Anisotropic Flow of Identified Particles in Au + Au Collisions at $\sqrt{s_{NN}}$ = 3.0 - 4.5 GeV from RHIC-STAR

Xing Wu

for the STAR Collaboration

Hot Quarks 2025, Hefei, China

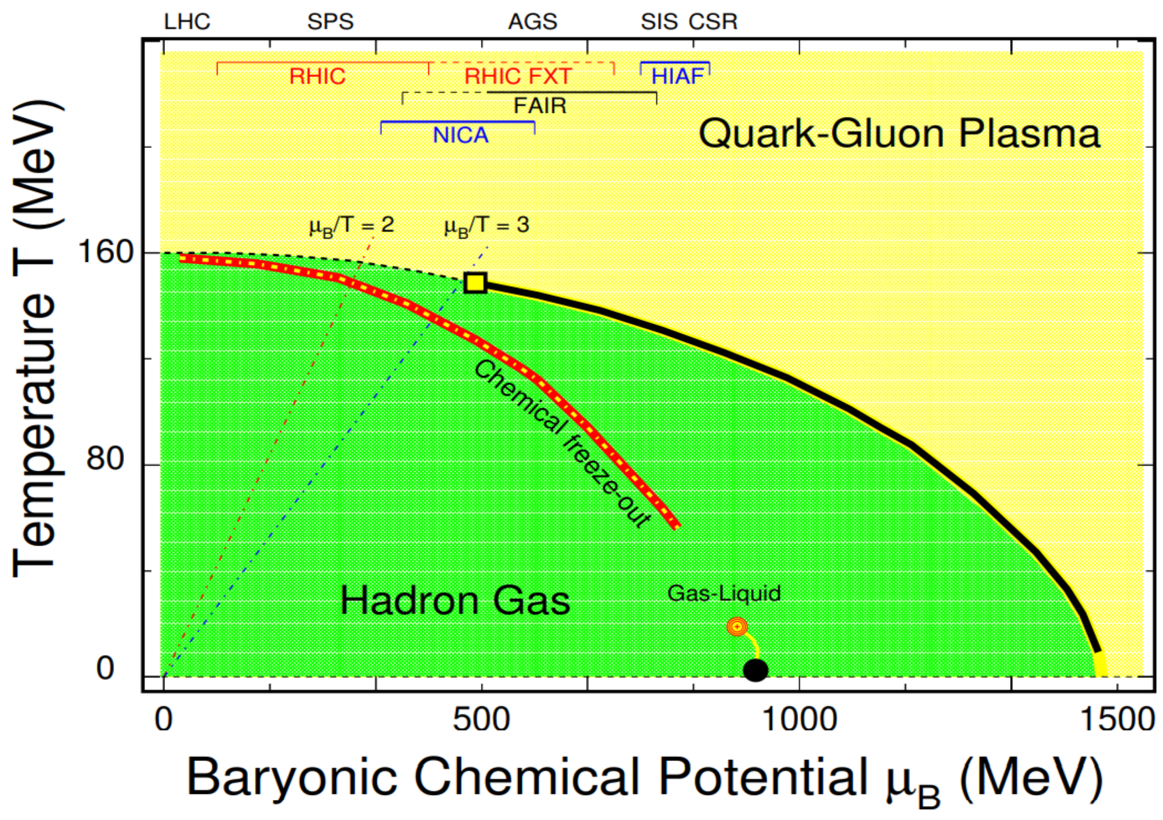
Supported in part by the
U.S. DEPARTMENT OF
ENERGY
Office of
Science

STAR collaboration

Outline

- Motivation
- Anti-flow of Mesons (STAR. arXiv:2503.23665)
- NCQ Scaling of v_2 (STAR. arXiv:2504.02531)
- Summary

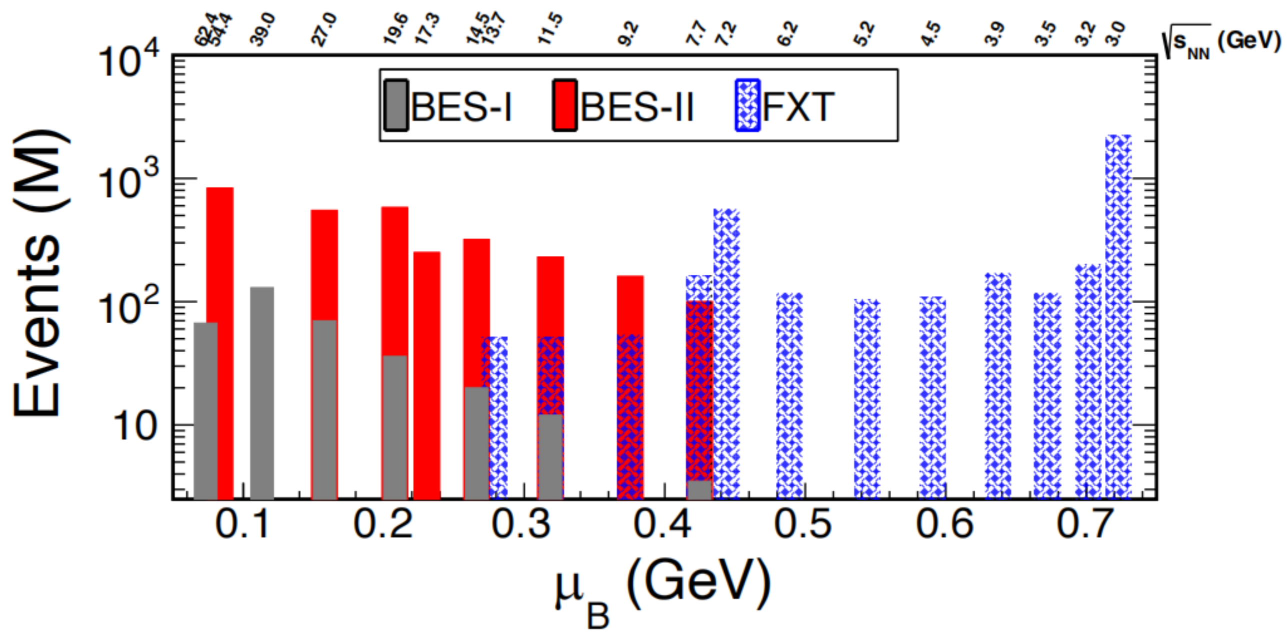
QCD Phase Diagram



X.Luo, S.Shi, Nu Xu et al. Particle 3, 278 (2020)

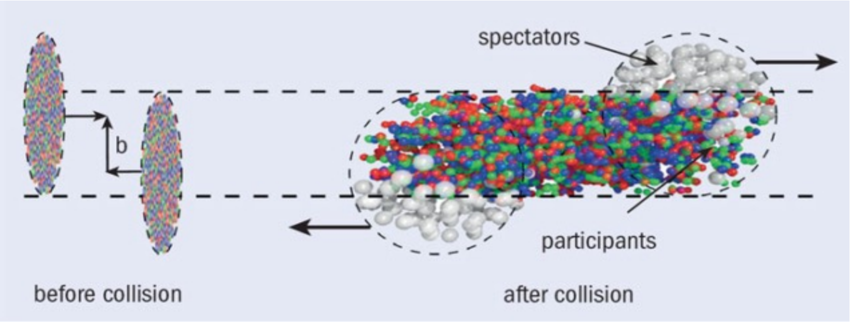
BES-I:
$\sqrt{s_{NN}}$ = 7.7 - 200 GeV (COL)

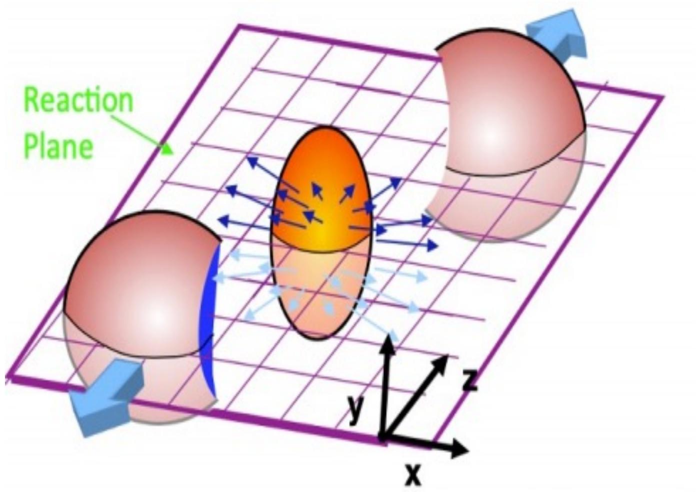
BES-II:
$\sqrt{s_{NN}}$ = 7.7 – 54.4 GeV (COL)
+
$\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV (FXT)



- Study the properties of QGP
- Search for the critical point and locate the first-order phase boundary
- Higher statistics, better detector performance and more energy points in BES-II

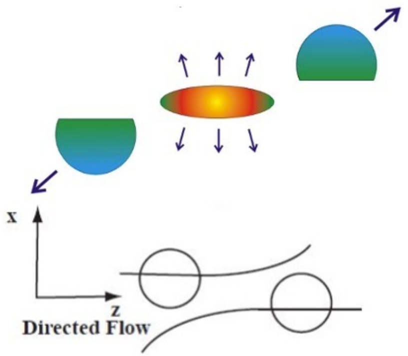
Anisotropic Flow



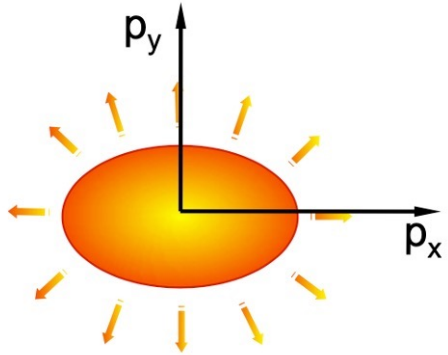


$$\frac{dN}{d(\phi-\Psi)} \sim 1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi))$$

- Directed flow:
  $v_1 = \langle \cos(\phi - \Psi) \rangle$



- Elliptic flow:
  $v_2 = \langle \cos 2(\phi - \Psi) \rangle$

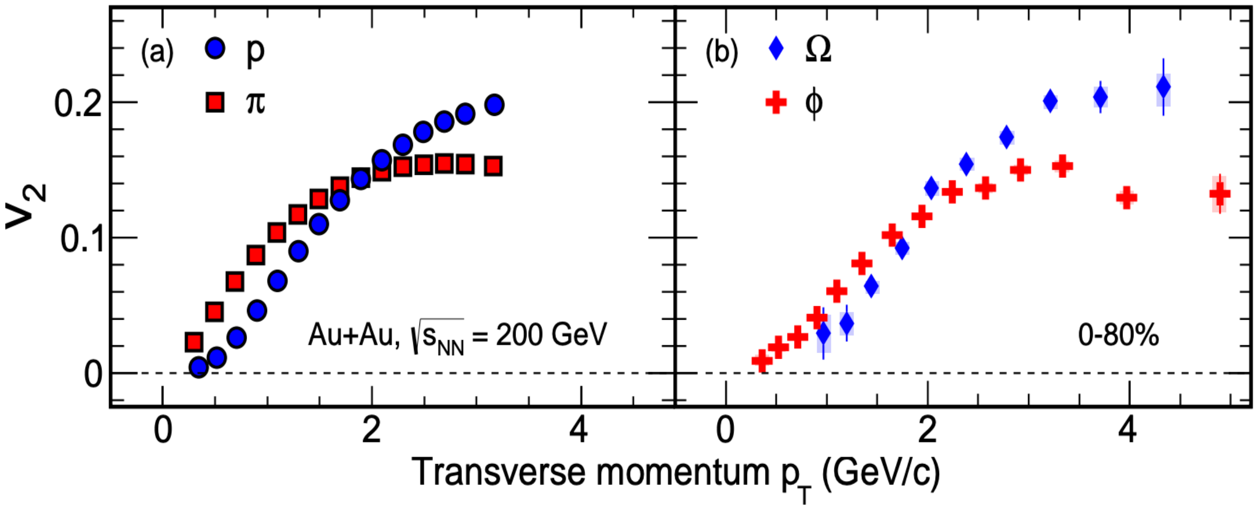


- v_1 is sensitive to the effective equation-of-state (EoS) and the details of the expansion
- v_2 can reflect the degree of freedom: partonic vs. hadronic

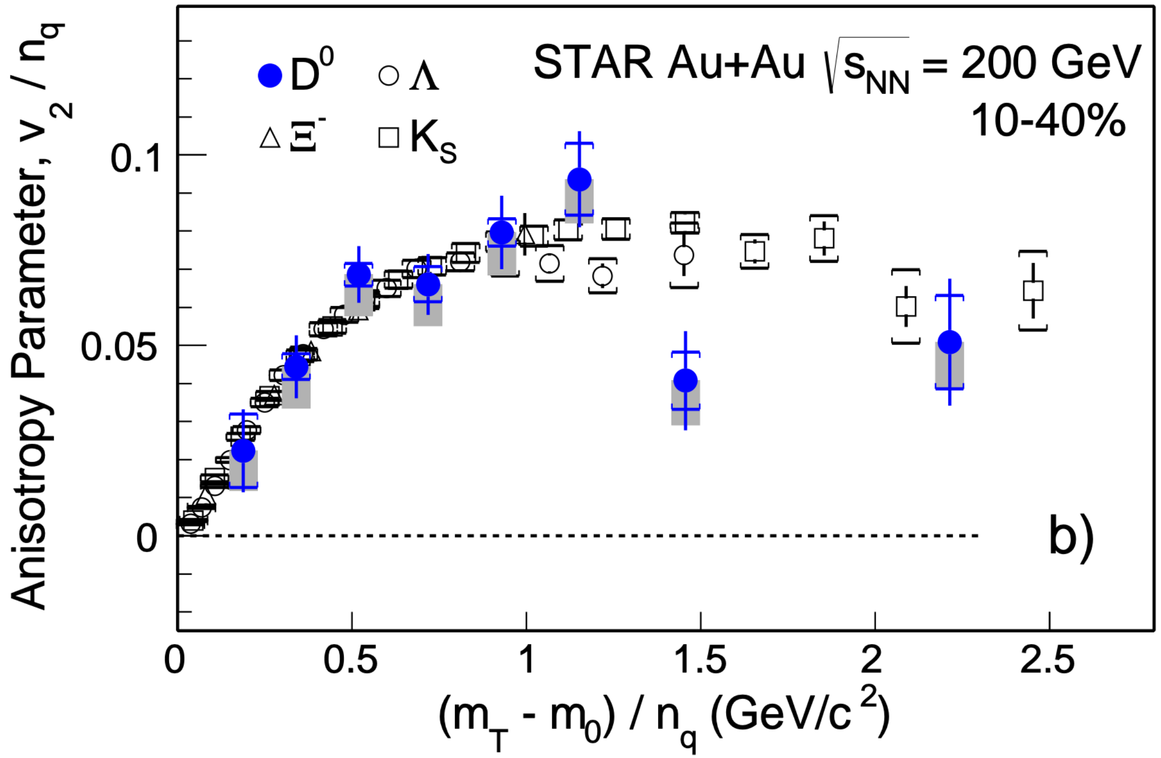
S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998).

Motivation

STAR Collaboration, Phys. Rev. Lett. **116**, 062301 (2016)

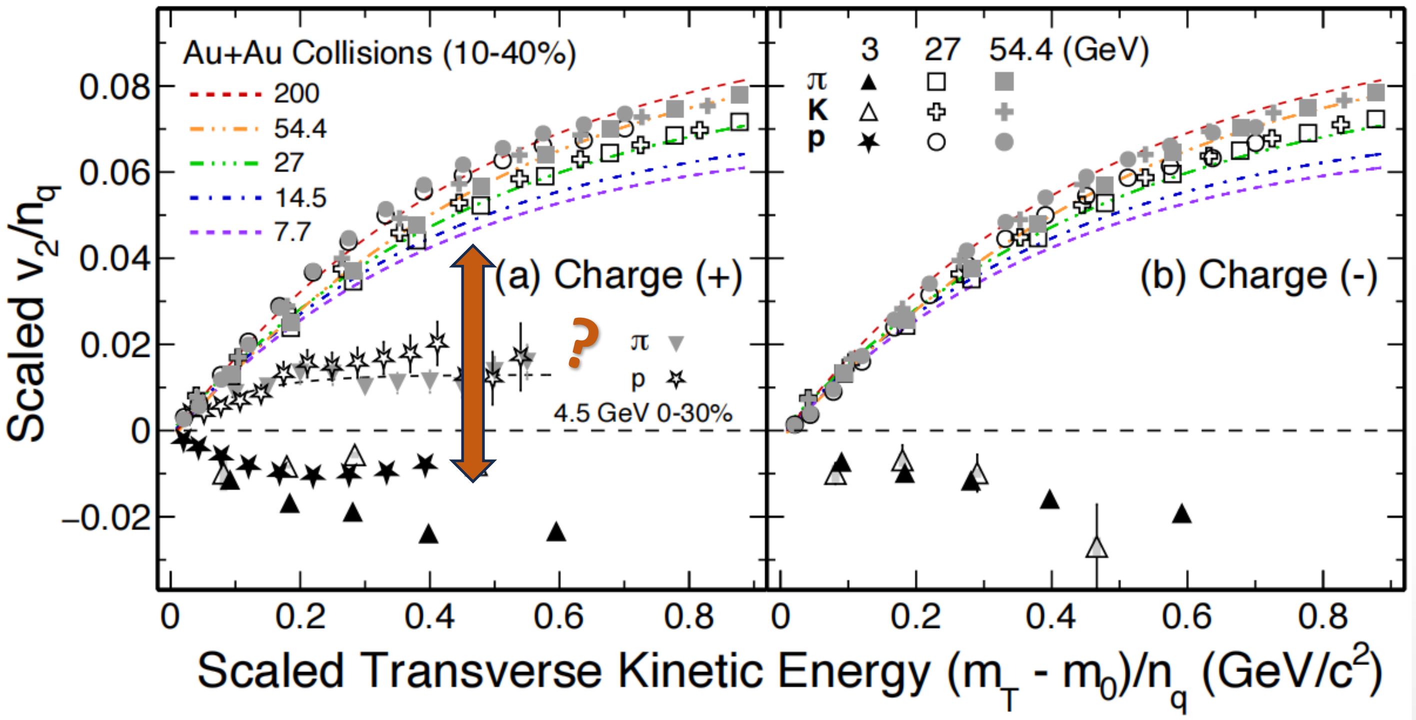


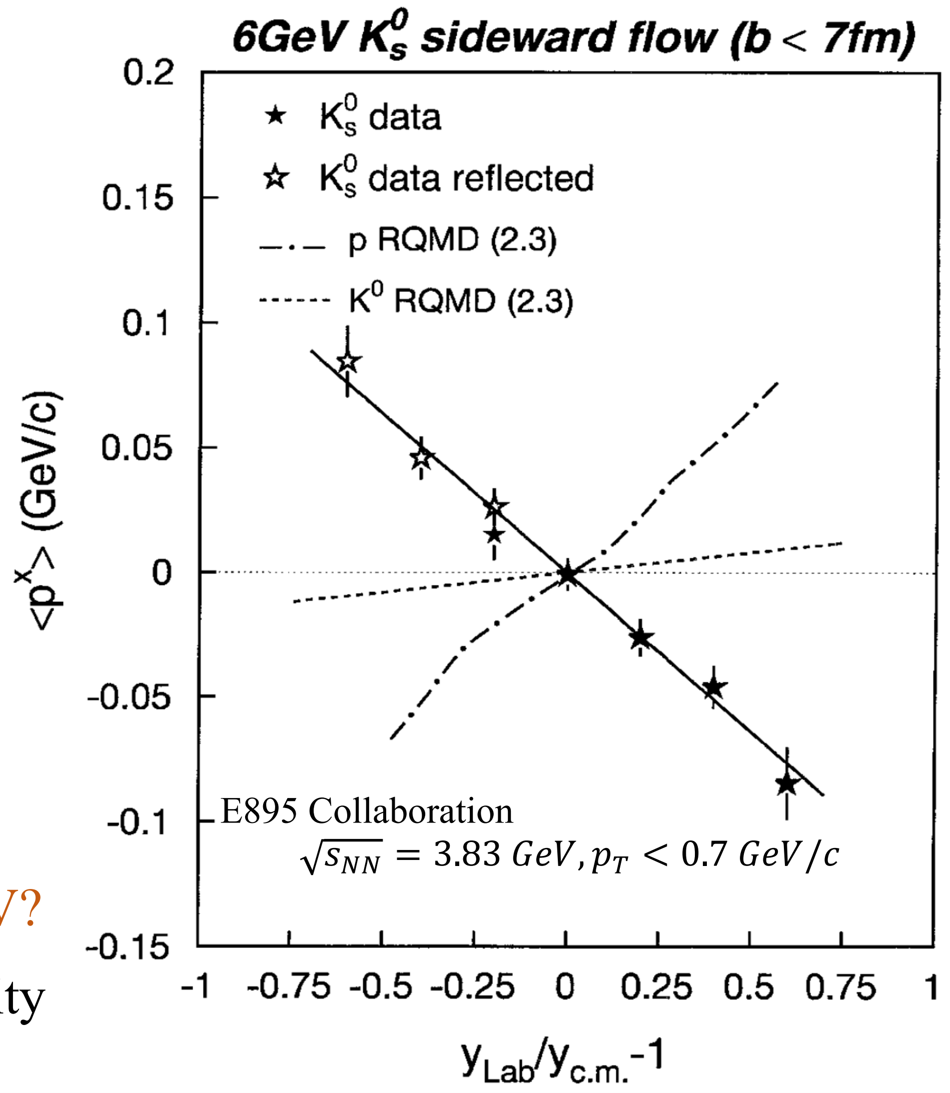
STAR Collaboration, Phys. Rev. Lett. **118**, 212301 (2017)



➢ Au + Au collisions 200 GeV: **partonic collectivity**

Motivation





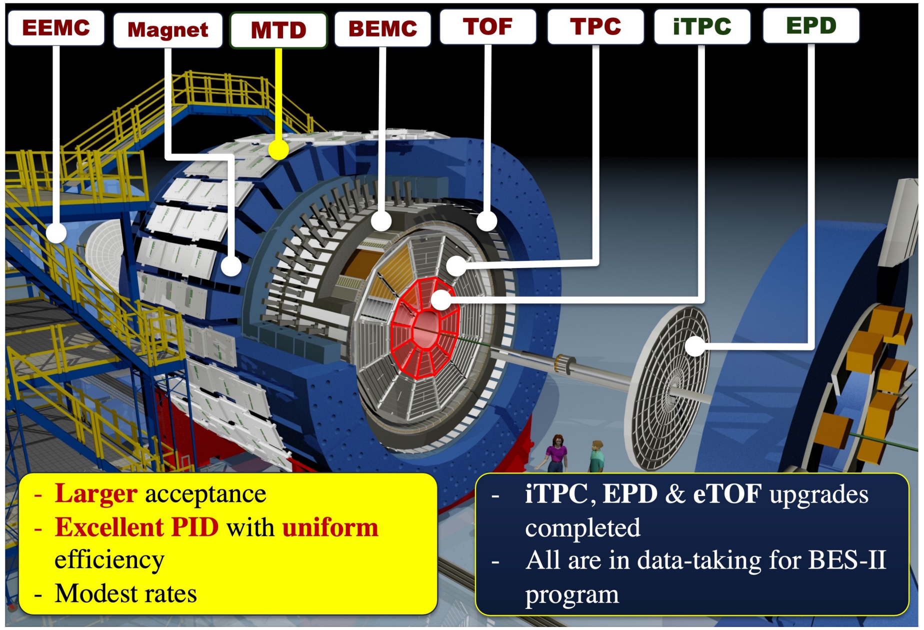
- 3 GeV: The hadronic degree of freedom dominated

  How does the degree of freedom change between 3.0 and 7.7 GeV?

- E895: Kaon vector potential plays an important role in high density nuclear matter

P. Chung et al. (E895 Collaboration), Phys. Rev. Lett. 85, 940(2000)
M. S. Abdallah et al. (STAR Collaboration), Phys. Lett. B 827 (2022) 137003

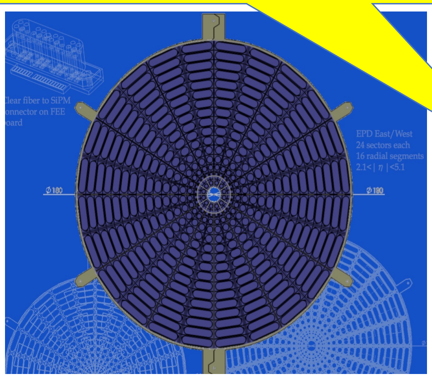
STAR Detector System



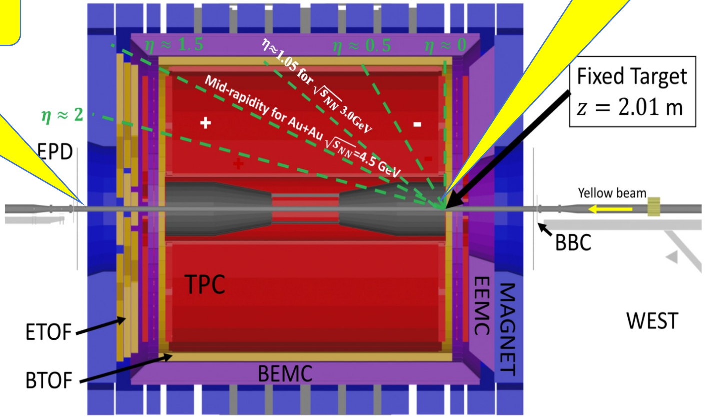
- ➢ inner TPC upgrade
  - Extends η coverage from 1.0 to 1.5
- ➢ Endcap TOF
  - Extends rapidity coverage for PID
  - Improves precision studies of observables rapidity dependence
- ➢ Event Plane Detector
  - Allows a better event plane resolution

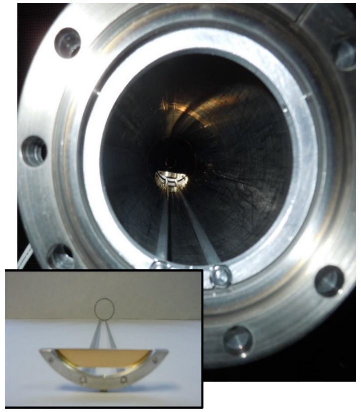
- ➢ **STAR Fixed Target Setup**

Event Plane Detector (EPD)

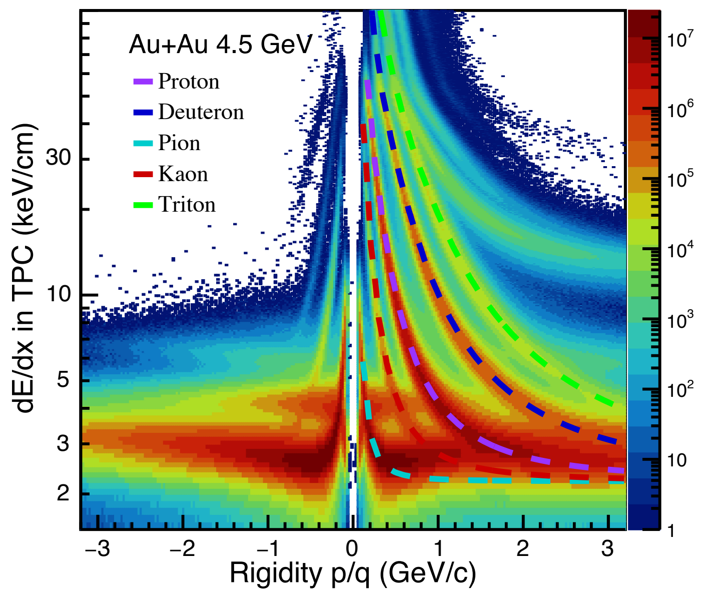


Au Target

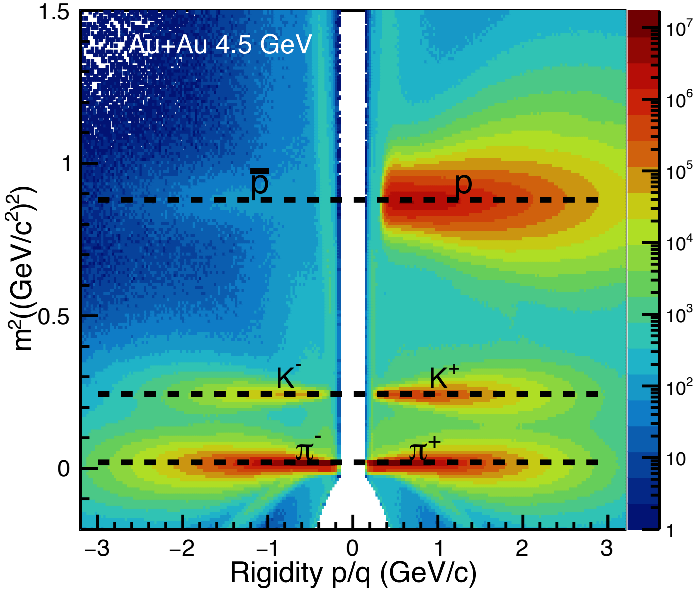


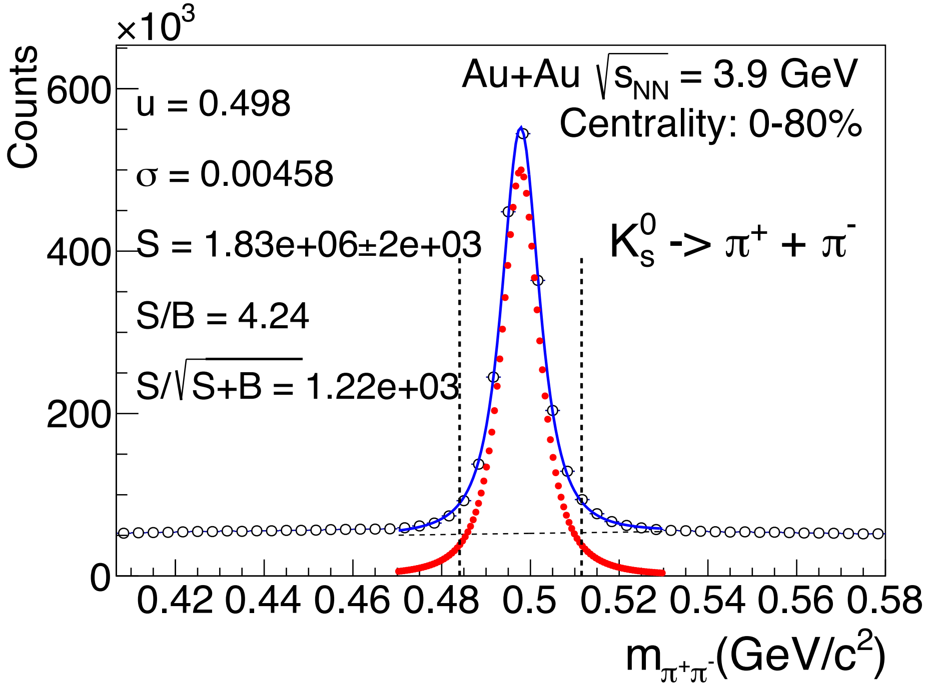


Particle Identification

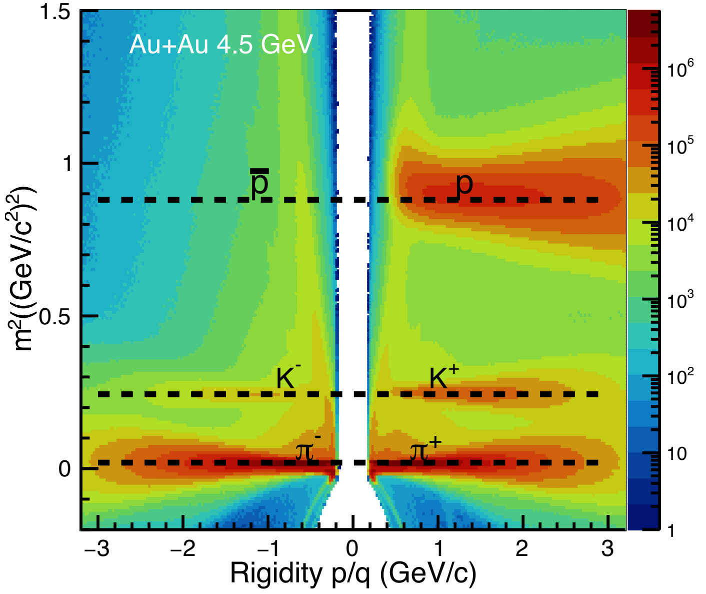


bToF





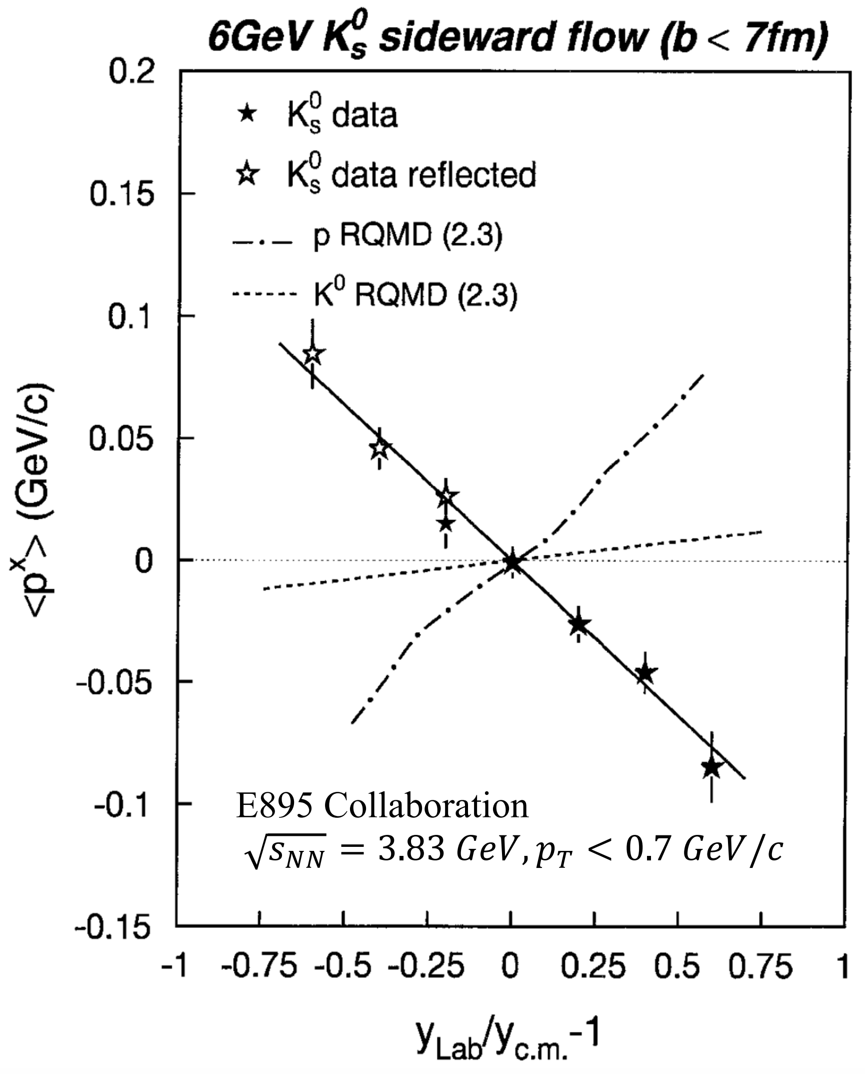
eToF

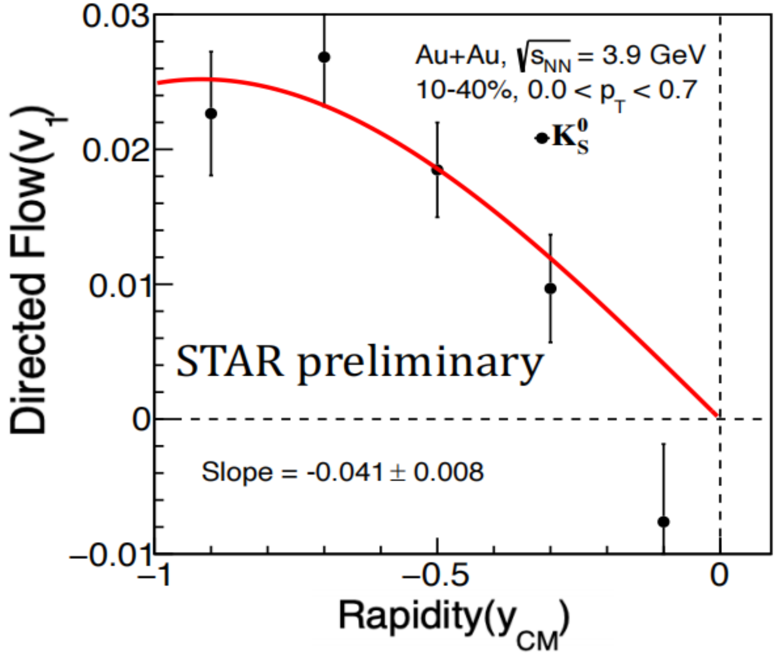


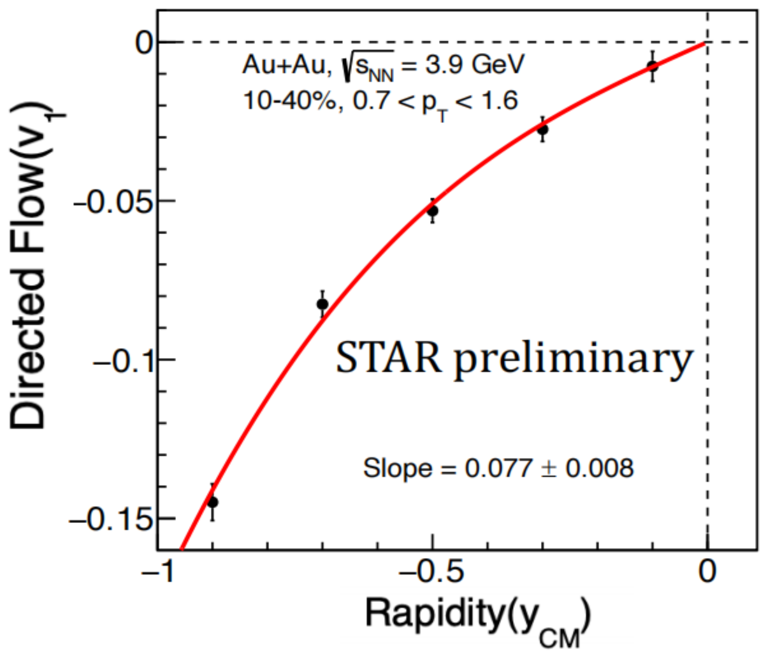
- ➢ Good capability of particle identification (PID) based on TPC and TOF
- ➢ Extend the phase space coverage by TOF
- ➢ Decayed particles are reconstructed by KF(Kalman Filter) particle package

A. Banerjee, I. Kisel and M. Zyzak, Int. J. Mod. Phys. A 35, 2043003 (2020)

Anti-flow of K_s^0





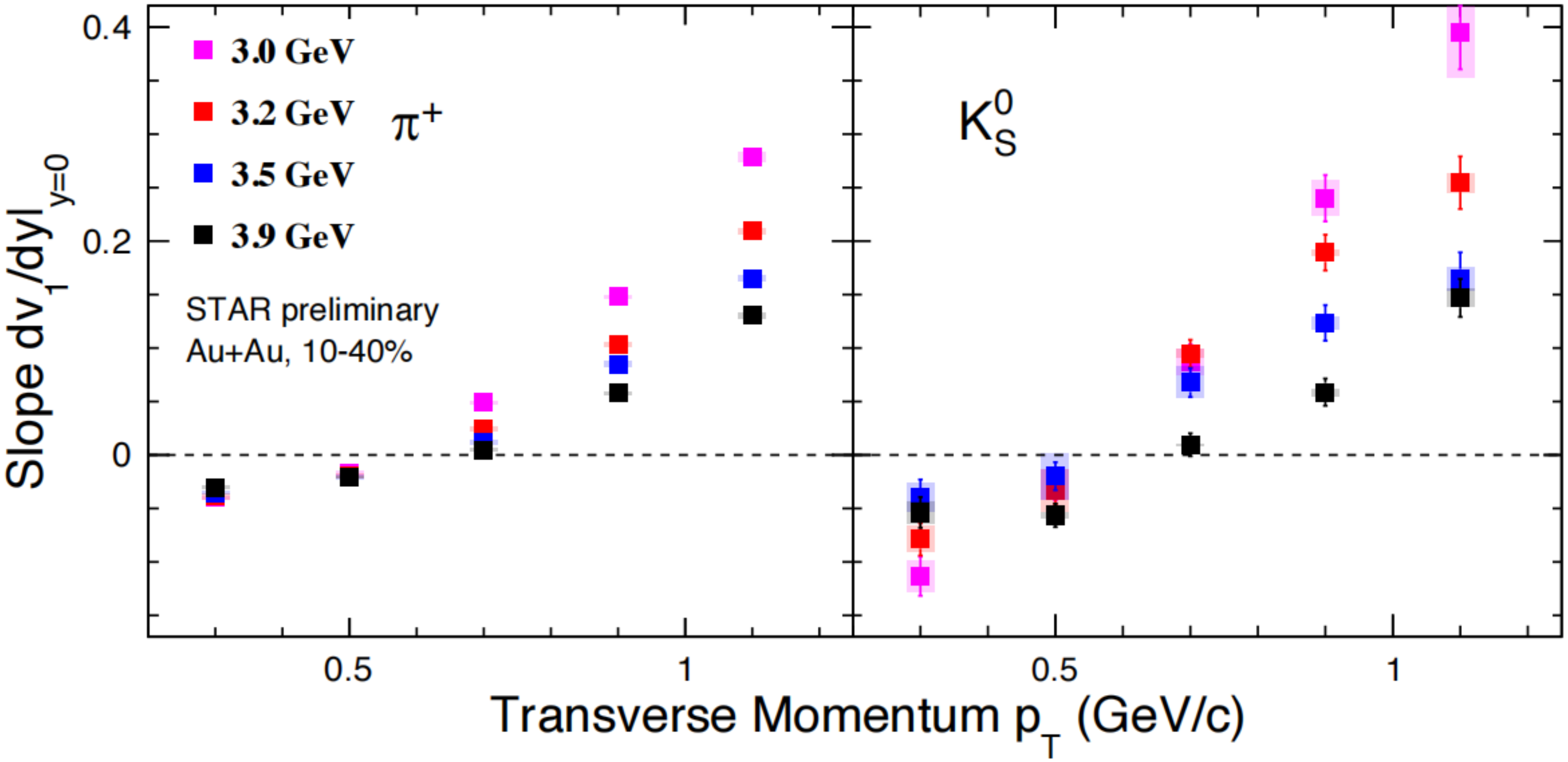


- Anti-flow of K_S^0 is observed at 3.9 GeV from RHIC – STAR BES-II (p_T < 0.7 GeV)

Note: fitting function: $v_1 = p_0 * y + p_1 * y^3$
Fitting range: $-1 < y_{CM} < 0$

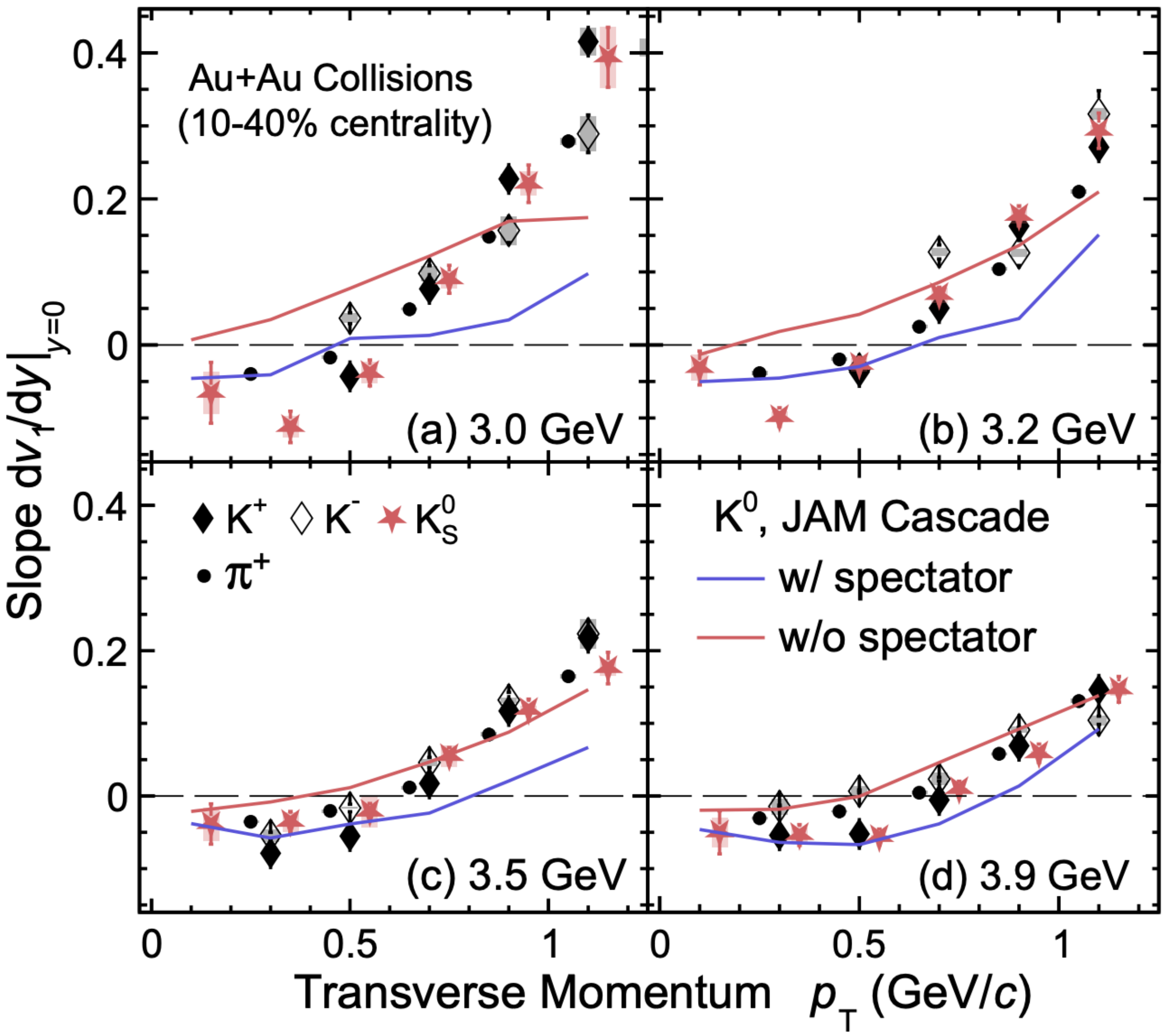
P. Chung et al. (E895 Collaboration), Phys. Rev. Lett. 85, 940(2000)

Anti-flow of K_s^0 and π^+



- v_1 slope of $\pi^+$and K_s^0 as a function of p_{T} measured for 10-40% centrality
- The v_1 slope decreases as the collision energy increasing
- Anti-flow of $\pi^+$and K_s^0 are observed in low p_T region at 3.0 - 3.9 GeV

Anti-flow of Mesons

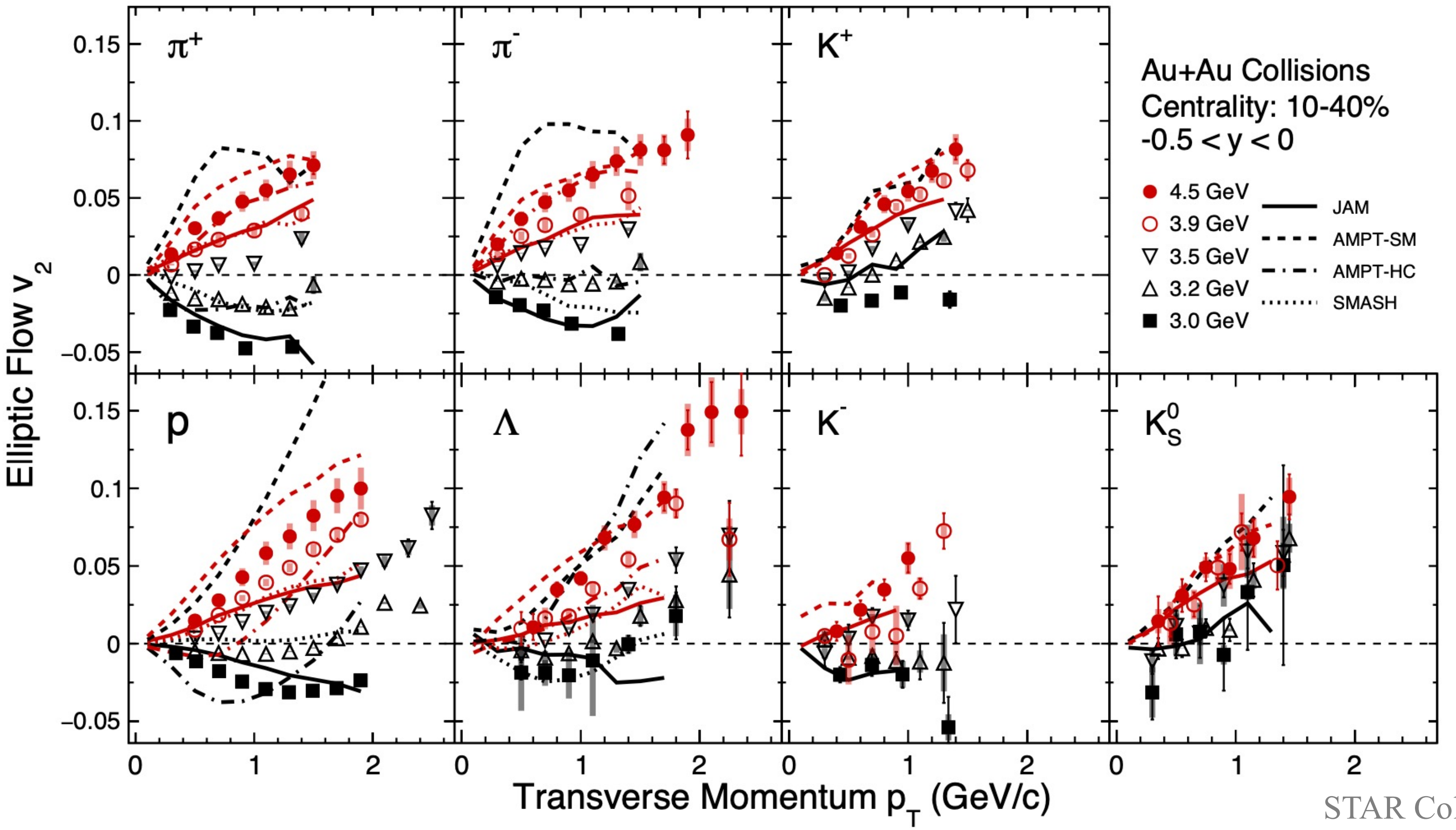


- JAM2 with and without spectator in cascade mode calculation of v_1 slope for 10-40% centrality bin at 3.0 - 3.9 GeV

- Shadowing effect from spectator leads to anti-flow at low p_T
  → Kaon potential is not necessary

STAR Collaboration. arXiv:2503.23665.

p_T Dependence of v_2 at 3 – 4.5 GeV

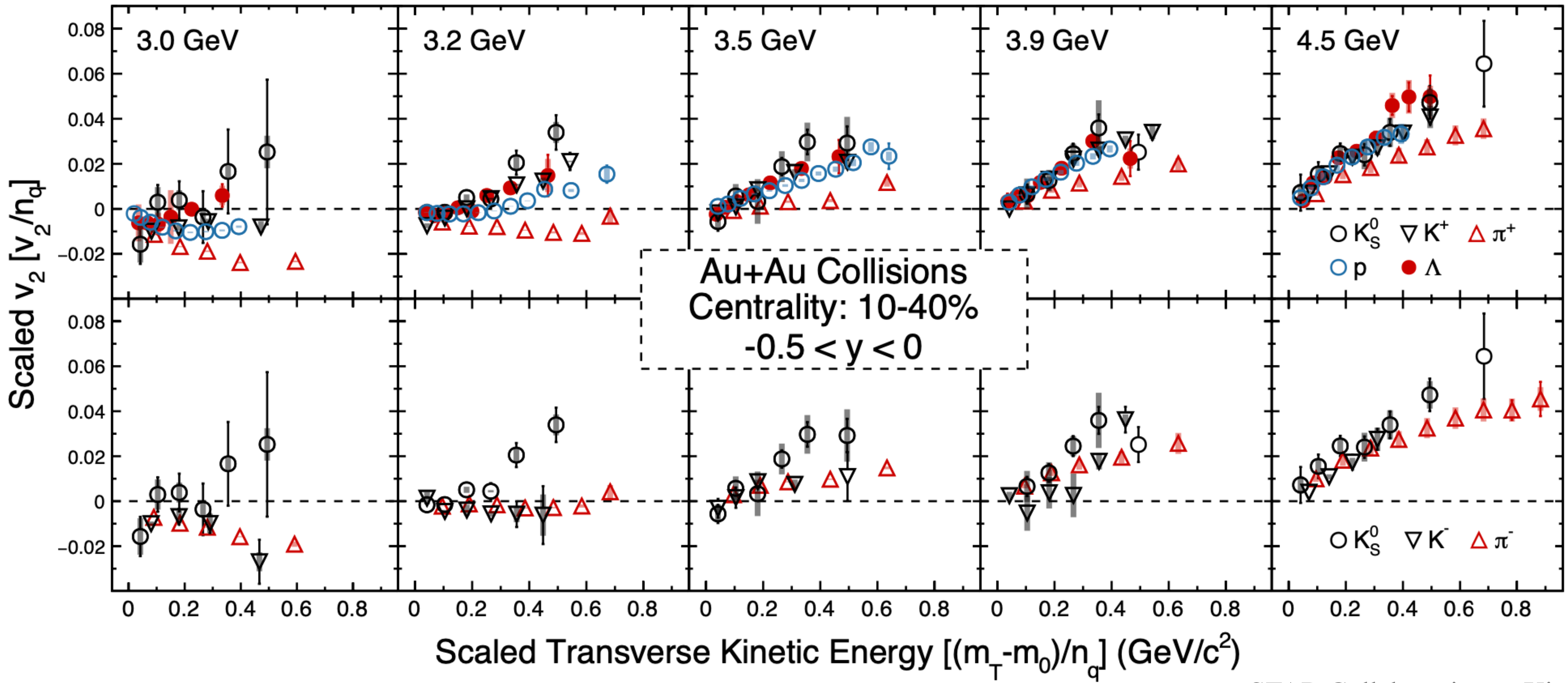


STAR Collaboration. arXiv:2504.02531.

- $v_2(p_T)$ changes from negative to positive between 3 GeV and 4.5 GeV: Shadowing effect
- 3 GeV: Hadronic models fit data well, while AMPT-SM model fails

  4.5 GeV: AMPT-SM model closer to data, while hadronic models underestimate

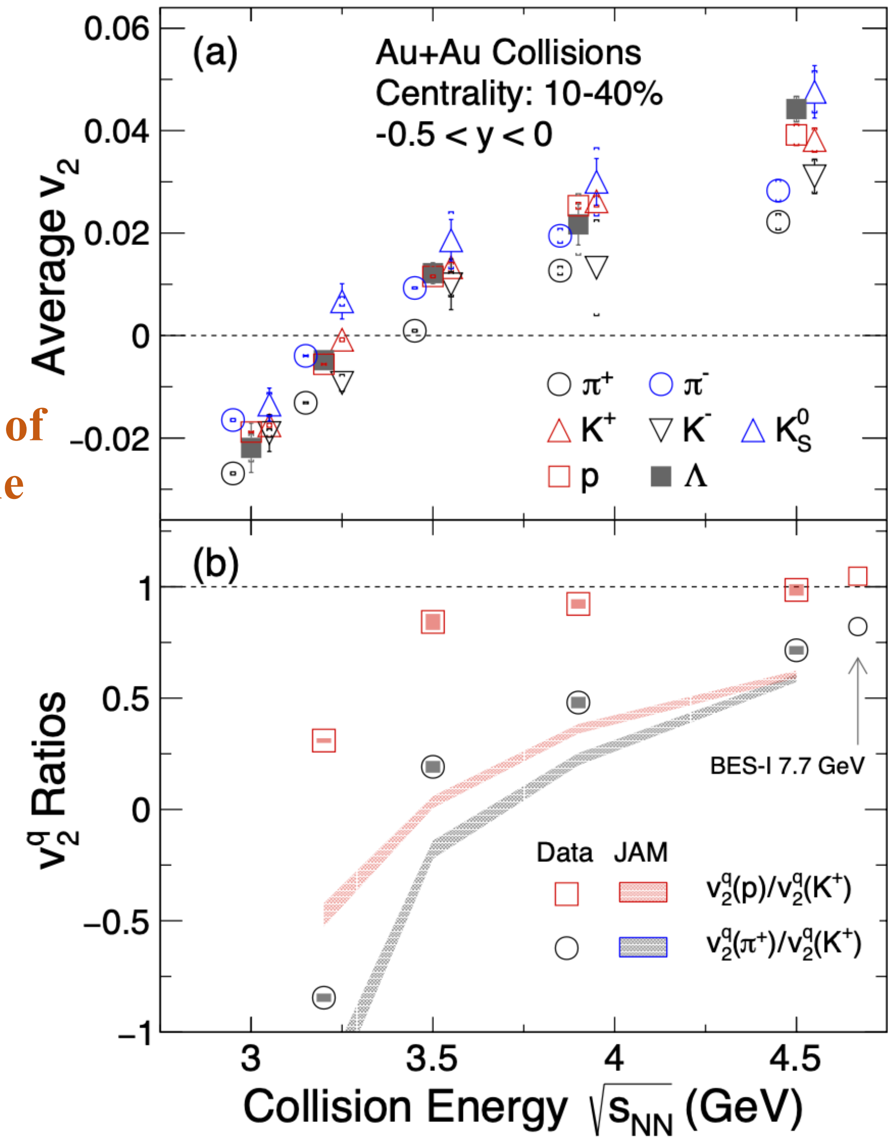
NCQ Scaling of v_2 at 3 – 4.5 GeV



STAR Collaboration. arXiv:2504.02531.

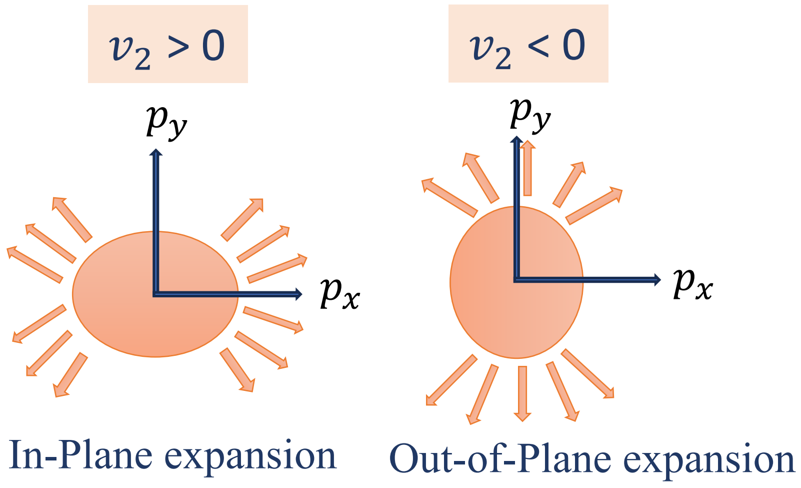
- NCQ scaling completely breaks below 3.2 GeV : Dominance of hadronic interactions
- NCQ scaling becomes better gradually from 3.2 to 4.5 GeV

Energy Dependence of Average v_2



In-plane expansion

Out of plane



- Negative to positive flow: 3- 4.5 GeV
- NCQ scaled v_2 ratio of p/K^+ close to unity at 3.9 and 4.5 GeV, while deviating largely from 1 at 3.2 GeV

  ⟶ Partonic interactions become more important at 4.5 GeV

STAR Collaboration. arXiv:2504.02531.

Summary

- Anti-flow of K_s^0 is observed at 3.0-3.9 GeV → Shadowing effect by spectators
- Energy dependence of v_2 → Out-of-plane to in-plane expansion
- NCQ Scaling breaks at 3.2 GeV and below → Hadronic interaction dominates
- The NCQ scaling gradually restores between 3.2 and 4.5 GeV

  → Emergence of partonic collectivity

*The results on v_2 at $\sqrt{s_{NN}}$ = 7.7 – 19.6 GeV will be presented in **Guoping Wang's talk***

Thank you for your attention!