Collision System Dependence of Anisotropic Flow, Flow Fluctuations and Mixed Harmonic Correlations at STAR

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Outline

- Introduction
  - ✓ Motivation
  - ✓ Analysis Methods
  - ✓ The STAR Detector

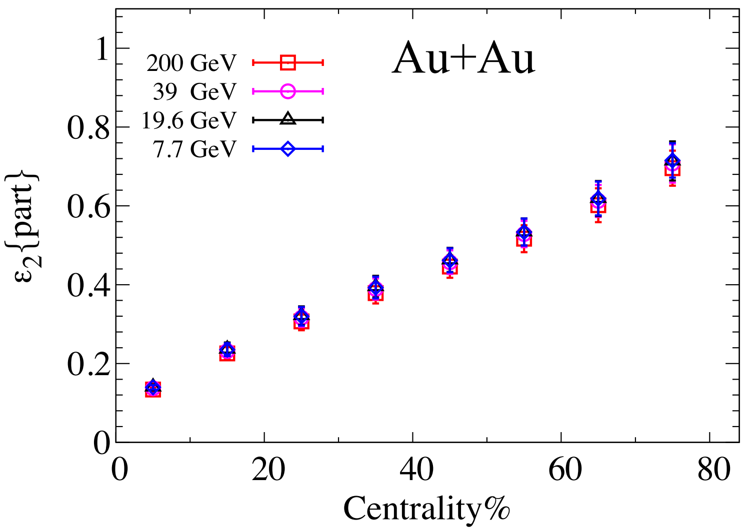
- Results
  I. Beam energy dependence of flow fluctuations and correlations
  II. System size dependence of flow fluctuations and correlations

- Conclusion

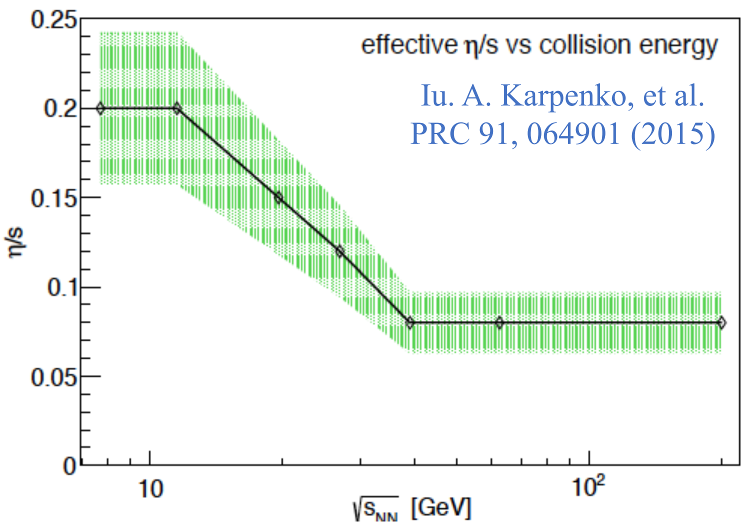
Motivation

- Anisotropic flow magnitude is sensitive to:
  - ✓ Initial-state spatial anisotropy
  - ✓ Flow fluctuations and correlations
  - ✓ Viscous attenuation ($\propto \frac{\eta}{s}(T)$)

I- Beam energy dependence for a given collision system:



Initial-state spatial anisotropy is approximately beam energy independent.

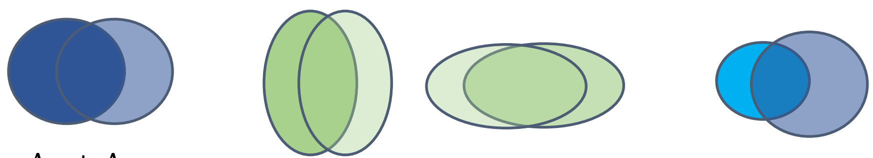


Viscous attenuation ($\propto \frac{\eta}{s}(T)$) is beam energy dependent.

What are the respective roles of ϵ_n and it's fluctuations, flow correlations and $\frac{\eta}{s}(T)$ as a function of beam energy?

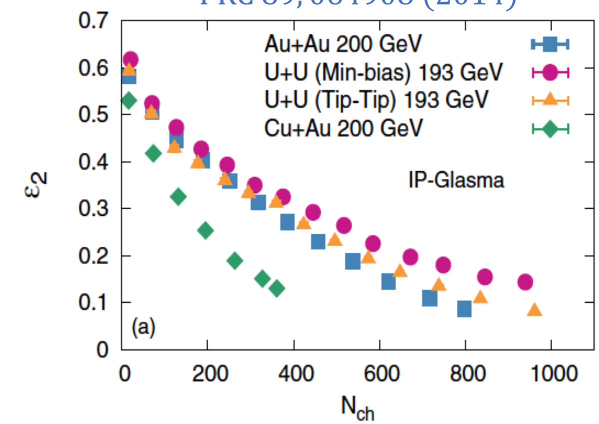
Motivation

II- Collision systems dependence at a given beam energy:

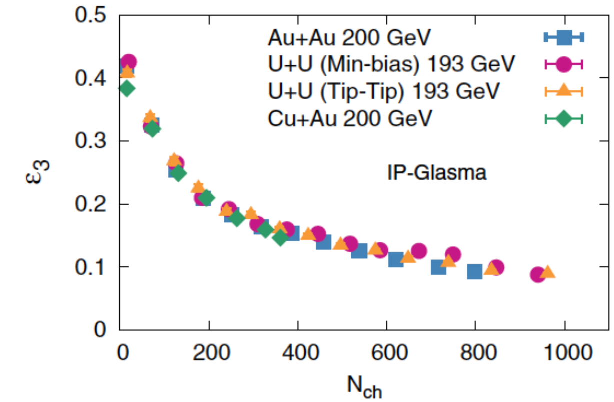


Au + Au U + U Cu + Au

B. Schenke, et al.
PRC 89, 064908 (2014)



The initial-state ϵ_2 is system dependent.



The initial-state ϵ_3 is system independent.

- Multi-particle correlation measurements are studied as a function of system size, $\sqrt{s_{NN}}$, $\langle N_{ch}\rangle$ and p_T:
  - ✓ Four-particle cumulants $C_n\{4\}$ are used to constrain the flow fluctuations
  - ✓ Symmetric cumulants $SC(n, m)$ are used to quantify the lowest-order correlations between different flow harmonics.

Analysis Methods

A. Bilandzic, et al. PRC 83, 044913 (2011)
J. Jia, et al. PRC 96,034906 (2017)

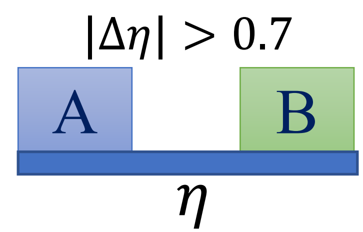
❖ Traditional Q-cumulants method is used to calculate $v_{nm}\{4\}$

$$\langle 2 \rangle_n = \left\langle e^{in(\phi_1 - \phi_2)} \right\rangle \qquad \langle 4 \rangle_{nm} = \left\langle e^{in(\phi_1 - \phi_2) + im(\phi_3 - \phi_4)} \right\rangle$$

$$v_n^4\{4\} = \langle 4 \rangle_{nn} - 2\,\langle 2 \rangle_n \langle 2 \rangle_n \qquad NSC(n,m) = \frac{\langle 4 \rangle_{nm} - \langle 2 \rangle_n \langle 2 \rangle_m}{\langle 2 \rangle_n^{Sub} \langle 2 \rangle_m^{Sub}}$$

❖ Two-subevent cumulants method is used to calculate $v_2\{2\}$ with $|\Delta\eta| > 0.7$

$$\langle 2 \rangle_n^{Sub} = \left\langle e^{in(\phi_A - \phi_B)} \right\rangle \qquad v_n^2\{2\} = c_n\{2\} = \langle 2 \rangle_n^{Sub}$$



❖ Using $v_n\{4\}$ and $v_n\{2\}$:

$$v_n^4\{4\} = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle \qquad \left[\frac{v_n\{4\}}{v_n\{2\}}\right]^4 = 2 - \frac{\langle v_n^4 \rangle}{\langle v_n^2 \rangle^2}$$

✓ Short-range non-flow contribution in $v_2\{2\}$ is suppressed by $|\Delta\eta| > 0.7$

✓ The ratio $v_n\{4\}/v_n\{2\}$ will reflect the flow fluctuations.

Analysis Methods

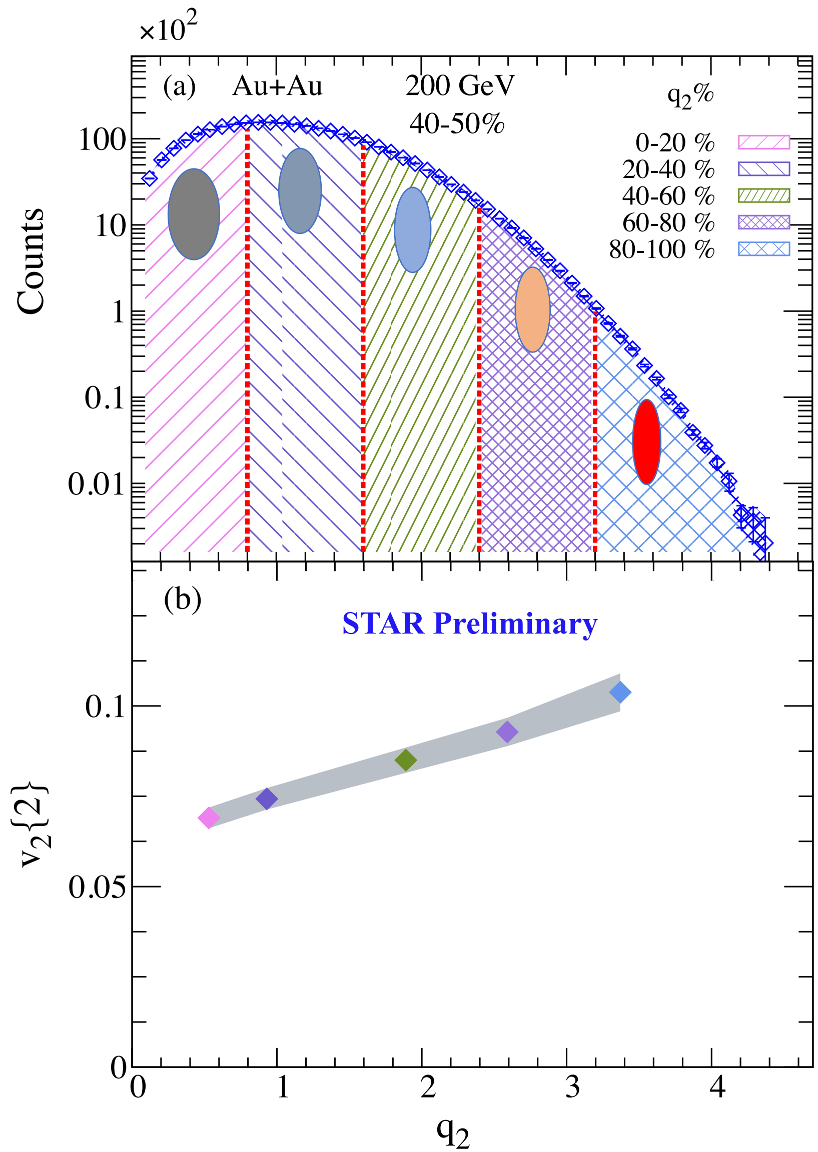
Event Shape Selection

- Events are further subdivided into groups with different q_2 magnitude:

$$Q_{2,x} = \sum_{i=1}^{M} \cos(2\,\varphi_i) \qquad Q_{2,y} = \sum_{i=1}^{M} sin(2\,\varphi_i)$$

$$|Q_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}$$

$$q_2 = \frac{|Q_2|}{\sqrt{M}}$$



- $v_2\{2\}$ increases linearly with q_2
  - ✓ q_2 is good event-shape selector

Data Analysis

➢ Data set:

- ✓ Au +Au BES $\sqrt{s_{NN}} = 7.7 - 200$ GeV
- ✓ U+U ($\sqrt{s_{NN}} = 193$ GeV) and Cu+Au ($\sqrt{s_{NN}} = 200$ GeV)

❖ In this analyses we used tracks with:

- $0.2 < p_T < 4$ GeV/c

❖ Efficiency corrected multiplicity density $\langle N_{ch} \rangle$ for $|\eta| < 0.5$ obtained from a parametrization of the measured multiplicity density:

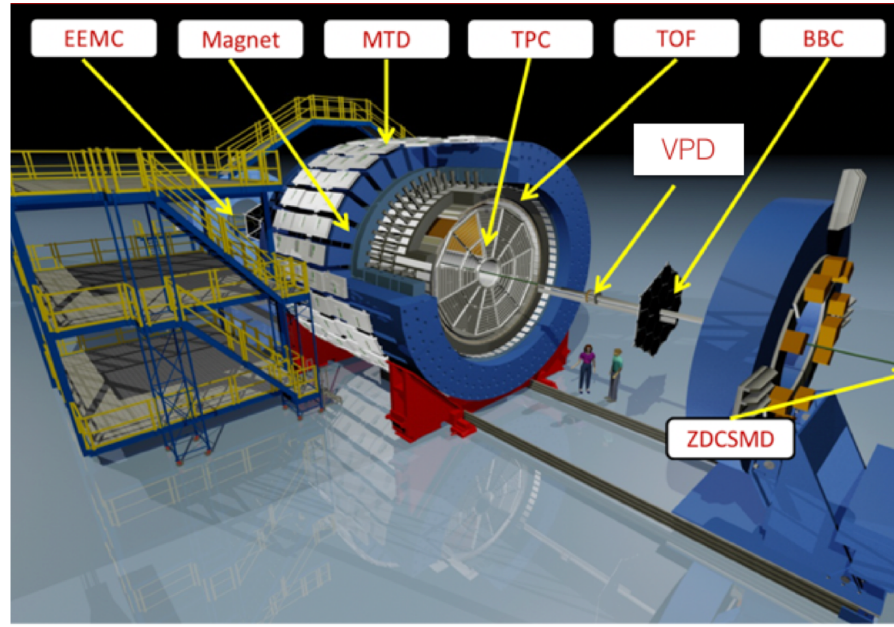
$$\langle N_{ch} \rangle = N_{qpp} \left[b_{AA} + M_{AA} \log(\sqrt{s})\right]^3$$

N_{qpp} is the number of quark participant pairs

$$b_{AA} = 0.530 \pm 0.008$$
$$M_{AA} = 0.258 \pm 0.004$$

Roy A. Lacey, et al.
arXiv:1601.06001

The STAR experiment at RHIC



➢ Time Projection Chamber

Tracking of charged particles with:

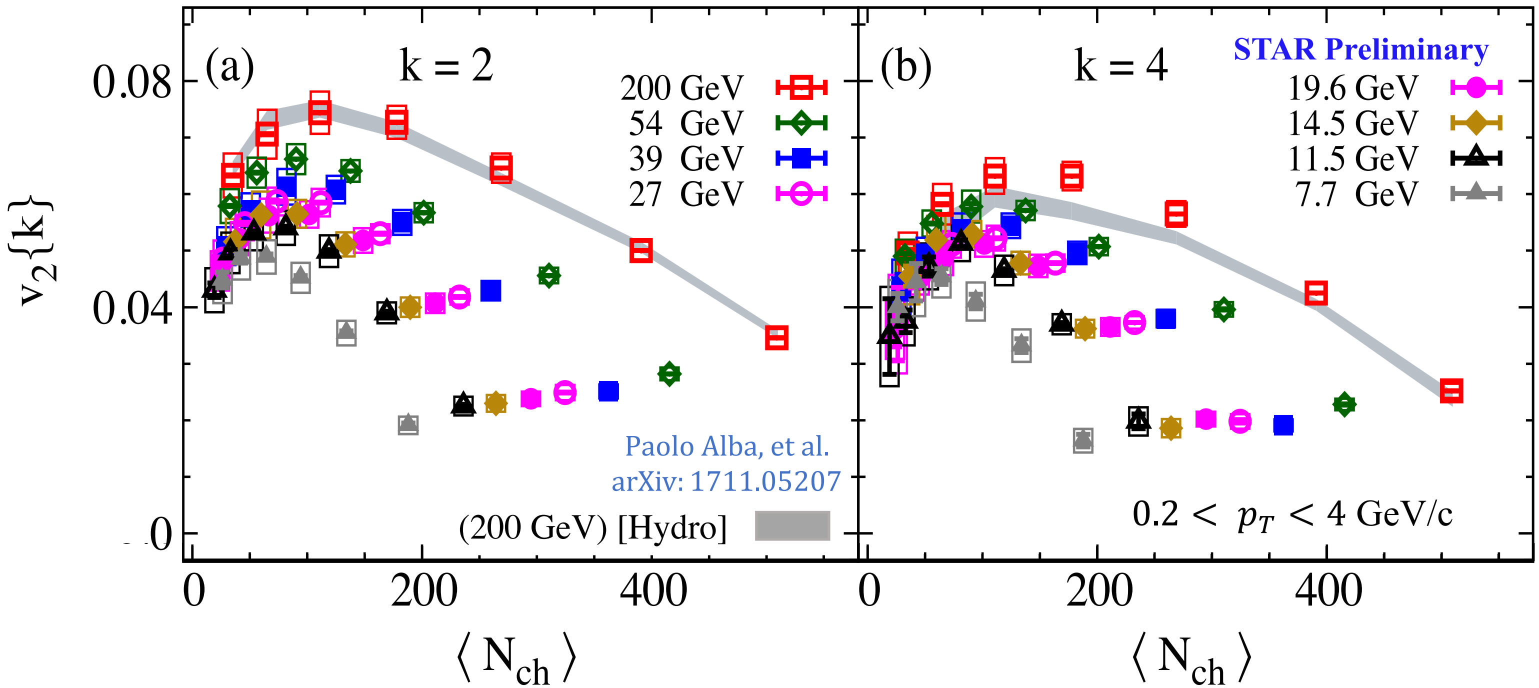
- ✓ Full azimuthal coverage
- ✓ $|\eta| < 1$ coverage
- ✓ PID for low momenta

➢ Time-Of-Flight

- ✓ PID for high momenta

Results

The $v_2\{2\}$ and $v_2\{4\}$ vs. $\langle N_{ch} \rangle$

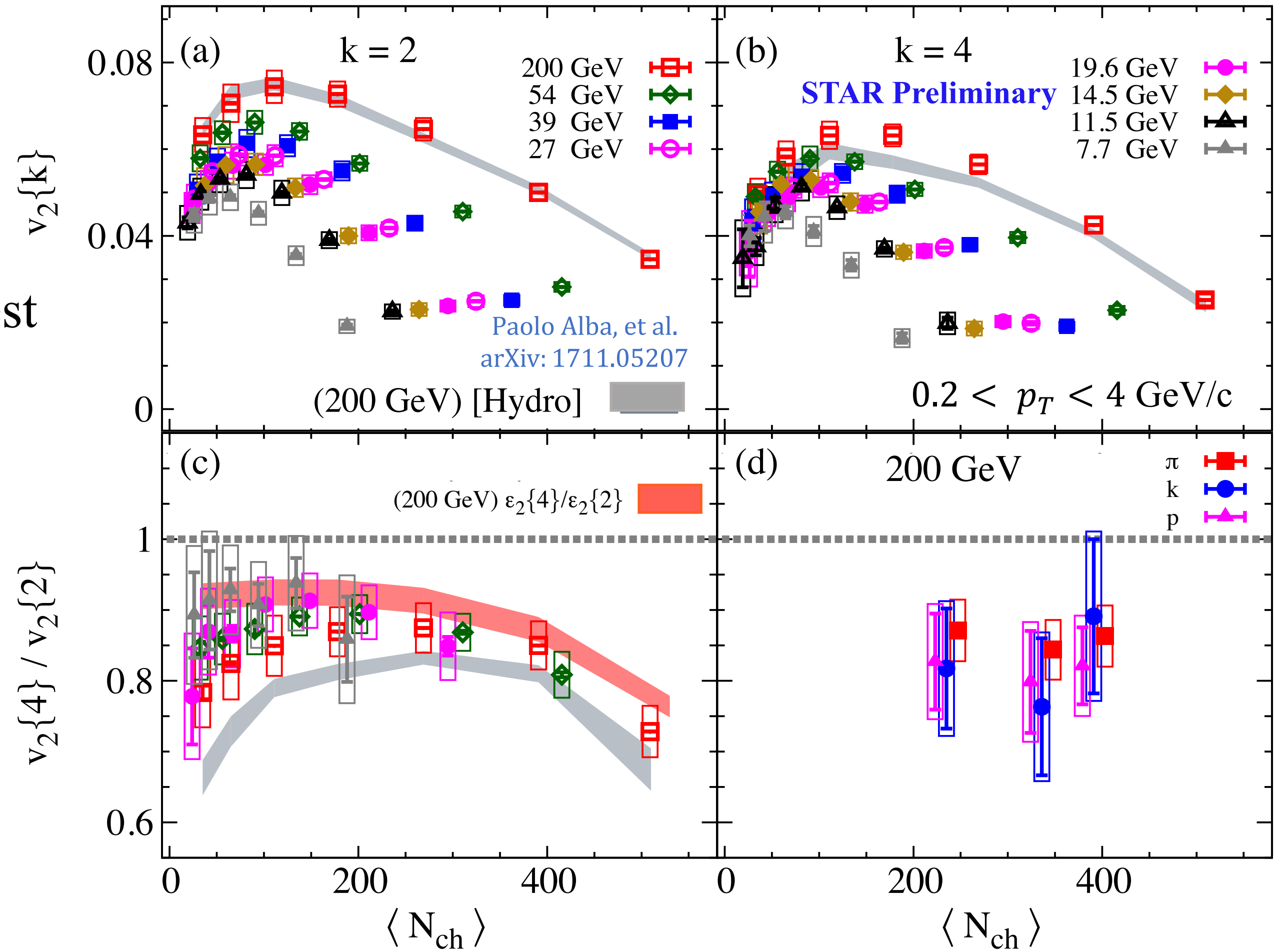


- $v_2\{2\}$ and $v_2\{4\}$ show characteristic dependence on $\langle N_{ch} \rangle$ and beam energy.
- Reasonable agreement with theoretical calculations at 200 GeV.

Results

The $v_2\{2\}$ and $v_2\{4\}$, and $(v_2\{4\}/v_2\{2\})$ vs. $\langle N_{ch} \rangle$

- $v_2\{4\}/v_2\{2\}$ show modest dependence on:
  - ✓ Centrality ($\langle N_{ch} \rangle$)
- $v_2\{4\}/v_2\{2\}$ show weak dependence on beam energy

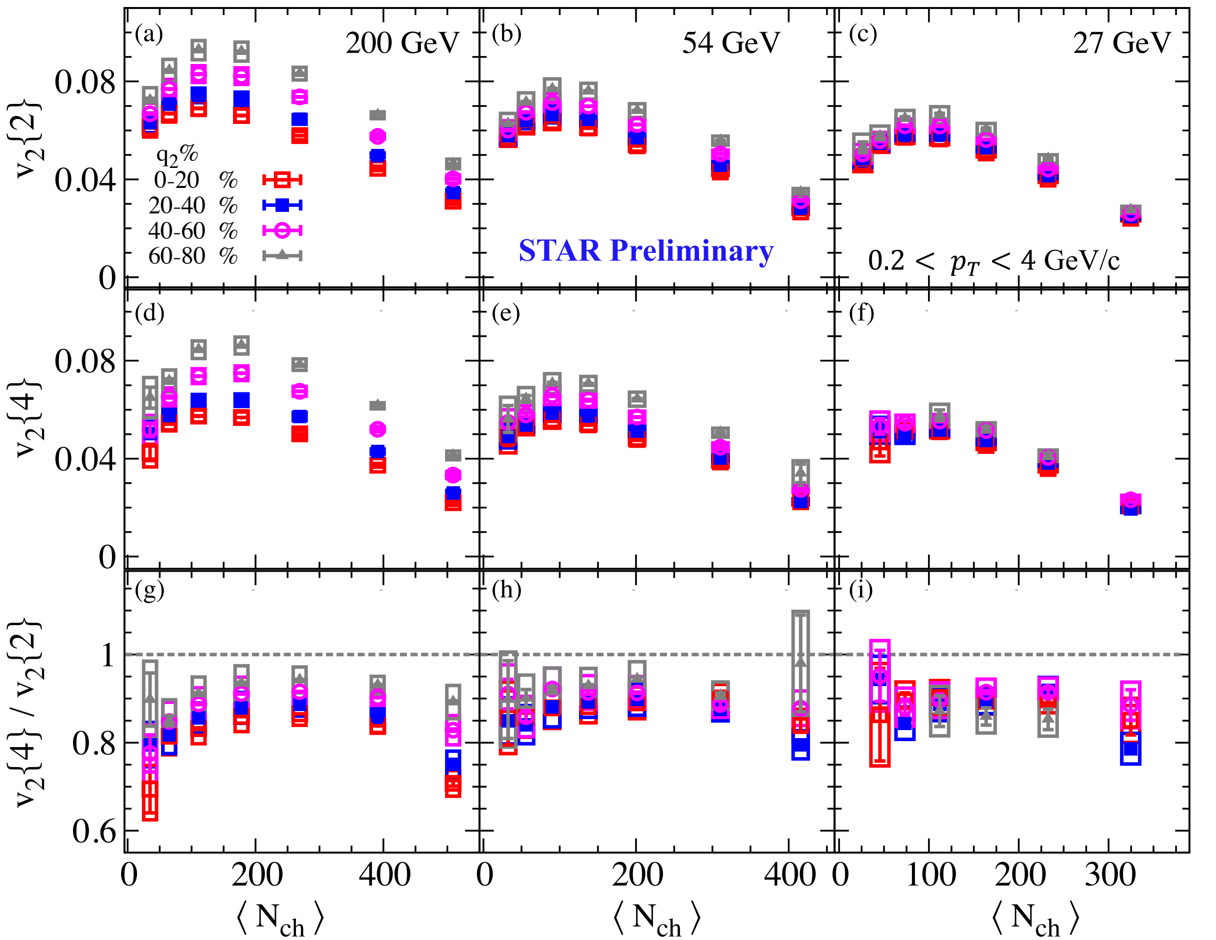


- Within uncertainties $v_2\{4\}/v_2\{2\}$ show weak dependence on particle species
- The model calculations for $(v_2\{4\}/v_2\{2\})$ and $(\epsilon_2\{4\}/\epsilon_2\{2\})$ bracket the data at 200 GeV

Results

The $v_2\{2\}$ and $v_2\{4\}$, and $(v_2\{4\}/v_2\{2\})$ vs. $\langle N_{ch} \rangle$
Different event shape selections

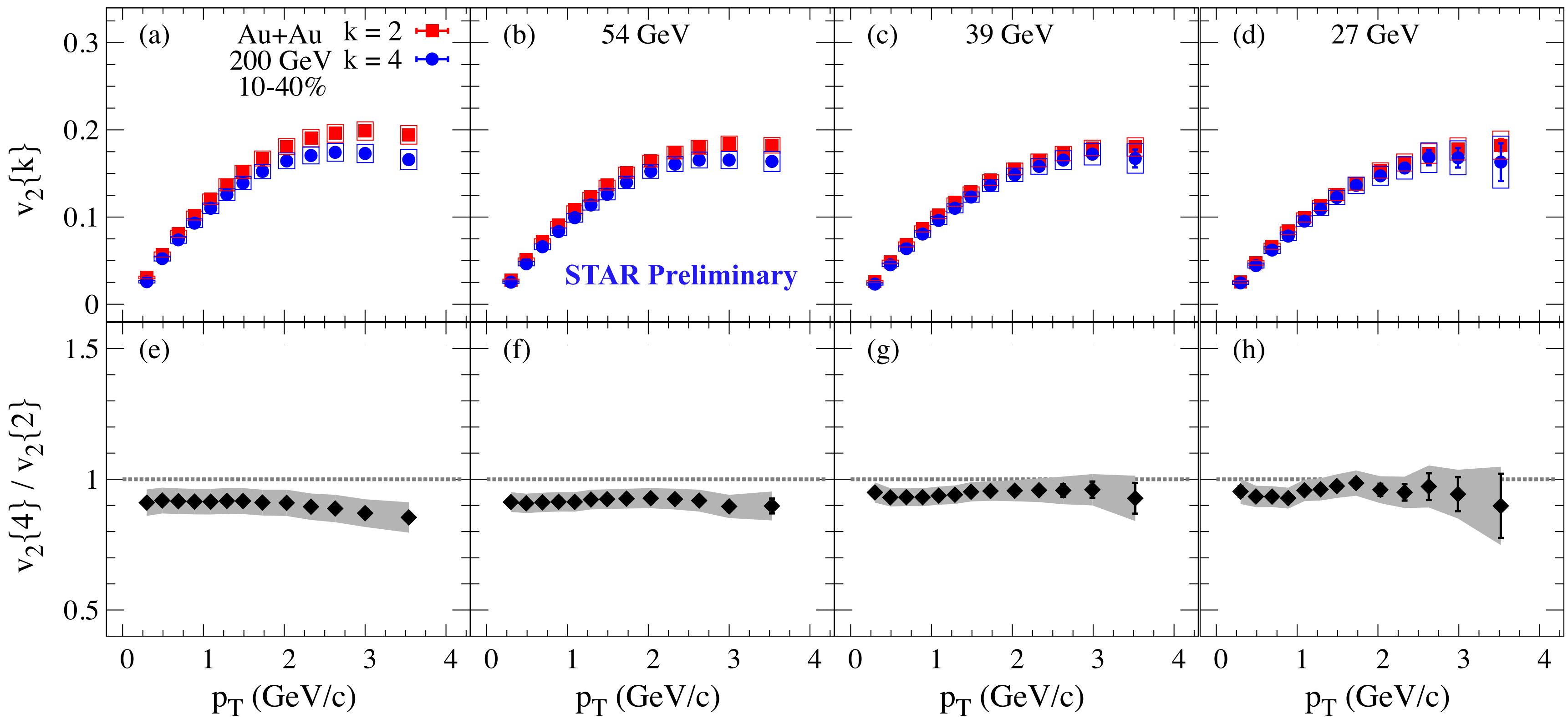
- $v_2\{2\}$ and $v_2\{4\}$ increase with event shape selections
  - ✓ Less increase for lower energies due to low event plane resolution



- $v_2\{4\}/v_2\{2\}$ shows modest dependence on:
  - ✓ Event shape selections

Results

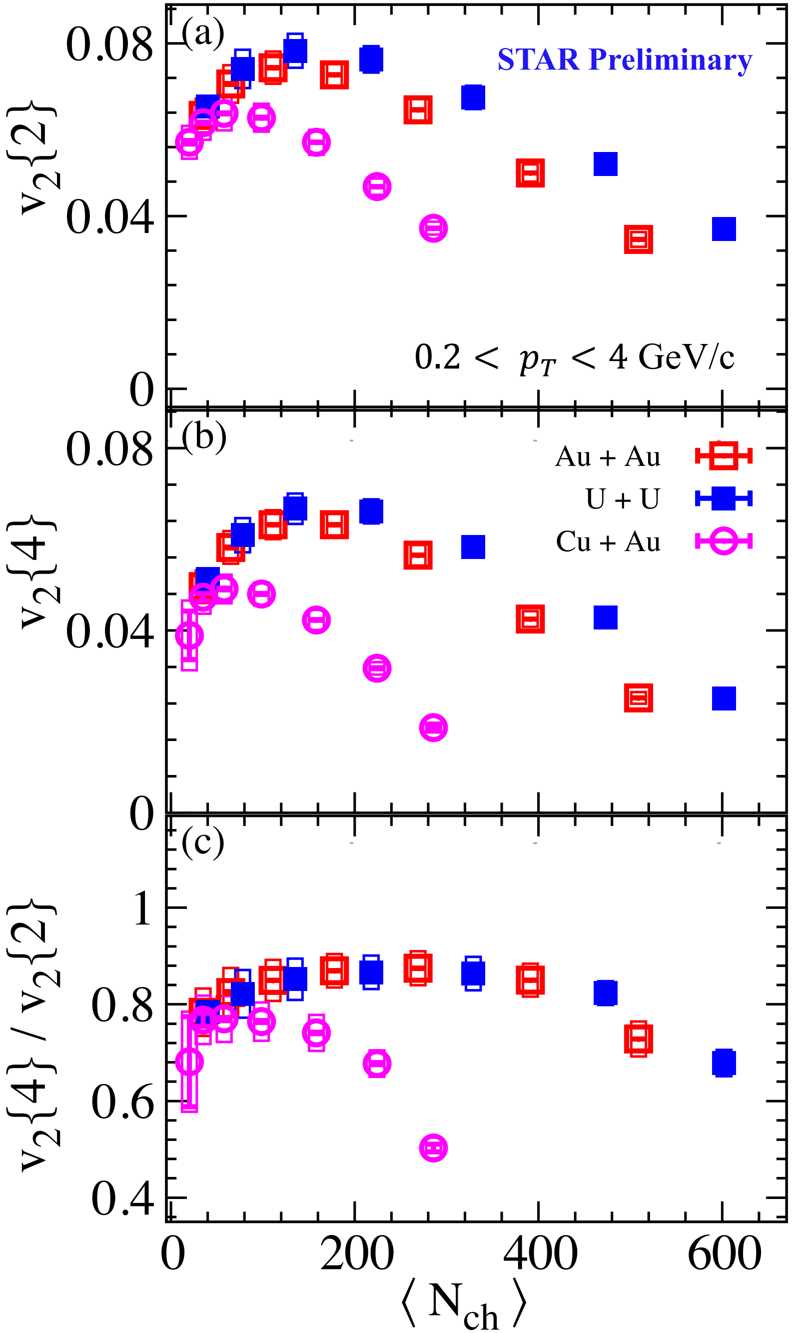
The $v_2\{2\}$ and $v_2\{4\}$, and $(v_2\{4\}/v_2\{2\})$ vs. p_T



- ❖ For different beam energies $v_2\{4\}/v_2\{2\}$ is p_T independent
  - ✓ Dynamical final-state fluctuations are significantly less than the initial-state fluctuations?

Results

The $v_2\{2\}$ and $v_2\{4\}$, and $(v_2\{4\}/v_2\{2\})$ vs. $\langle N_{ch} \rangle$



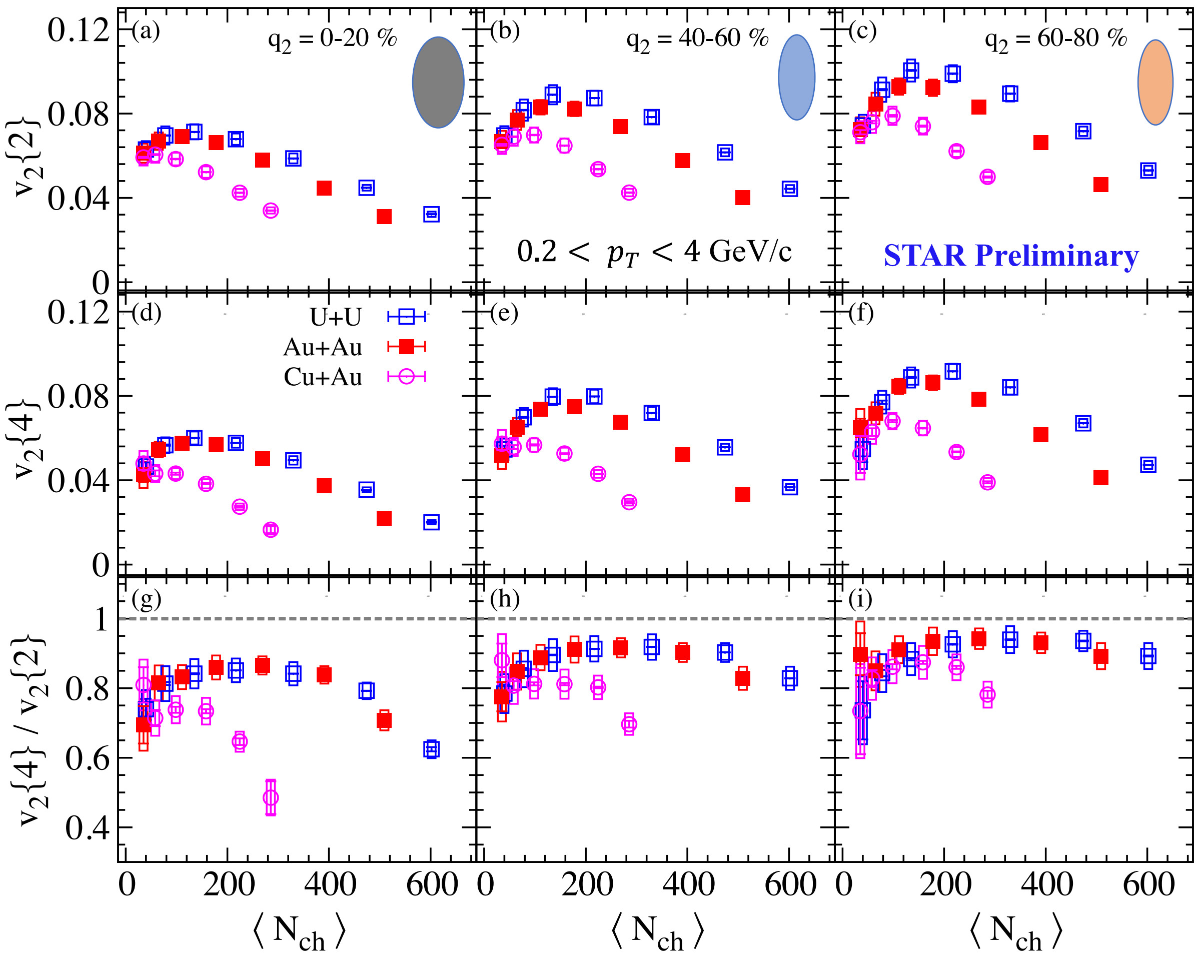
- For different collision systems:
  - ✓ $v_2\{2\}$, $v_2\{4\}$ and $v_2\{4\}/v_2\{2\}$ are system-size dependent

Results

The $v_2\{2\}$ and $v_2\{4\}$, and $(v_2\{4\}/v_2\{2\})$ vs. $\langle N_{ch} \rangle$ Different event shape selections

- As expected $v_2\{2\}$ and $v_2\{4\}$ increase with q_2

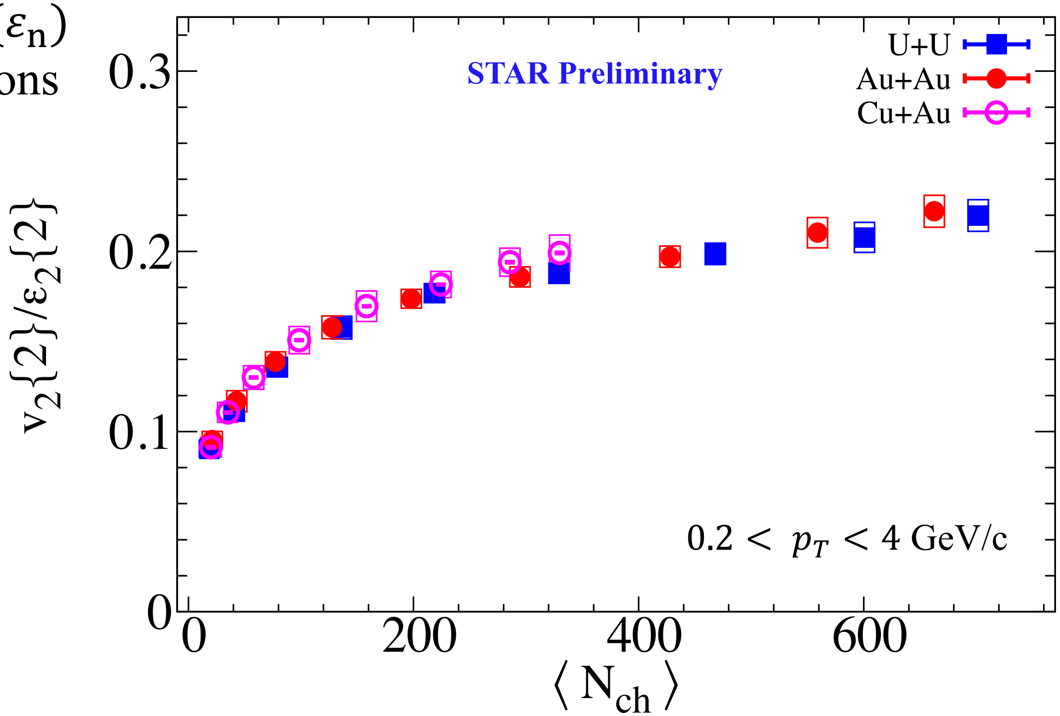
- $v_2\{4\}/v_2\{2\}$ from q_2 selected events is system dependent



Results

The $v_2\{2\}/\varepsilon_2\{2\}$ vs. $\langle N_{ch} \rangle$

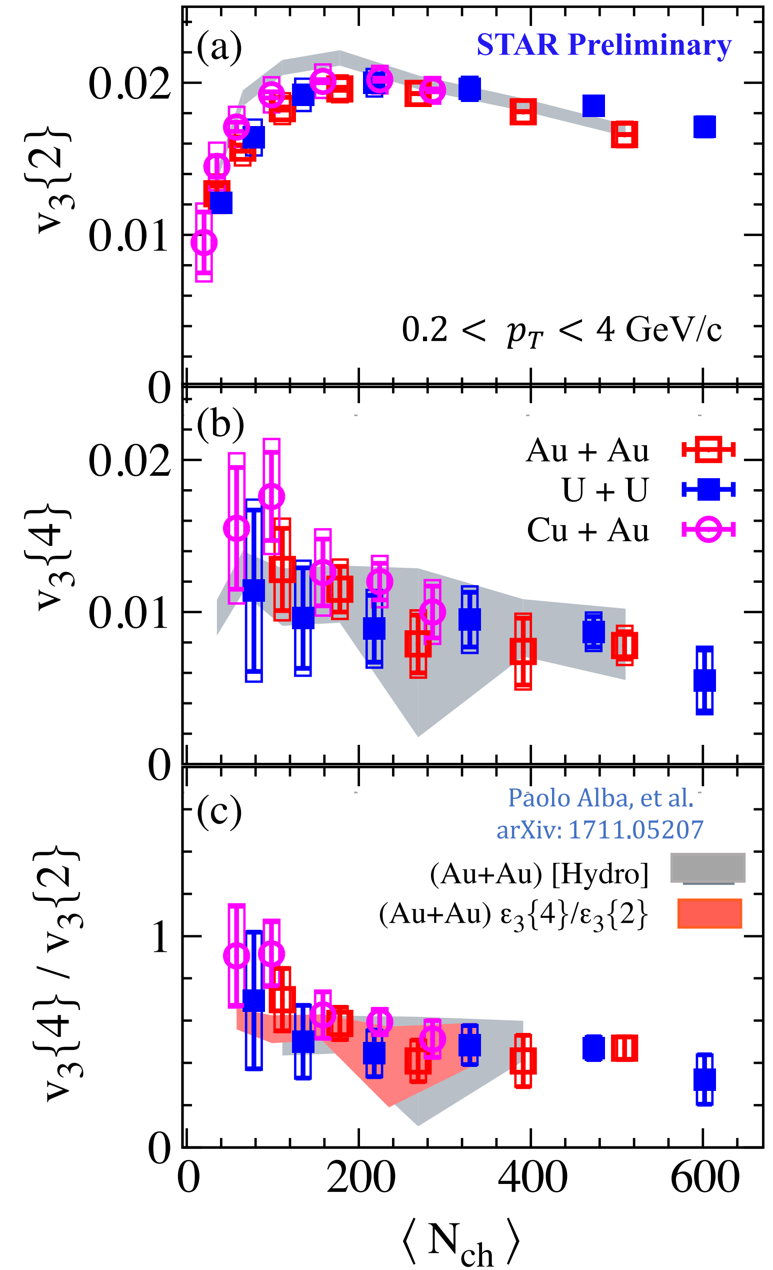
- Anisotropic flow magnitude is sensitive to:
  - ✓ Initial-state spatial anisotropy (ε_n)
  - ✓ Flow fluctuations and correlations
  - ✓ Viscous attenuation ($\propto \frac{\eta}{s}(T)$)



- $v_2\{2\}/\varepsilon_2\{2\}$ for these systems scales to a single curve
  - ✓ Similar viscous coefficient in U+U ($\sqrt{s_{NN}} = 193$ GeV), Au+Au and Cu+Au ($\sqrt{s_{NN}} = 200$ GeV)

Results

The $v_3\{2\}$ and $v_3\{4\}$, and ($v_3\{4\}/v_3\{2\}$) vs. $\langle N_{ch} \rangle$



- For different collision systems:
  - ✓ $v_2\{2\}$, $v_2\{4\}$ and $v_2\{4\}/v_2\{2\}$ are system-size independent

- Reasonable agreement with the theoretical calculations for Au+Au

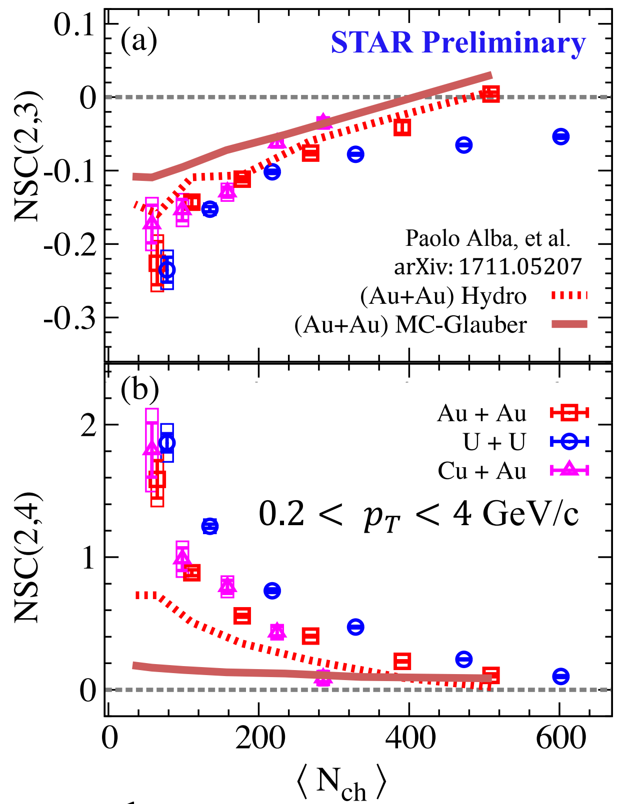
Comparison of the normalized symmetric cumulants, NSC(2,3) and NSC(2,4), vs. ⟨Nch⟩

$$NSC(n,m) = \frac{\langle 4\rangle_{nm} - \langle 2\rangle_n \langle 2\rangle_m}{\langle 2\rangle_n^{Sub} \langle 2\rangle_m^{Sub}}$$

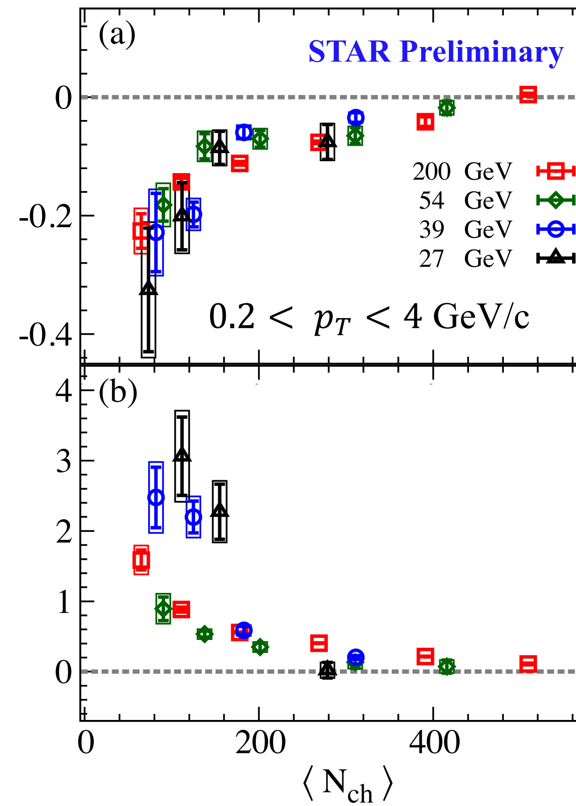
$$v_4^2 = (v_4^L)^2 + \chi_{2,2}(v_2)^2$$

Mode coupling

System dependence for $\sqrt{s_{NN}} \sim 200$ GeV



$\sqrt{s_{NN}}$ dependence for Au+Au



- Anti-correlation between v_2 and v_3
  - ✓ Consistent with the expected anti-correlation between ϵ_2 and ϵ_3
- Correlation between v_2 and v_4
  - ✓ Consistent with the expectations from mode coupling between v_2 and v_4

➢ This measurement could provide an additional constraint for models

Conclusion

Multi-particle correlations are used to extract and study $v_n\{2\}, v_n\{4\}, v_n\{4\}/v_n\{2\}$ and NSC(n,m) in Au+Au at BES ($\sqrt{s_{NN}} = 200 - 7.7$ GeV), U+U ($\sqrt{s_{NN}} = 193$ GeV) and Au+Cu ($\sqrt{s_{NN}} = 200$ GeV) collisions.

- Elliptic flow fluctuations show a weak dependence on $\sqrt{s_{NN}}$, q_2, particle species and p_T
- Elliptic flow and its fluctuations are system-size dependent.
- Triangular flow and its fluctuations are system-size independent.

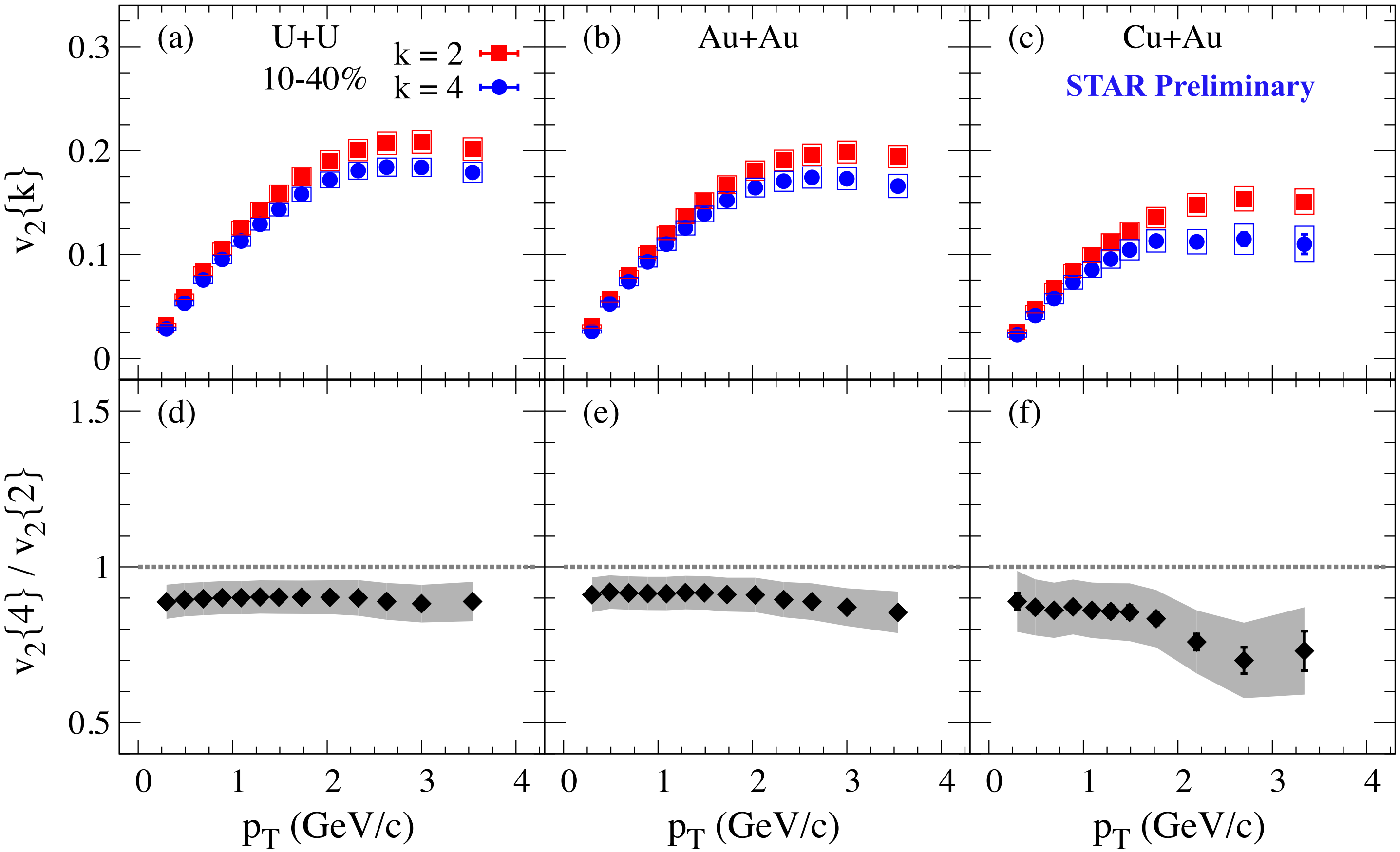
❖ The measured flow fluctuations are dominated by fluctuations of the initial-state eccentricity

❖ At the same energy, the scaling features suggest similar viscous coefficient for all presented systems.

These comprehensive measurements provide additional constraints for models, as well as for extraction of the temperature-dependent transport coefficients.

Backup

Two- and four-particle elliptic flow, $v_2\{2\}$ and $v_2\{4\}$, and their ratio ($v_2\{4\}/v_2\{2\}$) vs. p_T



- Within uncertainties, $v_2\{4\}/v_2\{2\}$ is p_T independent
  - ✓ Dynamical final-state fluctuations are significantly less than the initial-state fluctuations?