
Directed and elliptic flow of identified hadrons, high- p_T charged hadrons and light nuclei in Au+Au collisions at STAR

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Outline

☑ Motivation

☑ The STAR experiment

☑ Results

◎ Low p_T :

➤ Directed and elliptic flow of identified hadrons and deuteron

◎ High p_T :

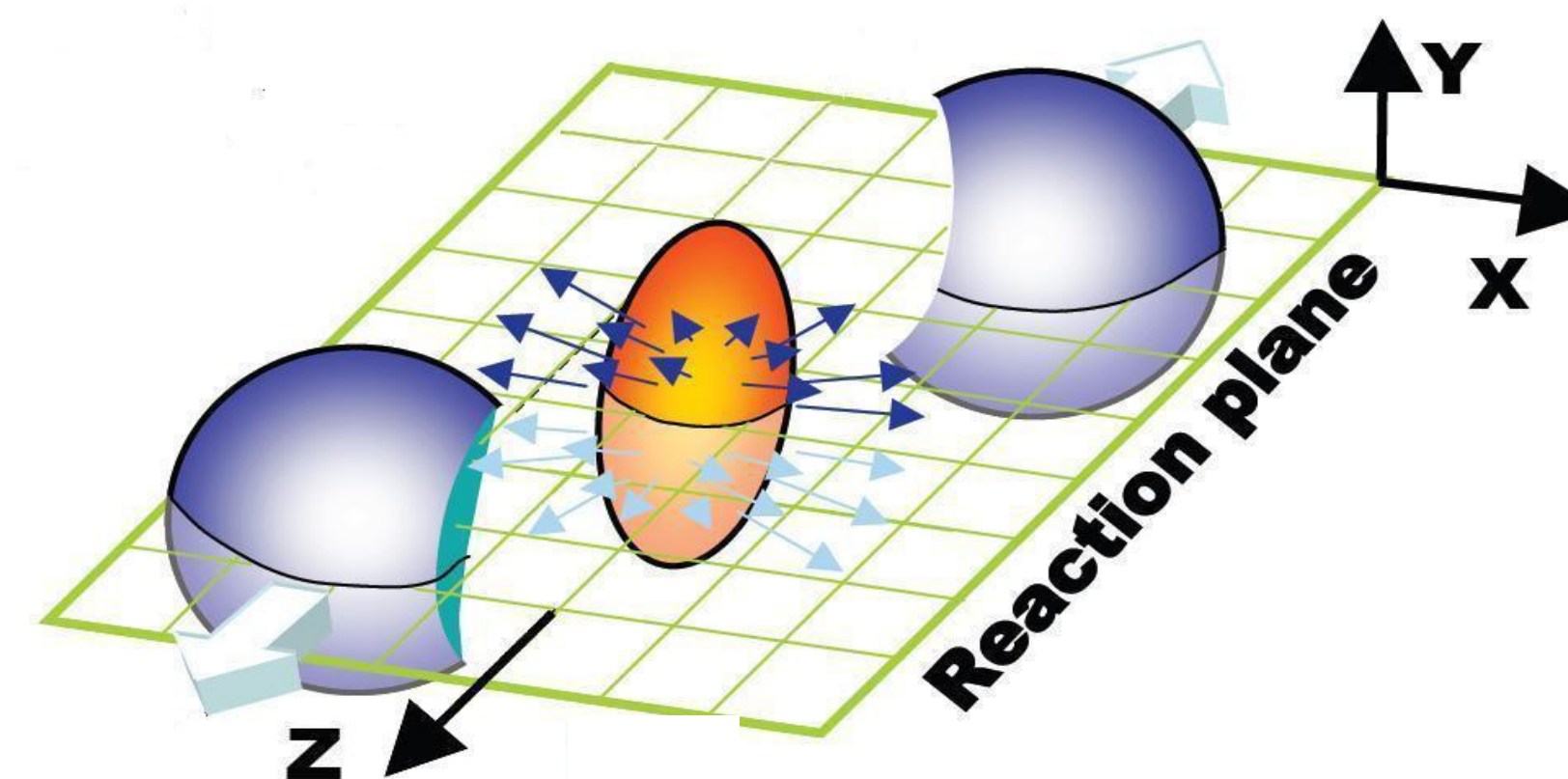
➤ Directed flow of charged hadrons

☑ Summary

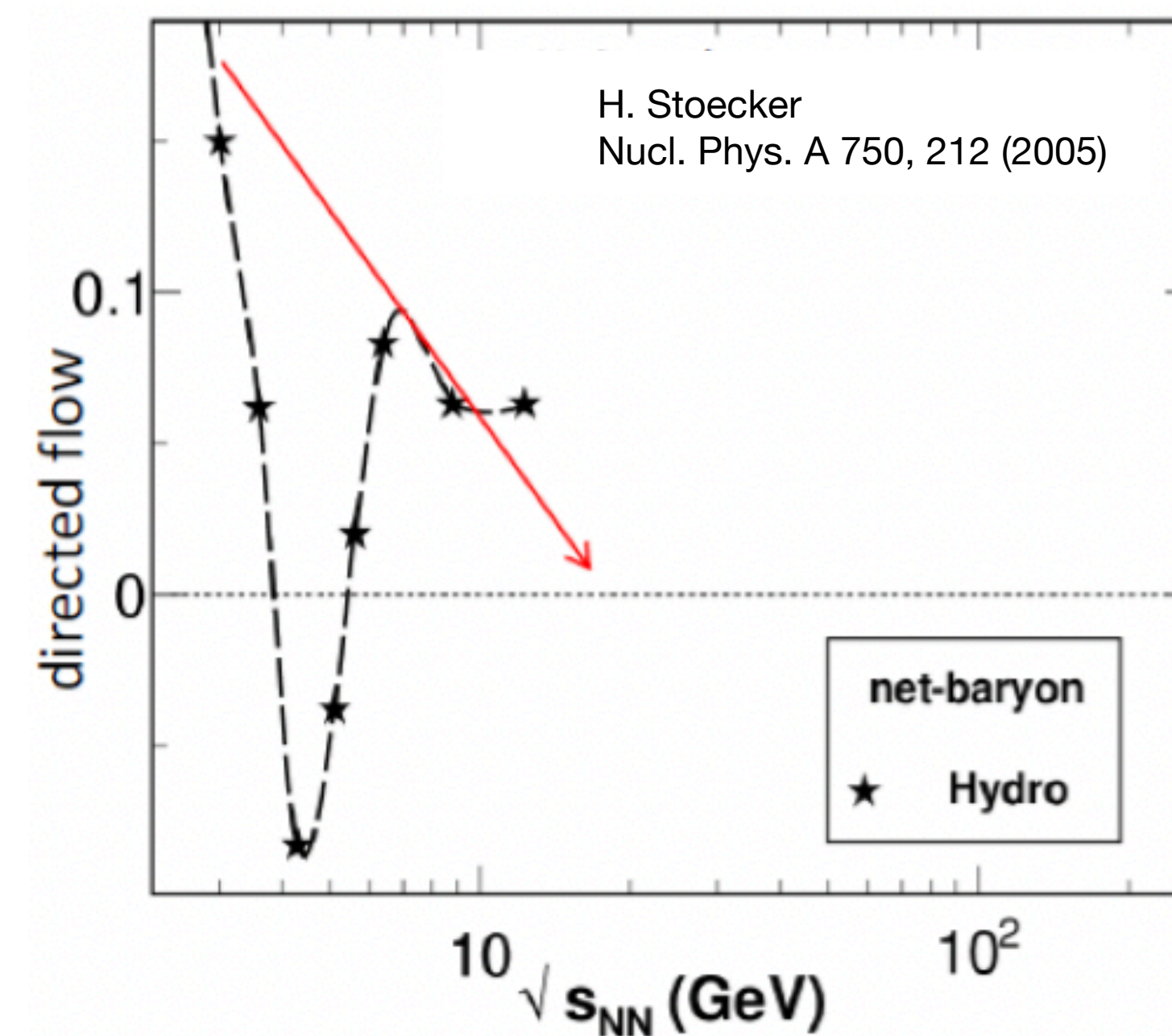
$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1} v_n \cos[n(\phi - \Psi_n)]$$

$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$$

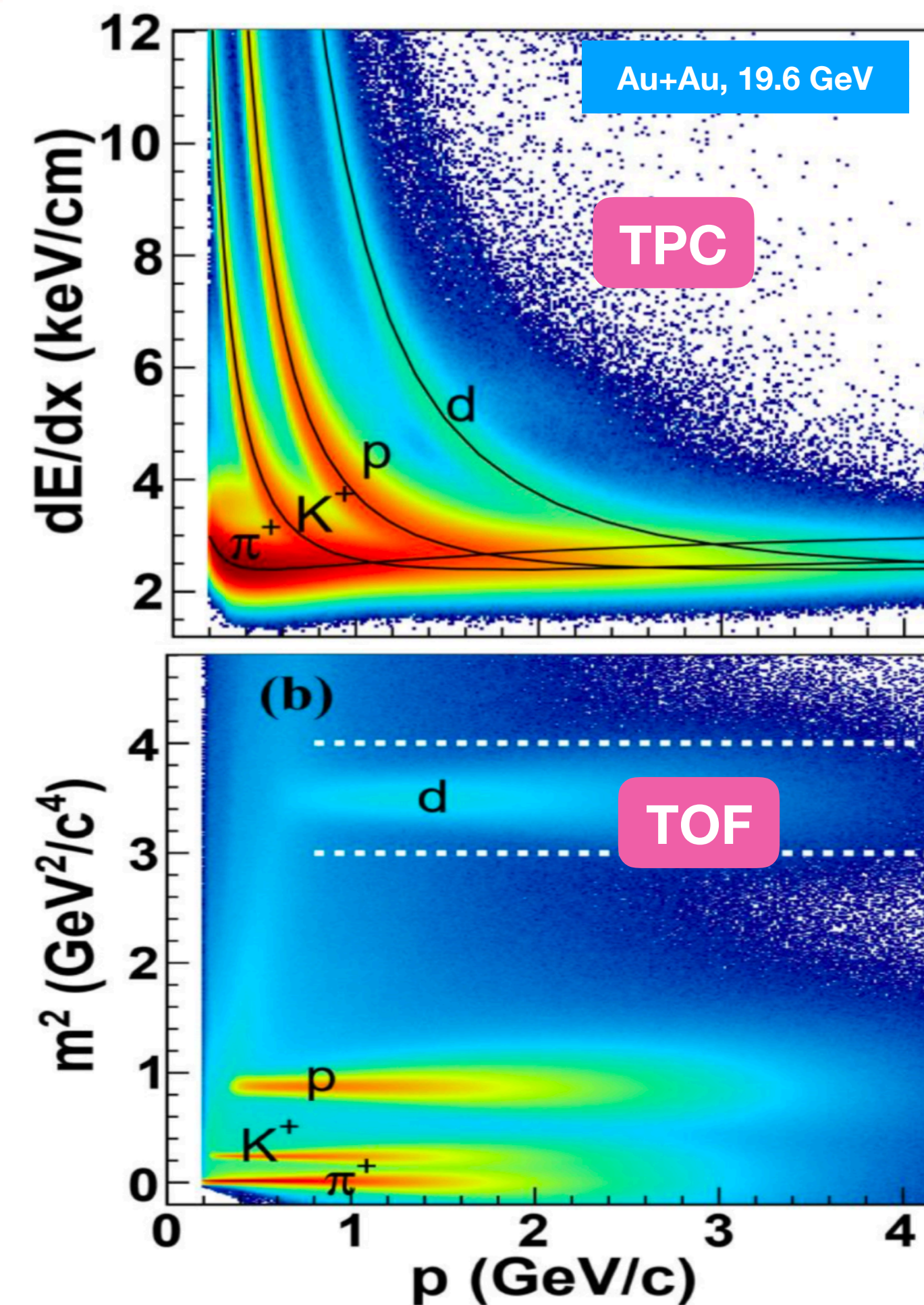
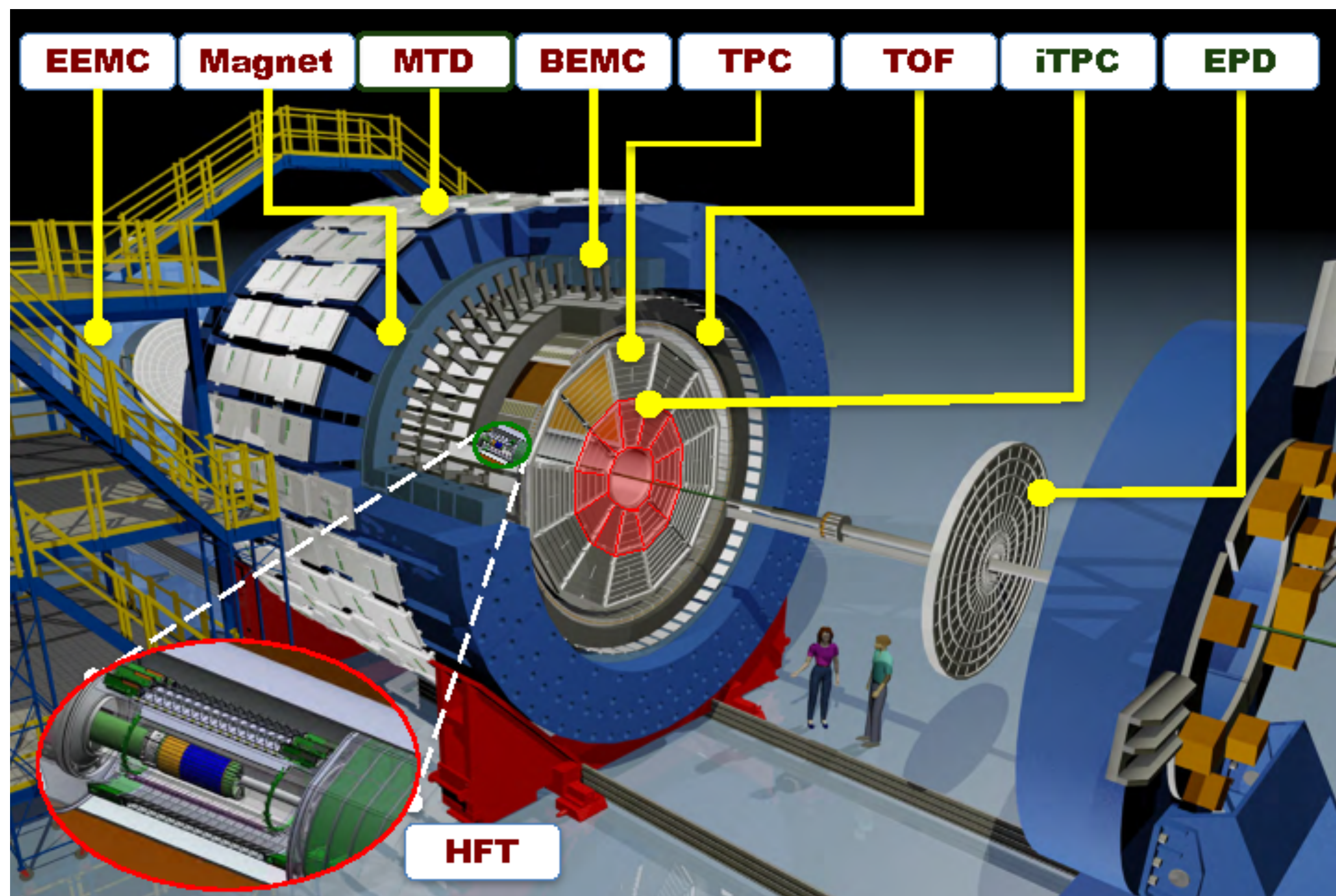
v_1 = Directed flow, v_2 = Elliptic flow



- ✓ Probes early stage of **collision dynamics**
- ✓ Hydrodynamics: EoS assuming the **1st-order PT**
 - Dip ("**Softest Point**") in v_1 vs $\sqrt{s_{NN}}$
 - Sensitive to **pressure**, Equation of State (EoS)



The STAR detector



- **Beam-Beam Counter (BBC)** [$3.3 < |\eta| < 5.0$]: 1st-order event plane for 54.4 GeV
- **Zero Degree Calorimeter ShowerMax Detector**: 1st-order event plane for 200 GeV
- **Event Plane Detector (EPD)** [$2.1 < |\eta| < 5.1$]: 1st-order event plane for 27 GeV
- **Time Projection Chamber** [$|\eta| < 1$] (TPC): 2nd-order event plane

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

| | Probes | Energy (GeV) | Analysis |
|------------|---------------------------|--------------|------------|
| Low p_T | Deuteron | 7.7 – 19.6 | v_1 |
| | Identified Hadrons | 27, 54.4 | v_1, v_2 |
| High p_T | Charged Hadrons | 200 | v_1 |

✓ Identified hadrons v_1 : $\pi^\pm, K^\pm, p, \bar{p}, \phi$ for 54.4 GeV and 27 GeV

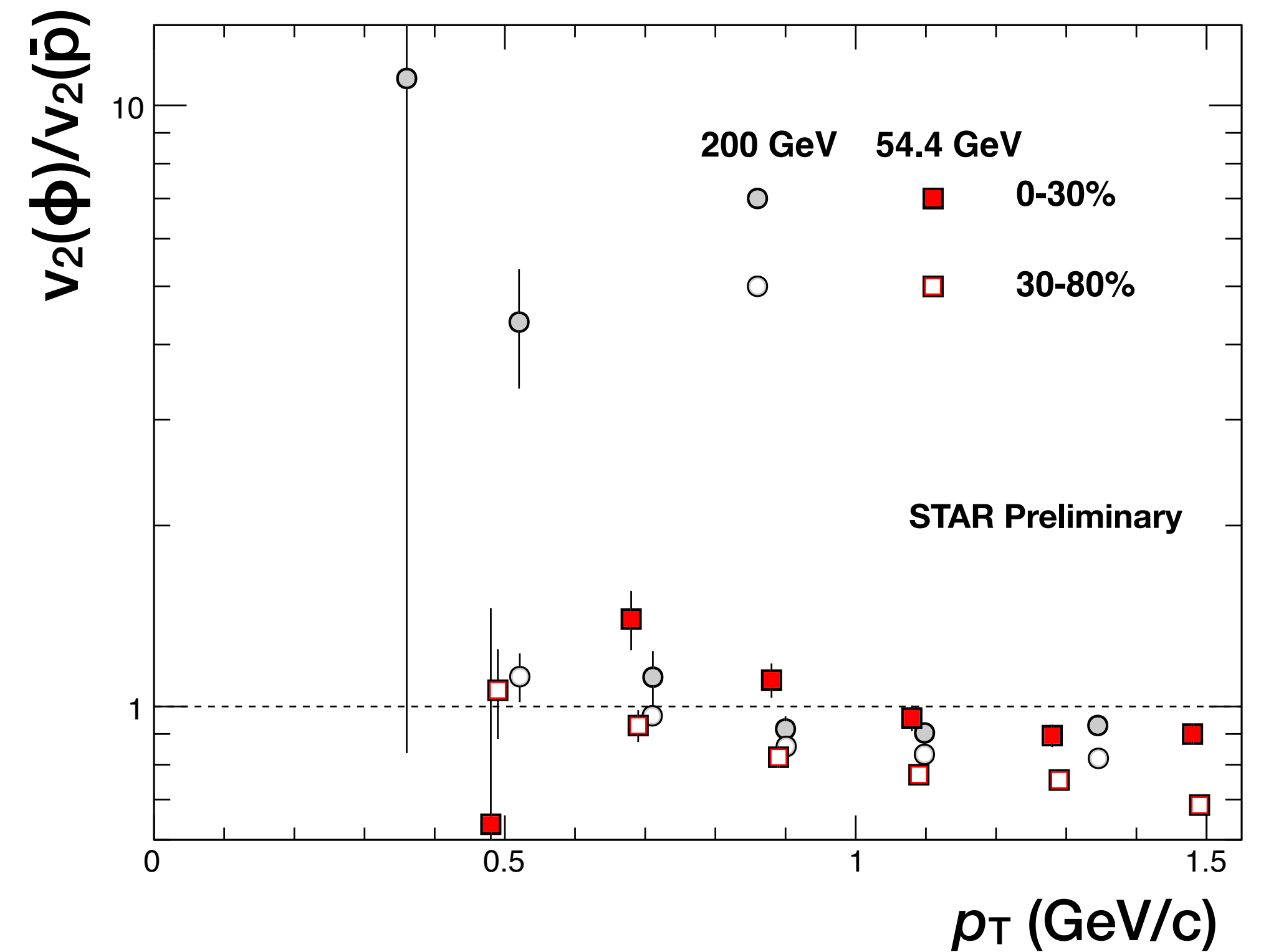
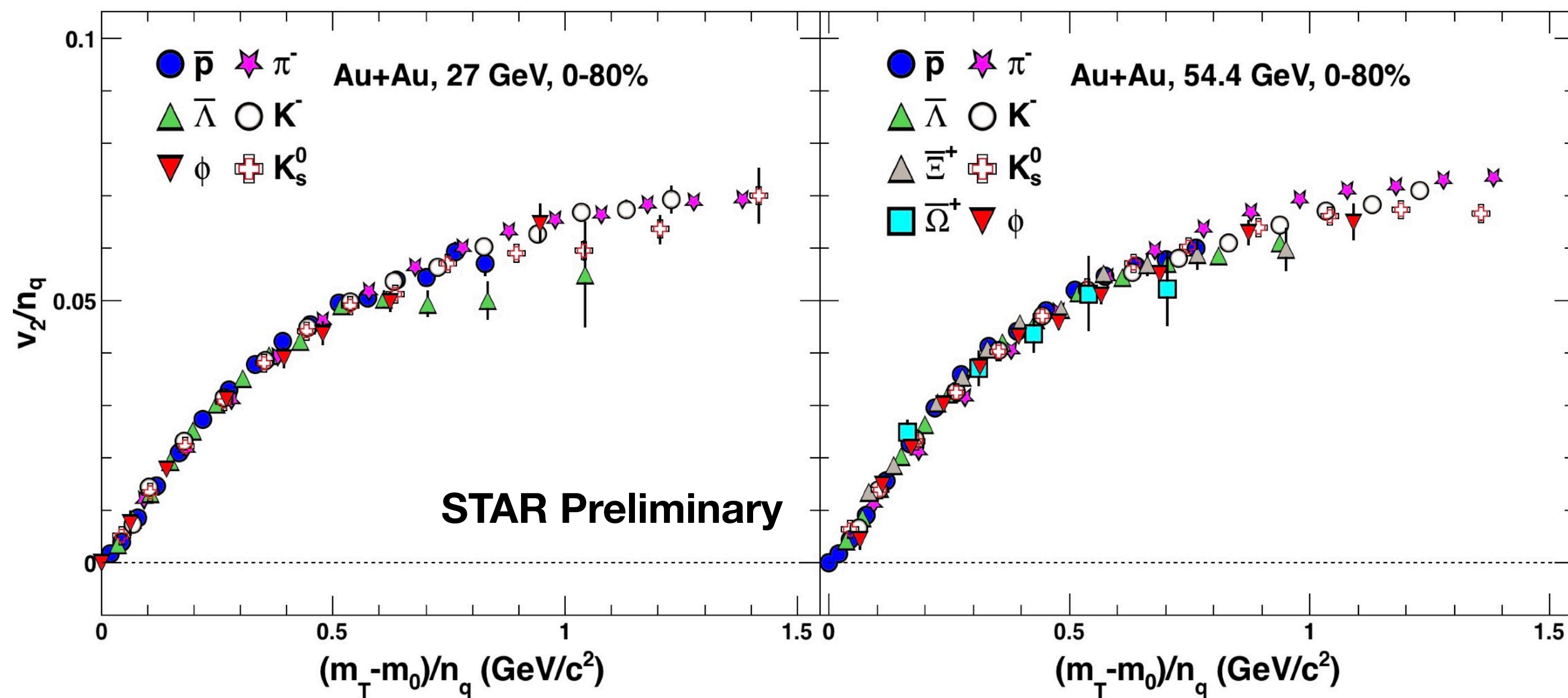
✓ Identified hadrons v_2 : $\pi^\pm, K^\pm, K_S^0, \Lambda, \bar{\Lambda}, \Xi, \bar{\Xi}, \Omega, \bar{\Omega}, p, \bar{p}, \phi$ ($\pi^\pm, K^\pm, K_S^0, \Lambda, \bar{\Lambda}, p, \bar{p}, \phi$)
for 54.4 GeV (27 GeV)



Low p_T : v_2 of identified hadrons



Testing NCQ scaling and mass ordering



✓ NCQ scaling for strange and multistrange hadrons

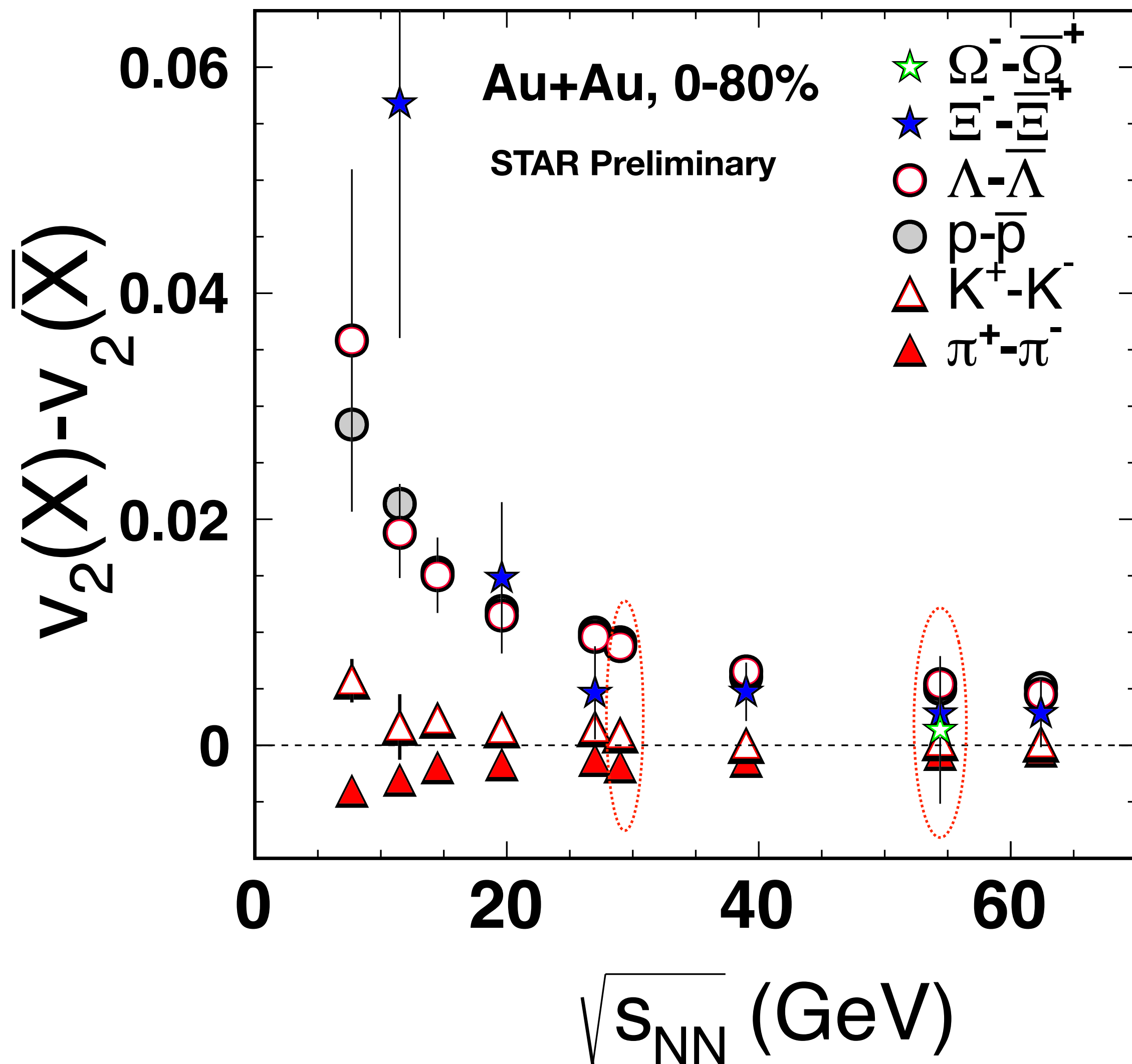
→ signature of partonic collectivity

✓ NCQ scaling is tested for Au+Au at 27 and 54.4 GeV

✓ $v_2(\phi)/v_2(\bar{p})$ ratio:

- ▶ Violation of mass ordering in central collisions at 54.4 and 200 GeV
- ▶ Energy and centrality dependence of hadronic rescattering effect

Energy dependence of $v_2(x)-v_2(\bar{x})$

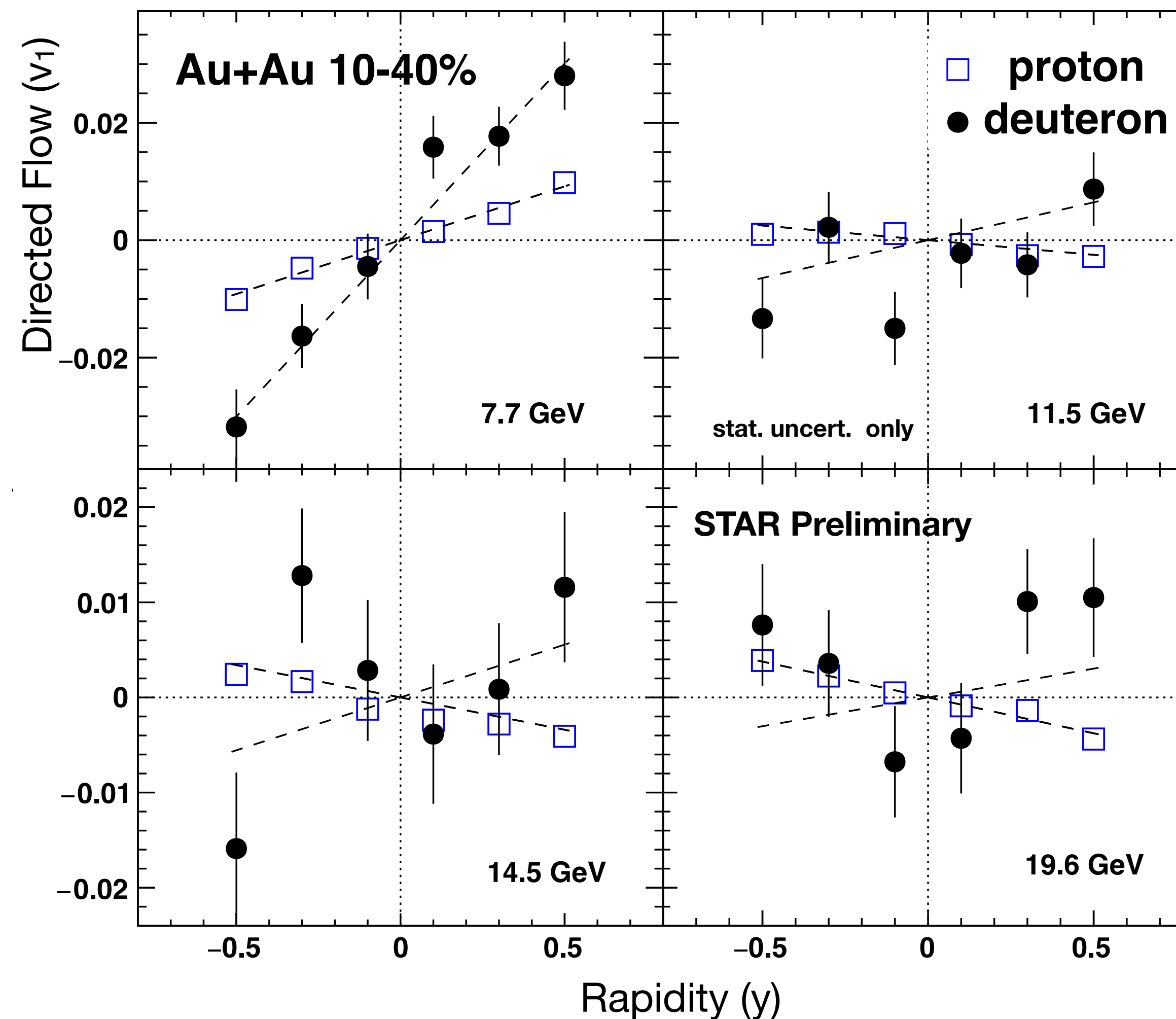
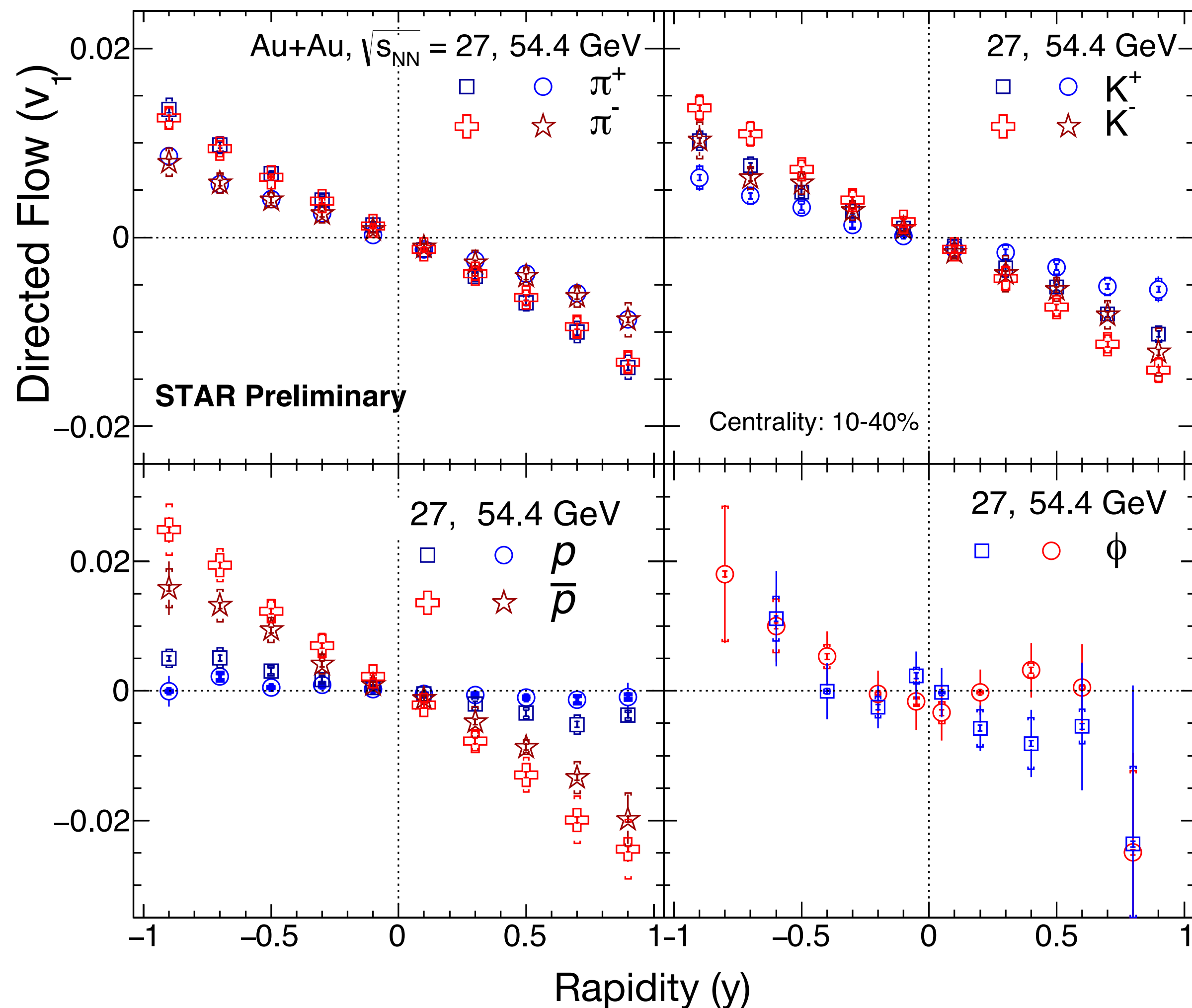


- ✓ Larger v_2 for baryons than antibaryons
- ✓ Breaking of NCQ scaling at low energy
- ✓ New measurements follow the energy trend

Low p_T :
 v_1 of identified hadrons and light nuclei



Rapidity dependence of v_1



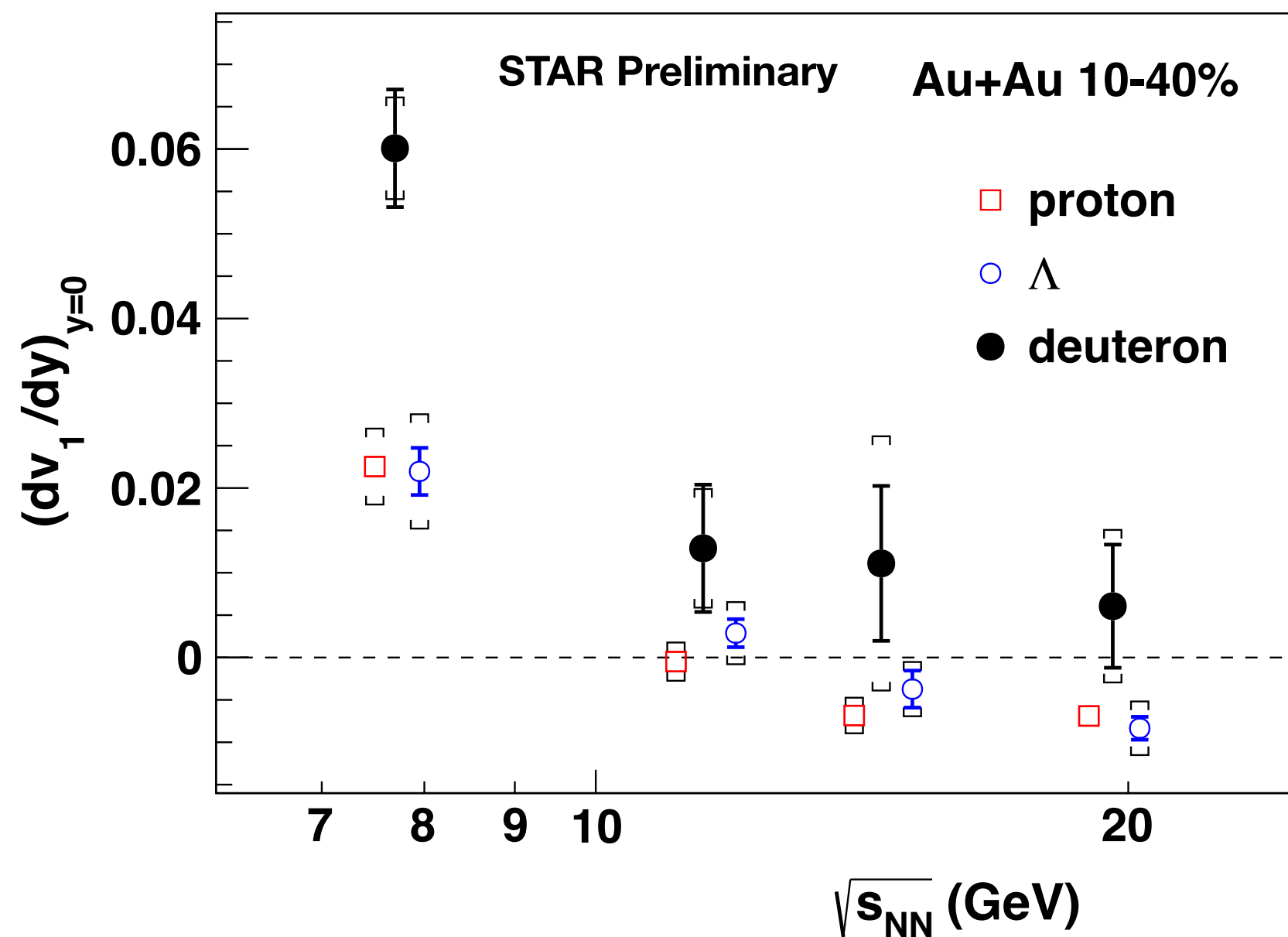
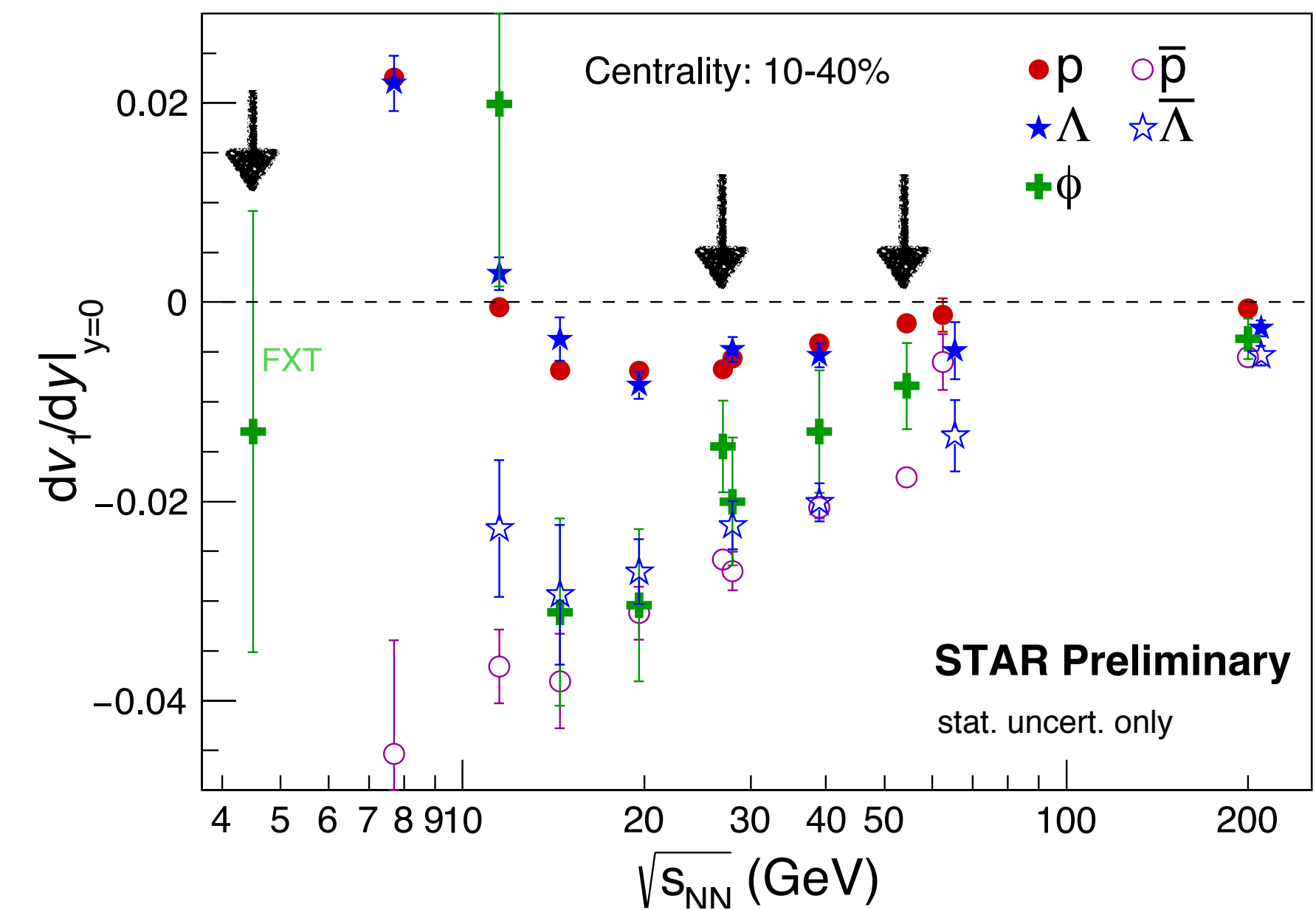
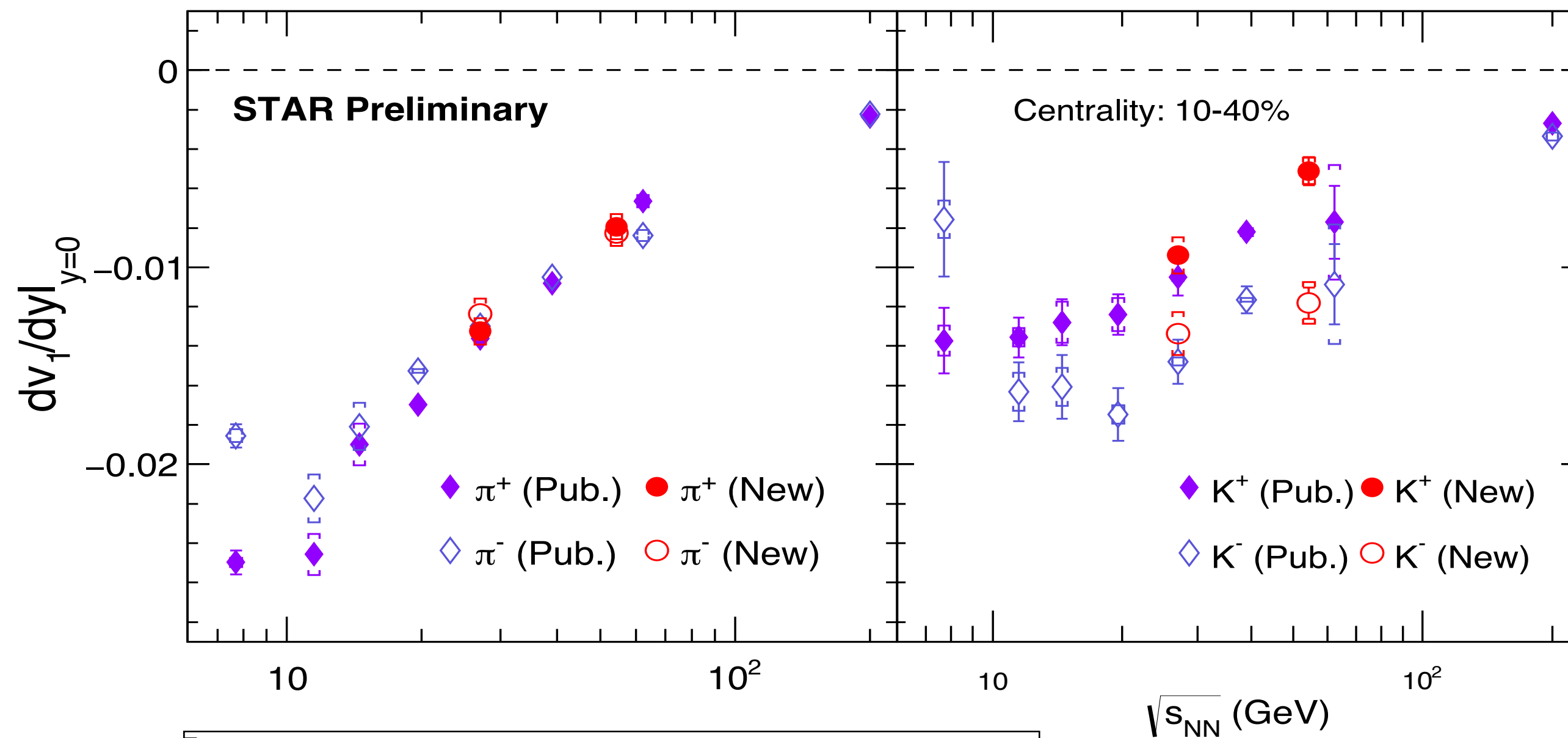
✓ v_1 vs. y is fitted with linear function, where slope = dv_1/dy

✓ The fitting range is $|y| < 0.6$ for deuterons and $|y| < 0.8$ for other hadrons

Phys. Rev. Lett. 112, 162301 (2014);
Phys. Rev. Lett. 120, 062301 (2018)



Energy dependence of dv_1/dy



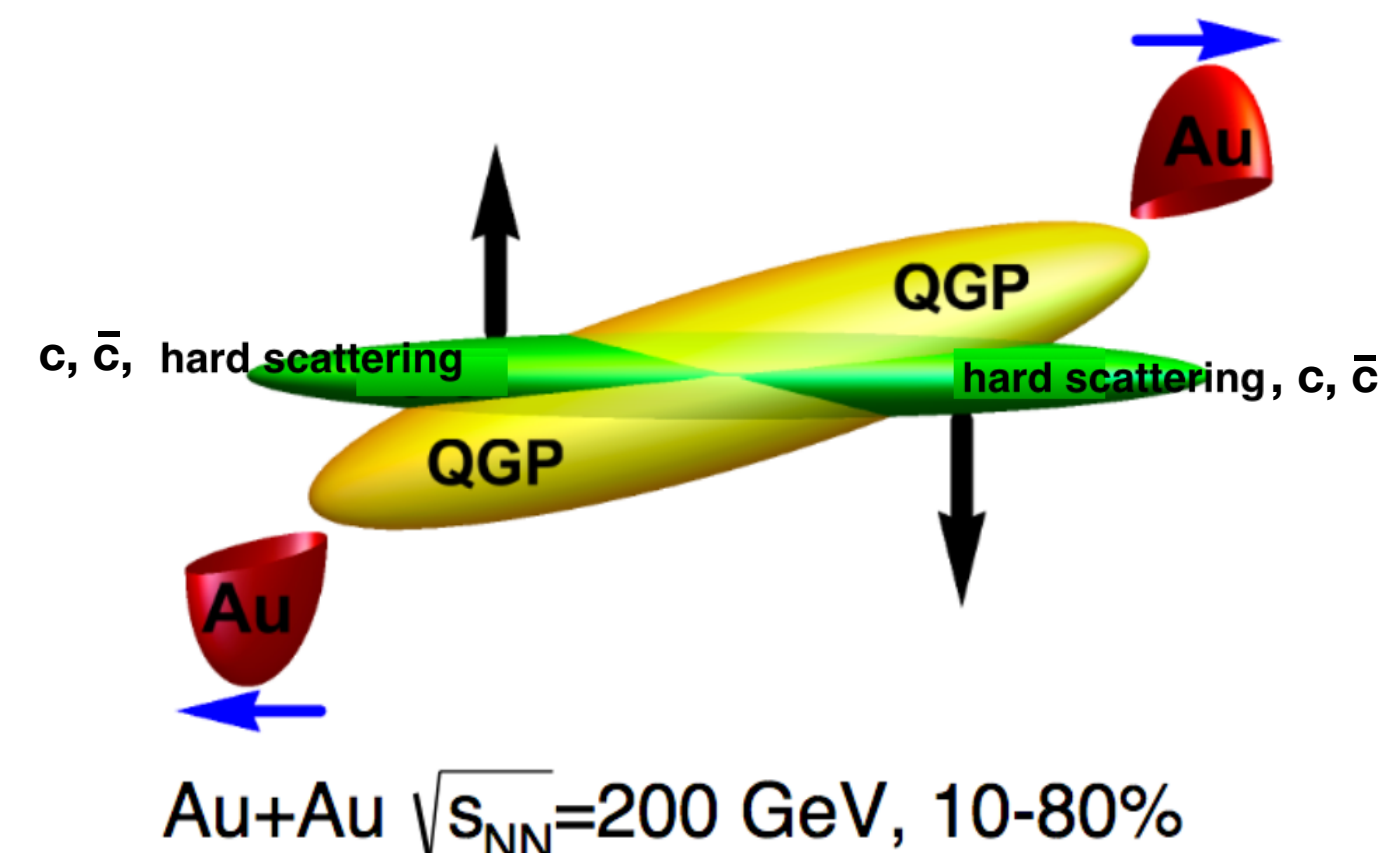
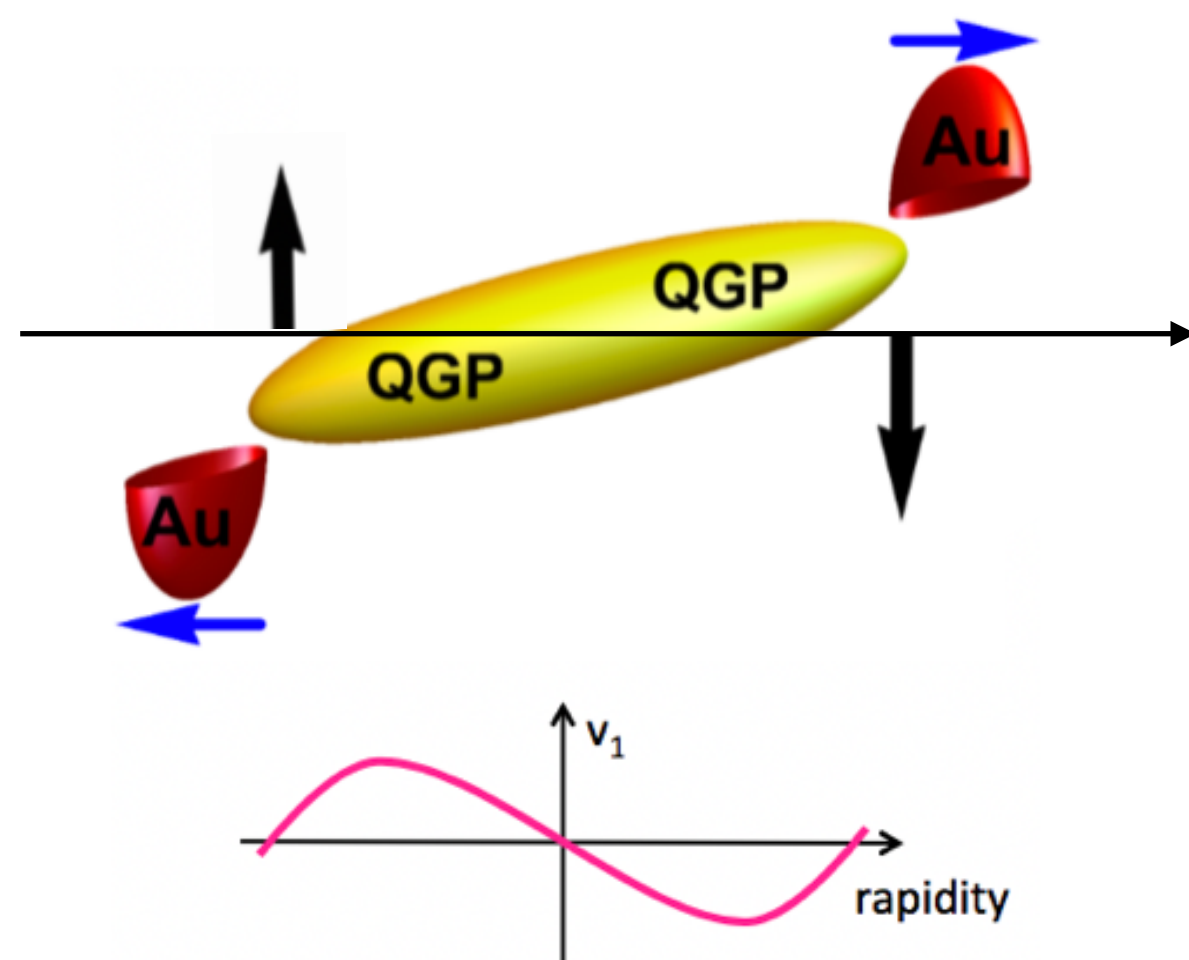
- ✓ Baryons change sign around 14.5 GeV
- ✓ Mesons and produced baryons have negative slope
- ✓ New measurements follow the energy trend
- ✓ Deuteron:
 - Positive or zero slope for all measured energies

Phys. Rev. Lett. 112, 162301 (2014)
Phys. Rev. Lett. 120, 062301 (2018)



High p_T : v_1 of charged hadrons

Motivation: v_1 of high p_T charged hadrons



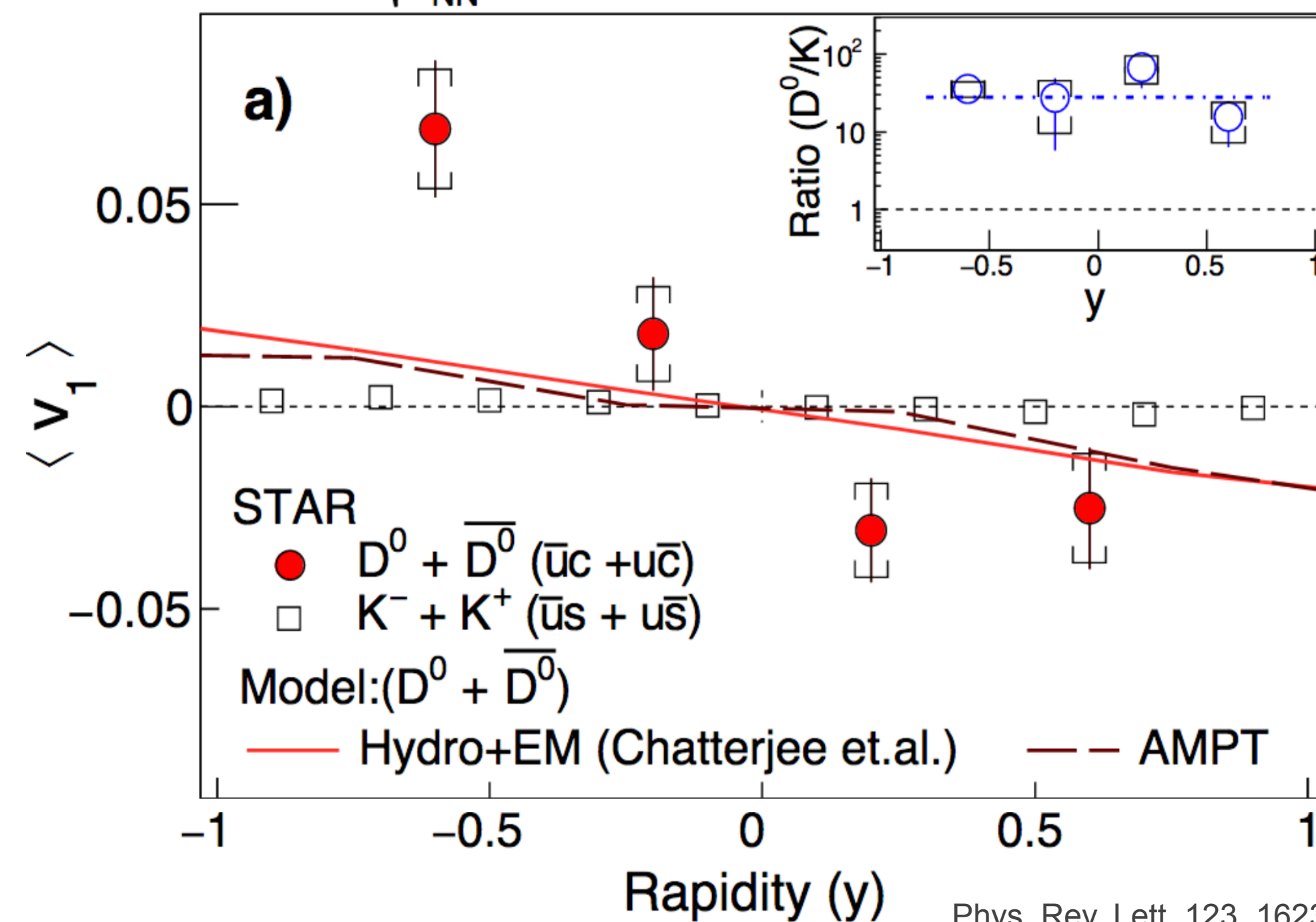
✓ QGP bulk tilted in rapidity, but hard scattering profile is symmetric

→ **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)

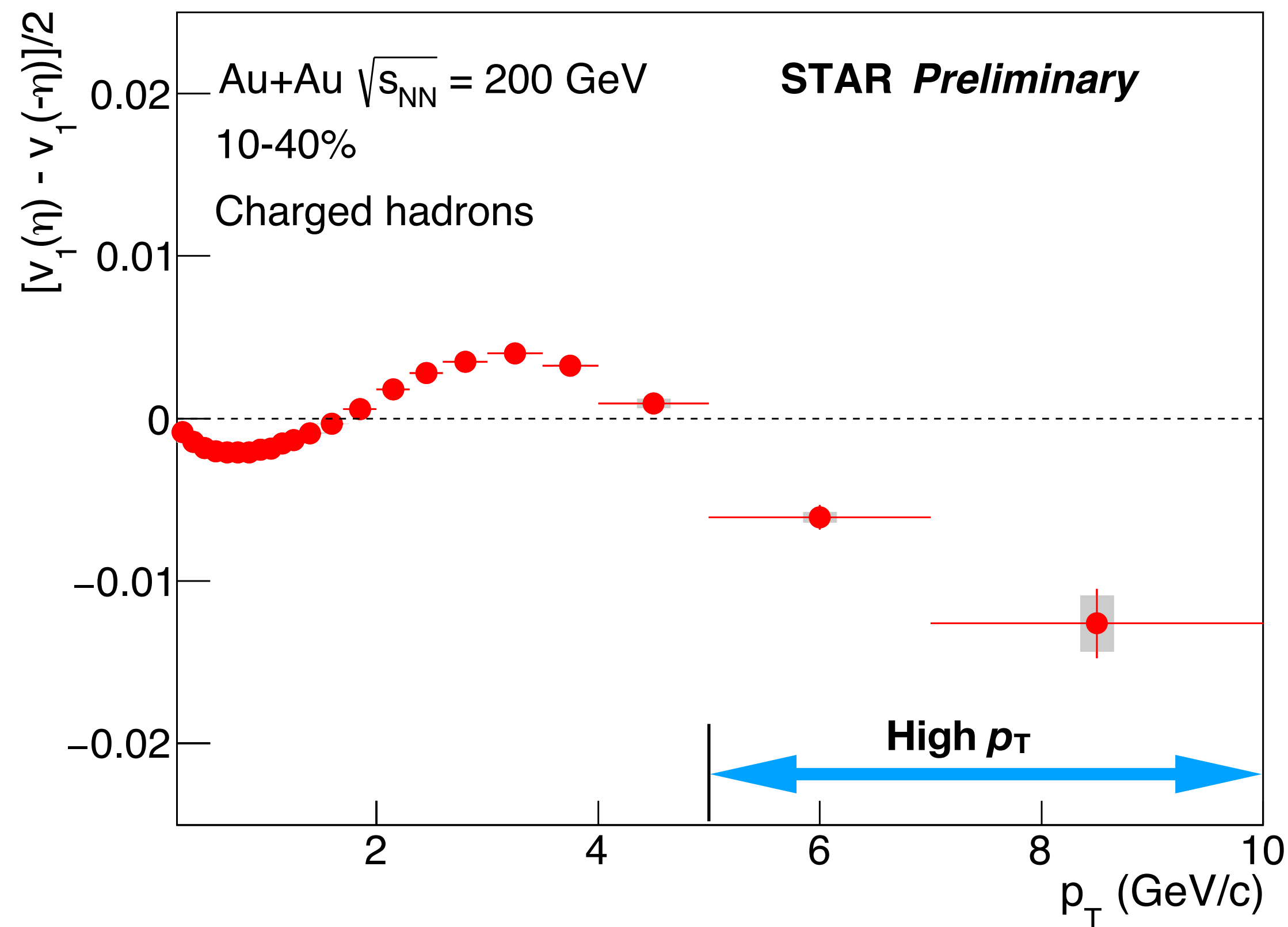
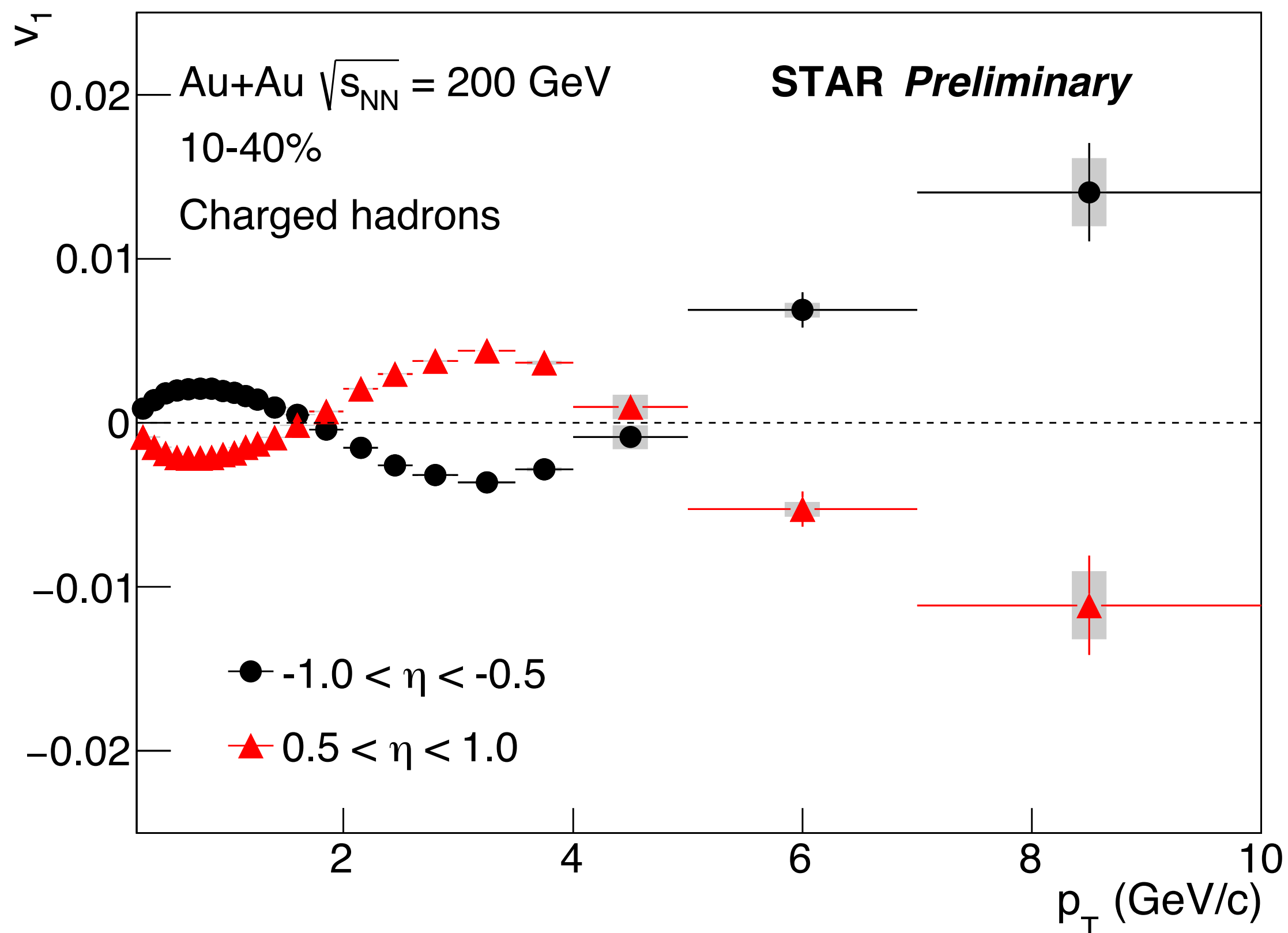
✓ Similar effect along with the drag by the bulk produces a large v_1 for D^0 meson



Phys. Rev. Lett. 123, 162301 (2019)

✓ **Probe to study path-length-dependent energy loss and initial conditions in longitudinal direction**

p_T dependence v_1 of charged hadrons

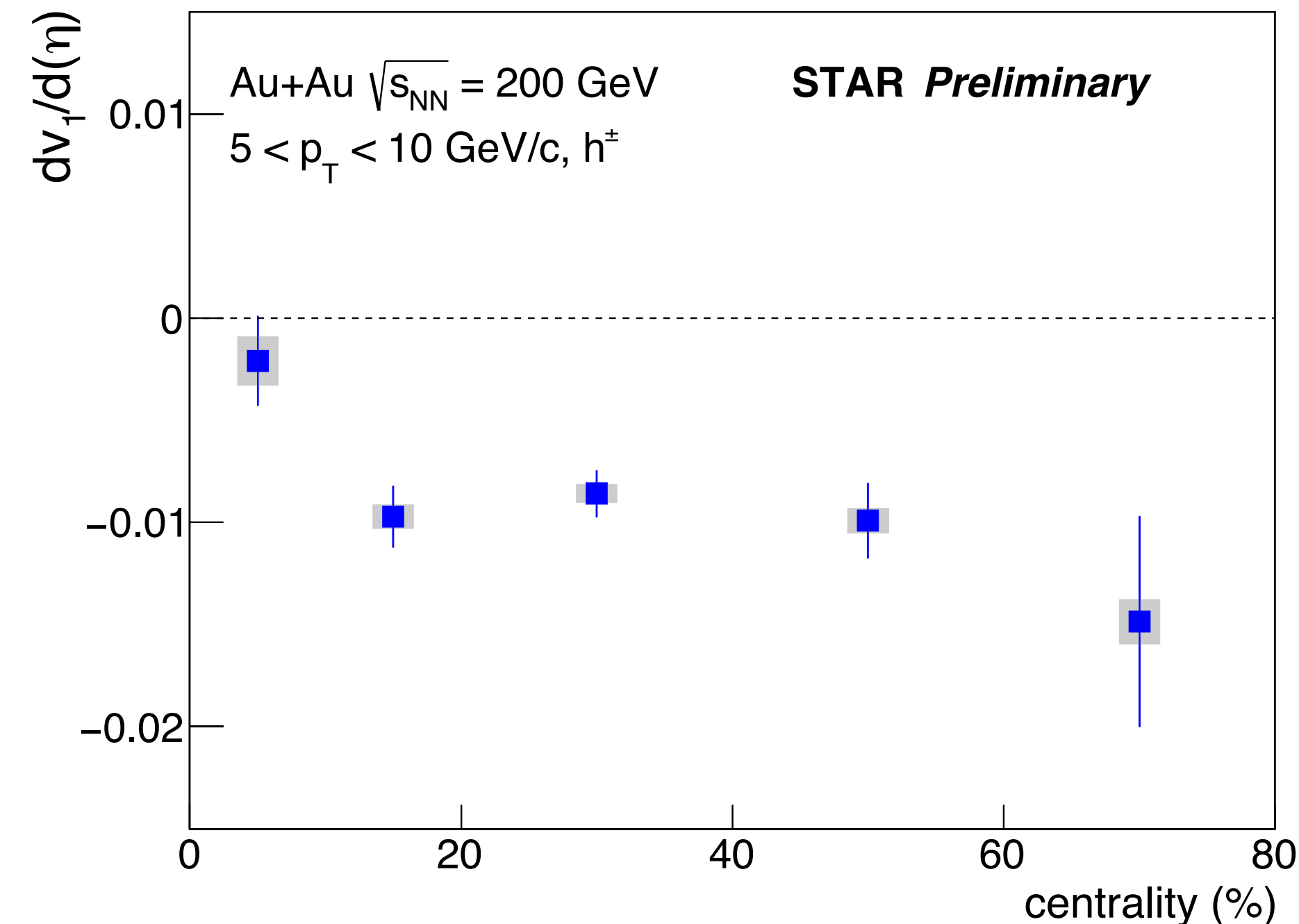
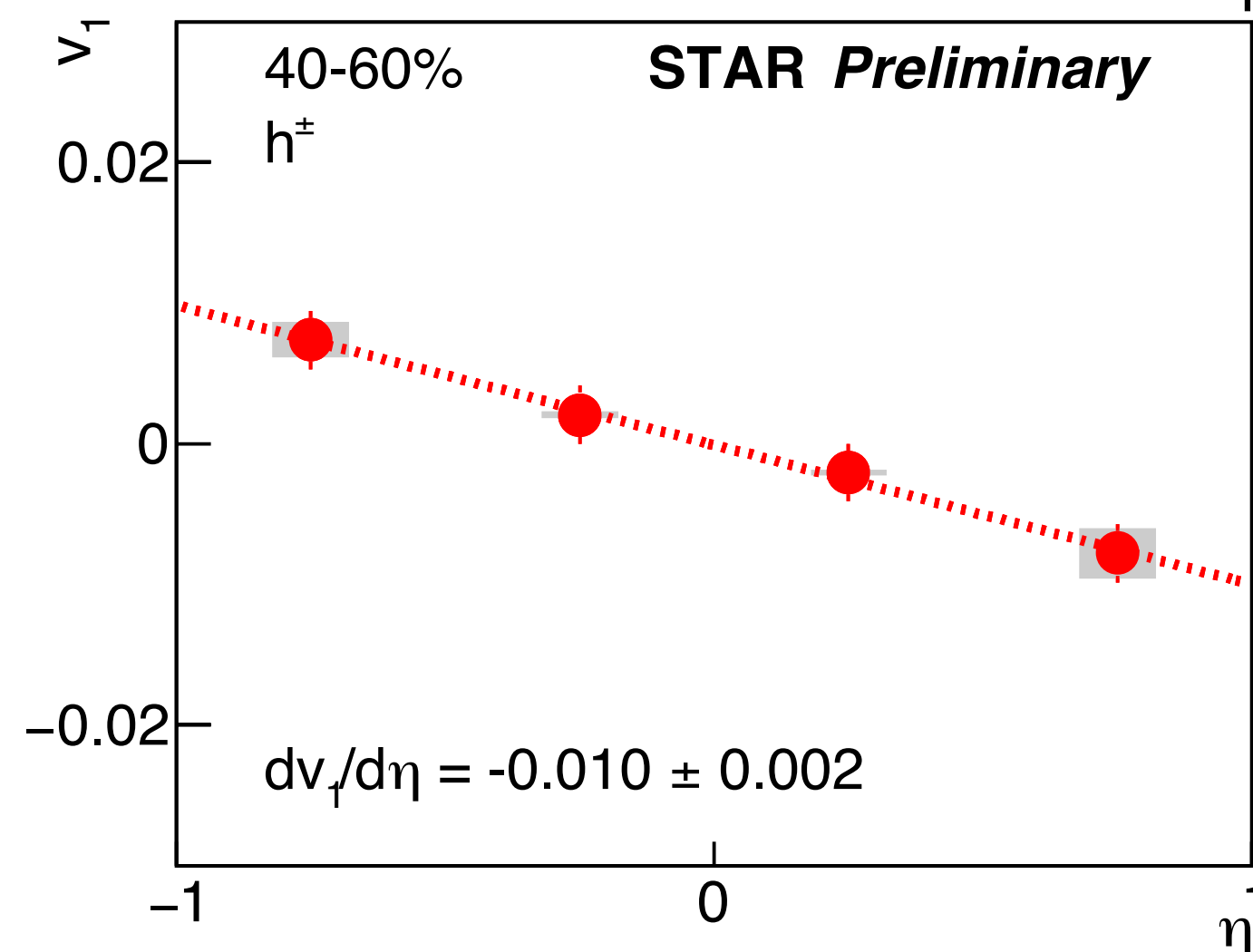
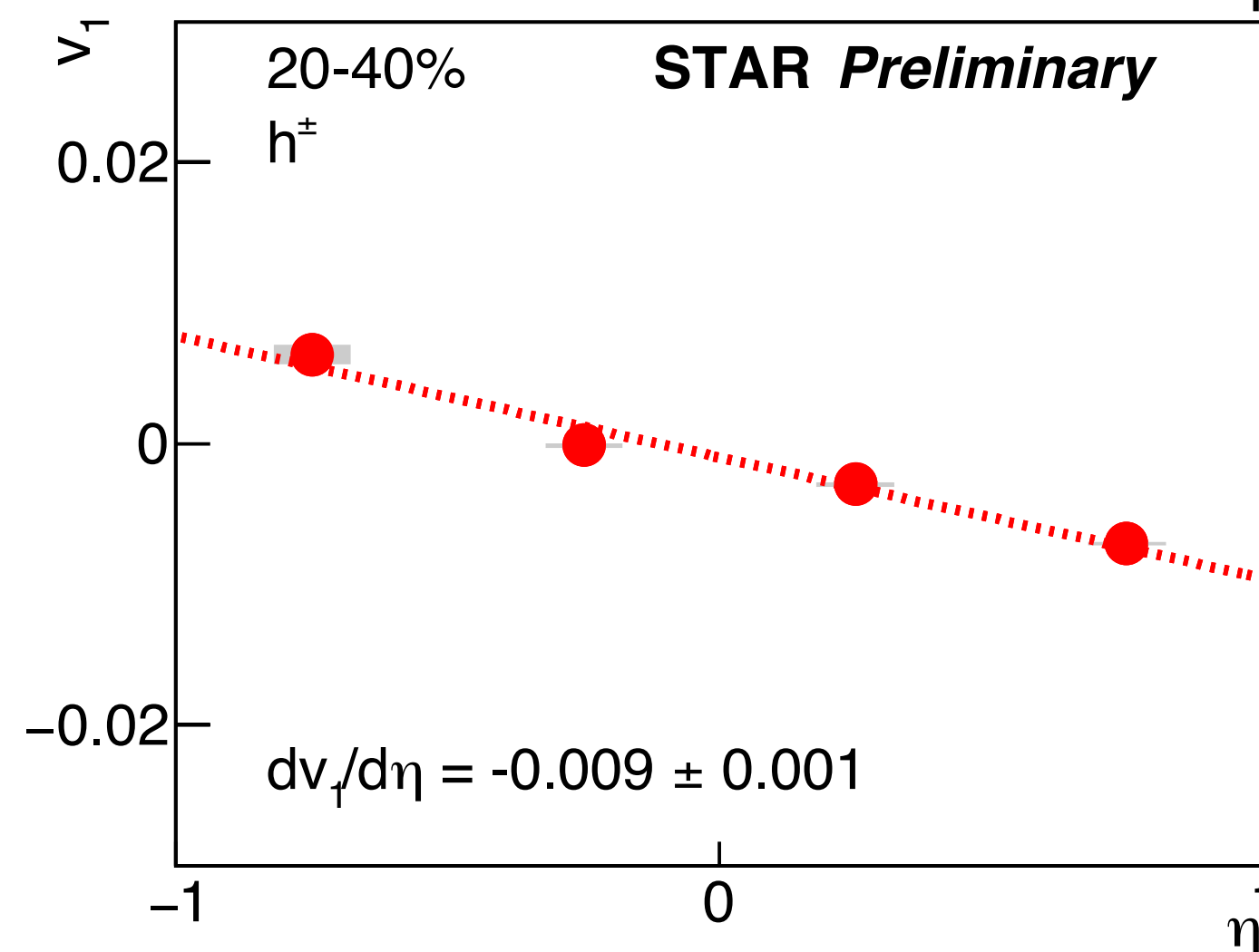
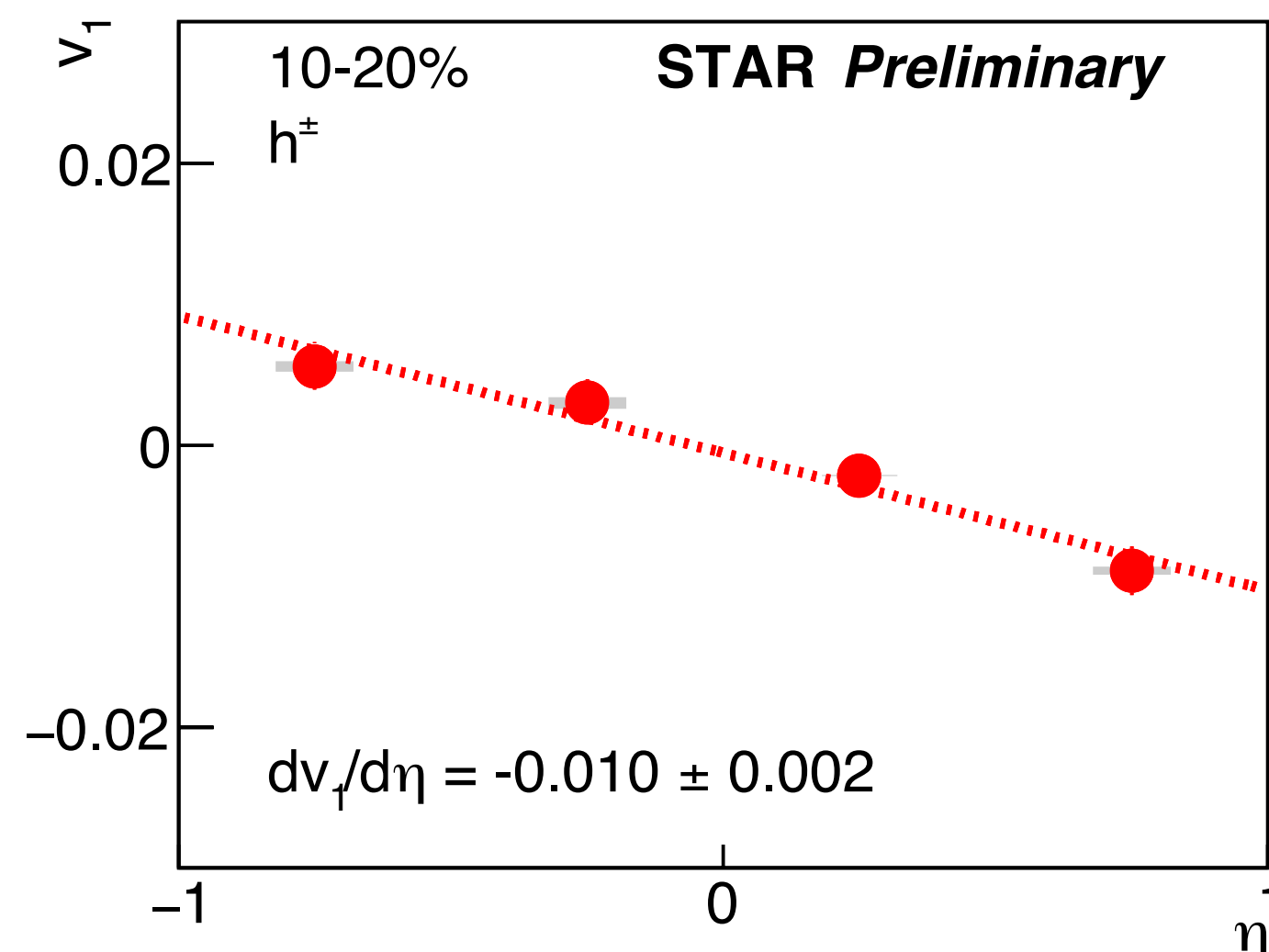
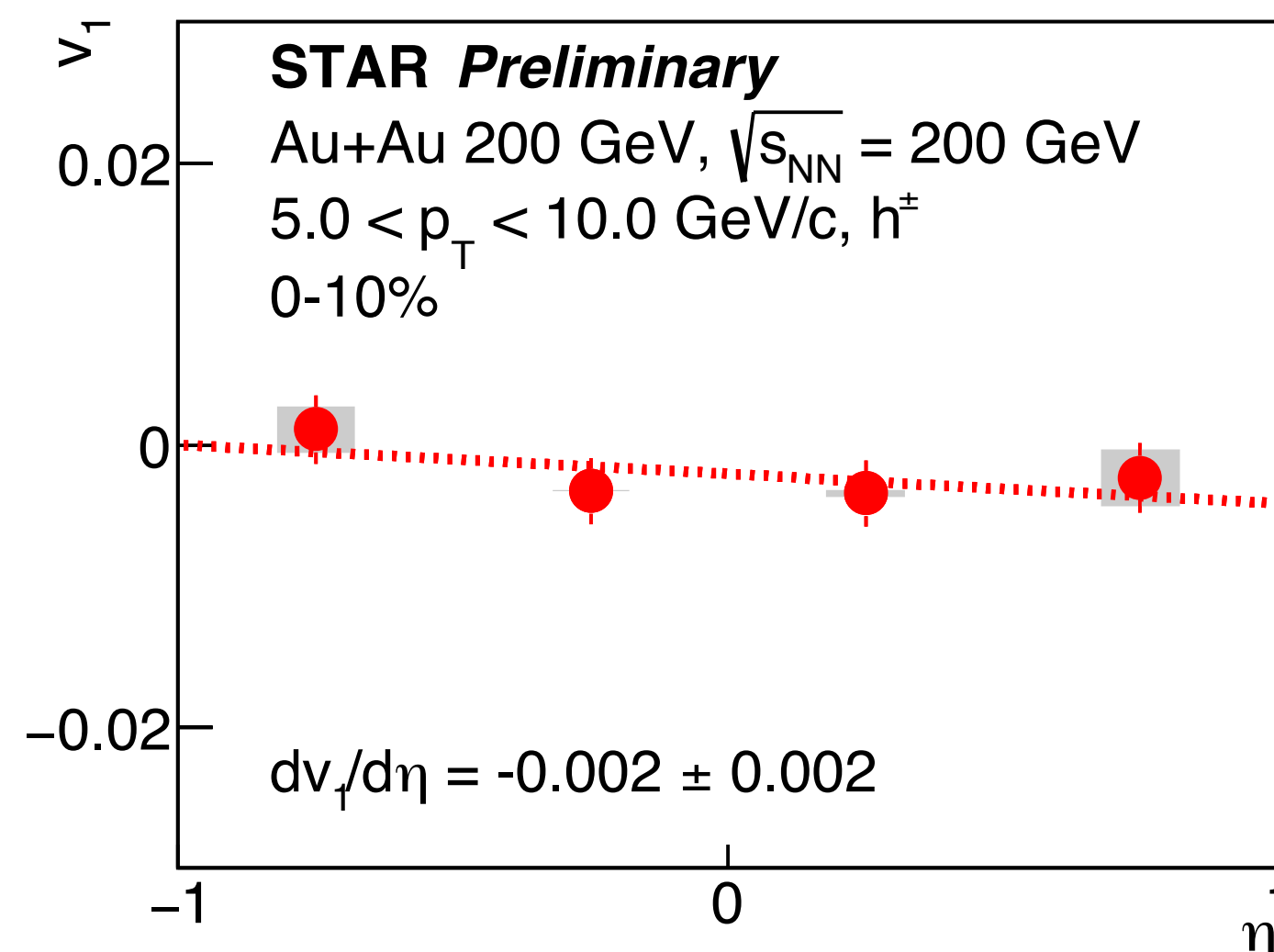


- ✓ v_1 changes sign twice with p_T
- ✓ At high- p_T shows large negative values, similar to D^0
- ✓ Suggests path-length-dependent energy loss for high p_T hadrons

★ See poster number 640 by S. Radhakrishnan

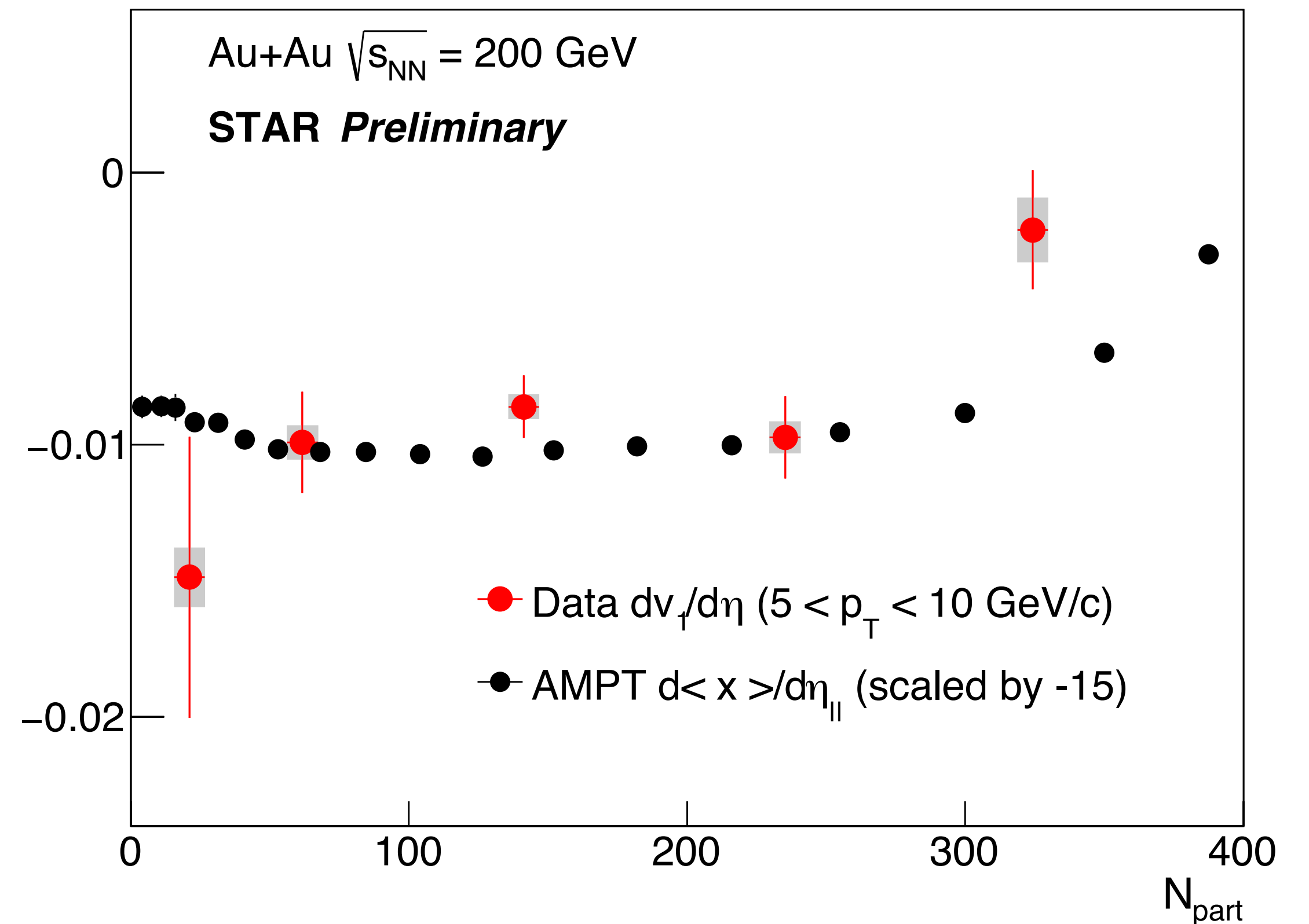
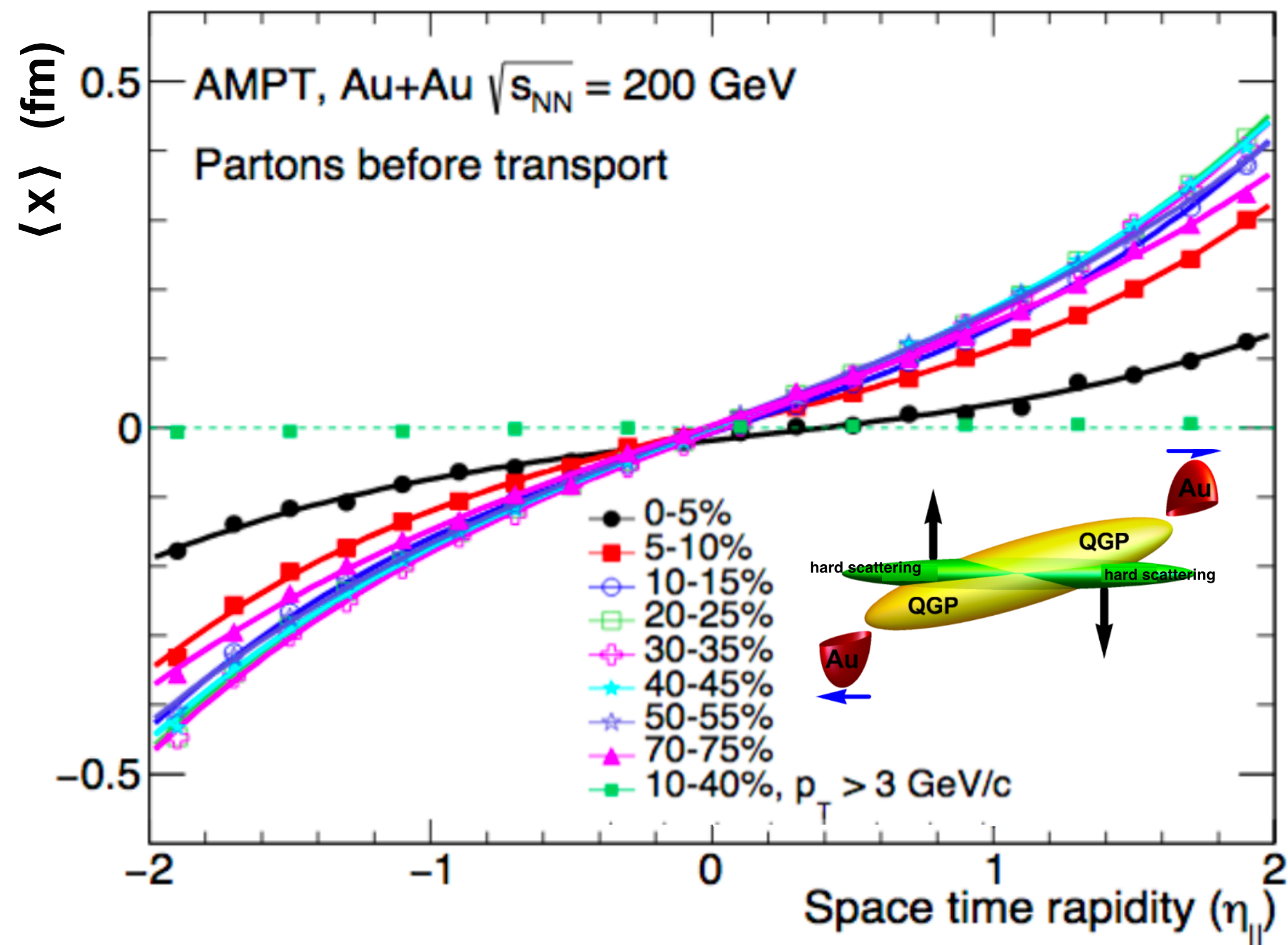


Centrality dependence of dv_1/dy



- ✓ Negative slope ($dv_1/d\eta$) for all centralities
- ✓ Slope shows weak centrality dependence
 - Close to zero in central collisions where initial asymmetry is expected to be small

AMPT: Comparison to initial asymmetry



❖ Average position of partons along the impact parameter direction, $\langle x \rangle$

→ Reflects the net density difference a high p_T parton sees as it passes through the bulk

❖ Similar centrality dependence i.e weak dependence in mid-central and smaller in most central collisions

→ Suggests origin from initial hard-soft asymmetry

Low p_T

★ v_2 of identified hadrons:

- ❖ NCQ scaling is tested for 27 GeV and 54.4 GeV
- ❖ Mass ordering violation for $v_2(\bar{p})$ and $v_2(\phi)$ in central collisions for 54.4 GeV and 200 GeV
→ hadronic rescattering

★ v_1 of identified hadrons and deuteron:

- ❖ Mesons and antibaryons have negative v_1 slope at $7.7 \leq \sqrt{s_{NN}} \leq 200$ GeV
- ❖ Deuteron v_1 measurements from 7.7 to 19.6 GeV are presented

High p_T

★ v_1 of charged hadrons:

- ❖ Suggests path-length-dependent energy loss for high p_T hadrons
- ❖ Centrality-dependent slope suggests origin from initial hard-soft asymmetry



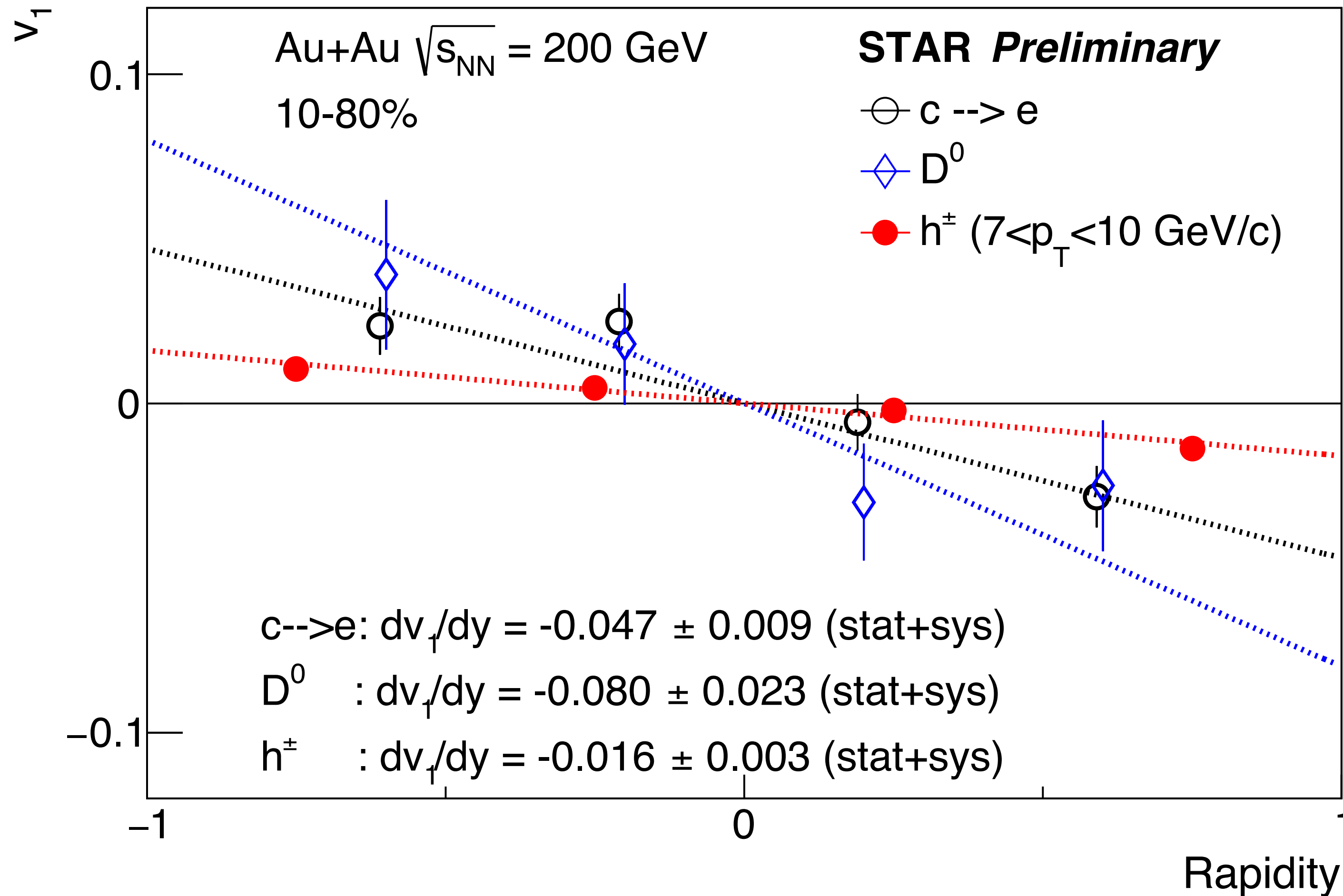
Thank you!



Backup



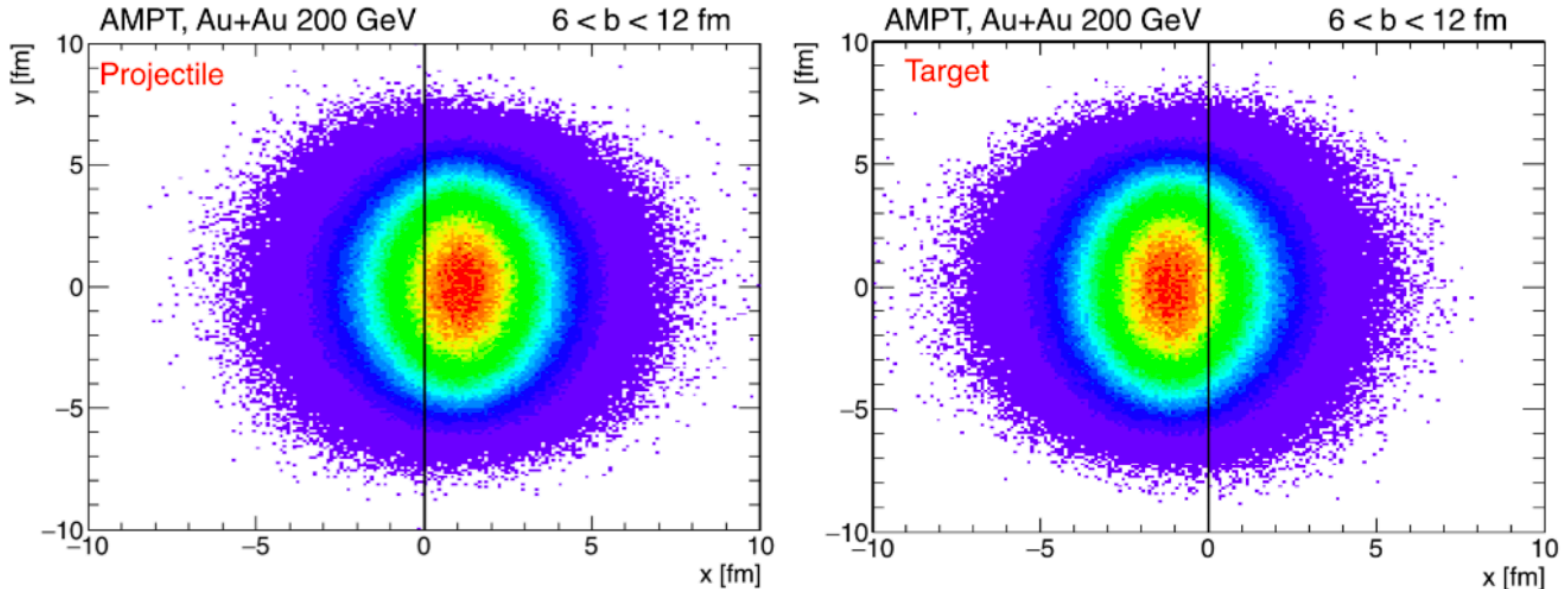
v_1 of high p_T charged hadrons and heavy flavours



✓ The slope of integrated v_1 is $\sim 0.001-0.002$ for 5-40% at 200 GeV

✓ The magnitude of slopes of all hard probes are about an order of magnitude larger than for soft hadrons

AMPT: Hard-soft asymmetry in initial state



- Nuclei are diffused, the radial density inside nucleus decrease outwards (Wood-Saxon profile)
- When two nuclei collide, participant nucleon distribution has a gradient along impact parameter, with opposite signs for projectile and target