Investigation of the linear and mode-coupled flow harmonics in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Niseem Magdy
For the STAR Collaboration
University of Illinois at Chicago
niseemm@gmail.com

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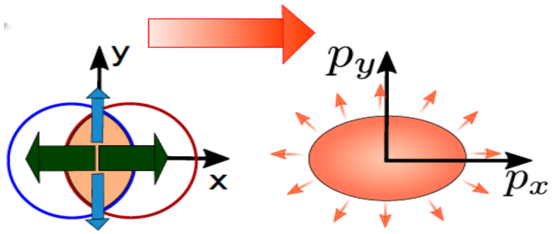
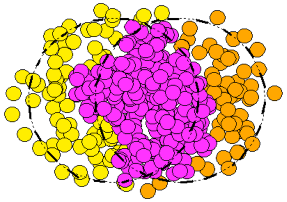
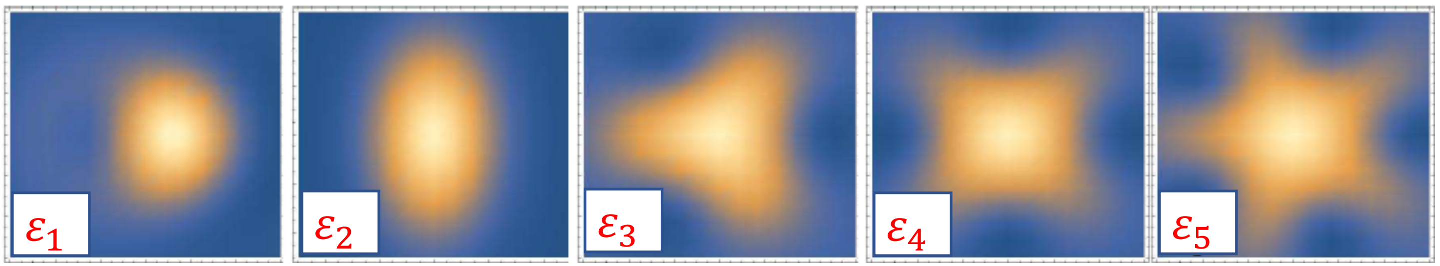
Introduction

Anisotropic flow

Asymmetry in initial geometry → Final-state momentum anisotropy







What are the respective roles of ε_n and its fluctuations, flow correlations and $\eta/s(T)$ on the v_n?

Anisotropic flow

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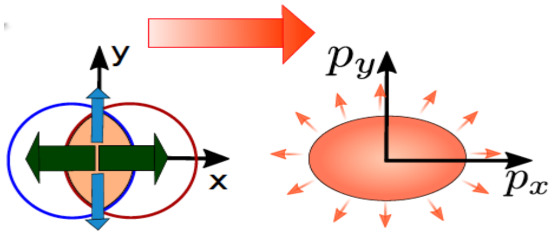

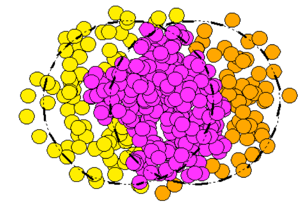

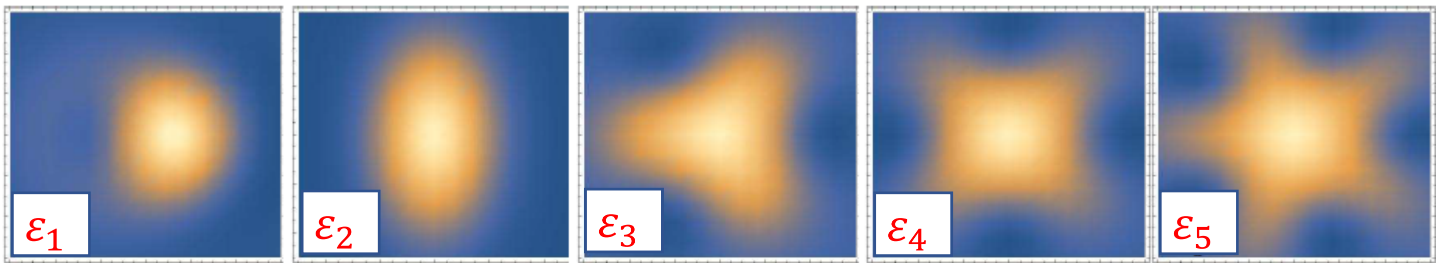

What are the respective roles of ε_n and its fluctuations, flow correlations and η/s(T) on the v_n?

Higher-order flow harmonics ($v_{\mathrm{n}>3}$) have multiple contributions:

- ✓ Linear response ∝ $\varepsilon_{\mathrm{n}>3}$
- ✓ Mode-coupled response ∝ ε_2 and/or ε_3 and the Event Plane (EP) correlations

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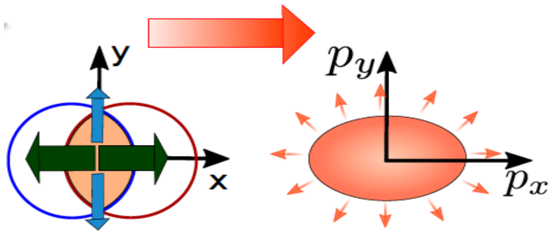
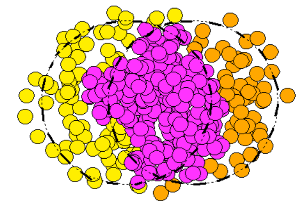
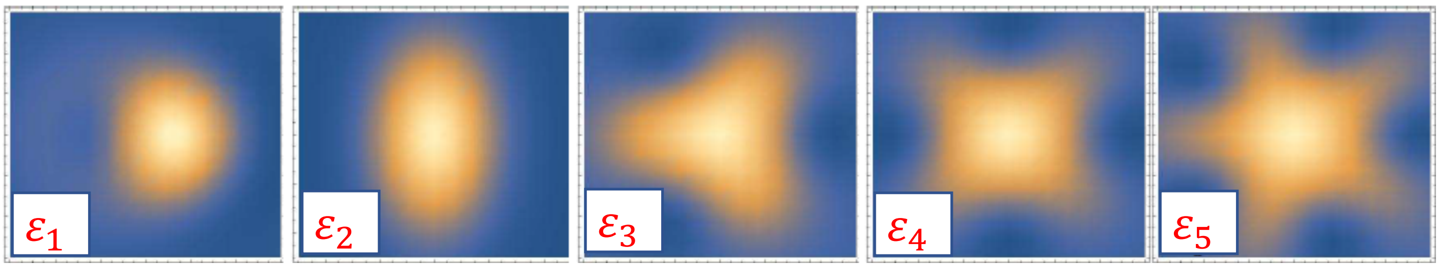






What are the respective roles of ε_n and its fluctuations, flow correlations and $\eta/s(T)$ on the v_n?

Higher-order flow harmonics ($v_{n>3}$) have multiple contributions:

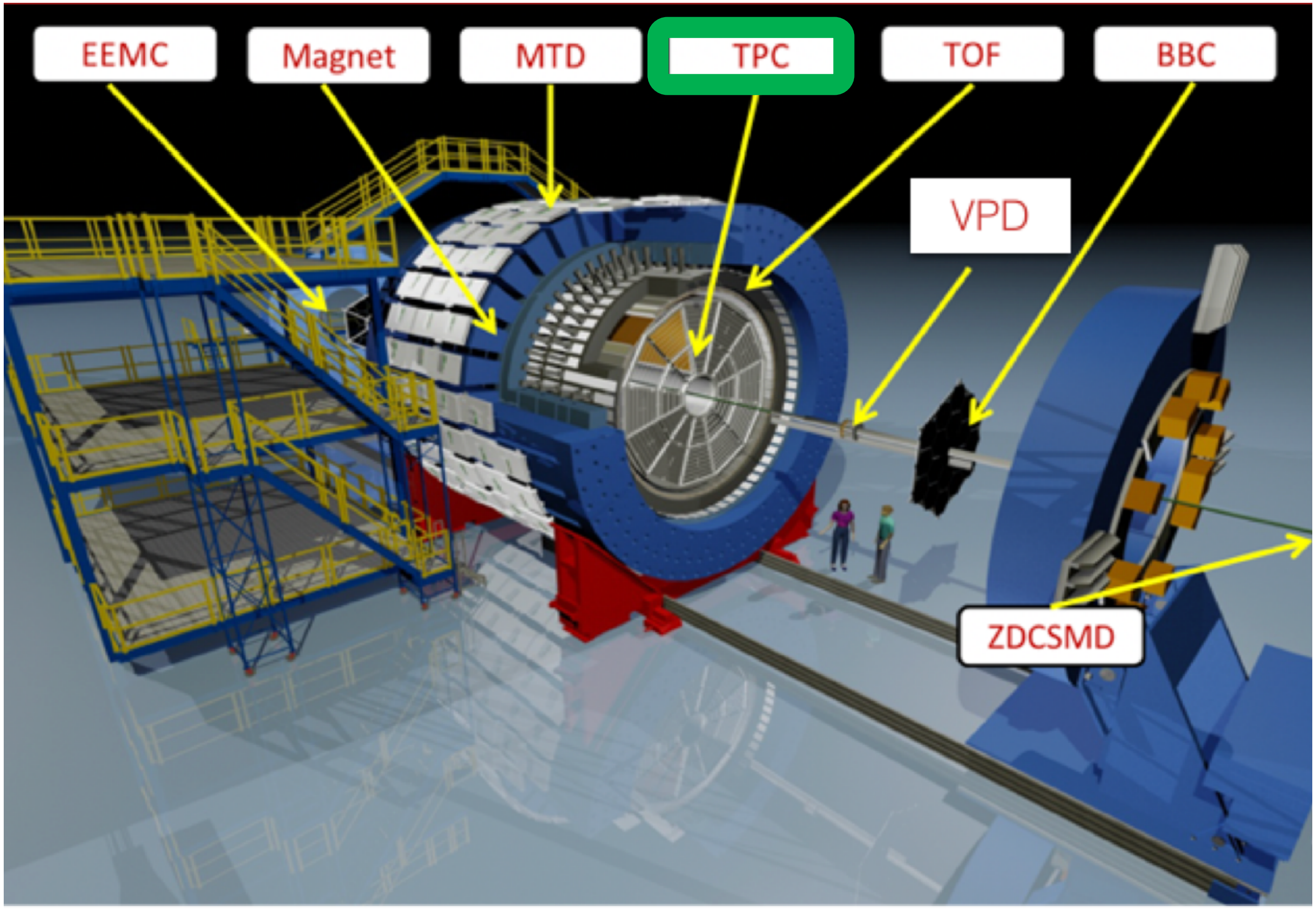
- ✓ Linear response $\propto \varepsilon_{n>3}$
- ✓ Mode-coupled response $\propto$ ε_2 and/or ε_3 and the Event Plane (EP) correlations

The focus of this work:

- ✓ Separate and study the linear and mode-coupled contributions
- ✓ Study the nature of the eccentricity coupling and the EP correlations

Introduction

The Solenoidal Tracker At RHIC



- ➢ Time Projection Chamber

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

Analysis Method

n= 2,3 k= $n+2$

$|\Delta\eta| > 0.7$

The two- and three-particle correlations:

$$C_{k,2n} = \left\langle\left\langle \cos((2+n)\varphi_1^A - 2\varphi_2^B - n\varphi_3^B) \right\rangle\right\rangle \qquad v_n^{Inclusive} = \left\langle\left\langle \cos\left(n\varphi_1^A - n\varphi_2^B\right) \right\rangle\right\rangle^{1/2}$$

The four-particle correlations:

$$\langle \mathrm{v}_2^4 \rangle = \langle\langle \cos(2\varphi_1 + 2\varphi_2 - 2\varphi_3 - 2\varphi_4) \rangle\rangle - 2\,\langle\langle \cos(2\varphi_1 - 2\varphi_2) \rangle\rangle^2 + 2\left\langle\left\langle \cos\left(2\varphi_1^A - 2\varphi_2^B\right) \right\rangle\right\rangle^2$$

$$\langle \mathrm{v}_2^2 \mathrm{v}_3^2 \rangle = \langle\langle \cos(3\varphi_1 + 2\varphi_2 - 3\varphi_3 - 2\varphi_4) \rangle\rangle - \langle\langle \cos(2\varphi_1 - 2\varphi_2) \rangle\rangle \langle\langle \cos(4\varphi_1 - 3\varphi_2) \rangle\rangle + \left\langle\left\langle \cos\left(2\varphi_1^A - 2\varphi_2^B\right) \right\rangle\right\rangle \left\langle\left\langle \cos\left(3\varphi_1^A - 3\varphi_2^B\right) \right\rangle\right\rangle$$

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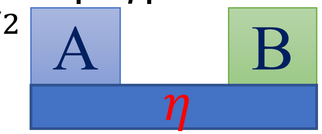

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Assume the orthogonality between linear and non-linear contributions

$$V_k = V_k^{Linear} + V_k^{Non-Linear}$$

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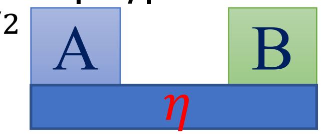

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- $v_k^{\mathrm{Non-Linear}}$ carry information about:
  - ✓ Viscous effects, EP angular correlations and Eccentricity coupling

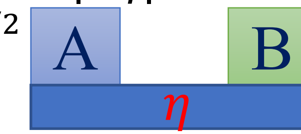
$$\begin{aligned} v_k^{Non-Linear} &= \frac{\mathrm{C}_{\mathrm{k,2,n}}}{\sqrt{\langle \mathrm{v}_2^2 \mathrm{v}_\mathrm{n}^2\rangle}}, \\ &= \frac{\langle \mathrm{v_k\, v_2\, v_n}\ \cos(\mathrm{k}\Psi_\mathrm{k} - \mathrm{n}\Psi_\mathrm{n} - 2\Psi_2)\rangle}{\langle \mathrm{v}_2^2 \mathrm{v}_\mathrm{n}^2\rangle}, \\ &\sim \langle \mathrm{v_k}\ \cos(\mathrm{k}\Psi_\mathrm{k} - \mathrm{n}\Psi_\mathrm{n} - 2\Psi_2)\rangle, \end{aligned}$$

$$v_k^{Linear} = \sqrt{(\mathrm{v}_\mathrm{k}^{\mathrm{Inclusive}})^2 - (\mathrm{v}_\mathrm{k}^{\mathrm{Non-Linear}})^2}.$$

Analysis Method

The two- and three-particle correlations: n= 2,3 k= $n+2$ $|\Delta\eta| > 0.7$

$$C_{k,2n} = \left\langle\left\langle \cos((2+n)\varphi_1^A - 2\varphi_2^B - n\varphi_3^B)\right\rangle\right\rangle \qquad v_n^{Inclusive} = \left\langle\left\langle \cos\left(n\varphi_1^A - n\varphi_2^B\right)\right\rangle\right\rangle^{1/2}$$



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- $v_k^{\mathrm{Non-Linear}}$ carry information about:
  - ✓ Viscous effects, EP angular correlations and Eccentricity coupling

$$v_k^{Non-Linear} = \frac{C_{k,2,n}}{\sqrt{\langle v_2^2 v_n^2\rangle}}, = \frac{\langle v_k\, v_2\, v_n\, \cos(k\Psi_k - n\Psi_n - 2\Psi_2)\rangle}{\langle v_2^2 v_n^2\rangle}, \sim \langle v_k\, \cos(k\Psi_k - n\Psi_n - 2\Psi_2)\rangle,$$

$$v_k^{Linear} = \sqrt{(v_k^{\mathrm{Inclusive}})^2 - (v_k^{\mathrm{Non-Linear}})^2}$$

✓ **EP angular correlations**

$$\rho_{k,2n} = \frac{v_k^{\mathrm{Non-Linear}}}{v_k^{\mathrm{Inclusive}}} = \langle\cos(k\Psi_k - 2\Psi_2 - n\Psi_n)\rangle$$

✓ **Eccentricity coupling**

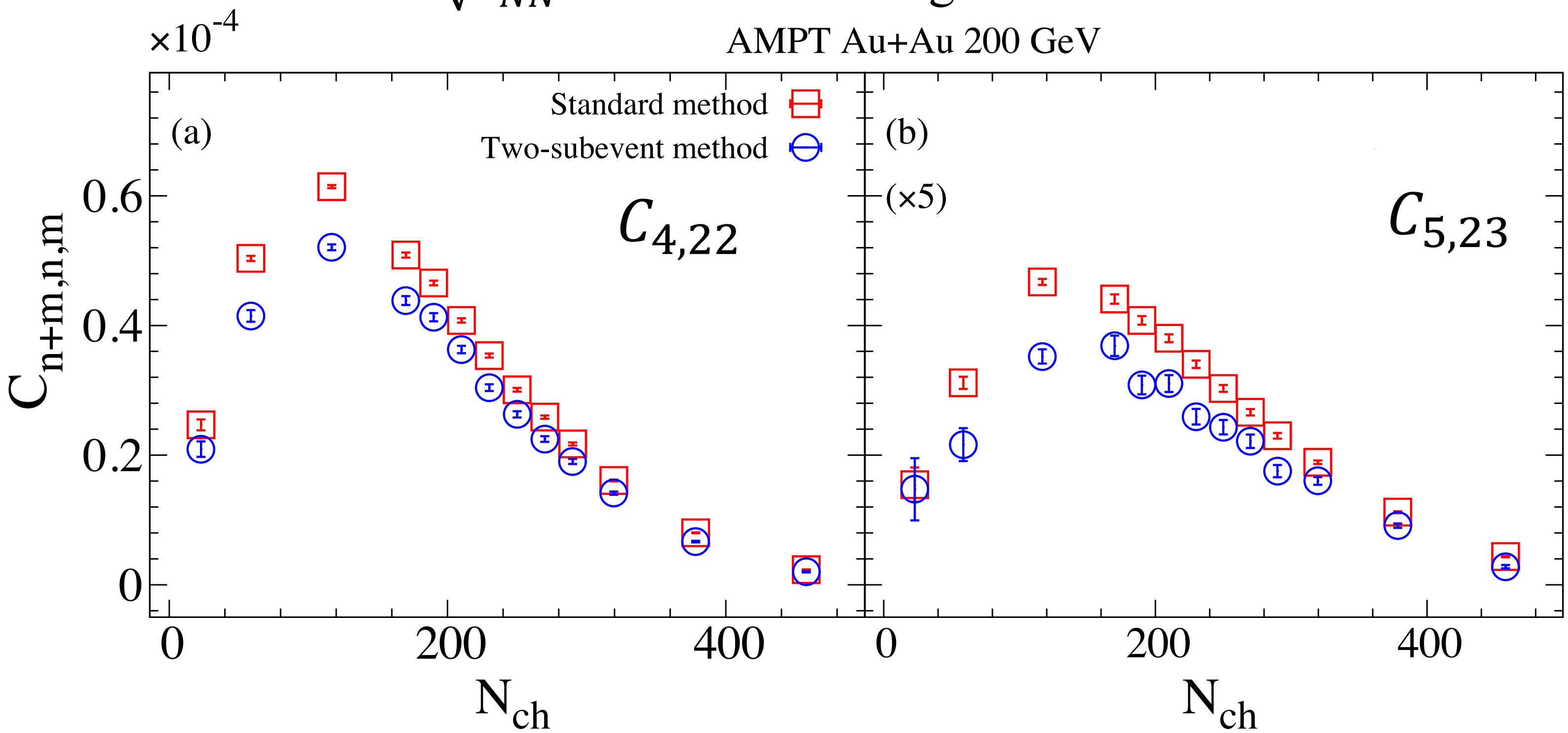
$$\chi_{k,2n} = \frac{v_k^{\mathrm{Non-Linear}}}{\sqrt{\langle v_2^2\, v_n^2\rangle}}$$

Weak viscous effect expected

P.Liu, R.Lacey PRC 98, 021902 (2018)

The short-range non-flow contributions in the three-particle correlations

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



- Two-subevents reduce the short-range non-flow effects in the three-particle correlation measurements

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

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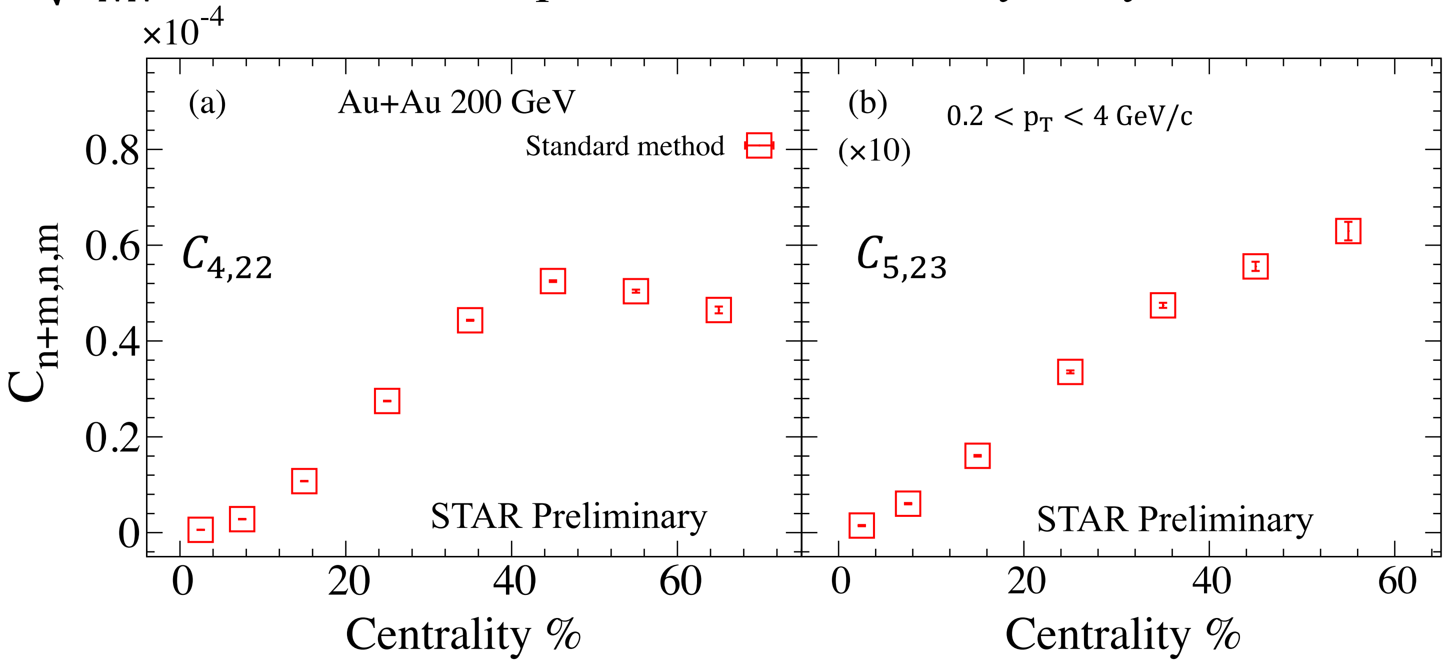
Results

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



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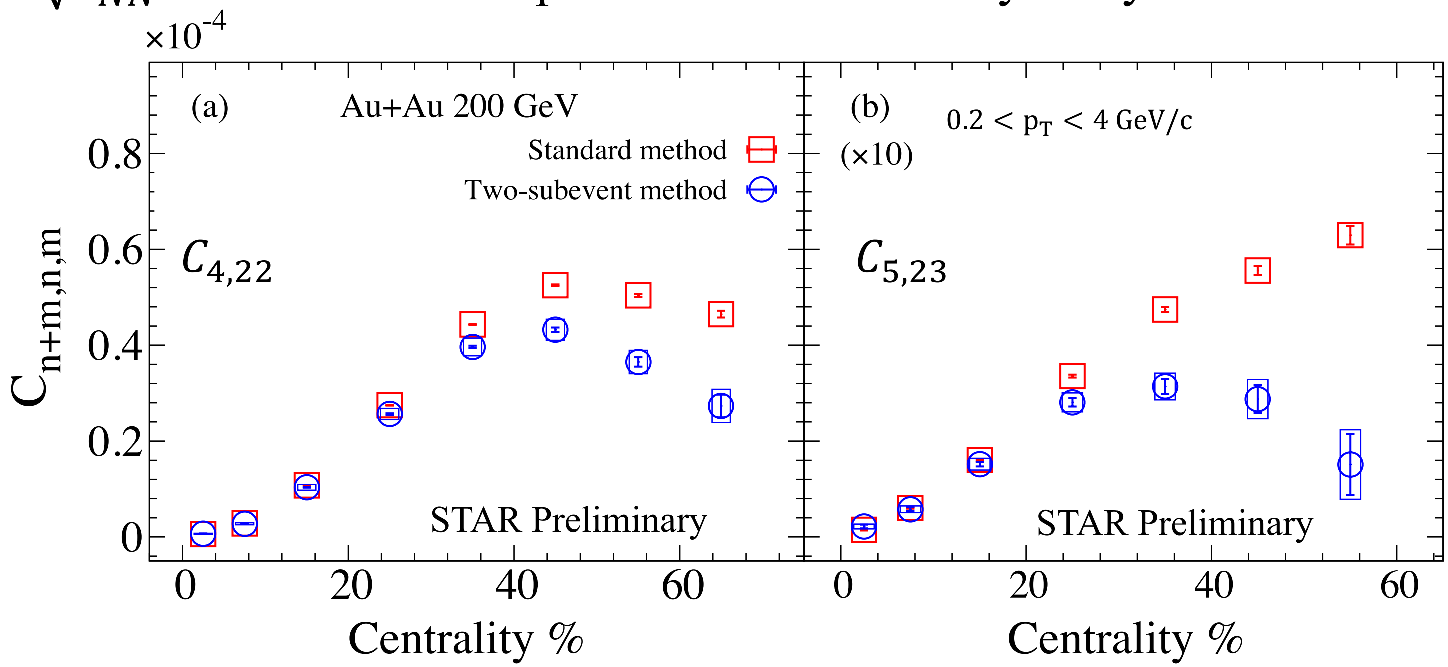

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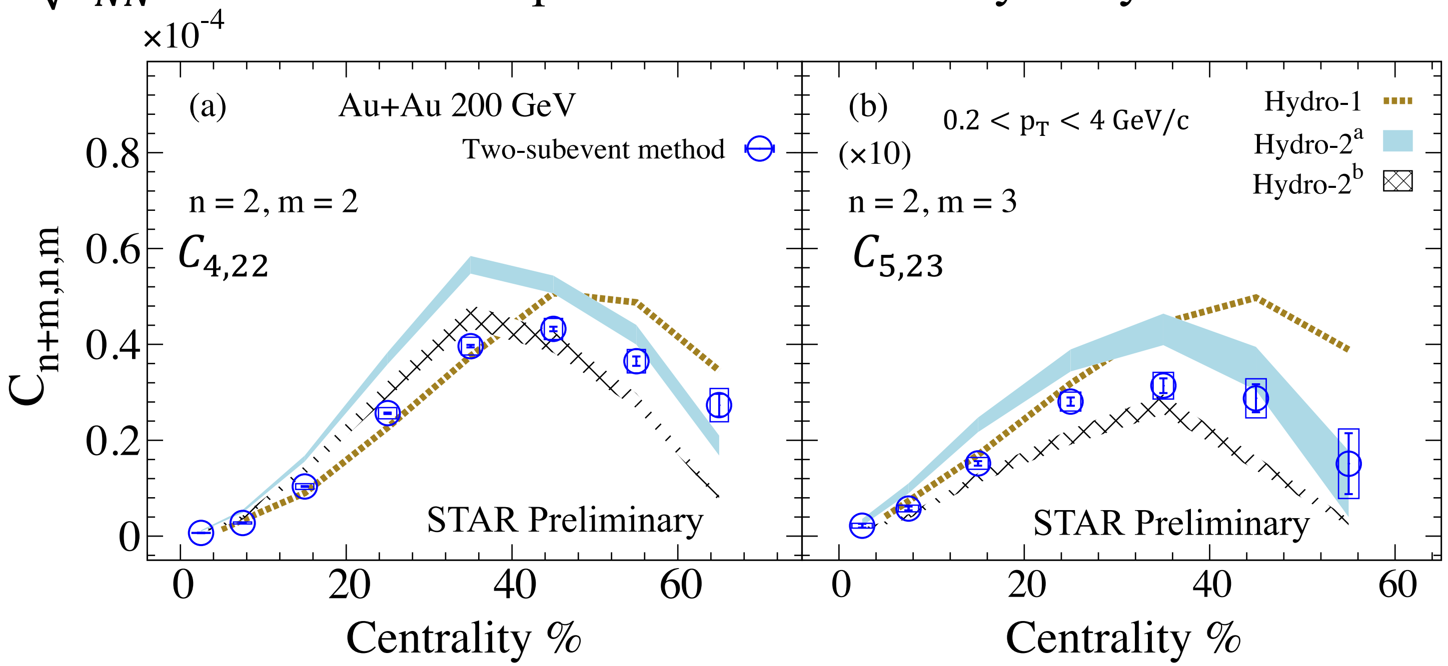

	Hydro−1	Hydro−2$^{a/b}$
η/s	0.05	0.12
Initial conditions	TRENTO Initial conditions	IP-Glasma Initial conditions
Contributions	Hydro + Direct decays	(a) Hydro + Hadronic cascade (b) Hydro only

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

- However both models fit the v_n they need additional constrains in order to describe the 3-particle correlations

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

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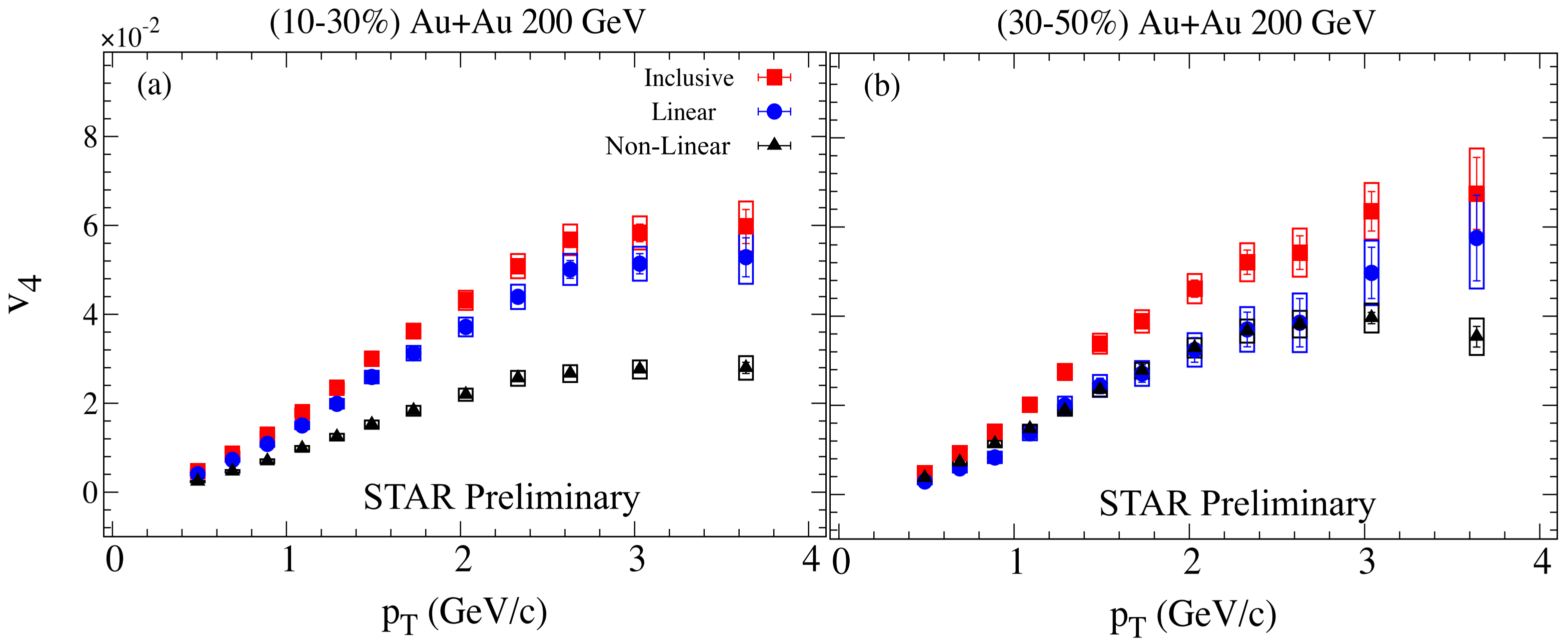
The p_T-differential dependence of the inclusive, linear and non-linear v_4 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are shown



➢ The inclusive, linear and non linear v_4 shows a characteristics p_T dependence

$$v_4^{Non-Linear} = \frac{C_{4,22}}{\sqrt{\langle v_2^4 \rangle}}$$

$$v_4^{Linear} = \sqrt{\left(v_4^{Inclusive}\right)^2 - \left(v_4^{Non-Linear}\right)^2}$$

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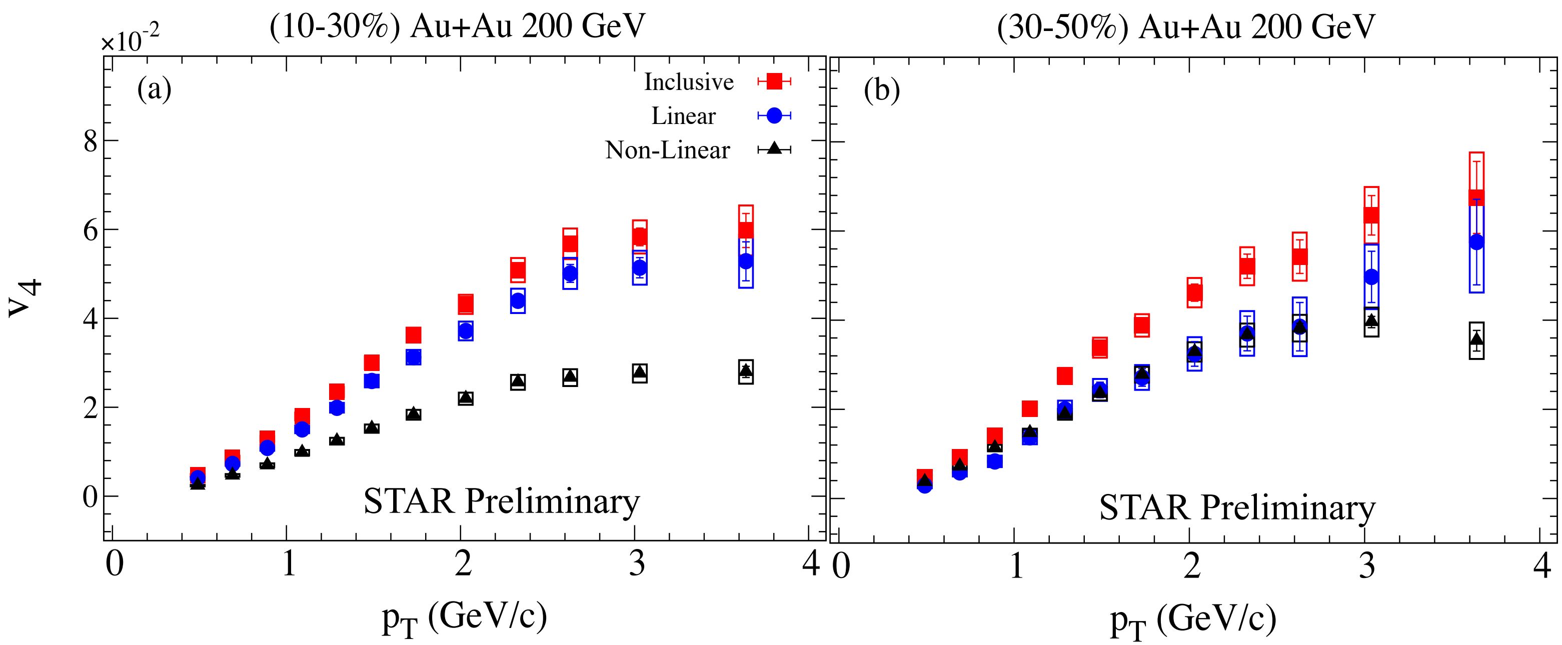


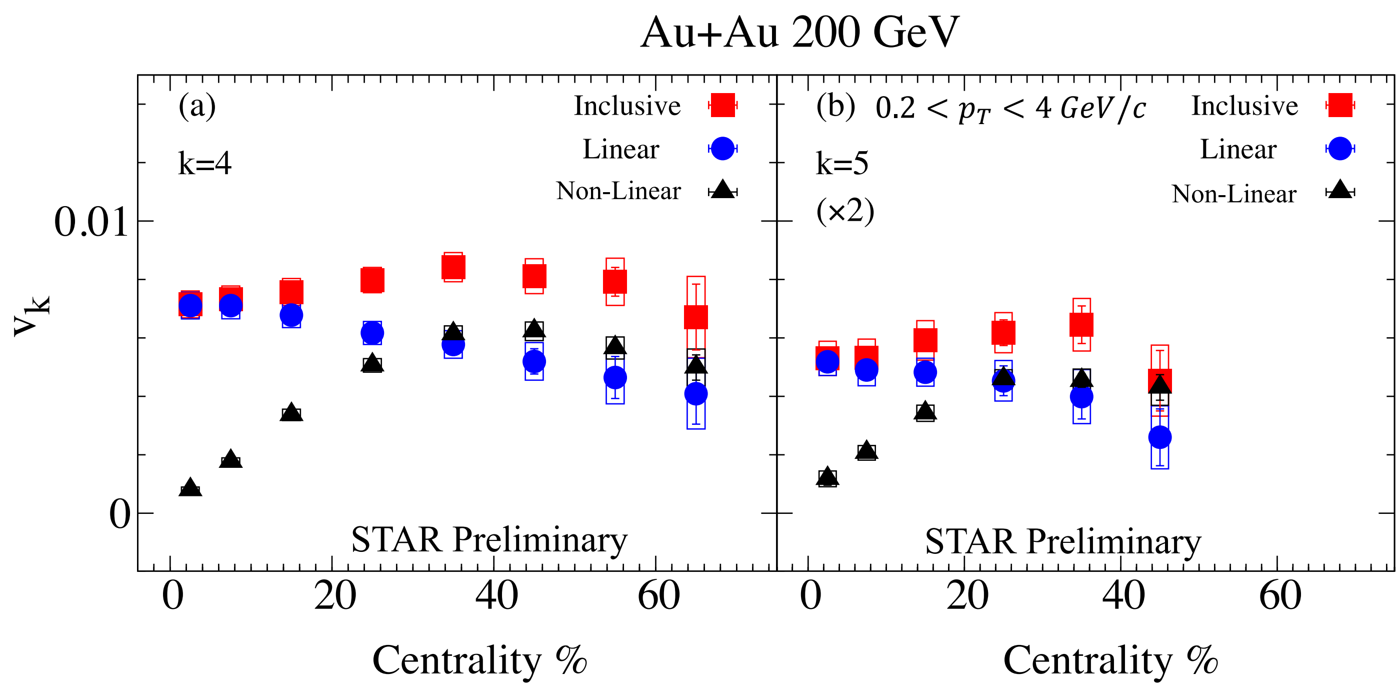
- The inclusive, linear and non linear v_4 shows a characteristics p_T dependence
- The linear v_4 term dominates in central collisions

$$v_4^{Non-Linear} = \frac{C_{4,22}}{\sqrt{\langle v_2^4 \rangle}}$$

$$v_4^{Linear} = \sqrt{\left(v_4^{Inclusive}\right)^2 - \left(v_4^{Non-Linear}\right)^2}$$

Results

Centrality dependence of the inclusive, linear and non-linear v_n (n=4,5) for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV



➢ The linear v_n (n=4,5) terms dominate in central collisions

$$v_{m+2}^{Non-Linear} = \frac{C_{m+2,2m}}{\sqrt{\langle v_2^2\, v_m^2 \rangle}}$$

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

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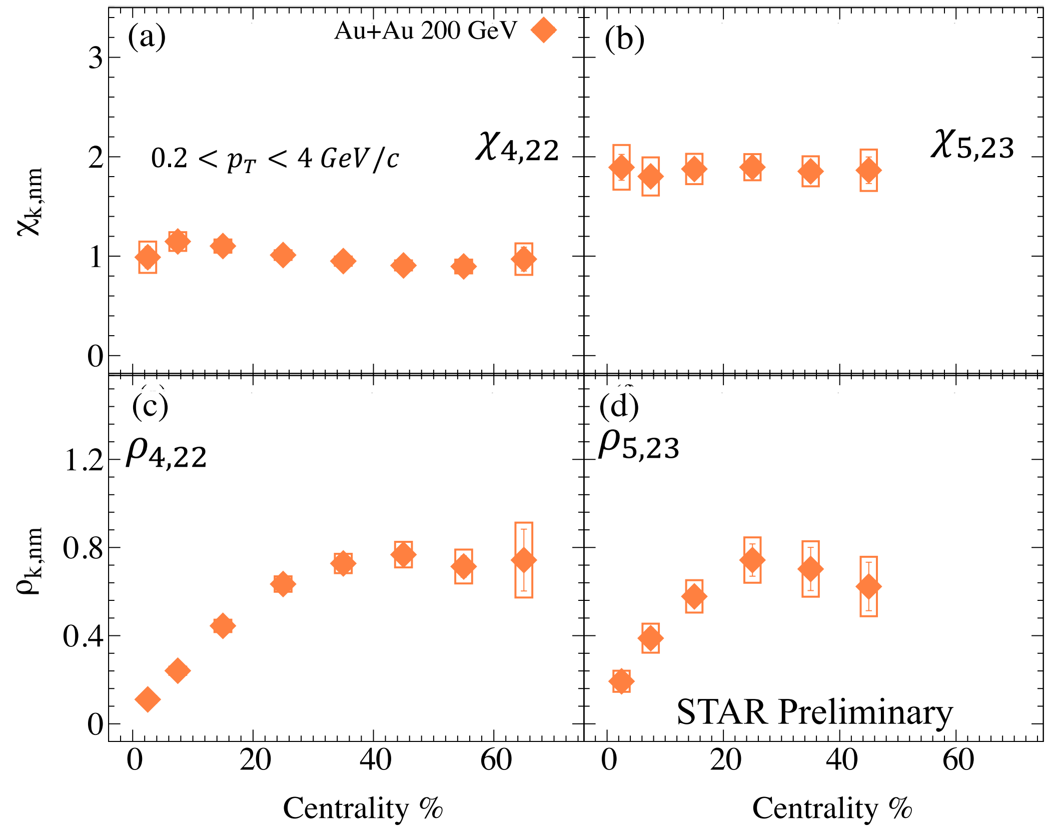
Centrality dependence of the non-linear mode-coupling coefficients, $\chi_{4,22}$ and $\chi_{5,23}$ and the EP angular correlations $\rho_{4,22}$ and $\rho_{5,23}$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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



$$\chi_{m+2,2m} = v_{m+2}^{Non-Linear} / \sqrt{\langle v_2^2\, v_m^2 \rangle}$$

$$\rho_{m+2,2m} = v_{m+2}^{Non-Linear} / v_{m+2}^{Inclusive}$$

m = 2,3

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Centrality dependence of the non-linear mode-coupling coefficients, $\chi_{4,22}$ and $\chi_{5,23}$ and the EP angular correlations $\rho_{4,22}$ and $\rho_{5,23}$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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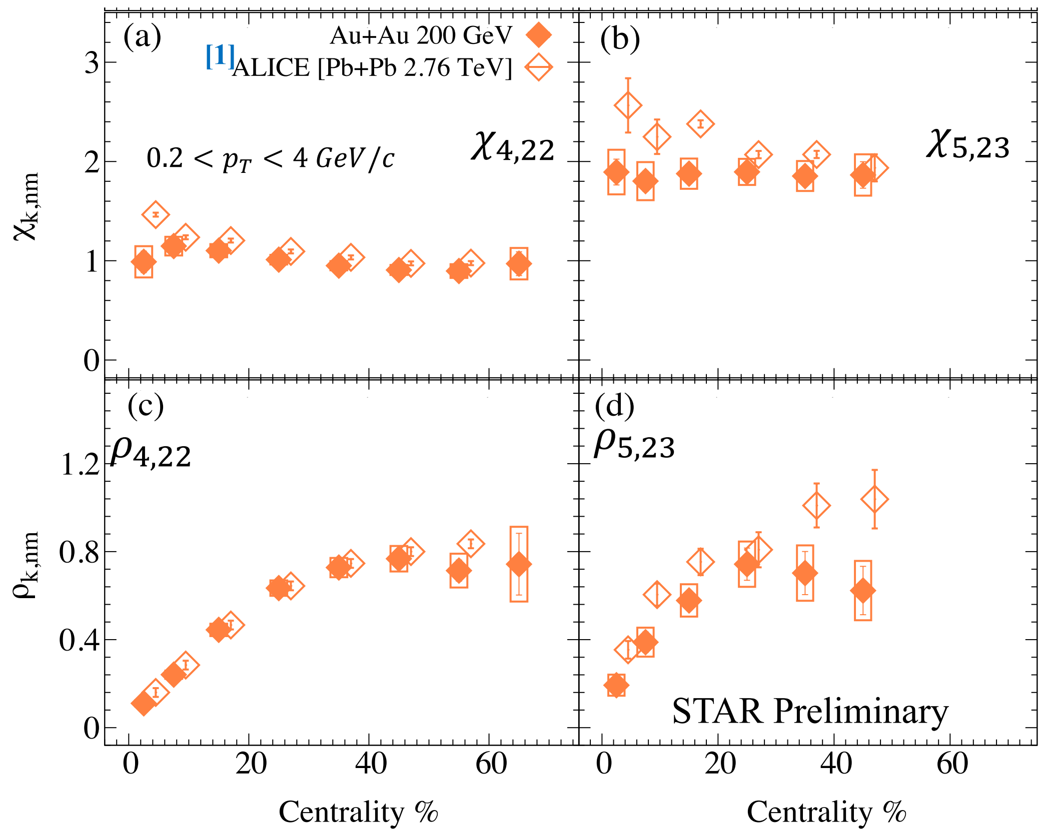
- $\rho_{k,nm}$ and $\chi_{k,nm}$ show a weak beam energy dependence



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[1]ALICE Collaboration PLB 773 68 (2017)

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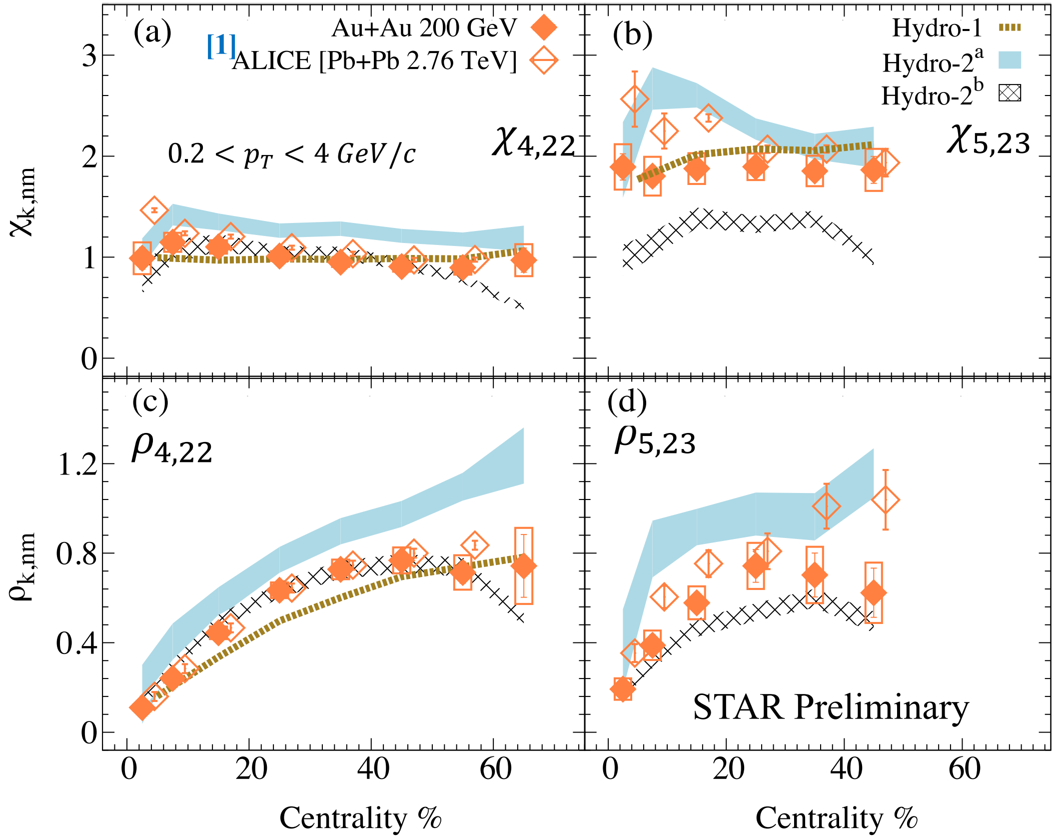

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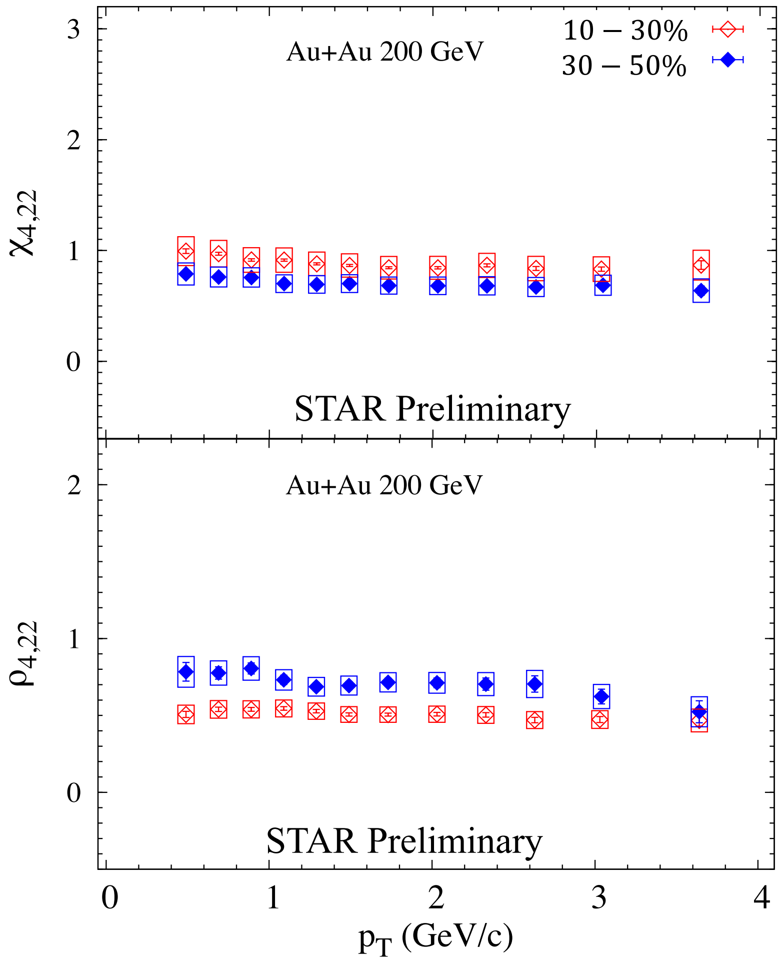


- $\chi_{4,22}$ shows a weak p_T dependence

- $\rho_{4,22}$ shows a weak p_T dependence

✓ Dynamical final-state effects are significantly less than the initial-state effect?

$$\chi_{m+2,2m} = v_{m+2}^{Non-Linear} / \sqrt{\langle v_2^2\, v_m^2 \rangle}$$

$$\rho_{m+2,2m} = v_{m+2}^{Non-Linear} / v_{m+2}^{Inclusive}$$

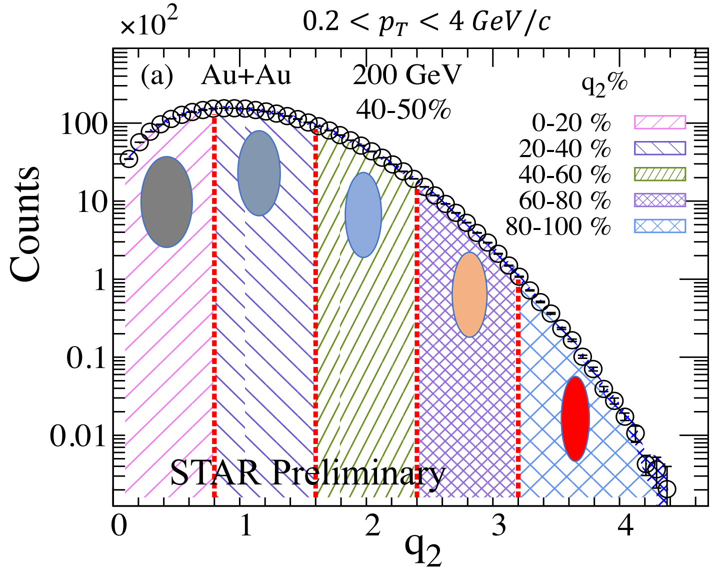
m = 2

The influence of event shape selection

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

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

$$|Q_n| = \sqrt{Q_{n,x}^2 + Q_{n,y}^2} \qquad q_n = \frac{|Q_n|}{\sqrt{M}}$$



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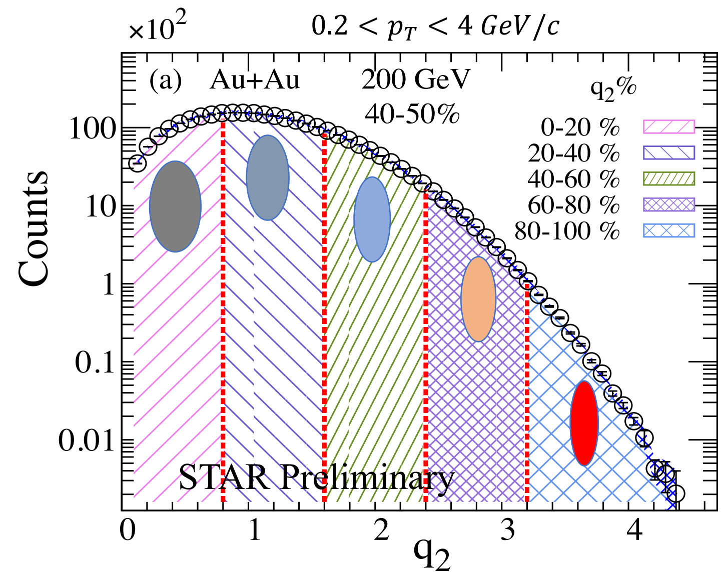

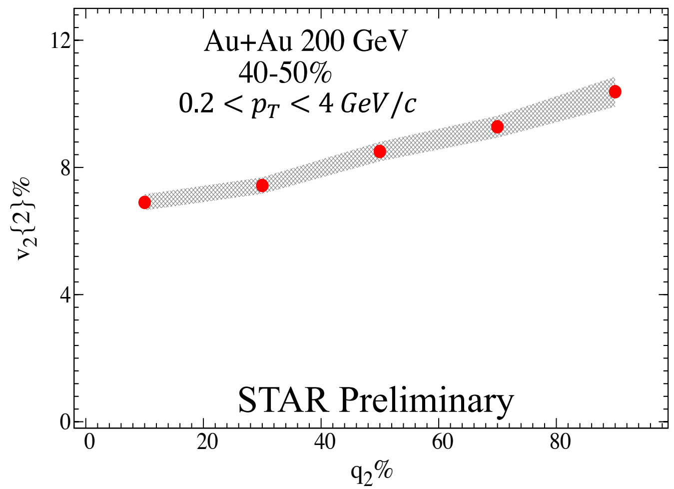

- $v_2\{2\}$ increases linearly with q_2

  q_2 is good event-shape selector

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The influence of event shape selection

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

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

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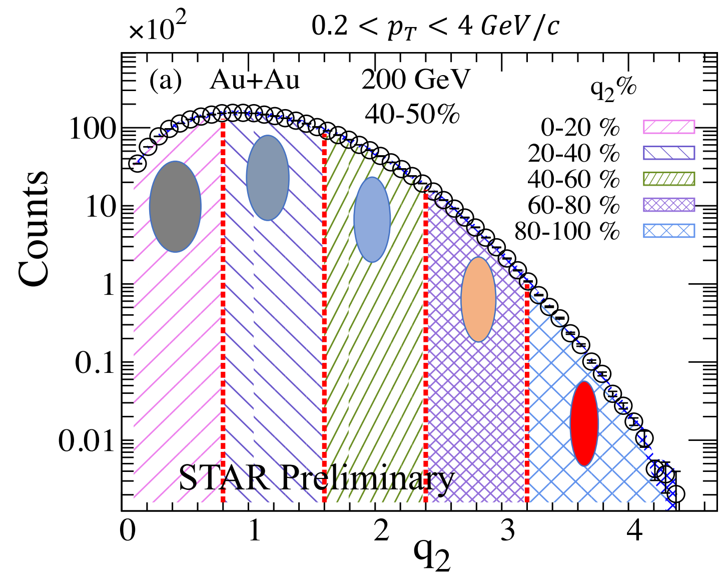

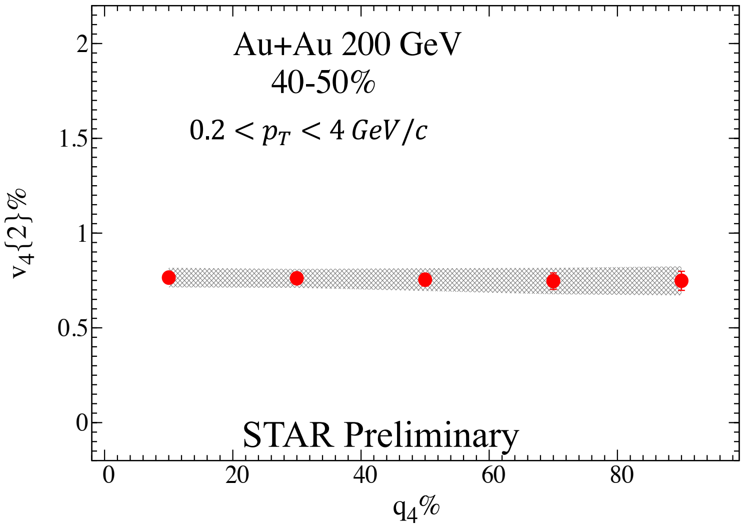

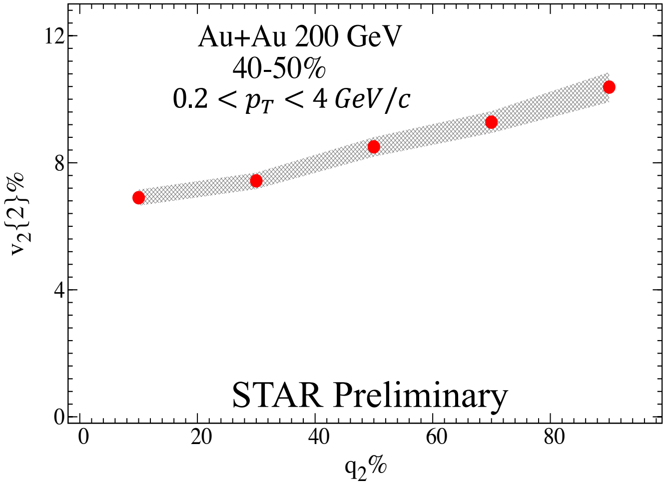

- $v_4\{2\}$ shows no sensitivity to q_4

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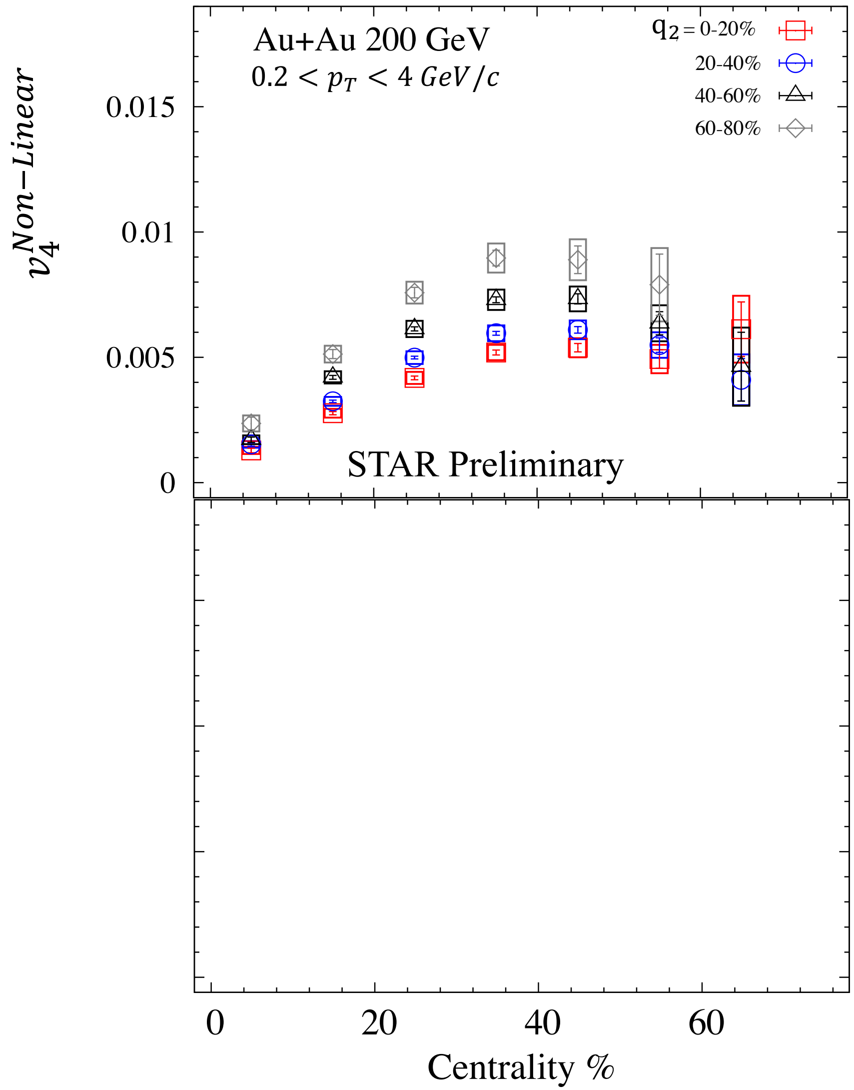
Results

Centrality dependence of the linear and non-linear v_4 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with different event shape selections (q_2%)



- The non-linear v_4 increases with q_2 selections

$$v_4^{Non-Linear} = \frac{C_{4,22}}{\sqrt{\langle v_2^4 \rangle}}$$

$$v_4^{Linear} = \sqrt{\left(v_4^{Inclusive}\right)^2 - \left(v_4^{Non-Linear}\right)^2}$$

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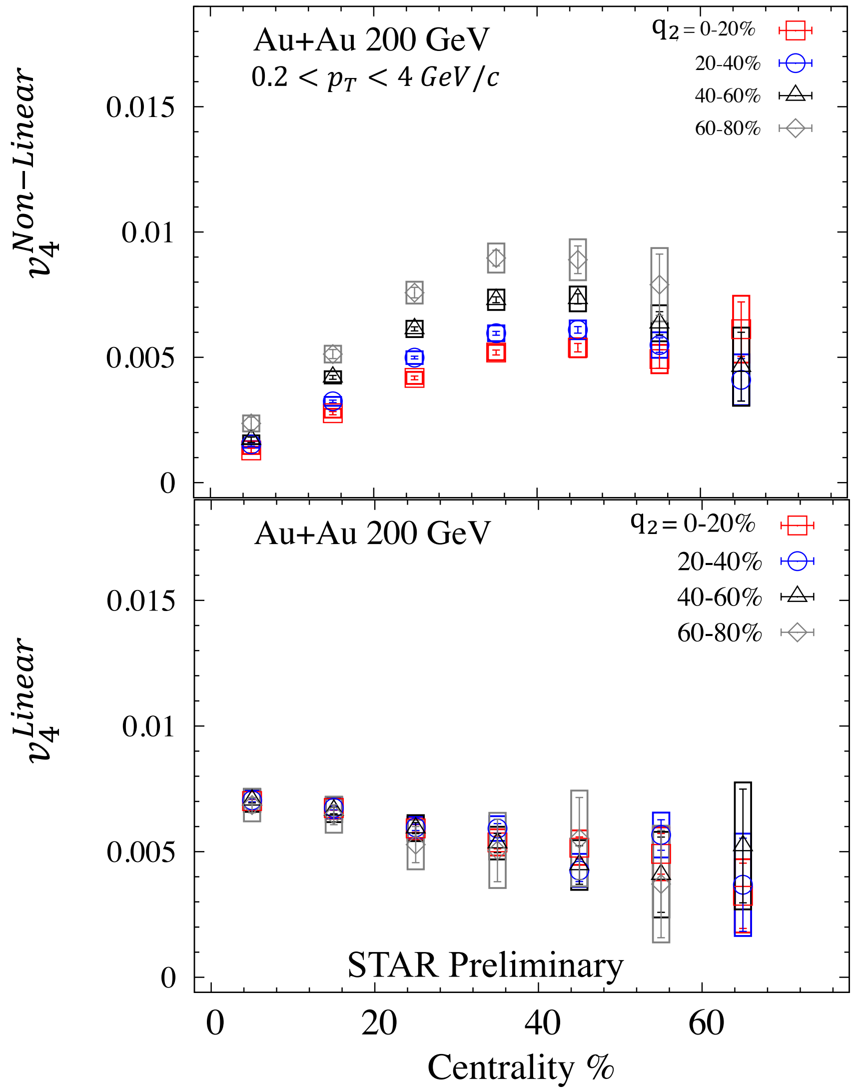

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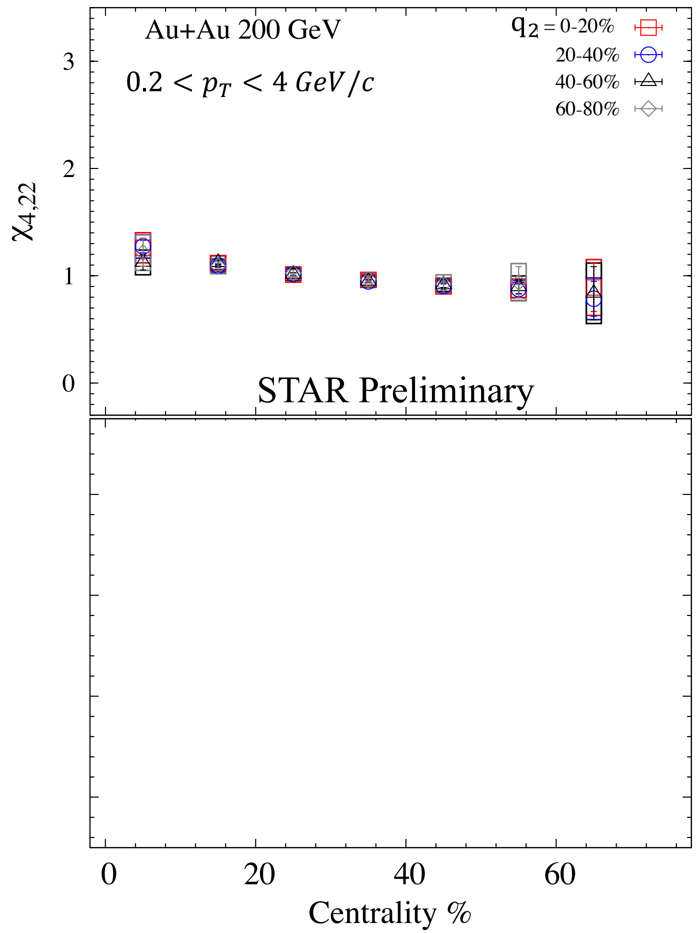
Centrality dependence of the $\rho_{4,22}$ and $\chi_{4,22}$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with different event shape selections (q_2)



- The $\chi_{4,22}$ shows a weak sensitivety to q_2 selections

$$\chi_{m+2,2m} = v_{m+2}^{Non-Linear} / \sqrt{\langle v_2^2\, v_m^2 \rangle}$$

$$\rho_{m+2,2m} = v_{m+2}^{Non-Linear} / v_{m+2}^{Inclusive}$$

m = 2

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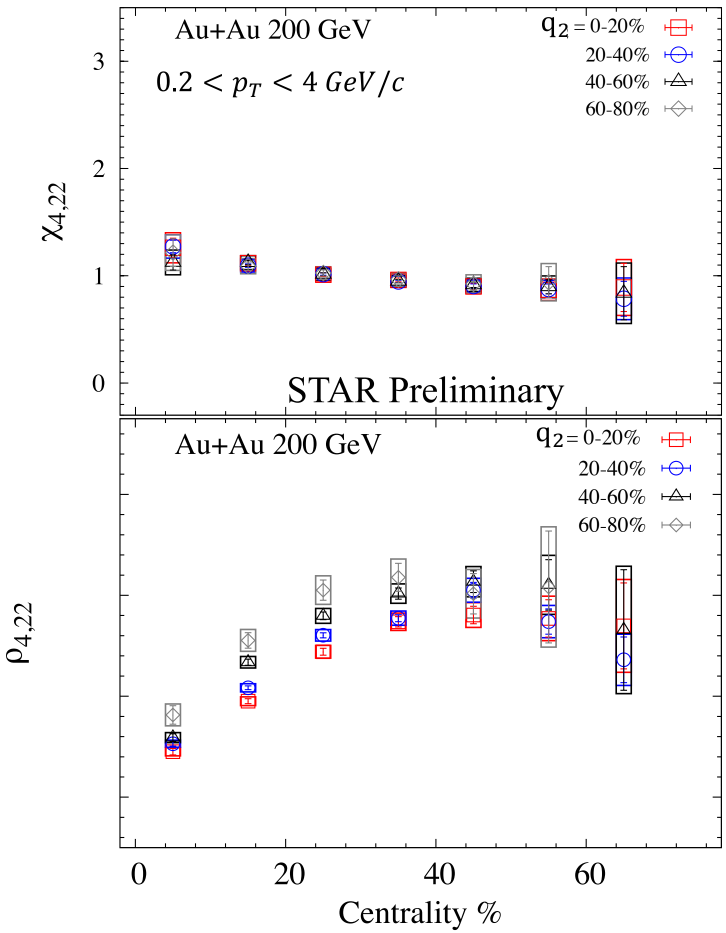

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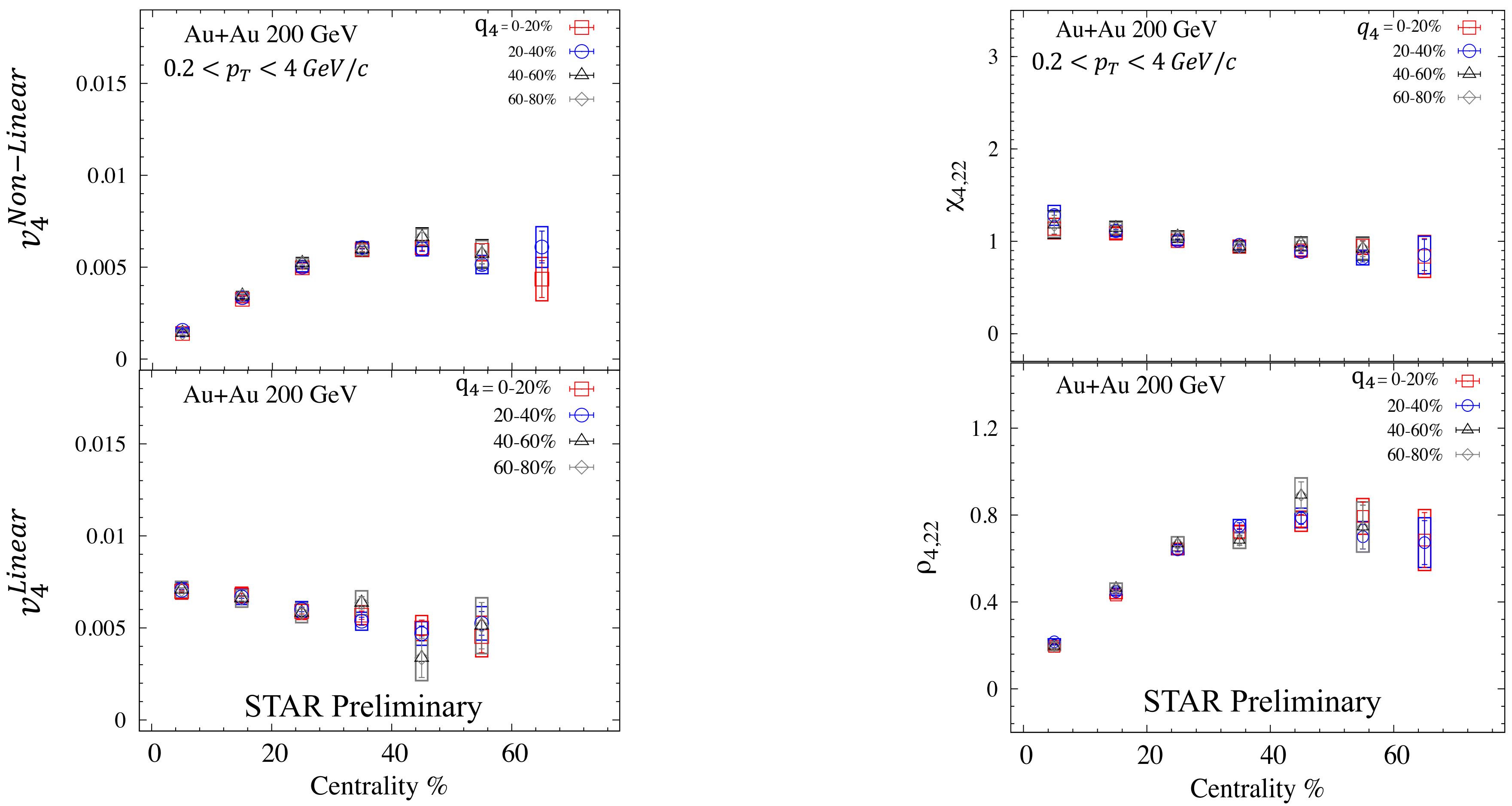
Results

Centrality dependence of the linear and non-linear v_4 and the assosatied $\rho_{4,22}$ and $\chi_{4,22}$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with different event shape selection (q_4)



➢ The (non)linear v_4 and the assosatied $\rho_{4,22}$ and $\chi_{4,22}$ show weak sensitivety to q_4 selections

Conclusion

The linear and mode-coupled contributions to the higher-order anisotropic flow coefficients v_4 and v_5, have been studied using two- and multi-particle correlations in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

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- Two-subevents reduce the short-range non-flow effect on in the three-particle correlations
- The linear v_n (n=4,5) terms dominate in central collisions
- The $\chi_{\mathrm{k,nm}}$ show a weak centrality dependence (weak viscous effects)
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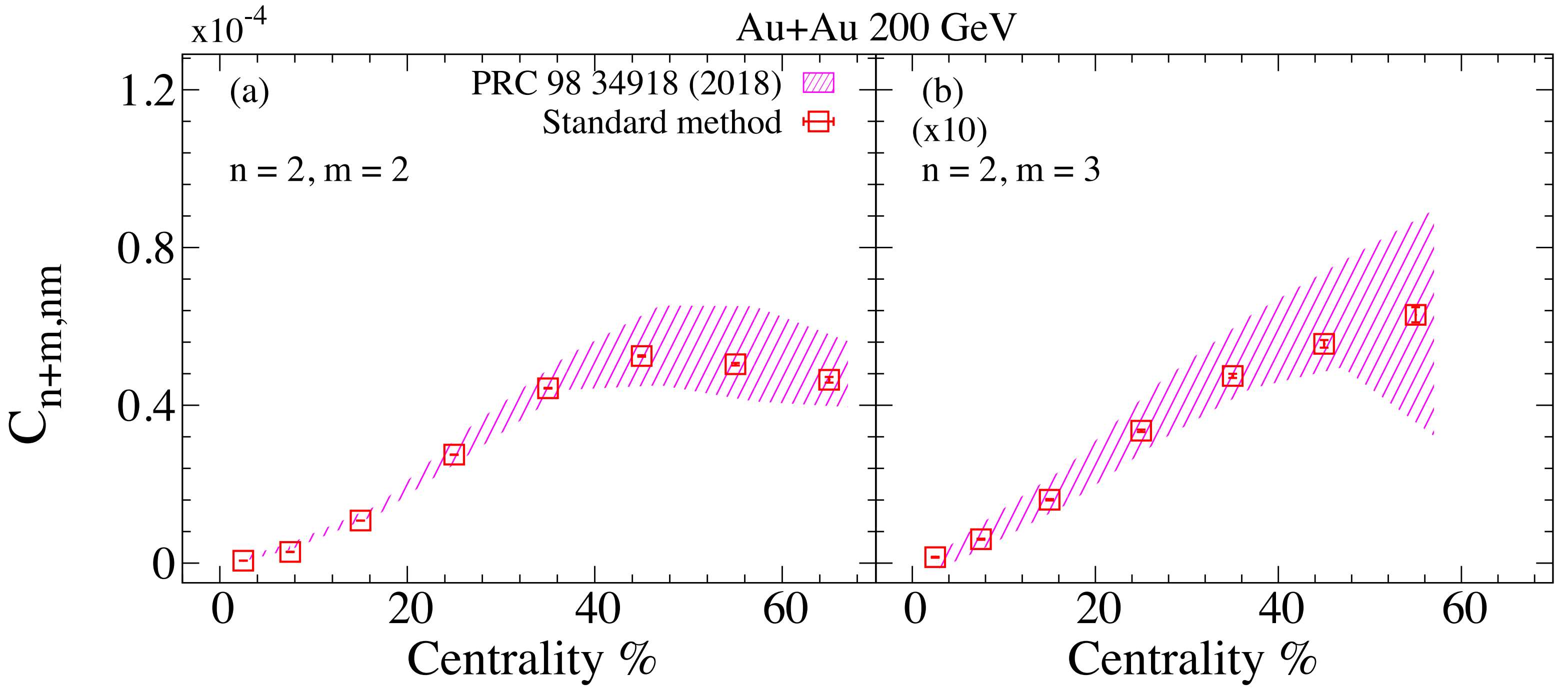
The integrated and differential measurements, which are compared to viscous hydrodynamic model calculations, will add important constraints for the initial- and finlal-state models

Thank You

Backup



Good agreement with the STAR published measurements