Anisotropic Flow of Identified Particles in Au + Au Collisions at $\sqrt{s_{NN}}$ = 3 – 19.6 GeV

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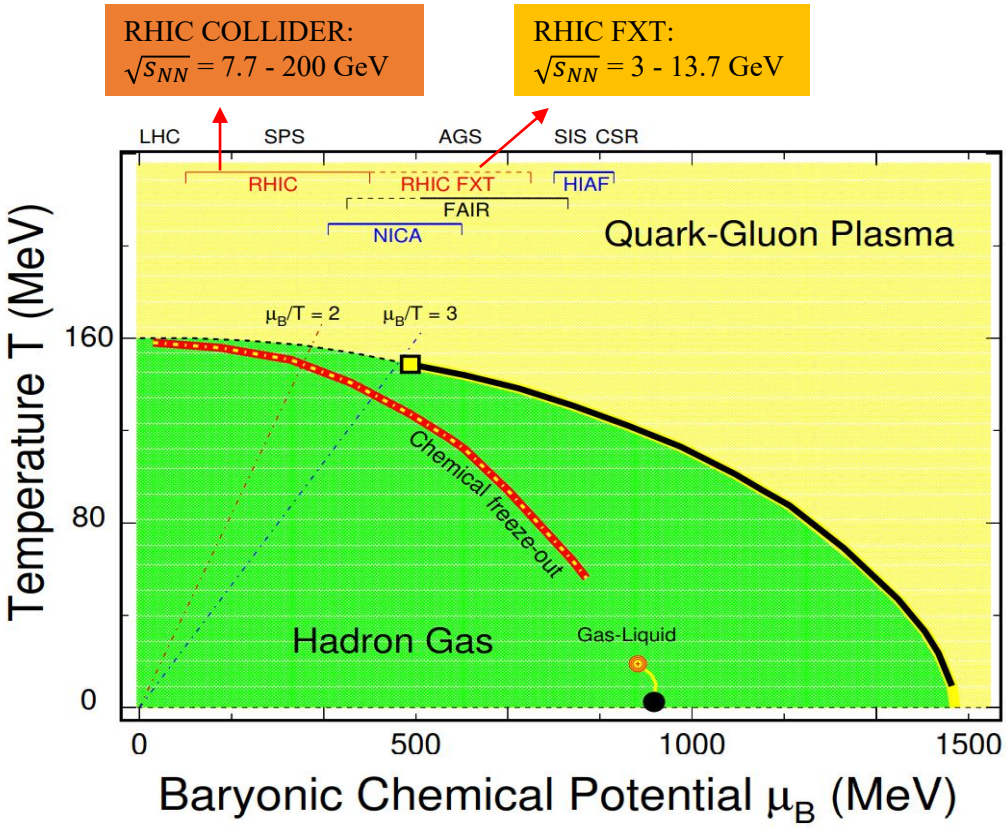
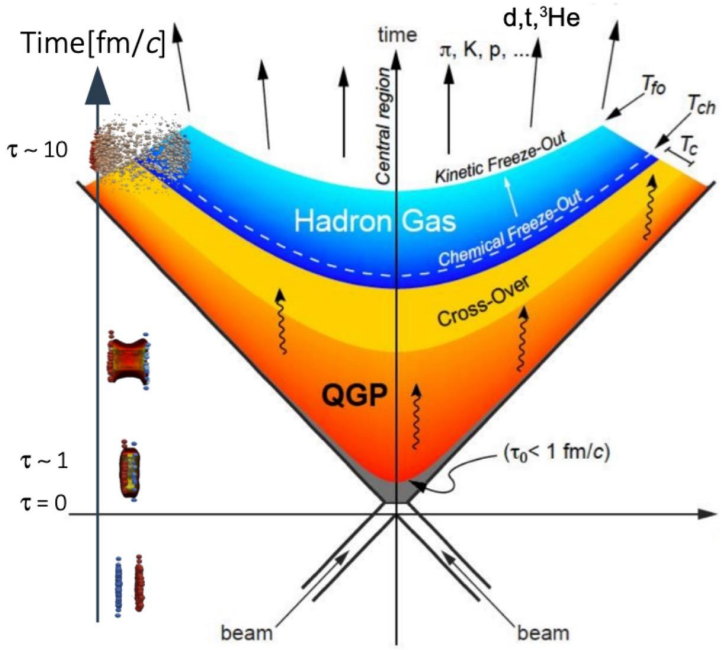
Outline

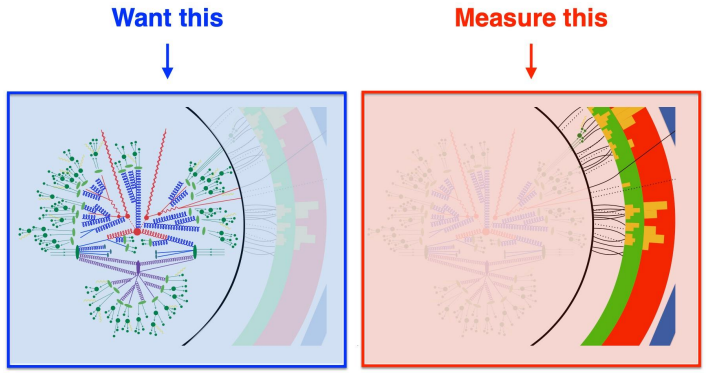
- Motivation
- Anti-flow of Mesons
- Energy Dependence of v_2
- NCQ Scaling
- Summary and Outlook

Motivation – QCD Phase Diagram



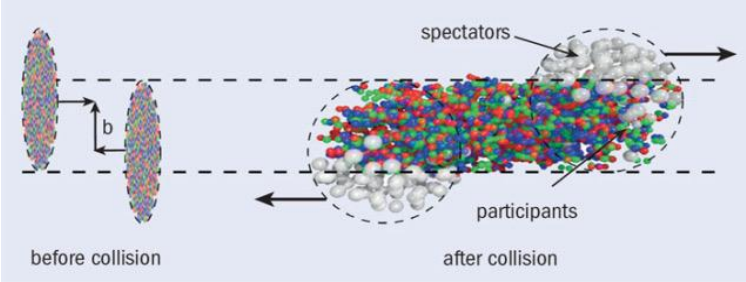
X.Luo, S.Shi, Nu Xu et al. Particle 3, 278 (2020)



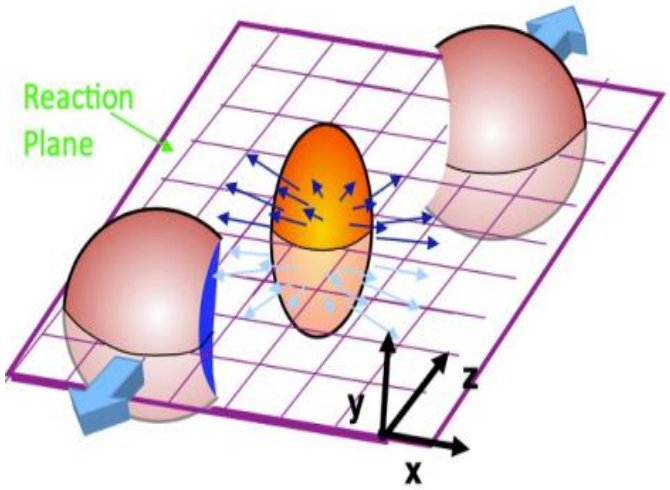


- Study the properties of QGP
- Search for the critical point and locate the first-order phase boundary

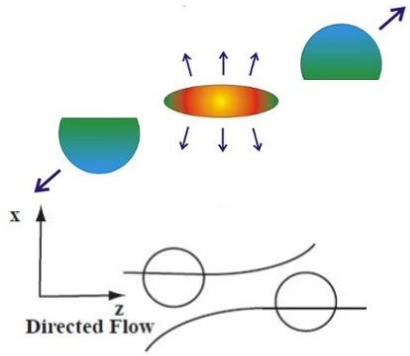
Motivation – Anisotropic Flow



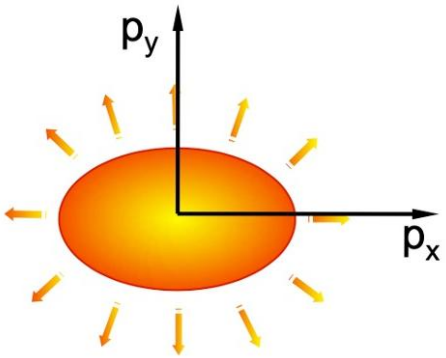
$$\frac{dN}{d(\phi-\Psi)} \sim 1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi))$$



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



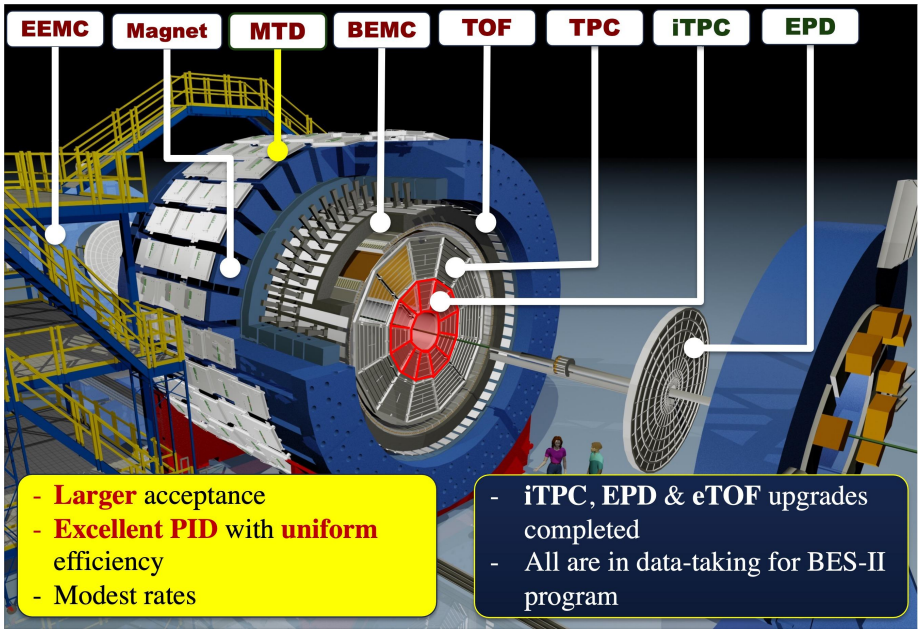
- Elliptic flow: $v_2 = \langle \cos 2(\phi - \Psi) \rangle$



- 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

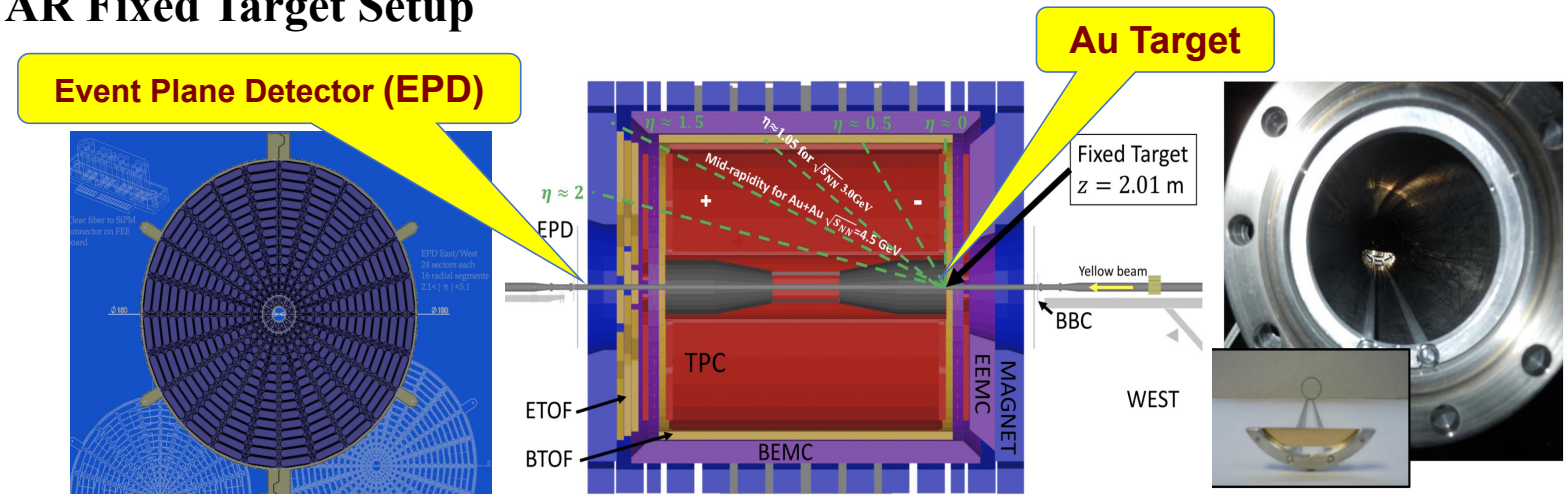
S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998).

STAR Detector System

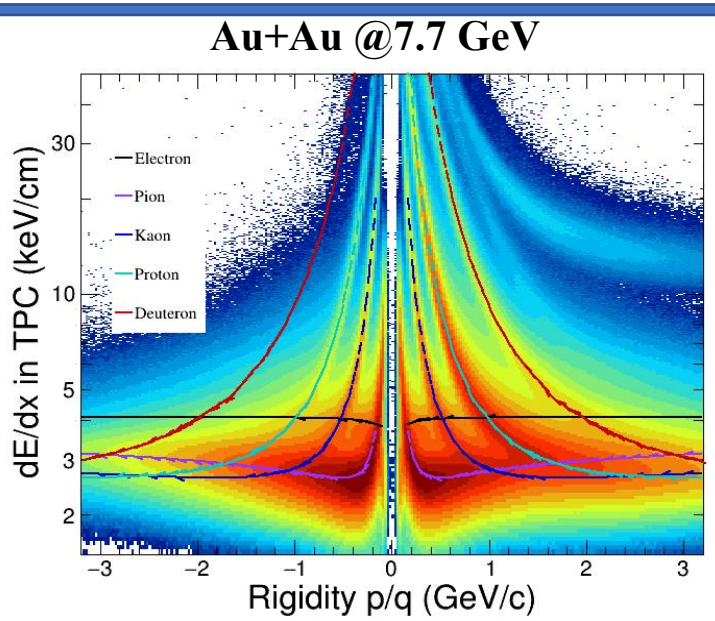


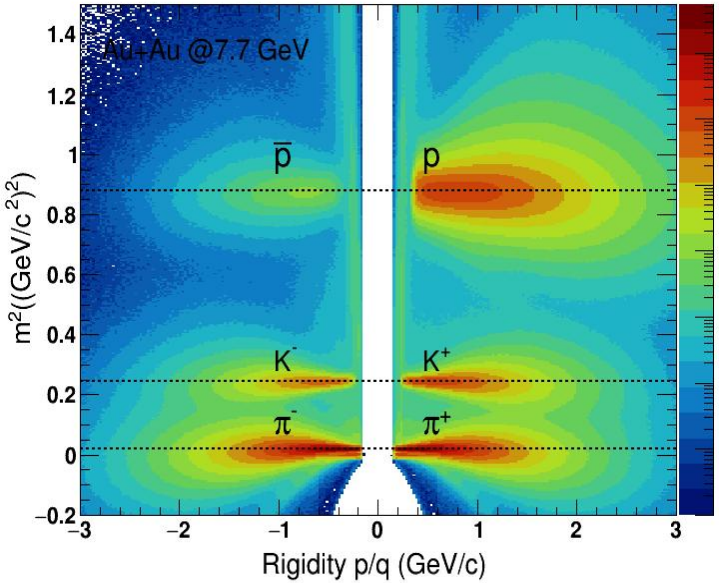
- inner TPC upgrade
  - Improves capability of PID
  - Extends η coverage from 1.0 to 1.5
- Endcap TOF
  - Extends rapidity coverage
  - Improves precision studies of observables rapidity dependence
- Event Plane Detector
  - Allows a better event plane resolution

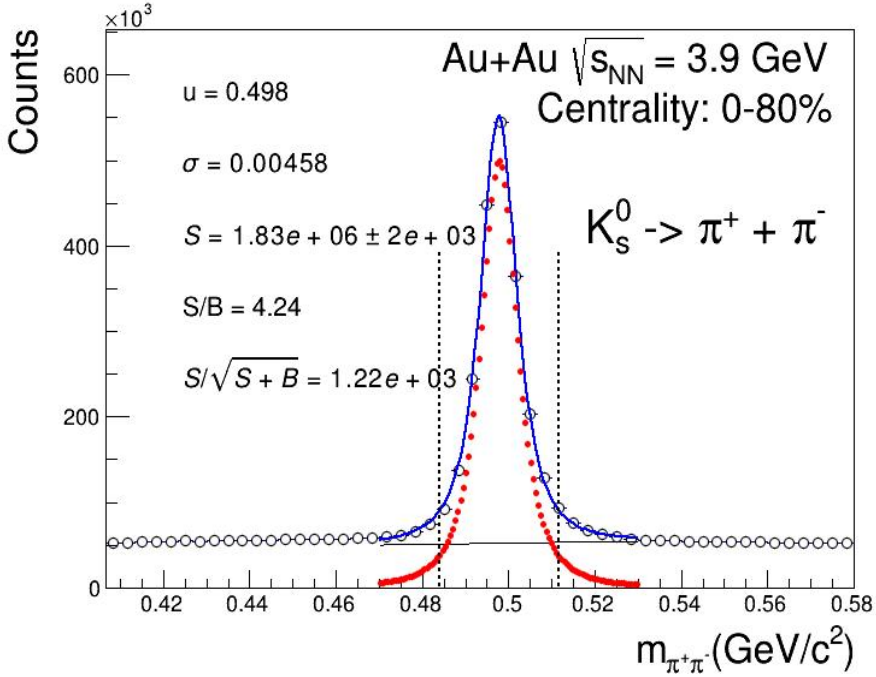
- **STAR Fixed Target Setup**



Particle Identification



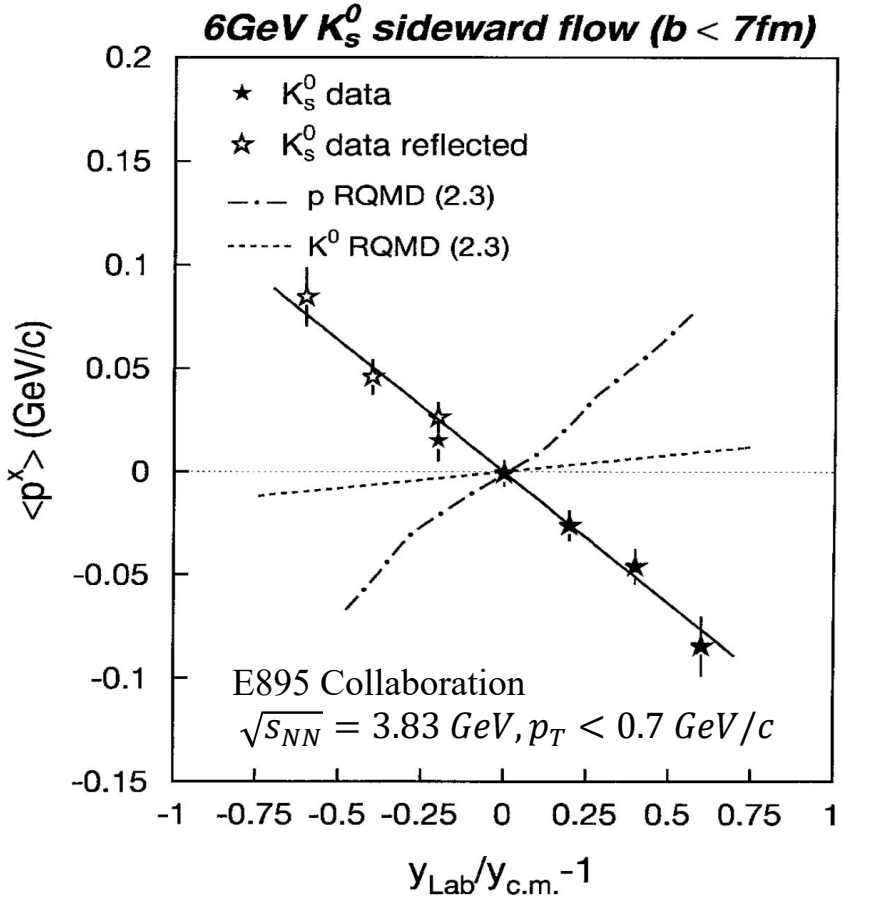




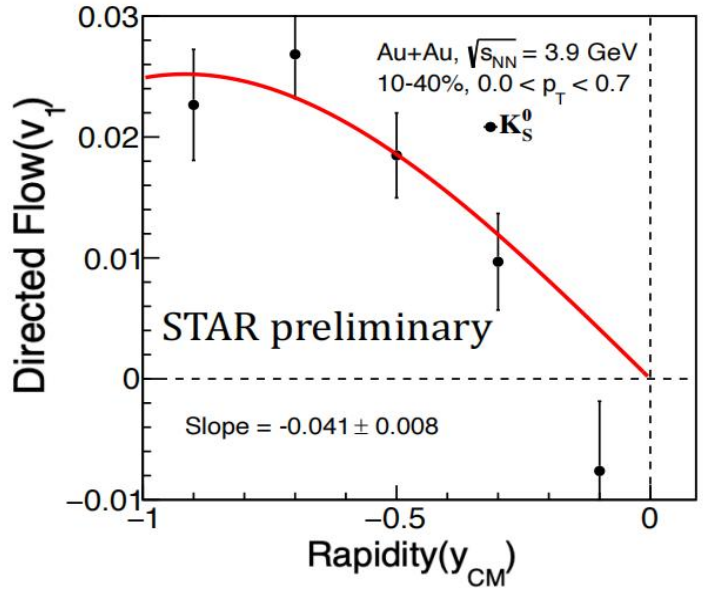
- Good capability of particle identification (PID) based on TPC and TOF
- Extend the phase space coverage by TOF
- Decayed particles are reconstructed by KF(Kalman Filter) particle package

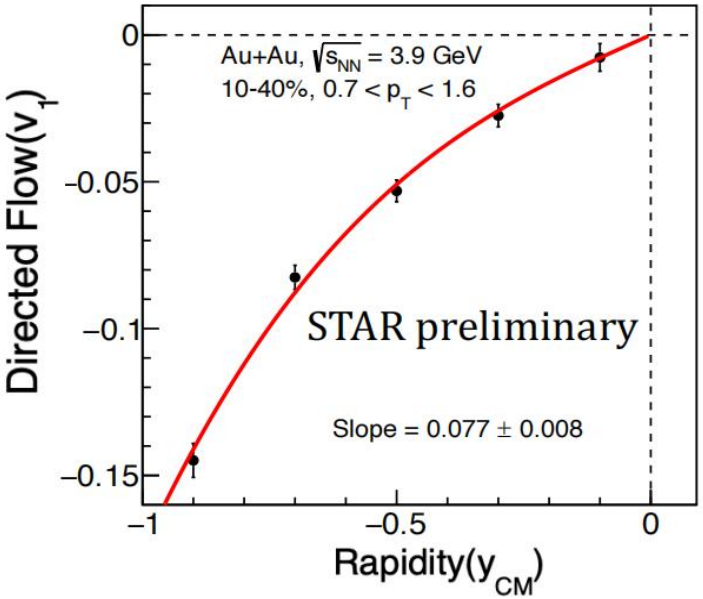
A. Banerjee, I. Kisel and M. Zyzak, Int. J. Mod. Phys. A 35, 2043003 (2020)

Anti-flow of K_s^0



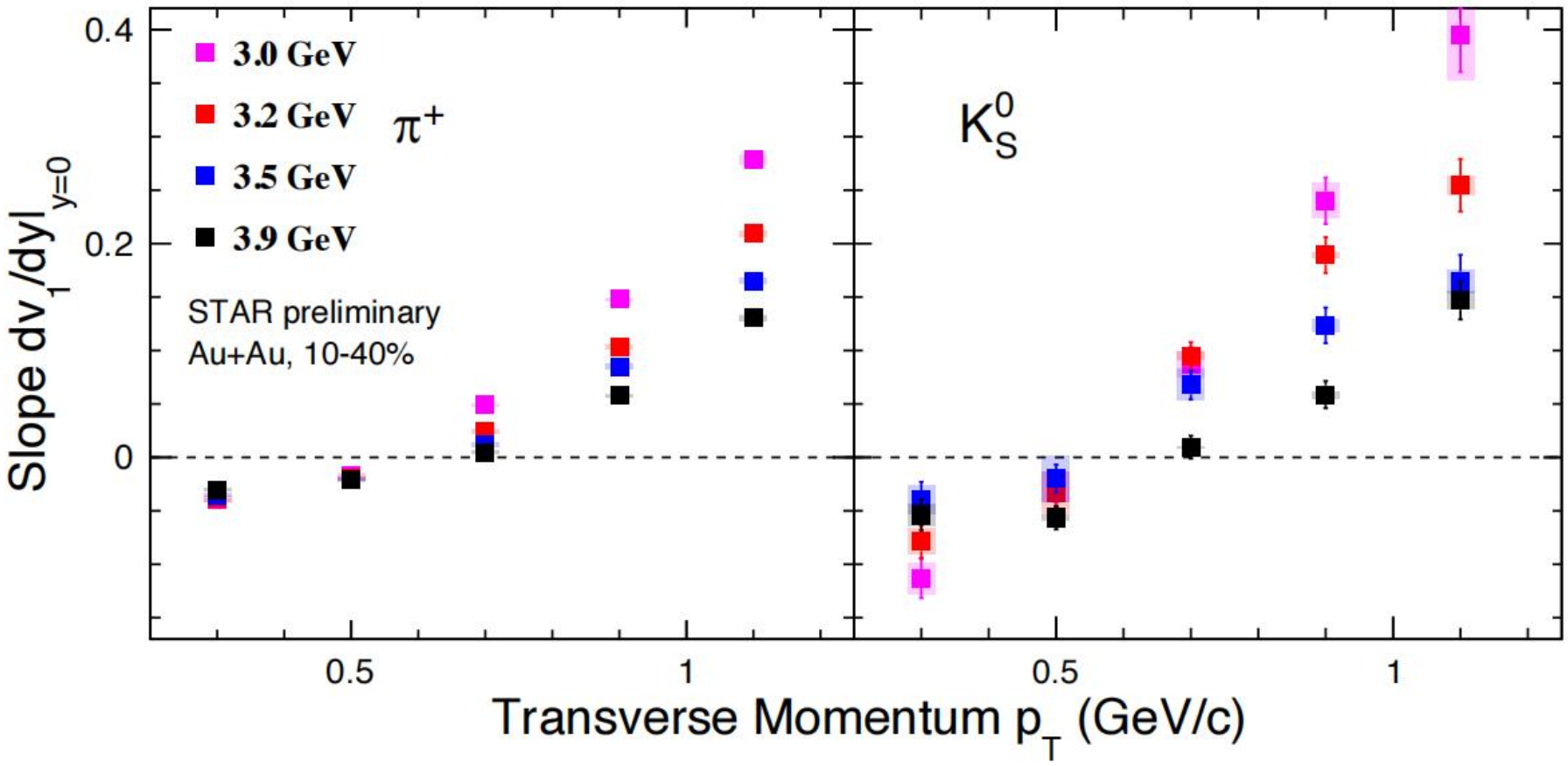
P. Chung et al. (E895 Collaboration), Phys. Rev. Lett. 85, 940(2000).





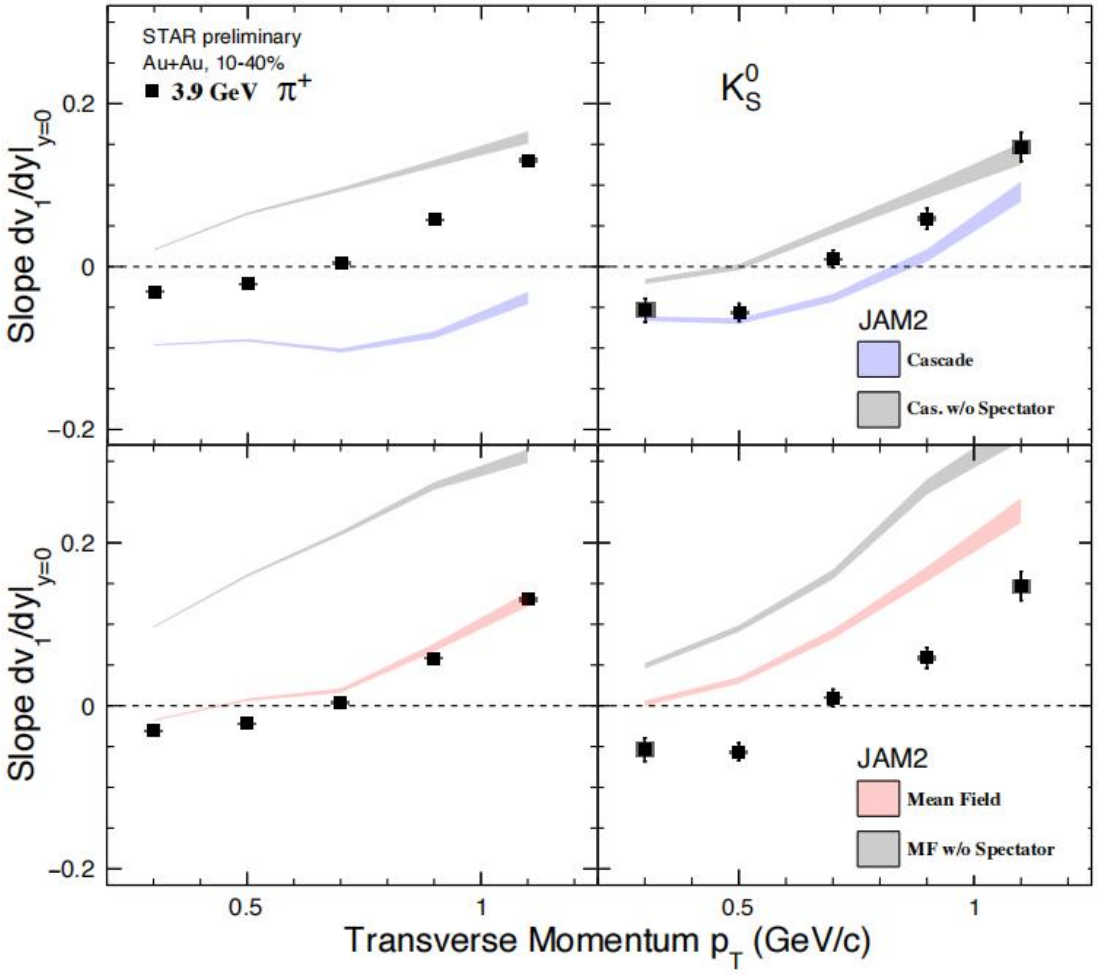
- E895: Kaon vector potential plays an important role in high density nuclear matter
- Anti-flow of K_s^0 is observed at 3.9 GeV (p_T < 0.7 GeV)

Anti-flow of Mesons



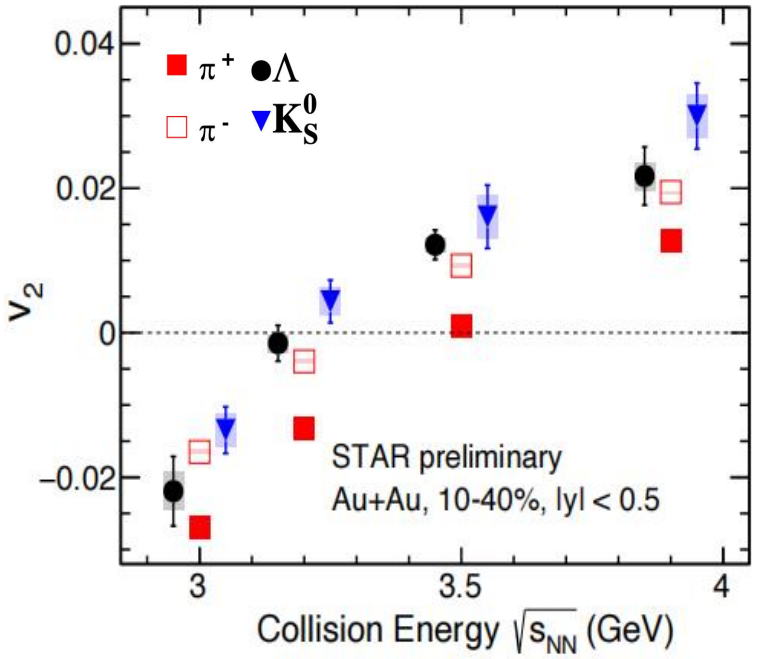
- v_1 slope of $\pi^+$and K_s^0 as a function of p_{T} measured for 10-40% centrality
- The v_1 slope decreases as the collision energy increasing
- Anti-flow of $\pi^+$and K_s^0 are observed in low p_T region at 3.0 - 3.9 GeV

Anti-flow of Mesons

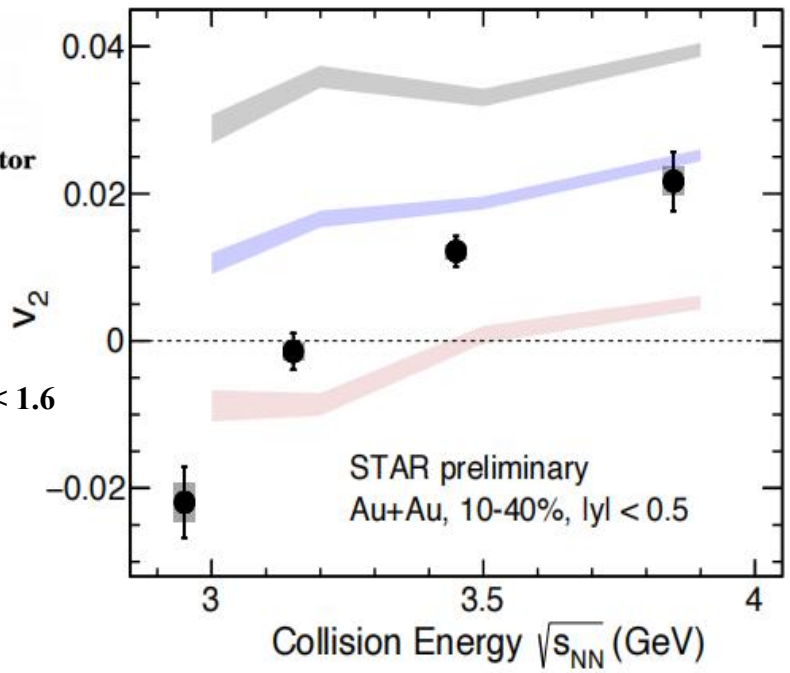


- JAM2 cascade mode and mean-field mode calculation of v_1 slope for 10-40% centrality bin at 3.9 GeV
- Shadowing effect from spectator may lead to anti-flow at low p_T

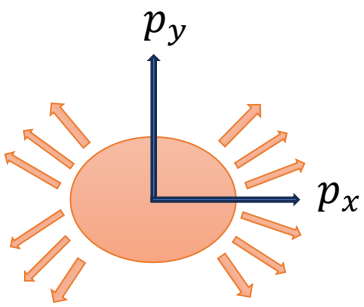
Energy Dependence of v_2



π/K^0_s:0.2/0.4 < p_T < 1.6
Λ:0.4 < p_T < 2.0

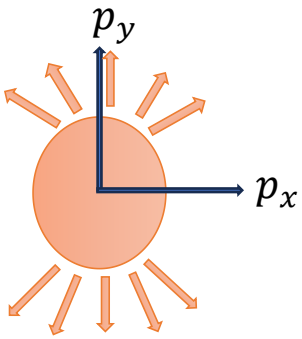


$v_2 > 0$



In-Plane expansion

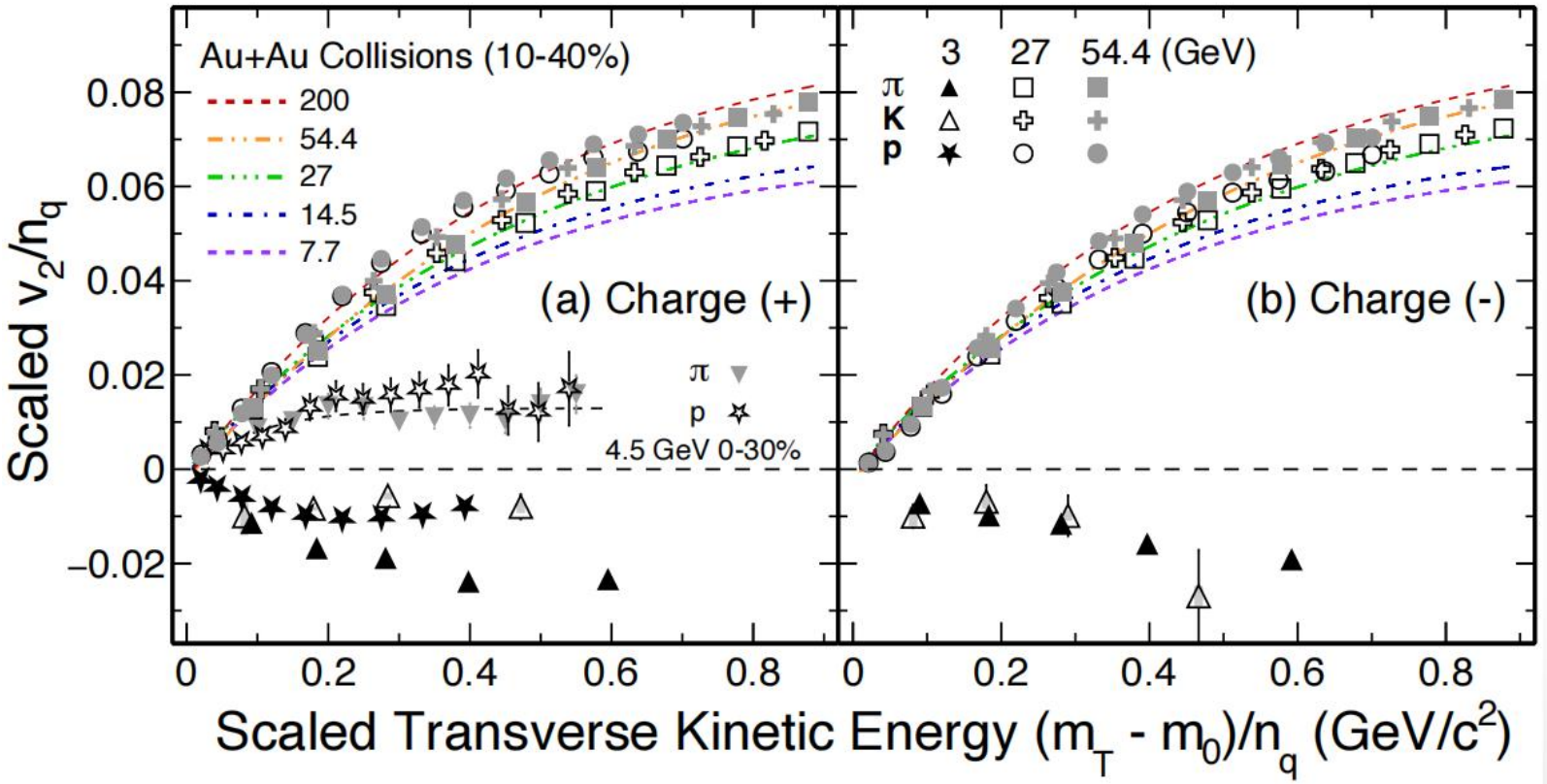
$v_2 < 0$



Out-of-Plane expansion

- Negative v_2 of all particles goes to positive value from 3 GeV to 3.9 GeV
- Squeeze-out effect from spectator result in sign change of v_2
- JAM2 calculations of mean-field with spectator reproduce sign change of v_2

NCQ Scaling of v_2 at 3 GeV

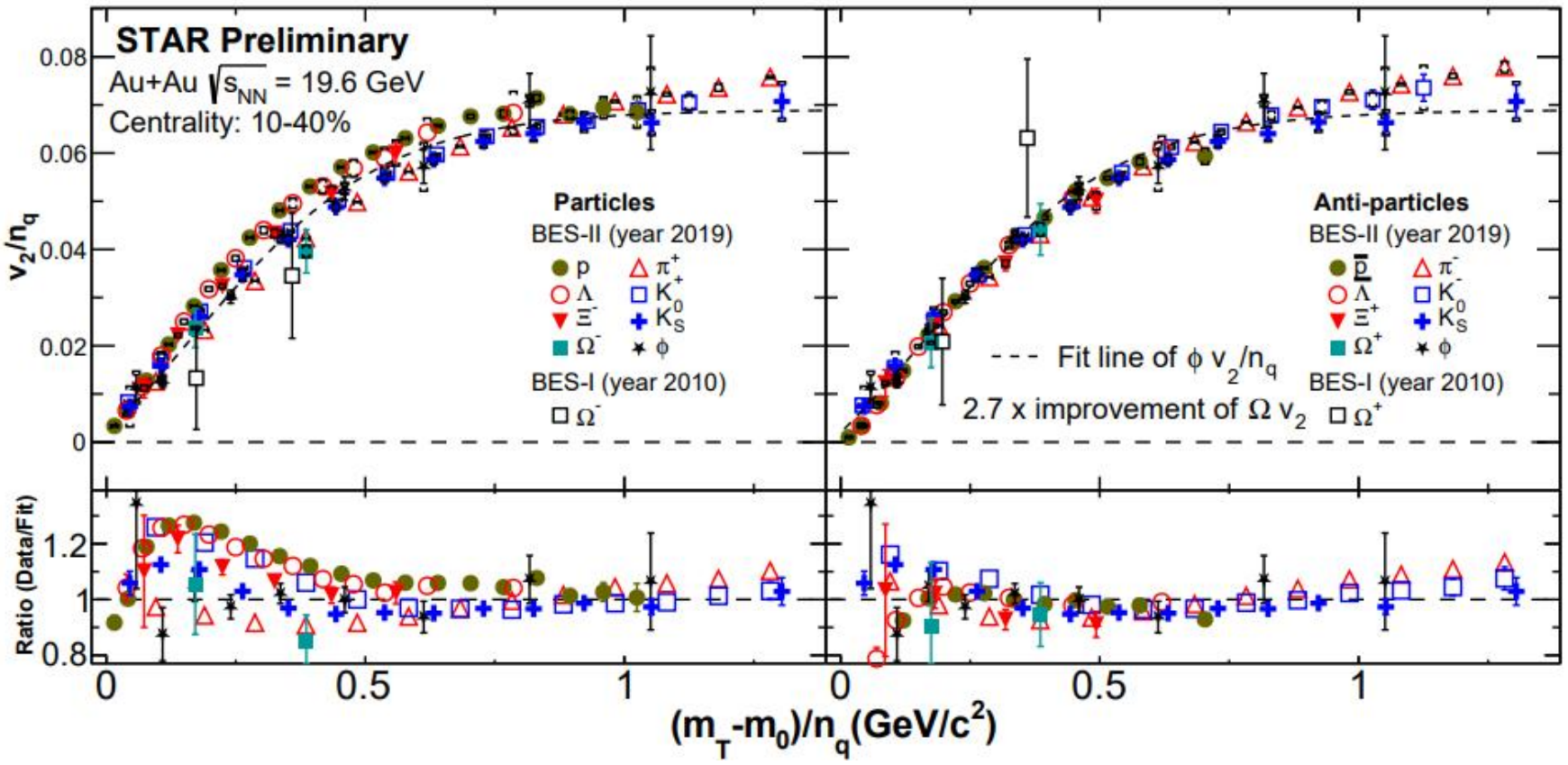


M. S. Abdallah et al. (STAR Collaboration), Phys. Lett. B 827 (2022) 137003

- At 3 GeV, the measured midrapidity v_2 for all particles are negative (positive at high energies) and NCQ scaling is absent
- Equation-of-State dominated by baryonic interactions

  → The hadronic degree of freedom dominated

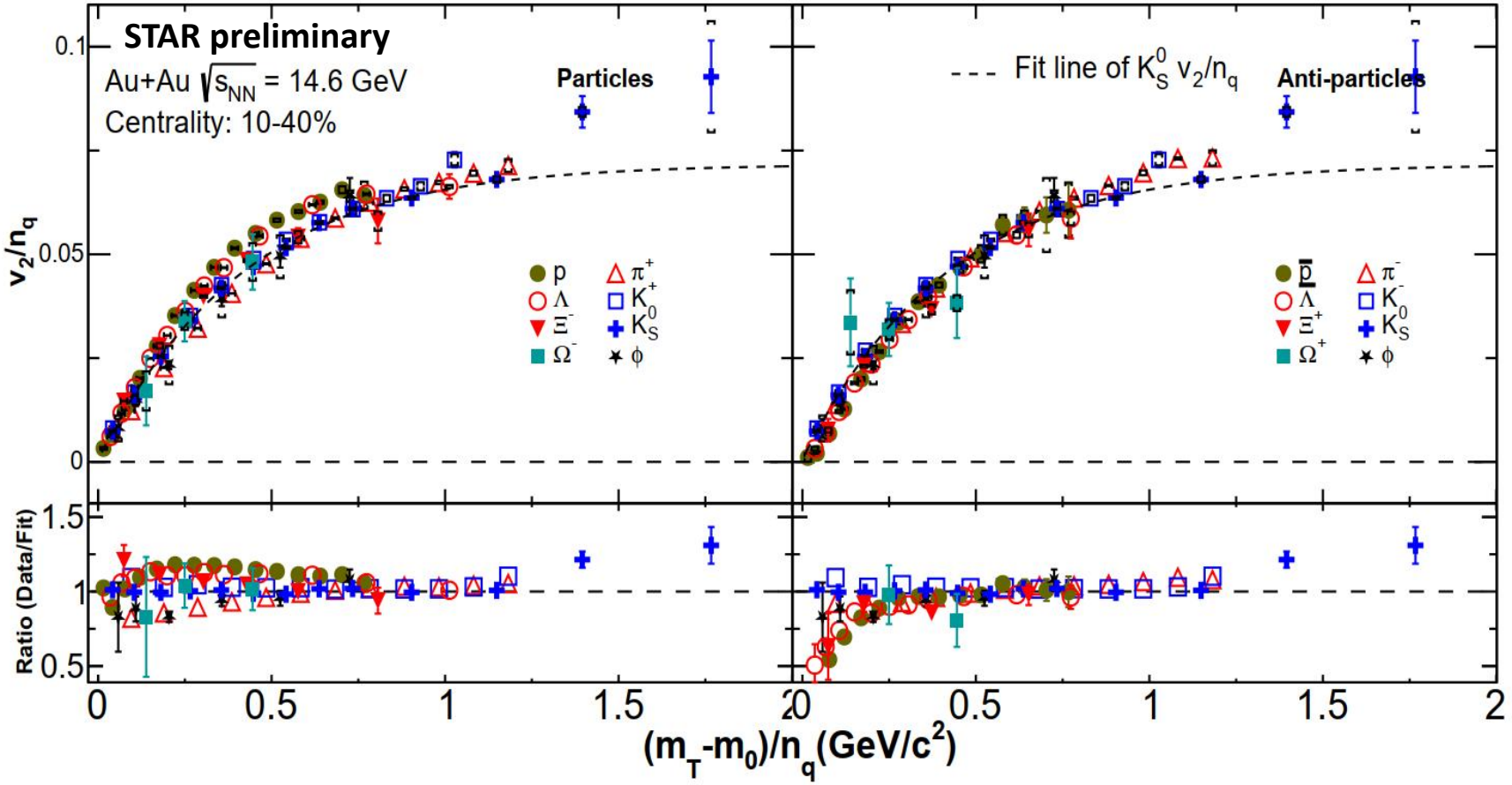
NCQ Scaling of v_2 at 19.6 GeV



- The NCQ scaling holds within 20% for particles and within 10% for anti-particles
- The NCQ scaling of anti-particles is better than particles: produced vs. transported quarks

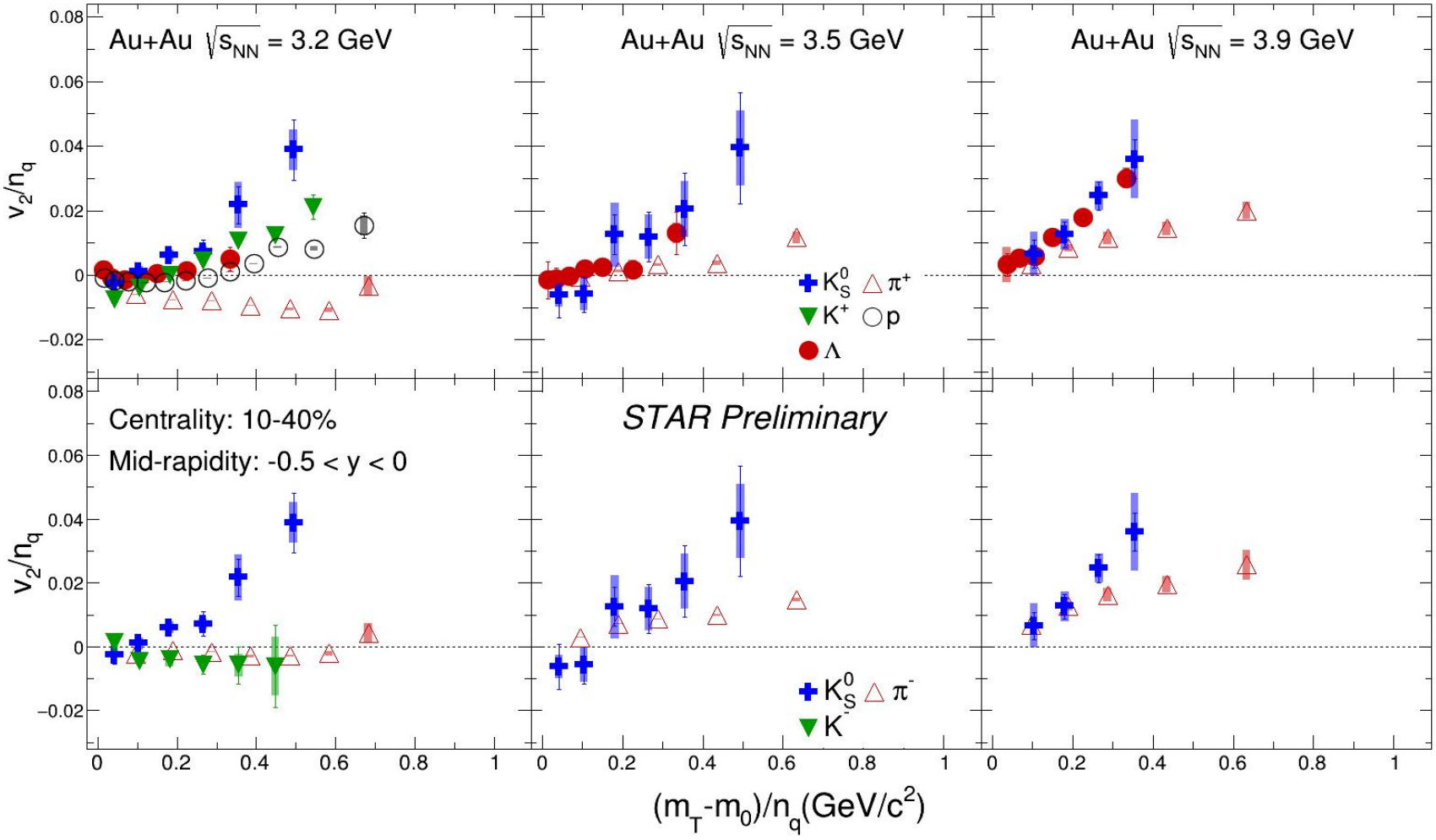
→ The collectivity has been built up in the partonic stage at 19.6 GeV

NCQ Scaling of v_2 at 14.6 GeV



- The NCQ scaling holds within 15% for anti-particles and within 25% for particles
  → Partonic collectivity at 14.6 GeV

NCQ Scaling of v_2 at 3.2 - 3.9 GeV

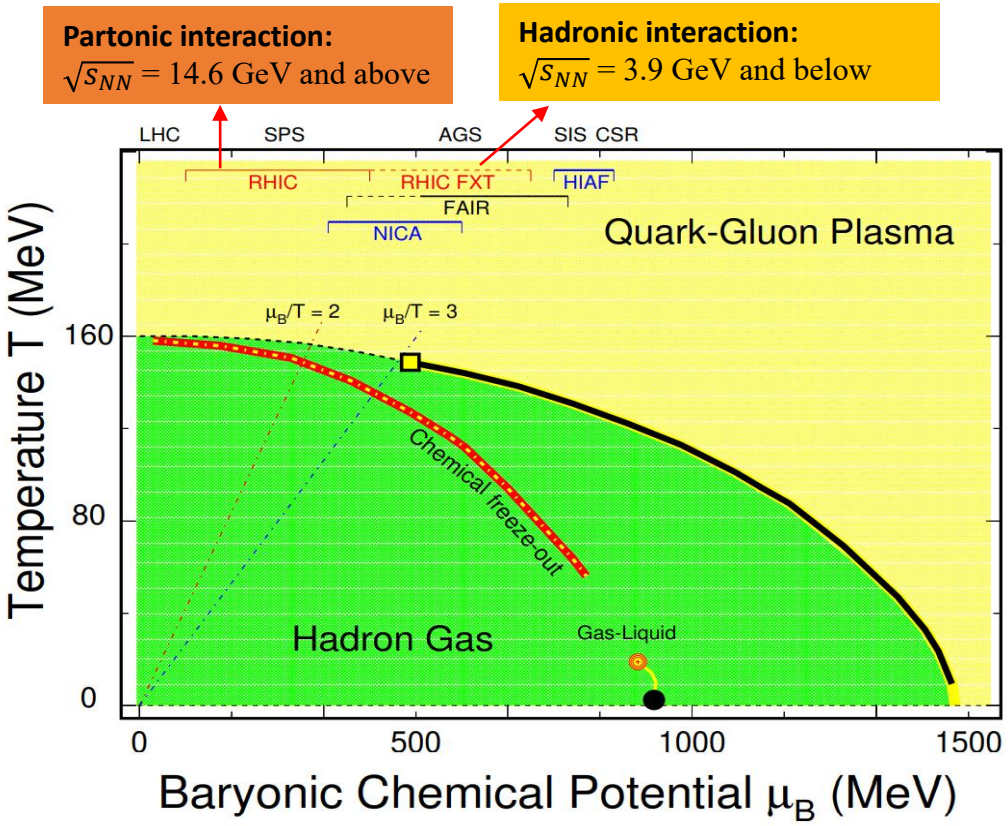


- The NCQ scaling breaks at 3.9 GeV and below

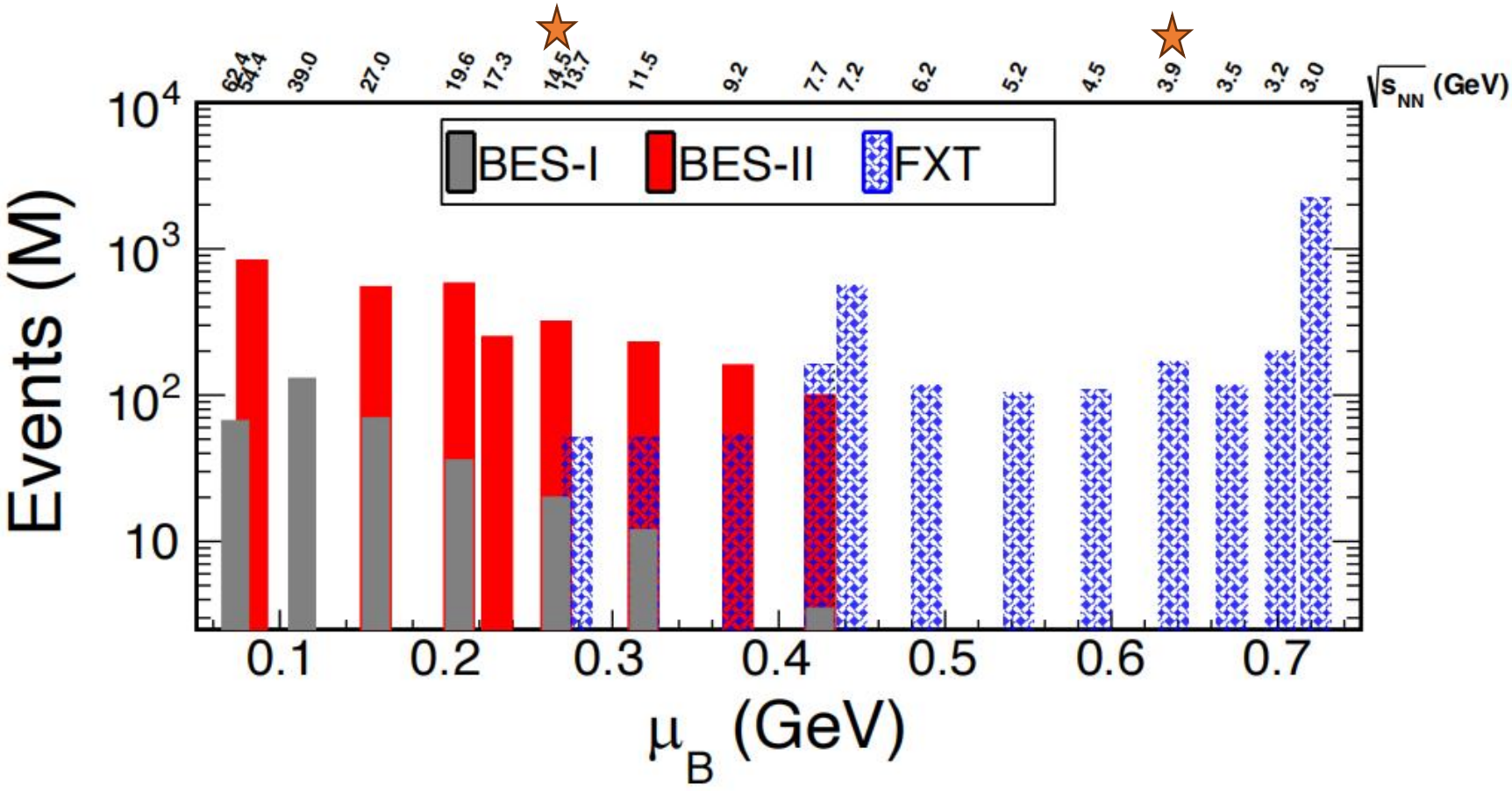
  → Hadronic interaction dominates

Summary and Outlook

- 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 holds at 14.6 GeV and above → Partonic interaction dominates
- NCQ Scaling breaks at 3.9 GeV and below → Hadronic interaction dominates



Summary and Outlook



- Higher statistics, better detector performance and more energy points in BES-II
- Explore the QCD phase diagram

Thank you for your attention!