Directed flow of identified hadrons in Au+Au collisions with the STAR experiment at RHIC

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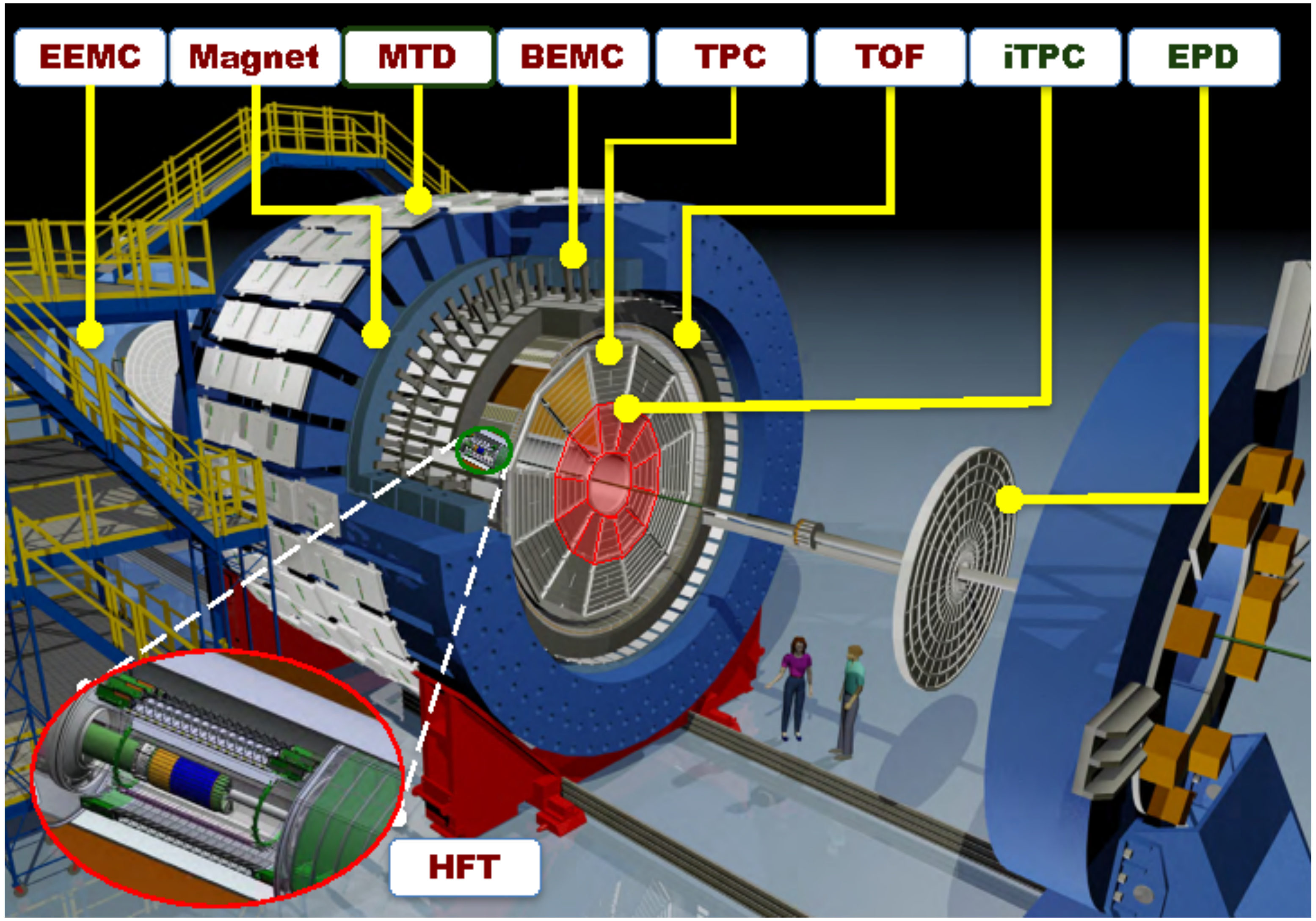
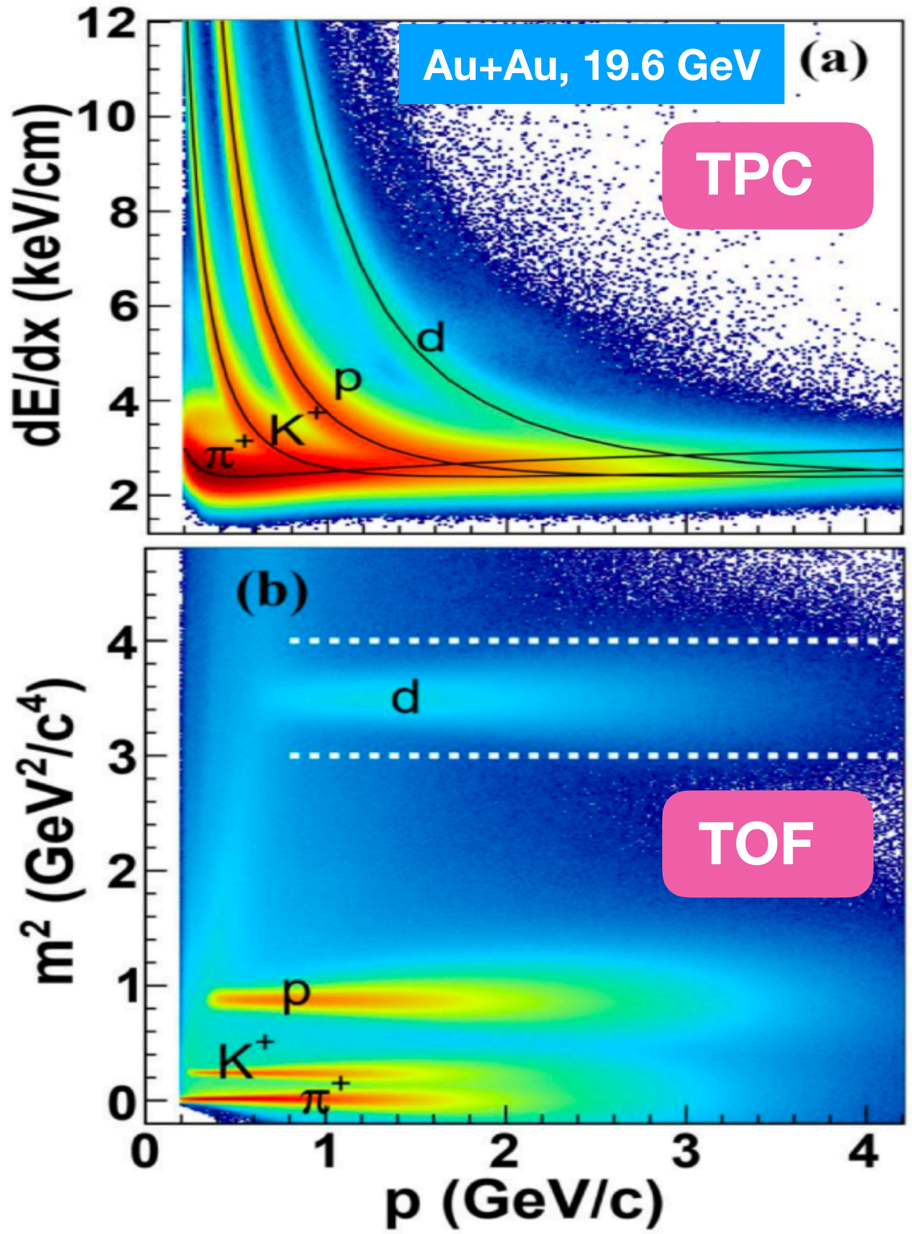
XXIV DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM
December 14 -18
2020 NISER

Outline

- Motivation
- The STAR detectors
- Results
  - *Directed flow (v_1) of identified hadrons*
  - *AMPT, Thermal model comparison*
  - *Testing Coalescence Sum Rule (NCQ scaling)*
- Summary

The STAR Detectors





- **1st-order Event Plane Detectors:**
  - ▶ **19.6, 54.4 GeV:** Beam-Beam Counter, BBC [3.3<|η|<5.0]
  - ▶ **27 GeV:** Event Plane Detector, EPD [2.1<|η|<5.1]

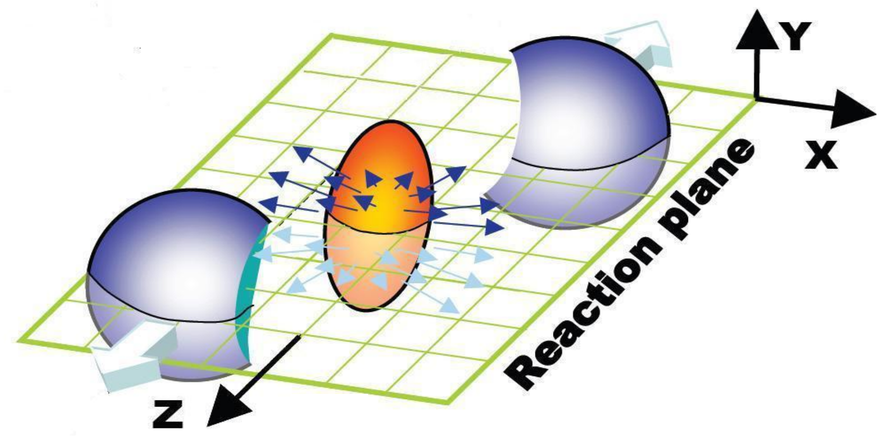
- Uniform Acceptance
- Full Azimuthal Coverage
- Excellent Particle Identification Capability

- **Systematic details**
  - ▶ DCA, nσ, TPC hits, TPC hits/Maximum hits: **Total systematic is** ~9-17%

Motivation

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos[n(\phi - \Psi_n)]$$

Directed flow, $v_1 = \langle \cos[(\phi - \Psi_1)] \rangle$

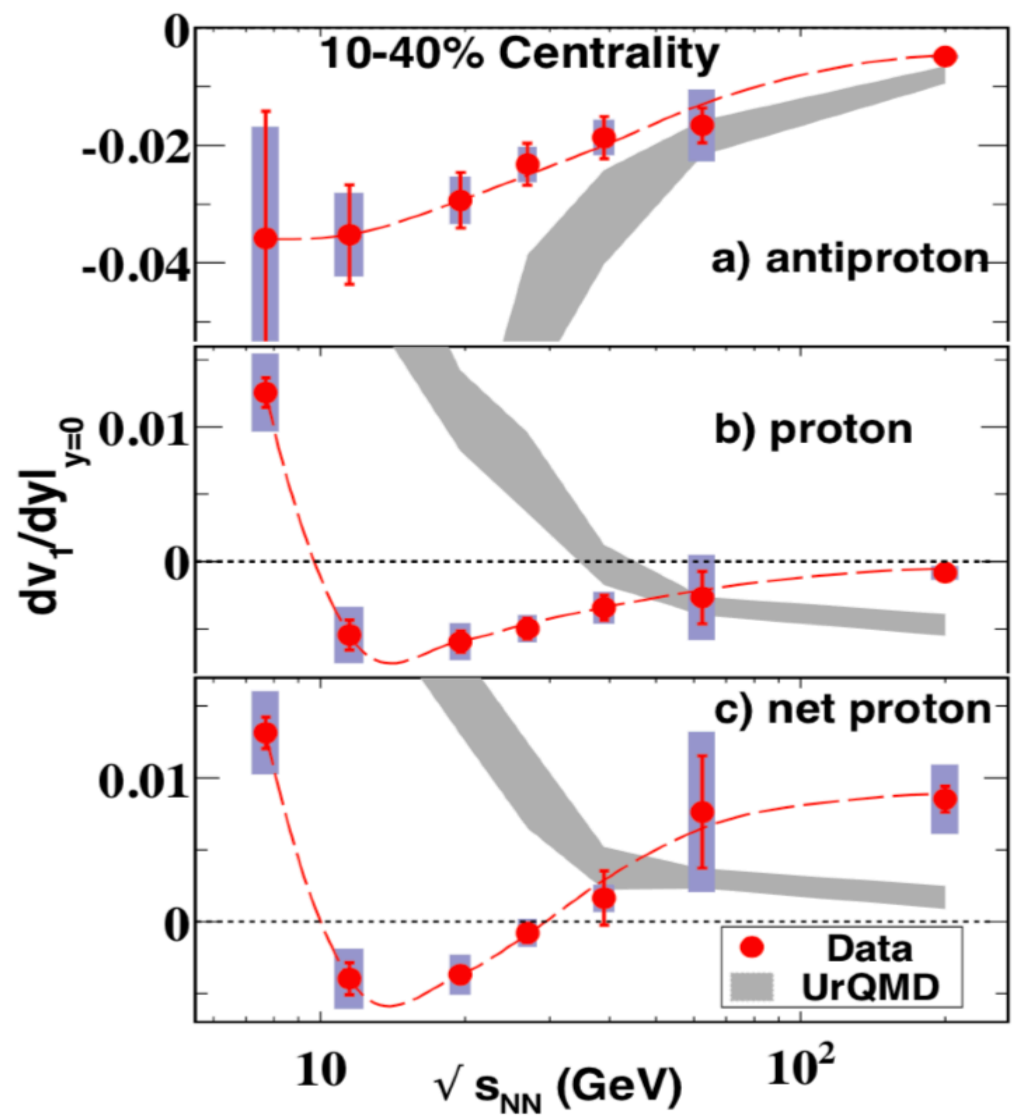


- **QCD Phase Transition**
  - *Signature of 1st order phase transition*

    →v_1 slope (dv_1/dy) of net-p: double sign change
- **Particle Production Mechanism**
  - *Coalescence sum rule: NCQ scaling*

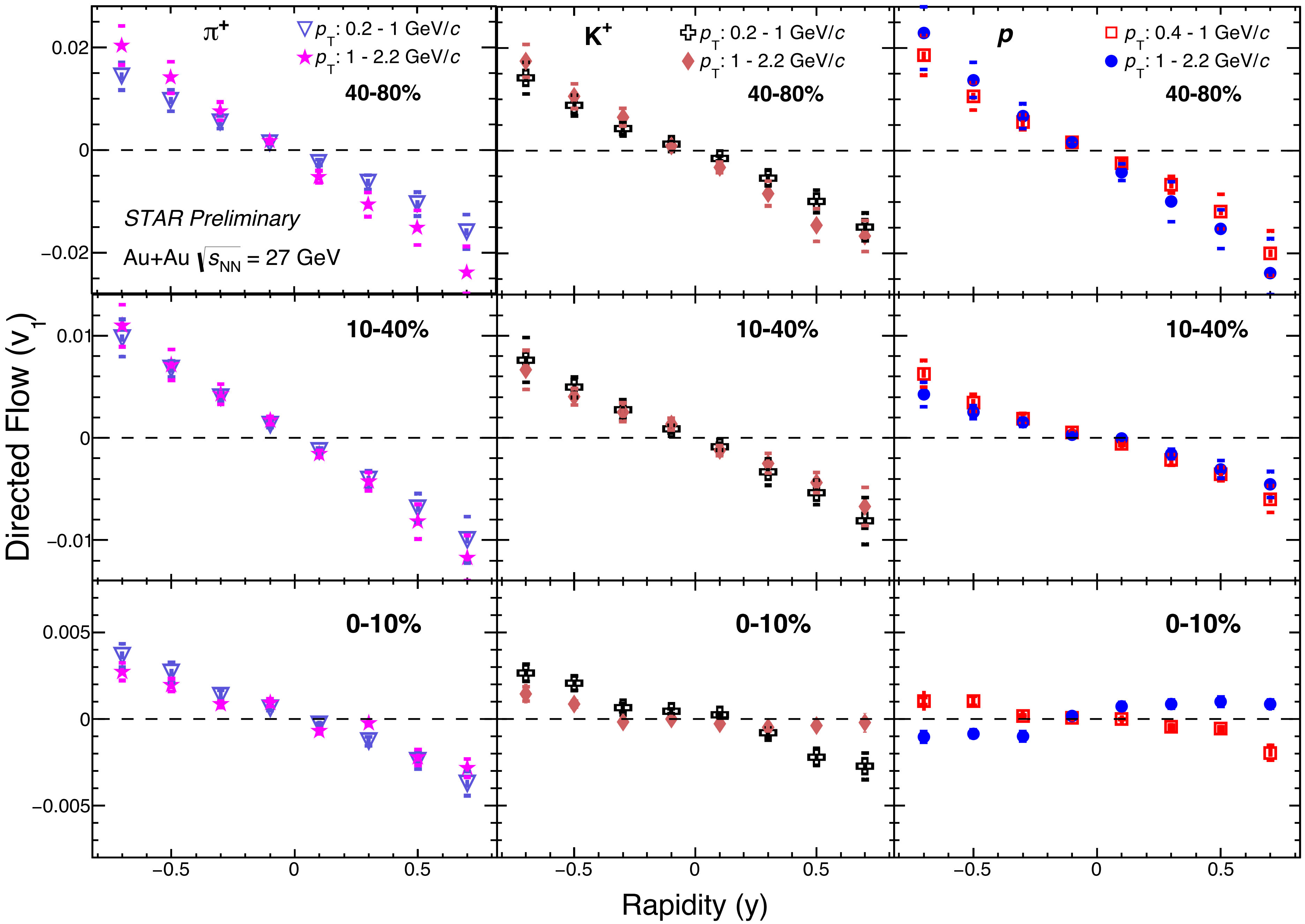
    → p_T dependent v_1 of identified hadrons
- **Initial Conditions**
  - *Understanding initial state*

    →Energy and centrality dependence of v_1 of identified hadrons (π, K, and $\bar{p}$)



STAR: Phys. Rev. Lett. 112,162301 (2014)

Rapidity dependence of v_1: 27 GeV



- Particle formation time is expected to be different for the hadrons at different → p_T regions:

  low-p_T : < 1 GeV/c

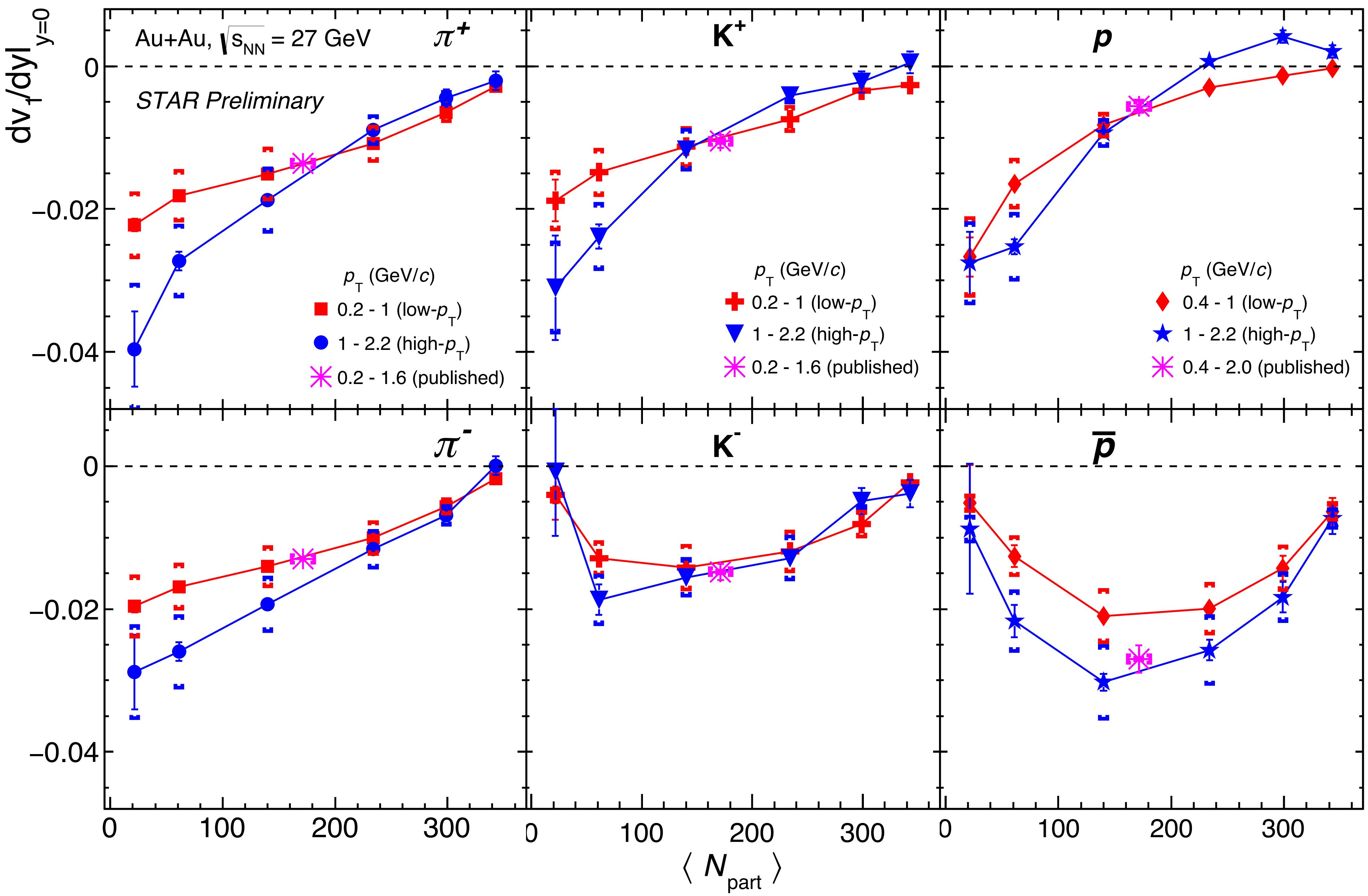
  high-p_T: $1 < p_T < 2.2$ GeV/c

- Fitting function:

$$v_1(y) = y\left[\frac{dv_1}{dy}\right] + Cy^3$$

- Anti-flow (negative slope) for measured hadrons in all centralities in both cases (low- & high-p_T)
- **Exception**: Proton for 0-10% centrality, high-p_T is having normal flow (positive slope)

Centrality dependence of dv_1/dy: 27 GeV

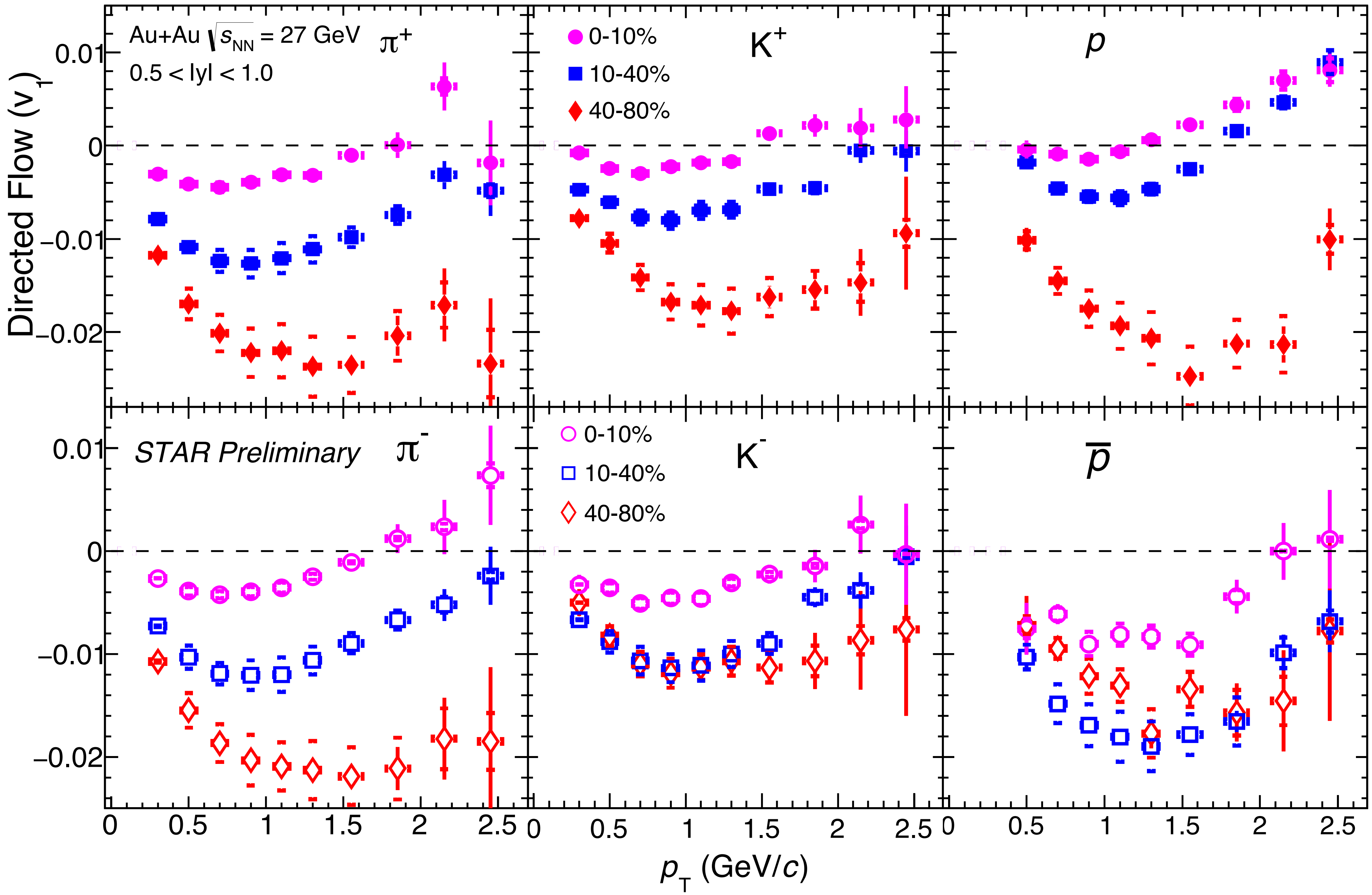


- Slope difference between low- and high-p_T is more prominent for peripheral collisions

- Monotonic (π^+, π^-, K^+ and p) and non-monotonic (K^- and $\bar{p}$) dependence with $\langle N_{part} \rangle$
- **Anti flow:** Peripheral collisions show more anti-flow than central collisions
- **Normal flow:** Proton for 0-5% and 5-10% centralities for high-p_T

STAR: Phys. Rev. Lett. 120,062301 (2018)

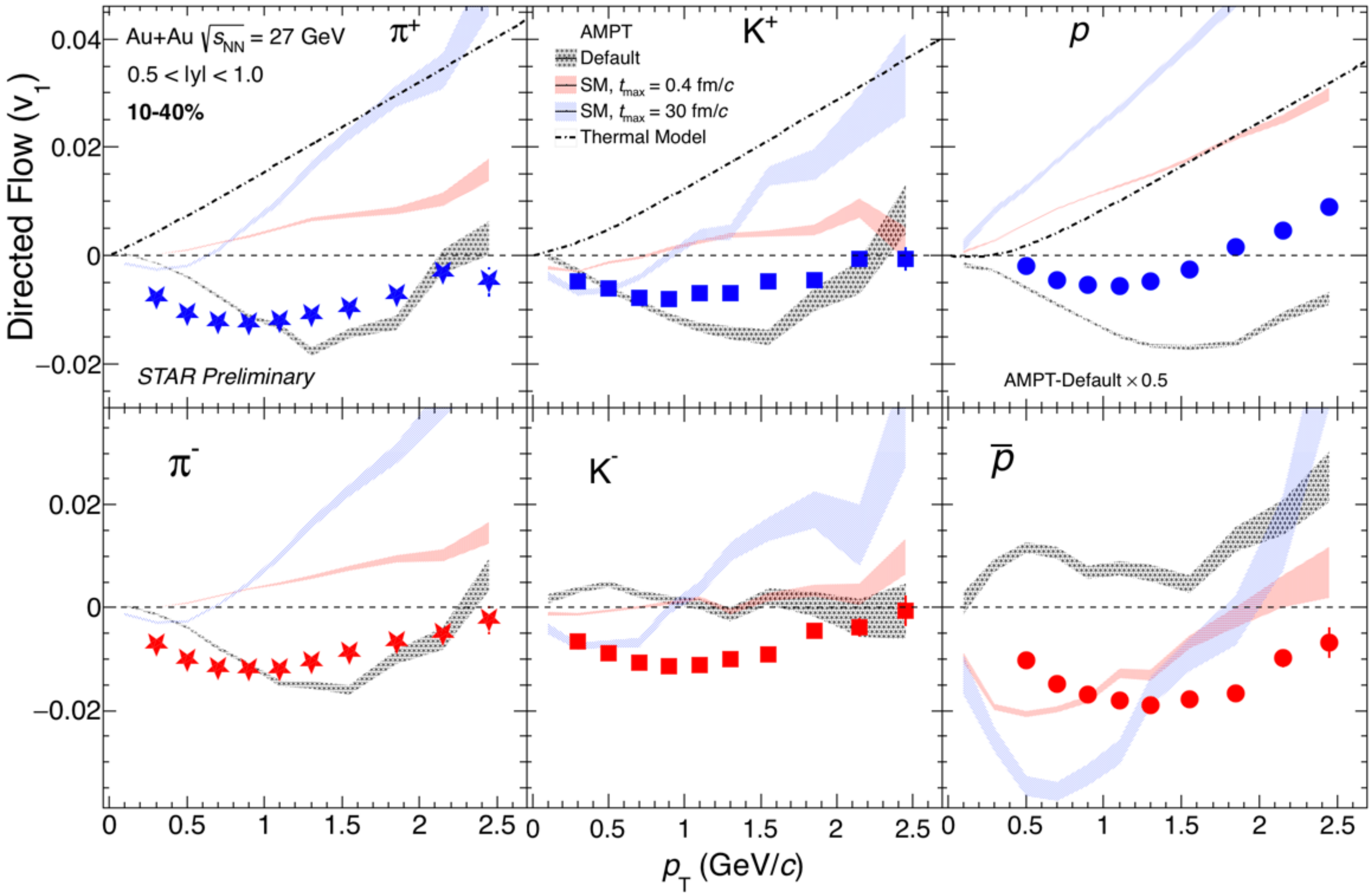
p_T & centrality dependence of v_1: 27 GeV



☑ Strong centrality dependence for π^+, K^+, p and π^- unlike K^- and $\bar{p}$

☑ Sign change for central (0-10%) collisions at high-p_T

Model comparison: 27 GeV



- **AMPT-Default**
  - → sign change for π^+, K+ and π^- unlike p, K- and $\bar{p}$
- **AMPT-SM** (σ_{pp}=1.5 mb)
  - → sign change for $\pi^{\pm}$, K± and $\bar{p}$ (except p)
- Produced particle (K-, $\bar{p}$)
  - → **Quark Coalescence**
- Finite nuclear thickness in **AMPT-Default** is incorporated partially

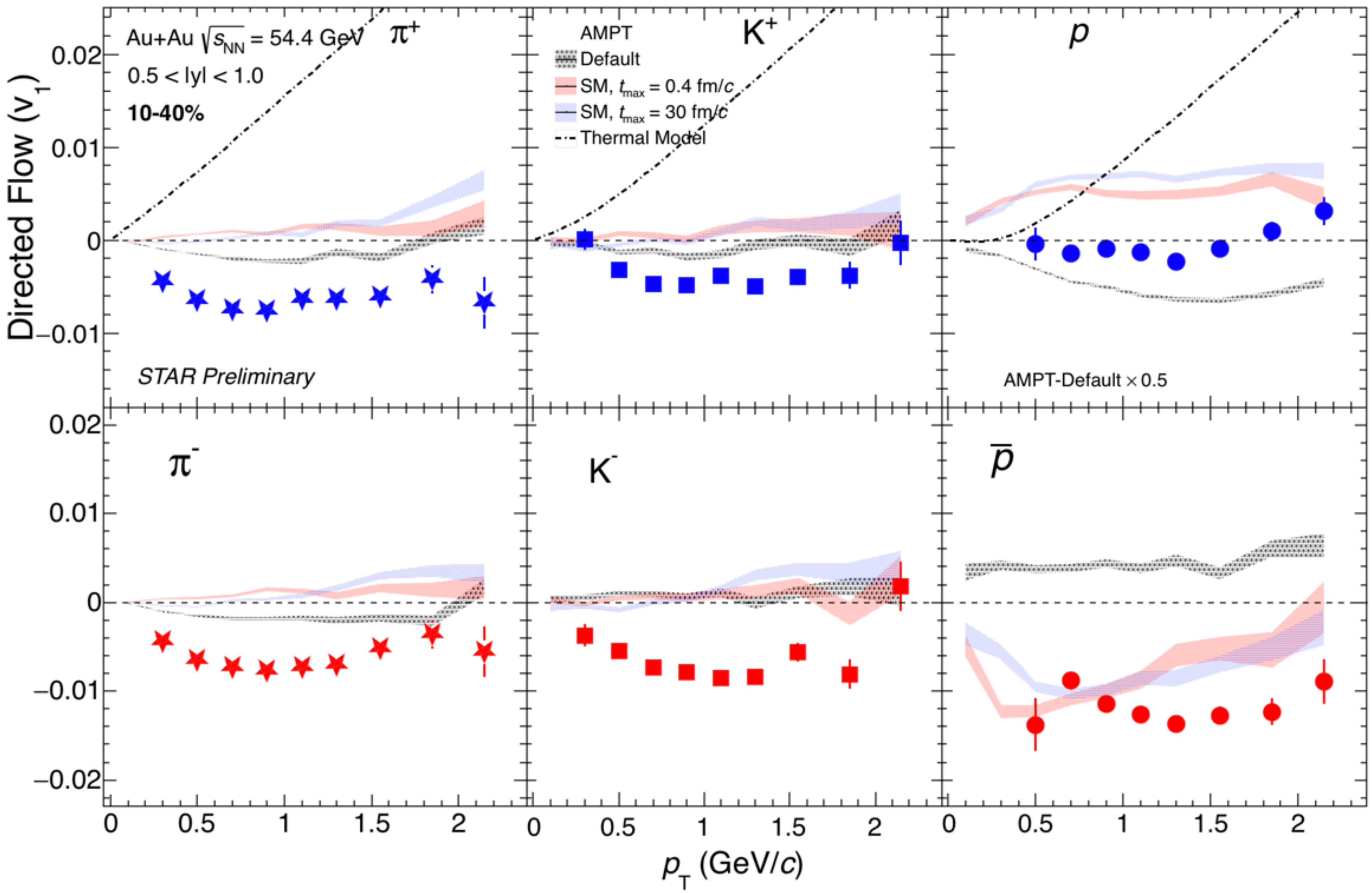
★ Thermal Model : $v_1(p_T) = \frac{p_T \beta_a}{2T}\left(1 - \frac{m\beta_0}{p_T}\frac{I_1(\zeta)}{I_0(\zeta)}\right);\ \zeta = \frac{\beta_0 p_T}{T}$

→ It predicts positive v_1 at all p_T for pion, kaon and proton

Explanation of negative v_1: *Interplay of radial expansion of thermalized source and the directed flow*
→*Particles moves in opposite to flow direction*

AMPT: K. Nayak, *et. al* Phys. Rev. C 100, 054903 (2019)
S. A. Voloshin, Phys. Rev. C 55, R1630 (R) (1997)

Model comparison: 54.4 GeV



☑ **AMPT-Default**
→ sign change for π^+, K+ and π^- unlike p, K- and $\bar{p}$

☑ **AMPT-SM** (σ_{pp}=1.5 mb)
→ sign change for $\pi^\pm$, $K^\pm$ and $\bar{p}$ (except p)

☑ Produced particle (K-, $\bar{p}$)
→ **Quark Coalescence**

☑ Finite nuclear thickness in **AMPT-Default** is incorporated partially

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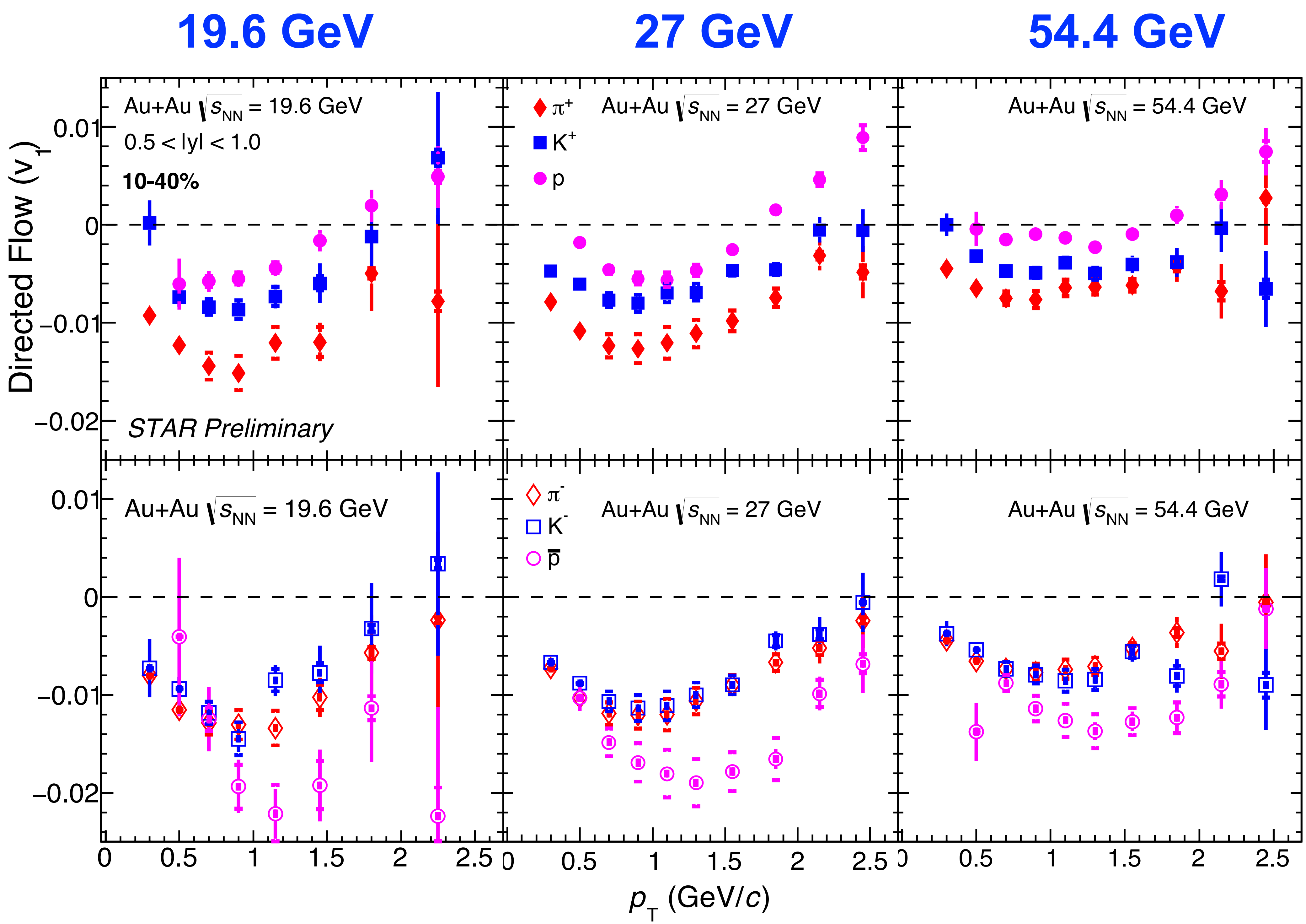
v_1 vs p_T: Energy dependence

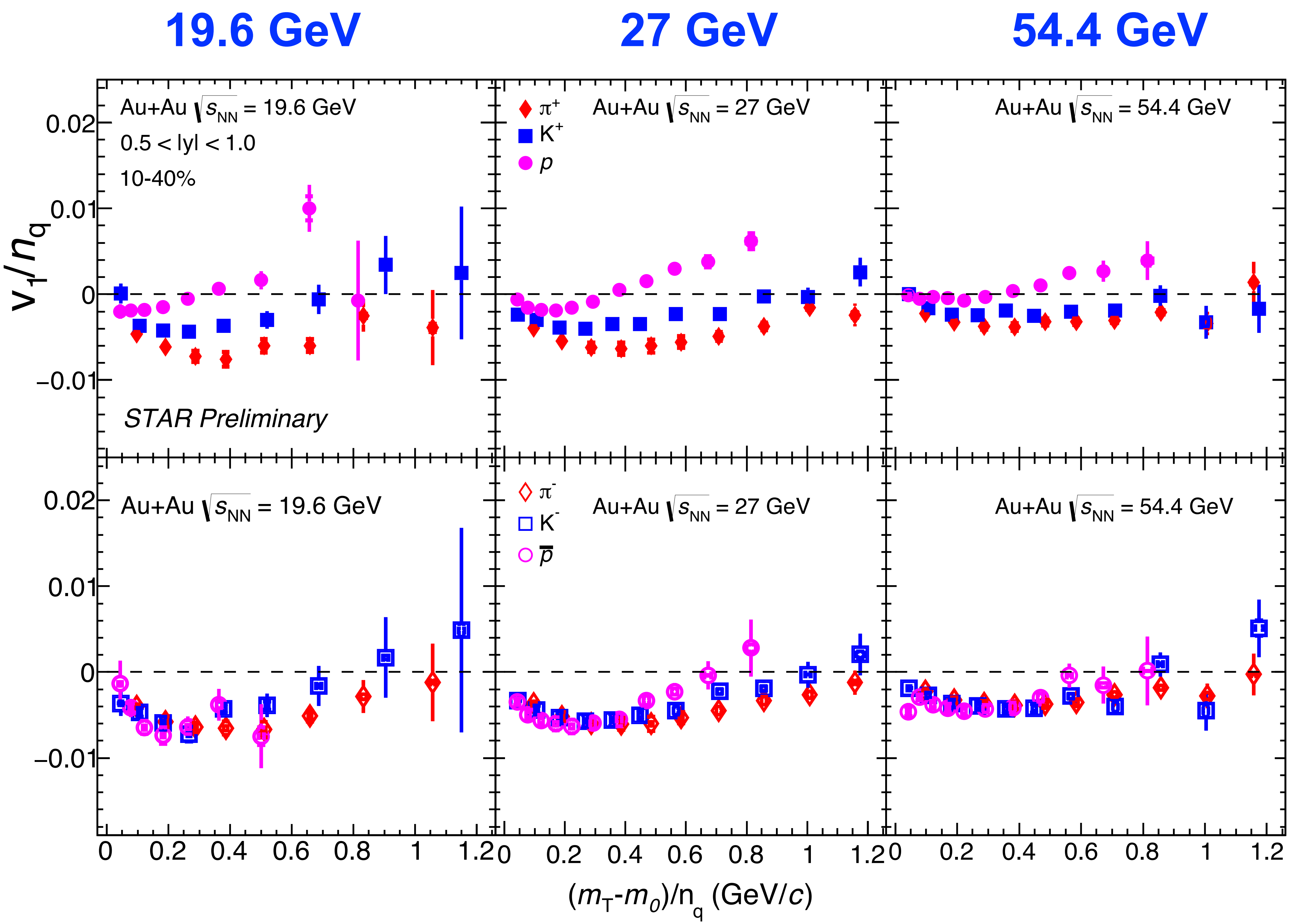


- v_1-slope becomes more negative as collision beam energy decreases
  → **Shadowing (or absorption)**

- Mass dependence for particles (π^+, K^+, p) at all observed energies
- Baryon-meson separation for anti-particles π^-, K^- and $\bar{p}$

R.J.M. Snellings *et al.*
Phys. Rev. Lett. 84, 2803-2805 (2000)

Testing of coalescence sum rule

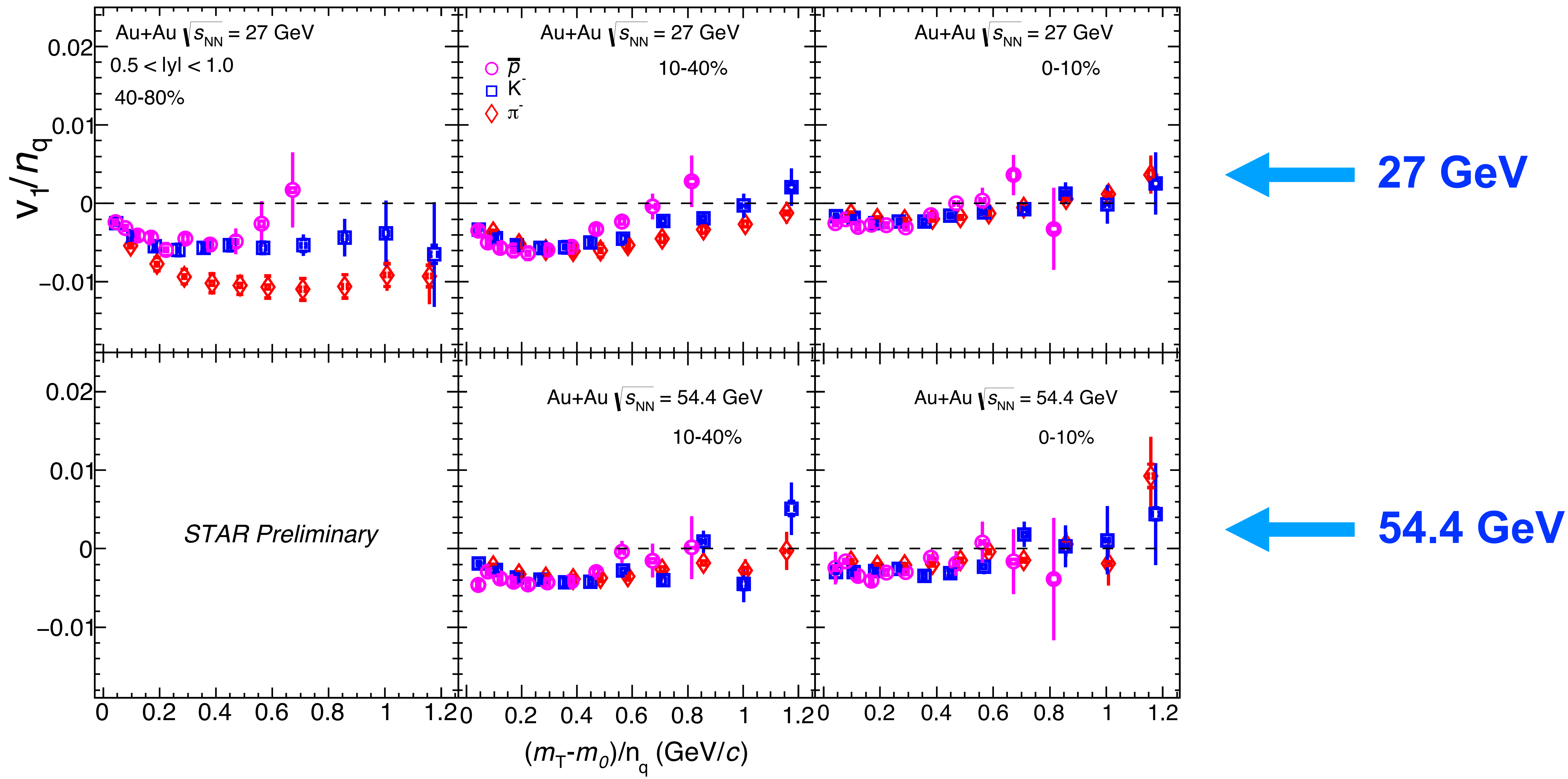


- **p, K+ and pions :**
  Transported + Produced
  → No NCQ scaling
- **Anti-proton and K- :**
  Produced
  → NCQ scaling

- Number of Constituent Quark (NCQ) scaling holds best at low m_T for $\bar{p}$, K^- and π^- in all three energies

→ **Quark Coalescence**

Centrality dependence of NCQ scaling



☑ NCQ scaling is observed at low-m_T for produced hadrons ($\bar{p}$ and K^-) in all measured centralities at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV

Summary

- Stronger p_T dependence for heavier hadrons. The produced hadrons show better NCQ scaling → **Coalescence is important for produced hadrons**

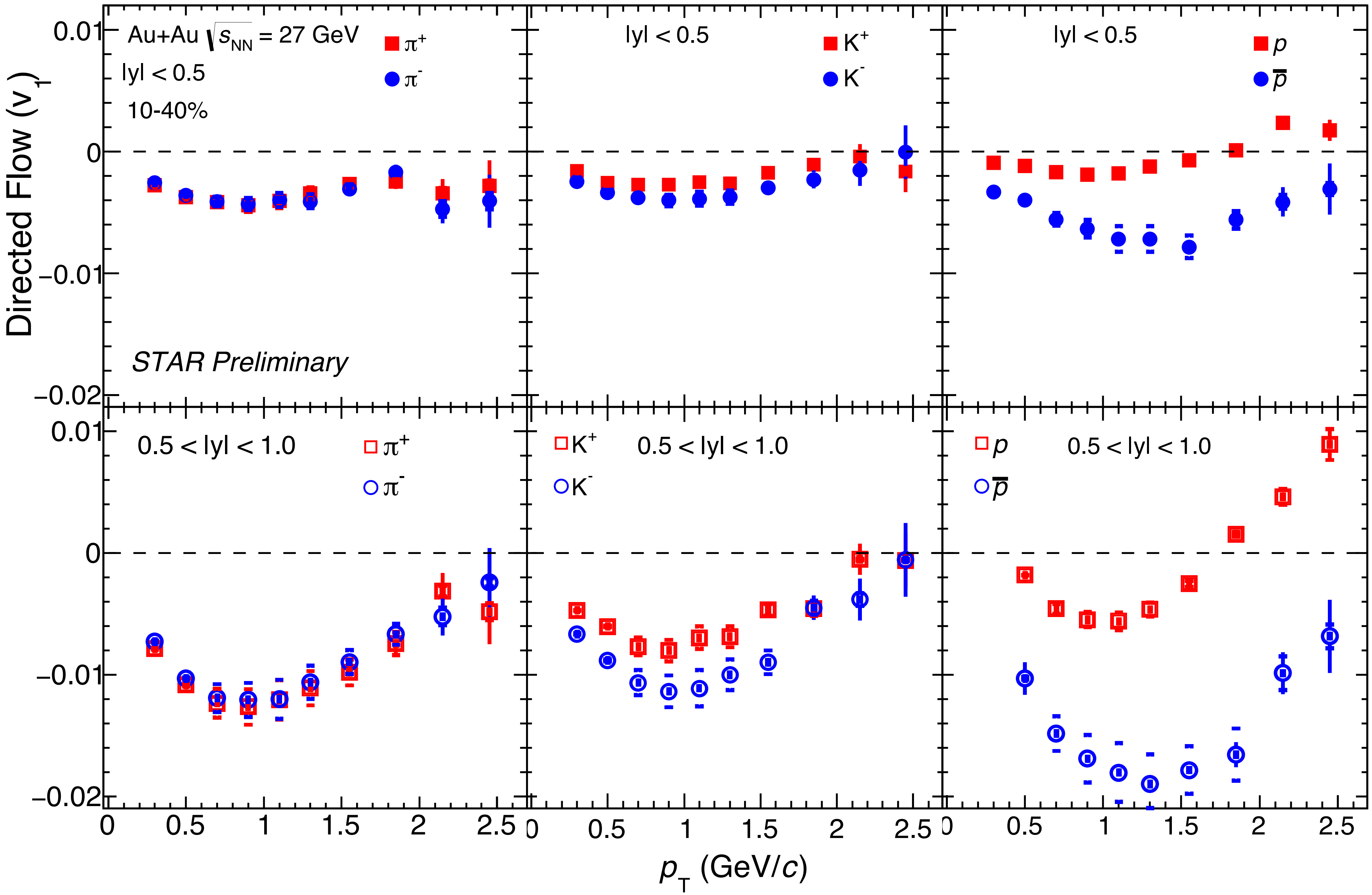
- v_1 slope becomes more negative as $\sqrt{s_{NN}}$ decreases, within 54.4 to 19.6 GeV
  → **Shadowing** (or absorptions) becomes more important in the system with lower $\sqrt{s_{NN}}$
  → Strong centrality dependence of v_1 slope of hadrons (except produced hadrons)
  → Slope difference between low- & high-p_T is more prominent for peripheral collisions

- **AMPT-Default** model explains the data reasonably well except for $\bar{p}$
  → Possibly because of partial incorporation of the finite nuclear thickness in AMPT-Default
- **AMPT-SM** well predicts the sign change for produced hadrons like K^- and $\bar{p}$.
  → Finite nuclear thickness is yet to be included in AMPT-SM.

Thank you!

Backup

p_T dependence of v_1: 27 GeV



- ☑ Larger difference between p and $\bar{p}$ compare to K^+ and K^-
  - *Might be due to transported quarks contribution*
- ☑ π^+ and π^- are consistent and it is similar to p_T-integrated