The small system flow measurements from the STAR experiment

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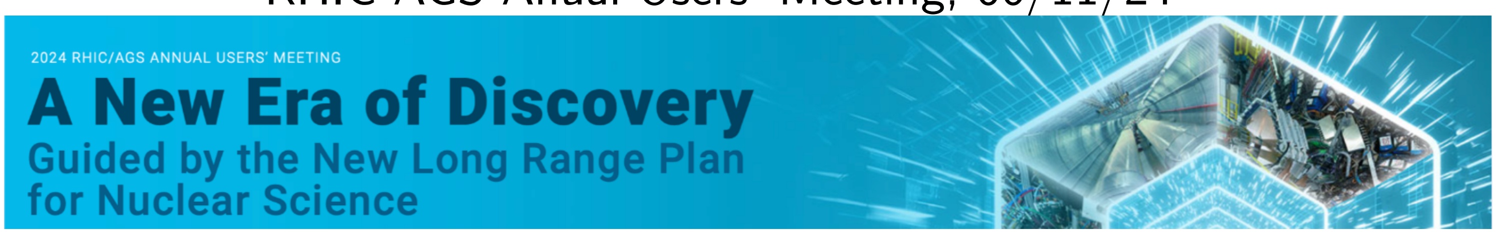

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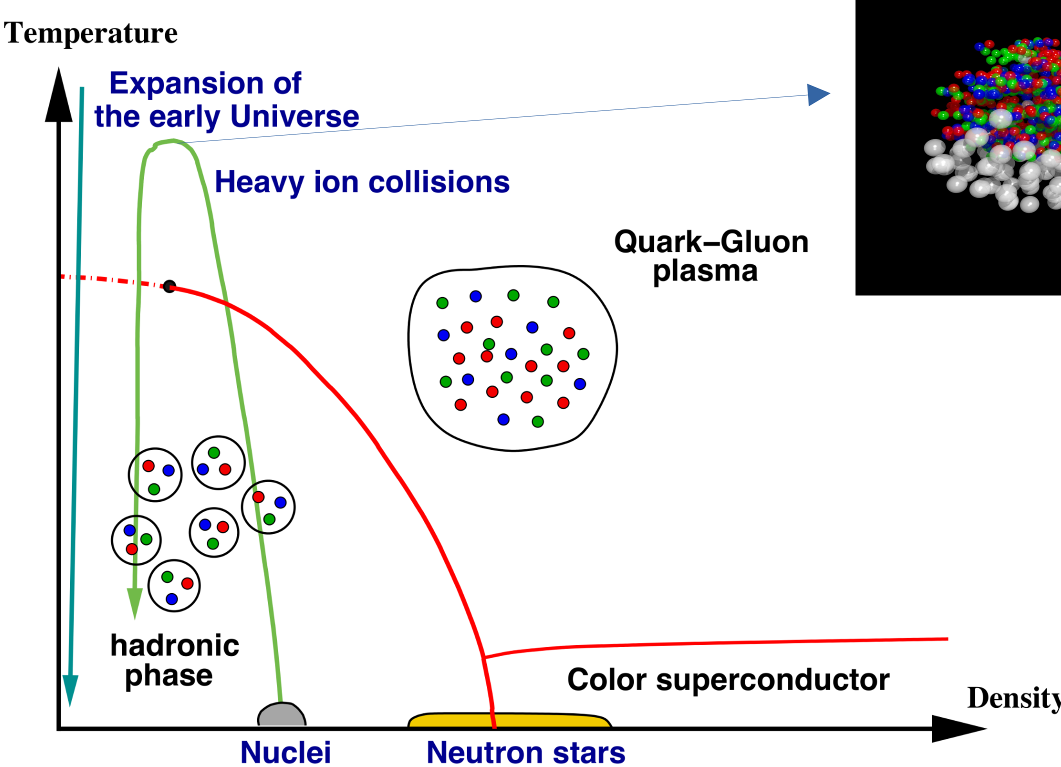
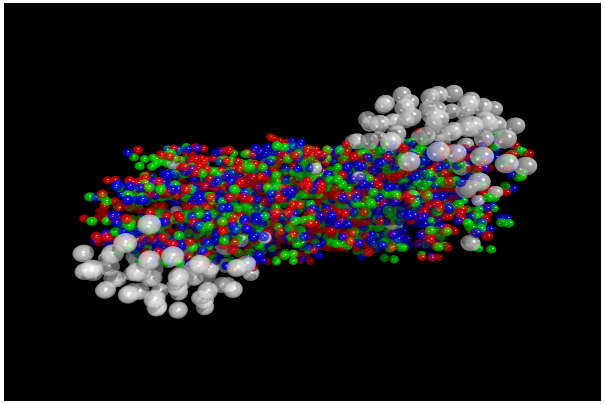
Outline

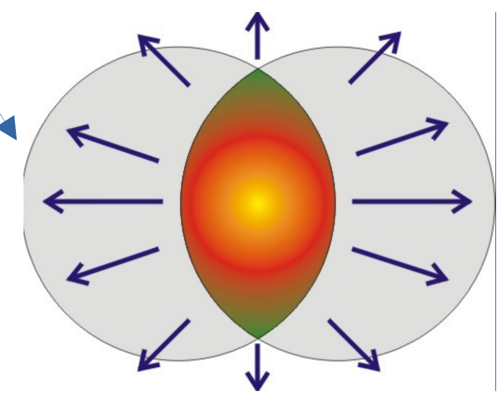
- Introduction
- Nucleon and subnucleon fluctuation
- Longitudinal decorrelation & non-flow
- Many-body correlation
  - O+O and d+Au data
- Collision geometry
- Summary and outlook

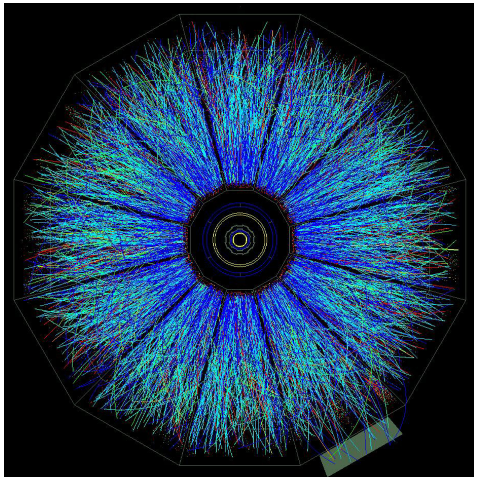
Physics context

- Highly compressed, hot matter forms Quark-Gluon Plasma(QGP) with quark and gluon degrees of freedom.
- Heavy-ion collision $\rightarrow$ study the properties of QGP.
  - Rapid expansion $\rightarrow$ converts spacial non-uniformity in QGP to transverse momentum anisotropy of emitted particles.
  - For large-ion collision, QGP evolution is well described by the relativistic viscous hydrodynamic models as liquid with minimal viscosity.

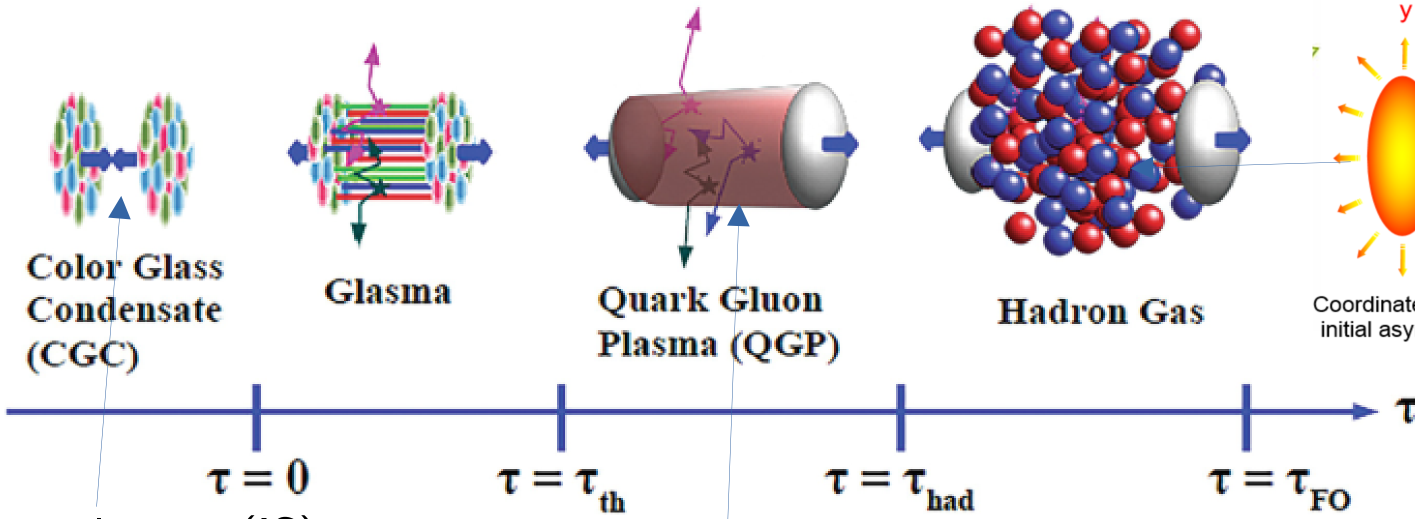


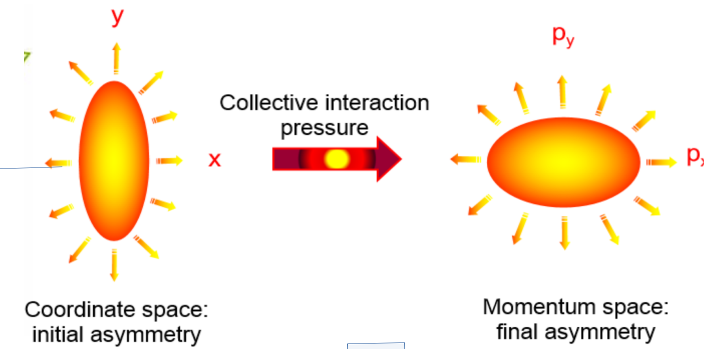






Flow in small system





$$v_n = k_n \varepsilon_n$$

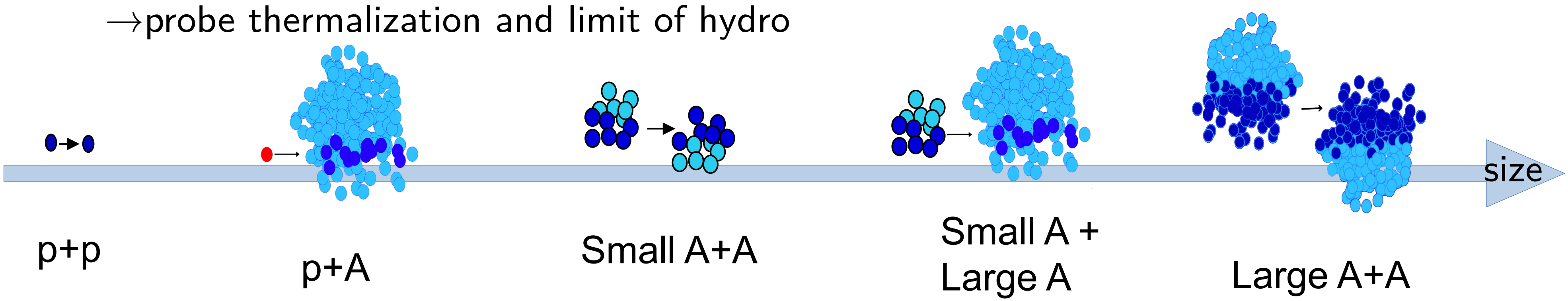
Initial state (IS) momentum correlation.

Final State (FS) collective response to geometry fluctuation

Particle distribution

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n\left(p_{\mathrm{T}}\right)\cos\left(n\left(\phi - \Phi_n\right)\right)$$

- QGP evolution process. How much contributions from IS and FS? $\rightarrow$ system size dependence?
- Collision frequency can depend on QGP size $\rightarrow$probe thermalization and limit of hydro



STAR scans whole range in size to study those effect!

2-particle correlation v_n

- Transverse hadron distribution in Fourier series:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n\left(p_{\mathrm{T}}\right)\cos\left(n\left(\phi - \Phi_n\right)\right)$$

- Associate and trigger particle pair distribution in azimuthal separation.
  - Corrected for acceptance using mixed-event distribution.
  - Pair distribution,

$$\frac{dN_{\mathrm{pairs}}}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} c_n\left(p_{\mathrm{T}}^{\mathrm{t}}, p_{\mathrm{T}}^{\mathrm{a}}\right)\cos(n\Delta\phi)$$

  - p_T dependence for trigger particles,

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

  - Where non-flow is extracted using c_1 method. Subtraction is robust with different methods..

$$c_n^{sub} = c_n - \frac{c_1}{c_1^{periph}} \times c_n^{periph}$$

PRC 58,1671
PRL. 130, 242301

$v_n = k_n \varepsilon_n$ up to n = 3. Trace the eccentricities though particle correlation

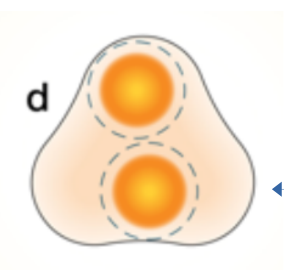
The role of (sub)nucleonic fluctuation on eccentricity

Geometry fluctuation response in FS depends on the degrees of freedom in the nucleus.

Model	a [33, 43] $\varepsilon_2^a(\varepsilon_3^a)$	c [31] $\varepsilon_2^c(\varepsilon_3^c)$
^{3}He+Au	0.50(0.28)	0.53(0.38)
d+Au	0.54(0.18)	0.53(0.36)
p+Au	0.23(0.16)	0.41(0.34)

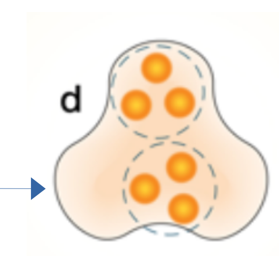
PRL 130, 242301

Default Glauber



vs.

Gaussian field around quarks



$$\varepsilon_2^{^3\text{He+Au}} \approx \varepsilon_2^{d\text{+Au}} > \varepsilon_2^{p\text{+Au}}$$
$$\varepsilon_3^{^3\text{He+Au}} > \varepsilon_3^{d\text{+Au}} \approx \varepsilon_3^{p\text{+Au}}$$

^{3}He+Au to have largest ε_3 due to nucleon geometry.

Where RMS $\varepsilon_n = \sqrt{\langle \varepsilon_n^2 \rangle}$

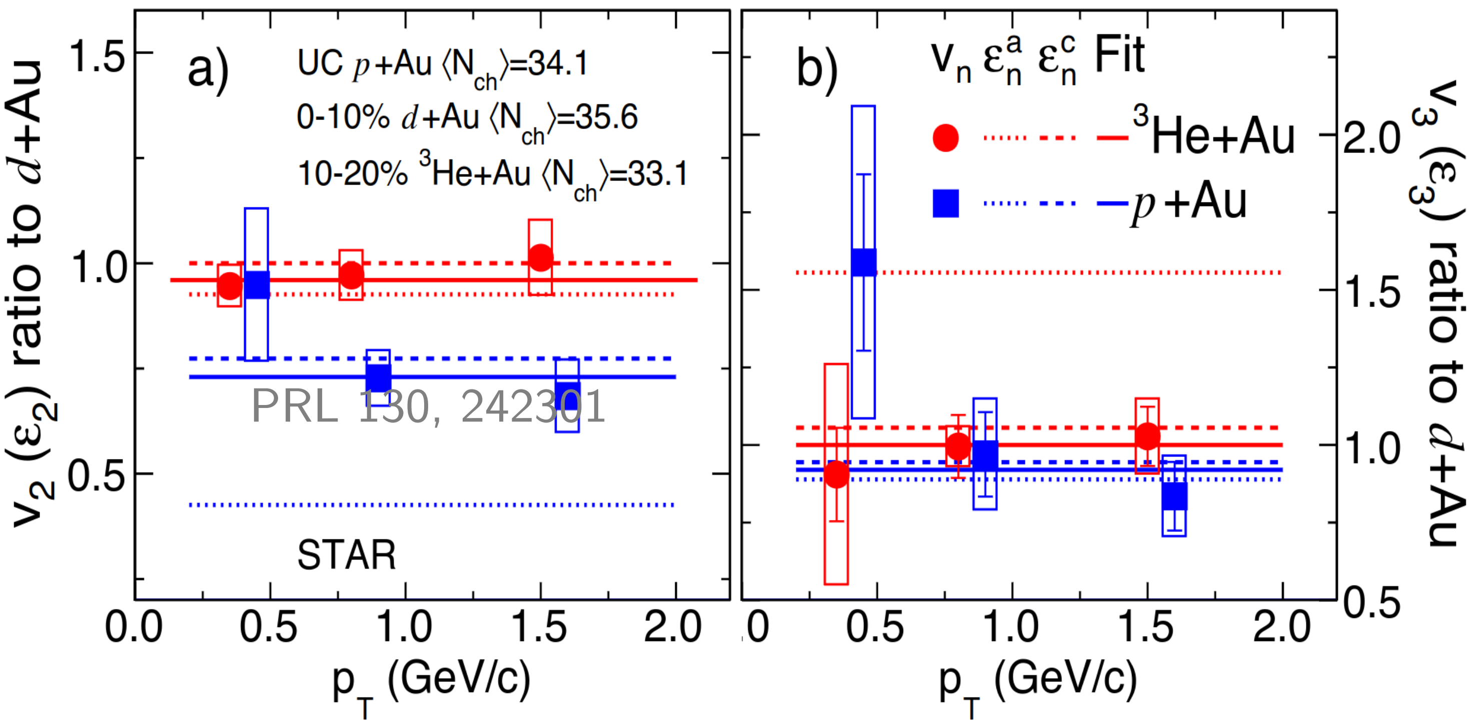
$$\varepsilon_2^{^3\text{He+Au}} \approx \varepsilon_2^{d\text{+Au}} > \varepsilon_2^{p\text{+Au}}$$
$$\varepsilon_3^{^3\text{He+Au}} \approx \varepsilon_3^{d\text{+Au}} \approx \varepsilon_3^{p\text{+Au}}$$

Similar triangular flow with sub-nucleon fluctuation.

Nucleon vs, quark picture different hierachy → Check by ratio between systems

The role of (sub)nucleonic fluctuation on eccentricity

Previous STAR result



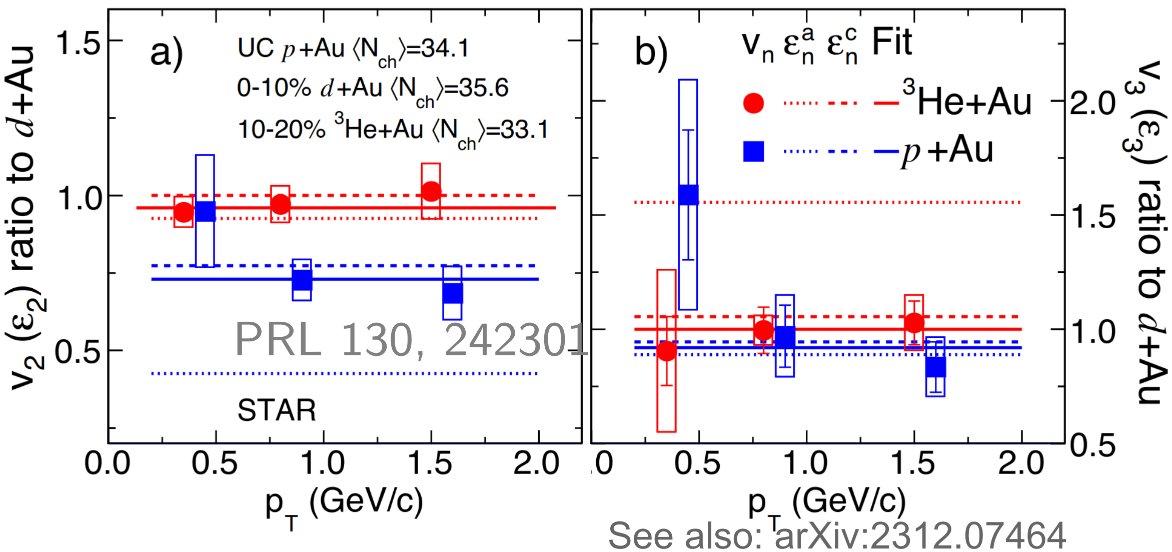
$v_n \rightarrow$ STAR data

Model c $\rightarrow$ Gaussian field around quarks

Compare v_n ratio in data and ε_n ratio in model

The role of (sub)nucleonic fluctuation on eccentricity

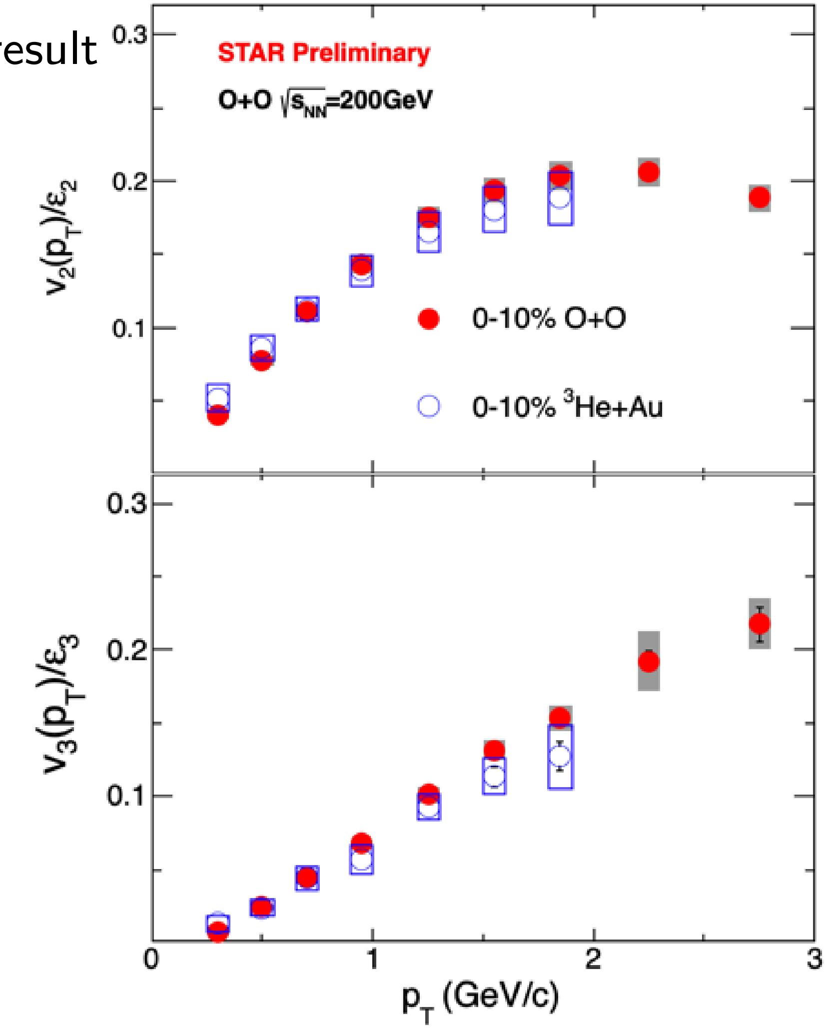
Previous STAR result



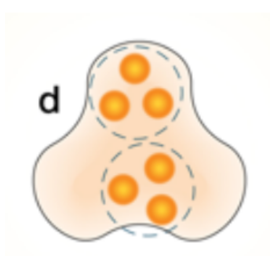
Model c → Gaussian field around quarks

Compare v_n ratio in data and ε_n ratio in model

O+O result



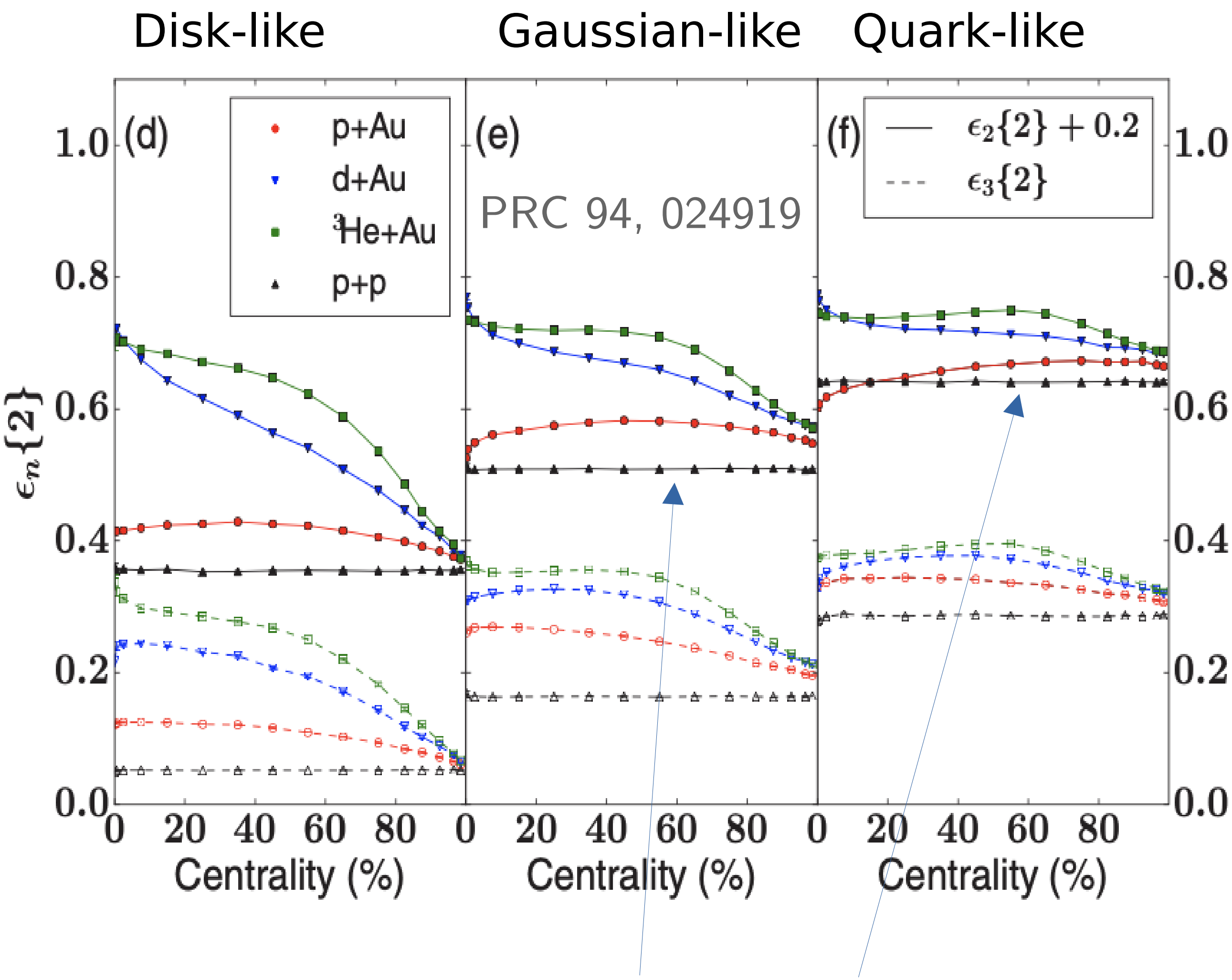
- ε_n with quark Glauber
- Same v_n/ε_n scaling to ^{3}He+Au.

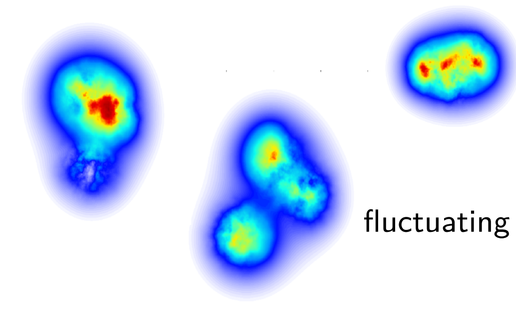


No evidence of larger triangular flow in He+Au than p+Au, d+Au
Scaling in O+O agrees with quark Glauber
Data prefer model with subnucleon fluctuation.

The role of (sub)nucleonic fluctuation on eccentricity

- p+p 200 GeV data taken in 2024.





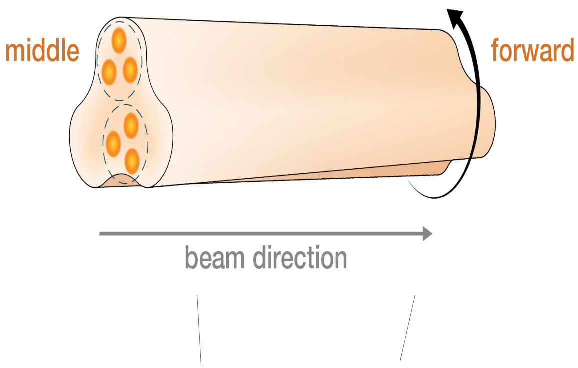
fluctuating proton

Large ε_2 difference, easier to measure compared to ε_3

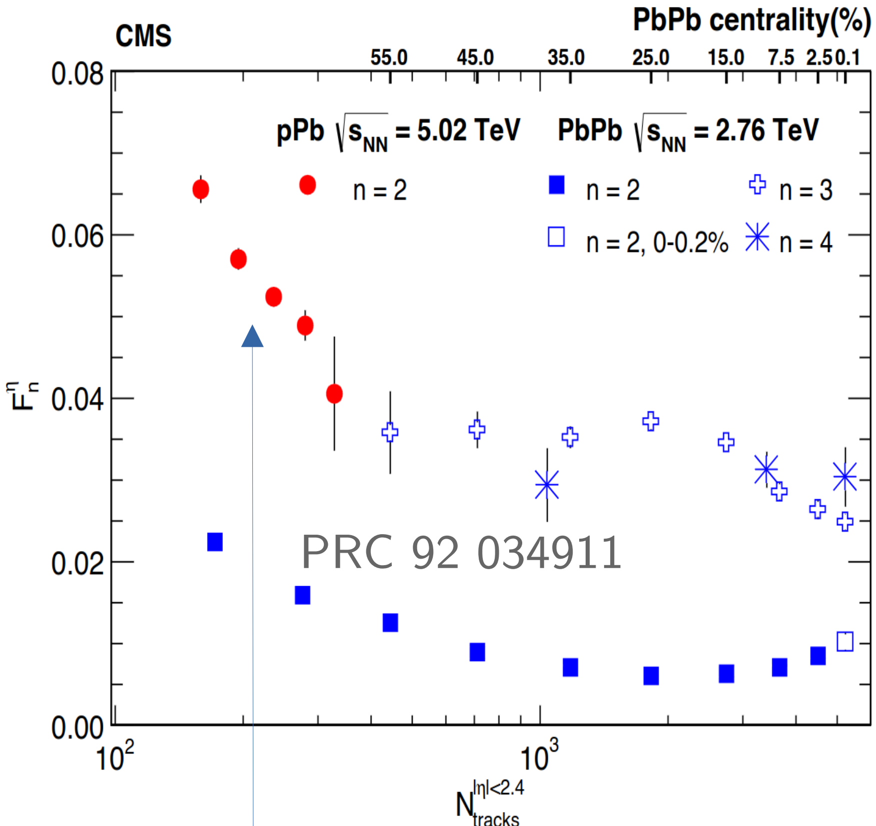
p+p can better distinguish (sub)nucleonic fluctuation

Longitudinal decorrelation & nonflow

- Eccentricity fluctuation in η + particle pair from different η = decorrelation in v_n

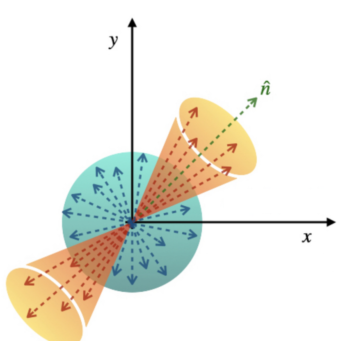


Unequal eccentricity vectors due to fluctuation



Rapidity factorization breaking is more evident for smaller system.

$$\cos\left\{n\left[\Psi_n\left(\eta^a\right)-\Psi_n\left(\eta^b\right)\right]\right\}=e^{-F_n^\eta\left|\eta^a-\eta^b\right|}$$

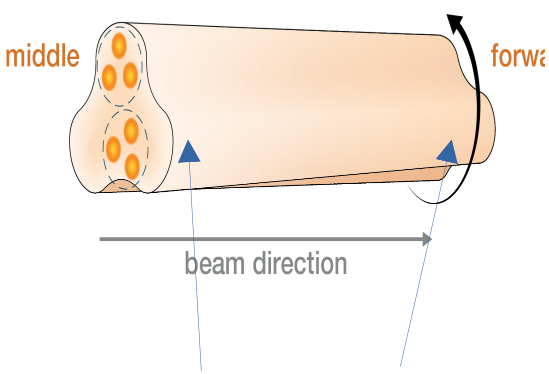


Measure 2-particle correlaiton with large η gap

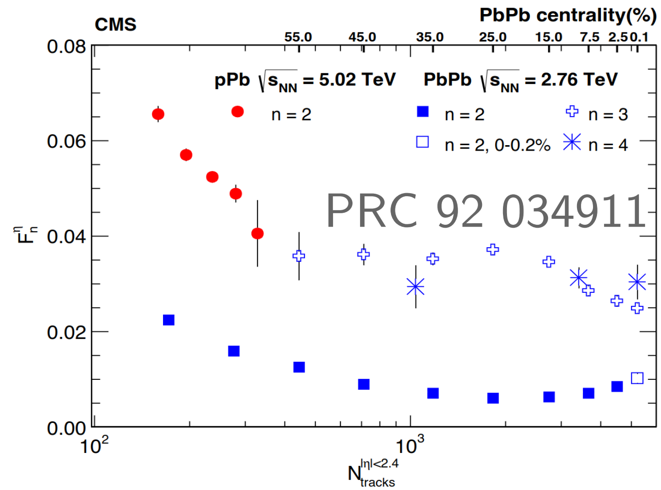
→ Suppress non-flow correlation such as particle decay.

Longitudinal decorrelation & nonflow

- Eccentricity fluctuation in η + particle pair from different η = decorrelation in v_n



Unequal eccentricity vectors due to fluctuation



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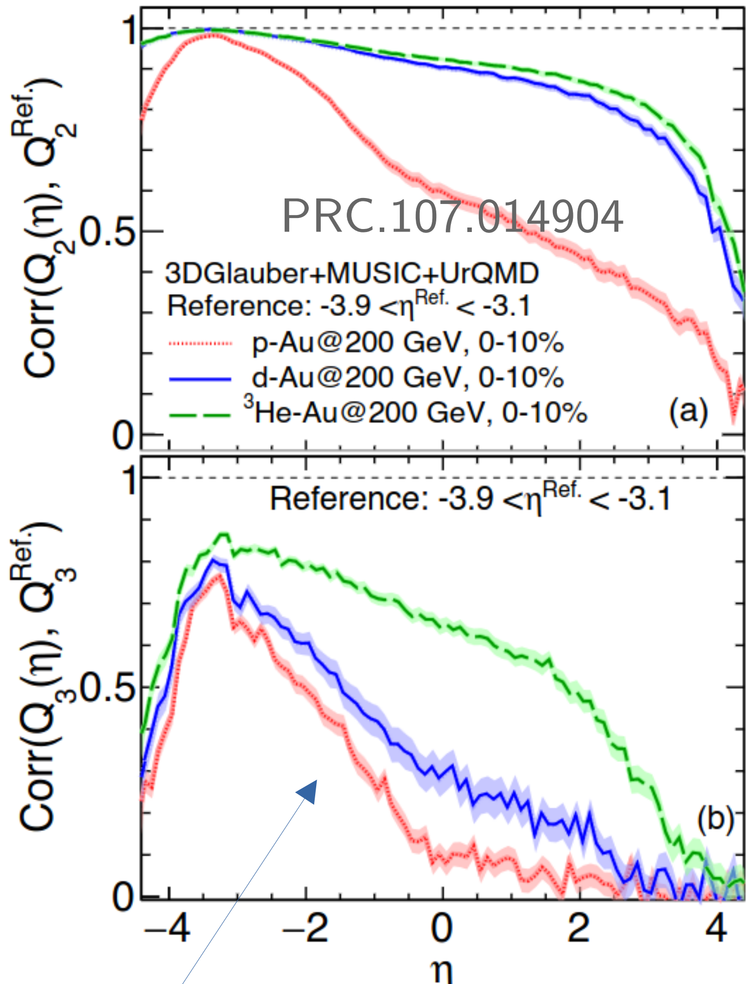
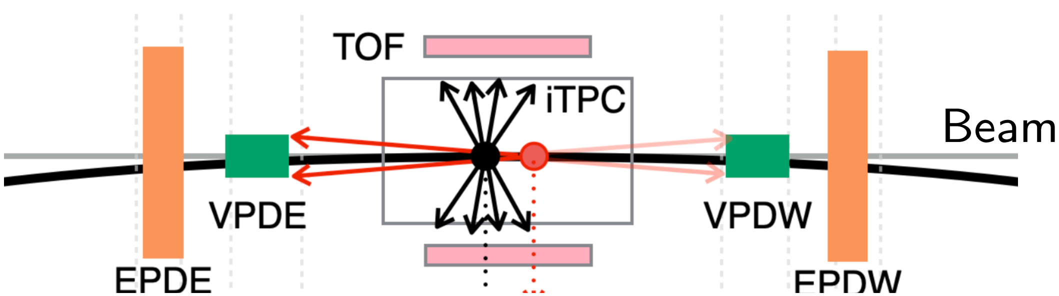


Wider η coverage helps suppressing nonflow

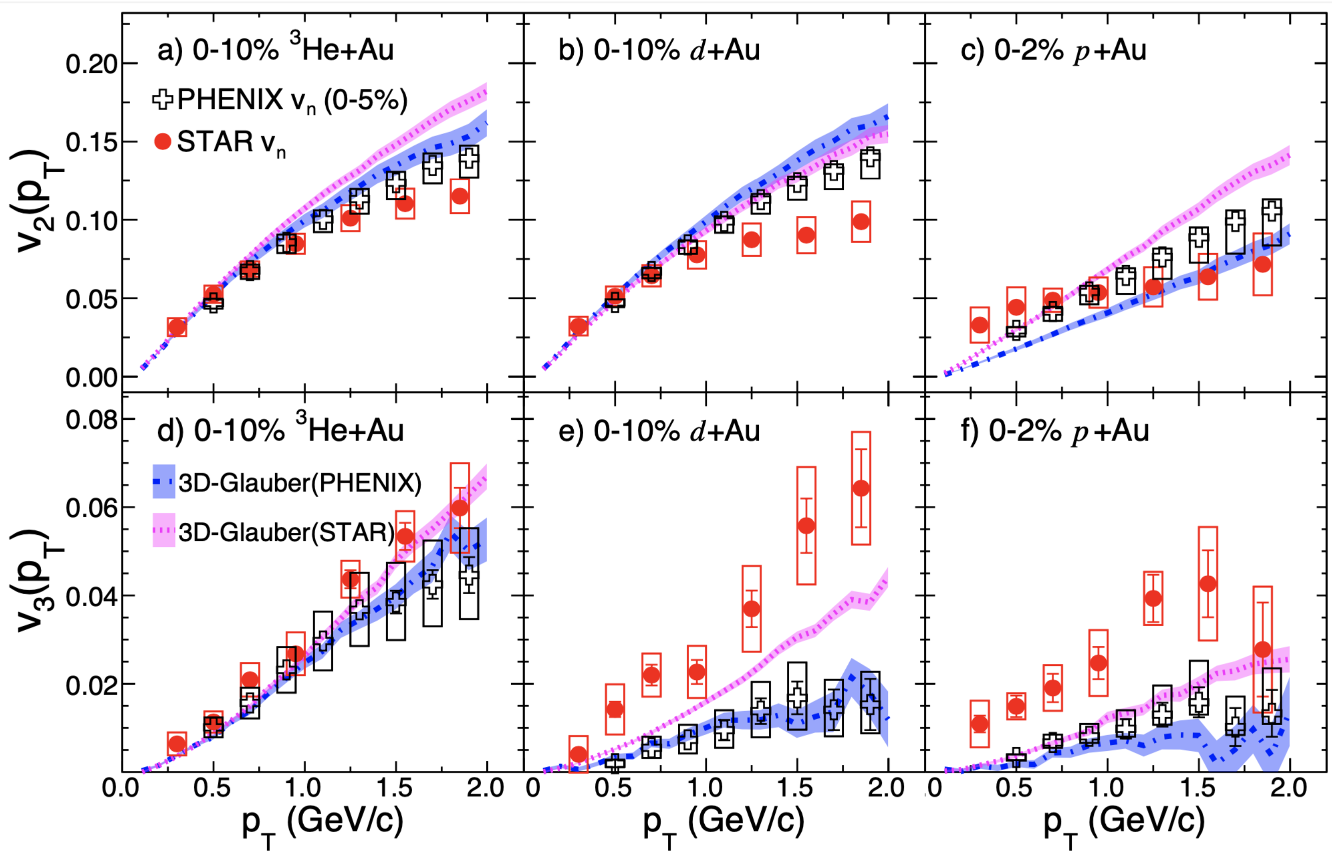


3+1D model shows non-boost-invariance

Upgraded STAR detector with wider η coverage is ideal for quantifying the decorrelation.

Longitudinal decorrelation & nonflow

Prevous publications



STAR: PRL 130, 242301
arXiv:2312.07464
PHENIX: Nature Phys. 15, 214
3D-Glauber: PRC 107, 014904

Large difference in v_3 for STAR and PHENIX in data and models.

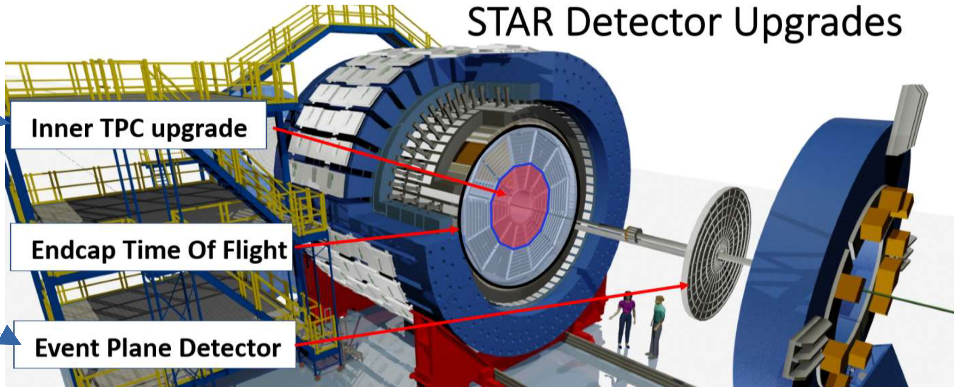
STAR use mid-rapidity: $|\eta| < 0.9$

PHENIX use mid-forward rapidity: $|\eta| < 0.35$ to $-3.0(3.9) < \eta < -1(-3.1)$

$\rightarrow$ Due to decorrrelation?

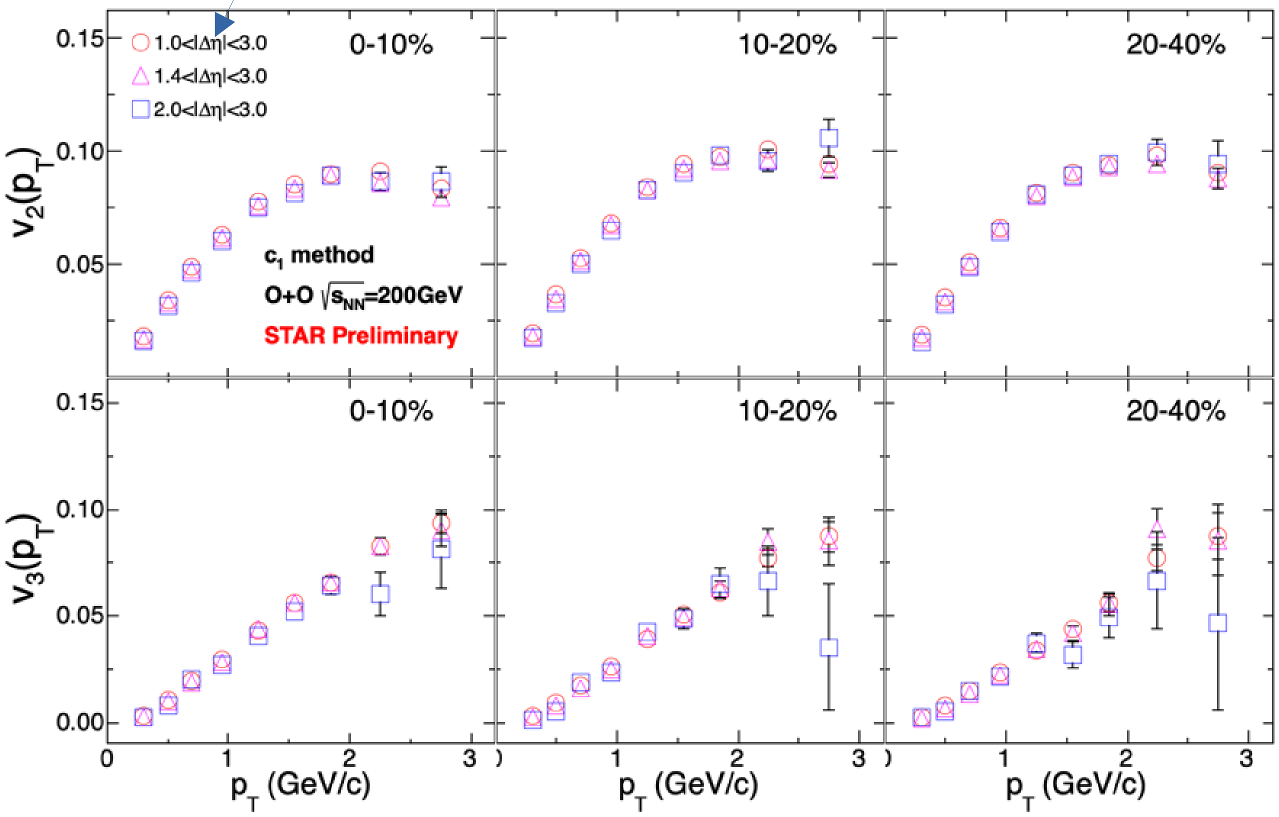
Flow in O+O

- New iTPC -1.5 < η < 1.5
- New EPD 2.1 < | η | < 5.1



Further separation in η →
- More decorrelation?
- Suppress short range non-flow?

Change η gap for two-particle correlation in TPC



Flow in O+O

- New iTPC $-1.5 < \eta < 1.5$
- New EPD $2.1 < |\eta| < 5.1$

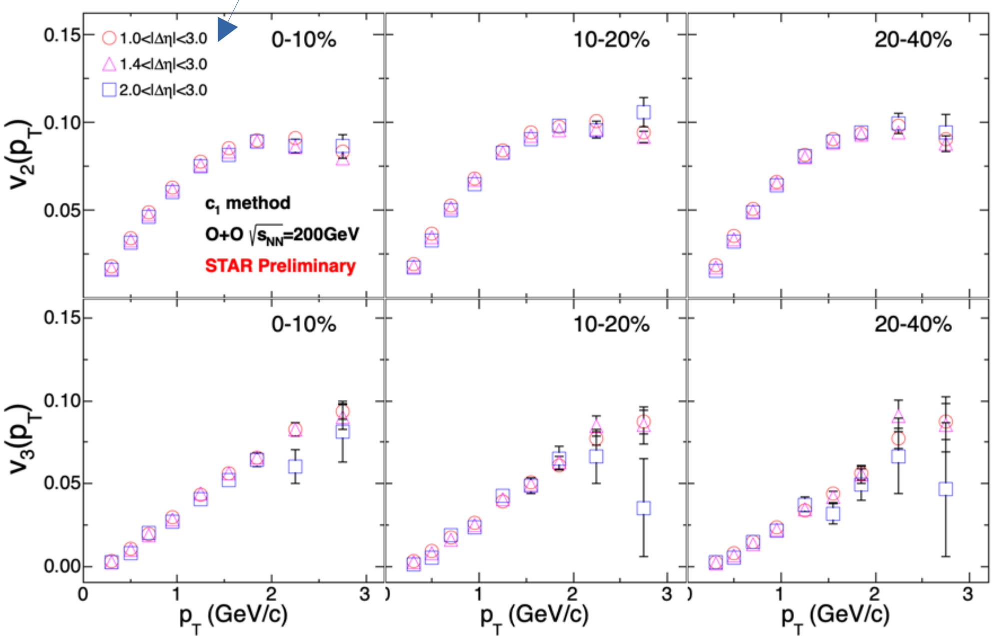
Further separation in η →
- More decorrelation?
- Suppress short range non-flow?

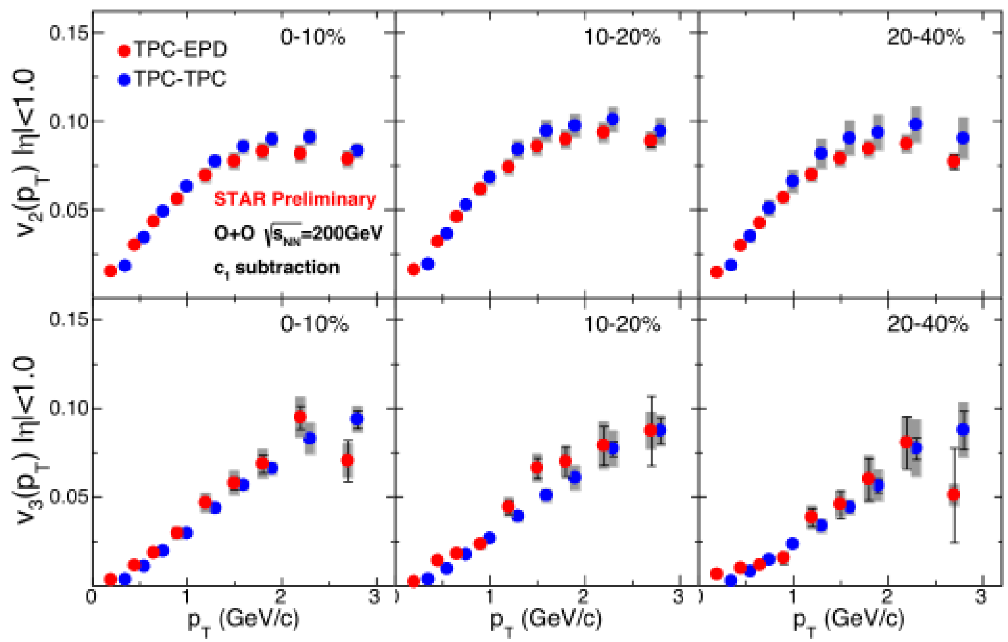
TPC-EPD two particle correlation

TPCa: $|\eta| < 1.0$
TPCb: $0.5 < \eta < 1.5$
TPCc: $-1.5 < \eta < -0.5$
EPD: $2.1 < |\eta| < 5.3$

$$v_n(TPCa, p_T) = \frac{Q_n^{TPCa} Q_n^{*EPD}}{\sqrt{\frac{(Q_n^{TPCb} Q_n^{*EPD}) \times (Q_n^{TPCc} Q_n^{*EPD})}{Q_n^{TPCb} Q_n^{*TPCc}}}}$$

Change η gap for two-particle correlation in TPC

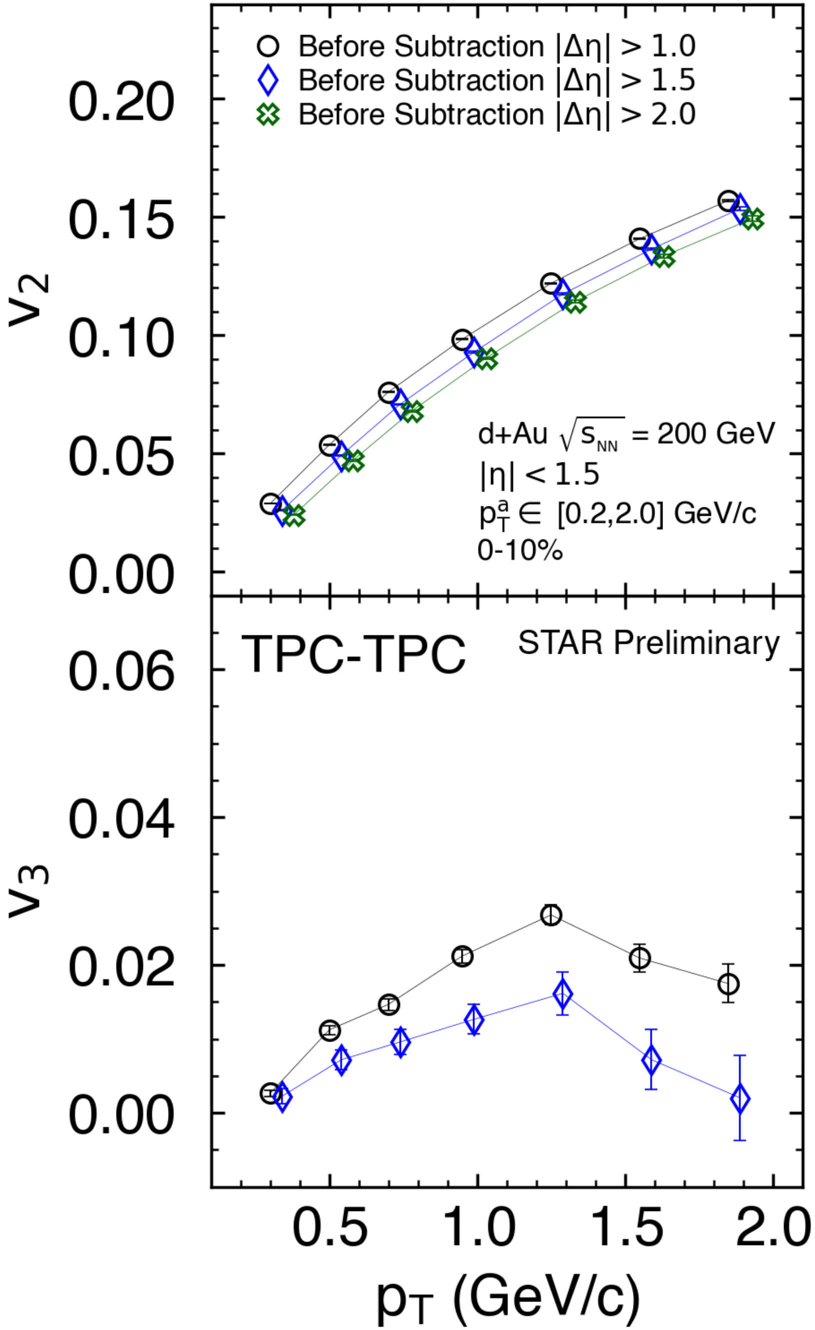


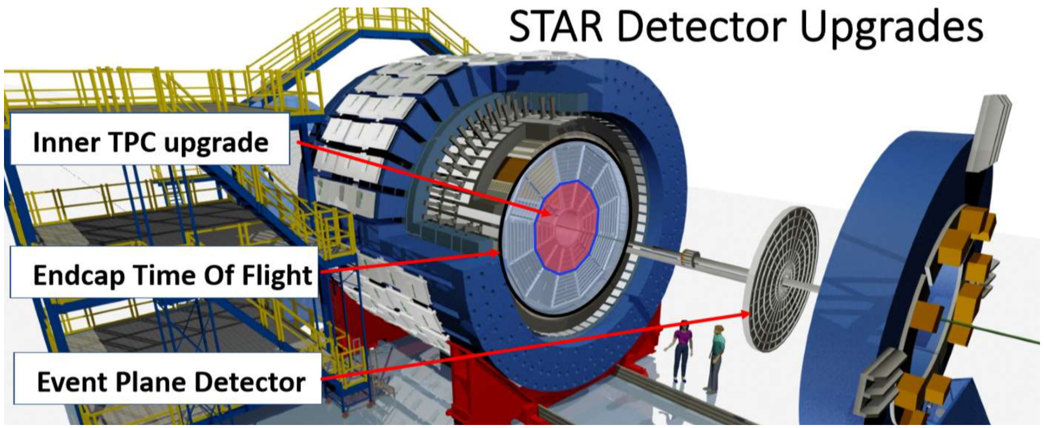


Do not observe significant change in flow magnitudes due to different η selections.

New: Flow in d+Au from Run 21

- Use new iTPC $-1.5 < \eta < 1.5$

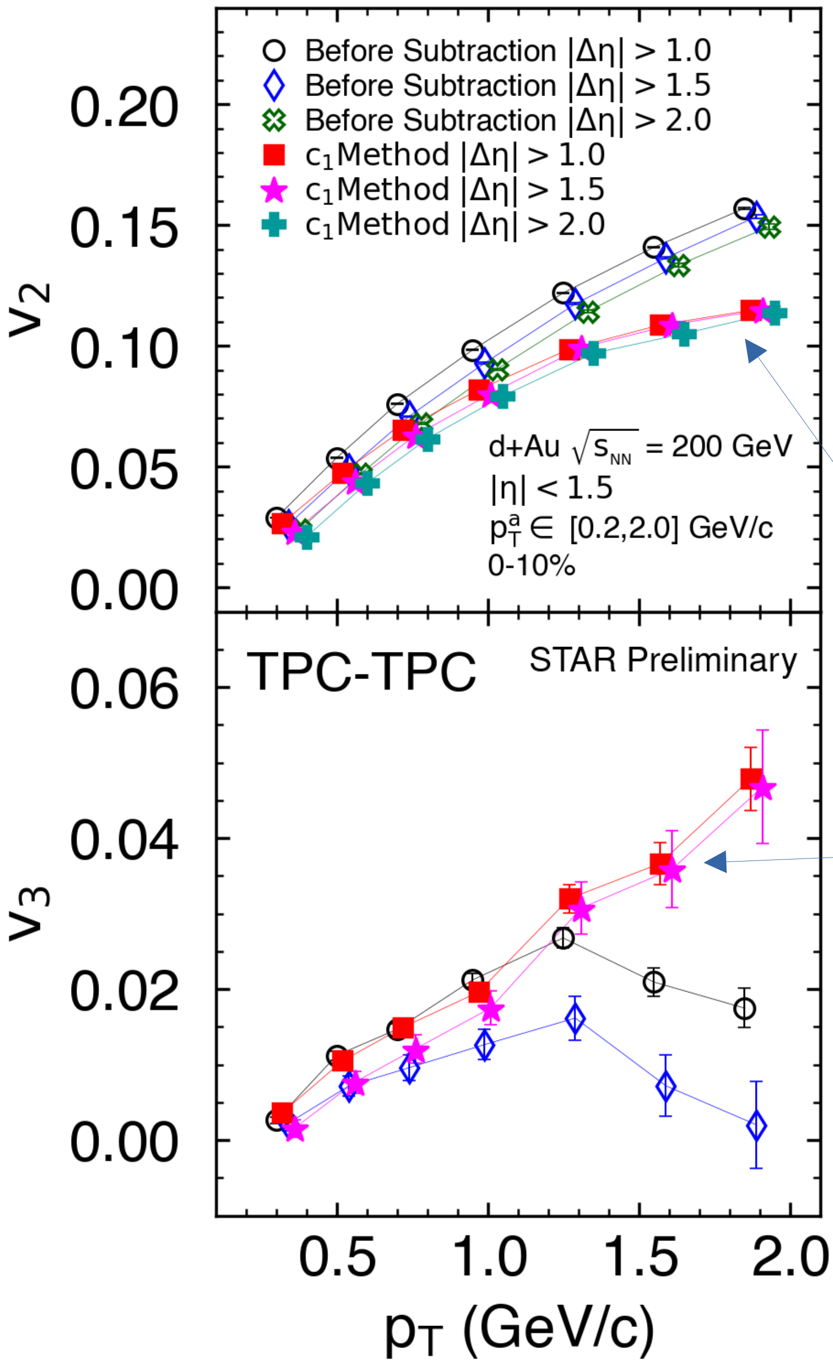


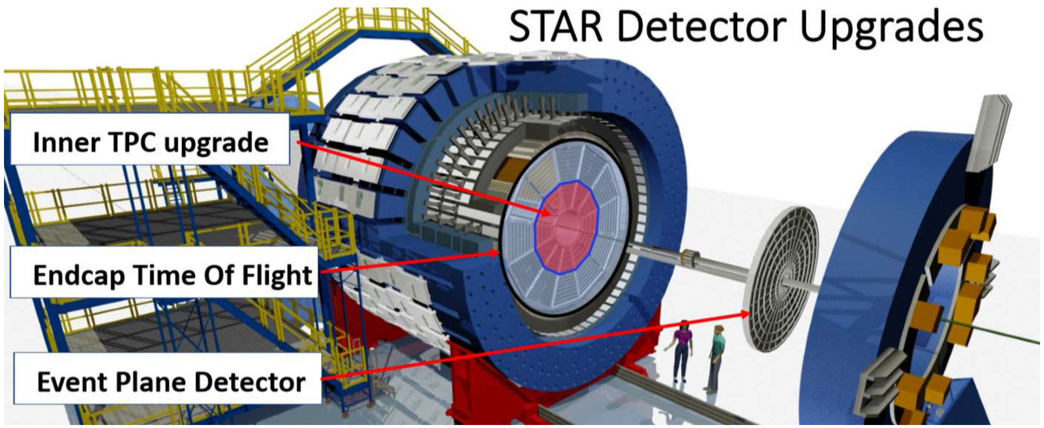


Raw flow magnitude affected by changing η acceptance.

New: Flow in d+Au from Run 21

- Use new iTPC $-1.5 < \eta < 1.5$

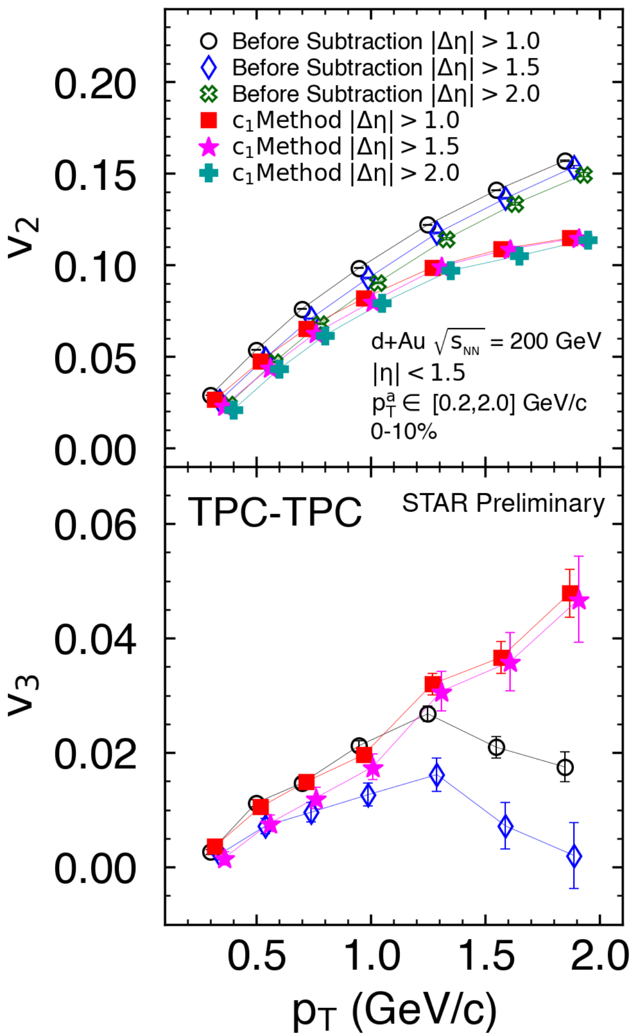




Consistent magnitudes after non-flow subtraction between difference acceptances.

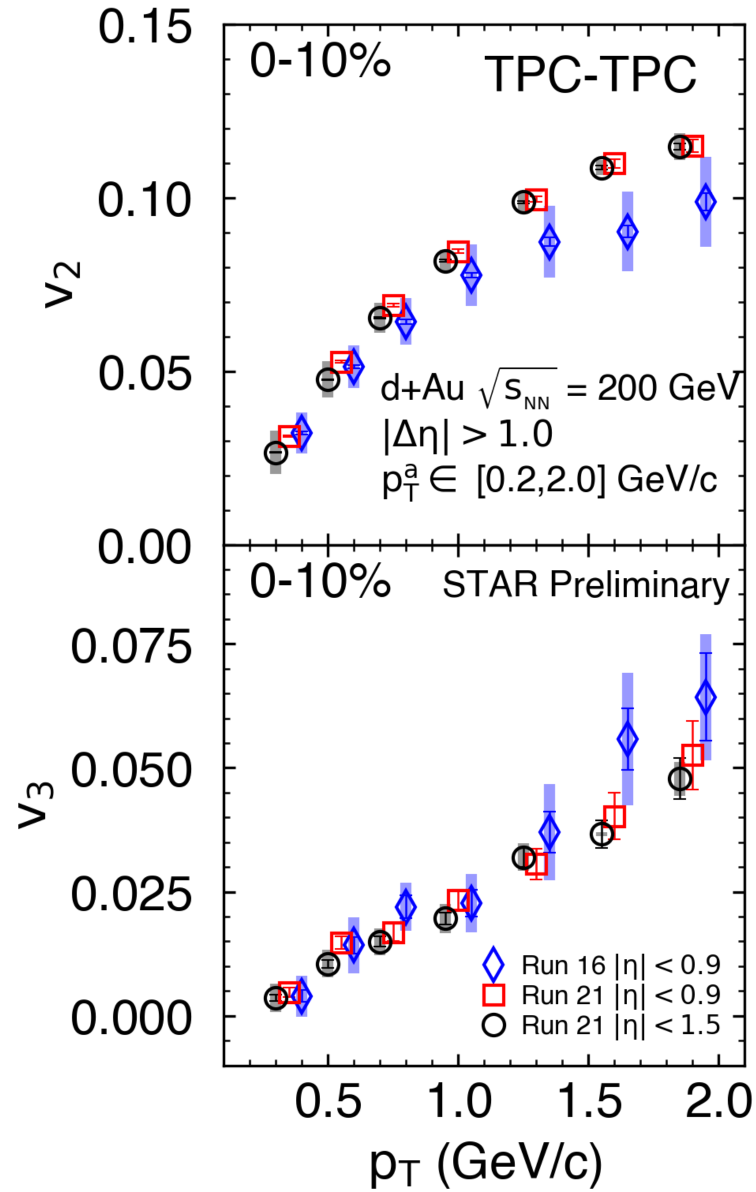
New: Flow in d+Au from Run 21

- Use new iTPC $-1.5 < \eta < 1.5$



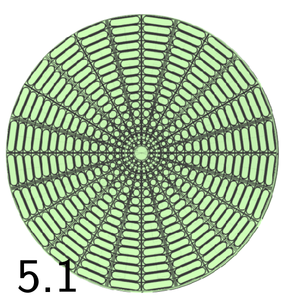
Compare to previous run:

- with same η acceptance or
- with larger η acceptance



New EPD

$2.1 < |\eta| < 5.1$

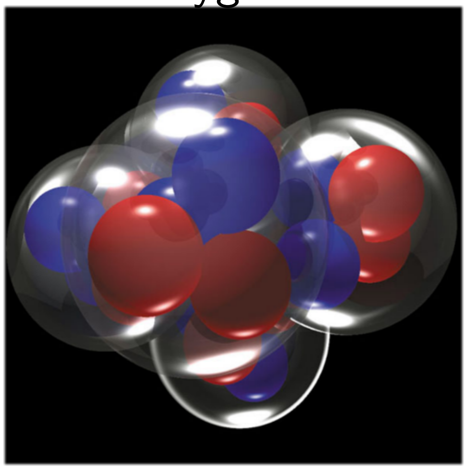


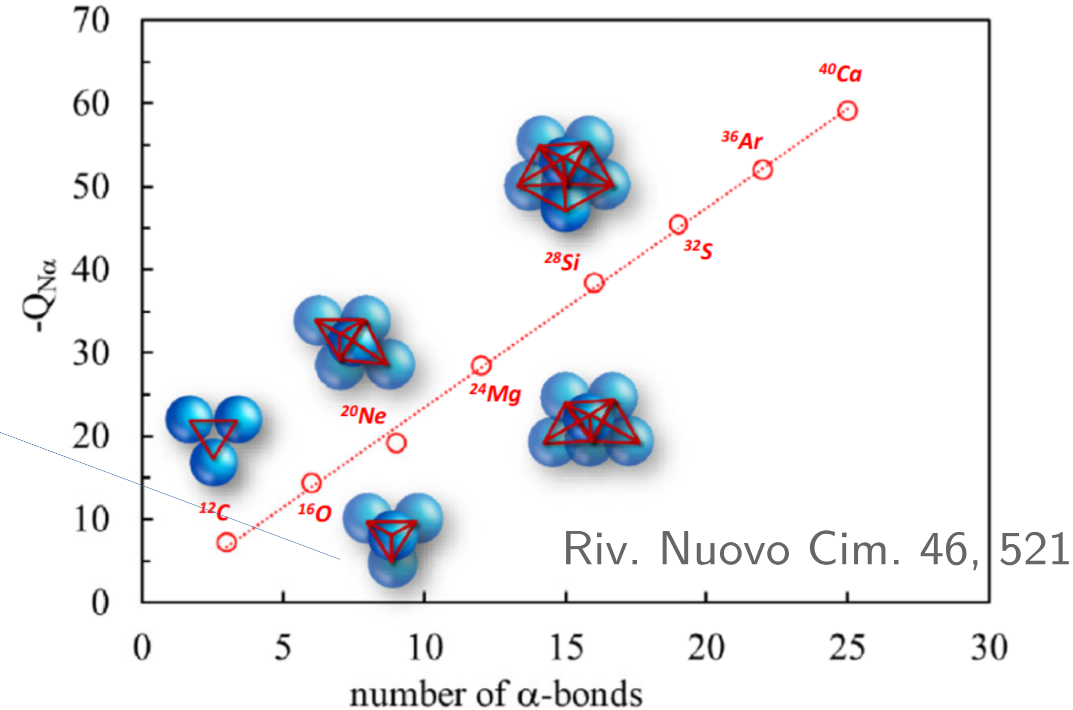
STAR results are robust with η gap change.
Measure wider η range with EPD. Work in progress.

Many-body correlation

- Inter-nucleon multi-body correlation and clustering in nucleus

^{16}Oxygen





Many-body correlation

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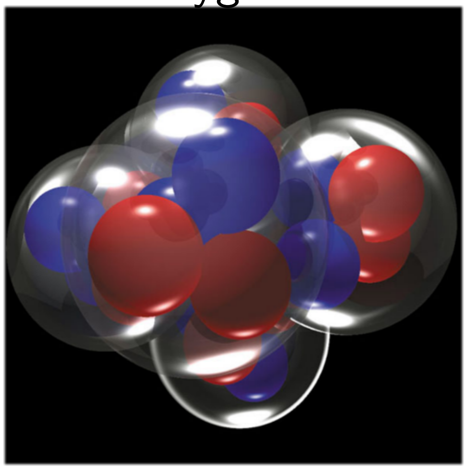
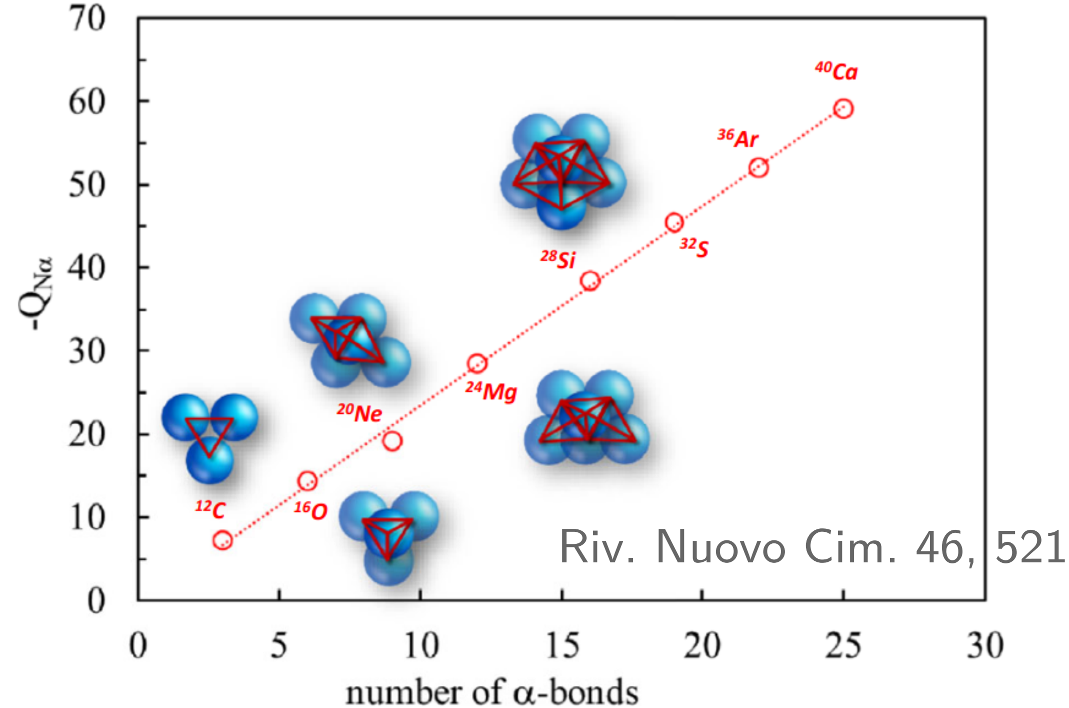
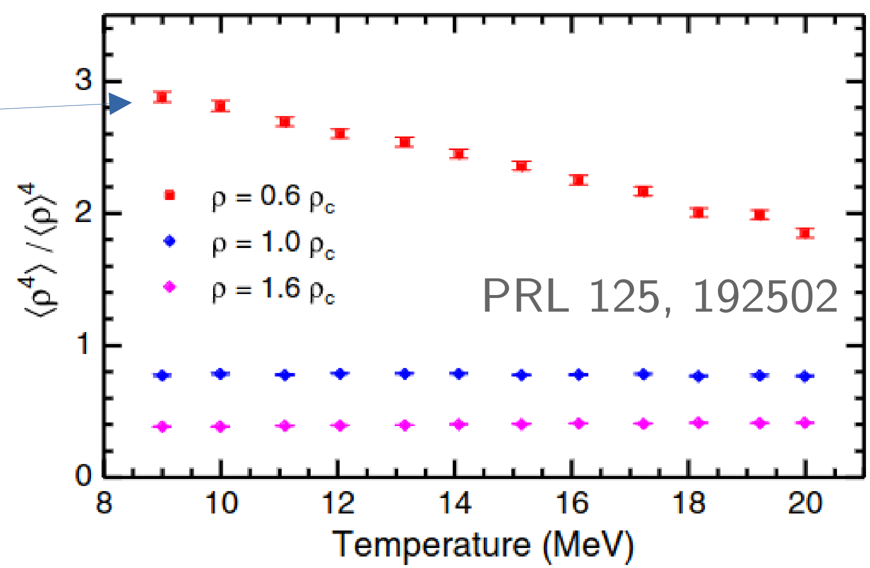




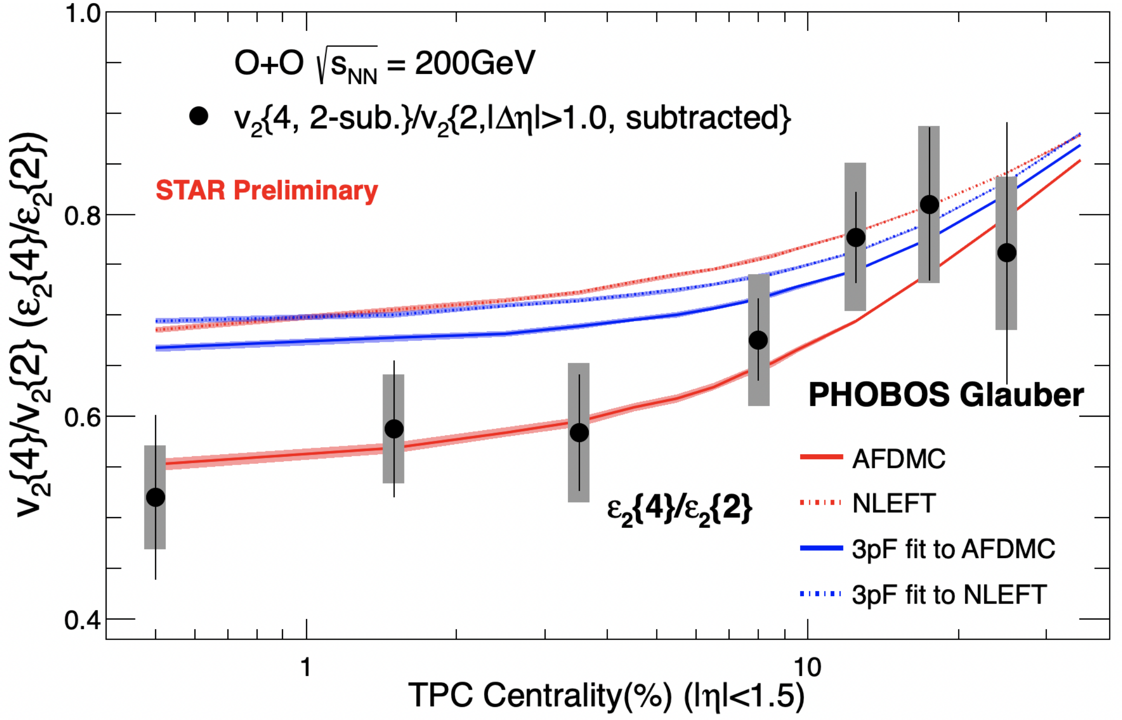
Ab initio thermodynamics calculation shows four-body clustering.

Also see O+O AMPT: arXiv:2404.08385

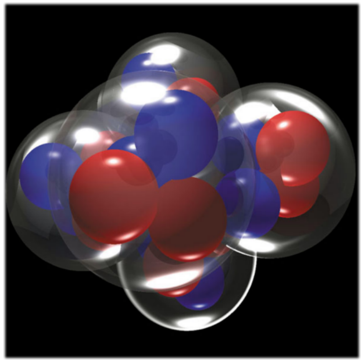


Can we see effect using multi-particle correlation observables?

Many-particle correlation in O+O



^{16}Oxygen



- Direct model input **with** many-body correlation
- 3-parameter-Fermi **without** many-body correlation

Ratio $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ decrease, amout dependent on model.

→ many body correlation enhances the flow fluctuation?

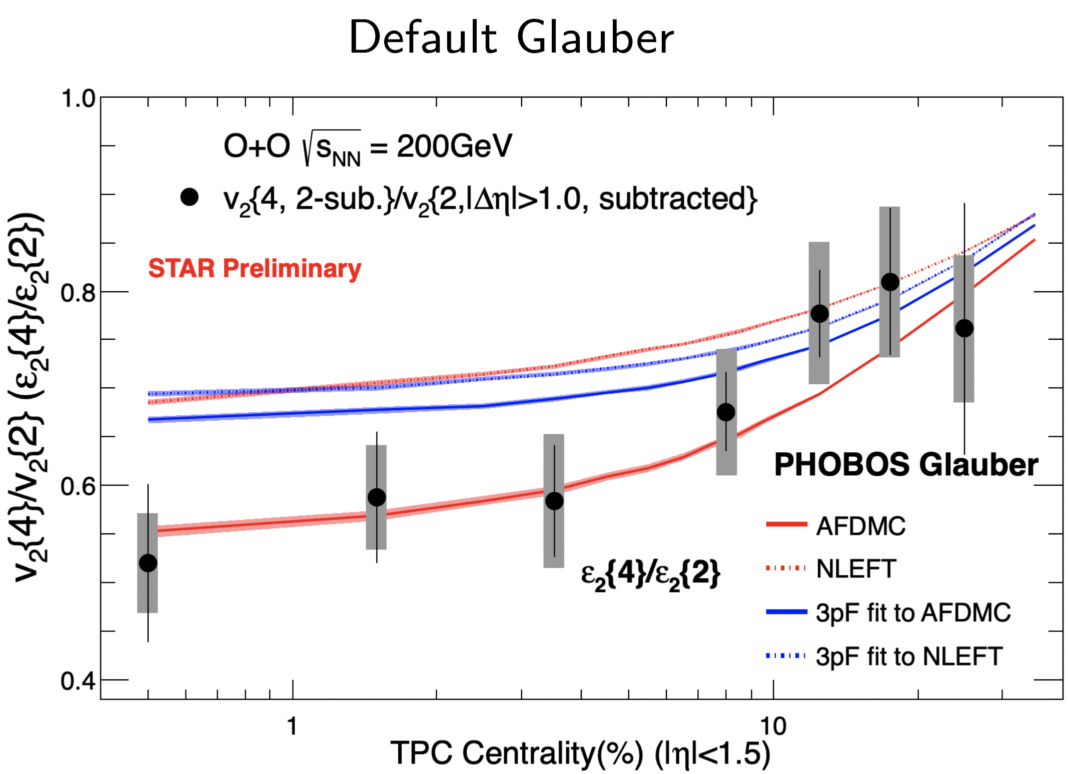
→ chage in average geometry?

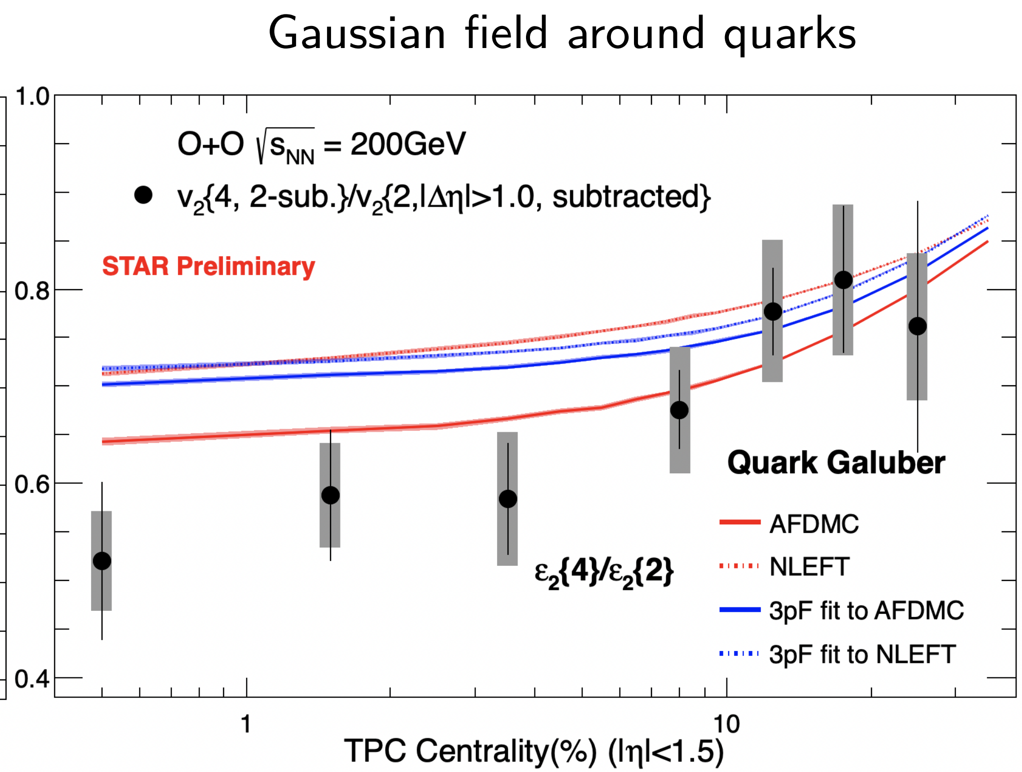
$$\sigma^2 = <\varepsilon_n^2> - <\varepsilon_n>^2$$

$$(\varepsilon_n\{2\})^2 = <\varepsilon_n^2> = <\varepsilon_n>^2 + \sigma^2$$

$$(\varepsilon_n\{4\})^2 = \sqrt{2<\varepsilon_n^2> - <\varepsilon_n^4>} \approx <\varepsilon_n>^2 - \sigma^2$$

Many-particle correlation in O+O





Sub-nucleon fluctuation reduce the effect of many-body correlation.

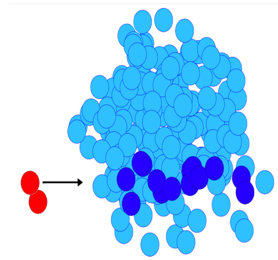
Multi-particle correlation in O+O can distinguish if many body correlation is present. Model dependent results.

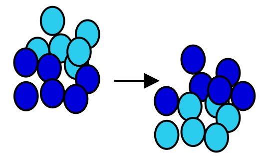
Collision geometry

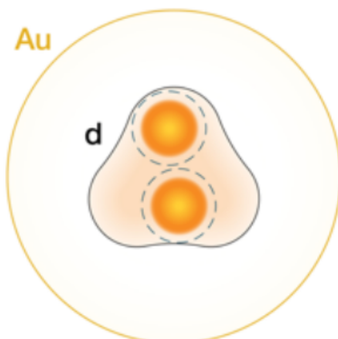
Similar size, drastically different collision geometry

d+Au

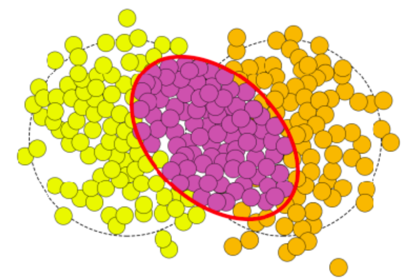
O+O





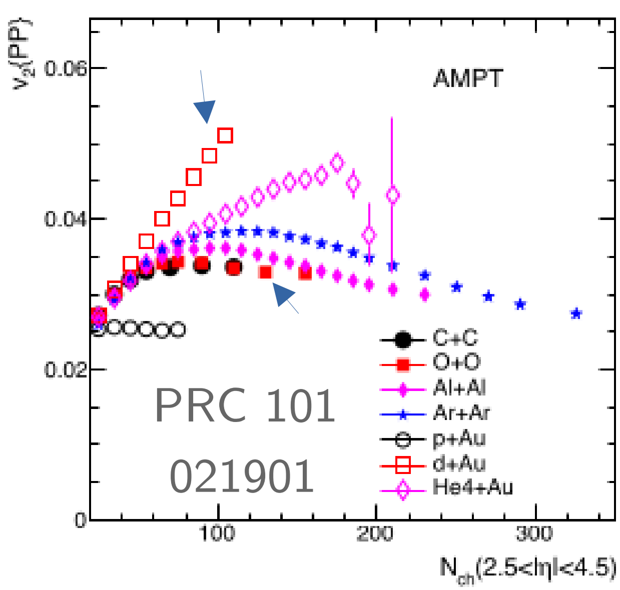


vs.



asymmetric

symmetric



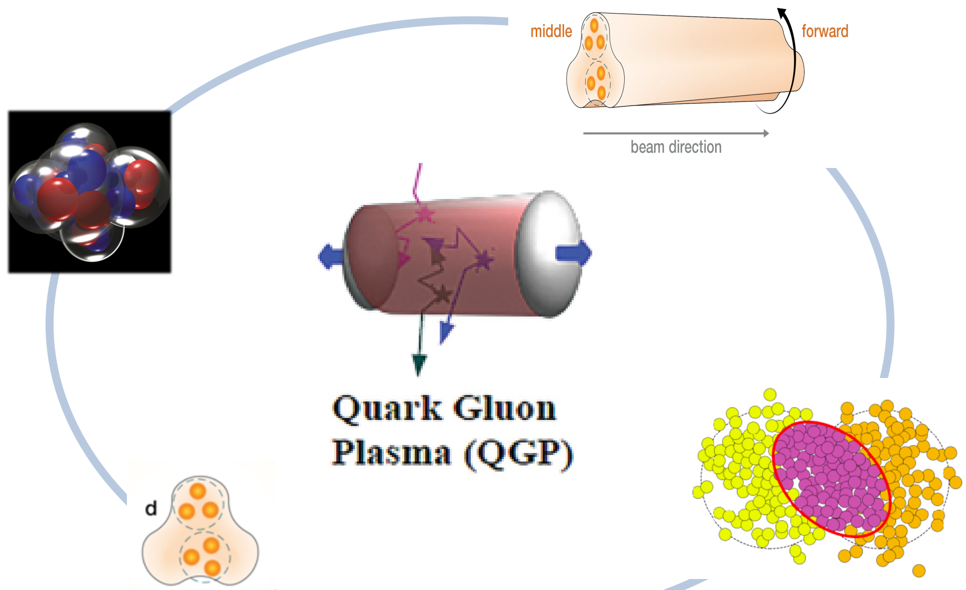
Different collision geometry

captured by N_{ch} dependence v_2

Compare d+Au and O+O flow to explore geometry. Work in progress

Summary and outlook

- New data (d+Au, O+O, p+p) taken with upgraded STAR detector provide wealth of opportunity to study different effects in the evolution of QGP
  - ^{3}He+Au is similar to O+O and other systems, indicating no nucleon scale geometry transmutation.
  - Robust flow measurements with variations in η gap and acceptance indicate consistent non-flow estimates and no evident decorrelation.
  - $v_2\{4\}/v_2\{2\}$ coud be used to probe multi-particle correlation in ^{16}oxygen.



  - Future flow measurements in d+Au and p+p to better distinguish (sub)nucleon geometry fluctuation response.
  - Look for decorrelation in d+Au with wider η range using EPD.
  - Explore unique collision geometries by comparing d+Au and O+O.

Thank you for your attention