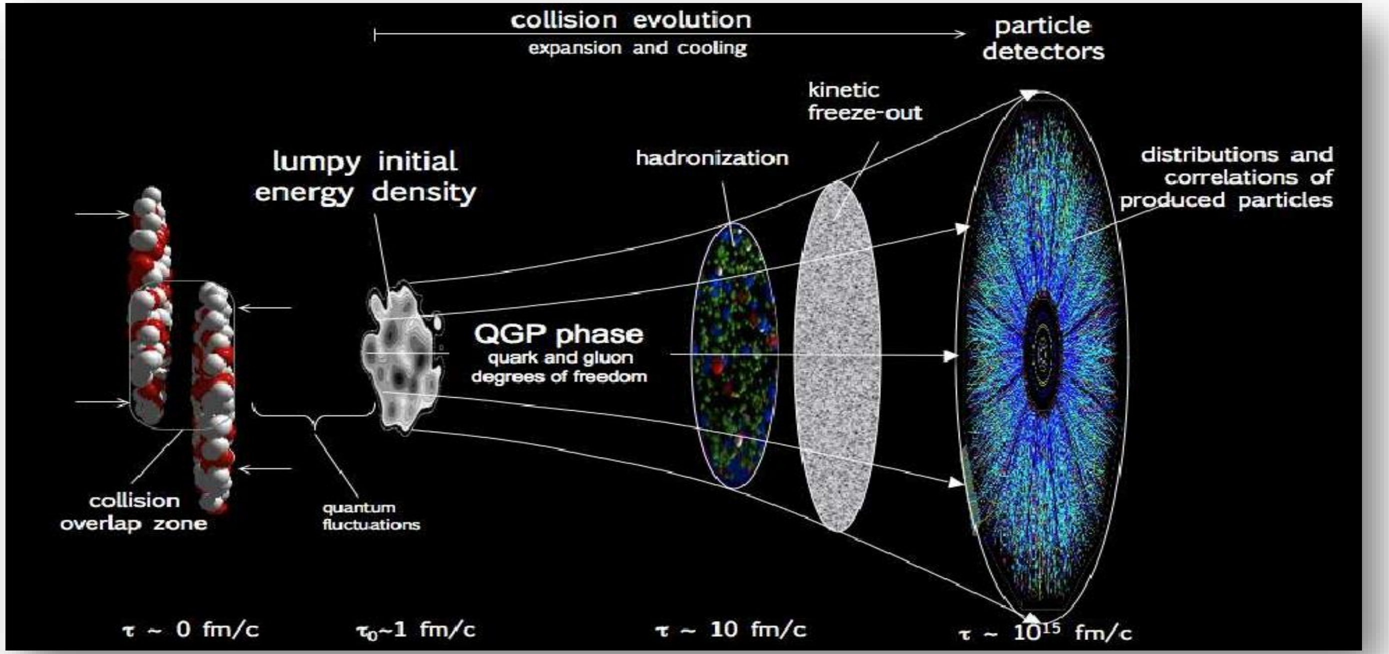
Flow and Isobars Overview



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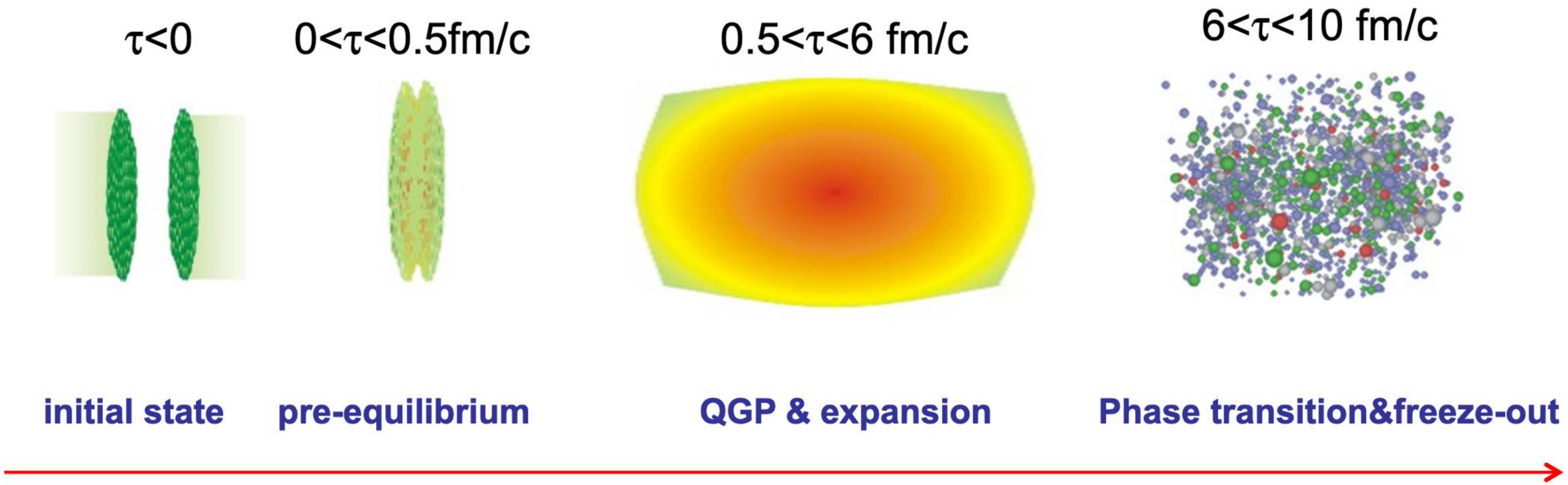
In part supported by

Motivation

Initial condition and emergence of collectivity

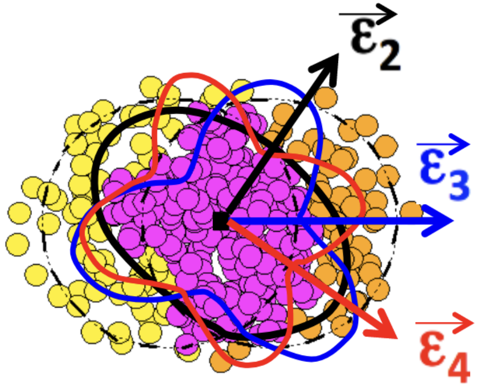


- The anisotropic flow (collectivity) measurements are sensitive to the QGP transport properties.

Motivation

Connecting the initial and final state

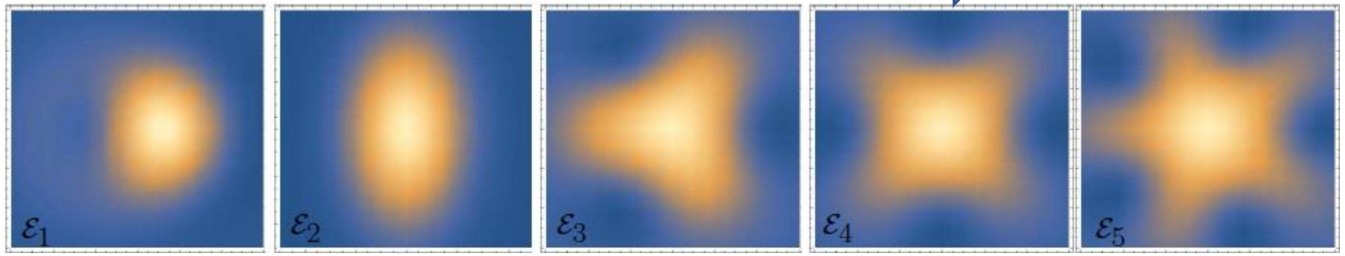
Initial state



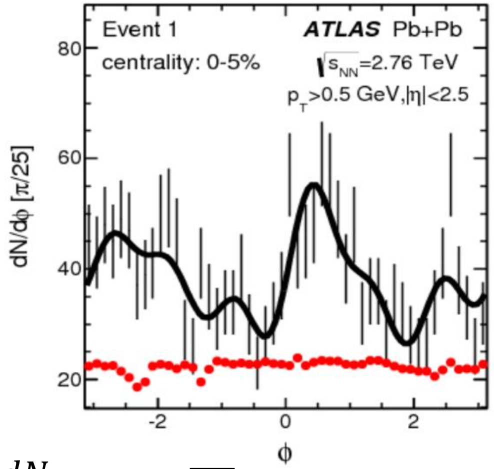
$\overrightarrow{\varepsilon_n} \equiv \varepsilon_n e^{in\Phi_n}$

Hydro-response

Space-time dynamics



Particle flow



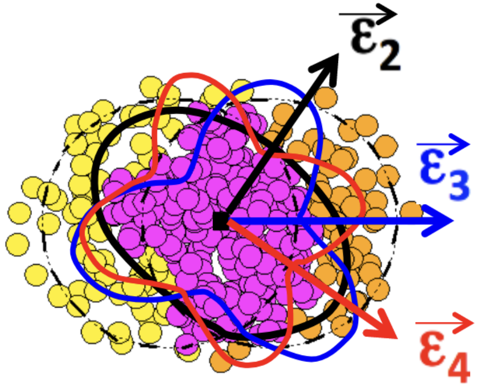
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_n V_n \cos(n(\varphi - \psi_n))$$

The flow harmonic coefficients v_n are influenced by eccentricities (ε_n), fluctuations, system size, speed of sound $c_s(\mu_B, T)$, and transport coefficient $\frac{\eta}{s}(\mu_B, T)$

Motivation

Connecting the initial and final state

Initial state



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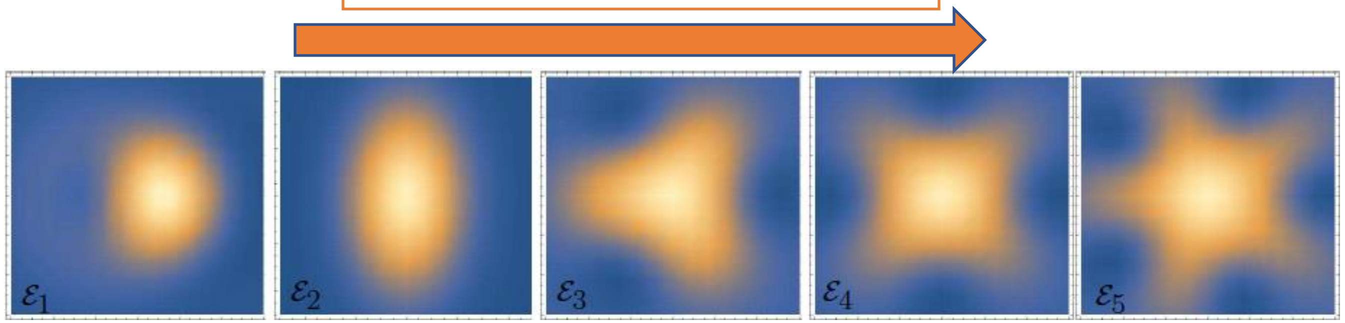
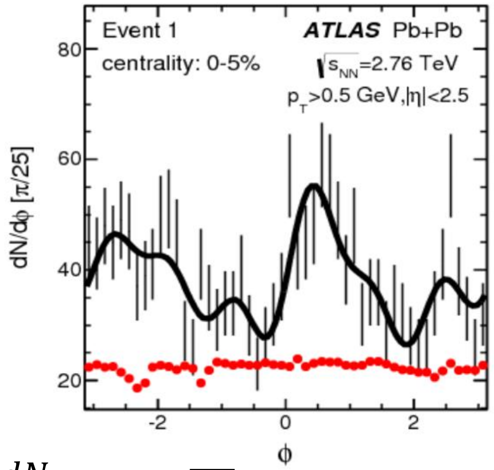
Hydro-response

Space-time dynamics



Particle flow



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_n V_n \cos(n(\varphi - \psi_n))$$

The flow harmonic coefficients v_n are influenced by eccentricities (ε_n), fluctuations, system size, speed of sound $c_s(\mu_B, T)$, and transport coefficient $\frac{\eta}{s}(\mu_B, T)$

- What is the nature of the flow fluctuation?
- What is the space-time evolution of the produced matter?
  - How are (ε_n, Φ_n) transferred to (v_n, ψ_n) event-by-event?
- What are the properties of the produced matter?

Azimuthal anisotropy measurements

Correlation function

Two particle correlation function $Cr(\Delta\varphi)$,

$$Cr(\Delta\varphi) = dN/d\Delta\varphi \quad \text{and} \quad v_{nn} = \frac{\sum_{\Delta\varphi} Cr(\Delta\varphi)\cos(n\,\Delta\varphi)}{\sum_{\Delta\varphi} Cr(\Delta\varphi)}$$

Azimuthal anisotropy measurements

Correlation function

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$n > 1$

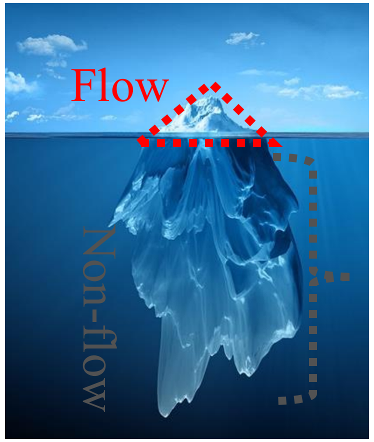
$$v_{nn} = v_n^a v_n^b + \delta_{short}$$

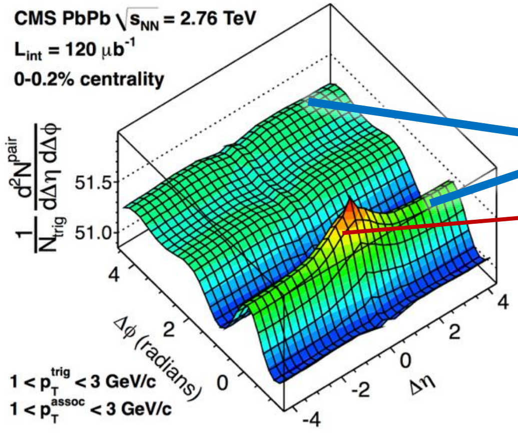
$n = 1$

$$v_{11} = v_1^a v_1^b + \delta_{long}$$

Flow

Non-flow





Long − range

Short − range

Momentum Conservation

HBT

Di−jets

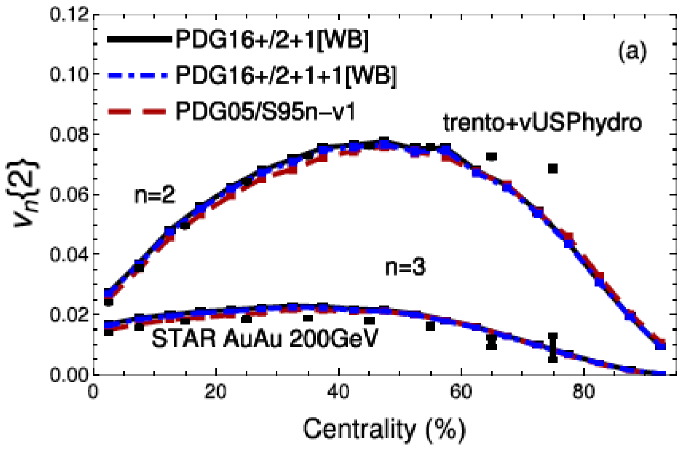
Decay

$\underbrace{}_{\text{Charge}}$

Non-flow suppression is needed

Models for comparisons

(1) P. Alba, et al. PRC 98 , 034909 (2018)

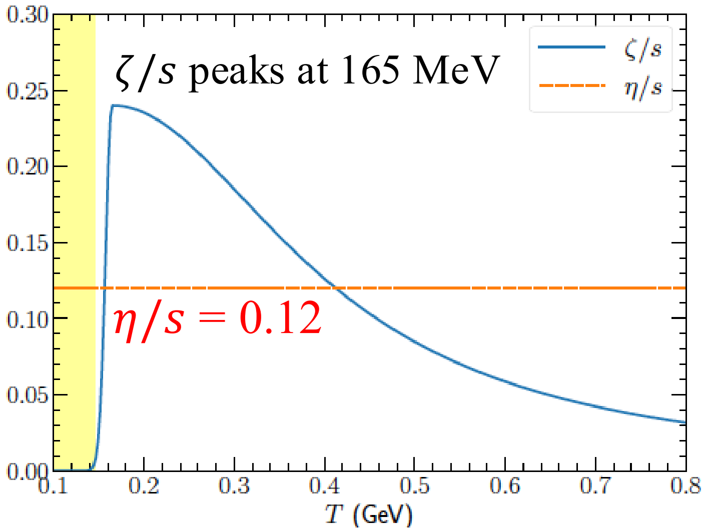


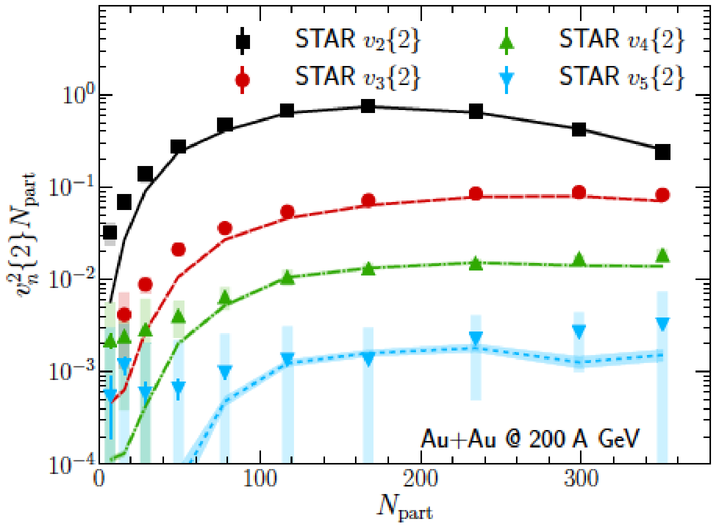
- The model use event-by-event fluctuating initial conditions generated by the TRENTO model with free parameters calibrated to fit experimental observables.
- The model use the smoothed particle hydrodynamics (SPH) Lagrangian code, v-USPhydro, to solve the viscous hydrodynamic equations taking into account shear viscous effects.
- The viscosity is determined by fitting $v_2\{2\}$ and $v_3\{2\}$ across centrality for different equation of state individually.

(2) B.Schenke , et al. PRC 99, 044908 (2019)

- The model used the impact parameter-dependent Glasma model to initialize the viscous hydrodynamic simulation MUSIC and employ the UrQMD transport model for the low-temperature region of the collisions.

Width, height, and position of ζ/s are free parameters





Analysis Method

Niseem Magdy PRC 107 (2023) 2, 024905
Niseem Magdy PRC 106 (2022) 4, 044911
Niseem Magdy, et al PRC 105 (2022) 4, 044901

The multi-particle correlations

Symmetric Correlations

Are sensitive to the interplay between initial- and final-state effects.

Asymmetric Correlations

Analysis Method

The multi-particle correlations

Niseem Magdy PRC 107 (2023) 2, 024905
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Niseem Magdy, et al PRC 105 (2022) 4, 044901

Are sensitive to the interplay between initial- and final-state effects.

Symmetric Correlations

- k-even particle correlations
- n-m flow harmonics correlations
- n-order flow harmonic fluctuations
- Differential flow angle fluctuations

Asymmetric Correlations

- k-odd particle correlations
- n-m mode-coupling
- Event plane angular correlations
- Transverse momentum flow correlations

Niseem Magdy PRC 107 (2023) 2, 024905
Niseem Magdy PRC 106 (2022) 4, 044911
Niseem Magdy, et al PRC 105 (2022) 4, 044901

The multi-particle correlations

Symmetric Correlations

Are sensitive to the interplay between initial- and final-state effects.

Asymmetric Correlations

Normalized Asymmetric Correlations

Normalized Asymmetric Correlations

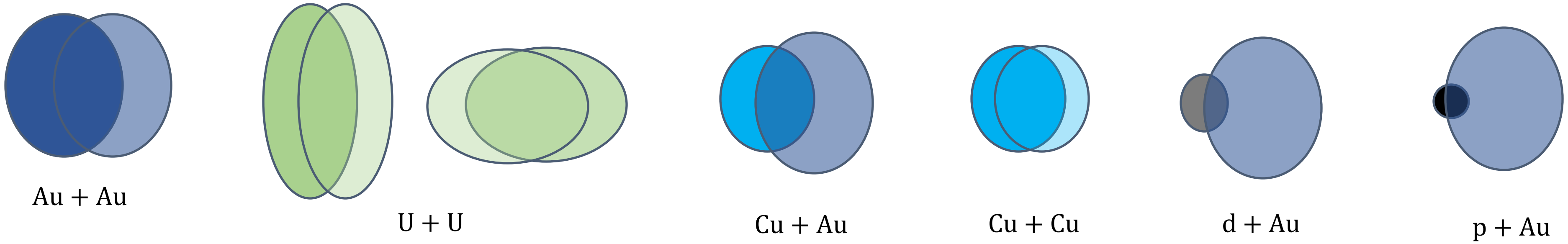
Are sensitive to the initial state effects.

The multi-particle correlations

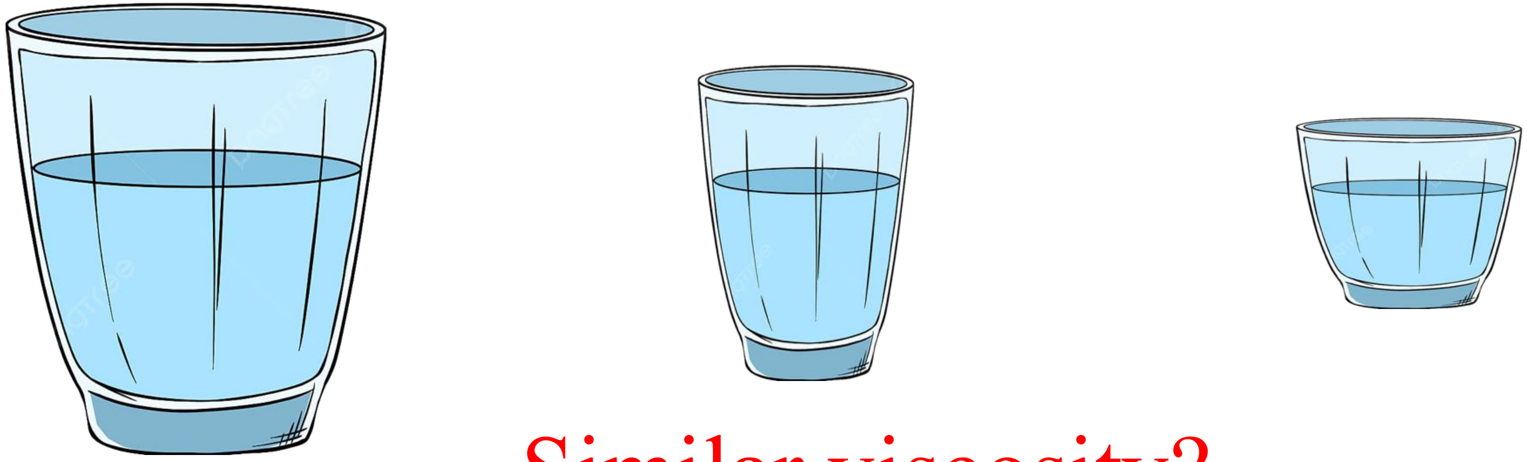
Motivation

Can we validate our understanding?

$$v_2 \;\propto\; k\, \varepsilon_2 \,\langle N_{Ch} \rangle^{-1/3}$$



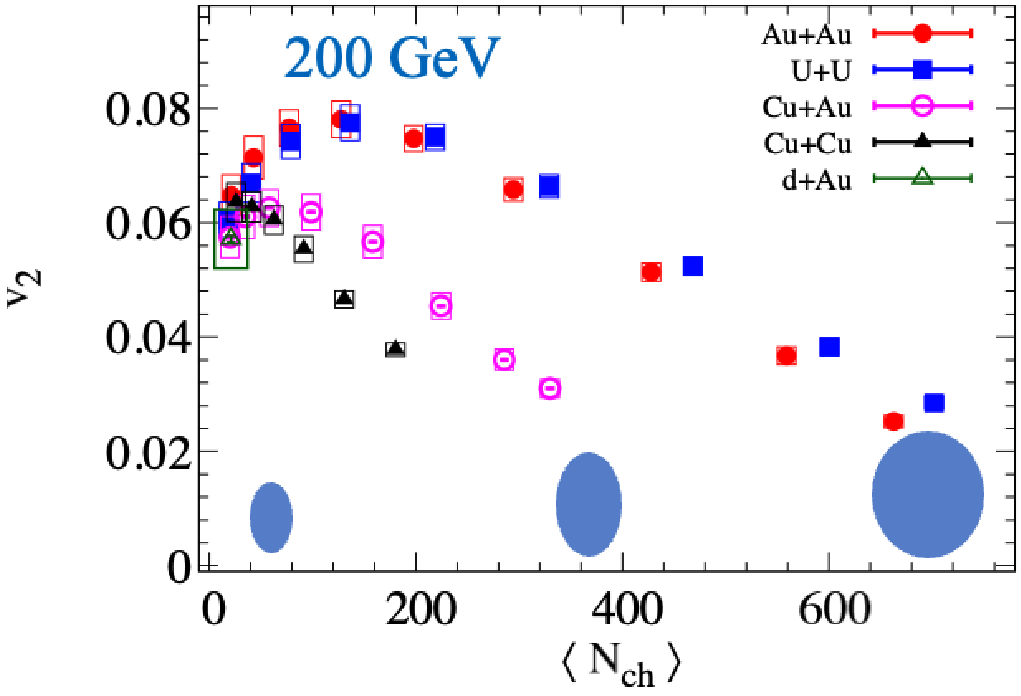
Different shapes
and sizes

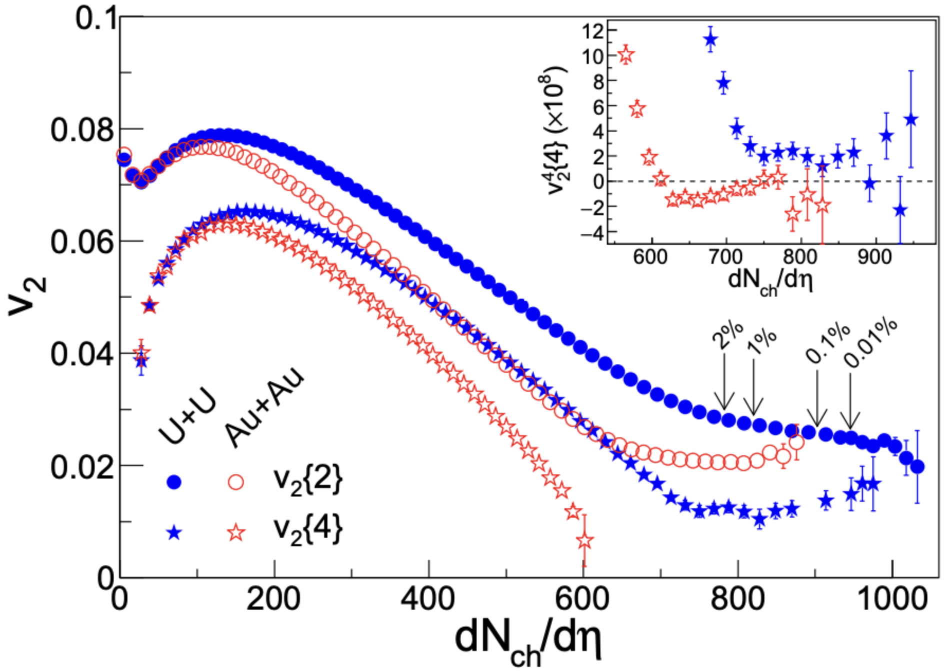


Similar viscosity?

Can we validate our understanding?

STAR Collaboration
PRC 105, 014901 (2022)
PRL 122 17, 172301 (2019)
PRL 129 25, 252301 (2022)
PRL 115 22, 222301 (2015)





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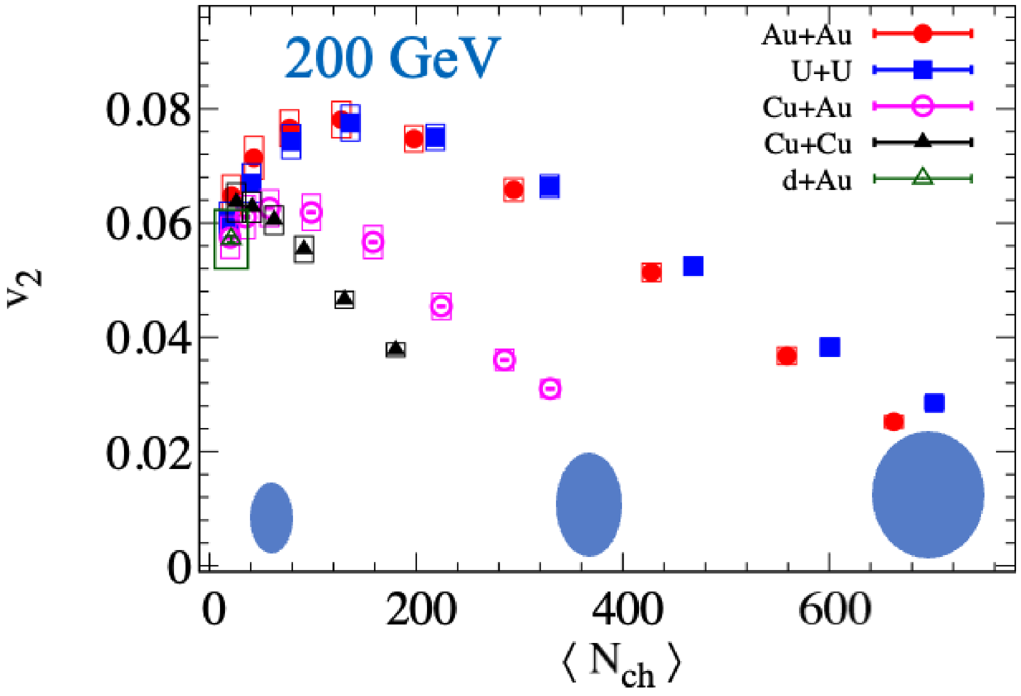

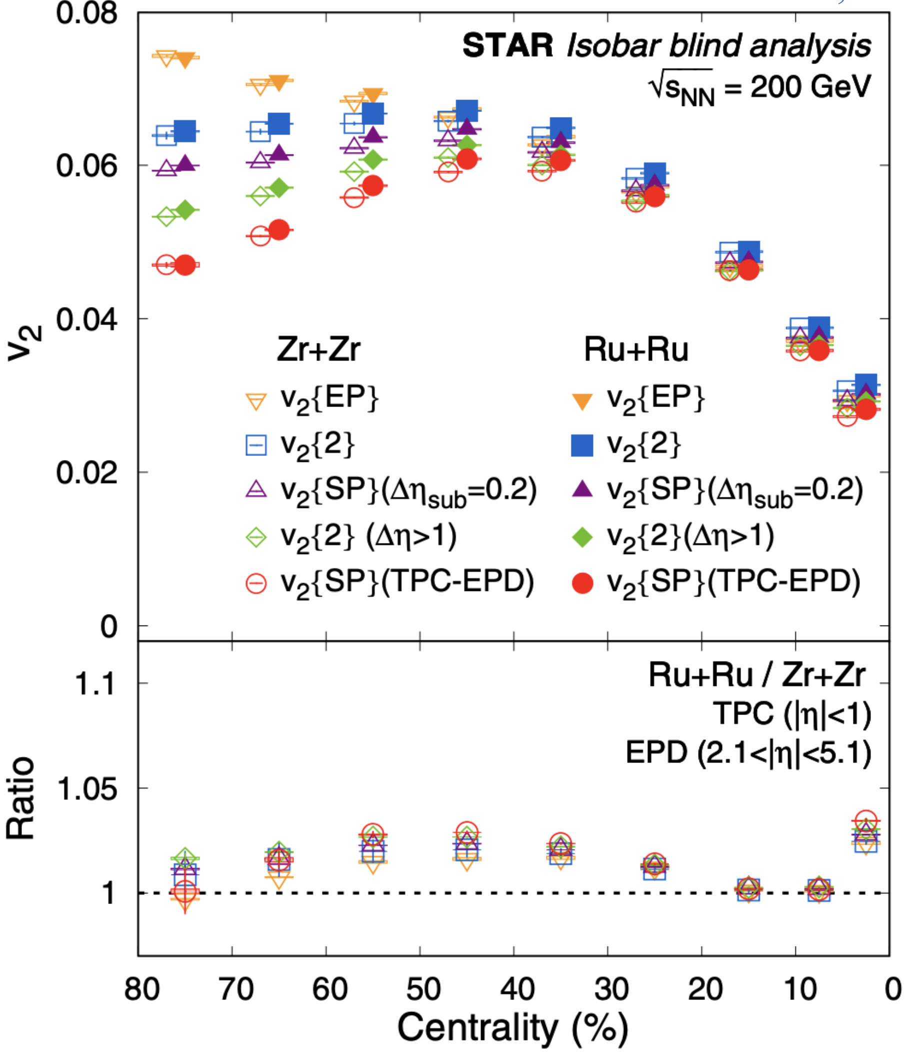

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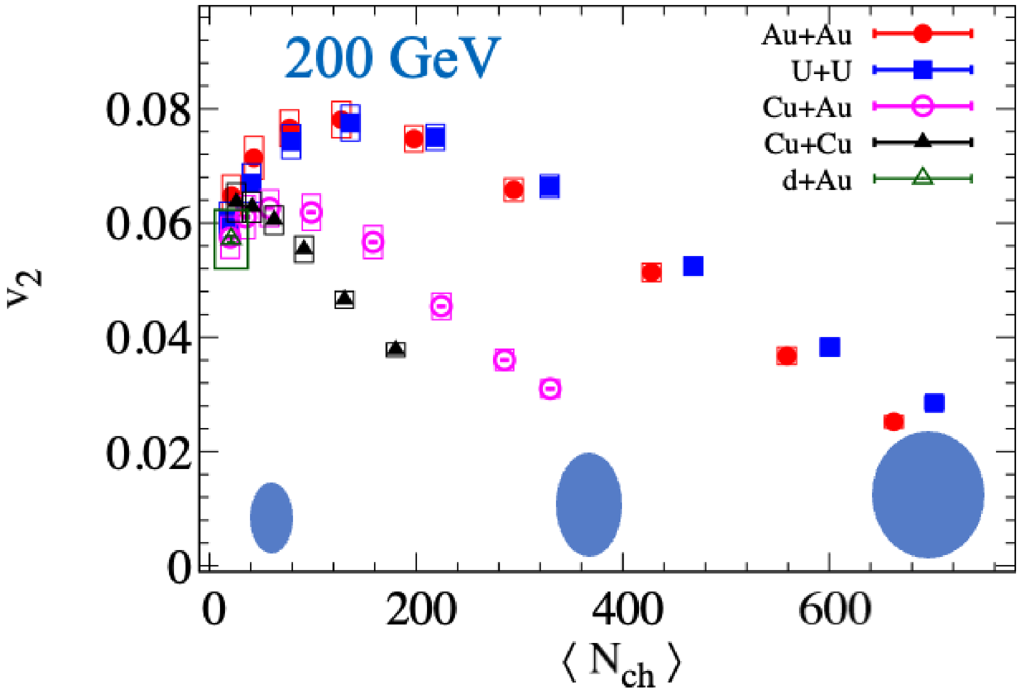
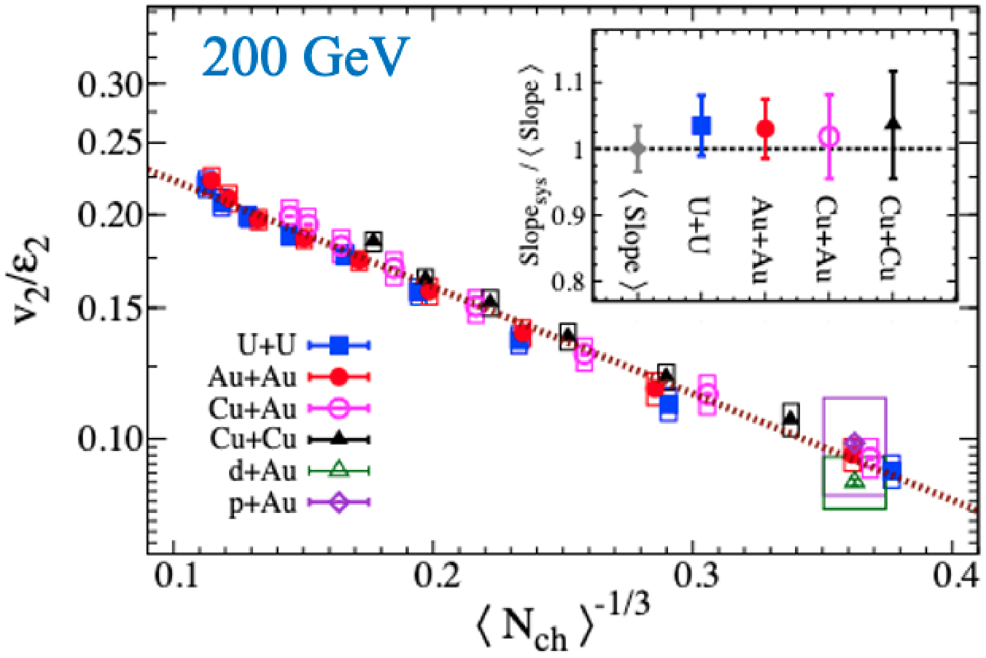
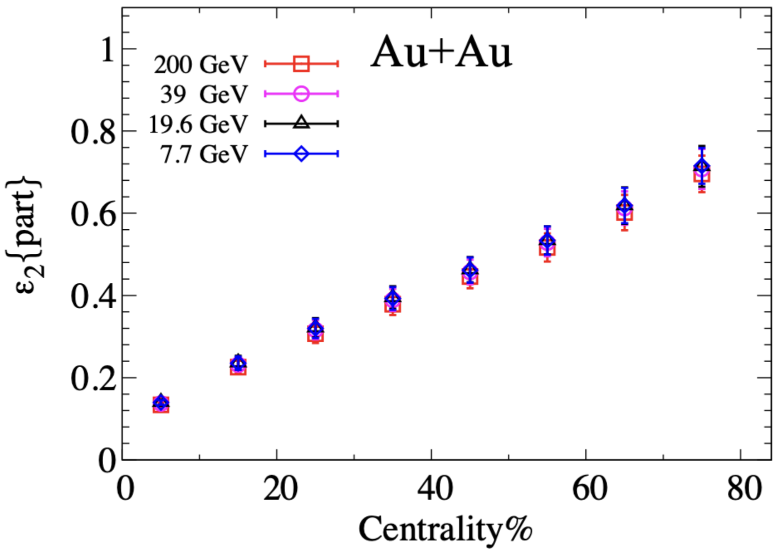


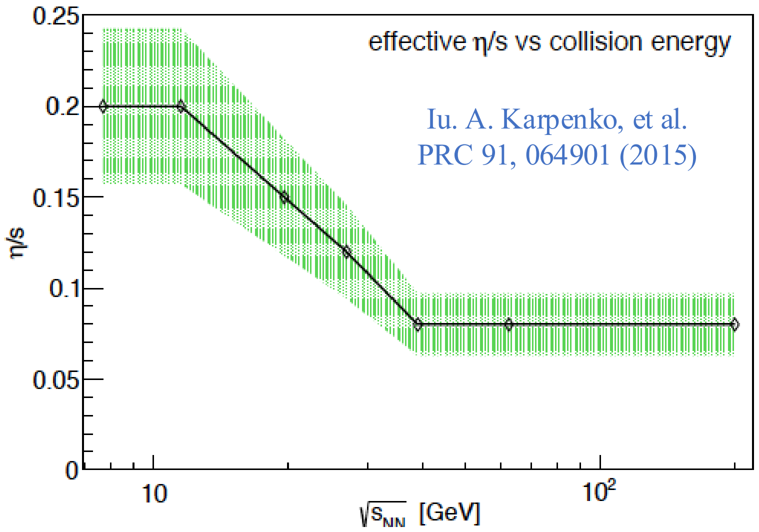


v_2/ϵ_2 for all systems scales to a single curve.

Similar slopes imply similar viscous coefficients for all presented systems

Can we validate our understanding?





Similar shapes and sizes

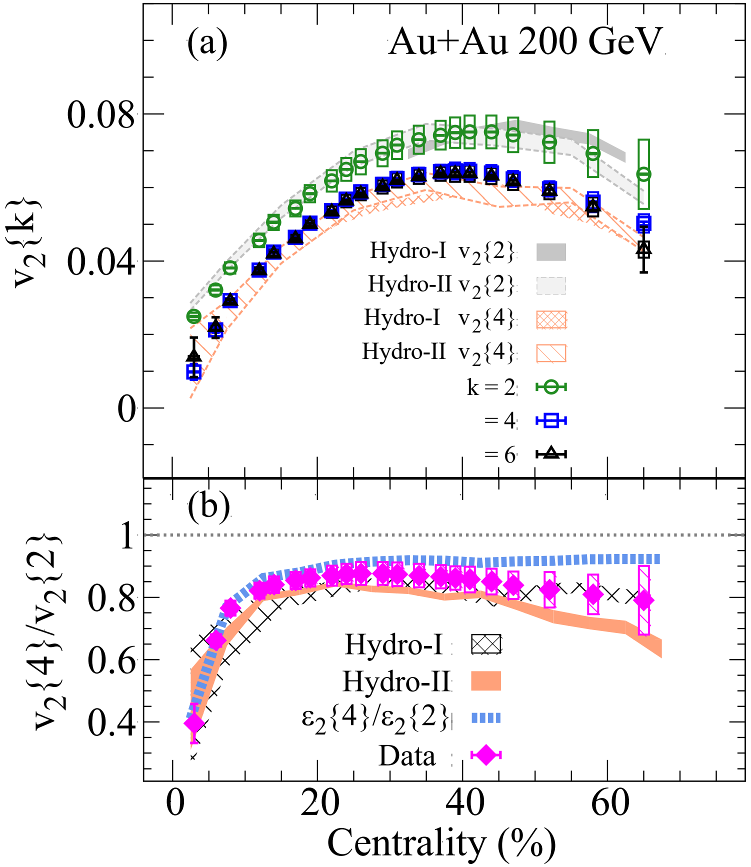
Different viscosity

Anisotropic Flow Fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)

The $v_2\{k\}$ and $(v_2\{4\}/v_2\{2\})$ centrality dependance

- $v_2\{k\}$ show centrality characteristic dependence.
  - Reasonable agreement with theoretical calculations.
- $v_2\{4\}/v_2\{2\}$ decrees from central to peripheral collisions
- The model calculations:
  - (I) $(v_2\{4\}/v_2\{2\})$ agrees well with the data
  - (II) $(v_2\{4\}/v_2\{2\})$ and $(\epsilon_2\{4\}/\epsilon_2\{2\})$ bracket the data



I- B.Schenke , et al. PRC 99, 044908 (2019)

II- P. Alba, et al. PRC 98 , 034909 (2018)

	Hydro-I	Hydro-II
η/s	0.12	0.05
Initial conditions	IP-Glasma	TRENTO
Contributions	Hydro + Hadronic cascade	Hydro + Direct decays

Anisotropic Flow Fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)

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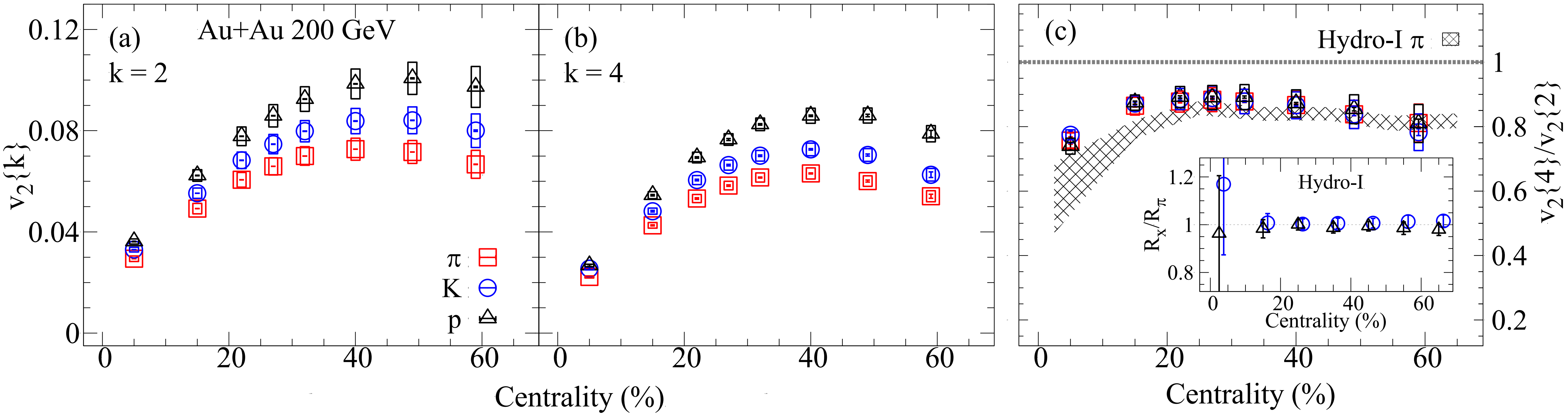


- $v_2\{4\}/v_2\{2\}$ show weak dependence on particle species.

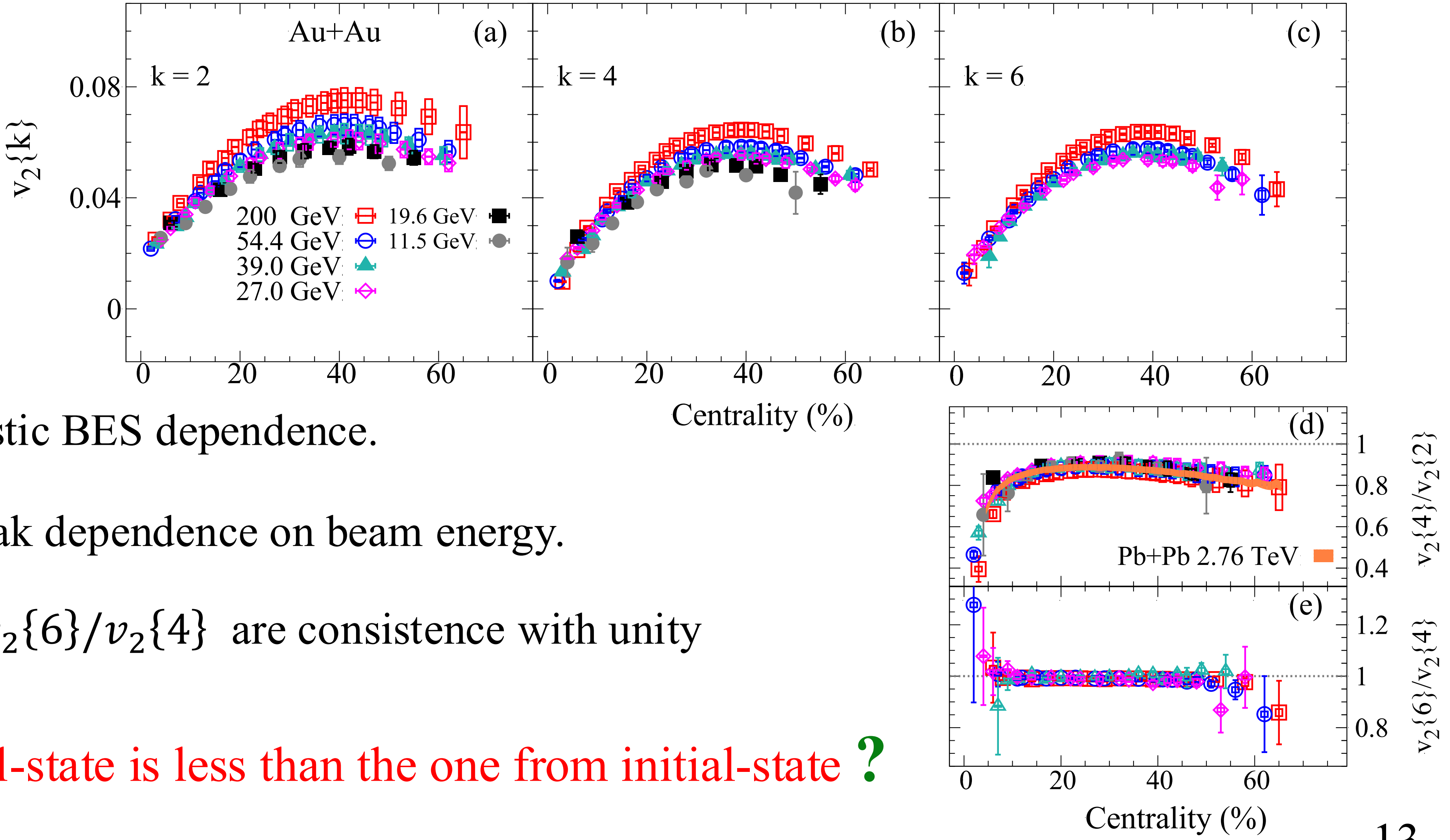
The influence from final-state is less than the one from initial-state ?

	Hydro-I	Hydro-II
η/s	0.12	0.05
Initial conditions	IP-Glasma	TRENTO
Contributions	Hydro + Hadronic cascade	Hydro + Direct decays

Anisotropic Flow Fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)

The $v_2\{k\}$, $\frac{v_2\{4\}}{v_2\{2\}}$, and $\frac{v_2\{6\}}{v_2\{4\}}$ BES dependance



- $v_2\{k\}$ show characteristic BES dependence.
- $v_2\{4\}/v_2\{2\}$ show weak dependence on beam energy.
- Within uncertainties, $v_2\{6\}/v_2\{4\}$ are consistence with unity

The influence from final-state is less than the one from initial-state ?

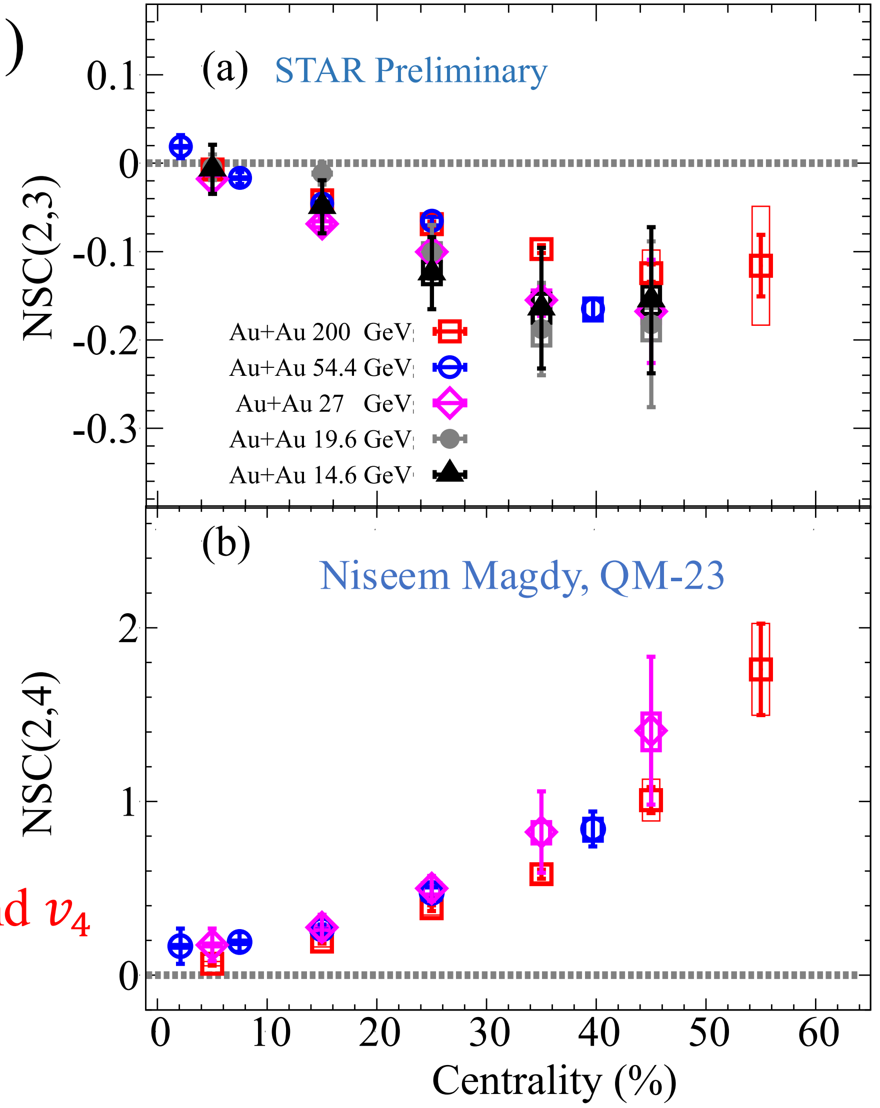
Anisotropic Flow Correlations

STAR Collaboration
PLB 839 137755 (2023)

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

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

$$v_4^2 = (v_4^L)^2 + \underbrace{\chi_{2,2}}_{\boxed{\text{Mode coupling}}}(v_2)^2$$



- ❖ 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
- ❖ NSC(n, m) show weak dependence on beam energy.

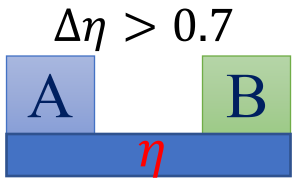
The influence from final-state is less than the one from initial-state ?

Asymmetric Correlations

STAR Collaboration PLB 839 137755 (2023)

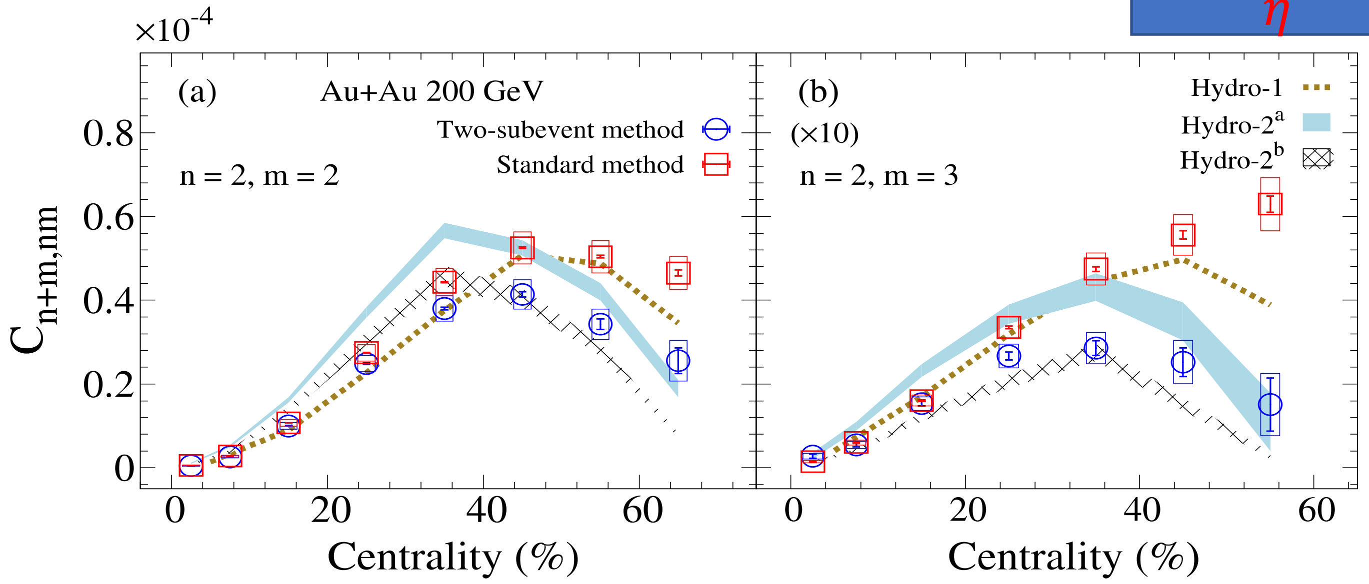
STAR Collaboration PLB 809 135728 (2020)

Three-particle correlations $C_{4,22}$ and $C_{5,23}$



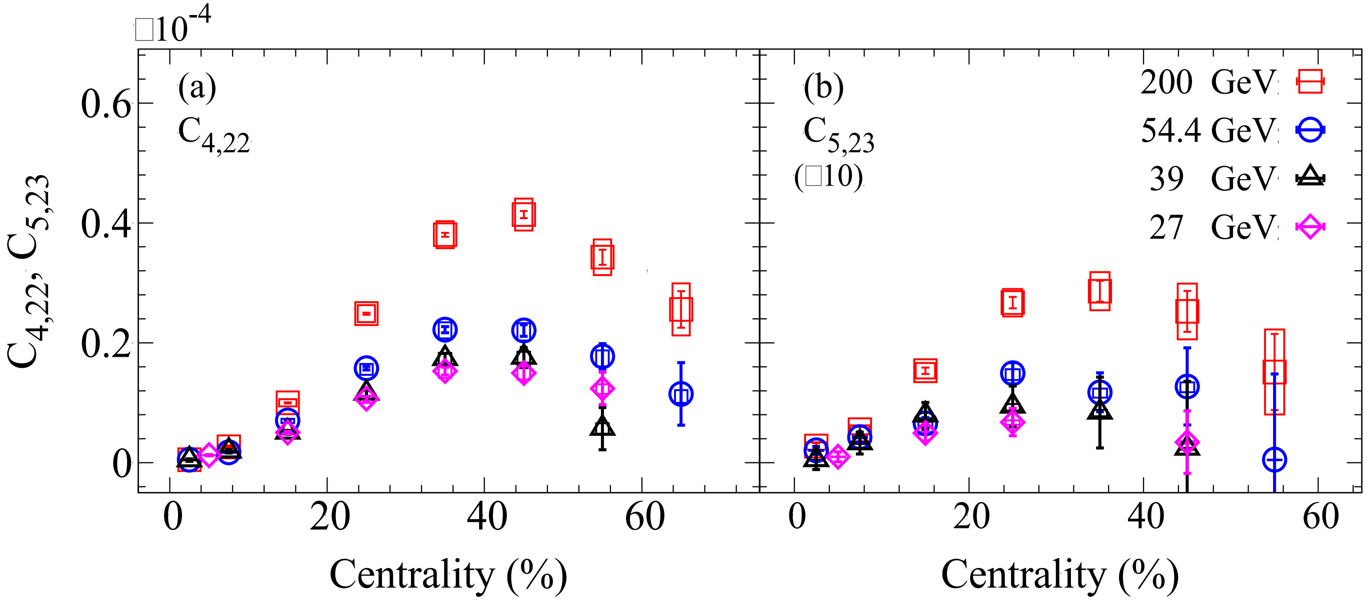
$$C_{4,22} = \langle\langle \cos(4\varphi_1^A - 2\varphi_2^B - 2\varphi_3^B) \rangle\rangle$$

$$C_{5,23} = \langle\langle \cos(5\varphi_1^A - 2\varphi_2^B - 3\varphi_3^B) \rangle\rangle$$



- Two-subevents reduce the short-range non-flow effect on the three-particle correlations.

Both models fit the single v_n; therefore, we need additional constraints in order to describe the data.



$C_{4,22}$ and $C_{5,23}$ show dependance on a beam energy

	Hydro−1 [67]	Hydro−$2^{a/b}$ [68]
η/s	0.05	0.12
Initial conditions	TRENTO Initial conditions	IP-Glasma Initial conditions
Contributions	Hydro + Direct decays	(a) Hydro + Hadronic cascade (b) Hydro only

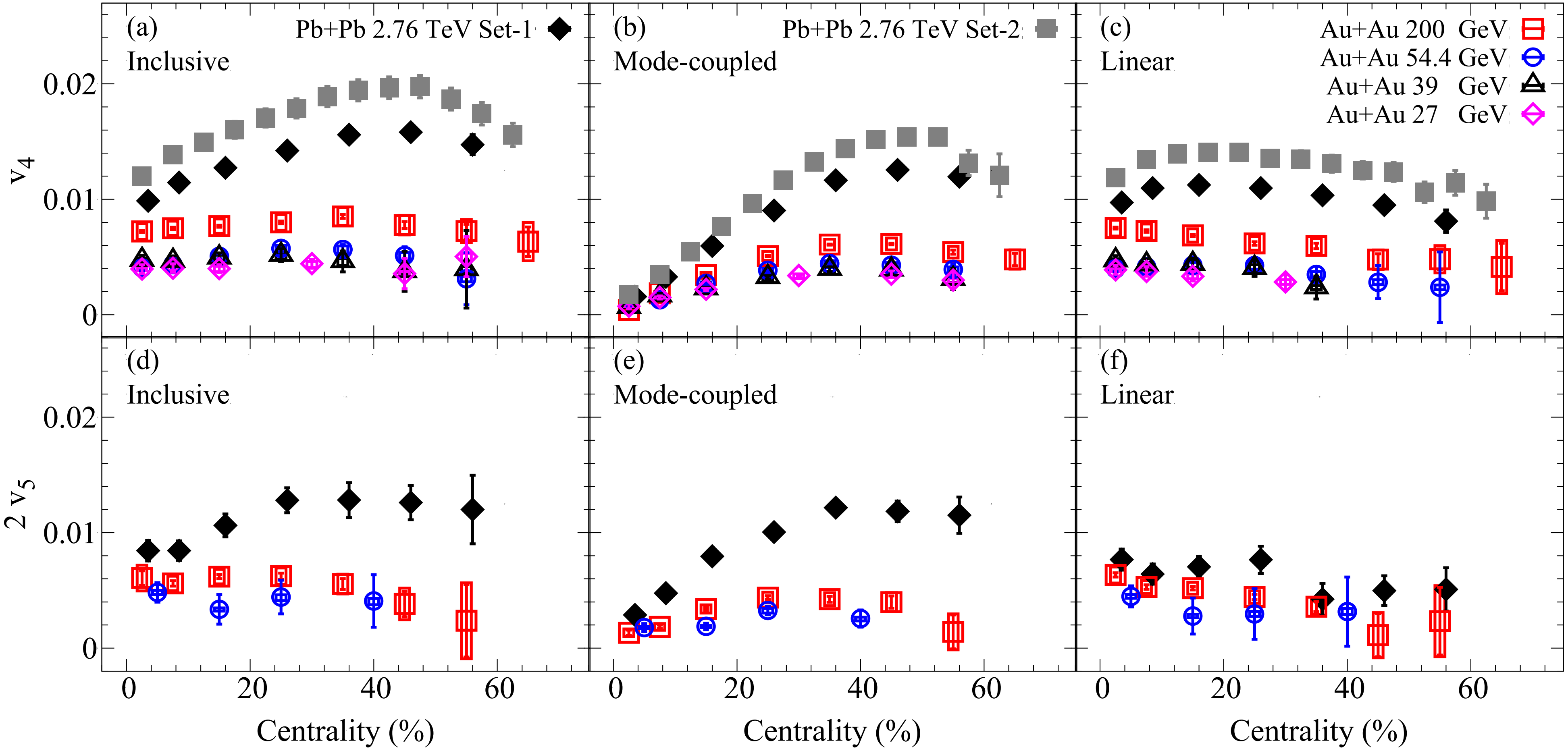
(I) P. Alba, et al. PRC 98 , 034909 (2018)

(II) B.Schenke , et al. PRC 99, 044908 (2019)

STAR Collaboration
PLB 839 137755 (2023)

Linear and non-linear flow v_k (k=4,5) decomposition

$\left\langle\left\langle \cos\left((n+2)(\varphi_1^A - \varphi_2^B)\right)\right\rangle\right\rangle^{1/2}$ $\qquad$ $\dfrac{\langle\langle \cos((n+2)\varphi_1^A - 2\varphi_2^B - n\varphi_3^B)\rangle\rangle}{\sqrt{\langle v_2^2 v_n^2\rangle}}$ $\qquad$ $\sqrt{(v_{n+2}^{Inclusive})^2 - (v_{n+2}^{MC})^2}$ $\qquad$ $n = 2,3$

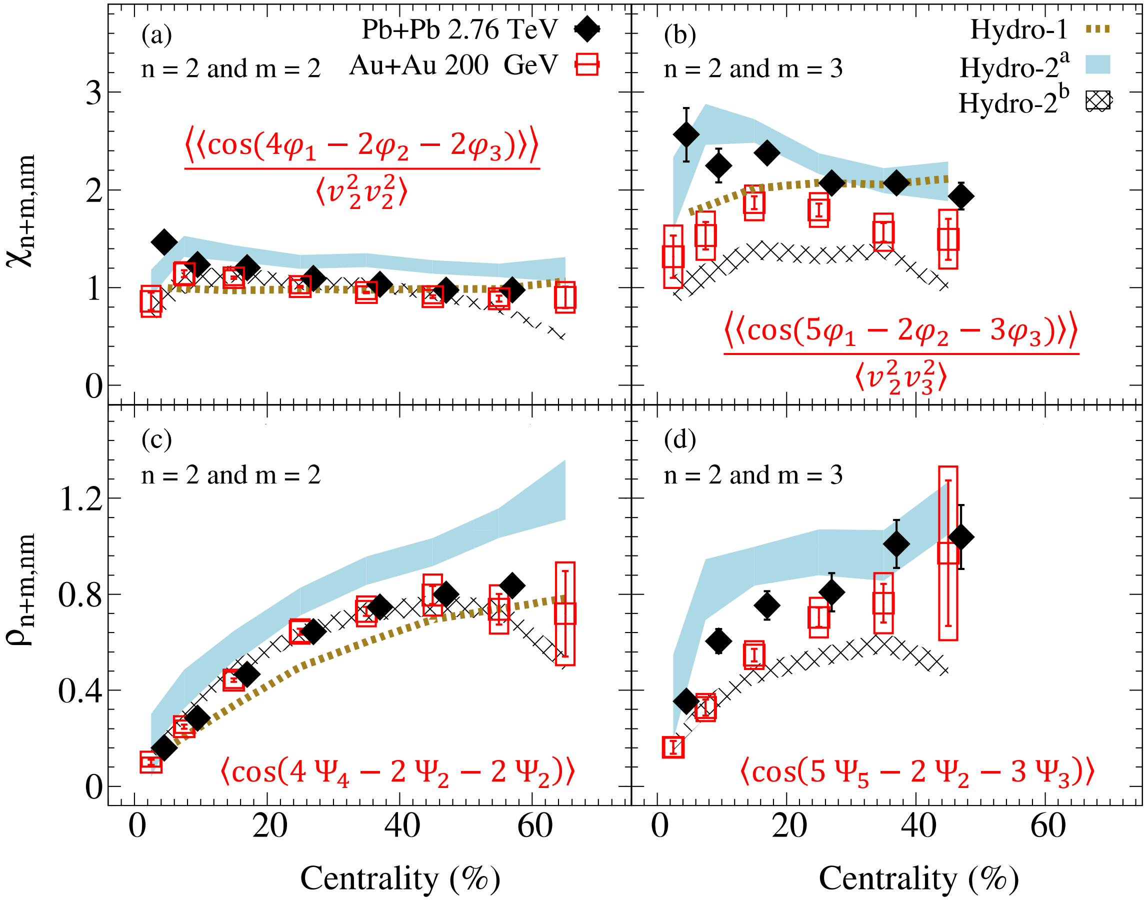


- The linear v_k (k=4,5) terms dominate in central collisions, while the non-linear terms take over or are comparable in peripheral collisions

Asymmetric Correlations

STAR Collaboration
PLB 809 135728 (2020)

Mode-coupling coefficient $\chi_{k,nm}$ and the E-P angular correlation $\rho_{k,nm}$



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(I) P. Alba, et al. PRC 98 , 034909 (2018)

(II) B.Schenke , et al. PRC 99, 044908 (2019)

- $\chi_{k,nm}$ shows a weak centrality dependence
- $\rho_{k,nm}$ shows a strong centrality dependence

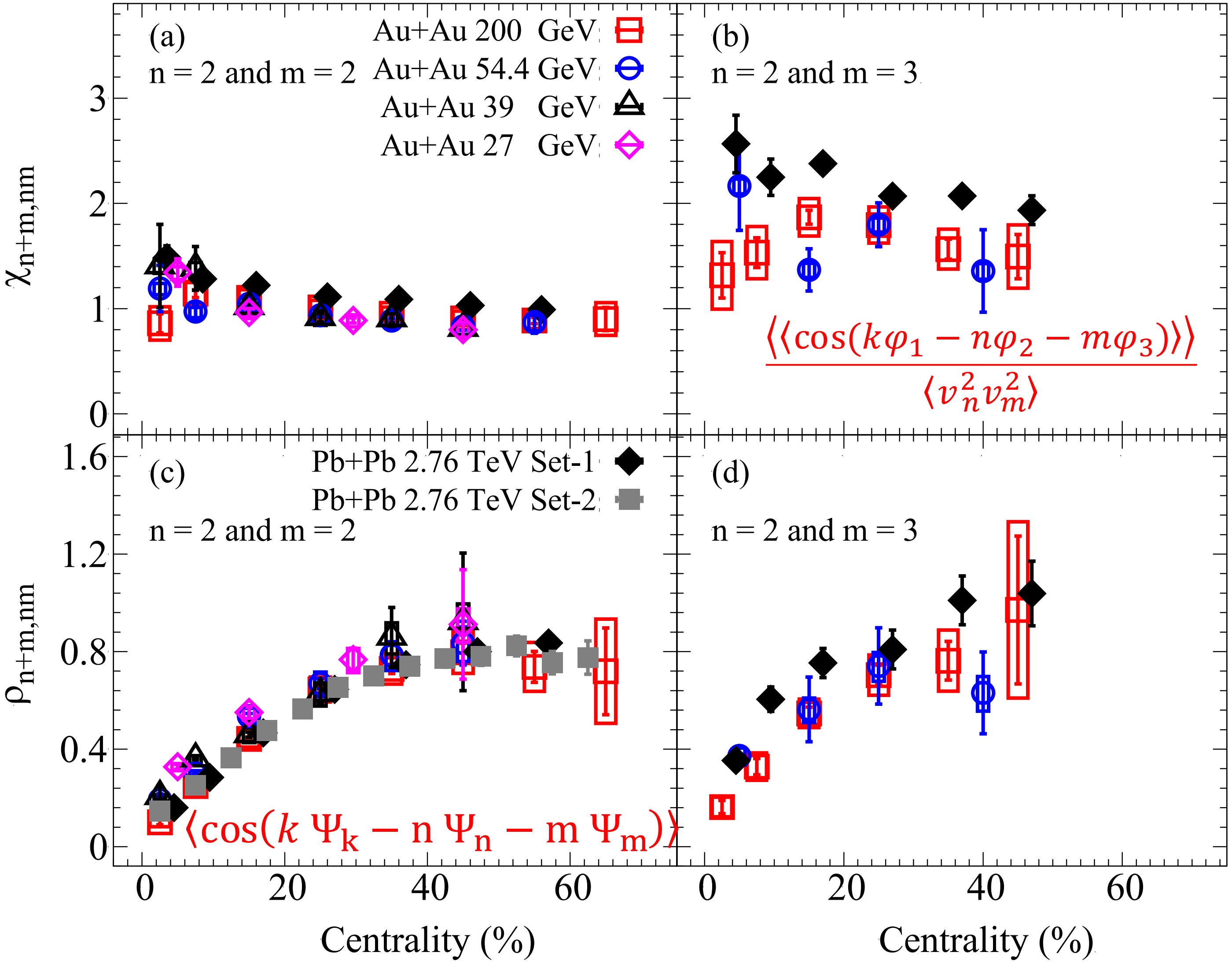
Asymmetric Correlations

STAR Collaboration
PLB 839 137755 (2023)

The mode-coupling coefficients $\chi_{k,nm}$ and the E-P angular correlations $\rho_{k,nm}$

- The non-linear mode-coupling coefficients $\chi_{k,nm}$ shows similar values and trends for different beam energies and a weak centrality dependence.

- The E-P angular correlations $\rho_{k,nm}$ shows similar values and trends for different beam energies and a strong centrality dependence.



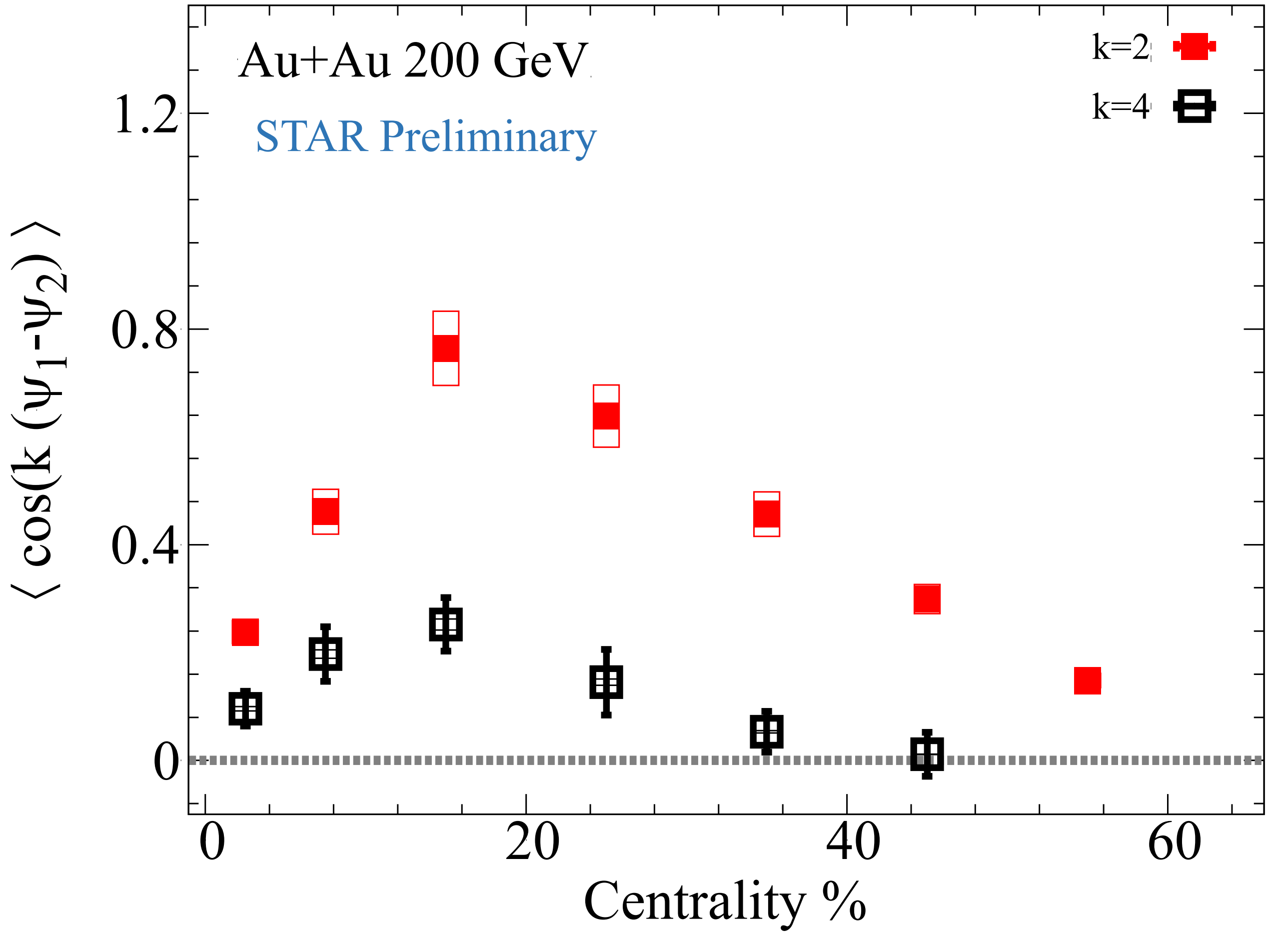
The influence from final-state is less than the one from initial-state ?

Event plane angular correlations

$$\langle\cos(2\psi_1 - 2\psi_2)\rangle = \langle v_1^2 v_2 \cos(2\psi_1 - 2\psi_2)\rangle / \sqrt{\langle v_1^4\rangle\langle v_2^2\rangle}$$

$$\langle\cos(4\psi_1 - 4\psi_2)\rangle = \langle v_1^4 v_2^2 \cos(4\psi_1 - 4\psi_2)\rangle / \langle v_1^4 v_2^2\rangle$$

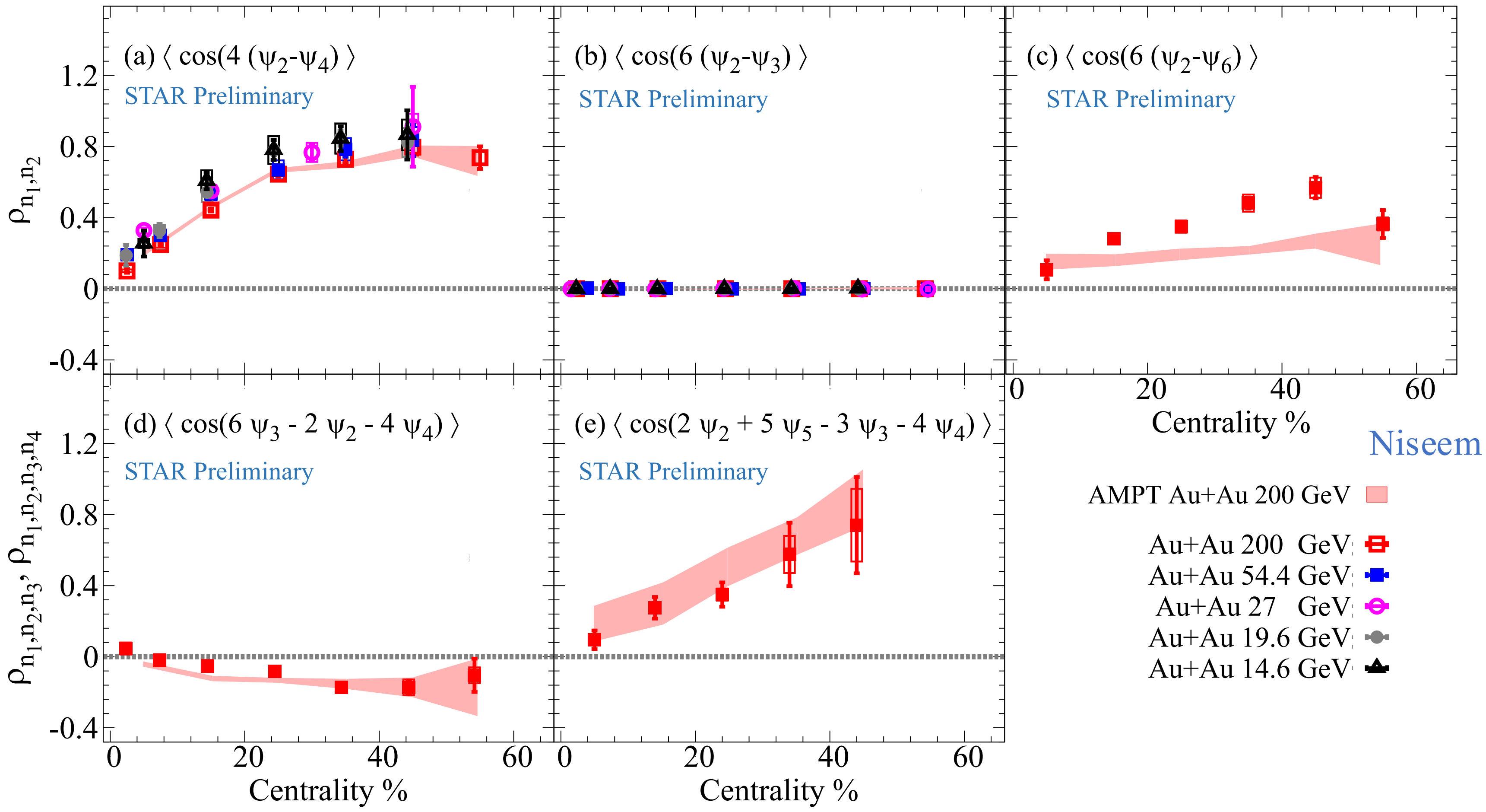
Niseem Magdy, QM-23



- ➢Similar trends were observed for $\langle\cos(k[\psi_1 - \psi_2])\rangle$, with k=2 and 4.
- ➢The $\langle\cos(4\psi_1 - 4\psi_2)\rangle$ is less affected by the global momentum conservation.
- ➢Positive correlations between ψ_1 and ψ_2 observed.

Event plane angular correlations

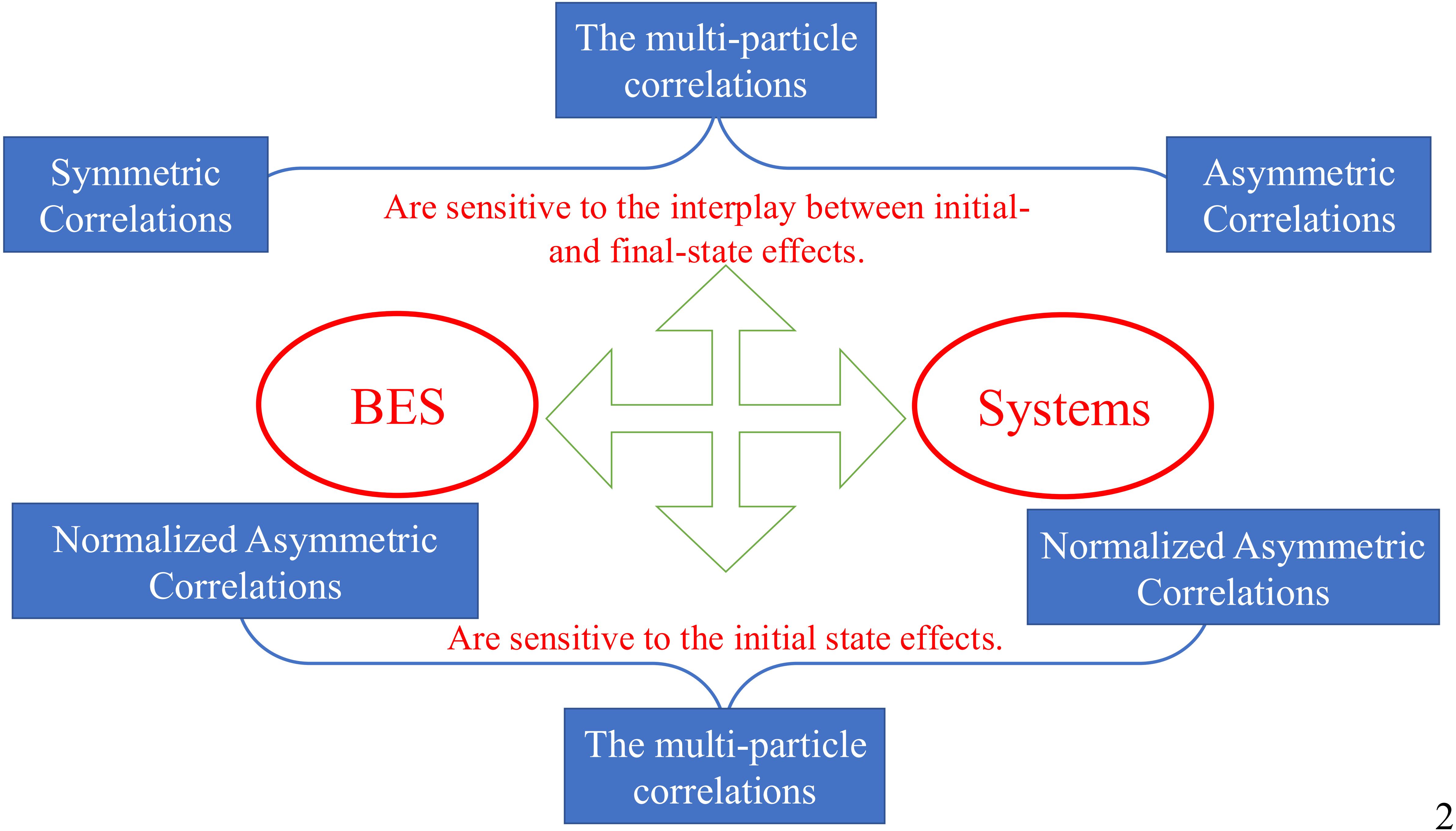
Comparison of the three-, four-, five- and six-particle event plan angular correlations vs. centrality



Niseem Magdy, QM-23

- The ψ_2-ψ_4 correlation shows similar values, however, ψ_2-ψ_3 correlation is consistent with zero for different beam energies
- No correlations were observed between $\psi_2$and ψ_3
- Except for $\rho_{2,6}$ we observe reasonable agreement with the AMPT model

The influence from the final state is less than from the initial state’s.


The multi-particle correlations
Symmetric Correlations
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BES
Systems
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The multi-particle correlations

Journal of Physics G: Nuclear and Particle Physics

Quantum Chromodynamics Evolution: The Current Legacy and the Electron-Ion Collider's Pioneering Horizons

Guest Editors

Niseem Magdy Abdelrahman, *Texas Southern University, USA*
Wenliang Li, *Mississippi State University, USA*
Wenbin Zhao, *Lawrence Berkeley National Laboratory, USA*

25 years of RHIC
Experimental and Theory
Collaborations and Individuals

The roadmap to EIC

Thank You