Collectivity in Heavy Ion Collisions from RHIC– STAR BES-II

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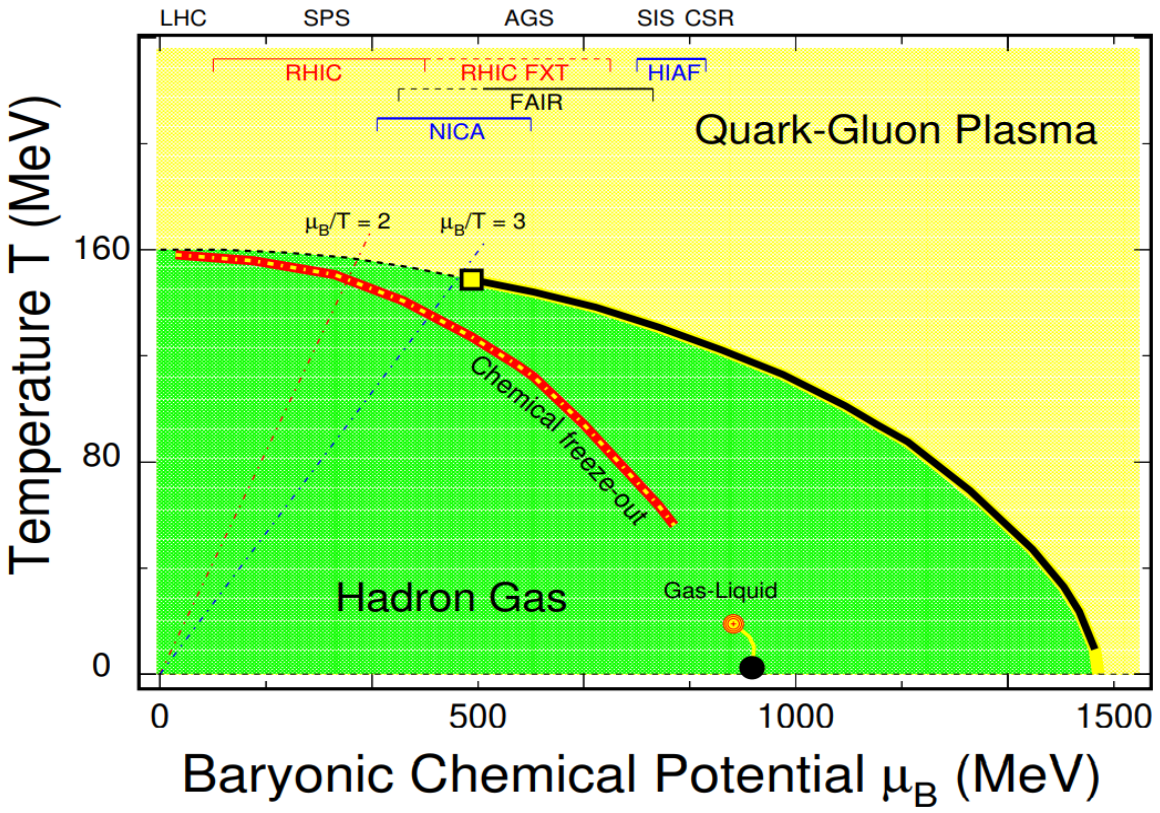
Outline

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

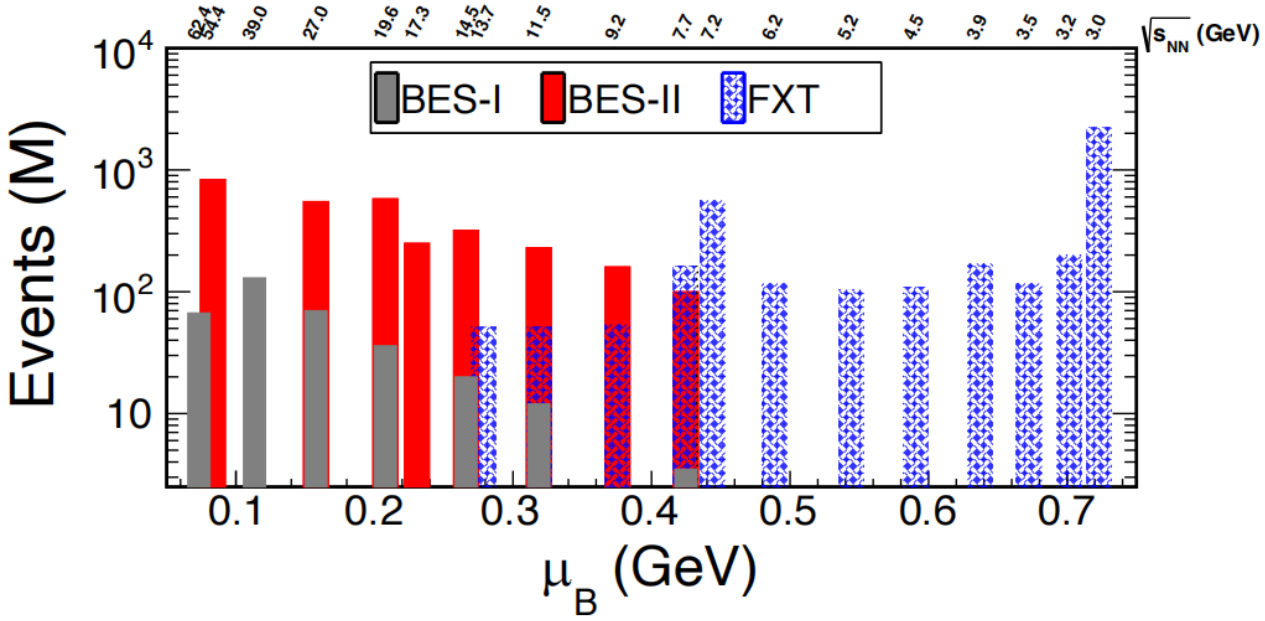
Motivation – QCD Phase Diagram



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

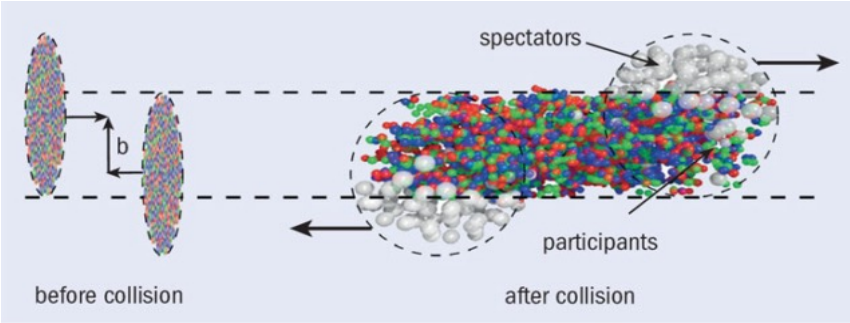
BES-I:
$\sqrt{s_{NN}}$ = 7.7 - 200 GeV (COL)

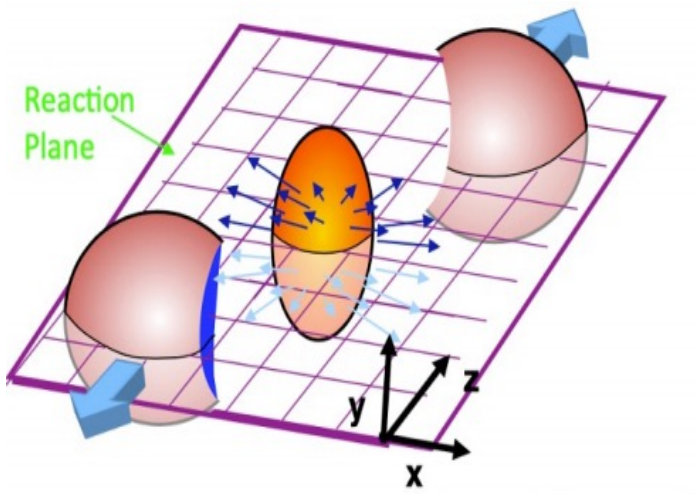
BES-II:
$\sqrt{s_{NN}}$ = 7.7 – 54.4 GeV (COL)
+
$\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV (FXT)



- 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

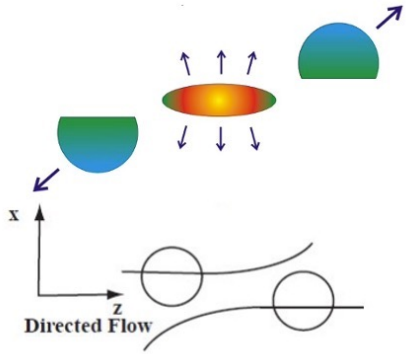
Motivation – Anisotropic Flow



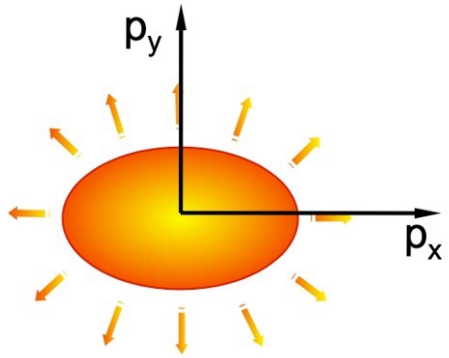


$$\frac{dN}{d(\phi-\Psi)} \sim 1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi))$$

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



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

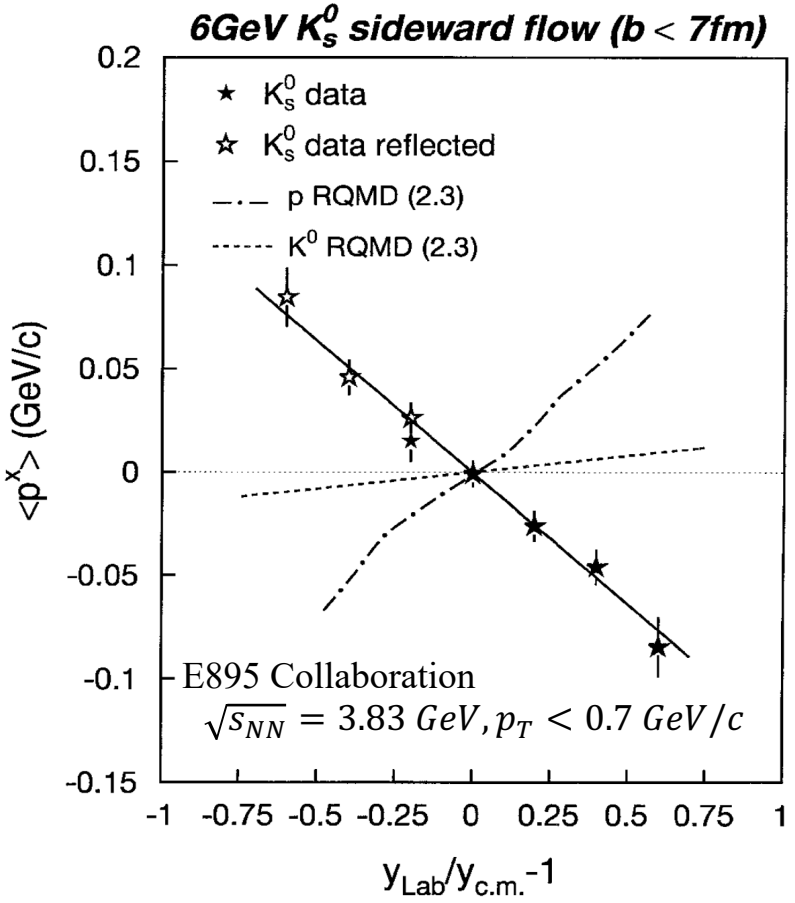


- v_1 is sensitive to the effective equation-of-state (EoS) and the details of the expansion
- v_2 can reflect the degree of freedom: partonic vs. hadronic

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

Motivation

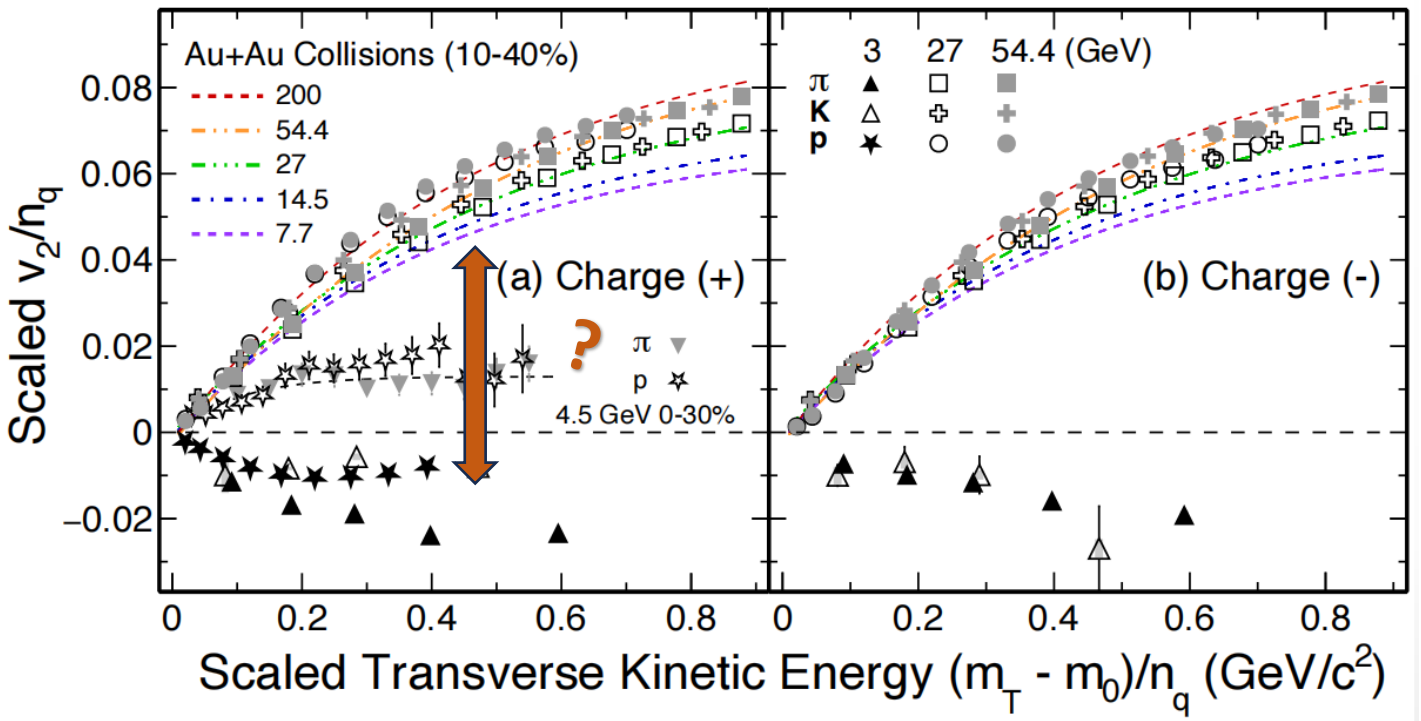
Directed Flow (v_1)



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

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

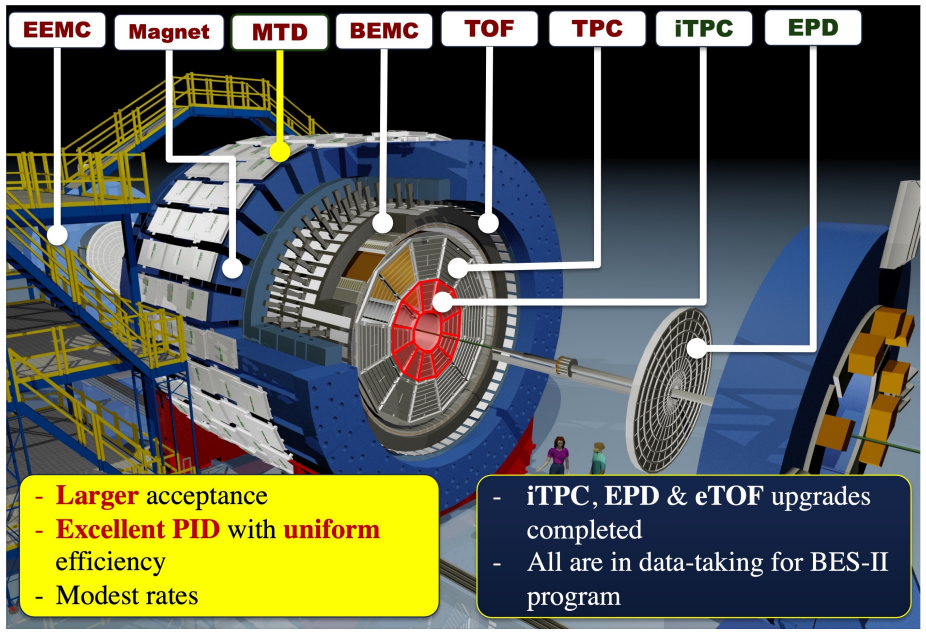
Elliptic Flow (v_2)



M. S. Abdallah et al. (STAR Collaboration), Phys. Lett. B 827 (2022) 137003

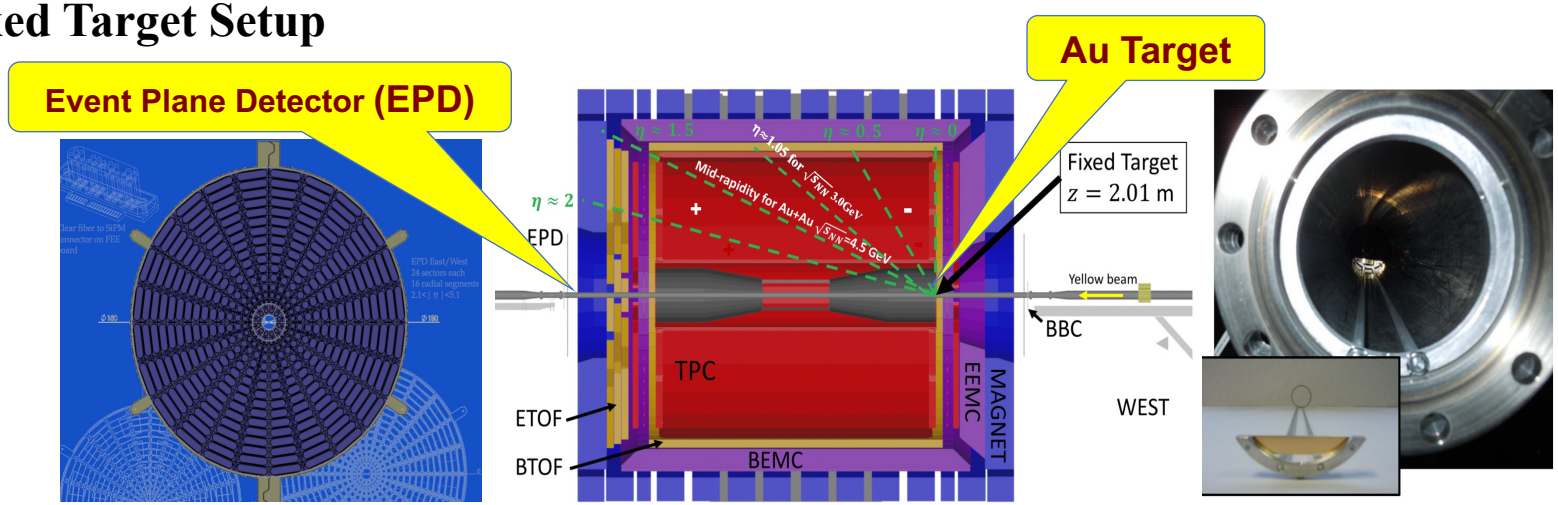
- At 3 GeV, the measured midrapidity v_2 for all particles are negative (positive at high energies) and NCQ scaling is absent

STAR Detector System

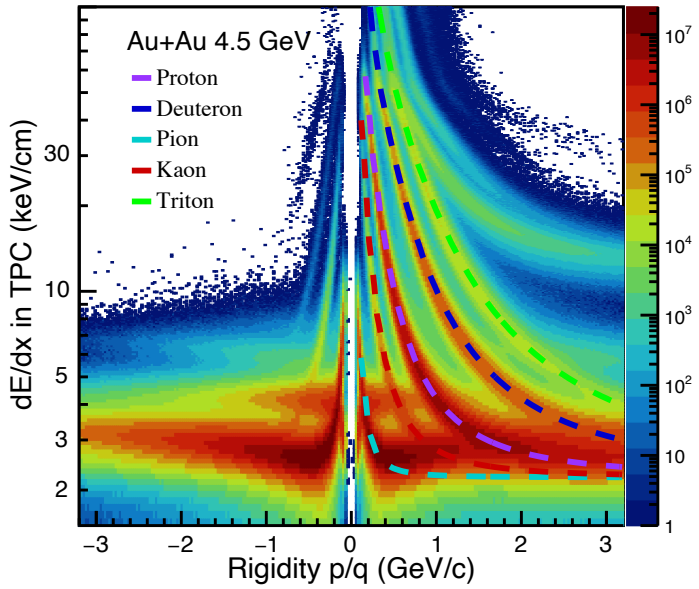


- inner TPC upgrade
  - Improves capability of PID
  - Extends η coverage from 1.0 to 1.5
- Endcap TOF
  - Extends rapidity coverage
  - Improves precision studies of observables rapidity dependence
- Event Plane Detector
  - Allows a better event plane resolution

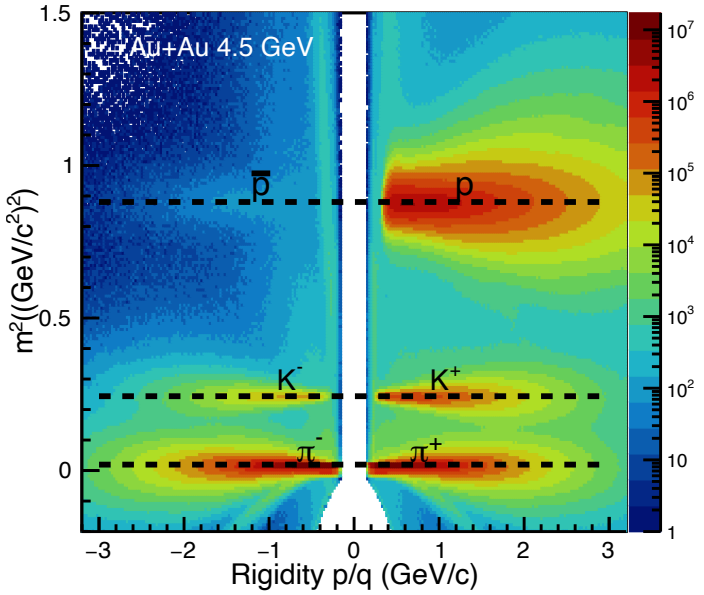
- **STAR Fixed Target Setup**

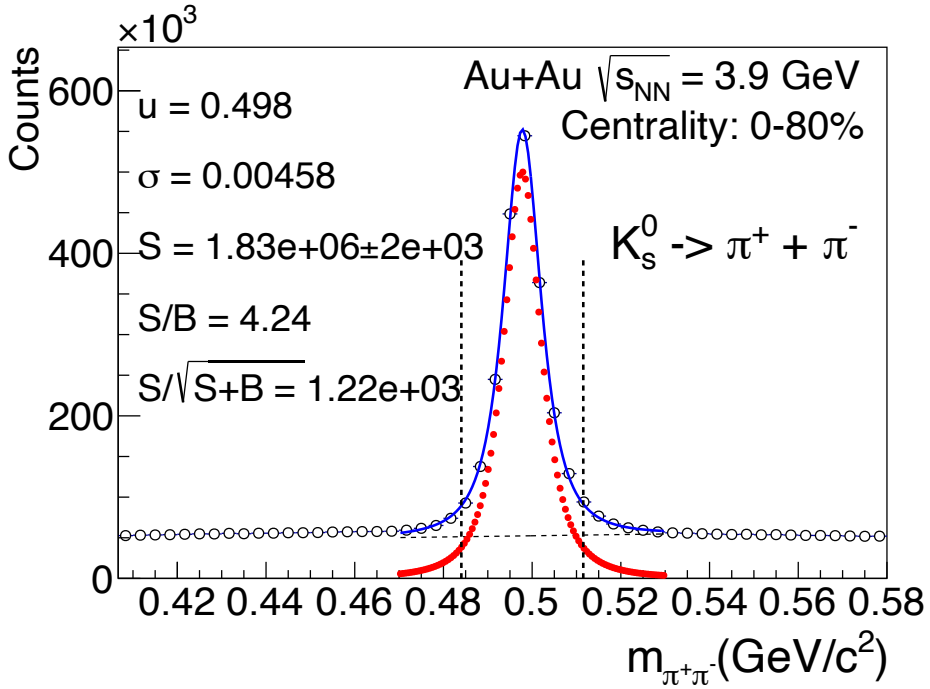


Particle Identification

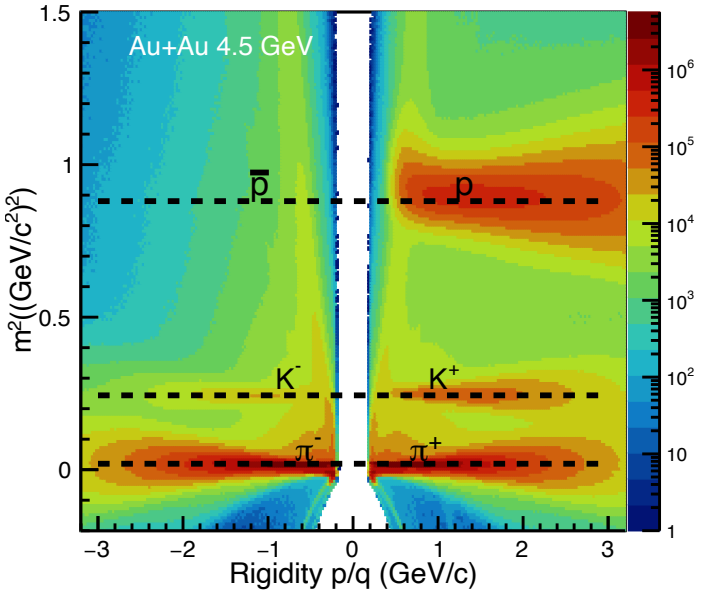


bToF





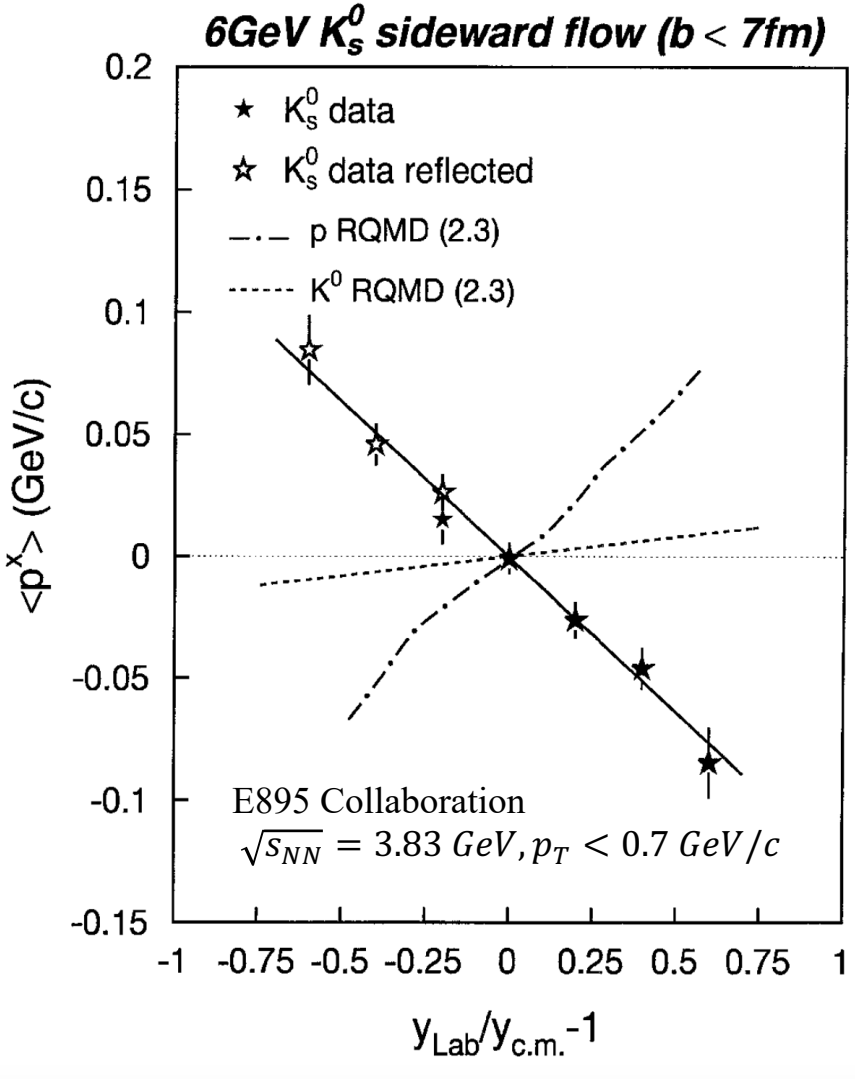
eToF

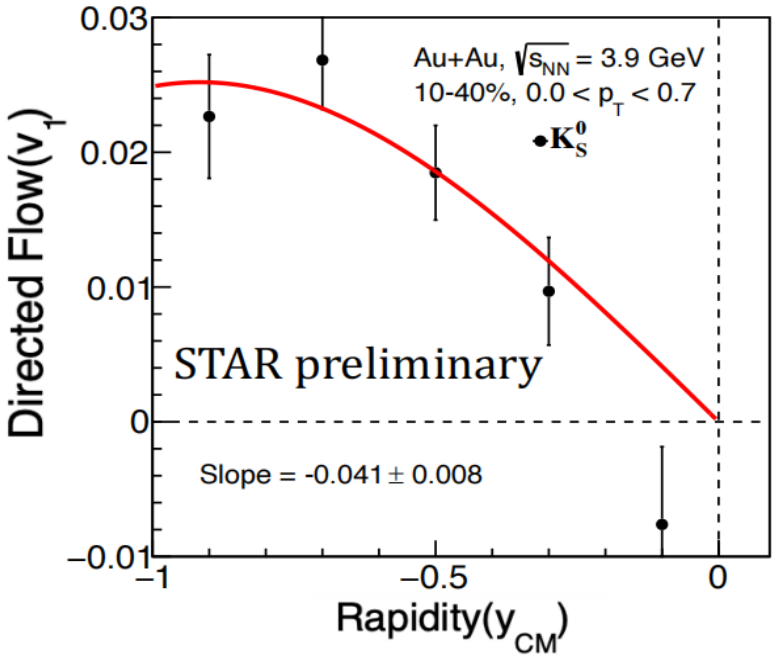


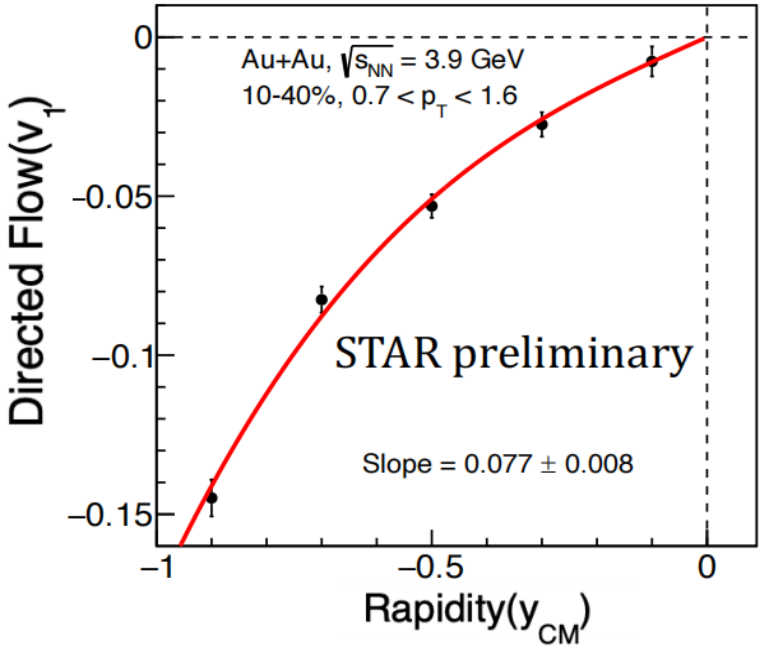
- Good capability of particle identification (PID) based on TPC and TOF
- Extend the phase space coverage by TOF
- Decayed particles are reconstructed by KF(Kalman Filter) particle package

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

Anti-flow of K_s^0





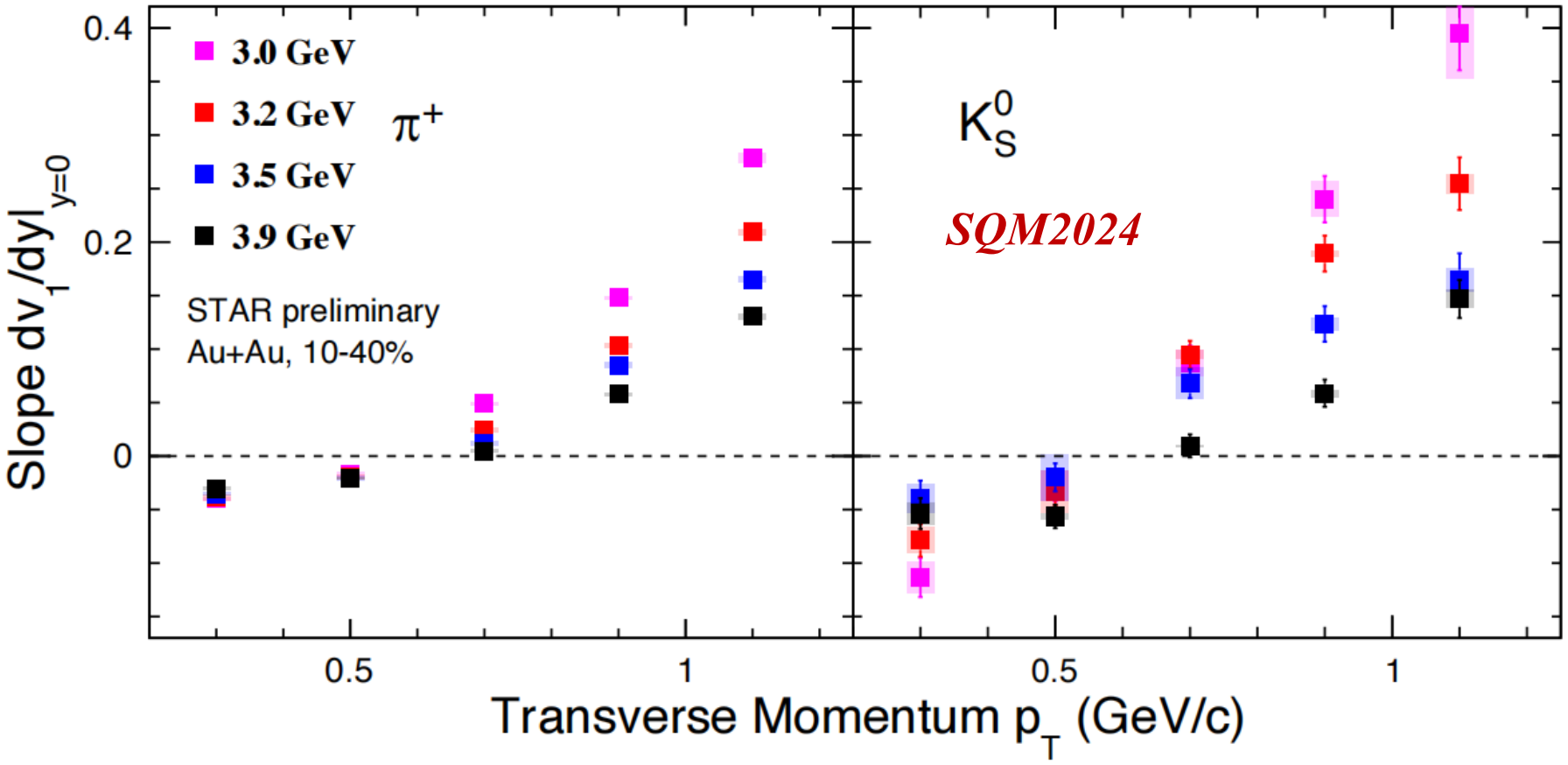


- Anti-flow of K_s^0 is observed at 3.9 GeV from RHIC – STAR BES-II (p_T < 0.7 GeV)

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

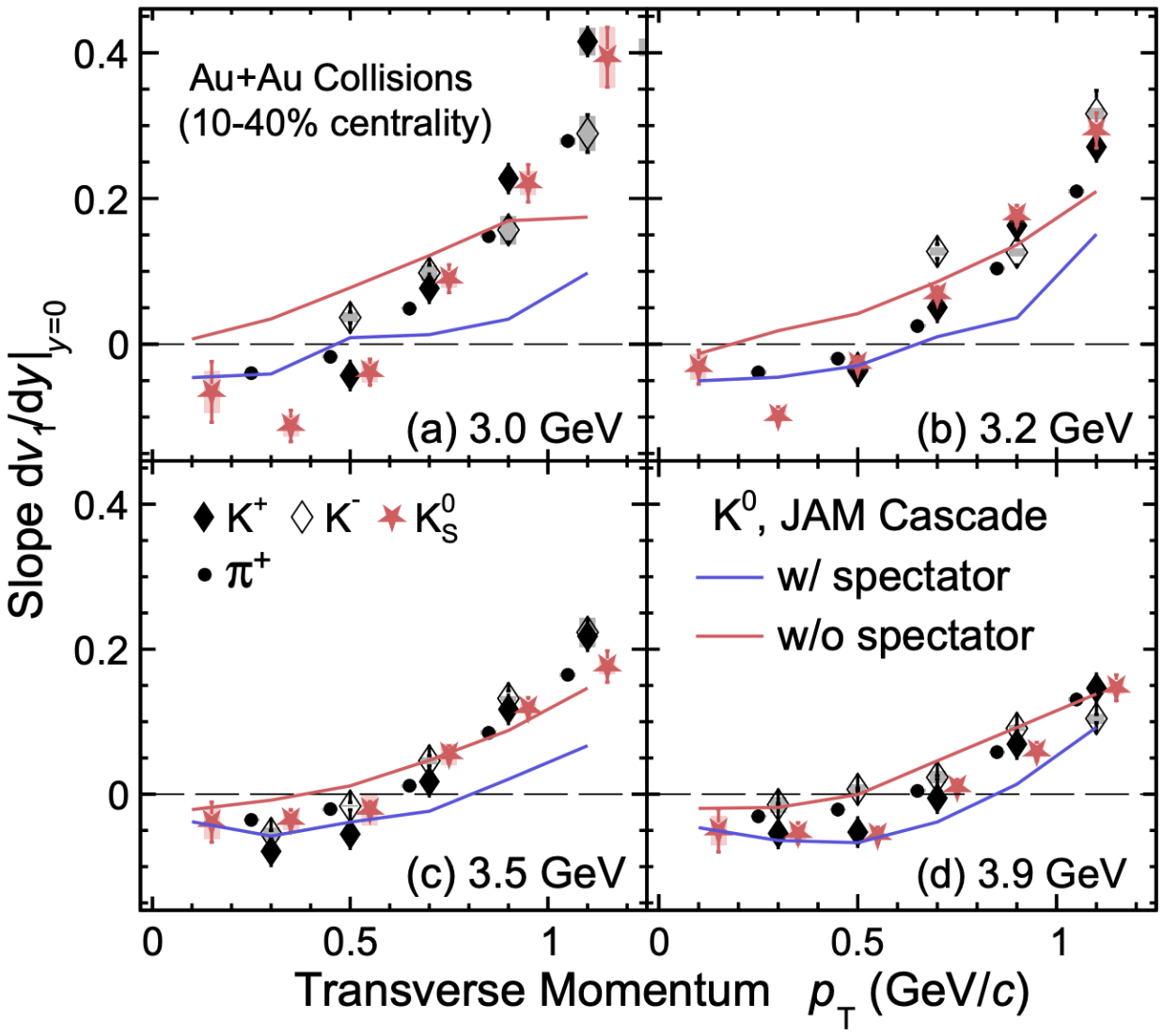
P. Chung et al. (E895 Collaboration), Phys. Rev. Lett. 85, 940(2000).

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

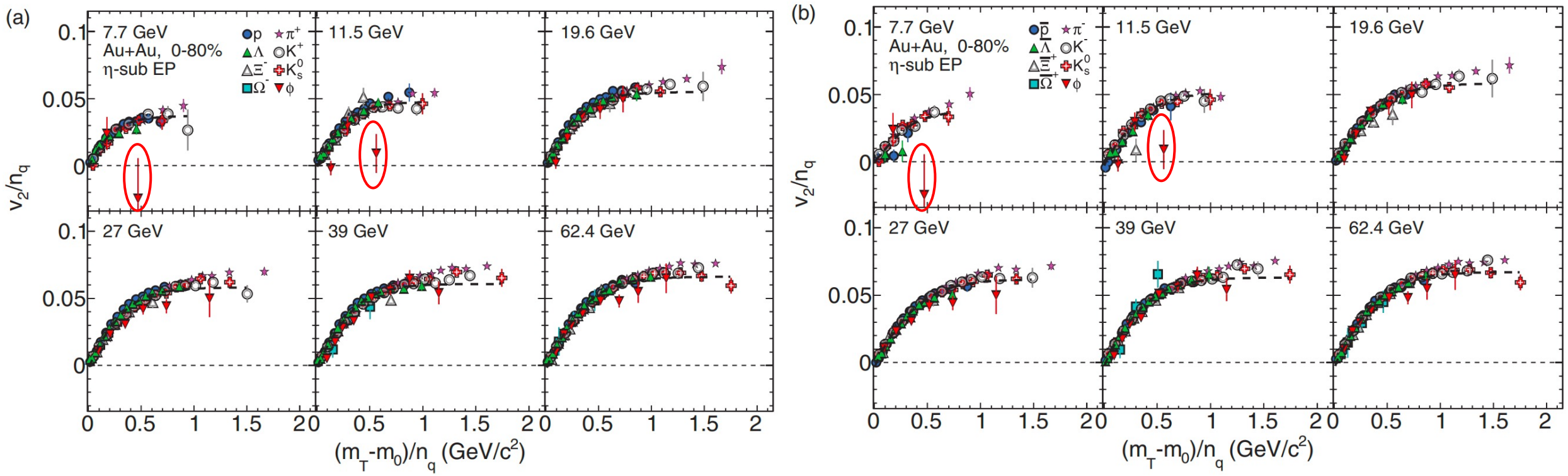


- JAM2 with and with no spectator cascade mode calculation of v_1 slope for 10-40% centrality bin at 3.0 - 3.9 GeV

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

STAR Collaboration. arXiv:2503.23665.

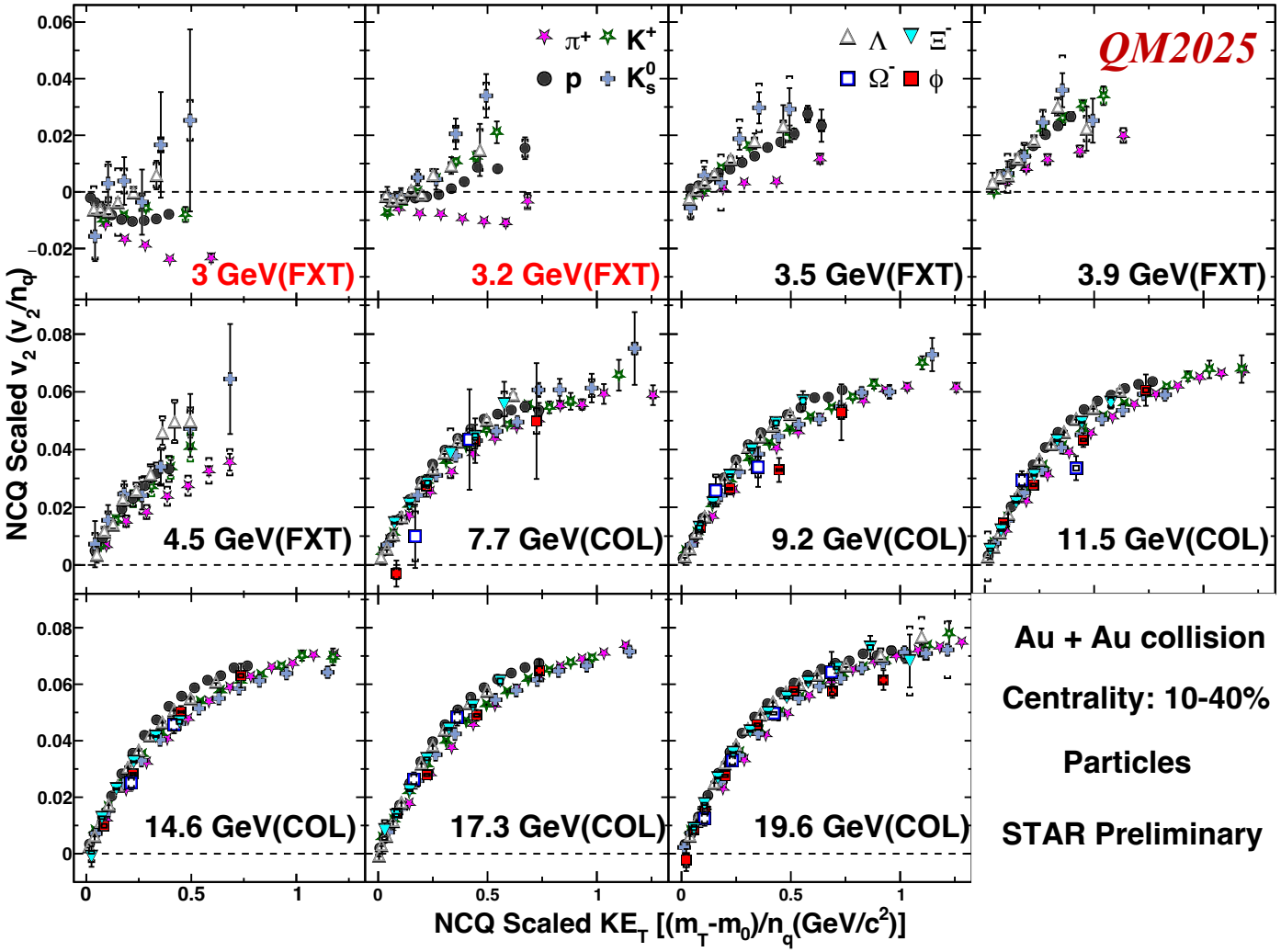
NCQ Scaling of v_2 from BES-I



- The ϕ meson v_2 at the highest measured $m_T - m_0$ value is low compared to other particles and anti-particles at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV with 1.8σ and 2.3σ respectively ***High-precision data needed***
- These observations may indicate that hadronic interactions become more important than partonic effects for the systems formed at collision energies $\lesssim$ 11.5 GeV

STAR Collaboration, Phys. Rev. C 88, 014902 (2013)
STAR Collaboration, Phys. Rev. Lett. 110, 142301 (2013)

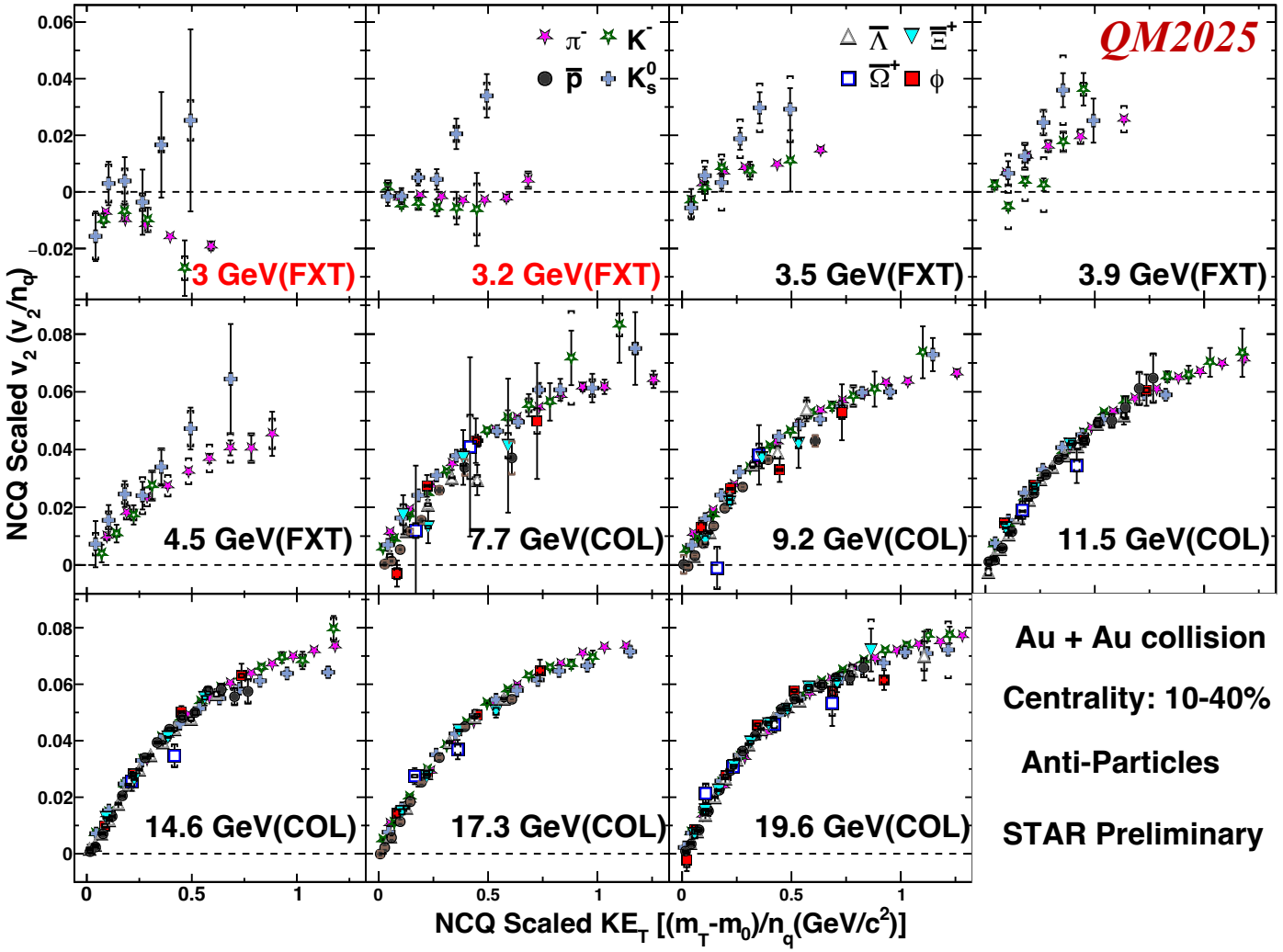
NCQ Scaling of particles v_2 from BES-II



- NCQ scaling of particles v_2 completely breaks below 3.2 GeV
- NCQ Scaling restoration at $\sqrt{s_{NN}} \geq 4.5$ GeV
  → Emergence of partonic collectivity
- The ϕ meson and multi-strange hadron v_2/n_q do not deviate from other particles at $\sqrt{s_{NN}} \geq 7.7$ GeV
  → Partonic collectivity

STAR Collaboration. arXiv:2504.02531.

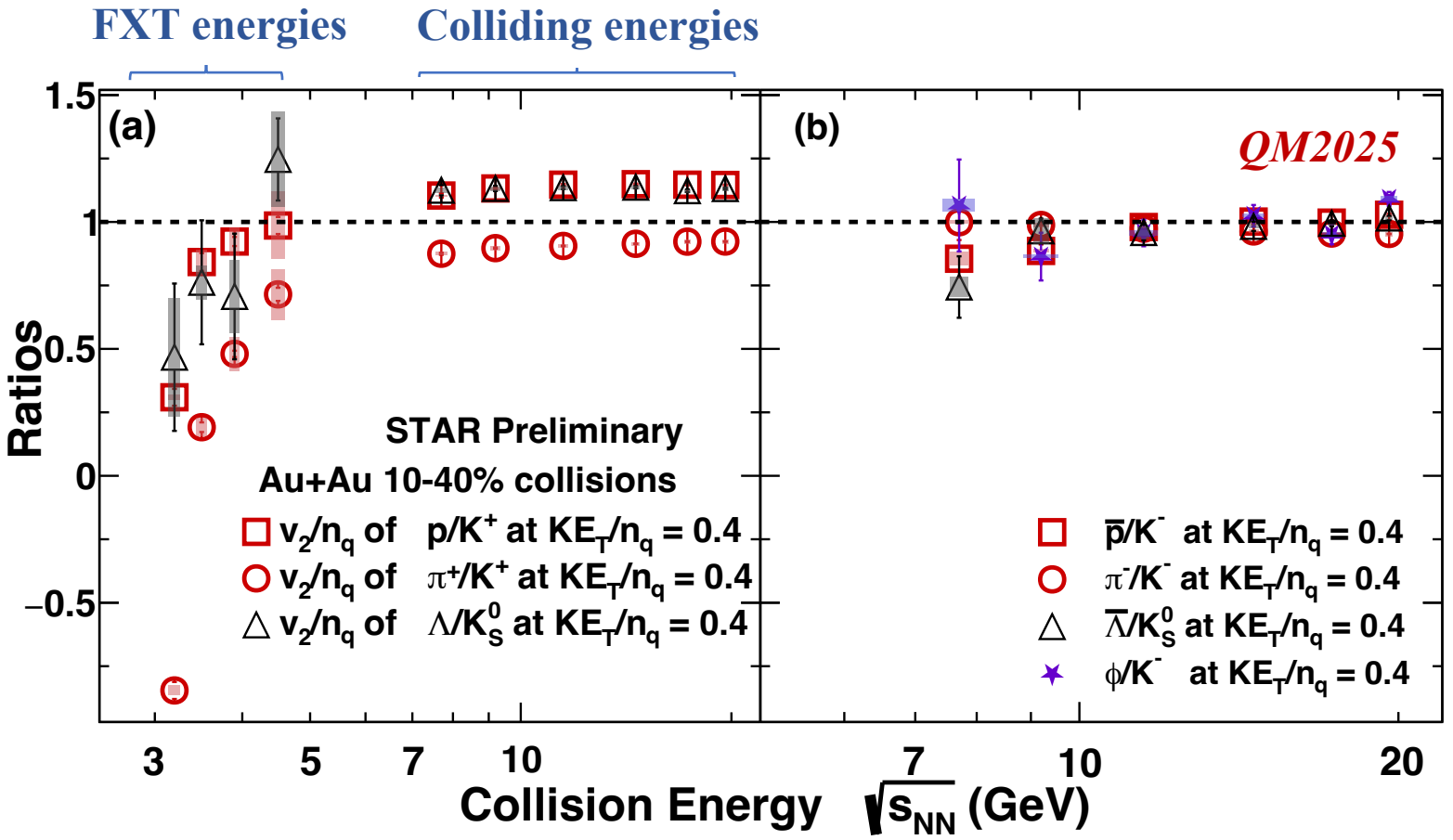
NCQ Scaling of anti-particles v_2 from BES-II



- NCQ scaling of anti-particles v_2 completely breaks below 3.2 GeV
- NCQ Scaling restoration at $\sqrt{s_{NN}} \geq 4.5$ GeV
  → Emergence of partonic collectivity
- The ϕ meson and multi-strange hadron v_2/n_q do not deviate from other anti-particles at $\sqrt{s_{NN}} \geq 7.7$ GeV
  → Partonic collectivity

STAR Collaboration. arXiv:2504.02531.

Energy Dependence of NCQ Scaling Ratios



- The NCQ scaled v_2 ratios are close to 1 at $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV and are less dependent on the collision energy

  → Partonic collectivity in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV

STAR Collaboration. arXiv:2504.02531.

Summary and Outlook

- Anti-flow of K_s^0 is observed at 3.0-3.9 GeV

  → Shadowing effect by spectators

- NCQ Scaling breaks at 3.2 GeV and below

  → Hadronic interaction dominates

- NCQ Scaling restoration at $\sqrt{s_{NN}} \geq 4.5$ GeV

  → Emergence of partonic collectivity

- The ϕ meson and multi-strange hadron v_2/n_q do not deviate from other particles and anti-particles at $\sqrt{s_{NN}} \geq 7.7$ GeV.

  → Partonic interaction dominates

Outlook:

- FAIR, NICA, HIAF, etc. future BES facilities: explore the QCD phase structure