# Probing Nuclear Structure of Heavy Ions at the Large Hadron Collider

**Wenbin Zhao**

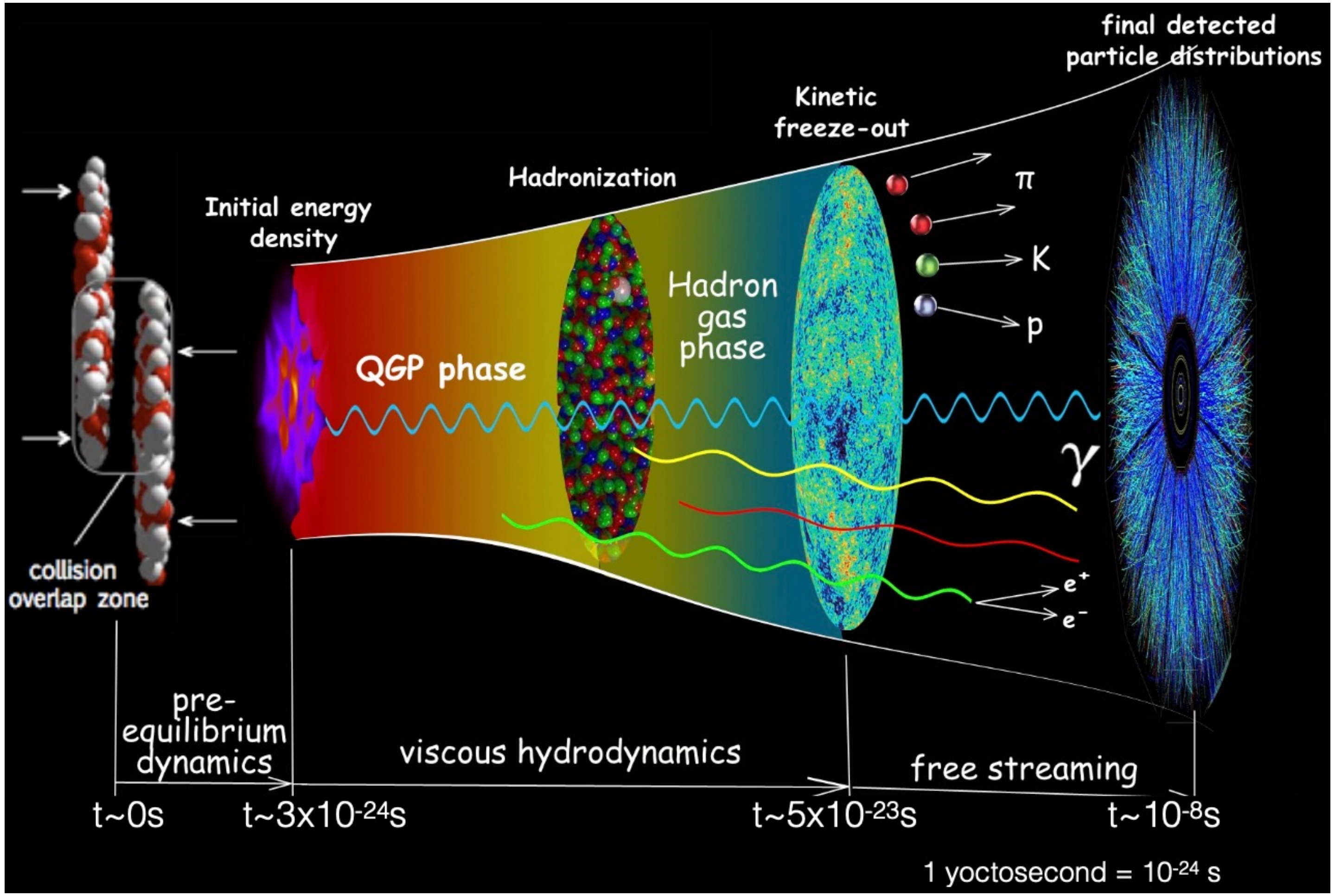
**Lawrence Berkeley National Laboratory**

**University of California, Berkeley**

Collaborators: **Heikki Mäntysaari, Björn Schenke, Chun Shen** and **Haojie Xu.**

**GHP, 2025, APS Topical Group on Hadronic Physics, Anaheim, CA, USA**

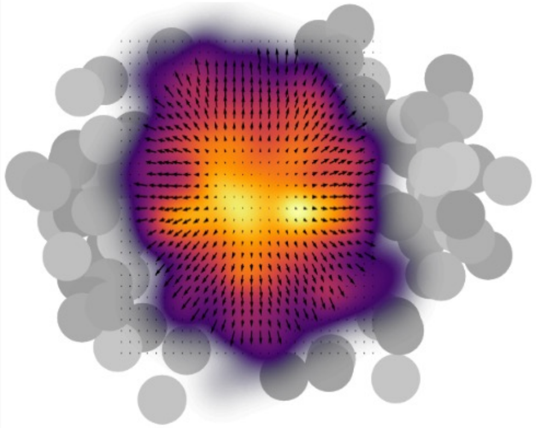
# Nuclear Matter under Extreme Conditions

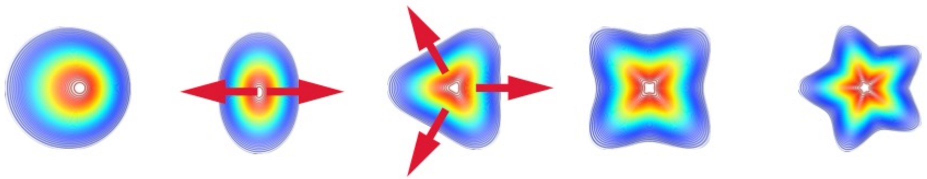



Credit: Chun Shen

- Heavy-ion collision dynamics is complex with multiple length/time scales.
- What is the **smallest QGP droplet**?
- What is the **structure of QCD phase diagram**?
- How does the strongly coupled liquid emerge from fundamental QCD interactions?
- Constrain the nuclear shape by final state observables (Inverse Problem).

# Anisotropic Flows





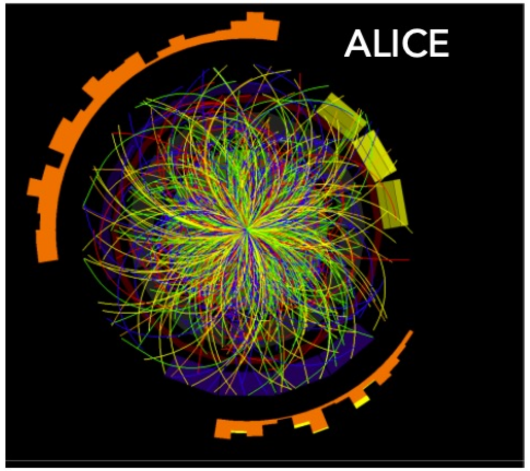
initial fluctuating geometric deformation can be decomposed into spatial eccentricities

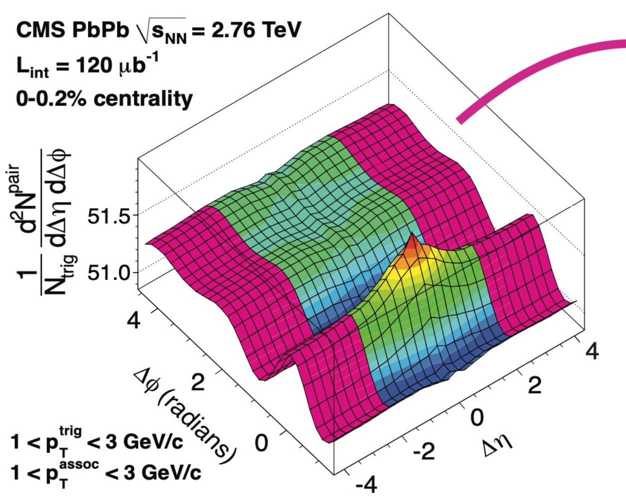
Initial spatial eccentricities

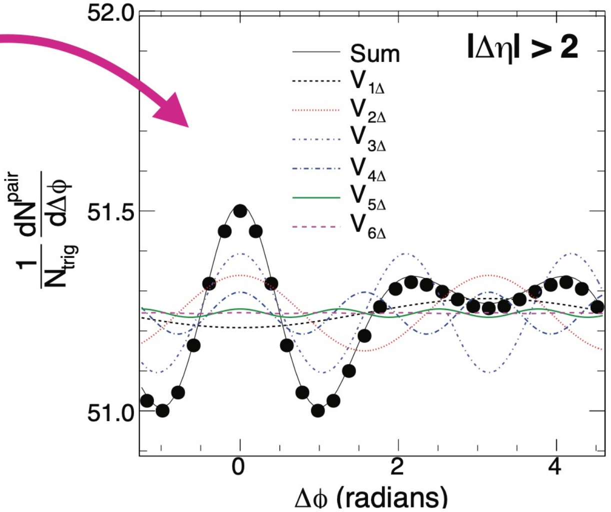
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}{\langle r^n \rangle^2}}$$

average over energy density

$\epsilon_2$ ellipticity, $\epsilon_3$ triangularity, ...




Fourier decomposition of final particle azimuthal distribution

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]\right)$$

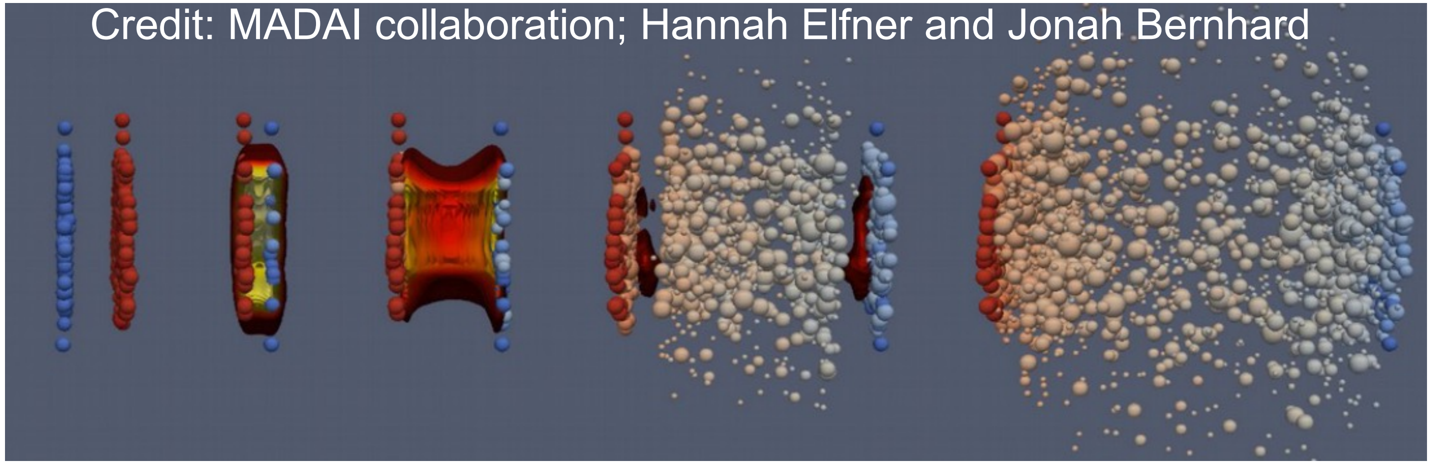
$$v_2 = \langle \cos[2(\phi - \Psi_2)] \rangle$$

average over azimuthal distribution

$v_2$ elliptic flow, $v_3$ triangular flow, ...

# Multistage Description of Heavy-Ion Collisions (Soft part)

- **Initial conditions** (3D-Glauber, TRENTo, IP-Glasma, AMPT, EKRT…)
- **Viscous hydrodynamics** (MUSIC, VISHew, CLVis, Trajectum… )
- **Hadron cascade afterburner** (UrQMD, SMASH, JAM…)





- Bulk dynamics: describe final soft particles $pT \lesssim 2$ GeV (more than 95% of the total particles)

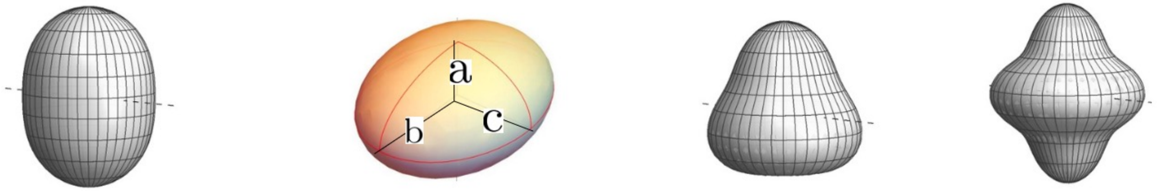
# Probing nuclear structure of heavy ions at the LHC

IP-Glasma → MUSIC → iSS → UrQMD

# Nuclear structure and sub-nucleon parameters

Generalized Woods-Saxon profile

$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$



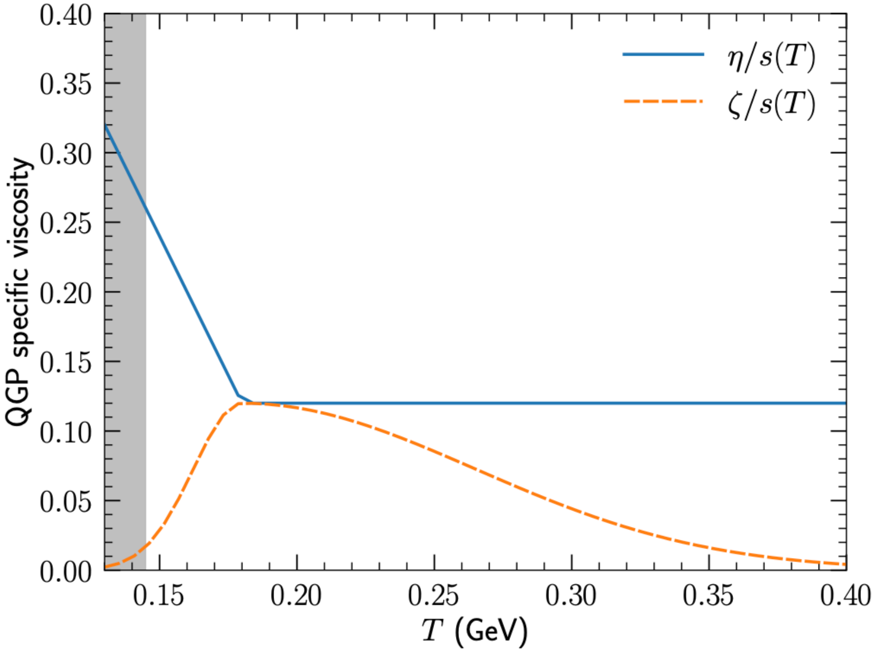

Taken from Giuliano's slide

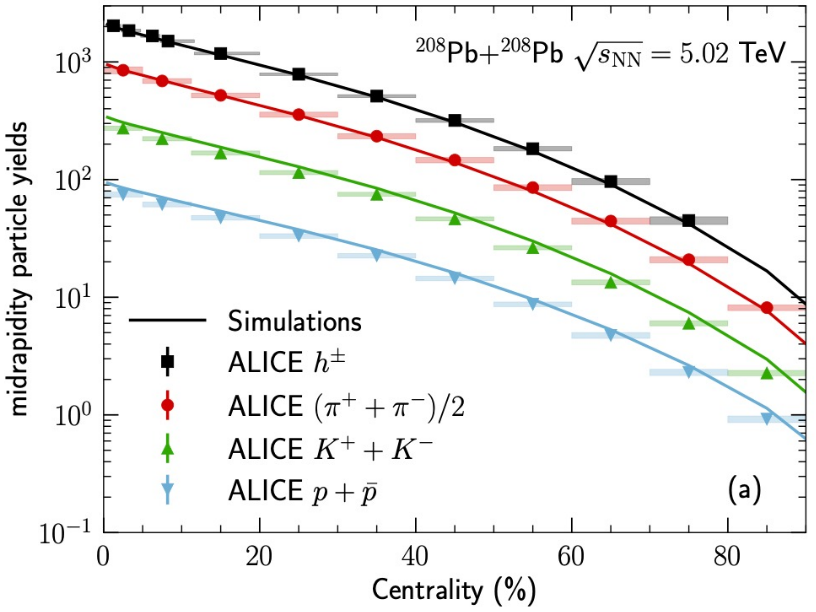
| Nucleus | $R_0^{WS}$ (fm) | $a^{WS}$ (fm) | $\beta_2^{WS}$ | $\beta_4^{WS}$ |
|---|---|---|---|---|
| $^{208}$Pb(default) | 6.647 | 0.537 | 0.006 | 0 |
| $^{129}$Xe(1) | 5.601 | 0.492 | 0.207 | -0.003 |
| $^{129}$Xe(2) | 5.601 | 0.57 | 0.207 | -0.003 |
| $^{129}$Xe(3) | 5.601 | 0.57 | 0.162 | -0.003 |
| $^{129}$Xe(4) | 5.601 | 0.57 | 0 | -0.003 |

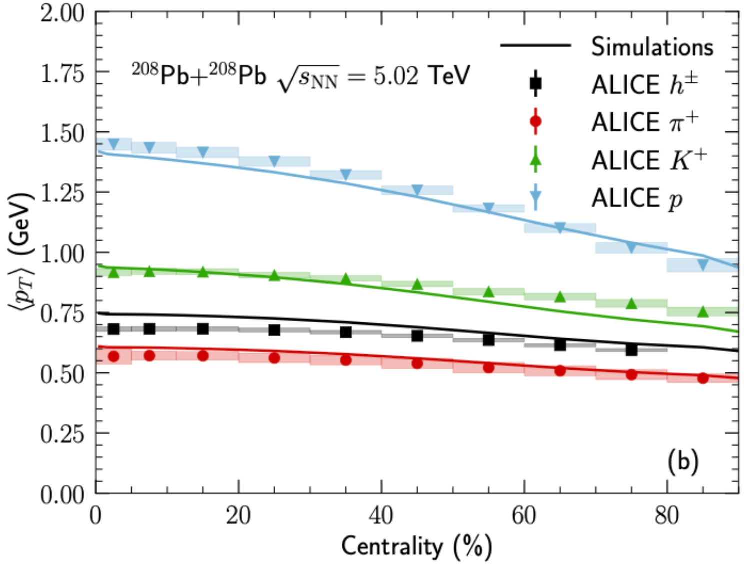
- The nucleon parameters are fixed by fitting the diffractive $J/\Psi$ data in e-p.

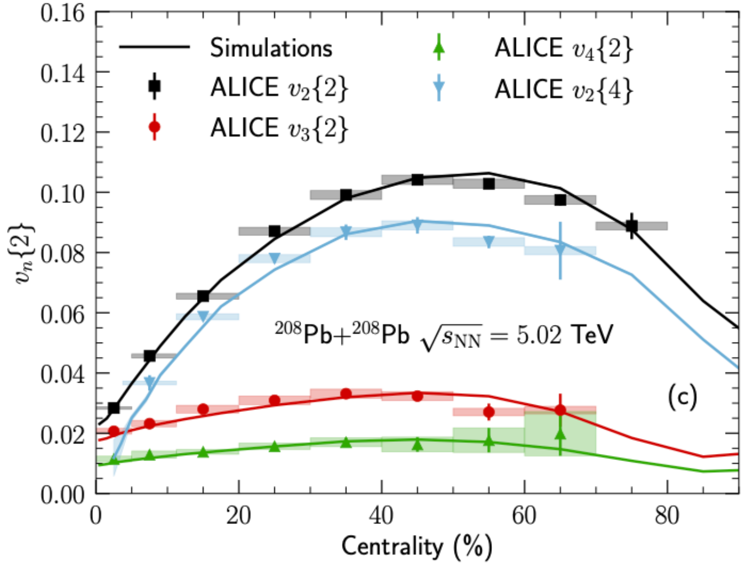

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).
H. Mantysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.
H. Mantysaari, B.Schenke, C. Shen and W. Zhao, [arXiv:2208.00396 [hep-ph]].

# Hydrodynamic parameters



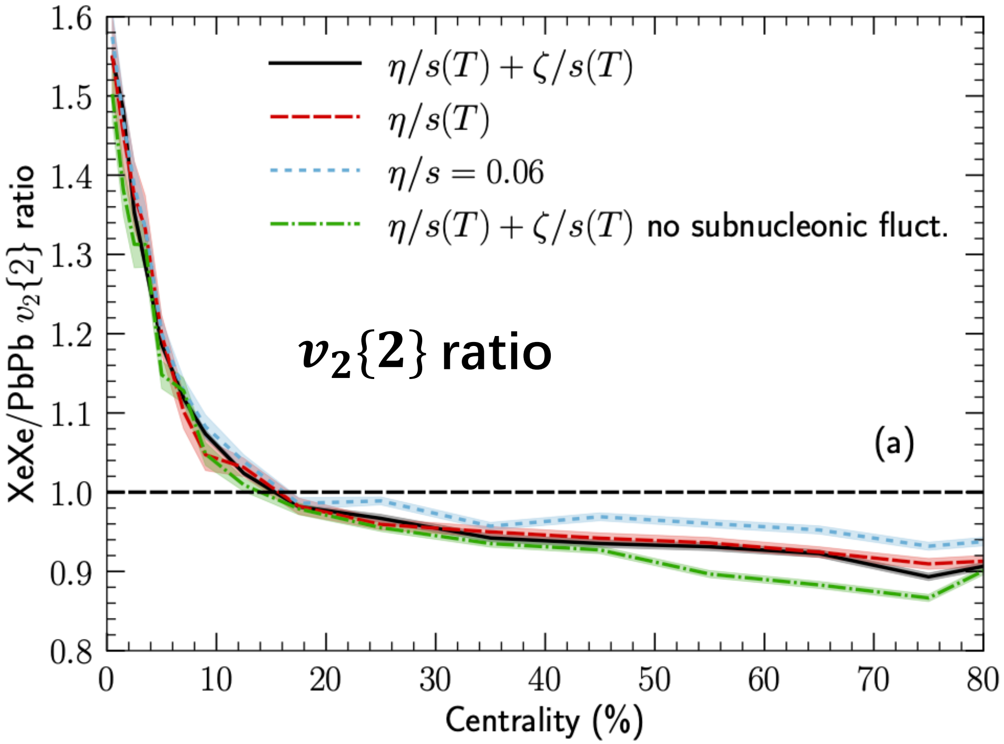



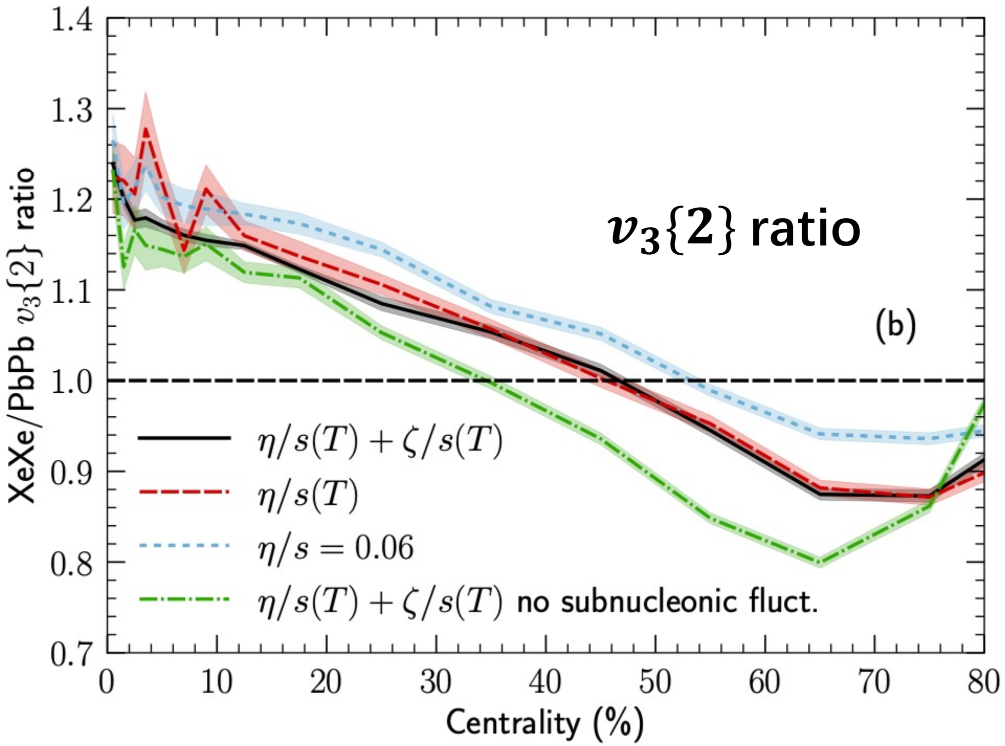




- Hydrodynamic parameters are turned to fit the multiplicity, mean $p_T$ and integrated flow in Pb-Pb.

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

# QGP Viscosities and Sub-nucleonic Structure

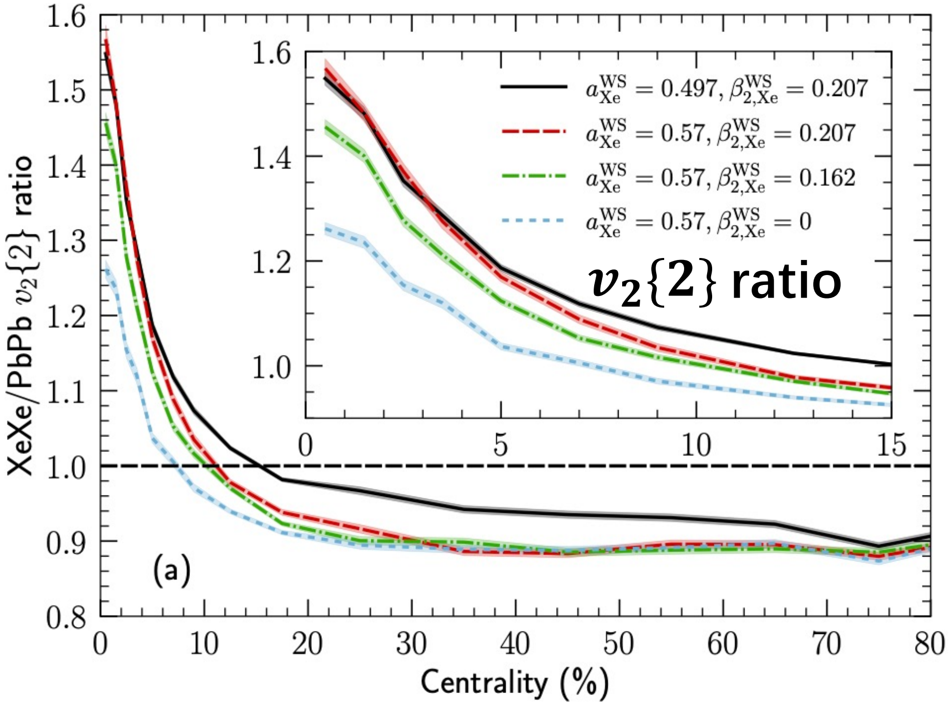


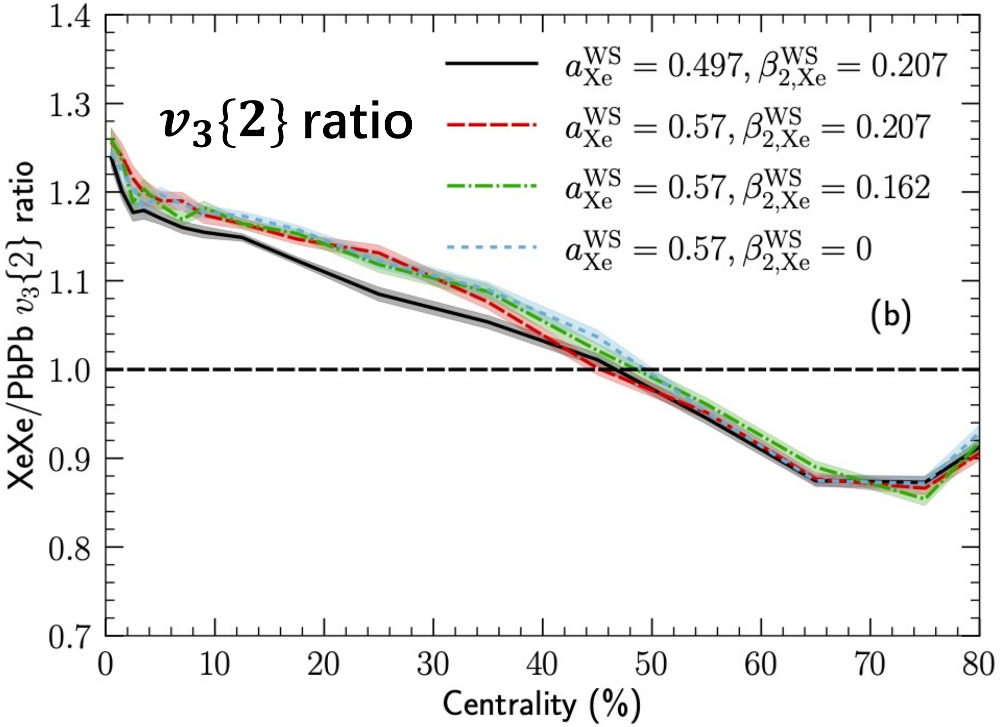




- $v_2$ ratios are largely insensitive to the QGP viscosity, despite the 25% smaller area in Xe+Xe than that in Pb+Pb at the same centrality.
- $v_3$ ratios shows some sensitivities to QGP's specific shear viscosity and sub-nucleonic fluctuations.

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

# $\beta_2$ and $a^{WS}$

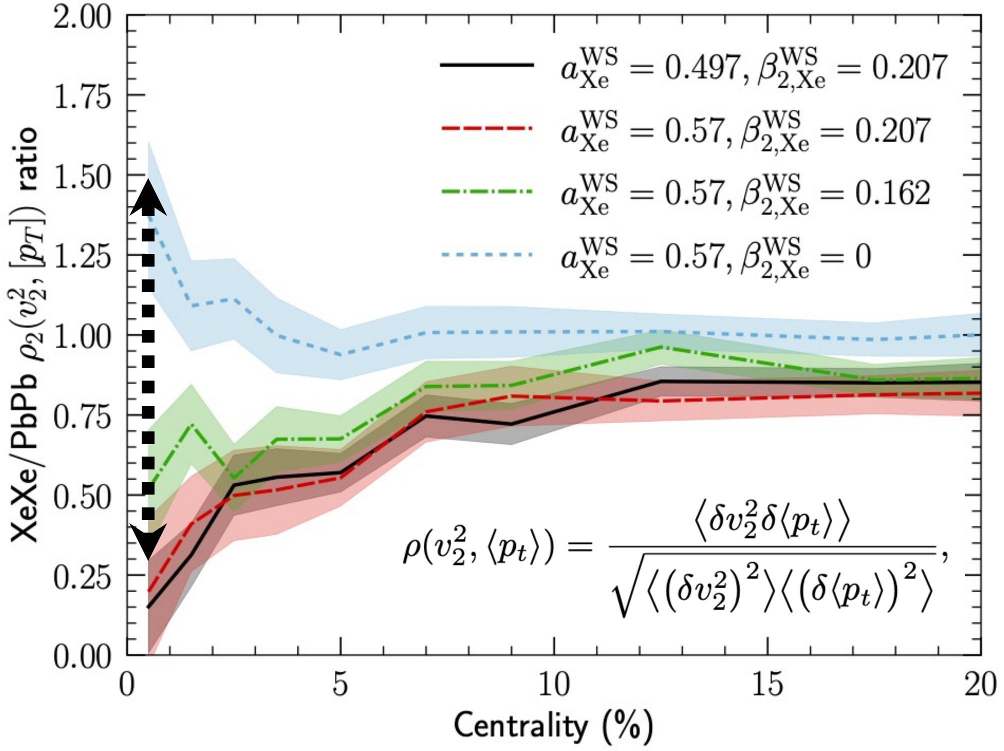


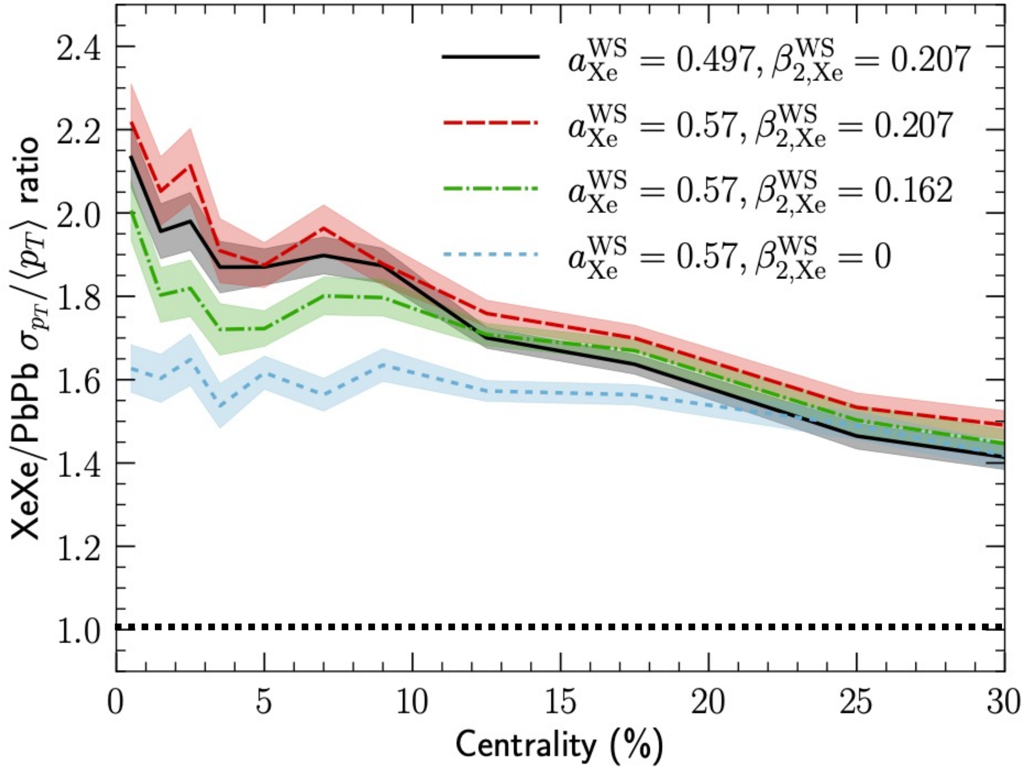




- $v_2$ ratios sensitive to $\beta_2$. $v_2$ ratio at mid-central sensitive to $a^{WS}$, smaller $a^{WS}$ leads to sharper edge in nuclear profile, impacts Pb and Xe nuclei differently with different radii.
- Combining the ratios of $v_2$ and $v_3$ could help to disentangle effects of sub-nucleonic fluctuations and skin thickness.

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

# $\beta_2$ and $a^{WS}$

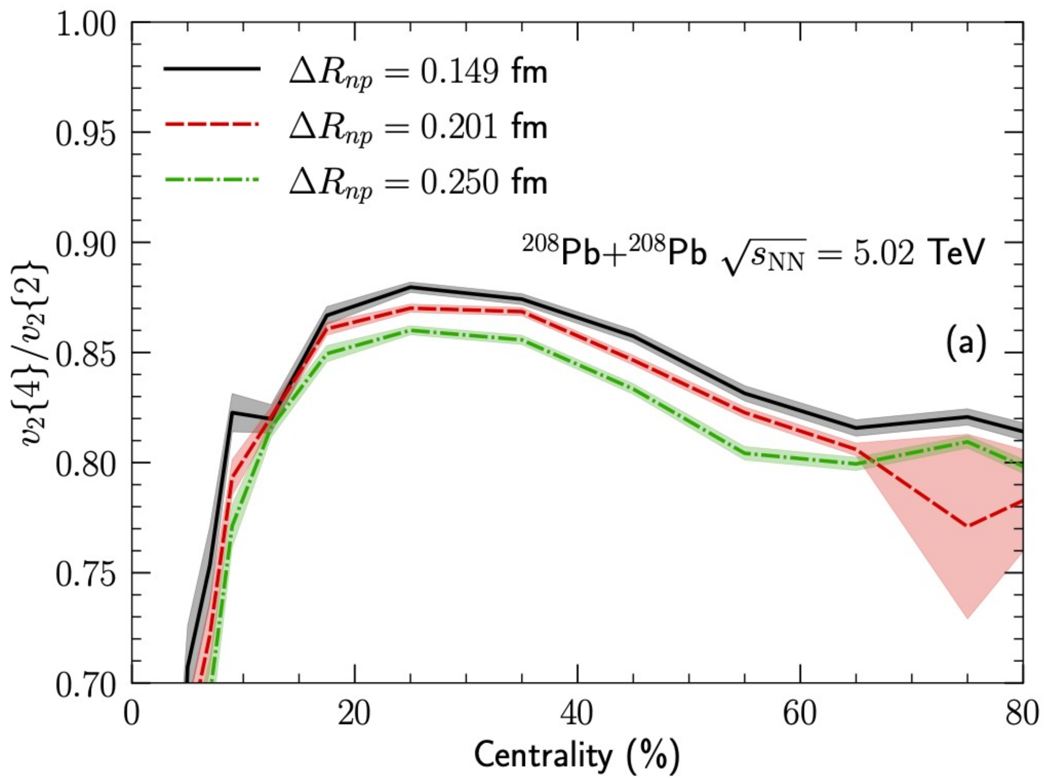


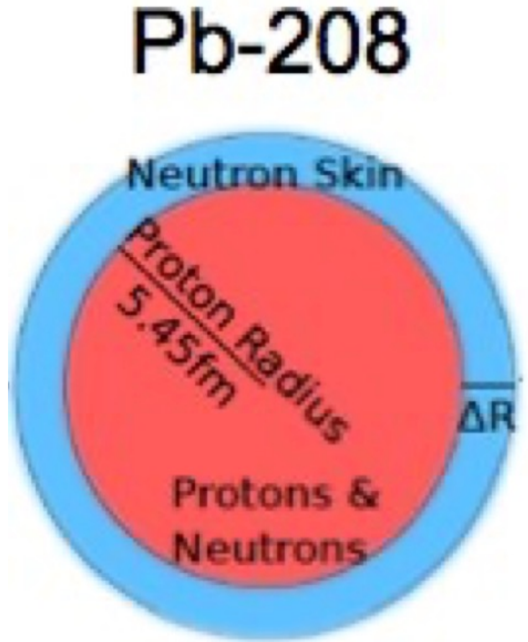




- Large $\beta_2$ deformation diminishes the relative contribution of shape fluctuations to the elliptic flow, which weak the $v_2 - [p_T]$ correlation.
- Larger $\beta_2$ leads to the greater normalized variance of $p_T$, non-zero $\beta_2$ introduces more shape and size fluctuations.

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

# Constraining the neutron skin of Pb-208



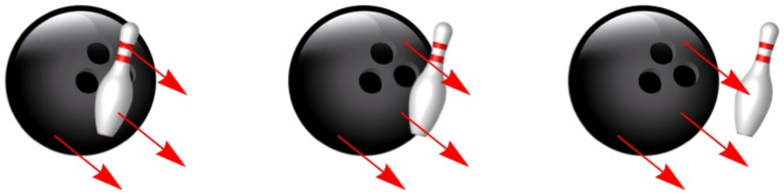

$$\Delta R_{np} = R_p - R_n,$$

$$R_{p,n} = \sqrt{\int d^3 r r^2 \rho^{WS}_{p,n}(r,\theta) \Big/ \int d^3 r \rho^{WS}_{p,n}(r,\theta)}.$$

- Larger nuclear skin depth allows nucleons to be more diffusively populated around the edge of the overlapping area, increasing the shape fluctuations, resulting more fluctuations in $v_2$.
- $v_2\{4\}/v_2\{2\}$ is a sensitive probe to skin depth of the nuclear mass density. Combining charge radius from low-energy experiments can deduce the size of the neutron skin of nuclei.

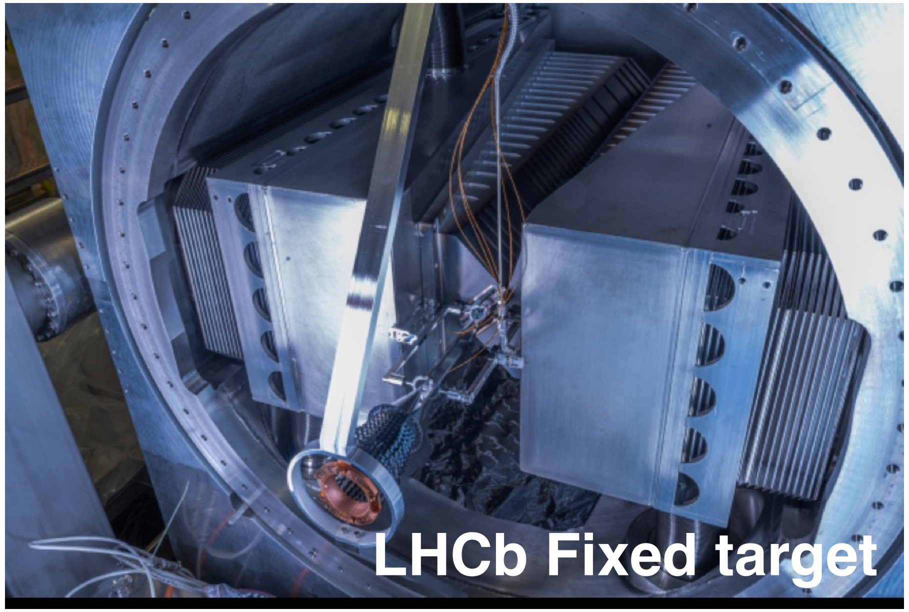
H. Mantysaari, B. Schenke, C. Shen and W. Zhao, Phys. Rev. C 110, no.5, 054913 (2024).

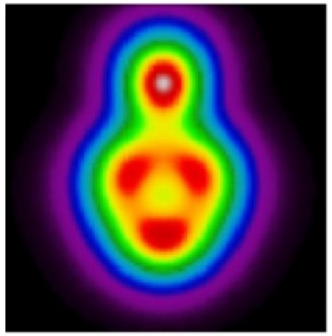
# Opportunities of light-ion Collisions



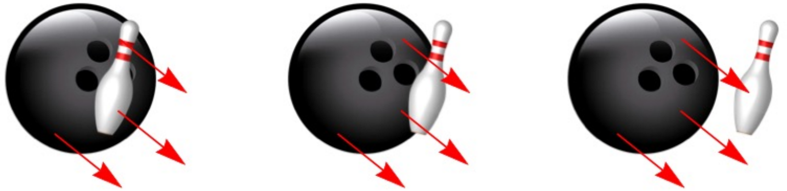
3D-Glauber → MUSIC → iSS ⟶ UrQMD

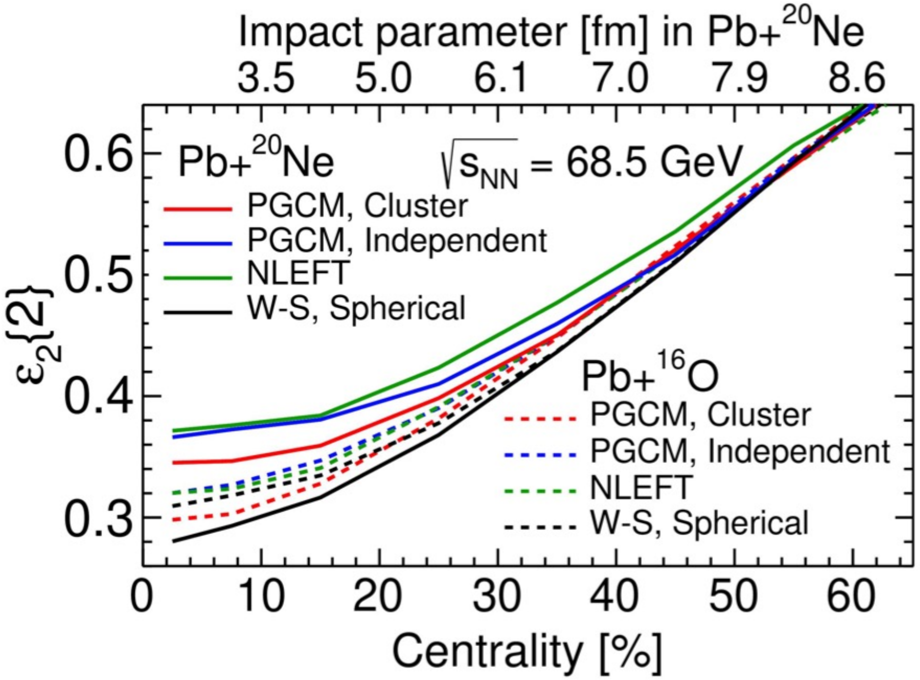
# High Energy Bowling Allay



$^{20}$Ne



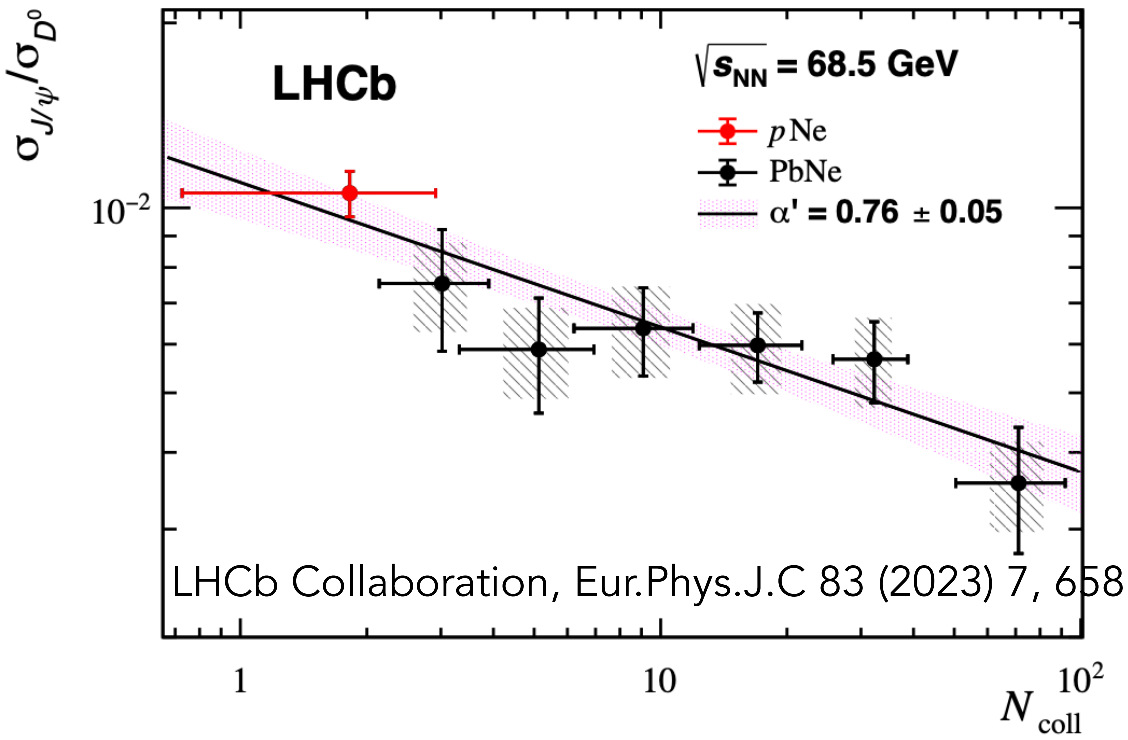


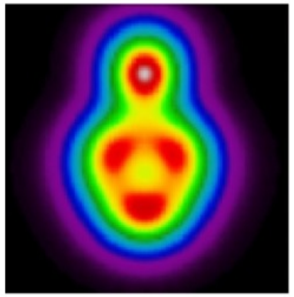

**Pb + Ne-20 collisions: A high energy bowling allay!**

G. Giacalone W. Zhao et al Phys. Rev. Lett. 134, 082301 (2025)

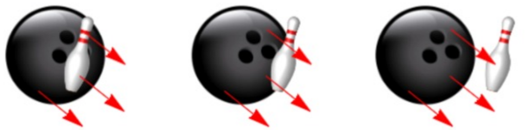
- Connecting *ab initio* inputs of light-nuclei with relativistic nuclear collisions.
- Easier to image the shapes of light-nuclei than symmetric light-ion collisions.

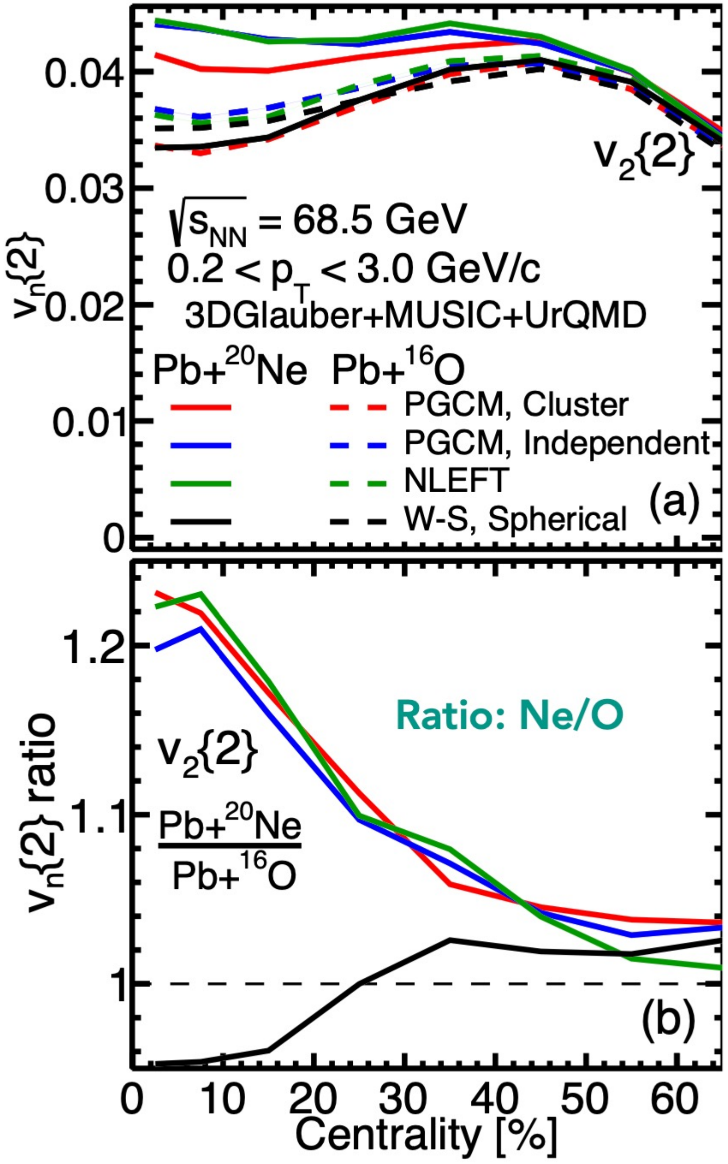
# A Probe of Quark-Gluon Plasma



$^{20}$Ne

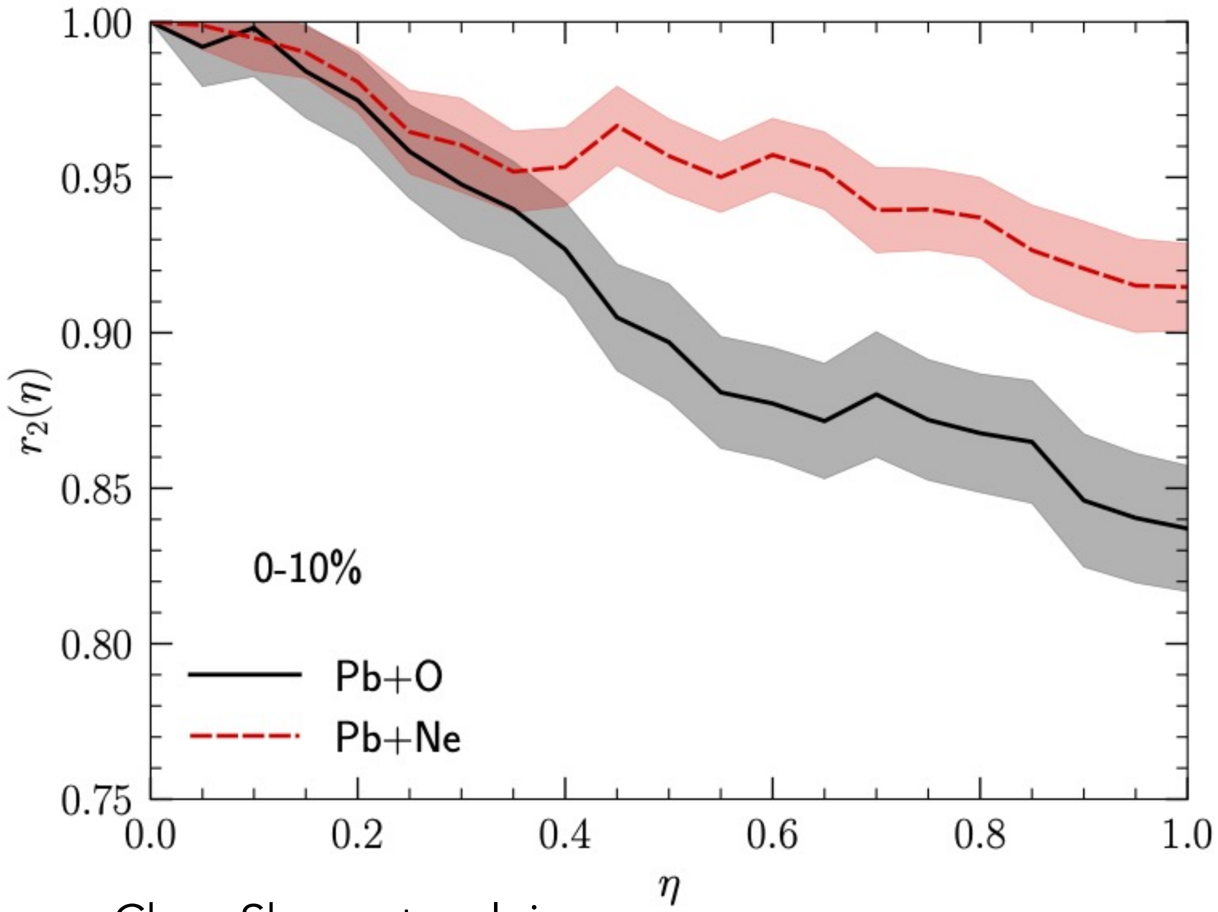




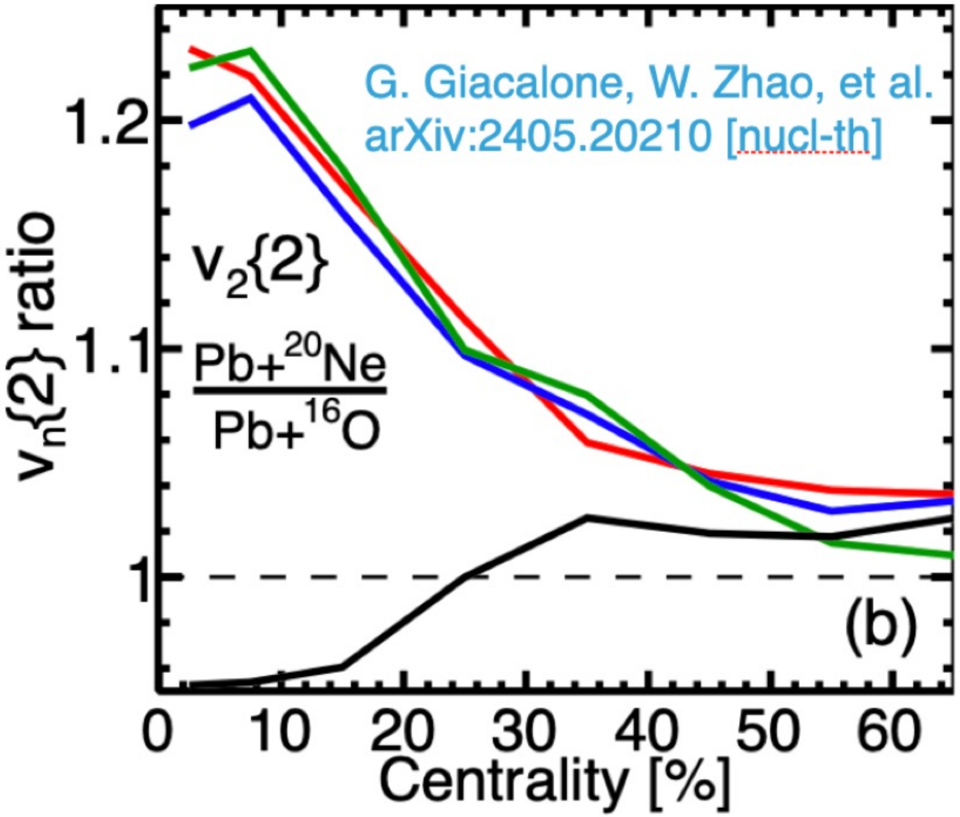

- No QGP-like $J/\psi$ suppression in Pb+Ne.
- Flow sensitive to shapes of Ne and O
- Searching the QGP at LHCb.

G. Giacalone W. Zhao et al Phys. Rev. Lett. 134, 082301 (2025)

# Longitudinal Dynamics




Chun Shen, etc, al. in progress.

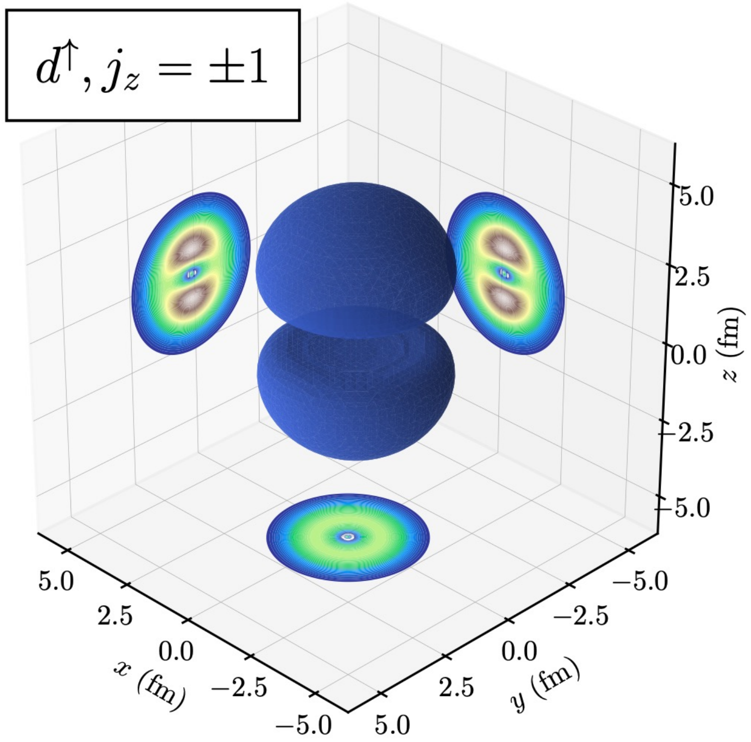


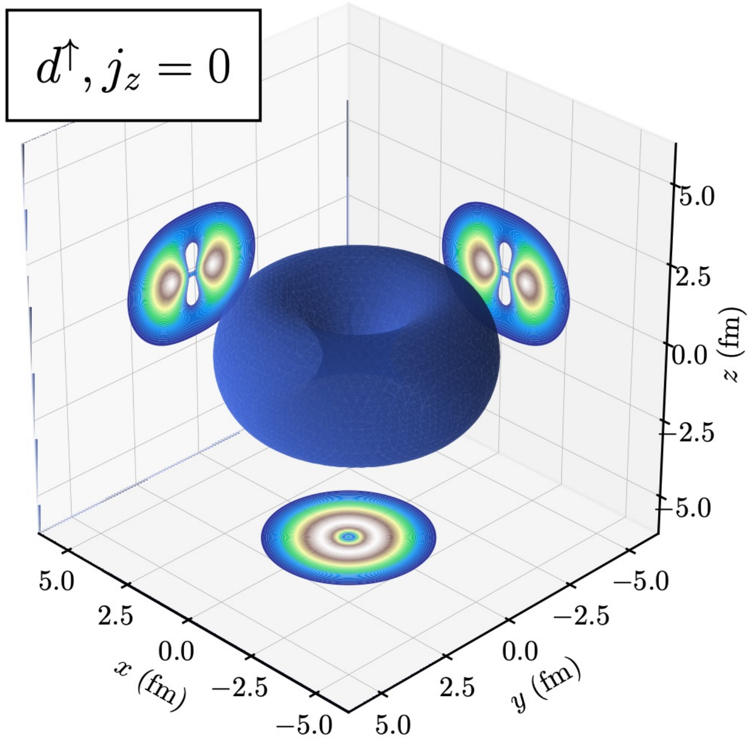

| 0–1% | $v_2\{2\}_{NeNe}/v_2\{2\}_{OO}$ |
|---|---|
| NLEFT | $1.174(8)_{stat.}(31)^{Traj.}_{syst.}(4)^{str.}_{syst.}$ |
| PGCM | $1.139(6)_{stat.}(27)^{Traj.}_{syst.}(28)^{str.}_{syst.}$ |

arXiv:2402.05995 [nucl-th]

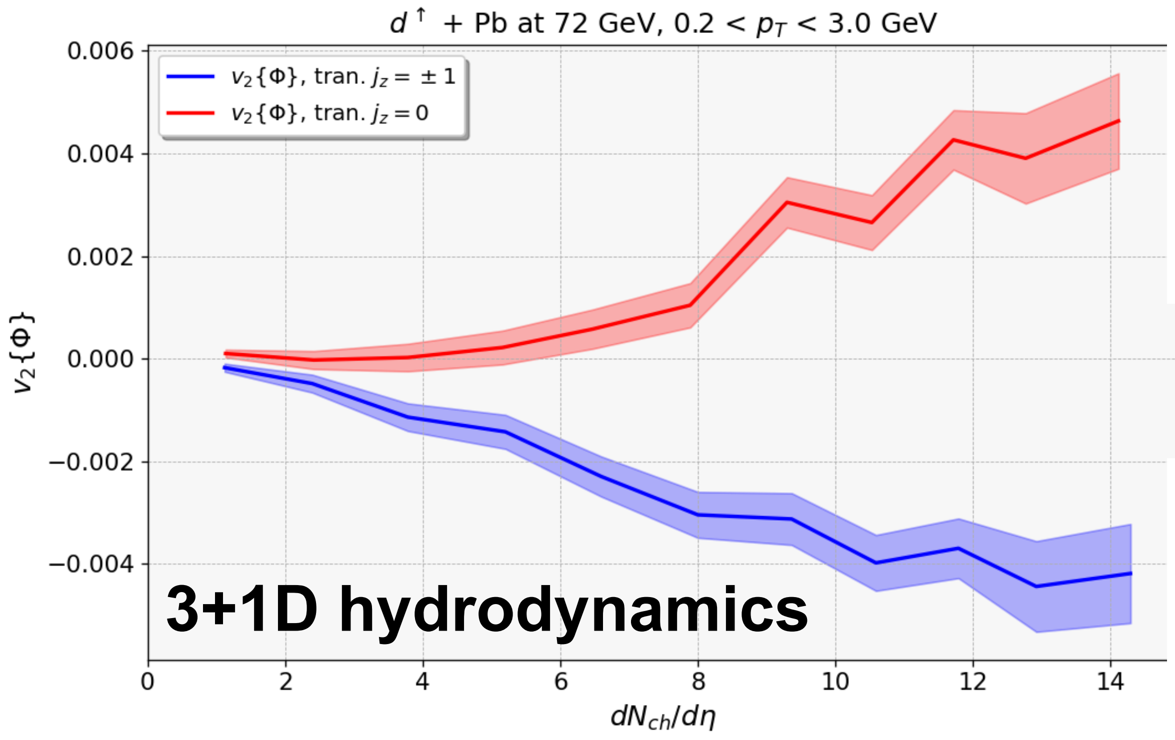
- The elliptic flow decorrelation in PbO is larger than in PbNe collisions.
- It leads to a larger $v_2\{2\}$ ratio than those results with boost- invariance in O+O and Ne+Ne collisions

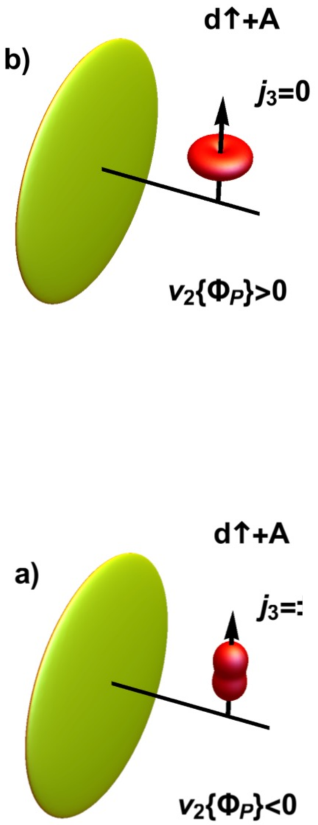
# Collectivity in Polarized deuterons + Ion



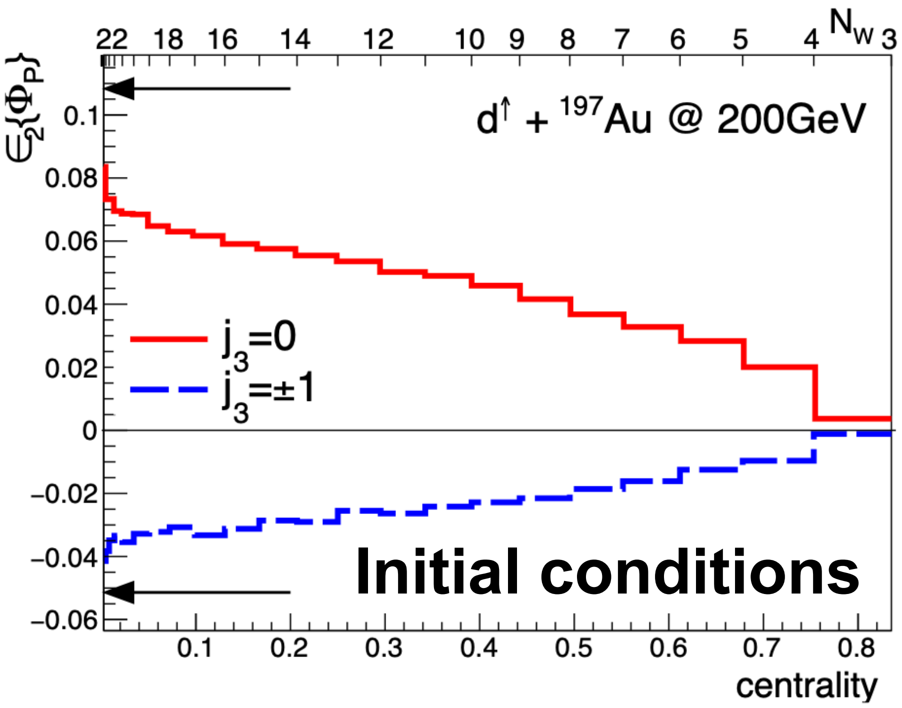



# Collective flow in Polarized deuterons + Nuclei




$$\vec{\epsilon}_n = -\frac{\int \rho d\rho d\alpha e^{in\alpha} \rho^n f(\vec{\rho})}{\int \rho d\rho d\alpha \rho^n f(\vec{\rho})}$$

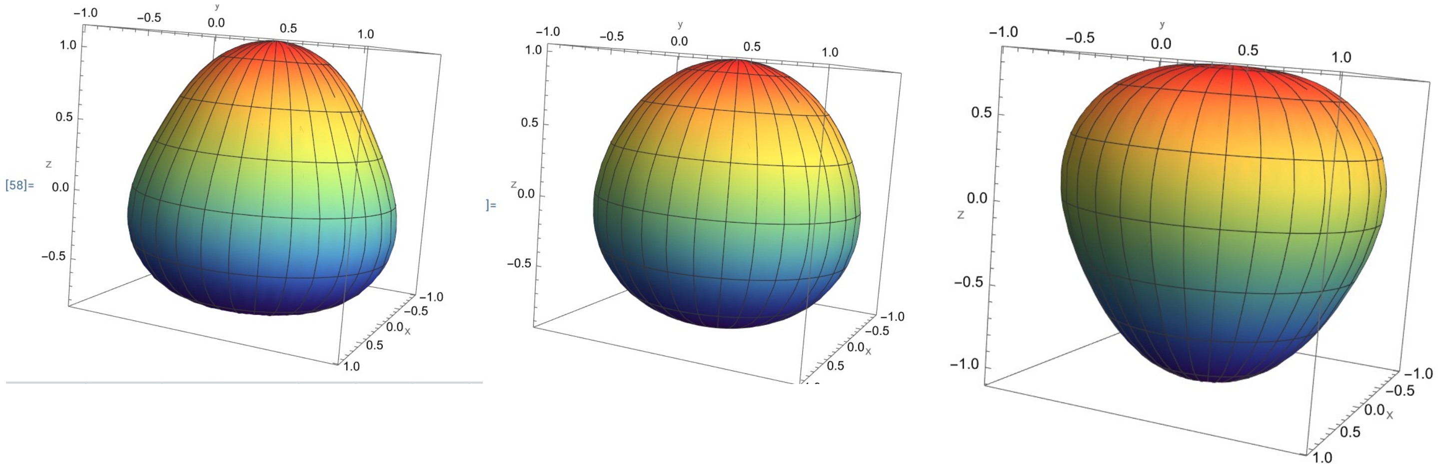



- Opposite sign of $v_2\{\Phi\}$ between $j_z = \pm 1$ and $j_z = 0$ in $d^{\uparrow} + Pb$.
- Could be tested in the coming LHCb measurement.

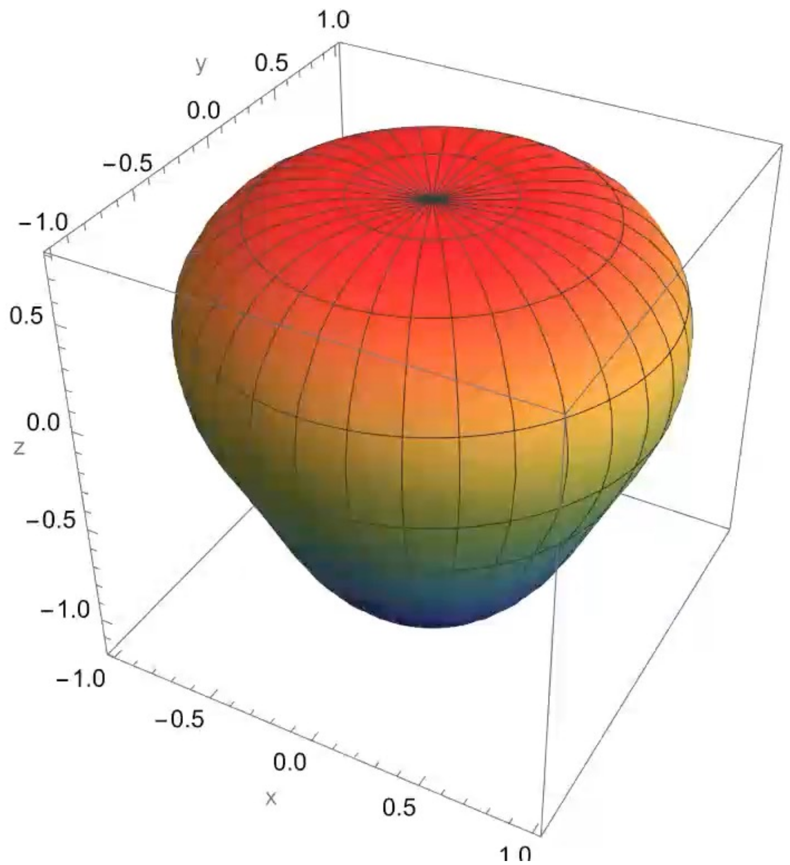
P. Bozek and W. Broniowski, PhysRevLett.121.202301

H.Mantysaari, B.Schenke, C. Shen and W. Zhao in progress.
LHCb: PoS SPIN2023, 036 (2024).

# Breathing Nuclei in Heavy-Ion Collisions

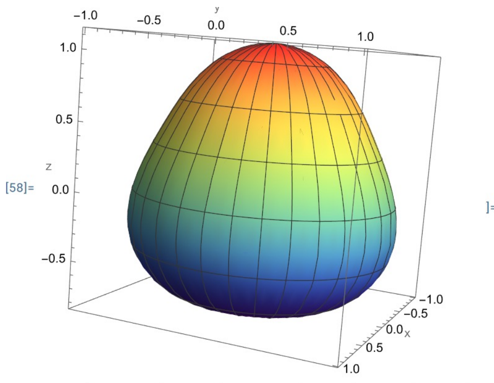


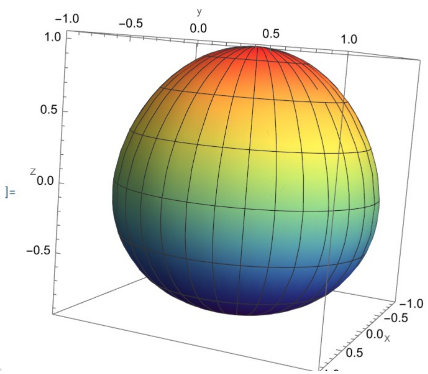
# Nuclear can "Breath"

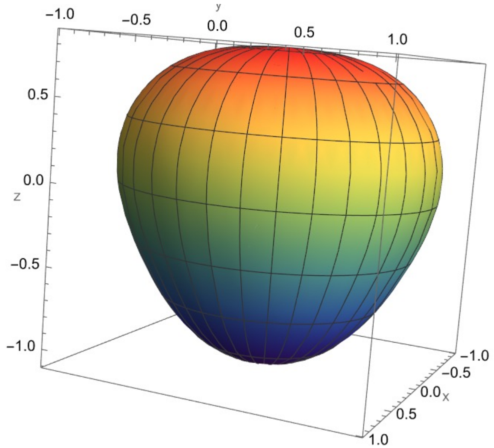



**Nuclear is breathing.**

- Heavy-ion collision takes an event-by-event snapshot of colliding nuclei.
- The nuclear can have the event-by-event $\beta_i$ fluctuation, which looks like the nucleus is breathing.

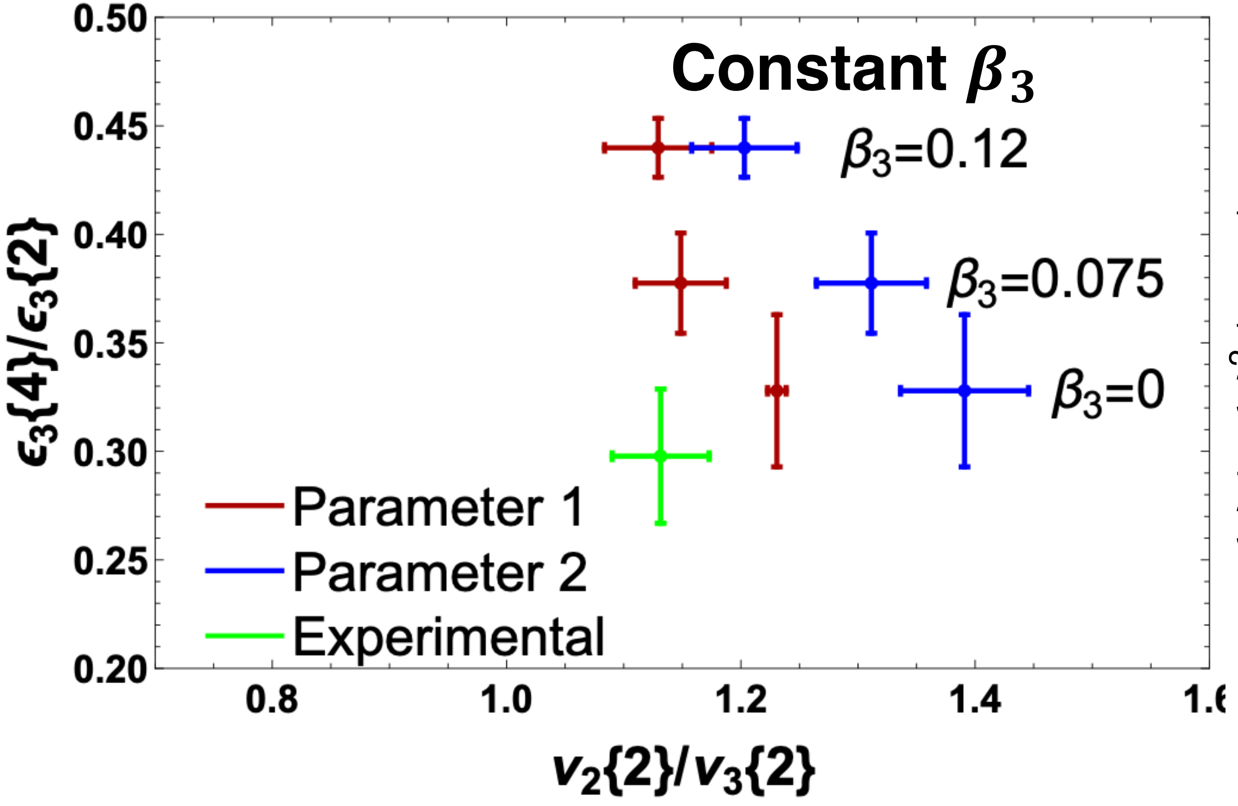


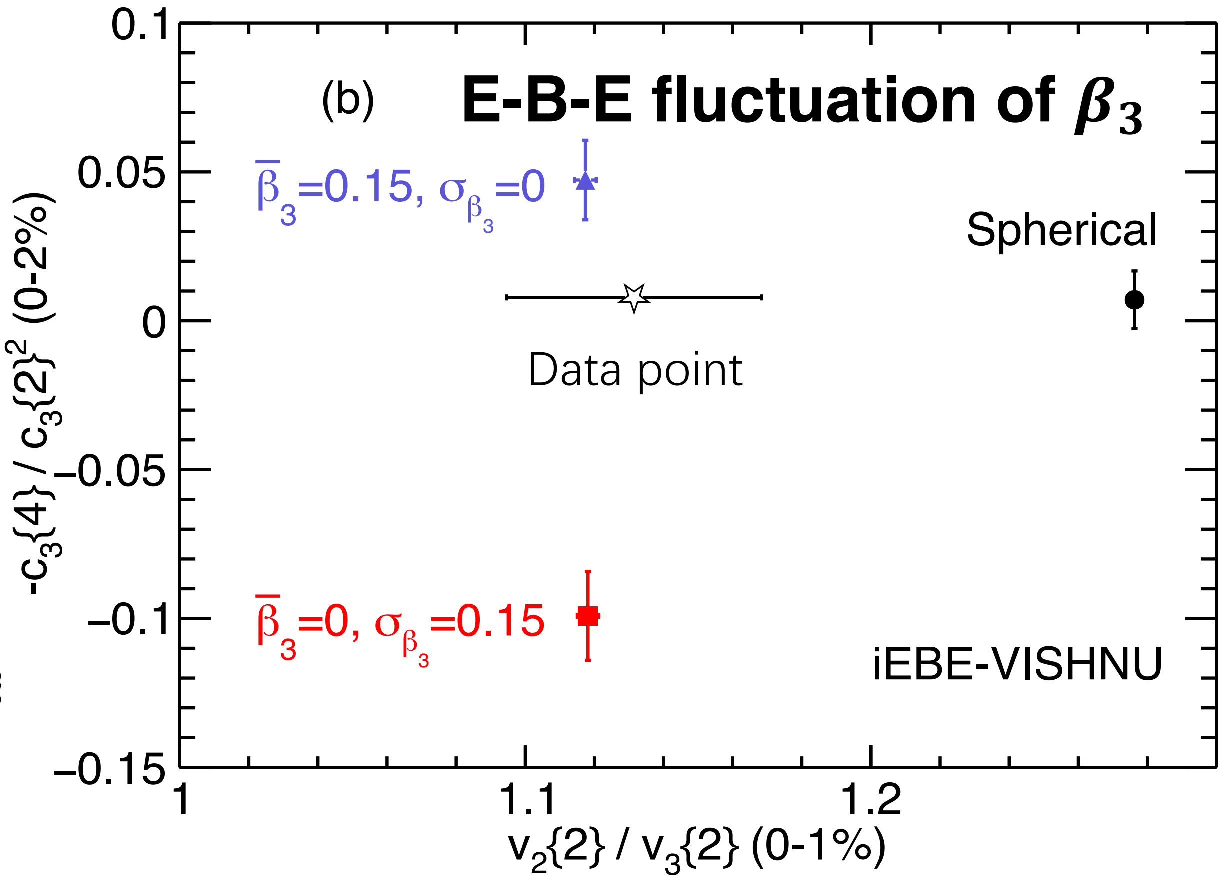




Haojie Xu, Wenbin Zhao, etc, al. in progress.

# Solving the ultra-central $v_2 - v_3$ puzzle *via* “Breathing” Pb




- Constant $\beta_3$ of Pb can’t reproduce the data in ultra-central Pb-Pb collisions.
- Event-by-event $\beta_3$ can solve the the ultra-central $v_2 - v_3$ puzzle in Pb-Pb.

P. Carzon, S. Rao, M. Luzum, M. Sievert and J. Noronha Hostler, Phys. Rev. C 102, 054905 (2020).
Haojie Xu, Wenbin Zhao, etc, al. in progress.

# Summary

- Hydrodynamic response to geometry enables event-by-event image shapes of nuclei.
- Connecting *ab-initio* nuclear structure inputs and heavy-ion collisions open a new venue to study QCD at different scales.
- Studying collectivity polarized light nuclei + heavy ion help to understand the mechanism of collectivity in small systems.
- Nuclei is breathing, heavy-ion collisions provide good opportunity to probe it.

**Thanks for Your Attentions!**

# Back Up