Exploring the Origin of Anisotropy in Small Systems:

From Symmetric (O+O) to Asymmetric (d+Au) Collisions

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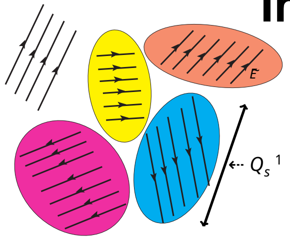
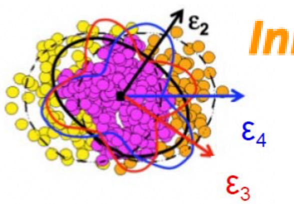
STAR Collaboration

Initial state vs. final state?

Initial state effect

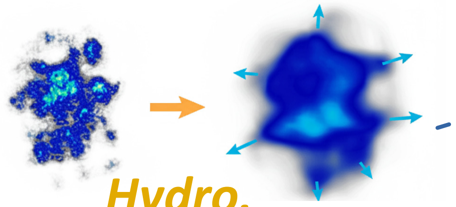


Initial momentum correlation(CGC): $\boldsymbol{\varepsilon_p}$



Initial eccentricity: ε_n

Final state effect



Hydro.

Measured flow

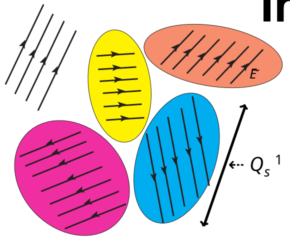
$\mathbf{v_2}$ $\mathbf{v_3}$

Effect on flow?

Test final state effect: change initial geometry w/ different collision systems

Initial state vs. final state?

Initial state effect



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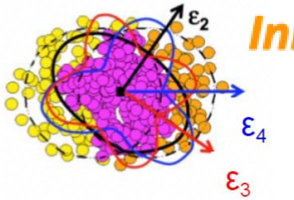
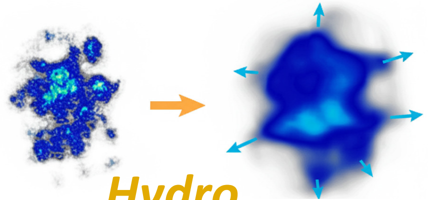


Initial eccentricity: $\boldsymbol{\varepsilon_n}$

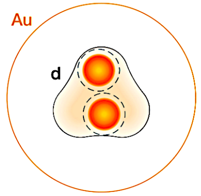
Final state effect



Hydro.

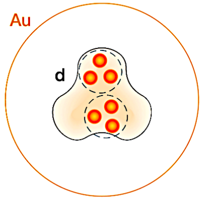
Measured flow

$\mathbf{v_2}$ $\mathbf{v_3}$



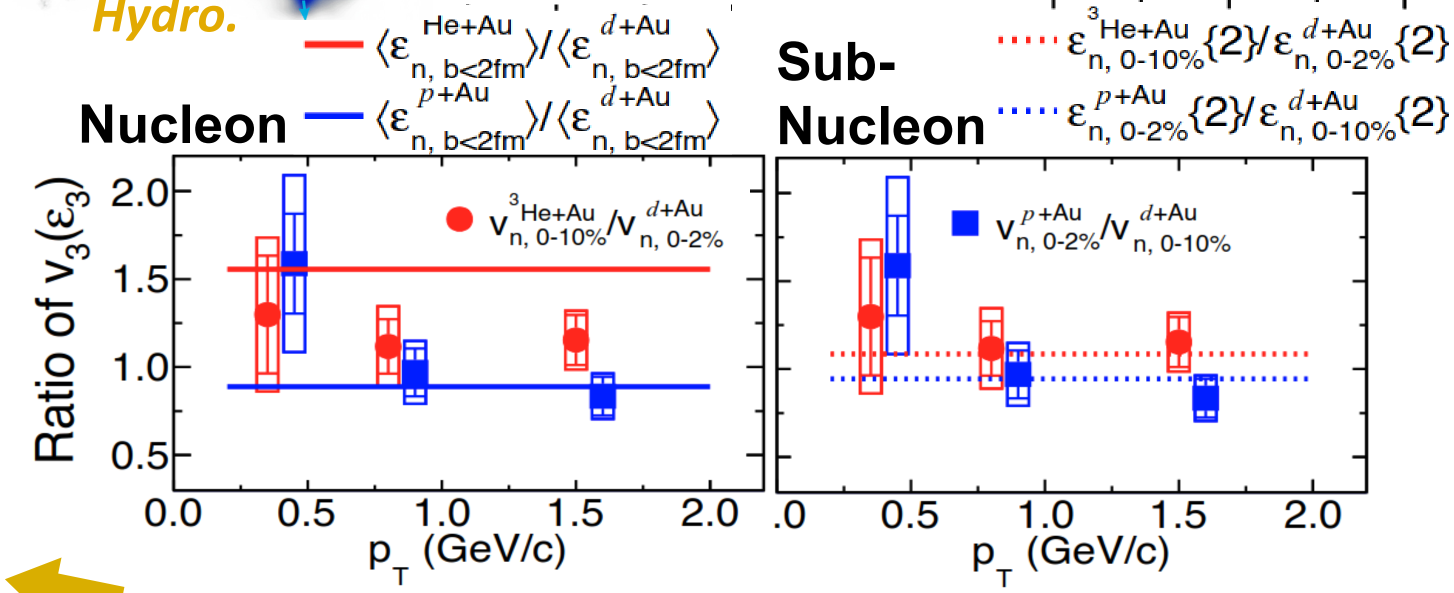
Nucleon fluctuation:

$\varepsilon_3(^3\text{He+Au})$ **>** $\varepsilon_3(\text{d+Au}) \sim \varepsilon_3(\text{p+Au})$



Sub-nucleon fluctuation:

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



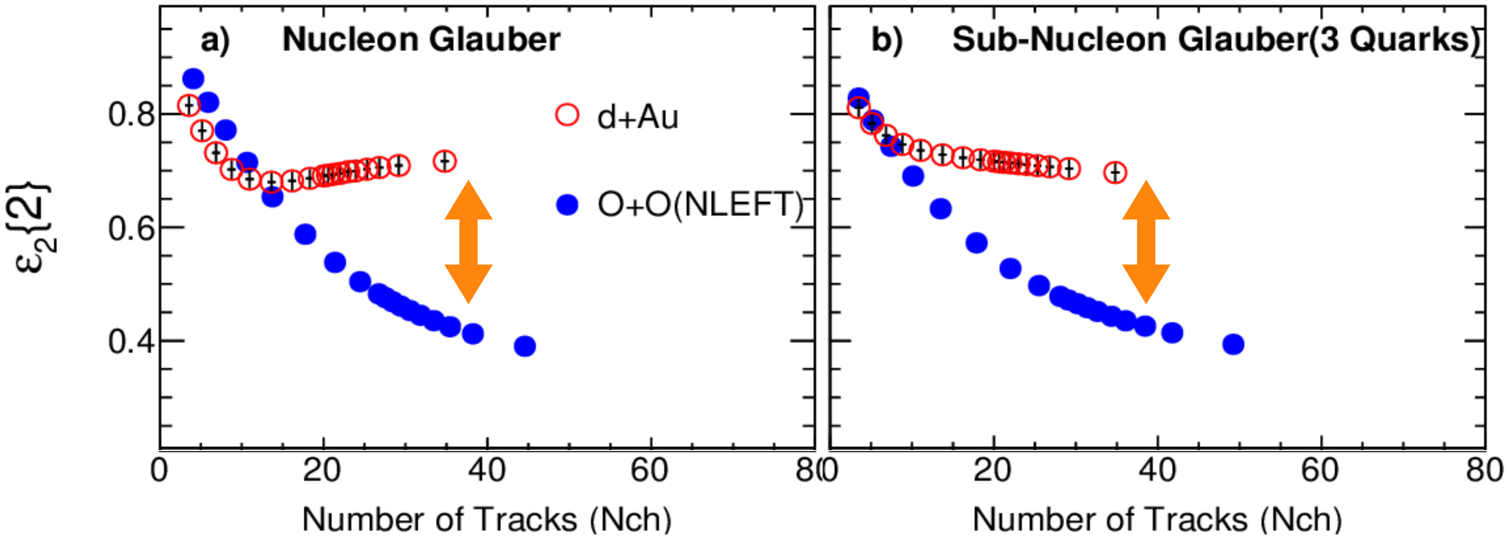
STAR measured $v_3(^3\text{He+Au}) \sim v_3(\text{d+Au}) \sim v_3(\text{p+Au})$

d+Au vs. O+O:

1) Provide new evidence for the geometry driven picture

2) Disentangle nucleon vs. sub-nucleon fluctuation

d+Au vs. O+O initial geometry



ε_n as a function of centrality

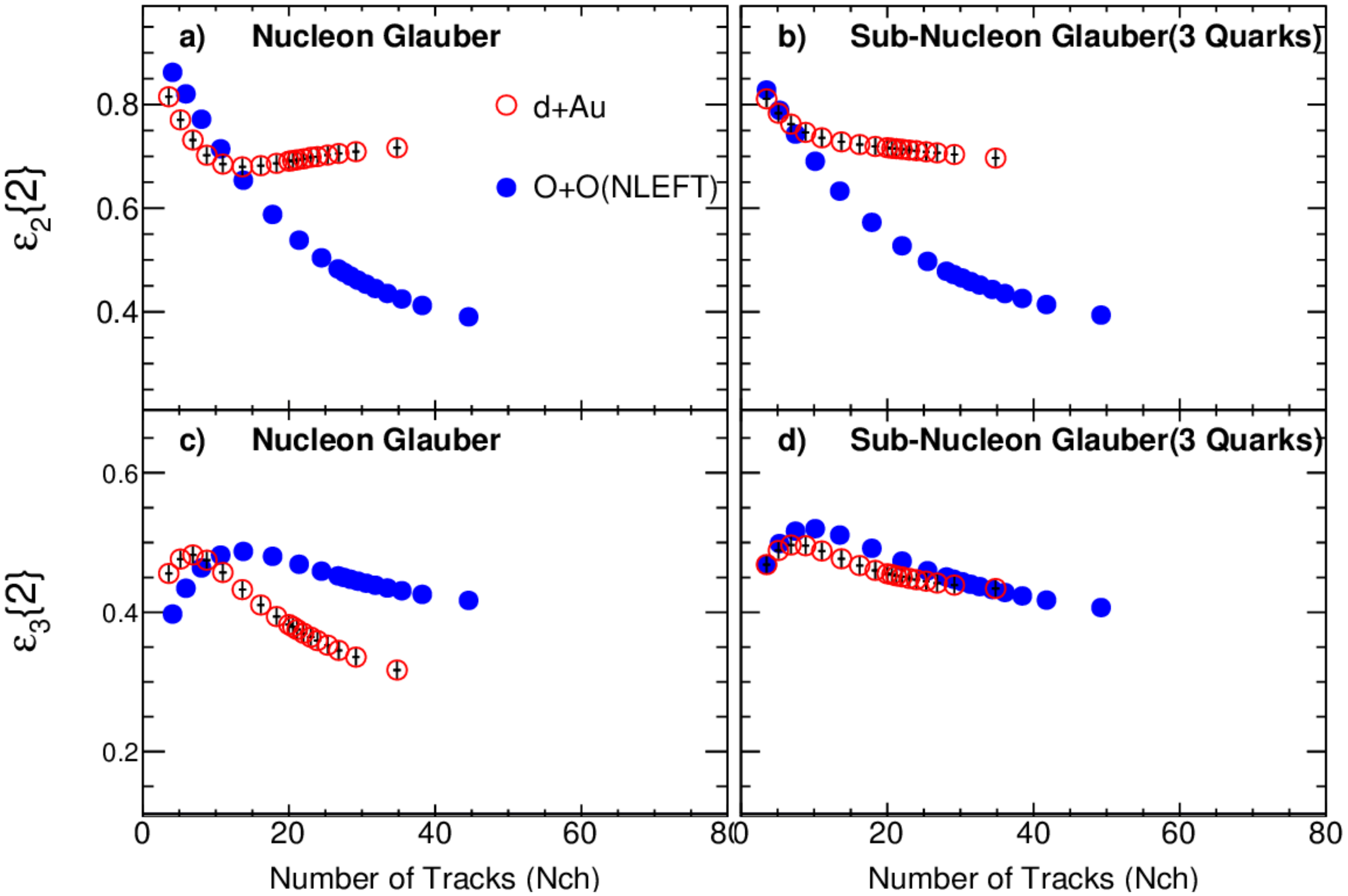
ε_2(d+Au) > ε_2(O+O)

Dominated by nucleon configurations

→Probe geometry

NLEFT: Lu *et al.*, PLB **797** (2019) 134863, Glauber: Loizides, PRC **94**, 024914 (2016)

d+Au vs. O+O initial geometry



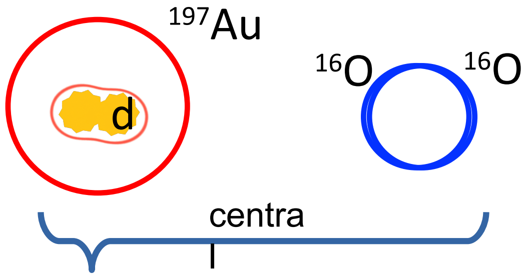
$\boldsymbol{\varepsilon}_n$ as a function of centrality

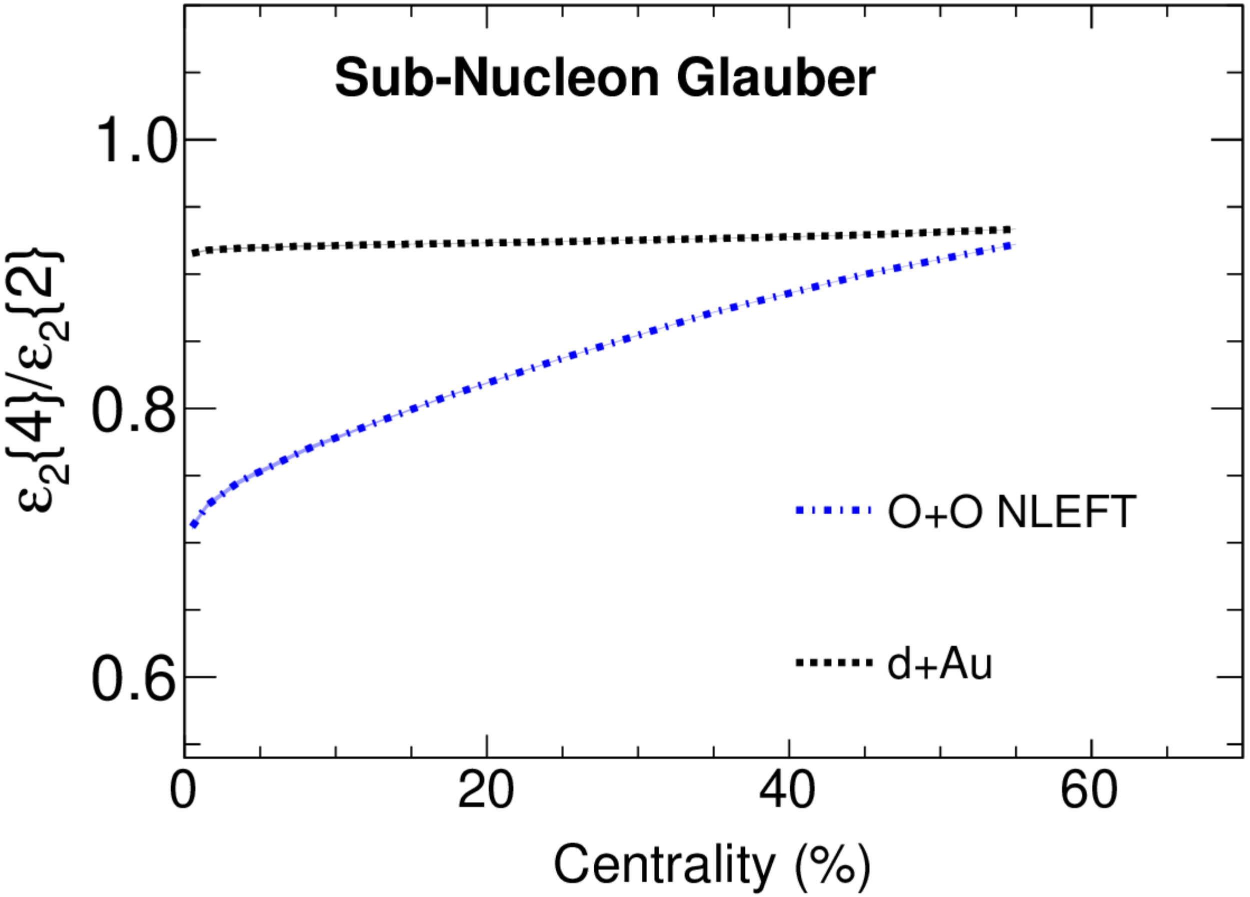
ε_2(d+Au) > ε_2(O+O)
Dominated by nucleon configurations
→Probe geometry

ε_3(d+Au) ? ε_3(O+O)
→Constrain sub-nucleon fluctuation

NLEFT: Lu *et al.*, PLB **797** (2019) 134863, Glauber: Loizides, PRC **94**, 024914 (2016)

d+Au vs. O+O eccentricity fluctuations





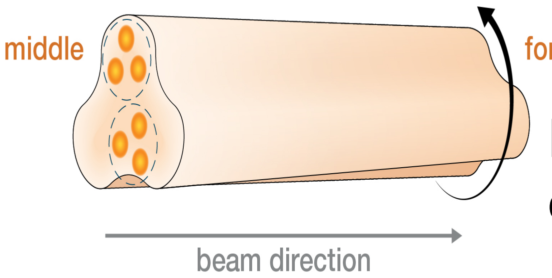
In central collisions:

- $\varepsilon_2\{4\} \approx \varepsilon_2\{2\}$ in d+Au. Dominated by average geometry.
- $\varepsilon_2\{4\} < \varepsilon_2\{2\}$ in O+O due to fluctuation.

Comparison with $v_2\{4\}$ and $v_2\{2\}$ to test the final state gemetry response to fluctuations.

NLEFT: Lu *et al.*, PLB **797** (2019) 134863, Glauber: Loizides, PRC **94**, 024914 (2016)

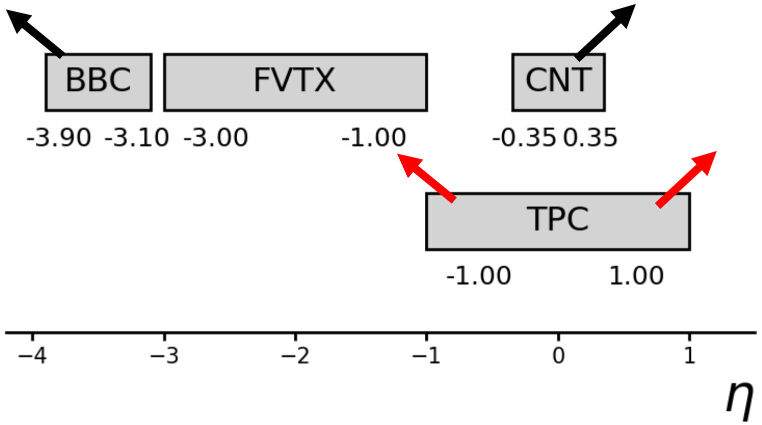
Longitudinal de-correlation



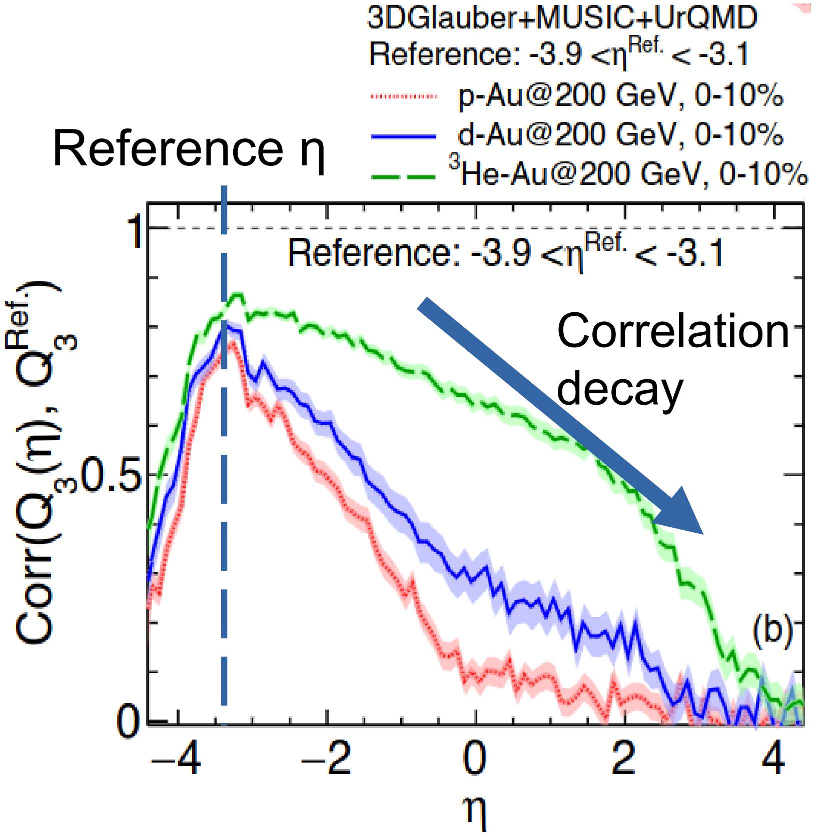
Rotated eccentricity vector

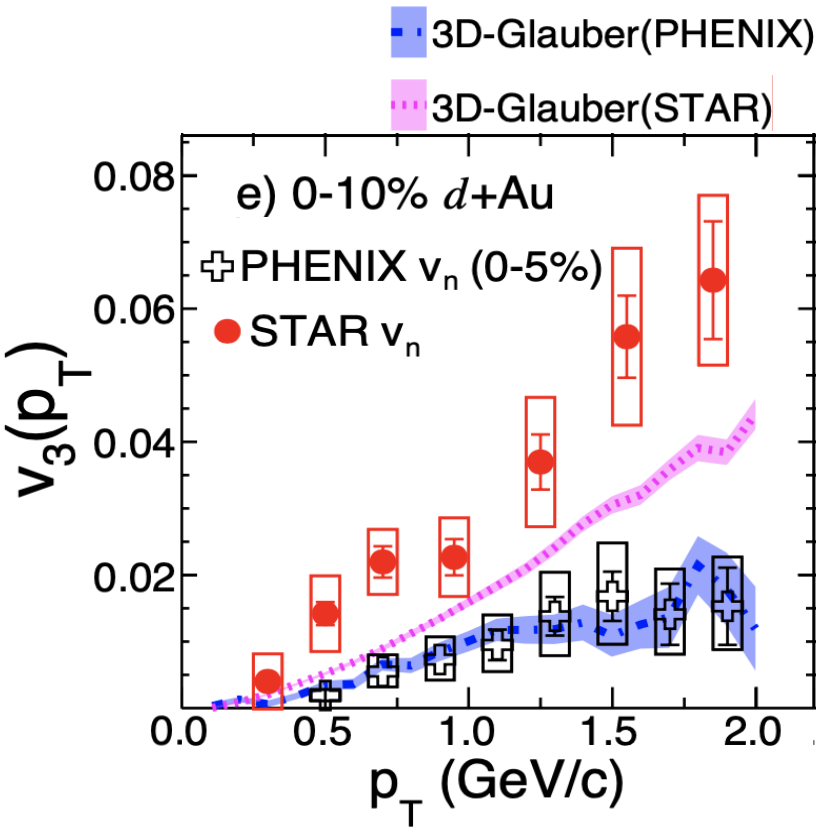
PHENIX Nature (Mid-Forward)

STAR PRL (Mid-Mid)



Reference η



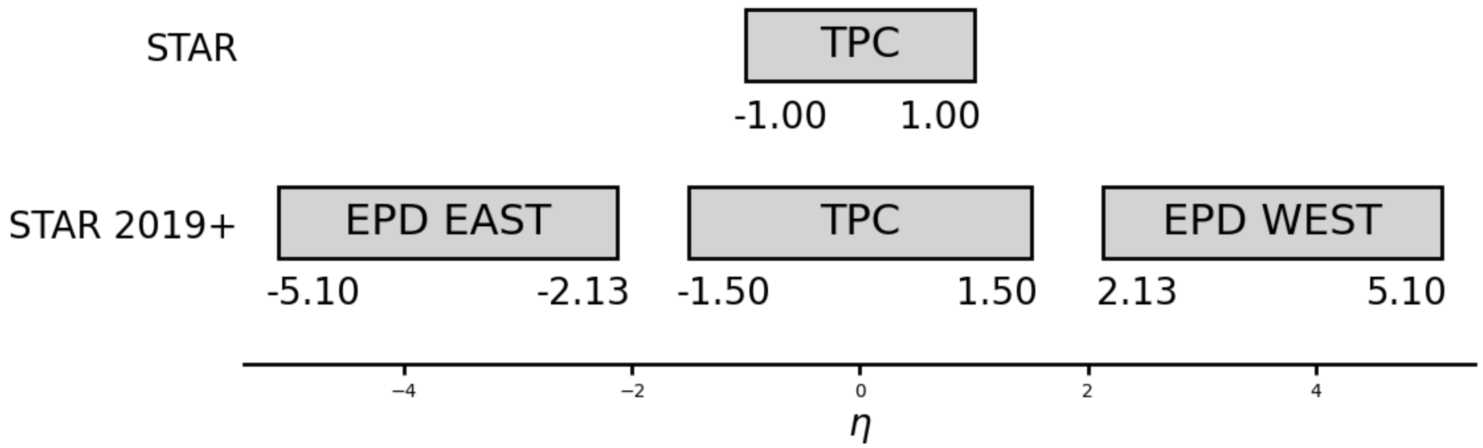


- 3 times difference STAR vs. PHENIX
- Large de-correlation as 3D-Glauber indicated? Model underestimates STAR's
- Crucial: Simultaneous STAR mid-mid/mid-fwd measurement

Zhao.*et al.*, PRC**107**(2023) 014904 PHENIX, Nature Physics **15**, 214-220 (2019), STAR, PRL 130, 242301(2023)

New run21 d+Au and O+O data

Detector upgrades



Wide η coverage, better handles on:

- De-correlation
- Non-flow

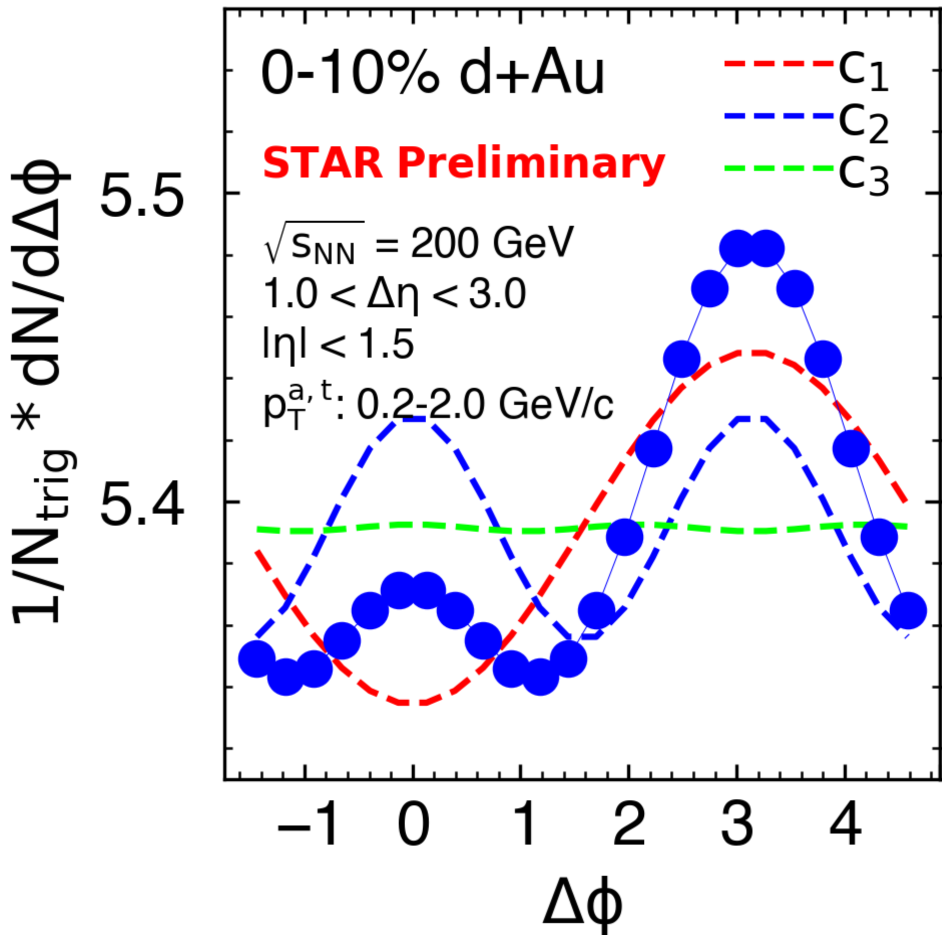
New data

Run21 d+Au: **High Multiplicity Trigger**: 70M Events
MB Trigger: 70M Events

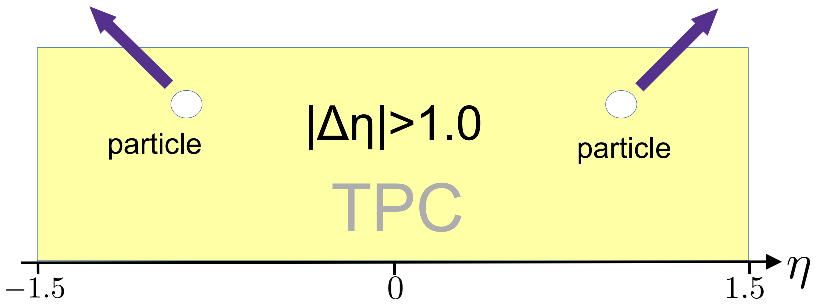
Run21 O+O: **High Multiplicity Trigger**: 510M Events
MB Trigger: 470M Events

Di-hadron correlation at mid-rapidity

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



Two-particle correlation method:



Non-flow subtraction

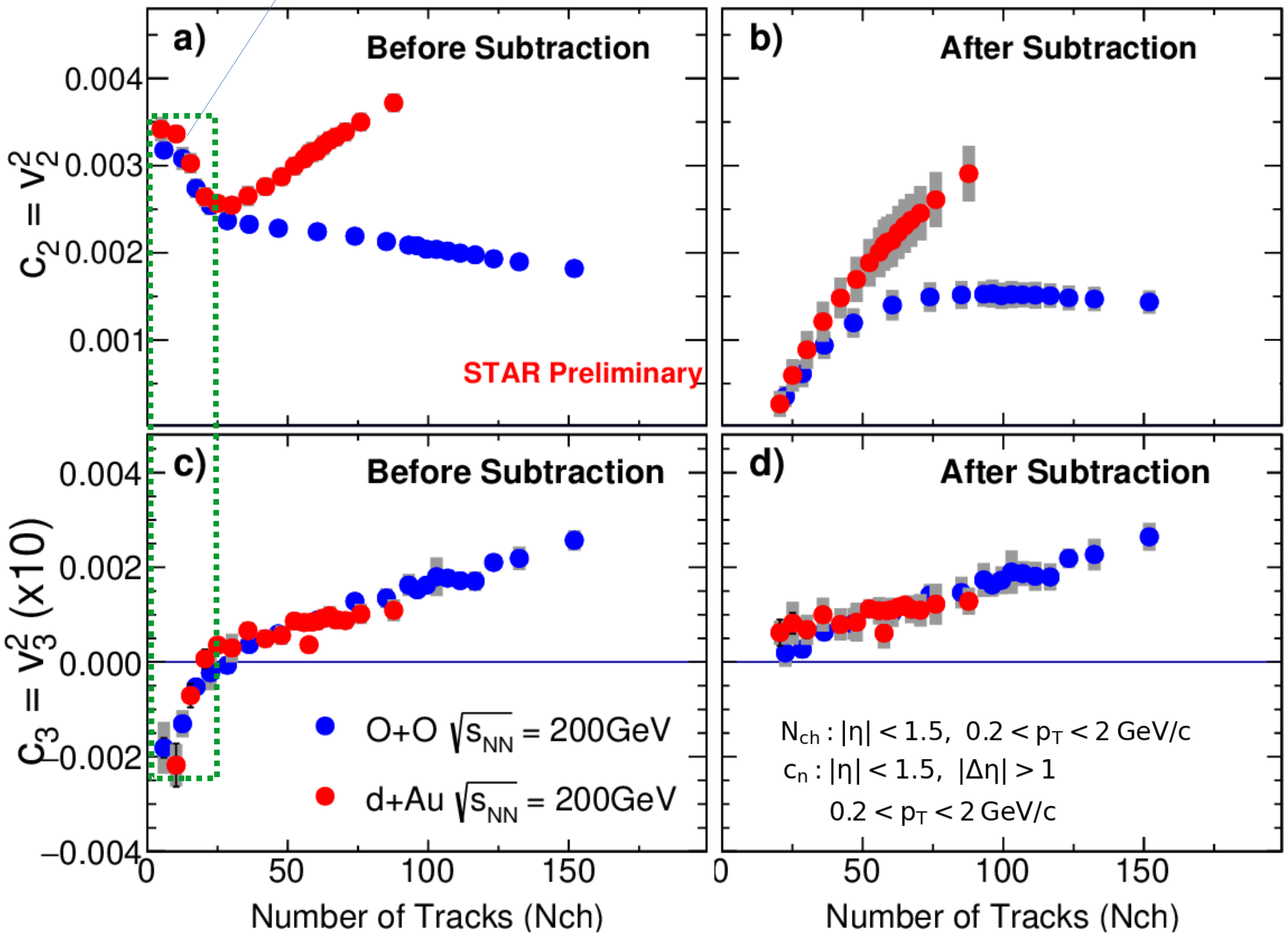
$$c_n^{\text{sub}} = c_n^{\text{raw}} - \frac{c_1^{\text{central}}}{c_1^{\text{peripheral}}} \times c_n^{\text{peripheral}}$$

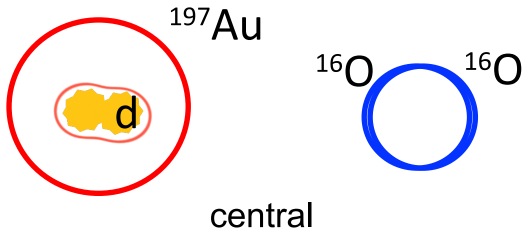
$$c_n^{\text{sub}} = c_n^{\text{raw}} - \frac{c_0^{\text{peripheral}}}{c_0^{\text{central}}} \times c_n^{\text{peripheral}}$$

$$v_n\left(p_{\mathrm{T}}^{\mathrm{t}}\right) = \frac{c_n\left(p_{\mathrm{T}}^{\mathrm{t}}, p_{\mathrm{T}}^{\mathrm{a}}\right)}{\sqrt{c_n\left(p_{\mathrm{T}}^{\mathrm{a}}, p_{\mathrm{T}}^{\mathrm{a}}\right)}}$$

Multiplicity dependence of c_2 and c_3

Non-flow dominant



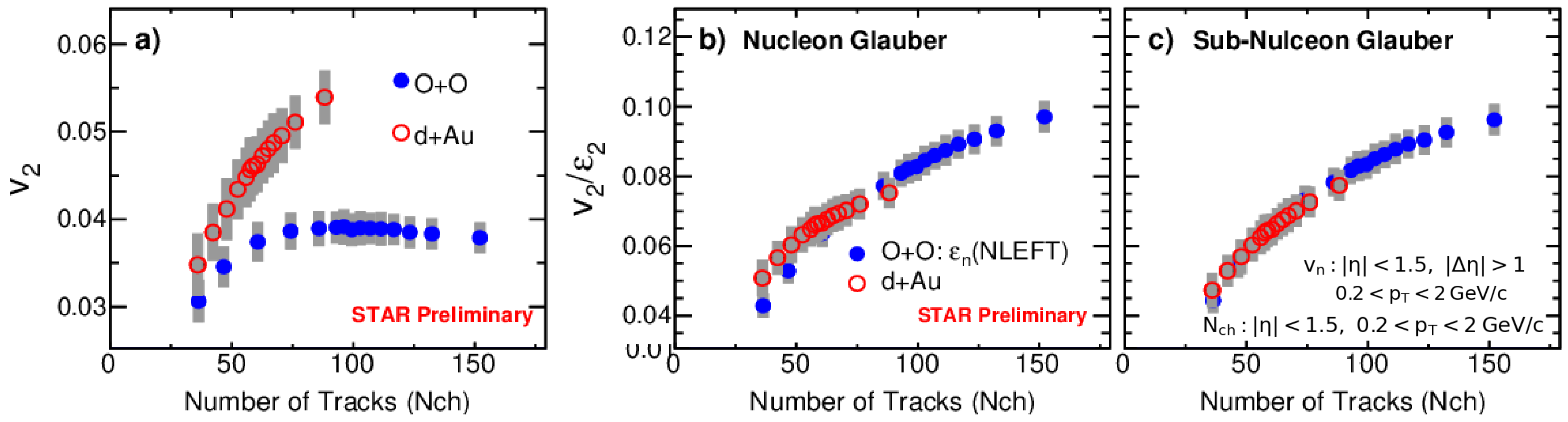


Non-monotonic d+Au c_2 : Non-flow dominance shift to flow dominance from peripheral to central

c_2(d+Au) > c_2(O+O) tracks initial geometry hierarchy

Similar c_3 in 2 systems

Multiplicity dependence of scaling ratio v_n/ε_n

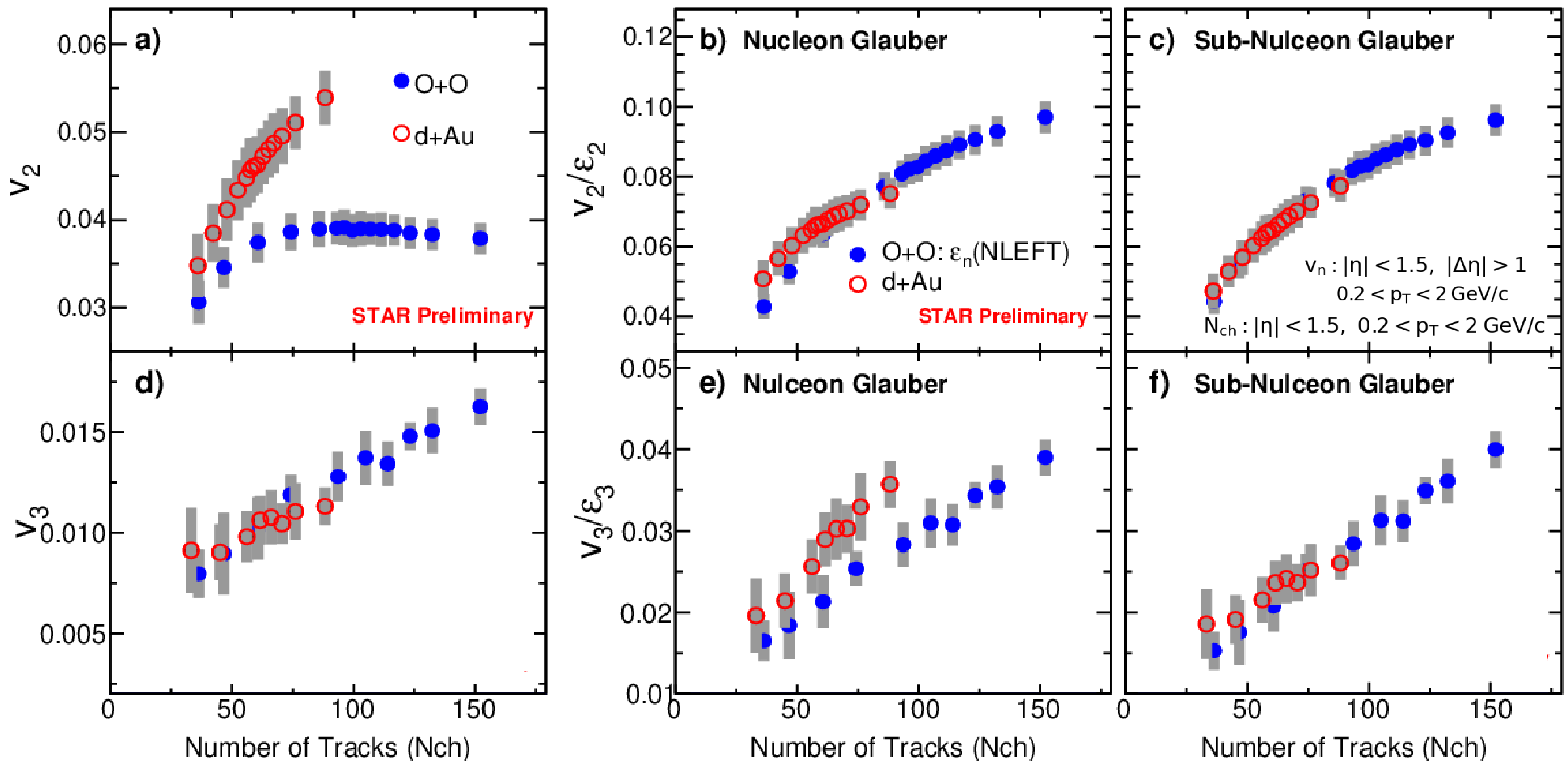


$$v_n\{2\} \propto \varepsilon_n\{2\}$$

v_2/ε_2 : d+Au and O+O show consistent collective response to geometry.

→ A QGP droplet in small system?

Multiplicity dependence of scaling ratio v_n/ε_n



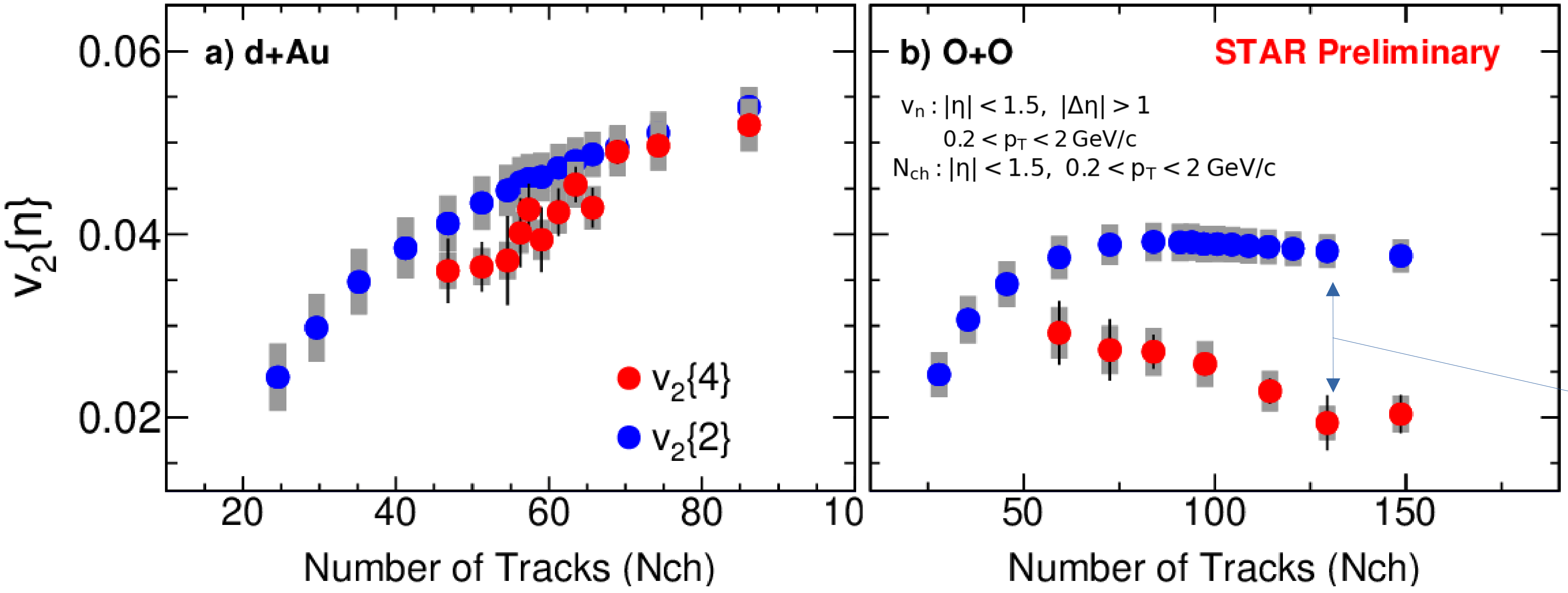
$$v_n\{2\} \propto \varepsilon_n\{2\}$$

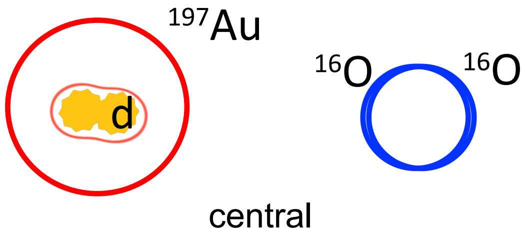
v_2/ε_2 : d+Au and O+O show consistent collective response to geometry.
→ A QGP droplet in small system?

v_3/ε_3 : Prefer sub-nucleon fluctuation

Wildly different initial geometries are converted to the final state flow
→ Hallmark of collective response from QGP in small systems

Flow fluctuations $v_2\{4\}$ and $v_2\{2\}$



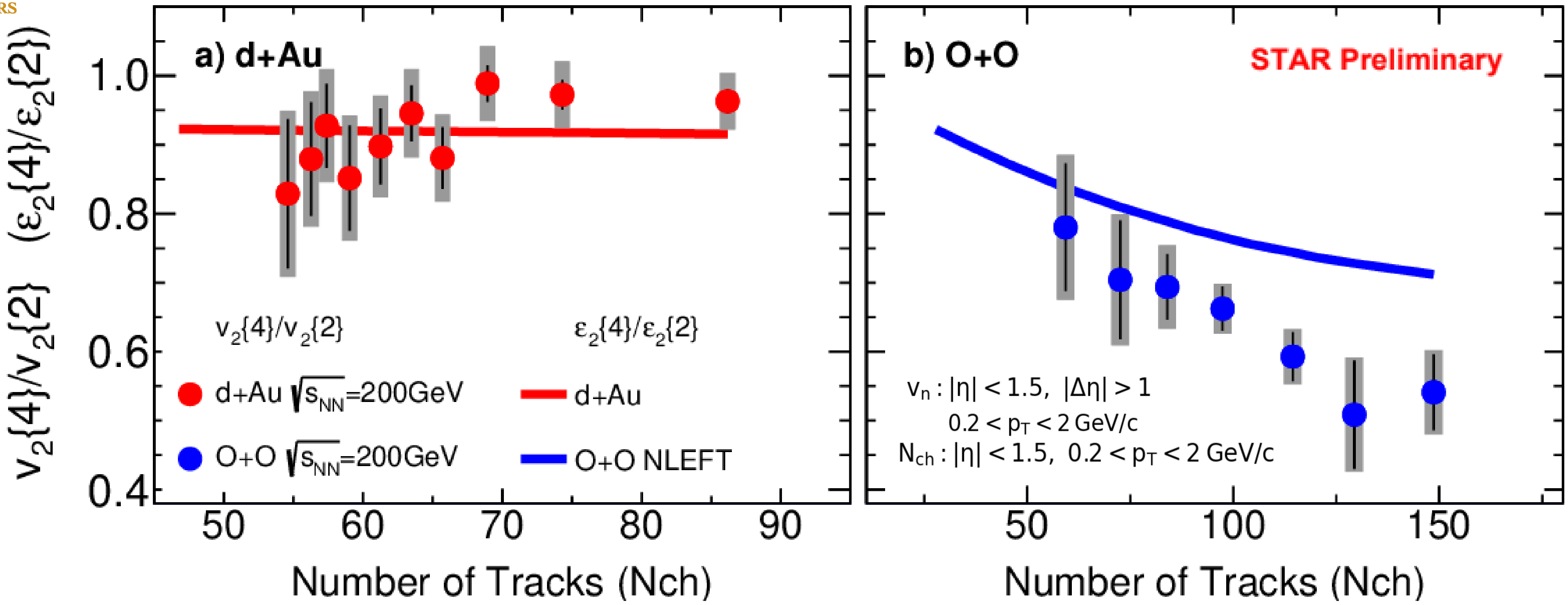


d+Au:
v_2 fluctuation is small

O+O:
v_2 fluctuation is larger in central collision

Ollitrault *et al.* ***arXiv:***nucl-th/0607009

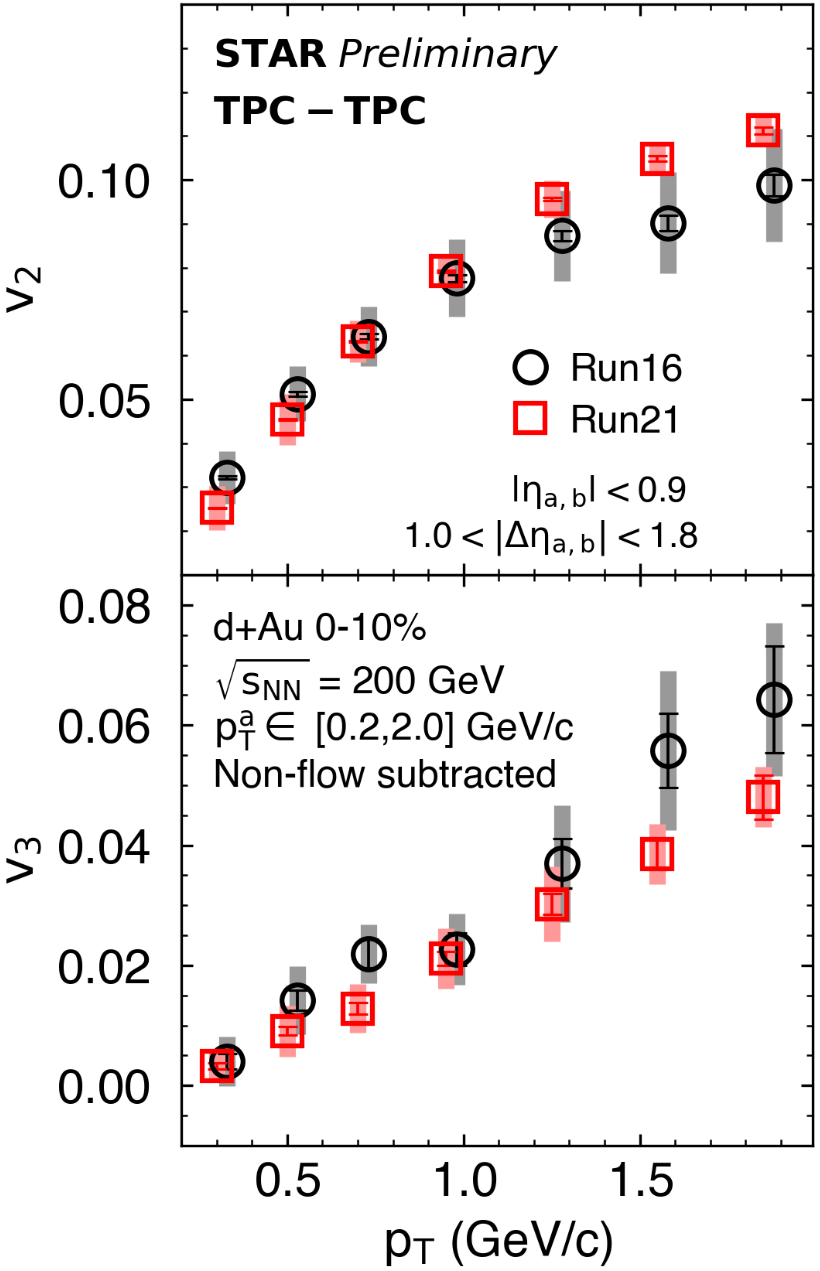
Flow fluctuation $v_2\{4\}/v_2\{2\}$

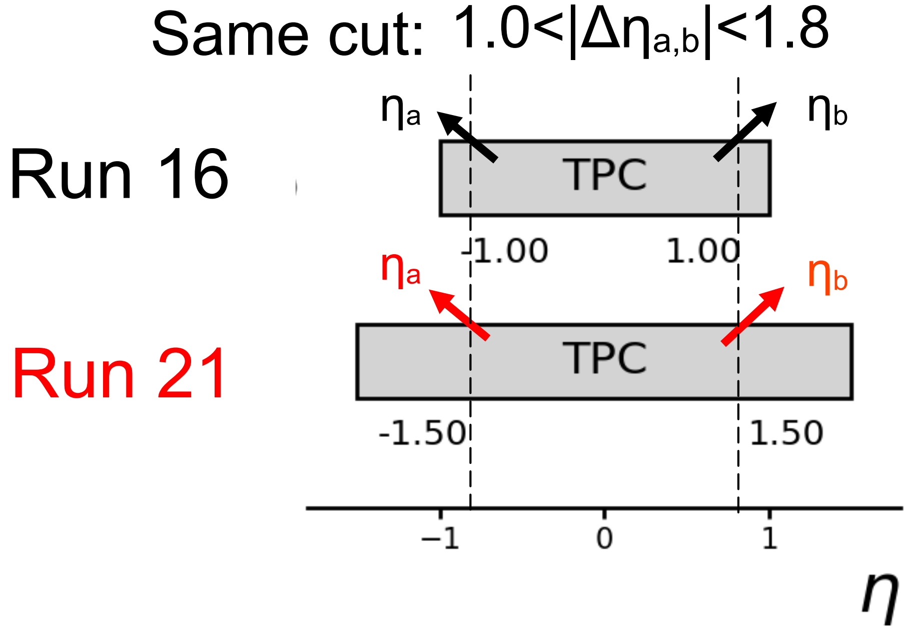


$$\frac{v_2\{4\}}{v_2\{2\}} \quad \text{vs.} \quad \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}}$$

Fluctuation in flow also scales with fluctuation in geometry
$\rightarrow$ collective response

Cross-check of the run 16 and run 21

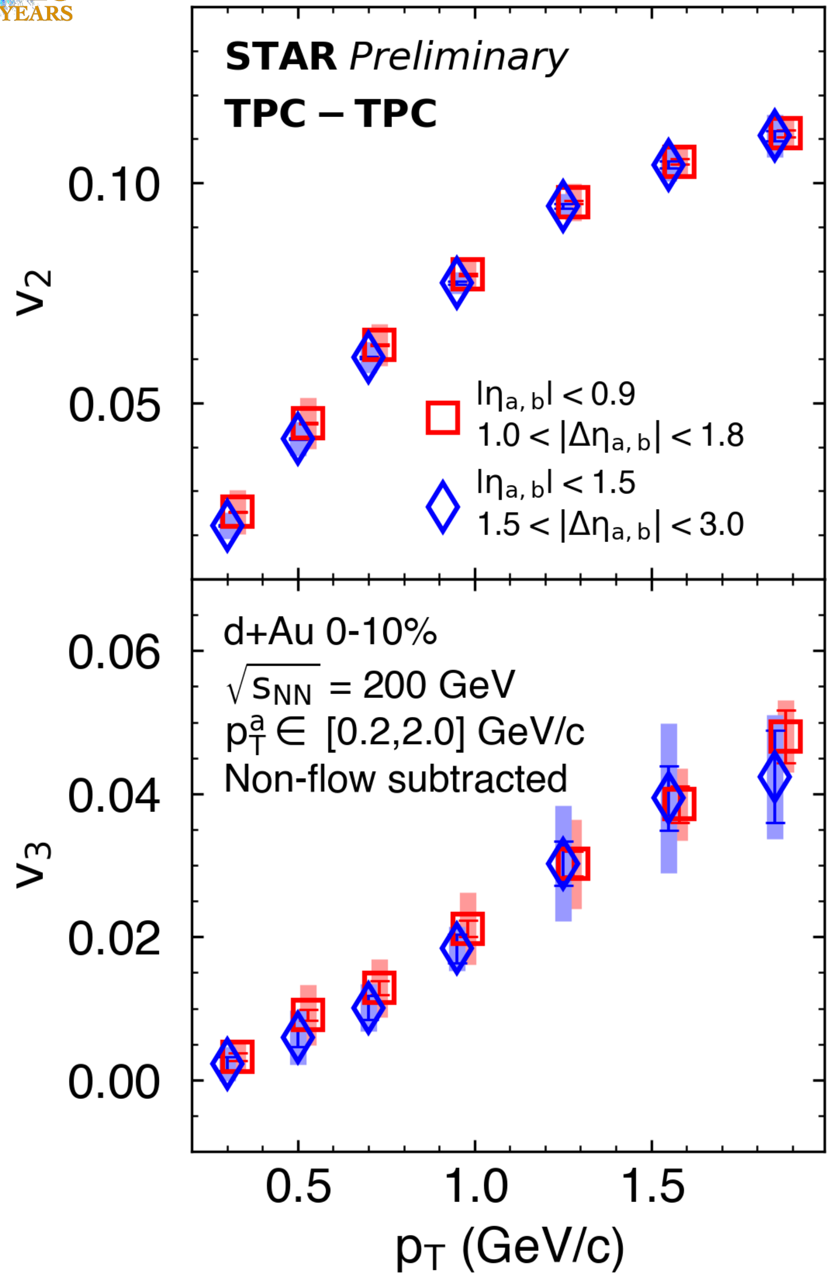




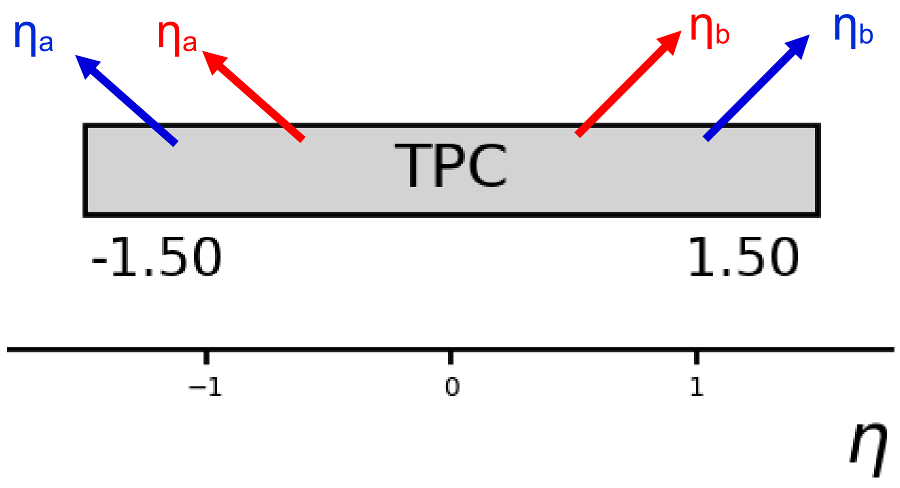
The results measured in mid-mid correlation are consistent between run 16 and run 21

STAR, PRL **130**, 242301(2023)

The role of longitudinal decorrelation



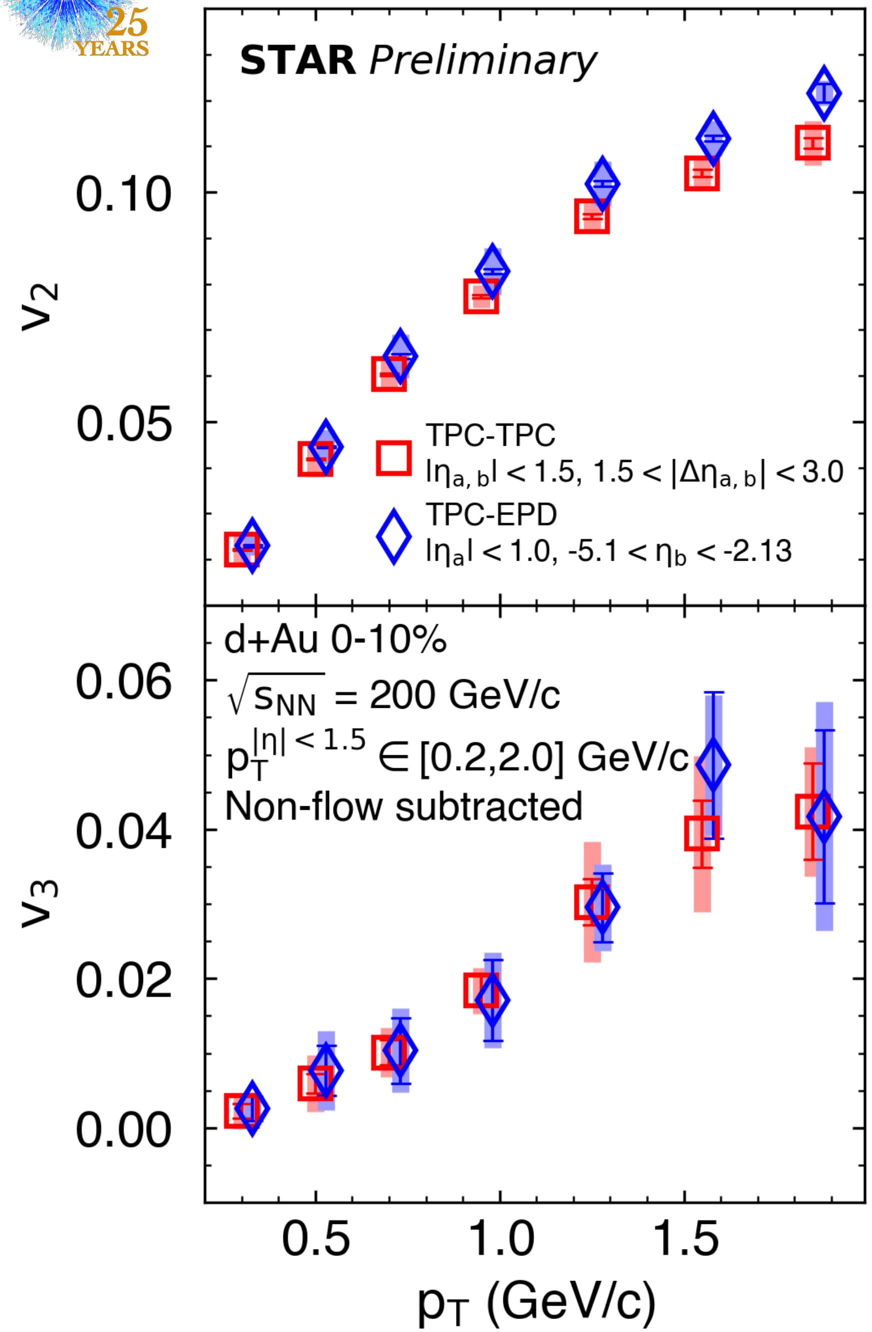
Run 21

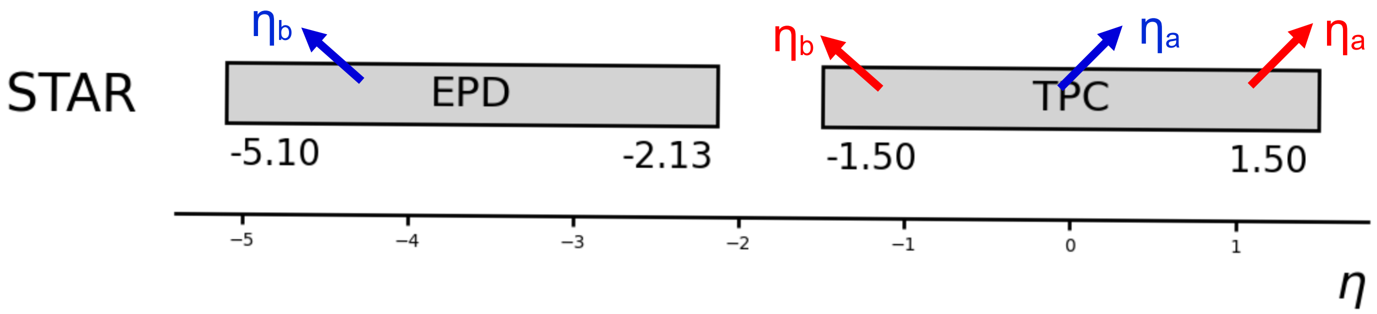


$1.0<|\Delta\eta_{a,b}|<1.8$ ⟺ $1.5<|\Delta\eta_{a,b}|<3.0$

Larger acceptance in mid-rapidity has minimal effect on the measured flow

Mid-mid vs. mid-forward





TPC-TPC: $1.5<|\Delta\eta_{a,b}|<3.0$ TPC-EPD: $|\eta_a|<1.0$, $-5.1<\eta_b<-2.13$

$$v_n(p_T) = \frac{\langle q_n^{TPCa}(p_T) Q_n^{*EPD}\rangle}{\sqrt{\frac{\langle Q_n^{TPCc} Q_n^{*EPD}\rangle \langle Q_n^{TPCd} Q_n^{*EPD}\rangle}{\langle Q_n^{TPCc} Q_n^{*TPCd}\rangle}}}$$

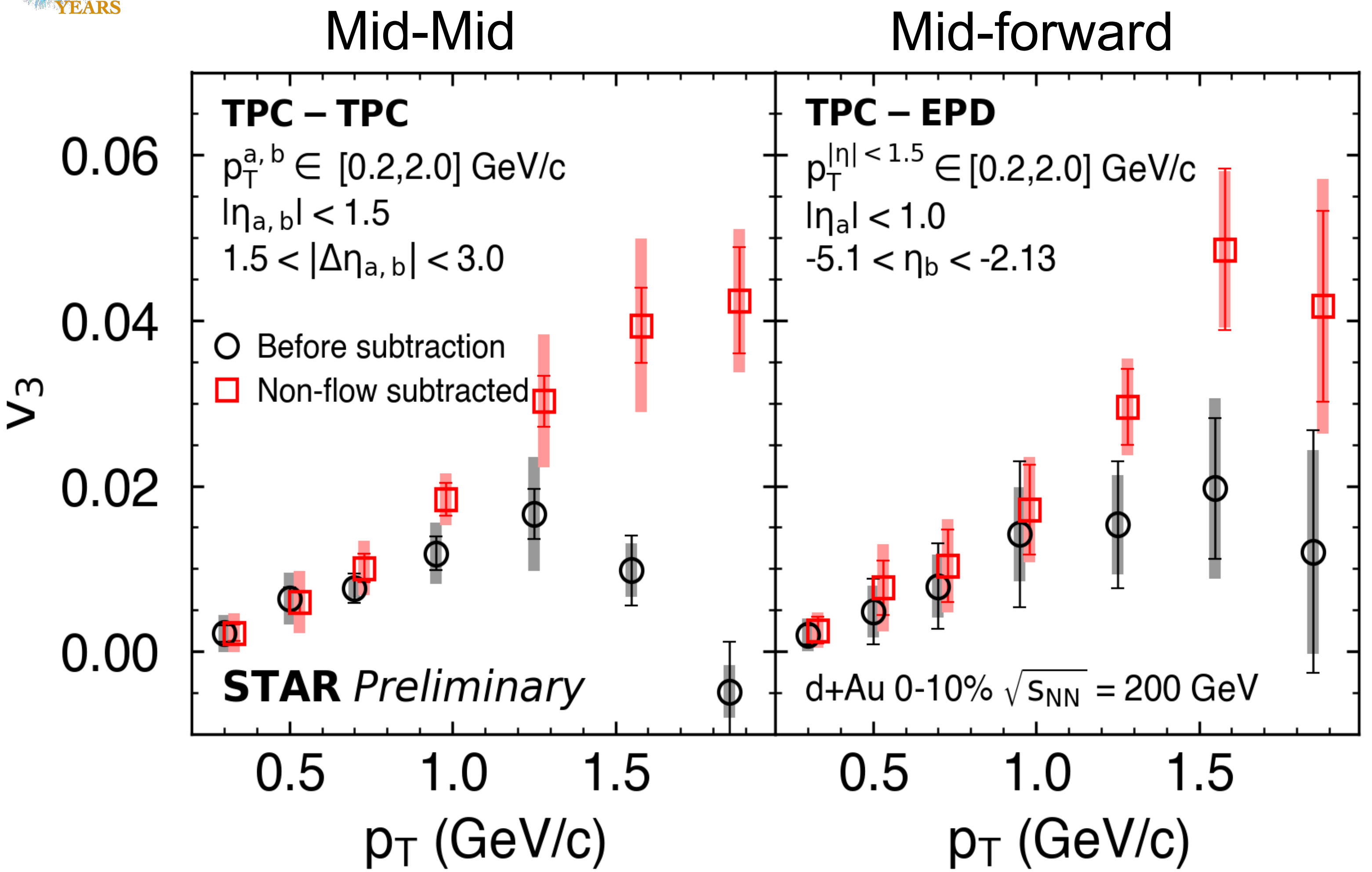
Denominator from 3 sub-event pairs. All non-flow subtracted.

- TPCc: $-1.5 < \eta < -0.5$
- TPCd: $0.5 < \eta < 1.5$
- EPD: $-5.1 < \eta < -2.13$

v_n(mid-mid) ≈ v_n(mid-forward)

Measured v_n shows no sign of de-correlation

Non-flow with large Δη gap



v_3 small before non-flow subtraction

Our results suggest potentially large negative non-flow for v_3 even with large Δη gap

New run 24 p+p @ 200 GeV: 3 billion min-bias + 3 billion high-multiplicity triggered events

1) Improve control over non-flow subtraction and de-correlation effects in small systems

2) Measure potential collectivity in p+p by subtracting min-bias from high-multiplicity events

Summary

1) Constraining geometry via v_2 and v_3 from d+Au and O+O:

- v_2(d+Au) > v_2(O+O): d+Au ε_2 average geometry dominated by the nucleon configurations in deuteron
- v_3(d+Au) ≈ v_3(O+O): v_3 consistent with ε_3 ordering that further includes sub-nucleon fluctuation

2) Non-flow subtracted v_n in d+Au with different Δη-gaps suggest:

- No significant de-correlation effect predicted by the 3D Glauber model was found
- Large Δη-gap does not eliminate non-flow in v_3 without subtraction
- Final v_n remains stable with varying reference particle acceptance