Collectivity at High Baryon Density from STAR BES-II

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for the STAR Collaboration

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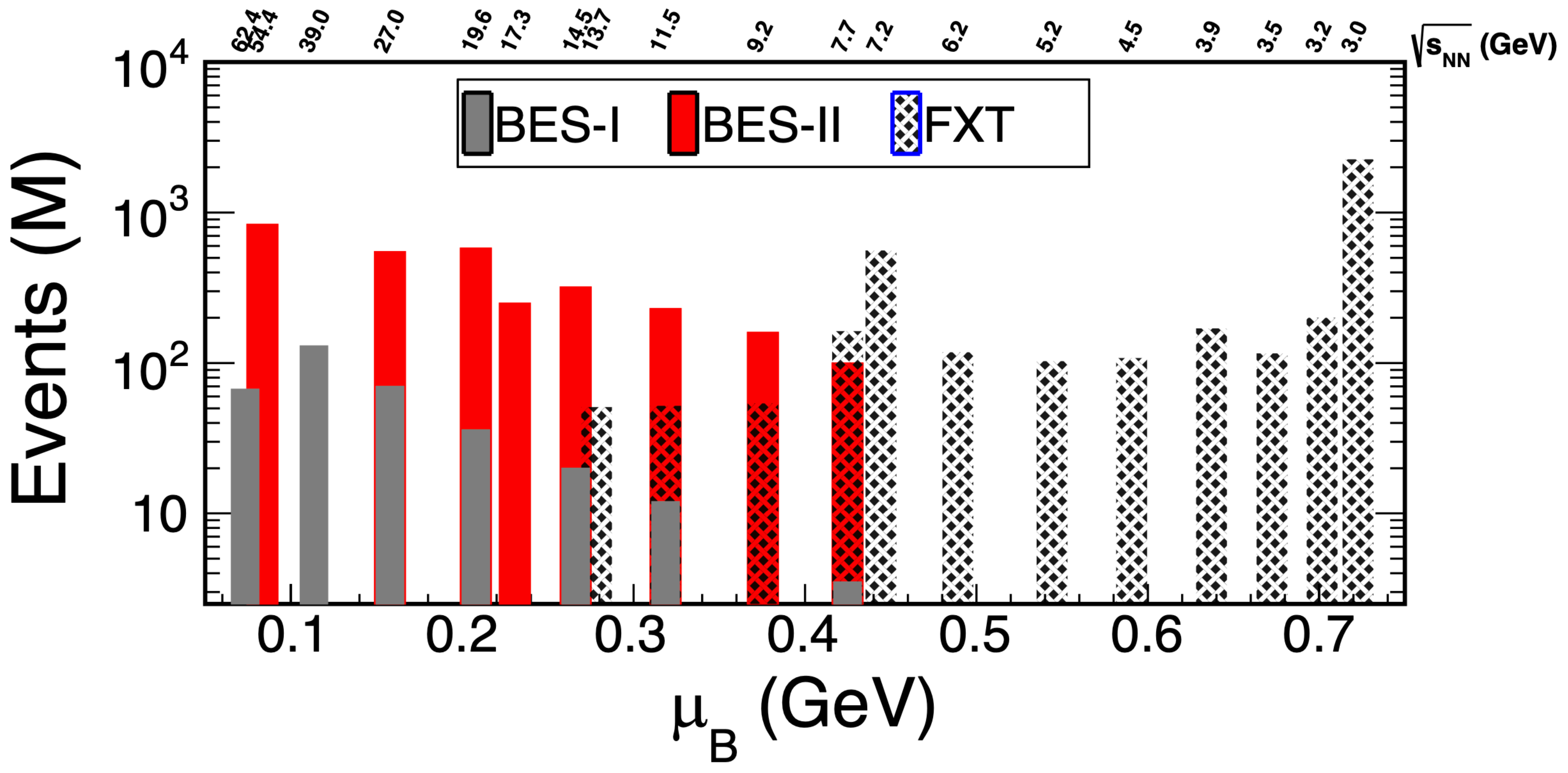
Outline

1) Motivation
2) Experimental Setup
3) Results and Discussion
    I) Directed flow (v_1) measurements
    II) Elliptic flow (v_2) measurements
4) Summary

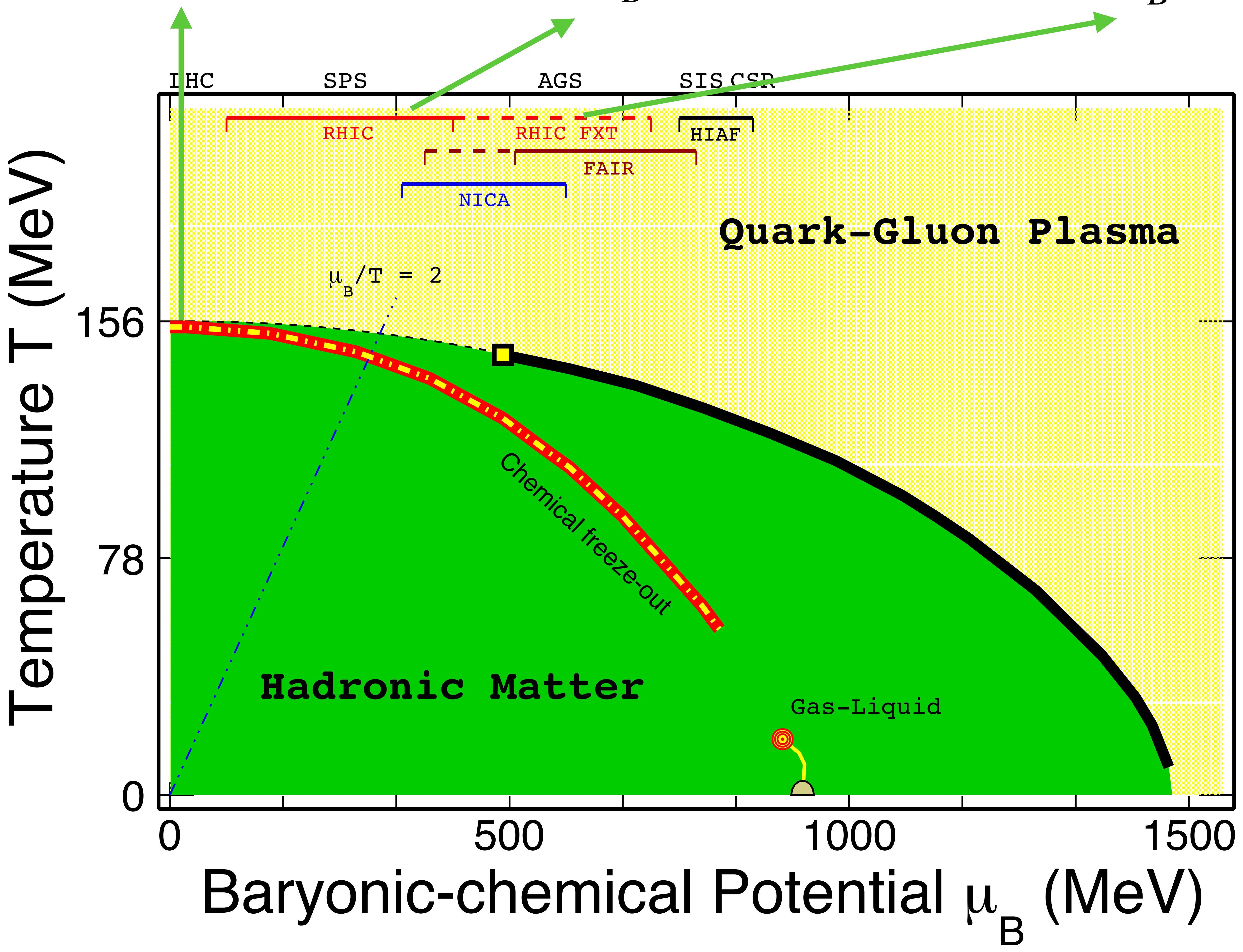


Motivation

LHC, RHIC 200 GeV
T_C

RHIC COL: 7.7-62.4 GeV
u_B: 420-73 MeV

RHIC FXT: 3.0-7.7 GeV
u_B: 750-420 MeV



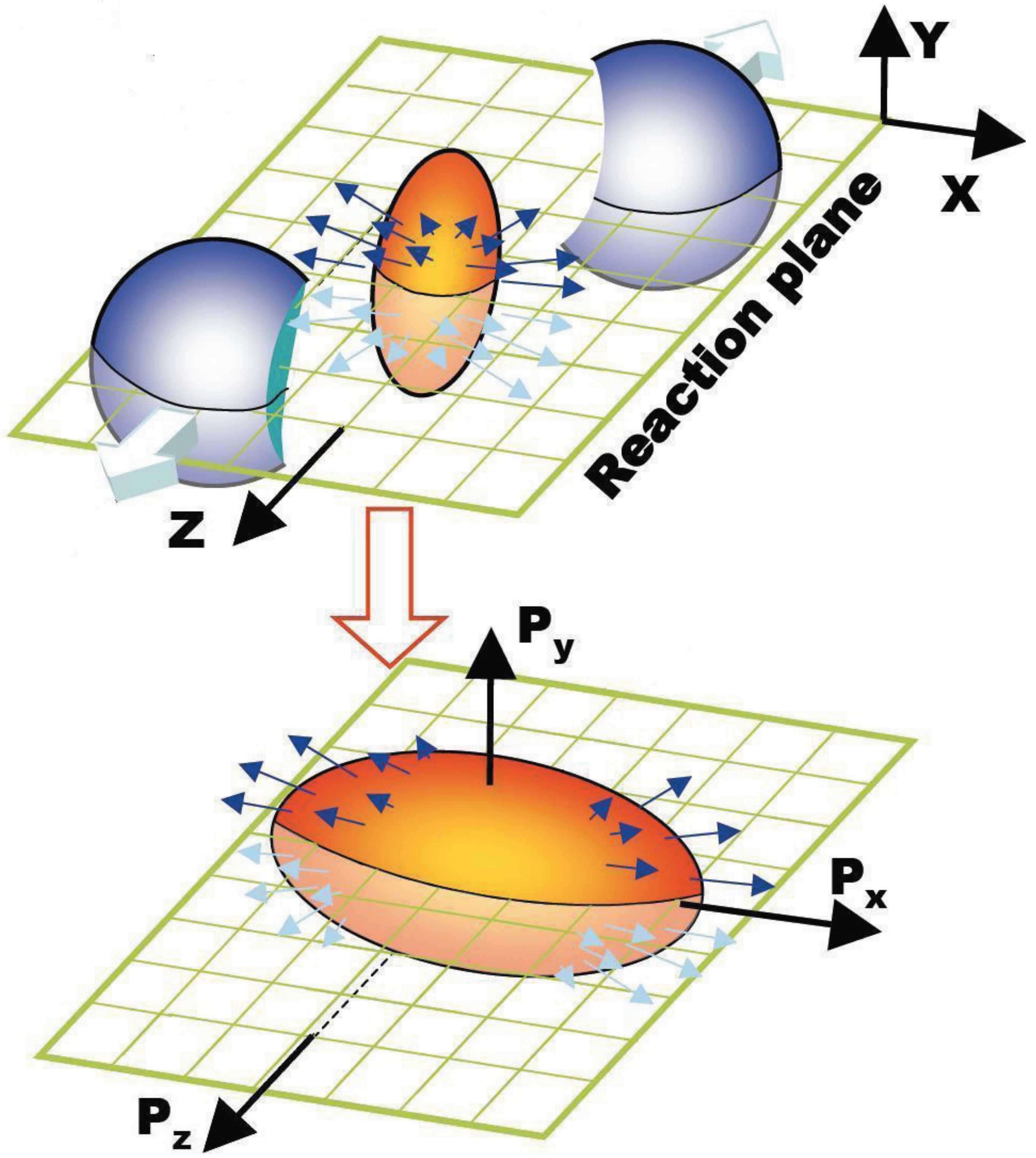
- RHIC 200 GeV and LHC
  - Small viscosity, high temperature
  - Evidence of Quark-Gluon Plasma
- Beam energy scan program
  - Locate the first-order phase boundary
  - Search for Critical Point

A. Bazavov et al., Phys. Rev. D 85, 054503 (2012); K. Fukushima and C. Sasaki, Prog. Part. Nucl. Phys, 72, 99 (2013)

Anisotropic flow

- Anisotropies in particle momentum distributions relative to the reaction plane

Initial spatial anisotropy → Pressure gradient → Momentum space anisotropy



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{1}^{\infty} 2v_n \cos\left[n\left(\phi - \psi_r\right)\right]\right)$$

$$v_1 = \cos\left(\phi - \psi_r\right) = \left\langle \frac{p_x}{p_T} \right\rangle$$ directed flow

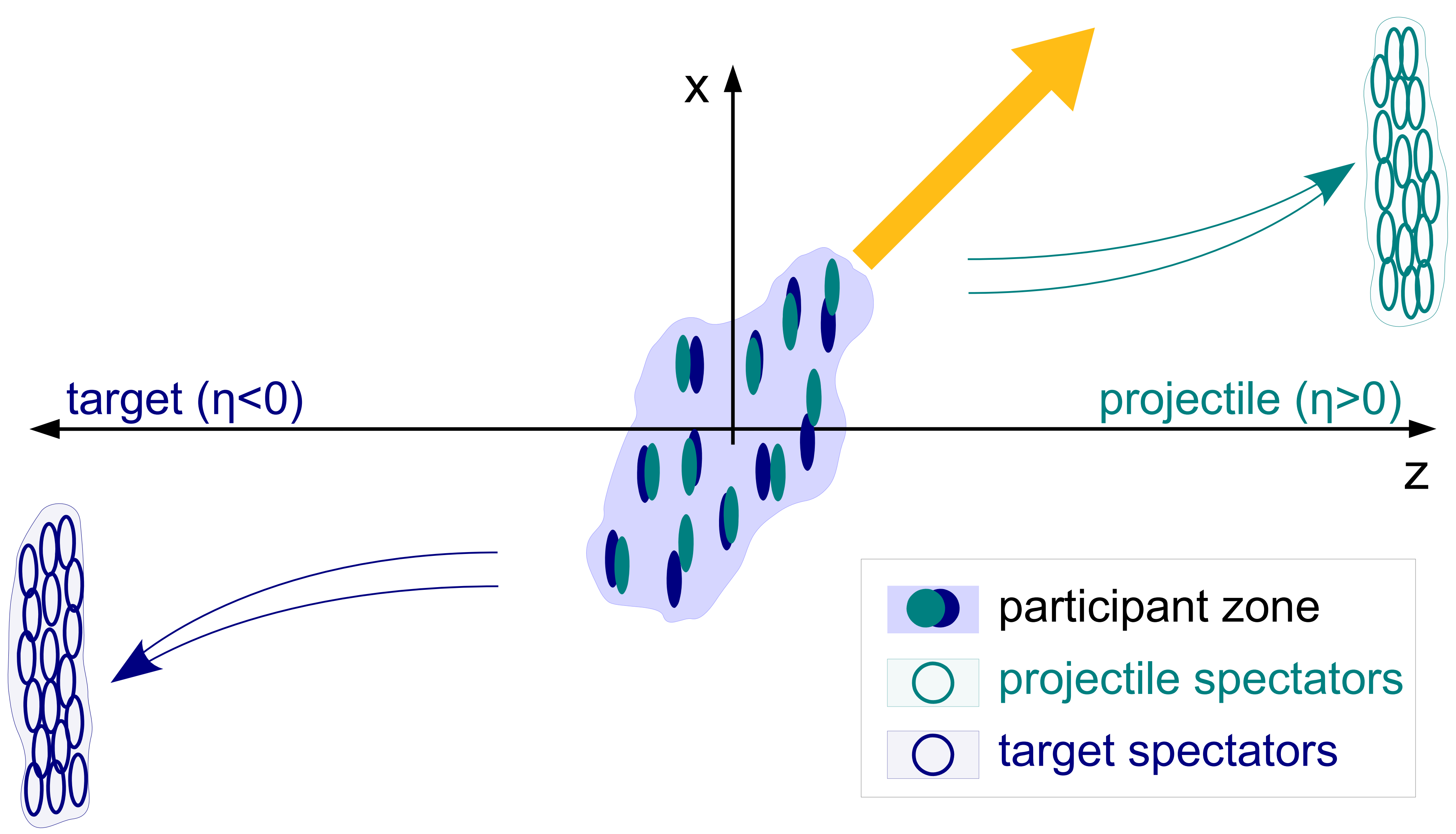
$$v_2 = \cos\left[2(\phi - \psi_r)\right] = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$ elliptic flow

1) Equation of State of the medium
2) Constituent interactions and degree of freedom

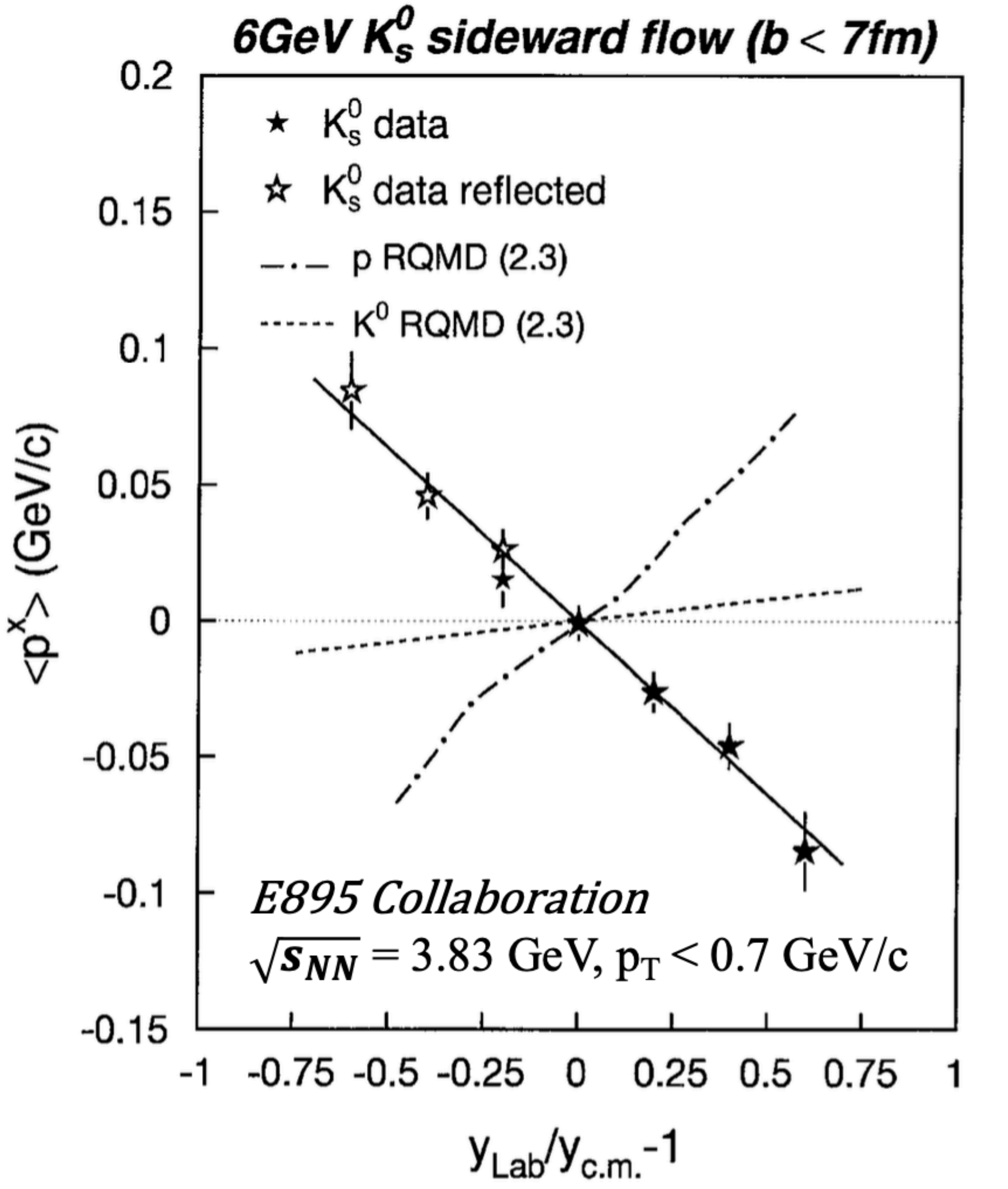
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998) P. Danielewicz, R. Lacey, Science 298 (2002) STAR Collaboration, Phys. Rev. Lett. 118, 212301 (2017)

Motivation: Anti-flow of v_1

Figure taken from: Phys. Rev. Lett. 111, 232302 (2013)



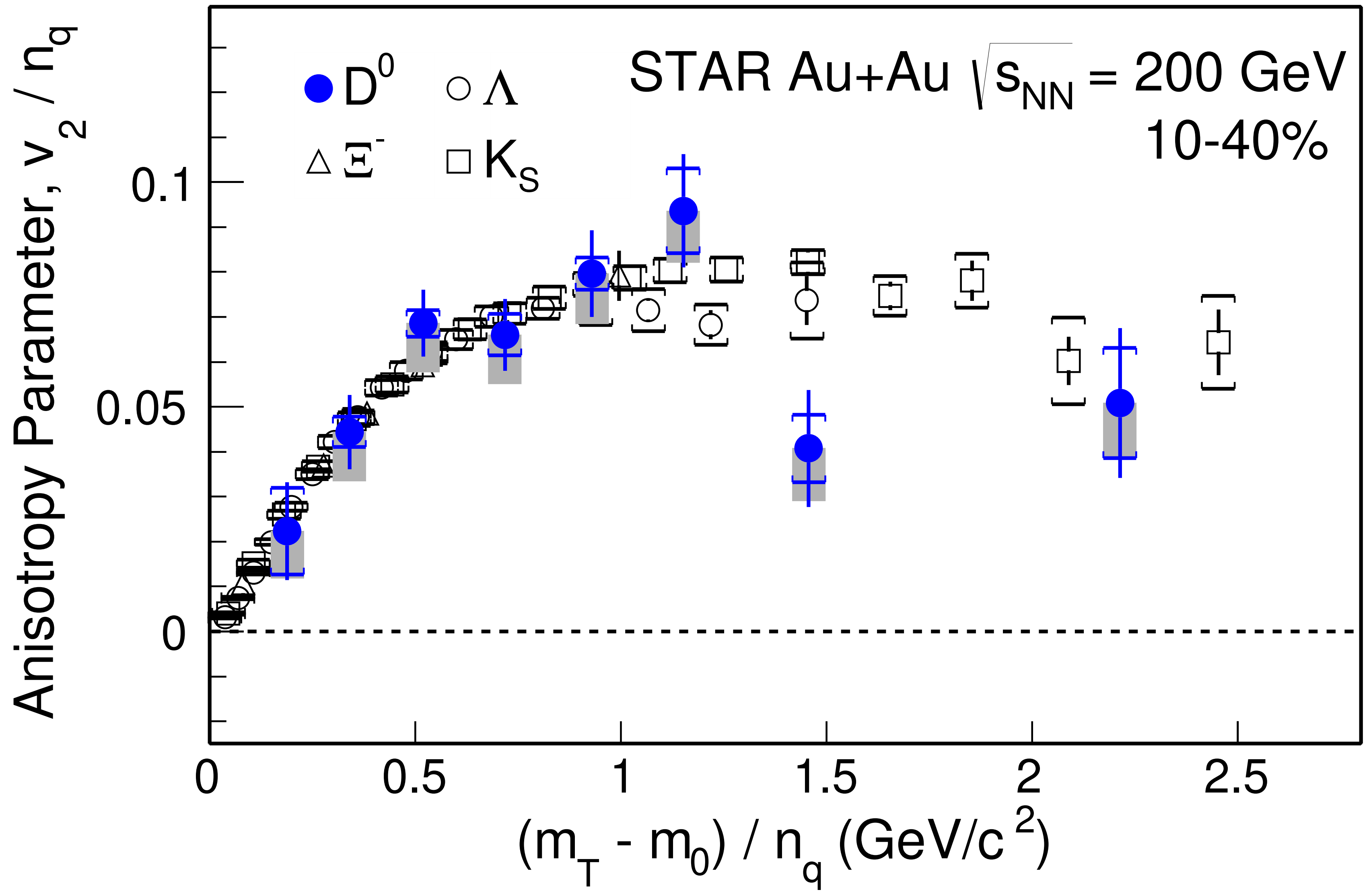
E895 Collaboration, Phys. Rev. Lett. 85, 940 (2000)



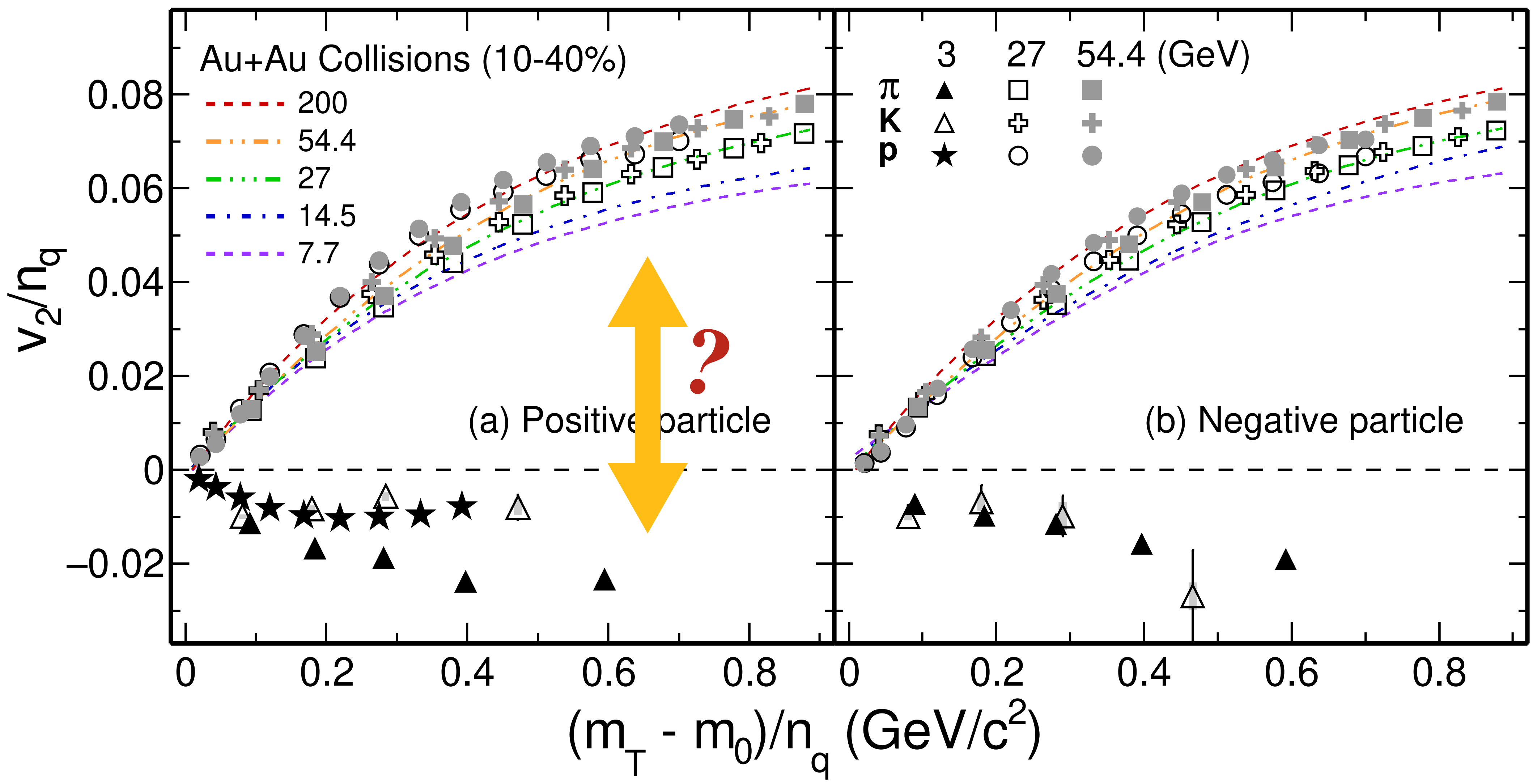
1) Bounce-off: Positive flow in positive rapidity
2) Au+Au 3.83 GeV: anti-flow of kaon at low p_T (< 0.7 GeV/c) → Kaon potential ?

Motivation: Elliptic flow

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



STAR Collaboration, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)

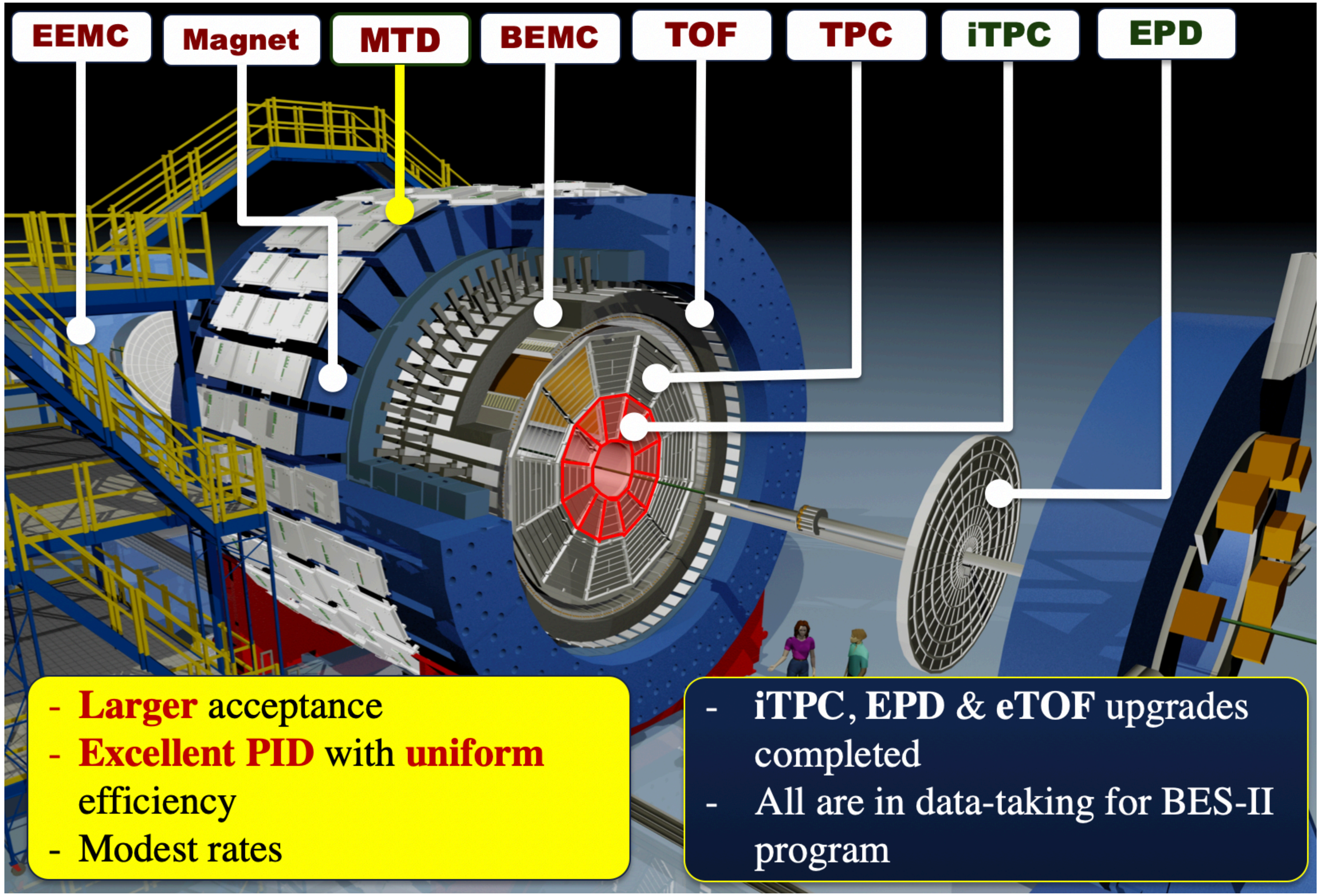


1) 200 GeV: Partonic collectivity

2) 3.0 GeV: Hadronic interaction dominates

3) Change of degree of freedom: 3.0 → 7.7 GeV ?

Experimental Setup

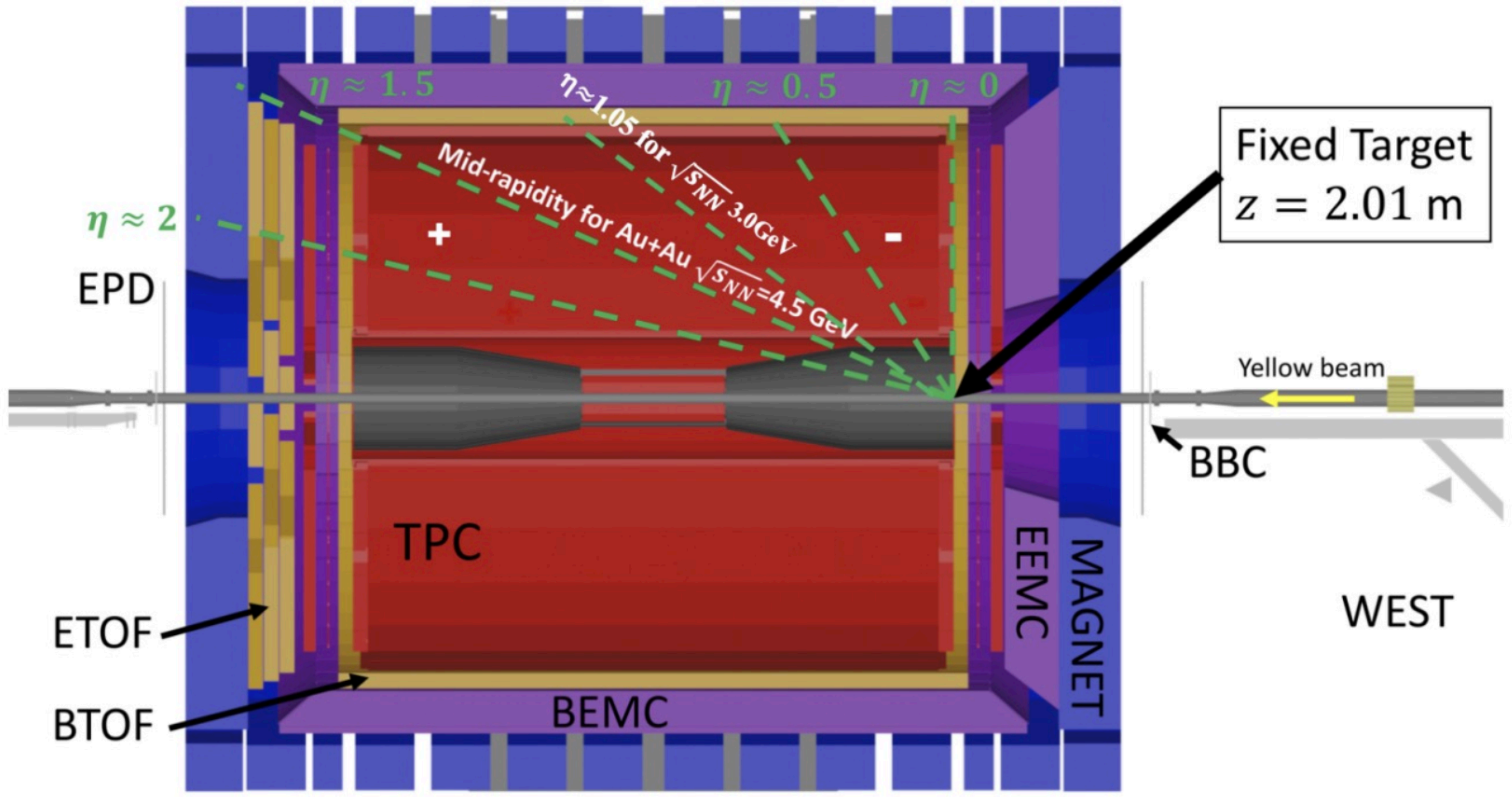


- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

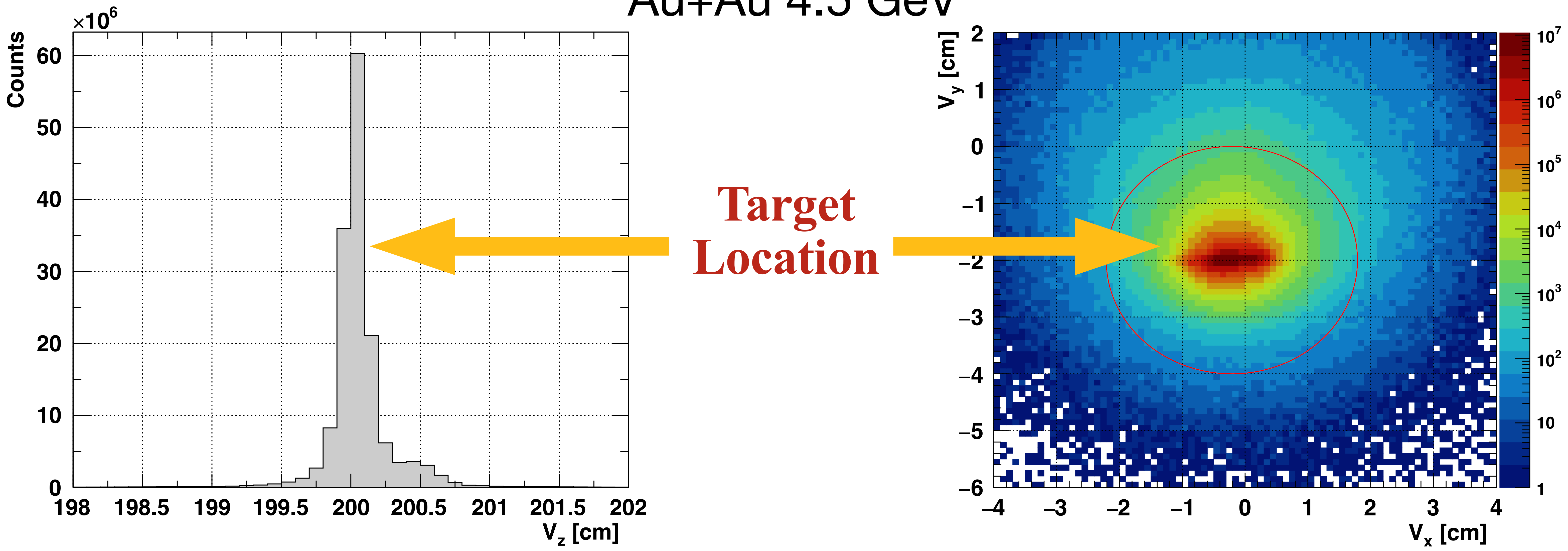
STAR Detector Upgrade:

1) **I**nner-**T**ime **P**rojection **C**hamber
   - Better track quality, Larger acceptance
2) **E**ndcap **T**ime **O**f **F**light
   - Particle identification
3) **E**vent **P**lane **D**etector
   - Event plane determination (2.1< |η| < 5.1)



FXT Event Statistics

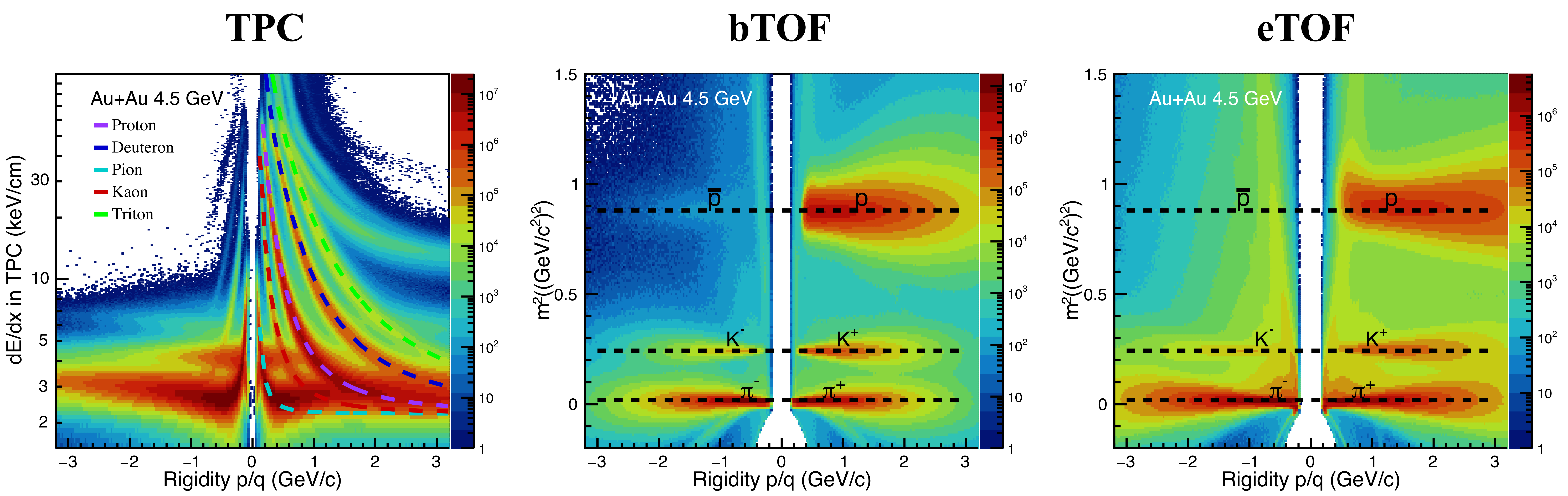
Au+Au 4.5 GeV



Au+Au (GeV)	**3.0**	**3.2**	**3.5**	**3.9**	**4.5**
Baryon chemical potential (~MeV)	750	700	670	635	590
Events analyzed (M)	260	206	107	94	128

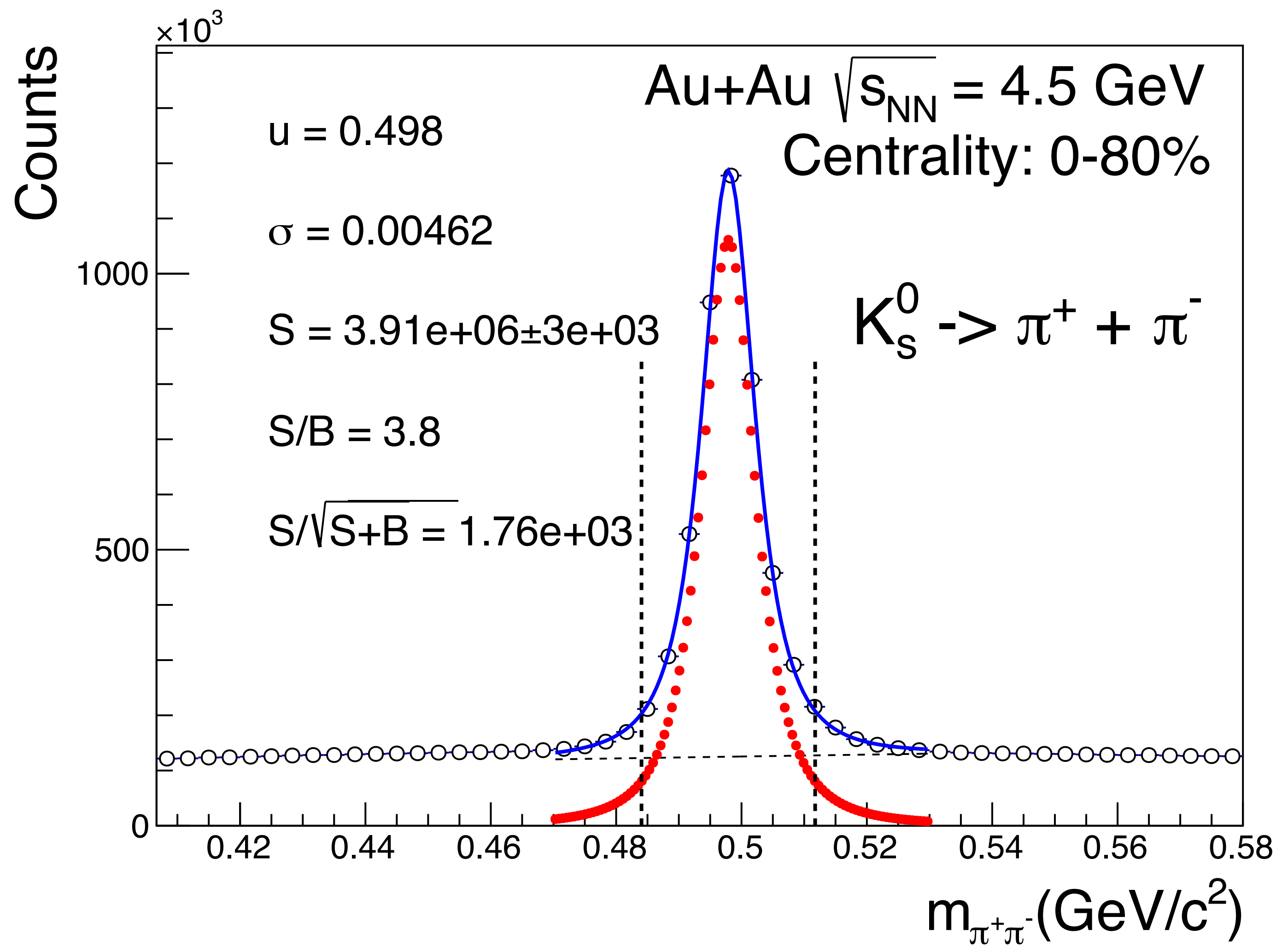
FXT data can provide good precision for collectivity measurement

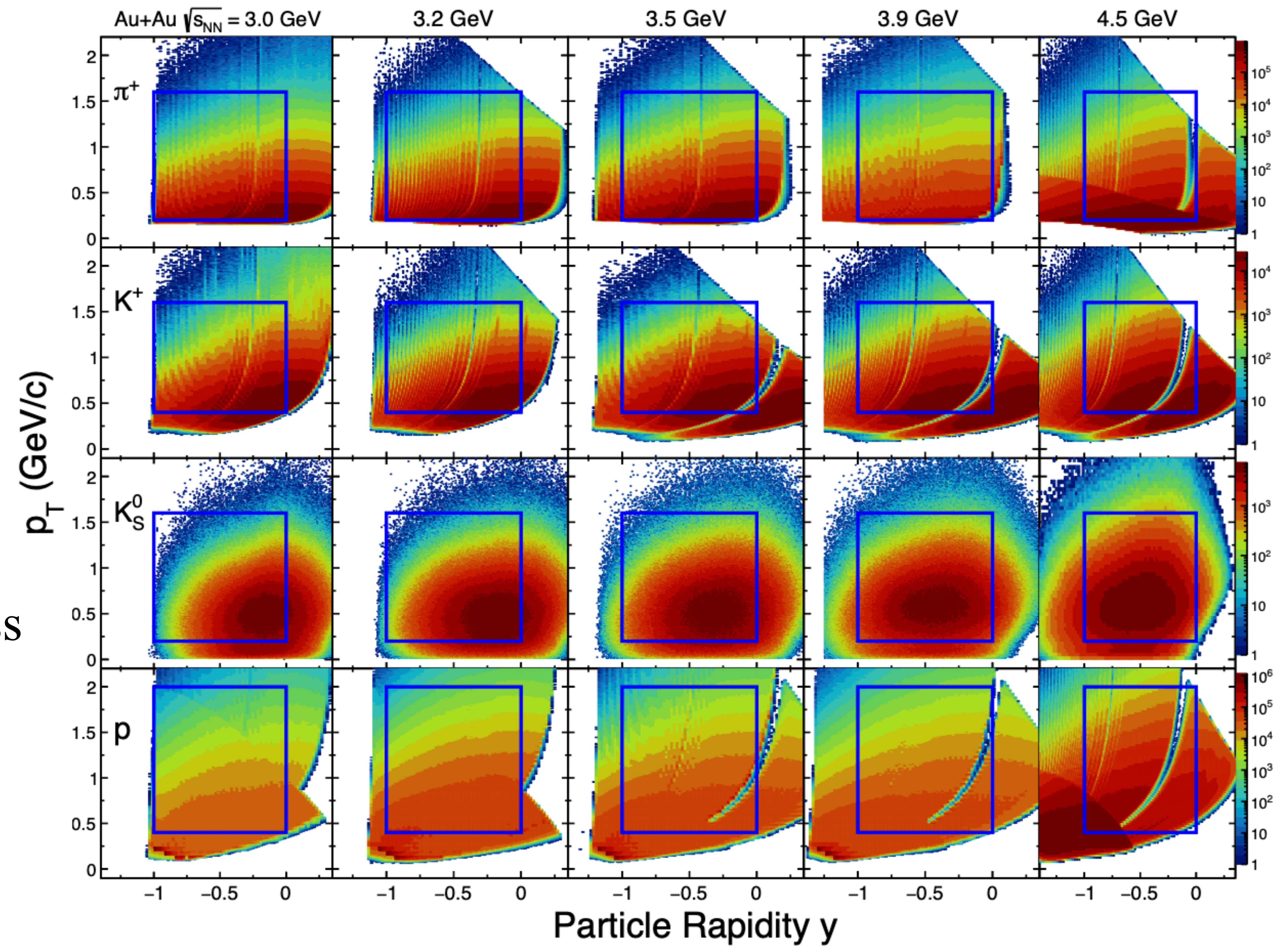
Particle Identification



Good particle identification capability based on TPC dE/dx and TOF m^2

Particle Acceptance



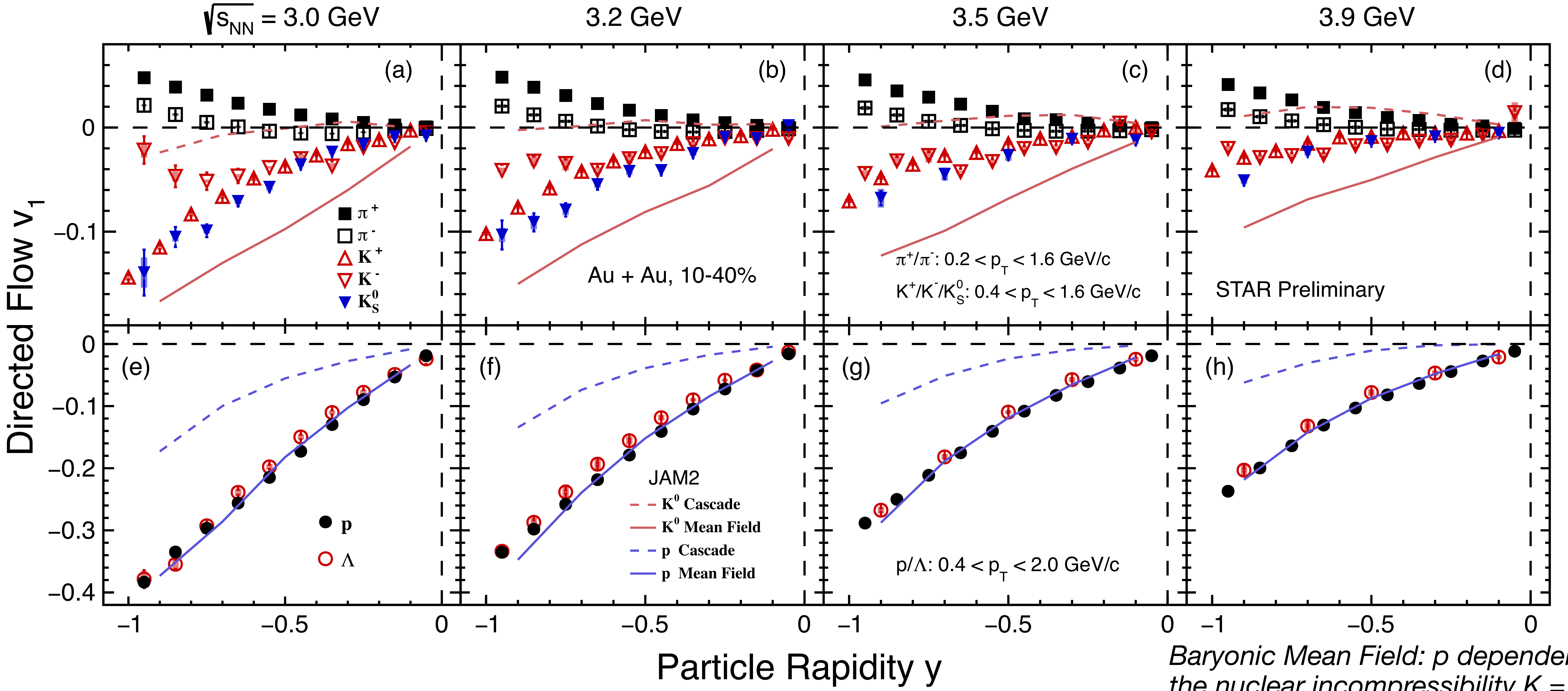


1) K_s^0, Λ are reconstructed by invariant mass method (KF particle package)

2) Particle rapidity coverage from -1 to 0 (blue boxes)

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

Rapidity dependence of v_1

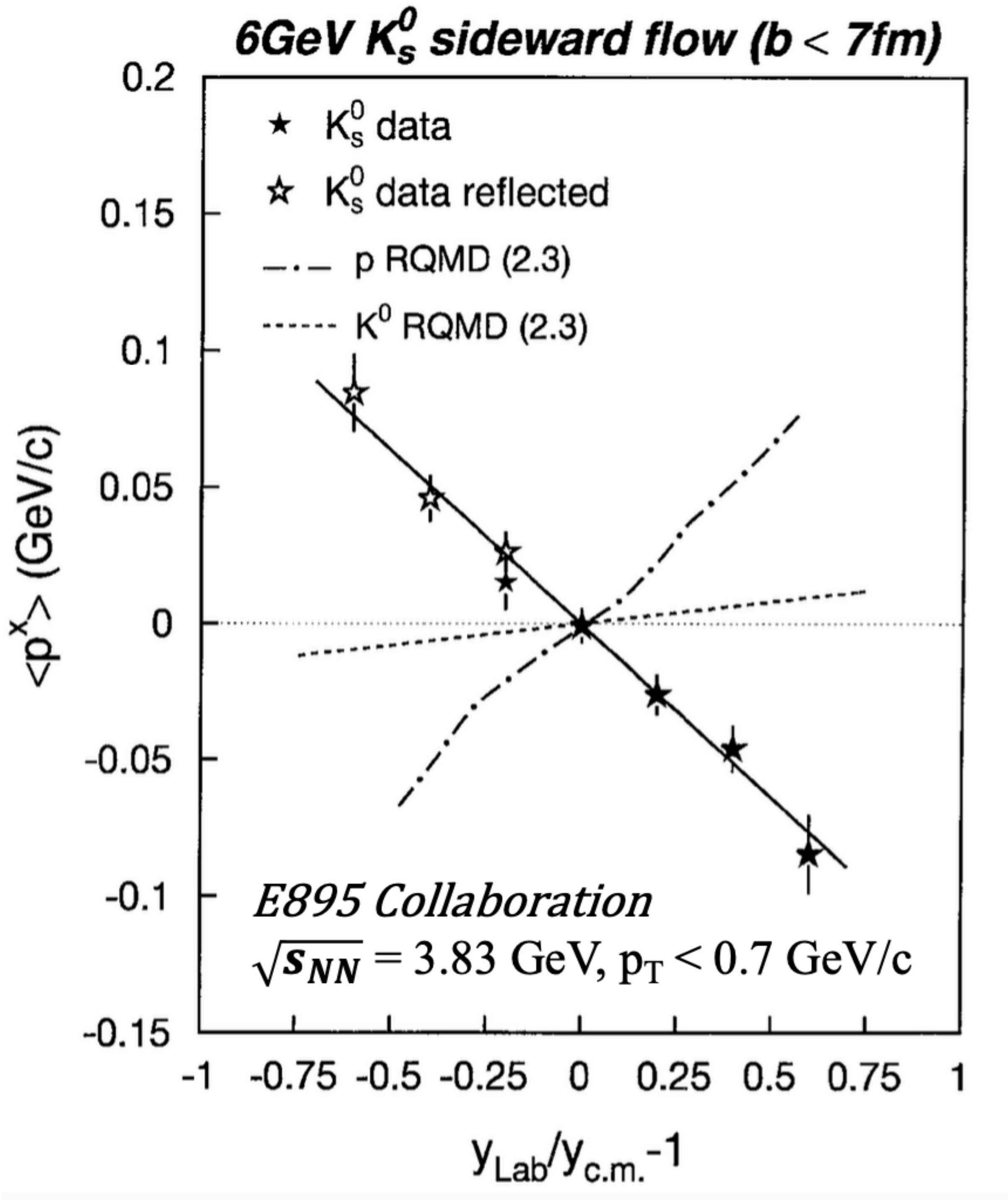


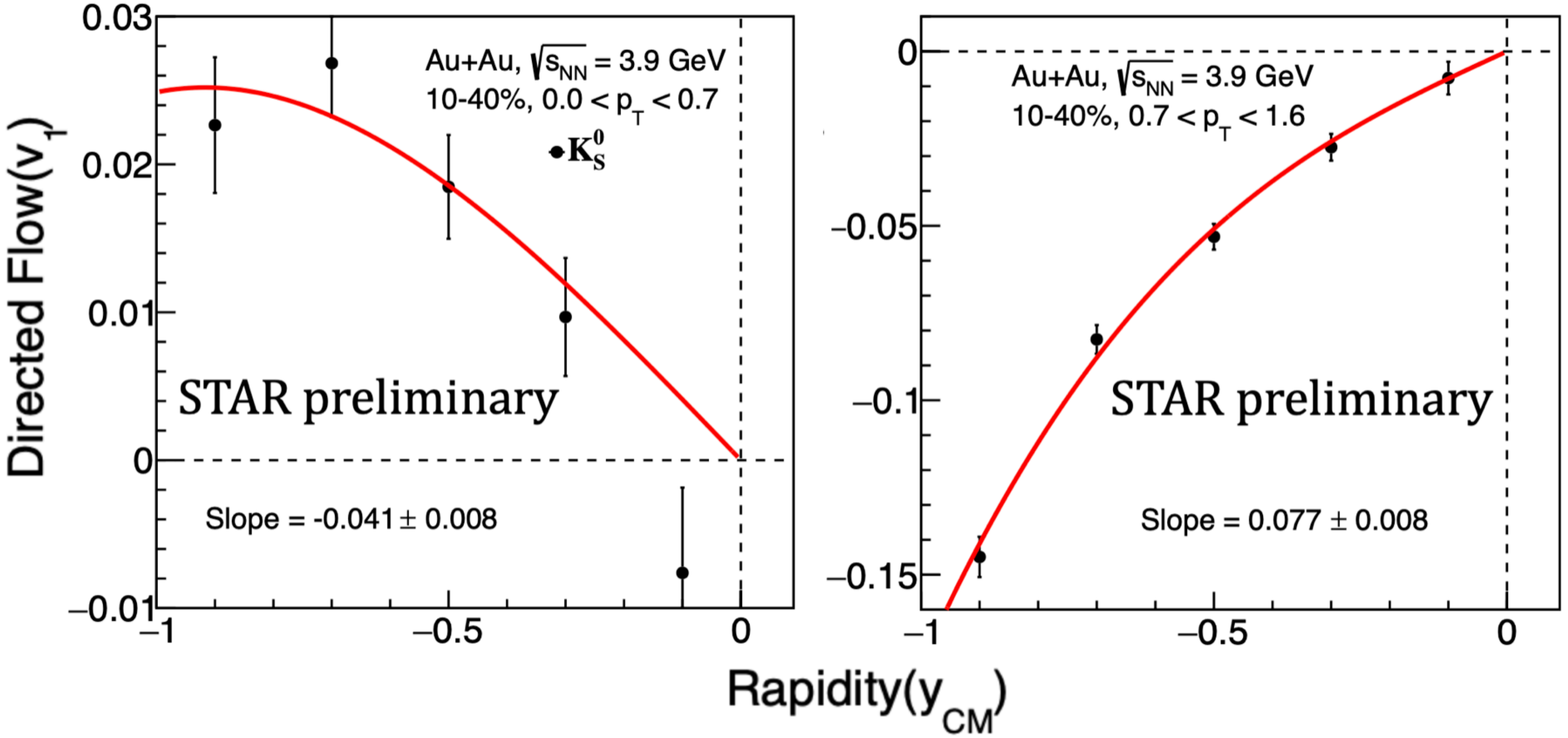
Baryonic Mean Field: p dependent Soft EoS
the nuclear incompressibility K = 210 MeV

Measurements of v_1 vs. rapidity for $\pi^{\pm}$, $K^{\pm}$, K^0_S, p, Λ at 3.0, 3.2, 3.5, and 3.9 GeV

Anti-flow of Kaon

E895 Collaboration, Phys. Rev. Lett. 85, 940 (2000)

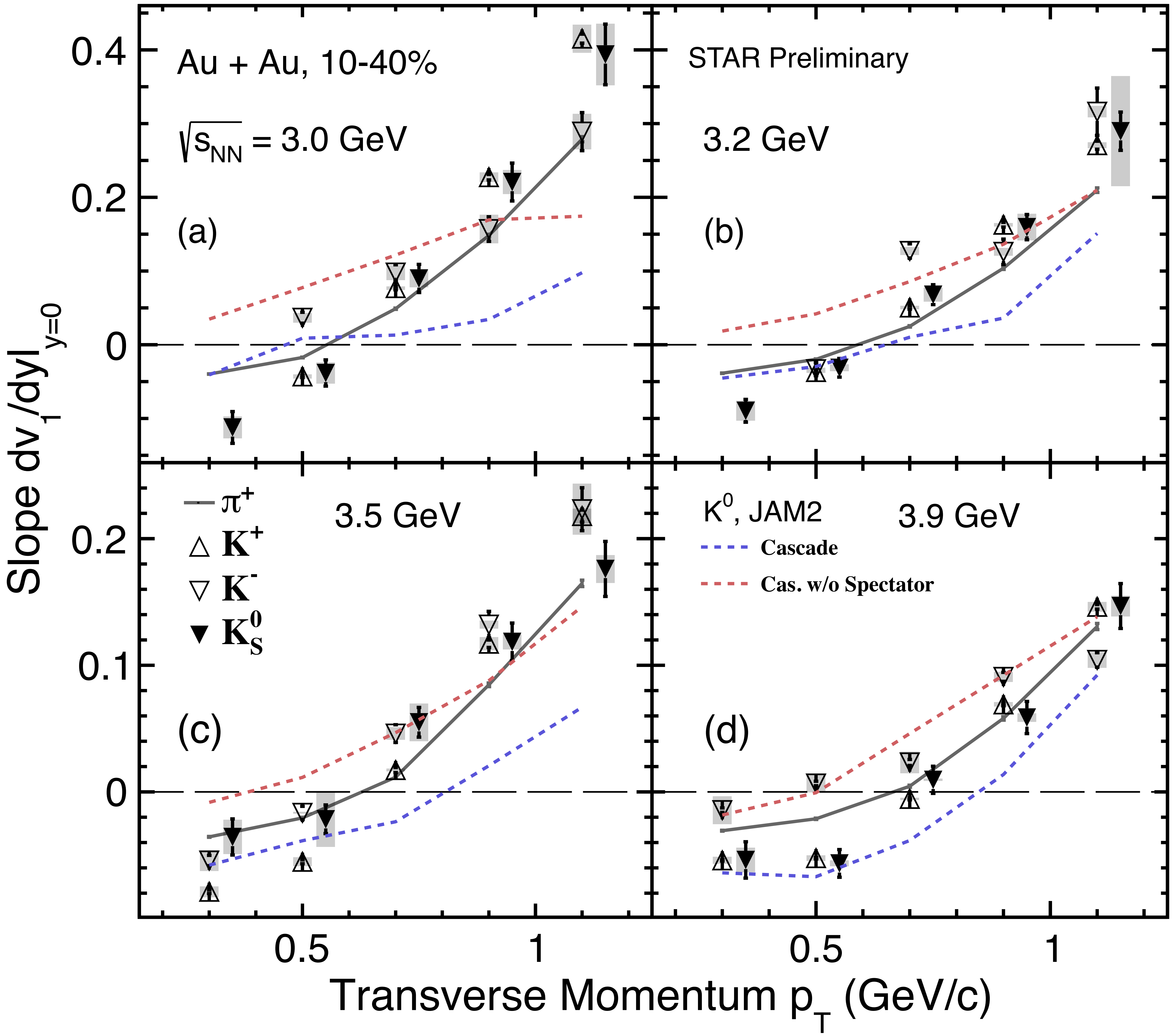




1) 3.9 GeV: anti-flow observed for K_S^0 at $p_T < 0.7$ GeV/c
2) Positive directed flow slope of K_S^0 at $p_T > 0.7$ GeV/c

Strong p_T dependence of K_S^0 v_1 slope

p_T dependence of v_1 slope

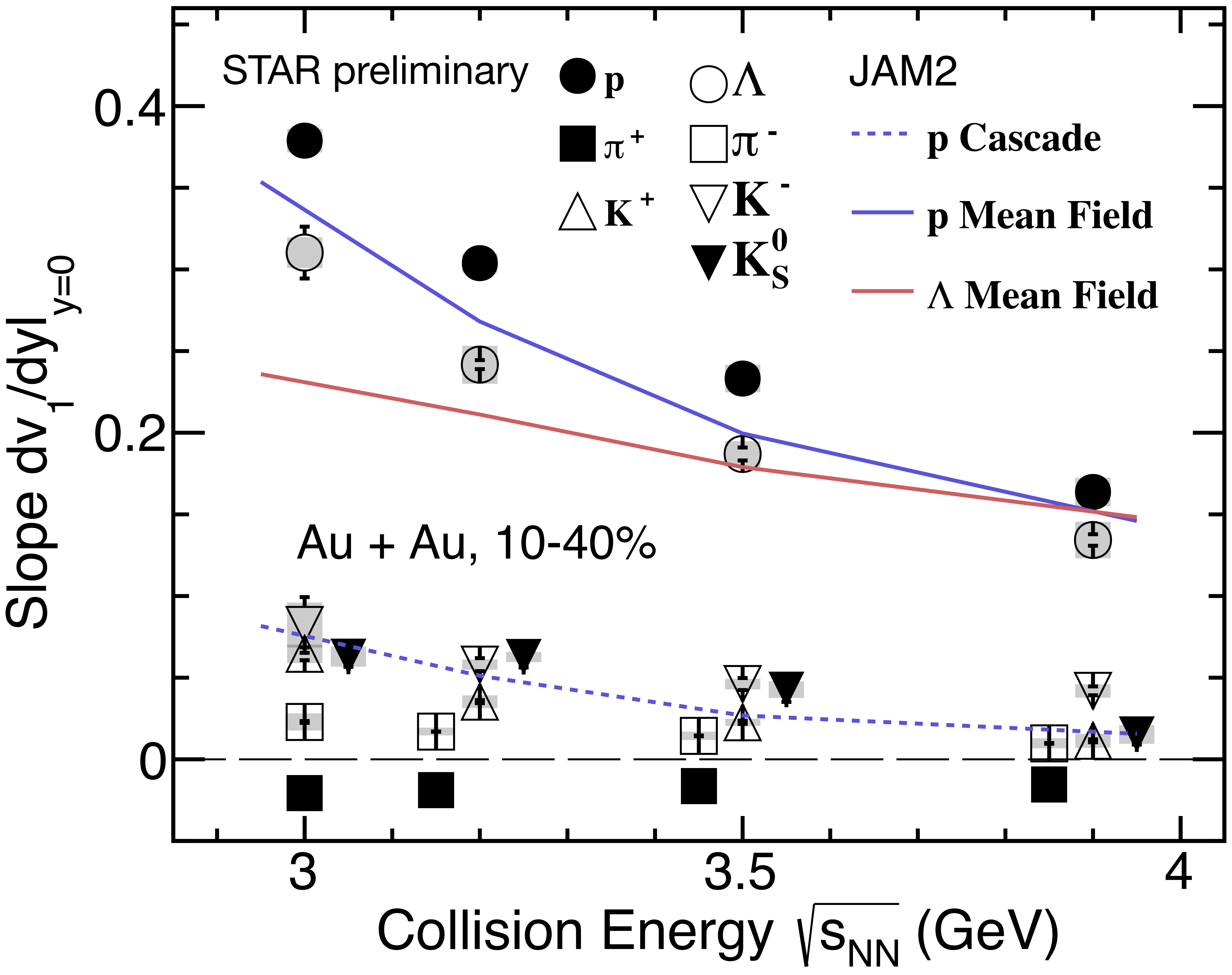


1) Anti-flow of π^+ and $K_S^0, K^{\pm}$ at low p_T
2) Anti-flow could be explained by shadowing effect from spectator, kaon potential is not necessary

Energy dependence of v_1 slope

π^+/π^-: $0.2 < p_T < 1.6$ GeV/c

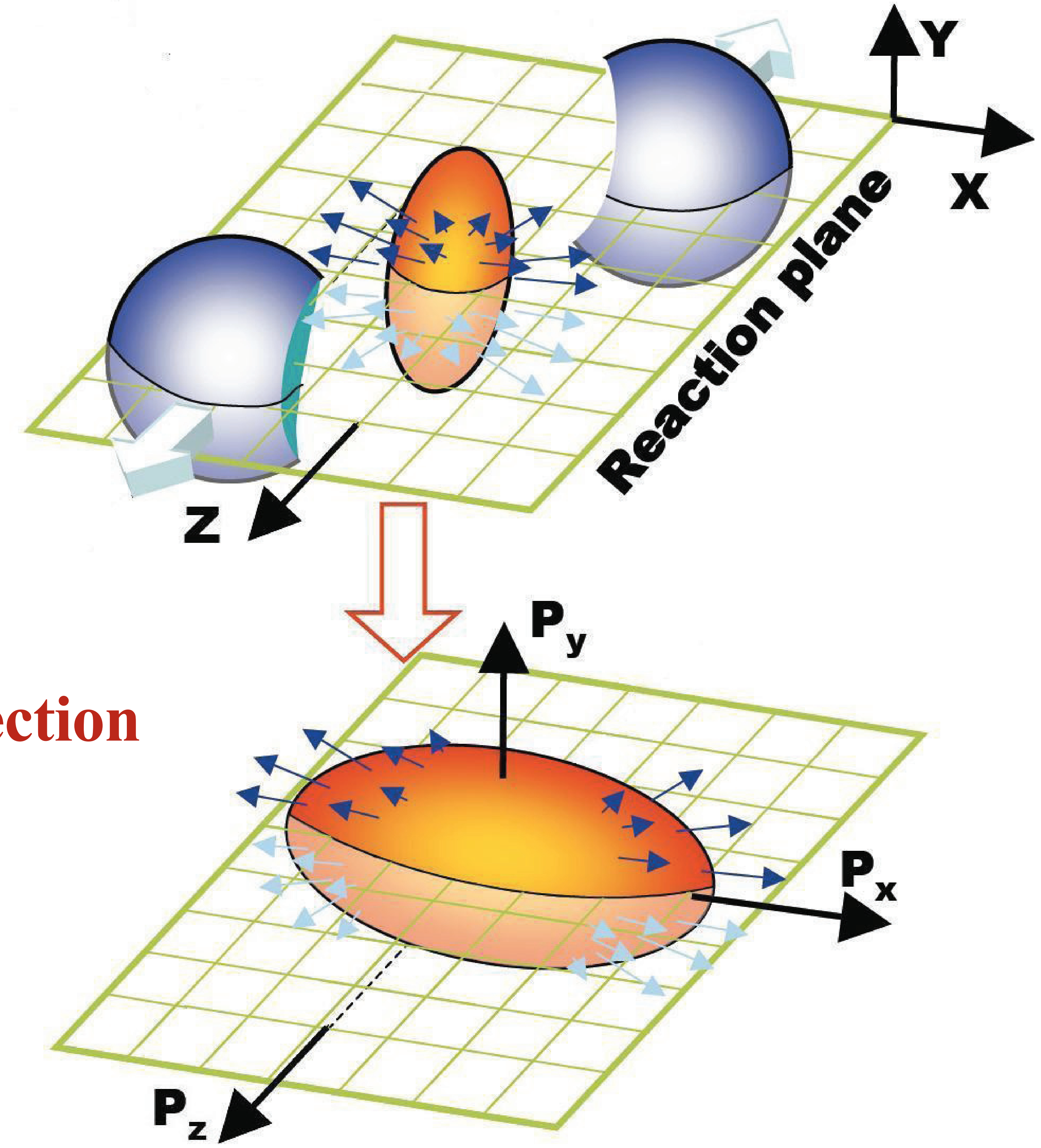
$K^+/K^-/K^0_S$: $0.4 < p_T < 1.6$ GeV/c p/Λ: $0.4 < p_T < 2.0$ GeV/c



1) v_1 slope of baryons drops as collision energy increases
2) JAM with baryonic Mean Field better describe data
   - Mean field potential play important role

Anisotropic flow

$$v_1 = \cos(\phi - \psi_r) = \left\langle \frac{p_x}{p_T} \right\rangle$$

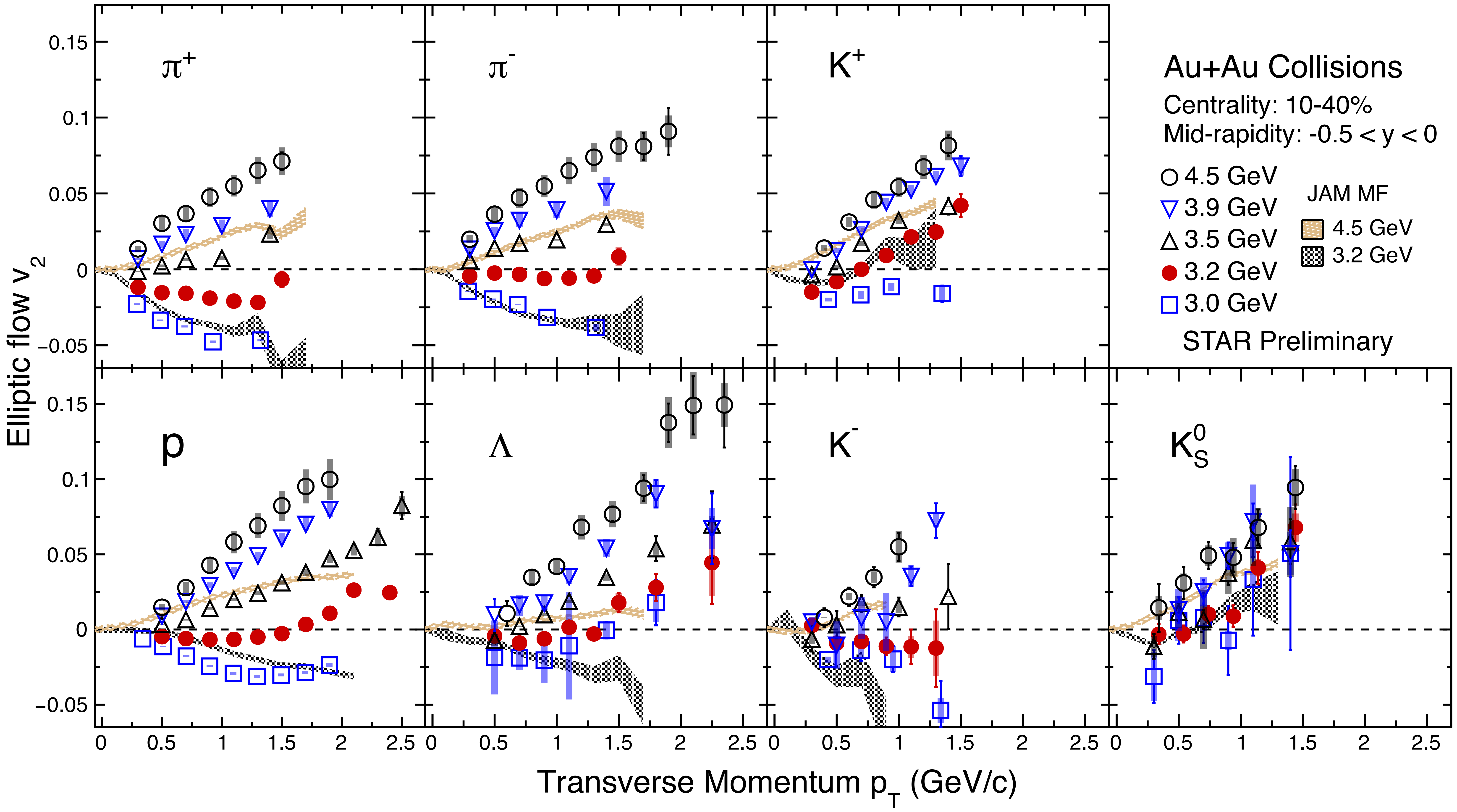


$$v_2 = \cos\left[2(\phi - \psi_r)\right] = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

v_1 reflect asymmetry along X direction

v_2 reflect asymmetry on X-Y plane

p_T dependence of v_2 at 3.0 - 4.5 GeV



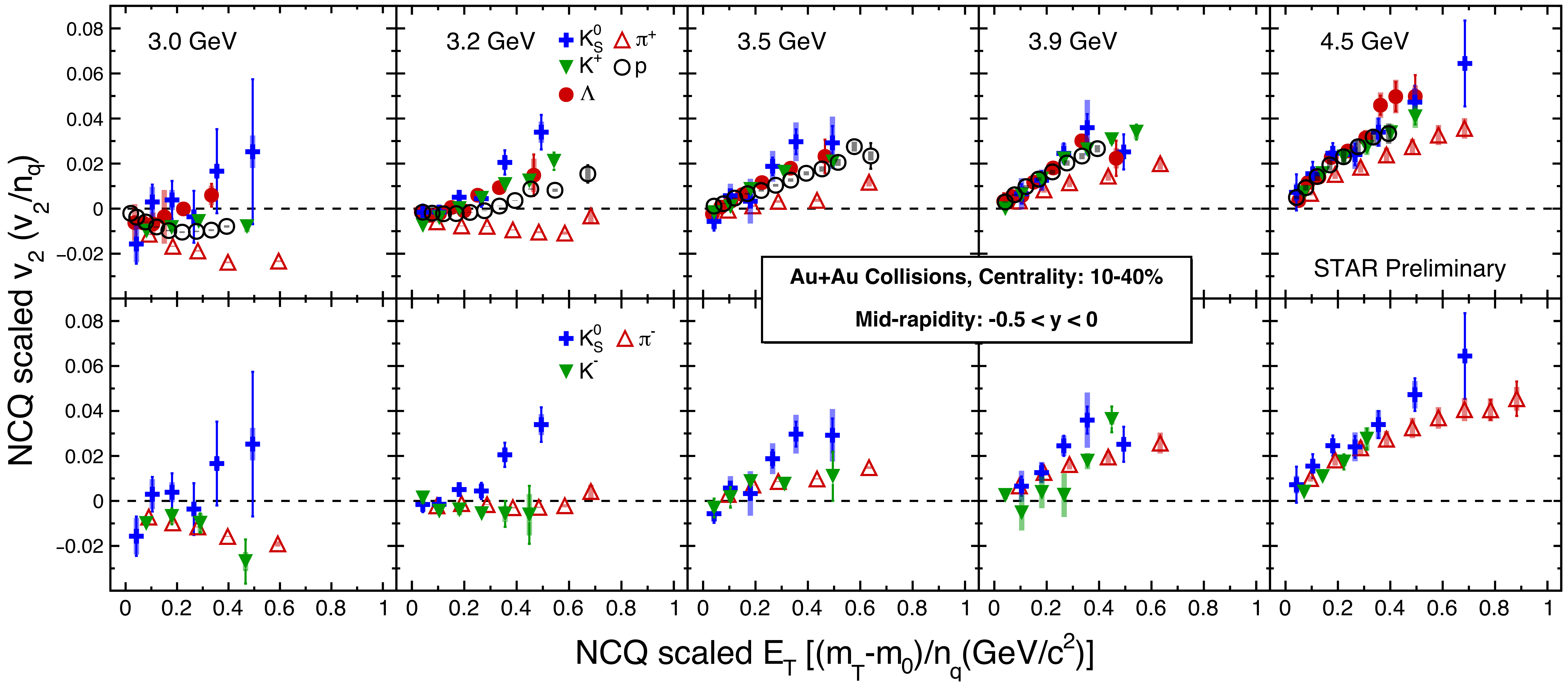
1) Clear energy dependence for $v_2(p_T)$ from negative to positive: **Shadowing effect**

2) JAM + baryonic Mean Field better describe the 3.2 GeV while underestimate 4.5 GeV data

Baryonic Mean Field: p dependent Soft EoS, the nuclear incompressibility K = 210 MeV

NCQ scaling of v_2 at 3 - 4.5 GeV

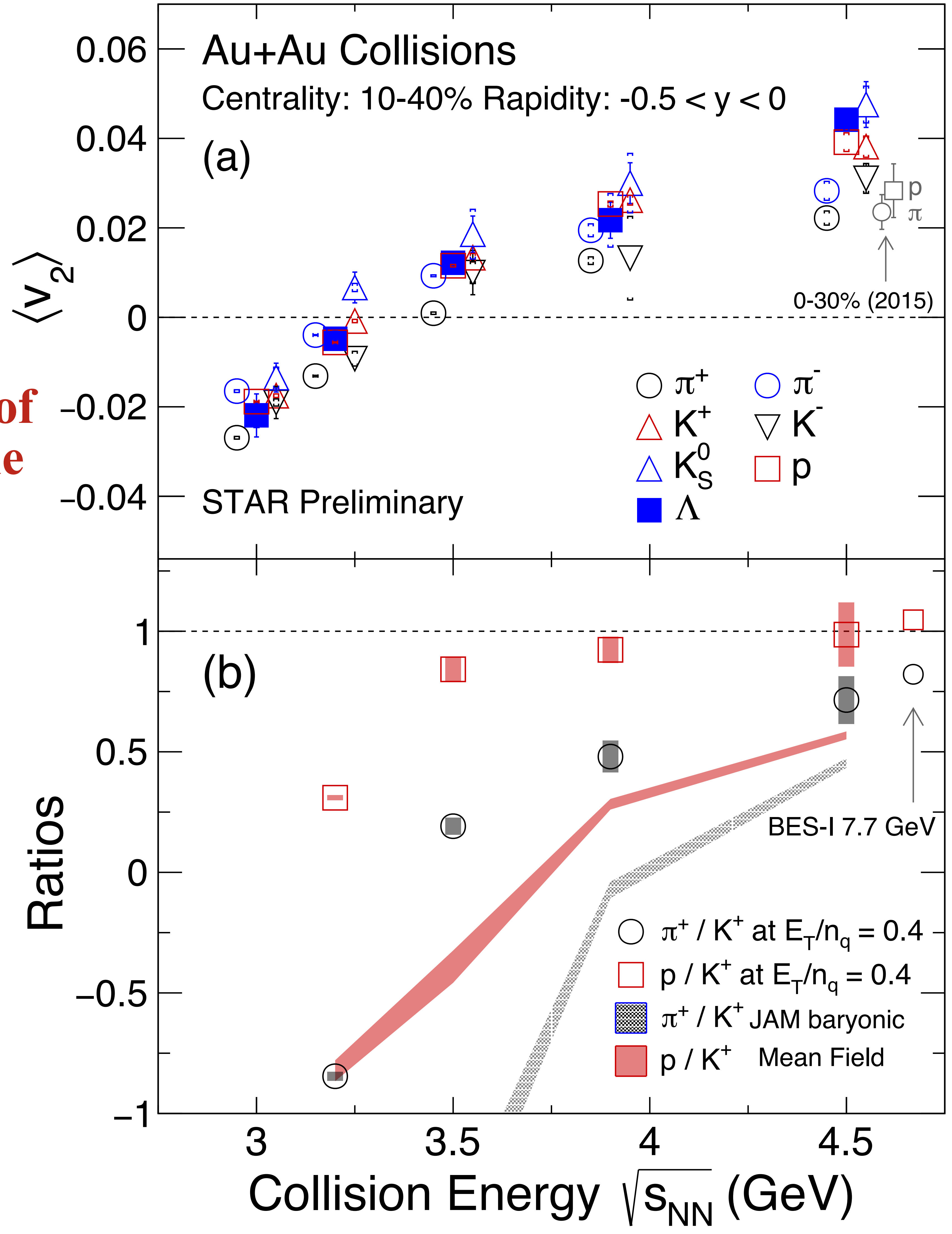
Hadronic interaction



Partonic collectivity

1) NCQ scaling completely breaks below 3.2 GeV
2) NCQ scaling becomes better gradually from 3.2 to 4.5 GeV

Energy dependence of $\langle v_2 \rangle$



In-plane expansion

Out of plane

1) Negative to positive flow: 3 → 4.5 GeV

2) NCQ scaled v_2 ratio of p/K^+ close to 1 at 3.9 and 4.5 GeV, while deviating largely from 1 at 3.2 GeV

STAR Collaboration, Phys. Rev. C 88, 14902 (2013), Phys. Rev. C 103, 34908 (2021)

Summary

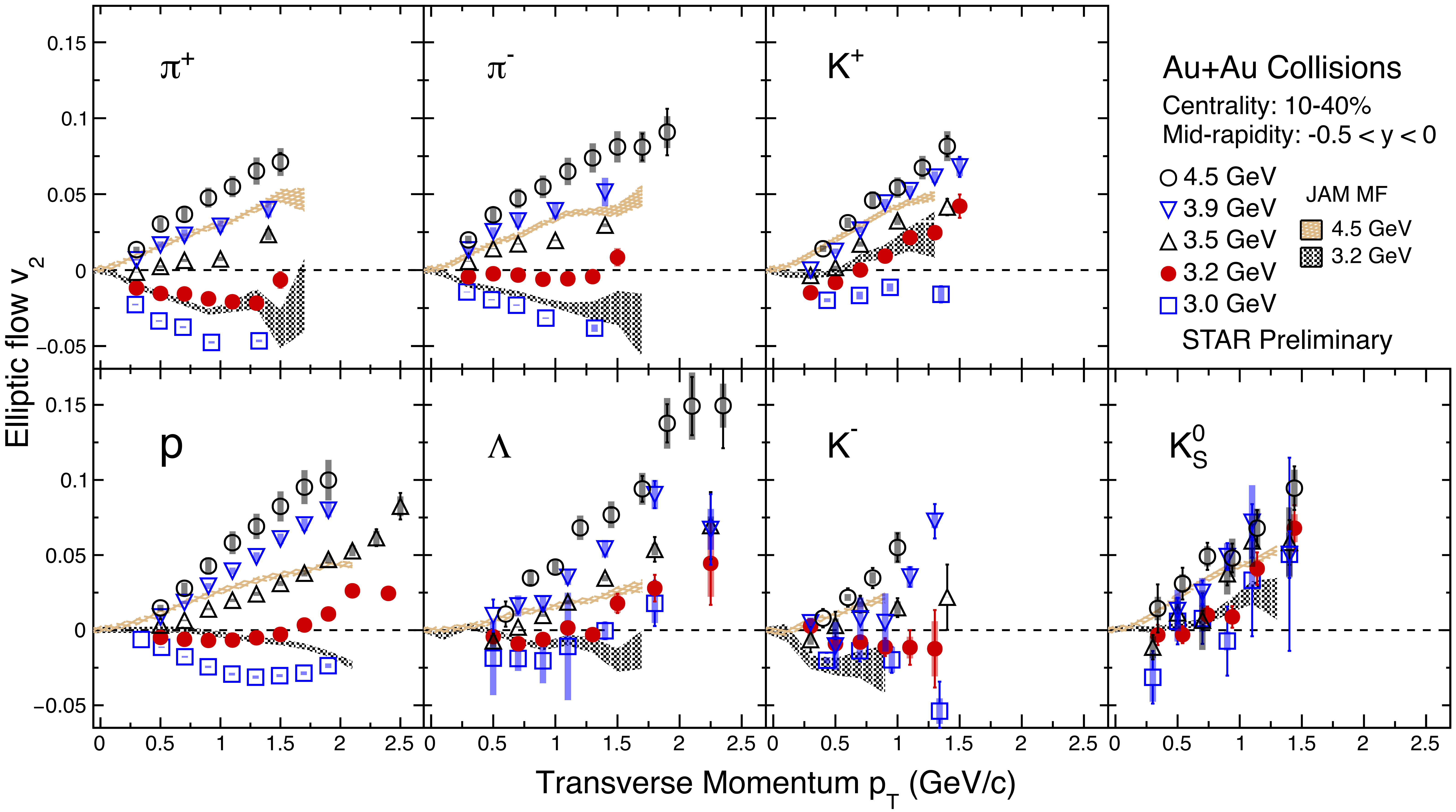
1) Anti-flow for K_S^0, $K^{\pm}$ and π^+ observed at low p_T ($\lesssim$ 0.6 GeV/c)

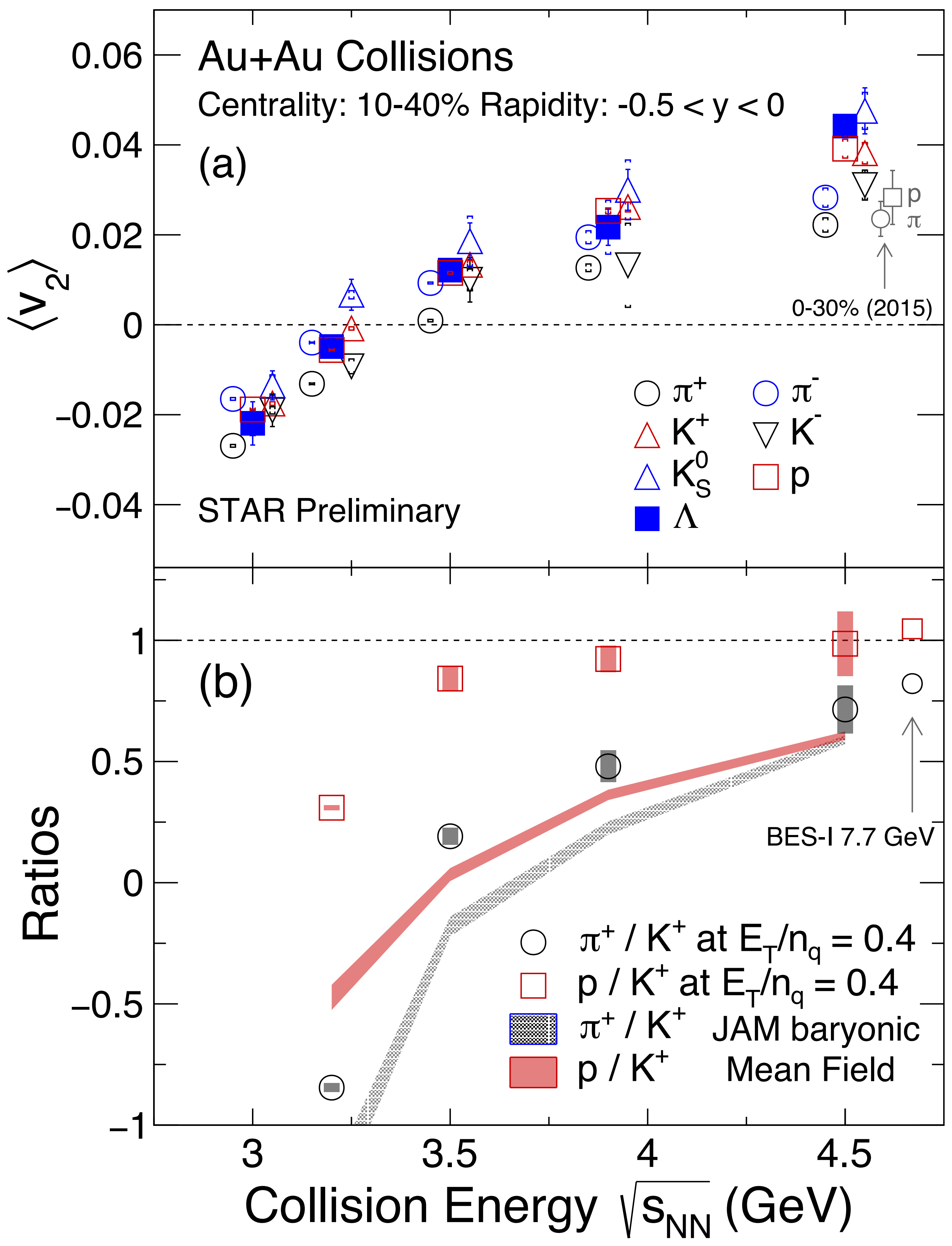
- **Shadowing effect is important, kaon potential is not necessary to reproduce kaon anti-flow**

2) NCQ scaling breaks at 3.0 and 3.2 GeV, and gradually restores from 3.0 to 4.5 GeV

- **Shadowing effect diminishes**
- **Dominance of partonic interactions at 4.5 GeV**

Backup





Baryonic Mean Field: non-p dependent Soft EoS, the nuclear incompressibility K = 210 MeV