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# *Recent Results on Collectivity Measurements at RHIC*

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# Outline

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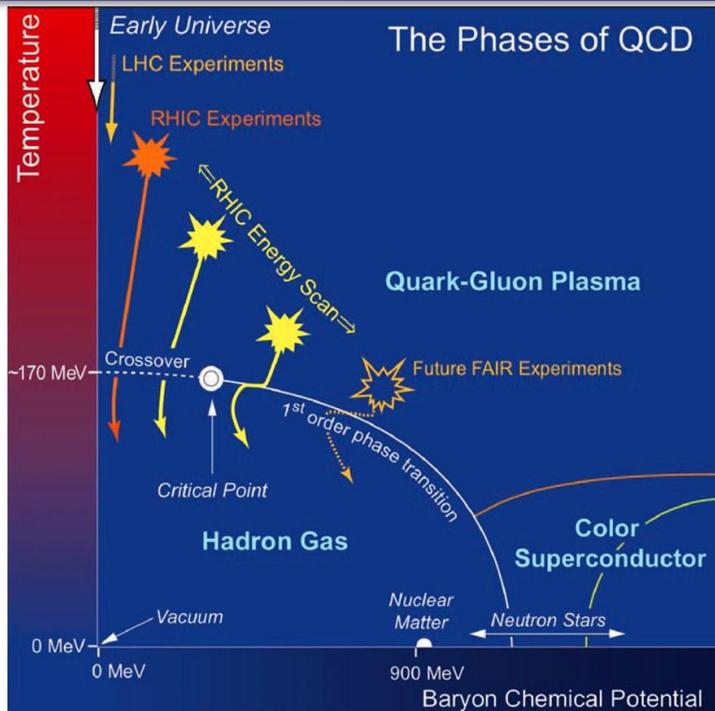
## ➤ Introduction

## ➤ Collectivity Measurements

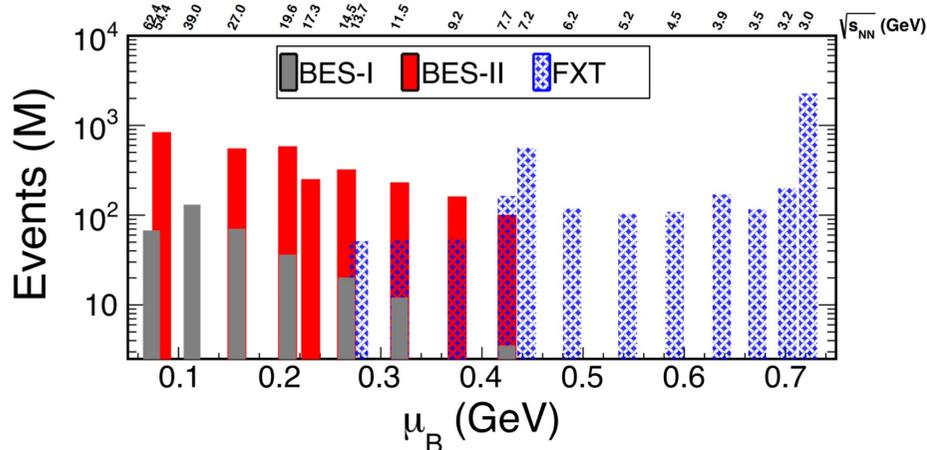
- ✓ Directed Flow at high  $\mu_B$
- ✓ Elliptic Flow and Partonic Collectivity
- ✓ Collectivity in Small Systems
- ✓ System Size and Shape Dependence

## ➤ Summary

# Introduction



<https://drupal.star.bnl.gov/STAR/starnotes/public/sn059>



## ✓ RHIC Top Energy

p+p, p+Al, p+Au, d+Au,  $^3\text{He}+\text{Au}$ , Cu+Au, O+O, Cu+Cu, Ru+Ru, Zr+Zr, Au+Au, U+U

- QCD at high energy density and/or temperature
- Properties of QGP, Equation of State
- Proton spin structure

## ✓ Beam Energy Scan

Au+Au  $\sqrt{s_{NN}} = 7.7, 9.2, 11.5, 14.5, 17.3, 19.6, 27, 39, 54.4, 62.4$  GeV

- QCD phase transition
- Search for critical point
- Turn-off of QGP signatures

## ✓ Fixed-Target Program

Au+Au  $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7$  GeV

- High baryon density regime ( $\mu_B \sim 420 - 720$  MeV)

# Collective Flow

- Collective flow describe the response of the medium produced in heavy-ion collisions

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, y) \cos(n(\phi - \Psi_R)) \right)$$

$$v_n = \langle \cos(n(\phi - \Psi_R)) \rangle, \quad \phi = \tan^{-1} \left( \frac{p_y}{p_x} \right)$$

- Different flow coefficients are sensitive to the initial state and properties of the medium

Phys. Rev, C 58 (1998) 1671  
arXiv:0809.2949

## Directed Flow ( $v_1$ ):

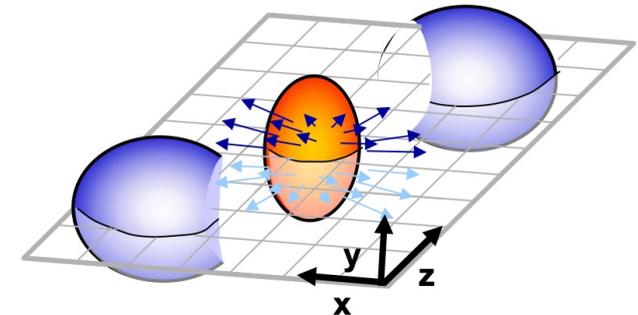
-- sideward collective motion of particles within the reaction plane (x-z)

## Elliptic Flow ( $v_2$ ):

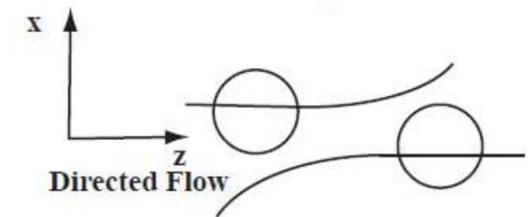
-- coordinate space anisotropy transforms to momentum space anisotropy

## Triangular Flow ( $v_3$ ):

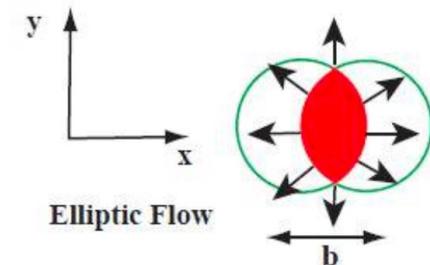
-- event-by-event fluctuations in the initial shape



Reaction plane: xz plane

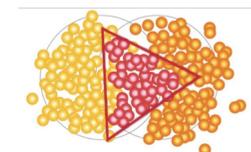


Directed Flow

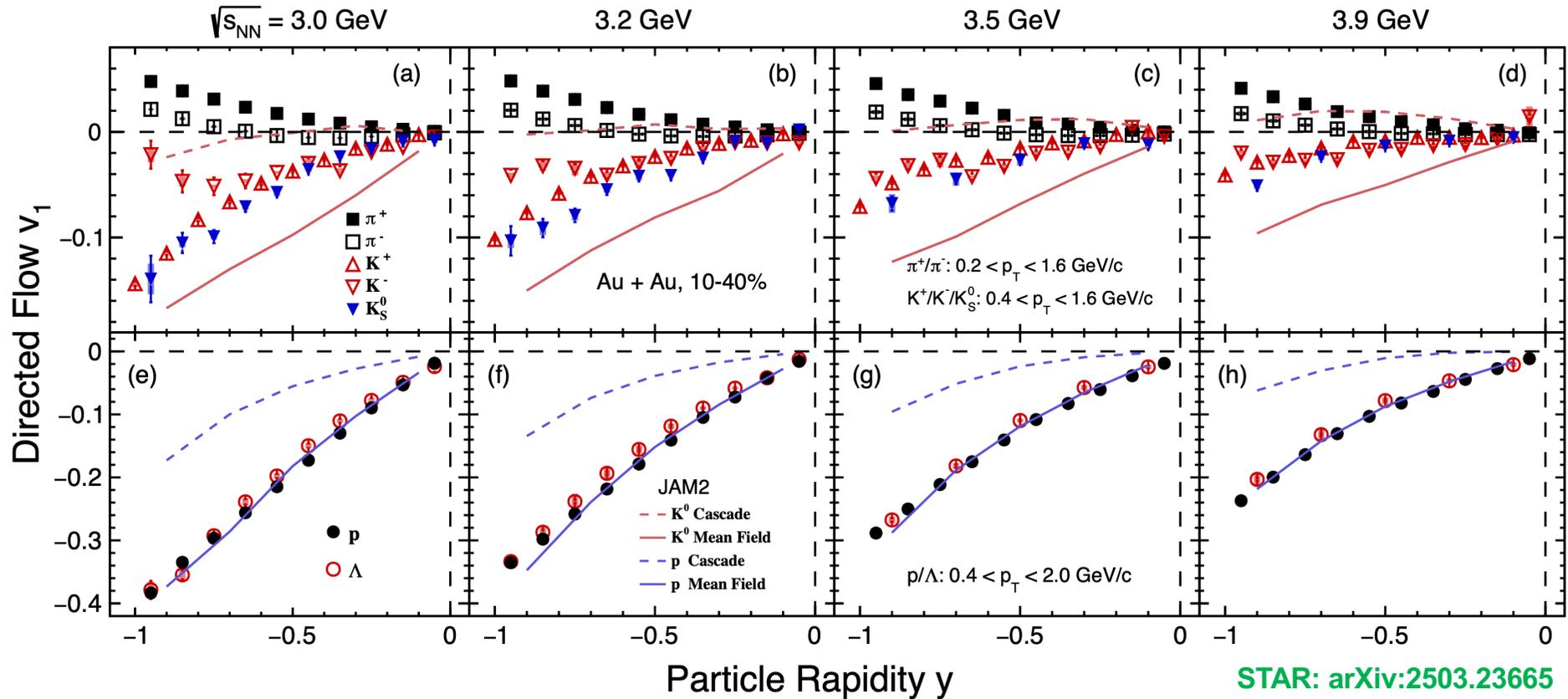


Elliptic Flow

Triangular Flow



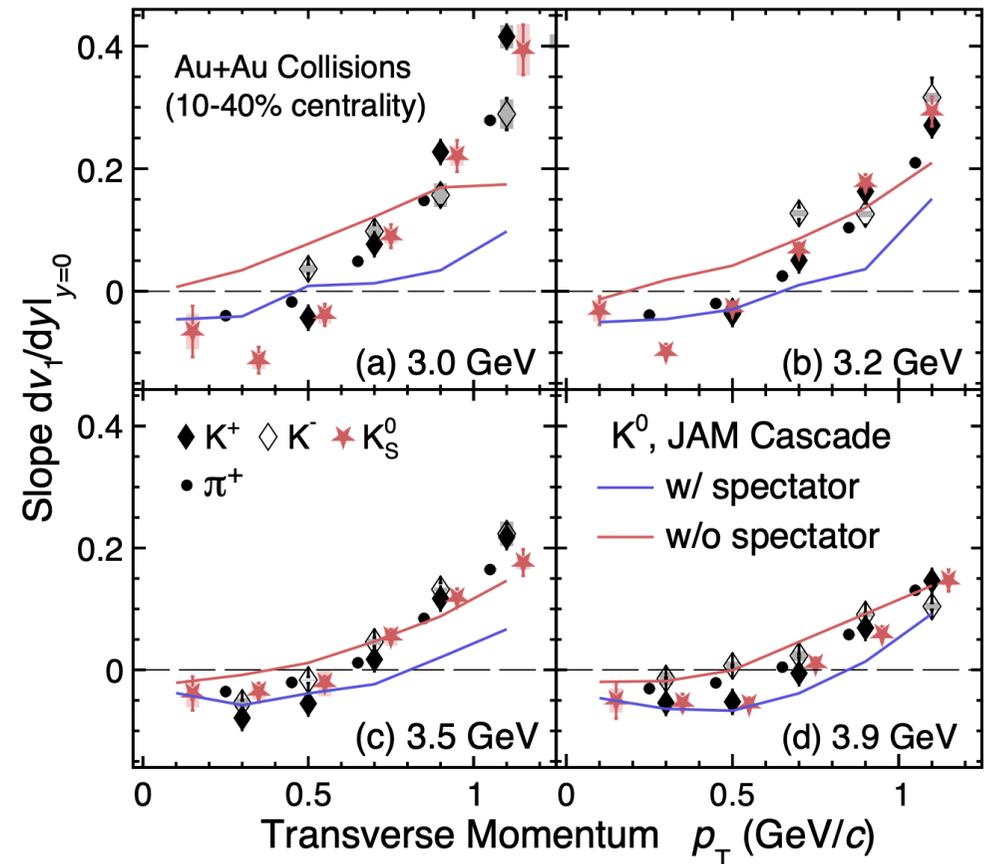
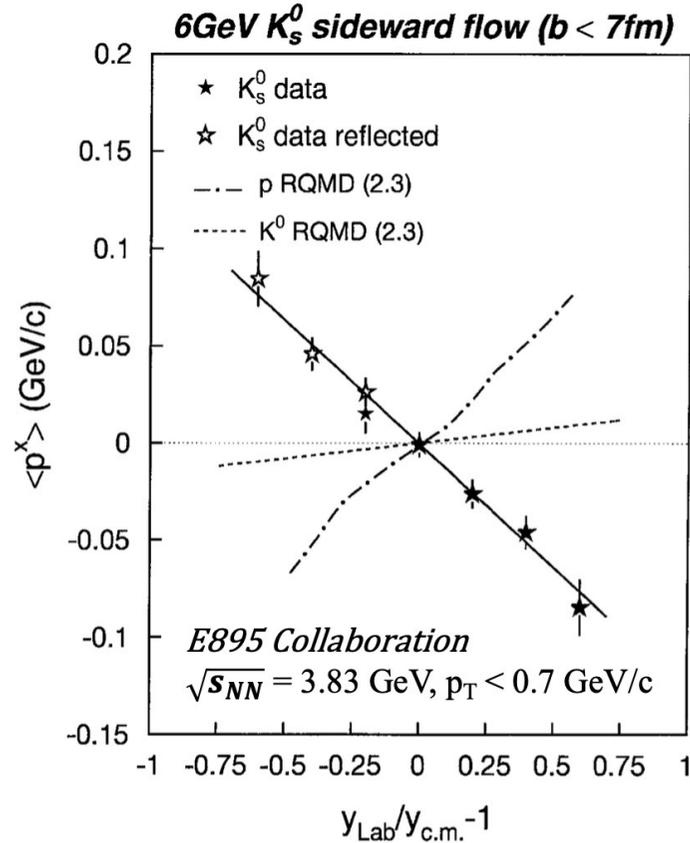
# Directed Flow at High $\mu_B$



- Measurements of rapidity dependence of  $v_1$  for  $\pi^\pm$ ,  $K^\pm$ ,  $K_S^0$ ,  $p$ ,  $\Lambda$  at 3.0, 3.2, 3.5, and 3.9 GeV
- JAM model with baryonic mean field (momentum dependent Soft EoS, the nuclear incompressibility  $k = 210$  MeV) describes proton  $v_1$

# Anti-flow of Kaon at High $\mu_B$

E895, Phys. Rev. Lett. 85, 940 (2000)

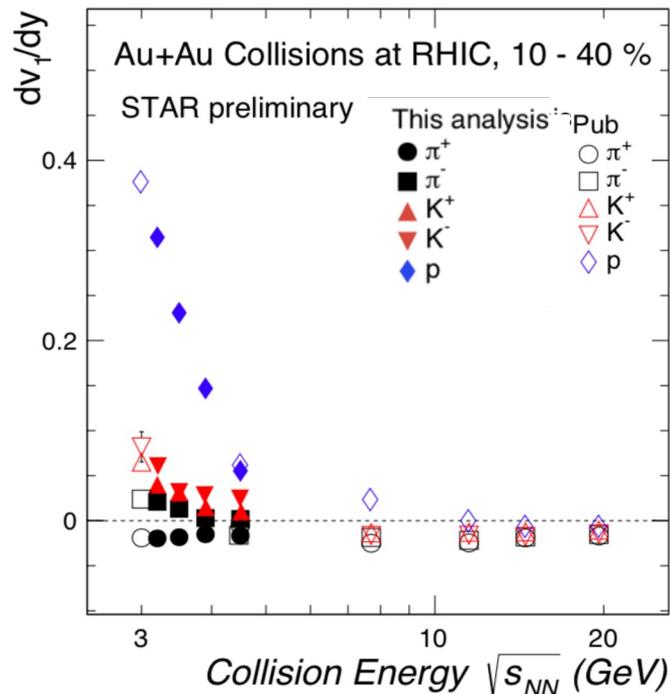


STAR: arXiv:2503.23665

- Anti-flow is observed for  $\pi^+$ ,  $K_s^0$ , and  $K^\pm$  at low  $p_T$
- Anti-flow could be explained by **shadowing effect from spectators**, kaon potential is not necessary

# Energy dependence of $v_1$ slope

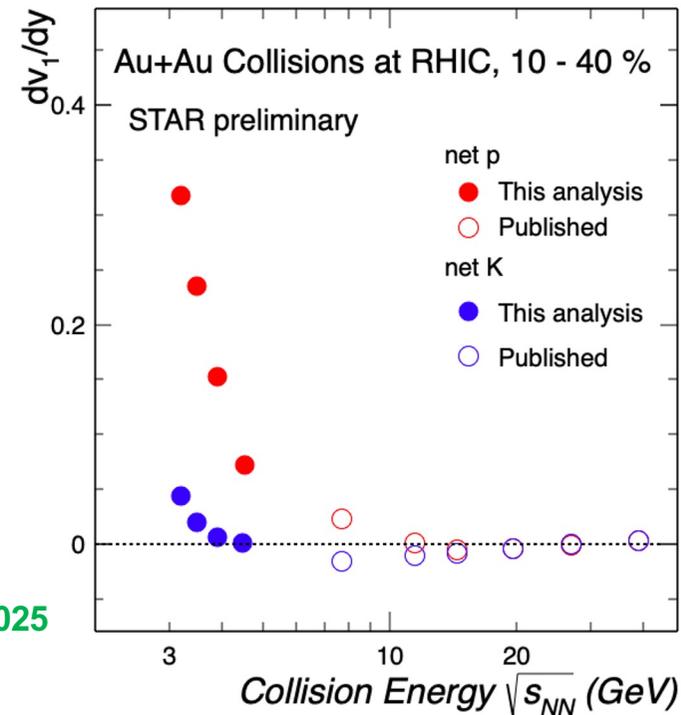
## Identified hadrons



STAR, QM2025

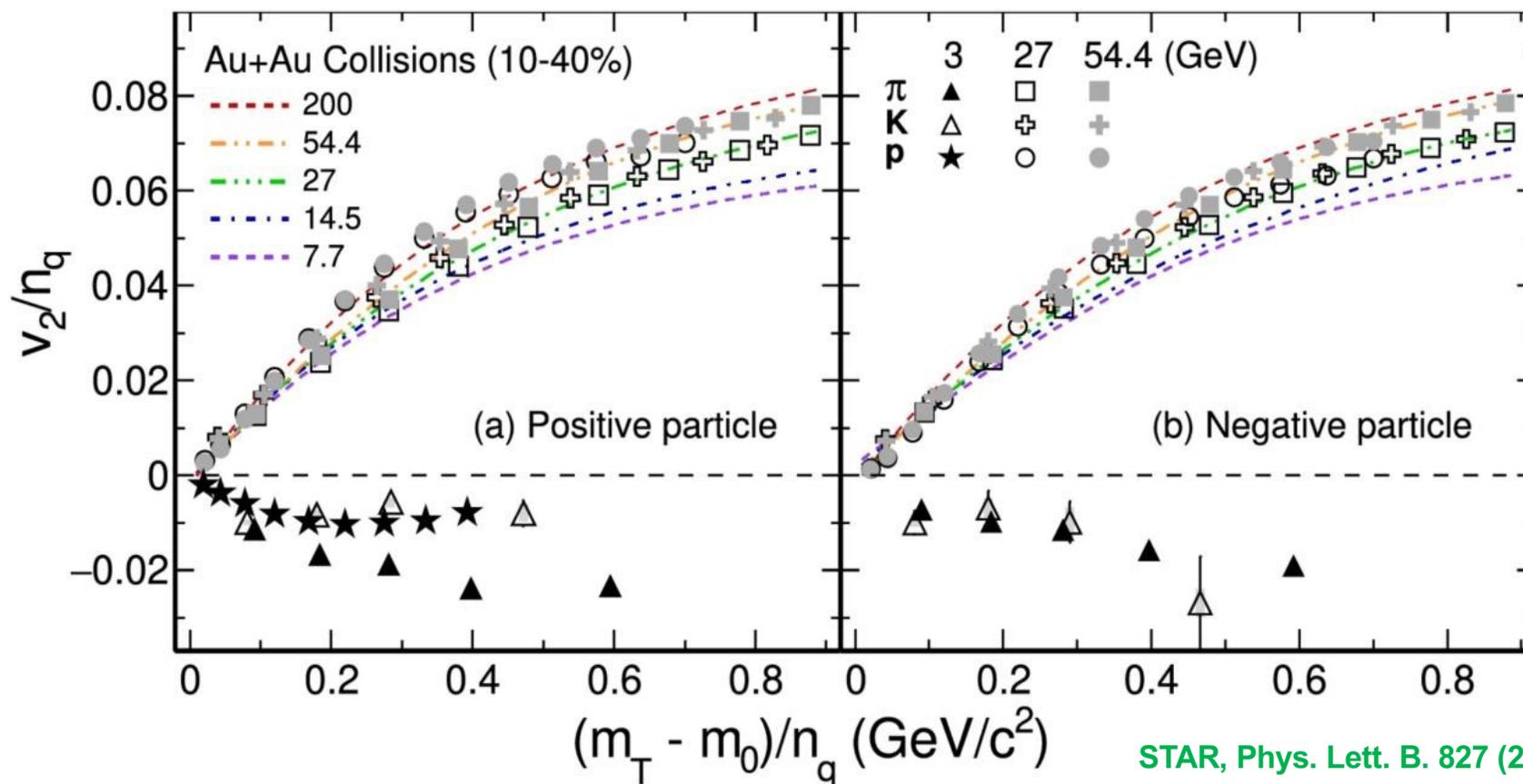
STAR: PRL120, 062301 (2018); PRC 102, 044906 (2020)

## Net-particle



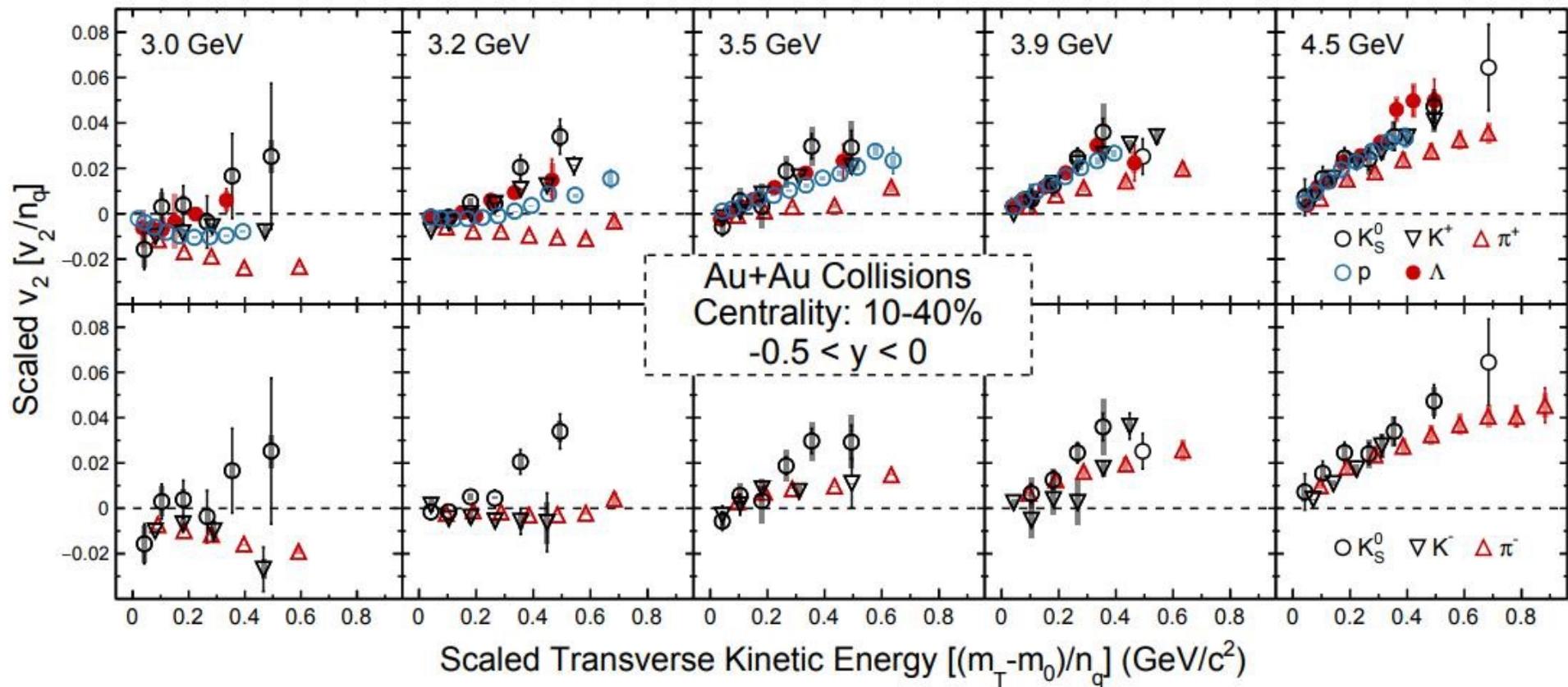
- $v_1$  slope decreases in magnitude as collision energy increases
- $v_1$  slope for  $\pi^+$  is negative whereas  $v_1$  slope for  $\pi^-$  positive, suggesting dominant effect of baryon stopping and coulomb interactions at low collision energies
- **Net-K** changes sign at lower collision energy (4.5 - 7.7 GeV) compared to **Net-p** (11.5 - 14.5 GeV)

# Elliptic Flow



- NCQ scaling holds in Au+Au collisions from top RHIC energy  $\sqrt{s_{NN}} = 200$  to 7.7 GeV  
-- Partonic collectivity
- Negative  $v_2$  values and breaking of NCQ scaling at  $\sqrt{s_{NN}} = 3$  GeV  
-- Indicative of medium dominated by hadronic interactions

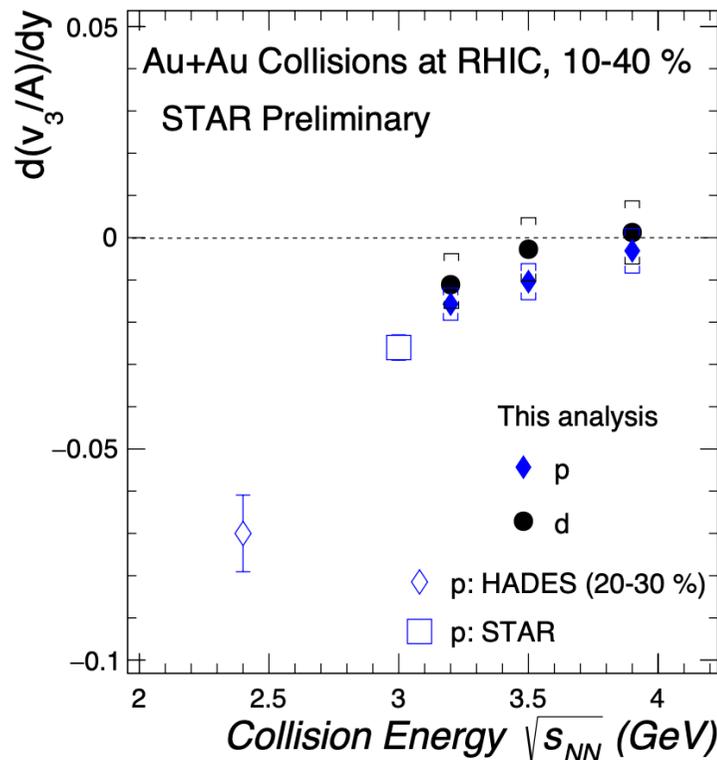
# Onset of partonic collectivity



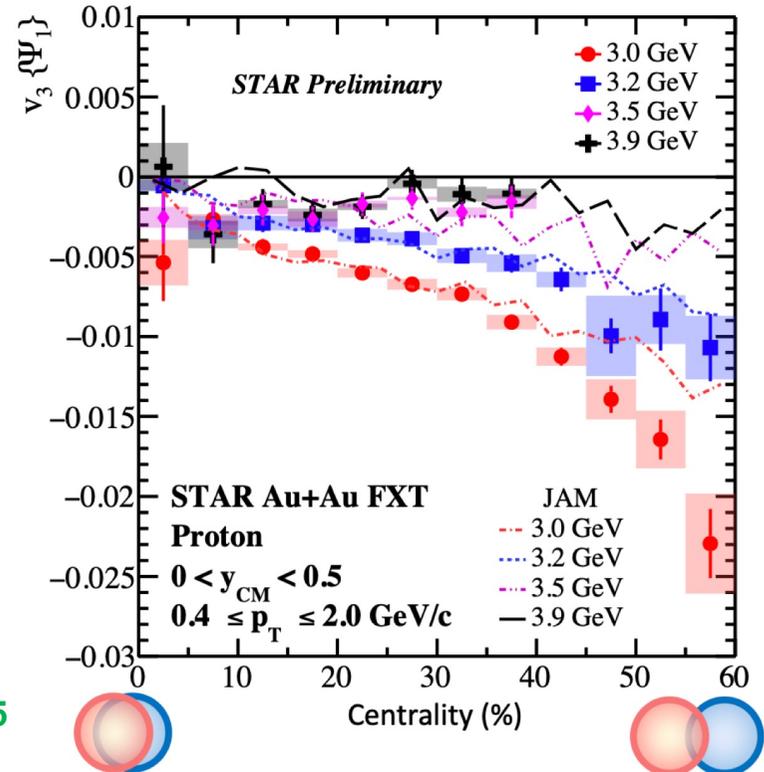
STAR: arXiv:2504.02531

- NCQ scaling is broken in Au+Au collisions below 3.2 GeV
- NCQ scaling gradually improves in Au+Au collisions from 3.2 to 4.5 GeV
  - Indication of transition from hadronic dominated medium to partonic medium

# Triangular Flow ( $v_3\{\Psi_1\}$ )



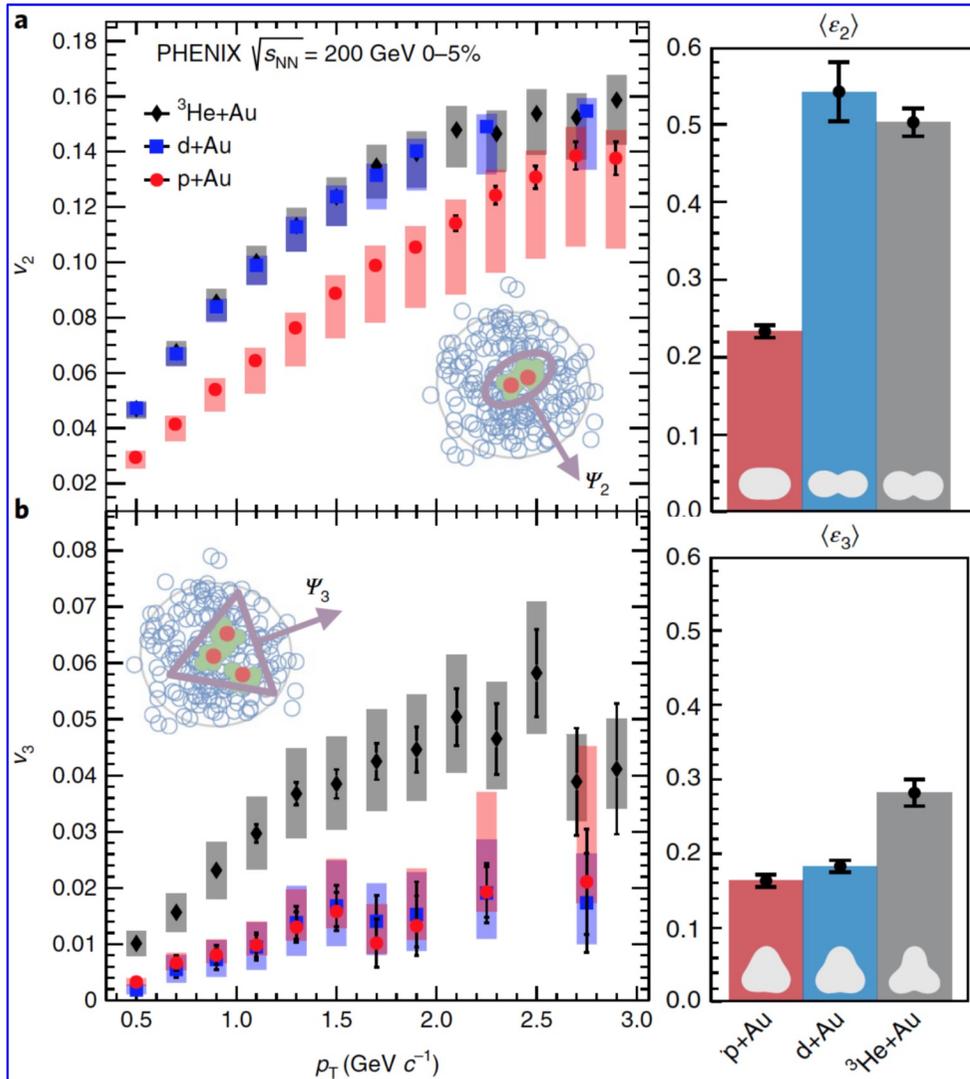
STAR, QM2025



HADES: *Eur. Phys. J. A* 59 4, 80 (2023), STAR: *Phys. Rev. C* 109, 044914 (2024)

- $v_3$  at higher energies results from fluctuations in shape of the initial condition and is not correlated to the reaction plane
- First observation of  $v_3$  correlated to first order reaction plane at 2.4 GeV (HADES)
- Non-zero  $|v_3\{\Psi_1\}|$ , increase towards peripheral collisions
  - ✓ Geometry driven  $v_3$  at lower energy
  - ✓ JAM describes the data implying importance of nuclear potential

# Collectivity in p+Au, d+Au and $^3\text{He}+\text{Au}$



PHENIX, Nature Phys. 15, 214 (2019)

$$\epsilon_2^{p+\text{Au}} < \epsilon_2^{d+\text{Au}} \approx \epsilon_2^{^3\text{He}+\text{Au}}$$



$$v_2^{p+\text{Au}} < v_2^{d+\text{Au}} \approx v_2^{^3\text{He}+\text{Au}}$$

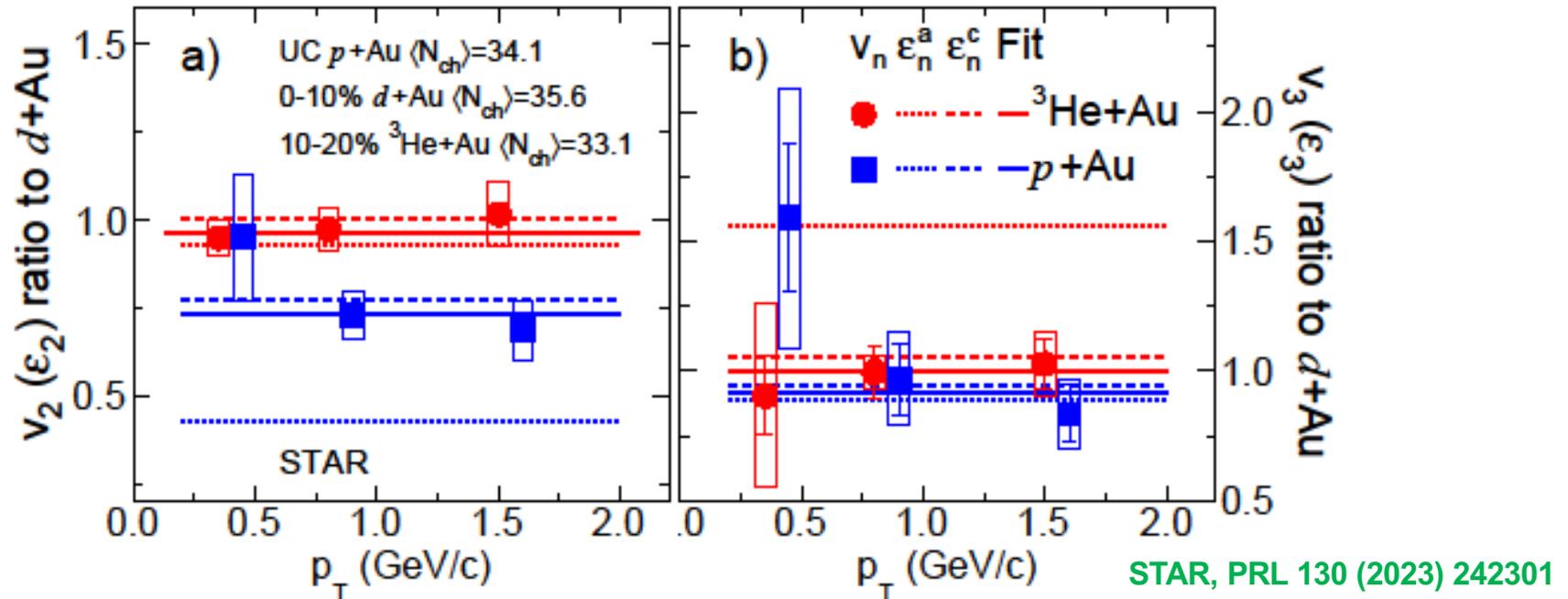
$$\epsilon_3^{p+\text{Au}} \approx \epsilon_3^{d+\text{Au}} < \epsilon_3^{^3\text{He}+\text{Au}}$$



$$v_3^{p+\text{Au}} \approx v_3^{d+\text{Au}} < v_3^{^3\text{He}+\text{Au}}$$

✓ Suggests flow is geometric in origin

# Collectivity in p+Au, d+Au and $^3\text{He}+\text{Au}$



$$v_2^{p+Au} < v_2^{d+Au} \sim v_2^{He+Au}$$

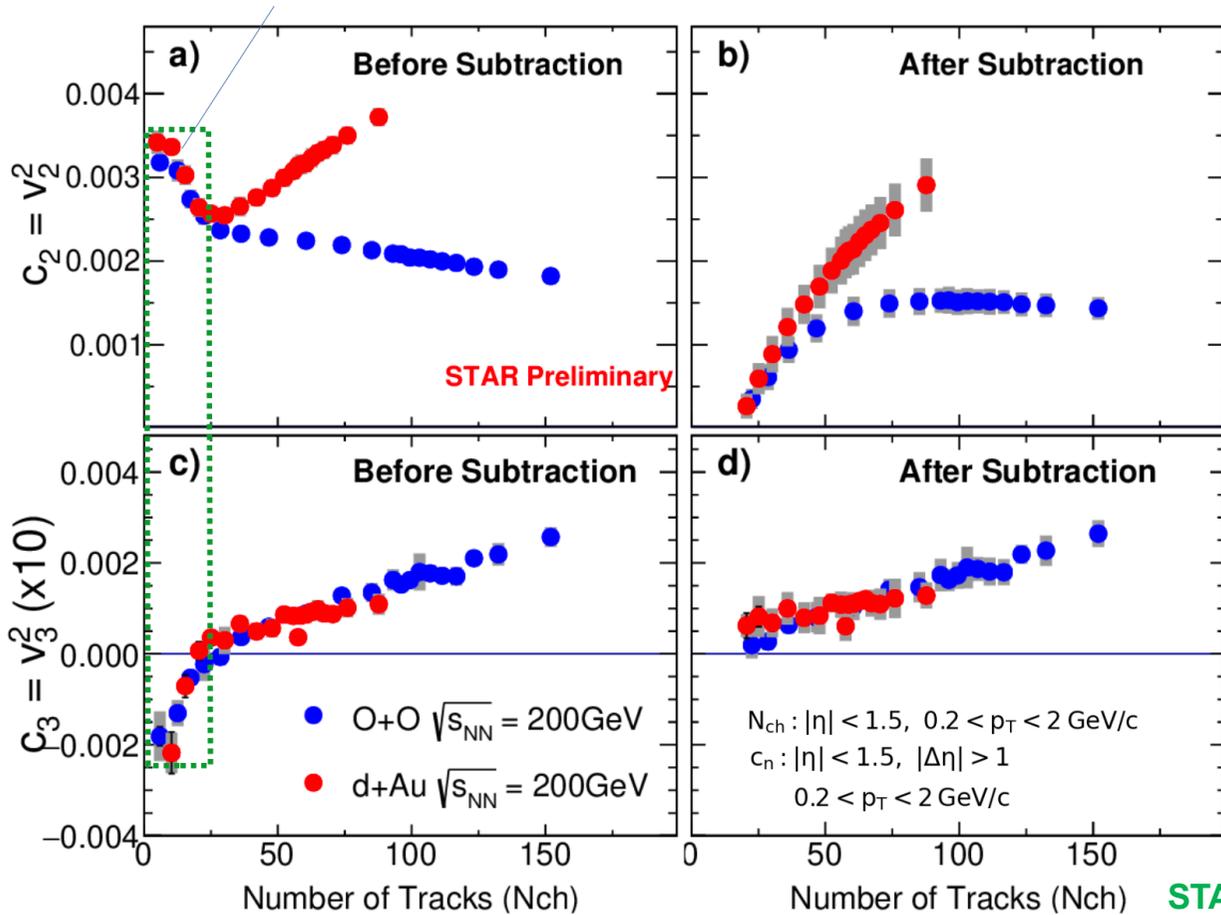
$$v_3^{p+Au} \sim v_3^{d+Au} \sim v_3^{He+Au}$$

	Nucleon Glauber	Sub-Nucleon Glauber
	$\epsilon_2(\epsilon_3)$	$\epsilon_2(\epsilon_3)$
0-5% pAu	0.23(0.16)	0.38(0.30)
0-5% dAu	0.54(0.18)	0.51(0.31)
0-5% $^3\text{He}+\text{Au}$	0.50(0.28)	0.52(0.35)

Nucleon Glauber: J. L. Nagle, et. al., PRL 113 (2014) 112301  
 Sub-nucleon: K. Welsh, et. al., PRC 94 (2016) 024919

➤ Suggests significant influence of sub-nucleonic fluctuations

# Collectivity in d+Au and O+O Collisions



Two particle correlation method:

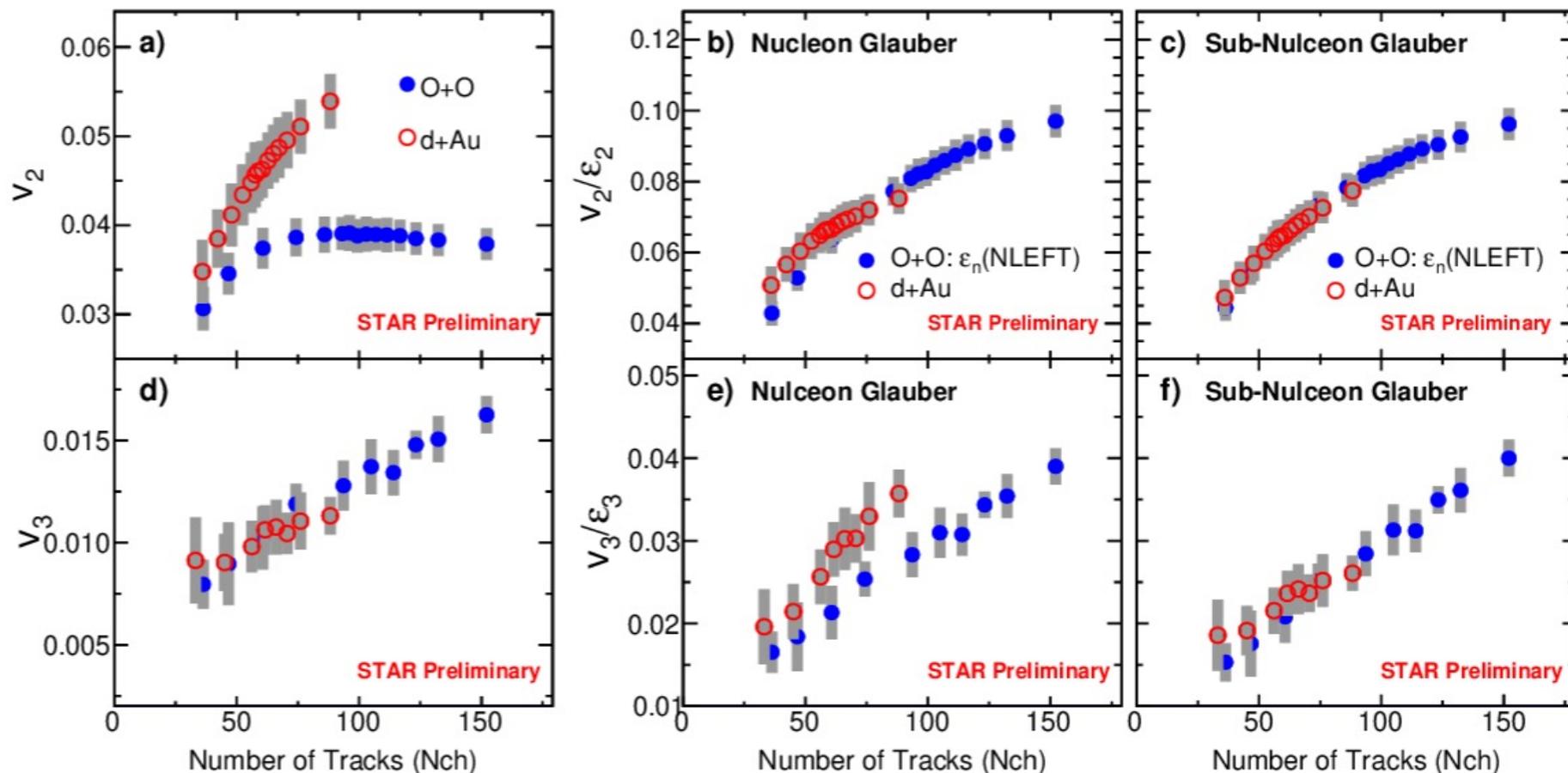
$$\frac{dN}{d\Delta\phi} \propto 1 + 2 \sum_{n=1}^{\infty} c_n(p_T^t, p_T^a) \cos(n\Delta\phi)$$

Non-flow subtraction:

$$c_n^{\text{sub}} = c_n^{\text{raw}} - \frac{c_1^{\text{central}}}{c_1^{\text{peripheral}}} \times c_n^{\text{peripheral}}$$

- Non-monotonic d+Au  $c_2$ : Transition from non-flow dominance (peripheral) to flow dominance (central).
- $c_2(\text{d+Au}) > c_2(\text{O+O})$ : reflects initial geometry hierarchy.
- Similar  $c_3$  values observed in both systems.

# Collectivity in Small Systems

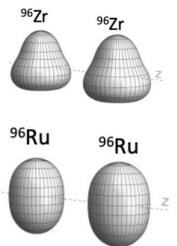
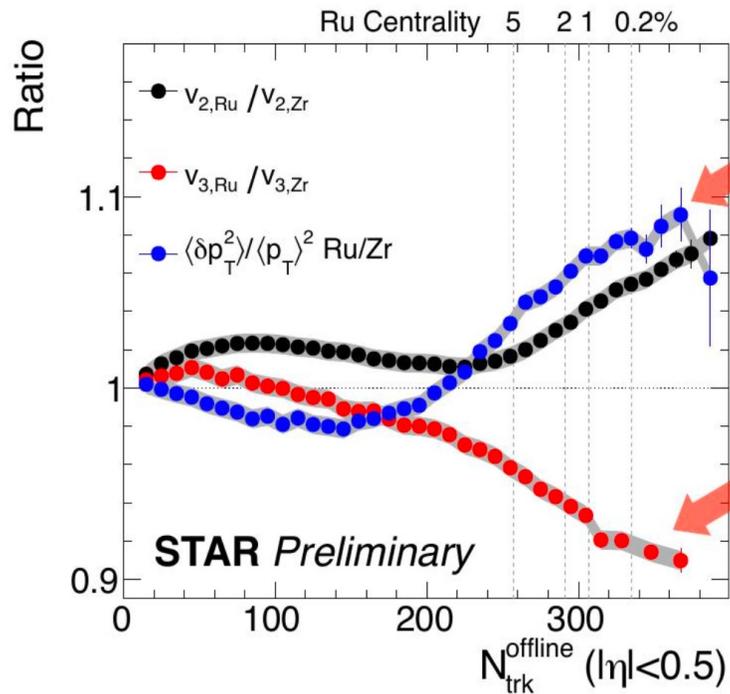


STAR, QM2025

- $v_2/\epsilon_2$  : d+Au and O+O show consistent collective response to geometry
- $v_3/\epsilon_3$  : Prefer sub-nucleon fluctuation

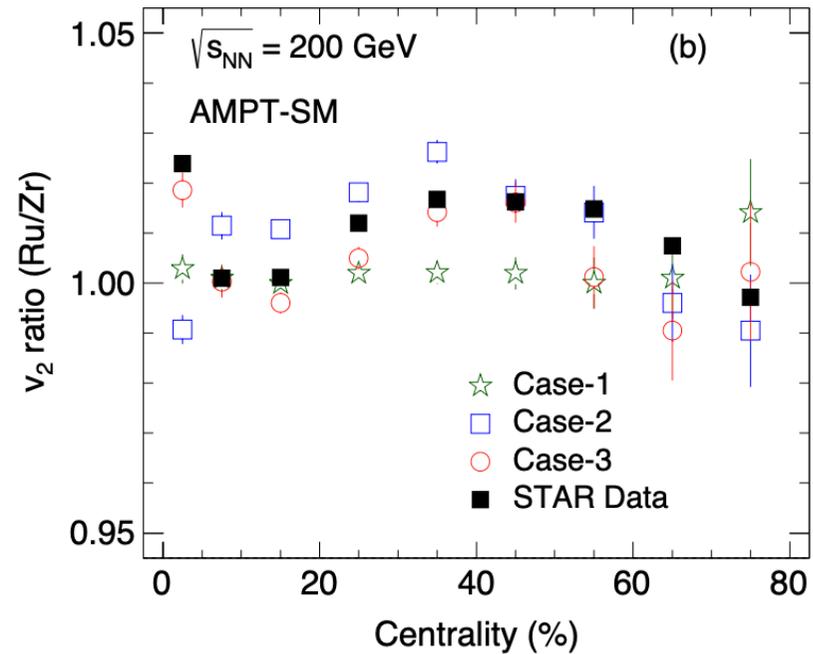
A QGP droplet in small system?

# Collectivity: Probing Nuclear Structure



$$\beta_2(\text{Ru}) > \beta_2(\text{Zr})$$

$$\beta_3(\text{Ru}) < \beta_3(\text{Zr})$$

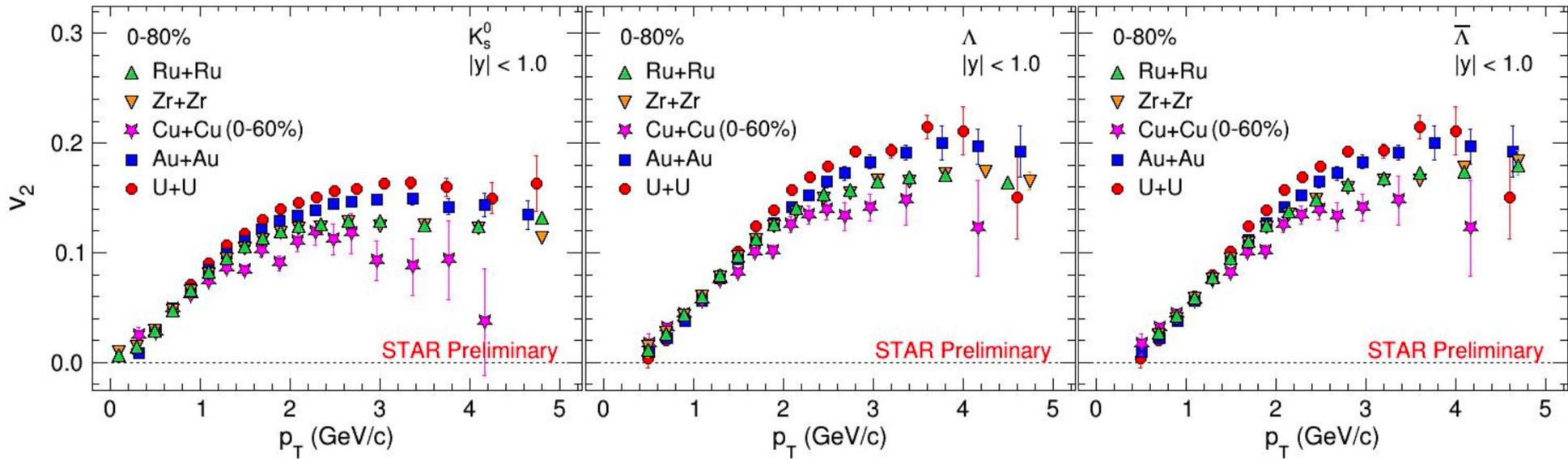


Case-3	$R_0$	$a$	$\beta_2$	$\beta_3$
Ru	5.09	0.46	0.162	0
Zr	5.09	0.52	0.060	0.2

P. Sinha, CJ et al., Phys. Rev. C 108, 024911 (2023)

- Ratio of integrated  $v_2$  between Ru+Ru and Zr+Zr collisions differs from unity
  - Indication of larger nuclear deformity in Ru nuclei than in the Zr nuclei

# Collectivity: System Size Dependence



- Elliptic flow of strange hadrons at high  $p_T$  increases with increasing system size

# Summary

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RHIC continues to deliver high-impact results on the QCD phase diagram and fundamental QCD properties.

- Anti-flow of mesons observed → hints of shadowing effects from spectators
- Breaking of NCQ scaling → Hadronic interactions dominate at lower collision energies
- Elliptic flow in small systems → initial geometry driven collectivity
- Elliptic flow shows system-size dependence at high  $p_T$ .
- $v_3$  correlated to  $\Psi_1$  decreases with increasing energy

*More interesting results from BES-II and top energy heavy-ion collisions are on the way.*

Stay Tuned!



*Thank You!*