



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

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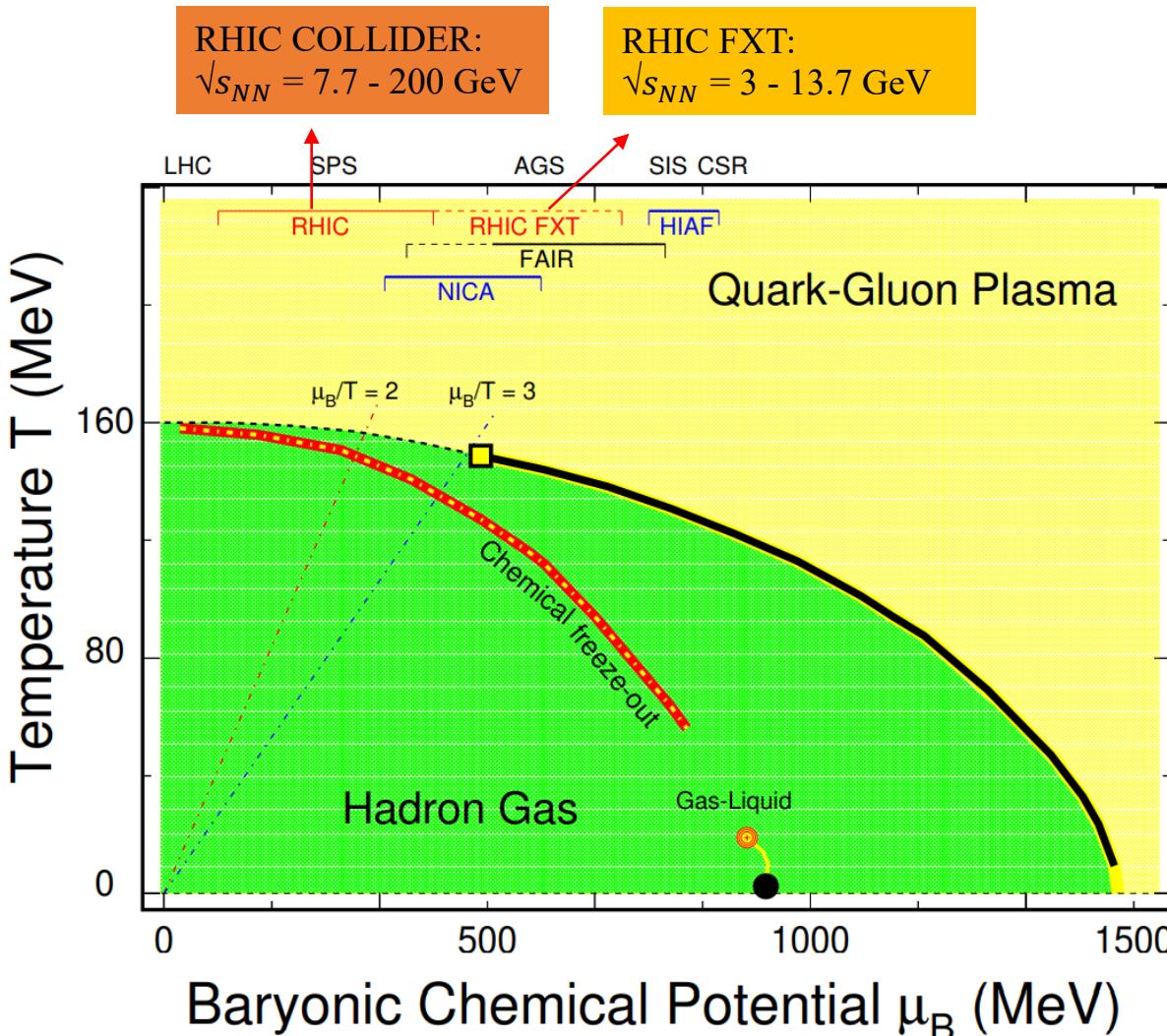
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# Outline

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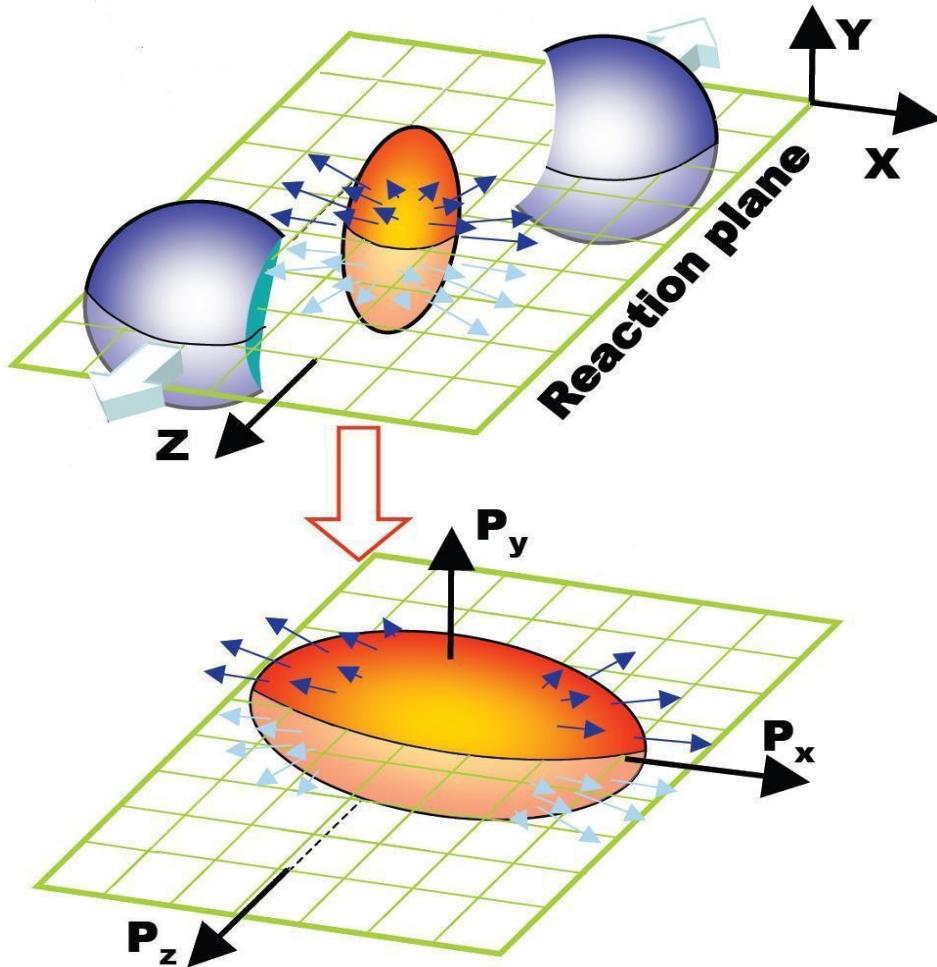
- Motivation
- Anti-flow of kaons
- Energy dependence of  $v_1, v_2$
- NCQ scaling of  $v_2, v_3$
- Summary

# Beam Energy Scan

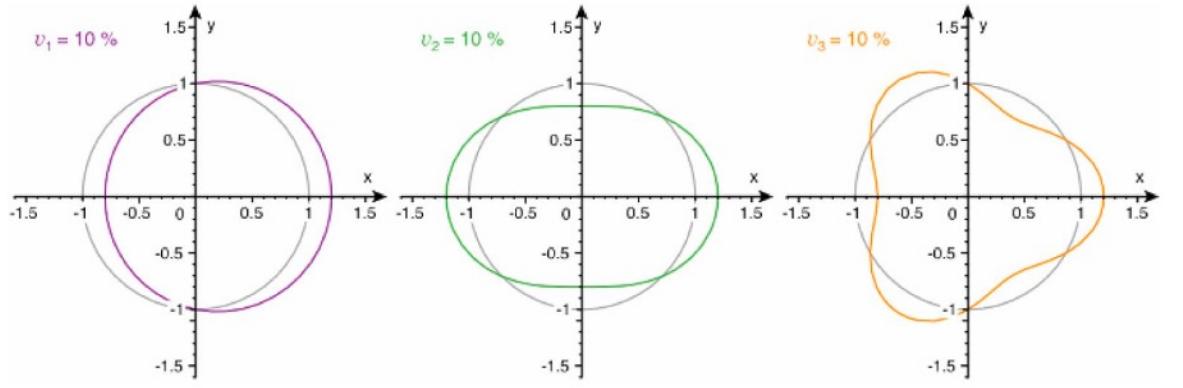


- RHIC Beam Energy Scan:
  - Collider mode:  $\sqrt{s_{NN}} = 7.7 - 200$  GeV
  - Fixed-target(FXT) mode:  $\sqrt{s_{NN}} = 3 - 13.7$  GeV
  
- Baryon density region:  $\mu_B = 25 - 720$  MeV
  - Study the properties of QGP.
  - Search for the critical point and locate the first-order phase boundaries.

# Anisotropic Flow



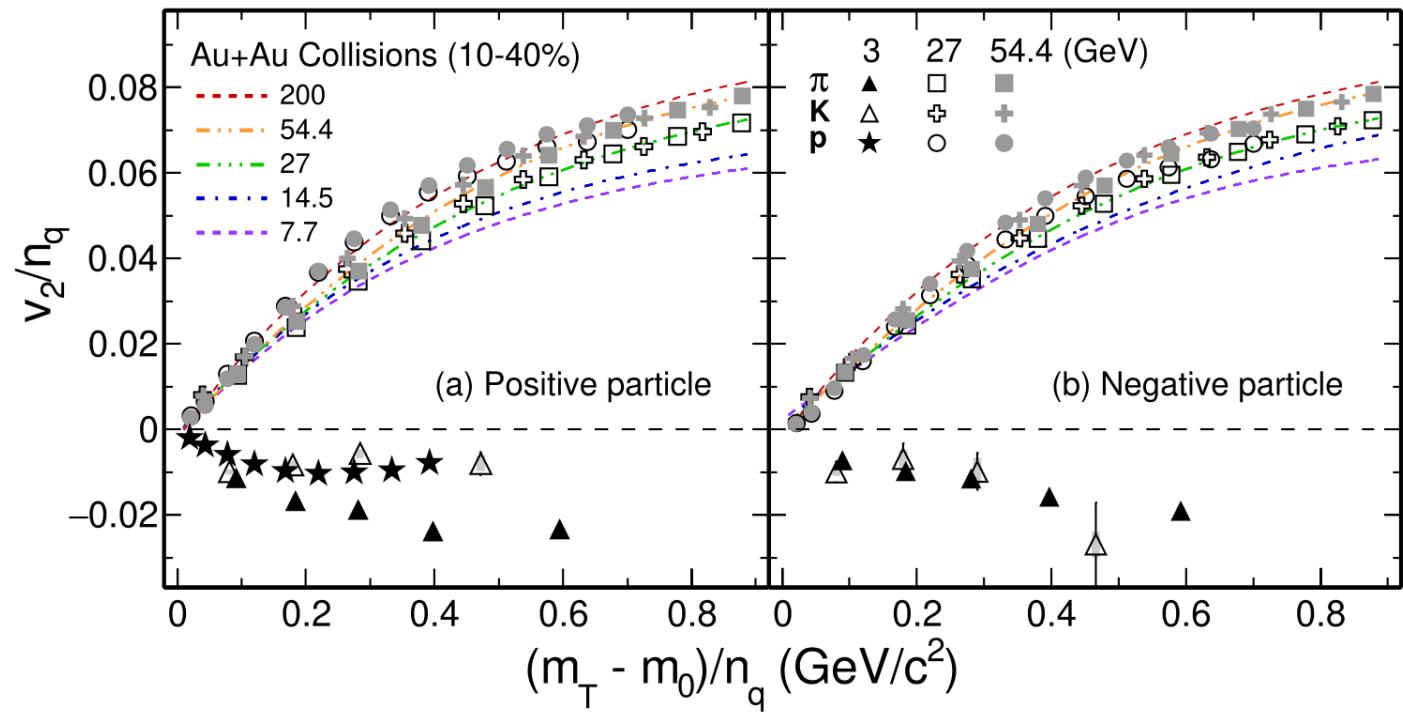
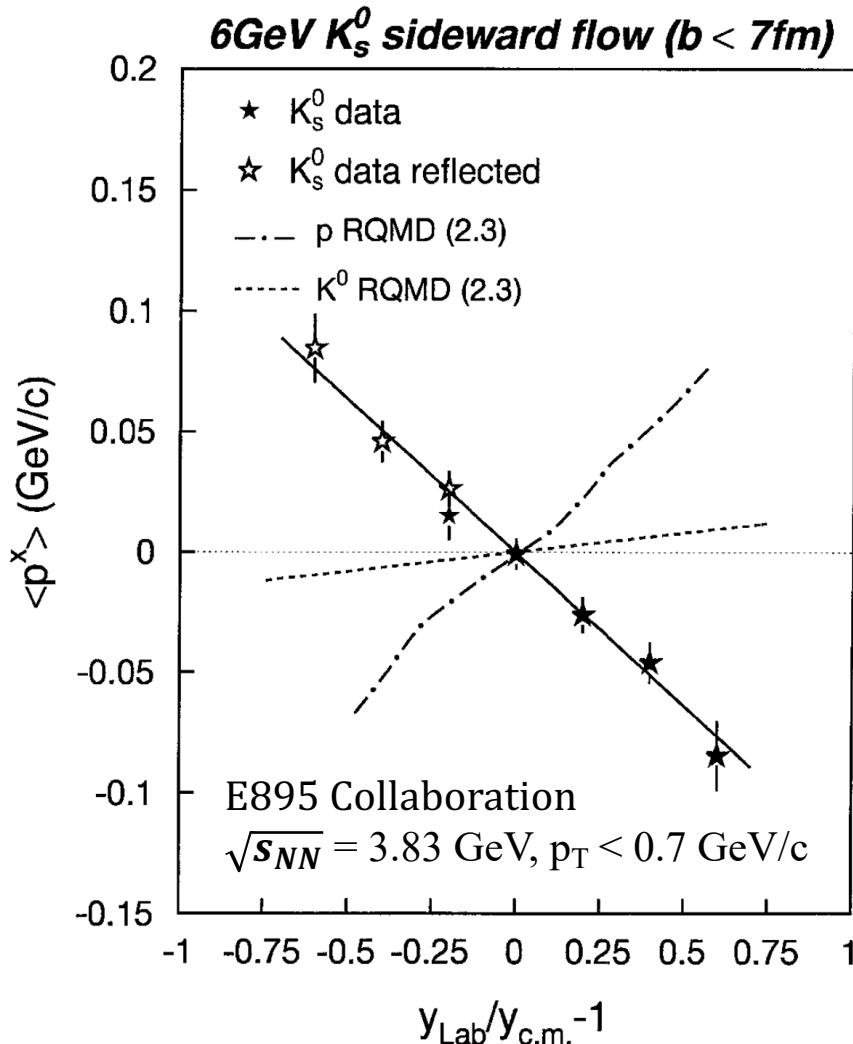
$$\frac{dN}{d(\phi - \Psi)} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi))$$



Directed flow( $v_1$ )      Elliptic flow( $v_2$ )      Triangular flow( $v_3$ )

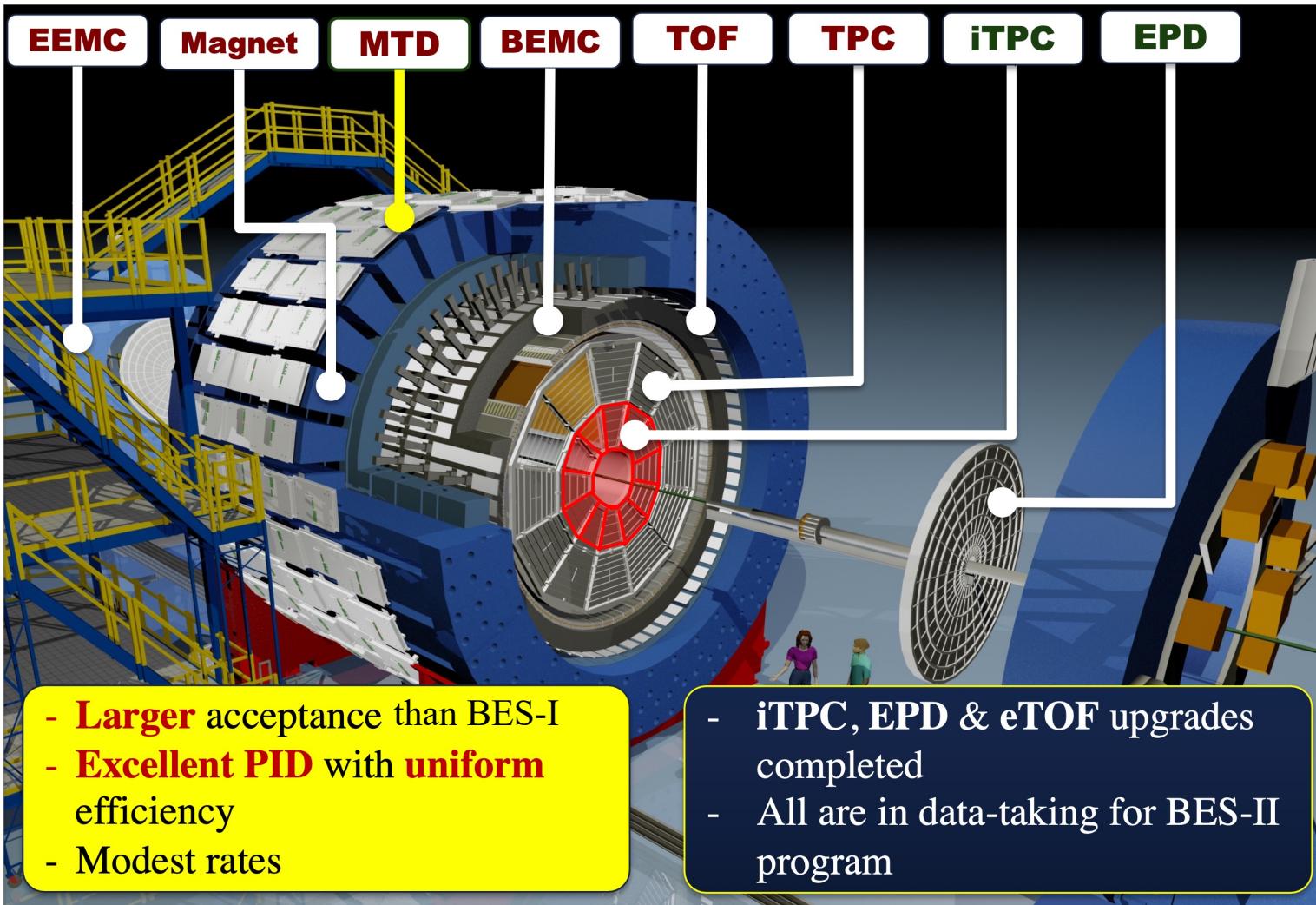
- $v_1$  reveals the interplay between initial compression and tilted expansion.
- $v_2$  and  $v_3$  are sensitive to event-by-event fluctuations, and provide insight on the constituent interactions and degree of freedom.

# Motivation

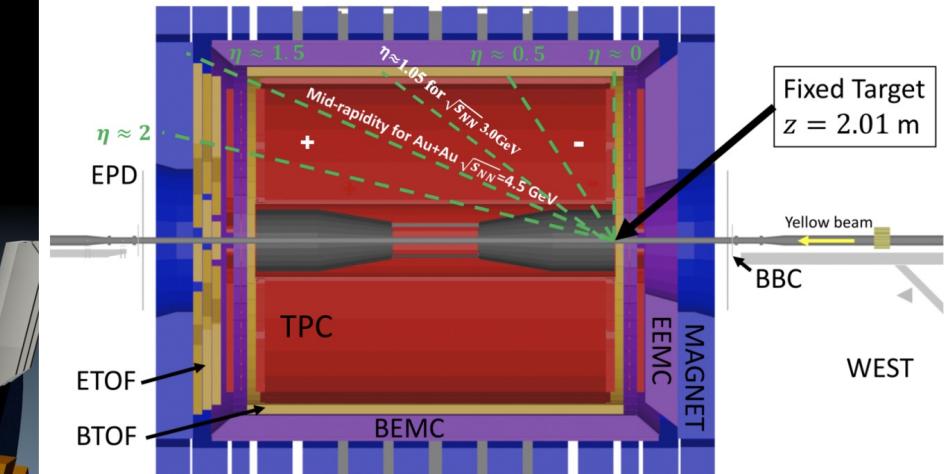


- E895: anti-flow of kaon at low  $p_T$ .  $\rightarrow$  Kaon potential ?
- NCQ scaling violation at 3 GeV.  
Degree of freedom: partonic  $\rightarrow$  hadronic ?

# STAR Detectors



FXT mode:



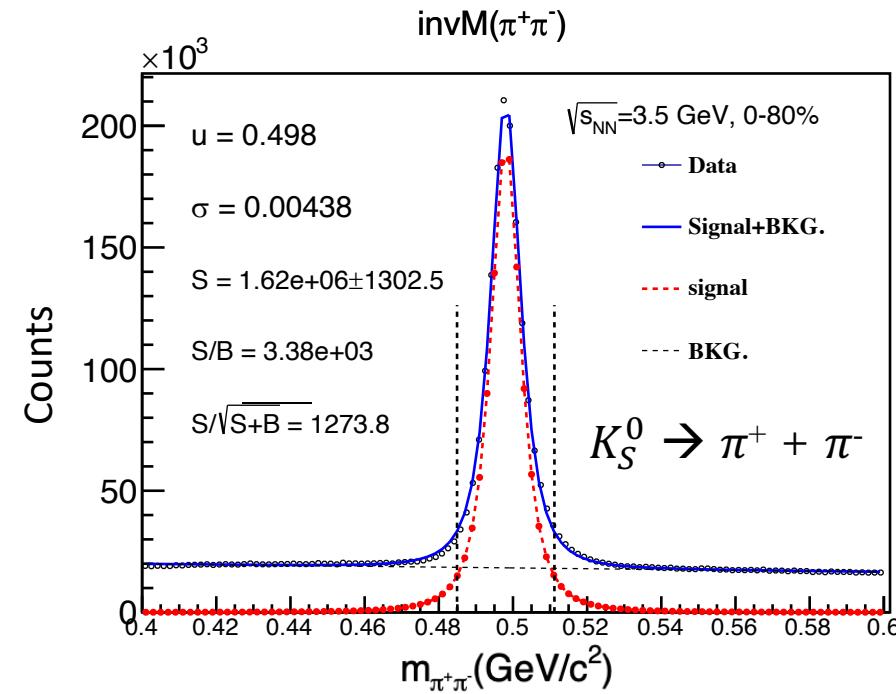
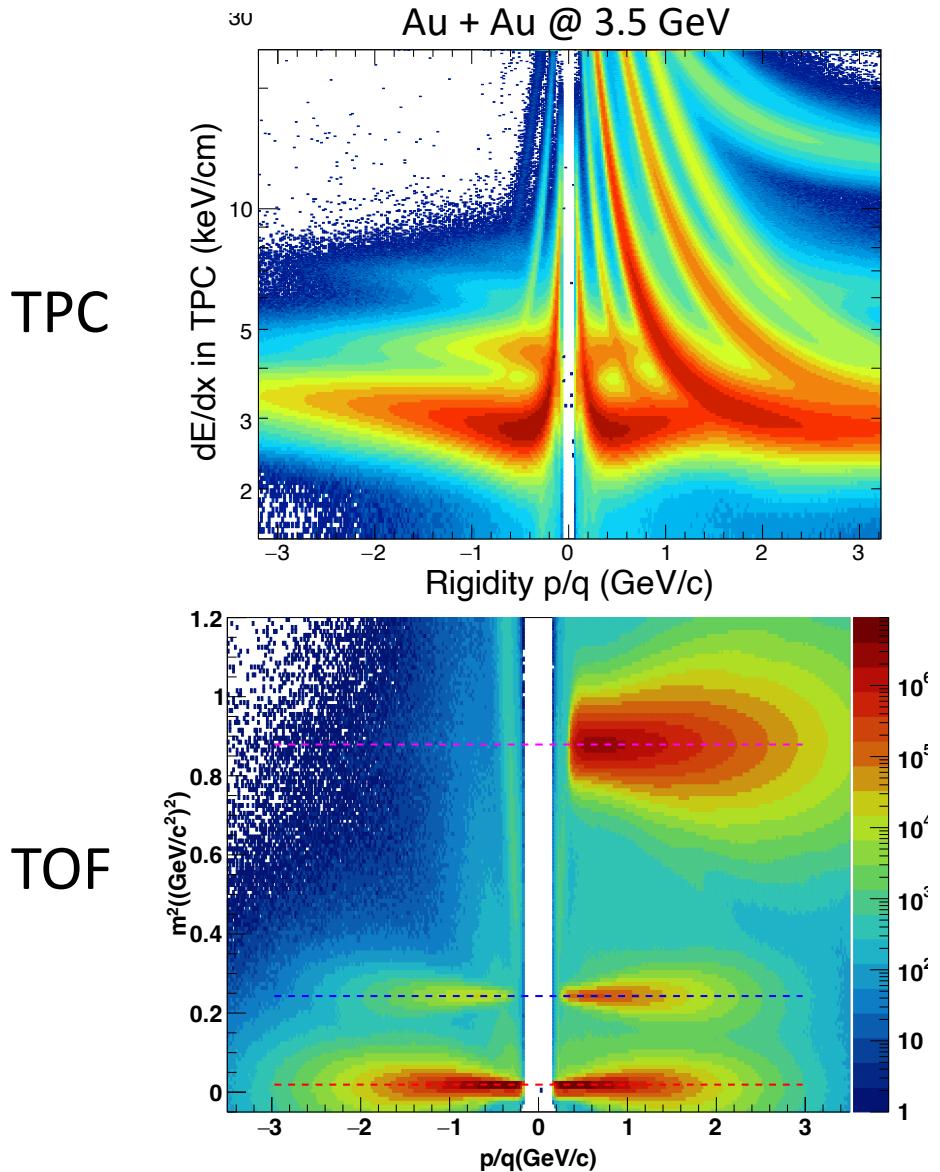
Tracking and particle identification:

- Time Projection Chamber
  - Charged particle tracking
  - Particle identification
- Time Of Flight
  - Particle identification

Event plane determination:

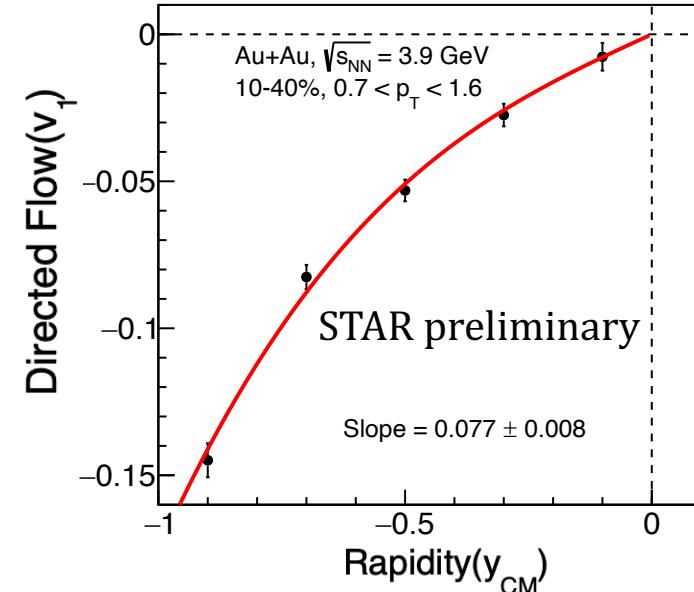
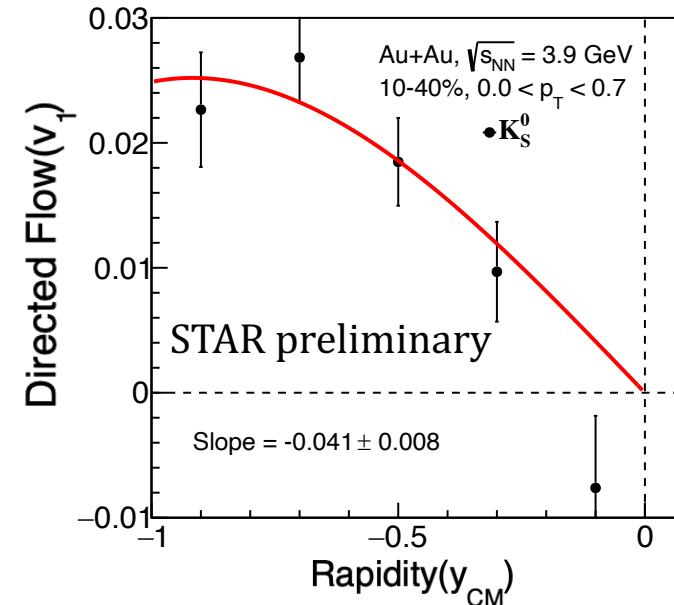
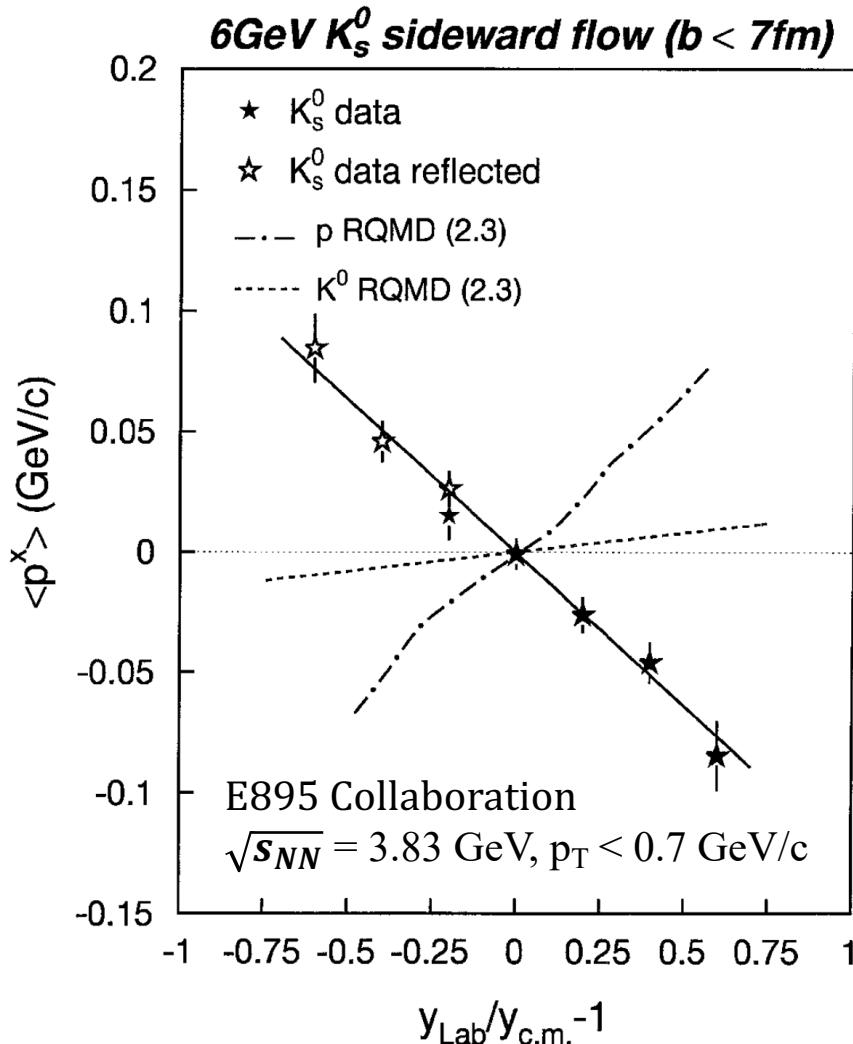
- Event Plane Detector
  - $2.1 < |\eta| < 5.1$

# Particle Identification



- Good particle identification capability based on TPC and TOF.
- Decayed particles are reconstructed by KF(Kalman Filter) particle package.

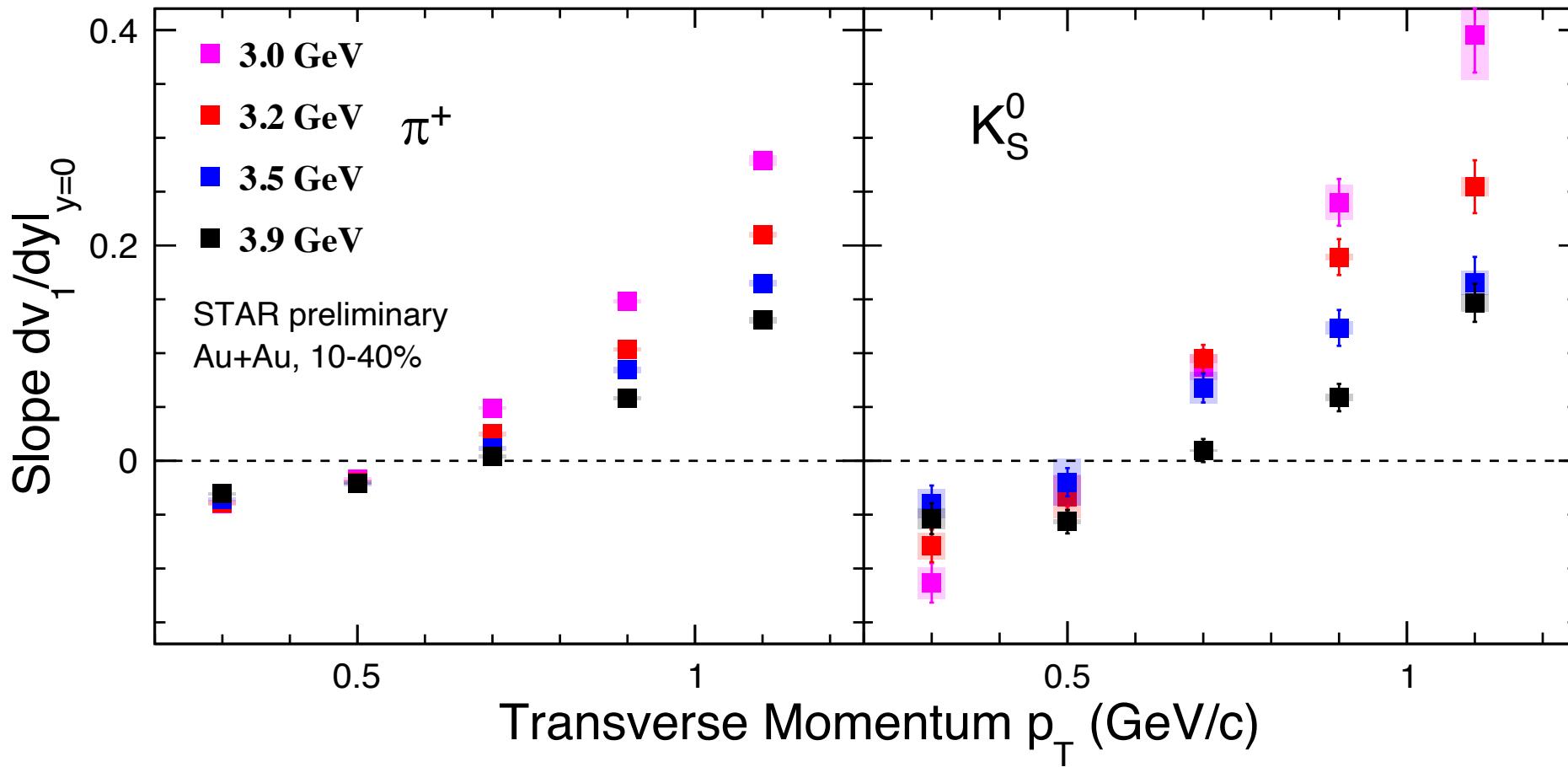
# Anti-flow of Kaon



- 3.9 GeV: anti-flow observed for  $K_S^0$  at  $p_T < 0.7 \text{ GeV}/c$ .
- Positive flow of  $K_S^0$  at  $p_T > 0.7 \text{ GeV}/c$ .  
→ Strong  $p_T$  dependence of  $K_S^0 v_1$  slope

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

# Anti-flow of Mesons

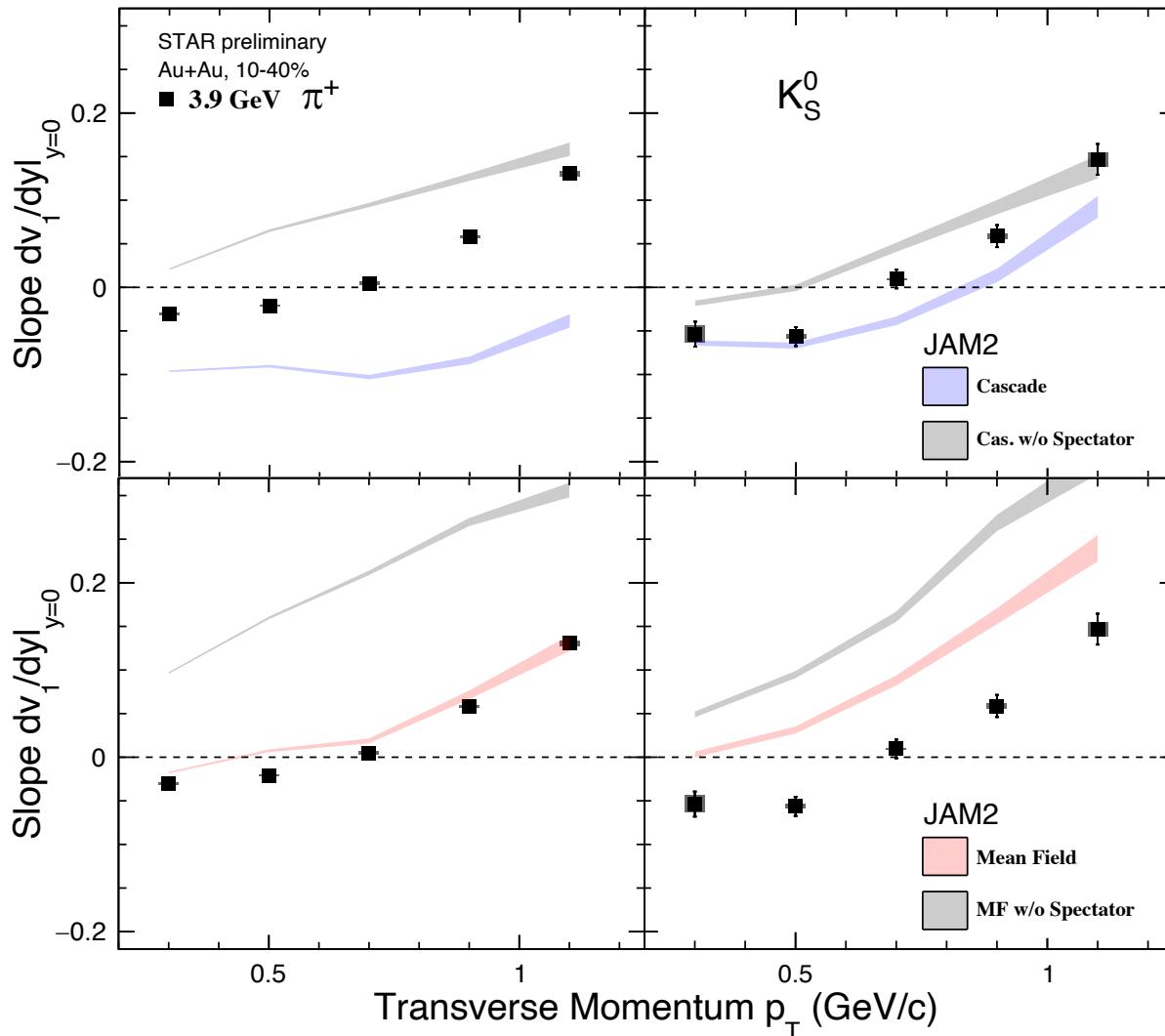


At low  $p_T$ :

- $\pi^+(u\bar{d})$  and  $K_S^0(d\bar{s})$  show negative  $v_1$  slope.
- Anti-flow observed at 3 – 3.9 GeV.

See also posters:  
Xing Wu: #673  
Guoping Wang: #551

# Anti-flow of Mesons

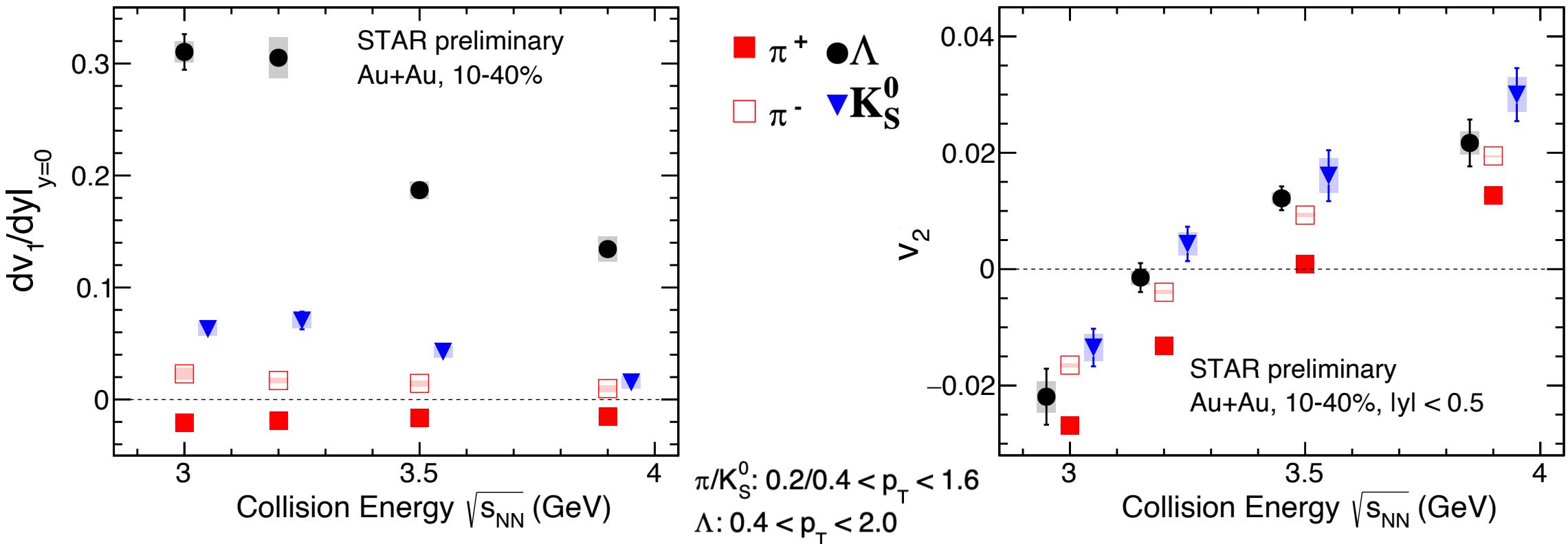


- 3.9 GeV: anti-flow of  $\pi^+$  and  $K_S^0$  at low  $p_T$ .
- JAM reproduces anti-flow at low  $p_T$  without incorporating kaon potential.
- Anti-flow could be explained by shadowing effect from spectator.

Note:

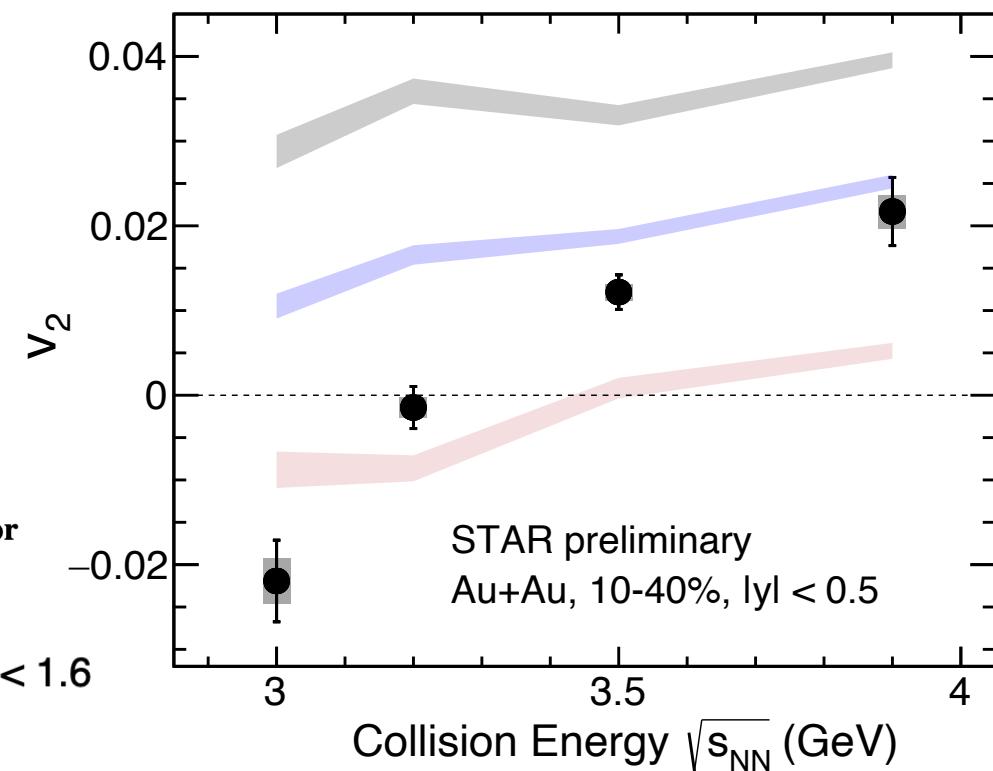
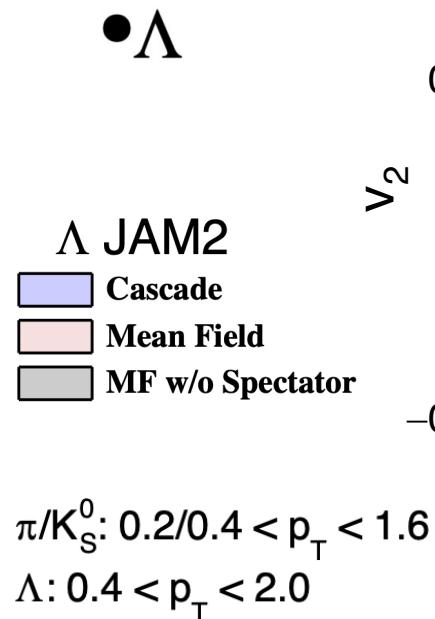
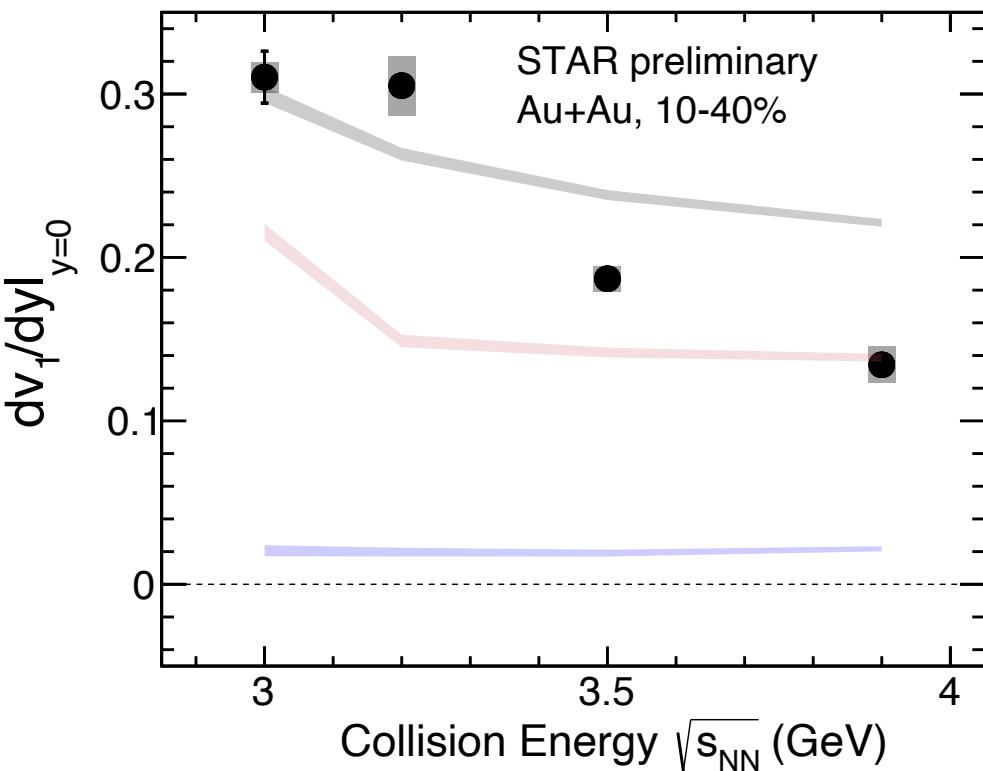
Soft EoS in JAM baryonic mean field:  
the nuclear incompressibility  $K = 210$  MeV

# Energy Dependence of $v_1$ , $v_2$



- $v_1$  slope decreases in magnitude as collider energy increases. → Stronger tilted expansion.
- Negative  $v_2$  turns to positive: Out-of-plane flow (spectator effect) → in-plane flow

# Energy Dependence of $v_1, v_2$



- Baryonic mean field enhances  $v_1$  slope.  
→ Strong mean field at high baryon density region.

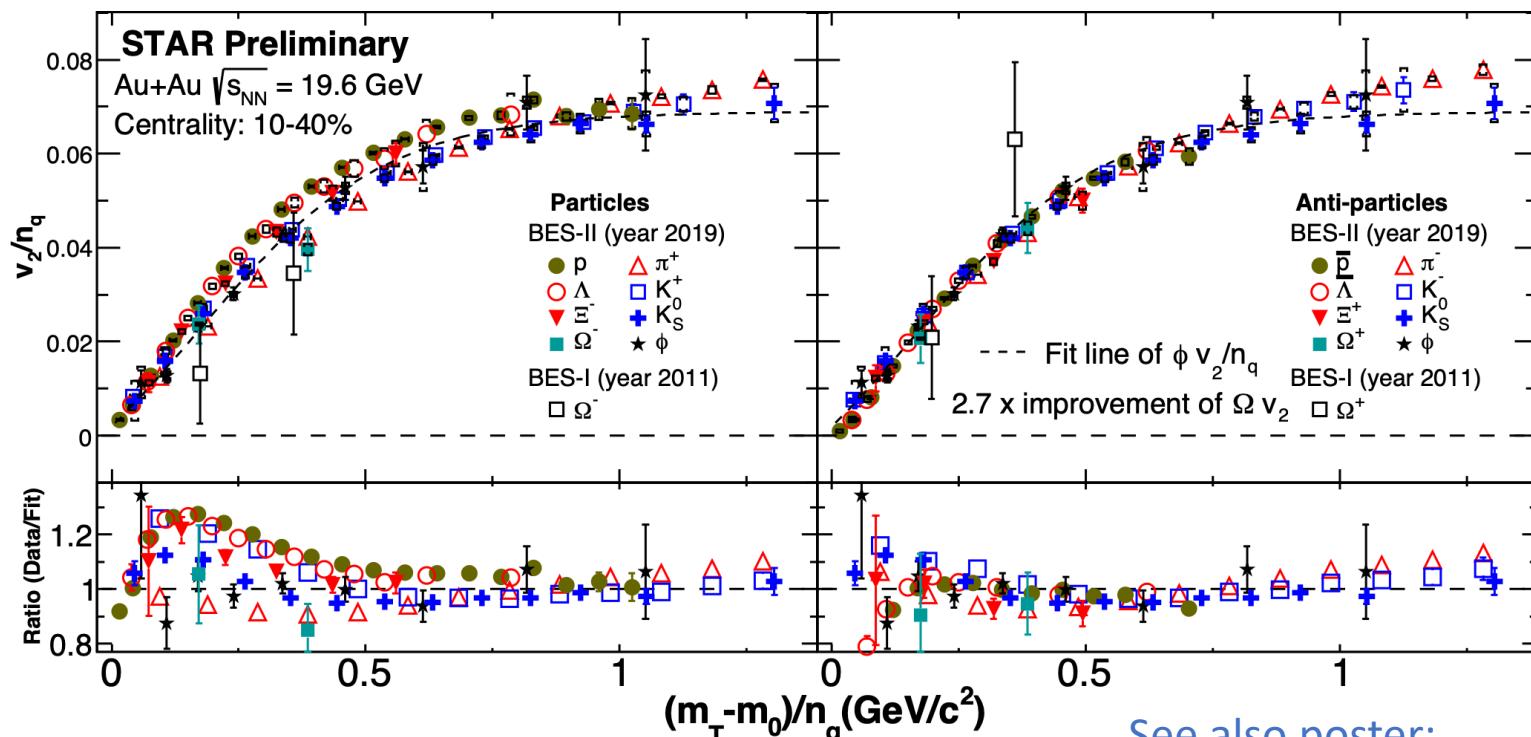
Note:

Soft EoS in JAM baryonic mean field:  
the nuclear incompressibility  $K = 210$  MeV

- Only baryonic mean-field with spectator shows sign change of  $v_2$ . → Mean-field and spectator shadowing play important roles.

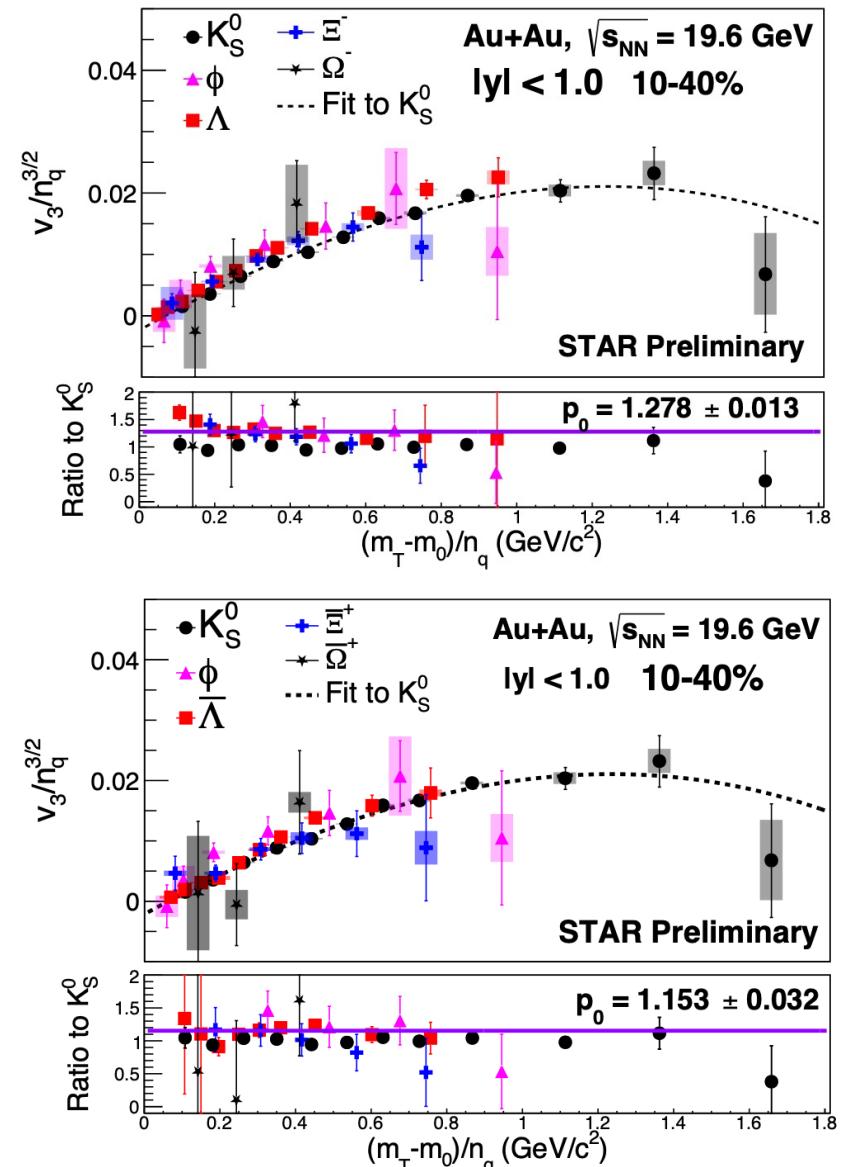
Yasushi Nara, Akira Ohnishi. Phys. Rev. C. 105, 014911(2022)

# NCQ Scaling of $v_2$ , $v_3$ at 19.6 GeV

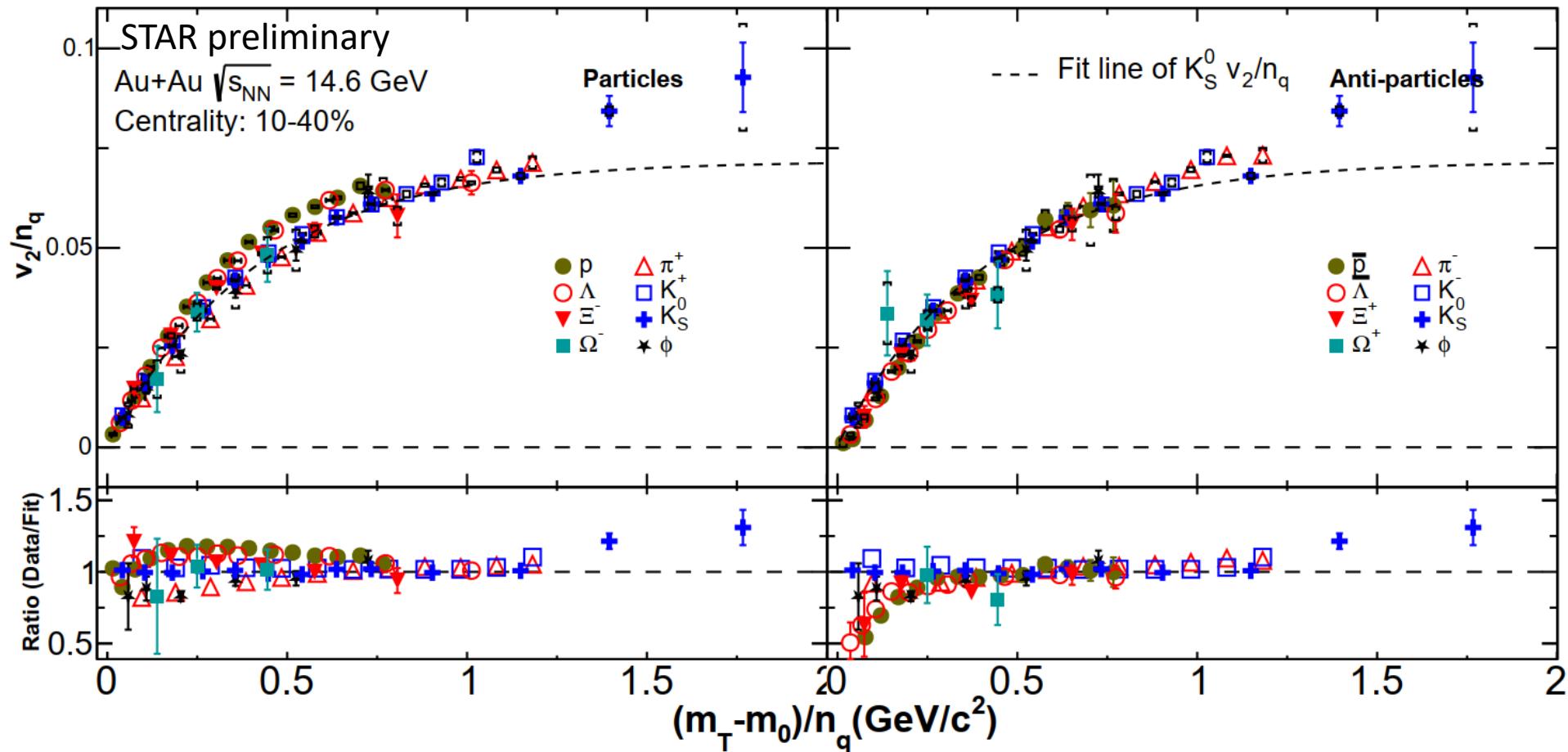


See also poster:  
 Li-ke Liu: #568

- Enhanced statistics from BES-II enable the test of NCQ scaling.
- NCQ scaling of  $v_2$  ( $v_3$ ) holds within 10(15)% for anti-particles, 20(30)% for particles.  
 → Partonic interaction plays important role at 19.6 GeV.

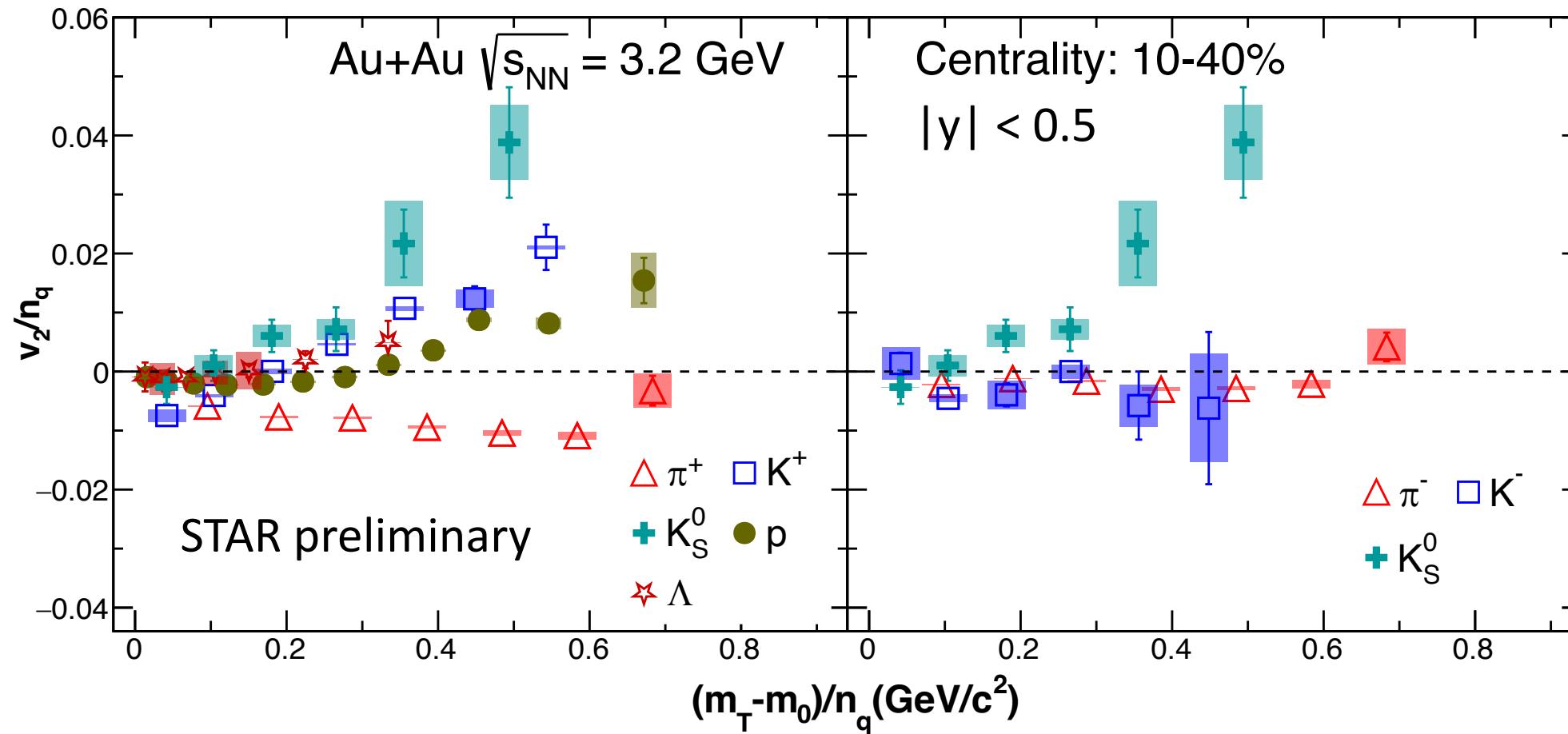


# NCQ Scaling of $v_2$ at 14.6 GeV



- NCQ scaling of  $v_2$  holds within 15% for anti-particles, 25% for particles.  
→ Partonic interaction plays important role at 14.6 GeV.

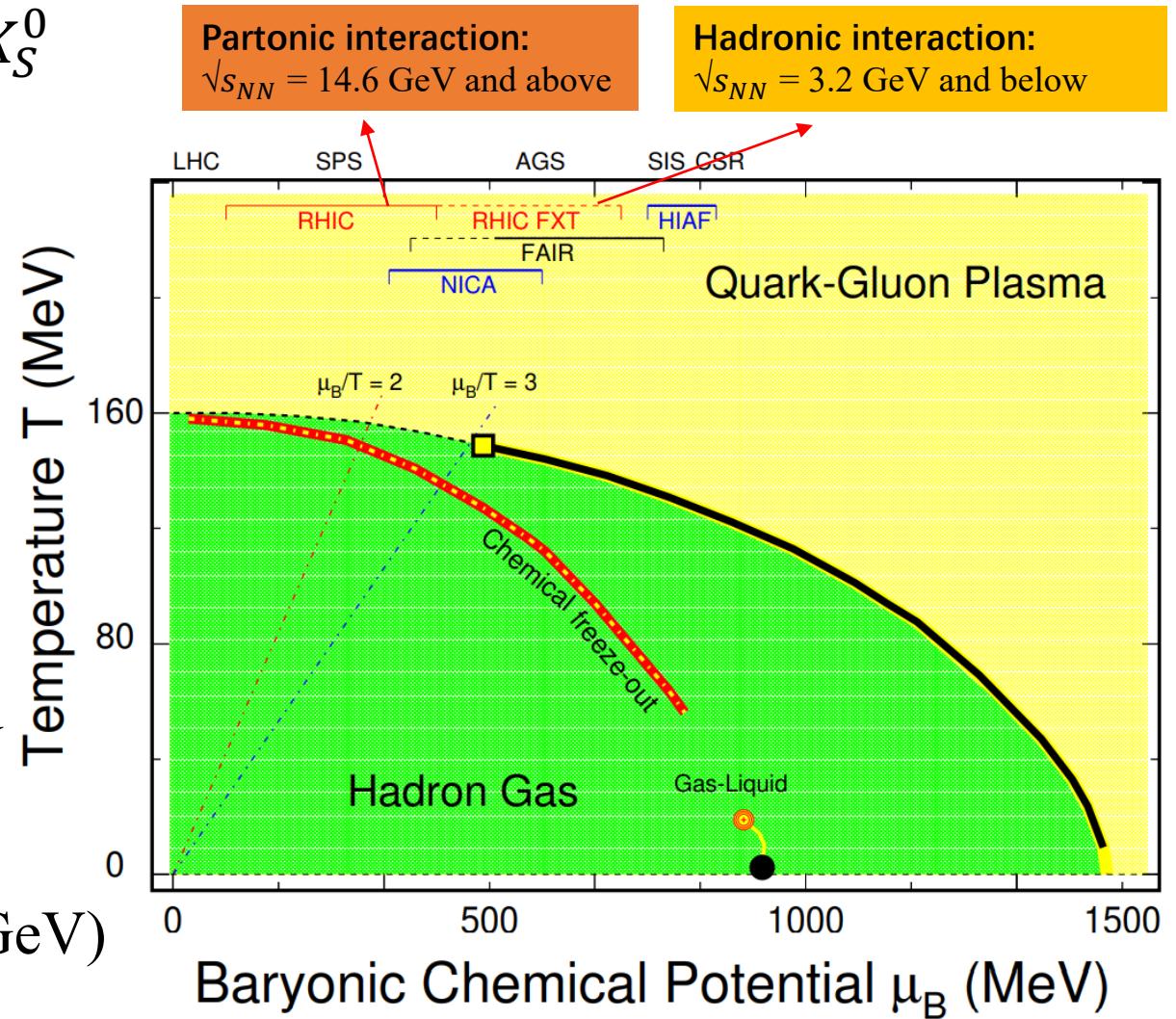
# NCQ Scaling of $v_2$ at 3.2 GeV



- NCQ scaling of  $v_2$  breaks completely at 3.2 GeV.  
 → Disappearing of partonic collectivity

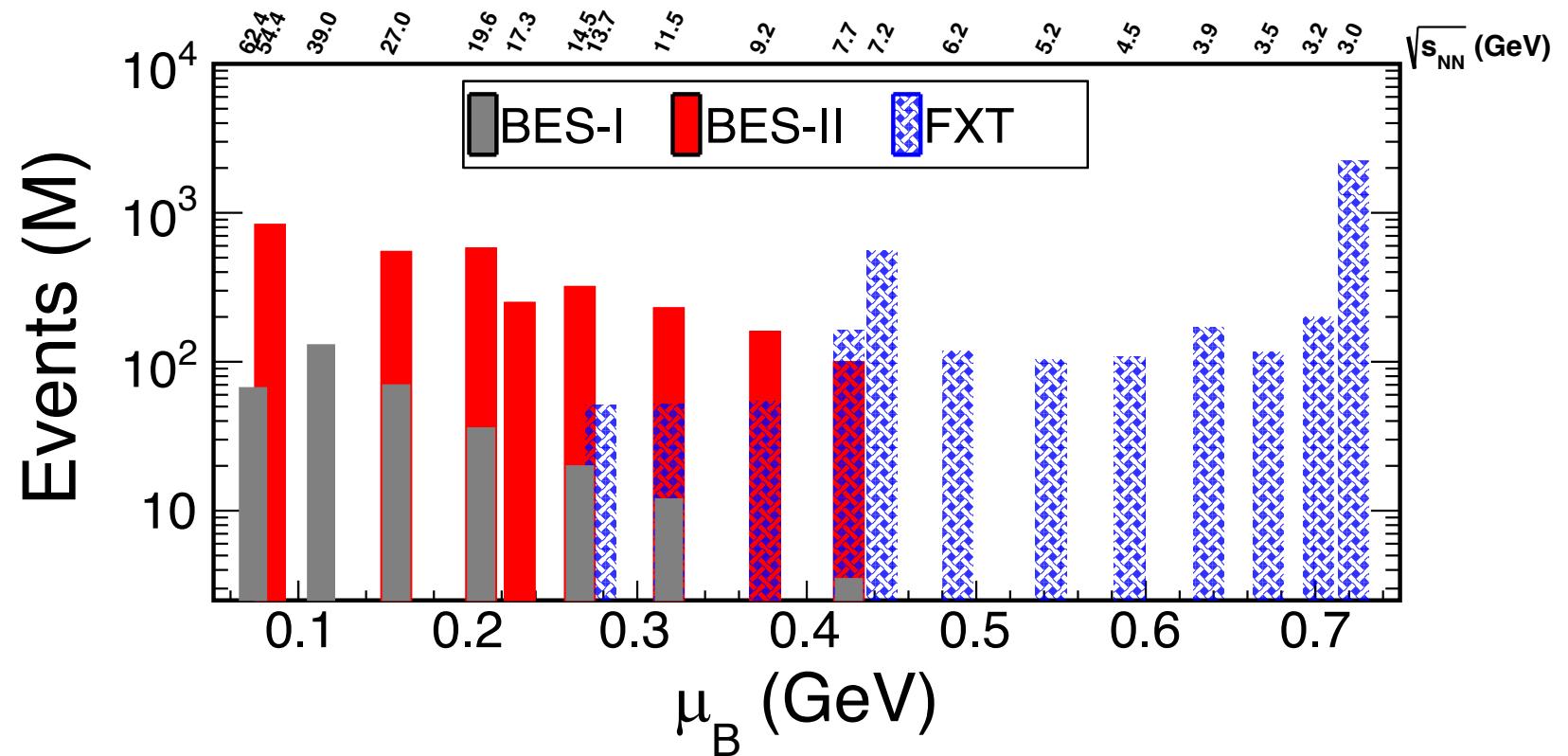
# Summary

- 3 – 3.9 GeV: anti-flow observed for  $\pi^+$  and  $K_S^0$  at low  $p_T$ .
  - Shadowing effect from spectator could result in anti-flow.
- Negative  $v_2 \rightarrow$  positive  $v_2$ 
  - The change of out-of-plane to in-plane expansion happens at 3 – 3.9 GeV.
- NCQ scaling of  $v_2, v_3$  holds at 14.6 GeV and above, in contrast to violation at 3.2 GeV and below.
  - Partonic( $> 14.6$  GeV) to hadronic( $< 3.2$  GeV) transition.



# Outlook

STAR BES-II (2019-2021):  
 $\sqrt{s_{NN}} = 3 - 19.6 \text{ GeV}$



- Enhanced statistics, upgraded detectors from BES-II.
- Explore the QCD phase diagram with BES-II 3 - 19.6 GeV data.

*Thank you for your attention!*