Center for Frontiers in Nuclear Science

Stony Brook University

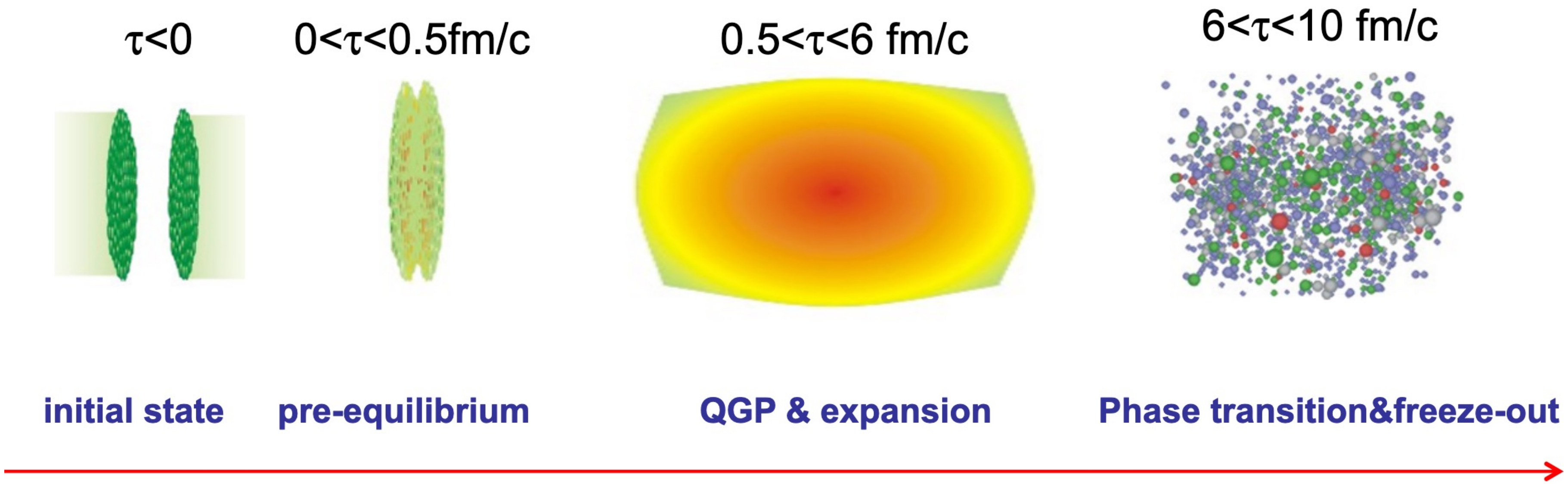
Experimental constraints on the initial stages of A+A collisions at lower energy

Niseem Magdy Abdelrahman
Stony Brook University

In part supported by
U.S. DEPARTMENT OF ENERGY | Office of Science

niseemm@gmail.com
Inspire-hep: 1305036
ORCID: 0000-0002-6458-6552

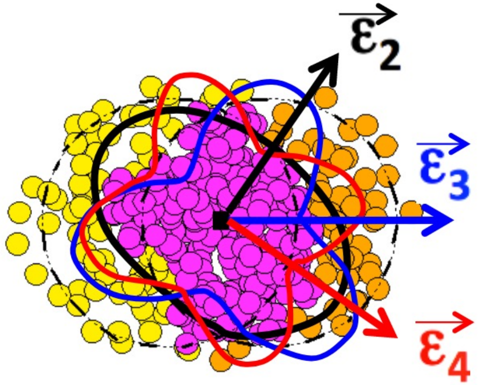
Initial condition and emergence of collectivity



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

Connecting the initial and final state

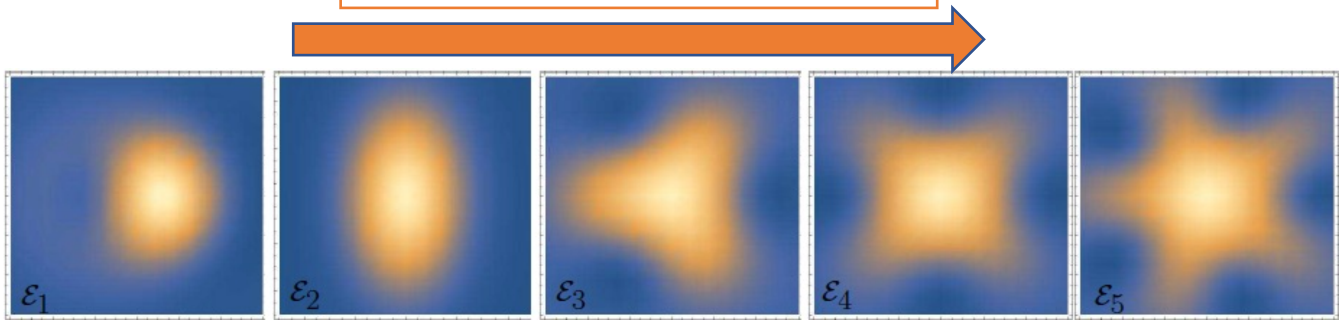
Initial state



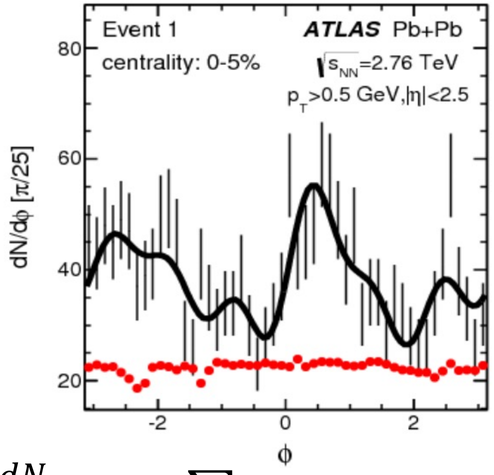
$\overrightarrow{\varepsilon_n} \equiv \varepsilon_n e^{in\Phi_n}$

Hydro-response

Space-time dynamics



Particle flow

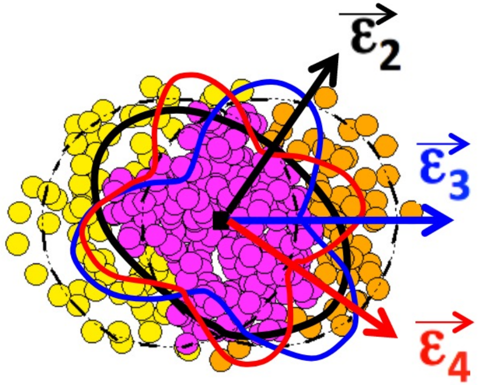


$$\frac{dN}{d\varphi} \propto 1 + 2\sum_n V_n \cos(n(\varphi - \psi_n))$$

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 $\frac{\eta}{s}(\mu_B, T)$

Connecting the initial and final state

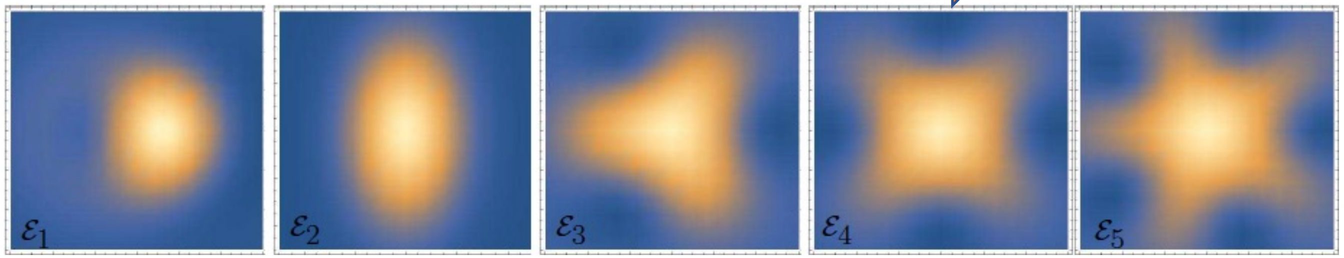
Initial state



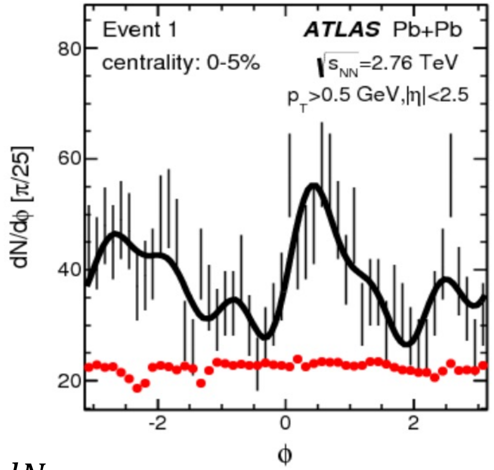
$\overrightarrow{\varepsilon_n} \equiv \varepsilon_n e^{in\Phi_n}$

Hydro-response

Space-time dynamics



Particle flow



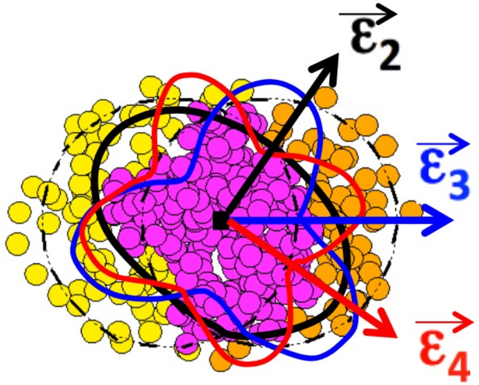
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_n V_n \cos(n(\varphi - \psi_n))$$

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 $\frac{\eta}{s}(\mu_B, T)$

- What is the nature of the flow fluctuation?

Connecting the initial and final state

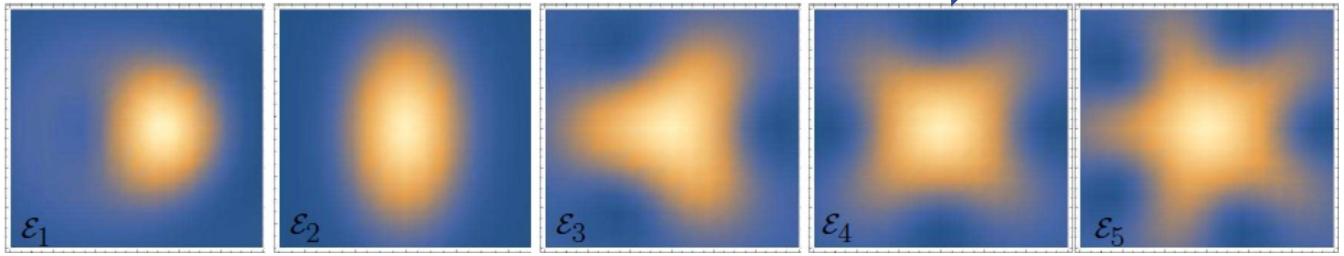
Initial state



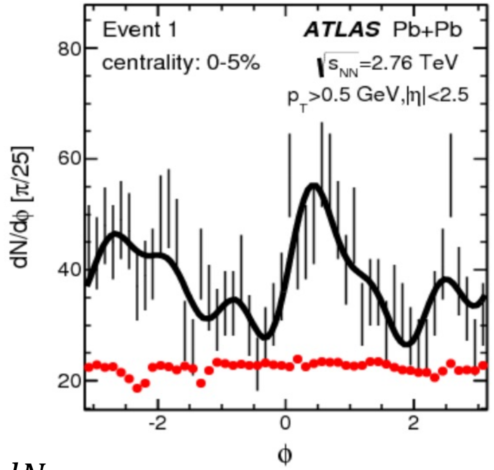
$\vec{\varepsilon_n} \equiv \varepsilon_n e^{in\Phi_n}$

Hydro-response

Space-time dynamics



Particle flow



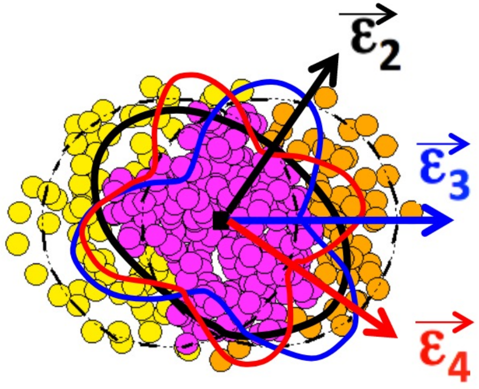
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_n V_n \cos(n(\varphi - \psi_n))$$

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 $\frac{\eta}{s}(\mu_B, T)$

- 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?

Connecting the initial and final state

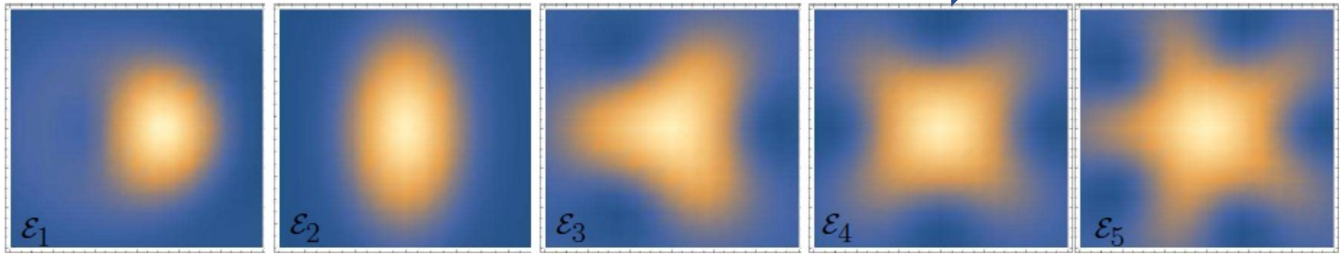
Initial state



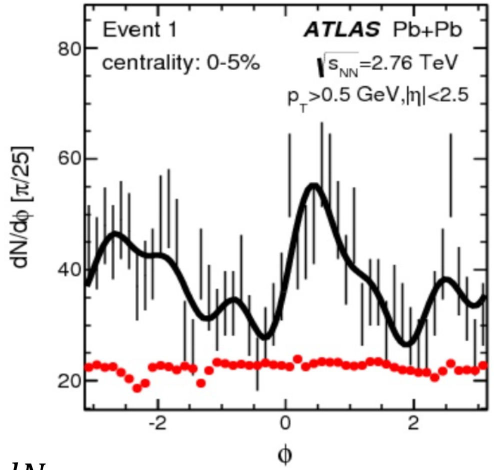
$\overrightarrow{\varepsilon_n} \equiv \varepsilon_n e^{in\Phi_n}$

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 $\frac{\eta}{s}(\mu_B, T)$

- 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?

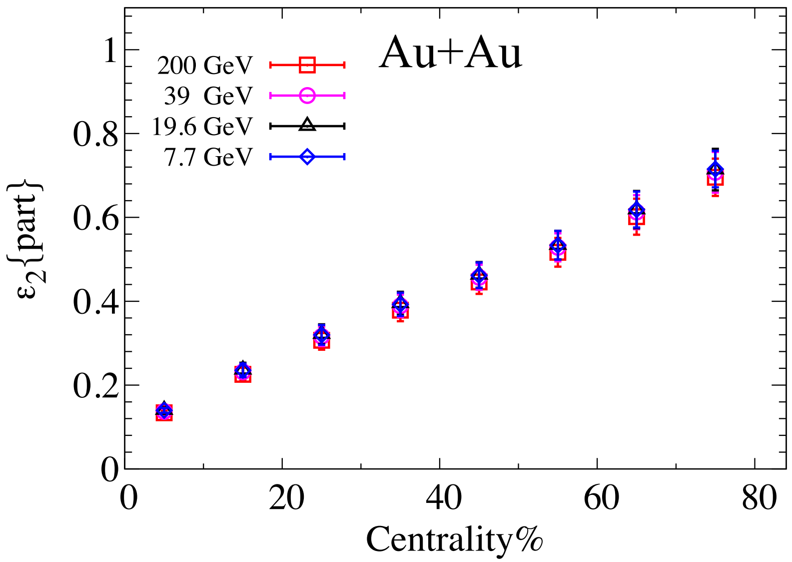
Motivation

- Flow harmonics are sensitive probes for $\frac{\eta}{s}(T)$ due to the enhanced viscous response
- Higher-order flow harmonics ($v_{\mathrm{n}=4,5}$) have multiple contributions:
  - ✓ Linear response $\propto \varepsilon_{\mathrm{n}}$
  - ✓ Mode-coupled non-linear response $\propto \varepsilon_2 \varepsilon_{\mathrm{m}} (m = 2,3)$ and Event-plane (E-P) correlations
- Flow harmonics can constrain $\frac{\eta}{s}(T)$ and differentiate between initial state models
- The difference between forward and backward event planes can probe the longitudinal fluctuations

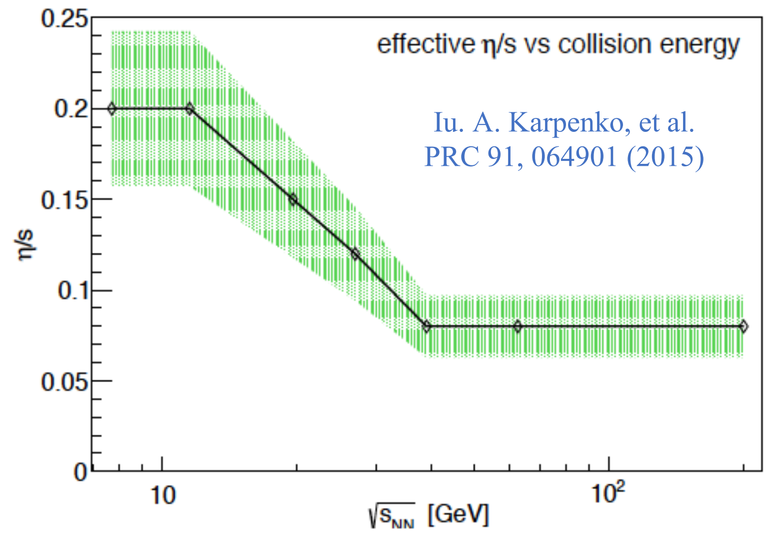
Motivation

- Flow harmonics are sensitive probes for $\frac{\eta}{s}(T)$ due to the enhanced viscous response
- Higher-order flow harmonics ($v_{\mathrm{n}=4,5}$) have multiple contributions:
  - ✓ Linear response $\propto \varepsilon_{\mathrm{n}}$
  - ✓ Mode-coupled non-linear response $\propto \varepsilon_2 \varepsilon_{\mathrm{m}}(m = 2,3)$ and Event-plane (E-P) correlations
- Flow harmonics can constrain $\frac{\eta}{s}(T)$ and differentiate between initial state models
- The difference between forward and backward event planes can probe the longitudinal fluctuations

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

Analysis Method

The multi-particle correlations

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

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

Analysis Method

The multi-particle correlations

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

Symmetric Correlations

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

Asymmetric Correlations

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

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**

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

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

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

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

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

$n > 1$

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

Flow

$n = 1$

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

Non-flow

Azimuthal anisotropy measurements

Correlation function

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

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

$n > 1$

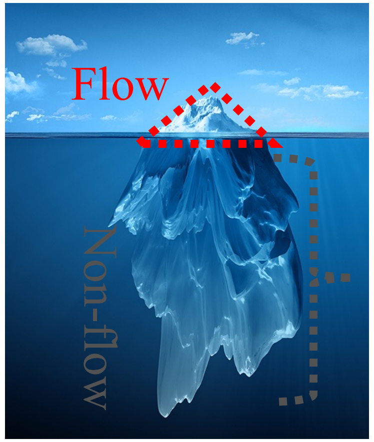
$$v_{nn} = v_n^a v_n^b + \delta_{short}$$

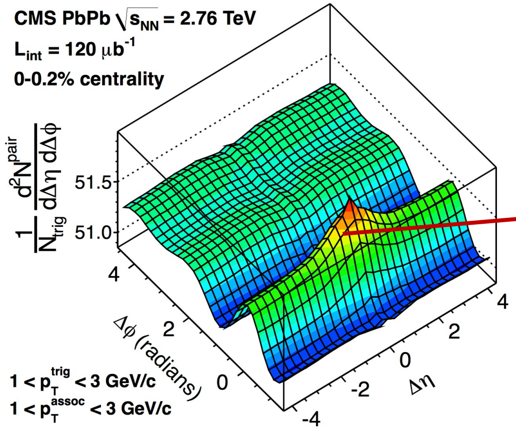
$n = 1$

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

Flow

Non-flow





Short – range

HBT

Decay

Charge

Azimuthal anisotropy measurements

Correlation function

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

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

$n > 1$

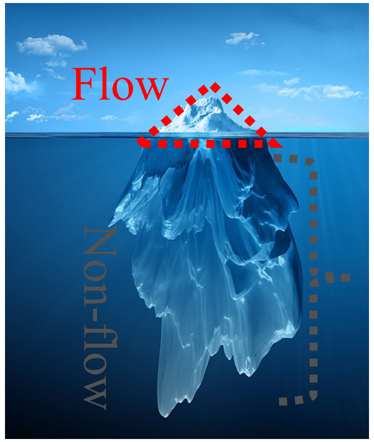
$v_{nn} = v_n^a v_n^b + \delta_{short}$

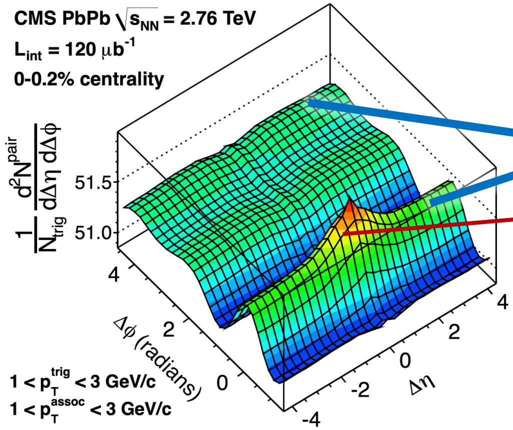
$n = 1$

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

Flow

Non-flow





Long − range

Momentum Conservation

Di−jets

Short − range

HBT

Decay

Charge

Non-flow suppression is needed

Symmetric Correlations

k-even particle correlations

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

$$\langle\langle 2m\rangle\rangle_n = \left\langle\left\langle e^{in\sum_{j=1}^{m}(\phi_{2j-1}-\phi_{2j})}\right\rangle\right\rangle$$

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

$$v_n^2\{2\} = \langle 2\rangle_n$$

$$v_n^4\{4\} = 2\,\langle 2\rangle^2{}_n - \langle 4\rangle_n$$

$$6\,v_n^6\{6\} = \langle 6\rangle_n - 9\langle 2\rangle_n\langle 4\rangle_n + \langle 2\rangle_n^3$$

Symmetric Correlations

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

k-even particle correlations

$$\langle\langle 2m\rangle\rangle_n = \left\langle\left\langle e^{in\sum_{j=1}^{m}(\phi_{2j-1}-\phi_{2j})}\right\rangle\right\rangle$$

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

$$v_n^2\{2\} = \langle 2\rangle_n$$

$$v_n^4\{4\} = 2\,\langle 2\rangle^2{}_n - \langle 4\rangle_n$$

$$6\, v_n^6\{6\} = \langle 6\rangle_n - 9\langle 2\rangle_n\langle 4\rangle_n + \langle 2\rangle_n^3$$

Are sensitive to the initial state effects.

n-m flow harmonics correlations

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

n-order flow harmonic fluctuations

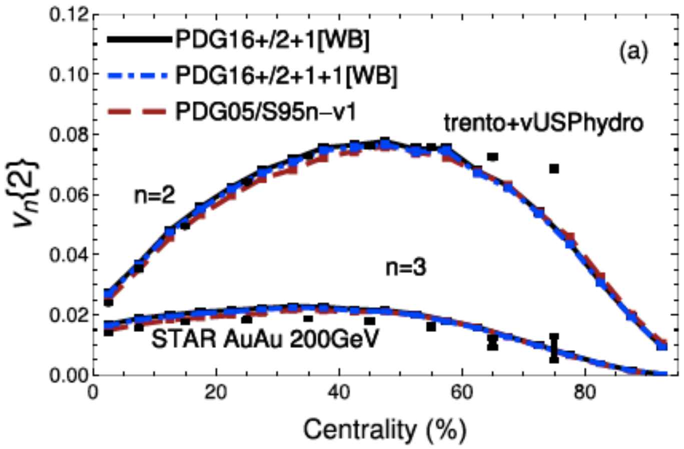
$$v_n\,\{4\}/v_n\,\{2\} \qquad v_n\,\{6\}/v_n\,\{4\}$$

Differential flow angle fluctuations

$$r_n(\eta) = \frac{\langle V_n(-\eta)V_n^*(\eta_{ref})\rangle}{\langle V_n(\eta)V_n^*(\eta_{ref})\rangle} = \frac{\langle v_n(-\eta)v_n(\eta_{ref})\cos\{n[\Psi_n(-\eta)-\Psi_n(\eta_{ref})]\}\rangle}{\langle v_n(\eta)v_n(\eta_{ref})\cos\{n[\Psi_n(\eta)-\Psi_n(\eta_{ref})]\}\rangle}$$

Models for comparisons

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

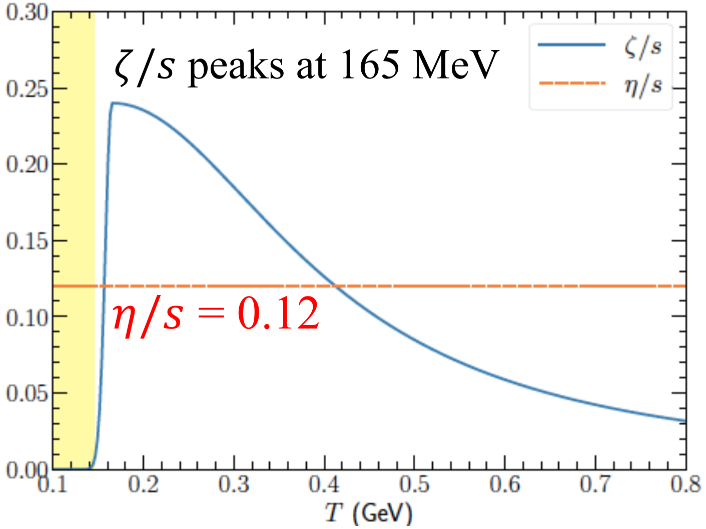


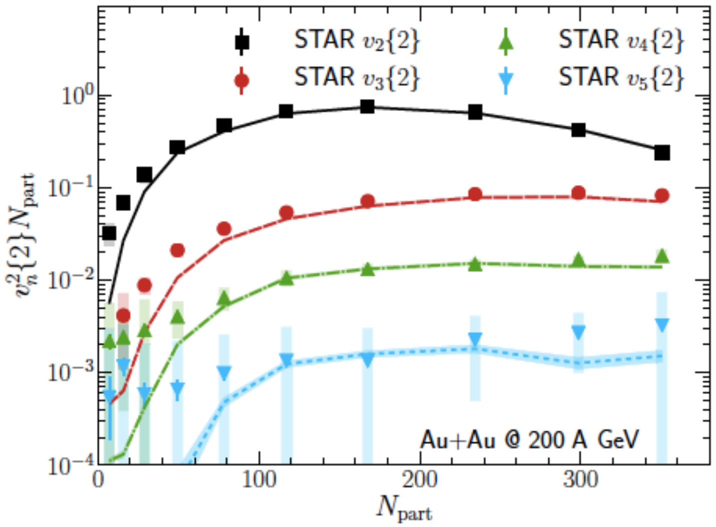
- ➢ The model use event-by-event fluctuating initial conditions generated by the TRENTO model with free parameters calibrated to fit experimental observables.
- ➢ The model use the smoothed particle hydrodynamics (SPH) Lagrangian code, v-USPhydro, to solve the viscous hydrodynamic equations taking into 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

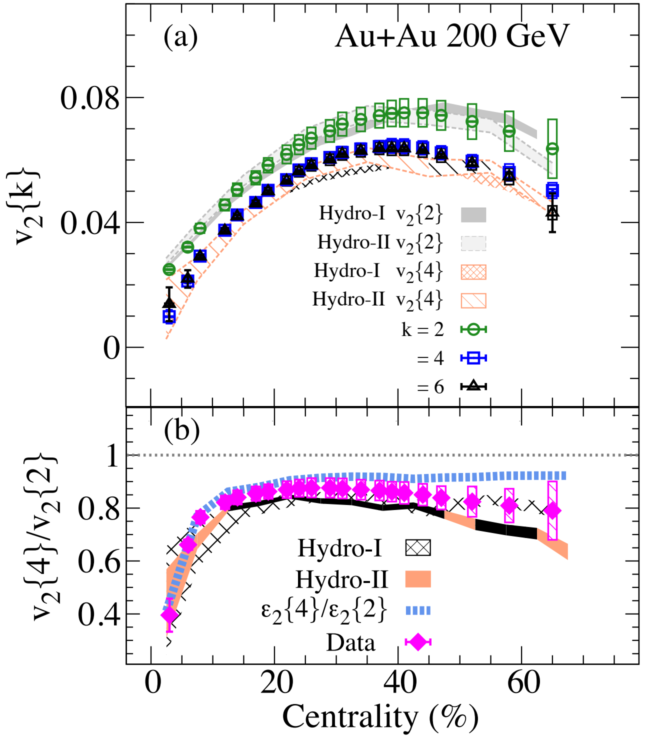




Anisotropic Flow Fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)

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



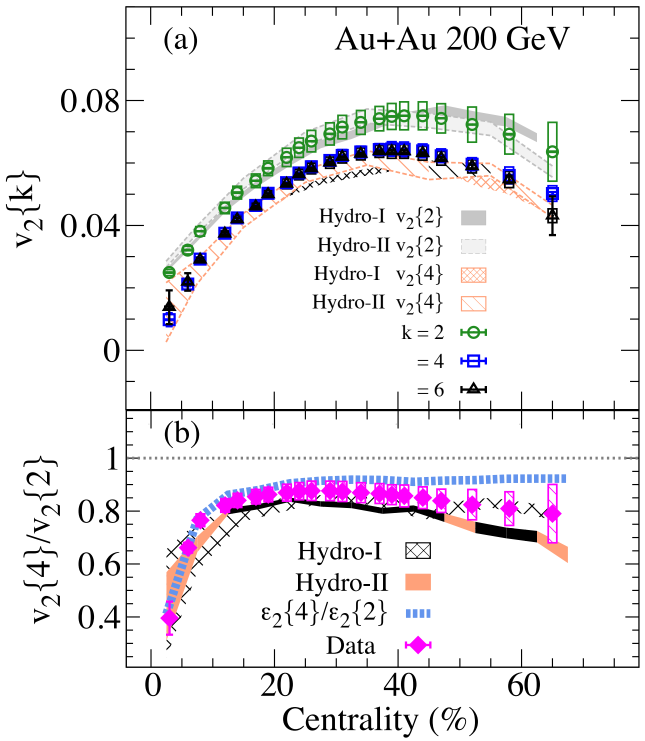
- $v_2\{4\}/v_2\{2\}$ decrees from central to peripheral collisions
- The model calculations:
  - (I) $(v_2\{4\}/v_2\{2\})$ agrees well with the data
  - (II) $(v_2\{4\}/v_2\{2\})$ and $(\epsilon_2\{4\}/\epsilon_2\{2\})$ bracket the data

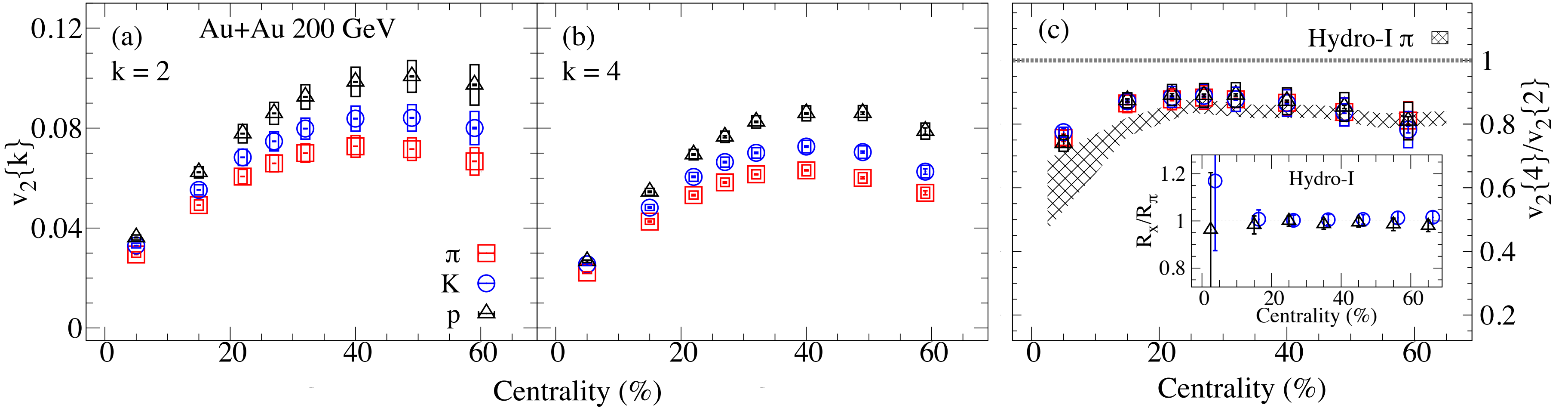
	Hydro-I	Hydro-II
η/s	0.12	0.05
Initial conditions	IP-Glasma	TRENTO
Contributions	Hydro + Hadronic cascade	Hydro + Direct decays

Anisotropic Flow Fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)

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





- $v_2\{4\}/v_2\{2\}$ 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

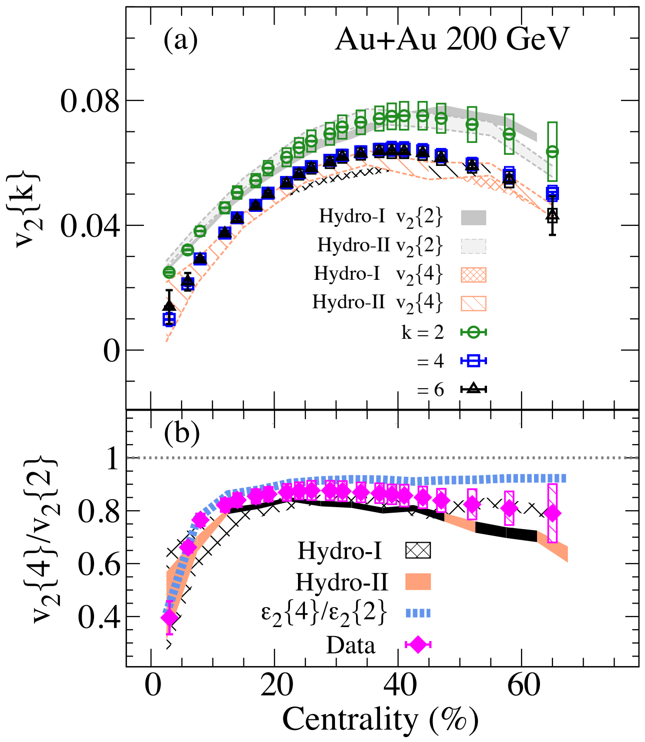
	Hydro-I	Hydro-II
η/s	0.12	0.05
Initial conditions	IP-Glasma	TRENTO
Contributions	Hydro + Hadronic cascade	Hydro + Direct decays

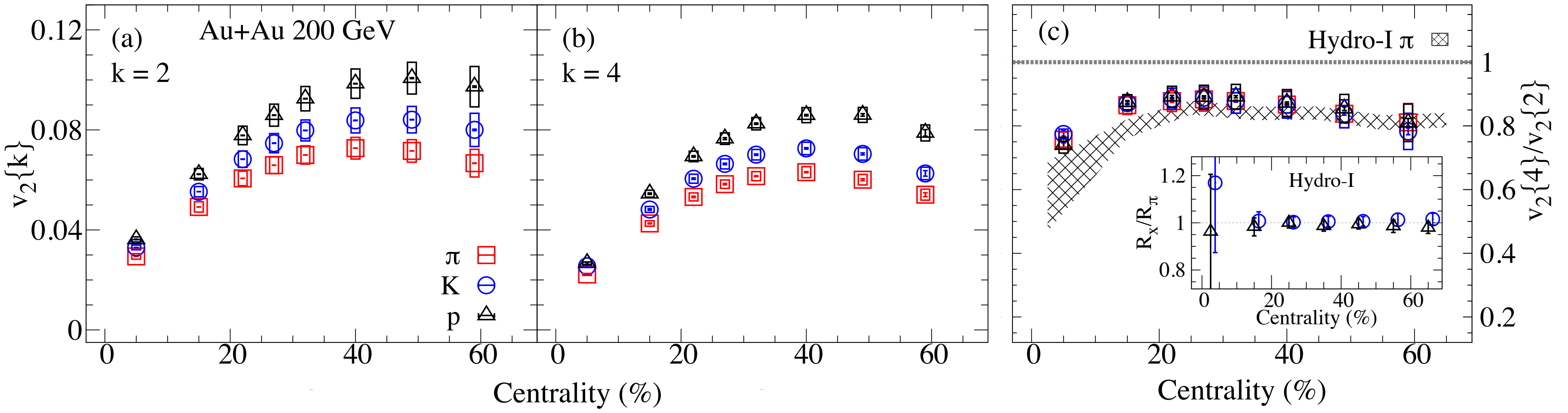
- $v_2\{4\}/v_2\{2\}$ show weak dependence on particle species.

Anisotropic Flow Fluctuations

STAR Collaboration
PRL 129 25, 252301 (2022)

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





- $v_2\{4\}/v_2\{2\}$ 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

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

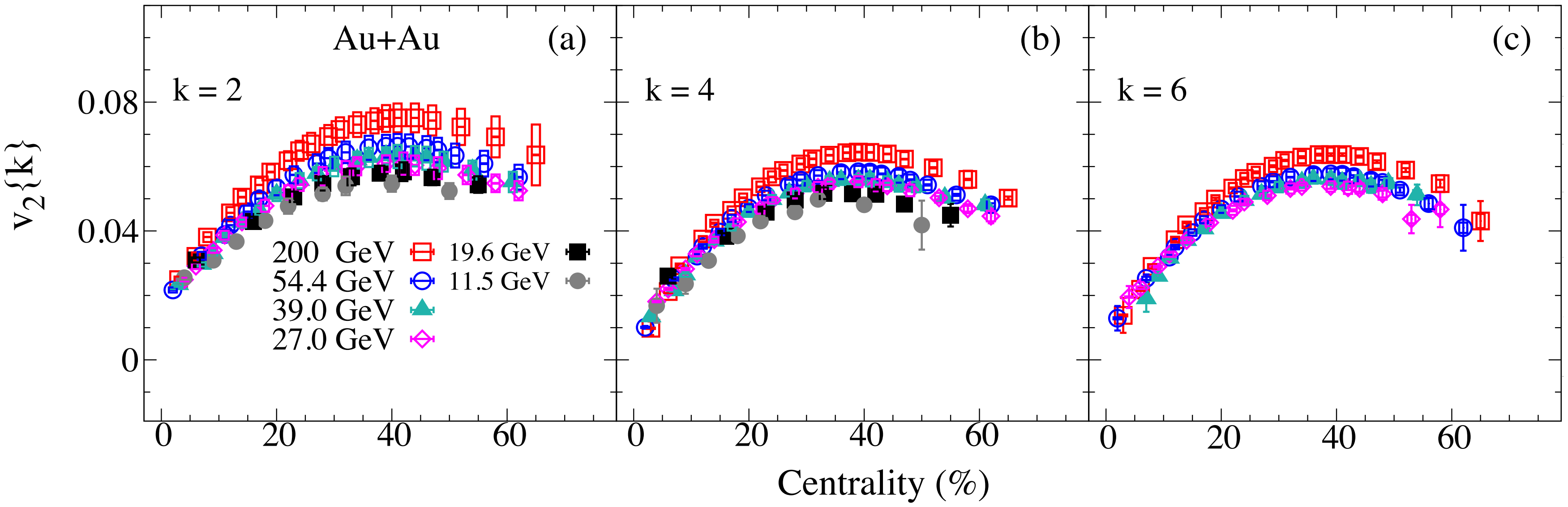
- $v_2\{4\}/v_2\{2\}$ show weak dependence on particle species.

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

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

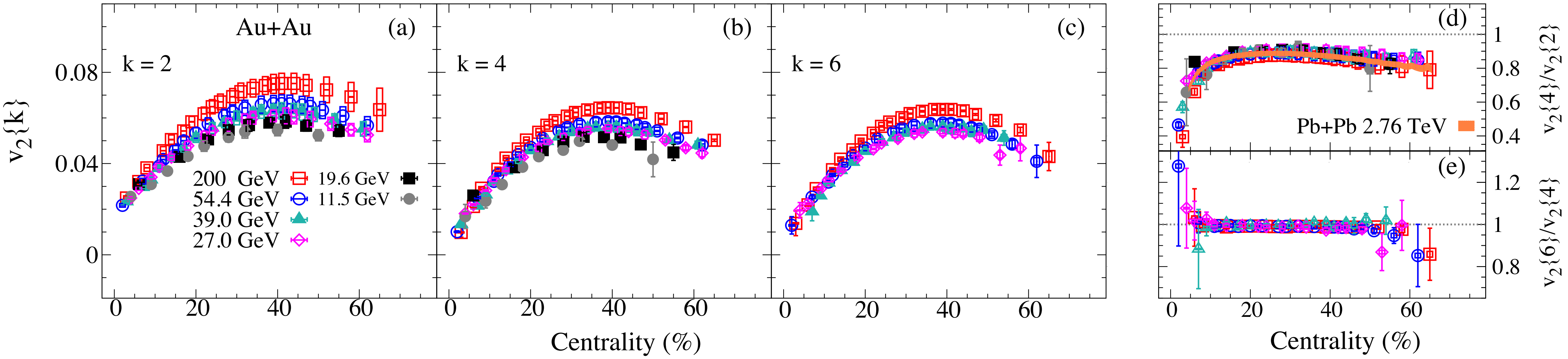


- ➢ $v_2\{k\}$ show characteristic BES dependence.

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

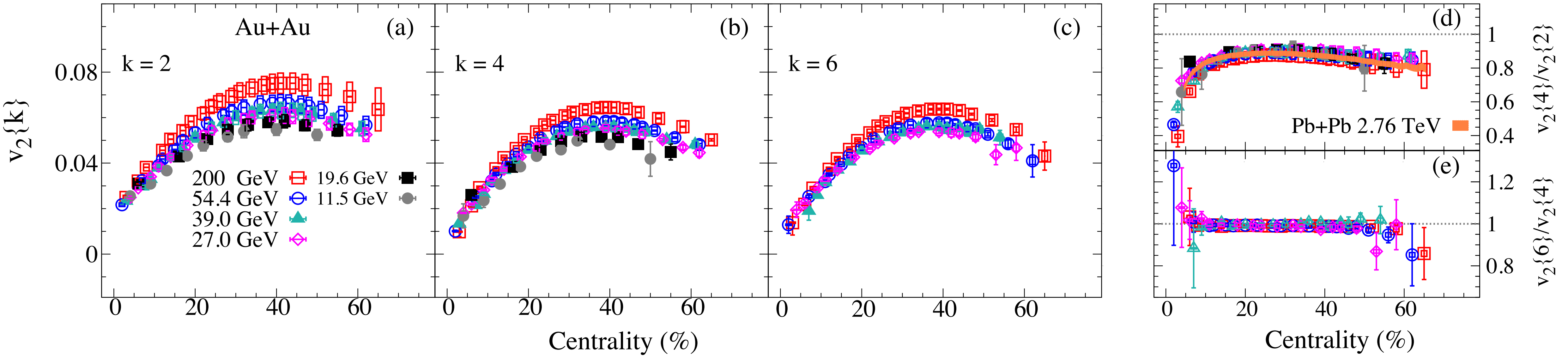


- v_2\{k\} show characteristic BES dependence.
- $v_2\{4\}/v_2\{2\}$ show weak dependence on beam energy.
- Within uncertainties, $v_2\{6\}/v_2\{4\}$ are consistence with unity

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)

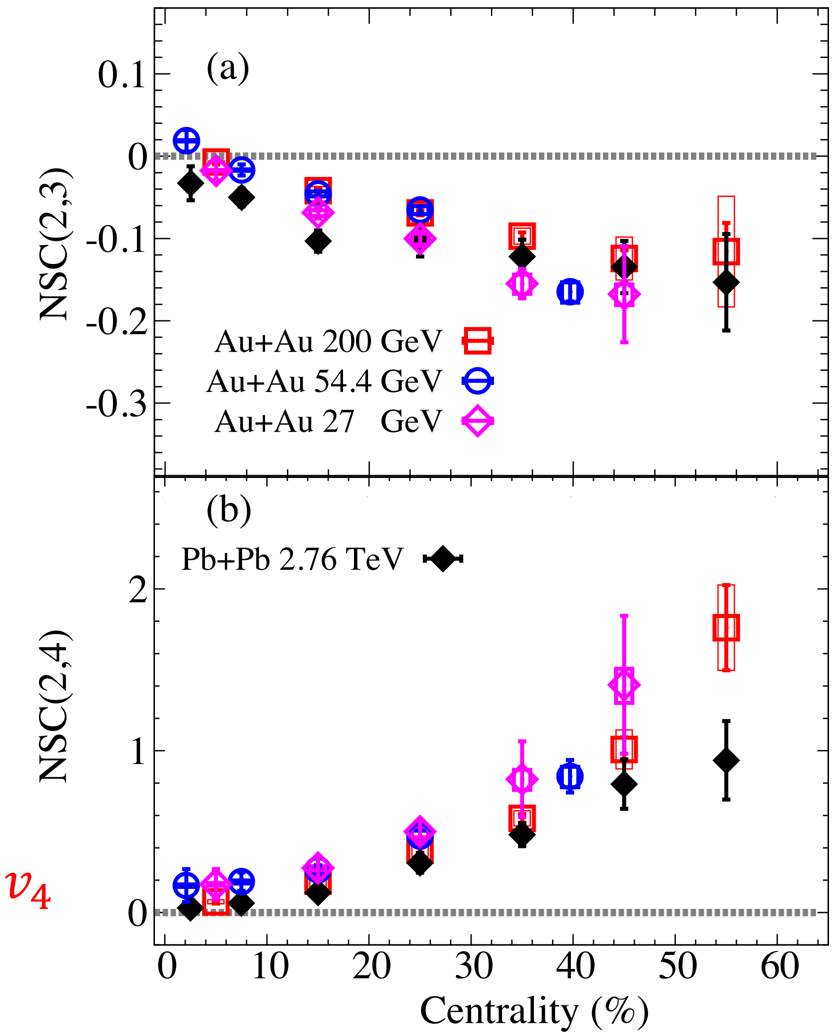
Comparison of the normalized symmetric cumulants, NSC(2,3) and NSC(2,4), vs. Centrality

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

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

Mode coupling

- ❖ 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



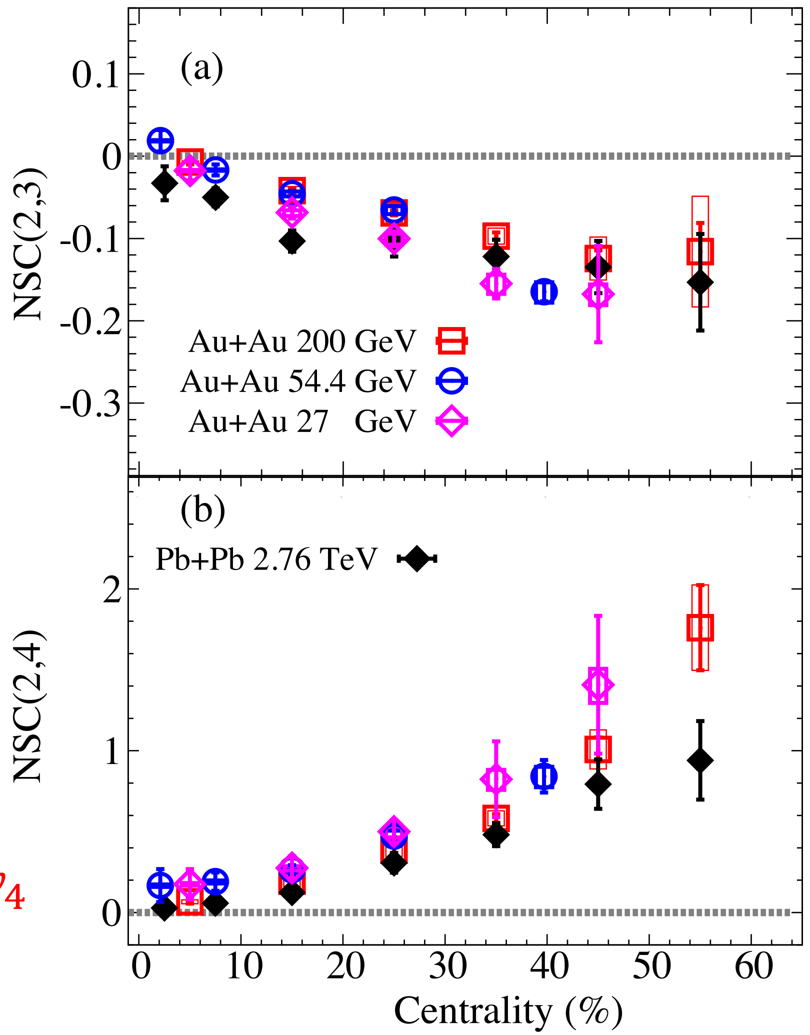
STAR Collaboration
PLB 839 137755 (2023)

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

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

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

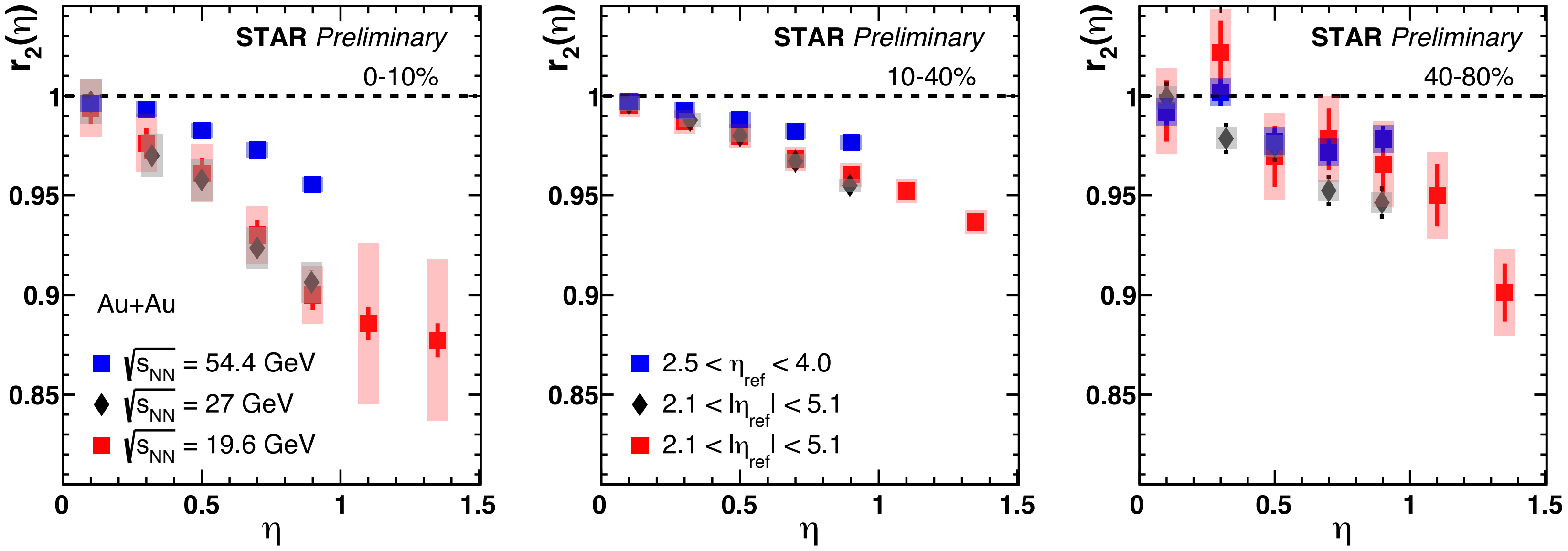
Mode coupling

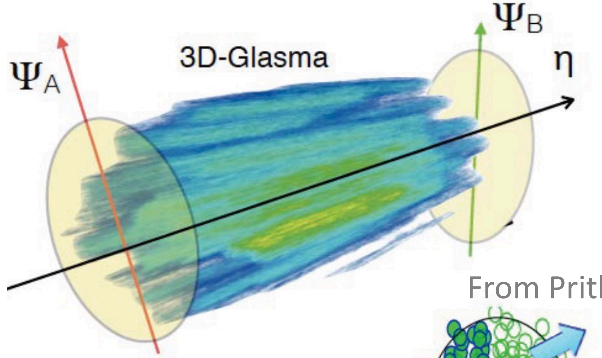


- Anti-correlation between v_2 and v_3
  - ✓ Consistent with the expected anti-correlation between ϵ_2 and ϵ_3
- Correlation between v_2 and v_4
  - ✓ Consistent with the expectations from mode coupling between v_2 and v_4
- NSC(n, m) show weak dependence on beam energy.

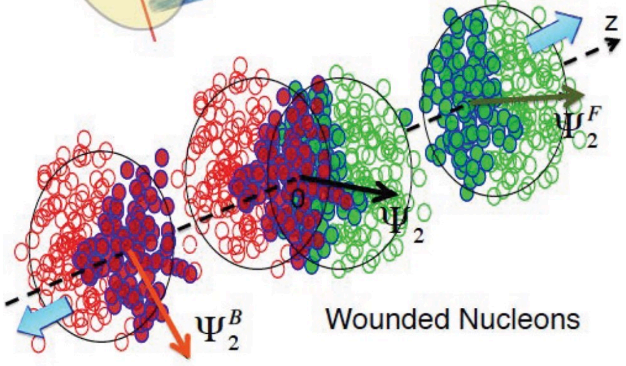
The influence from final-state is less than the one from initial-state ?

Longitudinal dynamics in heavy-ion collisions





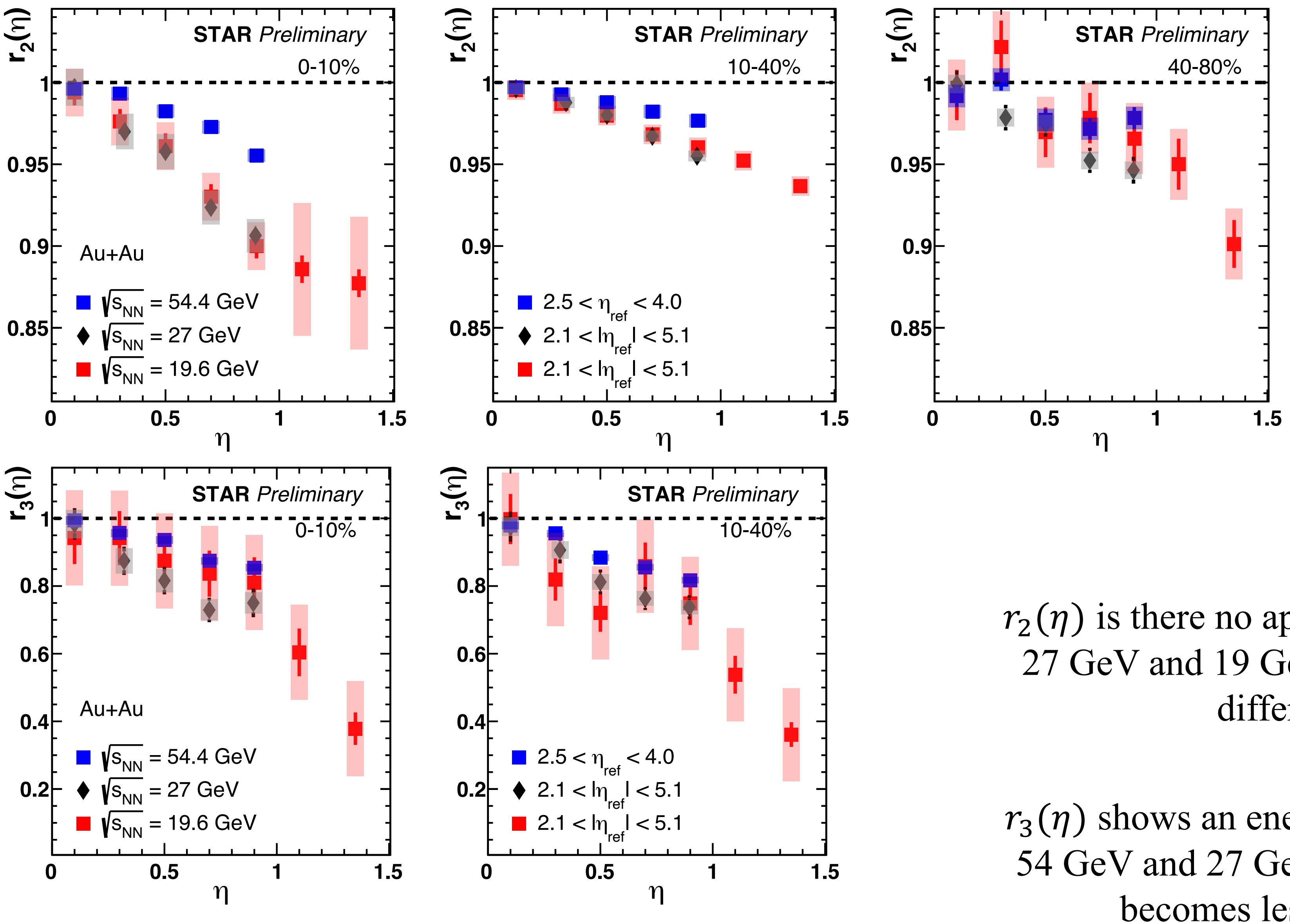
From Prithwish Tribedy

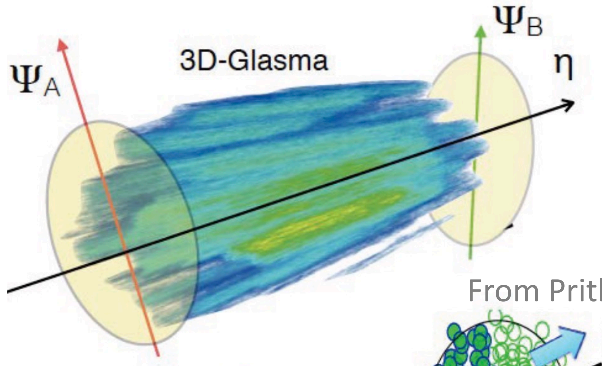


From Wei Li

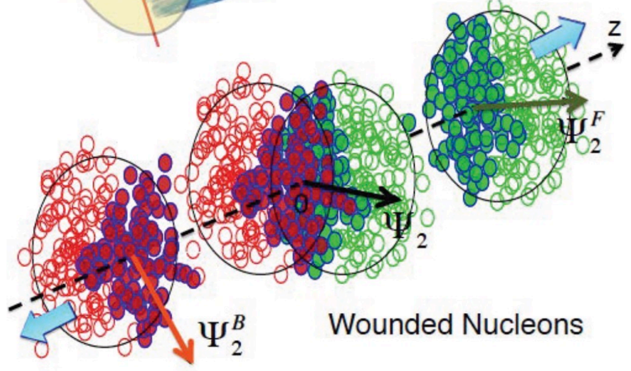
$r_2(\eta)$ is there no apparent difference between 27 GeV and 19 GeV because of their small different energy?

Longitudinal dynamics in heavy-ion collisions





From Prithwish Tribedy



From Wei Li

$r_2(\eta)$ is there no apparent difference between 27 GeV and 19 GeV because of their small different energy?

$r_3(\eta)$ shows an energy dependence between 54 GeV and 27 GeV because lower energy becomes less boost-invariant

Asymmetric Correlations

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

k-odd particle correlations

$$\langle 3\rangle_{n+m,nm} = \left\langle e^{i(n+m\,\varphi_1 - n\varphi_2 - m\varphi_3)}\right\rangle$$

n-m mode-coupling

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

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

Asymmetric Correlations

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

k-odd particle correlations

$$\langle 3 \rangle_{n+m,nm} = \left\langle e^{i(n+m\,\varphi_1 - n\varphi_2 - m\varphi_3)} \right\rangle$$

n-m mode-coupling

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

Are sensitive to the initial state effects.

Event plane angular correlations

$$\rho_{n+2,2n} = \frac{v_{n+2}^{Non\ Linear}}{v_{n+2}^{Inclusive}} \sim \langle \cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n) \rangle$$

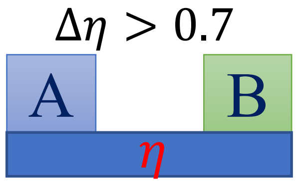
Transverse momentum flow correlations

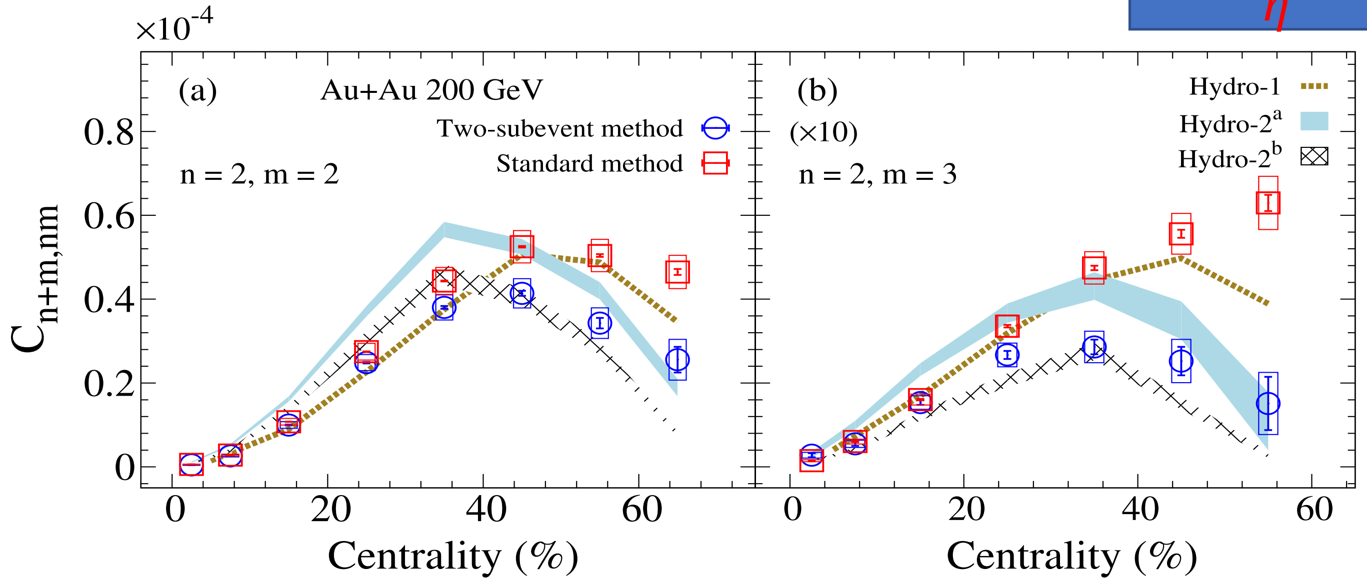
Asymmetric Correlations

STAR Collaboration PLB 839 137755 (2023)

STAR Collaboration PLB 809 135728 (2020)

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





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

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

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

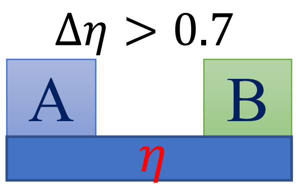
	Hydro−1 [67]	Hydro−2$^{a/b}$ [68]
η/s	0.05	0.12
Initial conditions	TRENTO Initial conditions	IP-Glasma Initial conditions
Contributions	Hydro + Direct decays	(a) Hydro + Hadronic cascade (b) Hydro only

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

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

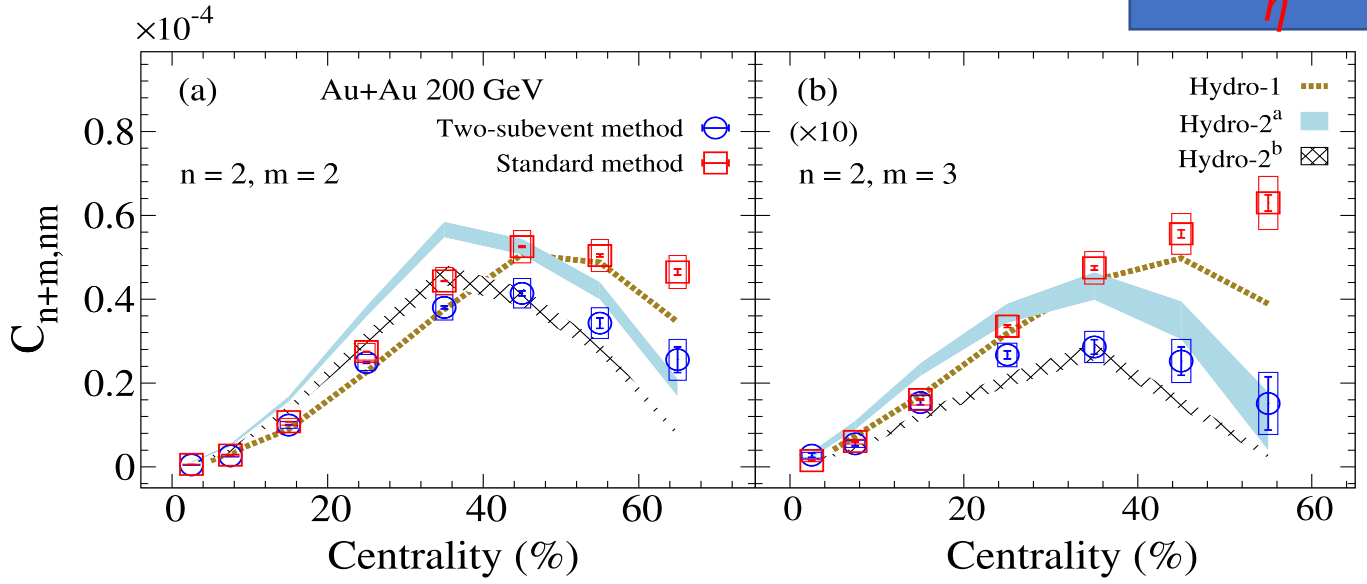
Asymmetric Correlations

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



STAR Collaboration PLB 839 137755 (2023)

STAR Collaboration PLB 809 135728 (2020)



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

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

- 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.

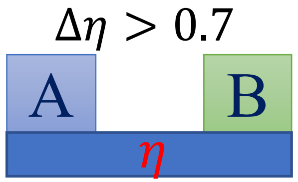
	Hydro−1 [67]	Hydro−$2^{a/b}$ [68]
η/s	0.05	0.12
Initial conditions	TRENTO Initial conditions	IP-Glasma Initial conditions
Contributions	Hydro + Direct decays	(a) Hydro + Hadronic cascade
		(b) Hydro only

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

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

Asymmetric Correlations

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

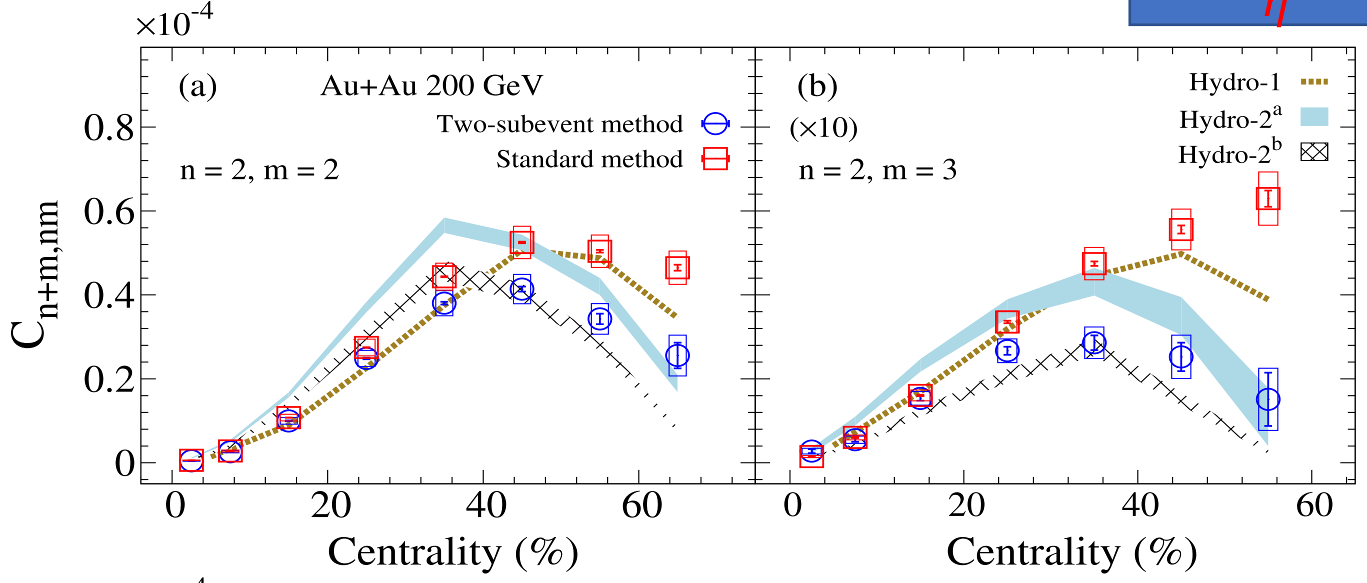


STAR Collaboration
PLB 839 137755 (2023)

STAR Collaboration
PLB 809 135728 (2020)

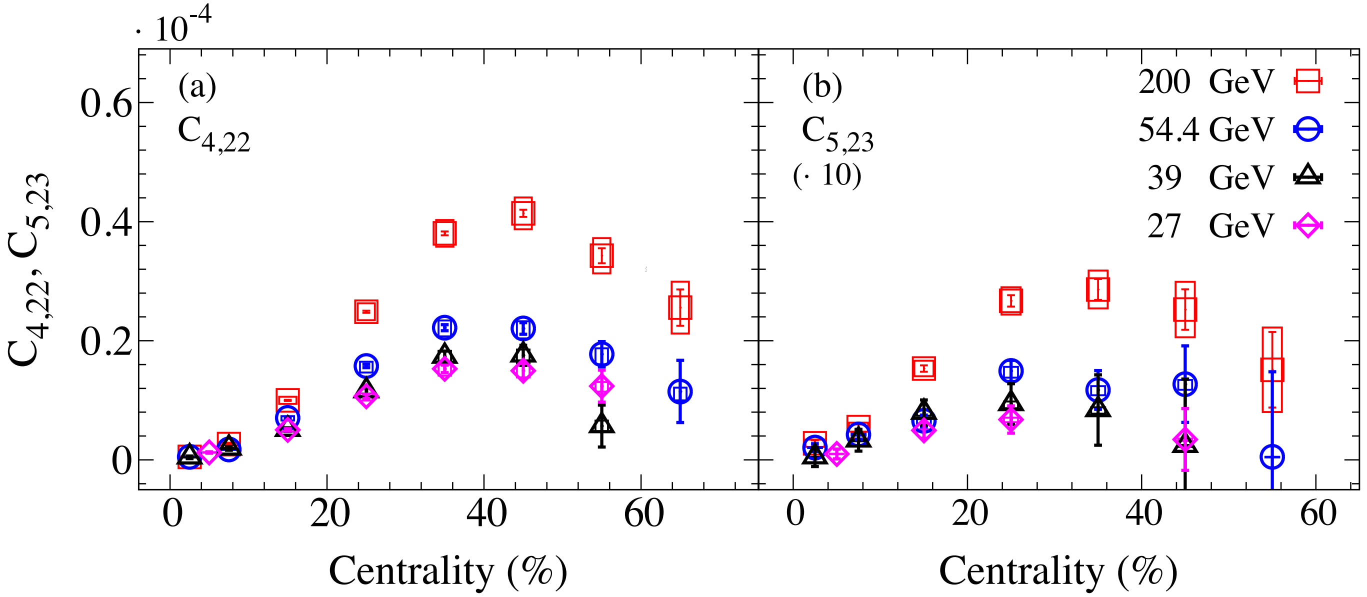
$$C_{4,22} = \langle\langle \cos(4\varphi_1^A - 2\varphi_2^B - 2\varphi_3^B) \rangle\rangle$$

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



- 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)

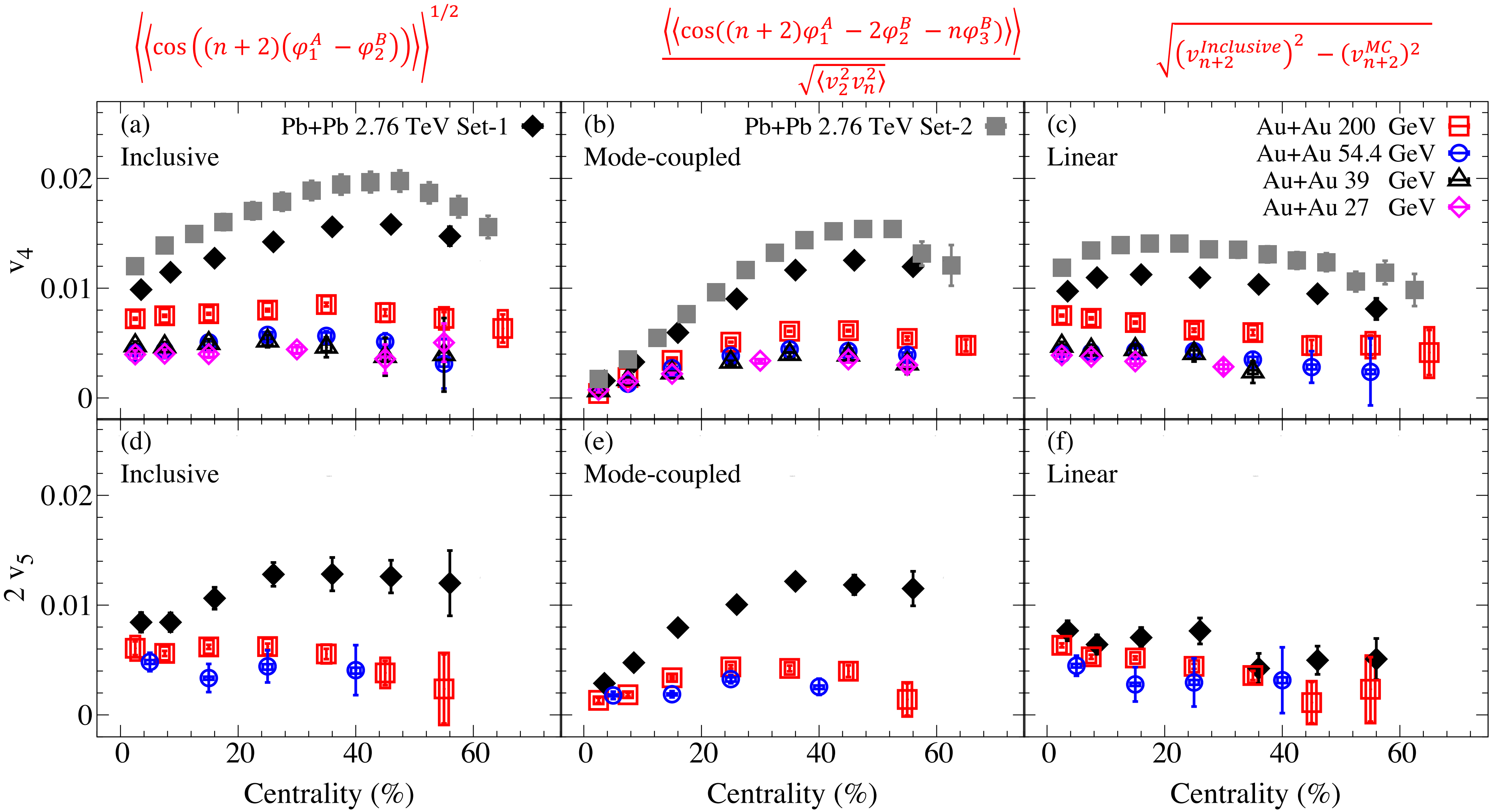
(II) B.Schenke , et al.
PRC 99, 044908 (2019)

Asymmetric Correlations

STAR Collaboration
PLB 839 137755 (2023)

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

$n = 2,3$



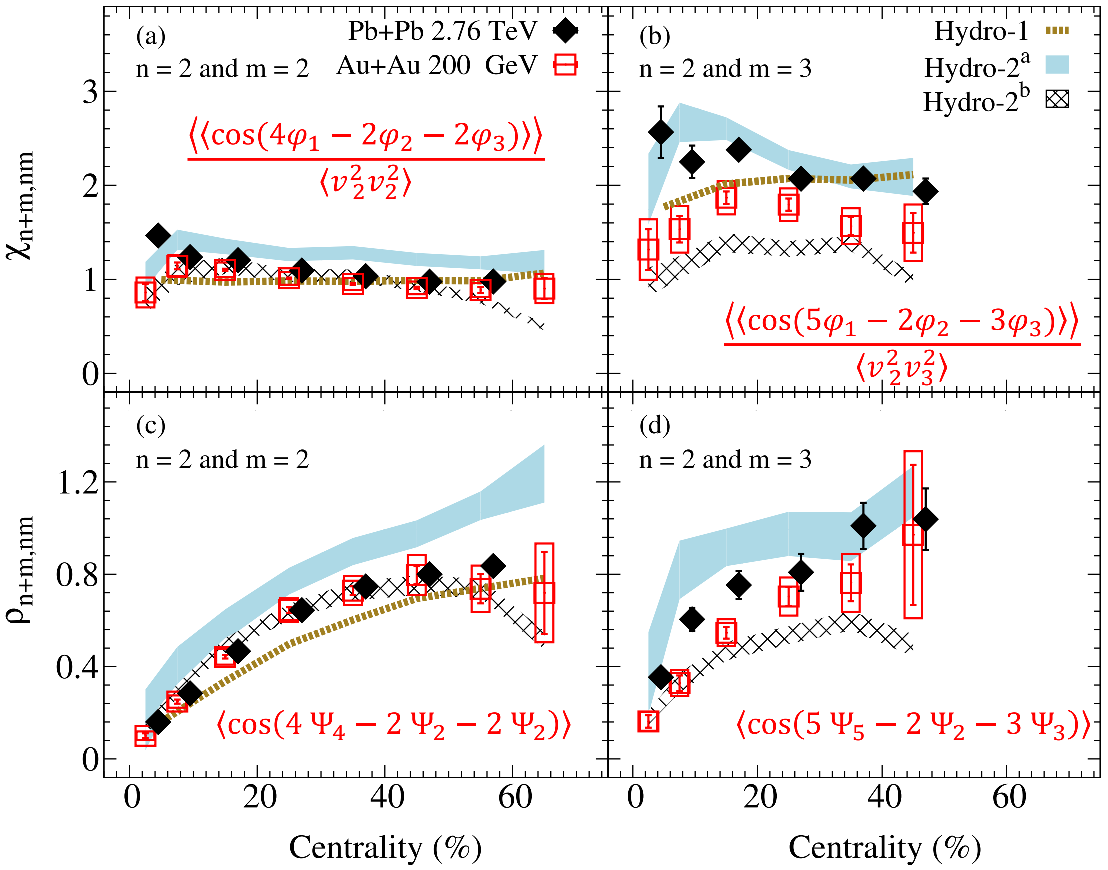
➢ The linear v_k (k=4,5) terms dominate in central collisions, while the non-linear terms take over or are comparable in peripheral collisions

Asymmetric Correlations

STAR Collaboration
PLB 839 137755 (2023)

STAR Collaboration
PLB 809 135728 (2020)

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



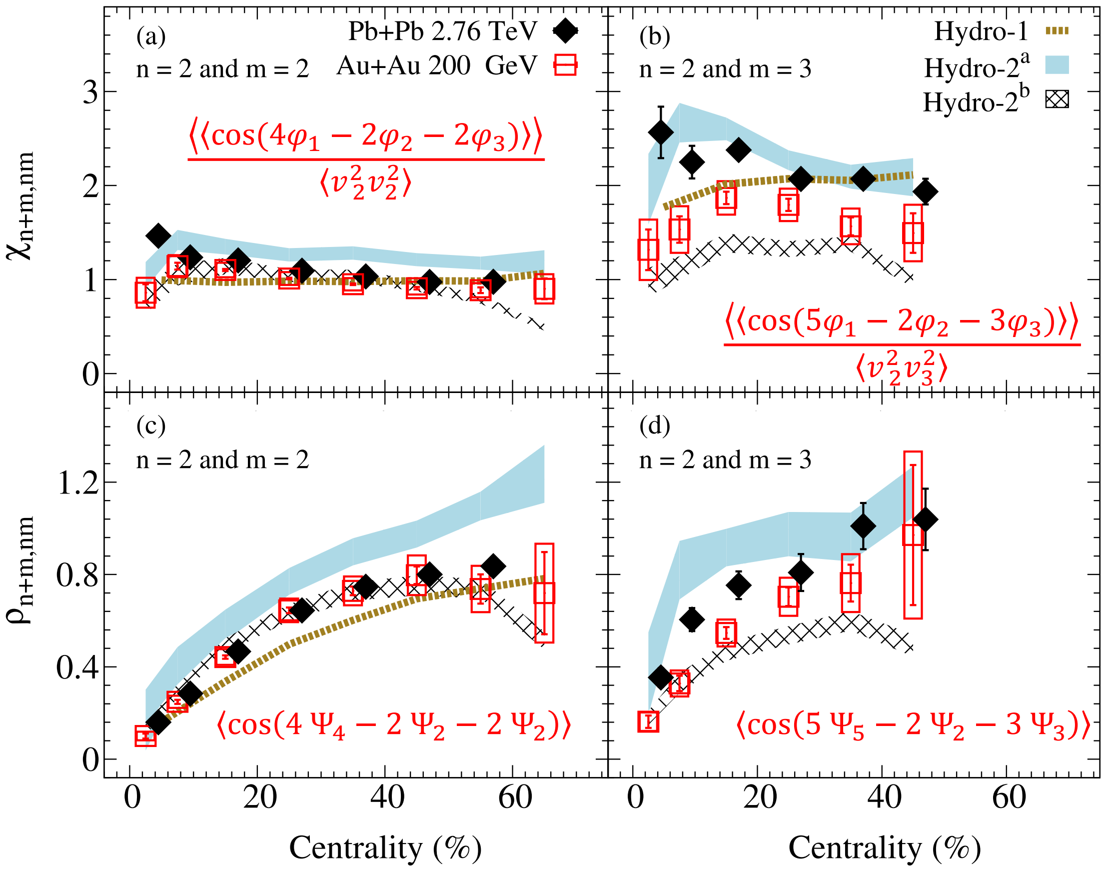
- $\chi_{k,nm}$ shows a weak centrality dependence
- $\rho_{k,nm}$ shows a strong centrality dependence

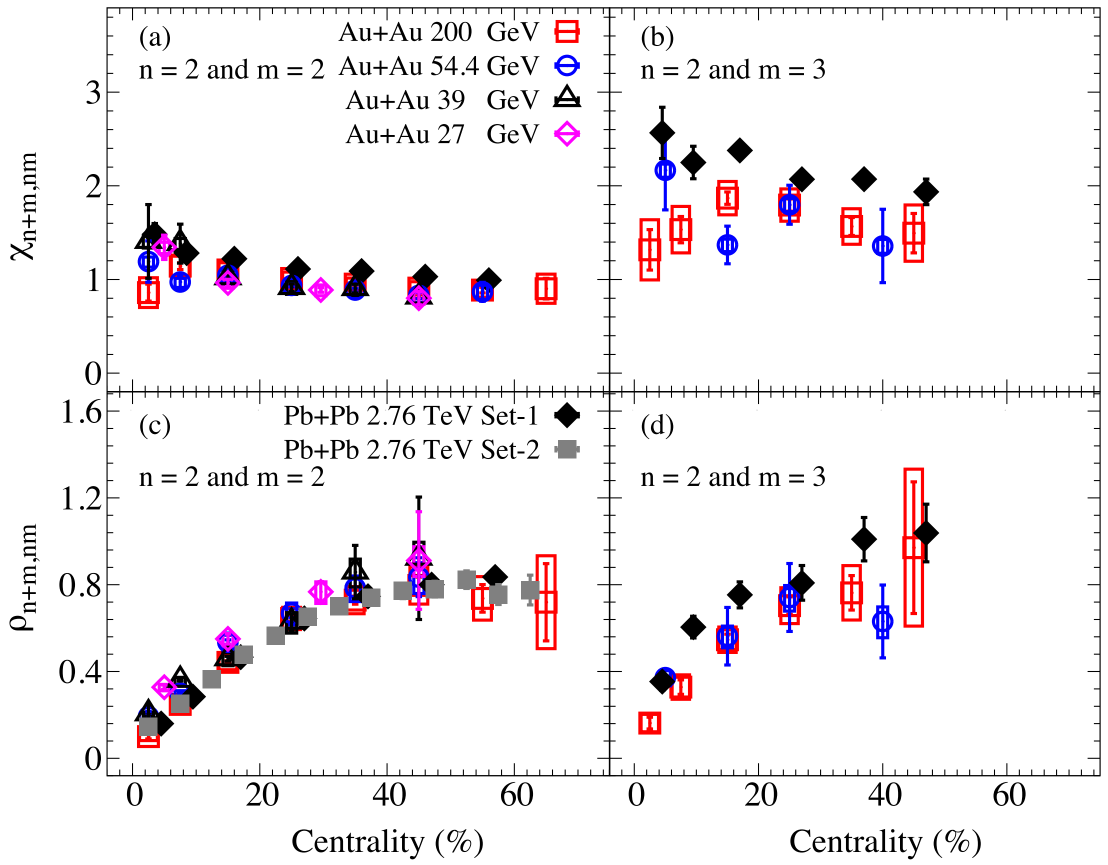
	Hydro−1 [67]	Hydro−2$^{a/b}$ [68]
η/s	0.05	0.12
Initial conditions	TRENTO Initial conditions	IP-Glasma Initial conditions
Contributions	Hydro + Direct decays	(a) Hydro + Hadronic cascade (b) Hydro only

Asymmetric Correlations

STAR Collaboration PLB 839 137755 (2023) STAR Collaboration PLB 809 135728 (2020)

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





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

	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

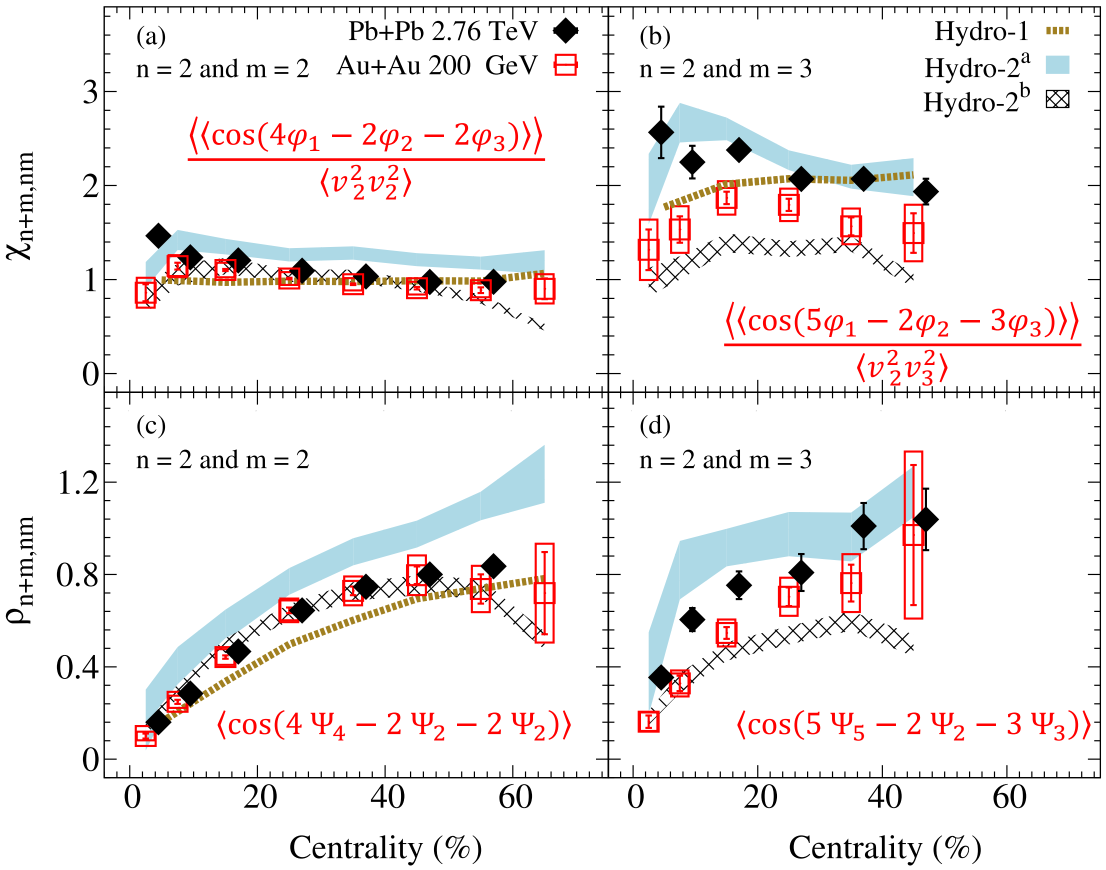
- The $\chi_{k,nm}$ and $\rho_{k,nm}$ show similar values and trends for different beam energies

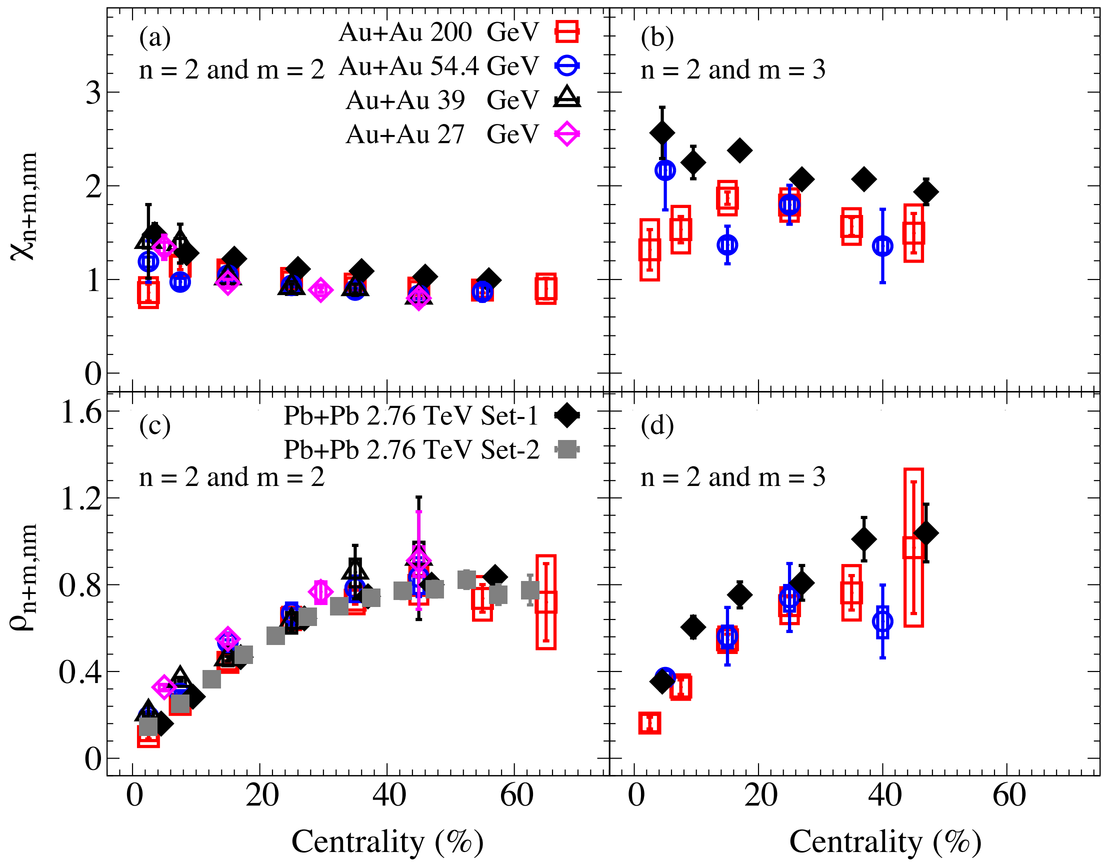
Asymmetric Correlations

STAR Collaboration PLB 839 137755 (2023)

STAR Collaboration PLB 809 135728 (2020)

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





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

	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

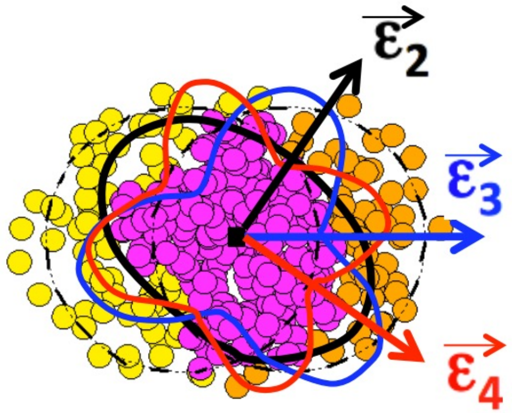
- The $\chi_{k,nm}$ and $\rho_{k,nm}$ show similar values and trends for different beam energies

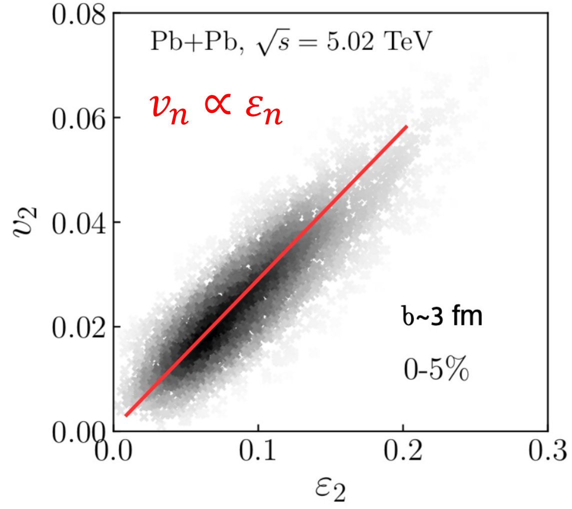
The influence from final-state is less than the one from initial-state ?

Transverse momentum flow correlations

- shape → anisotropic flow

$$\mathrm{Var}(v_n^2)_{dyn} = v_n^4\{2\} - v_n^4\{4\}$$

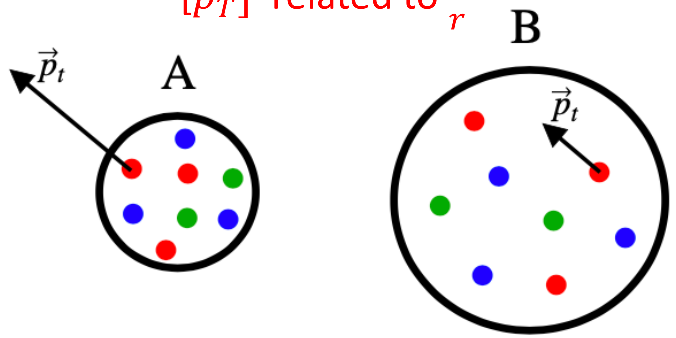




- size → radial flow

$$C_k = \langle (p_{T,i} - \langle [p_T] \rangle)(p_{T,j} - \langle [p_T] \rangle) \rangle$$

$[p_T]$ related to $\frac{1}{r}$



From Arabinda Behera

correlation between v_n^2 and average p_T

$$\mathrm{cov}(v_n^2, [p_T]) = \left\langle e^{in(\phi_i - \phi_j)} (p_{T,k} - \langle [p_T] \rangle) \right\rangle$$

Pearson coefficient：

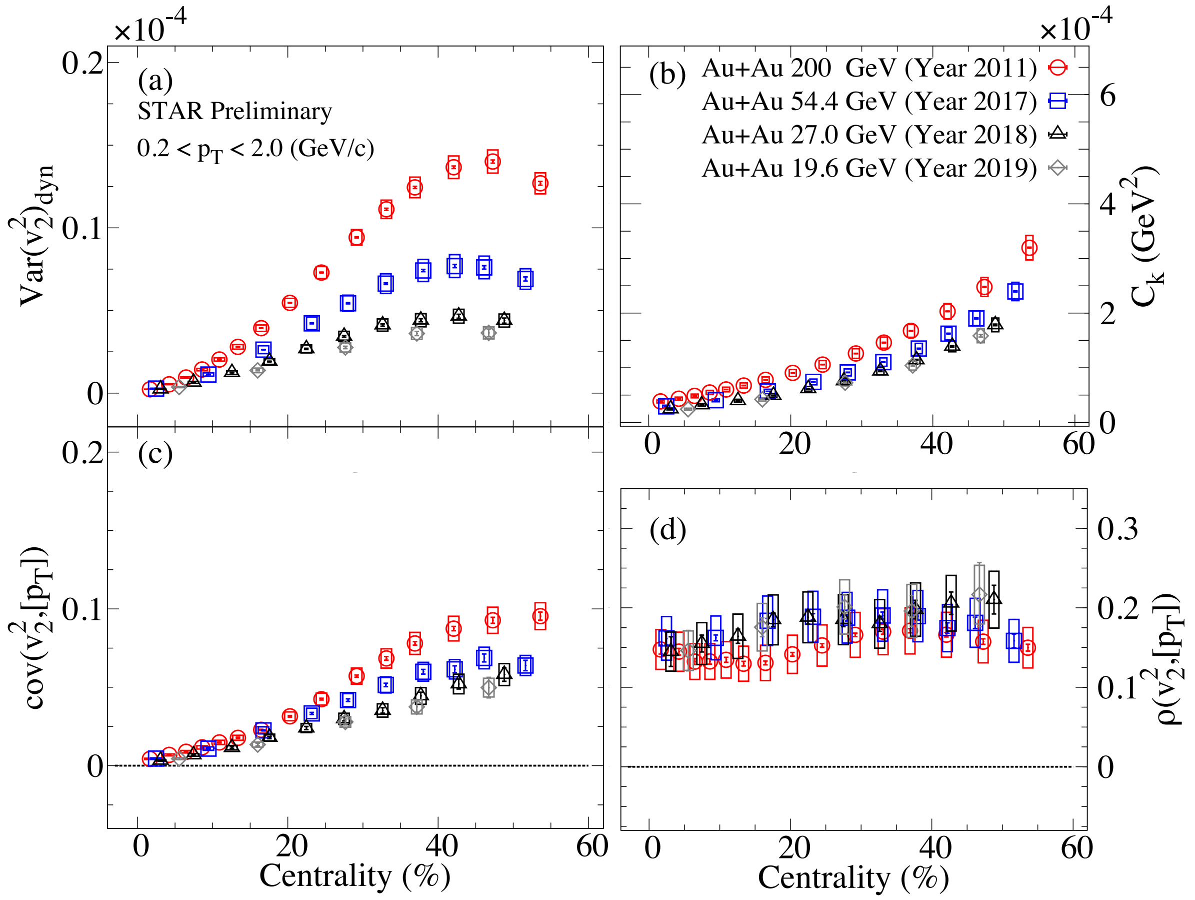
$$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{Var(v_n^2)_{dyn}\, C_{\{k\}}}}$$

correlation between

initial state shape and size →

P. Bozek, Phys. Rev. C 93 (2016) 4, 044908
G. Giacalone, B.Schenke, C.Shen, Phys. Rev. Lett. 128 (2022) 4, 042301

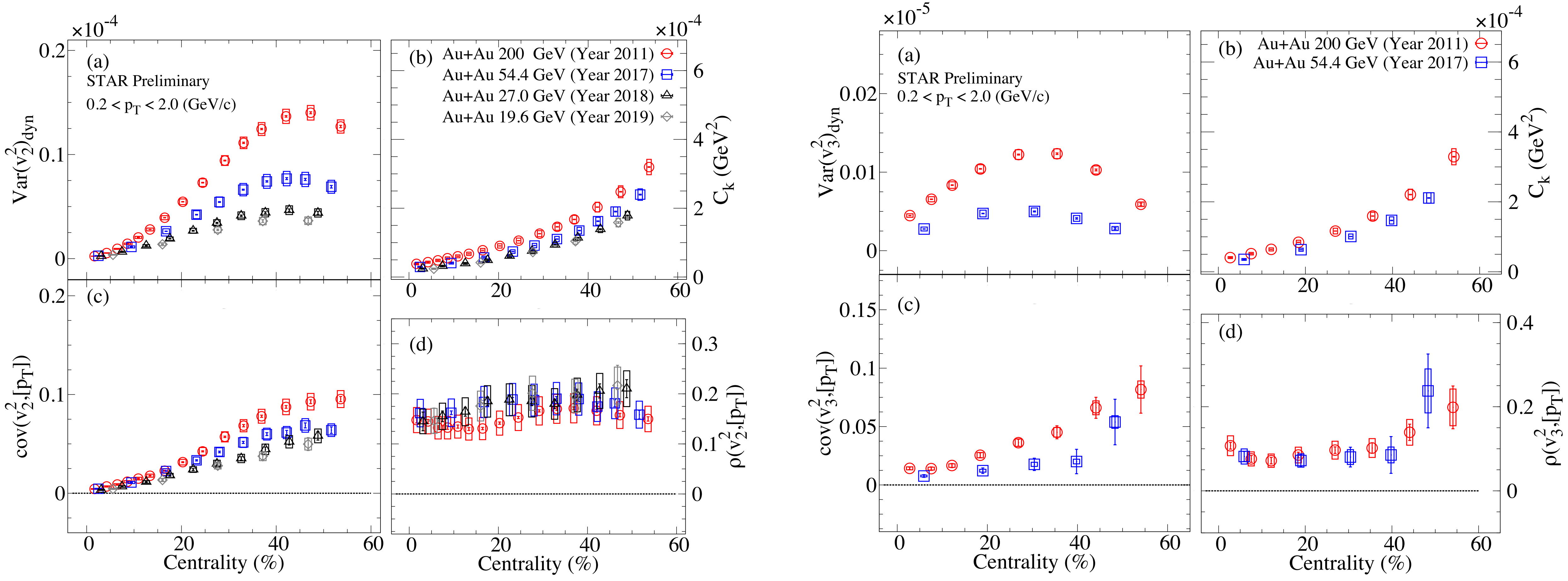
Transverse momentum flow correlations



- Pearson coefficient:

  $\rho(v_2^2, [p_T])$ shows hint of energy dependence

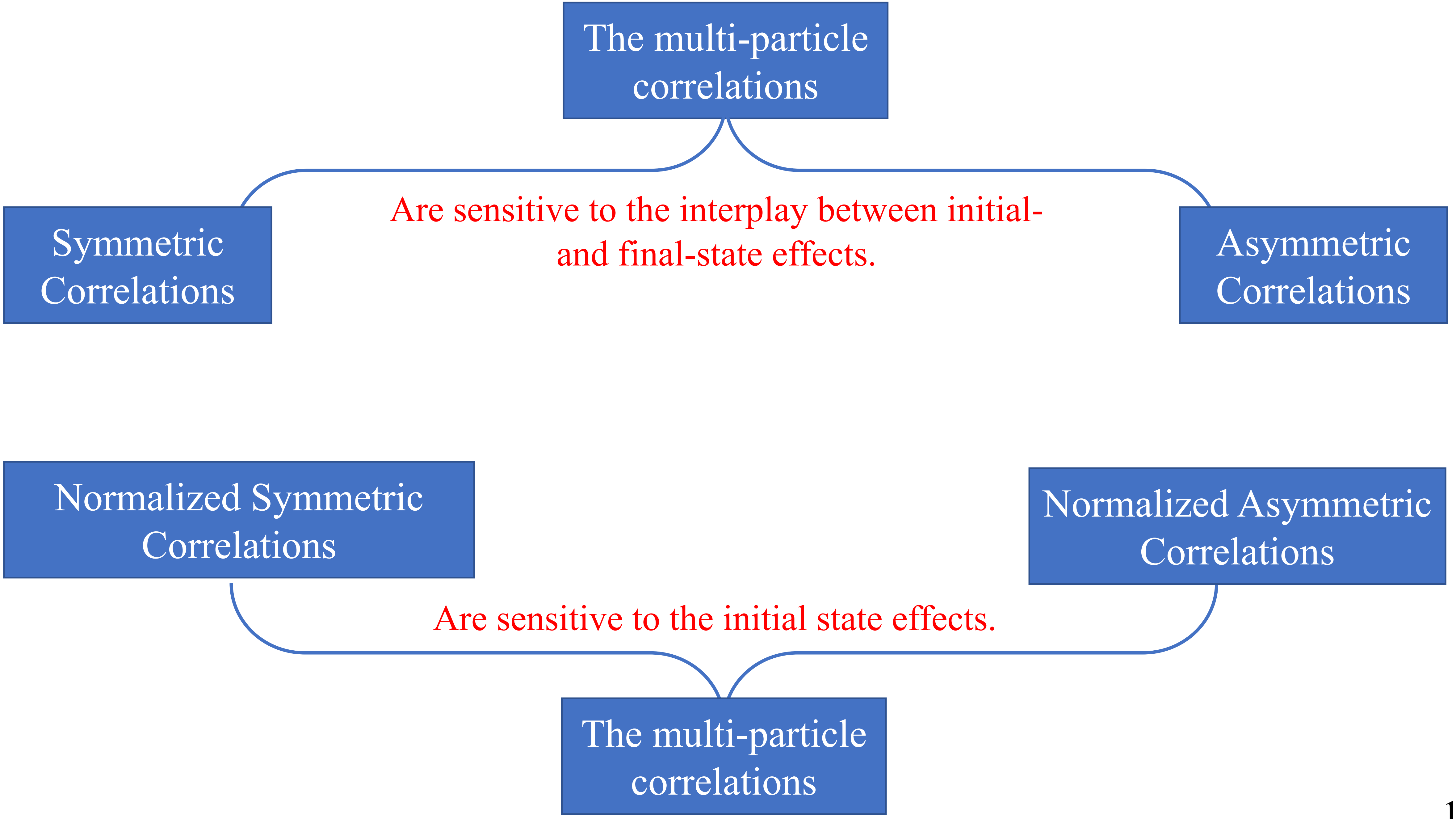
Transverse momentum flow correlations



- Pearson coefficient:

  $\rho(v_2^2,[p_T])$ shows hint of energy dependence

  $\rho(v_3^2,[p_T])$ shows weak energy dependence


The multi-particle correlations
Symmetric Correlations
Are sensitive to the interplay between initial- and final-state effects.
Asymmetric Correlations
Normalized Symmetric Correlations
Normalized Asymmetric Correlations
Are sensitive to the initial state effects.
The multi-particle correlations

Thank You