THE UNIVERSITY OF ILLINOIS AT CHICAGO

Beam-energy and collision-system dependence of the linear and mode-coupled flow harmonics from STAR

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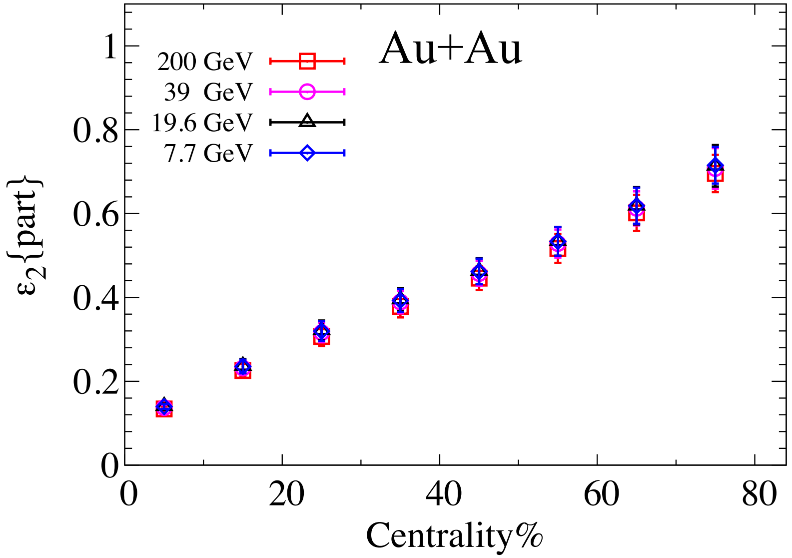
Outline

- Introduction
  - ✓ Motivation
  - ✓ Analysis methods
  - ✓ The STAR experiment
- Results
  - ✓ The linear and mode-coupled (non-linear) flow harmonics for Au+Au at 200 GeV
  - ✓ Beam-energy and system-size dependence of linear and mode-coupled (non-linear) flow harmonics
- Conclusion

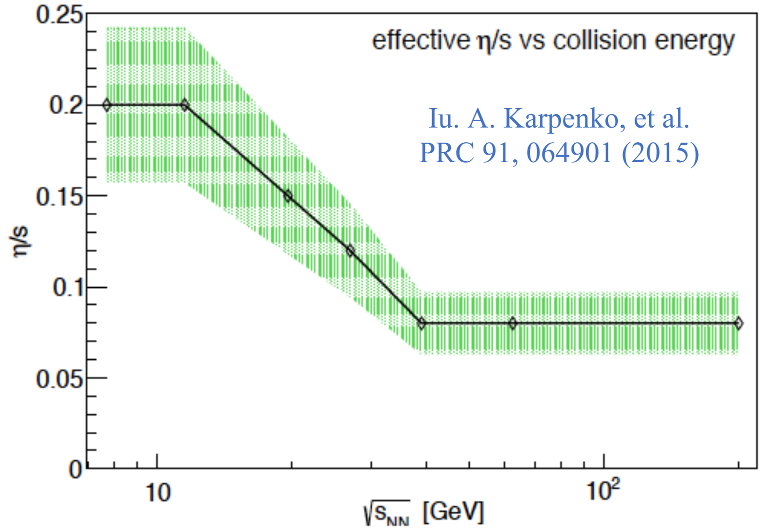
Motivation

- Higher-order flow harmonics are sensitive probes for $\frac{\eta}{s}(T)$ due to the enhanced viscous response
- These flow harmonics ($v_{n=4,5}$) have multiple contributions:
  - ✓ Linear response $\propto \varepsilon_n$
  - ✓ Mode-coupled non-linear response $\propto \varepsilon_2\varepsilon_m(m = 2,3)$ and Event-plane (E-P) correlations
- These flow harmonics ($v_{n=4,5}$) can constrain $\frac{\eta}{s}(T)$ and differentiate between initial state models

I- Beam-energy dependence for a given collision system:



Initial-state ε_2 is approximately energy independent



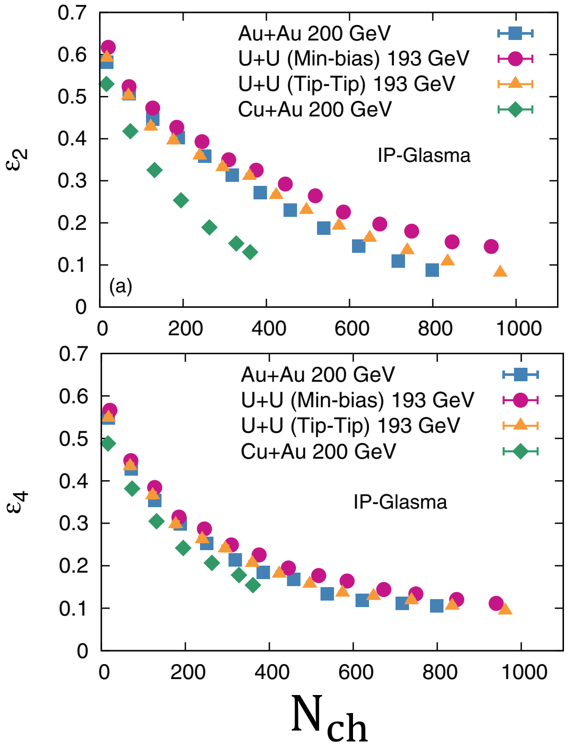
Viscous attenuation ($\propto \frac{\eta}{s}(T)$) is beam energy dependent

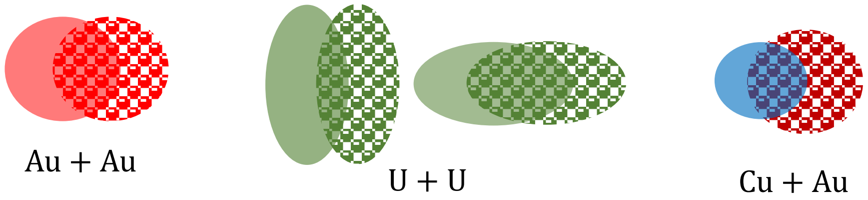
Motivation

- Higher-order flow harmonics are sensitive probes for $\frac{\eta}{s}(T)$ due to the enhanced viscous response
- These flow harmonics ($v_{n=4,5}$) have multiple contributions:
  - ✓ Linear response $\propto \varepsilon_n$
  - ✓ Mode-coupled non-linear response $\propto \varepsilon_2\varepsilon_m (m = 2,3)$ and Event-plane (E-P) correlations
- These flow harmonics ($v_{n=4,5}$) can constrain $\frac{\eta}{s}(T)$ and differentiate between initial state models

II- Collision systems dependence at a given beam energy:

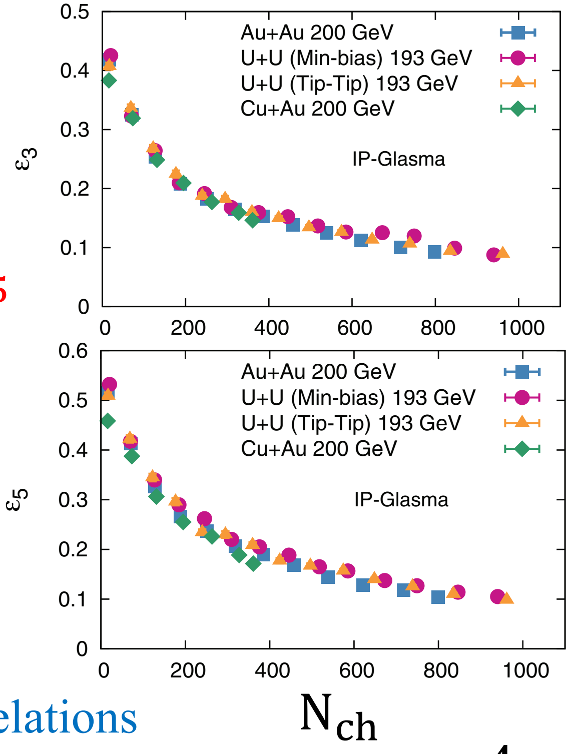
B. Schenke, et al.
PRC 89, 064908 (2014)





The initial-state ϵ_2 and ϵ_4 are system dependent

The initial-state ϵ_3 and ϵ_5 are system independent



- The focus of this work:
  - ✓ Separate and study the linear and mode-coupled contributions
  - ✓ Study the nature of the eccentricity coupling and the E-P correlations

Analysis Method

- The two- and three-particle correlations:

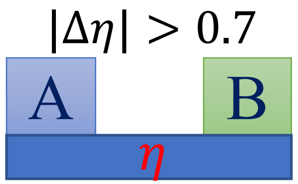
J. Jia, M. Zhou, A. Trzupek, PRC 96 034906 (2017)

(n= 2,3)

$$C_{n+2,2n} = \left\langle\left\langle \cos((n+2)\varphi_1^A - 2\varphi_2^B - n\varphi_3^B)\right\rangle\right\rangle$$

(m= 2,3,4,5)

$$v_m^{Inclusive} = \left\langle\left\langle \cos(m\varphi_1^A - m\varphi_2^B)\right\rangle\right\rangle^{1/2}$$



- The linear and non-linear v_n:

$$v_{n+2}^{Non\ Linear} = \frac{C_{n+2,2n}}{\sqrt{\langle v_2^2 v_n^2\rangle}}$$

$$\sim \langle v_{n+2} \cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n)\rangle$$

Assume the orthogonality between linear and non-linear contributions

$$v_{n+2}^{Linear} = \sqrt{\left(v_{n+2}^{Inclusive}\right)^2 - \left(v_{n+2}^{Non\ Linear}\right)^2}$$

- $v_{n+2}^{\mathrm{Non-Linear}}$ carry information about:
  - ✓ Viscous effects, E-P angular correlations and eccentricity coupling

- E-P angular correlations

$$\rho_{n+2,2n} = \frac{v_{n+2}^{Non\ Linear}}{v_{n+2}^{Inclusive}}$$

$$\sim \langle \cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n)\rangle$$

- Eccentricity coupling

$$\chi_{n+2,2n} = \frac{v_{n+2}^{Non\ Linear}}{\sqrt{\langle v_2^2 v_n^2\rangle}}$$

Weak viscous effect expected

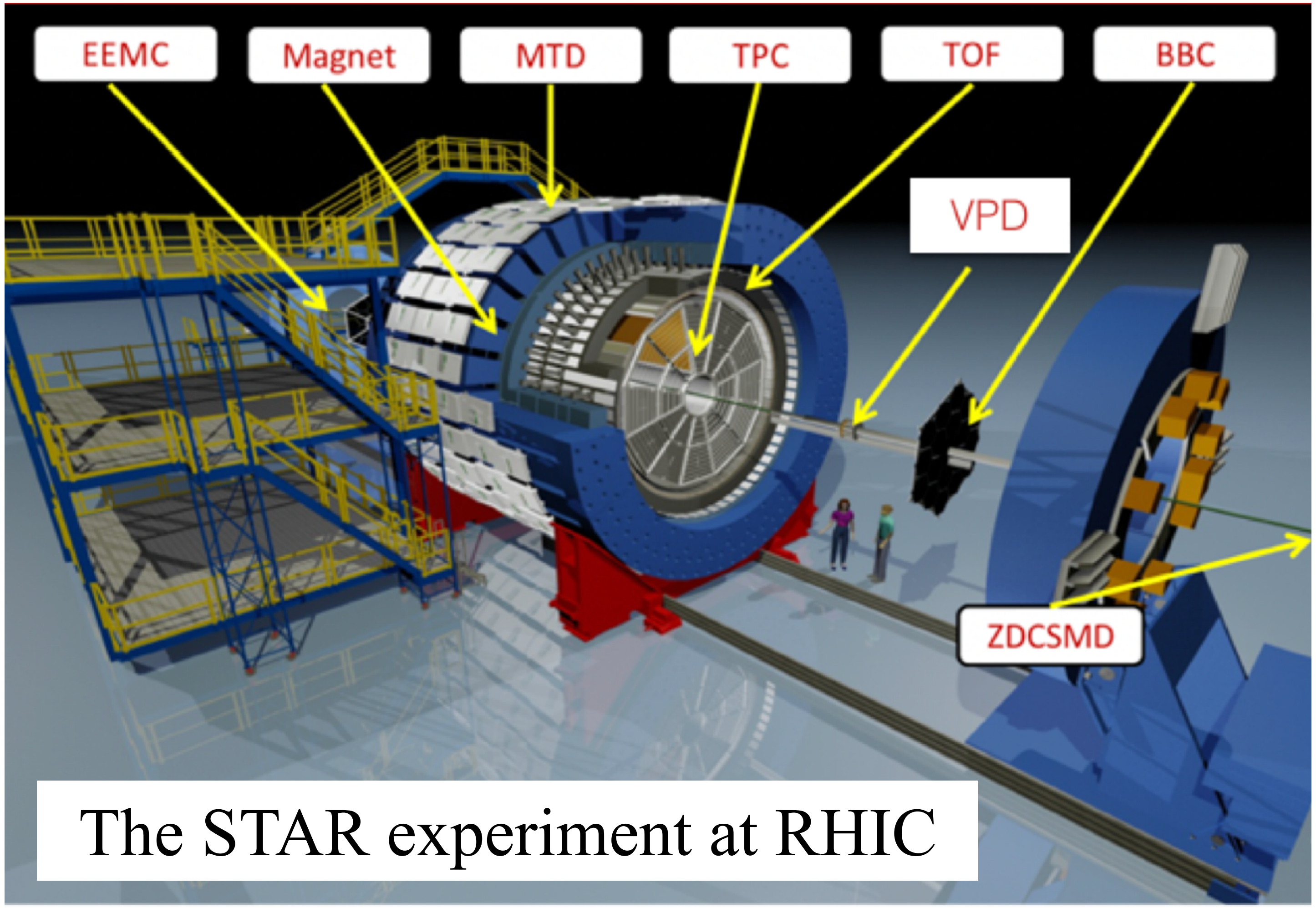
Experimental Setup and Data Analysis

- Data set:
  - ✓ Au +Au BES $\sqrt{s_{NN}} = 27 - 200$ GeV
  - ✓ U+U ($\sqrt{s_{NN}} = 193$ GeV) and Cu+Au, Au+Au ($\sqrt{s_{NN}} = 200$ GeV)

- Time Projection Chamber

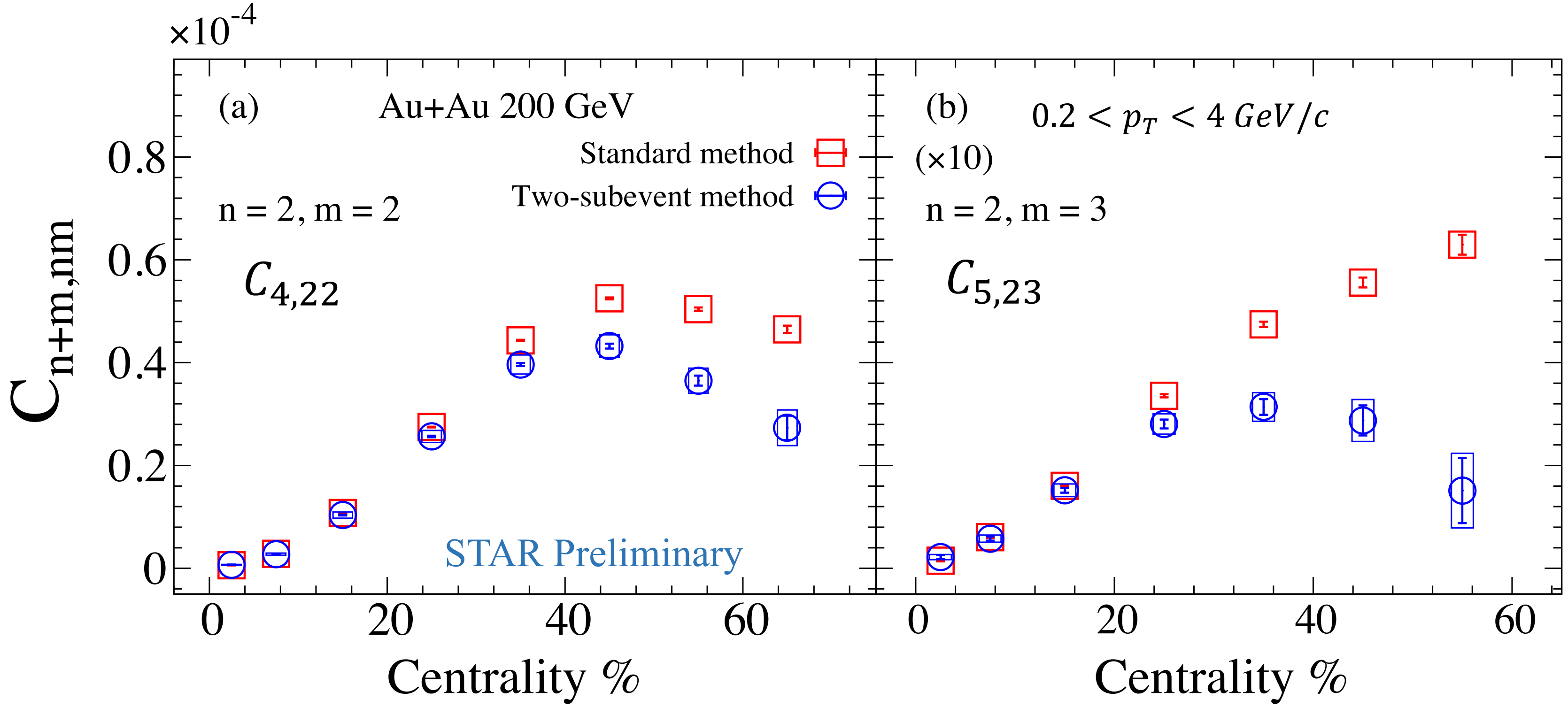
  Tracking of charged particles with:
  - ✓ Full azimuthal coverage
  - ✓ $|\eta| < 1$ coverage

- In this analysis, we used tracks with : $0.2 < p_T < 4$ GeV/c



Results

Three-particle correlations $C_{4,22}$ and $C_{5,23}$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV



✓ Standard method

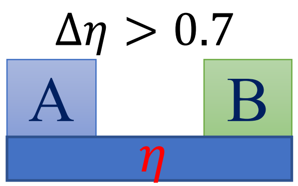
$$C_{4,22} = \langle\langle \cos(4\varphi_1 - 2\varphi_2 - 2\varphi_3) \rangle\rangle$$

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

✓ Two-subevents method

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

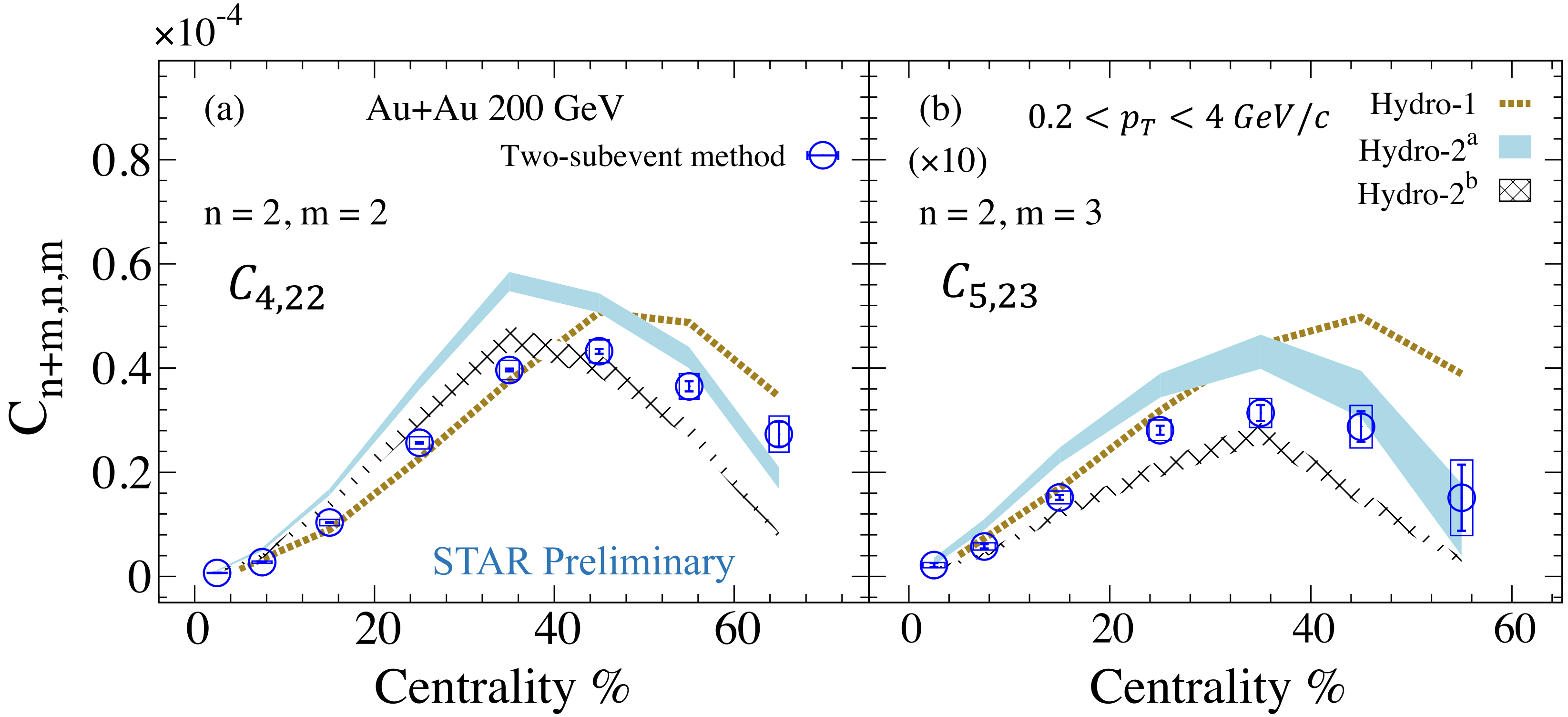
$$C_{5,23} = \left\langle\left\langle \cos(5\varphi_1^A - 2\varphi_2^B - 3\varphi_3^B) \right\rangle\right\rangle$$



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

Results

Three-particle correlations $C_{4,22}$ and $C_{5,23}$ with different hydrodynamic simulations



- ✓ Standard method

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

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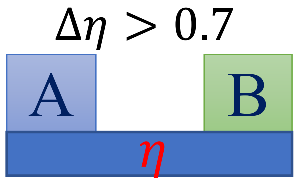
- ✓ Two-subevents method

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

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



	Hydro−1	Hydro−2$^{a/b}$
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

- (1) P. Alba, et al. PRC 98 , 034909 (2018)
- (2) B.Schenke, C.Shen, and P.Tribedy PRC 99, 044908 (2019)

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

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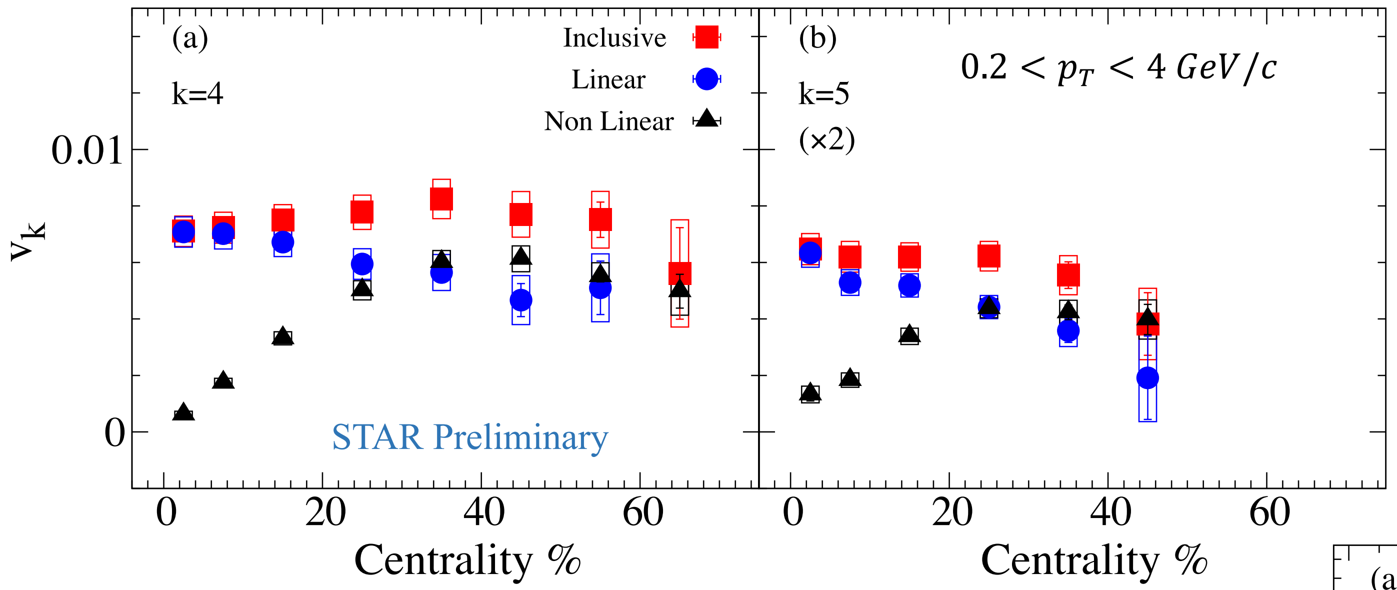
Results

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

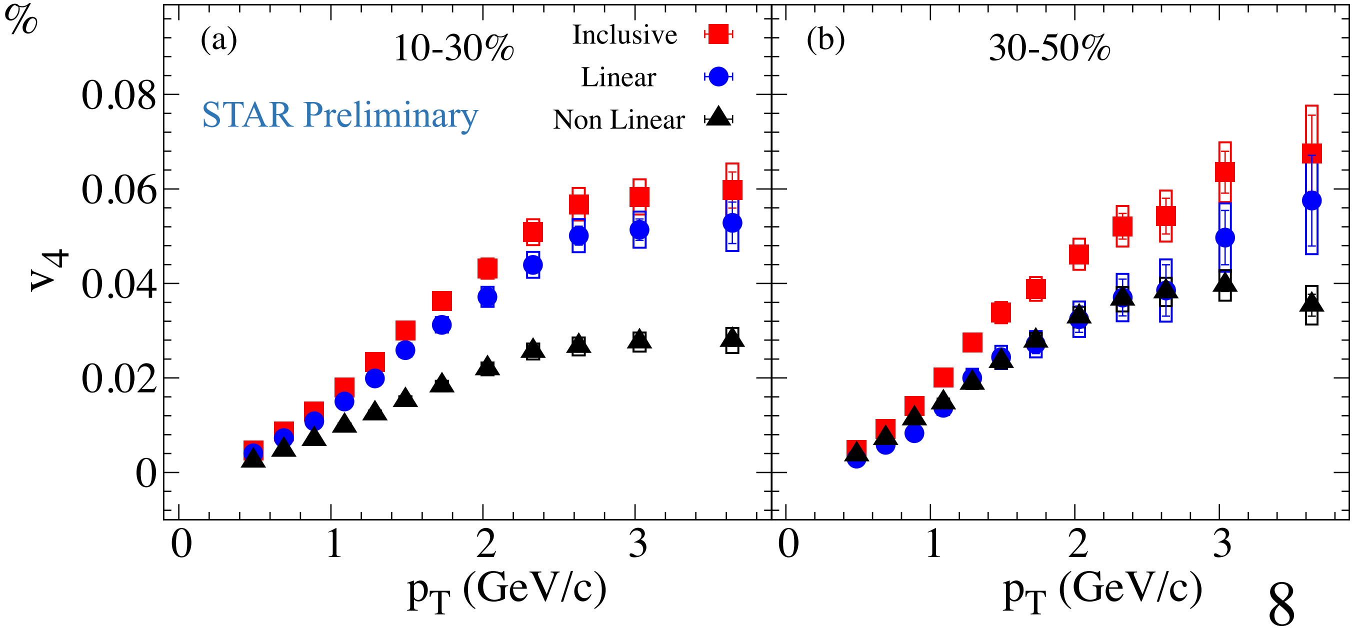


$n = 2,3$

$$v_{n+2}^{Inclusive} = \left\langle\left\langle \cos\left((n+2)\left(\varphi_1^A - \varphi_2^B\right)\right)\right\rangle\right\rangle^{1/2}$$

$$v_{n+2}^{Non\ Linear} = \frac{\langle\langle \cos((n+2)\varphi_1^A - 2\varphi_2^B - n\varphi_3^B)\rangle\rangle}{\sqrt{\langle v_2^2 v_n^2\rangle}}$$

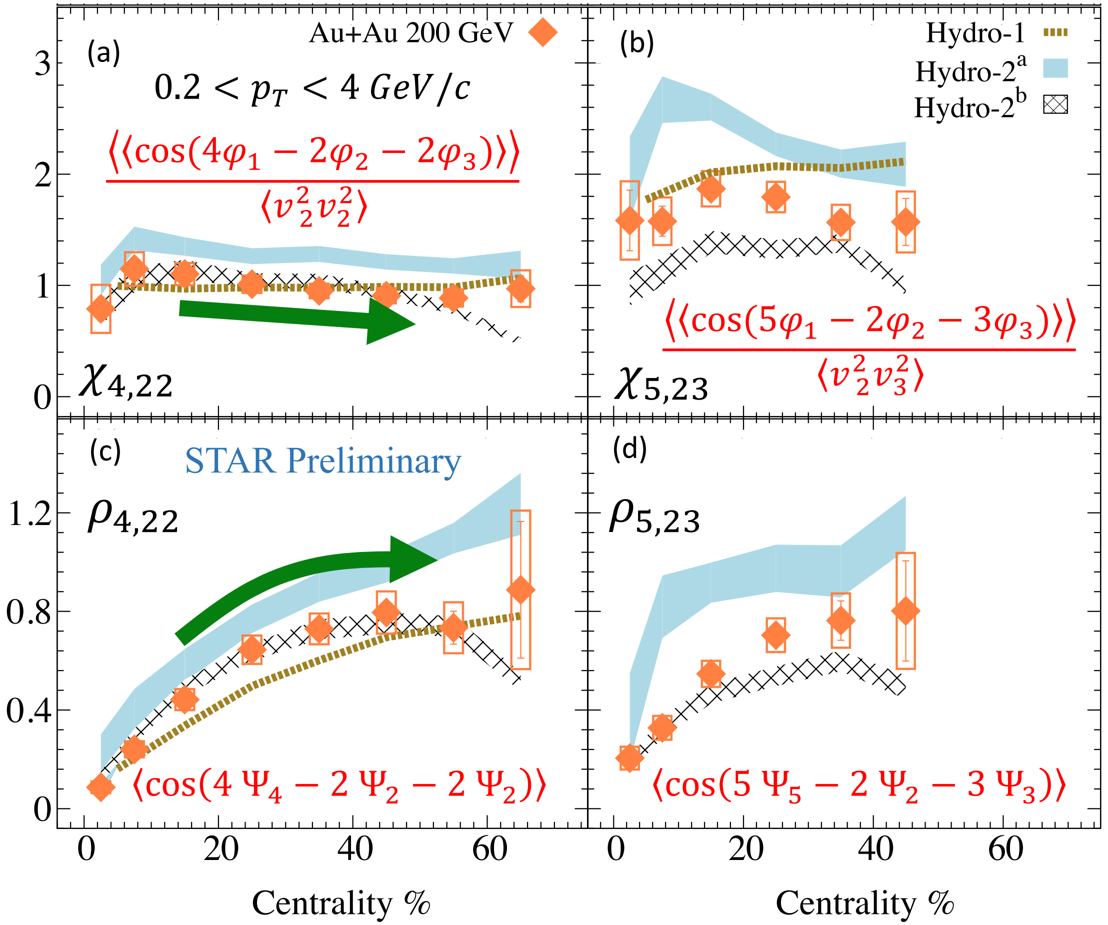
$$v_{n+2}^{Linear} = \sqrt{\left(v_{n+2}^{Inclusive}\right)^2 - \left(v_{n+2}^{Non\ Linear}\right)^2}$$



- 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

Results

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



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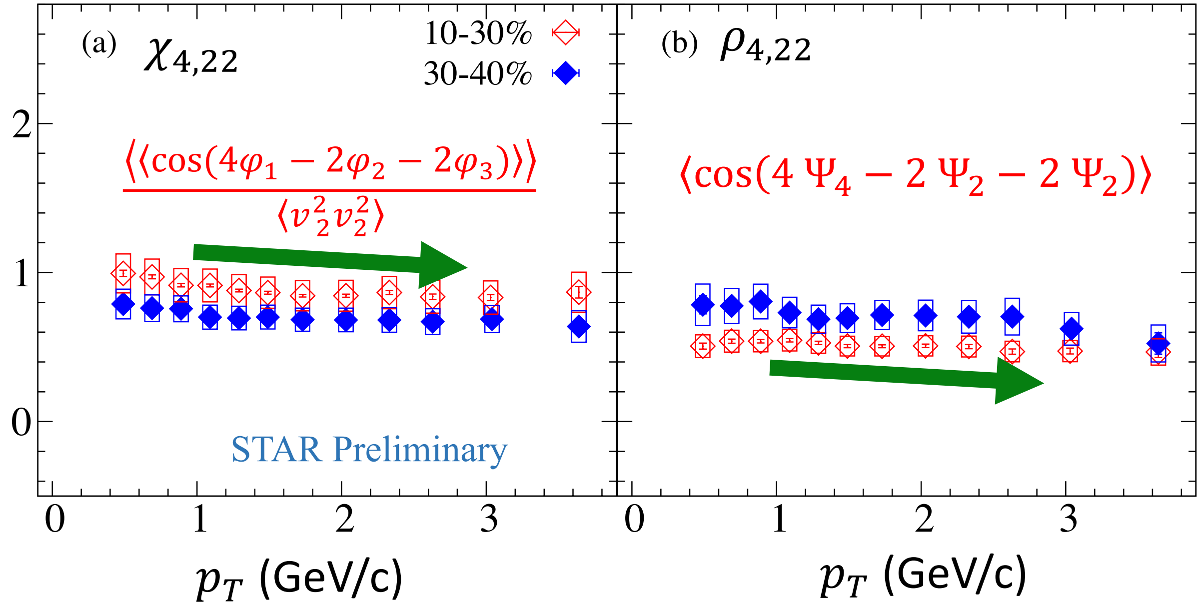


- $\chi_{k,nm}$ shows a weak centrality dependence
- $\rho_{k,nm}$ shows a strong centrality dependence
- $\rho_{4,22}$ and $\chi_{4,22}$ show a weak p_T dependence

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

Results Linear and non-linear flow v_4 decomposition with different beam energies and colliding systems

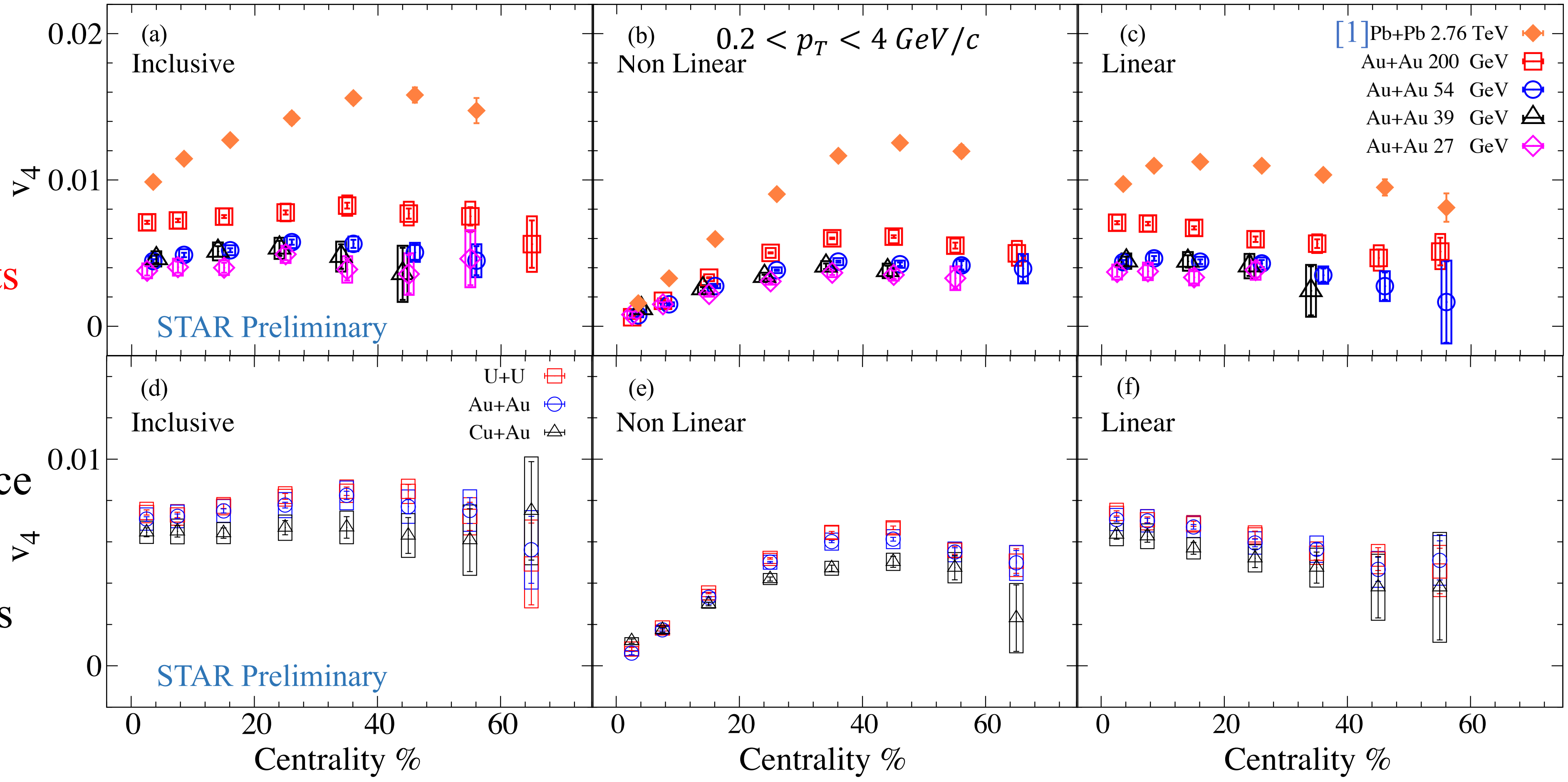
- The inclusive, linear and non-linear v_4 show strong beam-energy dependence

Possible temperature dependence of viscous effects

- The inclusive, linear and non-linear v_4 show weak collision-system dependence

- The linear terms dominates the central collisions

$\left\langle\left\langle \cos(4\varphi_1^A - 4\varphi_2^B)\right\rangle\right\rangle^{1/2}$ $\left\langle\left\langle \cos(4\varphi_1^A - 2\varphi_2^B - 2\varphi_3^B)\right\rangle\right\rangle / \left\langle v_2^2 v_2^2\right\rangle$ $\sqrt{(v_4^{Inclusive})^2 - (v_4^{Non\ Linear})^2}$



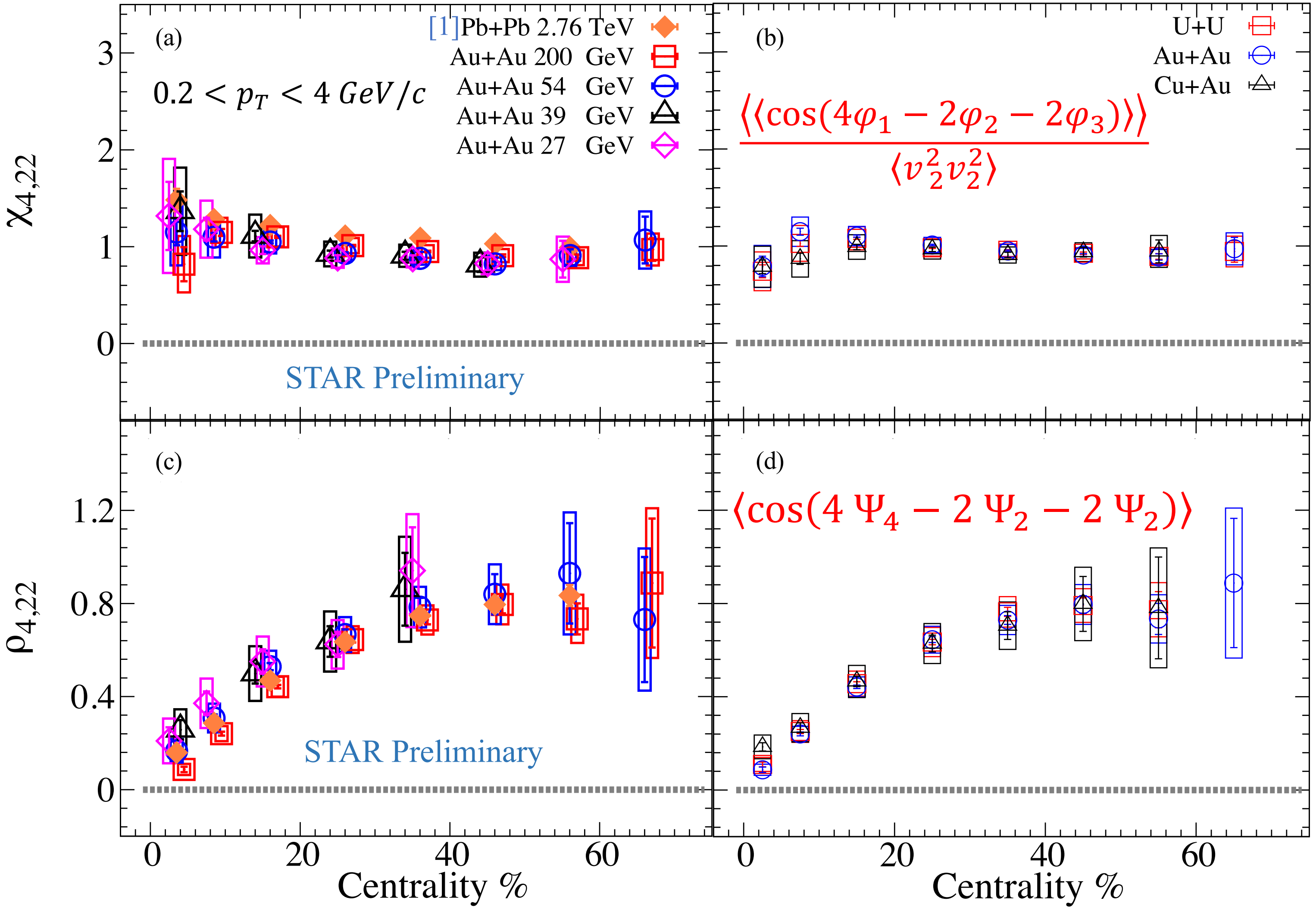
[1] The ALICE collaboration PLB 773 68-80, (2017) $0.2 < p_T < 5$ (GeV/c)

Results

The mode-coupling coefficients $\chi_{4,22}$ and the E-P angular correlations $\rho_{4,22}$

- The non-linear mode-coupling coefficients $\chi_{4,22}$ shows similar values and trends for different beam energies and for different collision systems, and a weak centrality dependence.
- The E-P angular correlations $\rho_{4,22}$ shows similar values and trends for different beam energies and for different collision systems, and a strong centrality dependence.

Dominated by the initial-state effects



[1] The ALICE collaboration PLB 773 68-80, (2017) $0.2 < p_T < 5$ (GeV/c)

Conclusion

The linear and non-linear contributions to v_4 and v_5 measurements for different collision systems at different beam energies

- For Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV:
  - ✓ Two-subevent method reduces the non-flow
  - ✓ The linear component of v_n (n=4,5) dominates in central collisions
  - ✓ The mode-coupling coefficients and the E-P angular correlations show a weak and a strong centrality dependences, respectively, and a common weak p_T dependence

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

- For different beam energies and collision systems:
  - ✓ The inclusive, linear and non-linear v_4 show strong beam energy and weak collision-system dependence
  - ✓ The mode-coupling coefficients and the E-P angular correlations show similar values and trends

These measurements compared to viscous hydrodynamic model calculation will provide constraints on the initial conditions and $\frac{\eta}{s}(T)$

Thank You

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Backup

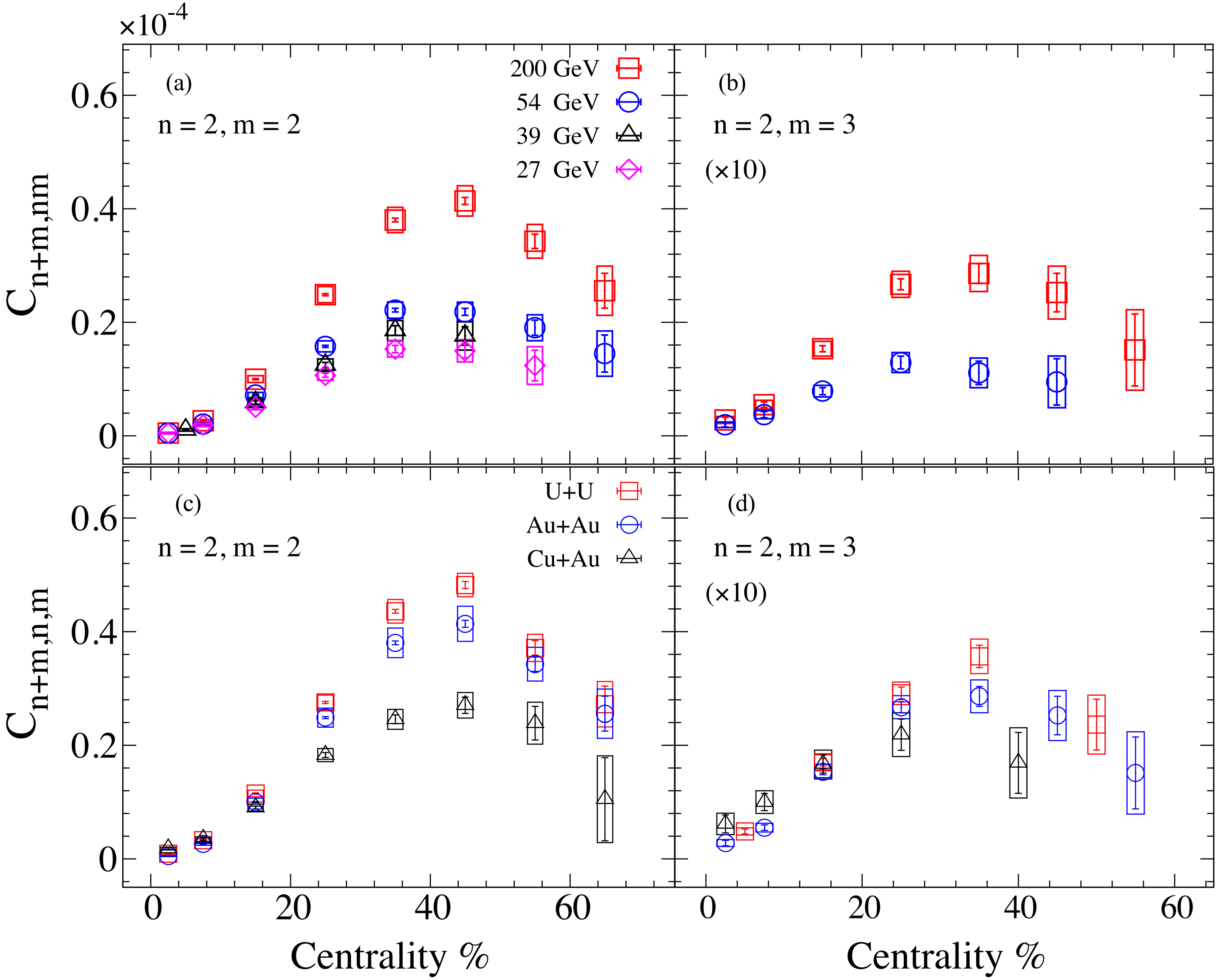
The three-particle correlations, $C_{4,22}$ and $C_{5,23}$ for Au+Au collisions at 200, 54, 39, and 27 GeV, U+U collisions at 193 GeV and Cu+Au at 200 GeV

- ➢ The three-particle correlations $C_{4,22}$ and $C_{5,23}$ show strong beam energy dependence

Strong sensitivity to viscous effects

- ➢ The three-particle correlations $C_{4,22}$ shows a collision-system dependence

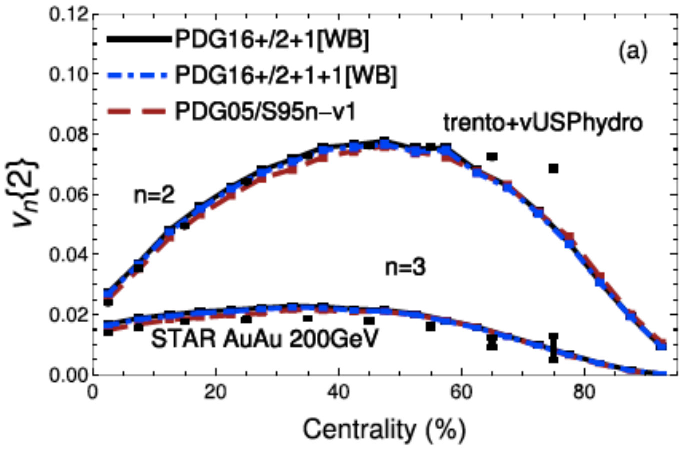
- ➢ The three-particle correlations $C_{4,22}$ shows a weak collision-system dependence



Backup

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

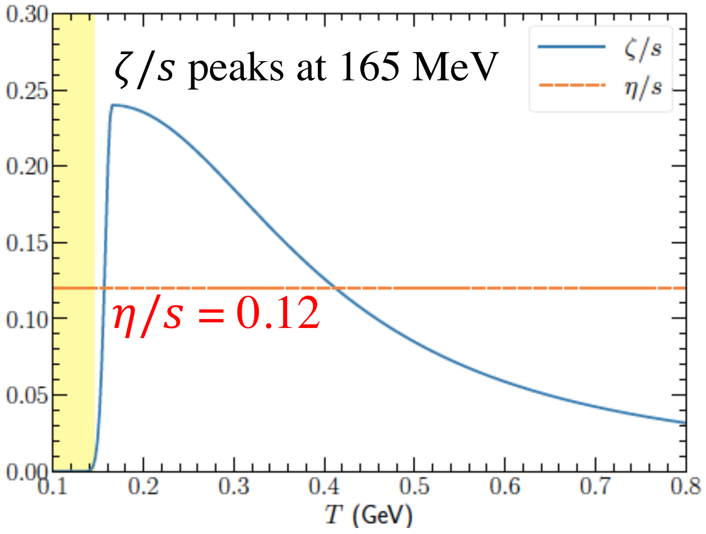
- The model use event-by-event fluctuating initial conditions generated by the TRENTO model with free parameters calibrated to fit experimental observables.
- The model use the smoothed particle hydrodynamics (SPH) Lagrangian code, v-USPhydro, to solve the viscous hydrodynamic equations taking into account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

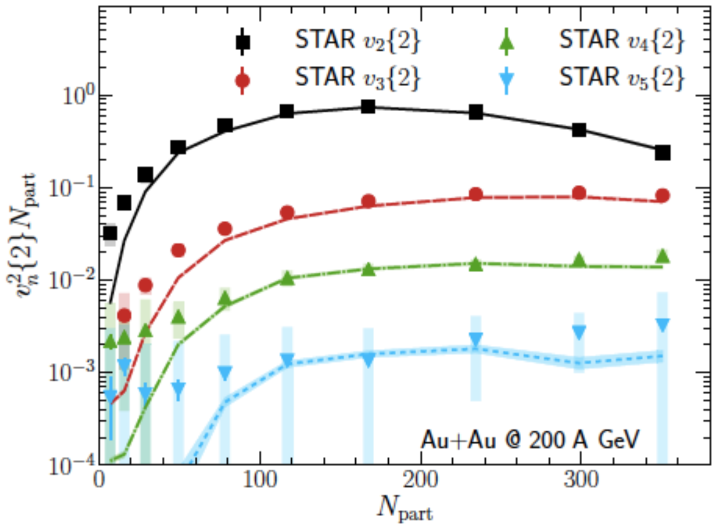


(2) B.Schenke , et al. PRC 99, 044908 (2019)

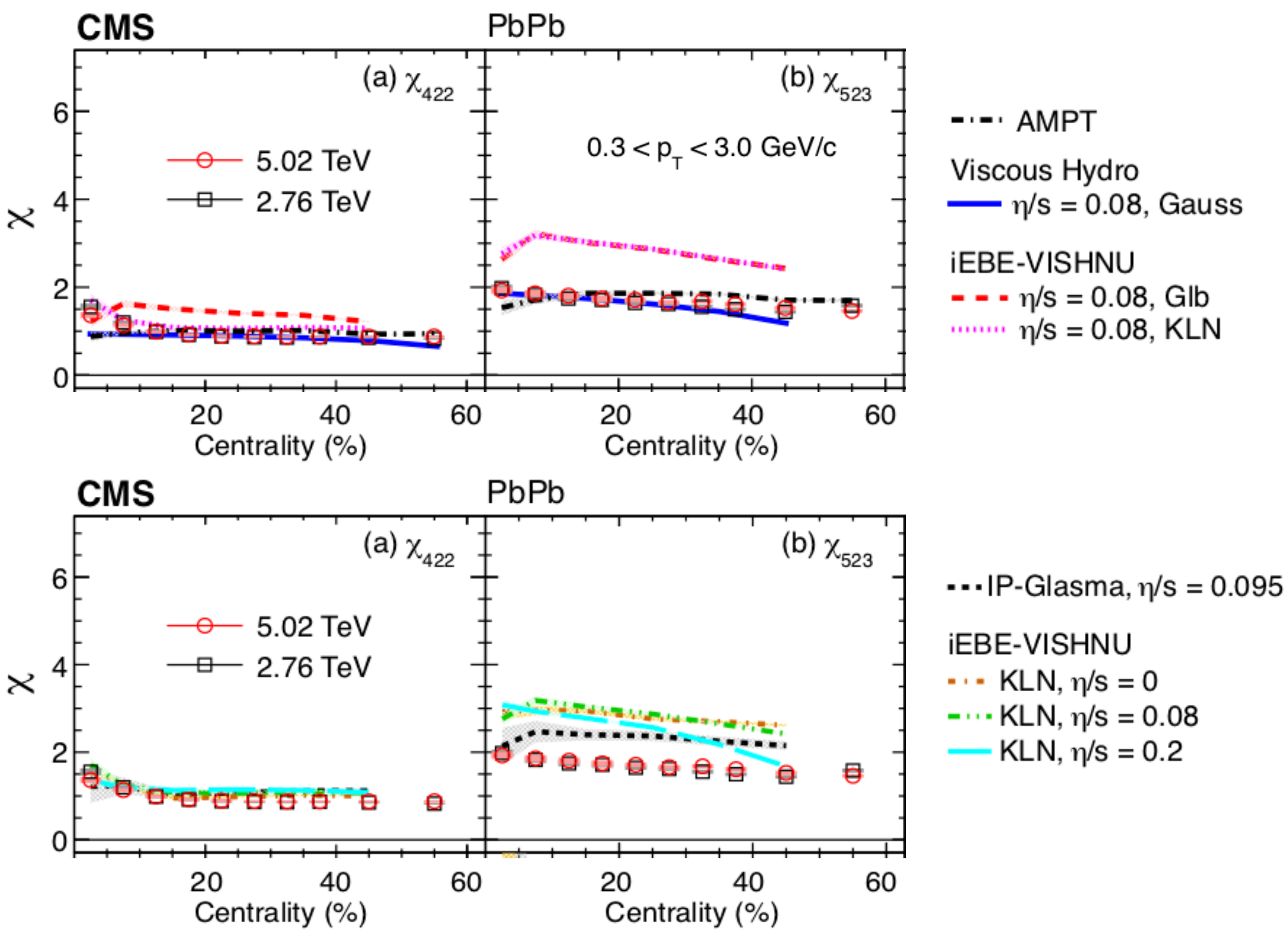
- The model used the impact parameter-dependent Glasma model to initialize the viscous hydrodynamic simulation MUSIC and employ the UrQMD transport model for the low-temperature region of the collisions.

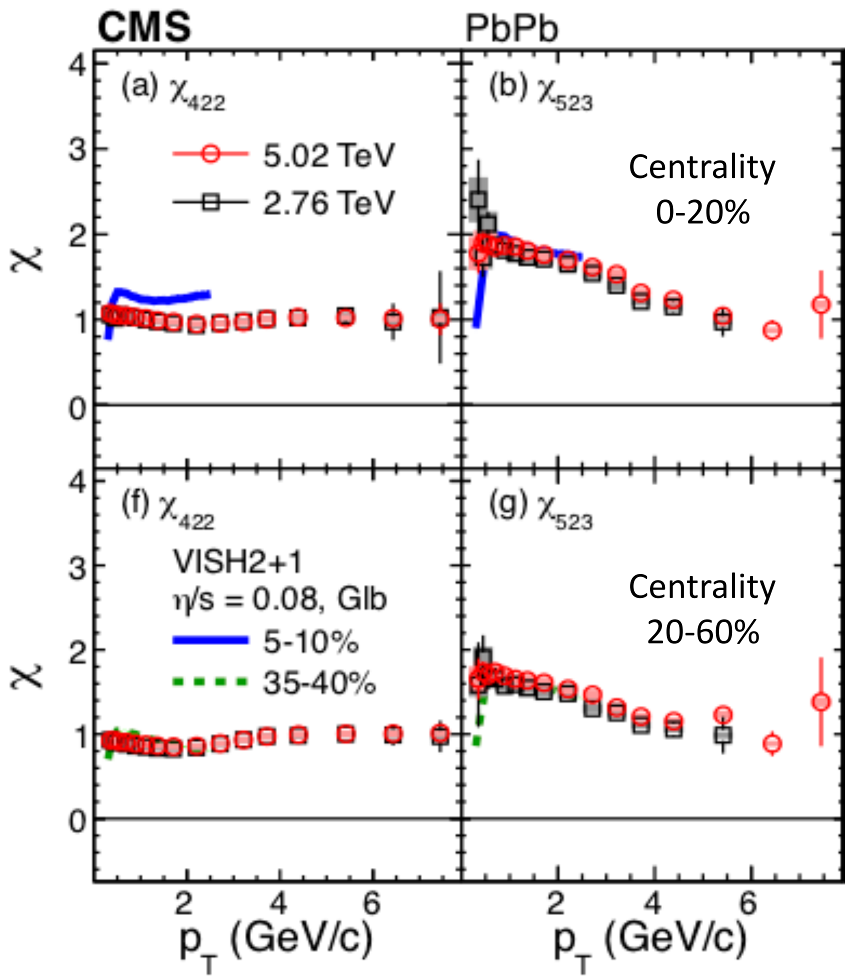
Width, height, and position of ζ/s are free parameters





LHC data, CMS-HIN-17-005, (arXiv:1910.08789)





J. Qian , U. Heinz, R. He and L. Huo, (arXiv:1703.04077)

Hydro MC-Glauber, τ_0 = 0.6 fm/c, η/s = 0.08, T_{dec} = 120 MeV

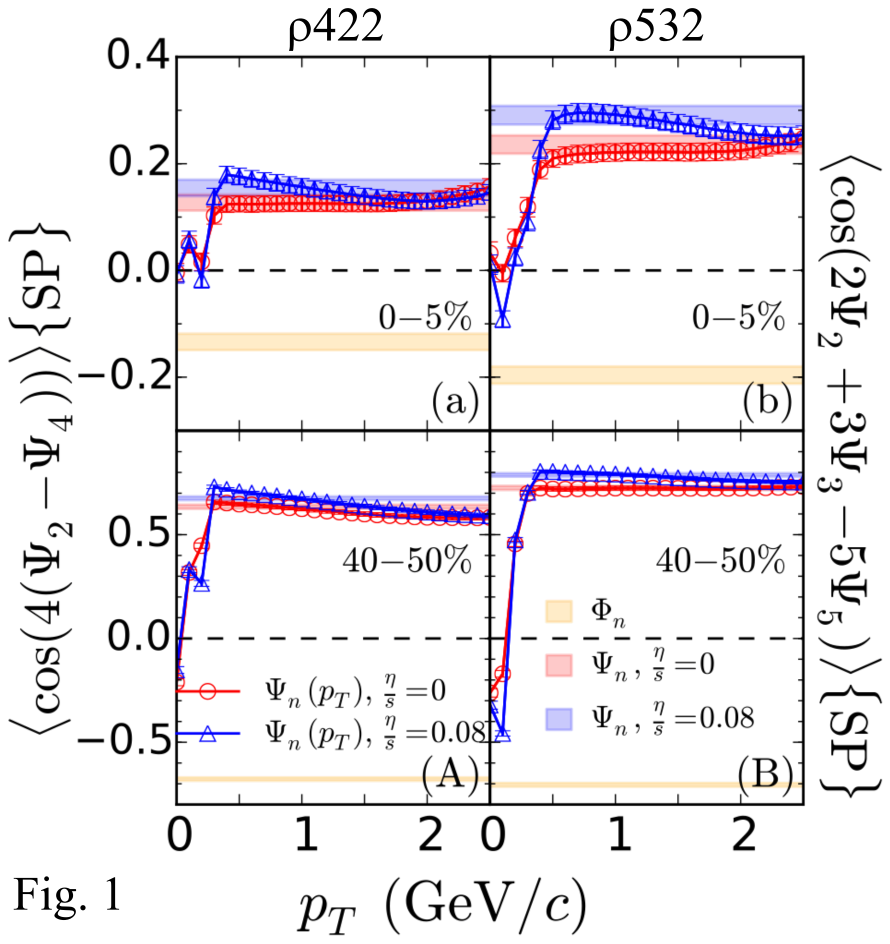


Fig. 1

FIG. 1. (Color online) p_T dependence of the two- and three-plane correlations $\langle\cos(4(\Psi_2-\Psi_4))\rangle\{SP\}$ and three-plane correlation $\langle\cos(2\Psi_2+3\Psi_3-5\Psi_5)\rangle\{SP\}$. Subgraphs (a-b) are for events of 0-5% centrality while (A-B) are for 40-50% centrality. In each centrality class 2000 hydrodynamic events are used for the analysis. Red and blue represent ideal and viscous hydrodynamic results, respectively. Markers show event-plane correlations for differential flows, and colored bands are those for the corresponding integrated flows shown for comparison. The corresponding participant plane correlations are shown as yellow bands. The widths of the bands indicate the corresponding variances due to event-by-event fluctuations.

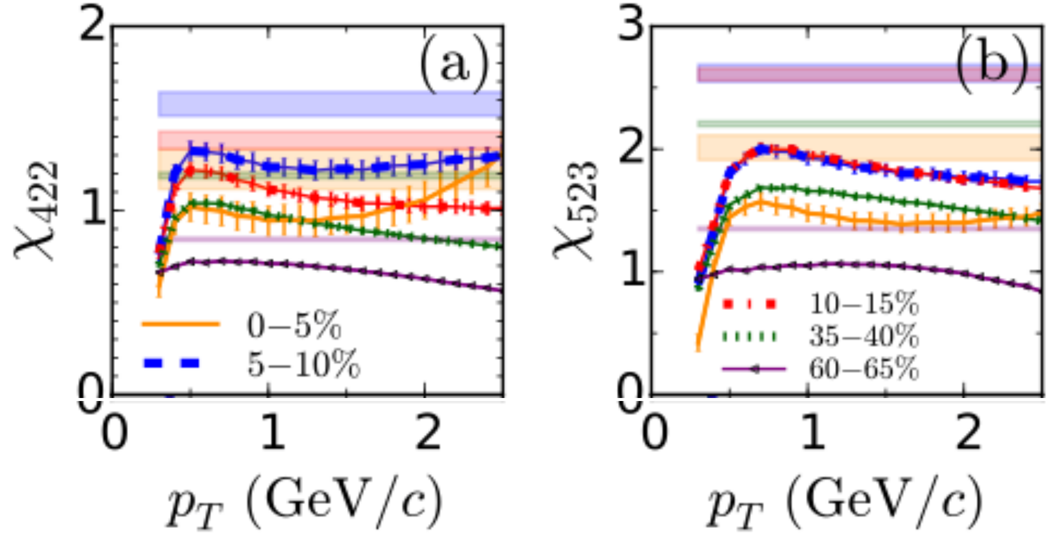


Fig. 4 : viscous hydrodynamics with η/s = 0.08