Supported in part by: U.S. DEPARTMENT OF ENERGY | Office of Science

Probing the Quark-Gluon Plasmas droplet though Anisotropic flow in small Symmetric and Asymmetric systems

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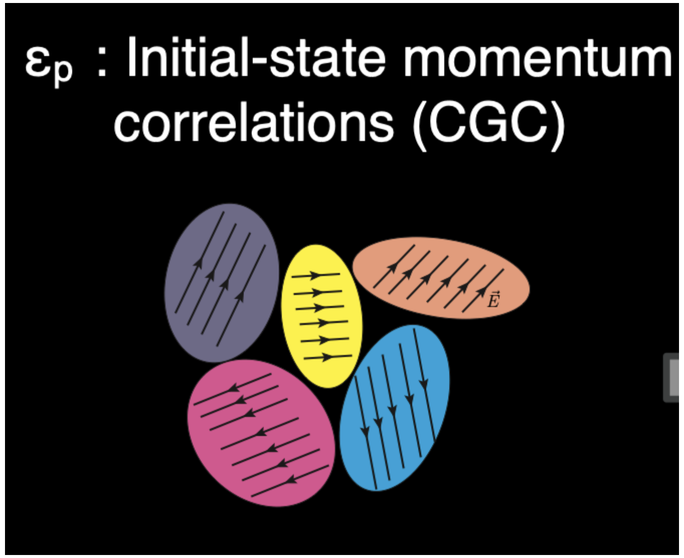
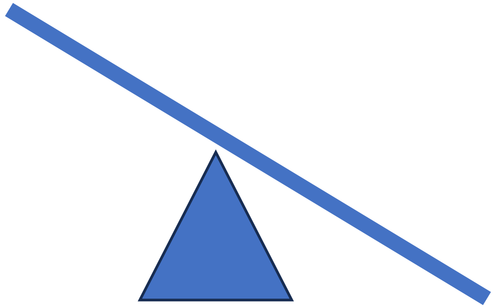
Origin of Collective in small system:
Initial State or Final State

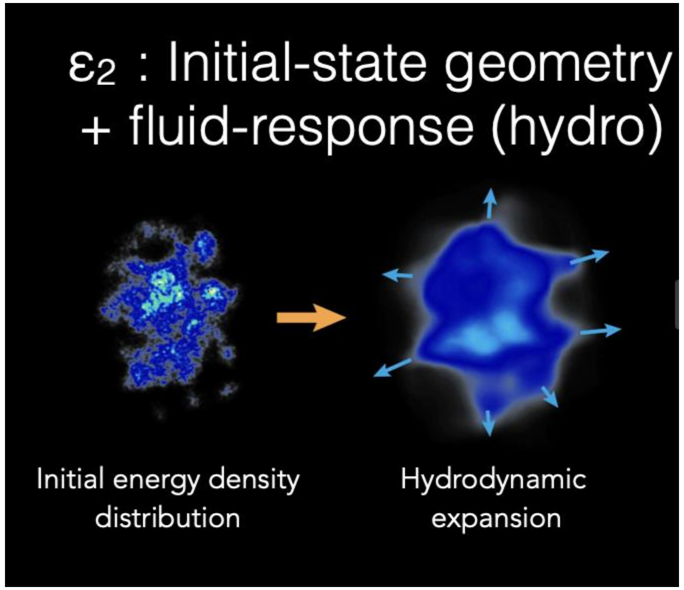
Initial State



Short-range correlation
Weakly depend on initial spatial geometry



Final State



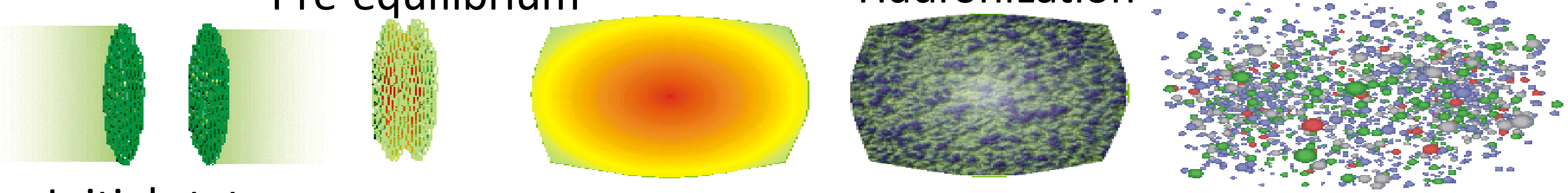
Long-range correlation
Strong depend on initial spatial geometry

Final State $\neq$ $Hdrodynamics\ Expasion$

$v_n^{Measure} \propto \varepsilon_n^{Init.}$ *is one of the key evidences for the hydro expansion*

Both $v_n^{Measure}$ *and* $\varepsilon_n^{Init.}$ need to be well controlled in order to test this linear relation

System Evolution in Small-Size System Collision



τ=0$^+$fm/c   0.5fm/c   A few fm/c

Initial eccentricity: ε_n^{Init}

Initial momentum correlation: ε_p

Pre-flow

Eccentricity as Hydro. starts: $\varepsilon_n^{Hydro.}$

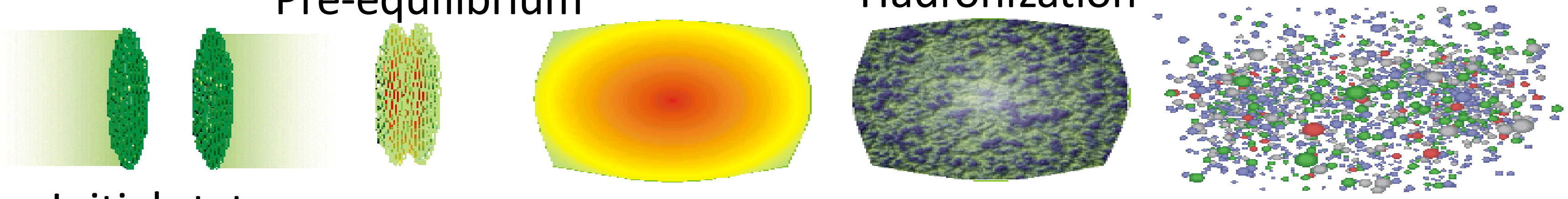
Hydro Flow: $v_n^{Hydro.}$

Measured Flow: $v_n^{Measure}$

System Evolution in Small-Size System Collisions

Pre-equilibrium

Hadronization



Initial state

QGP Droplet?

Freeze out

τ=0+fm/c   0.5fm/c   A few fm/c

Initial eccentricity: $\varepsilon_n^{Init.}$

Initial momentum correlation: ε_p

Pre-flow

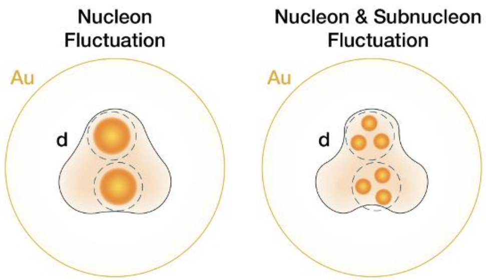
Eccentricity as Hydro. starts:

$\varepsilon_n^{Hydro.}$

Hydro Flow: $v_n^{Hydro.}$

Measured Flow: $v_n^{Measure}$

ε_n^{Init}: *(sub)nucleon fluctuation*



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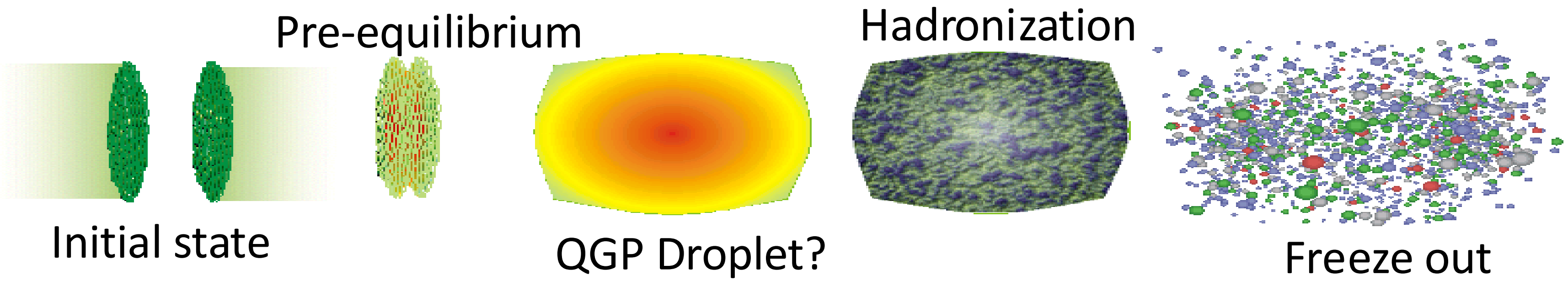
System Evolution in Small-Size System Collisions



τ=0$^+$fm/c   0.5fm/c   A few fm/c

Initial eccentricity: $\varepsilon_n^{Init.}$

Initial momentum correlation: ε_p

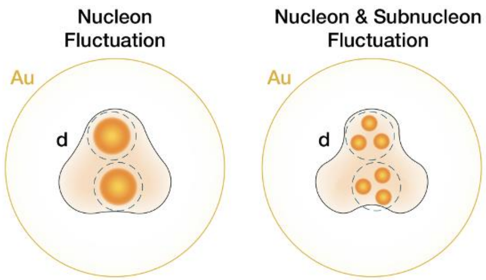
Pre-flow

Eccentricity as Hydro. starts: $\varepsilon_n^{Hydro.}$

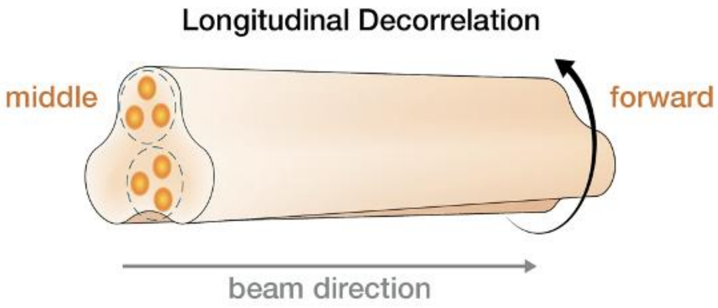
Hydro Flow: $v_n^{Hydro.}$

Measured Flow: $v_n^{Measure}$

ε_n^{Init}: *(sub)nucleon fluctuation*



$v_n^{Measure}$:*(nonflow + preflow + de-correlation)*



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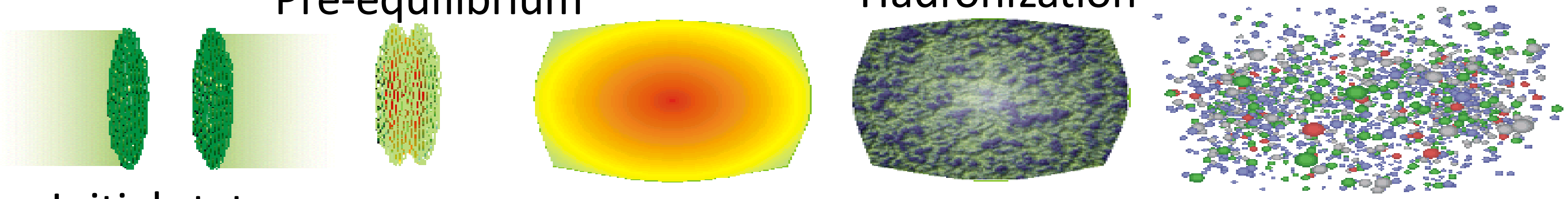
System Evolution in Small-Size System Collisions



τ=0^{+}fm/c   0.5fm/c   A few fm/c

Initial eccentricity: $\varepsilon_n^{Init.}$

Initial momentum correlation: ε_p

Pre-flow

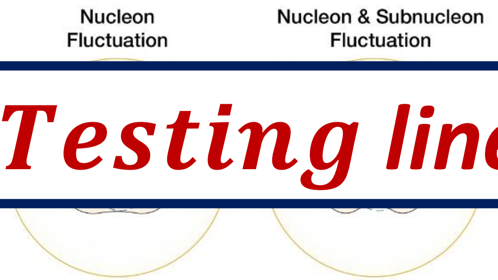
Eccentricity as Hydro. starts: $\varepsilon_n^{Hydro.}$

Hydro Flow: $v_n^{Hydro.}$

Measured Flow: $v_n^{Measure}$

ε_n^{Init}: *(sub)nucleon fluctuation*

$v_n^{Measure}$:*(nonflow + preflow + de-correlation)*



Testing linear relation ($v_n^{Measure} \propto \varepsilon_n^{Init}$) is challenge!

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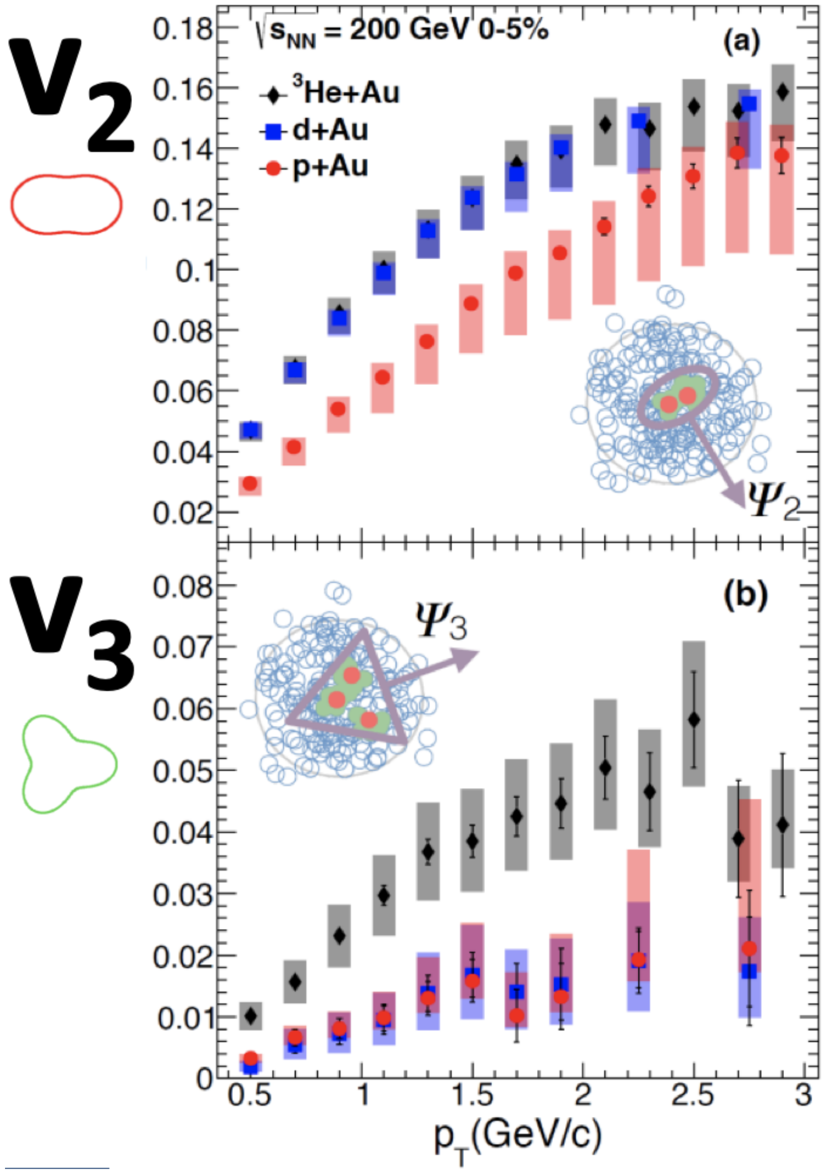
QGP Droplet? Geometry Scan at RHIC

p+Au(2015) d+Au(2016) ^{3}He+Au(2014)



$\frac{1}{3}v_3(^{3}\text{He+Au}) \approx v_3(\text{d+Au}) \approx v_3(\text{p+Au})$(***PHENIX***)

Nature Physics 15, 214-220 (2019)

STAR:PRC 110, 064902 (2024)

	Nucleon Glauber [30, 31]		Nucleon Glauber [14, 29]		Subnucleon Glauber [32]	
	$b < 2$ fm		0–5% centrality		0–5% centrality	
	$\langle\varepsilon_2\rangle$	$\langle\varepsilon_3\rangle$	$\sqrt{\langle\varepsilon_2^2\rangle}$	$\sqrt{\langle\varepsilon_3^2\rangle}$	$\sqrt{\langle\varepsilon_2^2\rangle}$	$\sqrt{\langle\varepsilon_3^2\rangle}$
^{3}He+Au	0.50	0.28	0.53	0.33	0.54	0.38
d+Au	0.54	0.18	0.59	0.28	0.55	0.35
p+Au	0.23	0.16	0.28	0.23	0.41	0.34

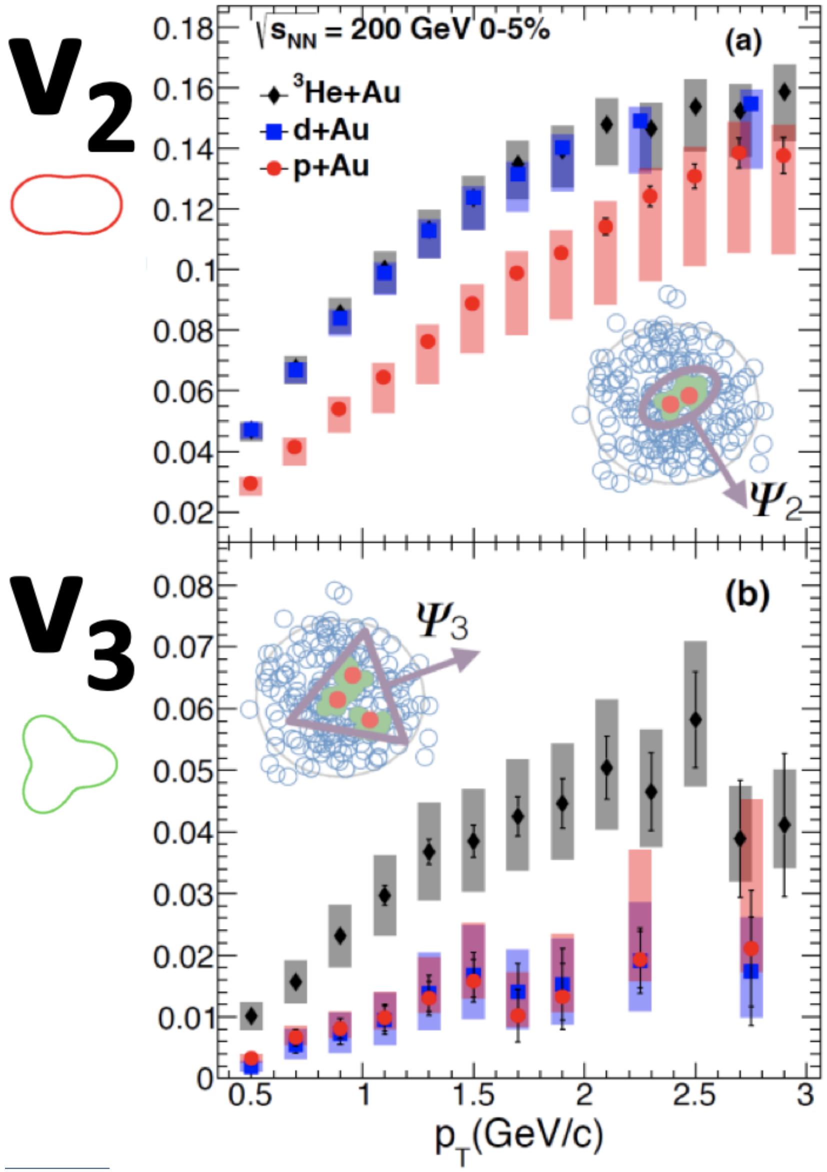
$$PHENIX: \frac{2}{3}\varepsilon_3(^{3}\text{He+Au}) \approx \varepsilon_3(\text{dAu}) \approx \varepsilon_3(\text{pAu})$$

However, such calculation is too simply:

1) Centrality can not be defined from b

2) Eccentricity should be $\sqrt{\langle\varepsilon_n^2\rangle}$

QGP Droplet? Geometry Scan at RHIC



p+Au(2015) d+Au(2008) ^{3}He+Au(2014)

STAR:arXiv:2312.07464

	Nucleon Glauber [30, 31]		Nucleon Glauber [14, 29]		Subnucleon Glauber [32]	
	$b < 2$ fm		0–5% centrality		0–5% centrality	
	$\langle\varepsilon_2\rangle$	$\langle\varepsilon_3\rangle$	$\sqrt{\langle\varepsilon_2^2\rangle}$	$\sqrt{\langle\varepsilon_3^2\rangle}$	$\sqrt{\langle\varepsilon_2^2\rangle}$	$\sqrt{\langle\varepsilon_3^2\rangle}$
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p+Au	0.23	0.16	0.28	0.23	0.41	0.34

$\varepsilon_3(^3\text{HeAu}) > \varepsilon_3(\text{dAu}) > \varepsilon_3(\text{pAu})$

1)Centrality from NBD⊗Npart

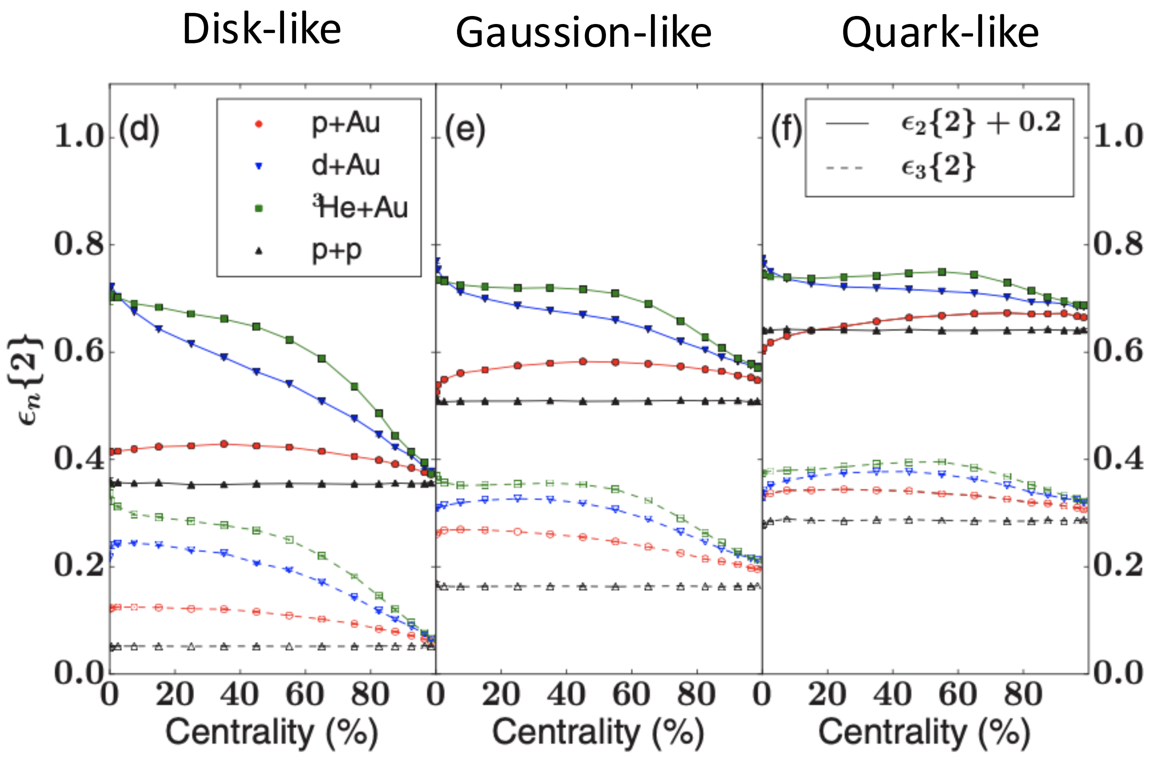
2)Eccentricity from $\sqrt{\langle\varepsilon_n^2\rangle}$

$\frac{1}{3}$ $v_3(^3\text{He+Au}) \approx v_3(\text{d+Au}) \approx v_3(\text{p+Au})$(***PHENIX***)

Nature Physics 15, 214-220 (2019)

Differ only by ***20%*** even with Nucleon Glauber

Sub-Nucleon Fluctuation in small system



PRC 94, 024919 (2016)

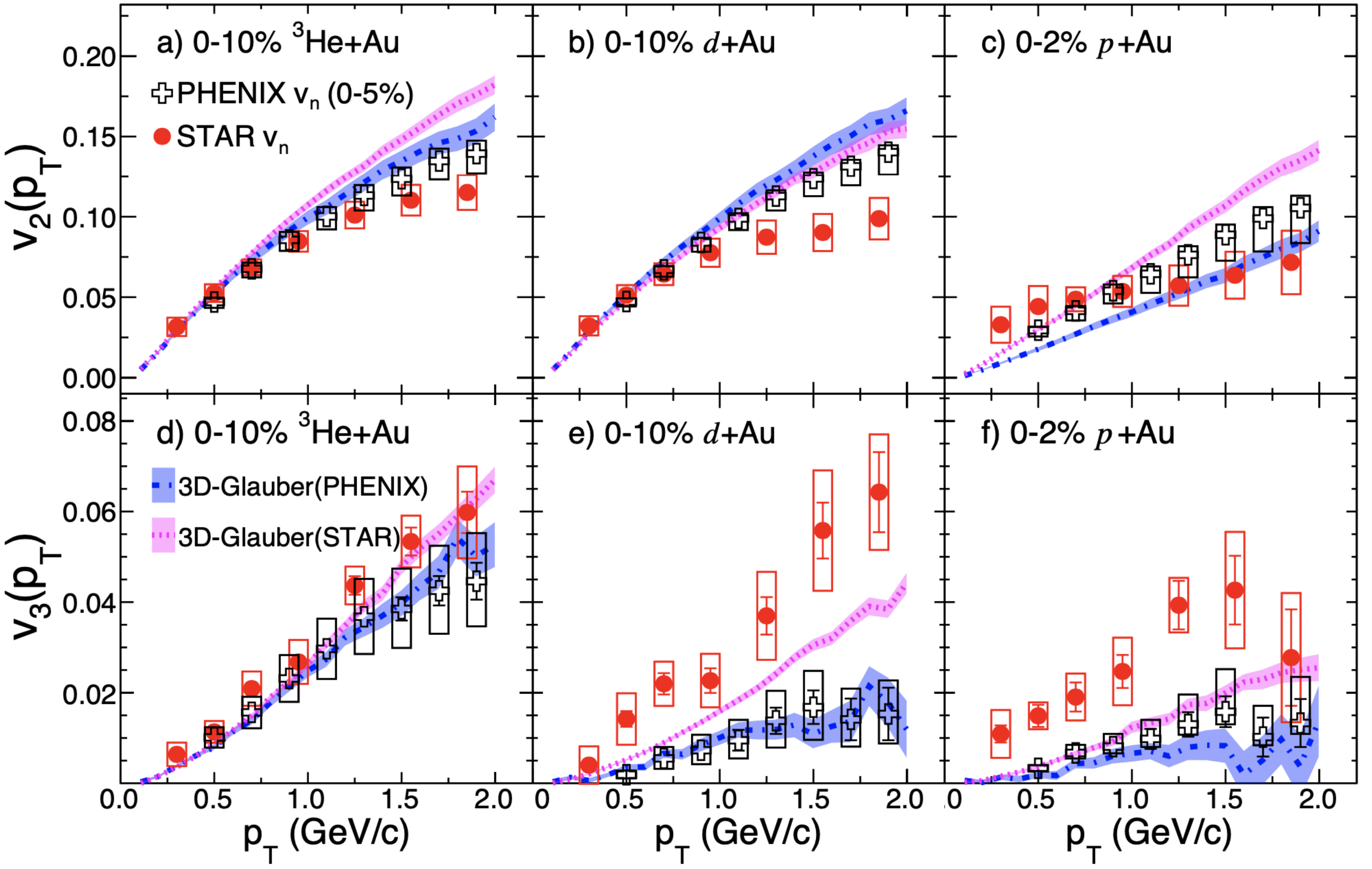
STAR: PRC 110, 064902 (2024)

	Nucleon Glauber [30, 31]		Nucleon Glauber [14, 29]		Subnucleon Glauber [32]	
	$b < 2$ fm		0–5% centrality		0–5% centrality	
	$\langle\varepsilon_2\rangle$	$\langle\varepsilon_3\rangle$	$\sqrt{\langle\varepsilon_2^2\rangle}$	$\sqrt{\langle\varepsilon_3^2\rangle}$	$\sqrt{\langle\varepsilon_2^2\rangle}$	$\sqrt{\langle\varepsilon_3^2\rangle}$
^{3}He+Au	0.50	0.28	0.53	0.33	0.54	0.38
d+Au	0.54	0.18	0.59	0.28	0.55	0.35
p+Au	0.23	0.16	0.28	0.23	0.41	0.34

$\varepsilon_3(^3\text{He+Au}) \approx \varepsilon_3(\text{d+Au}) \approx \varepsilon_3(\text{p+Au})$

Eccentricity difference between p+Au, d+Au and ^{3}He+Au is substantially mitigated by the sub-nucleon fluctuation

Measurements From STAR



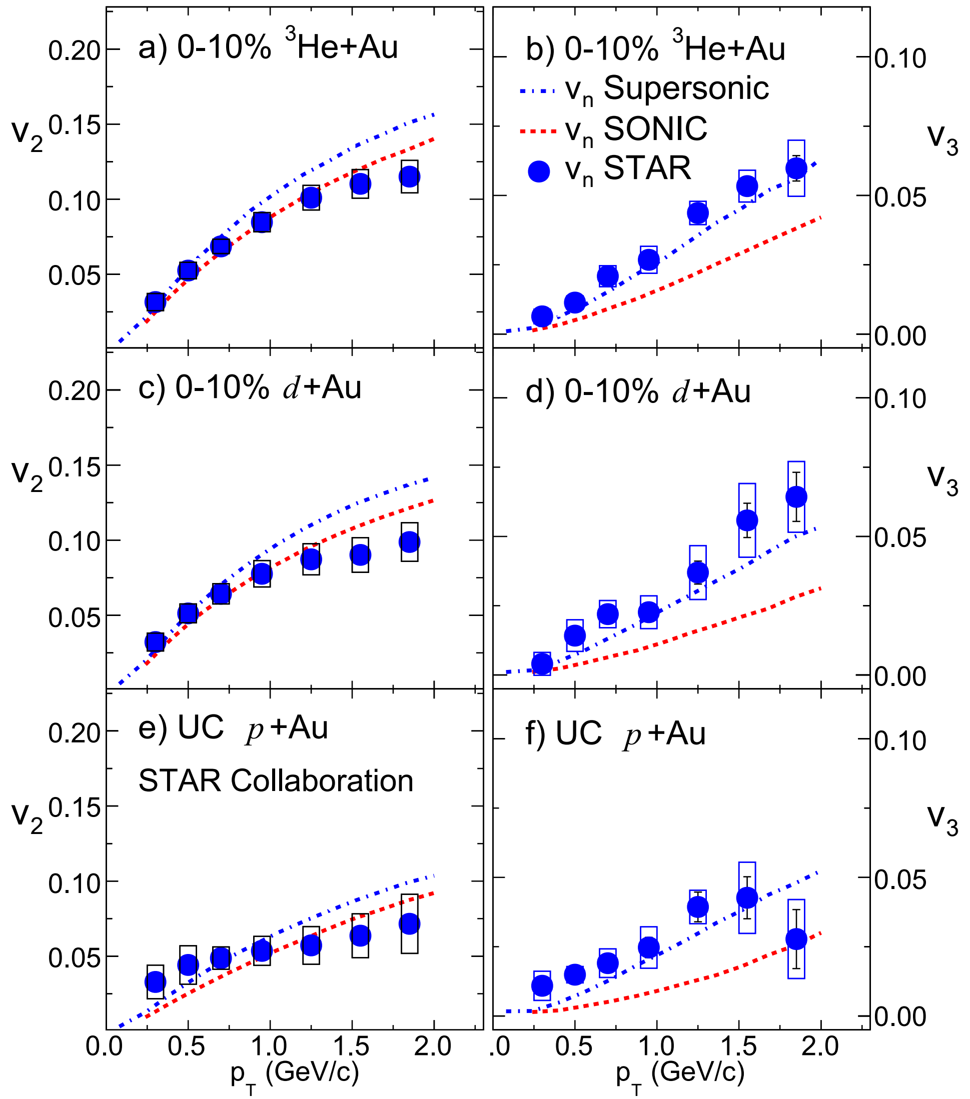
STAR: ***PRL 130, 242301(2023)***
PRC 110, 064902 (2024)
PHENIX: Nature Phys. 15, 214 (2019)

3D-Glauber: Chun & Wenbin, PRC 107, 014904 (2023)

Sub-nucleon + longitudinal fluctuation

Large $v_3(p_T)$ discrepancy between STAR and PHENIX
Large longitudinal de-correlation in PHENIX measurements as 3D-Glauber indicates!?
3D-Glauber still under-estimates STAR v_3 in p+Au and d+Au

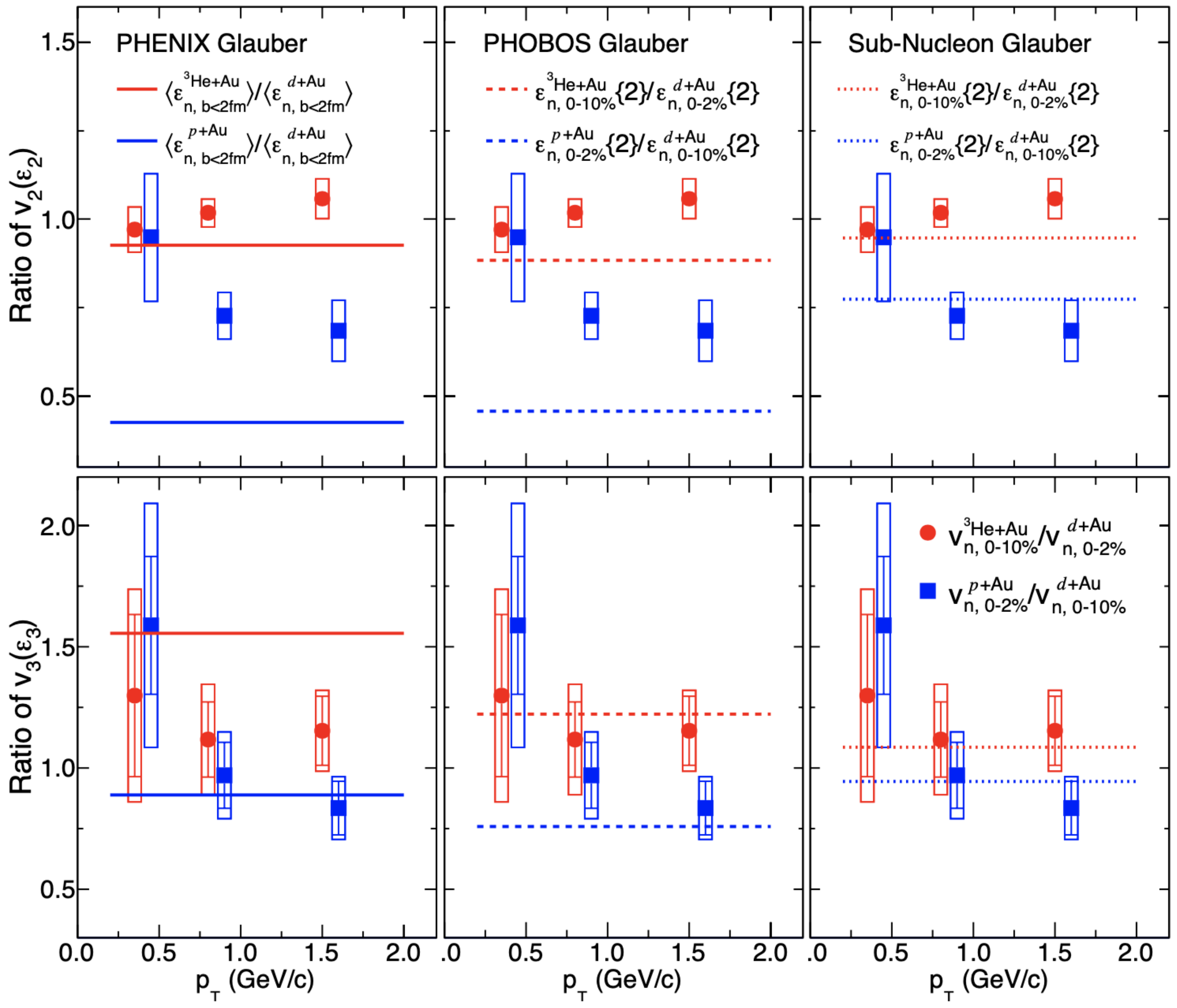
Pre-flow Effect: Sonic vs. superSONIC Model



- *(super)SONIC:* initial geometry eccentricity without sub-nuclear fluctuations
- *SONIC model* :without preflow, under-predicts v_3 in all systems
- ***superSONIC model: SONIC+preflow*** can reproduce the v_3 even without sub-nucleon fluctuations

SONIC: P. Romatschke *Eur. Phys.J.C* **75**, 305 (2015)

The system dependence between p/d/^{3}He+Au



*STAR:arXiv:*2312.07464

$v_2(^3He+Au) \approx v_2(d+Au) > v_2(p+Au)$

$v_3(^3He+Au) \approx v_3(d+Au) \approx v_3(p+Au)$

Sub-nucleon fluctuation or pre-flow or both?

Can we perform a real test of the linear response to initial eccentricity in small systems?

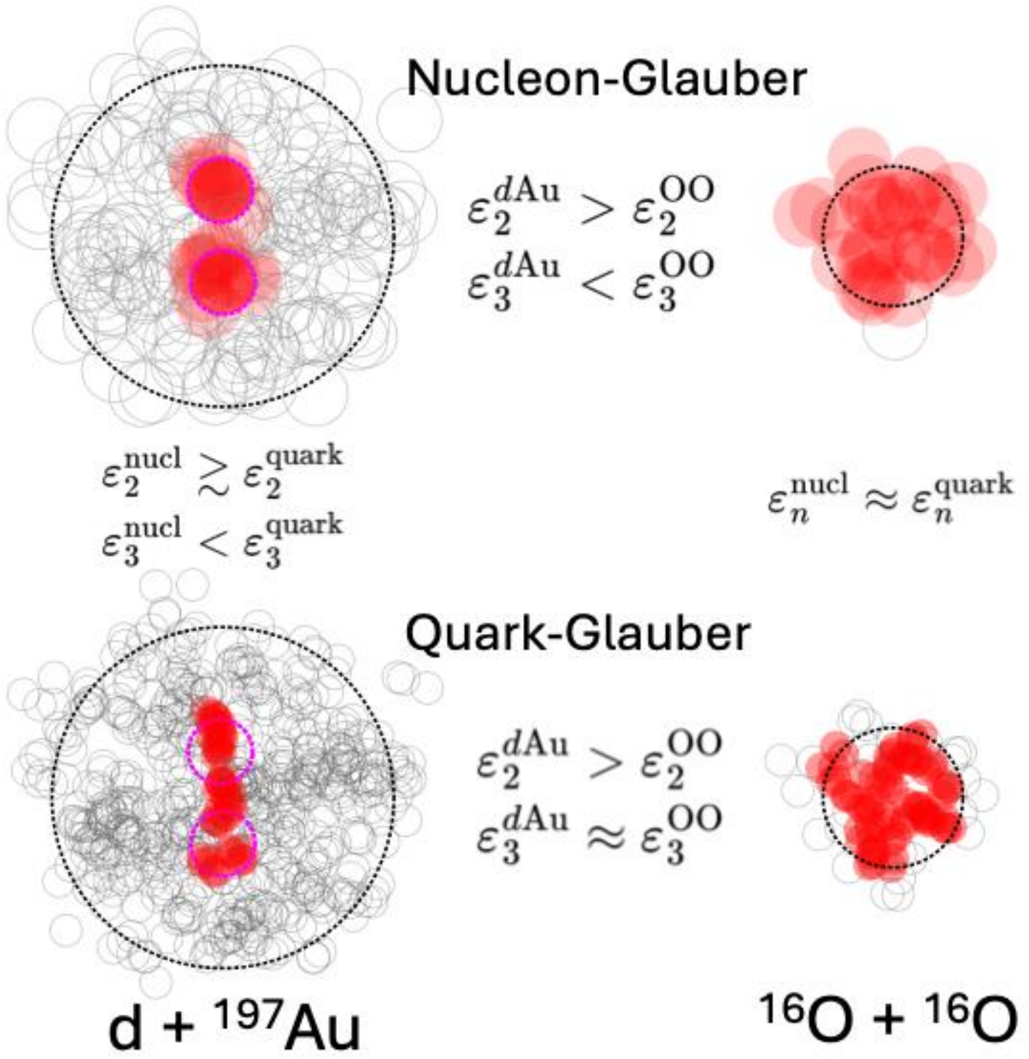
Lessons the from Asymmetric Systems Scan

- **Maximise the difference in initial geometry between systems.**

- **Minimise uncertainties in the initial geometry.**

- **Reduce contamination of flow observables from pre-flow, decorrelation, and nonflow.**

O+O(Symmetric) vs d+Au(Asymmetric) collisions



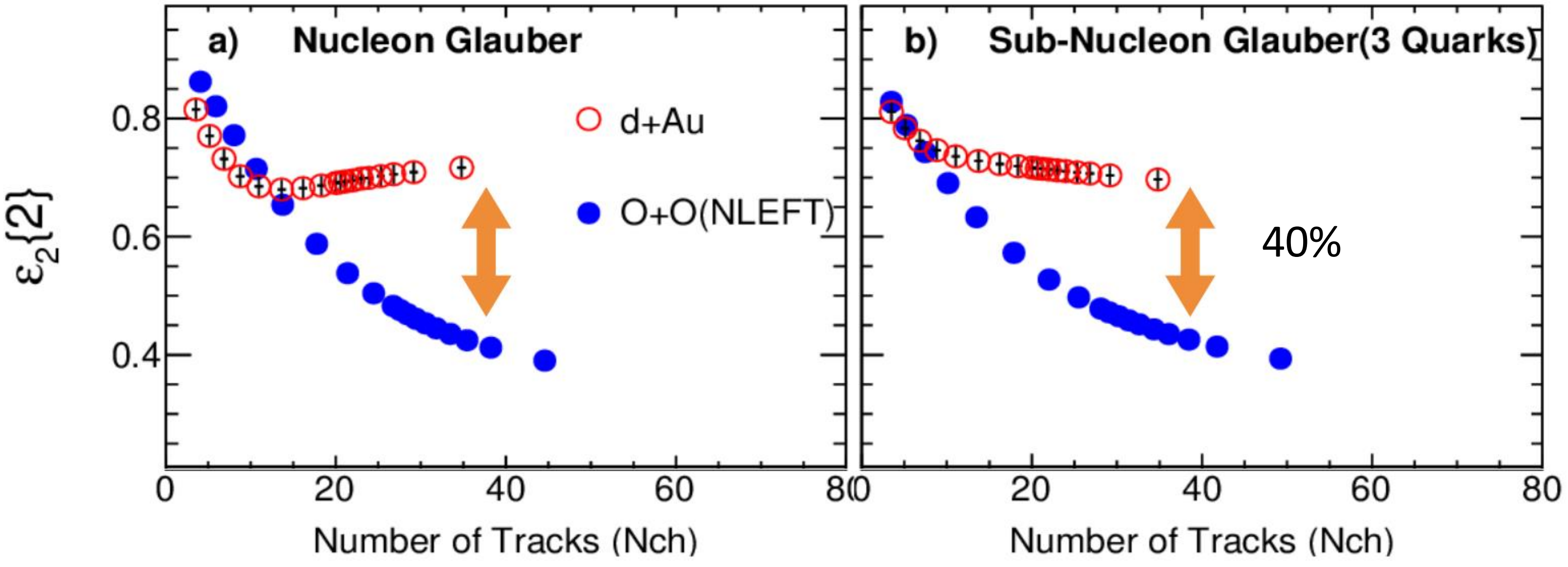
- Elongated deuteron vs. nearly round oxygen nuclei

- Vastly different initial geometries → ideal test of geometry–flow response

Eccentricity between d+Au and O+O (I)

Nucleon Glauber

Quark Glauber

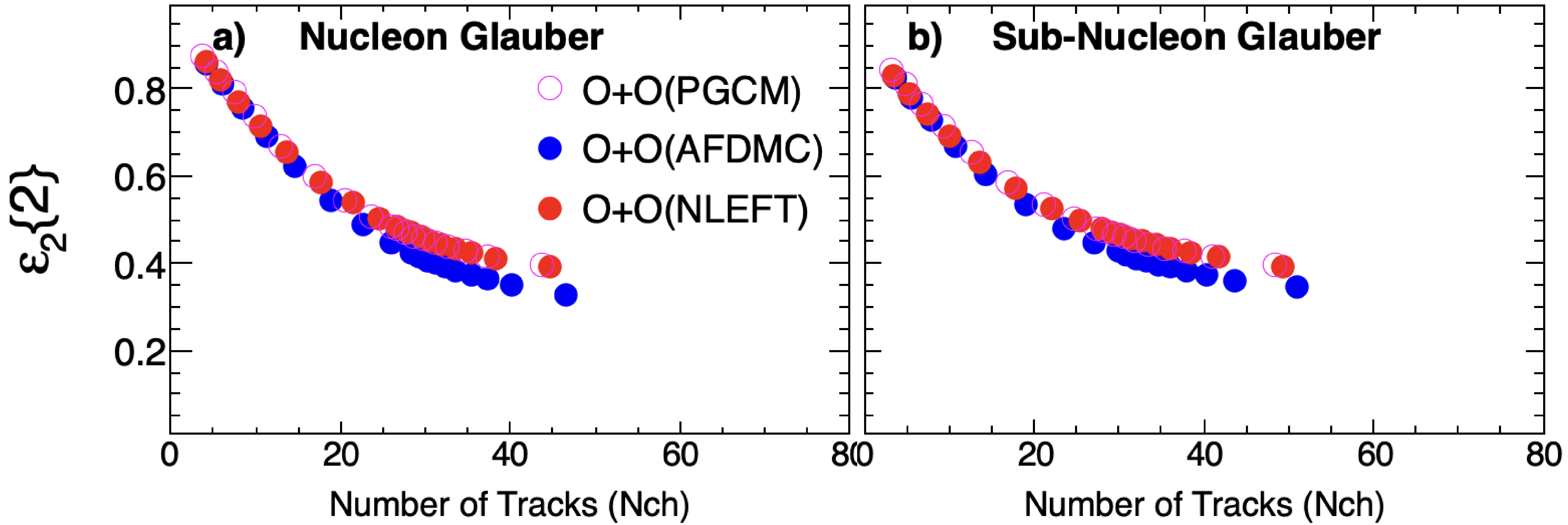


$\boldsymbol{\varepsilon}_2$(O+O) < $\boldsymbol{\varepsilon}_2$(d+Au)

Significant difference(~40%)

Regardless nucleon or sub-nucleon fluctuation

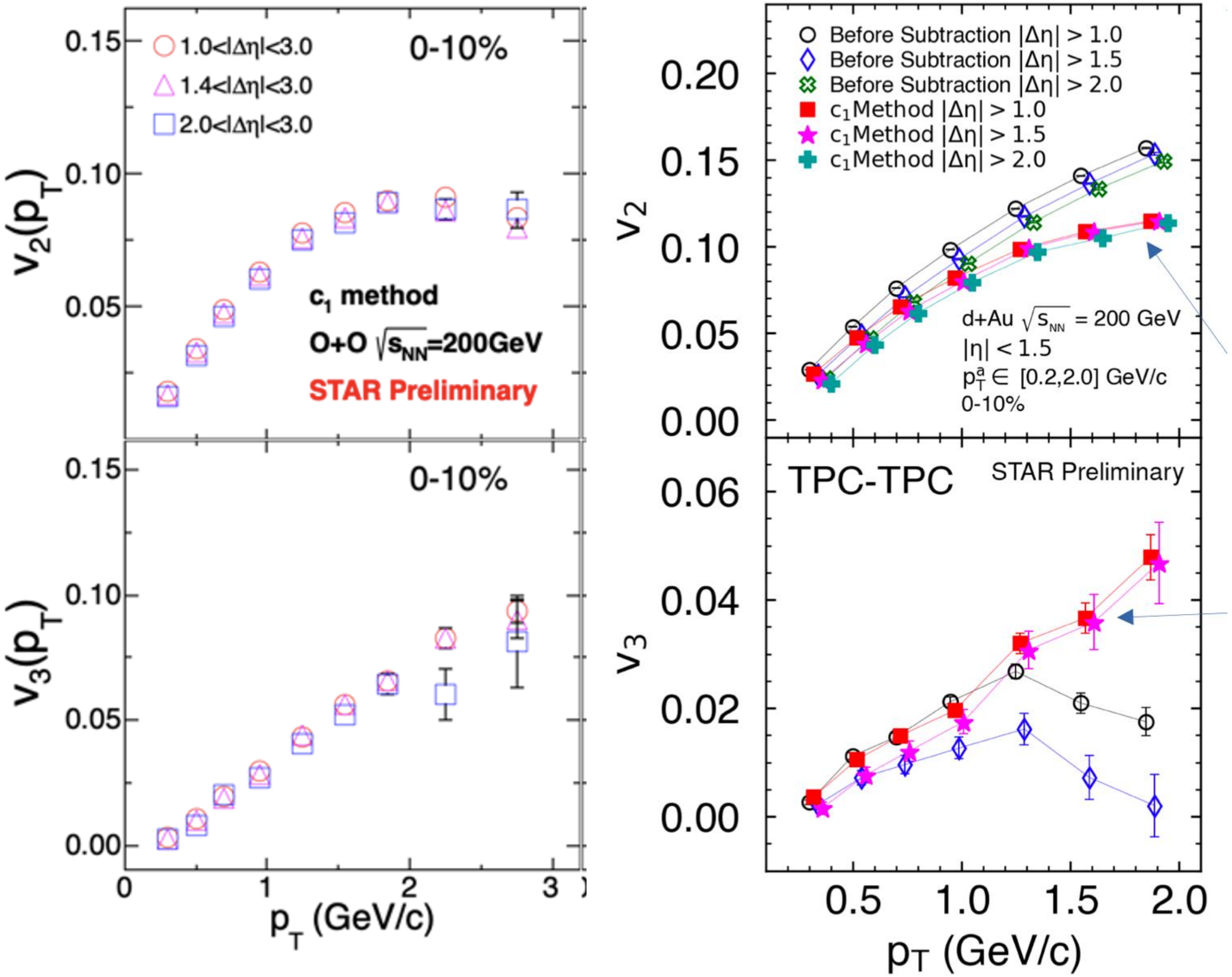
Different *ab initio Models*



The $\boldsymbol{\varepsilon}_2$(O+O) from different ab initio initial-state models agrees within ~10%

Middle-middle correlation from new Run21: v_n with different $\Delta\eta$ cut

O+O d+Au



After nonflow subtraction, v_n are independent of the $|\Delta\eta|$ selection

De-correlation is small in middle-middle correlation

A Golden Comparative Measurement

•**Maximise the difference in initial geometry between systems.**
40% difference with ε_2(O+O) < ε_2(d+Au)

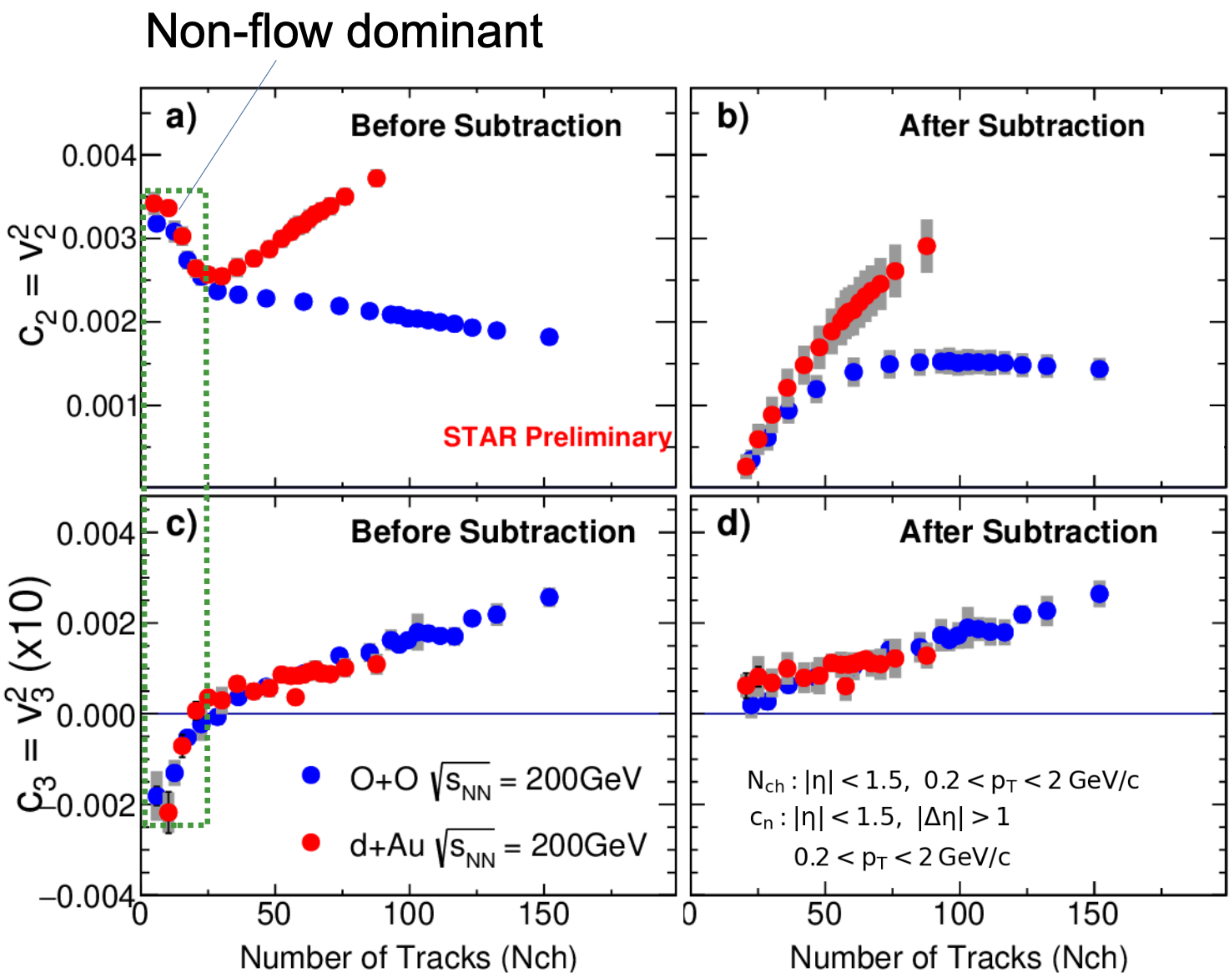
•**Minimise uncertainties in the initial geometry.**
ε_2 in O+O and d+Au is insensitive to sub-nucleon fluctuation and different ab initio models

.

•**Reduce contamination of flow observables from pre-flow, decorrelation, and nonflow.**
Minimum contamination from nonflow, preflow and de-correlations for v_2

A golden probe for the linear response between v_2 and ε_2!

c_2 and c_3 in d+Au and O+O



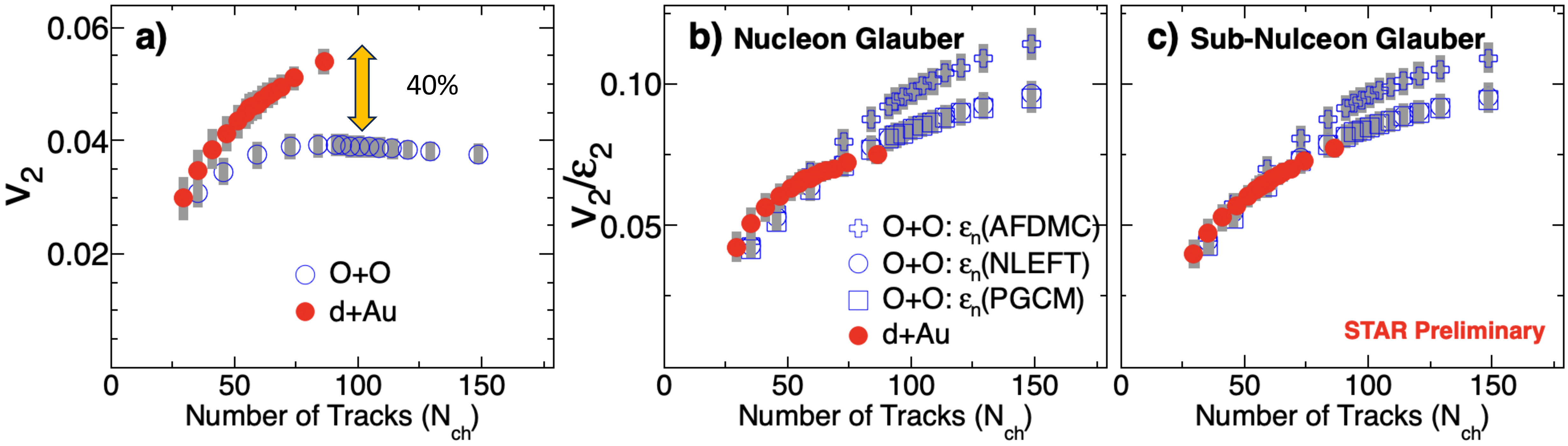
A non-monotonic behavior is found for c_2@d+Au vs. multiplicity

A clear interplay between "Flow" and "Nonflow"

c_2(d+Au) > c_2(O+O) at HM region

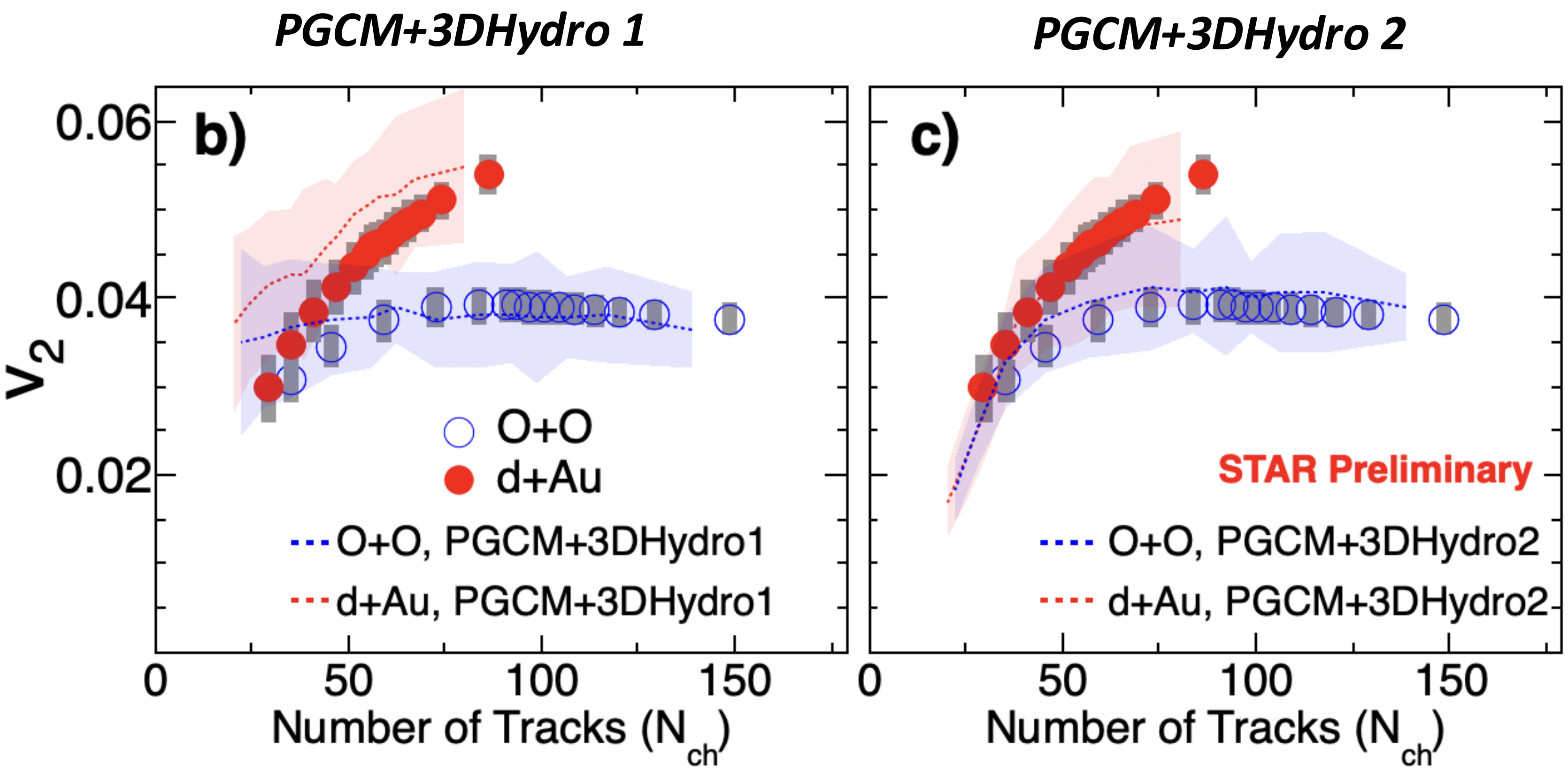
c_3(d+Au) ≈ c_3 (O+O)

V_2 vs. Multiplicity



- v_2 differs by ~40% between d+Au and O+O collisions.
- Response coefficient $k_2=v_2\{2\}/\varepsilon_2\{2\}$ is similar in both systems.
- Scaling improves when including sub-nucleon fluctuations.
- Splitting at high multiplicity provides leverage to discriminate between different ab-initio models

Comparing with Hydro v_2

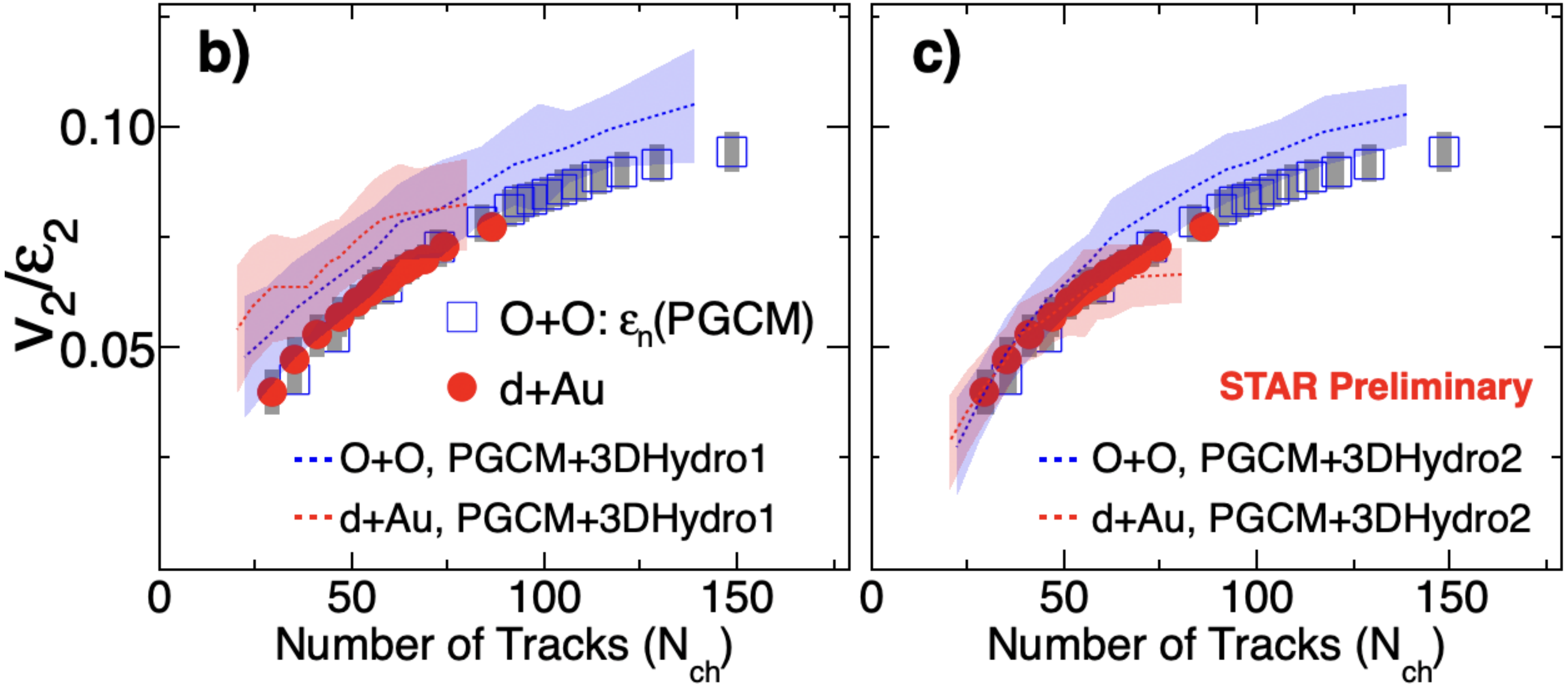


Hydro1
Large sub-nucleon fluctuation
Small η/s=0.04

Hydro2
Small sub-nucleon fluctuation
Large η/s=0.09

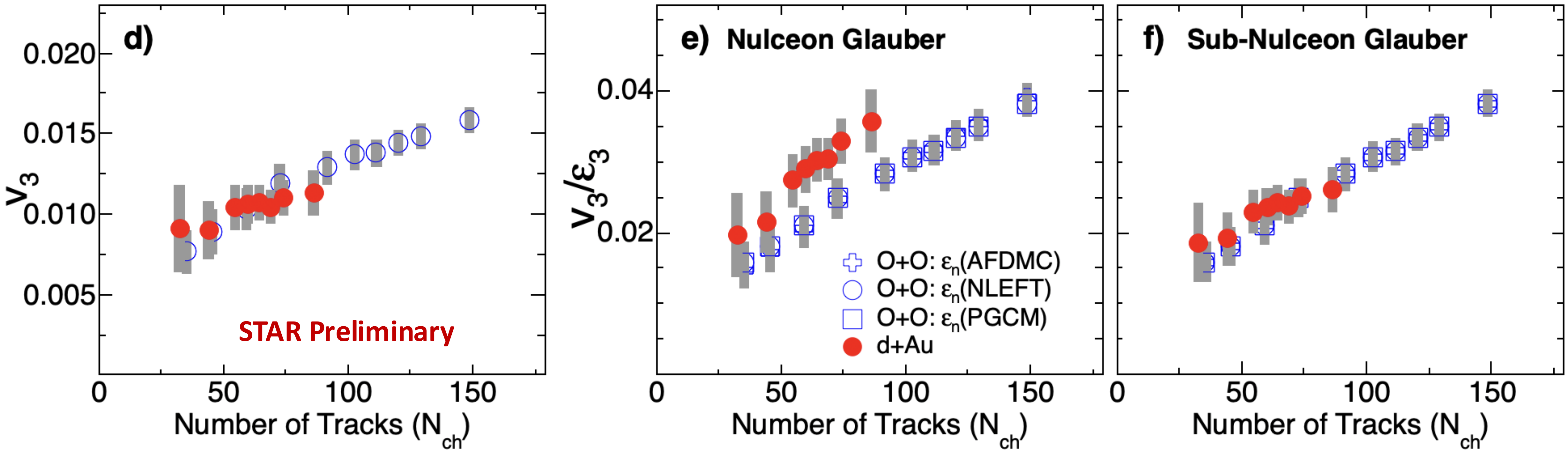
- Both hydrodynamic models reproduce the measured v_2.
- **Hydro 2** (larger η/s) gives a better description of v_2 in low-multiplicity events.

$v_2\{2\}/\varepsilon_2\{2\}$ in Hydro



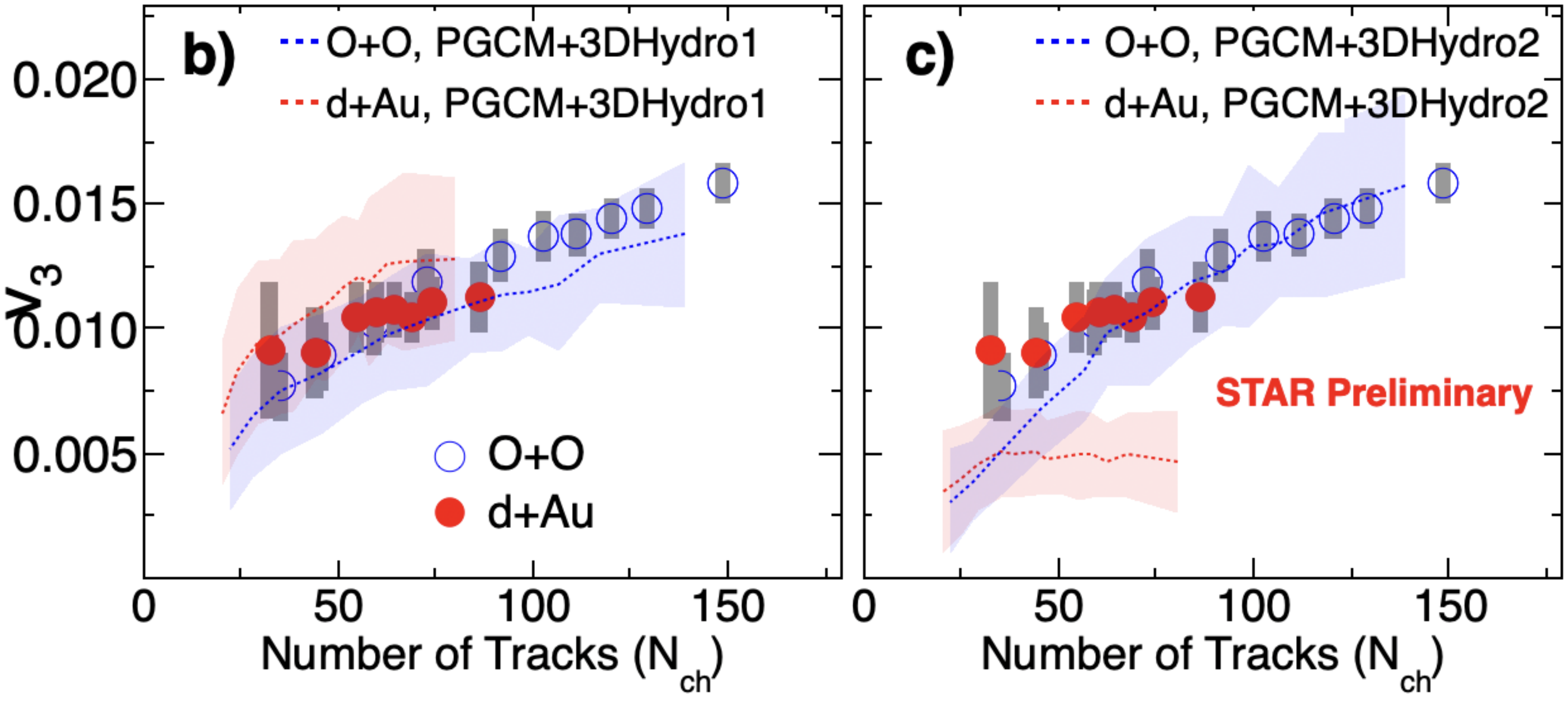
- By scaling with $\varepsilon_2\{2\}$ from hydro, the models reproduce the measured $v_2\{2\}/\varepsilon_2\{2\}$.
- A clear linear response is observed between initial $\varepsilon_2\{2\}$ and final $v_2\{2\}$ in d+Au and O+O.
- This provides strong evidence for hydrodynamic expansion in small systems.

V_3 vs. Multiplicity



- v_3 is similar between d+Au and O+O collisions.
- Scaling works **only when sub-nucleon fluctuations are included**
- This provides further confirmation of the crucial role of sub-nucleon fluctuations in small systems

Comparing with Hydro v_3

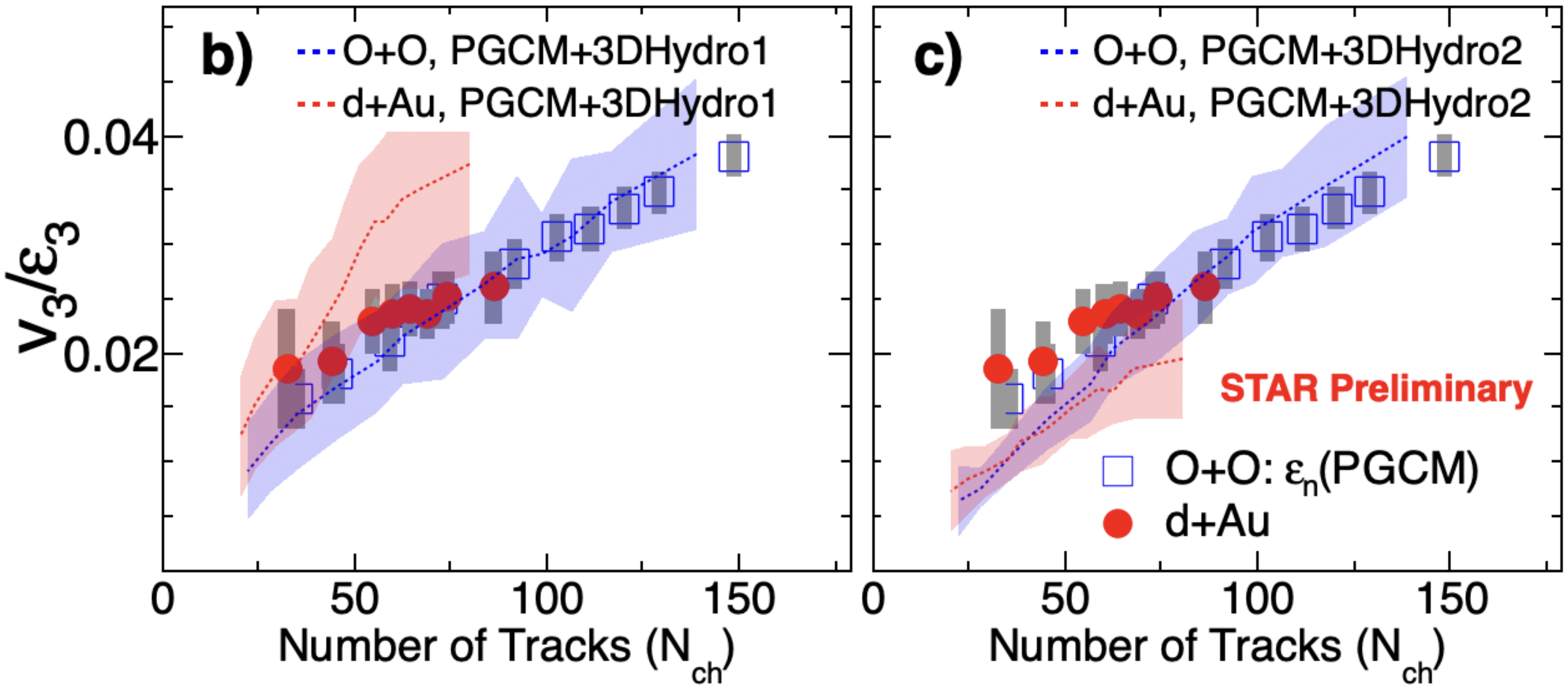


Hydro1
Large sub-nucleon fluctuation
Small η/s=0.04

Hydro2
Small sub-nucleon fluctuation
Large η/s=0.09

- Only hydrodynamic model with large sub-nucleon fluctuation can reproduce the measured v_3 in d+Au.

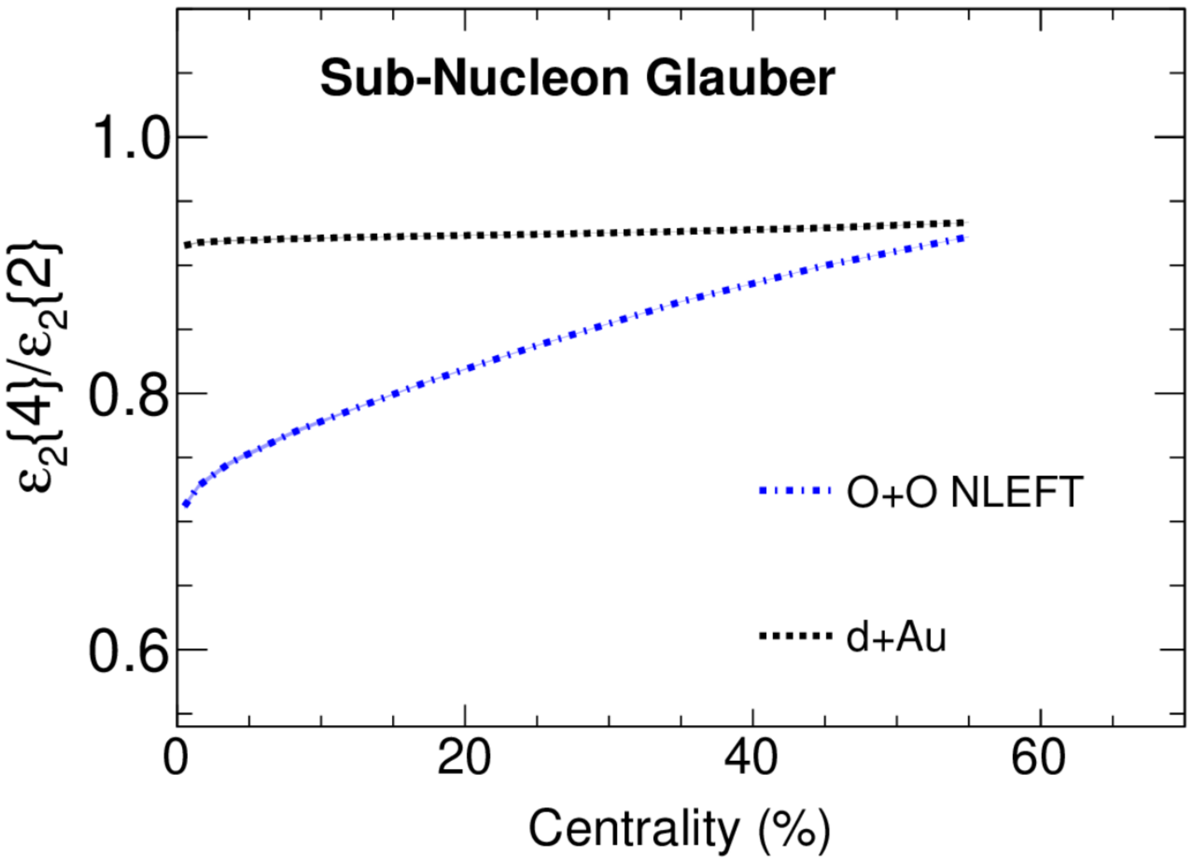
$v_3\{2\}/\varepsilon_3\{2\}$ in Hydro



•Linear response is observed between initial $\varepsilon_3\{2\}$ and final $v_3\{2\}$ in **Hydro 2** (large η/s)

•Nonlinear contributions are expected to become more pronounced for **smaller η/s**

Initial Geometry Fluctuation: $\varepsilon_2\{4\}/\varepsilon_2\{2\}$

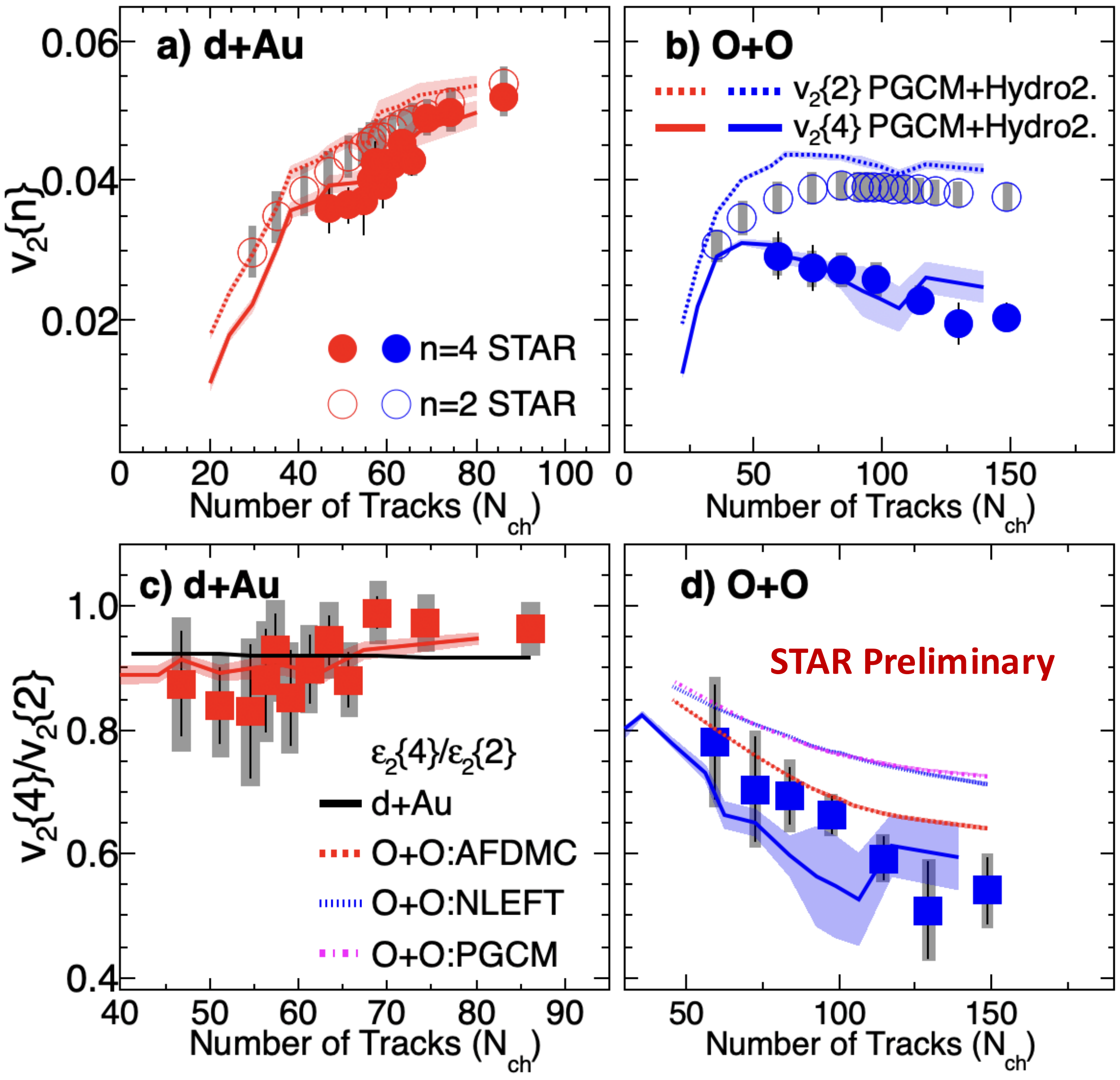


- **Central collisions:**
- $\varepsilon_2\{4\} \approx \varepsilon_2\{2\}$ in d+Au → dominated by dumbbell-shaped deuteron geometry.

- $\varepsilon_2\{4\} < \varepsilon_2\{2\}$ in O+O → fluctuation-dominated.

- If $v_2\{4\}/v_2\{2\}$ is controlled by $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ this also provides key evidence for hydrodynamic expansion.

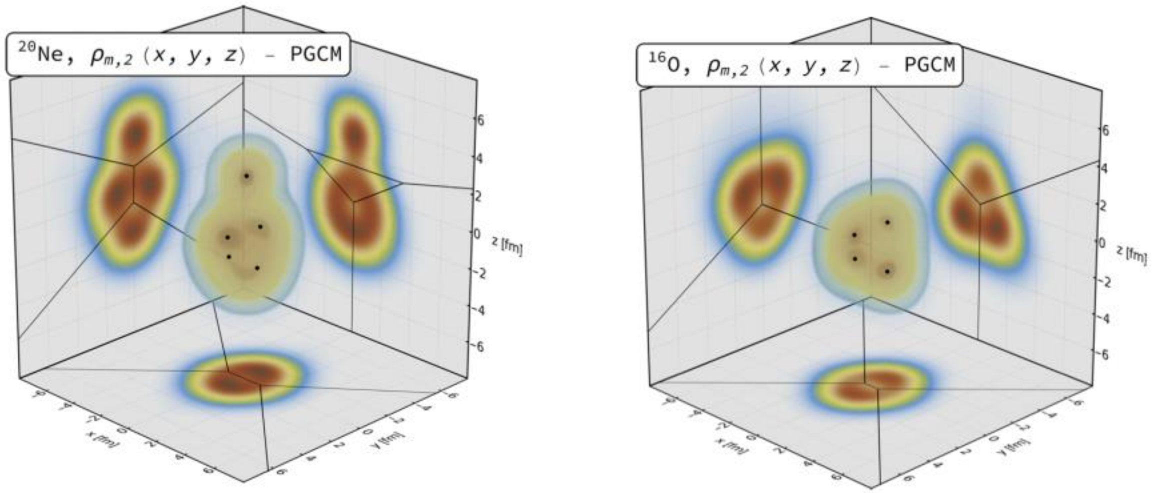
$v_2\{4\}/v_2\{2\}$ in d+Au and O+O

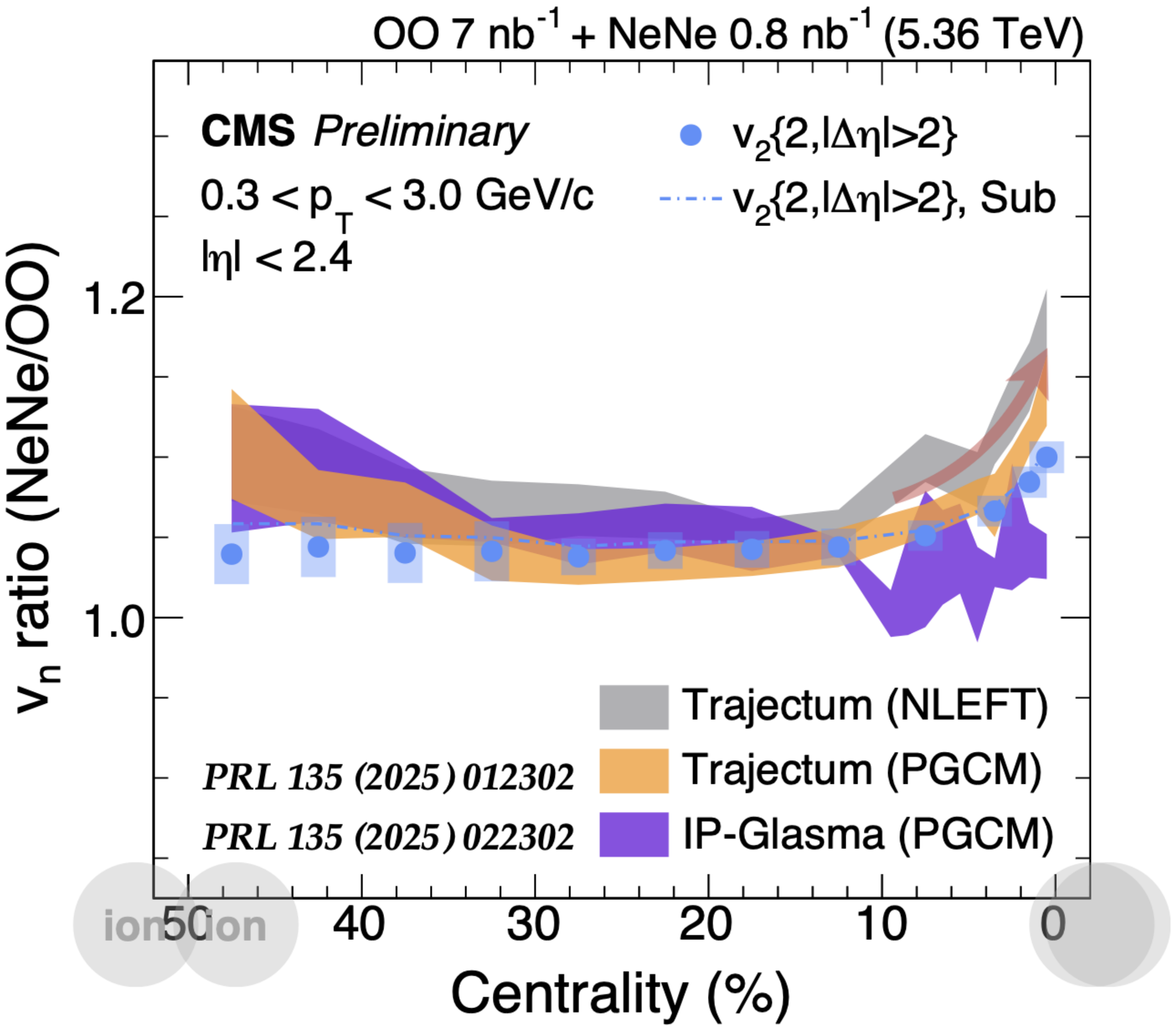


- $v_2\{4\}/v_2\{2\}$ strongly depends on $\varepsilon_2\{4\}/\varepsilon_2\{2\}$
- Hydro model with large η/s=0.09 reproduces the measurement.
- Hydro with small η/s=0.04 fails to generate $v_2\{4\}$ due to large nonlinear effects.
- **Implication:** Strong constraint on η/s in small systems.

Ne+Ne vs O+O in LHC

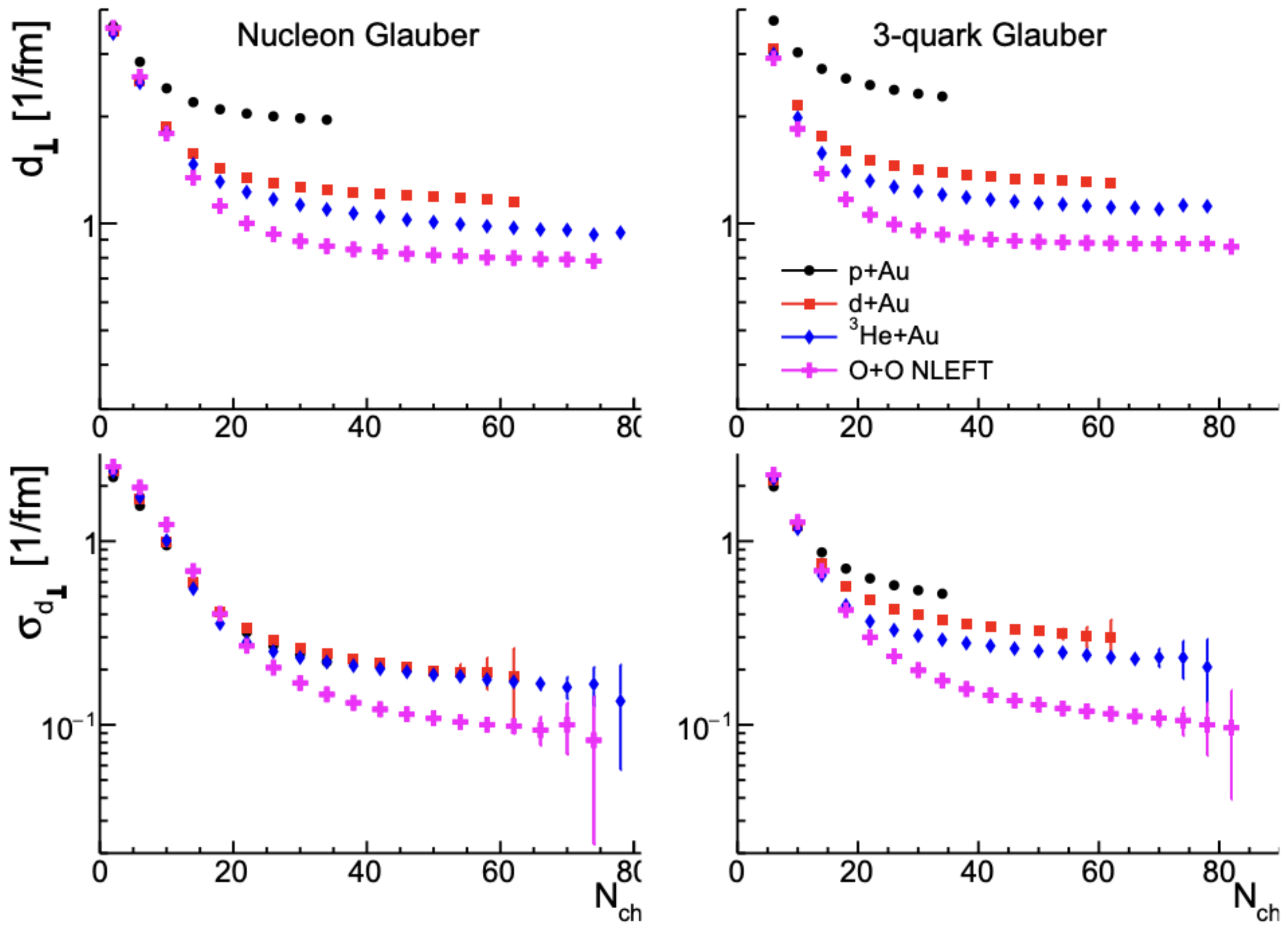
Phys. Rev. Lett. 135 (2025) 012302





- Deformed Ne+Ne collisions generate larger $\varepsilon_2\{2\}$ than O+O.
- ~10% difference observed at the LHC.
- Hydro model predicts ~20% difference.
- Model tends to overestimate the deformation parameter β_2

Outlook



S.Huang, J.Jia and C. Zhang arXiv:2507.16162

•Different size fluctuations between asymmetric (d+Au) and symmetric (O+O) small systems.

•⟨pT⟩~1/R⟨; differences in ⟨pT⟩ fluctuations between d+Au and O+O provide direct insight into radial flow effects in small systems.

Summary

Comparative study: d+Au vs O+O collisions (unprecedented geometric control)

Two Key observations:

1. $v_2\{2\}$ shows linear response to $\varepsilon_2\{2\}$ with 40% difference between d+Au and O+O.
2. $v_2\{4\}/v_2\{2\}$is controlled by $\varepsilon_2\{4\}/\varepsilon_2\{2\}$.

→ Both strongly support hydrodynamic expansion in small systems.

It is further confirmed by 3D Glauber + hydro calculations tuned from large systems.

Provides rich constraints for understanding formation criteria and properties of small QGP droplets.