Nuclear physics across energy scales

Engineering shape of QGP droplets by comparing flow in small symmetric-asymmetric collisions

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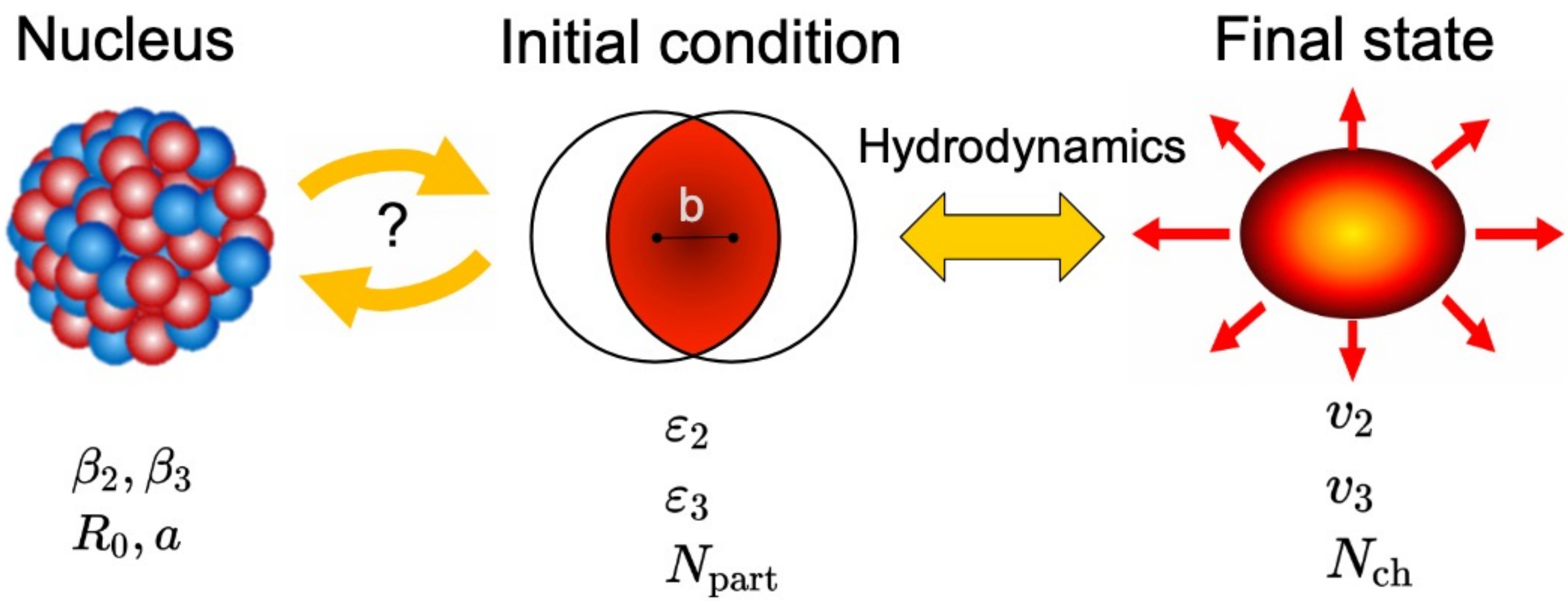
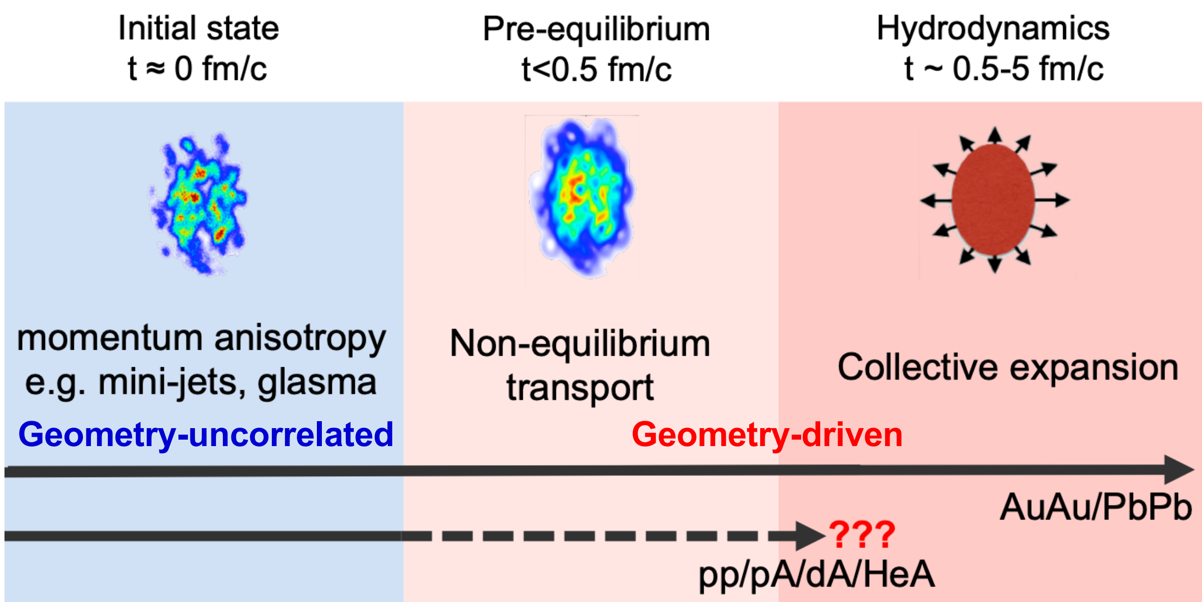
Collectivity in heavy-ion collisions



- Flow is hydrodynamic response to initial conditions.
- Initial conditions is a snapshot of the nuclear structure

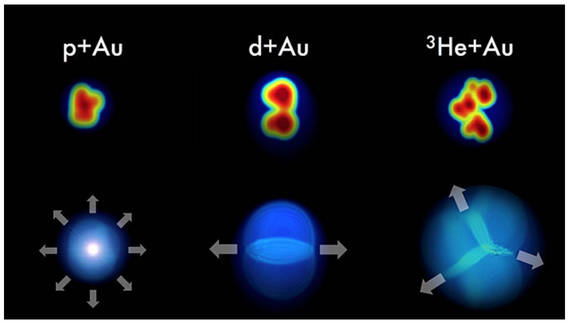
Collectivity in small systems



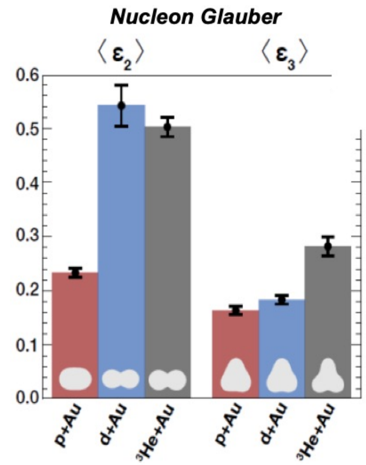
Cannot be turned off in small systems, seems driven by final-state response.
But hydrodynamics is not the unique explanation.

Geometry engineering in p/d/He+Au collisions

Strategy: Test final-state response by
varying initial geometry strongly



Asymmetric systems sensitive to both nuclear structure and subnucleon structure



$$\varepsilon_2^{3\mathrm{HeAu}} \approx \varepsilon_2^{d\mathrm{Au}} > \varepsilon_2^{p\mathrm{Au}}$$
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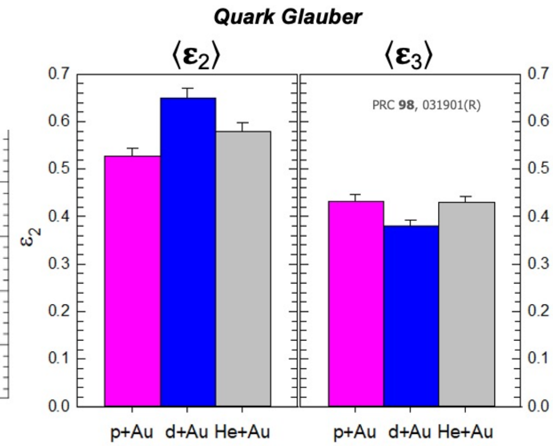

$$\varepsilon_2^{3\mathrm{HeAu}} \approx \varepsilon_2^{d\mathrm{Au}} \gtrsim \varepsilon_2^{p\mathrm{Au}}$$
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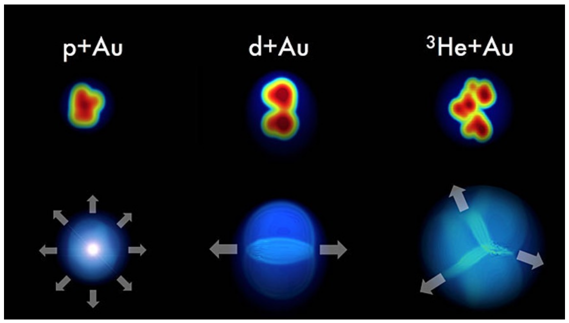

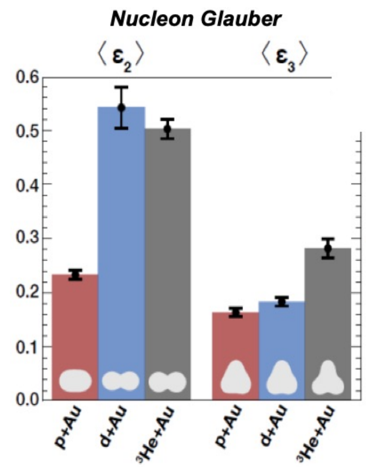

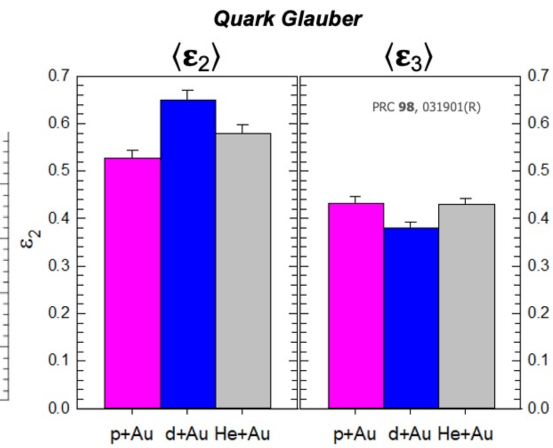

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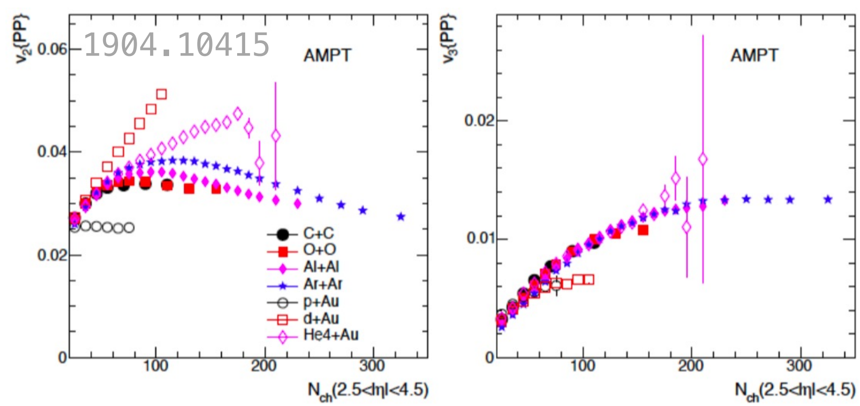


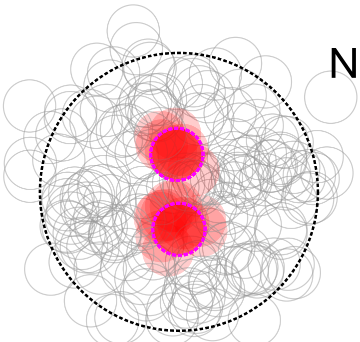
Disentangle two sources by comparing p+A with small symmetric systems, e.g. $^{16}O+^{16}O$

NB: Nuclear structures of small systems are well constrained from ab. Initio calculations.

Case study: d+Au vs O+O

$d_\perp = 1/\sqrt{[x^2]\,[y^2]}$

d + ^{197}Au



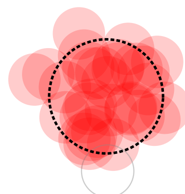
Nucleon-Glauber

$\varepsilon_2^{d\mathrm{Au}} > \varepsilon_2^{\mathrm{OO}}$

$\varepsilon_3^{d\mathrm{Au}} < \varepsilon_3^{\mathrm{OO}}$

$d_\perp^{d\mathrm{Au}} > d_\perp^{\mathrm{OO}}$

^{16}O + ^{16}O



dAu $\boldsymbol{\varepsilon}_2$ dominated by positions of two nucleons: large $\boldsymbol{\varepsilon}_2$ in all evts→narrow p($\boldsymbol{\varepsilon}_2$)→ $\boldsymbol{\varepsilon}_2\{4\}\approx\boldsymbol{\varepsilon}_2\{2\}$

dAu $\boldsymbol{\varepsilon}_3$ and OO $\boldsymbol{\varepsilon}_2$ $\boldsymbol{\varepsilon}_3$ dominate by nucleon fluctuation,

dAu $d_\perp = 1/\mathrm{area}$ is more compact,

→ more

radial flow in dAu.

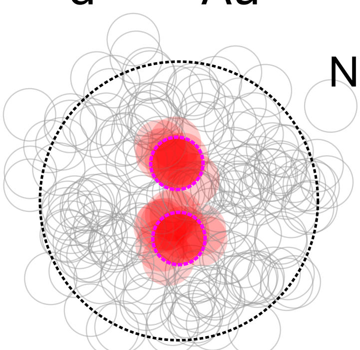
Source distribution p($N_s/\langle N_s\rangle$) is broader in OO

Case study: d+Au vs O+O

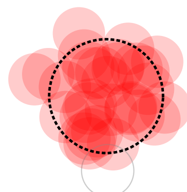
$d_\perp = 1/\sqrt{[x^2]\,[y^2]}$

d + ^{197}Au ^{16}O + ^{16}O

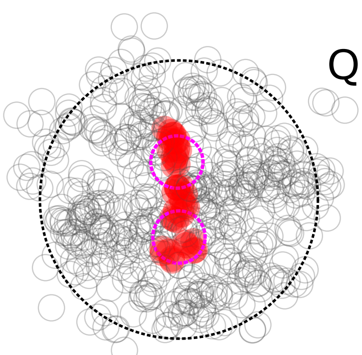
Nucleon-Glauber



$\varepsilon_2^{dAu} > \varepsilon_2^{OO}$
$\varepsilon_3^{dAu} < \varepsilon_3^{OO}$
$d_\perp^{dAu} > d_\perp^{OO}$



Quark-Glauber



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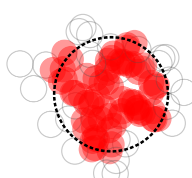


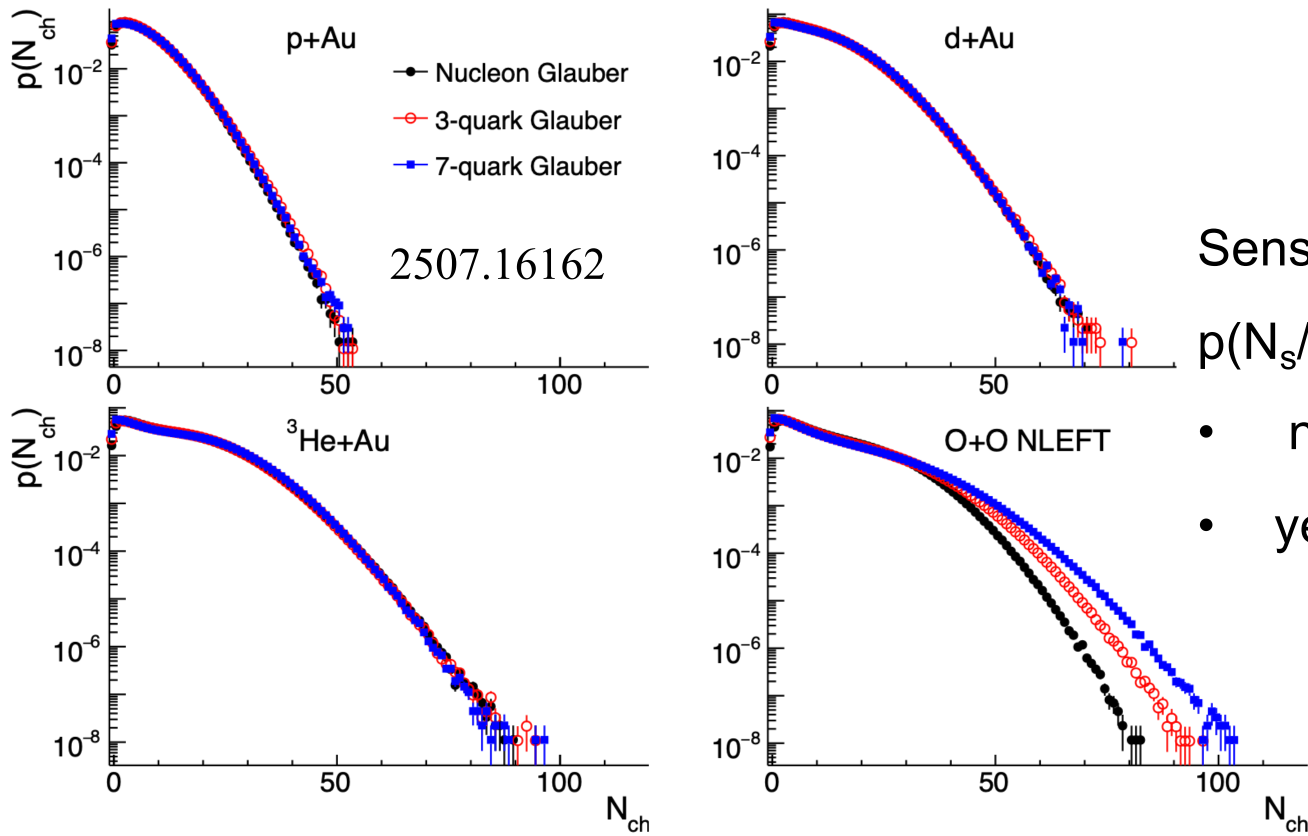
dAu $\boldsymbol{\varepsilon}_2$ dominated by positions of two nucleons: large $\boldsymbol{\varepsilon}_2$ in all evts→narrow p($\boldsymbol{\varepsilon}_2$)→ $\boldsymbol{\varepsilon}_2\{4\}\approx\boldsymbol{\varepsilon}_2\{2\}$ not affected much by subnucleon fluctuations

dAu $\boldsymbol{\varepsilon}_3$ and OO $\boldsymbol{\varepsilon}_2$ $\boldsymbol{\varepsilon}_3$ dominate by nucleon fluctuation, and influences by subnucleon fluctuations are more comparable.

dAu $d_\perp = 1/\mathrm{area}$ is more compact, even more compact with subnucleon fluctuations→ more radial flow in dAu and quark glauber.

Source distribution p($N_s/\langle N_s\rangle$) is broader in OO

Glauber model result



Sensitivity of distribution-shape $p(N_s/\langle N_s\rangle)$ to subnucleon structure:

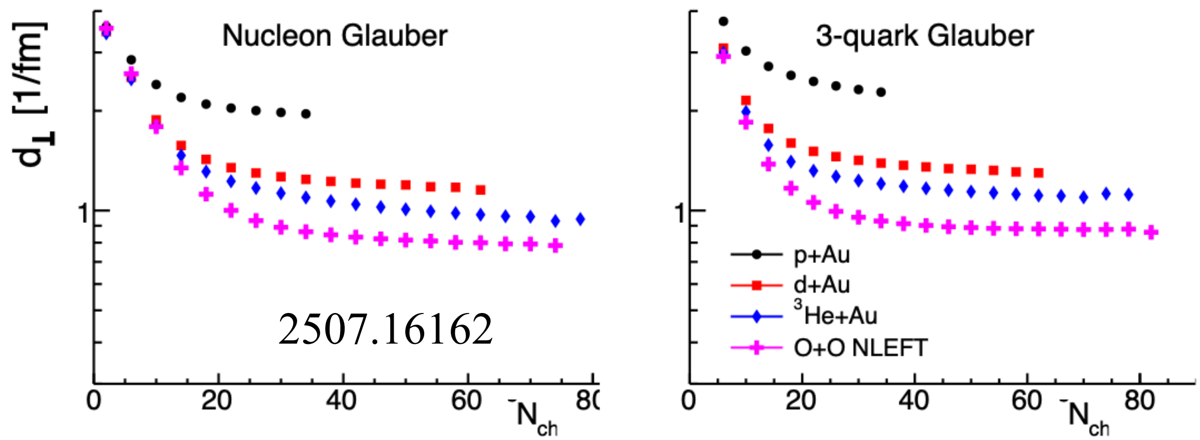
- no in asymmetric collisions,
- yes in symmetric collisions

p/d/He+Au: shape determined by p(source) in Au, insensitive to subnucleon
O+O: shape determined by p(source) in O, sensitive to subnucleon

Pressure gradient ($d_\perp = 1/\text{area}$) and its fluctuations

$$d_\perp = 1/\sqrt{[x^2]\,[y^2]}$$

Mean:
Larger $\langle d_\perp \rangle$ → Larger $\langle [p_T] \rangle$



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Mean:
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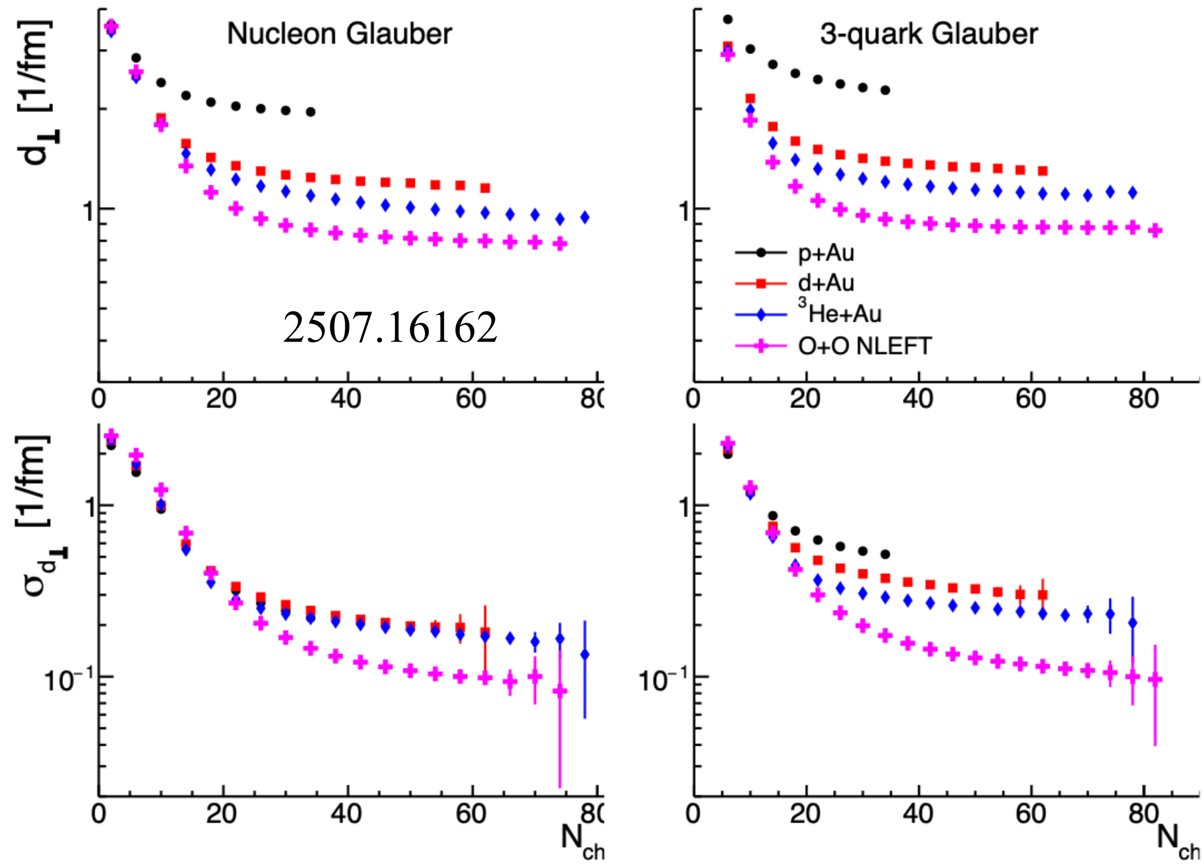
Fluctuations:

$$\delta d_\perp \propto \delta[p_\mathrm{T}]$$

$$\sigma_{d_\perp} = \sqrt{\langle (\delta d_\perp)^2 \rangle} \propto \sqrt{\langle (\delta[p_\mathrm{T}])^2 \rangle}$$



Expected p_T fluctuations➔

- nucleon-Glauber: p/d/He+Au agree but higher than OO
- quark-Glauber: clear ordering in all systems

ε_2 and fluctuations

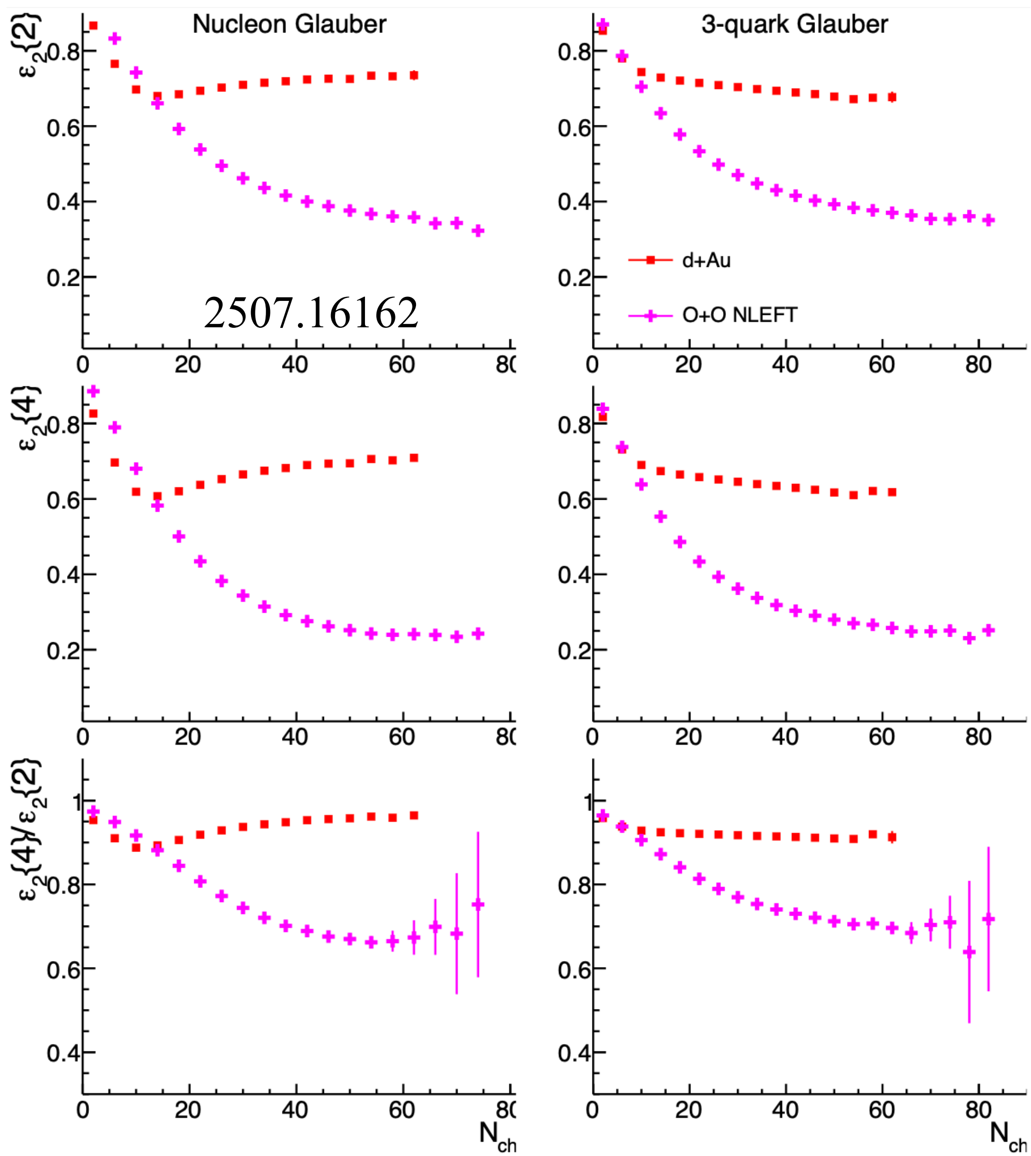
$$\varepsilon_2\{2\} = \sqrt{\langle \varepsilon_2^2 \rangle}$$

$$\varepsilon_2\{4\} = \sqrt[4]{2\langle \varepsilon_2^2 \rangle^2 - \langle \varepsilon_2^4 \rangle}$$

Indeed: $\varepsilon_2^{d\mathrm{Au}} > \varepsilon_2^{\mathrm{OO}}$

$$\varepsilon_2\{4\}^{d\mathrm{Au}} \sim \varepsilon_2\{2\}^{d\mathrm{Au}}$$

$$\varepsilon_2\{4\}^{\mathrm{OO}} < \varepsilon_2\{2\}^{\mathrm{OO}}$$



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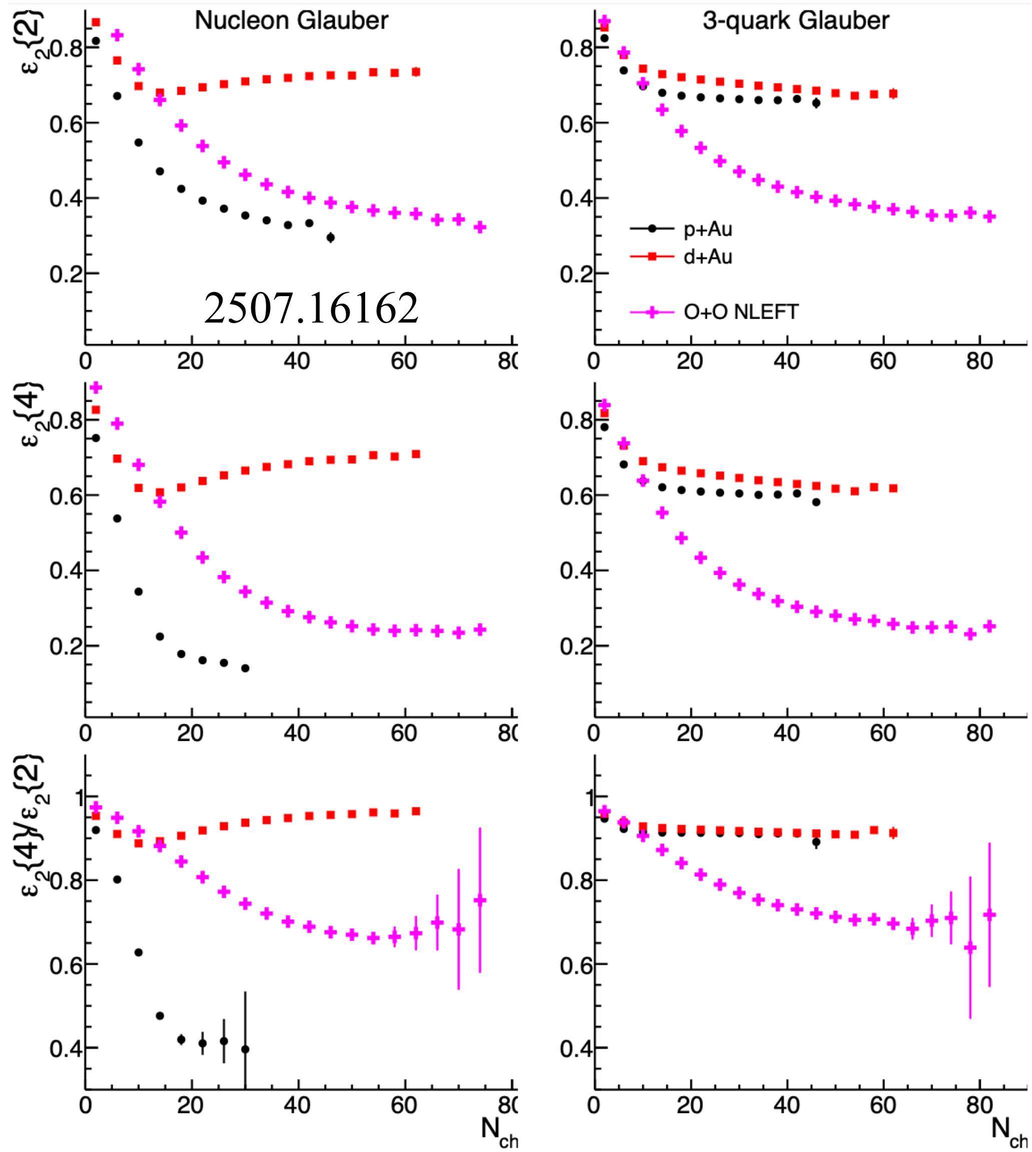
- pAu is most sensitive to subnucleon fluctuations



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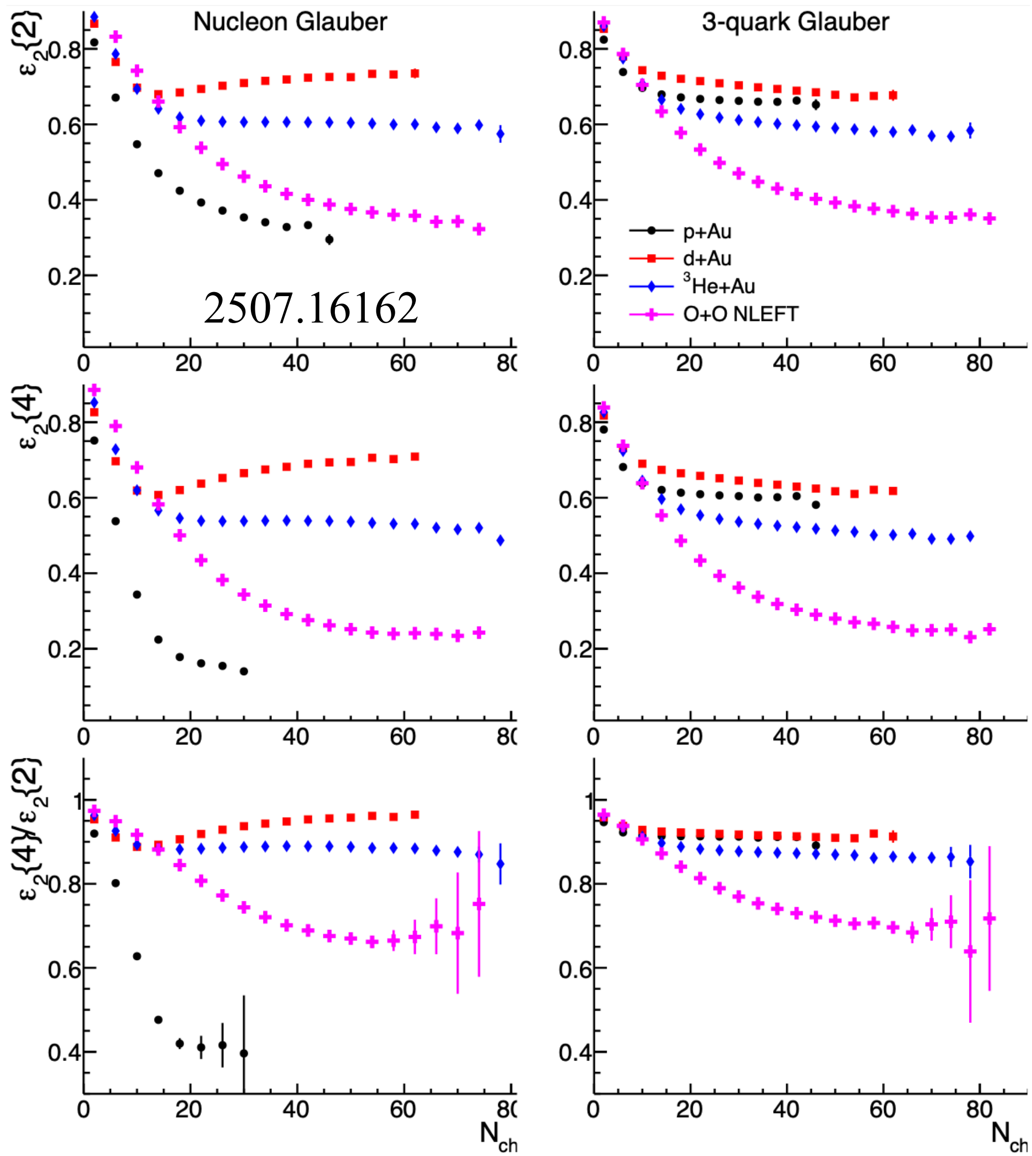
- pAu is most sensitive to subnucleon fluctuations
- dAu, ^{3}HeAu, OO have little sensitivity

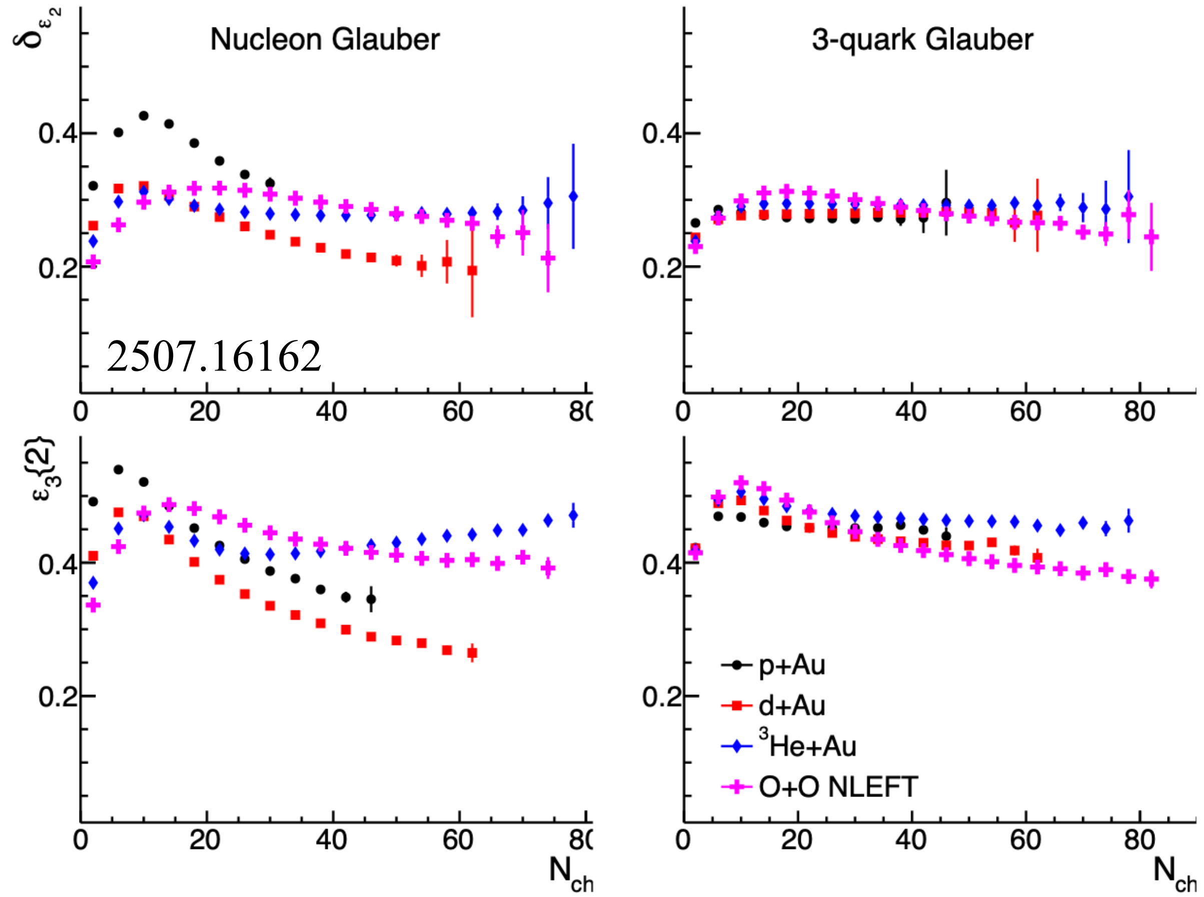


Scaling behavior of the fluctuation components

Isolate the fluctuation component of $\boldsymbol{\varepsilon}_2$:

$$\delta^2_{\varepsilon_2} = \varepsilon_2\{2\}^2 - \varepsilon_2\{4\}^2$$

and compared with $\boldsymbol{\varepsilon}_3\{2\}$, which is also dominated by fluctuations.



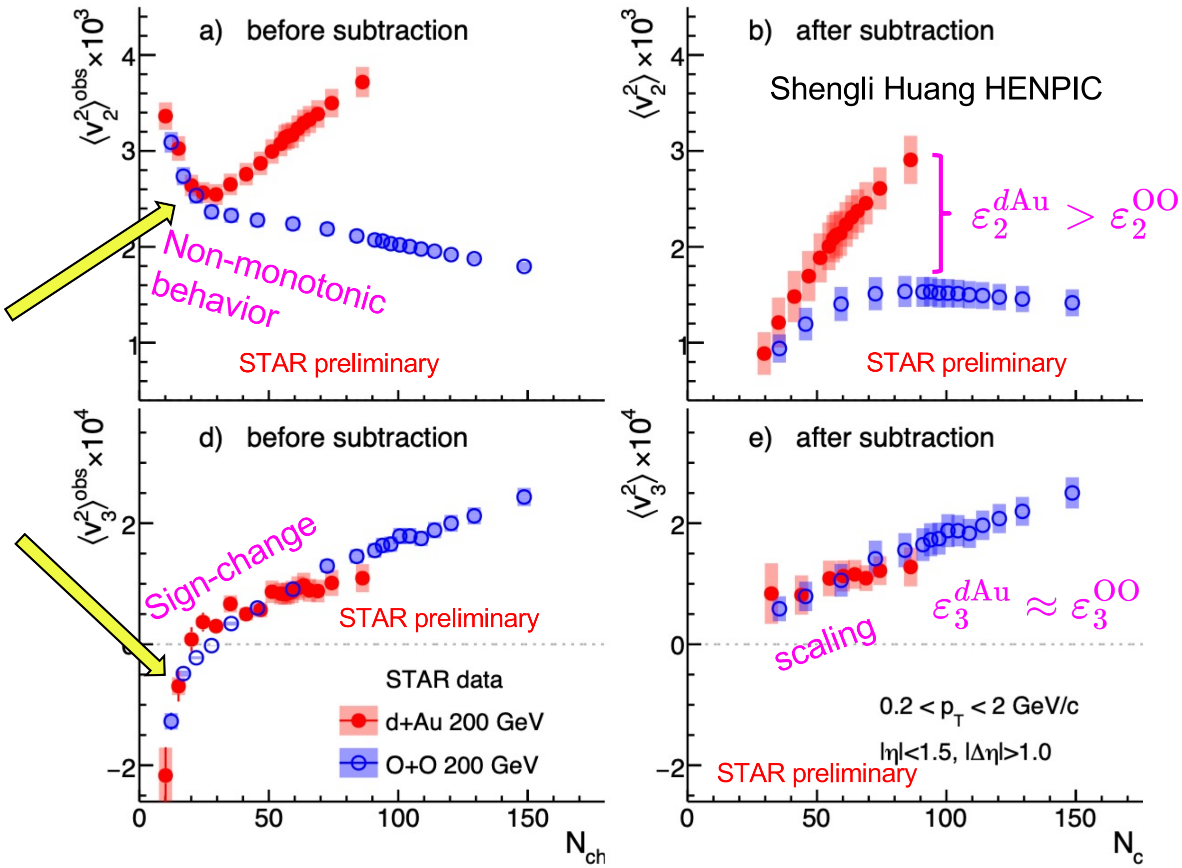
- Nucleon-Glauber: 20-30% level deviations observed.
- Quark-Glauber : Universal scaling among systems within 10%!

d+Au and O+O flow data

$$\langle v_n^2 \rangle = \langle v_n^2 \rangle^{\mathrm{obs}} - f \times \langle v_n^2 \rangle^{\mathrm{obs,LM}}$$

Non-flow subtraction

Clear interplay between flow and non-flow



Rich behaviors consistent with our expectation from non-flow and eccentricities

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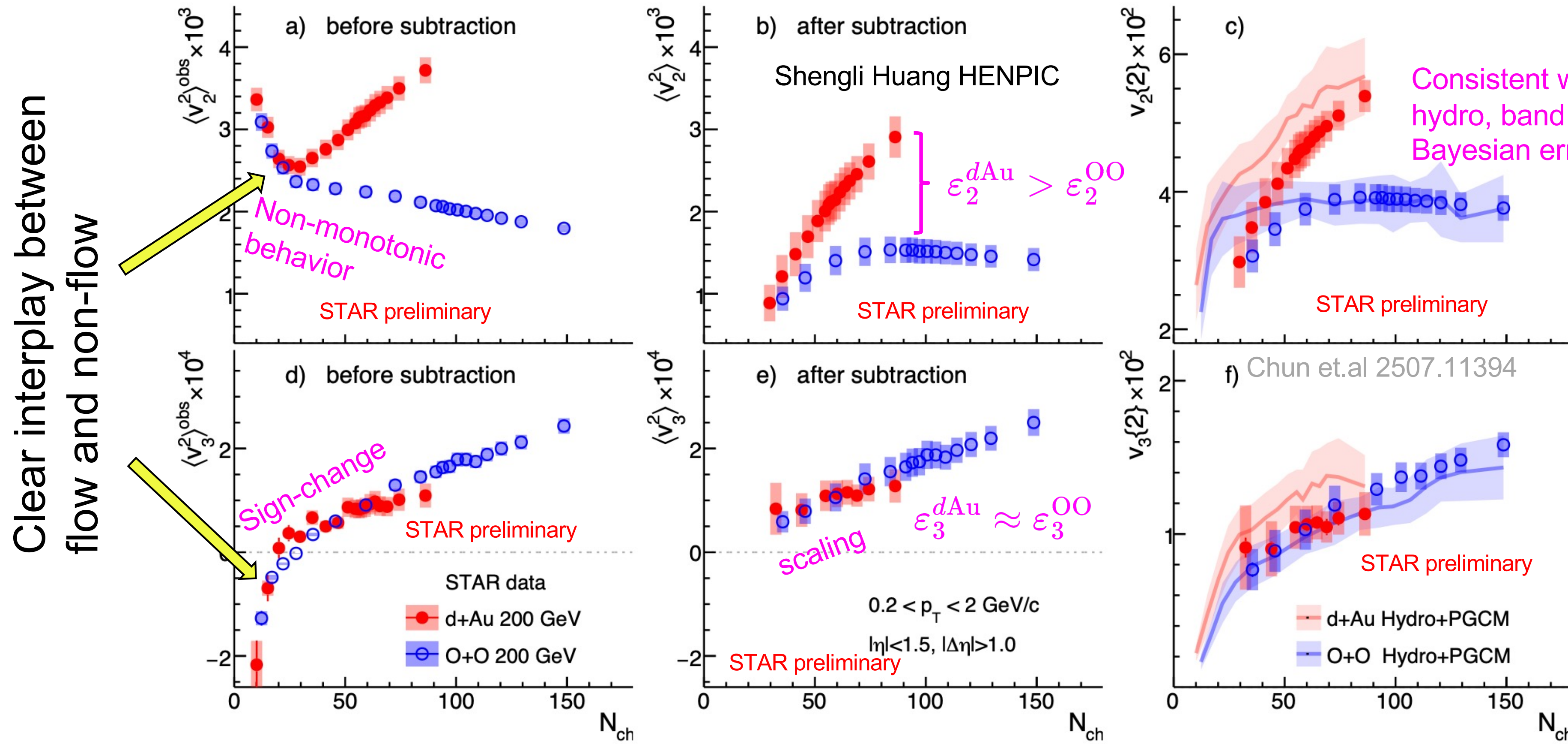


Rich behaviors consistent with our expectation from non-flow and eccentricities

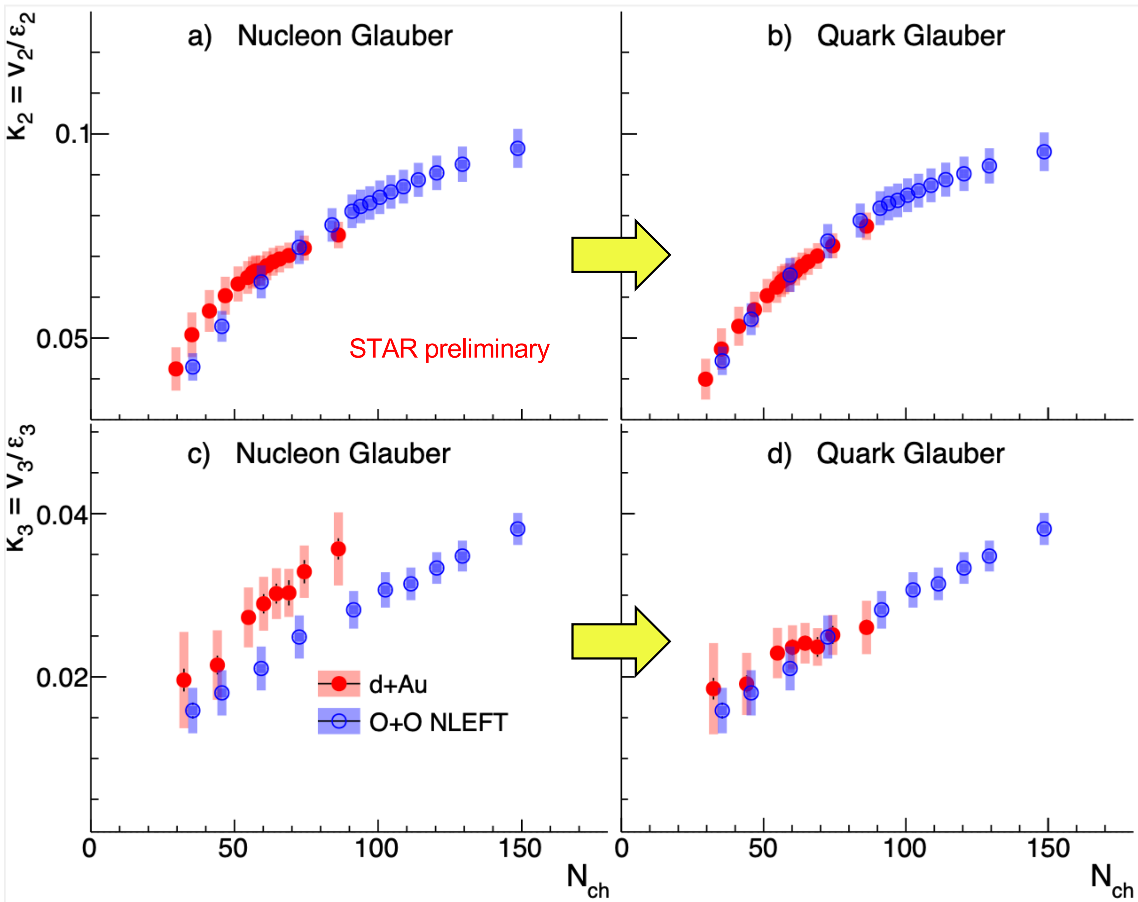
Agreement with 3D-Glauber+Music+UrQMD hydro model tuned to AuAu data

Final-state response coefficients

$k_n = v_n/\boldsymbol{\varepsilon}_n$ represents the ability of medium to generate flow

Controlled largely by N_{ch}.

dAu and OO share common scaling when considering subnucleon fluctuations



Final-state response coefficients

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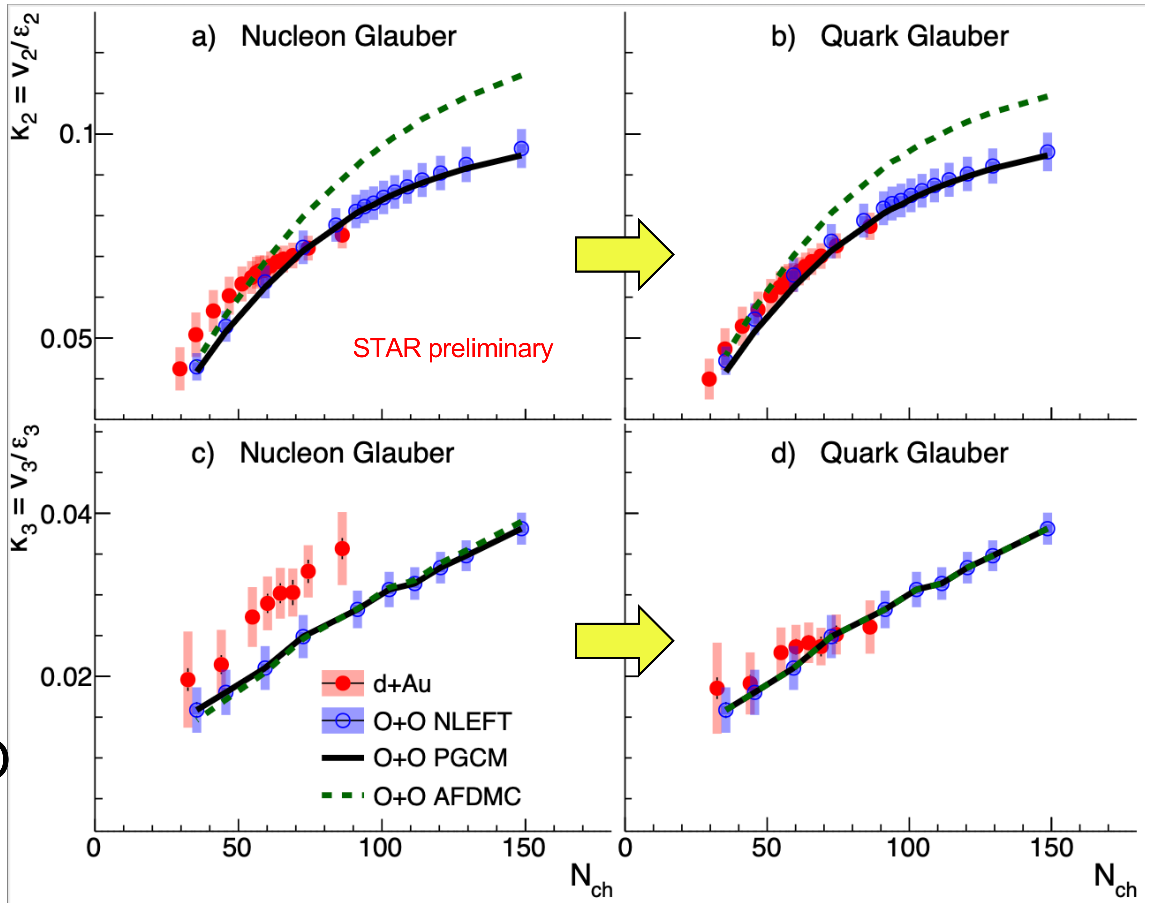
Some sensitivity to ab.initio models for nucleon configs of ^{16}O NLEFT, PGCM, AFDMC.



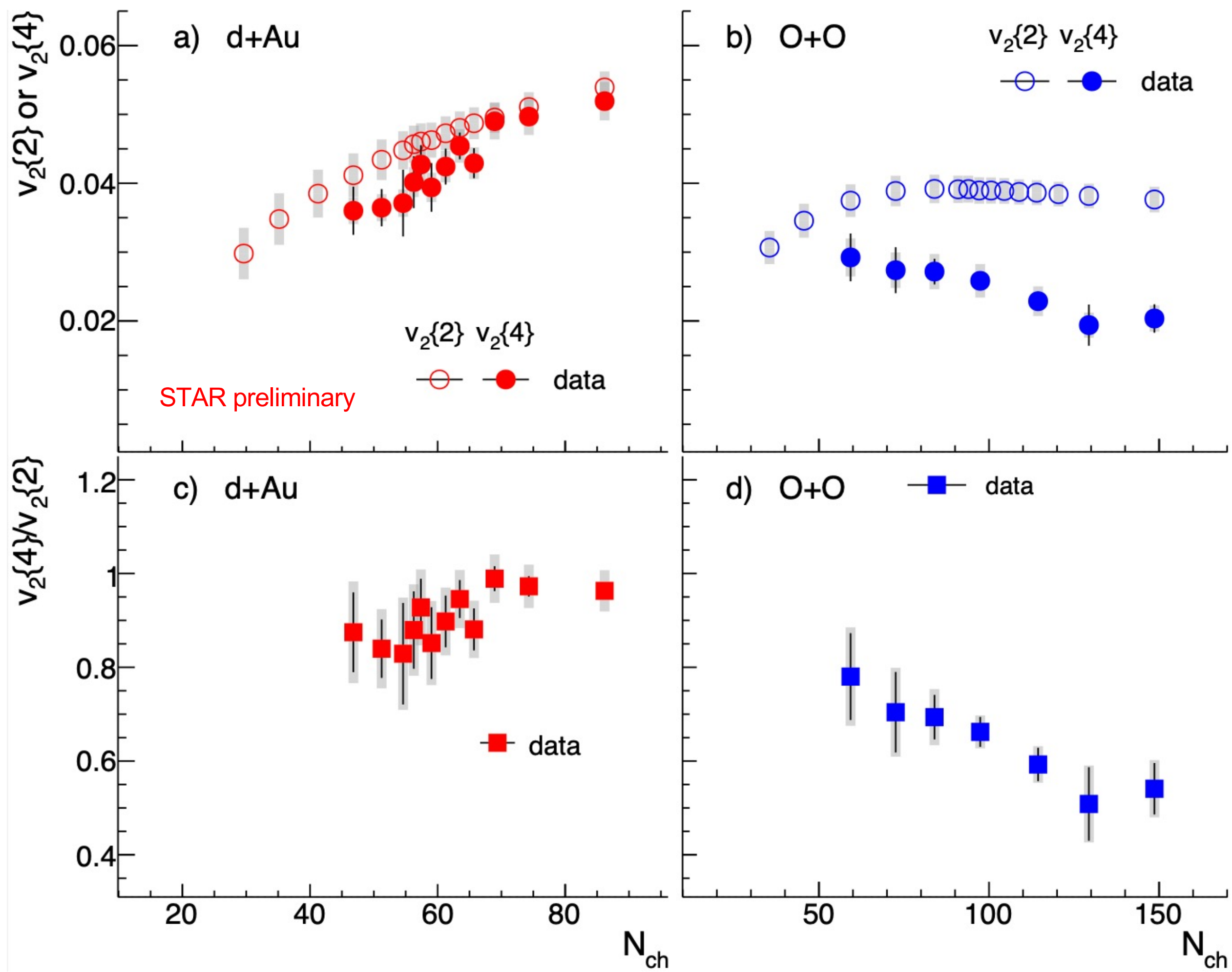
Elliptic flow fluctuations

$v_2^{dAu}\{4\} \lesssim v_2^{dAu}\{2\}$ reflects
$\boldsymbol{\varepsilon}_2^{dAu}\{4\} \lesssim \boldsymbol{\varepsilon}_2^{dAu}\{2\}$ ➔

$$\frac{v_2^{dAu}\{4\}}{v_2^{dAu}\{2\}} \approx \frac{\varepsilon_2^{dAu}\{4\}}{\varepsilon_2^{dAu}\{2\}} \approx 0.9$$

$v_2^{OO}\{4\} < v_2^{OO}\{2\}$ reflects
$\boldsymbol{\varepsilon}_2^{OO}\{4\} \lesssim \boldsymbol{\varepsilon}_2^{OO}\{2\}$ ➔

$$\frac{v_2^{OO}\{4\}}{v_2^{OO}\{2\}} \approx \frac{\varepsilon_2^{OO}\{4\}}{\varepsilon_2^{OO}\{2\}} \sim 0.6$$



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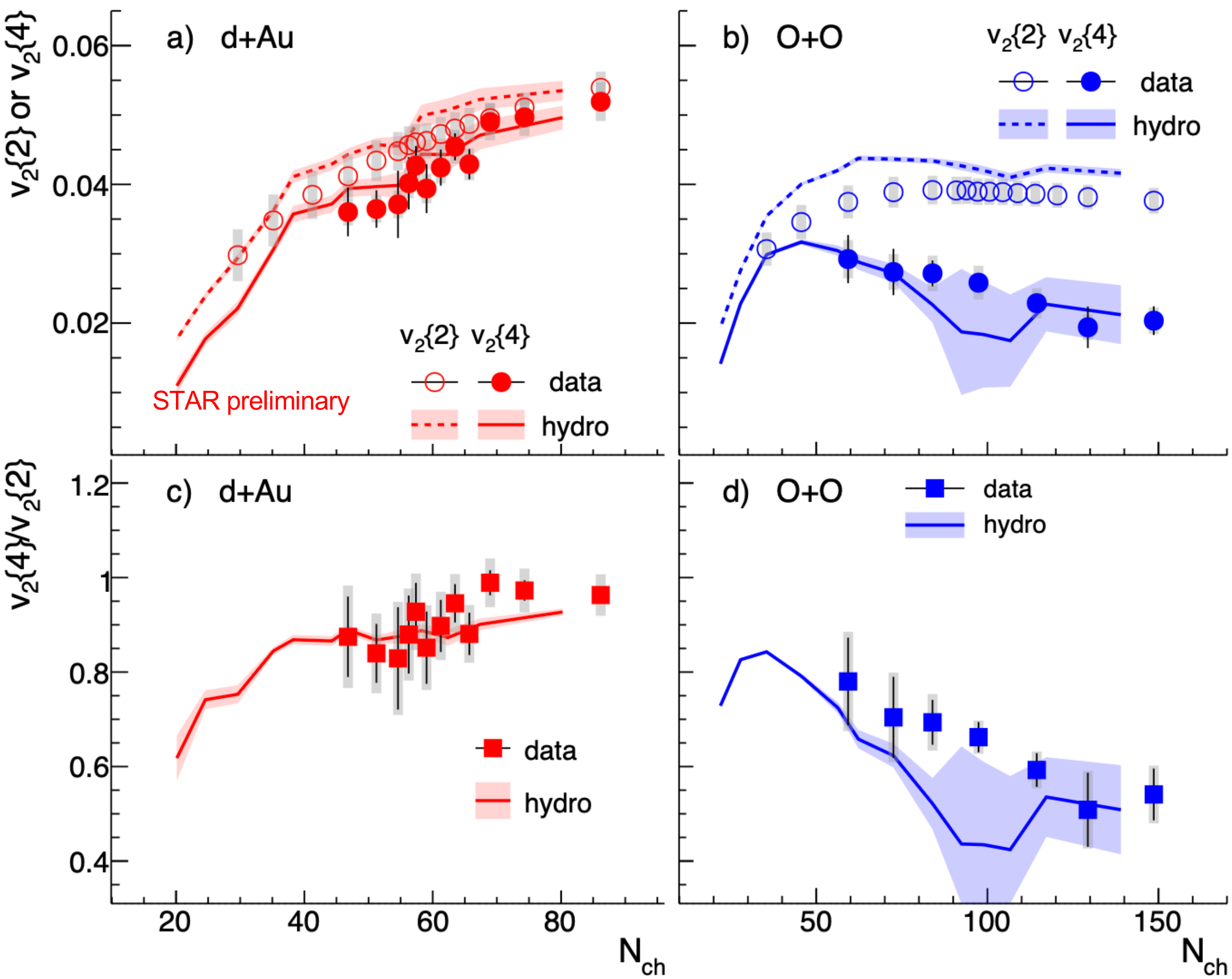
Hydro model tuned to AuAu data can reproduce most of the trends, consistent with creation of QGP droplet in these systems



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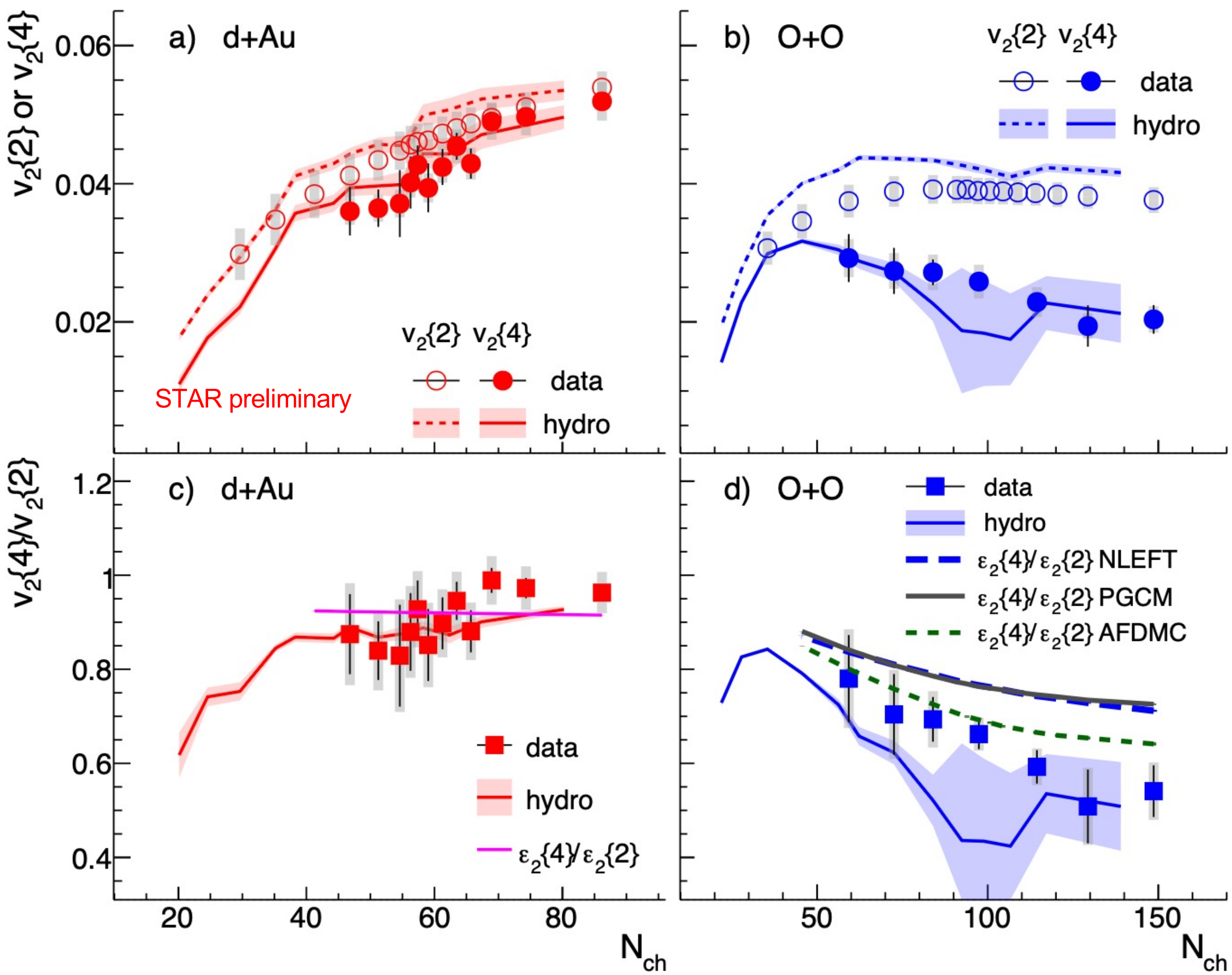
$v_2^{\mathrm{OO}}\{4\} < v_2^{\mathrm{OO}}\{2\}$ reflects
$\boldsymbol{\varepsilon}_2^{\mathrm{OO}}\{4\} \lesssim \boldsymbol{\varepsilon}_2^{\mathrm{OO}}\{2\}$ ➔

$$\frac{v_2^{\mathrm{OO}}\{4\}}{v_2^{\mathrm{OO}}\{2\}} \approx \frac{\varepsilon_2^{\mathrm{OO}}\{4\}}{\varepsilon_2^{\mathrm{OO}}\{2\}} \sim 0.6$$

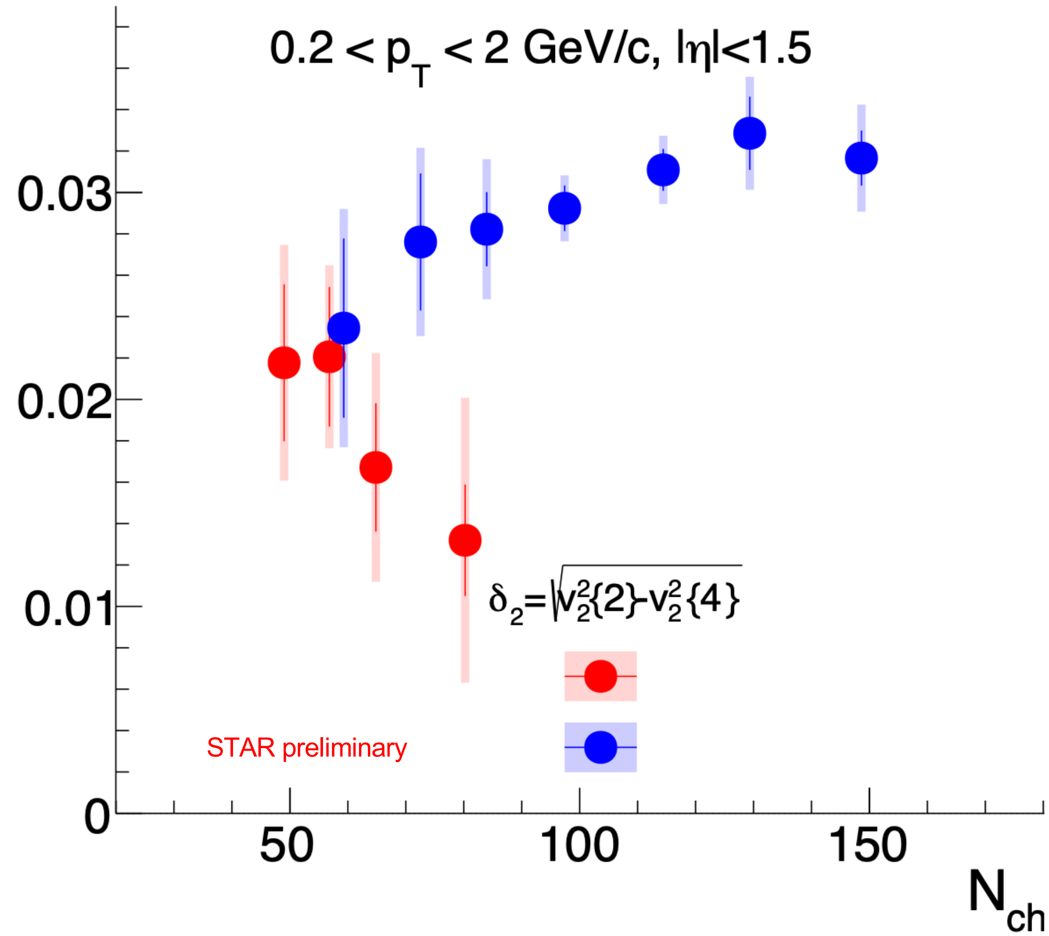
Ratio $\boldsymbol{\varepsilon}_2^{\mathrm{OO}}\{4\}/\boldsymbol{\varepsilon}_2^{\mathrm{OO}}\{2\}$ sensitive to ab initio models, could survive to $v_2^{d\mathrm{Au}}\{4\}/v_2^{d\mathrm{Au}}\{2\}$.



Scaling behavior of flow fluctuations

Isolate the fluctuation component of v_2: $\delta_{v_2}^2 = v_2\{2\}^2 - v_2\{4\}^2$

Within the large uncertainties, the two systems are not very different



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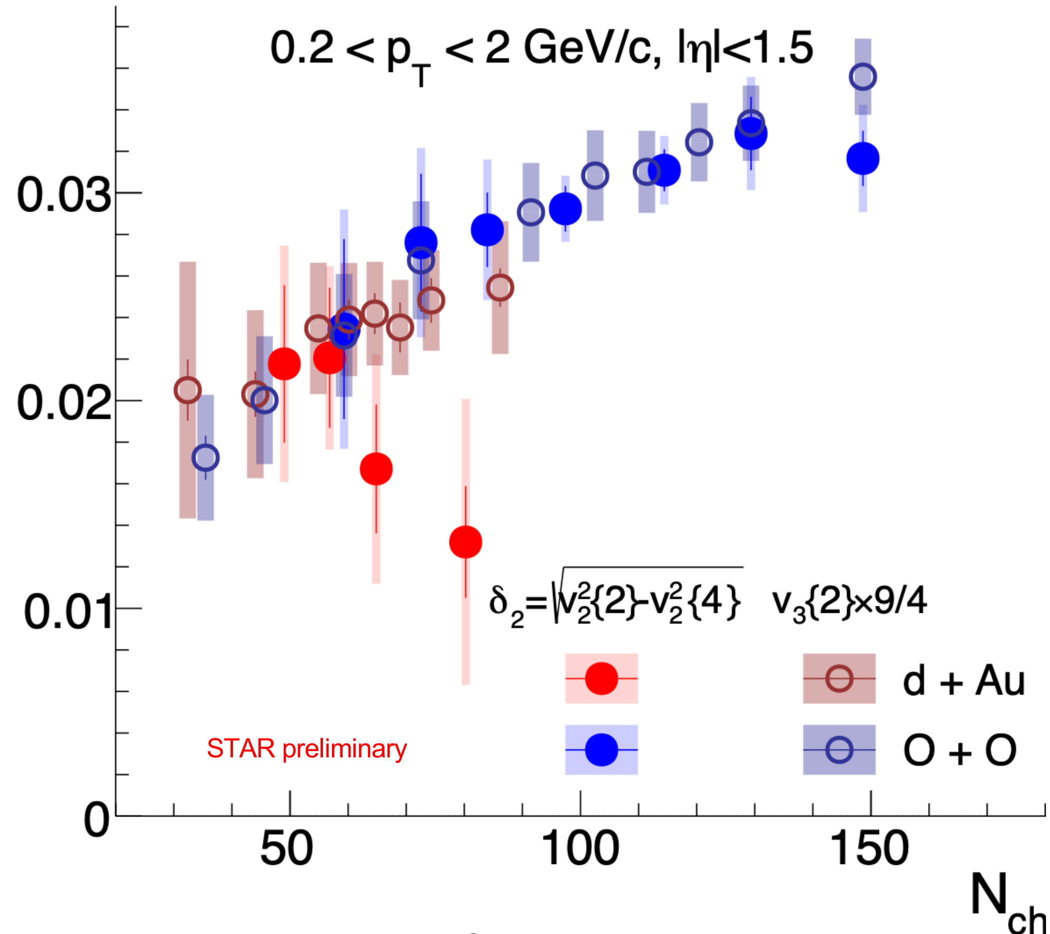
Similar N_{ch} dependence as $v_3\{2\}$, but differ by a factor of 9/4

Conformal scaling 1312.6770



Teaney& Yan 1206.1905: viscous correction for v_n scales as n^2.

Summary

- Demonstrated the ability to engineer the shape of QGP droplets by comparing v_2 and v_3 in symmetric OO collisions with asymmetric dAu collisions.
  - Provide a lever arm to test the effects of nuclear structure and subnucleonic fluctuations on the initial geometry.
- $v_2^{dAu} > v_2^{OO}$ and $v_3^{dAu} \approx v_3^{OO}$ consistent with the expected ordering in eccentricities for quark Glauber model
- v_2 in OO has larger fluctuation than dAu, also are sensitive between different ab. Initio models.
- Both nuclear structure and subnucleonic fluctuations are required to explain the data
- Results are consistent with hydro-model tuned to Au+Au data, providing strong evidence that the droplets created in these small systems have properties similar to those in large systems.