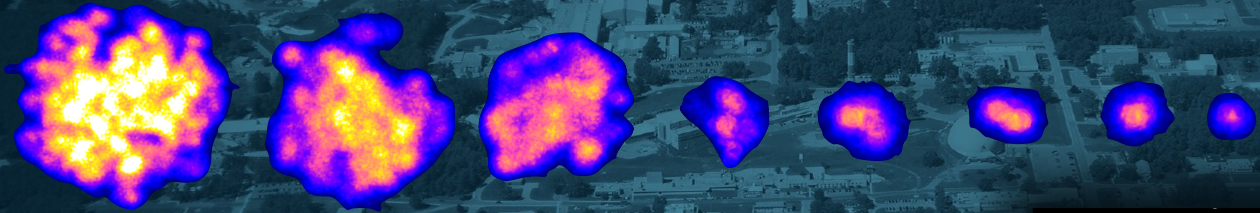
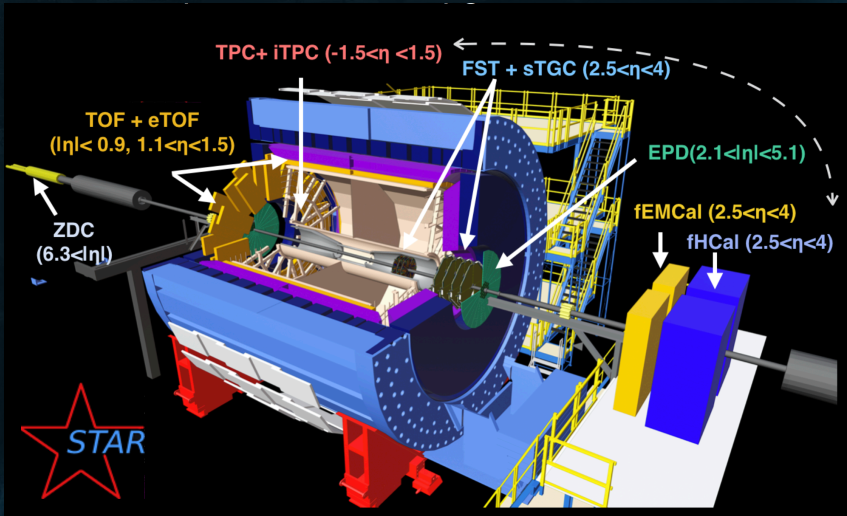
The present and future of small-systems collectivity search from STAR



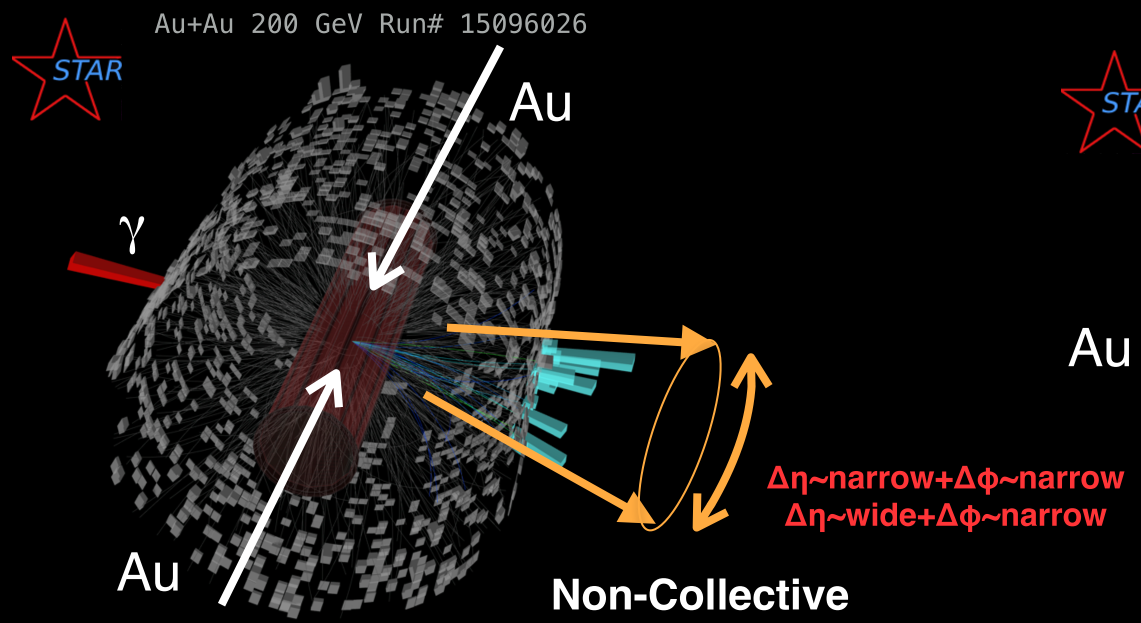
Prithwish Tribedy for the STAR collaboration
(Brookhaven National Laboratory)

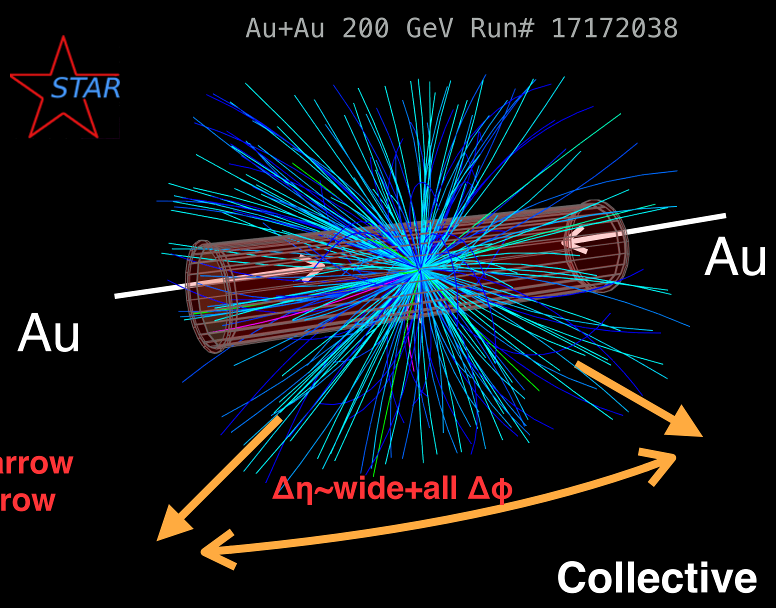
APS GHP meeting, March 13-16, 2025



Brookhaven National Laboratory
U.S. DEPARTMENT OF ENERGY

Search for collectivity





Pattern: Correlation over a **narrow phase space**
Players: A few constituents (a few-particle effect)
Source: Conservation, quantum process in QCD

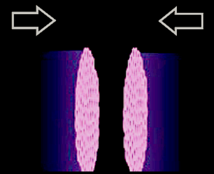
Patten: Correlation over **wide phase space**
Players: Most constituents (many-particle effect)
Source: Emergent phenomena in QCD

Goal: search for pattern of particle emission that span over a wide phase space: "collectivity" & how it evolves with system size

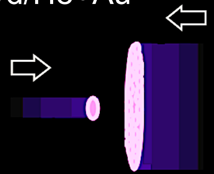
System scan at RHIC & collectivity search

STAR

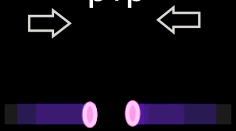
A+A



p/d/He+Au



p+p



γ + A

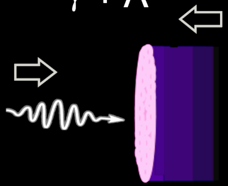
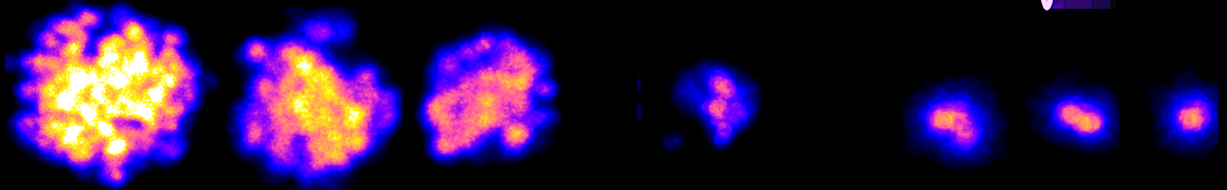
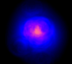


fig: Chun Shen QM19





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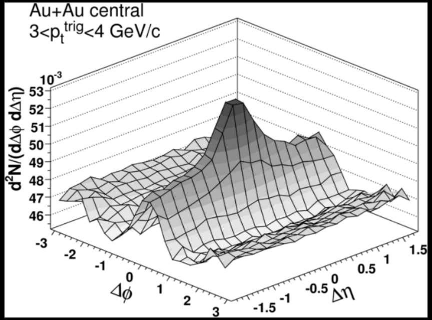
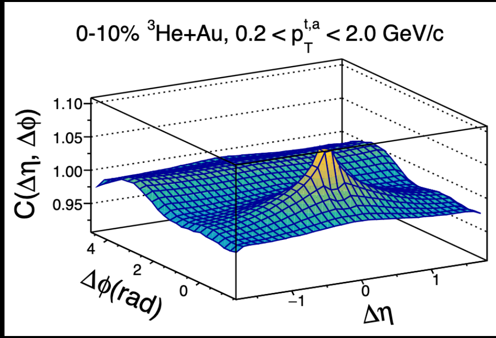
U+U Au+Au Ru+Ru O+O ^{3}He+Au d+Au p+Au p+p Photonuclear



STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912



STAR collaboration, Phys. Rev. C 110 (2024) 64902,
Phys.Rev.Lett. 130 (2023) 24, 242301

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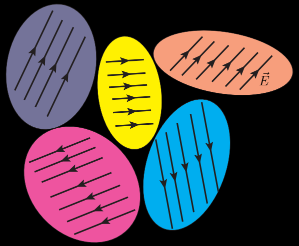
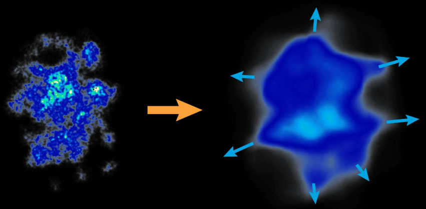
Sources of collectivity: initial state vs. final state

STAR

ε_p : Initial-state momentum correlations (CGC)



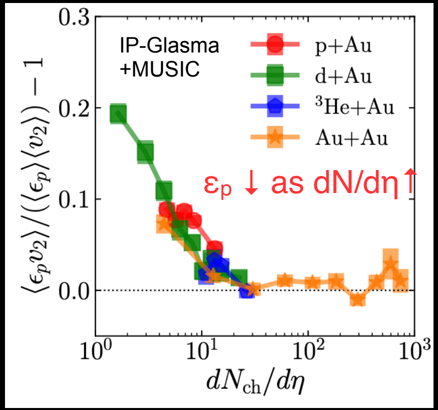
ε_2 : Initial-state geometry + fluid-response (hydro)

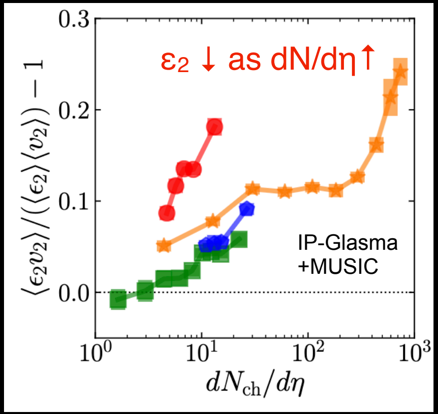


Initial energy density distribution

Hydrodynamic expansion

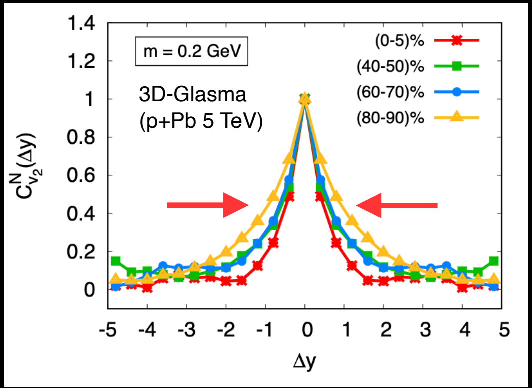
Contribution to measurable v_2



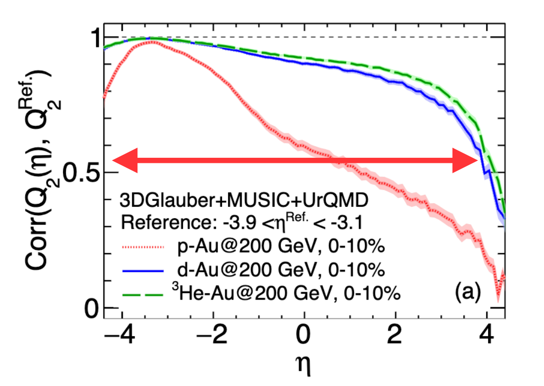


Schenke, Shen, PT, Phys. Lett. B 803, 135322 (2020)

Decorrelation with (pseudo)rapidity



Schenke, Schlichting, Singh, Phys. Rev. D 105, 094023 (2022)

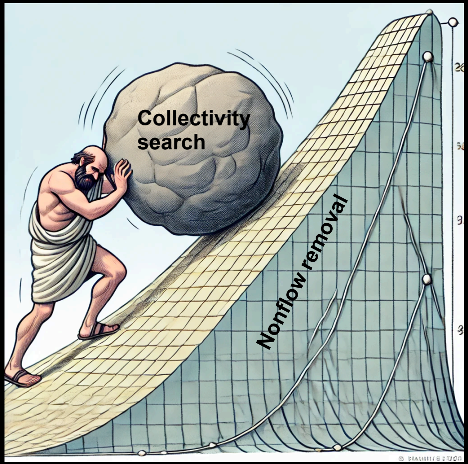


Zhao, Ryu, Shen, Schenke, Phys. Rev. C 107, 014904 (2023)

Nonflow: A Persistent Challenge in Collectivity Studies

STAR

Non-flow (non collective part) Removal: Major challenge, multiple approaches, still debated



1. Large Δη Gap: Suppresses near-side jet/resonance, away-side remains
2. Near-side subtraction: Removes excess non-flow using near-side yields

$$c_n^{\mathrm{sub}}(\mathrm{sys}) = c_n(\mathrm{sys}) - \frac{Y^{\mathrm{NS}}(\mathrm{sys})}{Y^{\mathrm{NS}}(\mathrm{pp})} \cdot \frac{c_0(pp)}{c_0(\mathrm{sys})} \times c_n(pp)$$

3. Template Fit: Compares high- vs. low-Nch to isolate near-side "ridge."

$$Y(\Delta\phi)^{\mathrm{template}}(sys) = F \times Y(\Delta\phi)(pp) + Y(\Delta\phi)^{\mathrm{ridge}}(sys)$$

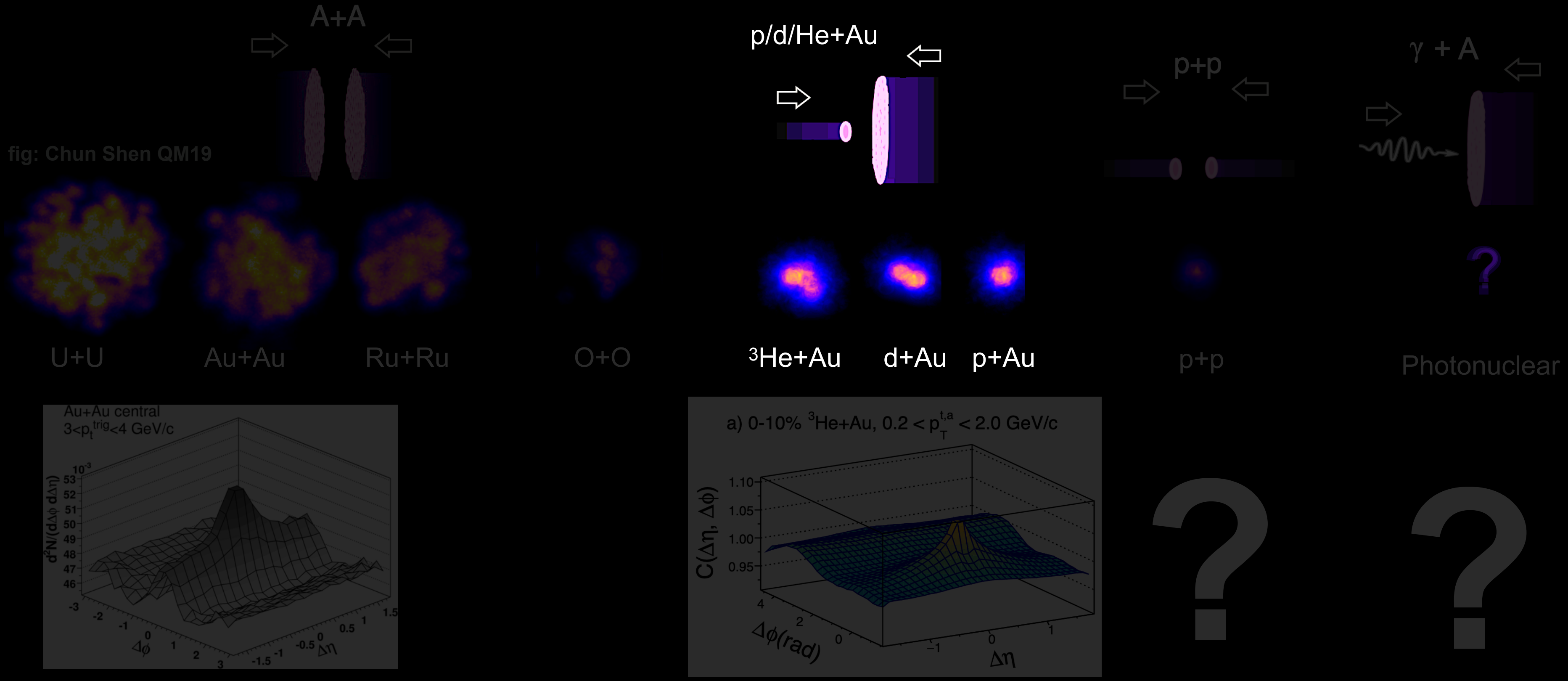
4. c_0 /c_1 Methods: Use first harmonic/pedestal to estimate & remove non-flow

$$c_n^{\mathrm{sub}}(\mathrm{sys}) = c_n^{\mathrm{raw}}(\mathrm{sys}) - c_n(pp)\frac{c_1(pp)}{c_1(\mathrm{sys})}$$

Closure-controlled used HIJING, residual biases in systematics

No single approach, cross-checking multiple subtraction methods is crucial & more reliable

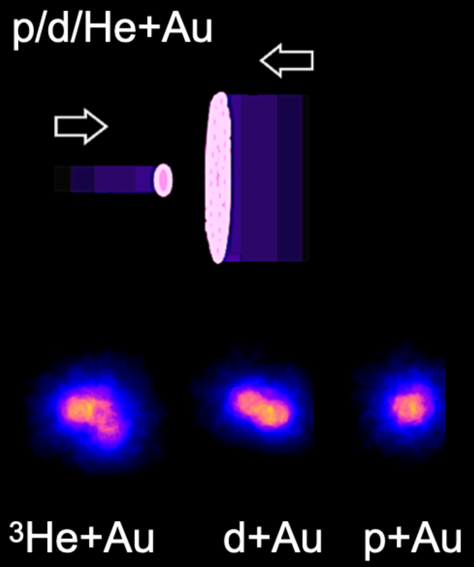
System scan at RHIC & collectivity search



STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912

STAR collaboration, Phys. Rev. C 110 (2024) 64902,
Phys.Rev.Lett. 130 (2023) 24, 242301

Search for geometry-driven Collectivity with p/d/^{3}He+Au:

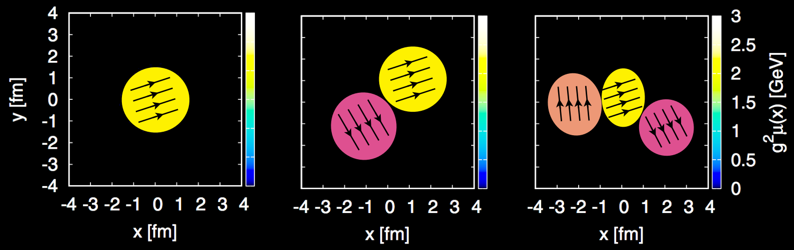


Outline:

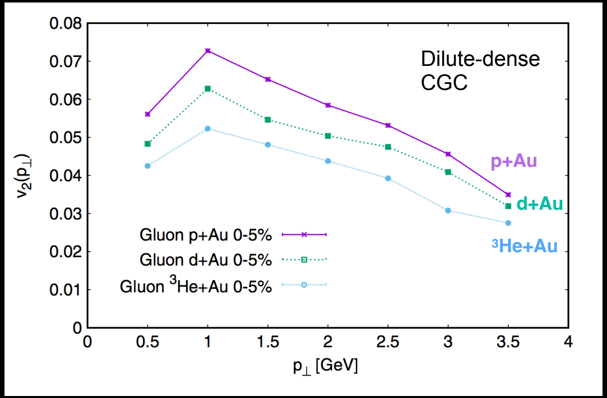
- Pioneering RHIC small-system scan: p/d/^{3}He+Au
- Test final-state geometry driven collectivity
- Does collectivity follow nucleon-scale geometry?

Qualitative difference in p+Au, d+Au, He+Au

Color Glass Condensate (oversimplified)

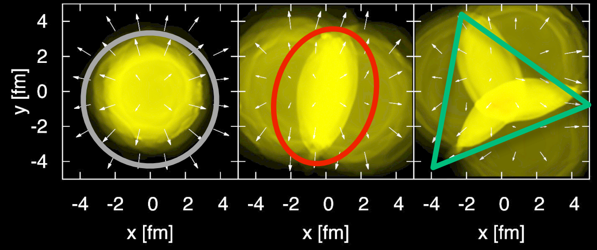


v_2(p+Au) > v_2(d+Au) > v_2(^{3}He+Au)

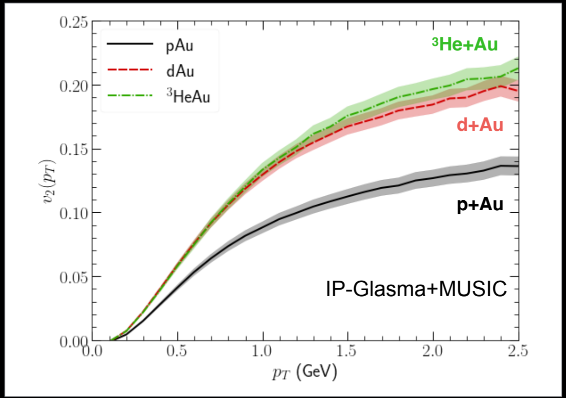


Mace, Skokov, PT, Venugopalan, Phys. Rev. Lett. Erratum 123, 039901(E) (2019)

Relativistic Hydrodynamics (oversimplified)



v_2(p+Au) < v_2(d+Au) ~ v_2(^{3}He+Au)

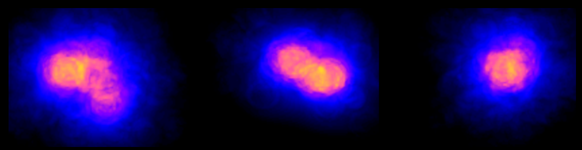


Schenke, Shen, PT, Phys. Rev. C 102, 044905 (2020)

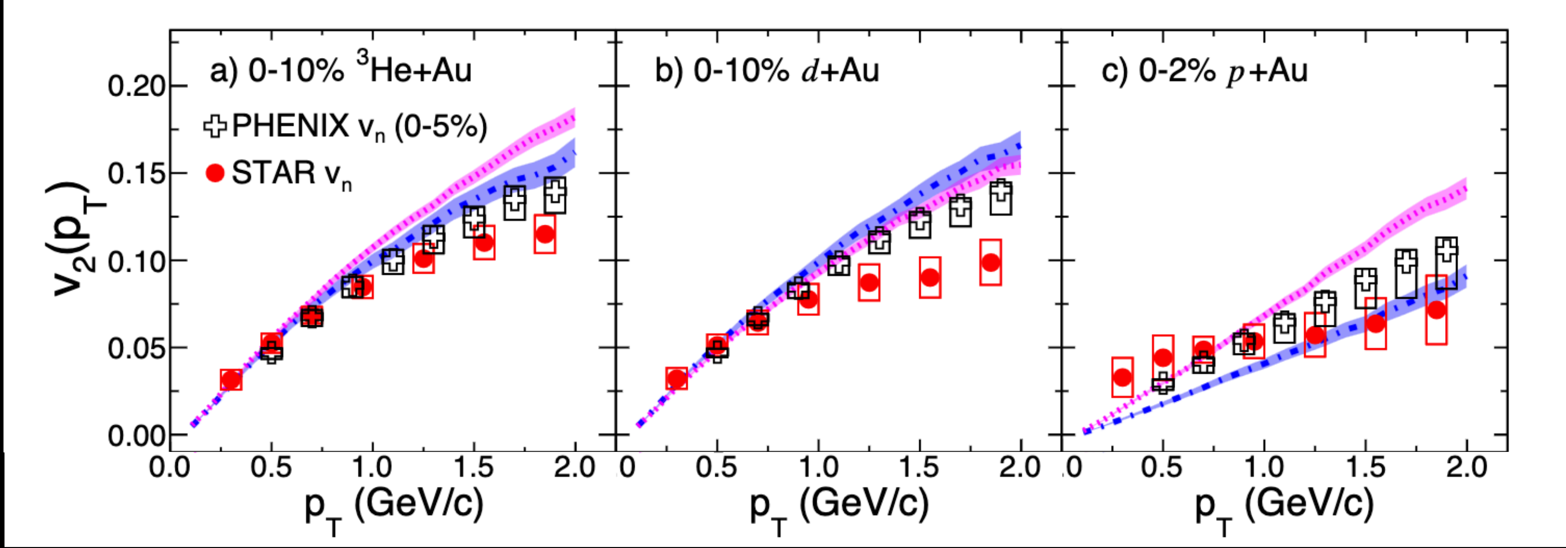
Two possible mechanisms, qualitatively different predictions: testable

Collectivity in p+Au, d+Au, He+Au

STAR collaboration, Phys. Rev. C 110 (2024) 64902,
Phys.Rev.Lett. 130 (2023) 24, 242301, PHENIX collab,
Nature Physics 15, 214–220 (2019), Phys. Rev. C 107, 024907 (2023)



STAR's closure-controlled nonflow removal:
Four different subtraction method (c0, c1, template, near-side)
Residual biases are covered in systematics
Short-range nonflow controlled with |Δη|>1 (gap varied)

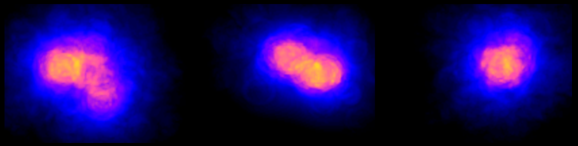


v_2(^{3}He+Au) ~ v_2(d+Au) > v_2(p+Au), ordering consistent with the dominance of final state effect

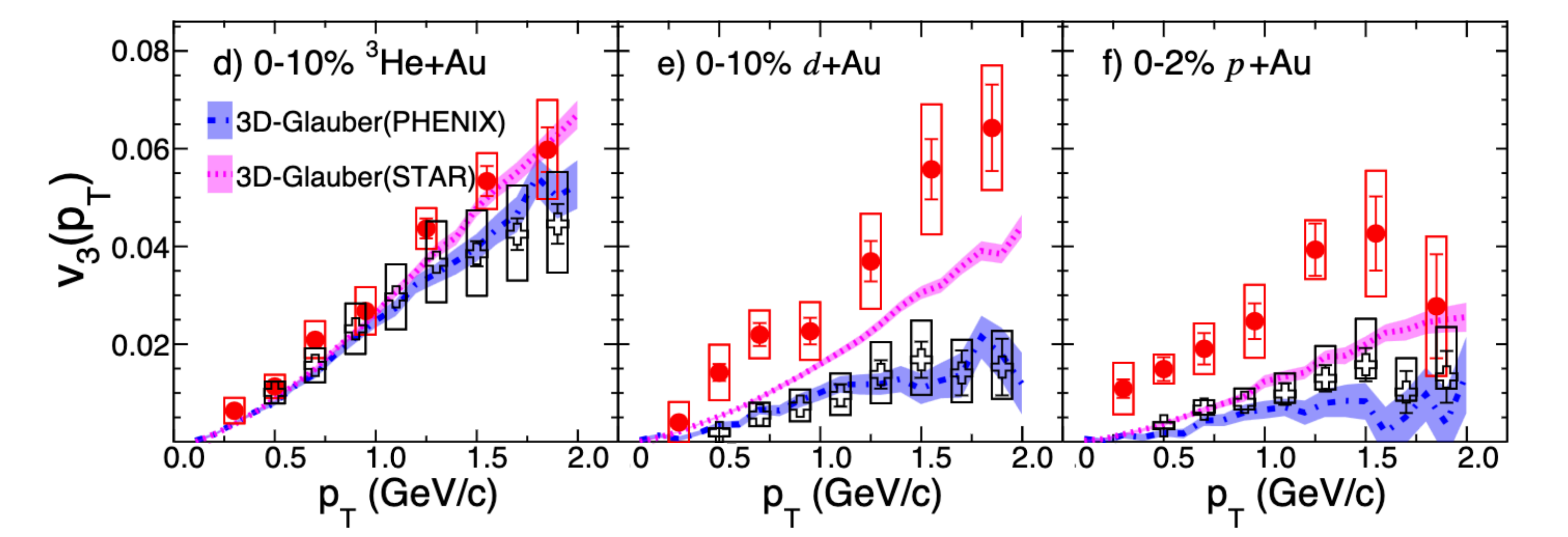
Collectivity in p+Au, d+Au, He+Au

STAR collaboration, Phys. Rev. C 110 (2024) 64902,
Phys.Rev.Lett. 130 (2023) 24, 242301, PHENIX collab,
Nature Physics 15, 214–220 (2019), Phys. Rev. C 107, 024907 (2023)

^{3}He+Au d+Au p+Au



Consistent results using different methods of non-flow subtraction that increases v_3

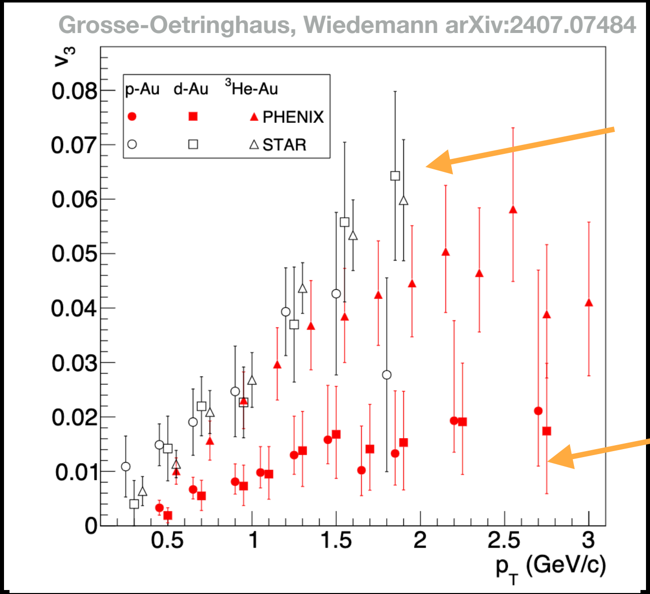


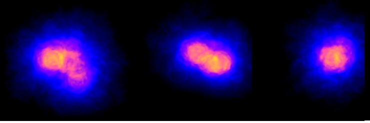
STAR results: v_3(^{3}He+Au) ~ v_3(d+Au) ~ v_3(p+Au) different from PHENIX: v_3(^{3}He+Au) > v_3(d+Au) ~ v_3(p+Au)
3D-Glauber model with de-correlation attempts to explain this discrepancy however p+Au data not fully described

Understanding v_3 : sub-nucleon fluctuations

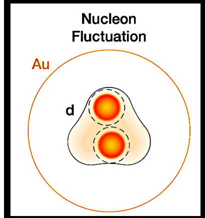
PHENIX: $v_3(^3He+Au) > v_3(d+Au) \sim v_3(p+Au)$

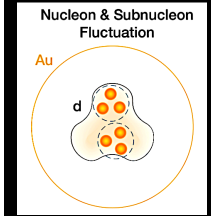
STAR: $v_3(^3He+Au) \sim v_3(d+Au) \sim v_3(p+Au)$





		^{3}He+Au		d+Au		p+Au
Nucleon Glauber [29, 30] $b < 2$ fm	$\langle\varepsilon_2\rangle$	0.50		0.54		0.23
	$\langle\varepsilon_3\rangle$	0.28	>	0.18	$\gtrsim$	0.16
Nucleon Glauber [14, 28] 0–5% centrality	$\langle\varepsilon_2\rangle$	0.49		0.55		0.25
	$\langle\varepsilon_3\rangle$	0.29		0.23		0.20
	$\sqrt{\langle\varepsilon_2^2\rangle}$	0.53		0.59		0.28
	$\sqrt{\langle\varepsilon_3^2\rangle}$	0.33	$\gtrsim$	0.28	$\gtrsim$	0.23
Subnucleon Glauber [31] 0–5% centrality	$\sqrt{\langle\varepsilon_2^2\rangle}$	0.54		0.55		0.41
	$\sqrt{\langle\varepsilon_3^2\rangle}$	0.38	$\approx$	0.35	$\approx$	0.34





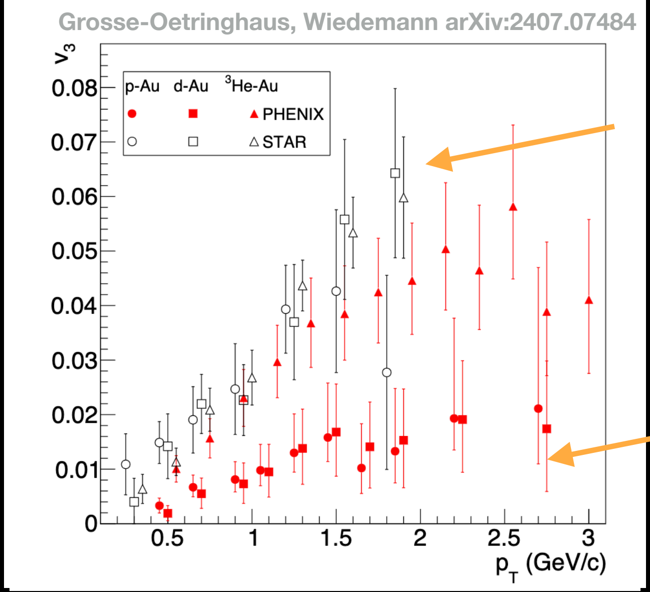
PHENIX collab, Nature Physics 15, 214–220 (2019), Phys. Rev. C 107, 024907 (2023)
STAR collaboration, Phys.Rev.Lett. 130 (2023) 24, 242301, Phys. Rev. C 110 (2024) 64902

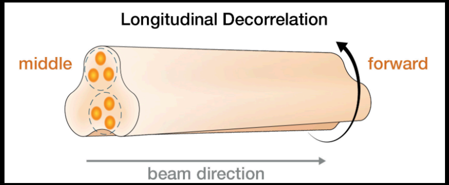
STAR v_3 results are consistent with expectation of sub-nucleon fluctuation

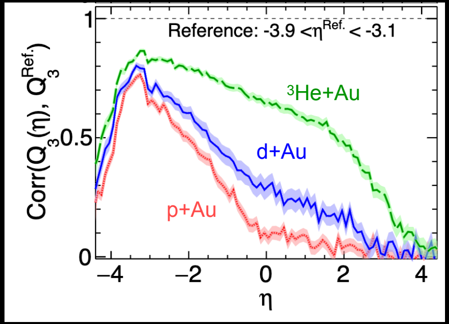
Understanding v_3 : de-correlation/nonflow

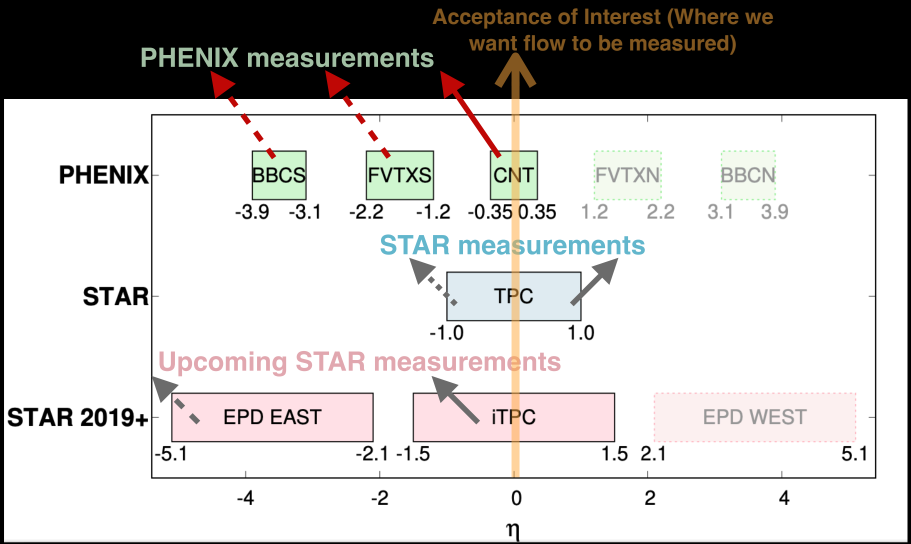
PHENIX: $v_3(^3He+Au) > v_3(d+Au) \sim v_3(p+Au)$

STAR: $v_3(^3He+Au) \sim v_3(d+Au) \sim v_3(p+Au)$





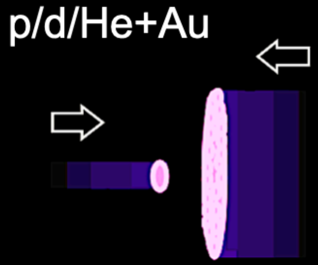


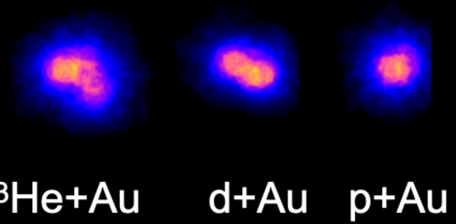


PHENIX collab, Nature Physics 15, 214–220 (2019), Phys. Rev. C 107, 024907 (2023)
STAR collaboration, Phys.Rev.Lett. 130 (2023) 24, 242301, Phys. Rev. C 110 (2024) 64902
Compilation: Grosse-Oetringhaus, Wiedemann arXiv:2407.07484

STAR's mid & forward upgrade & Run 21 d+Au will enable better cross-experiment comparison

Search for geometry-driven Collectivity with p/d/^{3}He+Au:





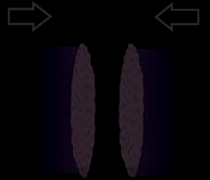
Summary:

— v_2 ordering aligns with geometry
— Triangular flow (v_3) needs more exploration
— Getting Nonflow under control remains key
— Sub-nucleon models & de-correlation attempted to explain data
— New d+Au measurements with extended acceptance from STAR coming

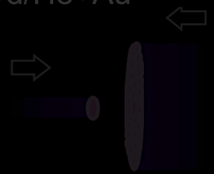
System scan at RHIC & collectivity search

STAR

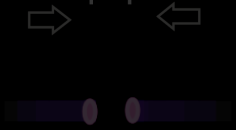
A+A



p/d/He+Au



p+p



γ + A

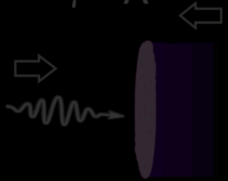
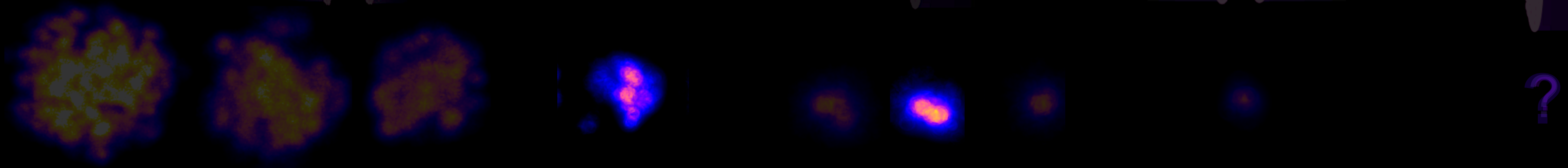
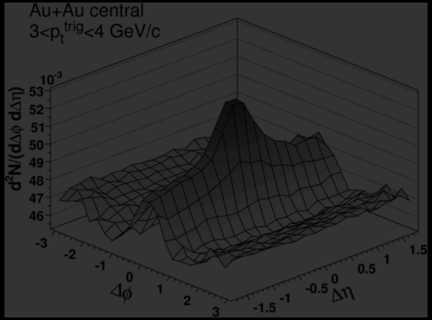
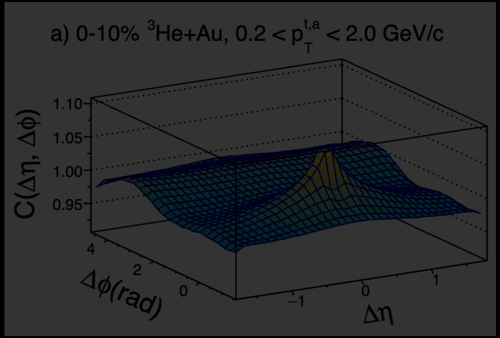


fig: Chun Shen QM19



U+U Au+Au Ru+Ru O+O ^{3}He+Au d+Au p+Au p+p Photonuclear





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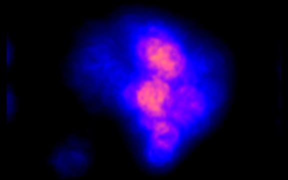
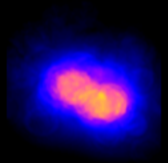
STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912

STAR collaboration, Phys. Rev. C 110 (2024) 64902,
Phys.Rev.Lett. 130 (2023) 24, 242301

Geometry-driven Collectivity with first O+O & d+Au



O+O



d+Au

Outline:

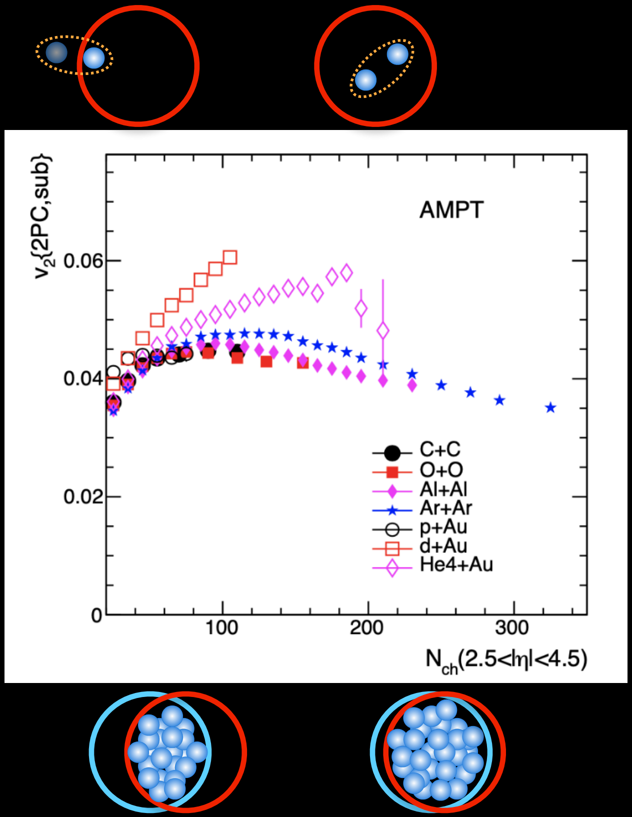
— Year 2021 gave first ever O+O at RHIC (& d+Au with STAR upgrade)

— Large lever-arm to test geometry-driven collectivity

— O+O (average geometry) vs. d+Au (two-nucleon geometry) & fluctuation

— Multi-nucleon correlations in O+O?

The promise of first O+O vs. d+Au collisions at RHIC



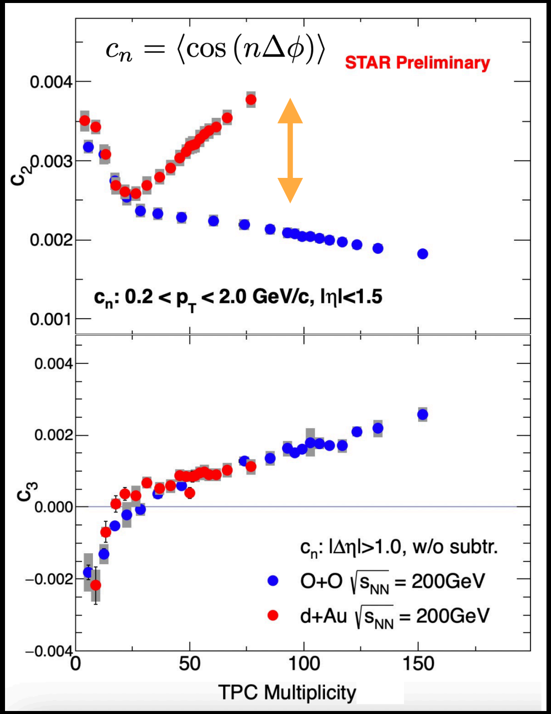
New system scan:

1. d+Au: intrinsic two-nucleon geometry
   b→0: v_2 ↑ as N_{ch} ↑
2. O+O: symmetric overlap geometry
   b→0: v_2 ↓ as N_{ch} ↑

O+O baseline testing geometry driven small-system collectivity:

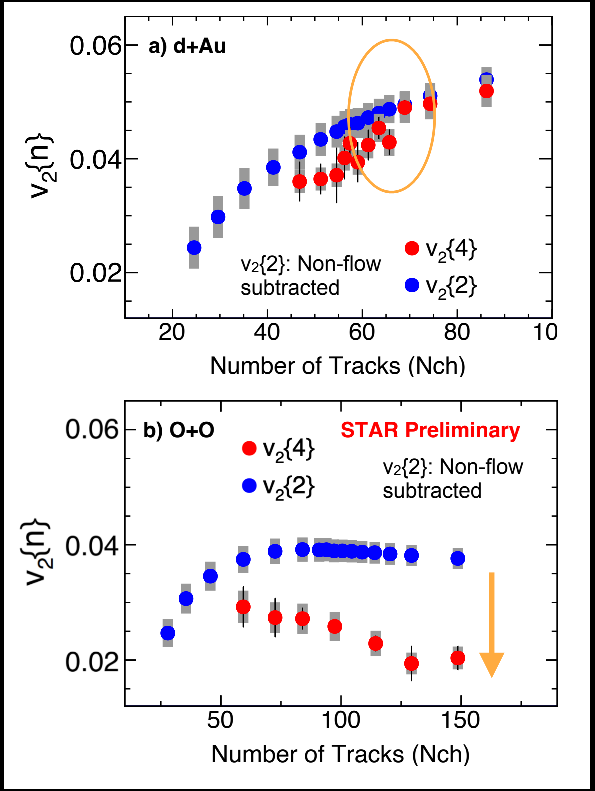
- Large N_{ch} lever-arm & reduced de-correlation
- Robust geometric ordering with d+Au even without nonflow removal

High-statistics O+O & d+Au data 2021 with iTPC (|η|<1.5) upgrade



Robust geometry-driven v_2 ordering observed in O+O vs. d+Au, v_3 remains system independent

Multi-Particle Correlations in O+O vs. d+Au



$v_2\{2\}$ vs. $v_2\{4\}$ reveals: intrinsic geom + fluctuations

$$v_2\{2\}^2 \approx \langle v_2 \rangle^2 + \sigma_{v_2}^2 \qquad v_2\{4\}^2 \approx \langle v_2 \rangle^2 - \sigma_{v_2}^2$$

$\langle v_2 \rangle = \langle \cos(2\phi) \rangle$: single particle anisotropy

d+Au: Two-nucleon geometry (stable $\langle v_2 \rangle^2$) persists at large N_{ch} → $v_2\{4\} \sim v_2\{2\}$, the fluctuations σ contribution is small

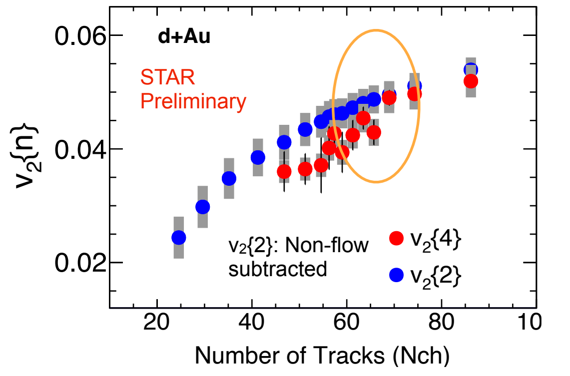
O+O: Overlap driven average geometry $\langle v_2 \rangle^2$ decreases at large N_{ch}

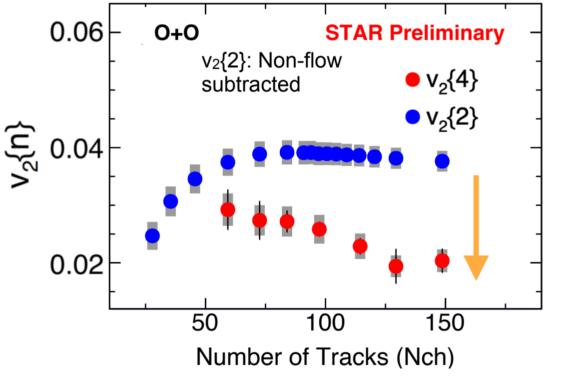
Additional fluctuations σ make $v_2\{2\}$ stable, but decrease $v_2\{4\}$ even more

O+O exhibits a stronger interplay of geometry and fluctuations

Multi-Particle Correlations in O+O vs. d+Au

Are there many-nucleon correlations in O+O ?



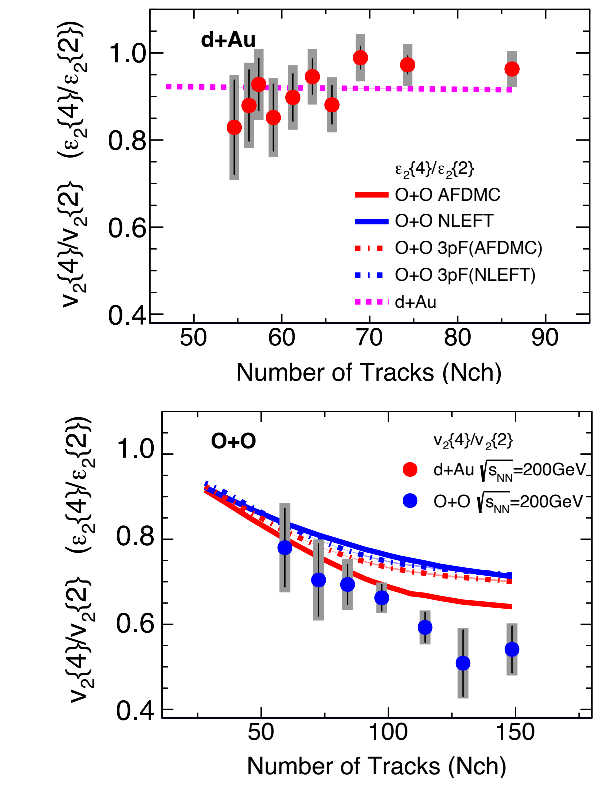


Comparison with initial geometry:

$$\frac{\epsilon_2\{4\}}{\epsilon_2\{2\}} \approx \sqrt{\frac{\langle\epsilon_2\rangle^2 - \sigma^2}{\langle\epsilon_2\rangle^2 + \sigma^2}}$$

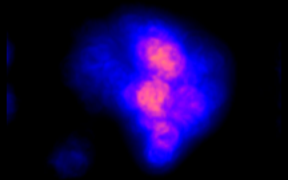
d+Au: conventional glauber well describe data

O+O: many and single nucleon (3pF) models compared to data

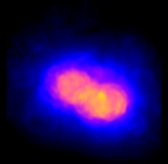


O+O data is closer to models with multi-nucleon correlation

Geometry-driven Collectivity with first O+O & d+Au



O+O



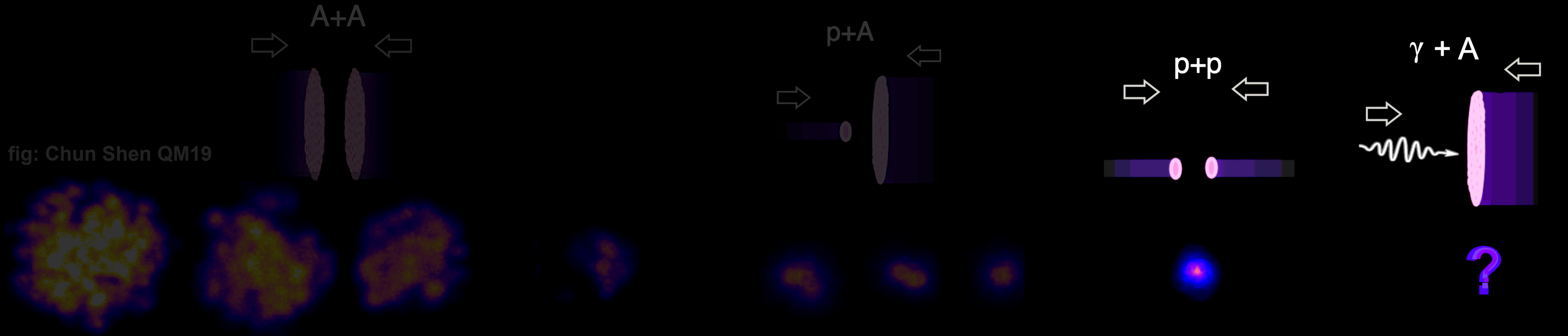
d+Au

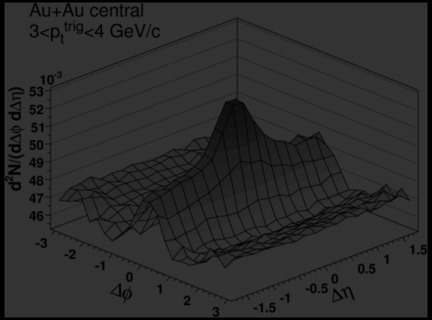
Summary:

— O+O vs. d+Au: Clear geometry driven v_2 ordering, stable beyond nonflow

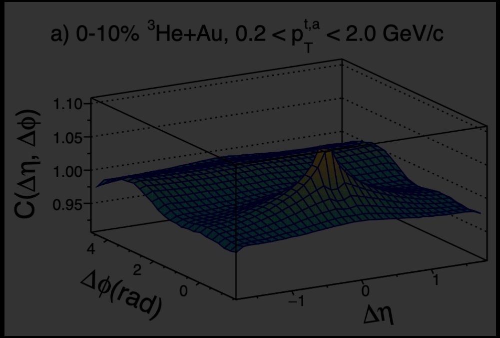
— O+O v_2 sees interplay of geometry & fluctuations

— Multi-nucleon correlations models compared to O+O data do well





STAR collaboration, Phys. Rev. Lett. 95, 152301
Phys. Rev. C 80 (2009) 64912



STAR collaboration, Phys. Rev. C 110 (2024) 64902,
Phys.Rev.Lett. 130 (2023) 24, 242301

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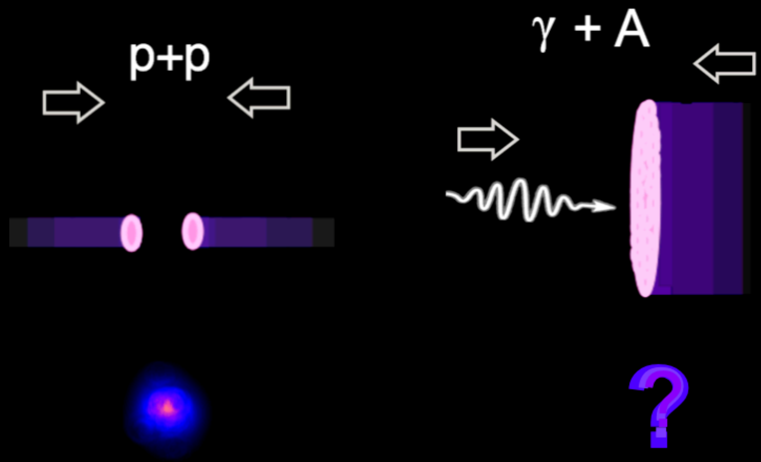
Pushing the limits of RHIC small-system scan with p+p & γ+Au

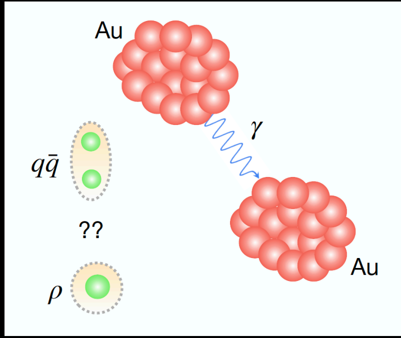


Outlook:

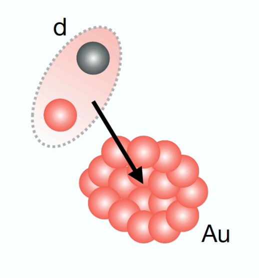
— Search for the tiniest fluid droplet at RHIC
— Photonuclear collisions: informative toward EIC
— p+p collisions: Special data collection at RHIC
— Challenges: Triggering, nonflow, pileup, limited acceptance

Collectivity search in photonuclear processes at RHIC

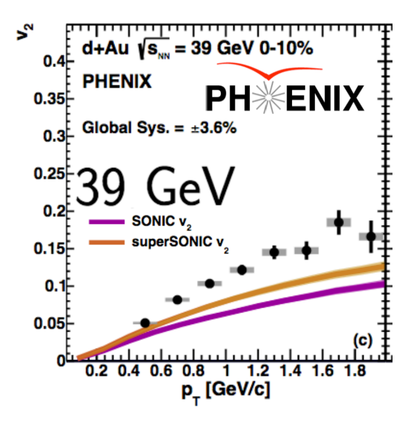
Search for tiniest fluid droplet at RHIC
Informative towards EIC science



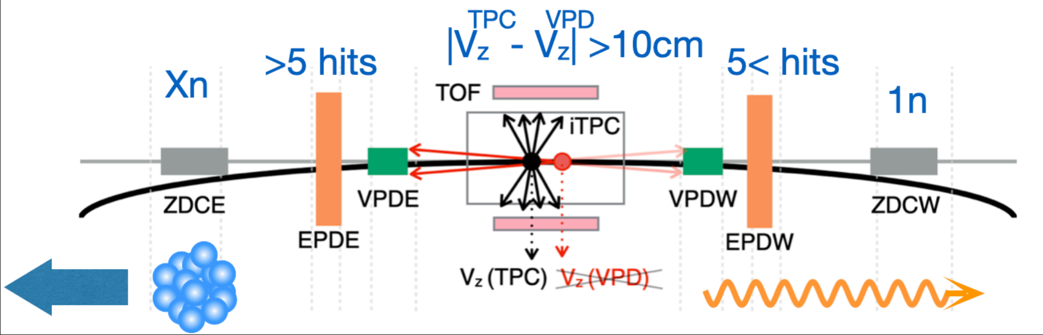
γ+Au ($\sqrt{s_{\gamma N}} \lesssim$ 34 GeV)

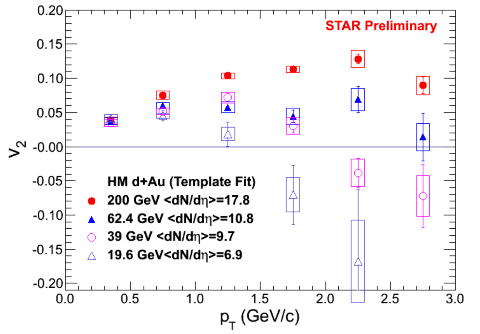


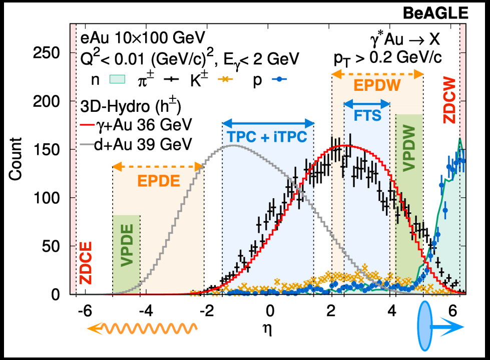
d+Au ($\sqrt{s_{NN}} \lesssim$ 34 GeV)



Asymmetric system, triggered EPDs & ZDC (1nXn) on Au+Au 200 GeV ultra-peripheral collisions

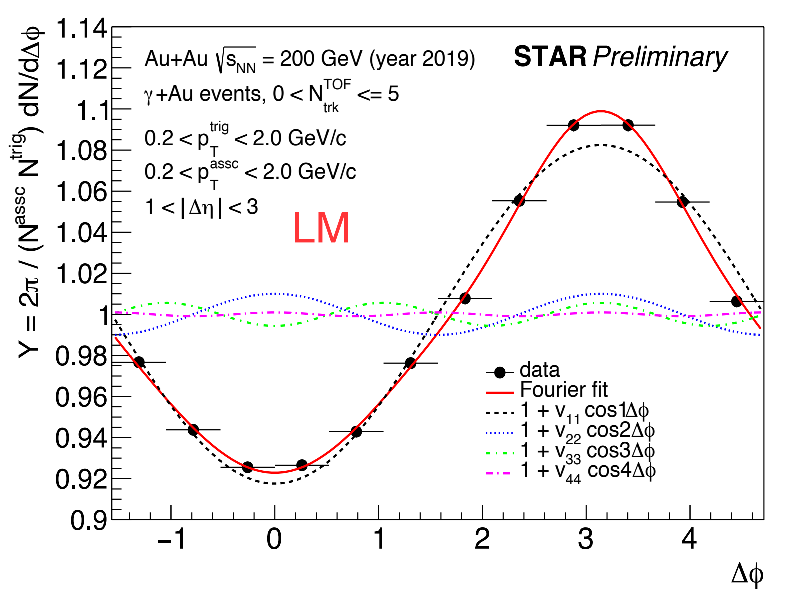


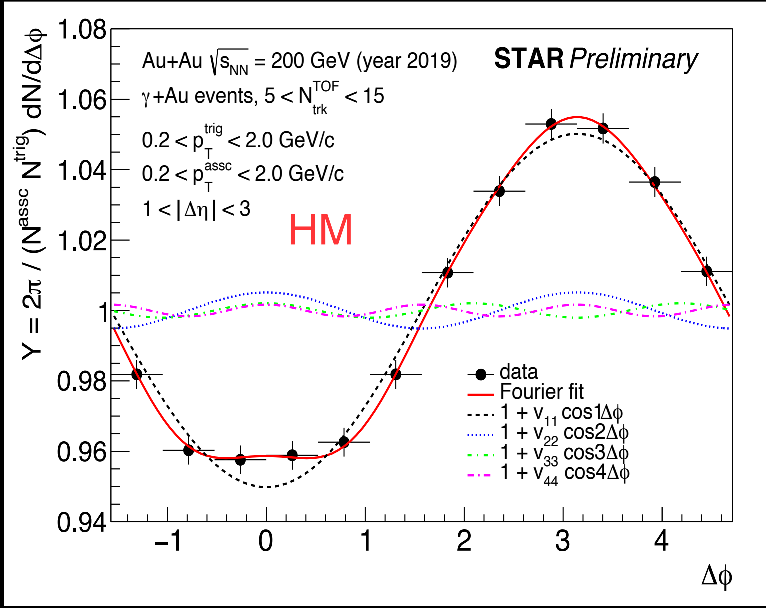




Collectivity search in photonuclear processes at RHIC

First look with limited year 2019 data



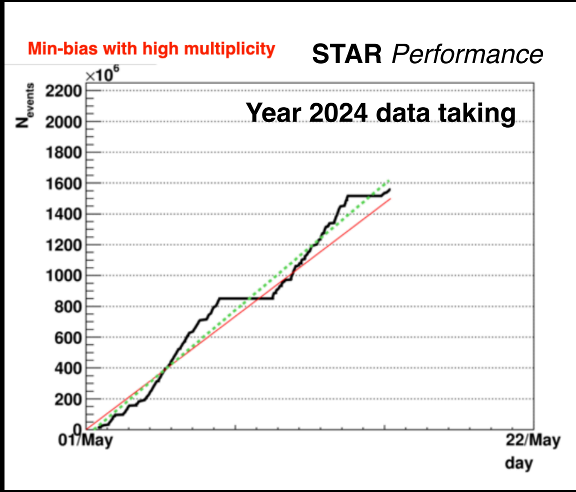


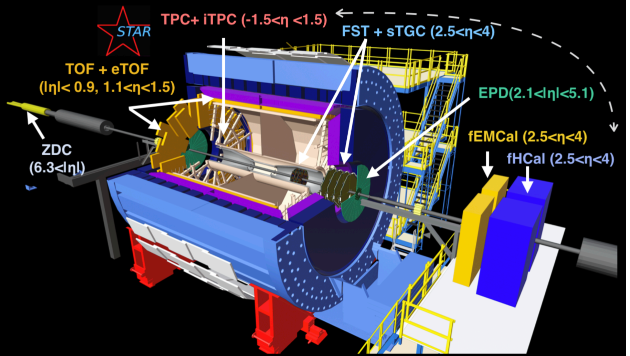
Di-hadron correlations between low and high activity event class compared
Opportunity with Run 2023 data: 6 M (1nXn) and 100 M (0nXn) γ+Au events collected

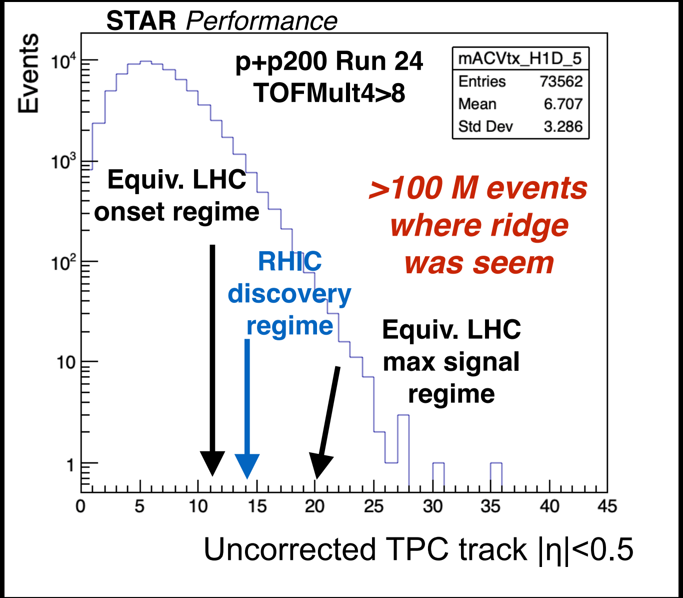
First photonuclear collectivity search at RHIC initiated

Collectivity search in p+p collisions

LHC high-multiplicity p+p revealed near-side ridge, pioneering small-system collectivity
RHIC searches were limited to min-bias p+p due to challenges



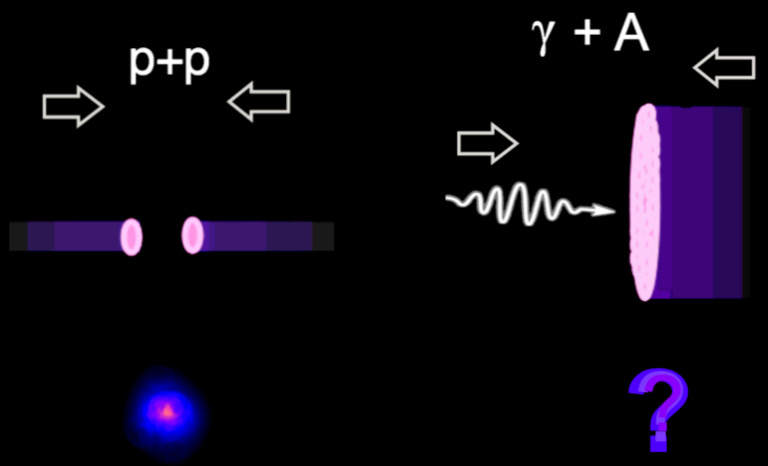




In 2024, 1.5B Min-bias and high-multiplicity events collected for p+p collectivity search
Key challenges are nonflow & pile-up: low-luminosity run + wide acceptance (STAR upgrade)

Anticipated collectivity search in high mult. p+p at RHIC coming to reality

Pushing the limits of RHIC small-system scan with p+p & γ+Au



Summary:

— Photonuclear collisions: first results with year 2019 data, correlation functions studied

— p+p collisions: higher stat. low-luminosity data in 2024, with forward upgrade

— Search underway for collectivity in tiniest system at RHIC

Summary

Geometry-Driven Collectivity p/d/^{3}He+Au:
Final-state dominated v_2 ordering confirmed; v_3 largely system-independent — cross-experiment comparison is under investigation

O+O vs. d+Au: Clear v_2 ordering driven by overlap geometry hints of many-nucleon correlations in O+O

Photonuclear process:
Chance to explore the smallest droplets at RHIC informative to EIC

p+p: Large-statistics run planned (1.5B MB + 1.5B high-mult events) to hunt for near-side ridge at RHIC energies.

Challenges: nonflow subtraction, role of sub-nucleon fluctuations, de-correlations
Opportunity: Wide acceptance upgrades (iTPC, EPD) & high-stat data offer unique leverage

Small-system collectivity search continues at STAR to reveal new facets & improve understanding

Thanks