Stony Brook University

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Imaging the longitudinal structure of the QGP using different shaped nuclei

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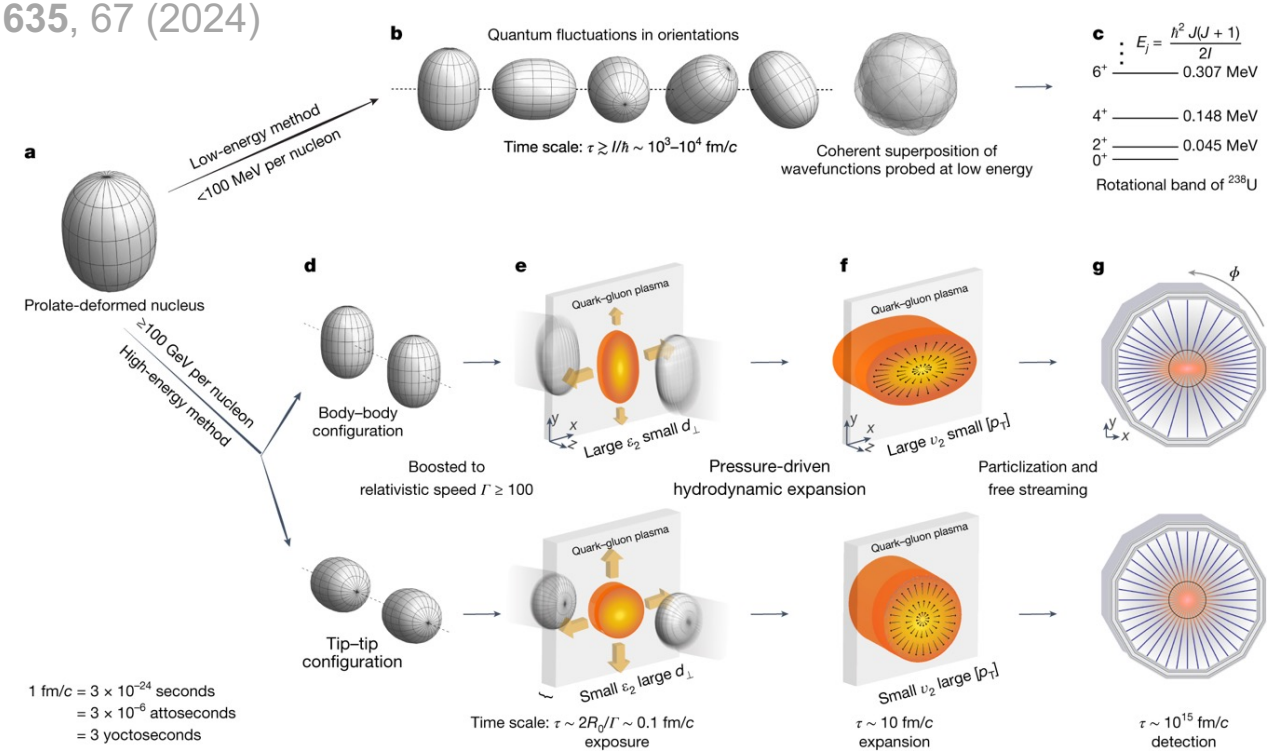
arXiv: 2405.08749 and Phys. Rev. Lett. **137**, 202301

with Chunjian Zhang, Shengli Huang, Somadutta Bhatta

Intersections of heavy ion and nuclear structure

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Nature **635**, 67 (2024)

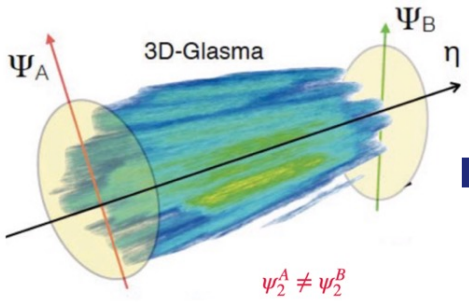


Earlier work used high-energy collisions to image the shape of atomic nuclei.

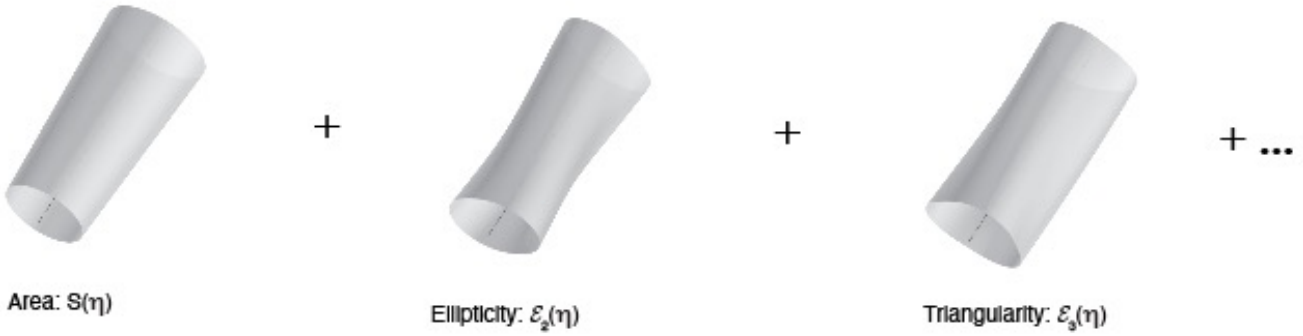
We reverse the logic: use the known nuclear shape to probe the QGP's initial state.

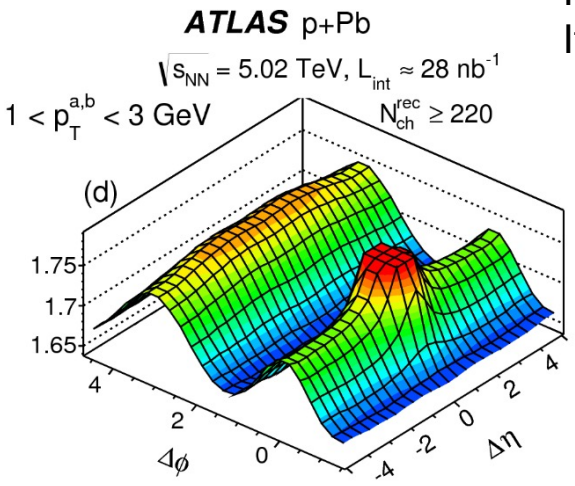
Longitudinal structure and the nonflow challenge

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Longitudinal profile

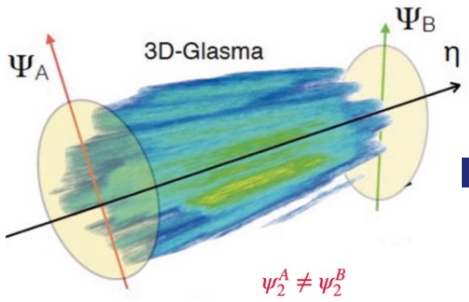




Initial geometry has rich event-by-event structure along η: S(η), $\varepsilon_2(\eta)$, $\varepsilon_3(\eta)$
It sets the final-state correlations

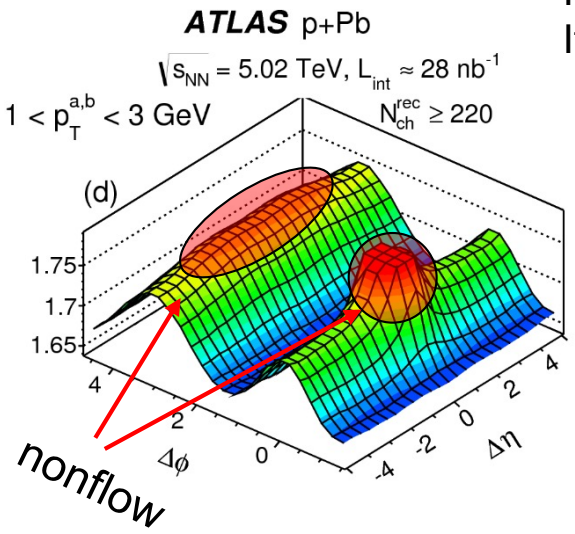
Longitudinal structure and the nonflow challenge

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Longitudinal profile





Initial geometry has rich event-by-event structure along η: S(η), $\varepsilon_2(\eta)$, $\varepsilon_3(\eta)$
It sets the final-state correlations, but near- and away-side **nonflow** obscure them

Ideally: full correlation matrix

$$R_2(\eta_1,\eta_2) = \frac{\langle V_2(\eta_1)V_2^*(\eta_2)\rangle}{\sqrt{\langle V_2(\eta_1)V_2^*(\eta_1)\rangle \langle V_2(\eta_2)V_2^*(\eta_2)\rangle}}$$

Denominator needs same-η pairs, where **nonflow is unavoidable**

In practice: factorization ratio

$$r_2(\eta) = \frac{\langle V_2(-\eta)V_2^*(\eta_{\rm ref})\rangle}{\langle V_2(\eta)V_2^*(\eta_{\rm ref})\rangle} \equiv \frac{R(-\eta,\eta_{\rm ref})}{R(\eta,\eta_{\rm ref})}$$

η gap suppresses nonflow, but r_2 relates to R_2 only **indirectly**

Is the correlation loss additive?

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Interpreting r_2 requires the additive assumption

$$R_2(\eta_1,\eta_2) = \exp\left(-F_2|\eta_1-\eta_2|\right) \approx 1 - F_2|\eta_1-\eta_2|$$

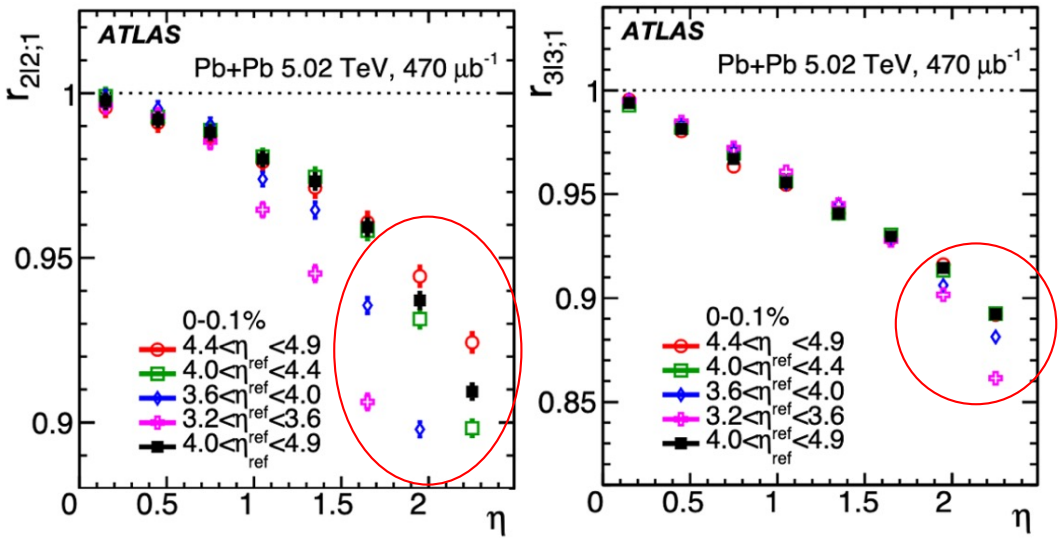
$$r_2(\eta) = \frac{\langle V_2(-\eta)V_2^*(\eta_{\rm ref})\rangle}{\langle V_2(\eta)V_2^*(\eta_{\rm ref})\rangle} = R_2(\eta,-\eta) \approx 1 - 2F_2\,\eta$$

η_{ref} drops out: $1 - r_2$ measures the decorrelation strength F_2

Puzzles in the existing data

Seen by CMS, ATLAS, ALICE and STAR

- r_2 depends **strongly on the η_{ref} choice**, unexpected if loss is additive
- r_3: much weaker η_{ref} dependence, closer to linear in η
- No explanation so far



Reason: longitudinal correlation loss is not additive.

The clever approach: change the nucleus

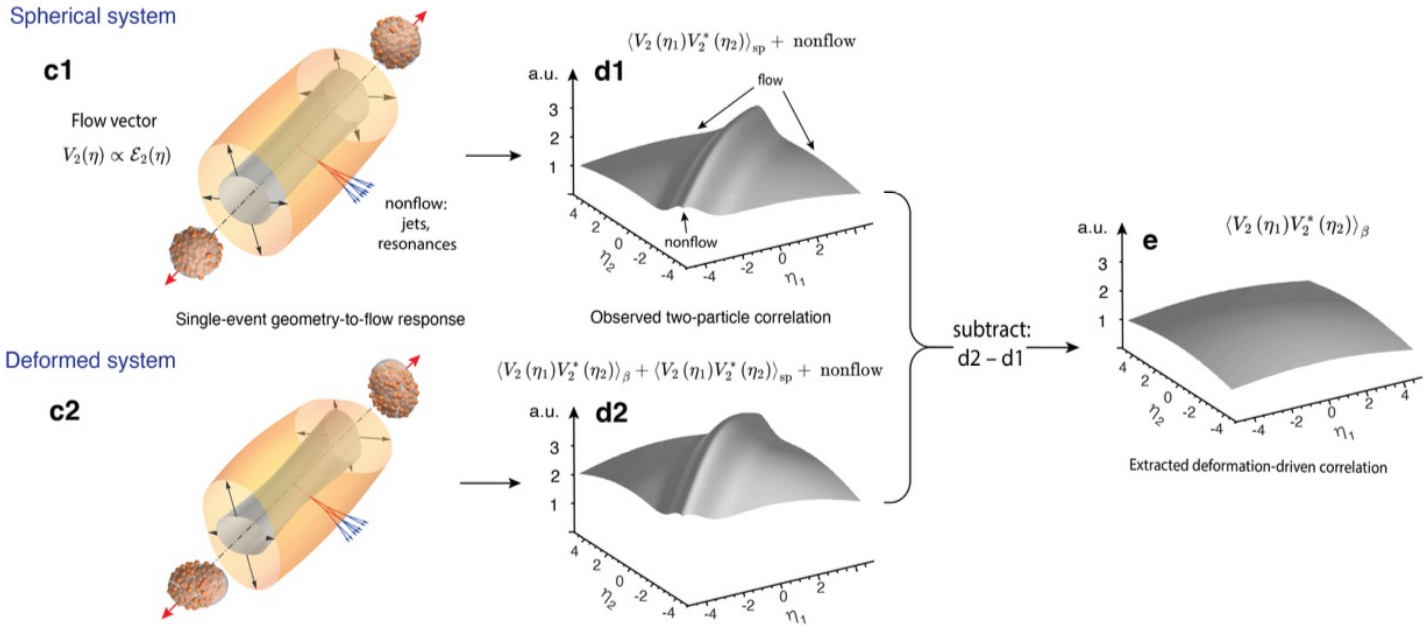
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How to get full map?

$R_2(\eta_1, \eta_2)$

$$V_{2\Delta} = a\,(\eta_1, \eta_2) + b\,(\eta_1, \eta_2)\beta^2 + \delta_{\rm nf}$$

baseline **deformation** **nonflow**

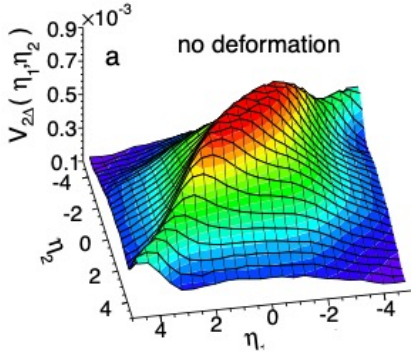


A shape contrast allow us to remove the nonflow and extract collective signal.

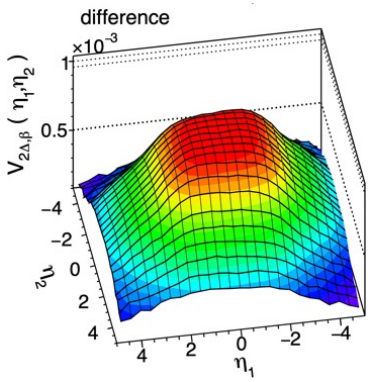
Watch the hidden decorrelation map emerge

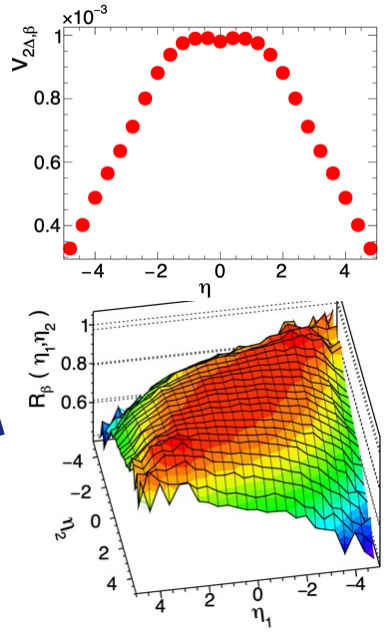
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AMPT: 0–5% U+U, $\sqrt{s_{NN}}$ = 193 GeV, 0.2 < p_T < 3 GeV/c



subtract





η dependence of flow

$$V_{2\Delta,\beta}(\eta,\eta) = \langle v^2_{2,\beta}(\eta)\rangle$$

Flow decorrelation

$$R_{2,\beta} = \frac{D_{12}}{\sqrt{D_{11}D_{22}}}$$

$$D = V_{2\Delta,\beta}$$

Deformation off → on:
$V_{2\Delta}$ increases by about x2.

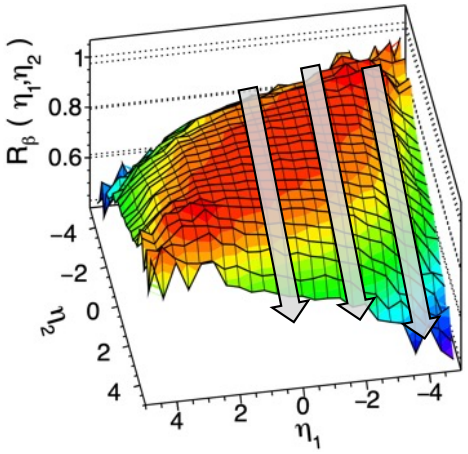
Subtract the two:
Nonflow ridge disappears

Factorize into:
η-dep. of flow and
flow decorrelations

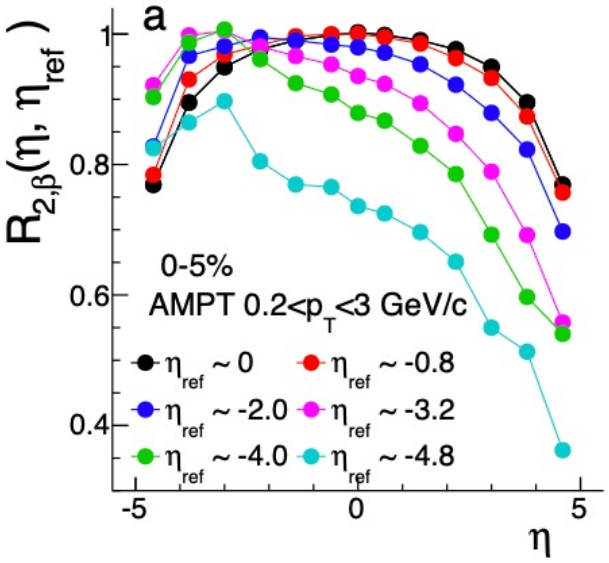
Nuclear shape as an instrument for recovering the hidden decorrelations

The map reveals limitation of r_2

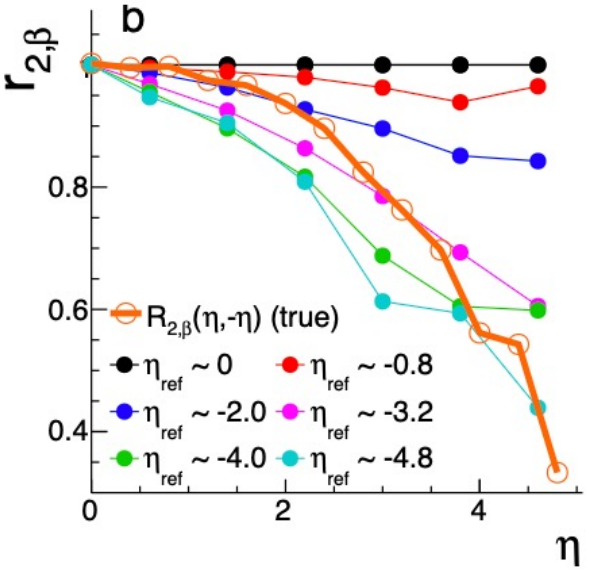
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Project different reference slices



$$r_2(\eta) = \frac{R(\eta, \eta_{\mathrm{ref}})}{R(-\eta, \eta_{\mathrm{ref}})}$$



$r_{2,\beta}$ differs from $R_{2,\beta}(\eta, -\eta)$
clear deviation from additive rule

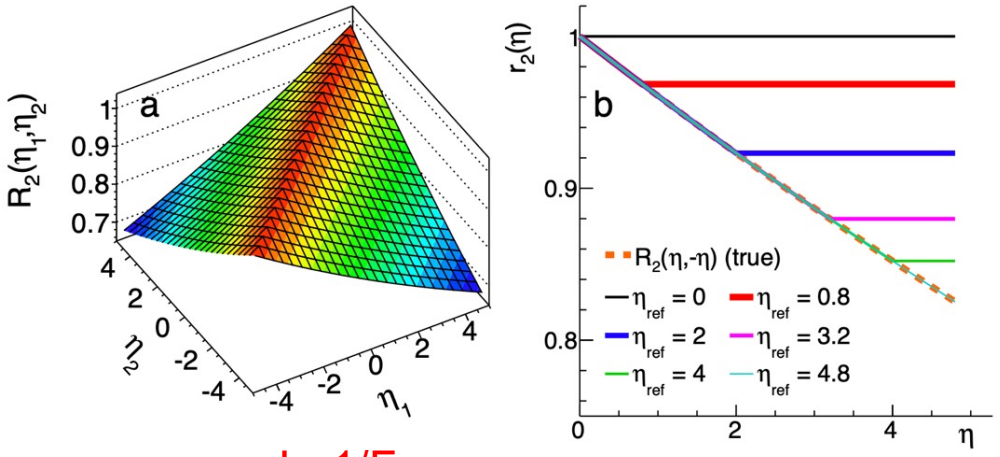
$r_2(\eta)$ is below the true correlation $R_2(\eta,-\eta)$: it overstates the decorrelation

The surprise: correlation loss is non-additive

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$R_2 \equiv \exp[-f(\eta_1,\eta_2)]$, additive means: $f(-a, a) = f(-a, 0) + f(0, a)$

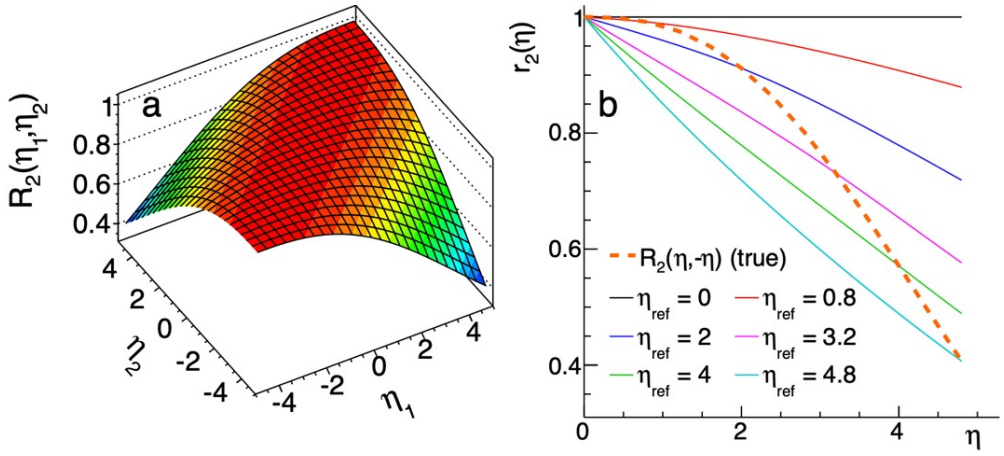
Additive loss



$L=1/F_2$

$R_2 = \exp[-|\Delta\eta|/L]$ → **Full gap = two half gaps**
→ r_2 curves collapse; bias cancels

Non-additive loss



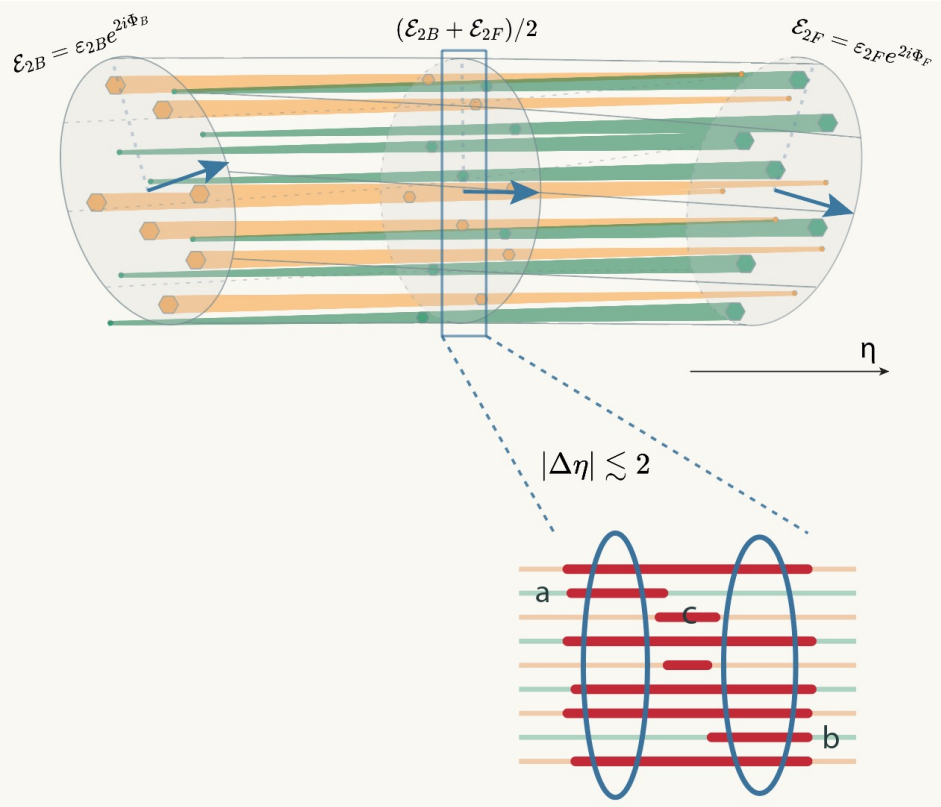
$R_2 = \exp[-(|\Delta\eta|/L)^p]$ → **Full-gap loss exceeds the sum**
→ r_2 curves separate, even without nonflow

$$p = 2.6,\ L = 10$$

AMPT results suggest a non-additive flow decorrelation

What is the origin of non-additivity?

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Nucleons deposit energy along their paths:

$$\mathcal{E}_2(\eta) = \frac{\sum_i w_i(\eta) r_i^2 e^{i2\phi_i}}{\sum_i w_i(\eta) r_i^2}$$

→ interpolating between ε_{2F} and ε_{2B};

→ string-length fluctuations add local fluctuations;

→ result: short- and long-range decorrelations.

$$R_2 = e^{-(|\Delta\eta|/L)^p}$$

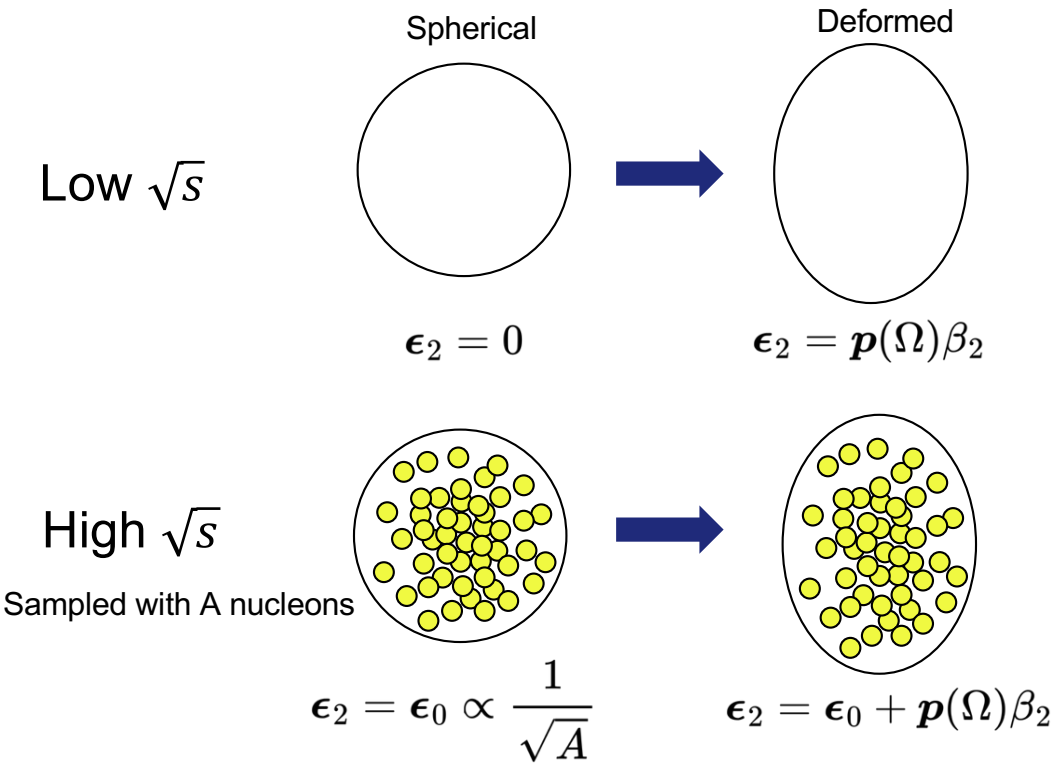
L: typical string length

p: how fast correlation is lost

Shared strings keep nearby rapidities correlated; beyond L it drops fast.

From the deformation map to the full map

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$$\mathcal{E}_2(\eta) = \frac{\sum_i w_i(\eta) r_i^2 e^{i2\phi_i}}{\sum_i w_i(\eta) r_i^2}$$

$$\mathcal{E}_2(\eta) = \mathcal{E}_{2,\mathrm{sp}}(\eta) + \mathcal{E}_{2,\beta}(\eta)$$

$$V_2(\eta) = \underbrace{V_{2,\mathrm{sp}}(\eta) + V_{2,\beta}(\eta)}$$

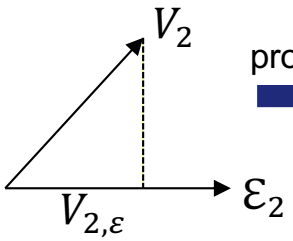
same decorrelations

The eccentricity depends only on where the nucleons are,
not on whether their positions come from fluctuations, nuclear correlations or deformation.

So the deformation map should image the full longitudinal structure.

Testing the shared decorrelation

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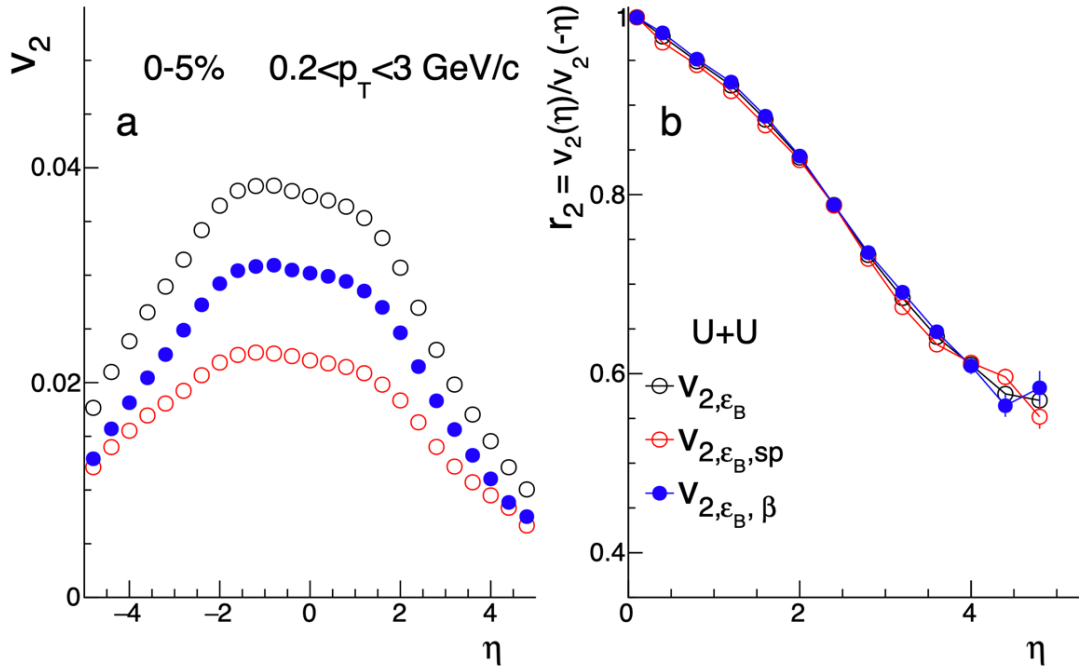
projection

$$v_{2,\varepsilon}(\eta) \equiv \frac{\langle V_2(\eta)\mathcal{E}_2^*\rangle}{\sqrt{\langle \mathcal{E}_2\mathcal{E}_2^*\rangle}}$$

nonflow drops out

Four projections: $$v_{2,X}(\eta) \equiv \frac{\langle V_2(\eta)X^*\rangle}{\sqrt{\langle XX^*\rangle}}$$

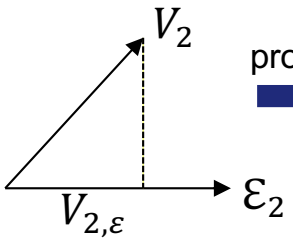
$$X \in \{\mathcal{E}_{2,\mathrm{B}}, \mathcal{E}_{2,\mathrm{B,sp}}, \mathcal{E}_{2,\mathrm{B},\beta}, V_2(\eta_{\mathrm{ref}})\}$$



Deformation changes the amplitude, not the longitudinal profile.

Testing the shared decorrelation

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projection

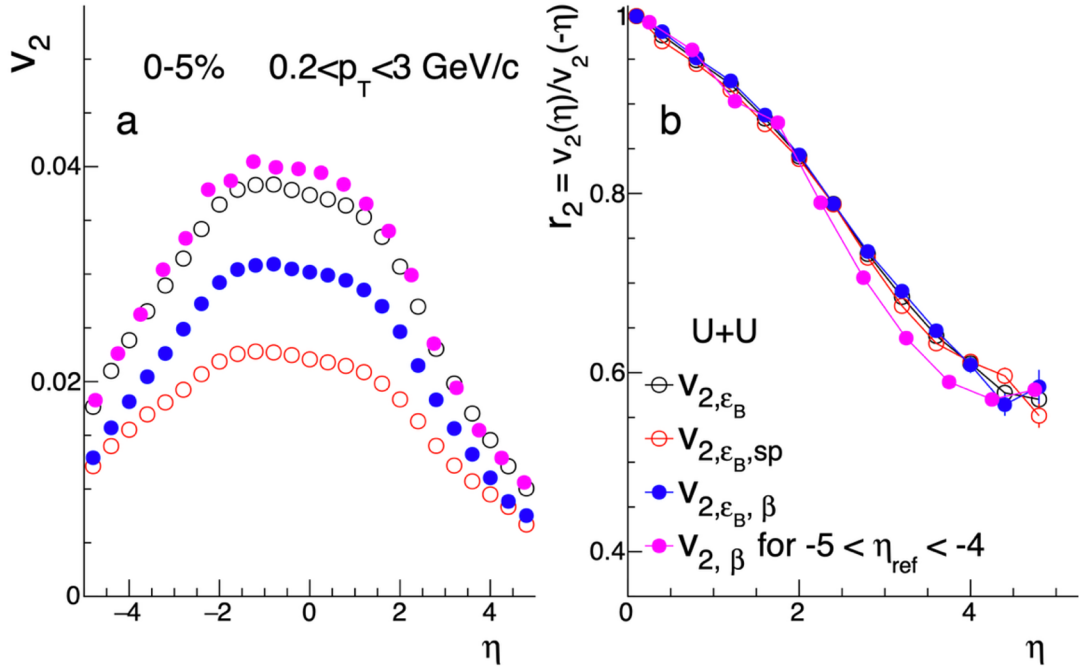
$$v_{2,\varepsilon}(\eta) \equiv \frac{\langle V_2(\eta)\mathcal{E}_2^*\rangle}{\sqrt{\langle \mathcal{E}_2\mathcal{E}_2^*\rangle}}$$

nonflow drops out

Four projections: $$v_{2,X}(\eta) \equiv \frac{\langle V_2(\eta)X^*\rangle}{\sqrt{\langle XX^*\rangle}}$$

$$X \in \{\mathcal{E}_{2,\mathrm{B}}, \mathcal{E}_{2,\mathrm{B,sp}}, \mathcal{E}_{2,\mathrm{B},\beta}, V_2(\eta_{\mathrm{ref}})\}$$

Backward V_2 is driven by backward ε_2: $V_2(\eta_{\mathrm{ref}}) \propto \mathcal{E}_{2,\mathrm{B}}$



Deformation changes the amplitude, not the longitudinal profile.

A real pair works too: U+U vs Au+Au

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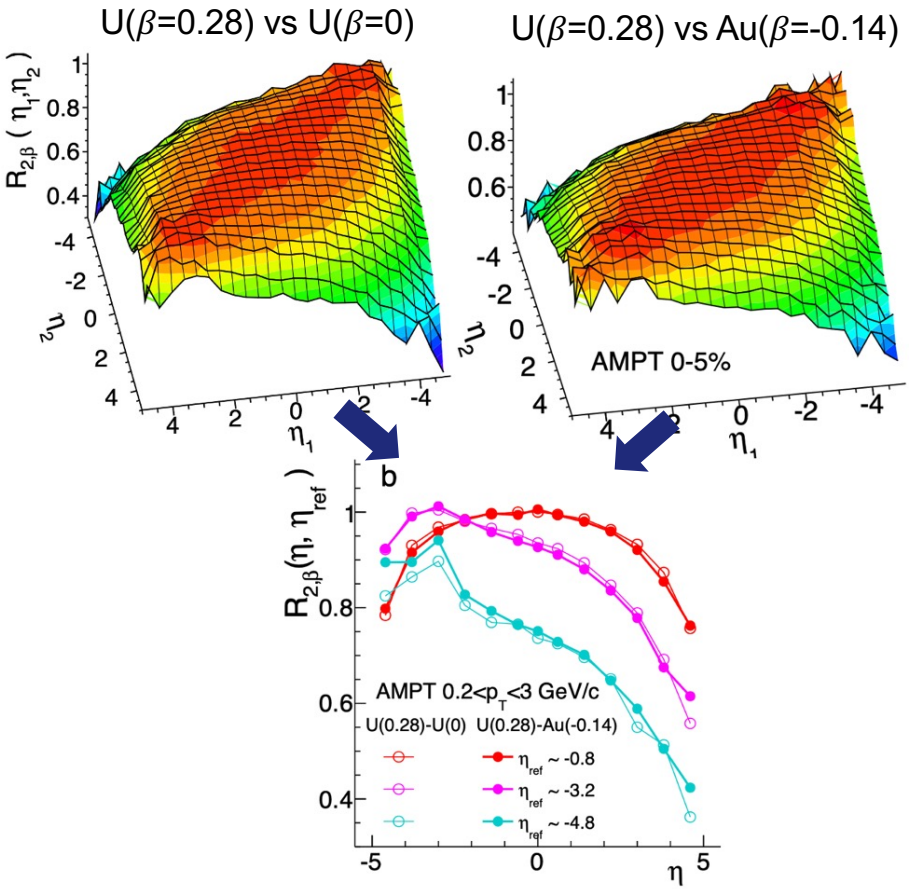
Matching uranium and gold

$$V_{2\Delta,\beta}^{\mathrm{U-Au}} = V_{2\Delta,\mathrm{U}} - \frac{\langle N_{\mathrm{ch}} \rangle_{\mathrm{Au}}}{\langle N_{\mathrm{ch}} \rangle_{\mathrm{U}}} V_{2\Delta,\mathrm{Au}}$$

- Au is mildly oblate (β ≈ −0.14): two real shapes
- Nonflow is diluted: $\delta_{nf} \propto 1/N_{ch} \propto 1/A$
- Ultra-central baseline flow: $V_{2\Delta,sp} \propto 1/A$
- **One multiplicity factor removes both mismatches**

Ideal switch vs real pair

- Open: ideal switch, U(β = 0.28) − U(0)
- Filled: real pair, U(0.28) − scaled Au(−0.14)
- **Maps and slices agree closely**



A real U/Au pair performs almost as well as the ideal deformation switch.

What have we learned so far?

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Nuclear shape reveals the full longitudinal decorrelation, free of nonflow.

The method

- A **nuclear-shape difference** removes nonflow and recovers the full longitudinal map.
- It works for a **real pair**, U+U vs Au+Au, despite their different mass numbers.

What the map tells us

- The correlation **persists, then drops steeply** beyond about two units of $\Delta\eta$.
  - It reflects the length distribution of the strings that deposit energy along the beam.
- The loss is **non-additive**: r_2 depends on η_{ref} even without nonflow.
- The **deformation-driven** part shares the longitudinal profile of the **total flow**.

Impact on standard flow measurements

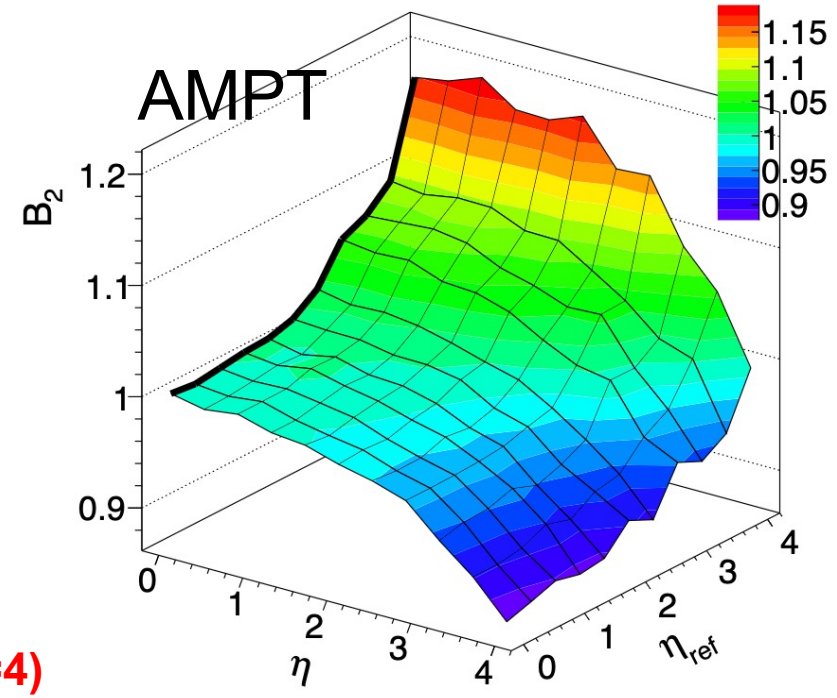
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Standard flow measurement: the three-subevent estimator

$$v_n^{\mathrm{est}} = \sqrt{\frac{\langle V_n V_n^*(\eta_{\mathrm{ref}})\rangle \langle V_n V_n^*(-\eta_{\mathrm{ref}})\rangle}{\langle V_n(\eta_{\mathrm{ref}}) V_n^*(-\eta_{\mathrm{ref}})\rangle}} = v_n B_n$$

$$B_n(\eta, \eta_{\mathrm{ref}}) = \sqrt{\frac{R_n(\eta, \eta_{\mathrm{ref}}) R_n(\eta, -\eta_{\mathrm{ref}})}{R_n(\eta_{\mathrm{ref}}, -\eta_{\mathrm{ref}})}}$$

- Numerator: two half gaps; denominator: full gap
- Decorrelation additive and $|\eta| < |\eta_{\mathrm{ref}}| \rightarrow B_n = 1$.
- Non-additive loss → $B_n > 1$, overestimate flow.



AMPT at midrapidity: $B_2 \approx 1.06$ (η_{ref}=3) and 1.16 (η_{ref}=4)

Non-additive decorrelation biases traditional flow measurements upward.

Outlook: decorrelation explains small-system flow puzzle?

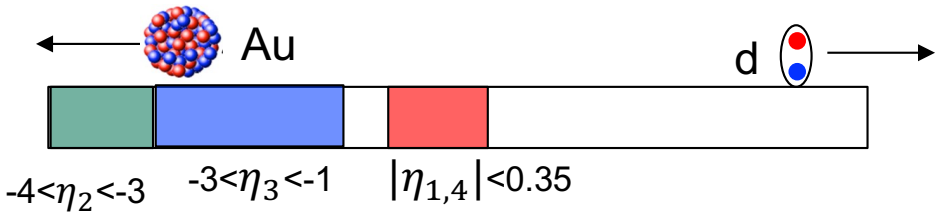
A prominent experimental puzzle

PHENIX and STAR report conflicting v_3 orderings in *p*+Au, *d*+Au and ^{3}He+Au.

The ordering tests nucleonic geometry versus subnucleonic fluctuations→ high stake

PHENIX: Au-going references.

STAR: references nearer mid-rapidity.



Acceptances sample different points

$$v_n^{\text{est.}} = v_n B_{n,4\text{sub}}$$

$$B_{n,4\text{sub}} = R_{12}\sqrt{\frac{R_{34}}{R_{32}R_{42}}},\ R_{ij} = R_n(\eta_i, \eta_j)$$

A quantitative next test

Measure the relevant R_3 map; calculate the bias for each detector combination.

Can the longitudinal map explain the PHENIX/STAR difference?

Outlook: extending the program of 3-D imaging

Jiangyong Jia



Longitudinal profile

Transverse size $S(\eta)$	Ellipticity $\varepsilon_2(\eta)$	Triangularity $\varepsilon_3(\eta)$
Pairs: different nuclear sizes **Map:** $\langle p_T \rangle$ correlation map **Images:** size along η **→ tests equation-of-state, neutron skin.**	**Pairs:** U/Au, Ru/Zr, O/Ne **Map:** $R_2(\eta_1, \eta_2)$ **Images:** ε_2 field along η **✓ shown in this talk**	**Pairs:** ε_3 contrast, e.g. Ru/Zr **Map:** $R_3(\eta_1, \eta_2)$ **Images:** ε_3 field along η **→ tests small-system puzzle**

Known nuclear shape can image the missing third dimension of the QGP.