Dependence of directed flow on system size and net conserved charges from quark coalescence in heavy-ion collisions

Kishora Nayak[1], ***Vipul Bairathi***[2], ***Zi-Wei Lin***[3] ***and Shusu Shi***[4]

[1]Panchayat College, SU, Bargarh 768028, India
[2]Universidad de Tarapac´a, Arica, 1000000, Chile
[3]East Carolina University, Greenville, NC, 27858, USA
[4]Central China Normal University, Wuhan, 430079, China

10th Asian Triangle Heavy-Ion Conference -ATHIC 2025, IISER, Berhampur, India

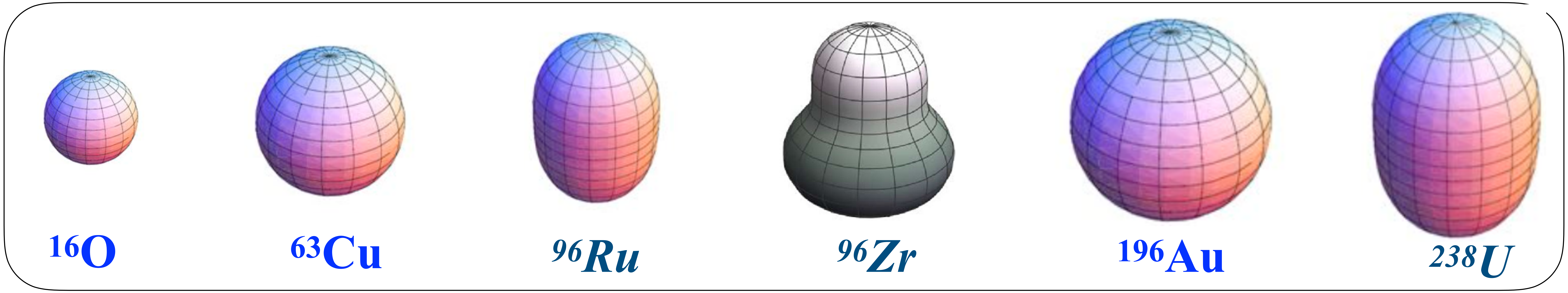
Outline

- **Motivation**
- **Analysis details**
- **Results**
  - **Part-I: System size dependence v_1**
  - **Part-II: Dependence of Δv_1 on conserved charges**
- **Summary**

Part-I

System Size Dependence v_1 Study

Motivation

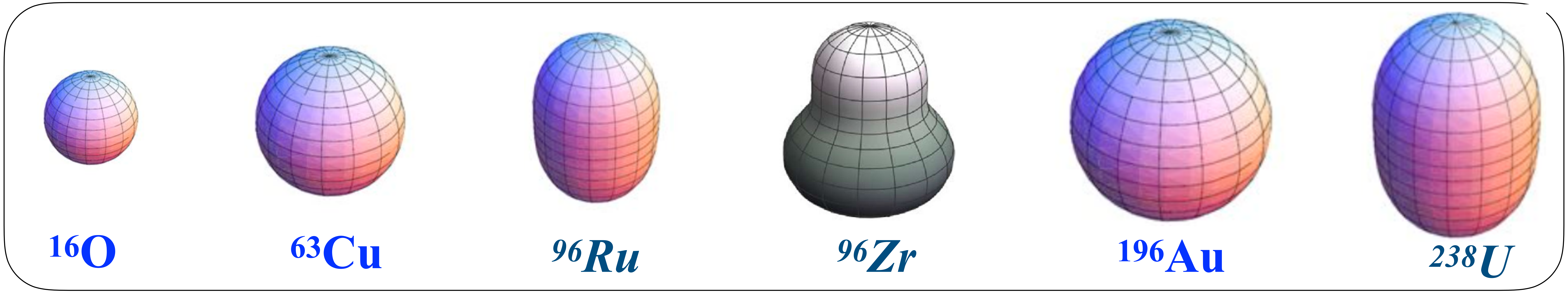


✓System size dependence v_1 study

→Help to estimate the participant-spectator contribution

→Improve understanding of EOS for symmetric nuclear matter

Motivation



✓System size dependence v_1 study

→Help to estimate the participant-spectator contribution

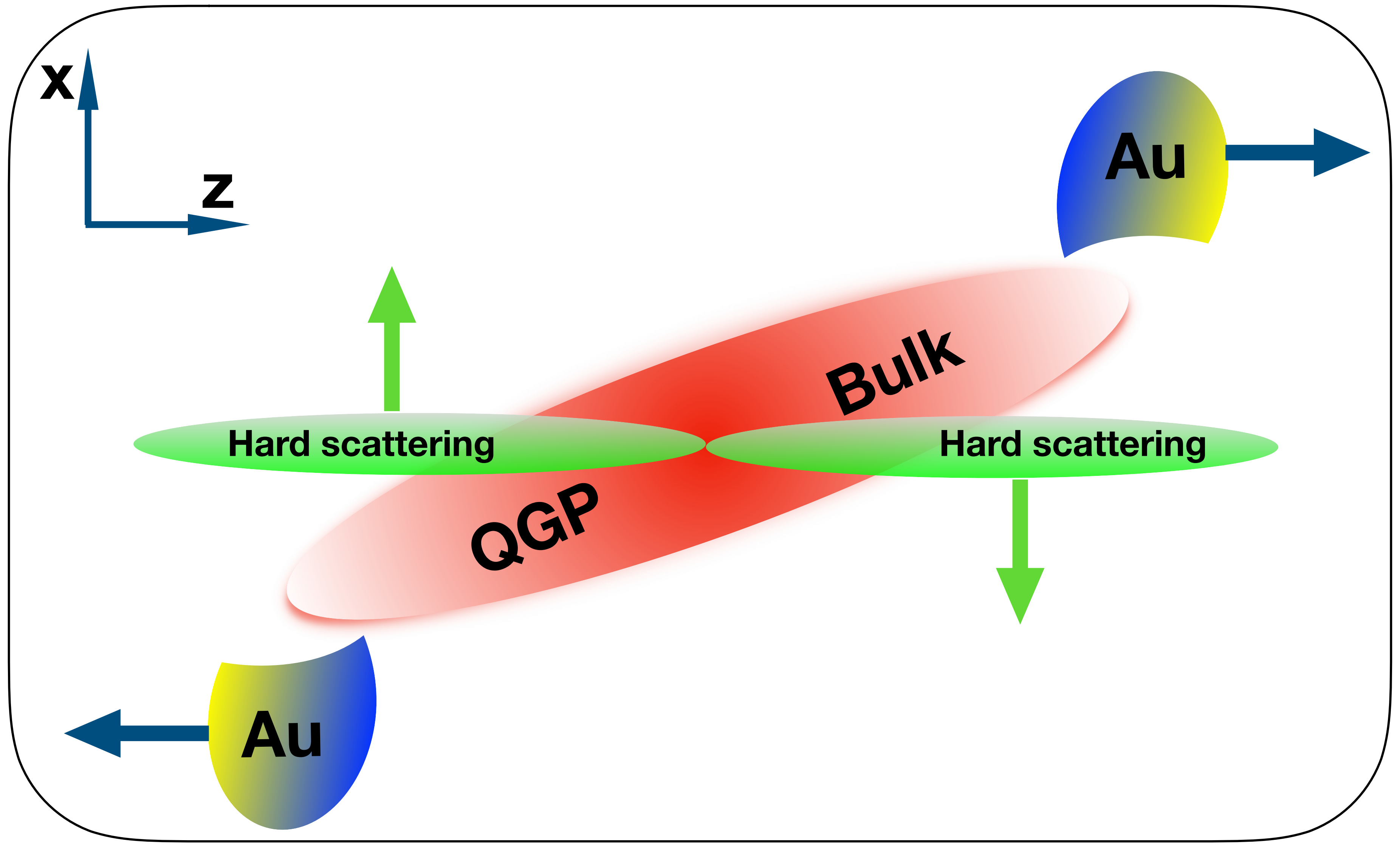
→Improve understanding of EOS for symmetric nuclear matter

✓QGP bulk (mostly soft particles) tilted in rapidity, unlike the hard scattering profile (symmetric)

→Hard-soft asymmetry in initial state

→Induces (negative) v_1 for hard partons

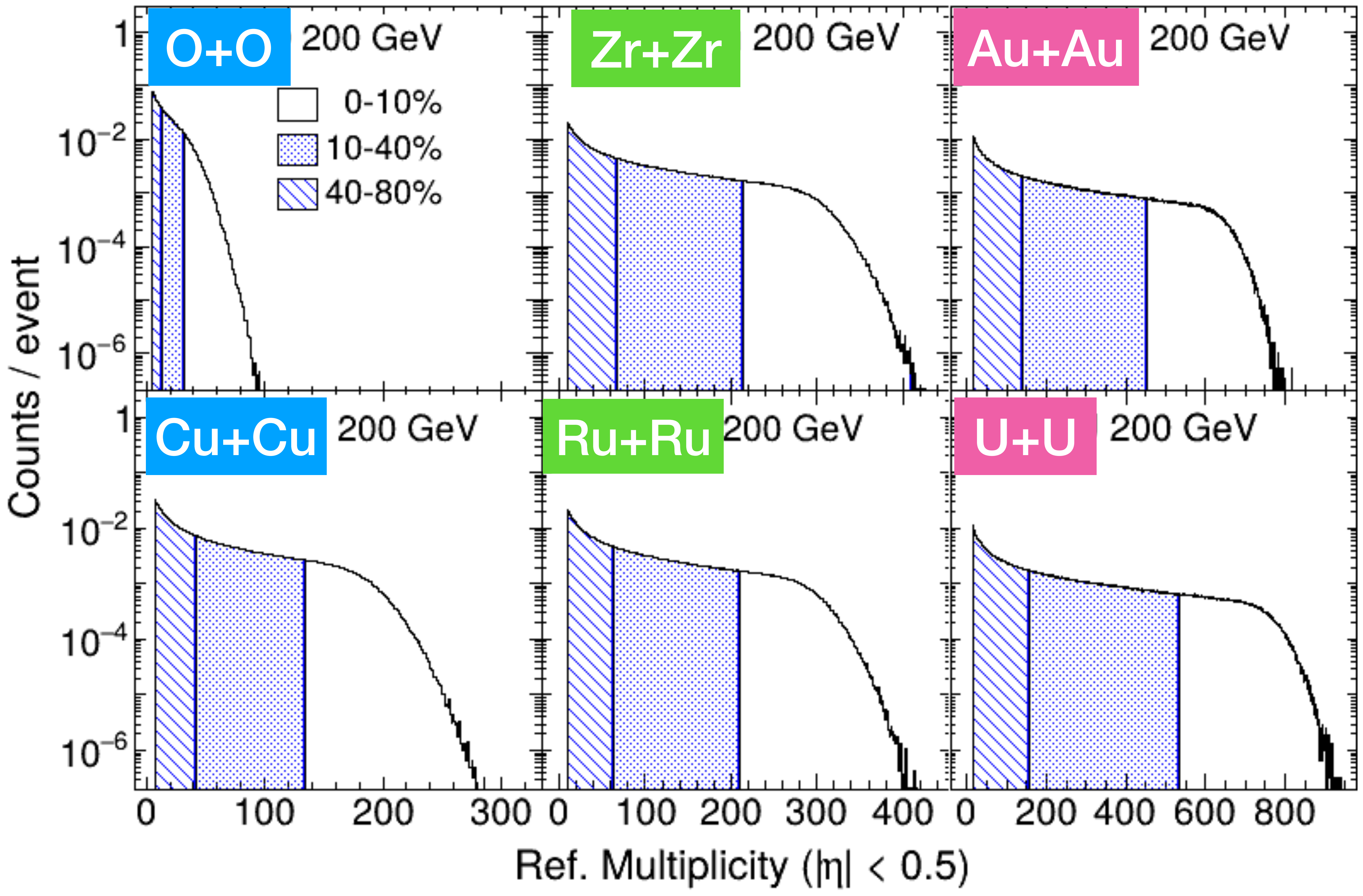
Phys. Rev. Lett. 120, 192301 (2018); Phys. Rev. C 72, 034907 (2005)



Analysis Details

System	Mass No.	#Events (M)
O+O	16	50
Cu+Cu	63	15
Zr+Zr	96	9
Ru+Ru	96	9
Au+Au	196	6
U+U	238	6

Deform Nuclei:
Ru, Zr, U,



✓ **Woods-Saxon function:**

$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{[\{r - R(\theta,\phi)\}/a]}}$$

- ρ_0 is the normal nuclear density
- a is the surface diffuseness parameter
- $R(\theta, \varphi)$ is the parameter characterizing the deformation of the nucleus:

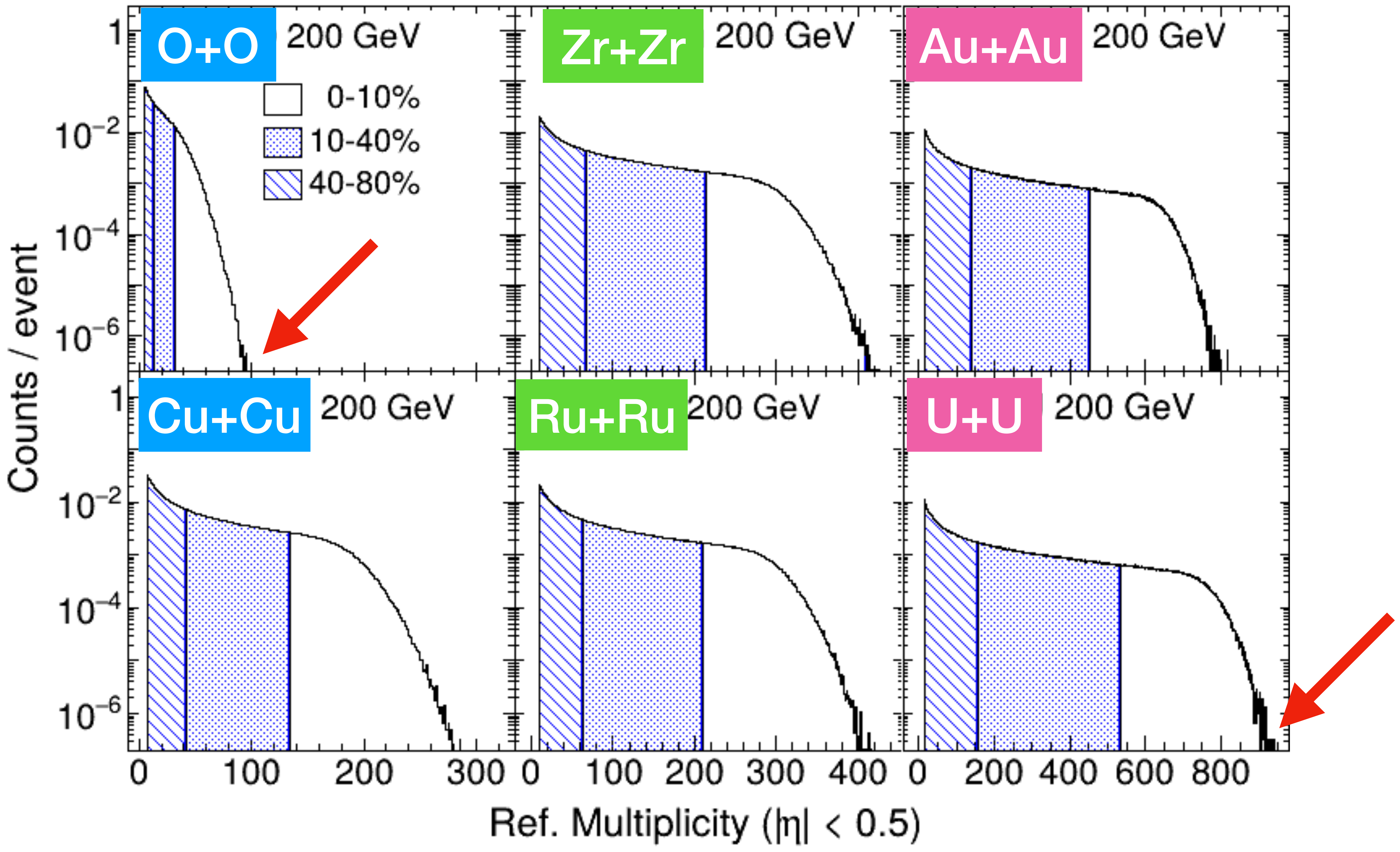
$$R(\theta,\phi) = R_0[1 + \beta_2 Y_{2,0}(\theta,\phi) + \beta_3 Y_{3,0}(\theta,\phi)]$$

- R_0 represents the radius parameter
- β_2: quadrupole, β_3: octupole deformities
- $Y_{l,m}(\theta, \phi)$ are the spherical harmonics

A new coalescence AMPT-SM model is used

Analysis Details

System	Mass No.	#Events (M)
O+O	16	50
Cu+Cu	63	15
Zr+Zr	96	9
Ru+Ru	96	9
Au+Au	196	6
U+U	238	6



Deform Nuclei: Ru, Zr, U,

✓ **Woods-Saxon function:**

$$\rho(r,\theta) = \frac{\rho_0}{1 + e^{[\{r - R(\theta,\phi)\}/a]}}$$

- ρ_0 is the normal nuclear density
- a is the surface diffuseness parameter
- R(θ, φ) is the parameter characterizing the deformation of the nucleus:

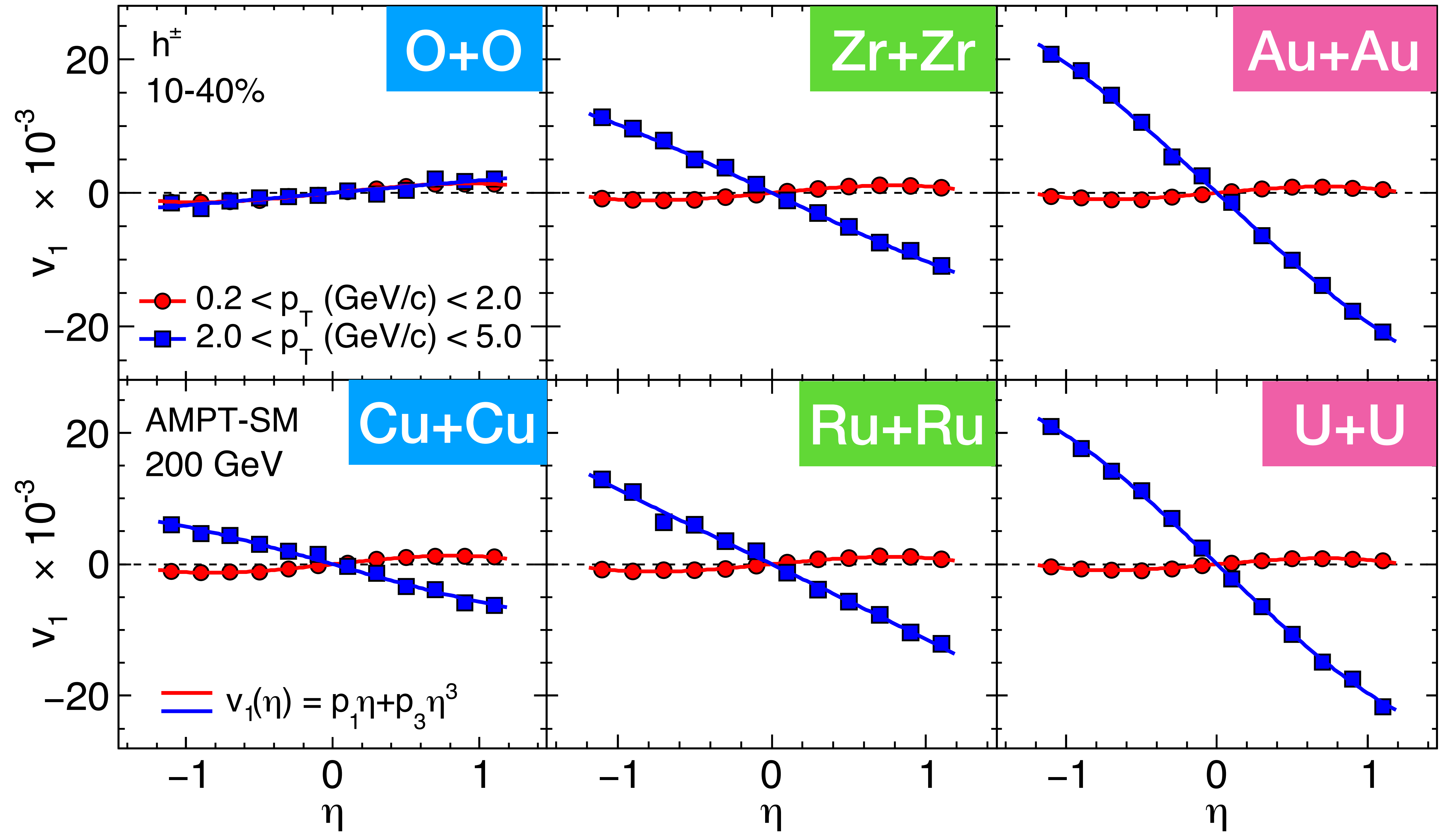
$$R(\theta,\phi) = R_0[1 + \beta_2 Y_{2,0}(\theta,\phi) + \beta_3 Y_{3,0}(\theta,\phi)]$$

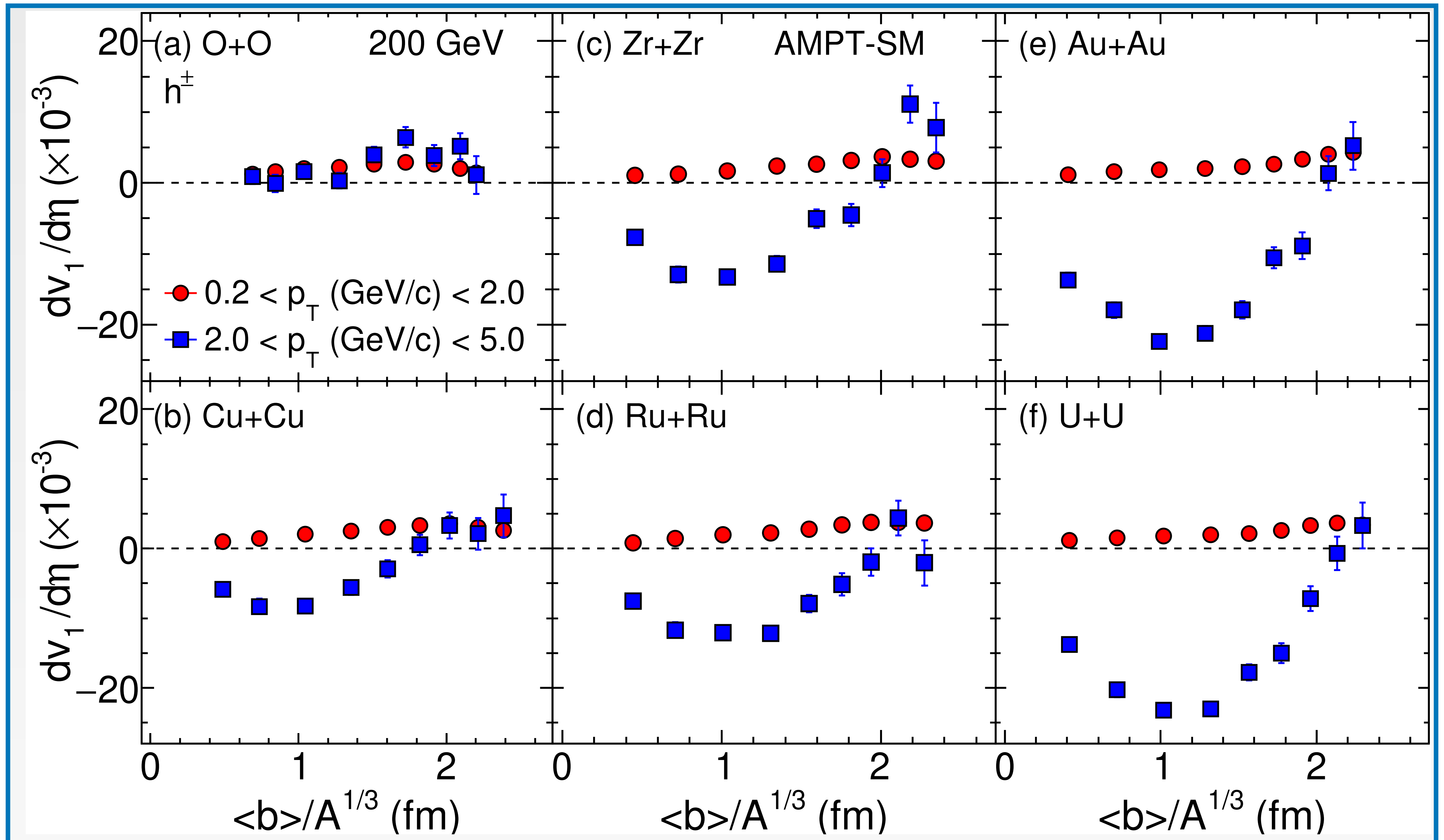
- R_0 represents the radius parameter
- β_2: quadrupole, β_3: octupole deformities
- $Y_{l,m}(\theta, \phi)$ are the spherical harmonics

A new coalescence AMPT-SM model is used

v_1 and $dv_1/d\eta$: Charged Hadrons

- Directed flow, $v_1 = \langle \cos(\phi - \Psi_R) \rangle$
- Particles are identified from their Pythia ID
- v_1 is fitted with a cubic function to extract slope





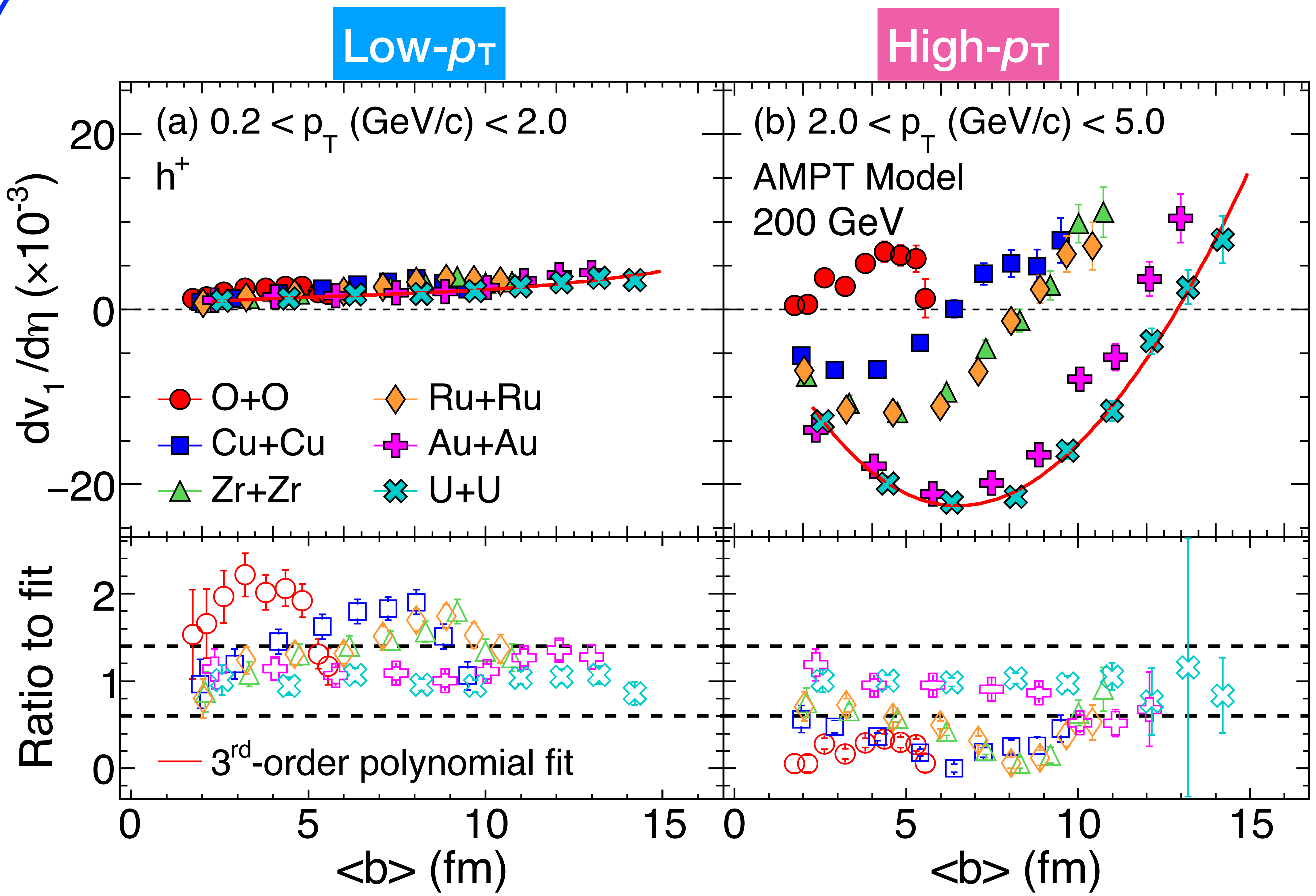
- To compare various systems, it was suggested to use the scaled impact parameter b_0 ($= b/b_{max}$) as a measure of centrality, $b_{max}=1.15(A_p^{1/3} + A_T^{1/3})$, symmetric systems ($A_T = A_P = A$)

W. Reisdorf *et al*. (FOPI Coll.), Nucl. Phys. A 1-60, **876** (2012)

- Flow is dominant for low-p_T and anti-flow for high-p_T with larger slope magnitude (except for O+O)

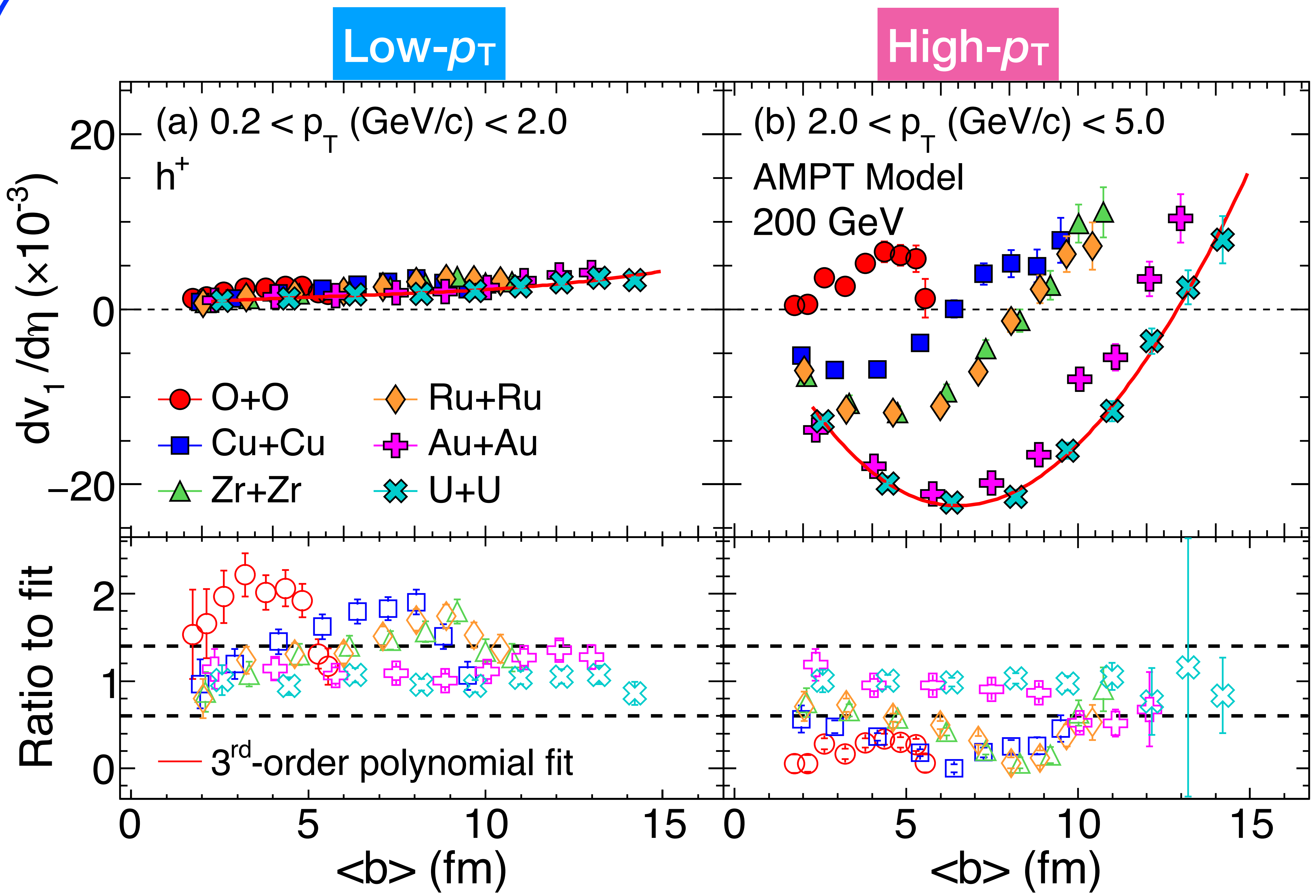
➔Had-soft asymmetry

Testing the Scaling Property of $dv_1/d\eta$

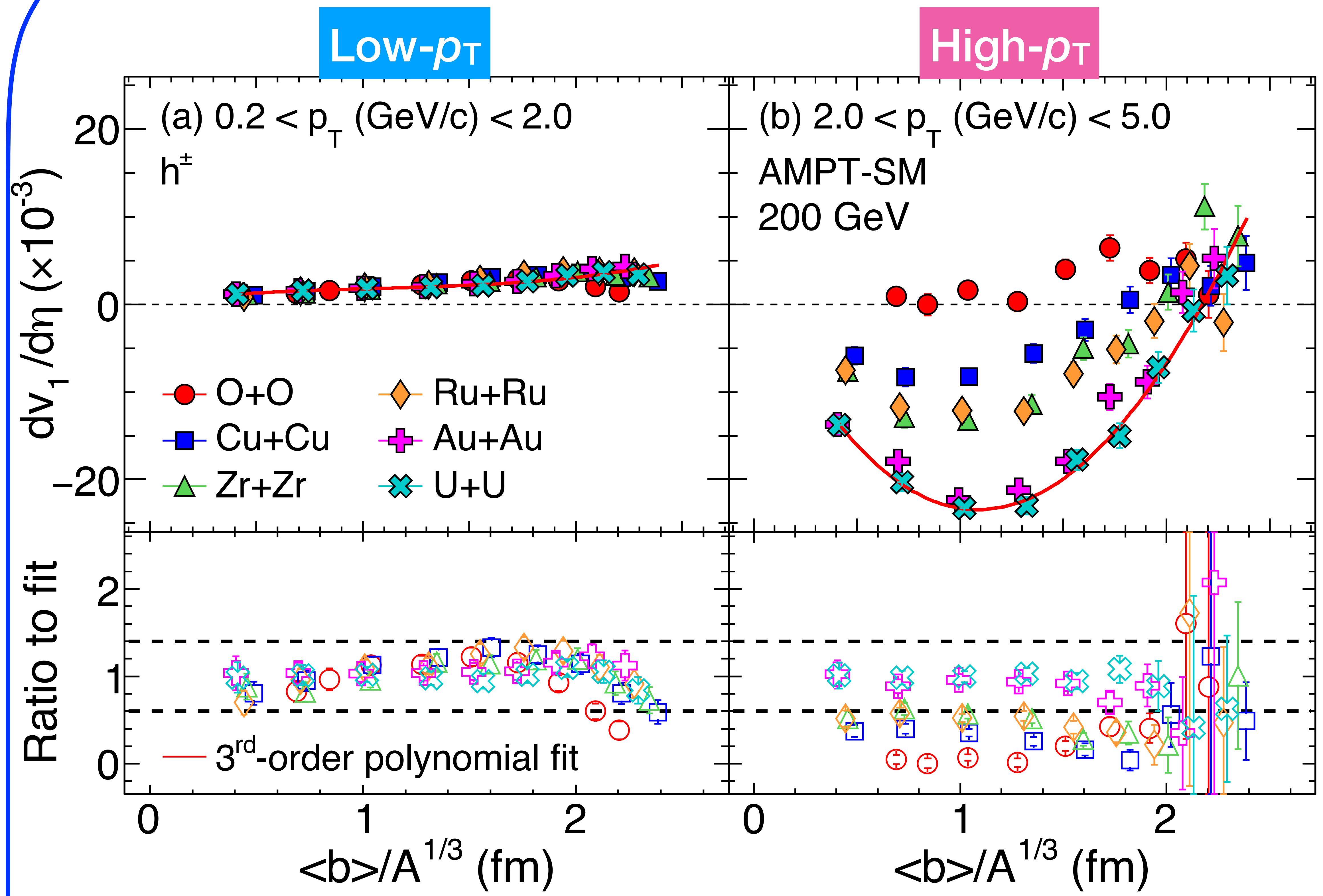


- QGP bulk is low-p_T dominated and a prominent positive flow is seen unlike the high-p_T
- Scaling of v_1-slope is not perfect

Testing the Scaling Property of $dv_1/d\eta$

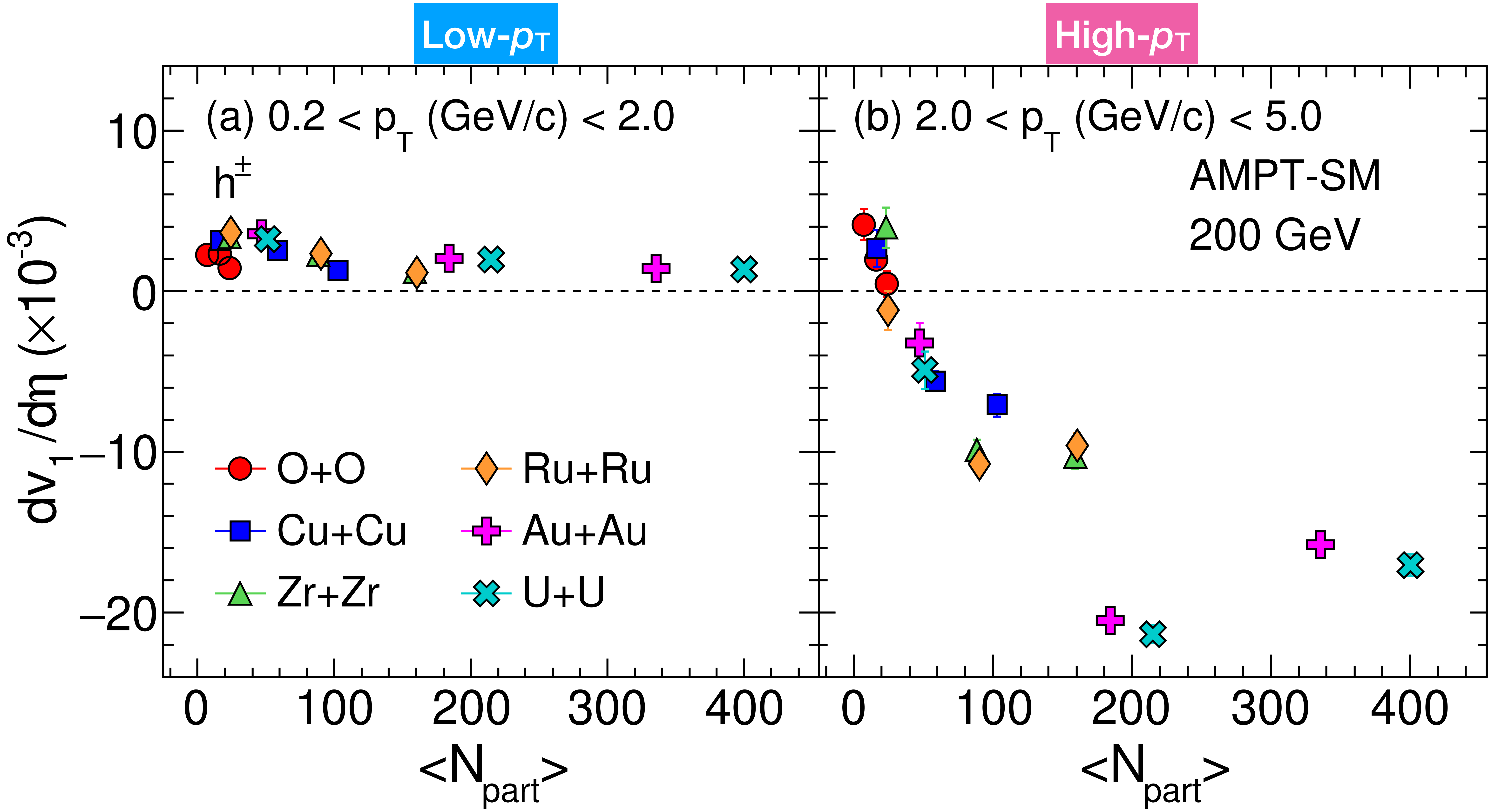


- QGP bulk is low-p_T dominated and a prominent positive flow is seen unlike the high-p_T
- Scaling of v_1-slope is not perfect



- Scaling is significantly improved for the bulk dominated unlike the high-p_T
- Scaling v_1-slope is not perfect for the high-p_T

System size independence at low-p_T



At low-p_T:

- A very weak centrality dependence
- System size independence

At High-p_T:

- Both centrality and system size dependence of v_1-slope is found
- Higher slope magnitude might be due to more interactions with the medium

- A system size independence is found in AMPT-SM, similar to the STAR experimental observation for Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

→ QGP bulk for all these systems are driven by multiplicity

Part-II

Dependence of Δv_1 on Conserved Charges

Motivation

- The v_1 depends on properties of the created matter in heavy ion collisions such as the Equation of State (EoS) and Electromagnetic Fields (EMF)
- The v_1 is expected to follow Coalescence Sum Rule (CSR) or NCQ scaling when initial matter is in parton degrees of freedom and hadronizes via quark coalescence
- Consider a combinations of 7 produced hadrons K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$ having same $N_{\bar{u}} + N_{\bar{d}}$ & $N_s + N_{\bar{s}}$
- Non-zero v_1 difference (Δv_1) especially if Δv_1 depends on Δq, it was proposed to be a consequence of EMF

STAR Collaboration, arXiv:2304.02831 (2023)

Index	Quark mass	Charge	Strangeness	Δv_1 combination
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s}) + K^-(\bar{u}s)] - [\bar{\Lambda}(\bar{u}\bar{d}\bar{s}) + \phi(s\bar{s})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{1}{3}$	$\Delta S = 0$	$\frac{1}{3}[\Omega^-(sss) + \bar{p}(\bar{u}\bar{u}\bar{d})] - [K^-(\bar{u}s)]$
4	$\Delta m \approx 0$	$\Delta q = \frac{2}{3}$	$\Delta S = 1$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{2}\phi(s\bar{s}) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
5	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
6	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
7	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [\phi(s\bar{s}) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
8	$\Delta m \approx 0$	$\Delta q = \frac{5}{3}$	$\Delta S = 2$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})]$
9	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$
10	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

A. Sheikh, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022) *T. Parida, S. Chatterjee arXiv:2305.08806 (2023)*

Motivation

- The v_1 depends on properties of the created matter in heavy ion collisions such as the Equation of State (EoS) and Electromagnetic Fields (EMF)
- The v_1 is expected to follow Coalescence Sum Rule (CSR) or NCQ scaling when initial matter is in parton degrees of freedom and hadronizes via quark coalescence
- Consider a combinations of 7 produced hadrons K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$ having same $N_{\bar{u}} + N_{\bar{d}}$ & $N_s + N_{\bar{s}}$
- Non-zero v_1 difference (Δv_1) especially if Δv_1 depends on Δq, it was proposed to be a consequence of EMF

STAR Collaboration, arXiv:2304.02831 (2023)

Index	Quark mass	Charge	Strangeness	Δv_1 combination
1	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
2	$\Delta m = 0$	$\Delta q = 0$	$\Delta S = 0$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s}) + K^-(\bar{u}s)] - [\bar{\Lambda}(\bar{u}\bar{d}\bar{s}) + \phi(s\bar{s})]$
3	$\Delta m \approx 0$	$\Delta q = \frac{1}{3}$	$\Delta S = 0$	$\frac{1}{3}[\Omega^-(sss) + \bar{p}(\bar{u}\bar{u}\bar{d})] - [K^-(\bar{u}s)]$
4	$\Delta m \approx 0$	$\Delta q = \frac{2}{3}$	$\Delta S = 1$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{2}\phi(s\bar{s}) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
5	$\Delta m \approx 0$	$\Delta q = 1$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
6	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
7	$\Delta m \approx 0$	$\Delta q = \frac{4}{3}$	$\Delta S = 2$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [\phi(s\bar{s}) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
8	$\Delta m \approx 0$	$\Delta q = \frac{5}{3}$	$\Delta S = 2$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})]$
9	$\Delta m = 0$	$\Delta q = 2$	$\Delta S = 6$	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$
10	$\Delta m \approx 0$	$\Delta q = \frac{7}{3}$	$\Delta S = 4$	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

A. Sheikh, D. Keane, P. Tribedy, Phys. Rev. C 105, 014912 (2022)   *T. Parida, S. Chatterjee arXiv:2305.08806 (2023)*

- How many independent set of equations are possible with 7 produced hadrons?
- Does Δv_1 depend only on Δq or also ΔS or both?
- What is the right methodology to find relationship between Δv_1, Δq and ΔS?

Methodology

There are only 5 independent hadron sets for such hadron combinations.

Set #	Δq_{ud}	ΔS	Δq	L (left side)	R (right side)
1	0	0	0	$v_1[K^-(\bar{u}s)] + v_1[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$	$v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$
2	0	0	0	$v_1\left[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})\right]$	$\frac{1}{2}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + \frac{1}{2}v_1[\bar{\Xi}^+(\bar{d}\bar{s}\bar{s})]$
3	0	0	0	$\frac{1}{3}v_1[\Omega^-(sss)] + \frac{1}{3}v_1[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})]$	$v_1[\phi(s\bar{s})]$
4	0	1	1/3	$\frac{1}{2}v_1[\phi(s\bar{s})]$	$\frac{1}{3}v_1[\Omega^-(sss)]$
5A	1/3	1	2/3	$\frac{1}{2}v_1[\phi(s\bar{s})] + \frac{1}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$	$v_1\left[K^-(\bar{u}s)\right]$
5B	1/3	1	2/3	$v_1\left[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})\right]$	$\frac{1}{2}v_1[\phi(s\bar{s})] + \frac{2}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$

K. Nayak, S. Shi & Z. W. L, Phys. Lett. B 849, 138479 (2024)

The differences between the two sides in electric charge, strangeness and baryon number are given by:

$$\Delta q \equiv q^L - q^R = \Delta N_{\bar{d}} + \frac{2}{3}\Delta N_{\bar{s}}$$

$$\Delta S \equiv S^L - S^R = 2\Delta N_{\bar{s}}$$

As per the CSR : $v_1^{\mathrm{H}}(p_{\mathrm{T}}^{\mathrm{H}}) = \sum_i v_1^i(p_{\mathrm{T}}^i)$

$$\Delta v_1 \equiv v_1^L - v_1^R = \sum_{i=\bar{u},\bar{d},s,\bar{s}} \Delta N_i v_{1,i}$$

$$\Delta v_1 = (v_{1,\bar{d}} - v_{1,\bar{u}})\Delta q + \left(\frac{v_{1,\bar{s}} - v_{1,s}}{2} - \frac{v_{1,\bar{d}} - v_{1,\bar{u}}}{3}\right)\Delta S$$

$$\mathbf{\Delta v_1 = c_q^* \Delta q + c_s^* \Delta S + c_0^*} \quad \cdots\cdots\cdots\cdots \quad (1)$$

Extraction coefficients

$$\Delta q_{ud} \equiv q_{ud}^L - q_{ud}^R = \Delta q + \frac{1}{3}\Delta S$$

$$\Delta B \equiv -\frac{1}{3}\Delta S$$

$$\Delta v_1 = c_q \Delta q_{ud} + c_B \Delta B + c_0$$

$$\Delta v_1 = (v_{1,\bar{d}} - v_{1,\bar{u}})\Delta q_{ud} + \left(\frac{v_{1,\bar{s}} - v_{1,s}}{2}\right)\Delta S$$

$$\mathbf{\Delta v_1 = c_q \Delta q_{ud} + c_s \Delta S + c_0} \quad \text{..........} \quad 2$$

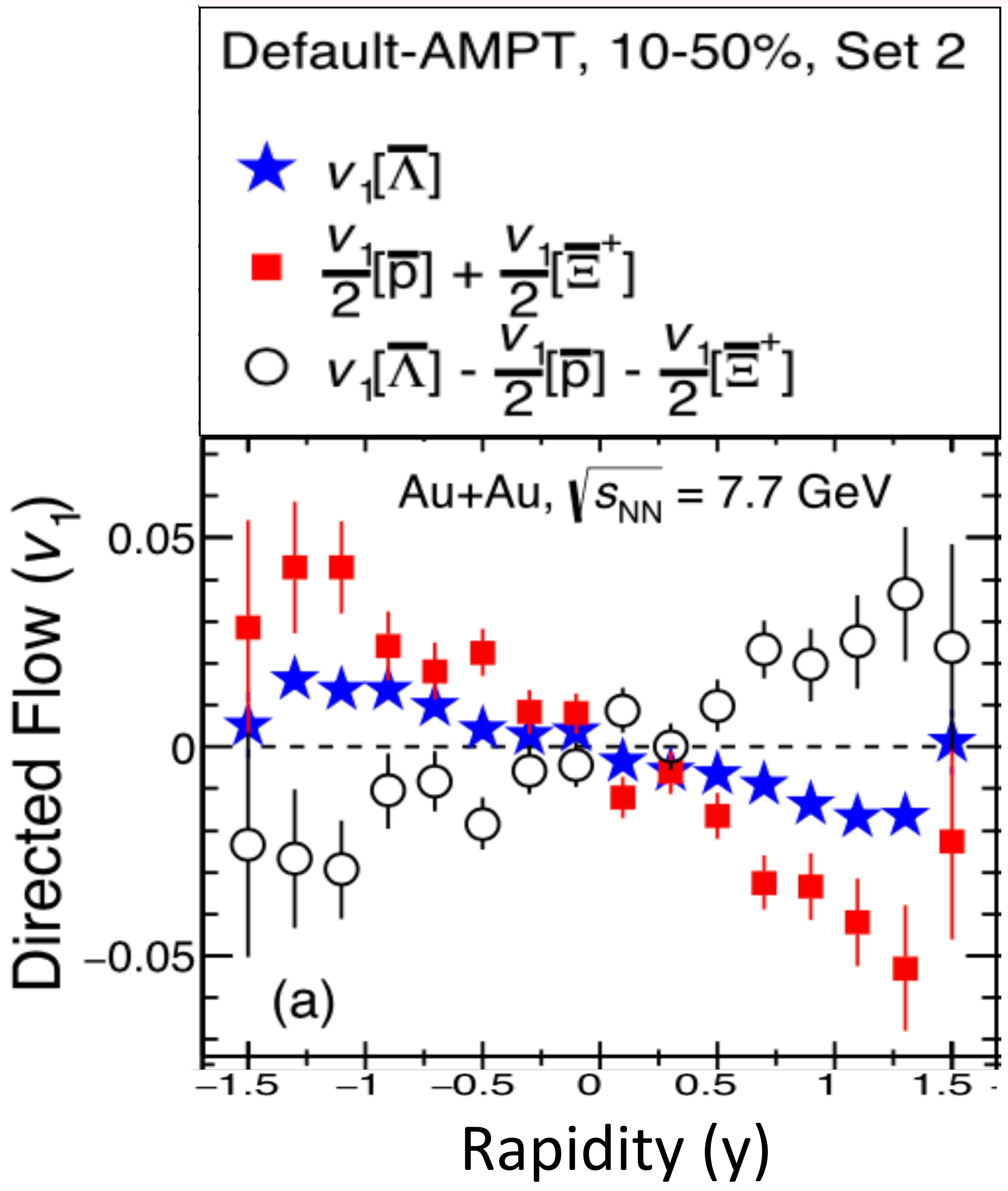
Hence, CSR predicts:

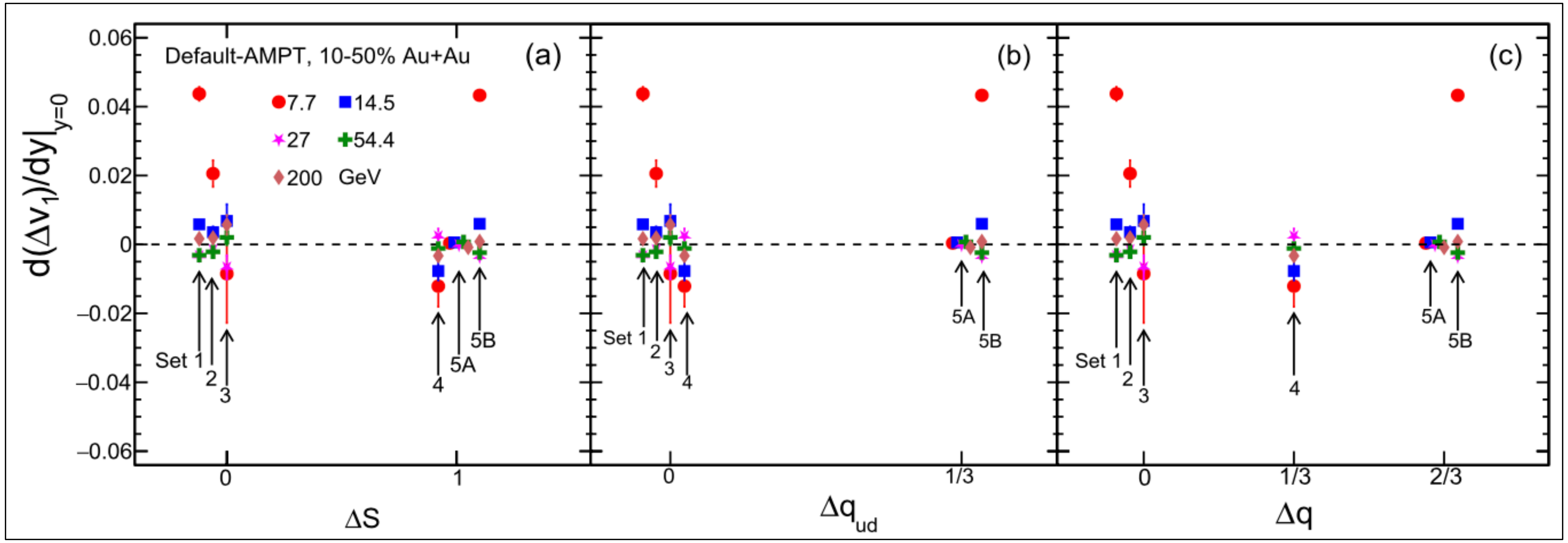
- ☑ Δv_1 depends linearly on both Δq and ΔS
- ☑ Coefficients reflect quark-level v_1 difference for quarks of different electric charges
  →Affected by EMF

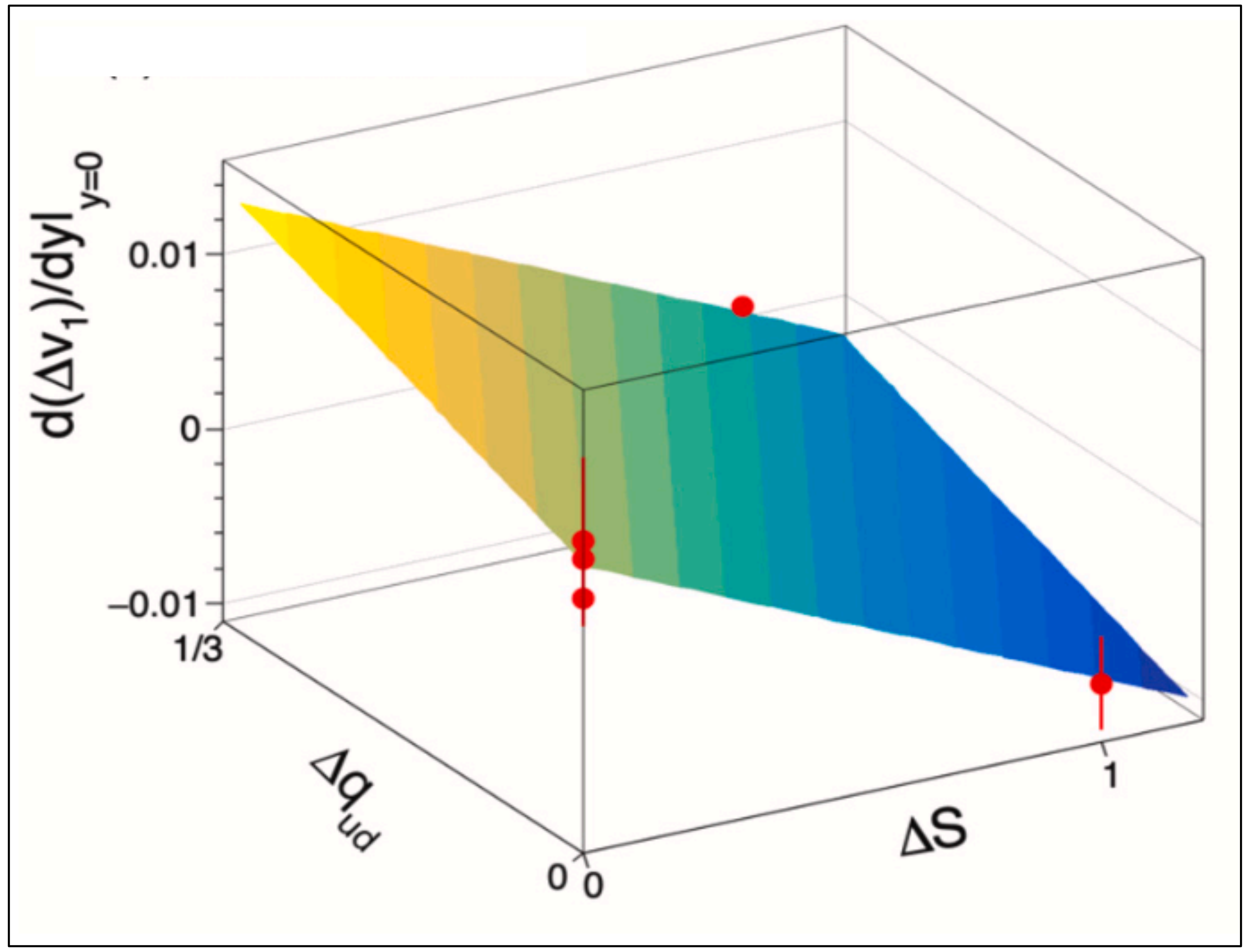
STAR Collaboration, arXiv:2304.02831 (2023)

Set/Index #	Δq	Δq_{ud}	ΔS	ΔB	Left side	Right side
Index 1	0	0	0	0	$v_1[\bar{p}(\bar{u}\bar{u}\bar{d})] + v_1[\phi(s\bar{s})]$	$v_1[K^-(\bar{u}s)] + v_1[\overline{\Lambda}(\bar{u}\bar{d}\bar{s})]$
Index 2	1	1/3	2	-2/3	$v_1[\overline{\Lambda}(\bar{u}\bar{d}\bar{s})]$	$\frac{1}{3}v_1[\Omega^-(sss)] + \frac{2}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$
Index 3	4/3	2/3	2	-2/3	$v_1[\overline{\Lambda}(\bar{u}\bar{d}\bar{s})]$	$v_1[K^-(\bar{u}s)] + \frac{1}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$
Index 4	2	0	6	-2	$v_1[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})]$	$v_1[\Omega^-(sss)]$
Index 5	7/3	1	4	-4/3	$v_1[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})]$	$v_1[K^-(\bar{u}s)] + \frac{1}{3}v_1[\Omega^-(sss)]$

Extraction of coefficients using 2D fitting







$$v_1 = [\frac{d(\Delta v_1)}{dy}]y + c$$

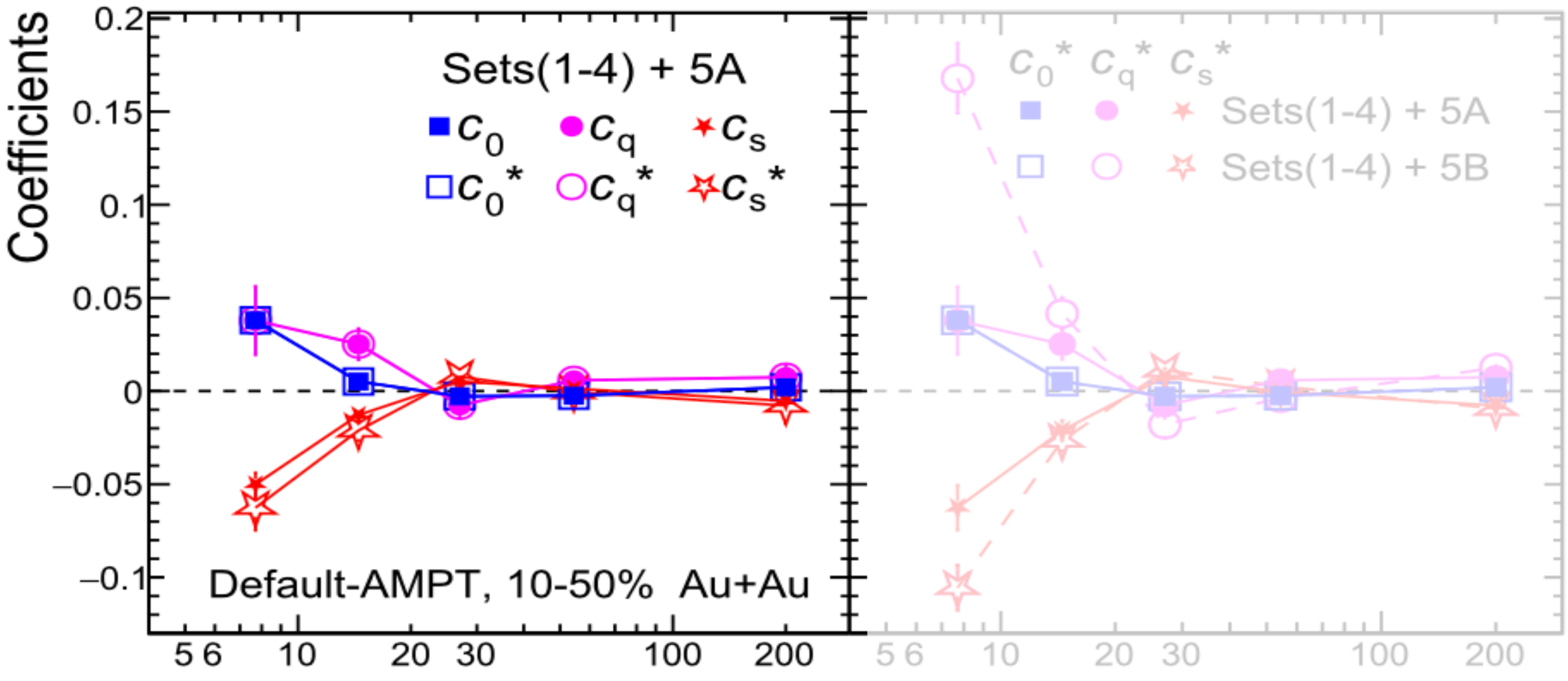
☑ **CSR expects:** $c_0 = 0$ and $c_0^* = 0$

☑ **Breaking of CSR:**

- A non-zero c_0 or c_0*
- A linear combination or scaling of hadron sets changes the value of non-zero c_0 or c_0*

➞Dependence of coefficients on the choice of hadron sets an indication of the breaking of CSR

Coefficients vs $\sqrt{s_{NN}}$



$$\Delta v_1 = (v_{1,\bar{d}} - v_{1,\bar{u}})\Delta q_{ud} + \left(\frac{v_{1,\bar{s}} - v_{1,s}}{2}\right)\Delta S + c_0$$

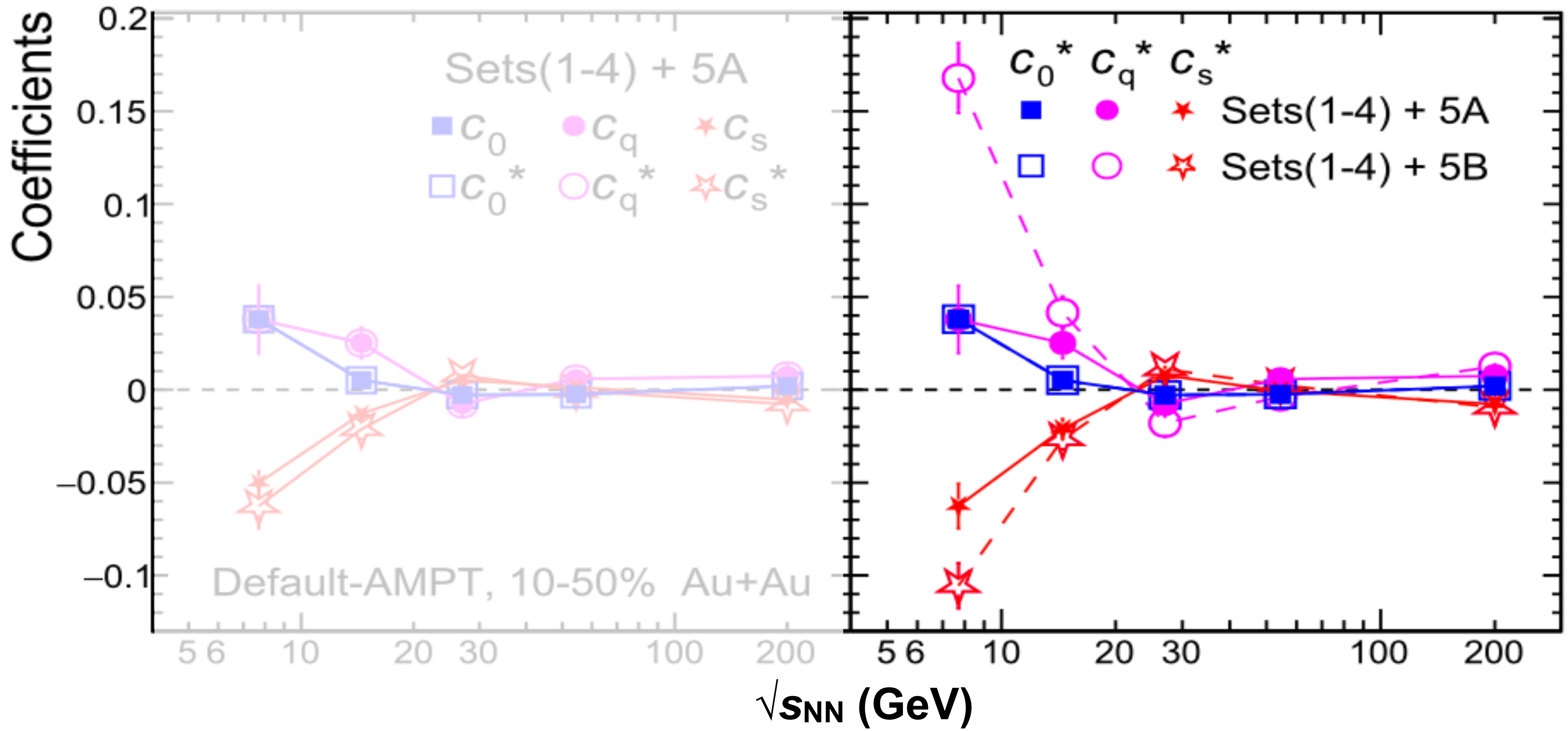
c_q c_s

$$\Delta v_1 = (v_{1,\bar{d}} - v_{1,\bar{u}})\Delta q + \left(\frac{v_{1,\bar{s}} - v_{1,s}}{2} - \frac{v_{1,\bar{d}} - v_{1,\bar{u}}}{3}\right)\Delta S + c_0^*$$

c_q^* c_s^*

✓The c_s and c_s* coefficients are different i.e more sensitive unlike c_0 (c_0^*) and c_q (c_q^*)

Coefficients vs $\sqrt{s_{NN}}$



$$\Delta v_1 = (v_{1,\bar{d}} - v_{1,\bar{u}})\Delta q + \left(\frac{v_{1,\bar{s}} - v_{1,s}}{2} - \frac{v_{1,\bar{d}} - v_{1,\bar{u}}}{3}\right)\Delta S + c_0^*$$

c_q^* c_s^*

✓Coefficients (*) are also sensitive to the choice of independent set of equations

✓It is incorrect to use a 1-D fitting method for coefficient extraction; 2-D is required.
The details can be found in the SQM-2024 talk by **Prof. Zi-Wei Lin:** https://shorturl.at/3cUJn

Summary

System Size Dependence v_1

- ✓ v_1-study is performed to in O+O, Cu+Cu, Zr+Zr, Ru+Ru, Au+Au, U+U collisions for understanding the system size dependence in the AMPT model at $\sqrt{s_{NN}} = 200$ GeV
- ✓ A system size independence v_1-slope (dv_1/dy) is found for charged hadron at low-p_T
- ✓ Centrality and p_T-dependent v_1-slope suggests the effect of initial hard-soft asymmetry

Dependence of Δv_1 on Conserved Charges

- ★ Δv_1-slope is very sensitive to the change in electric charge, strangeness content, choice of equations and collision beam energies.
- ★ The non-zero Δv_1 for non-identical set of equations suggests that v_1-splitting not may only be driven by electromagnetic effect → Strangeness of hadron might play important role

Thank you!