

# Engineering the shapes of quark-gluon plasma droplets by comparing anisotropic flow in small symmetric and asymmetric collision systems

## Source of initial-state fluctuation in small system

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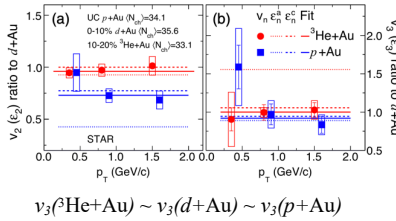


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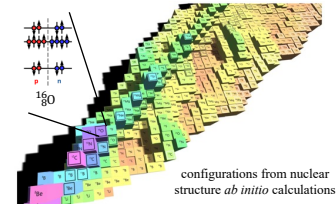
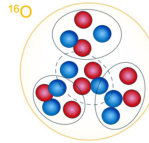


$$v_3(\text{He+Au}) \sim v_3(\text{d+Au}) \sim v_3(\text{p+Au})$$

Comparing asymmetric and symmetric systems can yield additional insights into geometry-driven picture and sub-nucleon fluctuations.

### Emergent phenomena of many-body quantum system

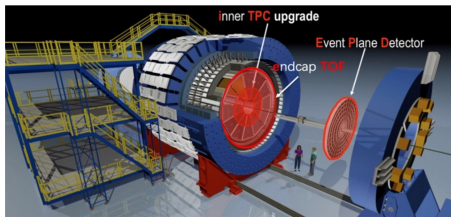
Vs.



configurations from nuclear structure *ab initio* calculations

$$\text{Woods-Saxon density: } \rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{(r-R(\theta, \phi))/a}}$$

### STAR detector



- ✓ O+O events: 500M MB and 380M HM; d+Au events: 76M MB and 70 M HM
- ✓ Large rapidity coverage due to iTPC  $|\eta| < 1.5$  and EPD  $(2.1 < |\eta| < 5.1)$
- ✓ Trigger on high multiplicity event at both middle and forward rapidity regions

### Measurements

Anisotropic flow  $v_n$  (two- and four-particle correlations):

$$v_n\{2\} = \sqrt{\langle v_n^2 \rangle},$$

$$v_n\{4\} = \left( 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle \right)^{1/4}$$

$$\langle v_n^2 \rangle^{\text{obs}} = \frac{\langle \sum_{i \neq j} w_i w_j \cos(n(\phi_i - \phi_j)) \rangle}{\sum_{i \neq j} w_i w_j}$$

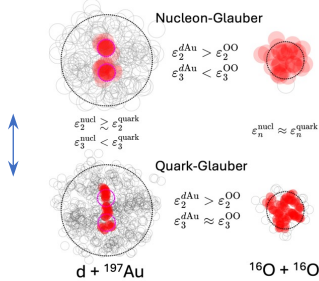
$$\langle v_n^4 \rangle^{\text{obs}} = \frac{\langle \sum_{i \neq j \neq k \neq l} w_i w_j w_k w_l \cos(n(\phi_i + \phi_j - \phi_k - \phi_l)) \rangle}{\sum_{i \neq j \neq k \neq l} w_i w_j w_k w_l}$$

- ✓ suppress non-flow correlations from near-side jets:
- ✓ suppress non-flow correlations from near-side jets:
- $f = \langle v_n^2 \rangle^{\text{obs}} / \langle v_n^2 \rangle^{\text{obs, LM}}$  ( $v_n^2$ -scaling method) as default
- $f = N_{\text{ch}}^{\text{LM}} / N_{\text{ch}}$  ( $N_{\text{ch}}$ -scaling) for estimating the nonflow systematics
- ✓  $v_2\{4\}$  measurements use the standard and subevent methods

STAR, PRL 130, 242301 (2023)  
STAR, PRC 110, 064902 (2024)

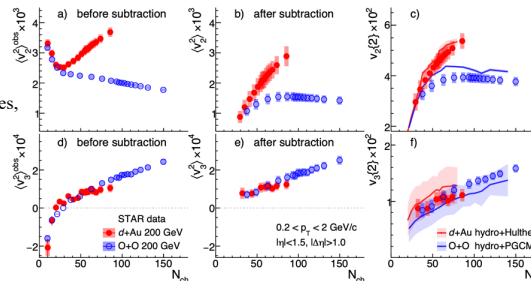
### Results and discussions

#### 1. Contrasting initial geometry in d+Au and O+O collisions



At low  $N_{\text{ch}}$ , non-flow dominates, At higher  $N_{\text{ch}}$ , genuine flow dominates the  $N_{\text{ch}}$ -dependent behavior.

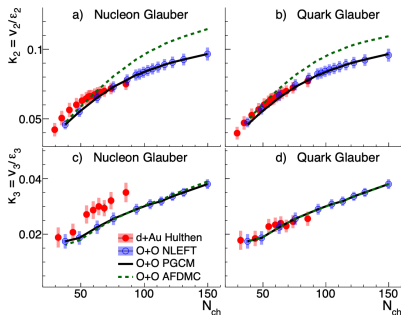
#### 2. Flow coefficients from two-particle correlation method



$v_2(\text{d+Au}) > v_2(\text{O+O})$  tracks initial geometry hierarchy

Similar gradual increase  $v_3$  in two systems, characteristic of a fluctuation-driven origin.

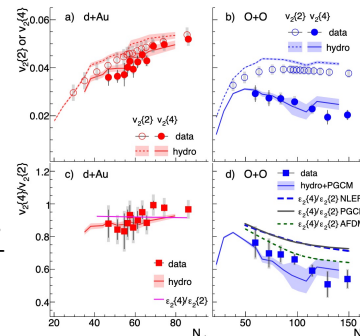
#### 3. Impact of nuclear and subnucleonic structures



$v_2$  reflects mainly nucleon configurations, while  $v_3$  is more sensitive to subnucleonic fluctuations.

At large  $N_{\text{ch}}$ ,  $k_2^{\text{OO}}$  shows divergence  
 $k_2^{\text{OO}} \approx \epsilon_2^{\text{NLEFT}} \approx \epsilon_2^{\text{PGCM}} > \epsilon_2^{\text{AFDMC}}$   
 $k_3^{\text{OO}}$  values agree among three model input, consistent with random fluctuation dominance for triangularity.

#### 4. Contrasting elliptic flow fluctuations



The pronounced elliptic shape in d+Au collisions enhances the average geometry component:  $\epsilon_2\{4\} \approx \epsilon_2\{2\}$ ,  $\epsilon_2^{\text{d+Au}}\{4\} \approx 0.95 \epsilon_2^{\text{d+Au}}\{2\}$

O+O collisions have a much smaller average geometry component:  $\epsilon_2\{4\} < \epsilon_2\{2\}$ ,  $\epsilon_2^{\text{O+O}}\{4\} \approx 0.5 \epsilon_2^{\text{O+O}}\{2\}$

modest sensitivity of  $\epsilon_2\{4\}/\epsilon_2\{2\}$  to *ab initio* nucleon configuration models

Unambiguously geometrical origin of  $v_2$ , differing markedly between symmetric and asymmetric collisions.

### Summary

- Comparable sizes and  $\epsilon_3$ , but with very different  $\epsilon_2$  and fluctuation patterns in d+Au and O+O systems: a powerful lever arm to test impacts of nucleon configuration and subnucleon fluctuations
- $\epsilon_2^{\text{d+Au}}\{2\} > v_2^{\text{O+O}}\{2\}$  at large  $N_{\text{ch}}$ : large intrinsic elliptic shape of the deuteron.  
 $\epsilon_2^{\text{d+Au}}\{2\} \approx v_2^{\text{O+O}}\{2\}$  across the full  $N_{\text{ch}}$  range, consistent with the fluctuation-driven scenario in the quark-Glauber model
- Flow patterns are quantitatively described by a hydrodynamic model: indicating efficient transformation of initial geometries to final-state anisotropies.
- Highlight the “Smashing-by-imaging” method in light-ion  $^{16}\text{O}$  structure, and further establish a novel benchmarking interdisciplinary connection between high- and low-energy.

### References

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