Understanding the effect of strangeness and electric charge on the NCQ scaling of directed flow

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Outline

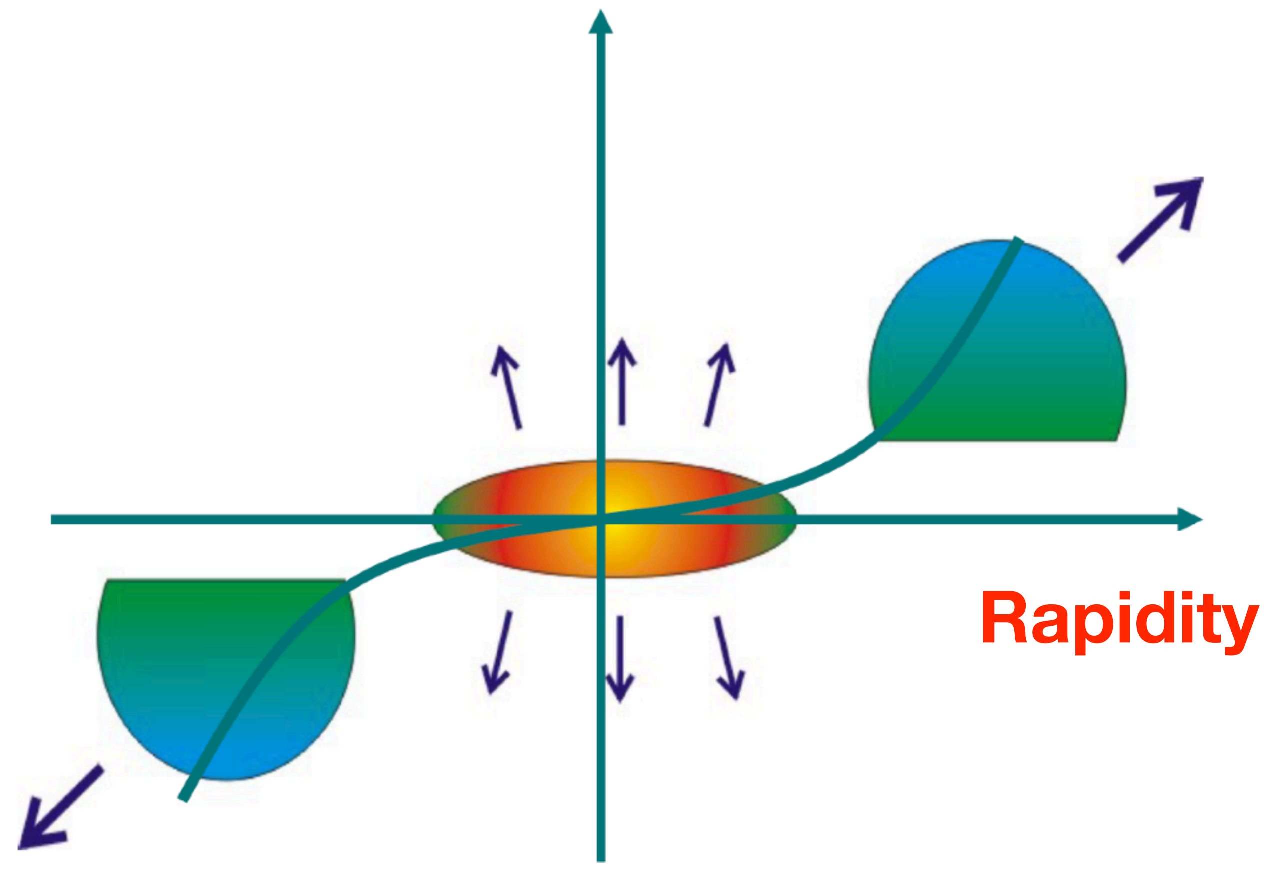
- Introduction and Motivation
- A Multi-Phase Trasport Model (AMPT)
- Analysis Details
  - Independent set of equations
  - Analytical solutions
- Testing the solution using Default-AMPT
- Summary

Introduction

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\mathbf{v_1}\, cos(\phi - \psi_R) + 2\mathbf{v_2}\, cos2(\phi - \psi_R) + \ldots\right)$$

Isotropic Directed Elliptic

$$v_1 = \langle cos(\phi - \psi_R)\rangle \qquad \phi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

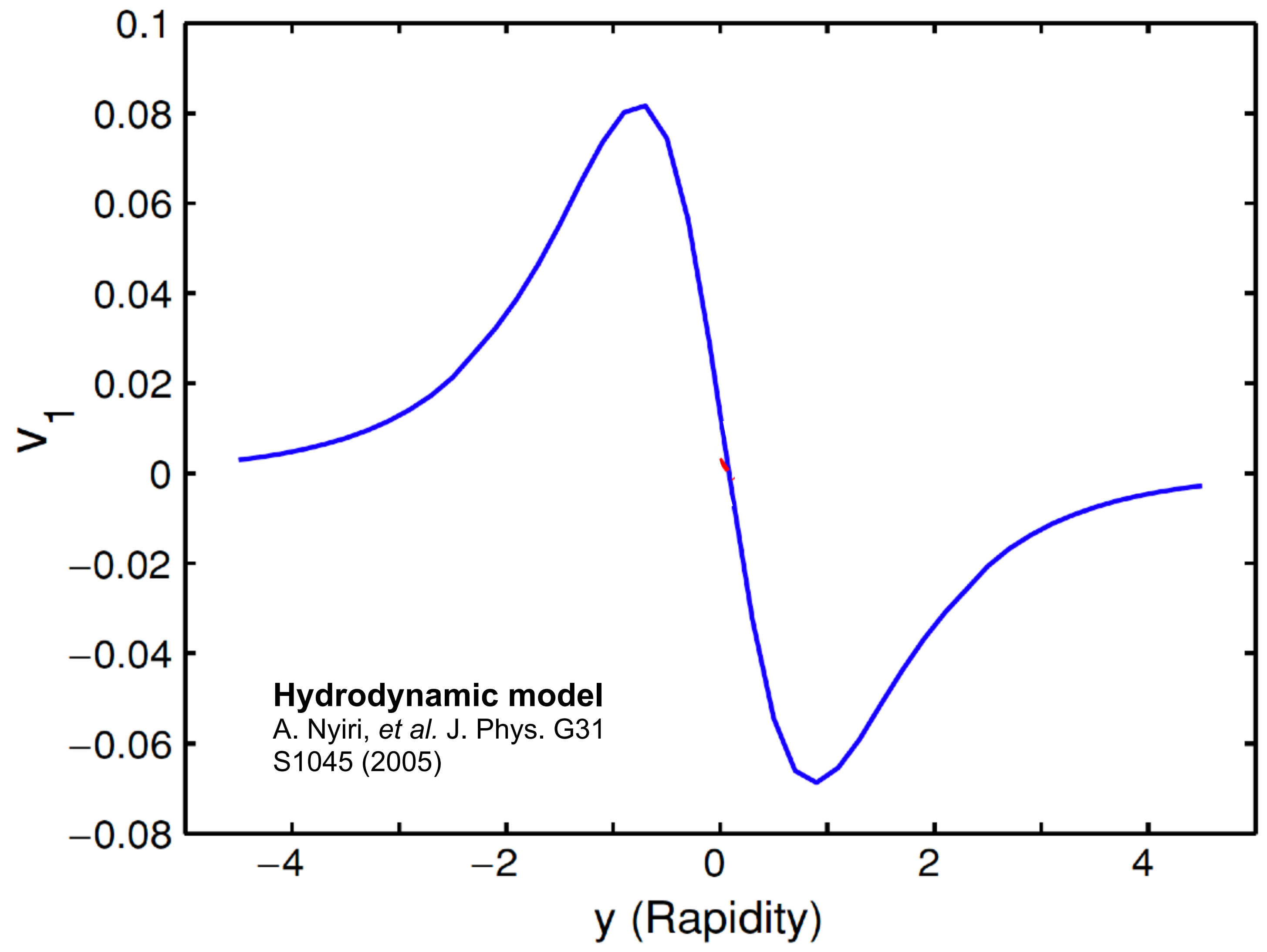


✓ **Directed flow (v_1):** 1st harmonic in the Fourier expansion of the azimuthal distribution of emitted particles relative to the reaction plane

- A collective sideward motion whose dominant component is an odd function of the particle rapidity (y)

✓ Probes early stage of **collision dynamics**

- Features a strong magnetic field (~10^{14}–10^{15} T) dominated by the passing spectator protons



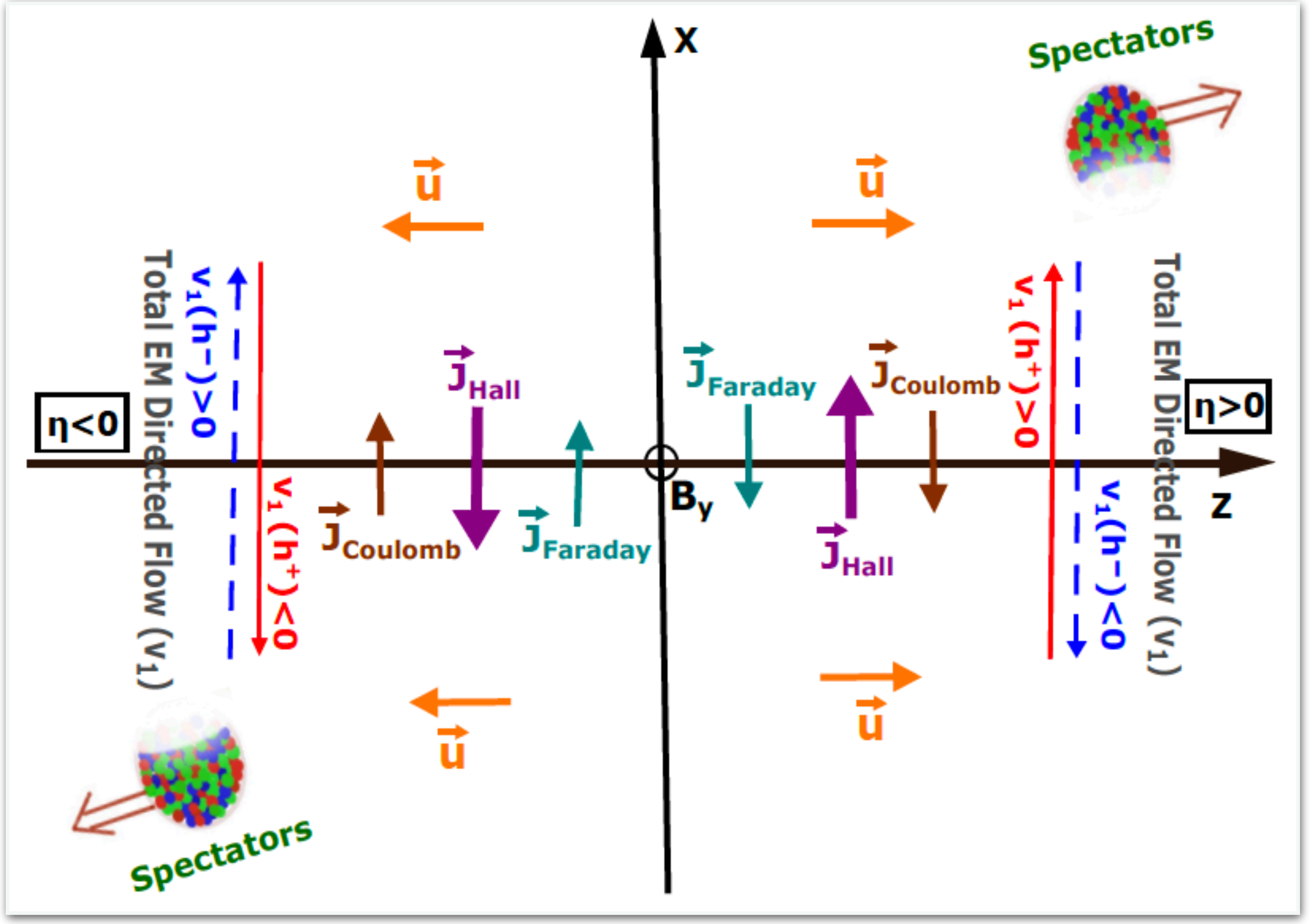
Motivation

- ✓ Quarks have velocity perpendicular to B direction, because of strong longitudinal flow velocity
- ✓ **Lorentz force** results in an electric current along x-axis ➞ *Hall effect*
- ✓ B decreases ➞ **Faraday current** is induced in the direction opposite to Hall effect
- ✓ **Coulomb force** exerted by the outgoing positively charged spectator on the produced plasma
- ✓ **Net electric current is sum of Faraday, Lorentz and Coulomb force resulting in a charge dependent v_1**

Does v_1-splitting (Δv_1) influence by the EM field (charge)?

Does it depend on the strangeness?

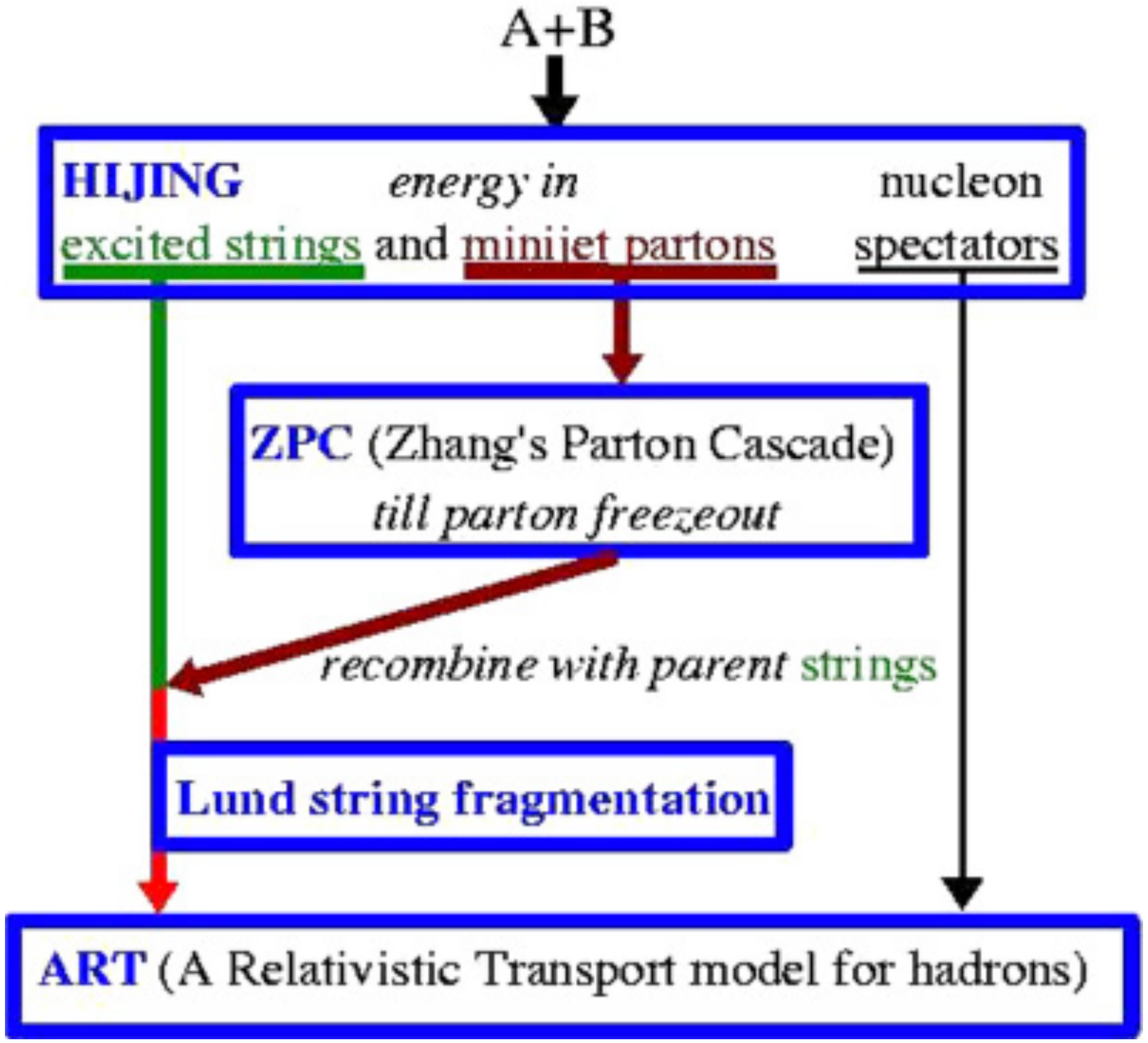
- ✓ A new method of testing of NCQ scaling using v_1 of produced hadrons (K^-, $\bar{p}$, $\overline{\Lambda}$, ϕ, $\overline{\Xi}^+$, Ω^-, $\overline{\Omega}^+$) in the same rapidity and p_T/N_{cq} phase space
- ✓ Need to understand the dependence of change in electric charge, strangeness content, choice of equations and collision beam energies
- ✓



STAR Collaboration, arXiv: 2204.02831 (2023)

Default-AMPT Model

✓AMPT model provides a comprehensive kinetic description of essential stages of high energy heavy ion collisions



✓Number of AMPT-Default events analysed: 3M

✓Au+Au, 10-50% centrality, $\sqrt{s_{NN}}$ = 7.7, 14.5, 27, 54.4 & 200 GeV

✓All the hadrons are identified via their corresponding Pythia-ID (PID)

✓Reaction plane angle (Ψ) = 0

Zi-Wei Lin *et al.*, Phys. Rev. C 72, 064901 (2005);

Analysis Details

✓ v_1 of a hadron (H) and its constituent quarks satisfying NCQ scaling:

$$v_{1,\mathrm{H}}(p_{\mathrm{T,H}}) = \sum_i v_{1,i}(p_{\mathrm{T}}, i)$$

Same quark masses

$$v_{1,\mathrm{H}}(N_{cq}\ p_{\mathrm{T,q}}) = N_{cq} v_{1,q}(p_{\mathrm{T,q}})$$

✓ Δv_1 values are obtained for two combinations:

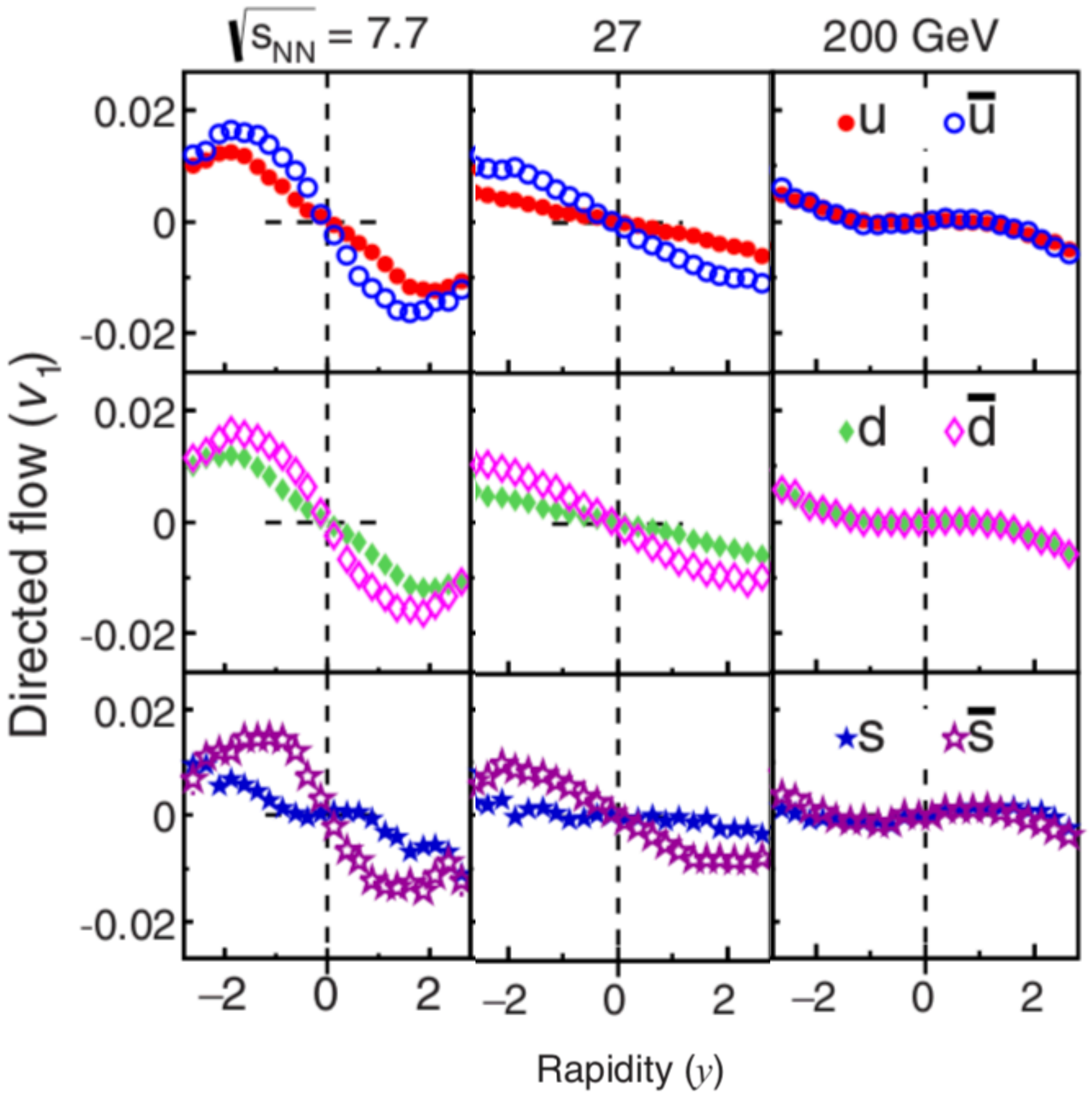
- Identical ($\Delta m = 0$, $\Delta q = 0$ and $\Delta S = 0$)
- Non-identical ($\Delta m = 0$, $\Delta q \neq 0$ and $\Delta S \neq 0$)

✓ Produced and transported quarks have different v_1

➡ Interpretation is challenging when hadrons having transported quarks are included

For NCQ scaling testing, assumptions are:

- $v_1(\bar{u}) \approx v_1(\bar{d})$;
- $v_1(s) \approx v_1(\bar{s})$



K. Nayak *et al*, Phys. Rev. C **100**, 054903 (2019)

Independent Equations

✓ The same number of light, strange quarks and anti-quarks on Left & Right hand side (R) with proper weighting factors

Example

$$\frac{1}{2}v_1[\phi(s\bar{s})] = \frac{1}{3}[\Omega^-(sss)]$$

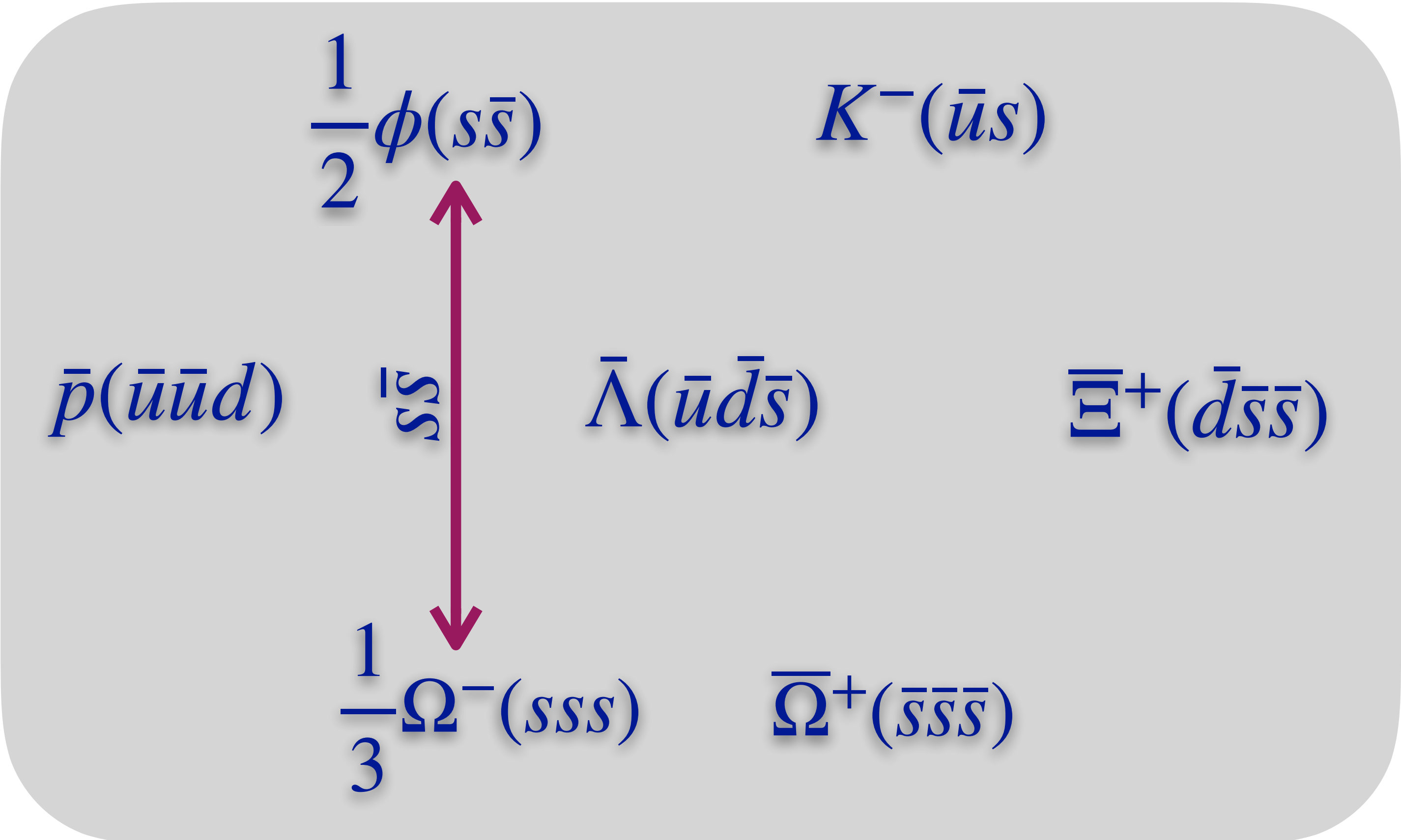
$$\Delta v_1 = v_1^L - v_1^R$$

$$\Delta S = S^L - S^R = 1$$

$$\Delta q = q^L - q^R = 1/3$$

$$\Delta q_{ud} = q^L - q^R = 0$$

Produced hadrons



A. I. Sheikh *et al*, Phys. Rev. C **105**, 014912 (2022)

	Set	Charge (Δq)	Δq_{ud}	Strangness (ΔS)	Expression
Identical	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	$v_1\left[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})\right] = \frac{v_1}{2}[\bar{\Xi}^+(\bar{d}\bar{s}\bar{s})] + \frac{v_1}{2}[\bar{p}(\bar{u}\bar{u}\bar{d})]$
	3	0	0	0	$\frac{v_1}{3}[\Omega^-(sss)] + \frac{v_1}{3}[\bar{\Omega}^+(\bar{s}\bar{s}\bar{s})] = v_1[\phi(s\bar{s})]$
Non-identical	4	1/3	0	1	$\frac{1}{2}v_1[\phi(s\bar{s})] = \frac{1}{3}[\Omega^-(sss)]$
	5A	2/3	1/3	1	$\frac{v_1}{2}\phi(s\bar{s})] + \frac{v_1}{3}[\bar{p}(\bar{u}\bar{u}\bar{d})] = v_1\left[K^-(\bar{u}s)\right]$
	5B	2/3	1/3	1	$v_1\left[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})\right] = \frac{v_1}{2}[\phi(s\bar{s})] + \frac{2}{3}v_1[\bar{p}(\bar{u}\bar{u}\bar{d})]$

Solution for Independent Equations

$\Delta N_i = N_i^L - N_i^R$

$\Delta N_{\bar{u}} + \Delta N_{\bar{d}} = 0$

$\Delta N_s + \Delta N_{\bar{s}} = 0$

$\Delta S = S^L - S^R$

$\Delta q = q^L - q^R$

$\Delta q_{ud} = q^L - q^R$

- $\Delta q_{ud} = \Delta N_{\bar{d}}/3 - 2\Delta N_{\bar{u}}/3 = \Delta N_{\bar{d}}$
- $\Delta S = 2\Delta N_{\bar{s}}$

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

$$\Delta v_1 = c_q \Delta q_{ud} + c_s \Delta S + c_0$$

Eq. 1

- c_s reflects v_1 difference between s and $\bar{s}$ quarks
- Similarly, c_q is the coefficient of Δq & c_0 is the intercept

Instead of Δq_{ud}, we could use the charge difference, where $\Delta q = \Delta q_{ud} + 2\Delta N_{\bar{s}}/3$

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

$$\Delta v_1 = c_q^* \Delta q + c_s^* \Delta S + c_0^*$$

Eq. 2

Analytical solution

✓Let's us take the average of Set 1-3 and denote it as Set A , Similarly

- Average of Set 1-3: **Set A**
- Set 4: **Set B**
- Set 5B: **Set C**

✓By considering these three sets (A, B, C) one can obtain three coefficients from Eq. 1 or Eq. 2

✓The Δv_1-slope also satisfy the same relation as $(\Delta v_1)_A$, $(\Delta v_1)_B$ and $(\Delta v_1)_C$

- $(\Delta v_1)_A = c_0,$
- $(\Delta v_1)_B = c_0 + c_s$
- $(\Delta v_1)_C = c_0 + c_q/3 + c_s$

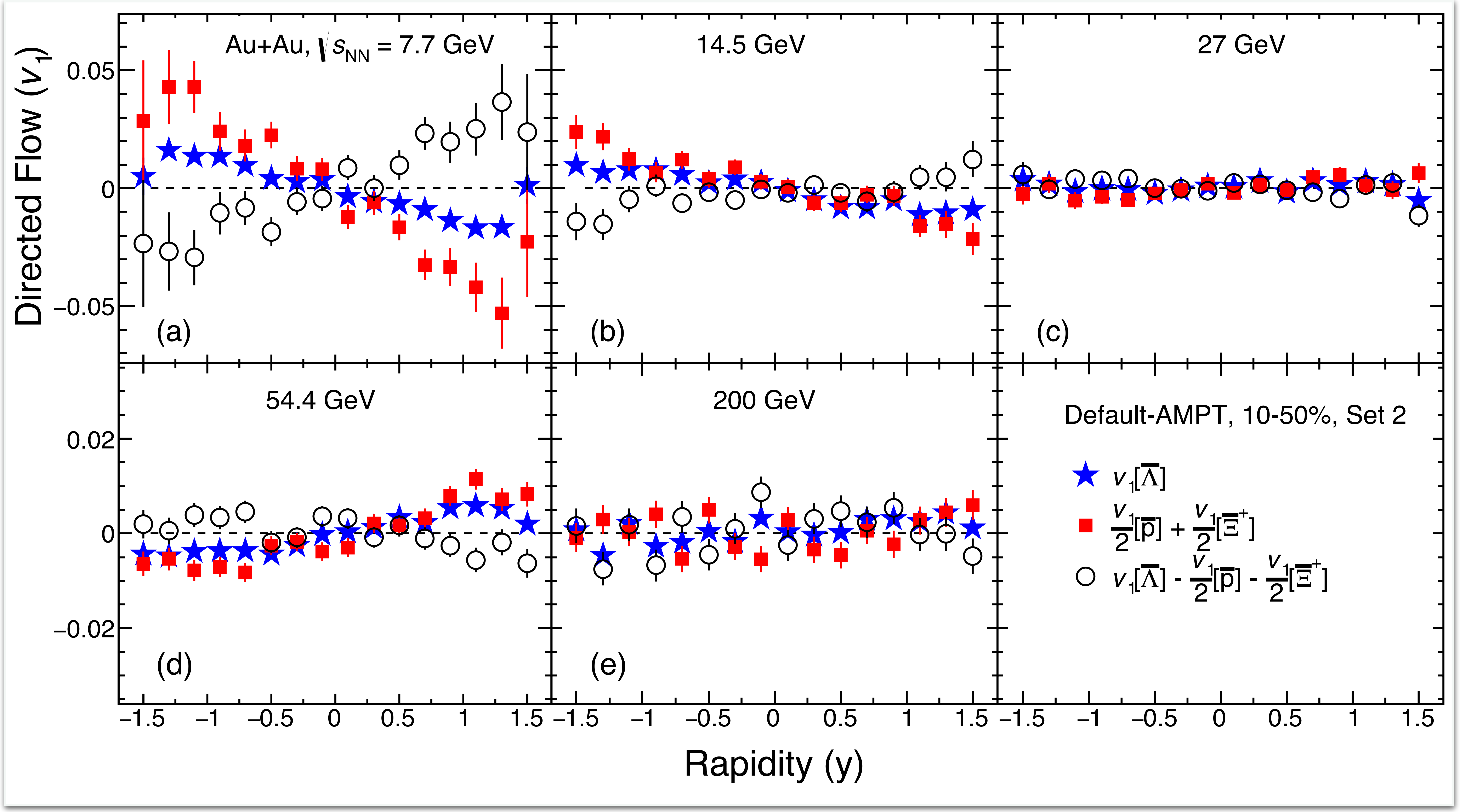
→

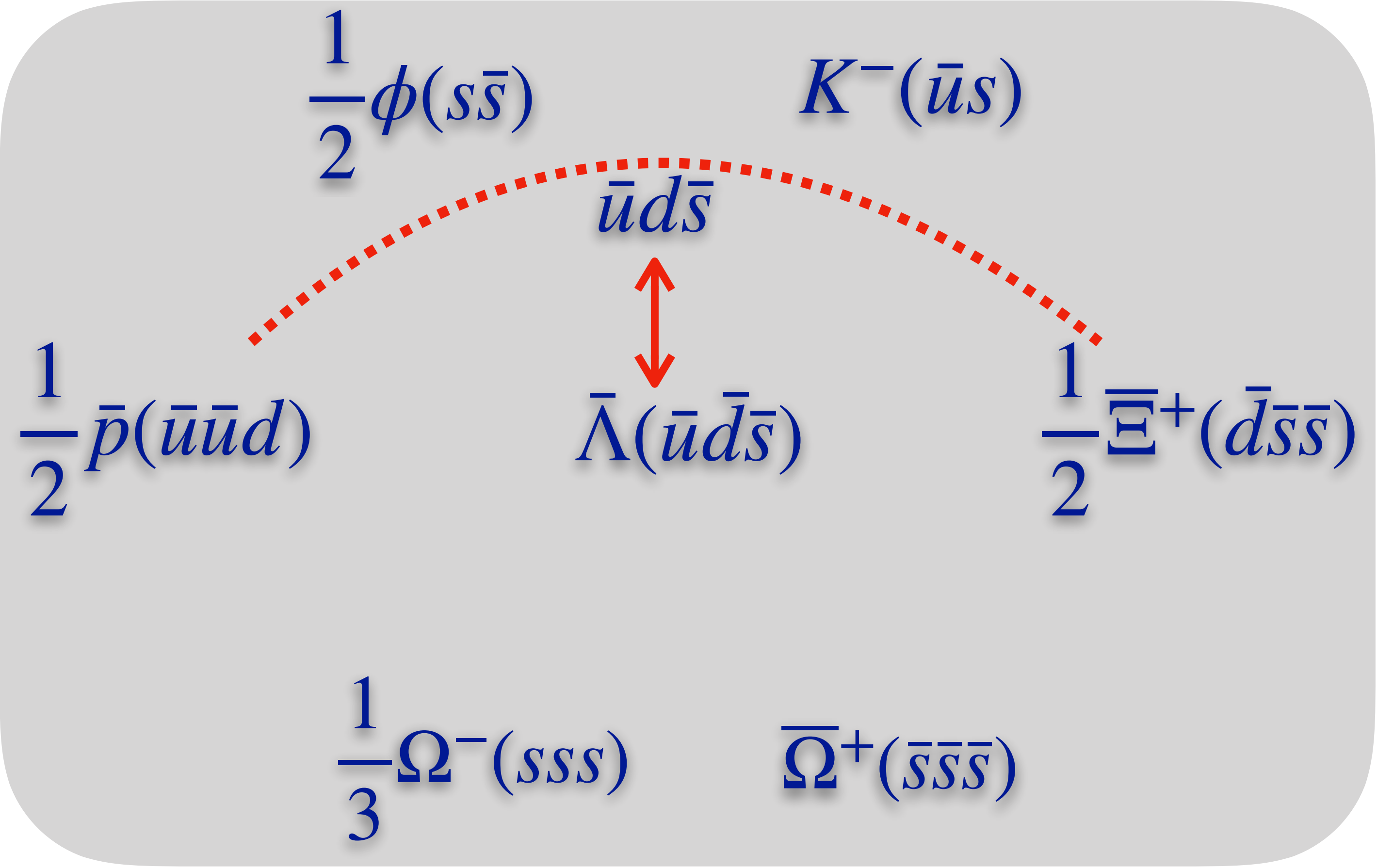
- $c_0 = (\Delta v_1)_A$
- $c_q = 3[(\Delta v_1)_C - (\Delta v_1)_B]$
- $c_s = (\Delta v_1)_B - (\Delta v_1)_A$

✓Similarly using Eq. 2:

- $c_0^* = (\Delta v)_A = c_0$
- $c_q^* = 3[(\Delta v_1)_C - (\Delta v_1)_B] = c_q$
- $c_s^* = 2(\Delta v_1)_B - (\Delta v_1)_A - (\Delta v_1)_C = c_s - c_q/3$

Rapidity dependence of v_1 and Δv_1



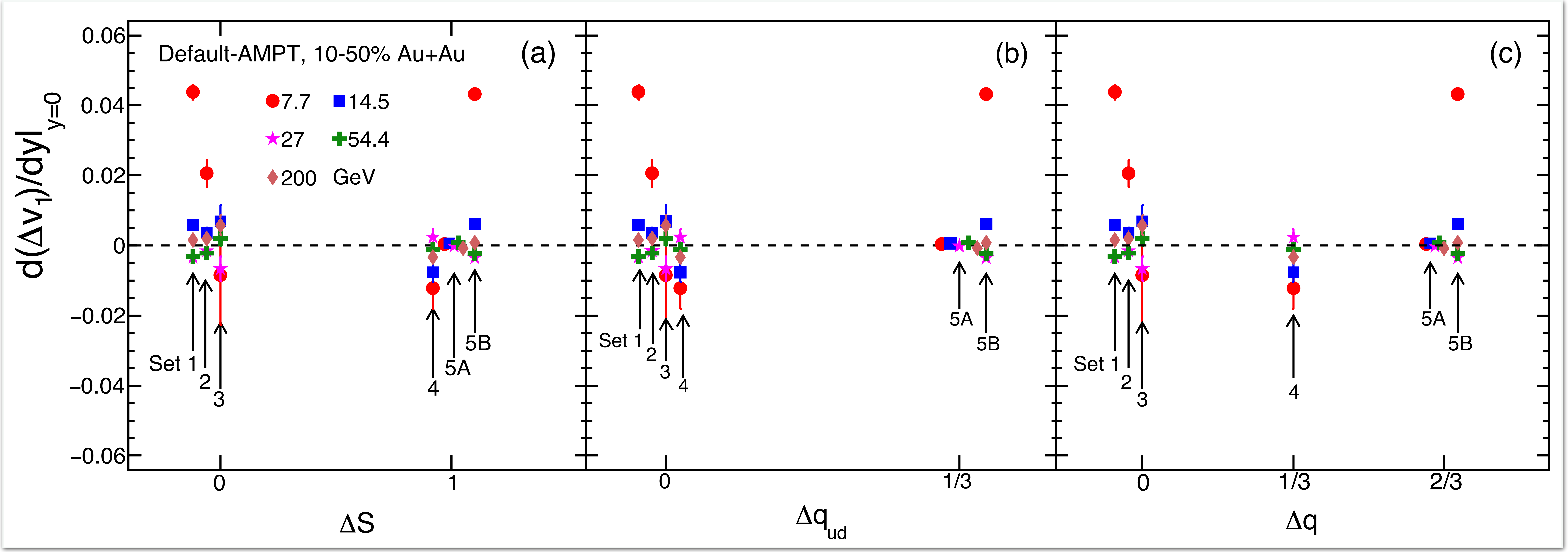


Fit function to get the slope $d(\Delta v_1)/dy$

$$f(y) = y \times [d(\Delta v_1)/dy] + c$$

- ✓ $\Delta q = 0$ and $\Delta S = 0$ (Set 2) in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 14.5, 27, 54.4 and 200 GeV
- ✓ Calculated in the same p_T region: Baryon 0-2 GeV and Meson 0-3 GeV

Δv₁-slope [d(Δv₁)/dy]



✓ Δv_1-slope is sensitive to the Δq, ΔS, choice of equations and collision beam energies

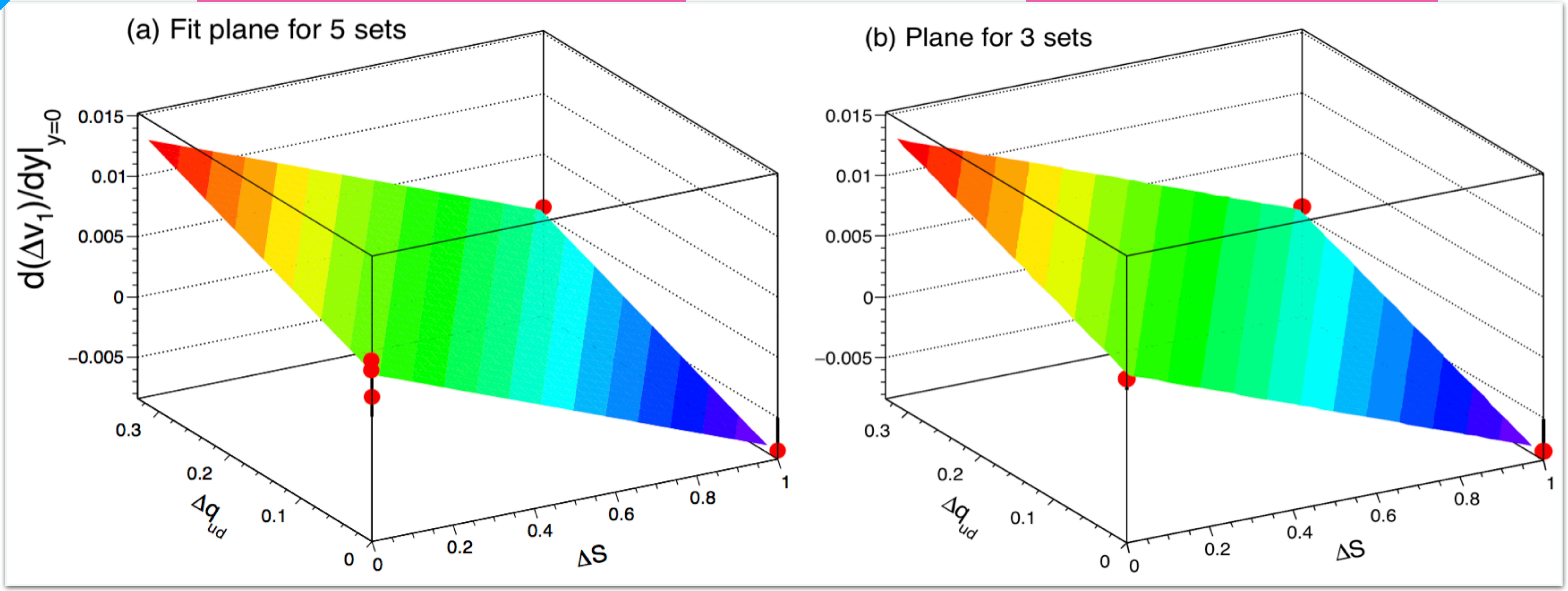
✓ A non-zero Δv_1-slope is found in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 14.5, 27, 54.4 and 200 GeV, 10-50% centrality in Default-AMPT

3D plane fitting of Δv_1-slope

AMPT-Default, Au+Au, 14.5 GeV, 10-50%

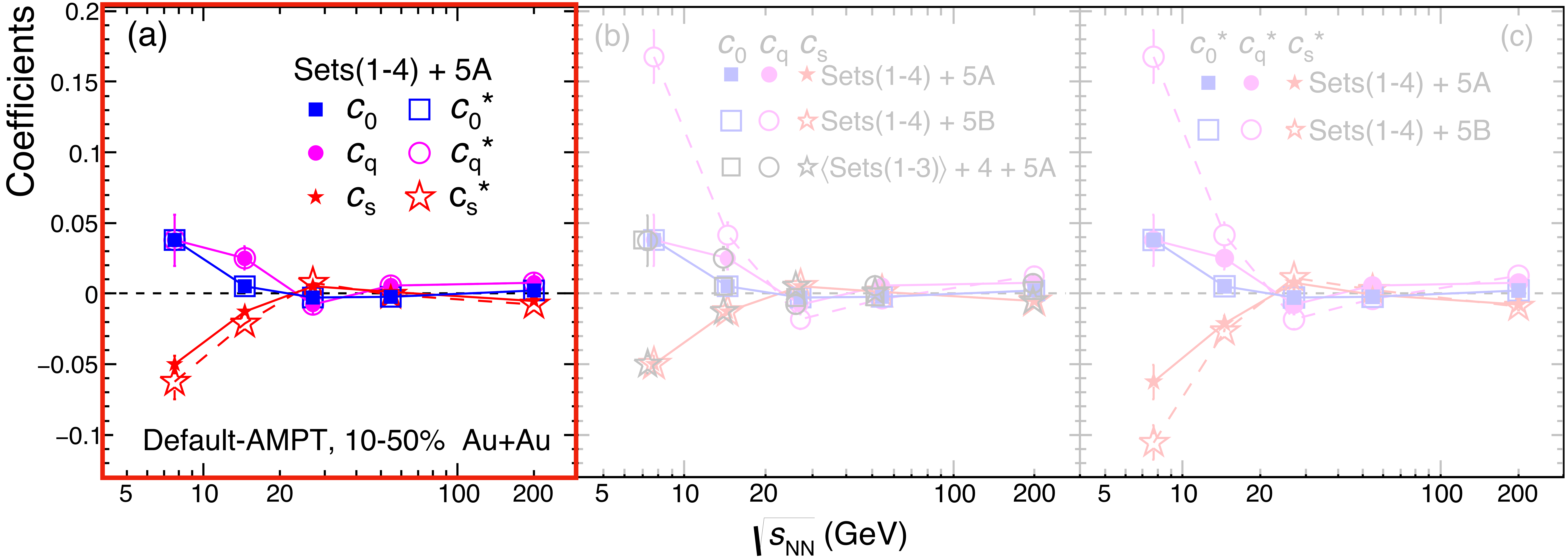
Testing independent equations

Testing analytical solution



✓Equation of the plane (surface): $d(\Delta v_1)/dy = c_q \Delta q_{ud} + c_s \Delta S + c_0$

Linear Coefficients



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

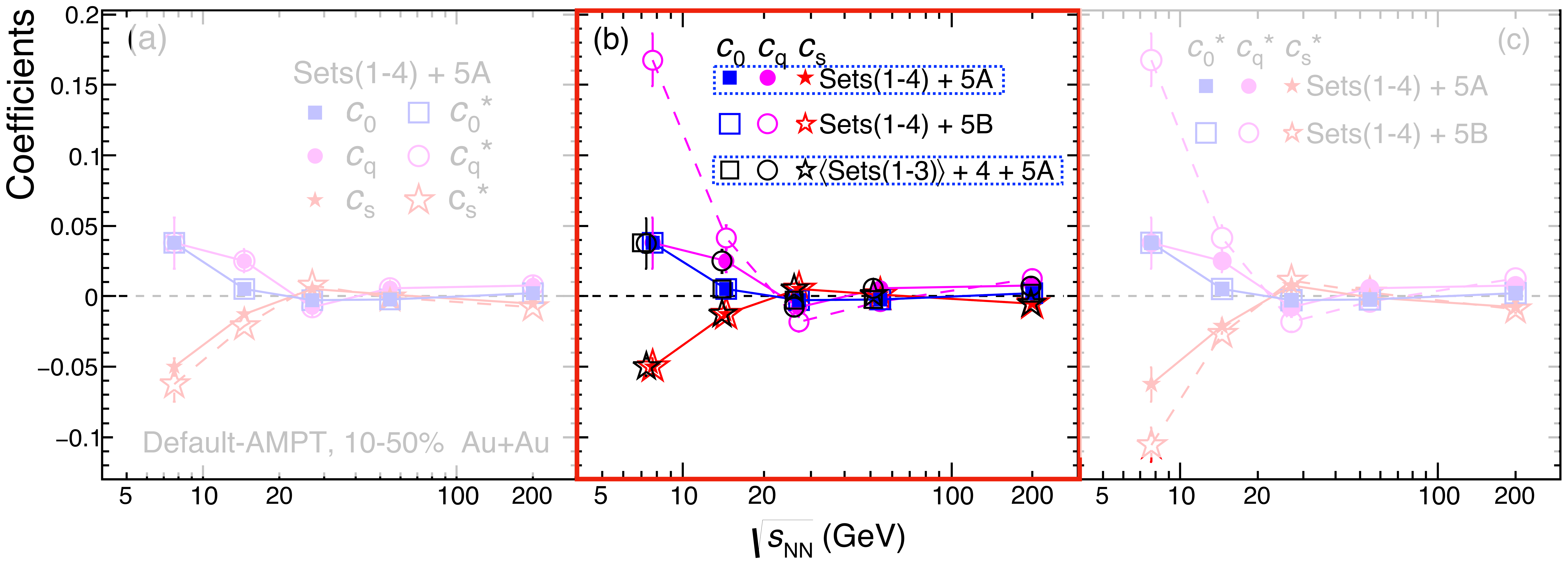
c_q c_s

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

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^*)

Linear Coefficients

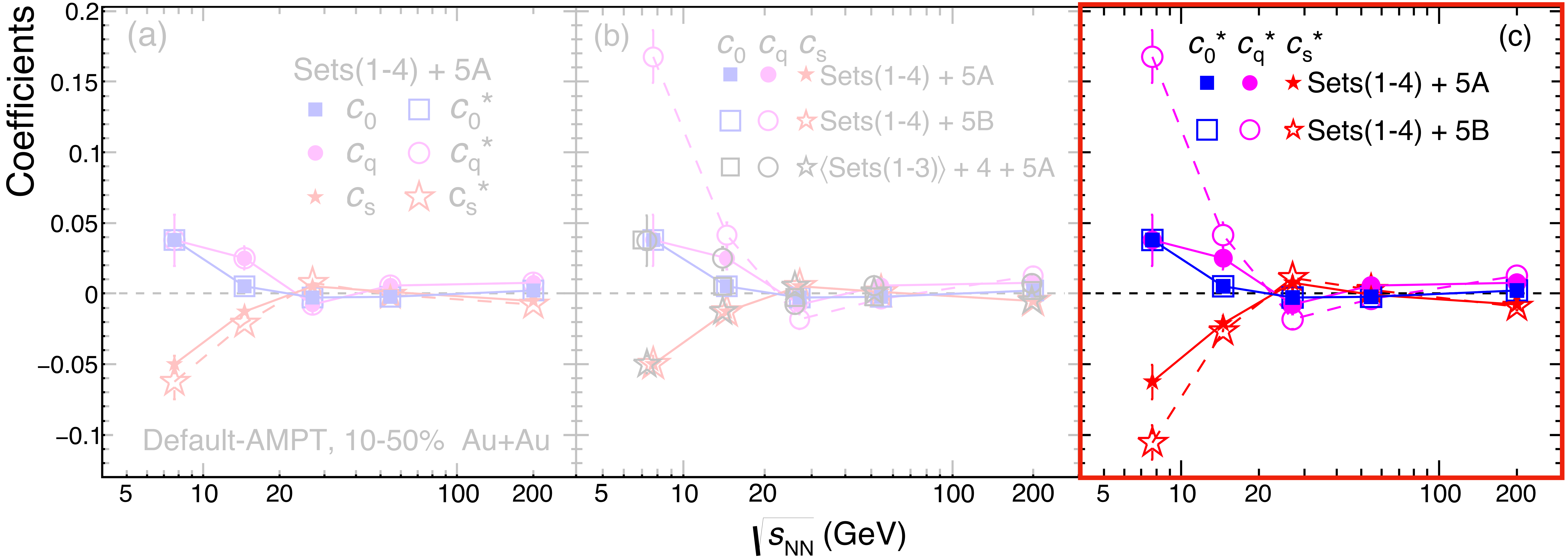


$$\Delta v_1 = \Delta q_{ud}(v_{1,\bar{d}} - v_{1,\bar{u}}) + \Delta S\left(\frac{v_{1,\bar{s}} - v_{1,s}}{2}\right) + c_0$$

c_q c_s

✓The analytical solution is in good agreement with the solution obtained using 5 independent equations

Linear Coefficients



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

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

c_q^* c_s^*

Summary

★ A new method of testing NCQ scaling of v_1 using produced hadrons is proposed

★ Considering 7 produced hadrons only 5 independent set of equations are possible

★ The testing should at least be performed by two combinations of independent set of equation

★ Δv_1-slope is very sensitive to the change in electric charge, strangeness content, choice of equations and collision beam energies.

★ The linear coefficient of ΔS i.e. c_S is found to be the most sensitive parameter for v_1-splitting or testing the NCQ scaling as compared to the corresponding Δq_{ud} (Δq) coefficient c_s (c_s^*)

★ 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!

Backup