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Probing collectivity in small collision systems using asymmetric d+Au and symmetric O+O collisions

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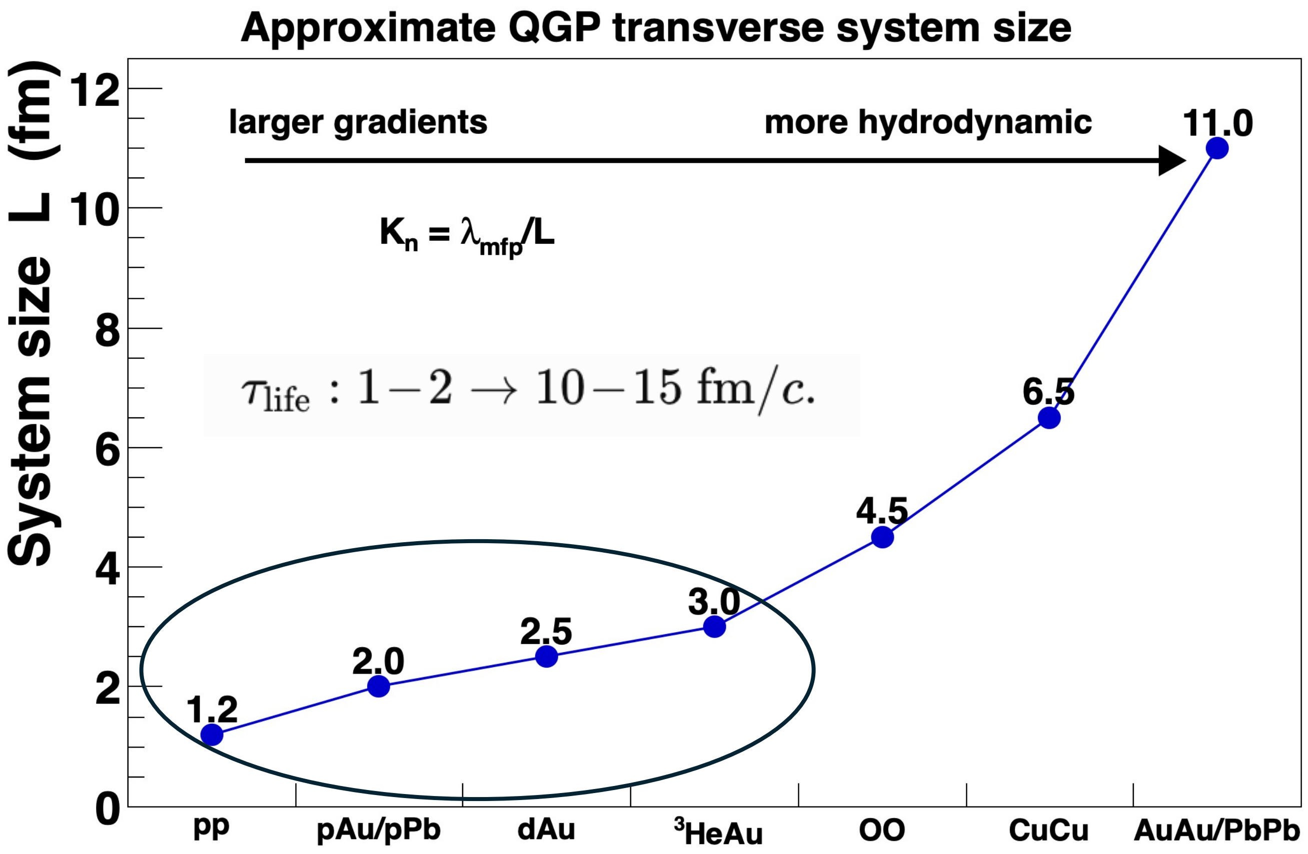
How Small Can a QGP Droplet Be?



smaller system ⇒ shorter lifetime ⇒ less time to convert $\varepsilon_n \rightarrow v_n$

Modern hydrodynamic calculations qualitatively reproduce the observed anisotropy in pp->^{3}HeAu with

$$\tau_{\rm hydro} < \tau_{\rm thermal}$$

The next frontier is quantitative tests of hydrodynamic response

1. Can we determine the response coefficient?
2. Can we identify where linear response breaks down?
3. Can we constrain the small QGP properties?

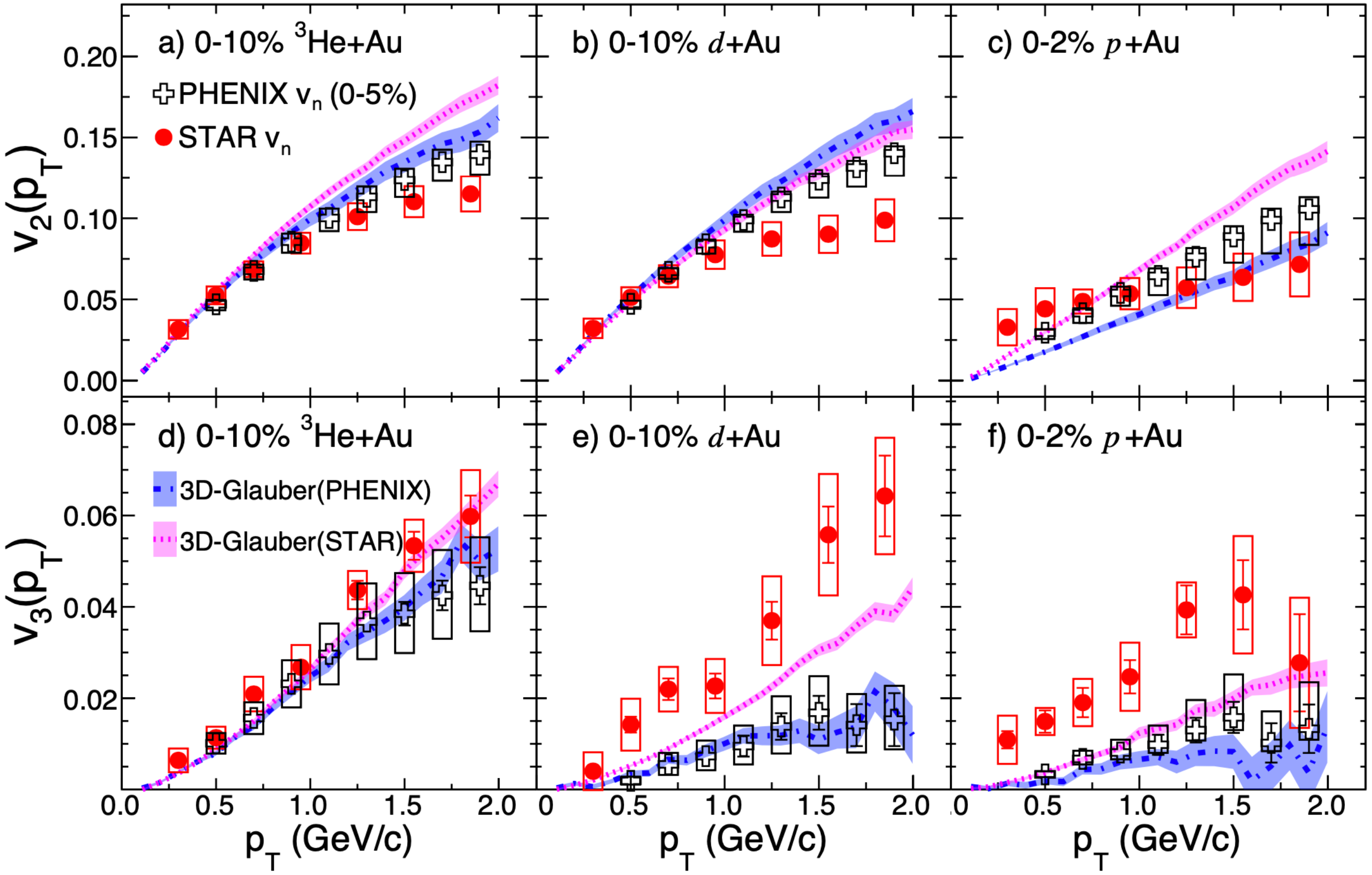
These questions motivate the work I will present today

Limitations of previous p/d/^{3}He+Au Scan

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

STAR: ***PRL 130, 242301(2023), PRC 94, 024919 (2016)***
PHENIX: Nature Phys. 15, 214 (2019)
3D-Glauber: Chun & Wenbin, PRC 107, 014904 (2023)

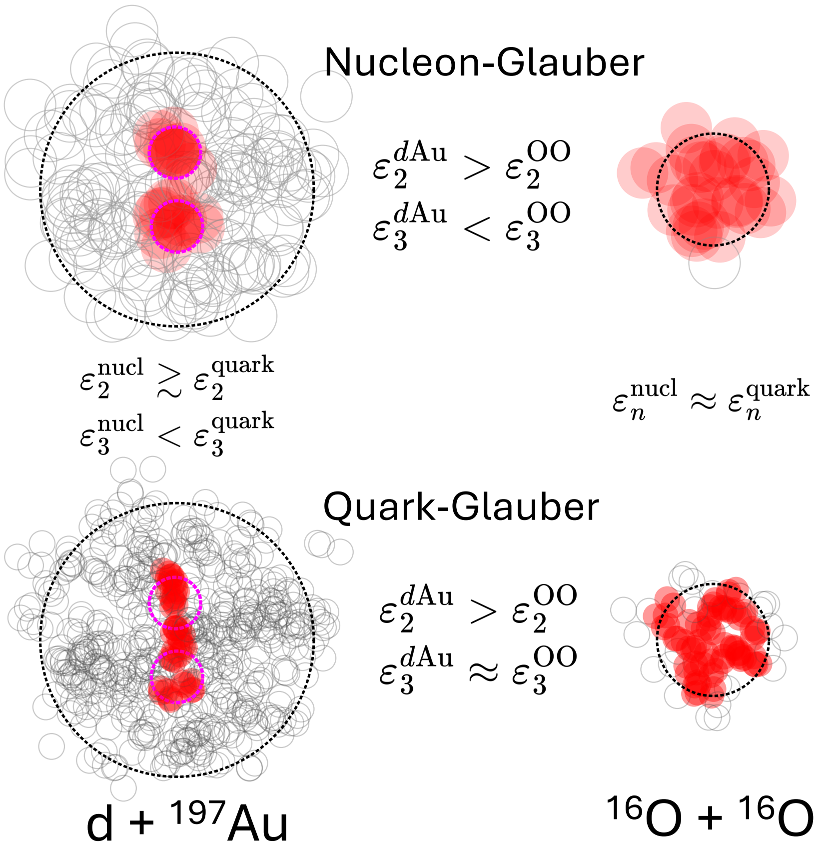


Three important limitations remain:

1. Large geometry uncertainty from sub-nucleon fluctuations
2. Large rapidity decorrelation→PHENIX v_3(^{3}HeAu)>v_3(dAu) ≈ v_3(pAu)
3. Limited understanding of the energy dependence (Temperature, life time, ...)

Can O+O provide a clean geometry reference?

Why d+Au vs O+O?

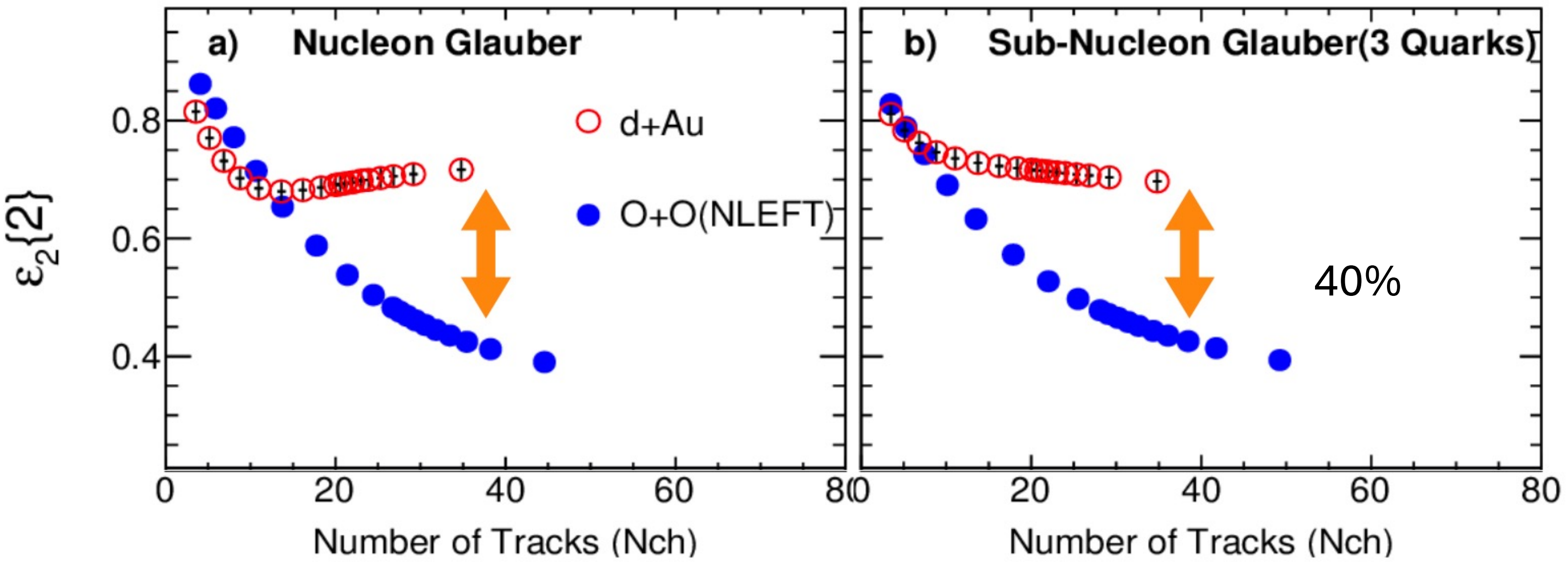


	d+Au	O+O
Initial geometry	Dominated by deuteron	More participating nucleons
Eccentricity	Large ε_2, small ε_3	small ε_2, fluctuation-driven ε_3
Sub-nucleon sensitivity	High	Low
Physics role	Geometry-rich system	Clean reference

- Similar medium size
- Very different initial geometry
- Opposite sensitivity to sub-nucleon fluctuations
- RHIC vs. LHC for OO provides unique energy scan

A clean geometry lever arm for quantitative test of hydrodynamics

I. A Large Geometry Lever Arm: ε_2



$\varepsilon_2(O + O)$ is about 40% smaller than $\varepsilon_2(d + Au)$.

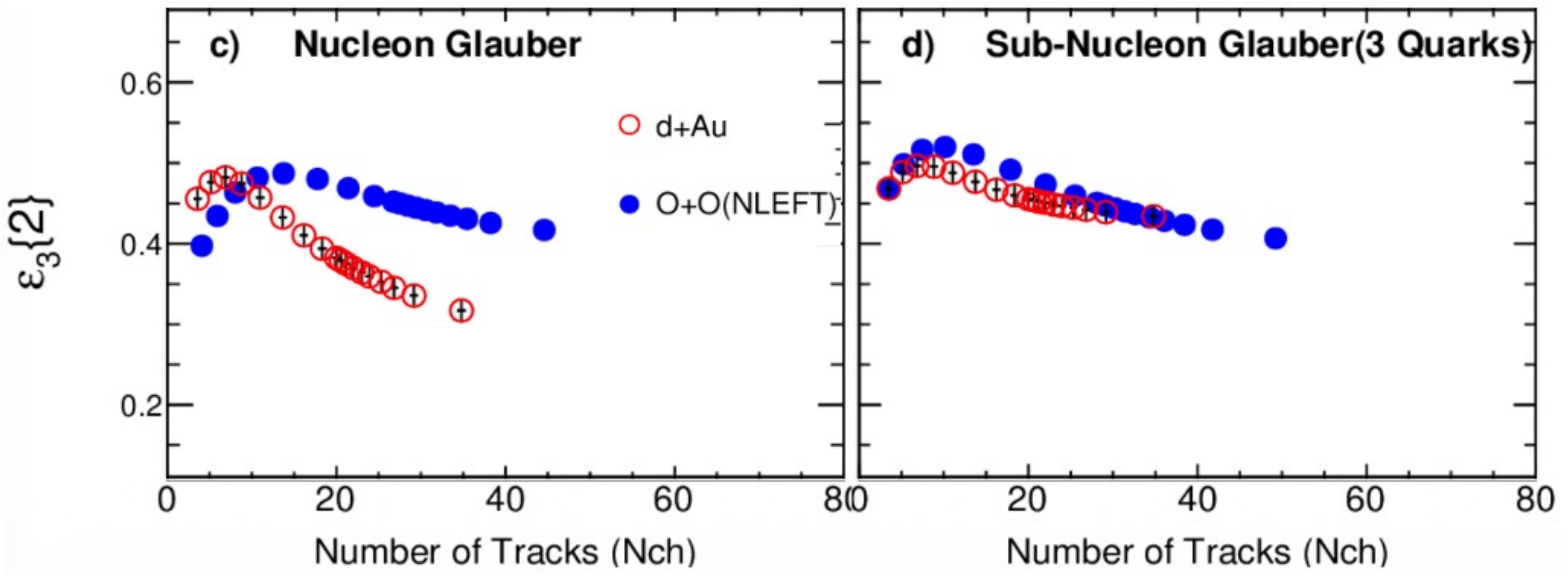
The large geometry difference is robust against point-like nucleon, gaussian-like nucleon and sub-nucleon fluctuation models.

A large, clean and well-controlled geometry lever arm to test the linear hydrodynamic response.

II. Good Reference for Sub-nuclear Fluctuation: ε_3

Nucleon Glauber

3-quark Glauber



S. Huang, J. Jia: PLB (870),2025, 139926

O+O is largely insensitive to sub-nucleon fluctuations, whereas d+Au exhibits moderate sensitivity

III. O+O for Collision Energy Dependence

Property	RHIC	LHC
Collision energy √sNN	200 GeV	5.36 TeV
Initial temperature T0	~300–350 MeV	~450–550 MeV
Initial energy density	1x	~2–3x
QGP lifetime	~4–5 fm/c	~6–8 fm/c

B. Schenke, C. Shen, P. Tribedy,
Phys. Rev. C **102**, 044905 (2020)

G. Giacalone et al.,
Phys. Rev. C **104**, 024904 (2021)

C. Shen and B. Schenke,
Phys. Rev. C **105**, 064905 (2022)

Study how hydrodynamic response changes with temperature, energy density and lifetime while keeping the initial geometry fixed

Quantitative Tests of Hydrodynamics

✓ Linear response ($v_2\{2\}$,$v_3\{2\}$)

✓ Flow fluctuations ($v_2\{4\}$)

✓ Nonlinear response($v_4\{2\}$)

Hydrodynamic Response

✓ RHIC vs LHC

✓ Acoustic scaling

✓ Constrain η/s

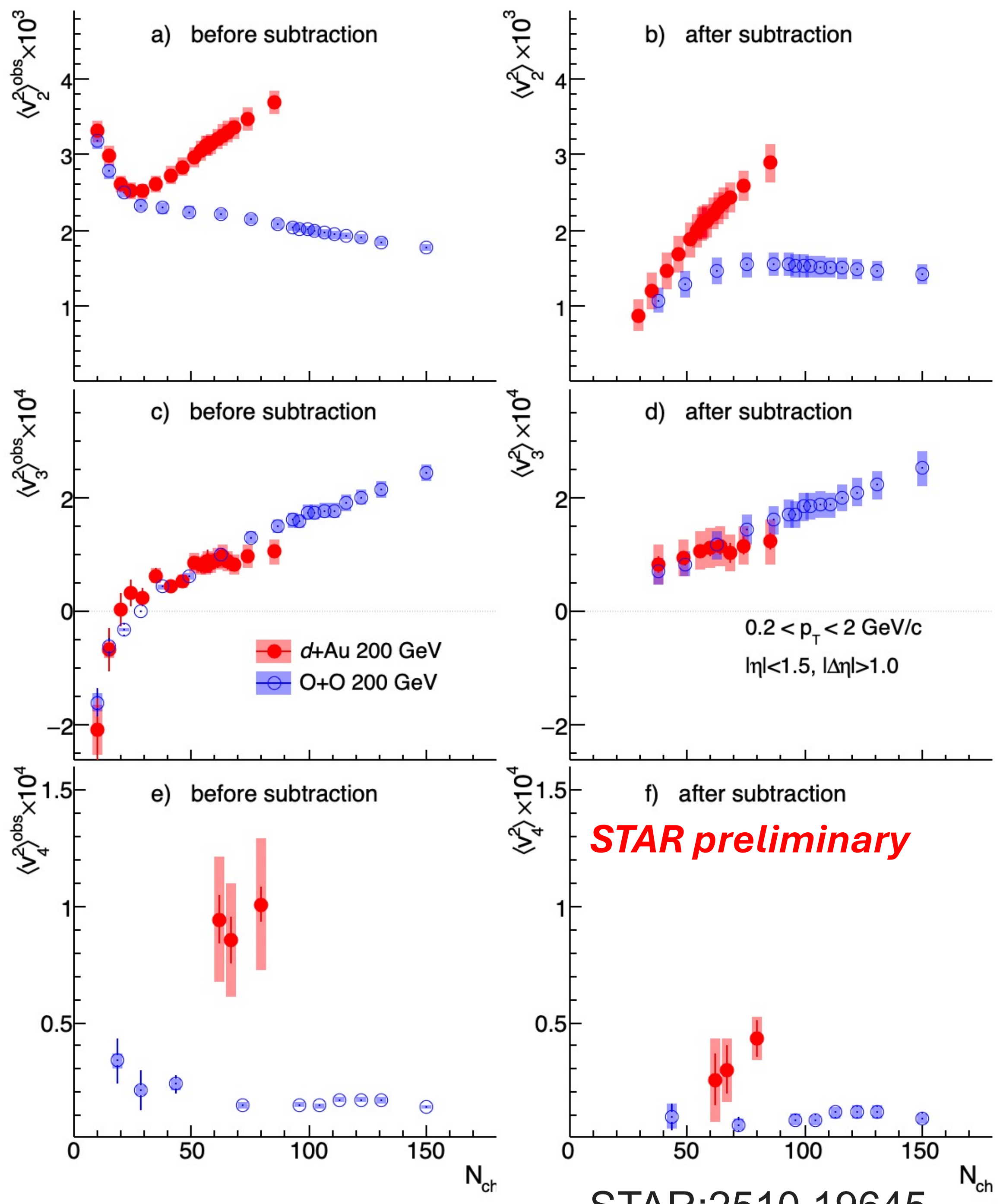
QGP Properties

✓ Nuclear structure (α-clustering)

✓ System-size and shape correlation: v_n-pt correlation

Future Opportunities

$c_n = v_n^2$ in dAu and OO



STAR:2510.19645

Raw correlations

Competition between **nonflow** and **collective flow**

c_2: non-monotonic with multiplicity

c_3: negative → positive

After nonflow subtraction

Larger c_2 in d+Au

Similar c_3 in d+Au and O+O

Larger c_4 in d+Au

Initial geometry is reflected in the measured collective flow

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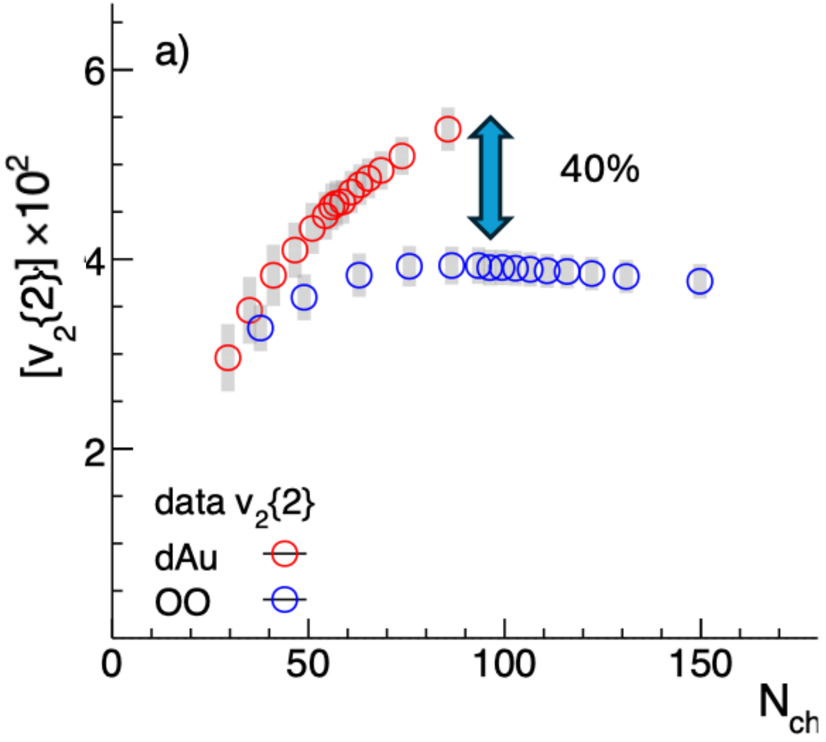
v_2, v_3 and v_4 in d+Au and O+O Collisions



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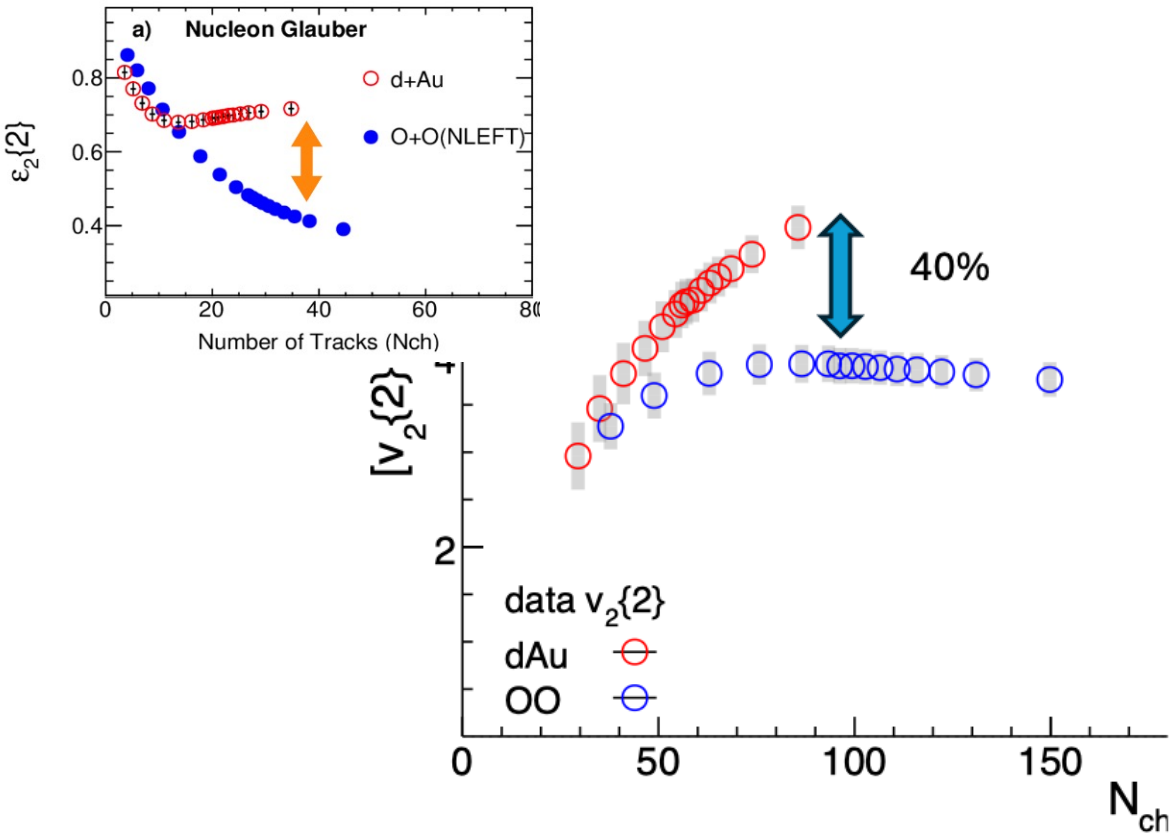
v_2 differs by ~40% between d+Au and O+O collisions:

v_2, v_3 and v_4 in d+Au and O+O Collisions



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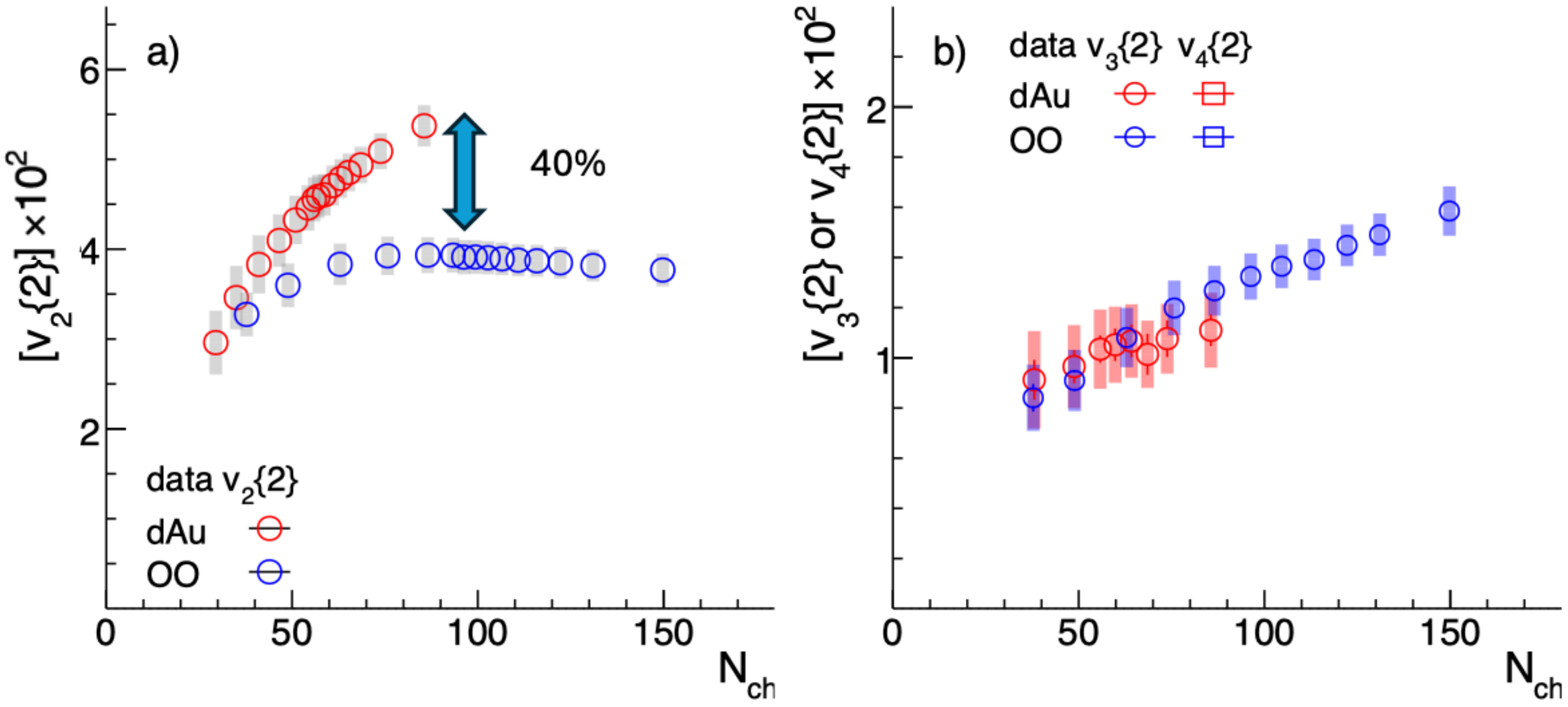
v_2, v_3 and v_4 in d+Au and O+O Collisions



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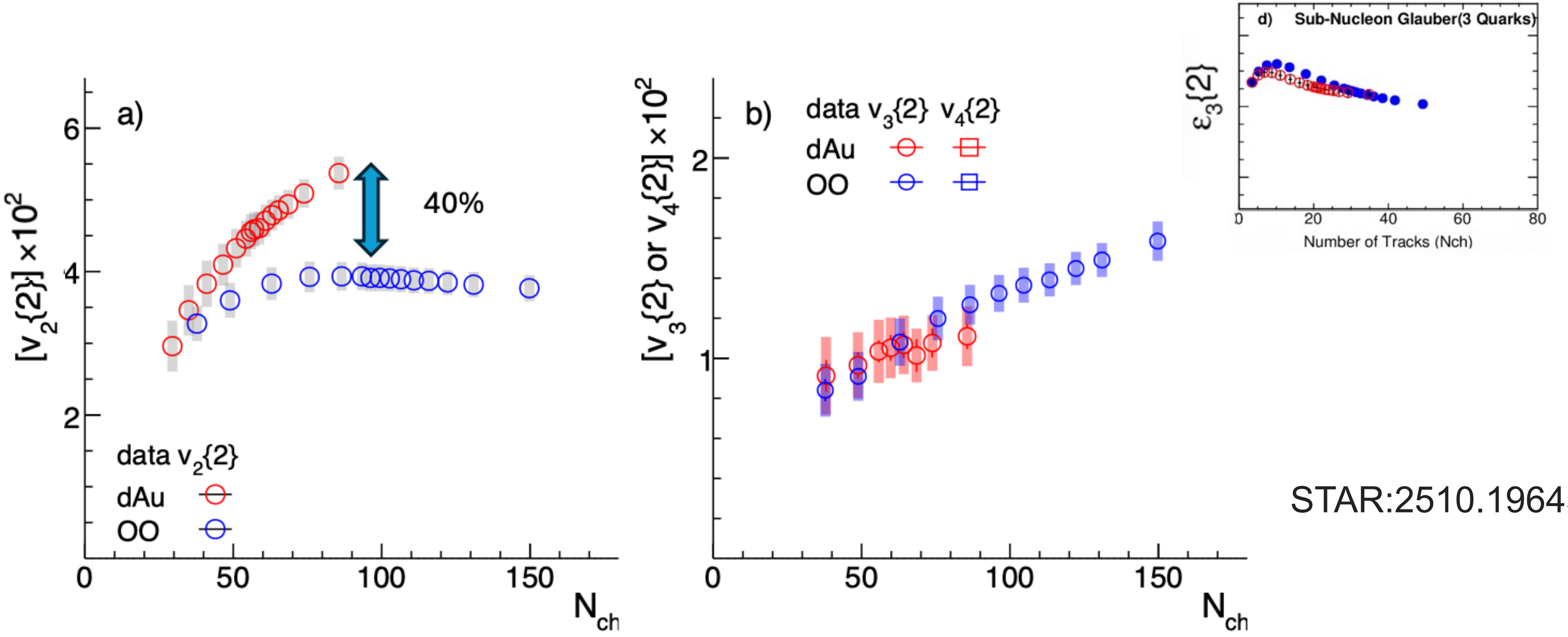

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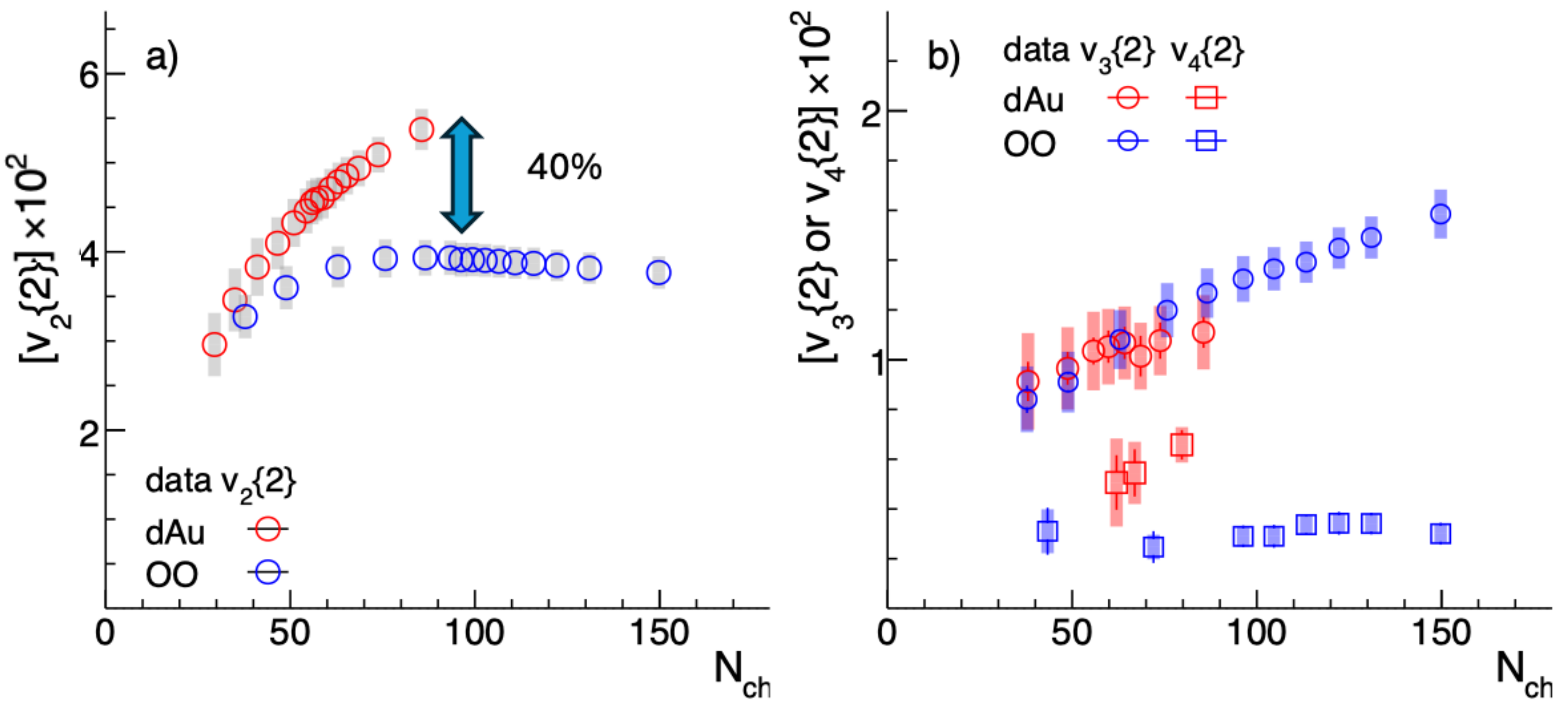
v_3 is similar between d+Au and O+O collisions: **similar e_3 from sub-nuclear fluc.**

v_2, v_3 and v_4 in d+Au and O+O Collisions



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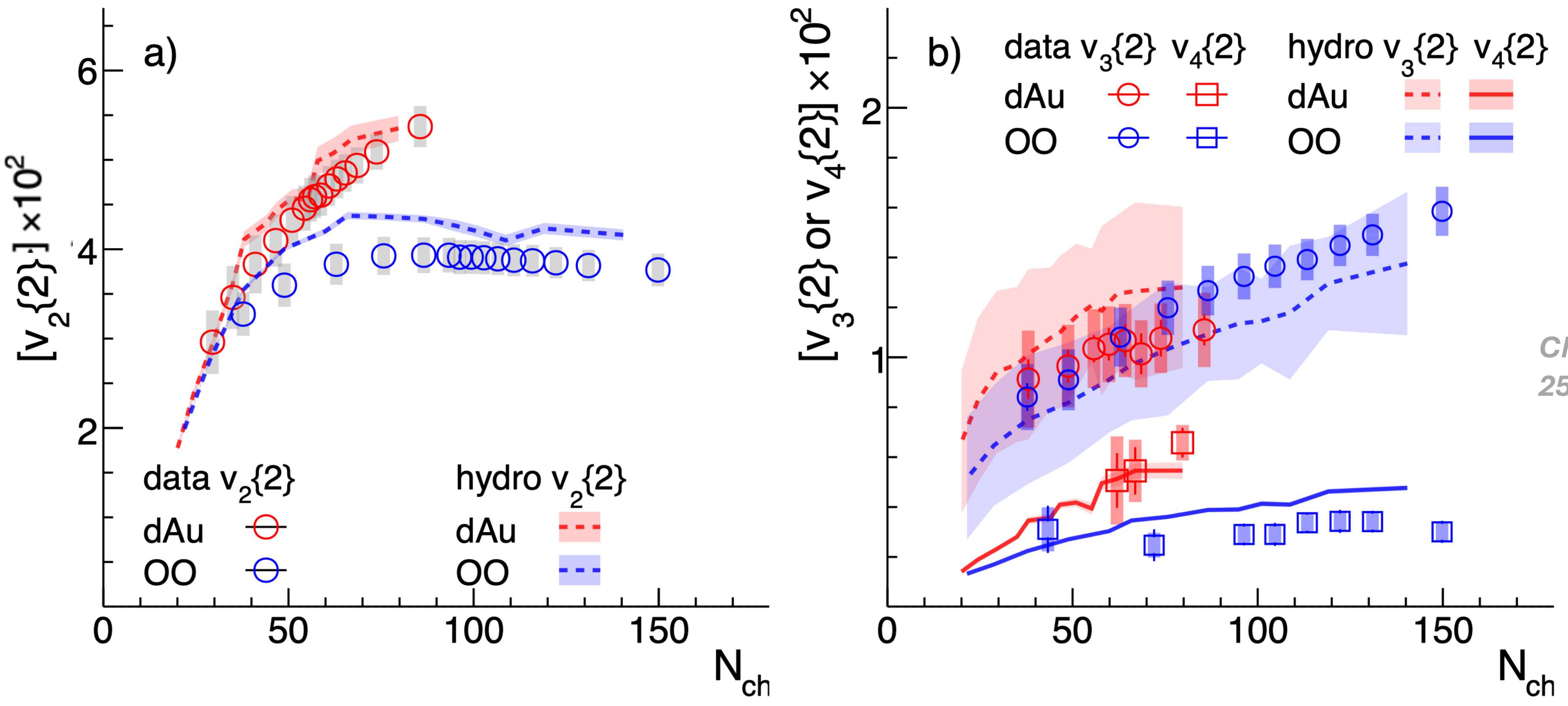
v_3 is similar between d+Au and O+O collisions: **similar e_3 from sub-nuclear fluc.**

v_4 (d+Au) > v_4(O+O): **$e_2\{2\}$ or $e_4\{2\}$?**

Compare with Hydro

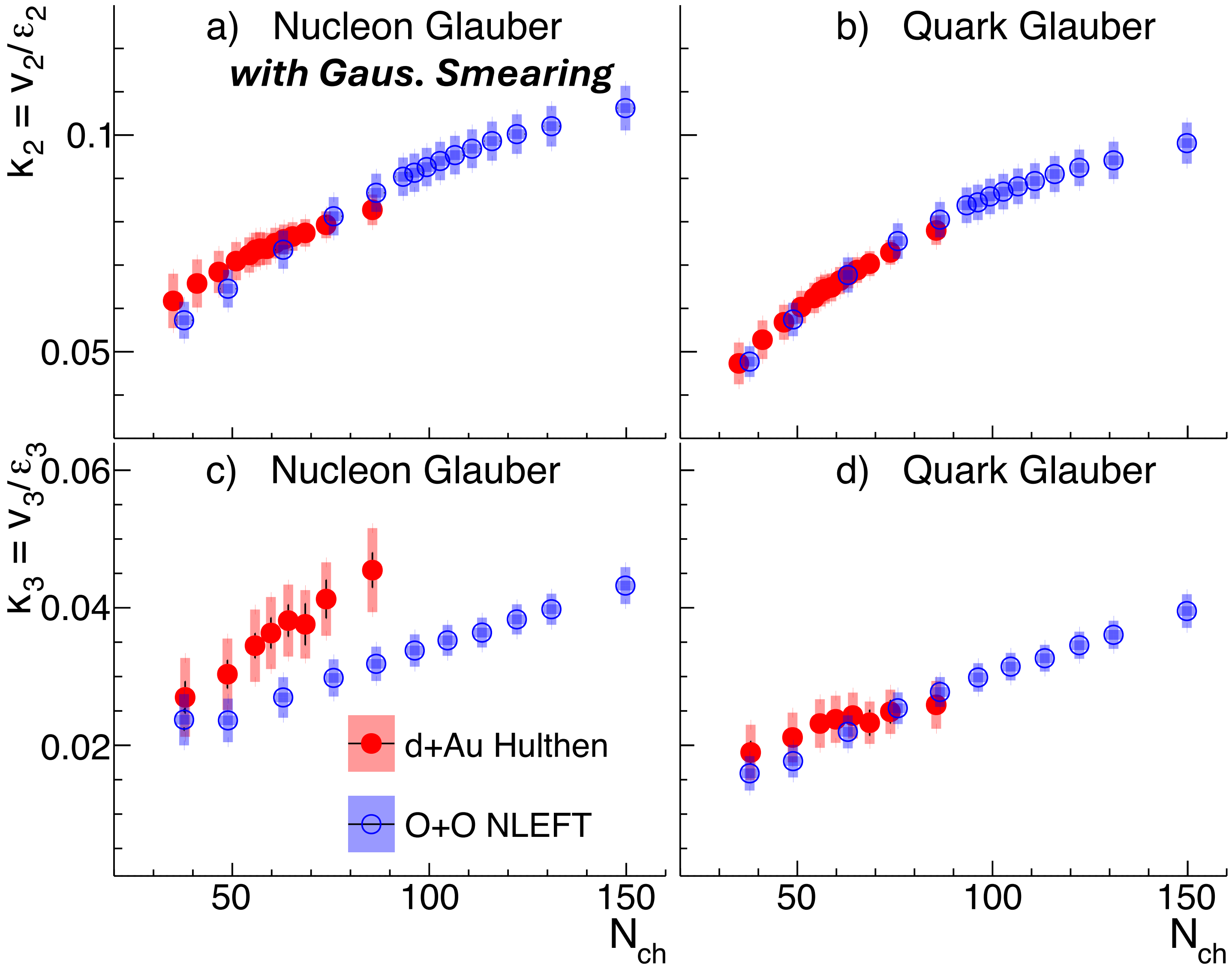


Chun et.al
2507.11394

3D-Glauber+Music+UrQMD hydro model tuned to Au+Au data

One hydrodynamic model simultaneously describes d+Au and O+O

Linear Response of Eccentricity



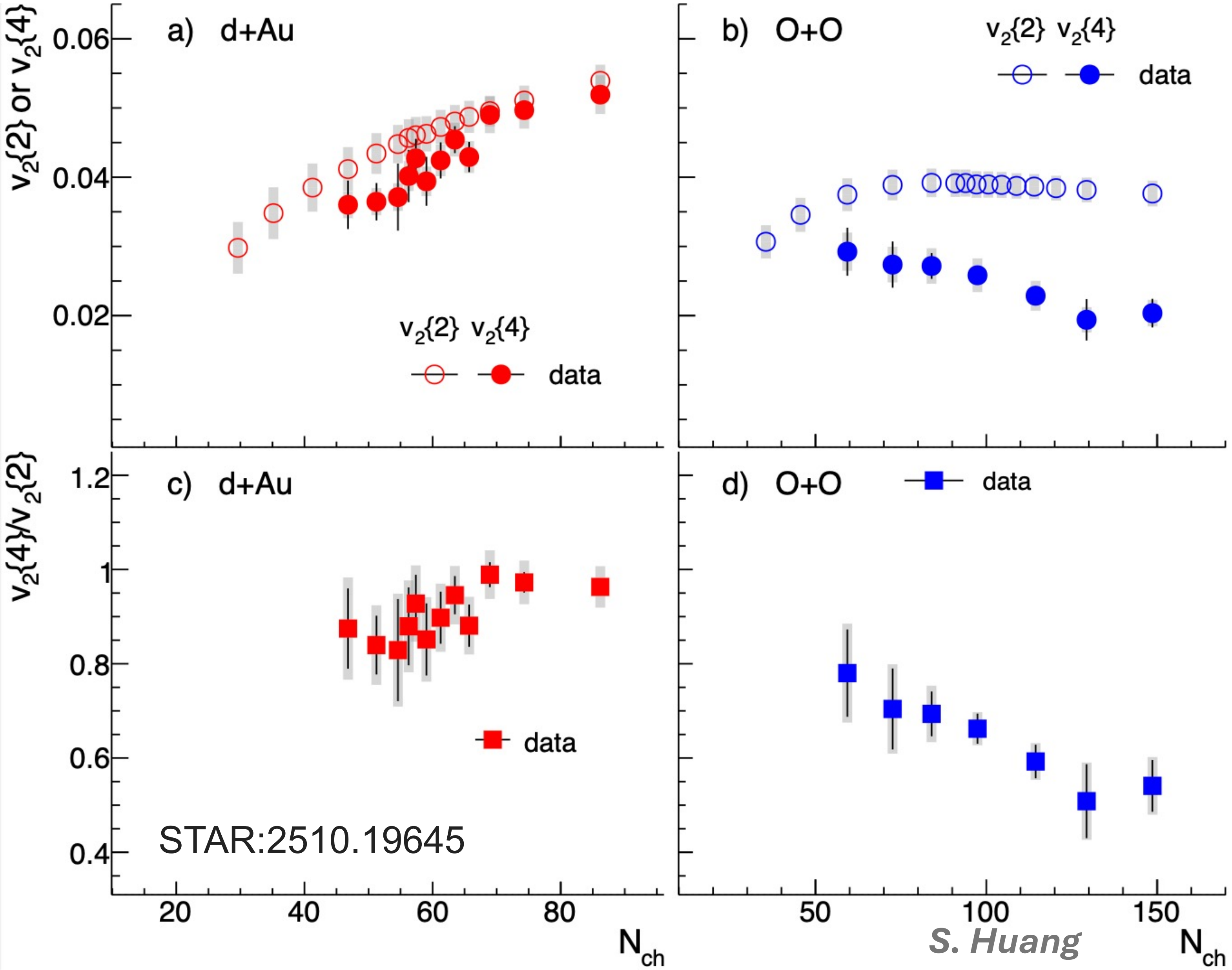
STAR:2510.19645

Response coefficient
$k_n=v_n\{2\}/\varepsilon_n\{2\}$
is similar in both systems

Scaling improves when including sub-nucleon fluctuations.

Flow response is linear to eccentricity, how about the flow fluctuation?

How do fluctuations propagate?



In d+Au, $v_2\{4\}$ is similar to $v_2\{2\}$;$v_2\{4\}/v_2\{2\}$ ~0.9

In O+O, $v_2\{4\}$ is much smaller than $v_2\{2\}$; the ratio decreases with multiplicity 0.8→ 0.6

Flow fluctuations remain strongly system dependent

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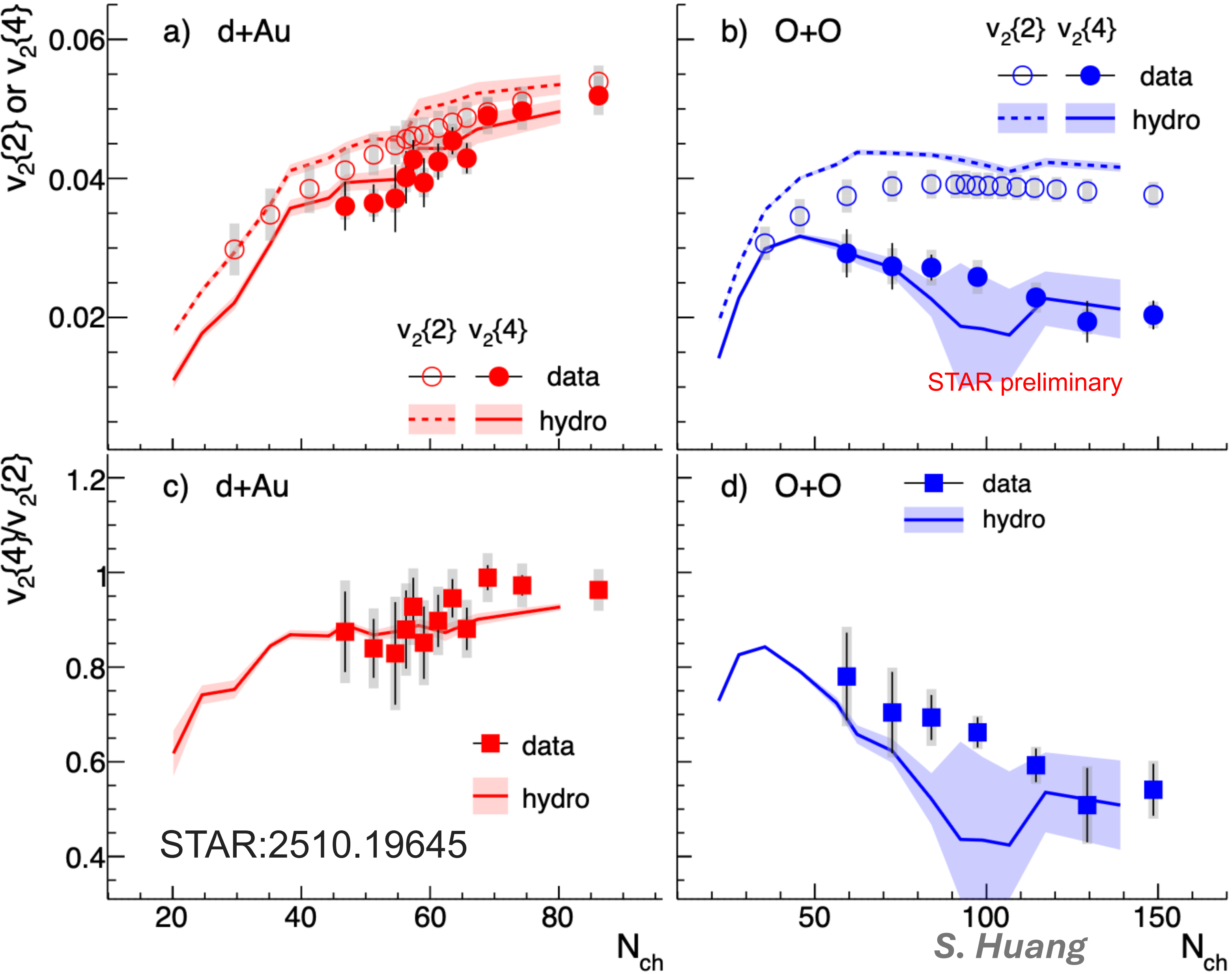
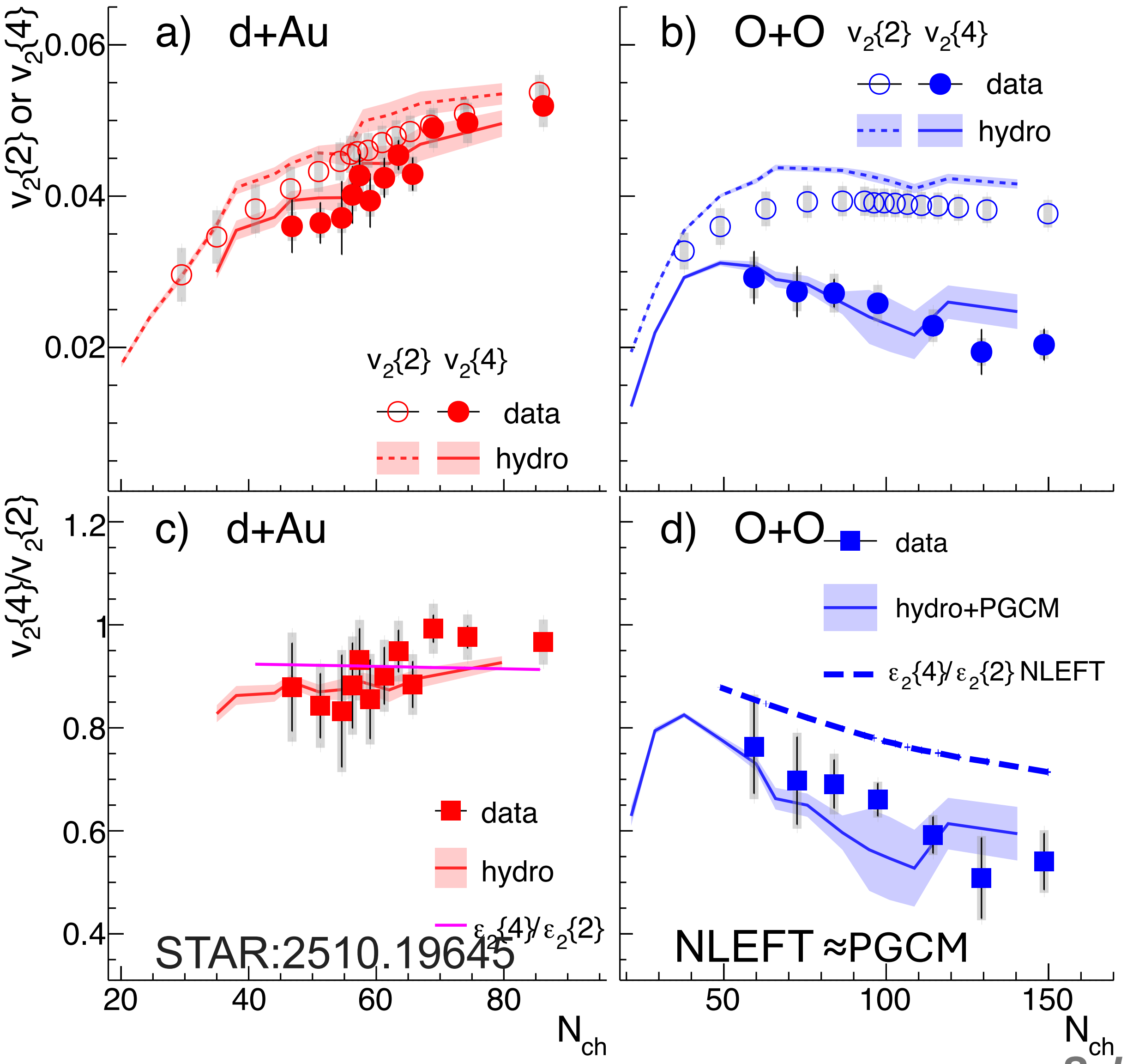
Compare with Hydro.



Hydro model reproduces the measurement.

Consistent with creation of QGP droplet in these systems

Compare $v_2\{4\}/v_2\{2\}$ and $\varepsilon_2\{4\}/\varepsilon_2\{2\}$



d+Au

$$\frac{v_2\{4\}}{v_2\{2\}} \approx \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}},$$

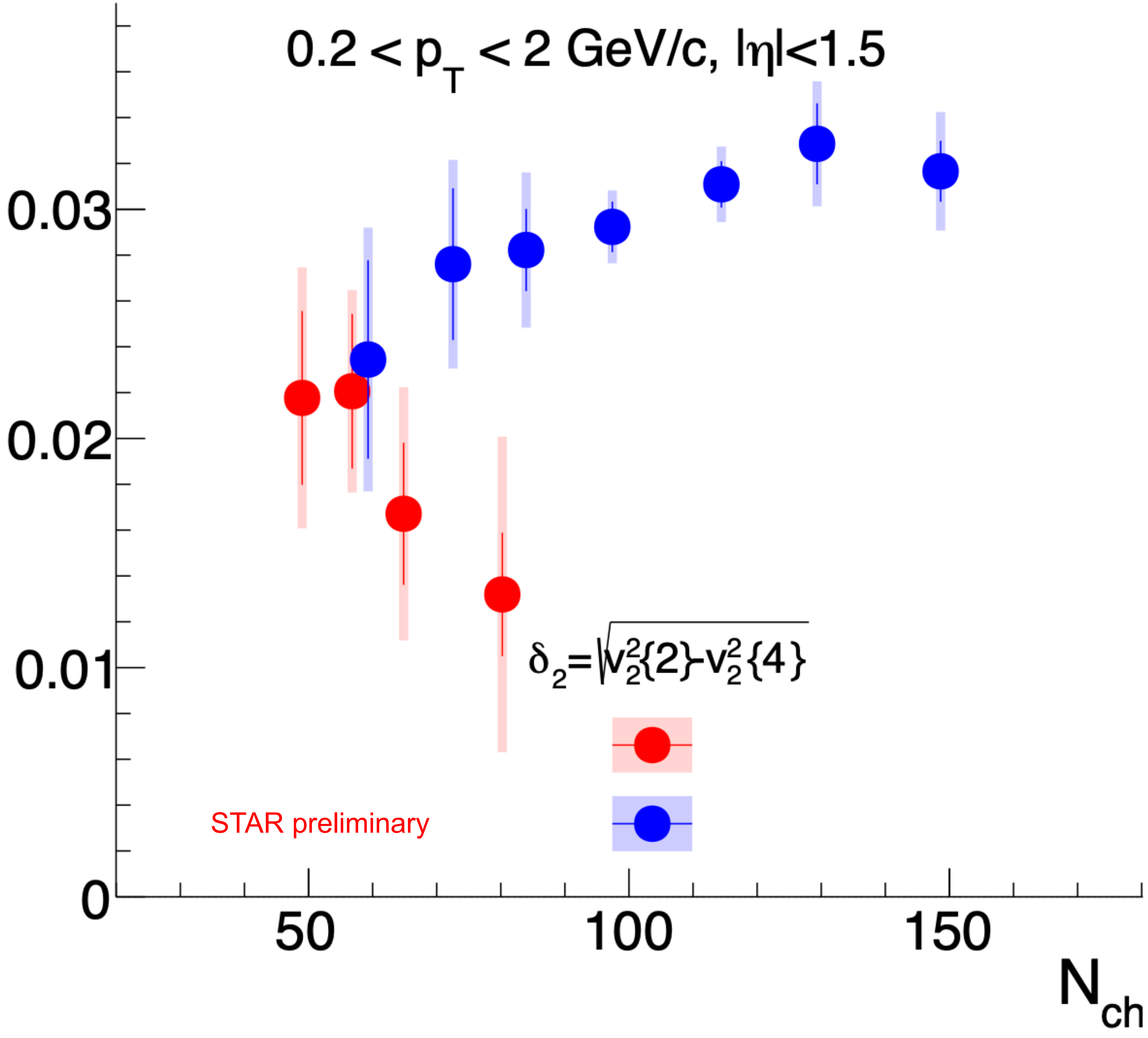
O+O

$$\frac{v_2\{4\}}{v_2\{2\}} < \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}},$$

The response of flow fluctuations to initial eccentricity fluctuations exhibits a clear system dependence

Scaling of Flow fluctuations

v_2 fluctuation: $\delta_{v_2}^2 = v_2\{2\}^2 - v_2\{4\}^2$



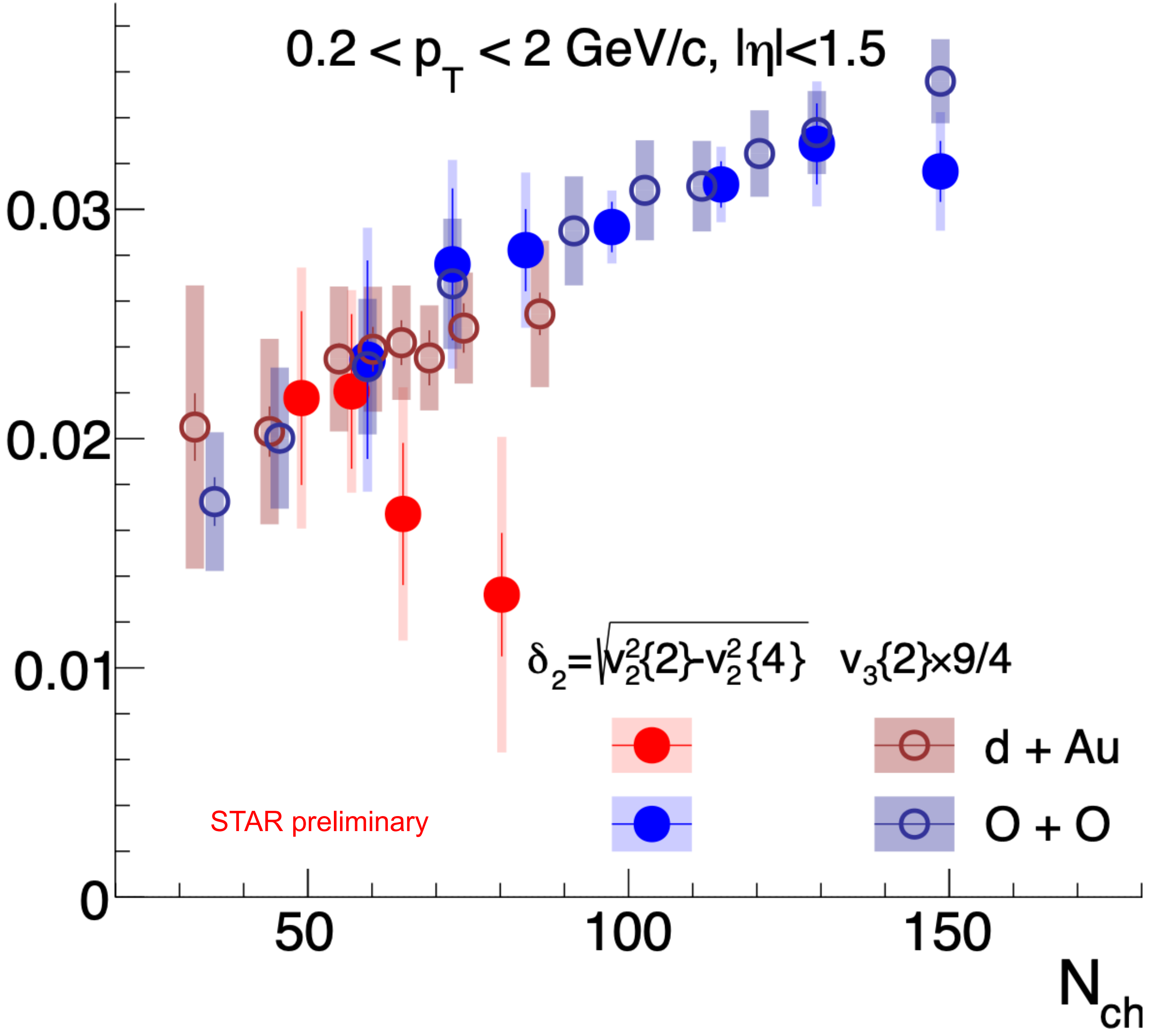
Scaling of Flow fluctuations

v_2 fluctuation: $\delta_{v_2}^2 = v_2\{2\}^2 - v_2\{4\}^2$

Similar N_{ch} dependence as $v_3\{2\}$, but differ by a factor of 9/4

Viscous correction for v_n scales as n^2.

Conformal scaling 1312.6770
Teaney& Yan 1206.1905



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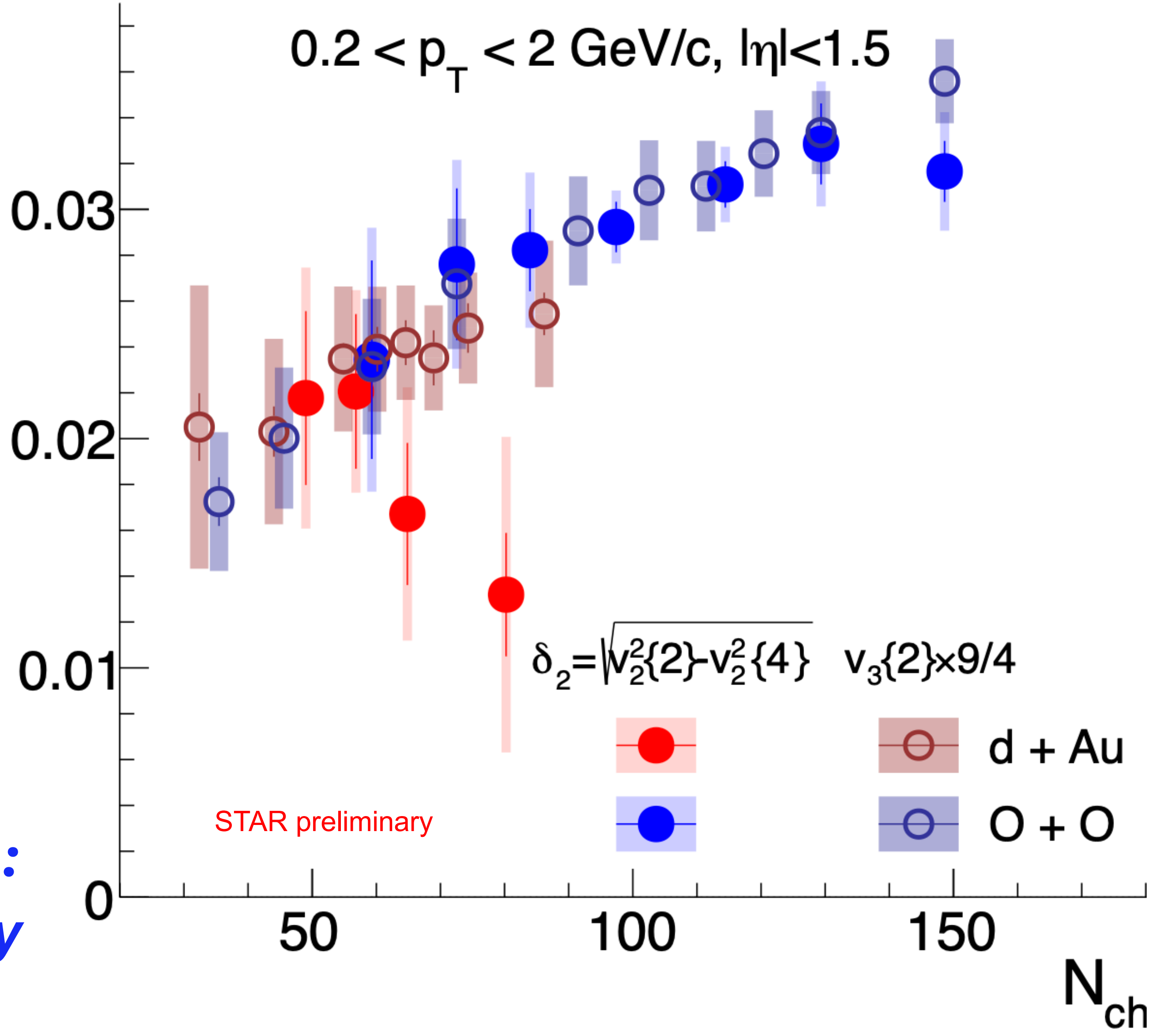
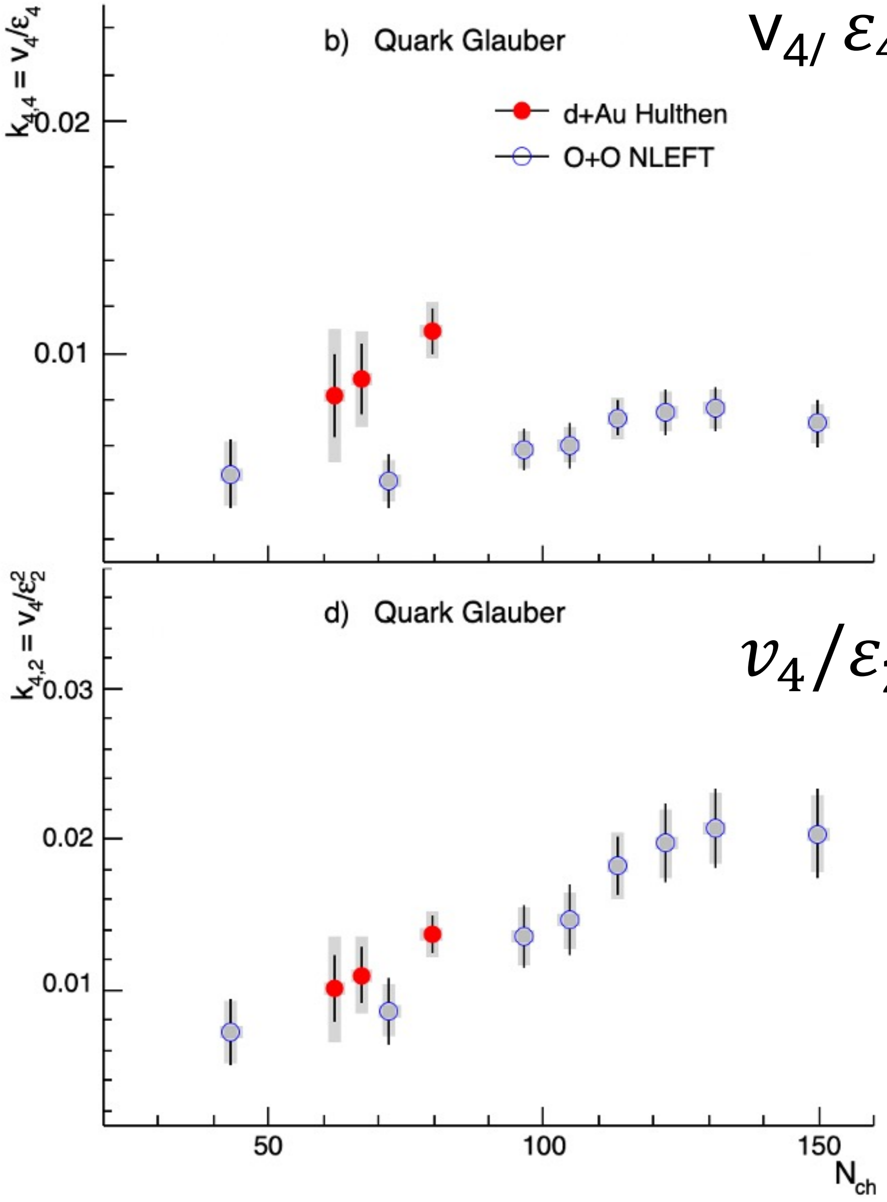


Acoustic Scaling of Flow Fluctuations: even the fluctuation observables obey the same viscous damping law predicted by hydrodynamics

Nonlinear Mode Coupling :$v_4\{2\}$



$v_{4/}\ \varepsilon_4$

v_4/ε_2^2

$$v_4 \approx v_4^{\mathrm{L}} + \chi_{422}\, v_2^2$$

$$v_4^L \propto \varepsilon_4 \qquad v_4^{NL} \propto \varepsilon_2^2$$

v_4 scales much better with ε_2^2 than with ε_4.

v_4 is dominated by nonlinear mode coupling

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Hydrodynamic Response

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QGP Properties

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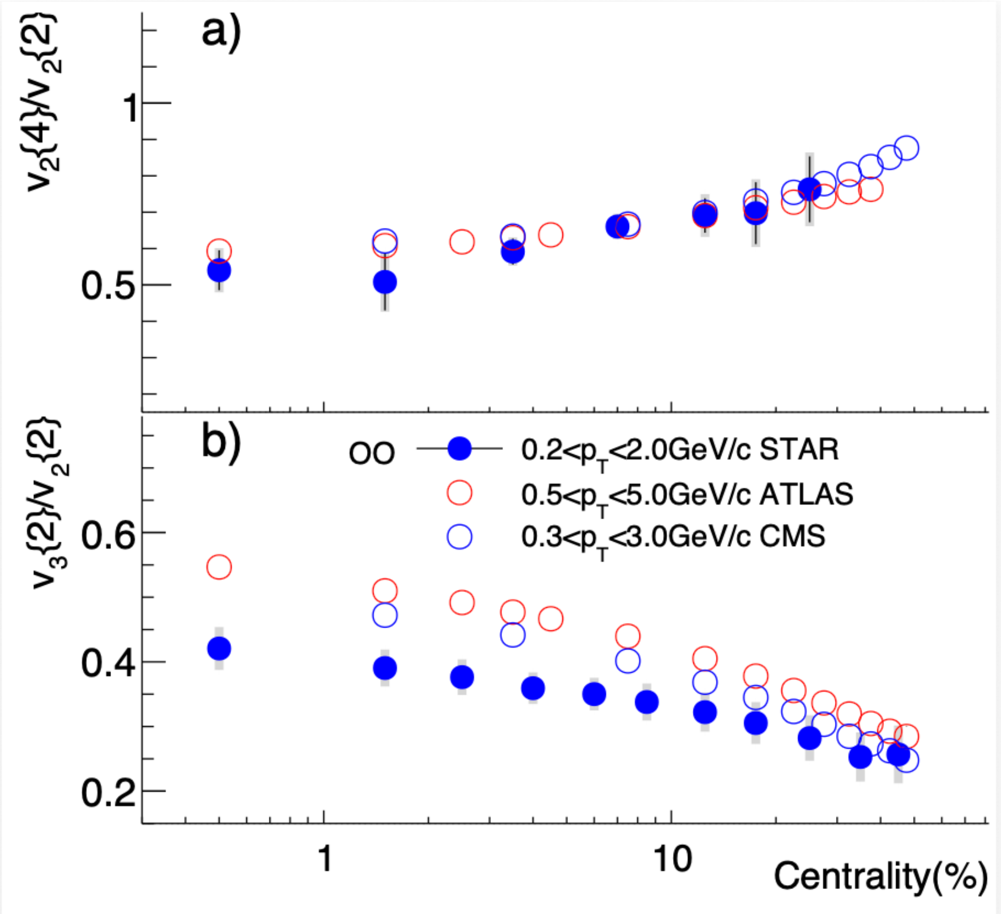
Future Opportunities

RHIC vs. LHC:Universal Flow Fluctuations

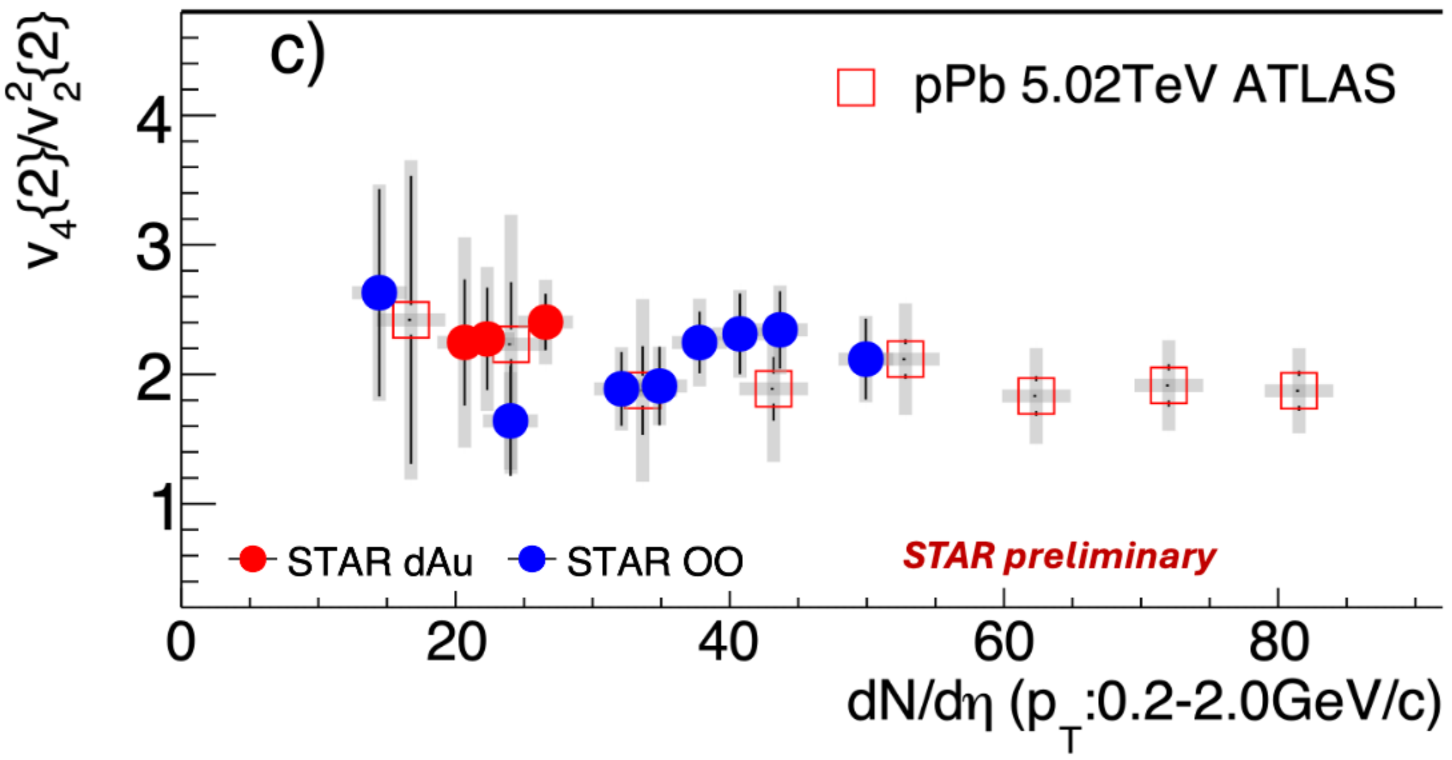


The ratio $v_2\{4\}/v_2\{2\}$ is nearly identical from RHIC to the LHC.

The ratio $v_3\{2\}/v_2\{2\}$ is also similar from RHIC to the LHC.

Fluctuations are remarkably insensitive to collision energy

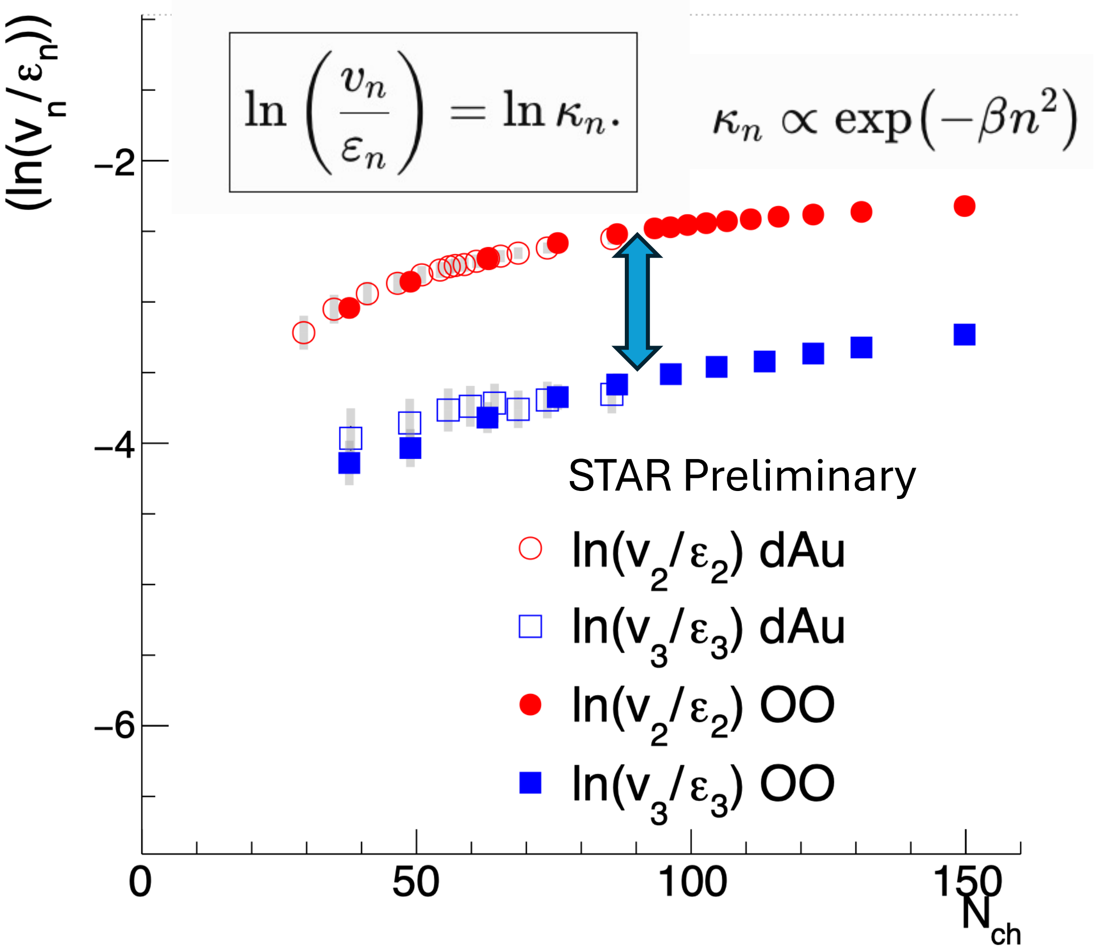
RHIC vs. LHC: Universal nonlinear response

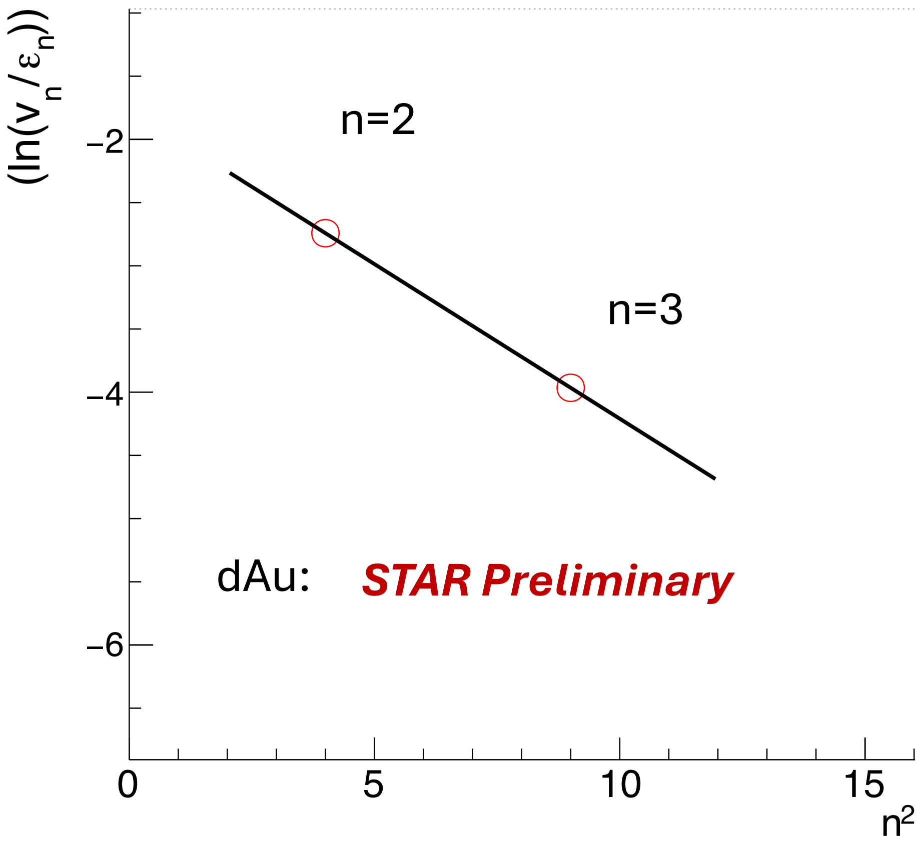


The ratio $v_4\{2\}/v_2\{2\}^2$~2 is remarkably similar from RHIC to the LHC

Universal nonlinear response remains nearly unchanged

Constraining QGP Transport





β :slop of $\ln(v_n/\varepsilon_n)$ vs. n^2

R. A. Lacey et al. PRL. **114**, 142301 (2015).
Teaney& Yan 1206.1905

β quantifies viscous attenuation and is proportional to η/s

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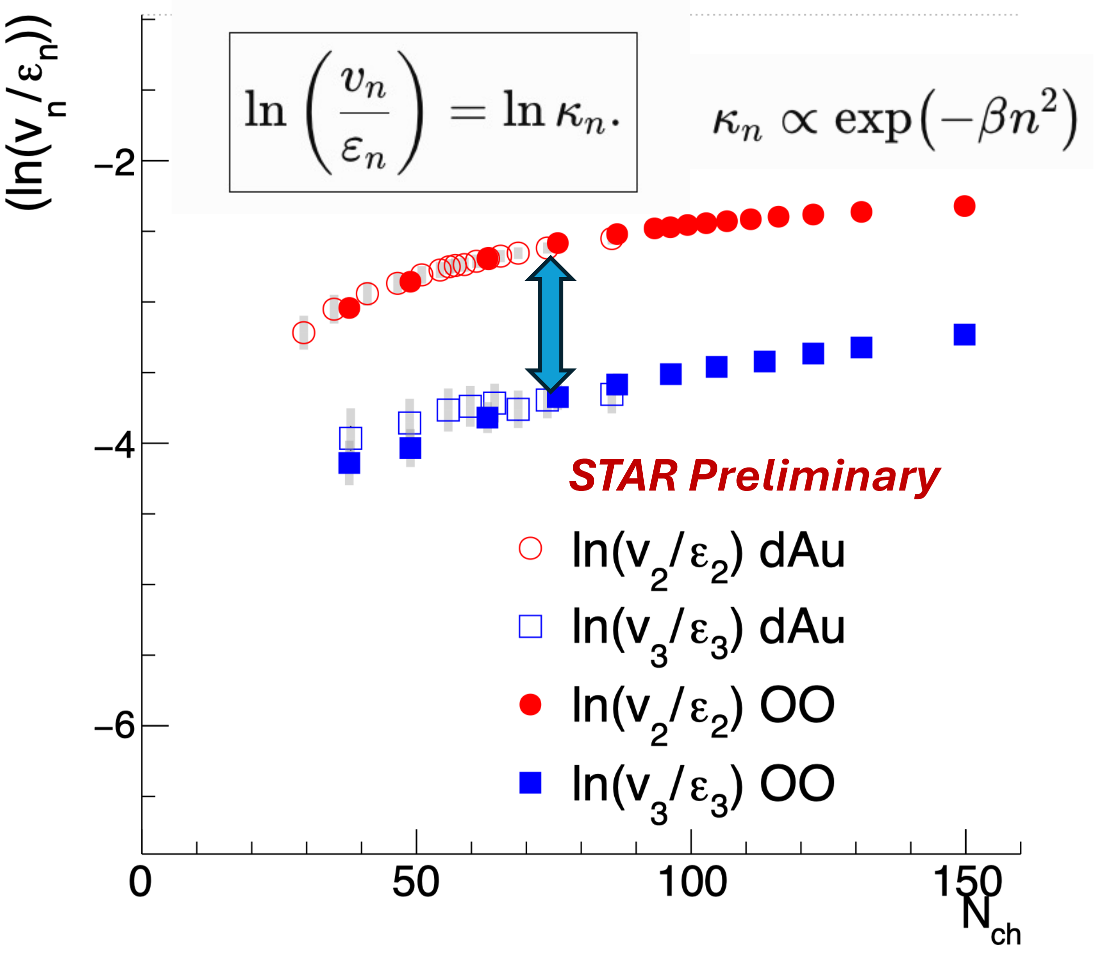
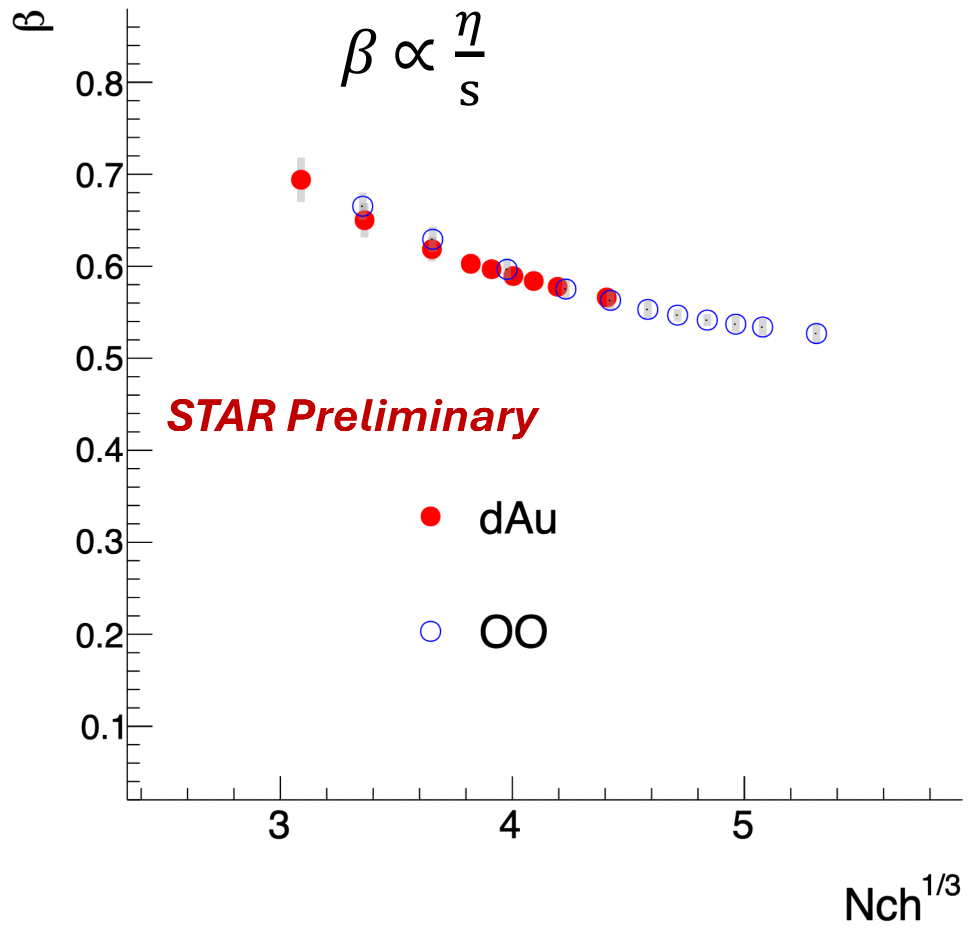
Constraining QGP Transport





A universal hydrodynamical response is found between dAu and OO for same $N_{\rm ch}$

Consistent with smaller viscous attenuation at higher multiplicity

Quantitative Tests of Hydrodynamics

✓ Linear response ($v_2\{2\}$,$v_3\{2\}$)

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Hydrodynamic Response

✓ RHIC vs LHC

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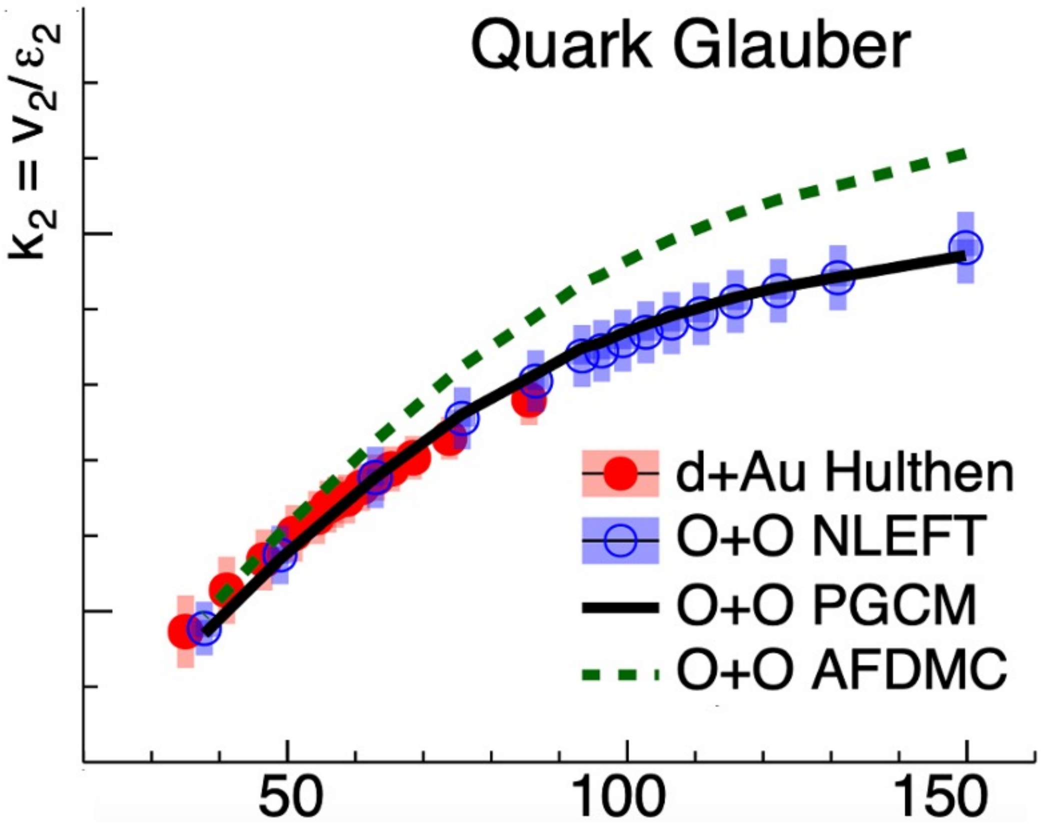
QGP Properties

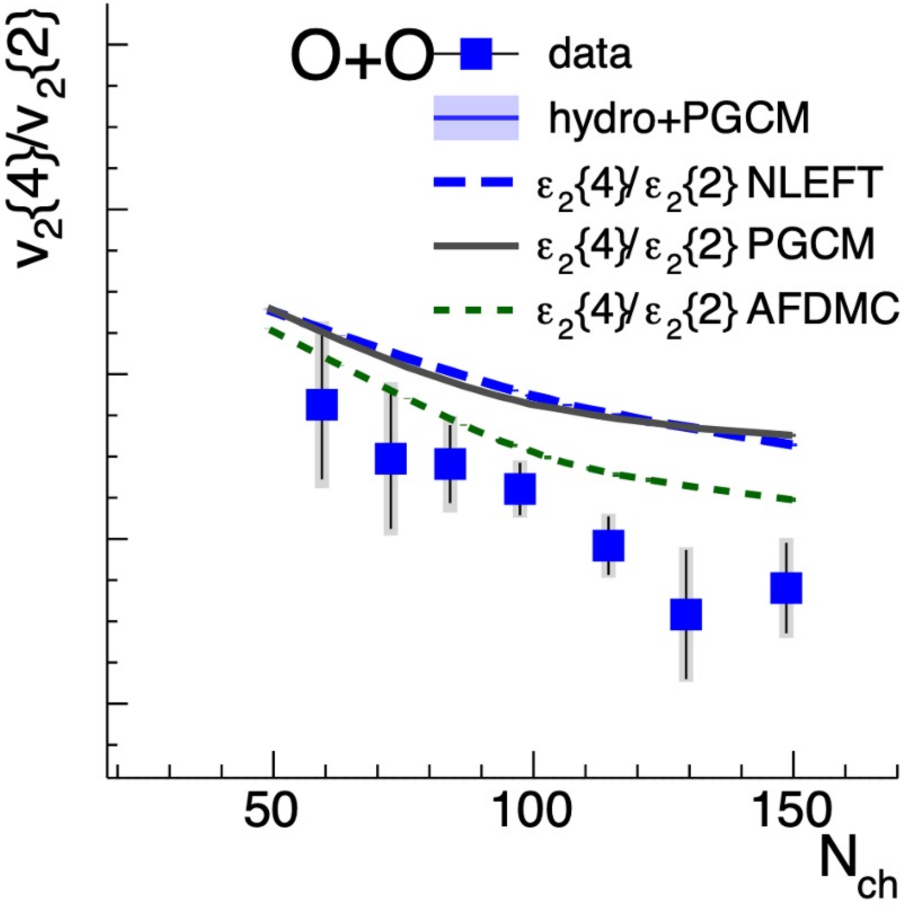
✓ Nuclear structure (α-clustering)

✓ System-size and shape correlation: v_n-pt correlation

Future Opportunities

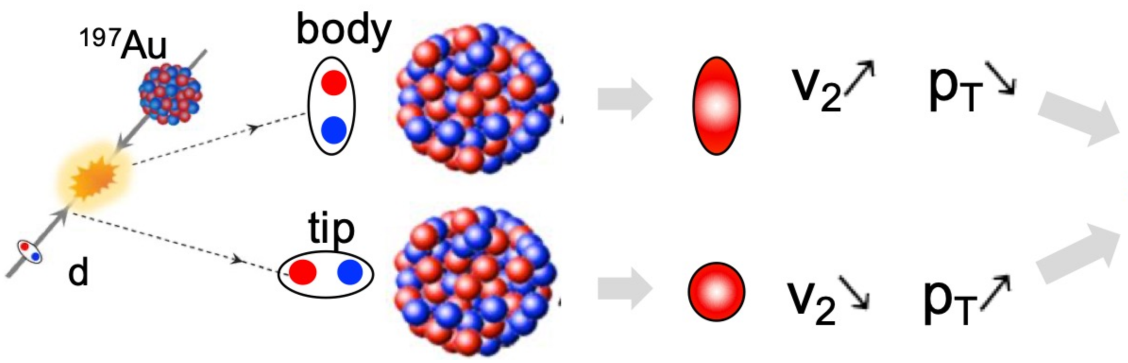
Toward Oxygen Nuclear Structure



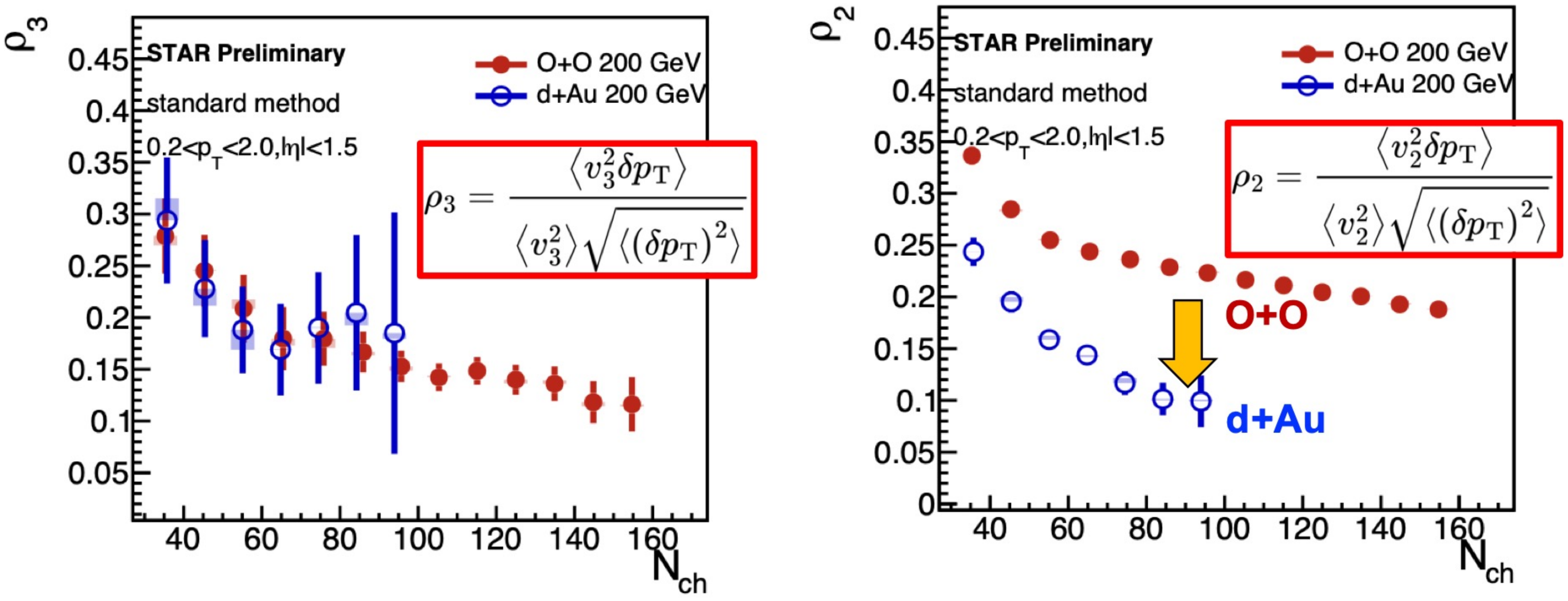


High-multiplicity O+O collisions discriminate among different *ab initio* nuclear structure models

Size-shape correlation: prolate deuteron



$$\langle v_2^2 \delta p_{\mathrm{T}} \rangle = a - b\beta_2^3$$



Consistent with QGP response to the prolate shape of deuteron

Summary

✓ d+Au and O+O provide a clean geometry lever arm

Main Results

✓ Universal linear response
✓ Strong nonlinear response
✓ System-dependent flow fluctuations
✓ Universal RHIC–LHC behavior

Physics Impact

✓ Constrain QGP transport
✓ Test the limits of hydrodynamics
✓ Probe oxygen nuclear structure

Small collision systems have become a quantitative laboratory for studying both the QGP and nuclear structure.