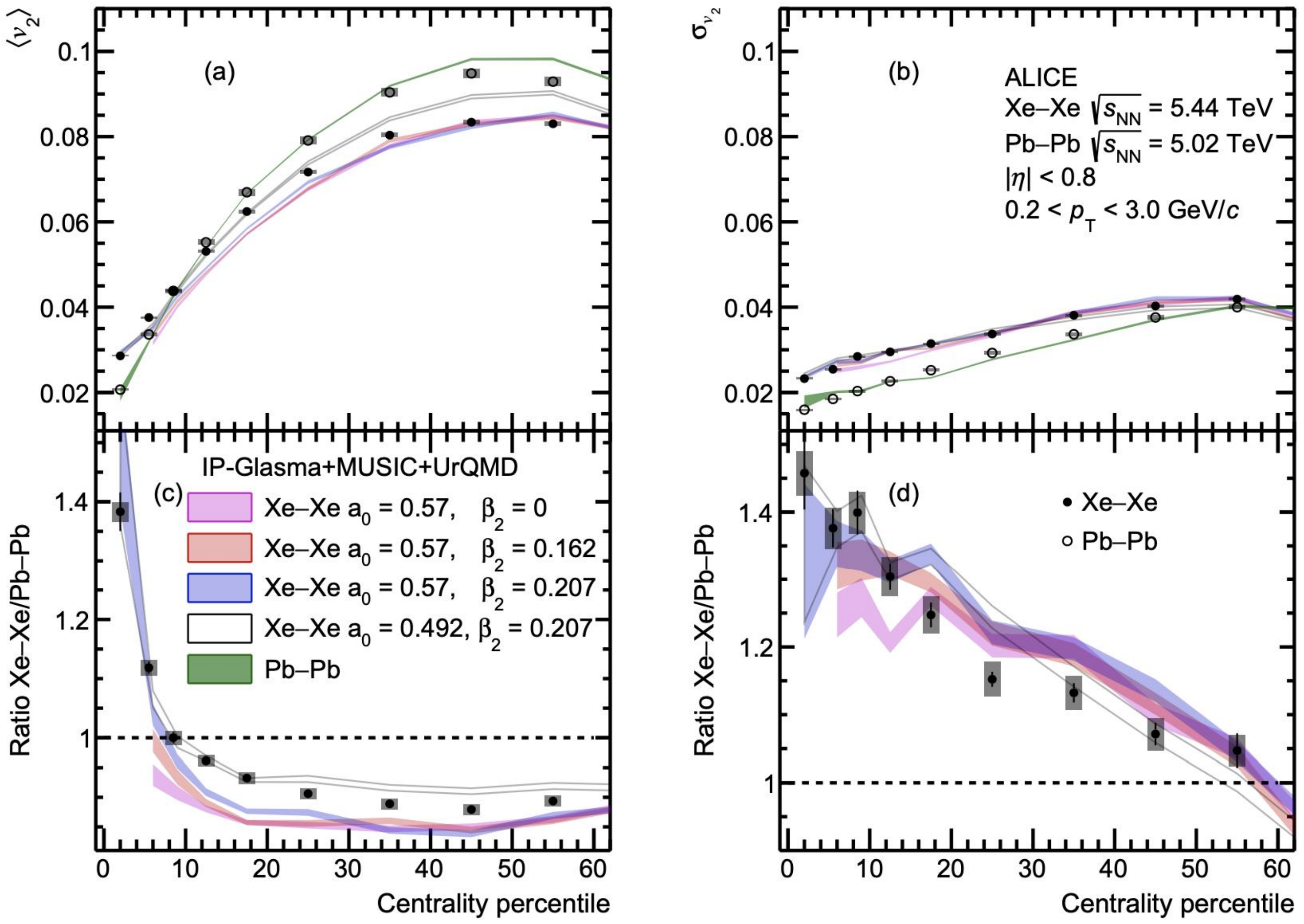
$\langle v_2 \rangle = \sqrt{(v_2\{2\}^2 + v_2\{4\}^2)/2}$;

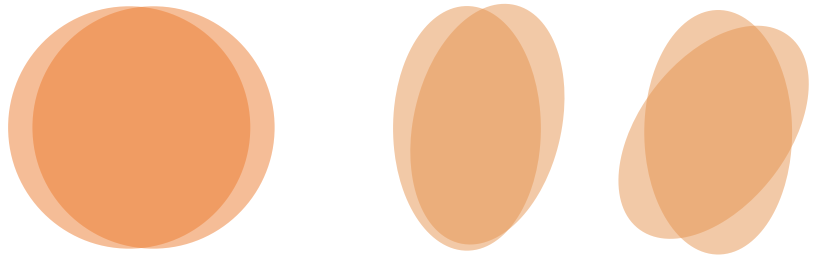
$\sigma_{v_2} = \sqrt{(v_2\{2\}^2 - v_2\{4\}^2)/2}$



ALICE, arxiv: 2409.04343

- $\langle v_2 \rangle$: similar trends with $v_2\{2\}$ and $v_2\{4\}$
- σ_{v_2}: Xe–Xe larger than Pb–Pb in 0-60% centrality (larger flow flucutation in smaller system)
- σ_{v_2} model with $\beta_2 = 0$ is smaller in 0-15% centrality

Indeformed nuclei Deformed nuclei



Larger flow flucutation due to random orientations of colliding nuclei

Need further confirmation from model

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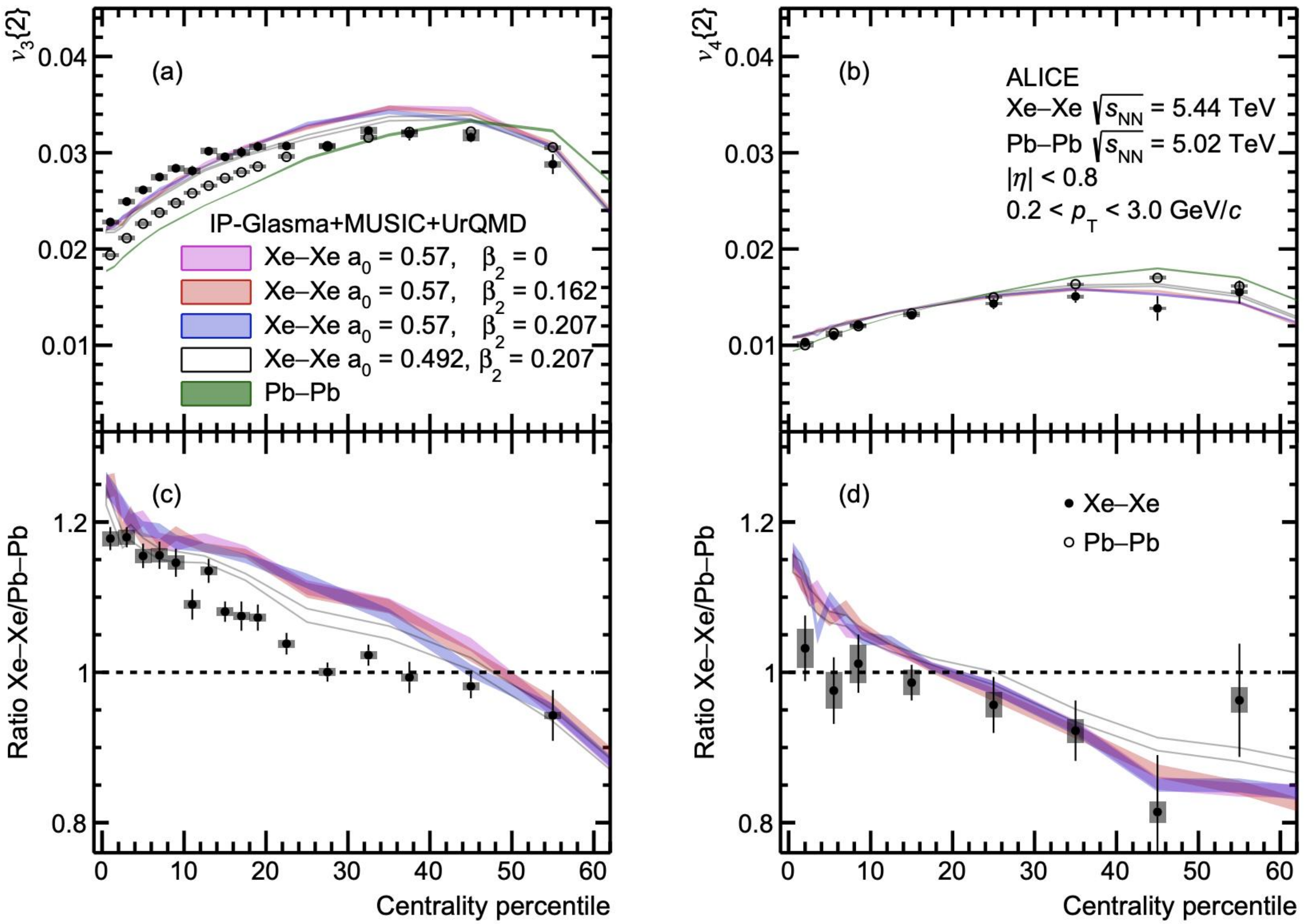
Results: $v_3\{2\}$, $v_4\{2\}$

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$ n=3,4 with two particle correlation



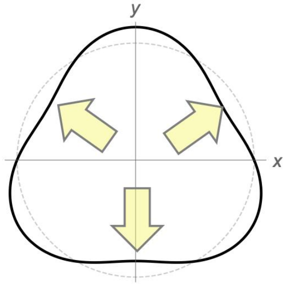
ALICE, arxiv: 2409.04343

- $v_3\{2\}$,$v_4\{2\}$ (Xe–Xe/Pb–Pb): decrease steadily with increasing centrality
- Insentive to quadrupole deformation β_2

ε_n: initial anisotropy

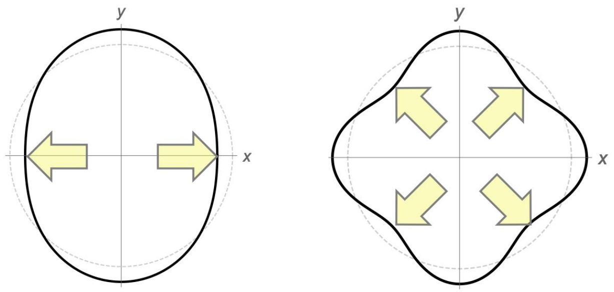
$v_3 \propto \varepsilon_3 \propto \beta_3$

H. Niemi, etc., Phys. Rev. C 87 (2013) 054901
H. Song, etc., Phys. Rev. Lett. 106 (2011) 192301



$v_4 \propto \varepsilon_2, \varepsilon_4$

R. S. Bhalerao et al., Phys. Lett. B742 (2015) 94–98



- $v_4\{2\}$ is suppressed by nuclear diffueseness a_0 in midcentral collisions

Results: v_4 component

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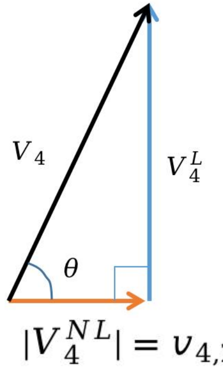
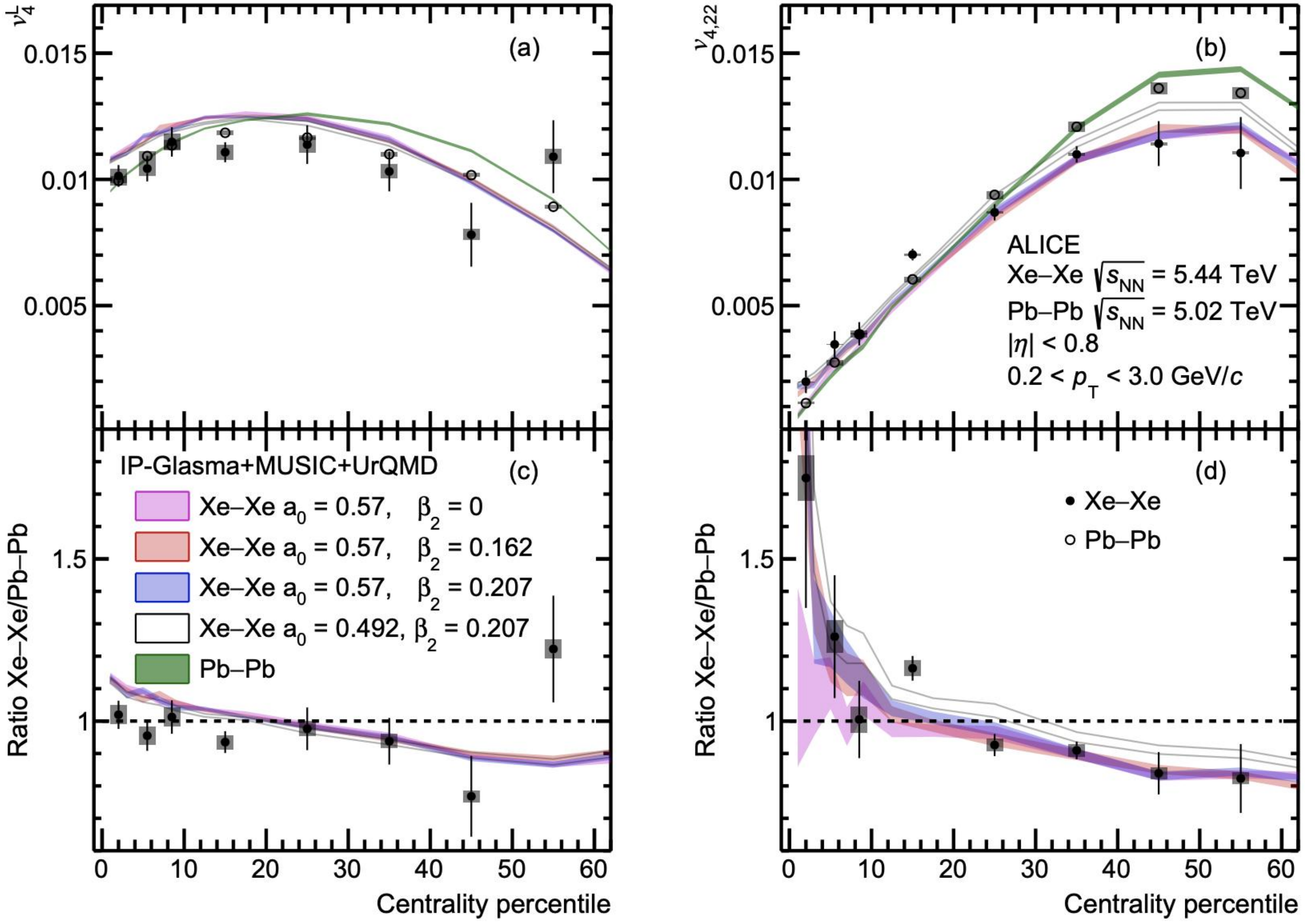




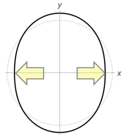
ALICE, arxiv: 2409.04343

ε_n: initial anisotropy

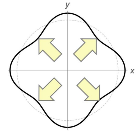
v_4 stems from ε_4 (linear component) and ε_2 (nonlinear component)

- $v_{4,22}$ (Xe–Xe/Pb–Pb) decreases with centrality, v_4^L (Xe–Xe/Pb–Pb) has milder centrality dependence
- $v_{4,22}$ shows sensitivities to β_2 and a_0, while v_4^L does not.

$$v_{4,22} \propto \varepsilon_2 \propto \beta_2$$



$$v_4^L \propto \varepsilon_4$$



For $v_4\{2\}$,

- Central: v_4^L dominate, insensitive to β_2 and a_0
- Midcentral: compatible $v_{4,22}$, sensitive to a_0

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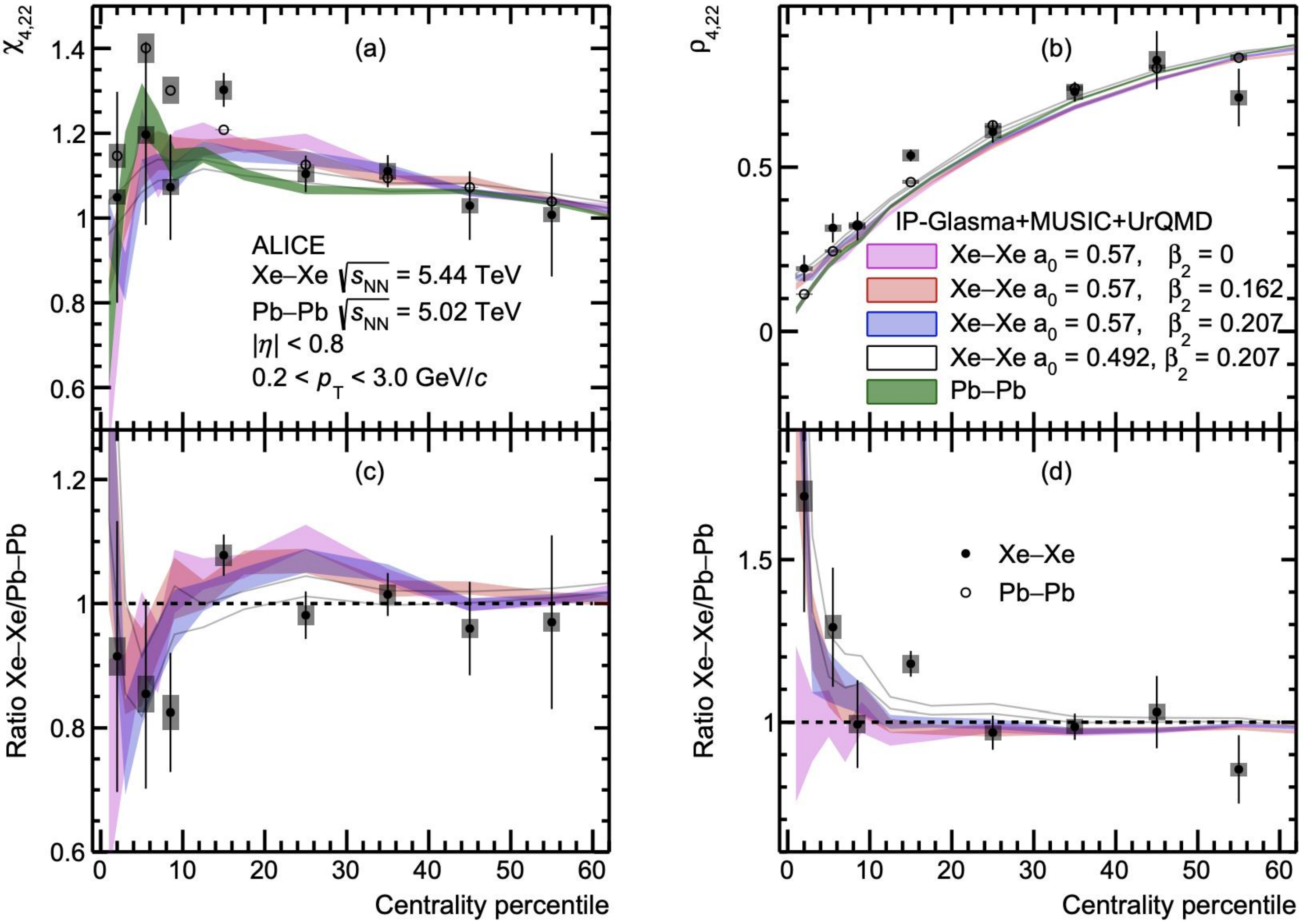
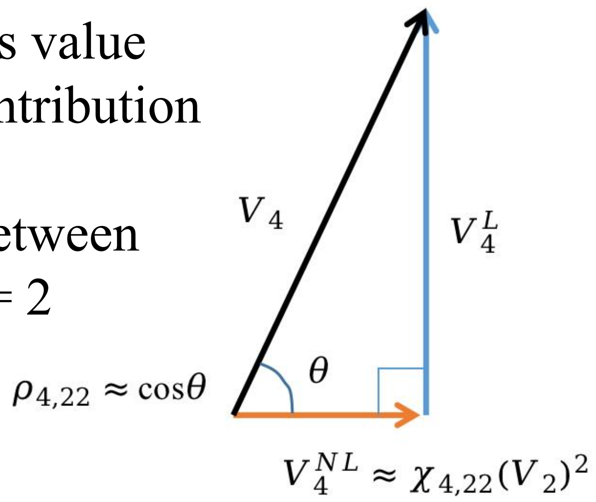
Results: nonlinear coefficient and correlation



ALICE, arxiv: 2409.04343

$\chi_{4,22}$: dimensionless value quantifying the contribution from ε_2

$\rho_{4,22}$: correlation between order n = 4 and n = 2



- χ_{422} seems independent of β_2 and a_0

➡ The sensitives of $|V_4^{NL}| = v_{4,22}$ are largely from $(V_2)^2$

- $\rho_{4,22}$: enhanced by deformation in central collisions
- $\rho_{4,22} \approx v_{4,22}/v_4\{2\}$: sensitivity to a_0 is cancelled by the ratio

Results: theory fitness

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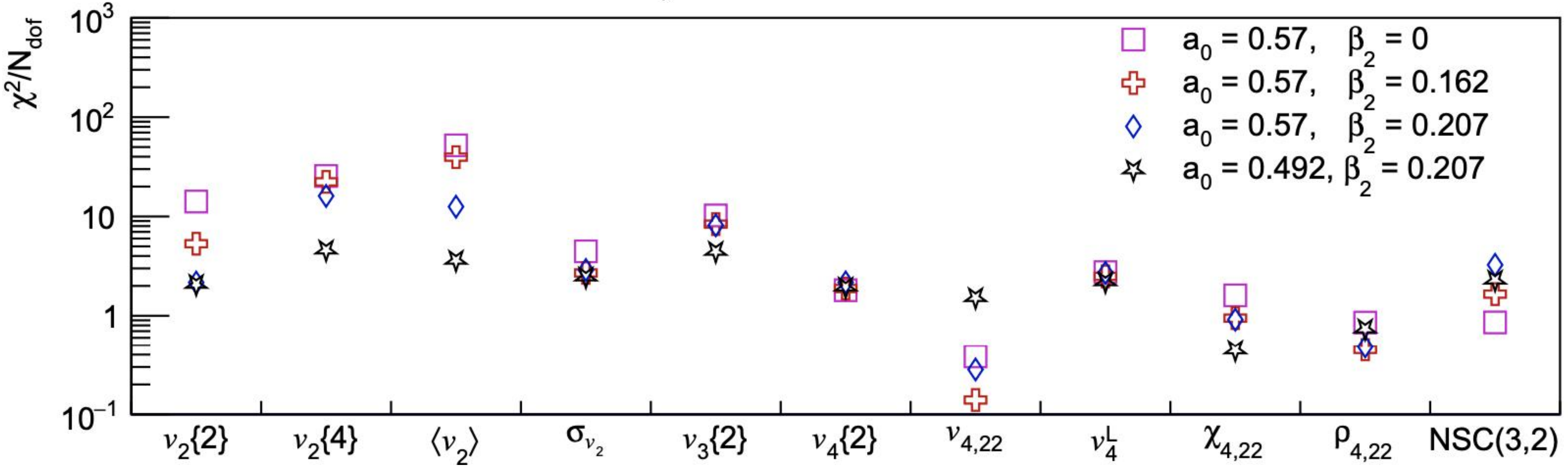
$$\chi^2/N_{\mathrm{dof}} = \frac{1}{N_{\mathrm{dof}}}\sum\frac{(y_i - f_i)^2}{\sigma_i^2}$$

y_{i}: measurement of Xe–Xe/Pb–Pb
f_{i}: model of Xe–Xe/Pb–Pb
σ_{i}: measurement uncertainty + model uncertainty



IPGlasma+MUSIC+UrQMD hydrodynamic model

- $\beta_2 = 0.207$ generally provide better descriptions, except $v_{4,22}$ (large uncertainties in central collision)
- $a_0 = 0.492$ demonstrate better agreement, except $v_{4,22}$, $\rho_{4,22}$ and NSC(3,2)
- $v_2\{2\}$ has better discrimination on β_2, while $v_2\{4\}$,$\langle v_2\rangle$ have better discrimination on a_0.

Sensitivity to γ

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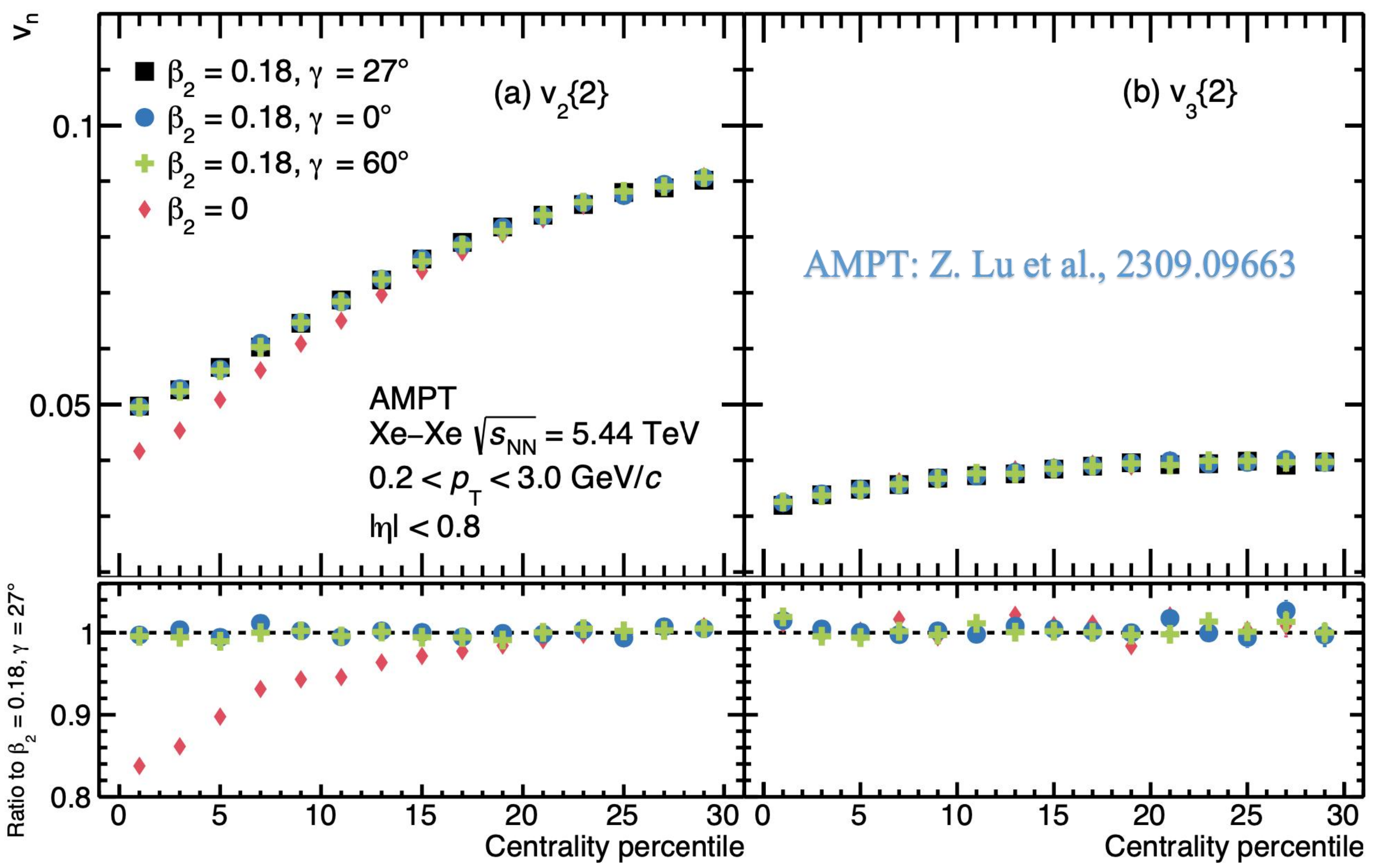
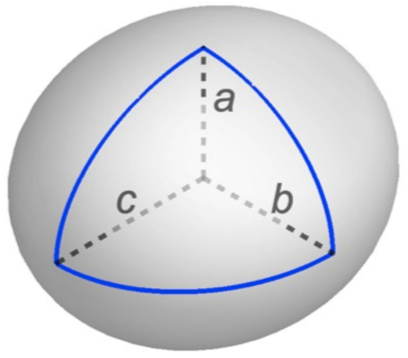


β_2=0.2, γ=30°



$a \neq b \neq c$

- Discussion on previous slides missed the contribution of γ, which represents the imbalance of the radius
- According to the last AMPT simulations, none of the “standard” flow observables are sensitive to γ
- New observables, i.e., $v_n - p_T$ correlation can probe γ

ALICE, Phys. Lett. B834 (2022) 137393

Summary

- A systematic study on the centrality dependence of various flow observables in Xe–Xe and Pb–Pb collisions
- Several flow observables exhibit pronounced differences between Xe–Xe and Pb–Pb, anticipated from the quadrupole deformation of ^{209}Xe
- IP-Glasma+MUSIC+UrQMD model with $a_0 = 0.492$, $\beta_2 = 0.207$ is favored by the presented measurements

✓ **Experimental measurements at the LHC enable a novel tool to probe the nuclear structure, complementary to the low-energy studies**

Thanks for your attention!

Backup

Observables

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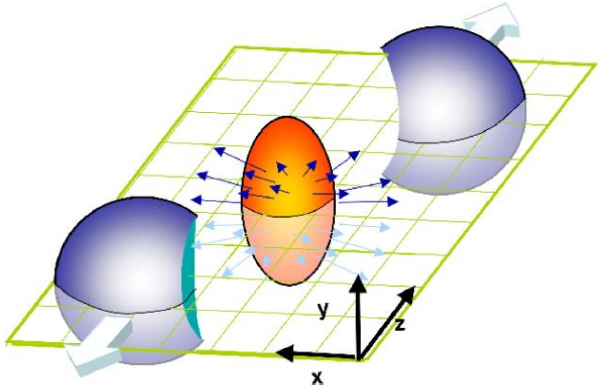
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$



Experimentally use multi-particle correlation $\cos(n_1\varphi_1+n_2\varphi_2+...+n_m\varphi_m)$
because event plane Ψ_n estimation contains additional uncertainties

- **flow coefficients with 2- and 4-particle:** $v_n\{2\}(n = 2,3,4)$, $v_2\{4\}$
- **mean elliptic flow:** $\langle v_2\rangle = \sqrt{(v_2\{2\}^2 + v_2\{4\}^2)/2}$
- **elliptic flow fluctuations:** $\sigma_{v_2} = \sqrt{(v_2\{2\}^2 - v_2\{4\}^2)/2}$ — Y. Zhou, Phys.Rev.C 93 (2016) 3, 034909
- **nonlinear flow modes** ($v_{4,22}$, $\chi_{4,22}$, $\rho_{4,22}$) — R. S. Bhalerao et al., Phys. Lett. B742 (2015) 94–98
- **normalized symmetric cumulants** (NSC(3,2)) — A. Bilandzic et al., Phys.Rev.C 89 (2014) 6, 064904

Measured for the first time in Xe–Xe collisions
Compared to results in Pb–Pb collisions

The first systematic study on nuclear structure with various flow observables at the LHC energies!

Final state cancellation

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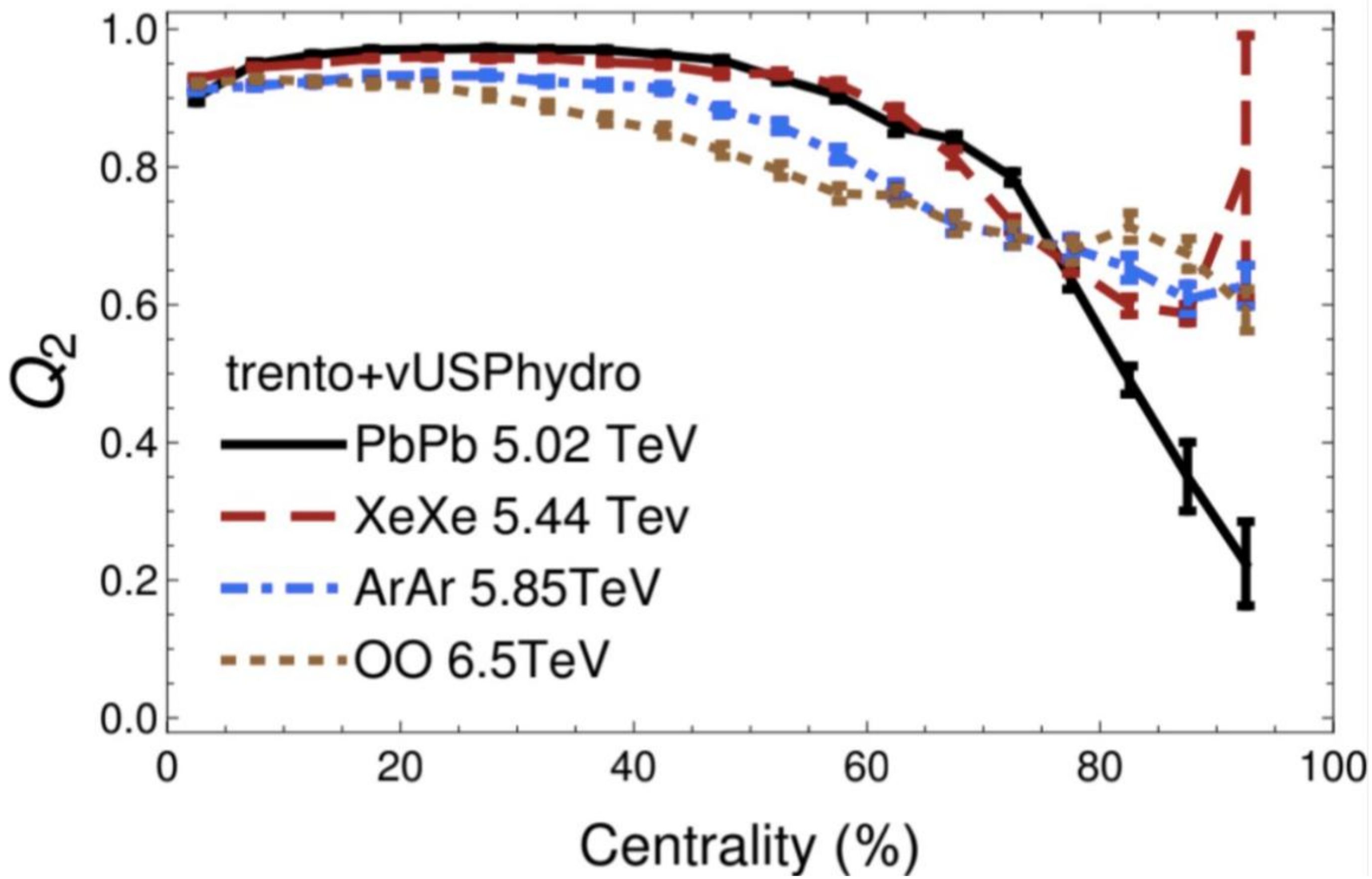
- the cancellation can be seen in the PCC correlation between the initial state and final state
- Basically, the two systems have the same linear correlation between initial and final, which suggests the same final state effects.

$$Q_n = \frac{\langle v_n \varepsilon_n \cos n\left(\psi_n - \phi_n\right)\rangle}{\sqrt{\langle v_n^2\rangle\langle \varepsilon_n^2\rangle}}$$



Results: normalized symmetric cumulant

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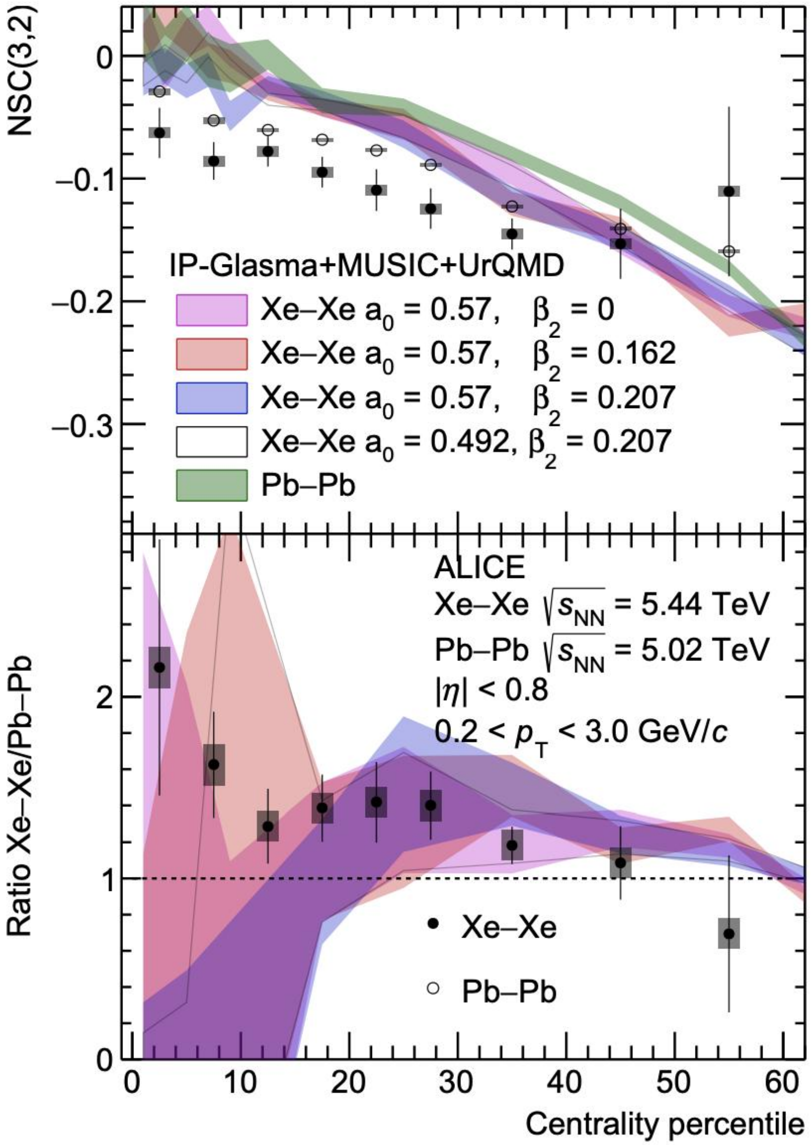

ALICE, arxiv: 2409.04343

NSC(3,2): the correlation between v_3^2 and v_2^2
(positive: correlated, zero: uncorrelated, negative: anticorrelated)

- anticorrelation between v_3 and v_2 in Xe–Xe is larger than Pb–Pb
- insensitive neither to β_2 nor a_0
- model deviates from the data in central region