Exploring Electromagnetic Field Effects and Constraining Transport Parameters of QGP Using STAR BES II Data

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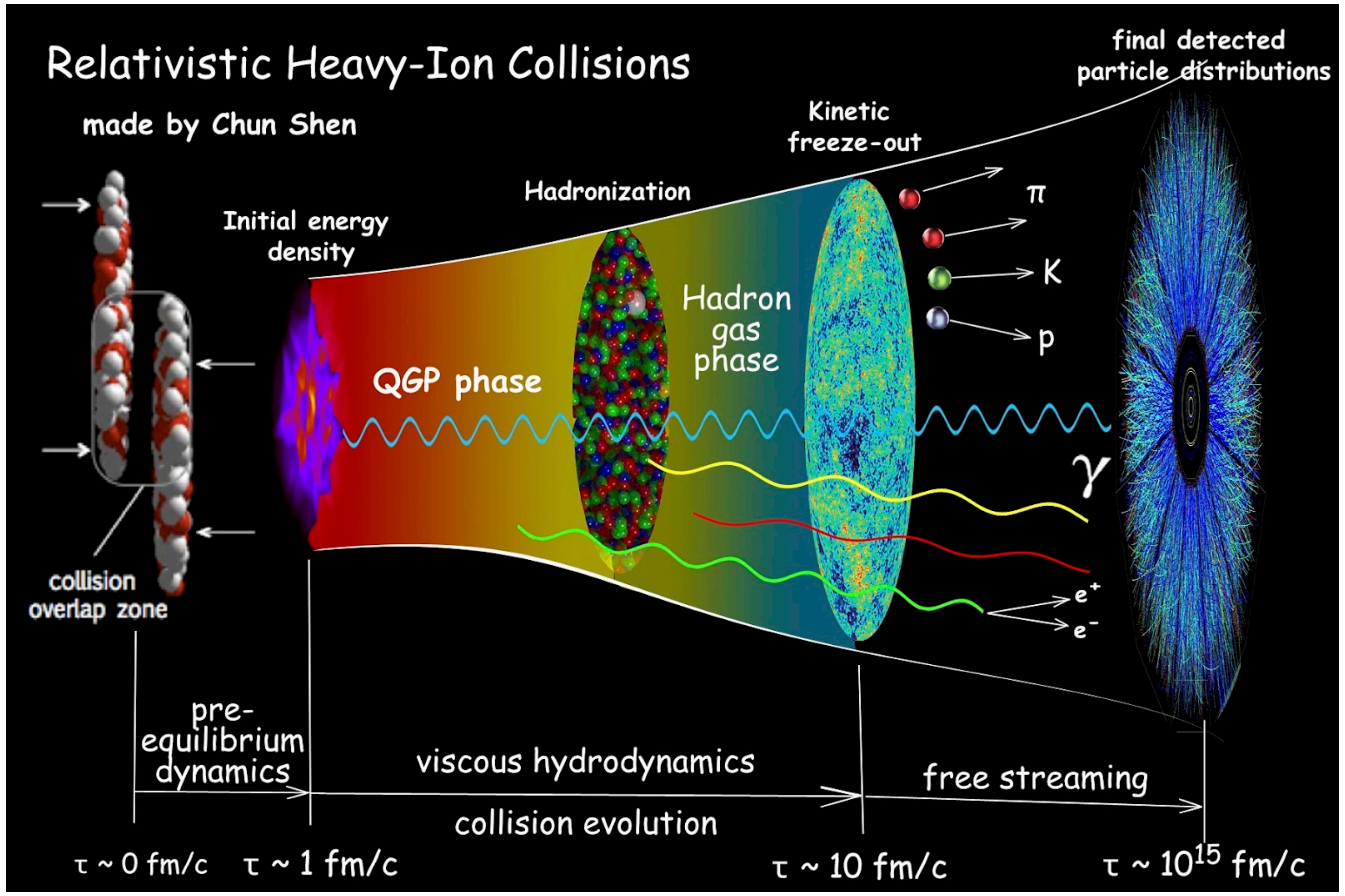
Motivation

- The medium formed in a heavy ion collision undergoes many stages in its evolution
- Crucial to disentangle initial and final stage effects
- We present measurements sensitive to initial electromagnetic fields and 3D initial state



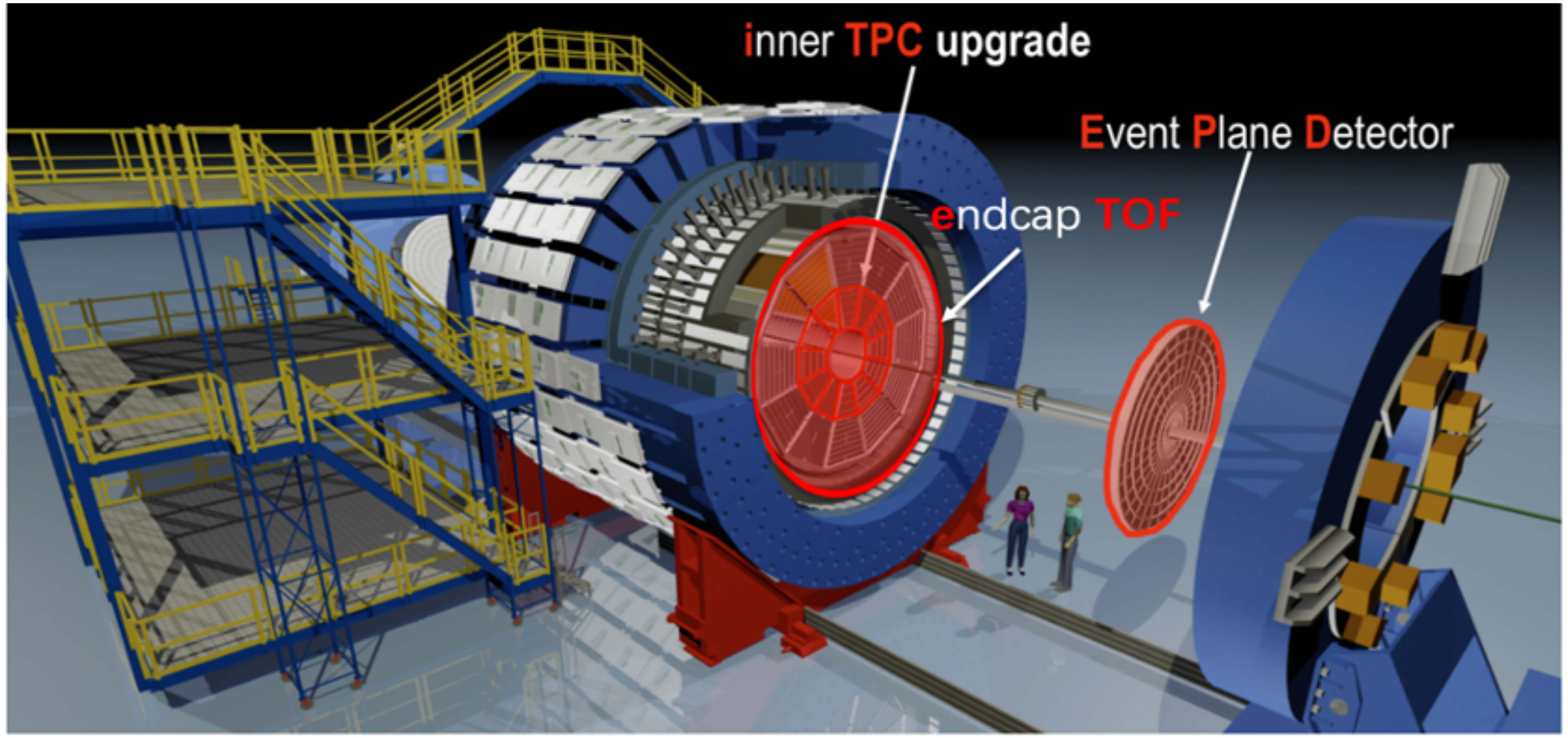
https://u.osu.edu/vishnu/2014/08/06/sketch-of-relativistic-heavy-ion-collisions/

STAR experiment

Collision System: Au+Au
Beam Energies: 200, 54.4,19.6, 14.6 and 7.7 GeV in BES-II

Time Projection Chamber
Tracking of charged particles with full azimuthal coverage

Time of Flight
Extends particle identification to higher momenta,
full azimuthal coverage



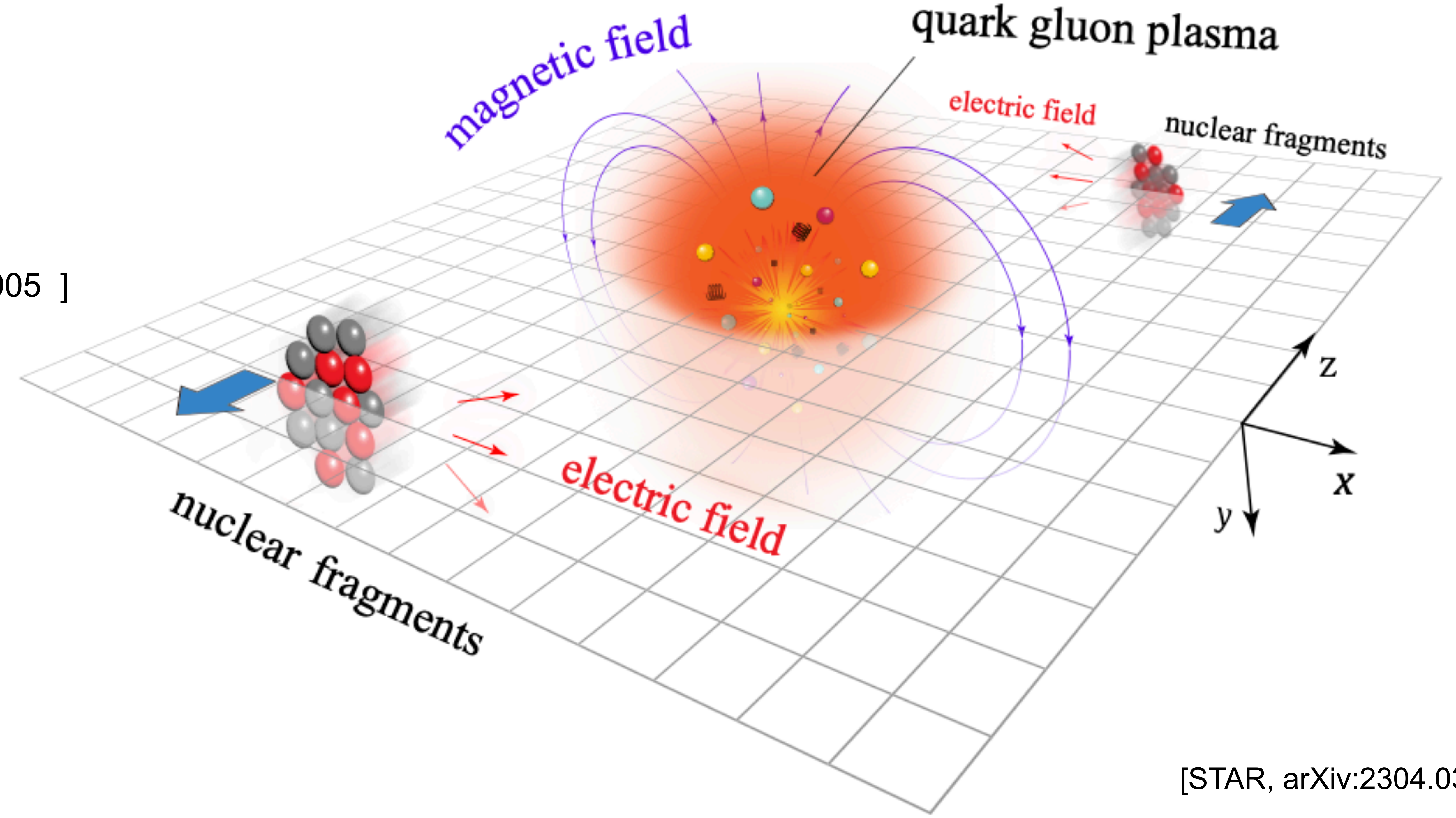
The STAR detector

Event Plane Detector and Zero Degree Calorimeter
Used for event plane reconstruction, EPD ($2.1<|\eta|<5.1$), ZDC-SMD($|\eta|>6.3$)

Motivation

- Ultra strong magnetic fields ~10^{18} Gauss are expected in very early stages of Heavy Ion Collisions.
- Decays fast ~ sensitive to formation time of quarks and QGP conductivity
- Important to understand QGP evolution in presence of EM fields

[U. Gürsoy et al. PRC 98,055201, PRC 89 054905]



[STAR, arXiv:2304.03430]

Directed Flow

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi))\right)$$

v_1 is called directed flow and can be estimated by

$$v_1 = \langle \cos(\phi - \Psi_{EP}) \rangle / R\{\Psi_{EP}\}$$

[A. M. Poskanzer et al. PRC 58 1671]

ϕ=azimuthal angle of particle momentum
Ψ_{EP}= event plane azimuthal angle
$R\{\Psi_{EP}\}$= Event plane resolution

EM field effects on directed flow

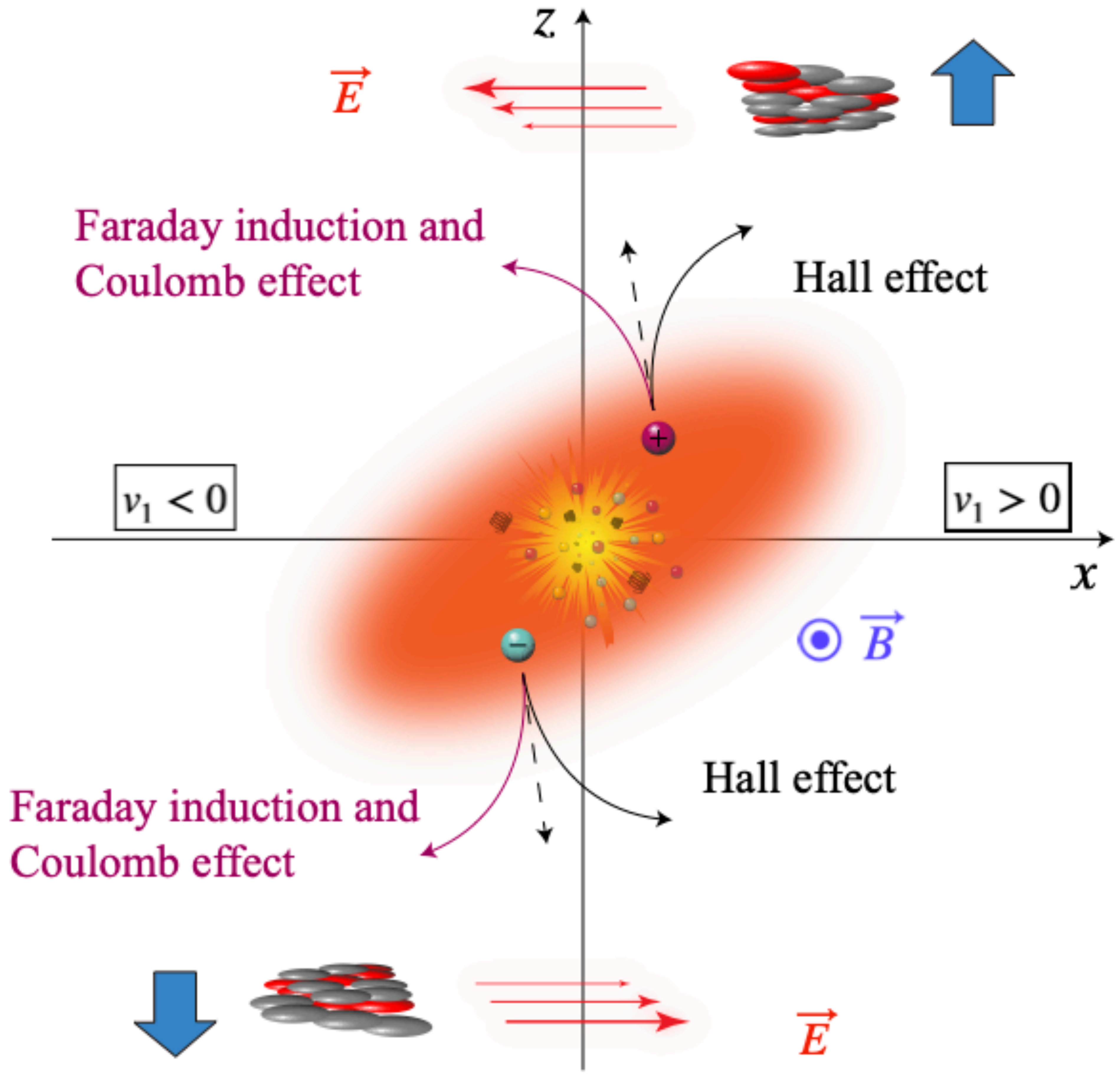
Quarks in the expanding medium experience different forces due to

1. **Hall Effect**: **F**= q(**v**×**B**)
2. **Coulomb Effect**: **E** generated by spectators
3. **Faraday Induction**: Generated by decreasing magnetic field as spectators fly away

[U. Gürsoy et al. PRC 98,055201, PRC 89 054905]

These EM forces give opposite v_1 to particles with opposite charges

Transported quark effect: Quarks transported from incoming nuclei can have different v_1 than that of quarks produced in the interaction region. **It can affect hadrons having u and d quarks.**

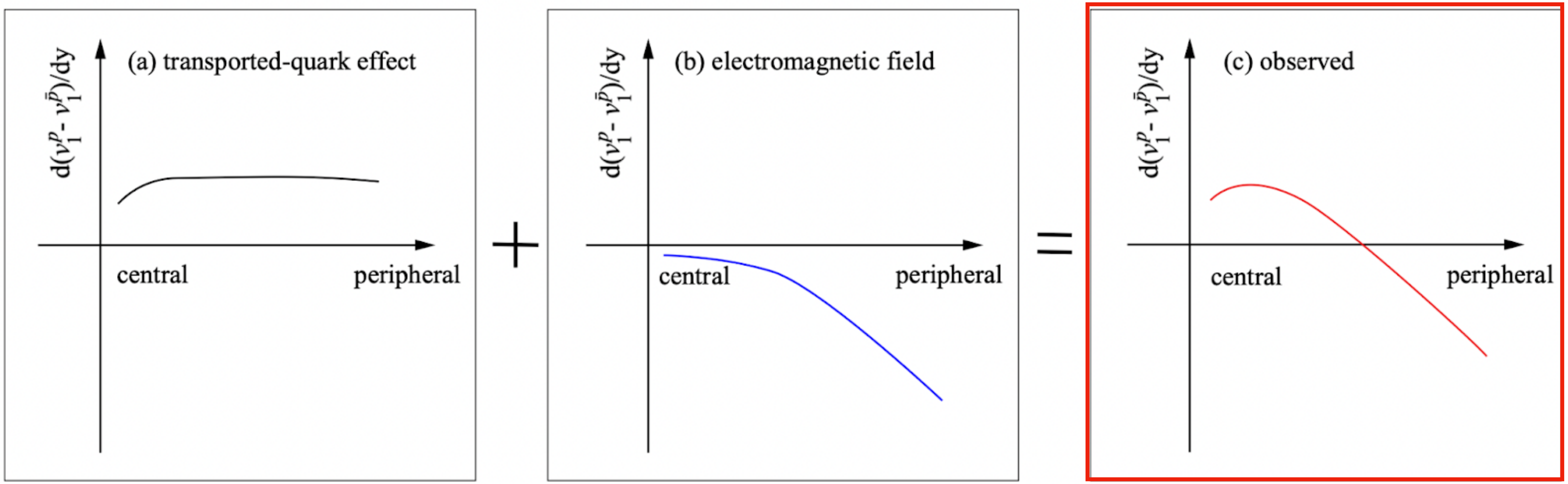


[STAR, arXiv:2304.03430]

EM field effects on directed flow

STAR

Demonstration for protons



$\Delta dv_1/dy = dv_1(h^+)/dy - dv_1(h^-)/dy$

[STAR, arXiv:2304.03430]

Models show positive dv_1/dy for transported quarks [1].

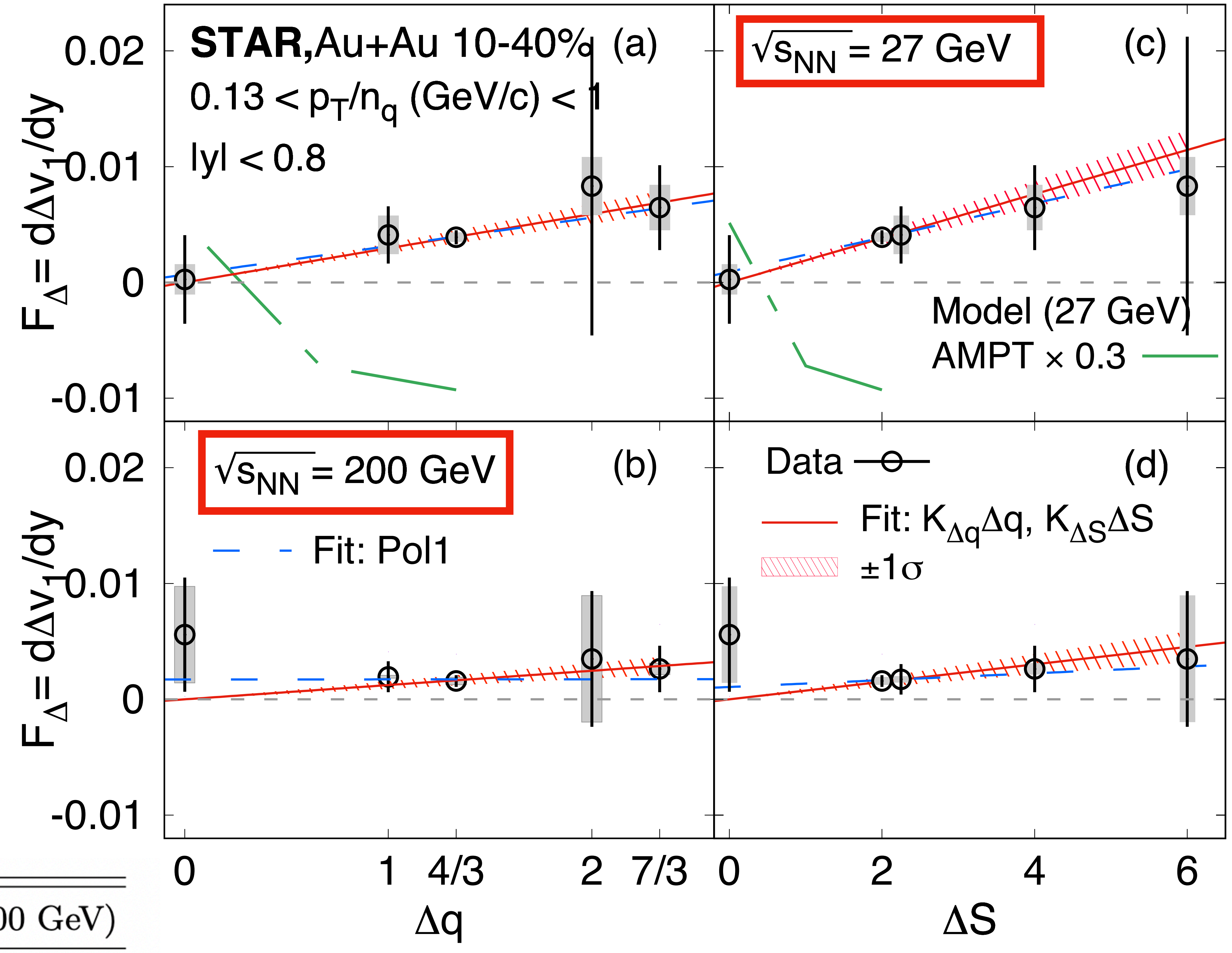
$\Delta dv_1/dy$ sign change could reveal effects of electromagnetic fields in QGP

Transported quark effects on pions should give opposite $\Delta dv/dy_1$ compared to protons and kaons assuming quark coalescence

[1] Y. Guo et al. PRC **86**, 044901, K. Nayak et al. PRC **100**, 054903, P. Bożek PRC **106**, L061901

dΔv_1/dy in 10-40% centrality (mid central)

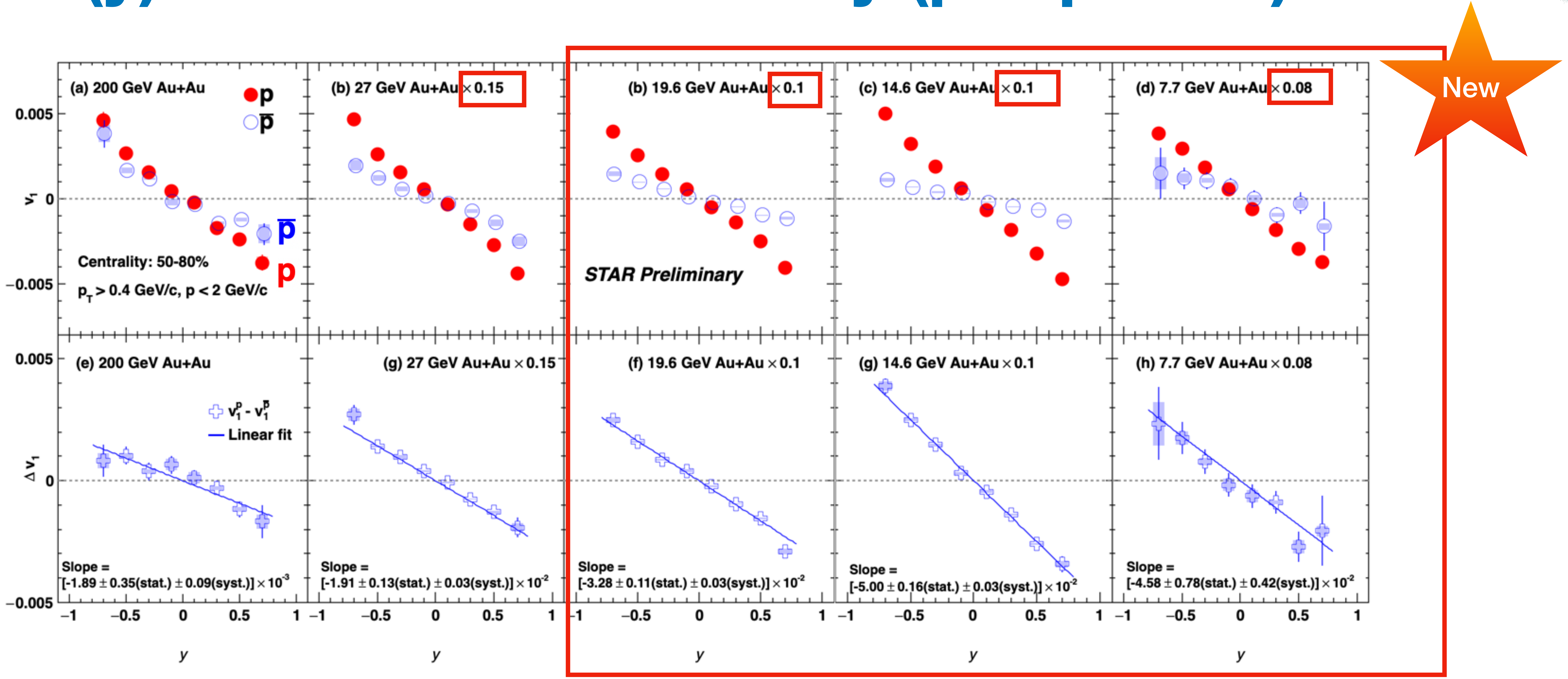
- ➢ Δv_1 difference of particles with pair-produced quarks eg. $\bar{p}(\bar{u}\bar{u}\bar{d})$ and $K^{-}(\bar{u}s)$
- ➢ The dΔv_1/dy combinations (fit constrained to origin) show positive slope and increase with Δq and ΔS
- ➢ Hall effect could be dominant in mid central collisions



Index	Quark mass	Δq	ΔS	Δv_1 combination	$F_\Delta \times 10^4$ (27 GeV)	$F_\Delta \times 10^4$ (200 GeV)
1	$\Delta m = 0$	0	0	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^{-}(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$	$03 \pm 43 \pm 13$	$56 \pm 49 \pm 41$
2	$\Delta m \approx 0$	1	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^{-}(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$	$41 \pm 25 \pm 16$	$19 \pm 13 \pm 01$
3	$\Delta m \approx 0$	$\frac{4}{3}$	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$	$39 \pm 07 \pm 03$	$16 \pm 05 \pm 03$
4	$\Delta m = 0$	2	6	$[\bar{\Omega}^{+}(\bar{s}\bar{s}\bar{s})] - [\Omega^{-}(sss)]$	$83 \pm 130 \pm 25$	$35 \pm 58 \pm 54$
5	$\Delta m \approx 0$	$\frac{7}{3}$	4	$[\bar{\Xi}^{+}(\bar{d}\bar{s}\bar{s})] - [K^{-}(\bar{u}s) + \frac{1}{3}\Omega^{-}(sss)]$	$64 \pm 36 \pm 19$	$26 \pm 20 \pm 04$

[STAR, arXiv:2304.02831]

$v_1(y)$ for 50-80% centrality (peripheral)



- ➢ **In peripheral collisions (50-80%), proton Δv_1 slope turns negative**
- ➢ Significantly negative slopes (from linear fit) in all considered energies

[STAR, arXiv:2304.03430]

Particle species and centrality dependence

➢ **BES-II results of negative Δ(dv$_1$/dy) in peripheral collisions meet expectation from electromagnetic effects**

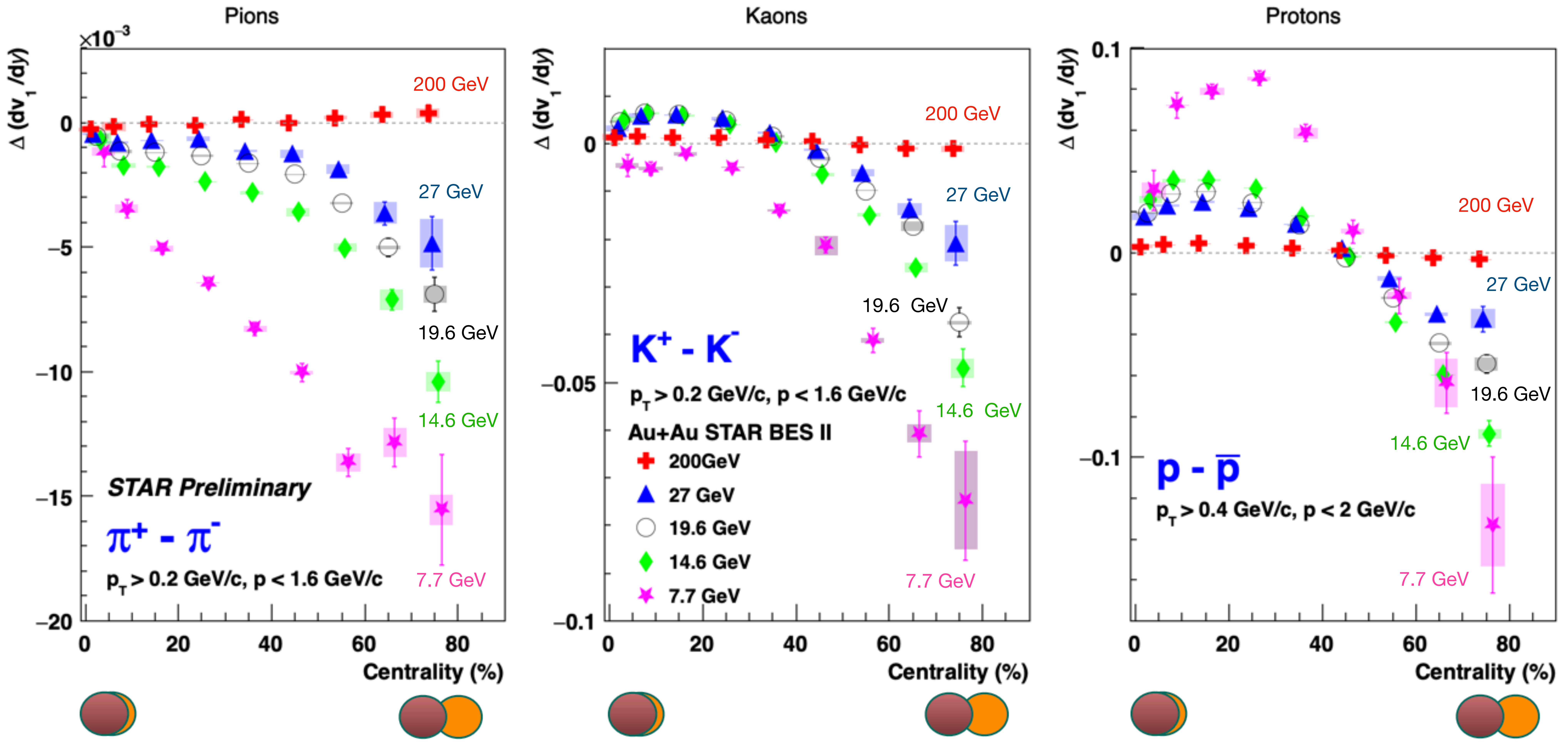
➢ Consistent with dominance of Faraday+Coulomb effect in peripheral collisions (other mechanisms are under investigation)

[T. Parida et al. arXiv:2305.10371]

➢ Data at 200 GeV are comparable to IEBE-VISHNU+EM field calculations with conductivity $\sigma = 0.023$ fm^{-1} from lattice QCD

[U. Gürsoy et al. PRC 98,055201, PRC 89 054905, STAR arXiv:2304.03430]

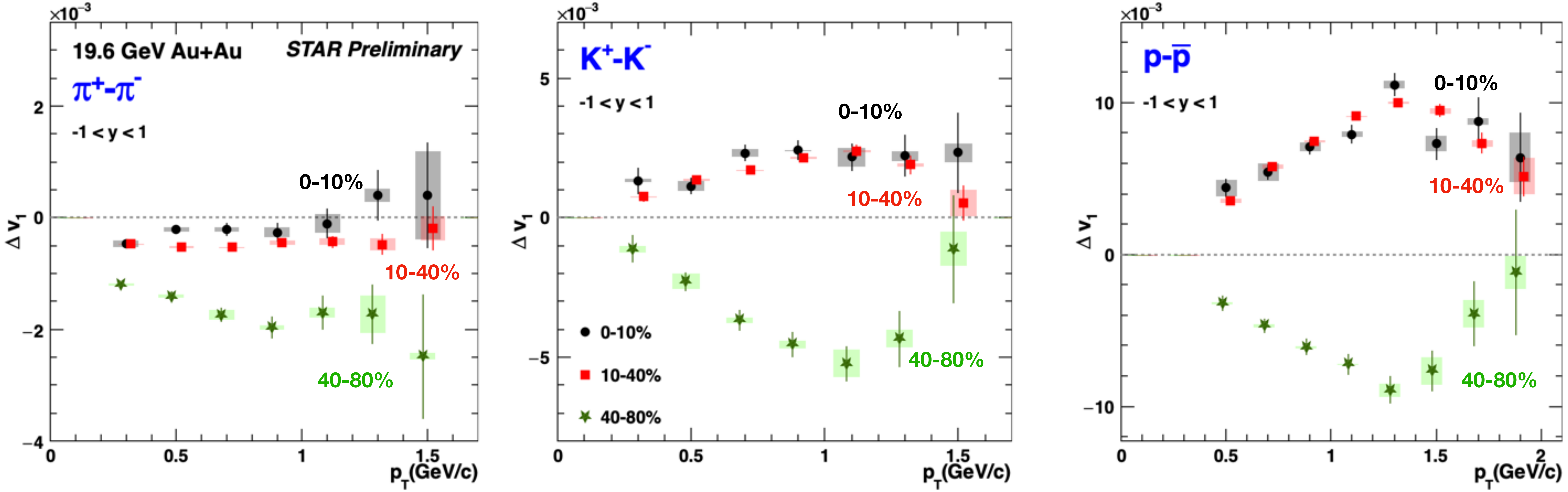
Beam energy dependence for a given particle



- ➢ **Δ(dv$_1$)/dy in peripheral collisions is more negative at lower collision energies for each species**
- ➢ $t_{passage}$ (2R/γ) larger, hence lifetime(EM field) should be longer.
- ➢ Lifetime(fireball) is shorter at lower energies.

[U. Gürsoy et al. PRC 98,055201, PRC 89 054905, STAR arXiv:2304.03430]

Δv_1 as a function of p_T



➢ Negative Δv_1 for p_T ranges considered in this analysis in **peripheral collisions**

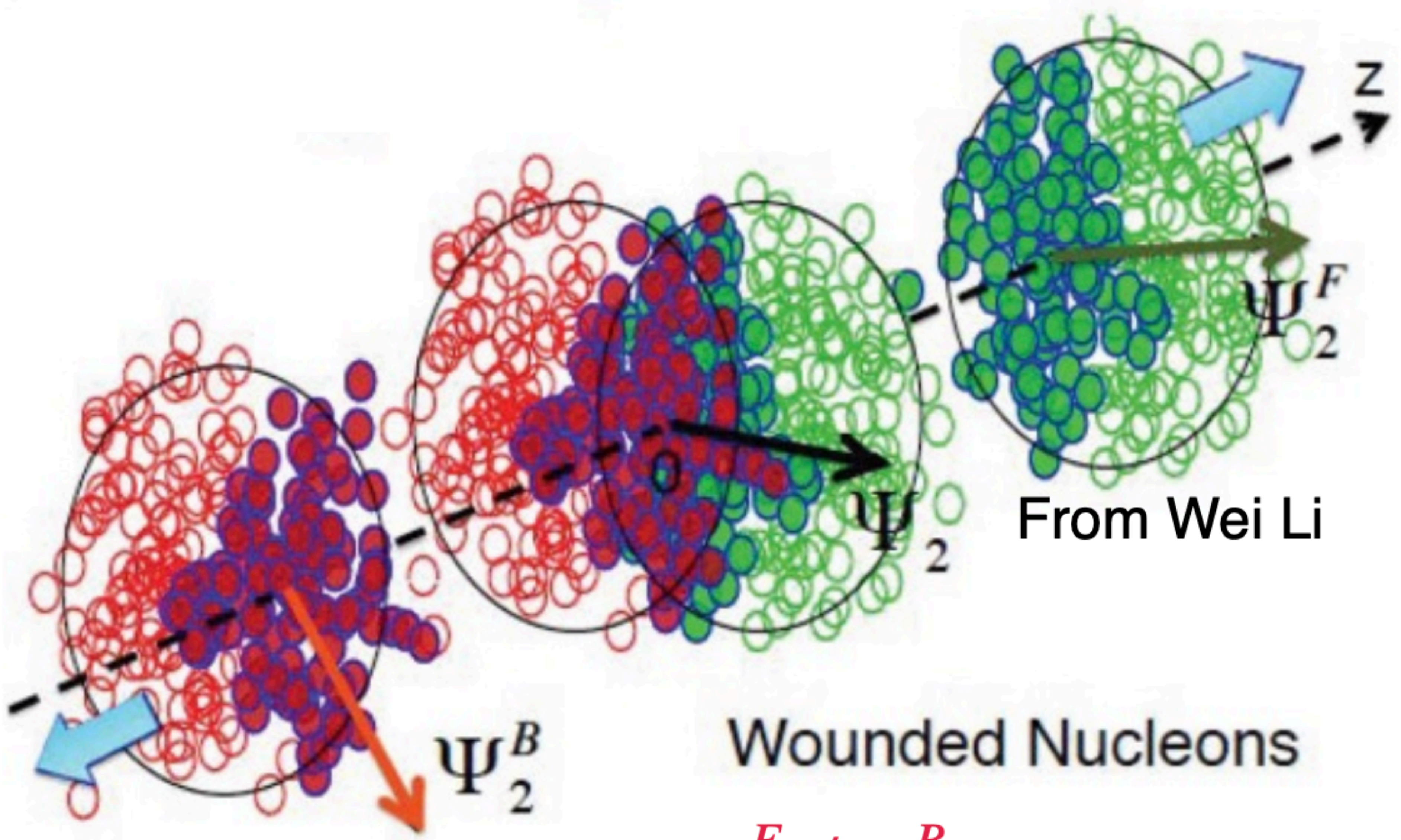
➢ **Indication of larger splitting at higher p_T as expected from theory** [U. Gürsoy et al. PRC 98,055201, PRC 89 054905]

Longitudinal Decorrelation

- $r_n(\eta)$ reflects decorrelation between event planes at η and -η
- $r_n(\eta)=1$ when there is no decorrelation or non-flow effects

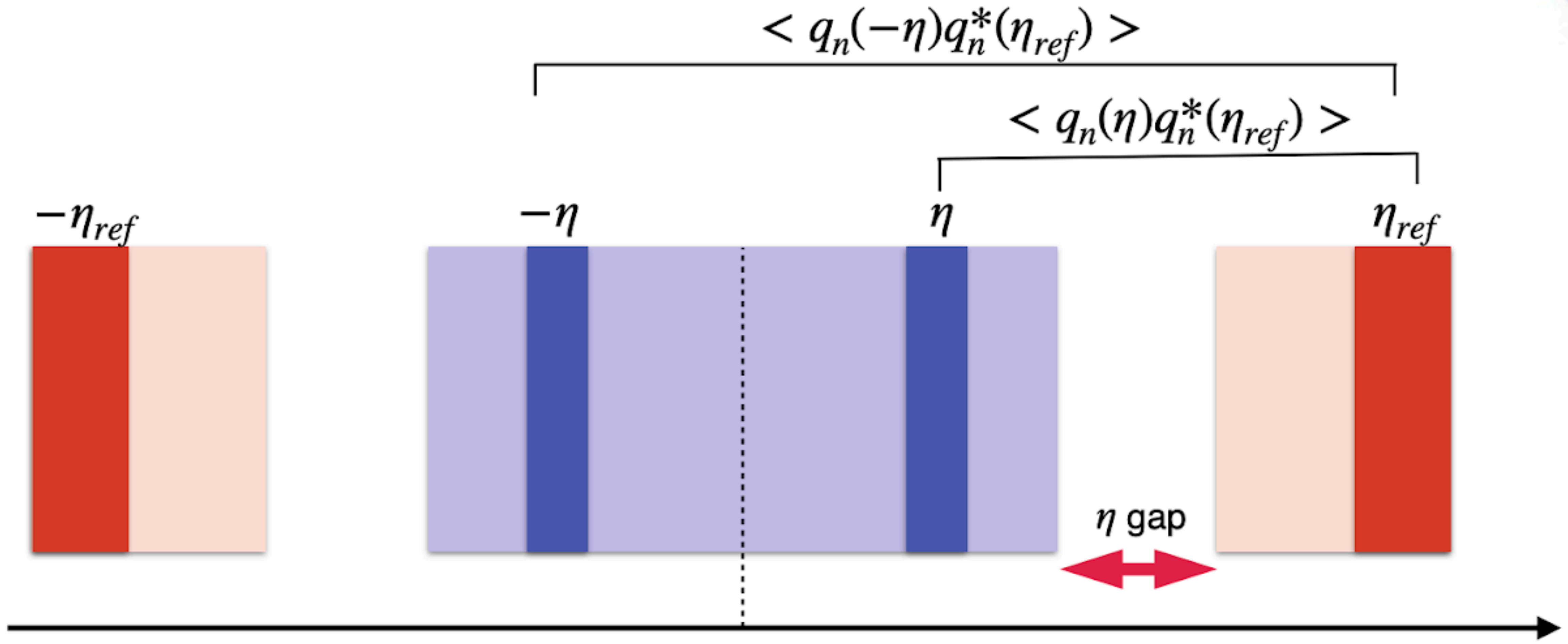
[CMS, PRC 92 (2015) 03491]

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



$\psi_2^F \neq \psi_2^B$

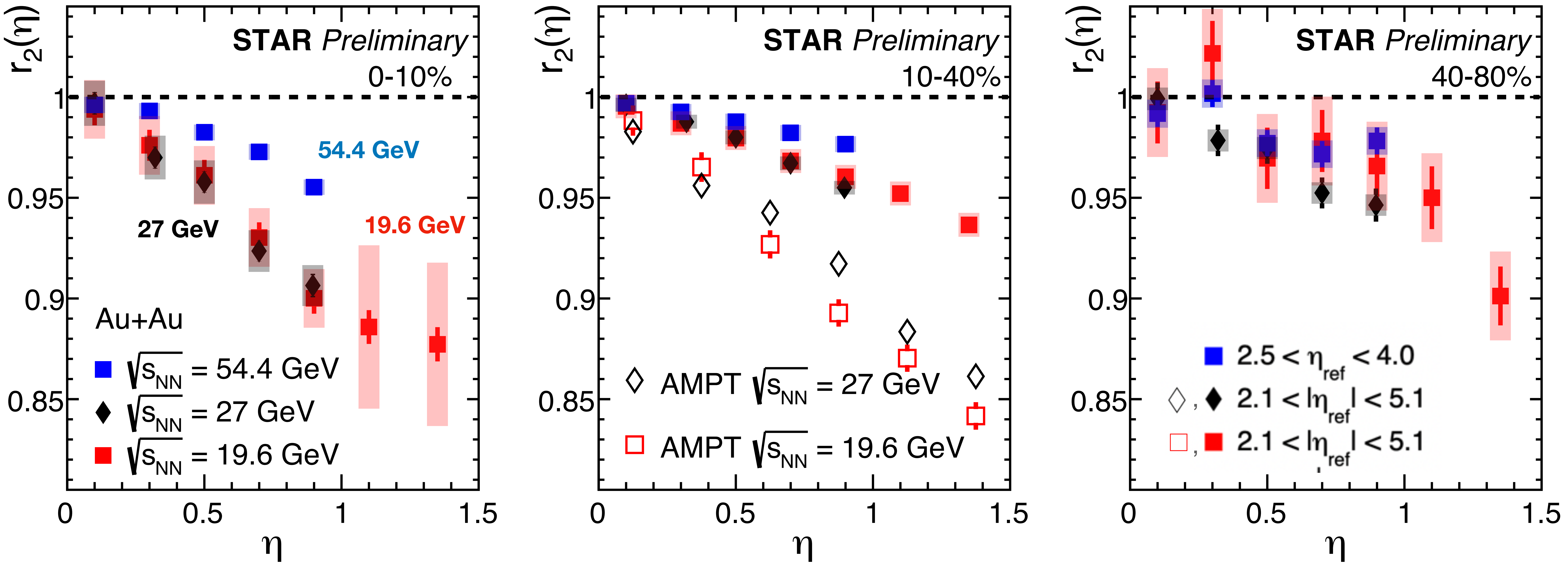
[J. Jia et al. PRC 90 (2014) 034905, G. Yan, ATHIC 2023]



From Maowu Nie

A large η gap can avoid short-range correlation

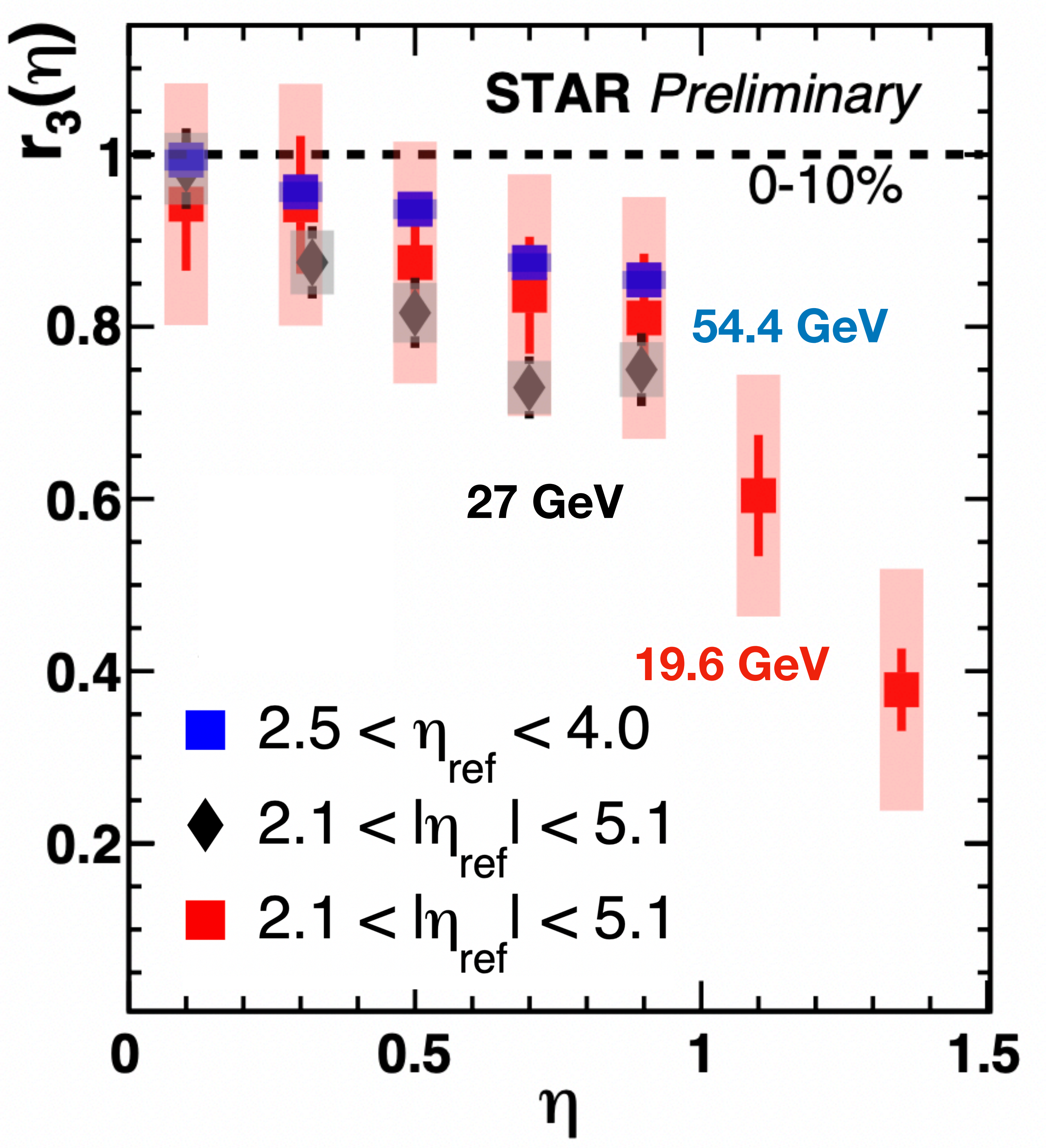
Measurement of $r_2(\eta)$

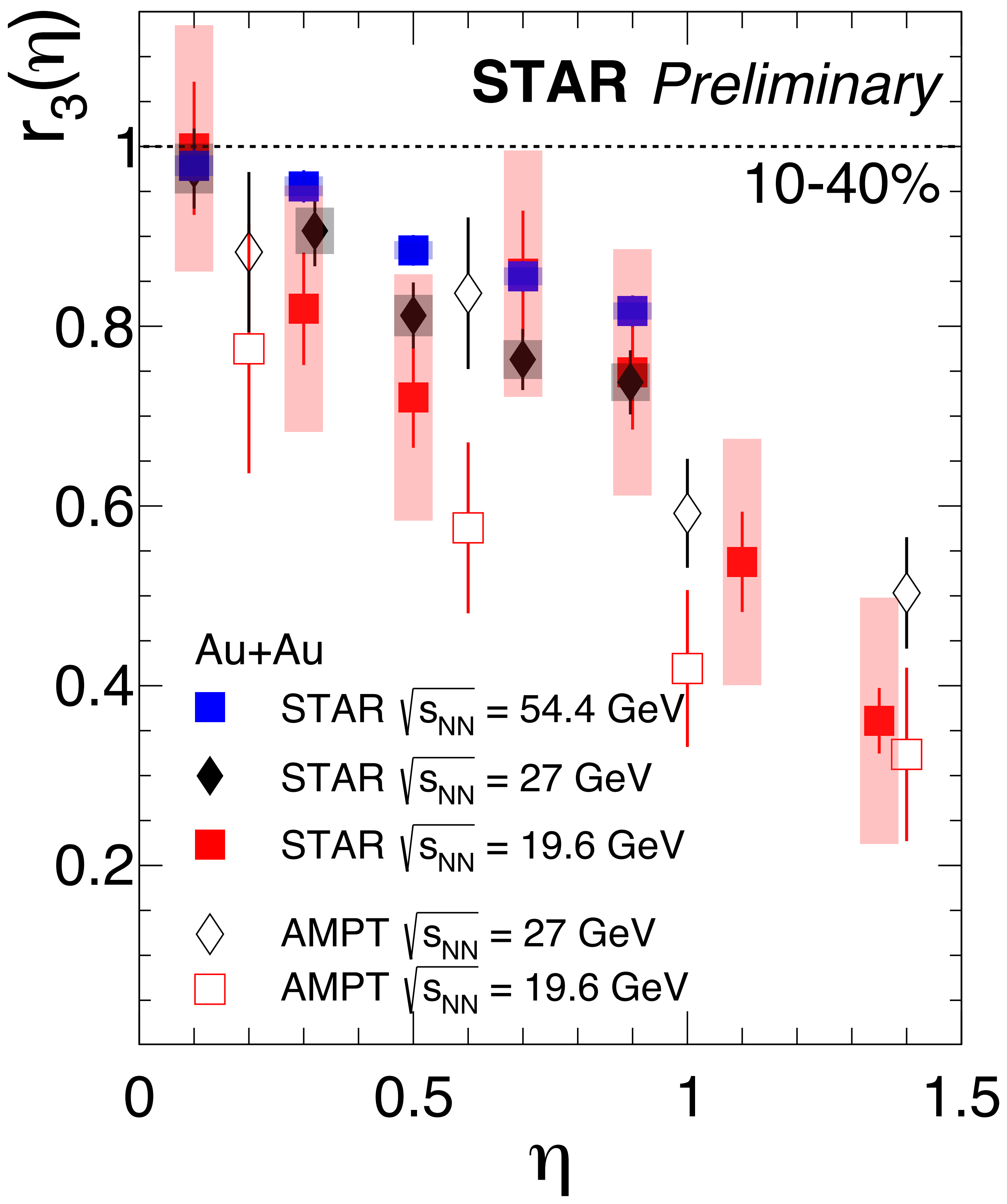


- ➢ **Significant deviation from unity at RHIC energies**
- ➢ Effect is strongest in central collisions
- ➢ 27 and 19.6 GeV show larger effect than 54.4 GeV in central collisions
- ➢ AMPT(10-40%) shows stronger deviation than data (can be used to constrain initial longitudinal structure)

[P. Dixit et al. arXiv:2307.08406]

Measurement of $r_3(\eta)$

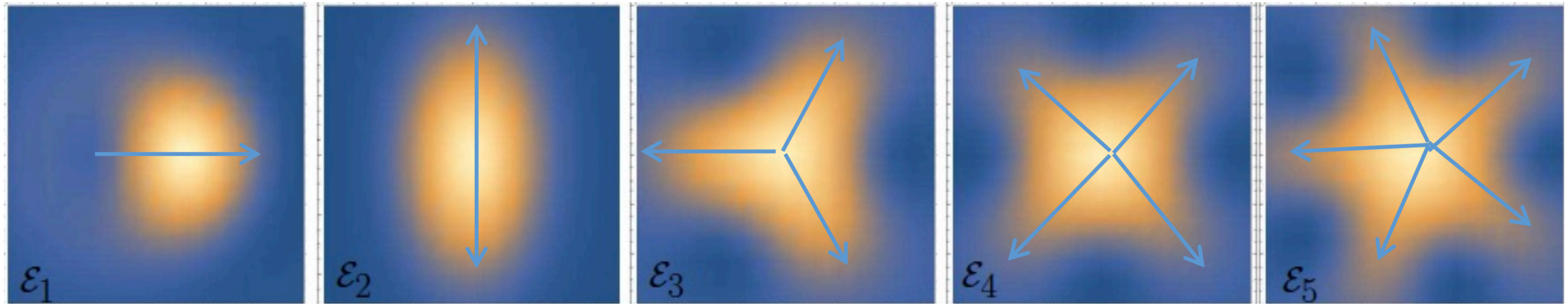




- ➢ **$r_3(\eta)$ is 2-3 times stronger than $r_2(\eta)$**
- ➢ $r_3(\eta)$ shows weak centrality dependence
- ➢ Hints of larger deviation at lower beam energies
- ➢ AMPT (10-40%) shows comparable magnitude (can be used to constrain initial longitudinal structure)

[P. Dixit et al. arXiv:2307.08406]

Constraining initial state using correlations



Event planes ψ_1 ψ_2 ψ_3 ψ_4 ψ_5

Normalized higher-order flow correlations:

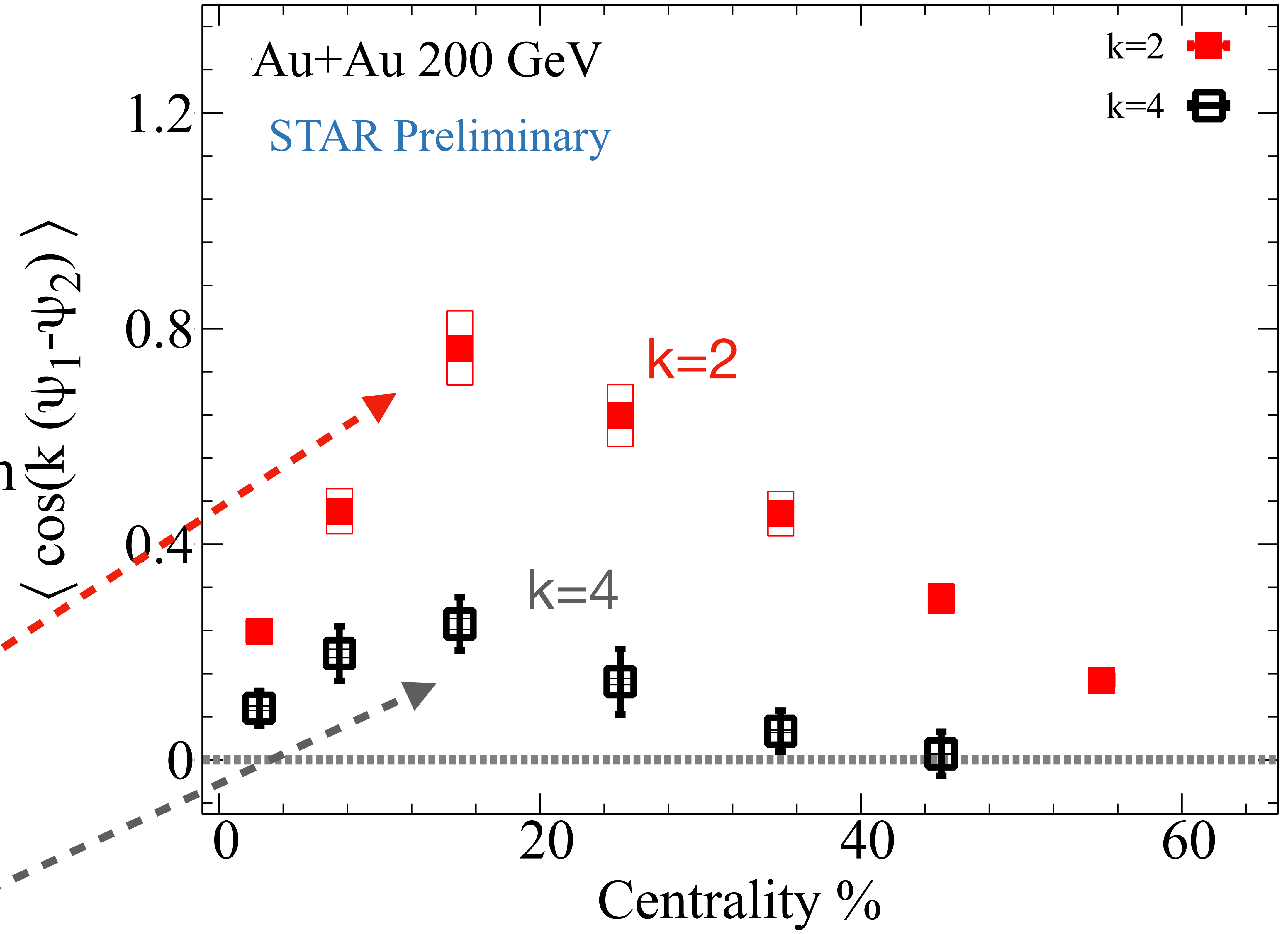
- ➢ Gives the correlation strength between different flow harmonics (magnitudes and directions)
- ➢ Less sensitive to the medium properties, i.e., $\frac{\eta}{s}(T)$
- ➢ More sensitive to the heavy ion collisions' initial state

[N. Magdy PRC 107 (2023) 2, 024905, J. Jia et al. PRC 96 034906 (2017)]

Event plane angular correlations

The event plane angular correlations between ψ_1 and ψ_2 for Au+Au collisions at 200 GeV

- ➢ Positive correlations between ψ_1 and ψ_2 observed.
- ➢ Similar trends were observed for k=2 and 4.
- ➢ $\langle \cos(4\psi_1 - 4\psi_2) \rangle$ is expected to suppress the global momentum conservation effect.
- ➢ Can be used to constrain the initial state models.



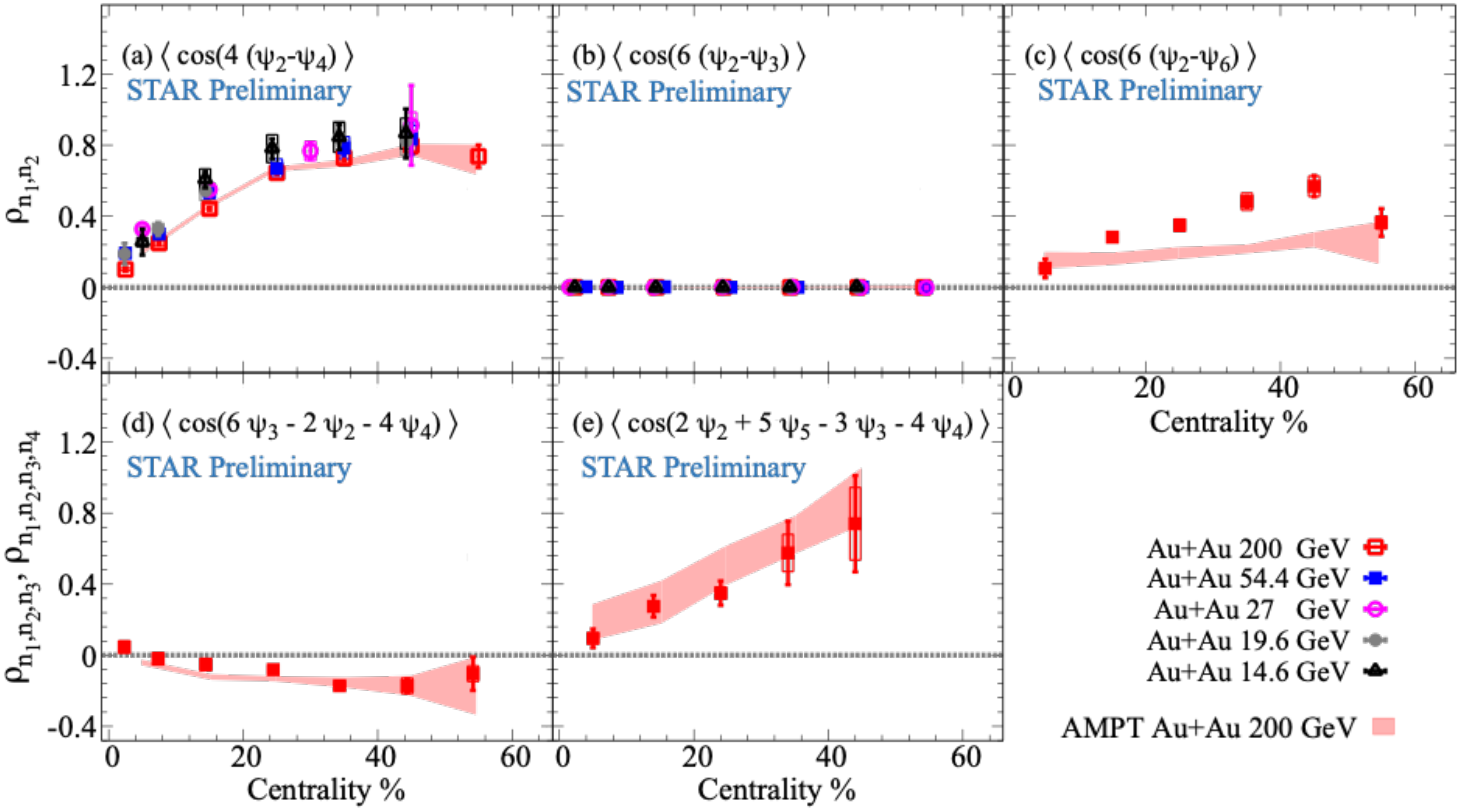
$$\langle \cos(2\psi_1 - 2\psi_2) \rangle = \langle v_1^2 v_2 \cos(2\psi_1 - 2\psi_2) \rangle / \sqrt{\langle v_1^4 \rangle \langle v_2^2 \rangle}$$

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

[N. Magdy PRC 107 (2023) 2, 024905, A. Bilandzic et al. PRC 102 2 024910 (2020), M. Luzum et al. PRC 87, 044907]

Event plane angular correlations

- The $\rho_{2,4}$ and $\rho_{2,3}$ show weak beam energy dependence
- Correlations between ψ_2 and ψ_3 consistent with 0
- Except for $\rho_{2,6}$ we observe reasonable agreement with the AMPT model
- Non-vanishing correlations are observed for higher order event plane angular correlations



Suggests the influence from the initial state is more than from the final-state

[STAR, Phys.Lett.B 839 137755 (2023)]

Flow harmonics correlations

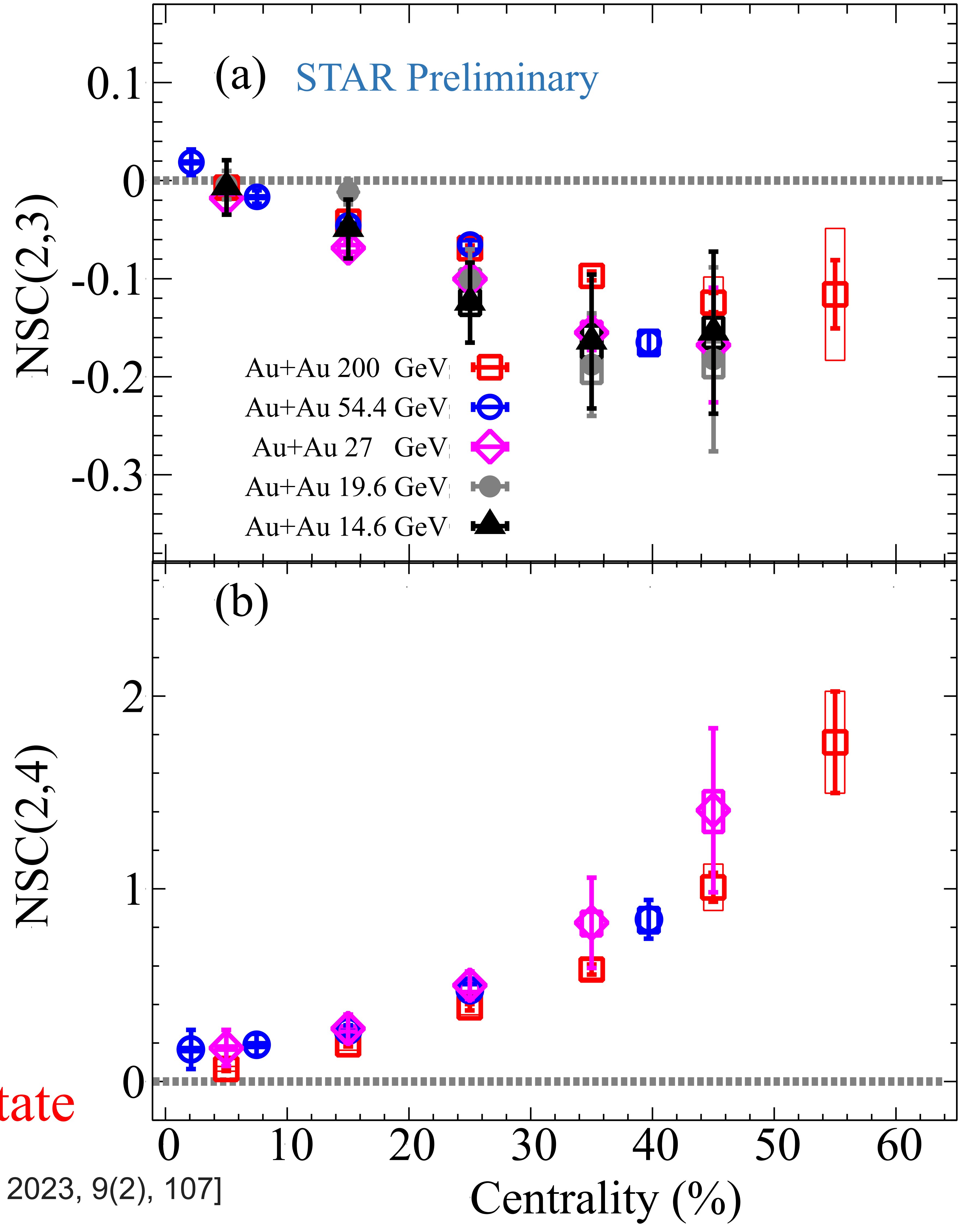
Comparison of the normalized symmetric cumulants, NSC(2,3) and NSC(2,4), vs. centrality

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

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

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) shows weak dependence on beam energy.



Suggests the influence from the initial state is more than that from the final-state

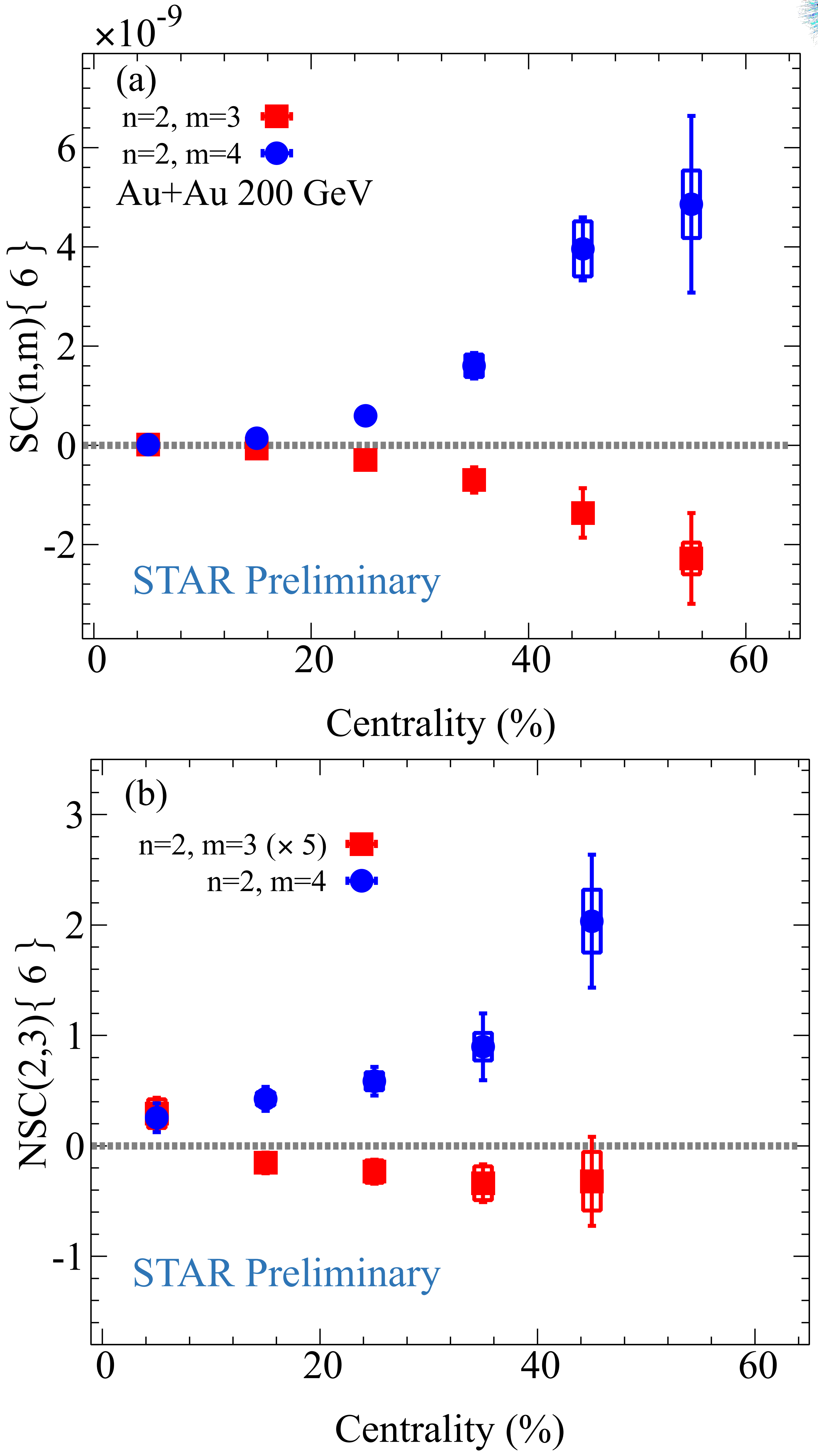
[STAR Phys.Lett.B 839 137755 (2023), A. Bilandzic et al. PRC 89, 064904, R.A. Lacey et al. arXiv:1311.1728, N. Magdy Universe 2023, 9(2), 107]

Flow harmonics correlations

Comparison of the six-particles (normalized) symmetric cumulants, vs. centrality

$$SC(n,m)\{6\} = \langle 6\rangle_{nnm} - \langle 4\rangle_{nn}\langle 2\rangle_{m} - 2\langle 4\rangle_{nm}\langle 2\rangle_{m} + 2\langle 2\rangle_{n}^{2}\langle 2\rangle_{m}$$

$$NSC(n,m)\{6\} = \frac{SC(n,m)\{6\}}{\langle 2\rangle_{n}^{Sub}\langle 2\rangle_{n}^{Sub}\langle 2\rangle_{m}^{Sub}}$$



- ❖ 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

Can be used to constrain the initial state models

[A. Bilandzic et al. PRC 102 2 024910 (2020), N. Magdy PRC 107, 024905 (2023)]

Summary

We present preliminary measurements of Δv_1, $r_n(\eta)$ and flow harmonics correlations

Δv_1

- Consistent with models using strong EM fields and conductivity from lattice QCD
- $\Delta(dv_1/dy)$, negative in peripheral collisions ⟶ consistent with dominance of Faraday+Coulomb effect
- $\Delta(dv_1/dy)$ in peripheral collisions, more negative for lower collision energies ⟶ consistent with longer lifetime of the electromagnetic field and shorter lifetime of the fireball

$r_2(\eta)$ and $r_3(\eta)$

- Significant deviation from unity at RHIC energies
- Different centrality and beam energy dependence for $r_2(\eta)$ and $r_3(\eta)$

Event plane and flow harmonics correlations

- $\rho_{2,3}$, $\rho_{2,4}$, NSC(n,m) show weak dependence on beam energy

Our results can help constrain conductivity of QGP and the 3D initial state through model comparisions

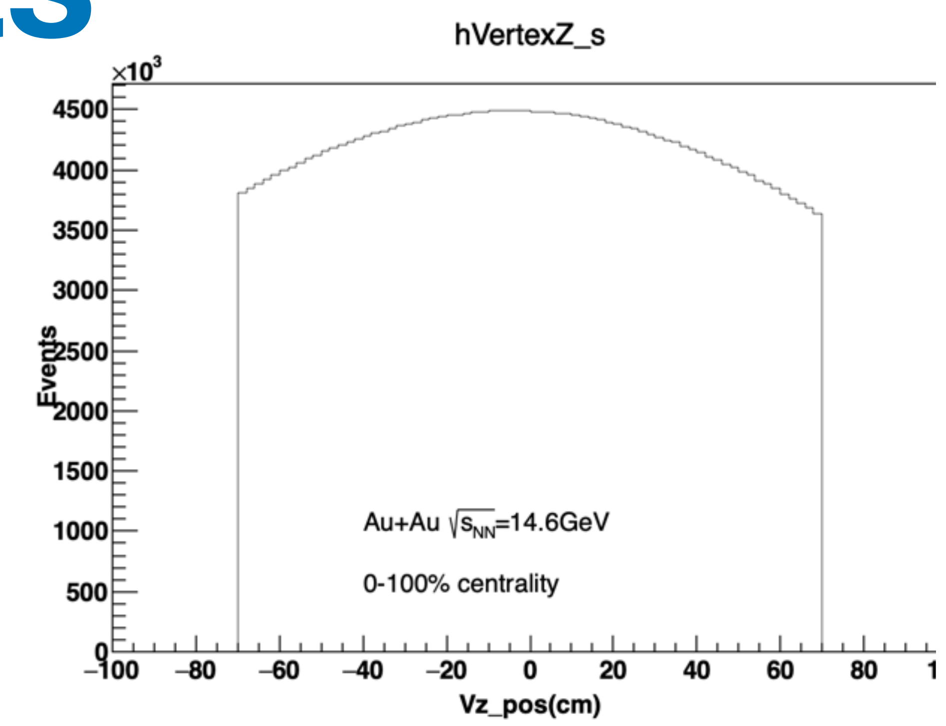
Thanks!

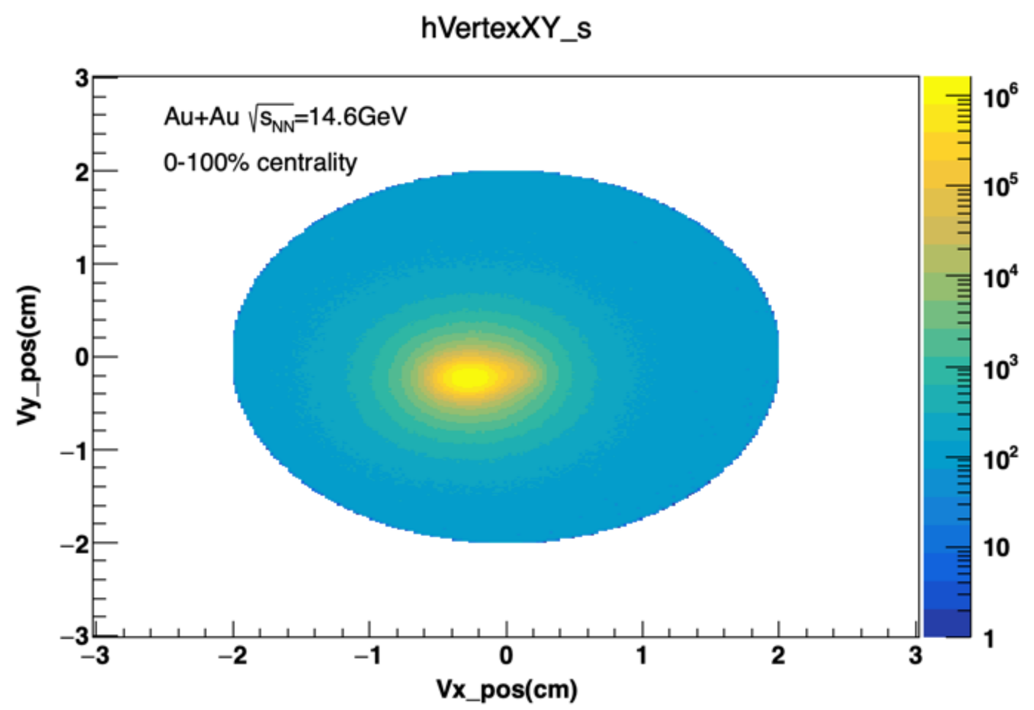
Backup

Dataset and Quality Assurance cuts

Collision System: Au+Au

Beam Energies: 19.6 GeV,14.6 GeV and 7.7 GeV in BES-II

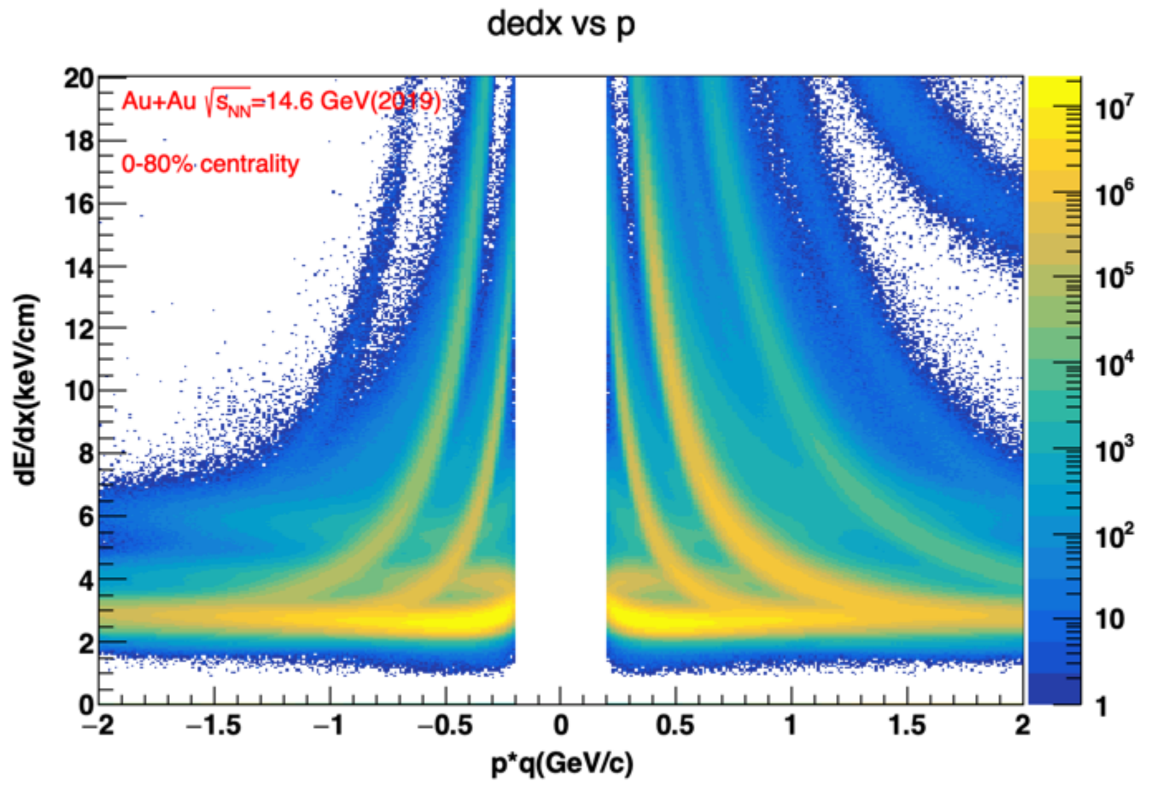




Event Selection

Variable	Accepted values	Reason
$\|v_z\|$	< 70cm	to ensure uniform acceptance
$\|v_r\|$	< 2cm	to exclude events having collision of nuclei with beam pipe and other material

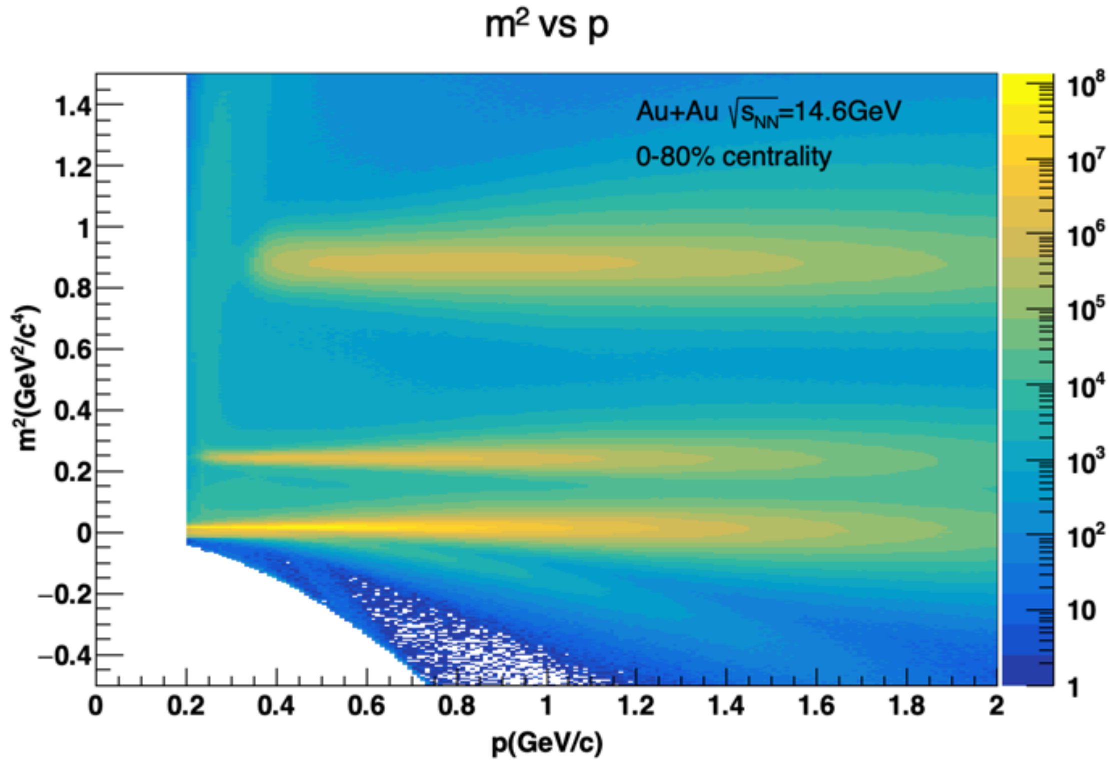
Figures are from Au+Au collisions at $\sqrt{s_{NN}} = 19.6, 14.6$ and 7.7 GeV



1. -dE/dx as a function of p*q using TPC

Tracks selection

Variable	Accepted values	Reason
Transverse momentum (p_T)	(0.2,2.0) GeV/c	optimized for detector performance
Distance of closest approach (dca)	≤ 2cm	to reduce contributions from secondary tracks
Psueudorapidity (η)	(-1,1)	optimized for TPC acceptance
nHitsFit	≥ 15	to ensure proper track reconstruction



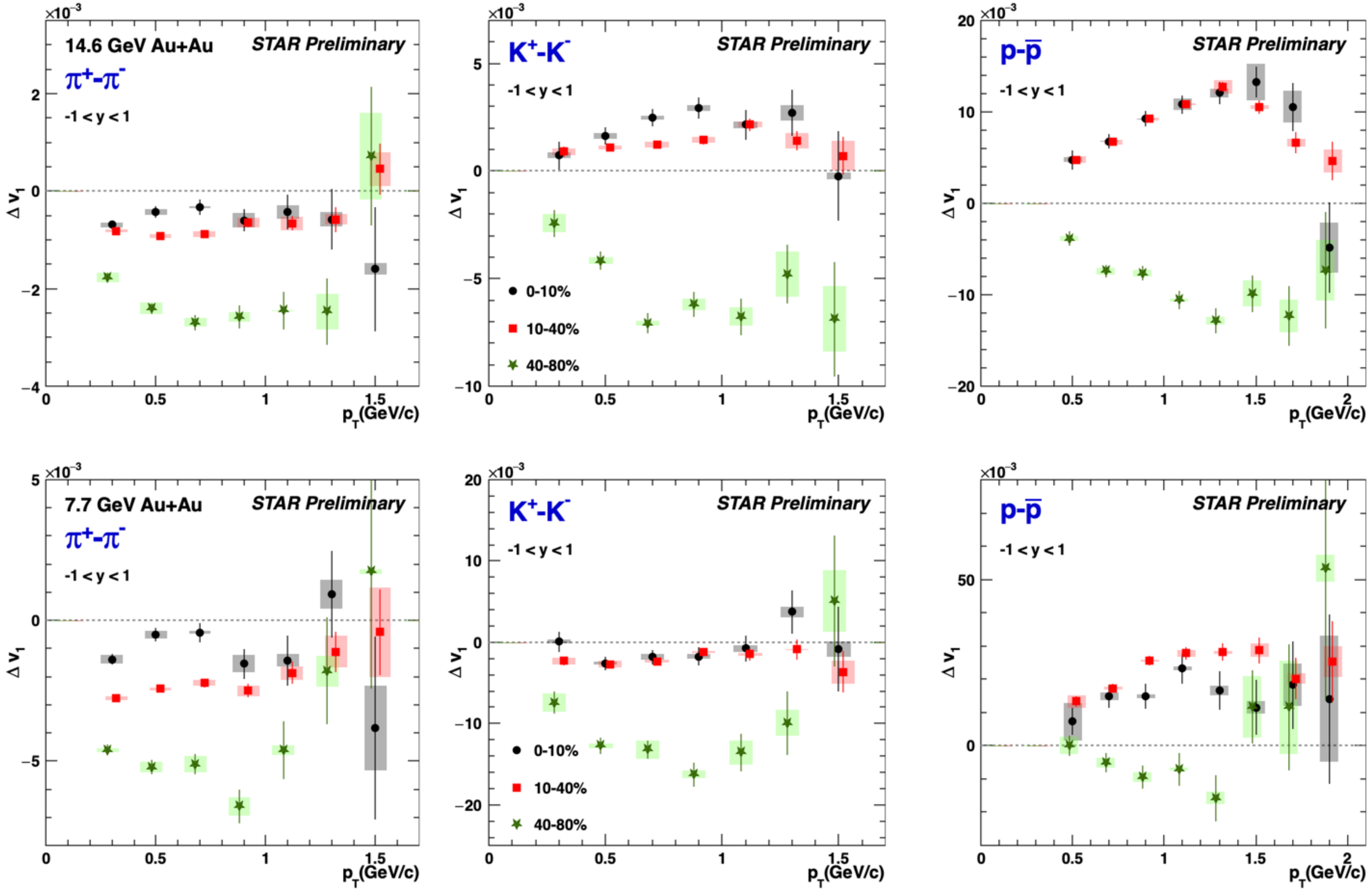
(b) m^2 as a function of momentum (p) using TOF

PID selection

Particle	$\|n\sigma\|$	nHitsDedx	p_T (GeV/c)	p (GeV/c)	$m^2(GeV^2/c^4)$
Protons	< 2	≥ 15	> 0.4	< 2	(0.80,1.00)
Pions	< 2	≥ 15	> 0.2	< 1.6	(-0.01,0.10)
Kaons	< 2	≥ 15	> 0.20	< 1.6	(0.2,0.35)

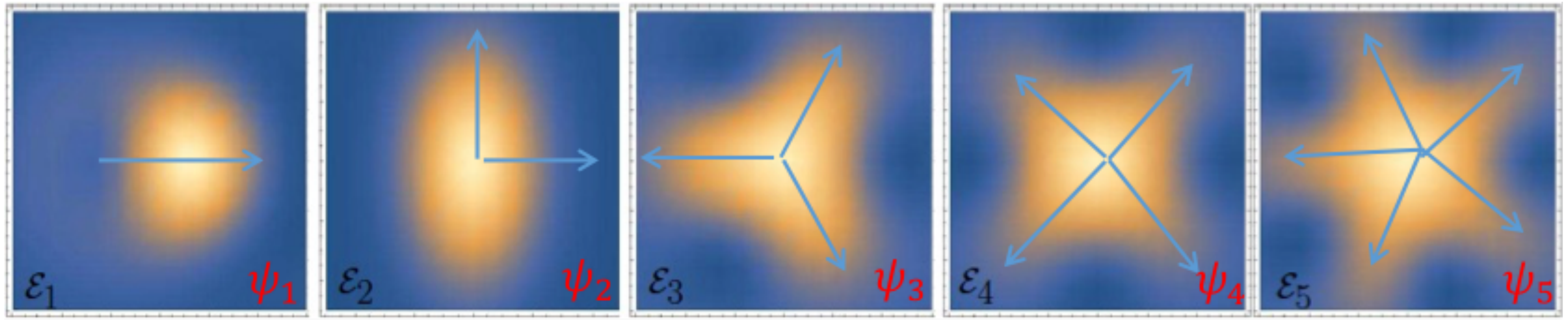
*p_T dependent nσ cuts were used for 19.6GeV

Δ$v_1(p_T)$ at 14.6GeV and 7.7GeV



- Similar p_T dependence trend at 19.6, 14.6 GeV and 7.7 GeV
- **Indication of larger splitting at higher p_T as expected from theory** [U. Gürsoy et al. PRC 98,055201, PRC 89 054905]

Constraining heavy ion collisions' initial state



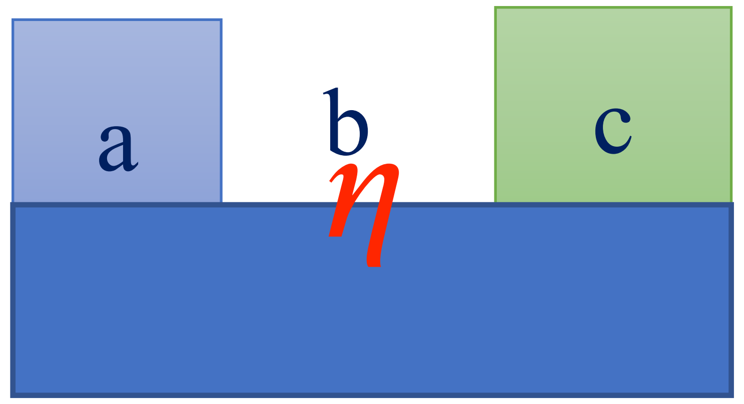
Normalized higher-order flow correlations:

- ➢ Gives the correlation strength between different flow harmonics magnitudes and directions
- ➢ Less sensitive to the medium properties, i.e., $\frac{\eta}{s}(T)$
- ➢ More sensitive to the heavy ion collisions' initial state

❖ Our measurements are accomplished using two- and multi-particle correlations

Measurements k-Particle correlations	Analyses method
Two	Two Subevents
Three	Two Subevents
Four	One Subevent
Five	One Subevent
Six	One Subevent

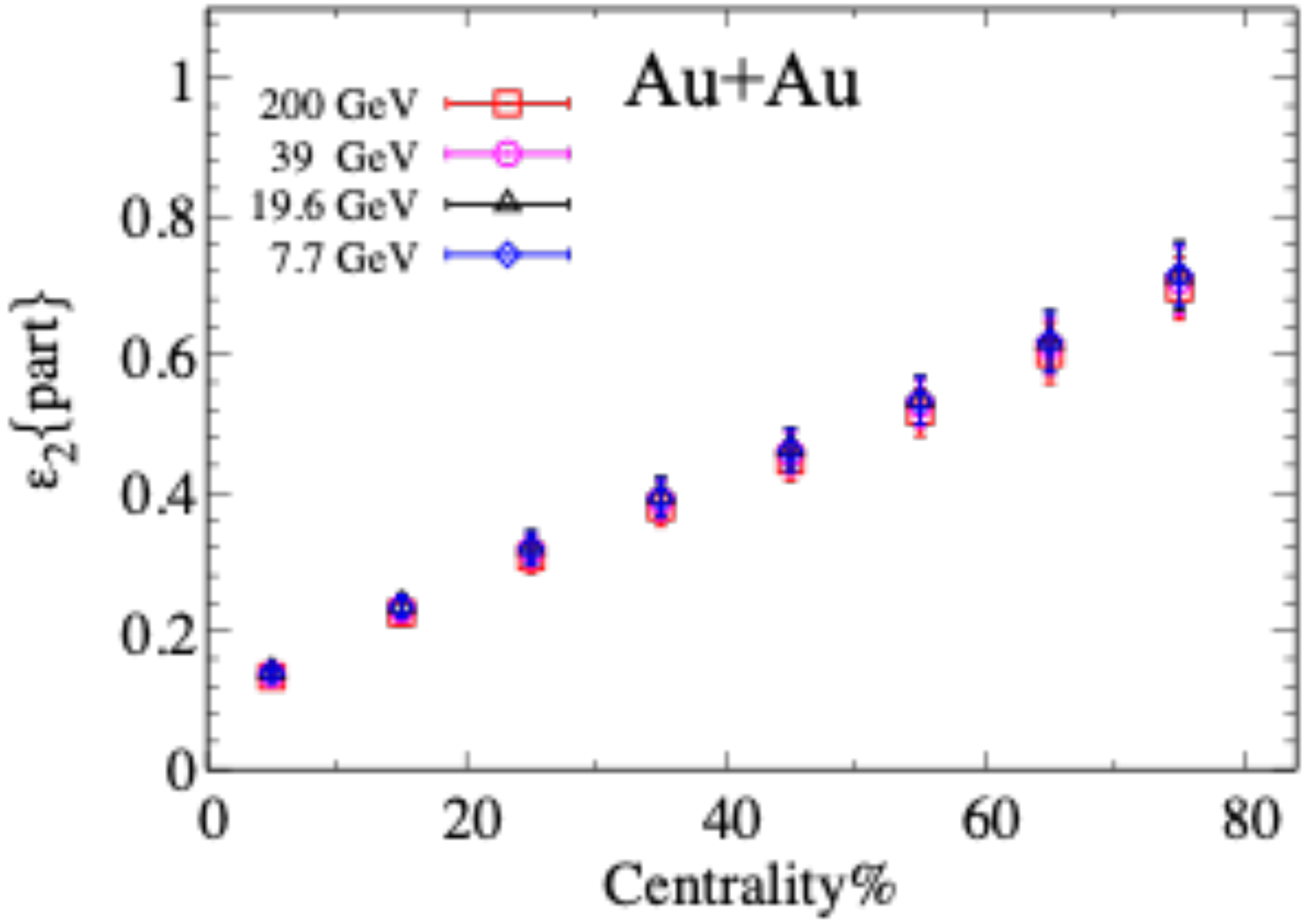
$|\Delta\eta| > 0.7$



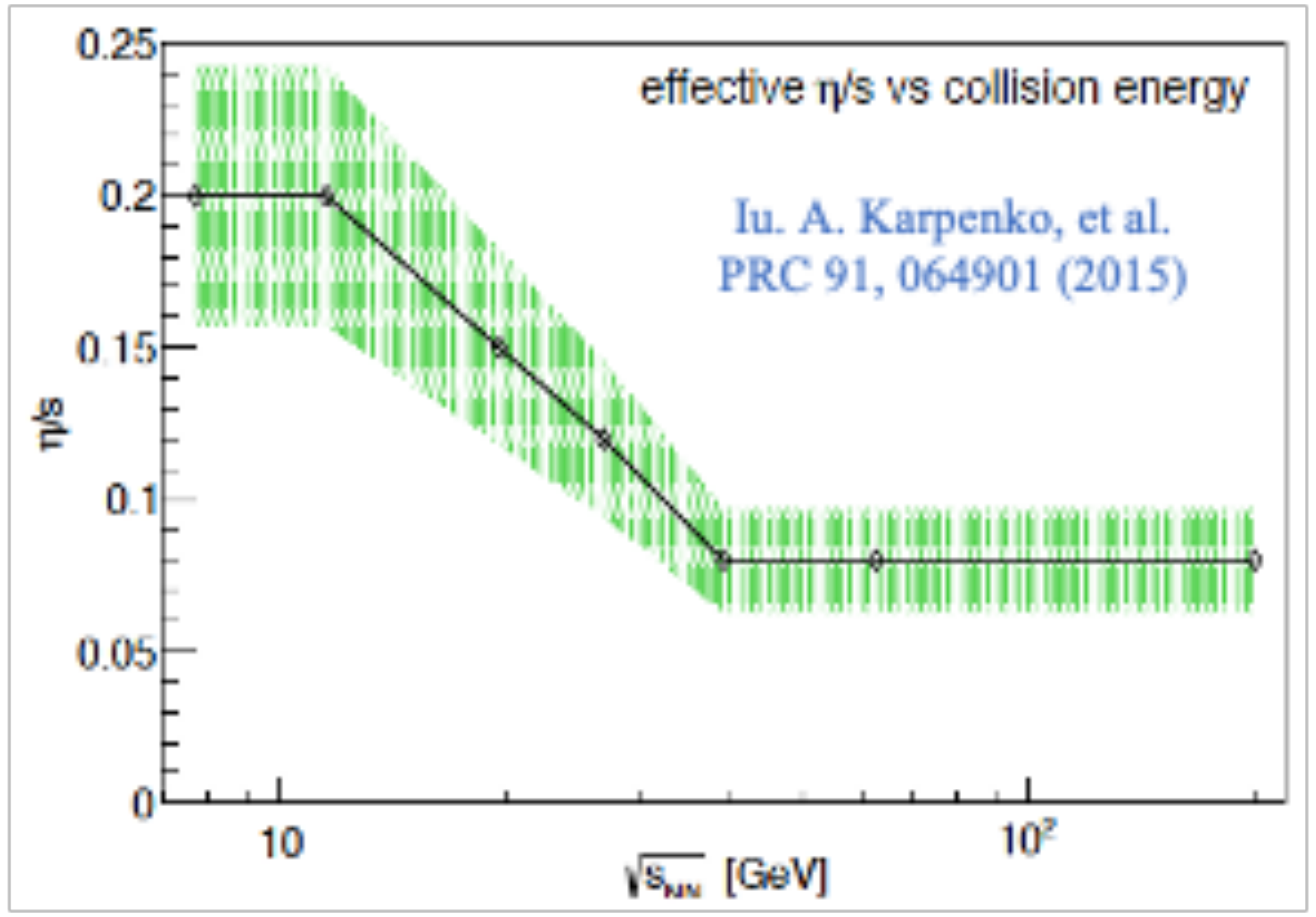
[N. Magdy PRC 107, 024905 (2023), J. Jia et al. PRC 96 034906 (2017)]

Beam energy dependence and stage sensitivity

- Higher order flow harmonics are sensitive probes for $\frac{\eta}{s}(T)$ due to enhanced viscous response
- These flow harmonics and their fluctuations and correlations can be used to constrain $\frac{\eta}{s}(T)$ and differentiate between initial state models



Initial-state spatial anisotropy is approximately beam energy independent.



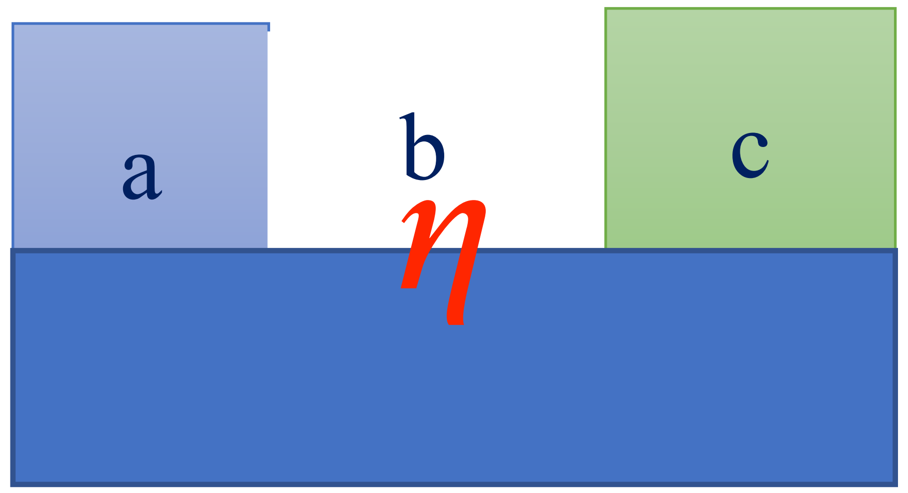
Viscous attenuation ($\propto \frac{\eta}{s}(T)$) is beam energy dependent.

[N. Magdy QM2022]

Analysis procedure

Symmetric correlations

$|\Delta\eta| > 0.7$



2PC → $CF(n_1 = -n_2,)\{2\}$ "φ_1 from sub event A and φ_2 from B"

$$\langle \cos[n_1\varphi_1 + n_2\varphi_2] \rangle = \langle \mathrm{v}_{\mathrm{n1}}^2 \rangle$$

4PC → $CF(n_1 = -n_3, n_2 = -\mathrm{n}_4)\{4\}$ "φ_1 and φ_2 from sub event A, φ_3 and φ_4 from B"

$$\langle \cos[n_1\varphi_1 + n_2\varphi_2 + n_3\varphi_3 + n_4\varphi_4] \rangle = \langle \mathrm{v}_{\mathrm{n1}}^2 \mathrm{v}_{\mathrm{n2}}^2 \rangle$$

6PC → $CF(n_1 = -4, n_2 = -\mathrm{n}_5\ , n_3 = -\mathrm{n}_6)\ \{6\}$ "One subevent"

$$\langle \cos[n_1\varphi_1 + n_2\varphi_2 + n_3\varphi_3 + n_4\varphi_4 + n_5\varphi_5 + n_6\varphi_6] \rangle = \langle \mathrm{v}_{\mathrm{n1}}^2 \mathrm{v}_{\mathrm{n2}}^2 \mathrm{v}_{\mathrm{n3}}^2 \rangle$$

Symmetric Cumulants

$$SC(n_1, n_2) = CF(n_1, n_2)\{4\} - CF(n_1)\{2\}\ CF(n_1)\{2\}$$

$$SC(n_1, n_2, n_3) = CF(n_1, n_2, n_3)\{6\} - CF(n_1, n_1)\{4\}\ CF(n_1)\{2\}$$
$$-2\ CF(n_1, n_2)\{4\}\ CF(n_2)\{2\}$$
$$+2\ CF(n_1)\{2\}\ CF(n_1)\{2\} CF(n_2)\{2\}$$

Normalized Symmetric Cumulants

$$NSC(n_1, n_2) = \frac{SC(n_1, n_2)}{CF(n_1)\{2\}\ CF(n_1)\{2\}}$$

$$NSC(n_1, n_2, n_3) = \frac{SC(n_1, n_2)}{CF(n_1)\{2\}\ CF(n_1)\{2\} CF(n_3)\{2\}}$$

[J. Jia PRC 96 034906 (2017), N. Magdy PRC 107, 024905 (2023)]

Analysis procedure

Asymmetric correlations

3PC → ASC($n_1, n_2, n_3 = -n_1 - n_2$)
φ_1 and φ_2 from sub event A and φ_3 from B"

$$ASC_{n_1 n_2 n_3} = \langle \cos[n_1\varphi_1 + n_2\varphi_2 + n_3\varphi_3] \rangle$$
$$= \langle v_{n1} v_{n2} v_{n3} \cos[n_1\Psi_{n1} + n_2\Psi_{n2} + n_3\Psi_{n3}] \rangle$$

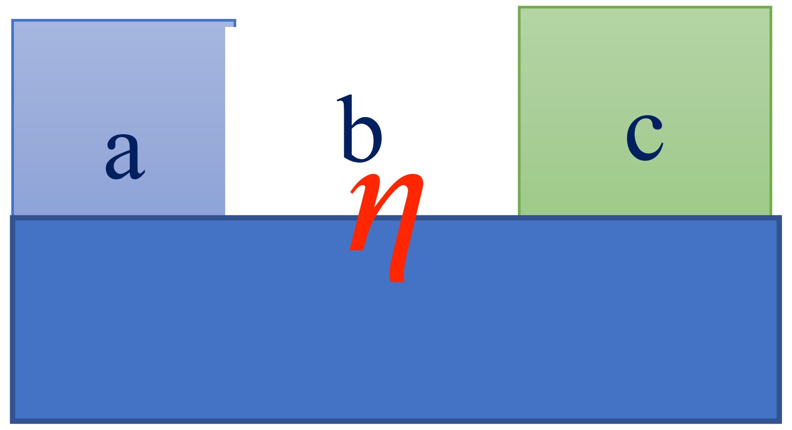
4PC → ASC($n_1 + n_2 = -n_3 - n_4$)
φ_1 and φ_2 from sub event A, φ_3 and φ_4 from B

$$ASC_{n_1 n_2 n_3 n_4} = \langle \cos[n_1\varphi_1 + n_2\varphi_2 + n_3\varphi_3 + n_4\varphi_4] \rangle$$
$$= \langle v_{n1} v_{n2} v_{n3} v_{n4} \cos[n_1\Psi_{n1} + n_2\Psi_{n2} + n_3\Psi_{n3} + n_4\Psi_{n4}] \rangle$$

5PC → ASC($n_1 + n_2 + n3 = -n_4 - n_5$)
One subevent

$$ASC_{n_1 n_2 n_3 n_4 n_5} = \langle \cos[n_1\varphi_1 + n_2\varphi_2 + n_3\varphi_3 + n_4\varphi_4 + n_5\varphi_5] \rangle$$
$$= \langle v_{n1} v_{n2} v_{n3} v_{n4} v_{n5} \cos[n_1\Psi_{n1} + n_2\Psi_{n2} + n_3\Psi_{n3} + n_4\Psi_{n4} + n_5\Psi_{n5}] \rangle$$

$|\Delta\eta| > 0.7$



$$\rho_{n_1,n_2,n_3} = \frac{ASC(n_1,n_2,n_3)}{\sqrt{|SC(n_1,n_2,-n_1,-n_2)SC(n_3,-n_3)|}}, \sim \langle \cos(n_1\psi_{n_1} + n_2\psi_{n_1} + n_3\psi_{n_3}) \rangle;$$

$$\rho_{n_1,n_2,n_3,n_4} = \frac{ASC(n_1,n_2,n_3,n_4)}{\sqrt{|SC(n_1,n_2,n_3,-n_1,-n_2,-n_3)SC(n_4,-n_4)|}}, \sim \langle \cos(n_1\psi_{n_1} + n_2\psi_{n_1} + n_3\psi_{n_3} + n_4\psi_{n_4}) \rangle;$$

$$\rho_{n_1,n_2,n_3,n_4,n_5} = \frac{ASC(n_1,n_2,n_3,n_4,n_5)}{\sqrt{|SC(n_1,n_2,n_3,-n_1,-n_2,-n_3)SC(n_4,n_5,-n_4,-n_5)|}}, \sim \langle \cos(n_1\psi_{n_1} + n_2\psi_{n_1} + n_3\psi_{n_3} + n_4\psi_{n_4} + n_5\psi_{n_5}) \rangle.$$

[J. Jia et al. PRC 96 034906 (2017), N. Magdy PRC 107, 024905 (2023)]

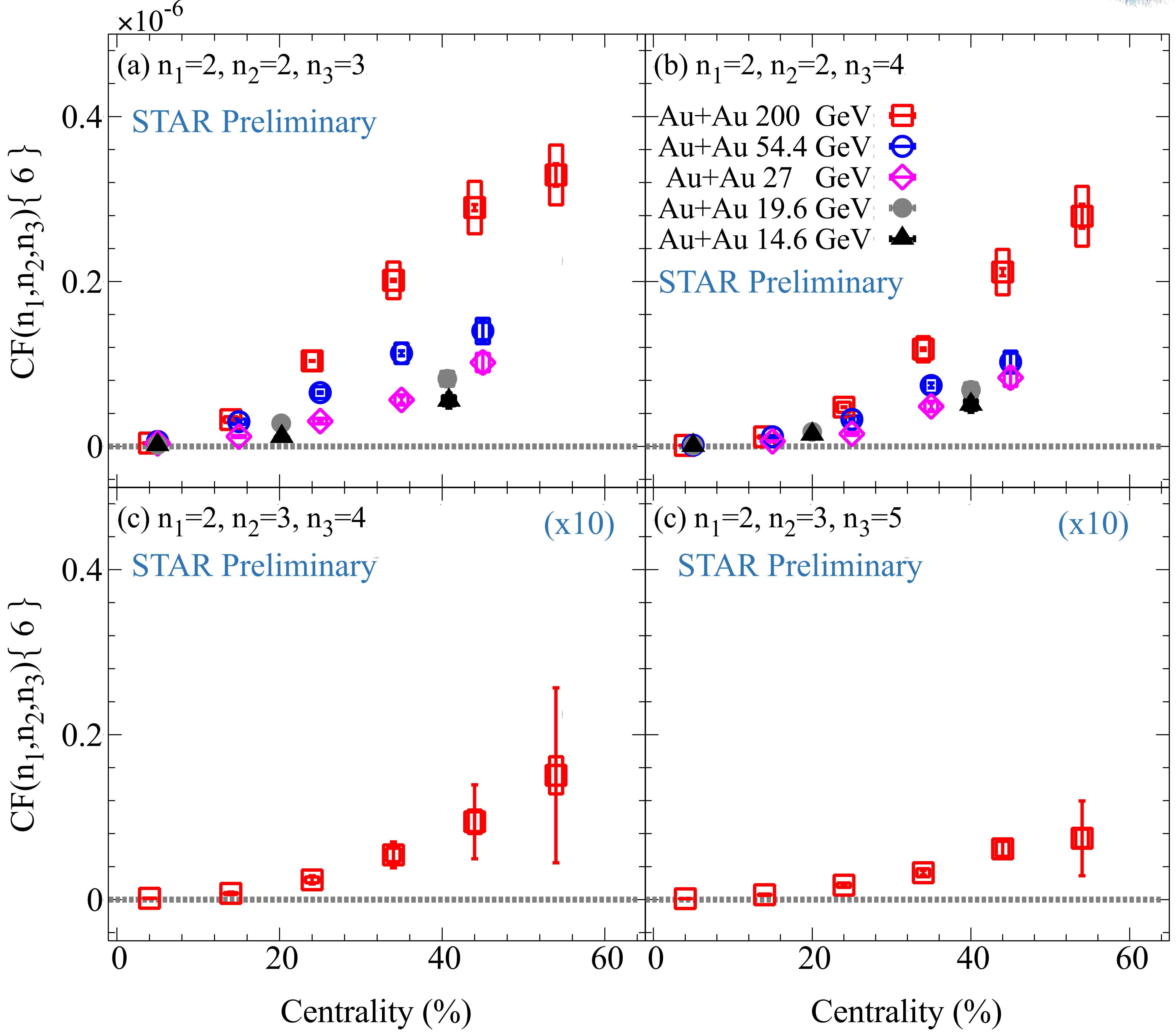
Symmetric Cumulants

Comparison of the six-particle correlation function vs. centrality

- ❖ Beam energy dependence was observed for CF(2,2,3) and CF(2,2,4)
- ➢ Consistent with the expected energy dependence of viscous damping

- ❖ Smaller non vanishing values was observed for CF(2,3,4) and CF(2,3,5)

Sensitive to the interplay between final- and initial-state effects.



[STAR Phys.Lett.B 839 137755 (2023), J. Jia et al. PRC 96 034906 (2017), N. Magdy PRC 107, 024905 (2023)]