Collectivity in Heavy-Ion Collisions at High Baryon Density from STAR BES-II

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for the STAR Collaboration

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QCD & High Energy Interactions

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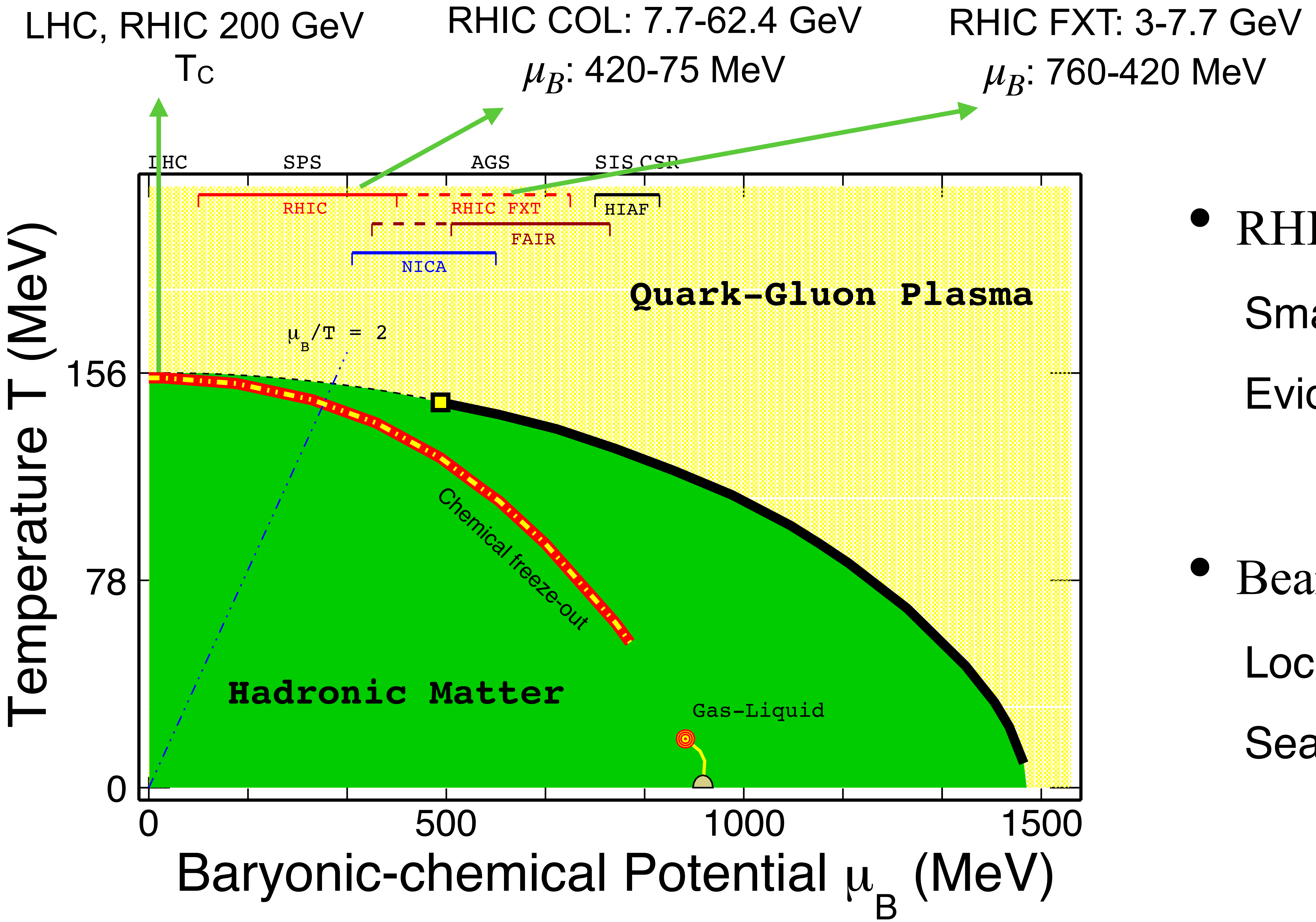
Outline

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

Motivation



- 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)

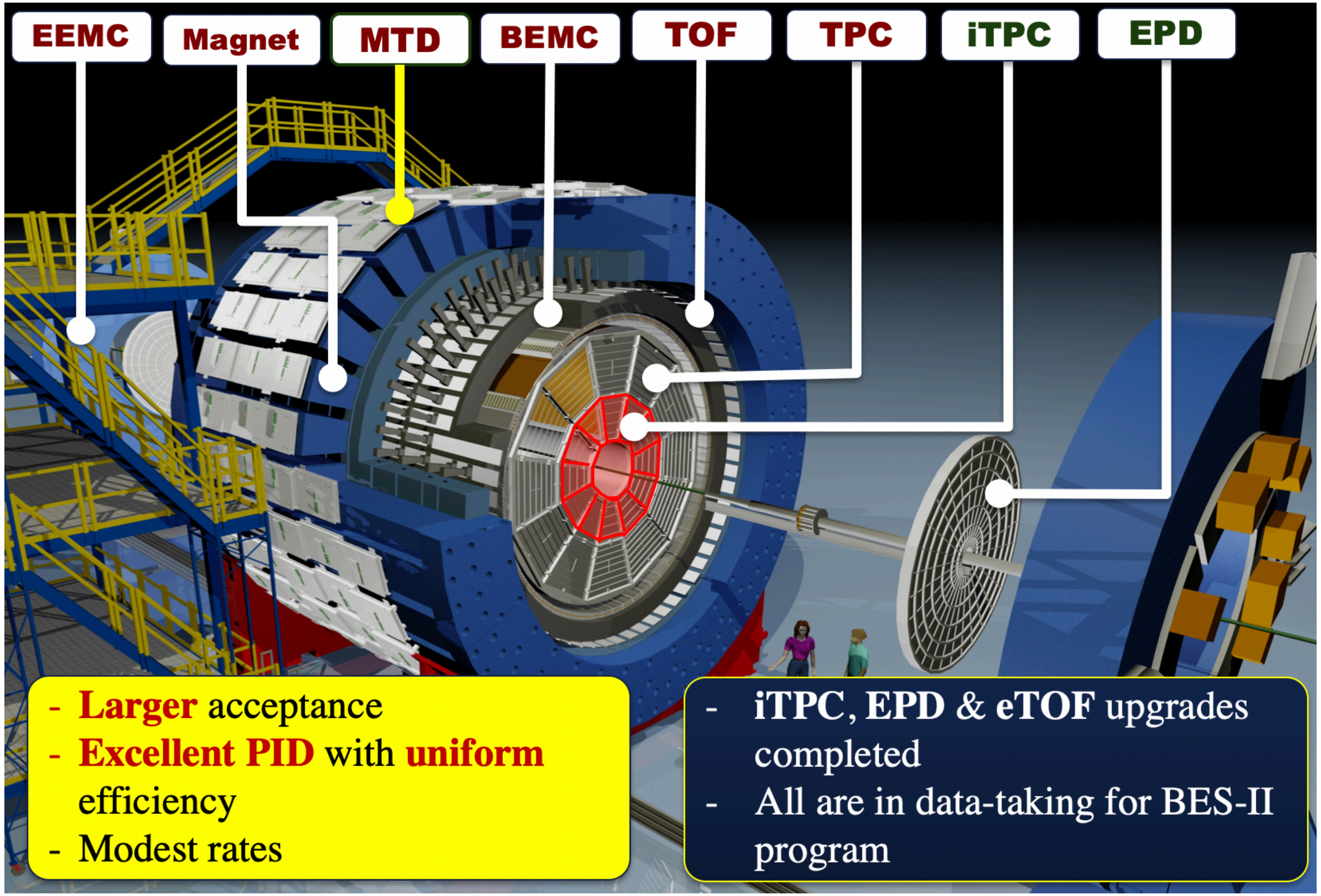
STAR Beam Energy Scan

Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	2000 M	**25** MeV	5.3	Run-14, 16	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	235 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	**3.0** (3.85)	2000 M	**760** MeV	-1.05	Run-18, 20

The widest map of the QCD phase diagram

$3 < \sqrt{s_{NN}} < 200$ GeV; $760 > \mu_B > 25$ MeV

Experimental Setup

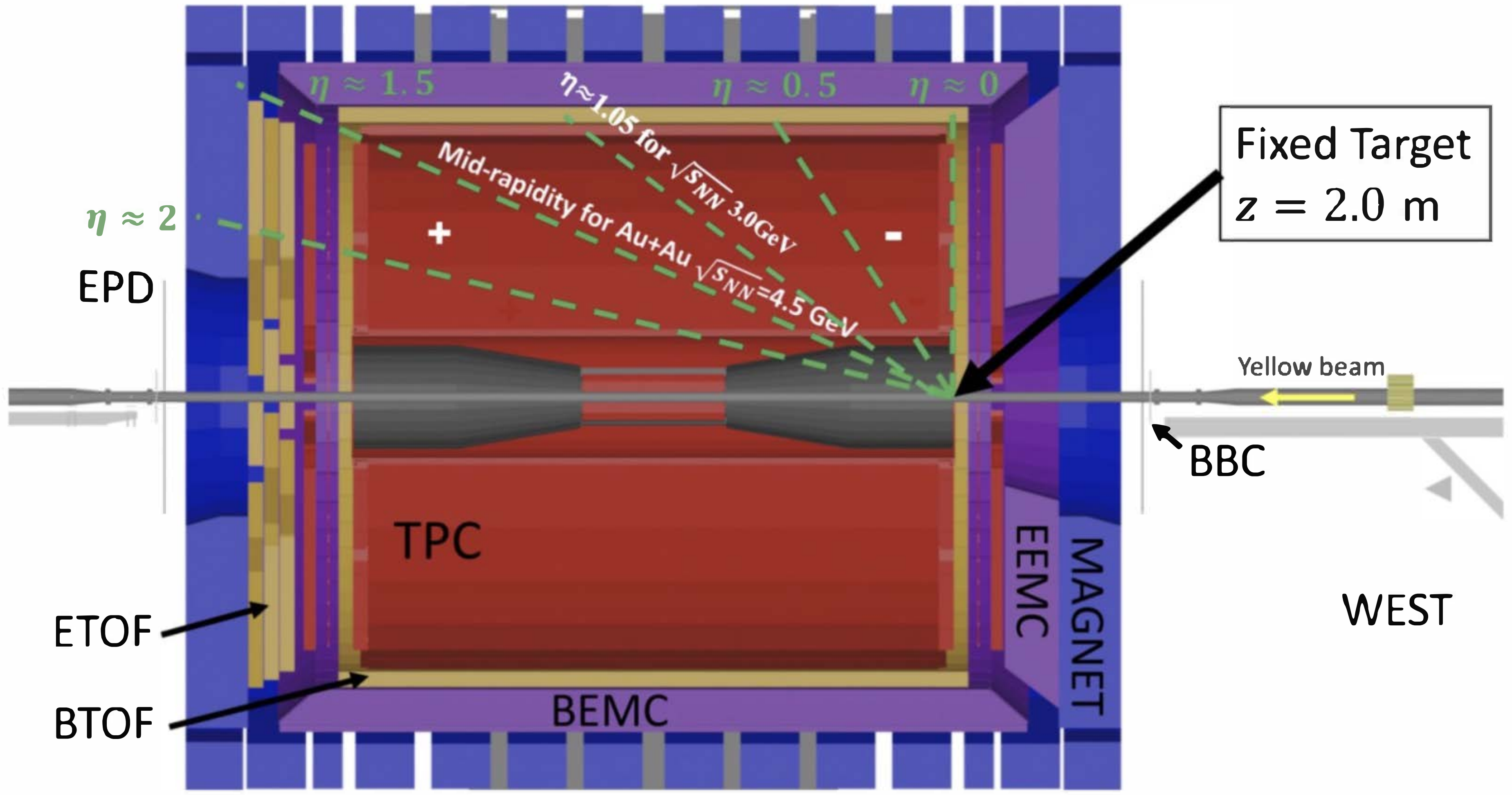


- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

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

STAR Detector Upgrade:

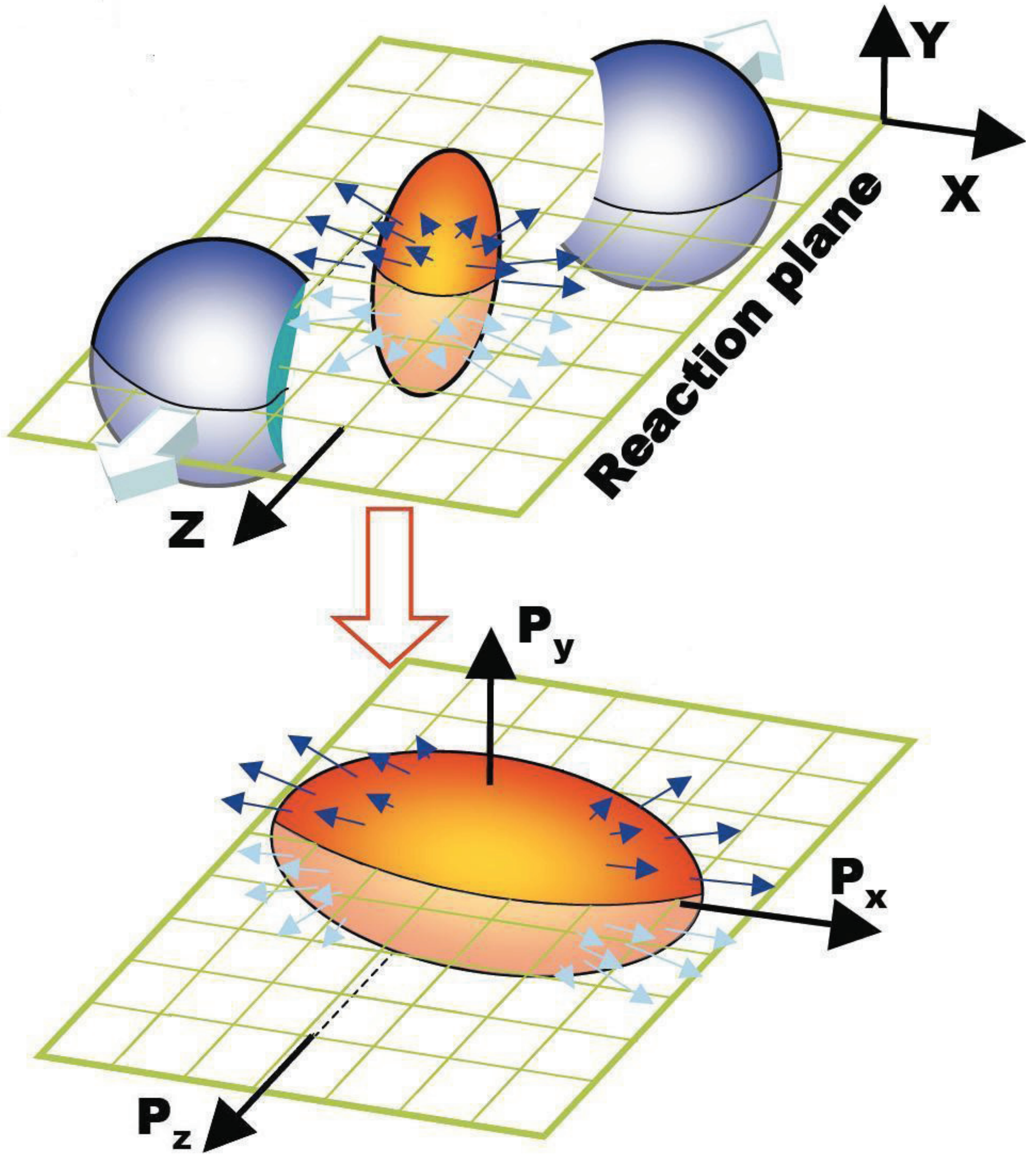
1) **I**nner-**T**ime **P**rojection **C**hamber
   - Better track quality, Larger acceptance
2) **E**ndcap **T**ime **O**f **F**light
   - Particle identification
3) **E**vent **P**lane **D**etector
   - Event plane determination (2.1< |η| < 5.1)



Anisotropic flow

Anisotropies in particle momentum distributions relative to the reaction planes or symmetry planes

Initial spatial anisotropy → Pressure gradient → Momentum space anisotropy



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_1^{\infty} 2v_n \cos\left[n\left(\phi - \psi_r\right)\right]\right)$$

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

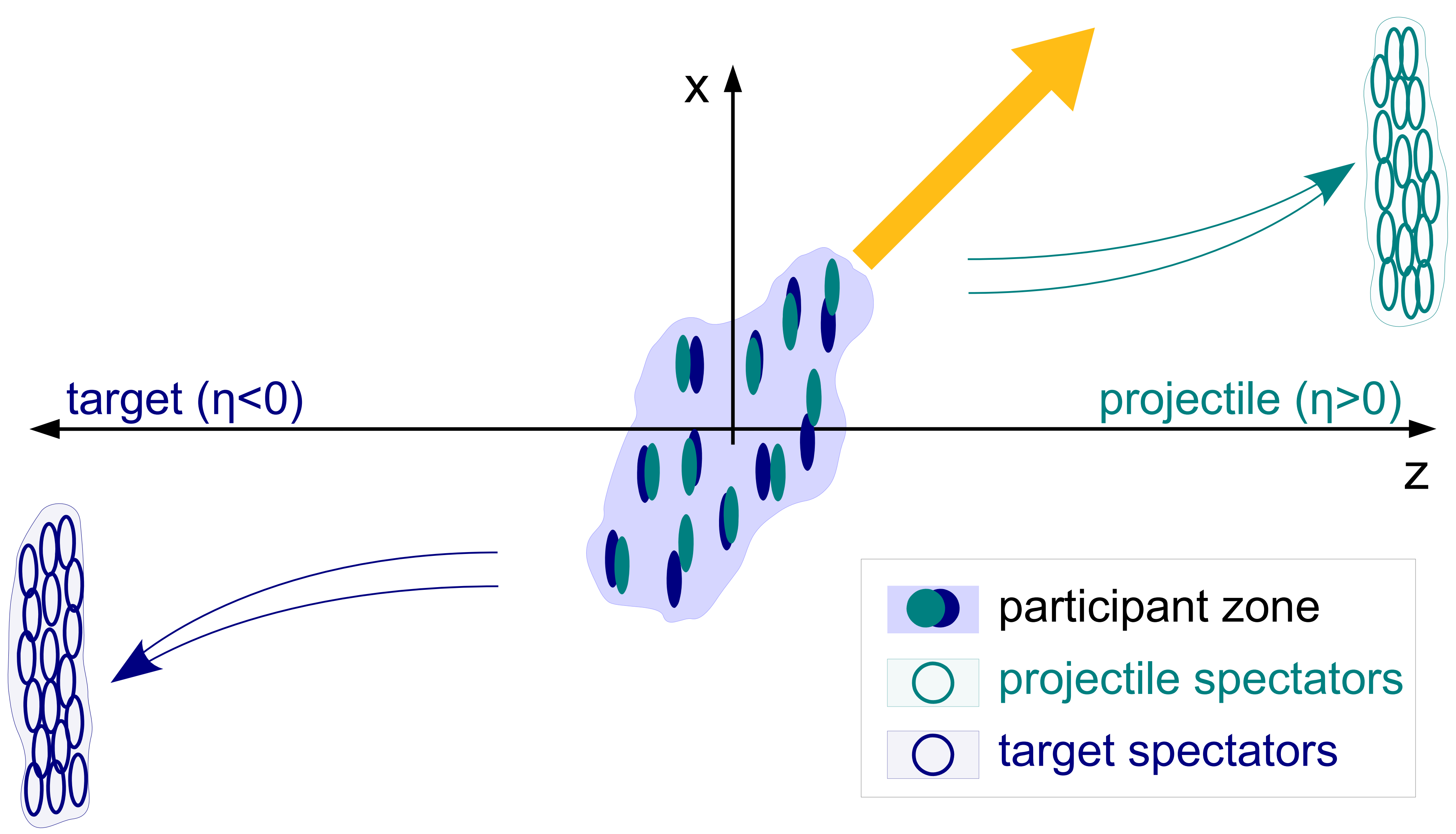
$$v_2 = \left\langle \cos\left[2(\phi - \psi_r)\right]\right\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2}\right\rangle$$ elliptic flow

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

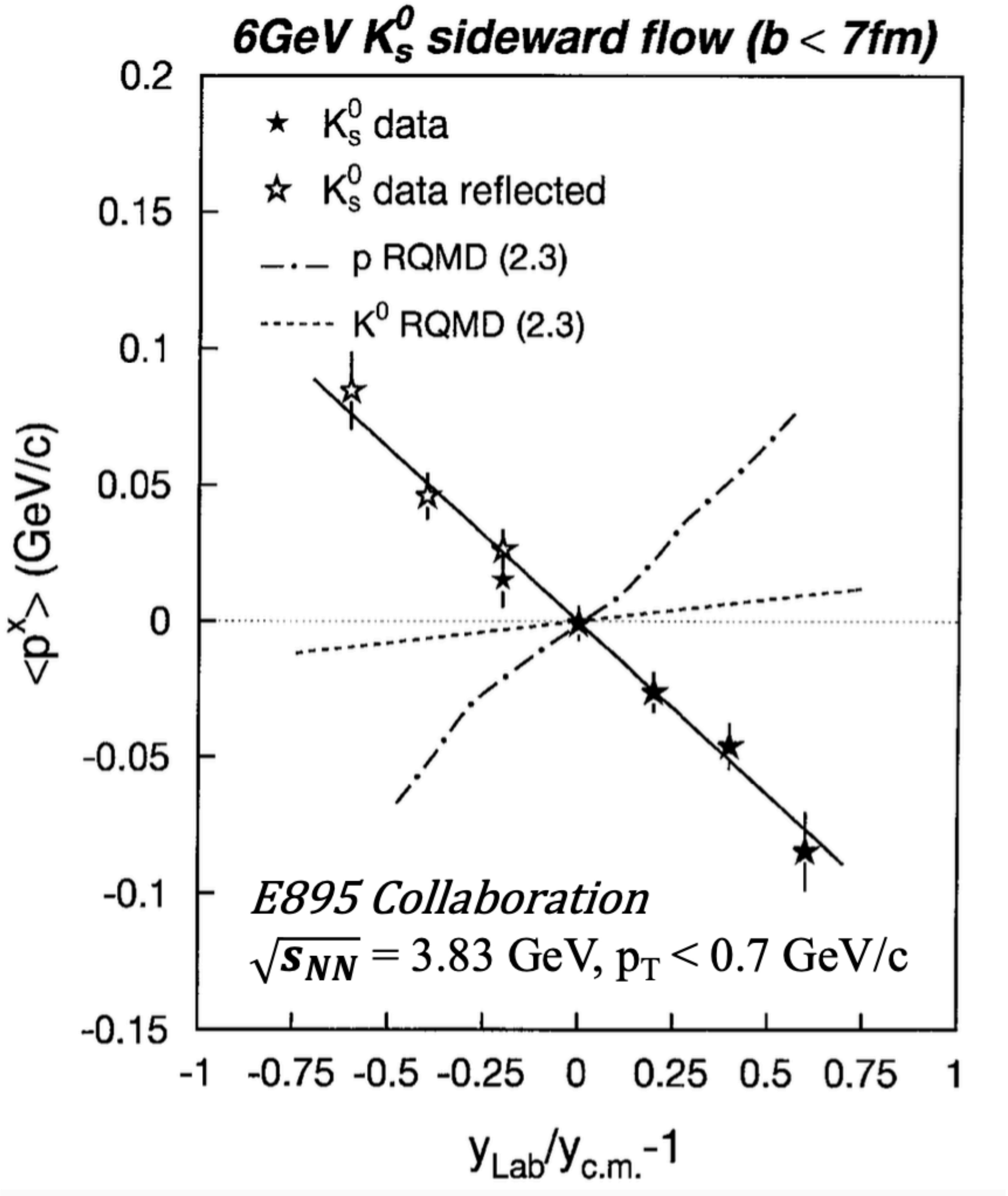
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998) P. Danielewicz, R. Lacey, Science 298 (2002) STAR Collaboration, Phys. Rev. Lett. 118, 212301 (2017)

Motivation: Anti-flow of kaons

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



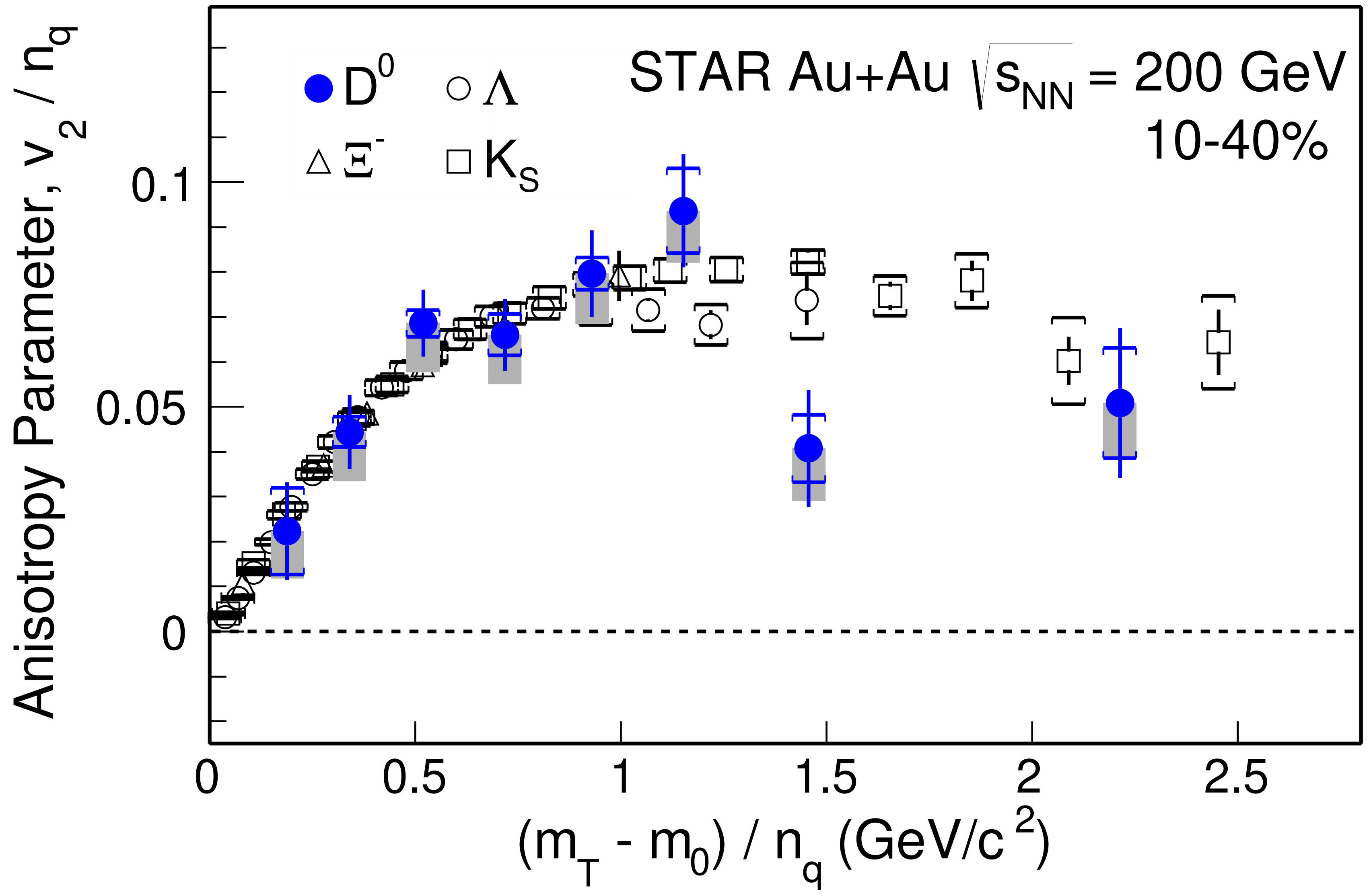
E895 Collaboration, Phys. Rev. Lett. 85, 940 (2000)



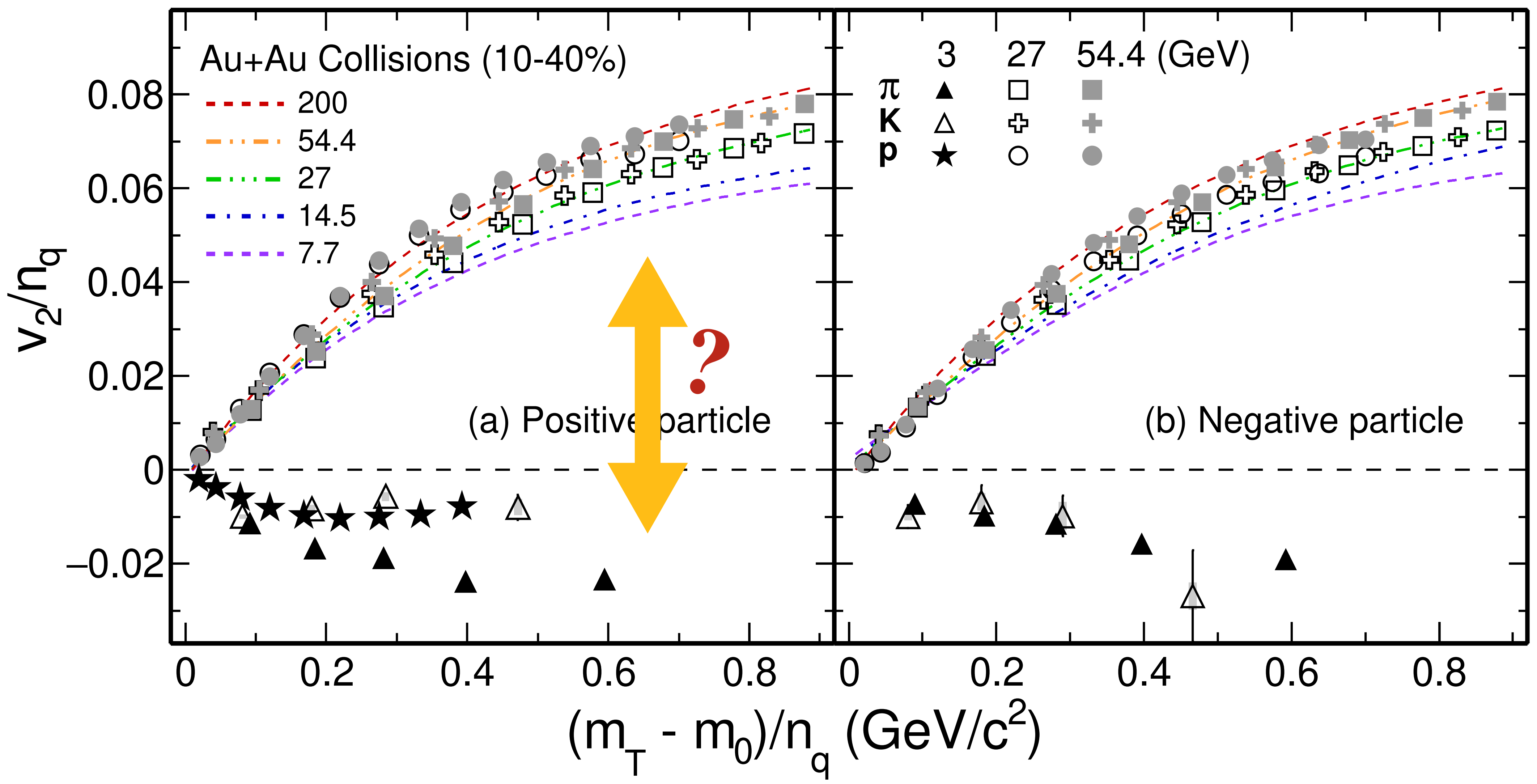
1) Bounce-off: Positive flow in positive rapidity
2) Au+Au 3.83 GeV: anti-flow of kaon at low p_T (< 0.7 GeV/c) → Kaon potential ?

Motivation: Elliptic flow

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

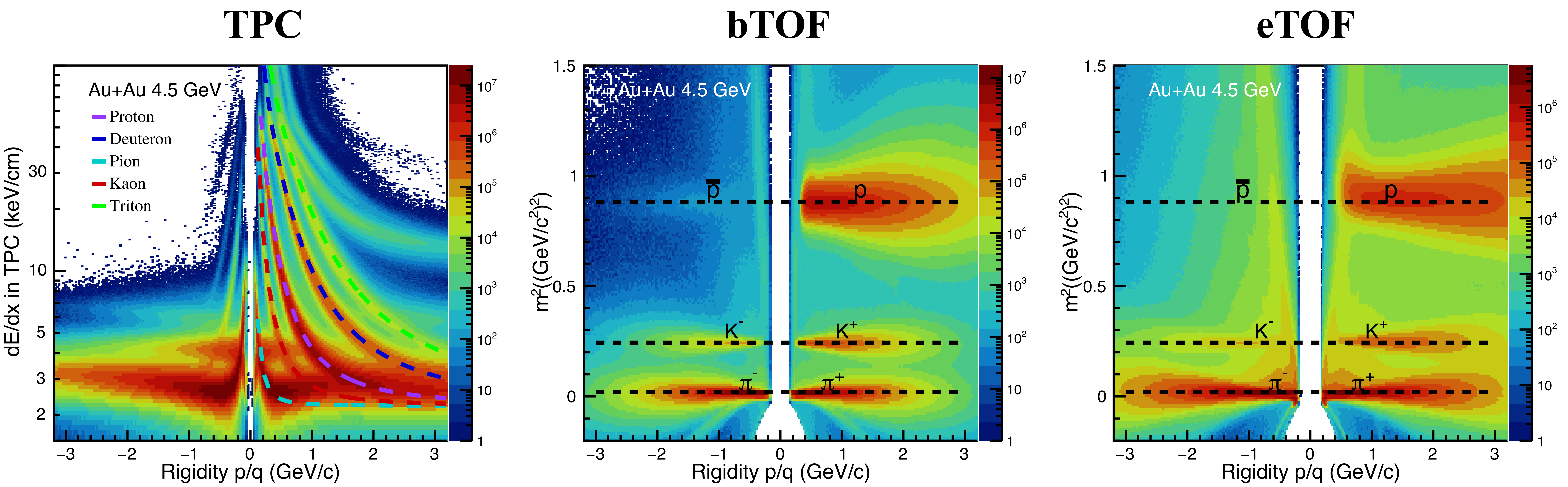


STAR Collaboration, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)



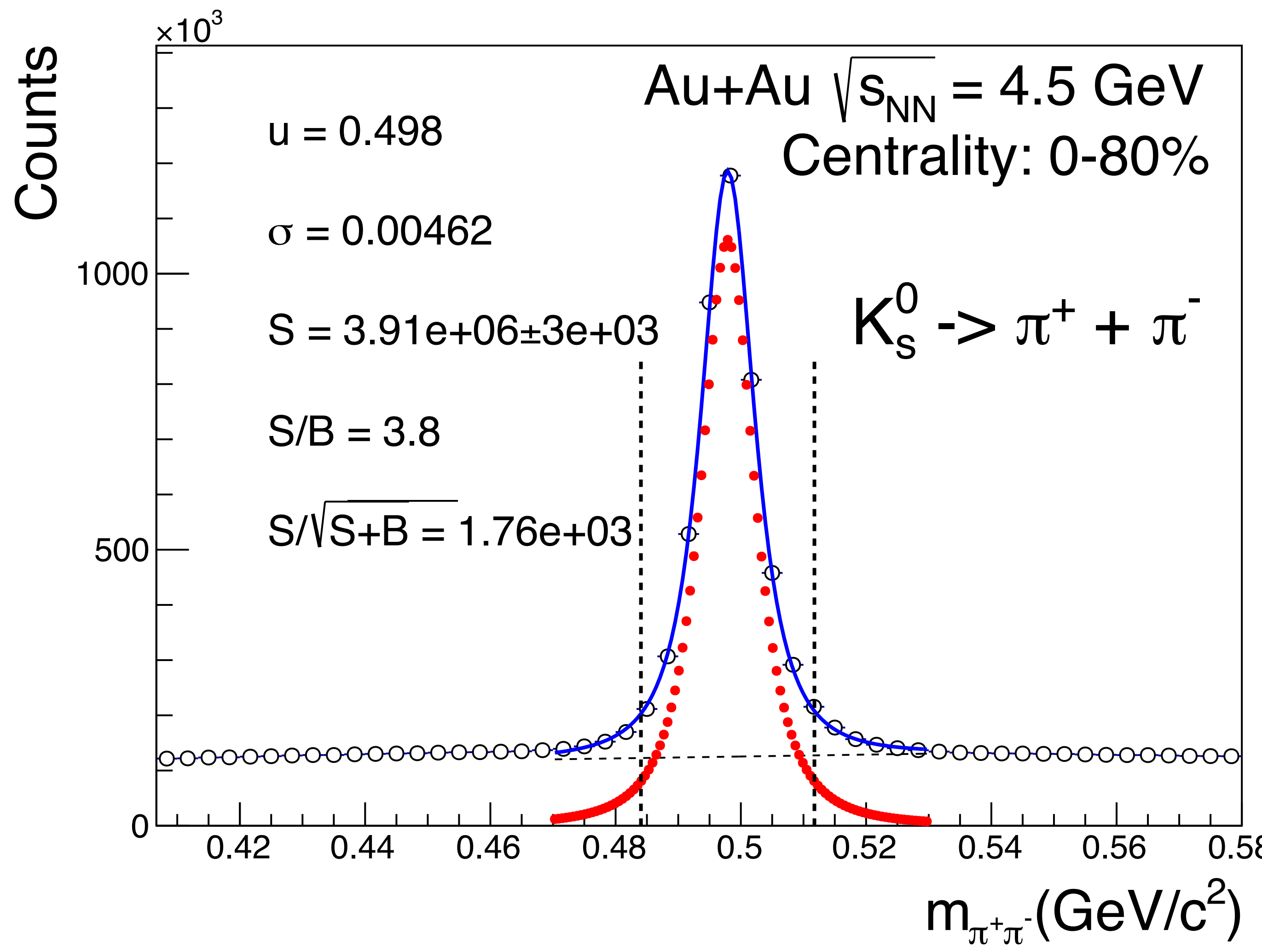
1) 200 GeV: Partonic collectivity
2) 3.0 GeV: Hadronic interaction dominates
3) Change of degree of freedom: 3.0 → 7.7 GeV ?

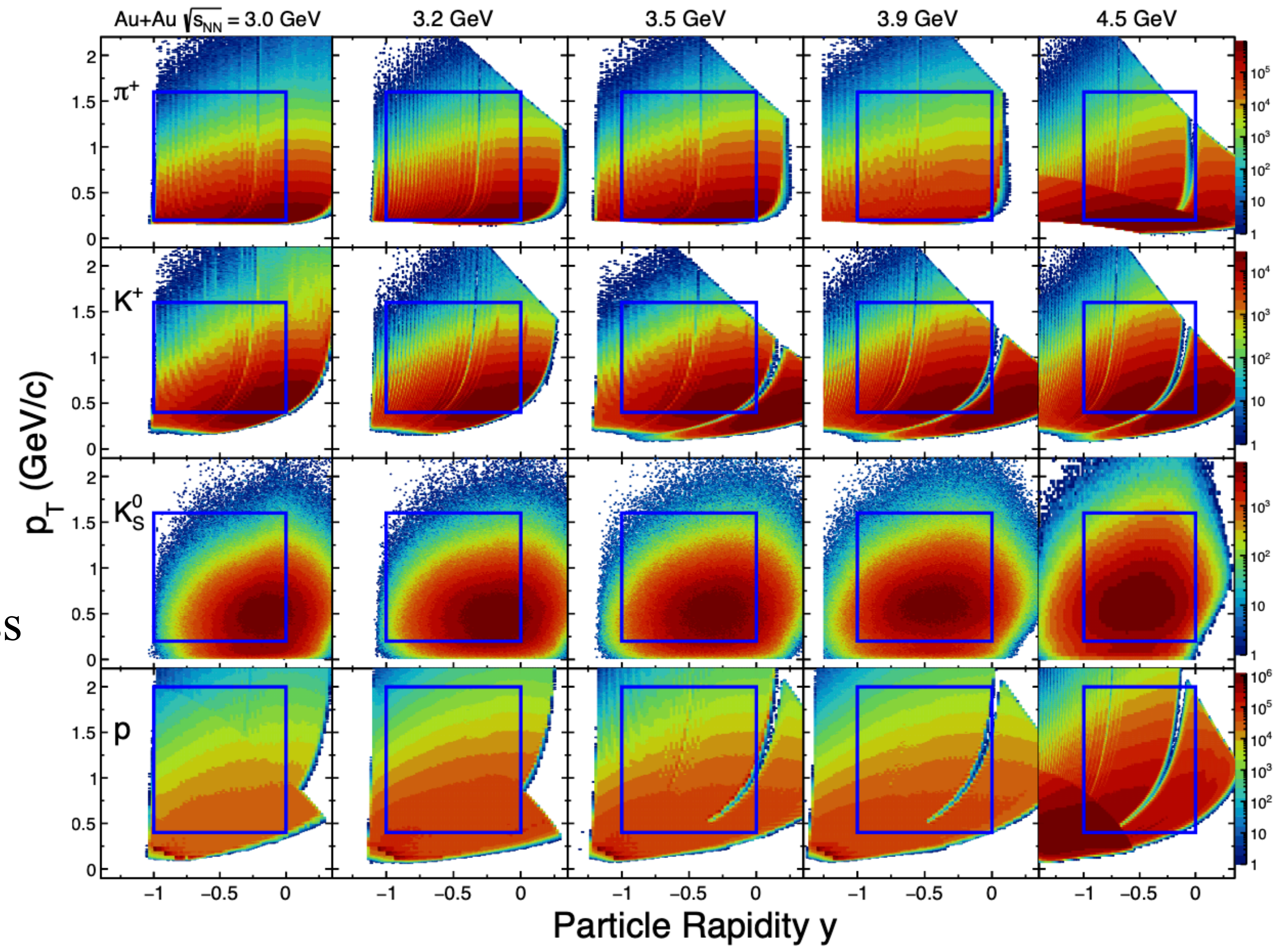
Particle Identification



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

Particle Acceptance





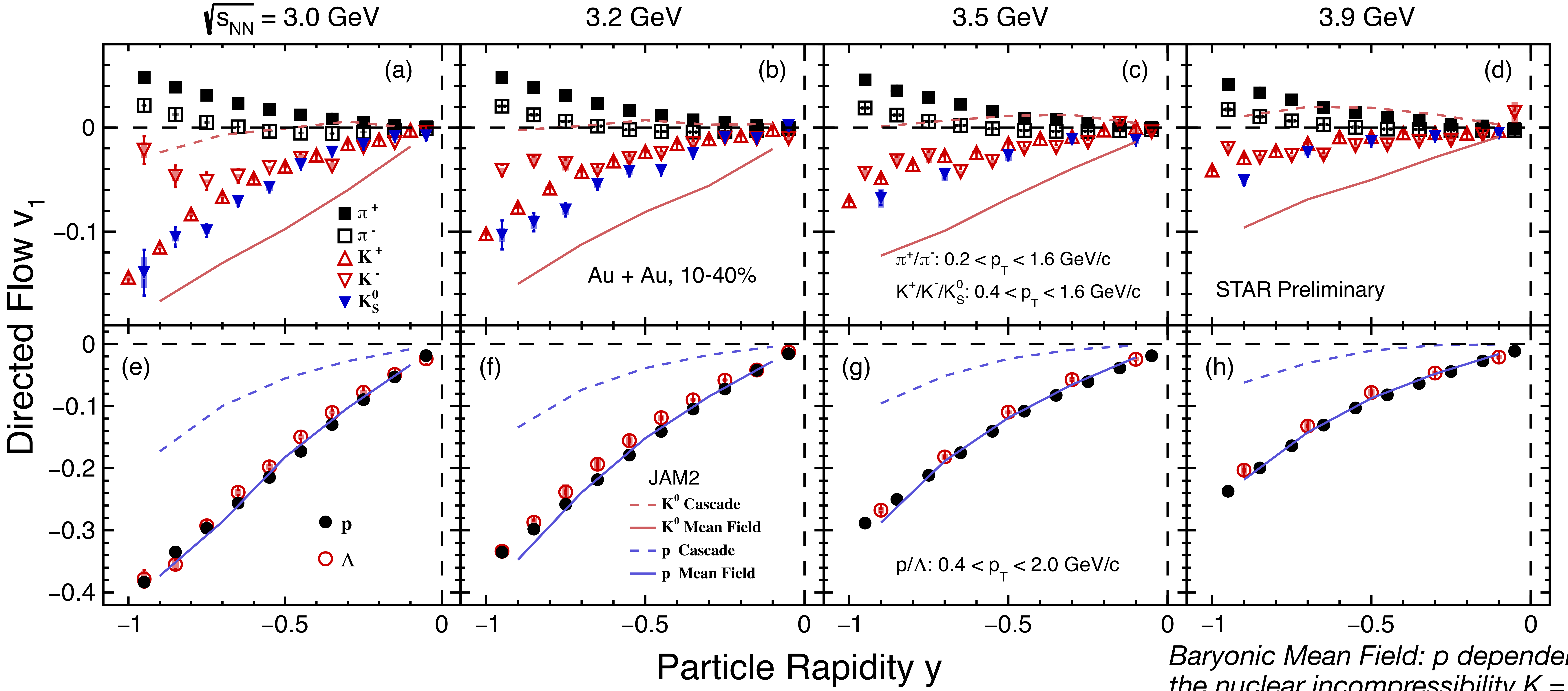
1) K_s^0, Λ are reconstructed by invariant mass method (KF particle package)

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

STAR: CPOD2024, SQM2024

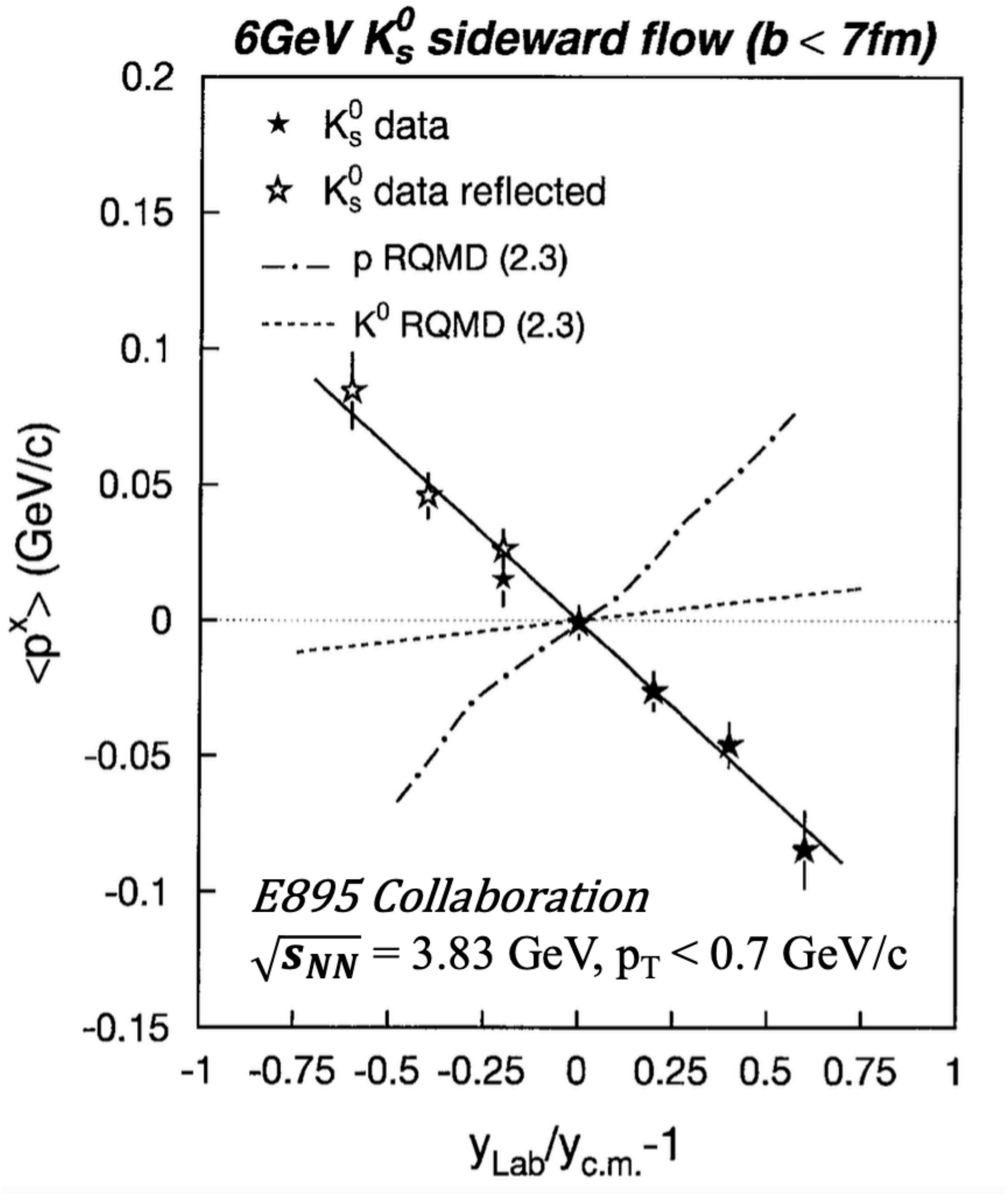


Baryonic Mean Field: p dependent Soft EoS
the nuclear incompressibility K = 210 MeV

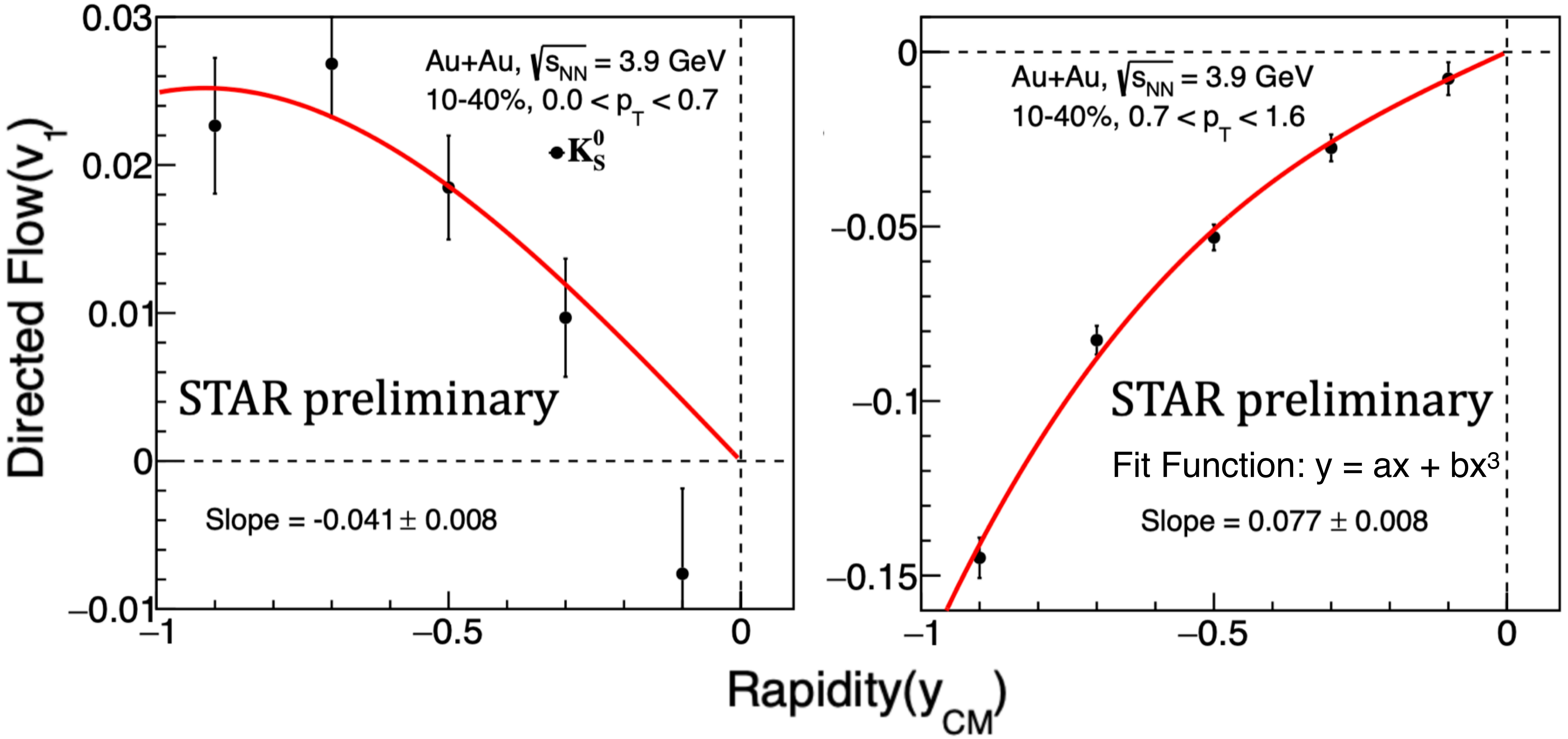
Measurements of v_1 vs. rapidity for $\pi^{\pm}, K^{\pm}, K^0_S, p, \Lambda$ at 3.0, 3.2, 3.5, and 3.9 GeV

Anti-flow of Kaon

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



STAR: CPOD2024, SQM2024

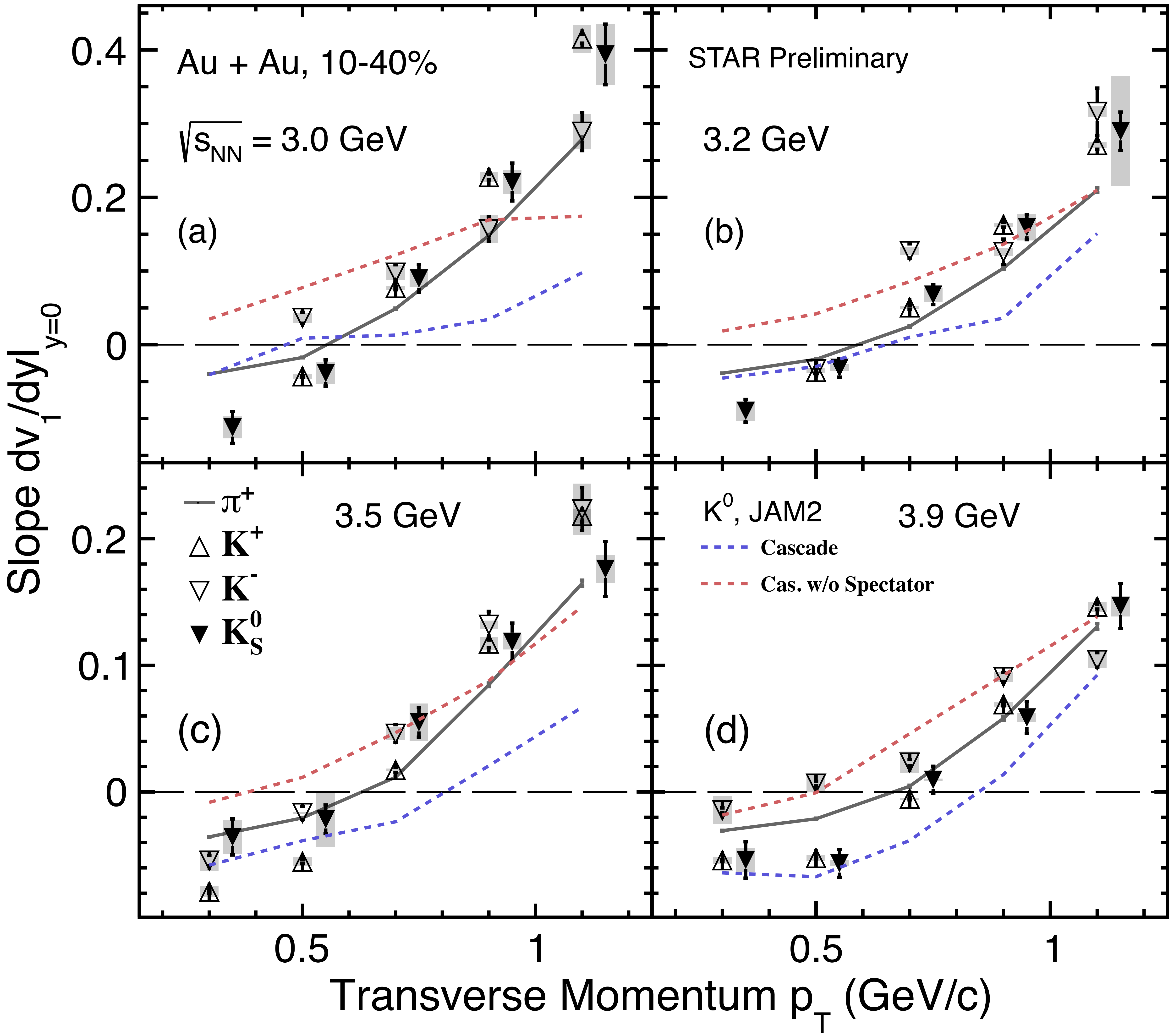


1) 3.9 GeV: anti-flow observed for K_S^0 at p_T < 0.7 GeV/c
2) Positive directed flow slope of K_S^0 at p_T > 0.7 GeV/c

Strong p_T dependence of K_S^0 v_1 slope

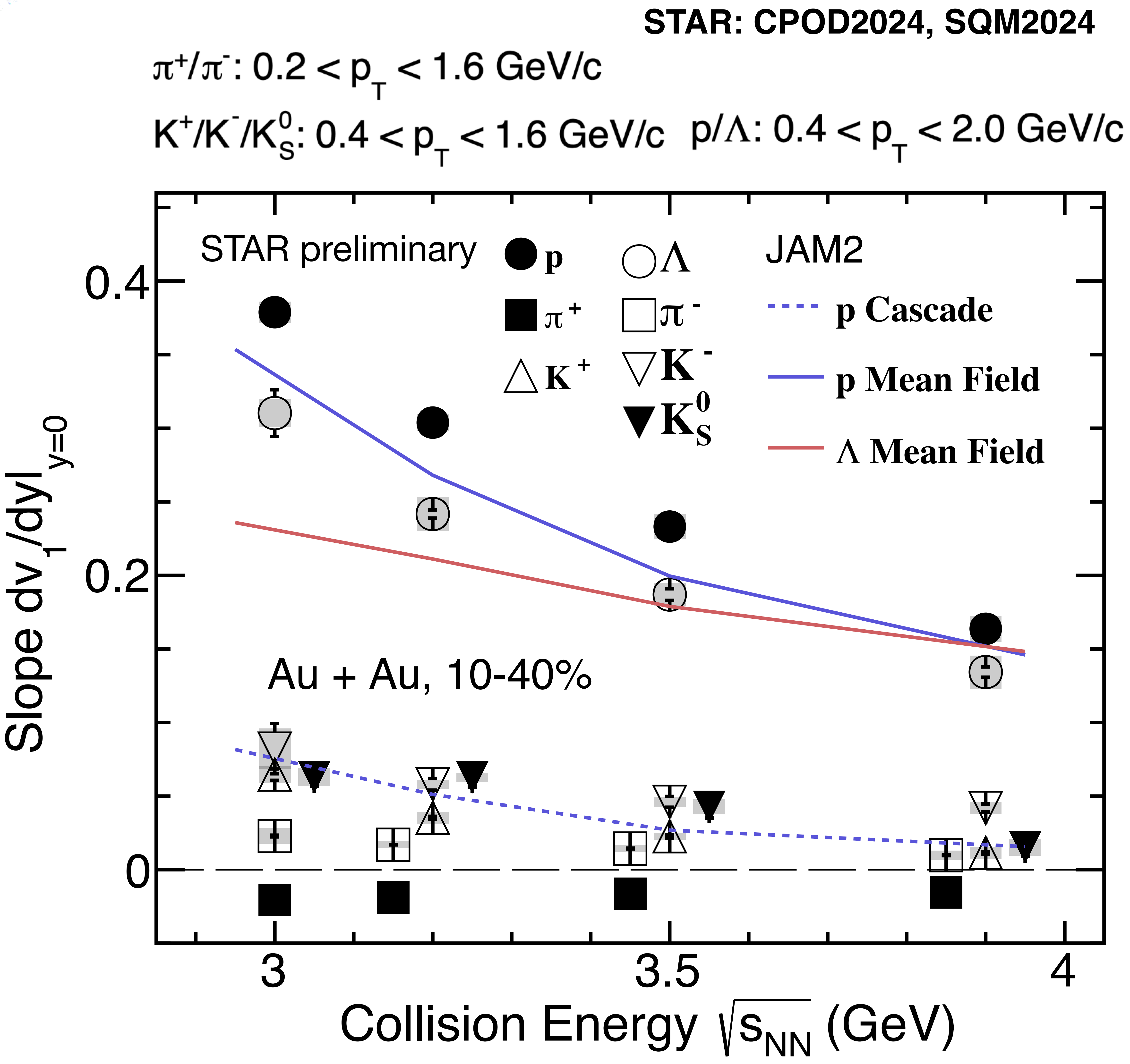
p_T dependence of v_1 slope

STAR: CPOD2024, SQM2024



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

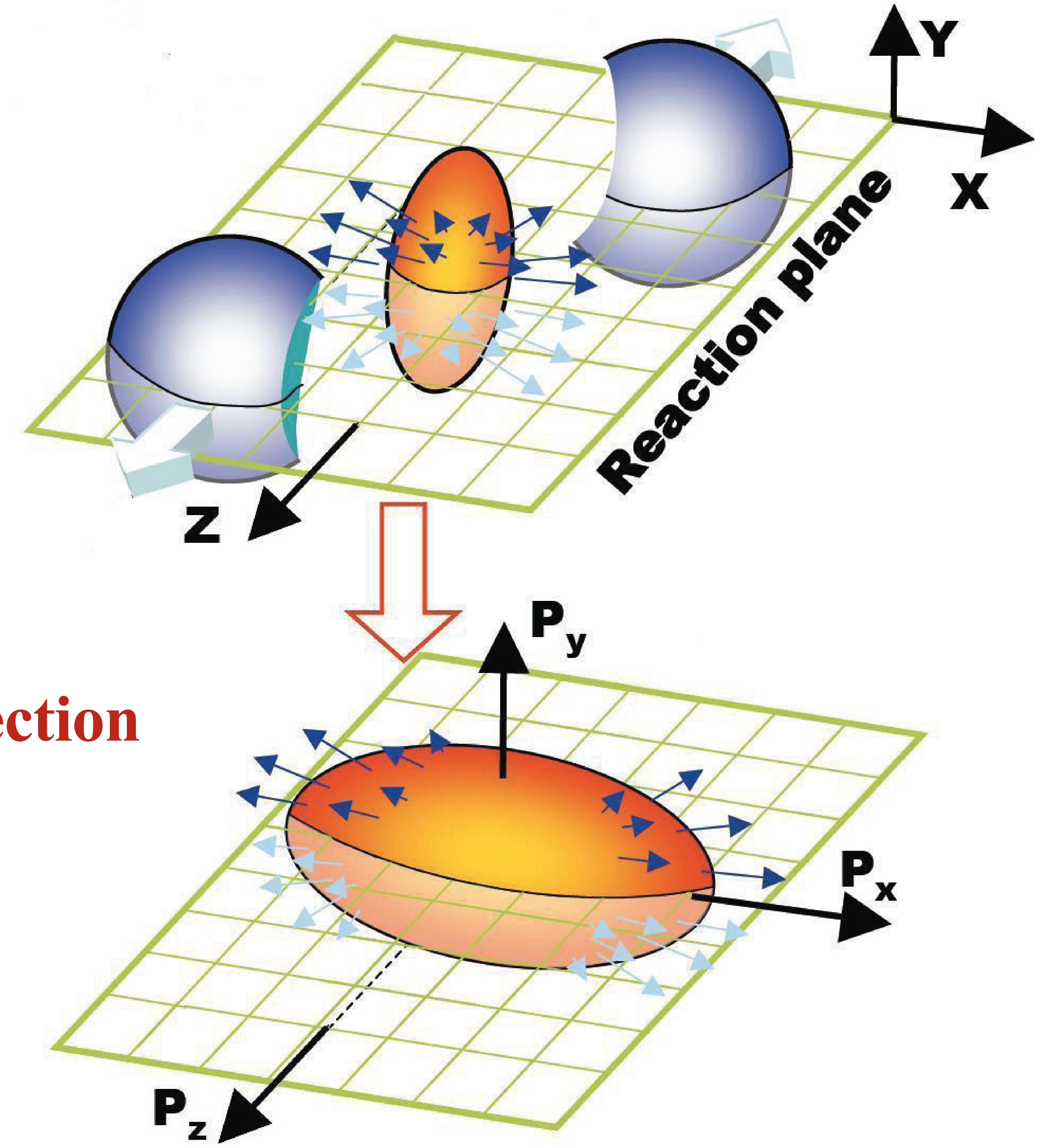
Energy dependence of v_1 slope



1) v_1 slope of baryons drops as collision energy increases
2) JAM with baryon mean field better describes data
   - For both p and Λ, Baryon mean field is important at high baryon density region

Anisotropic flow

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



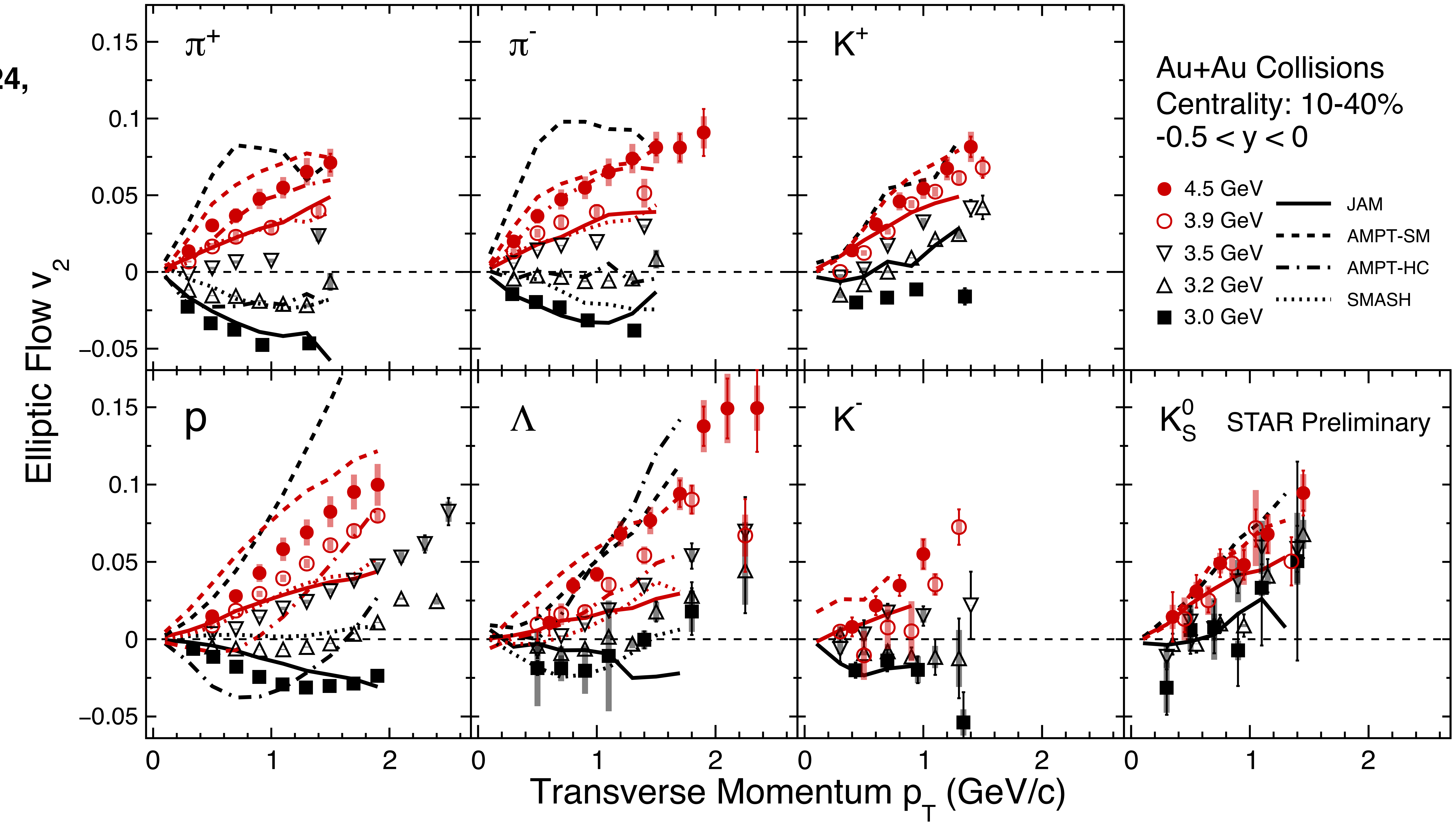
$$v_2 = \cos\left[2(\phi - \psi_r)\right] = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

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

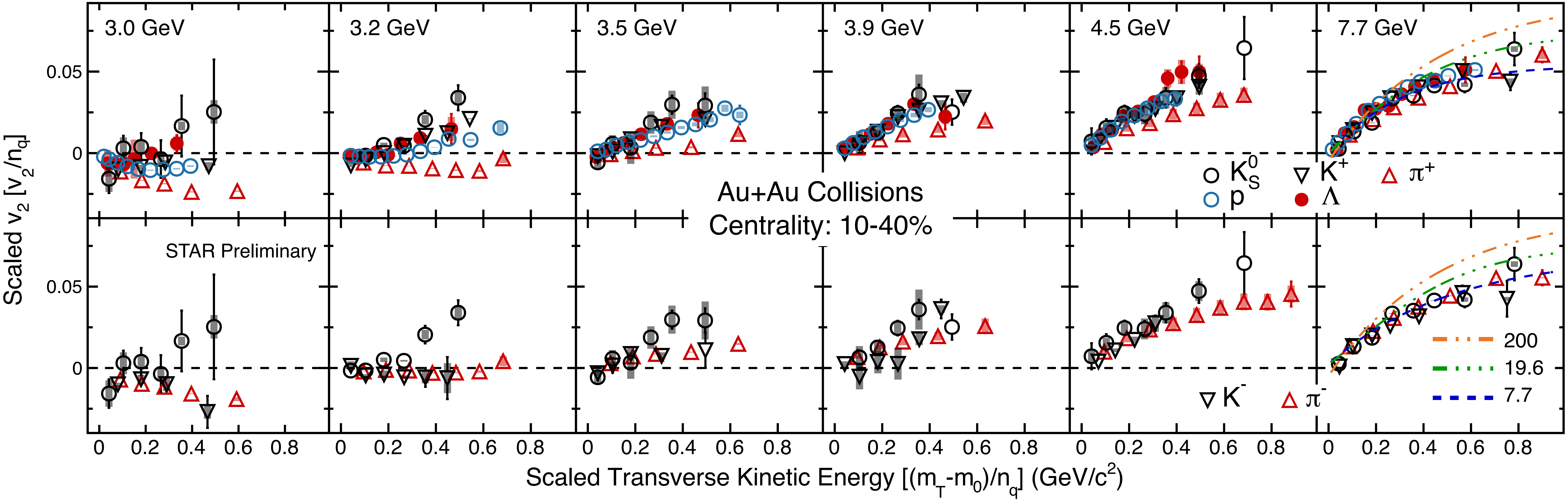
STAR: CPOD2024, SQM2024



1) As collision energy is increasing, passing time reduced and the effect of shadowing is diminished
2) Hadronic models fit 3.0 GeV data, while AMPT-SM fails,
   AMPT-SM matches 4.5 GeV data, while hadronic models underestimate

NCQ scaling of v_2 at 3 - 7.7 GeV

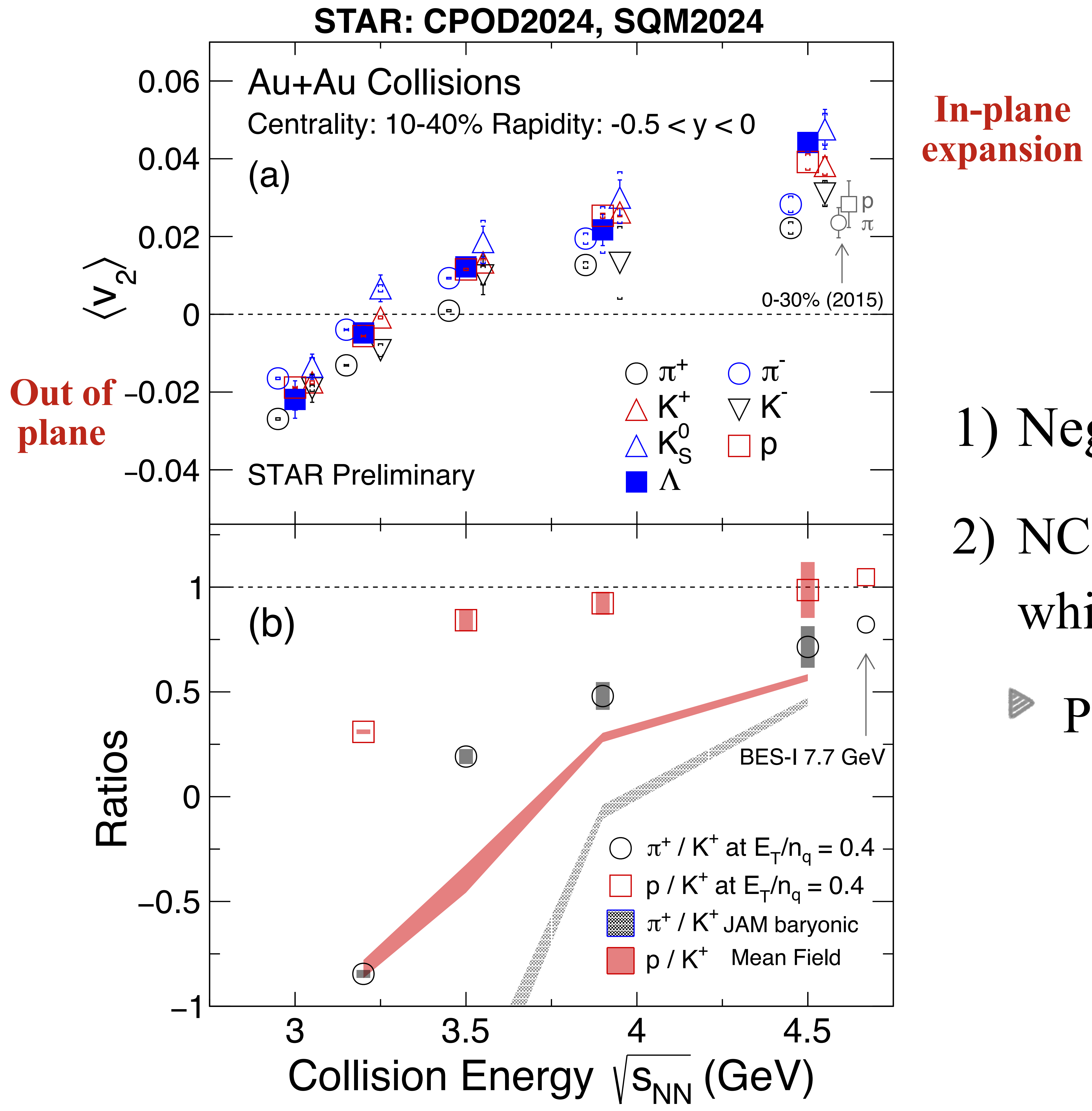
STAR: CPOD2024, SQM2024



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 $\langle v_2 \rangle$



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

- Partonic interactions become more important at 4.5 GeV

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

Summary

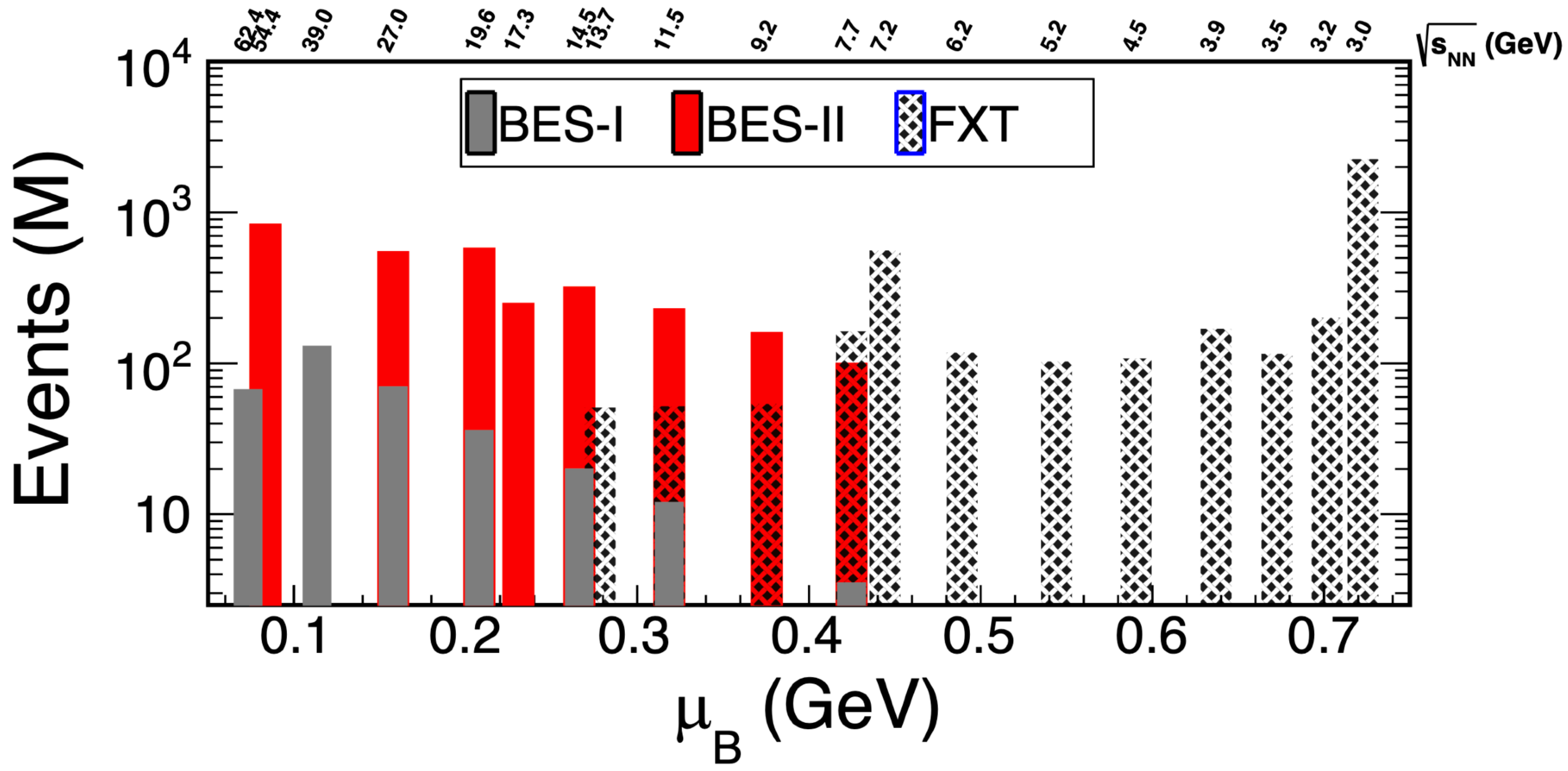
1) Anti-flow for K_S^0, $K^{\pm}$ and π^+ observed at low p_T ($\lesssim$ 0.6 GeV/c) in 3 - 3.9 GeV collisions

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

2) NCQ scaling breaks at 3 and 3.2 GeV, gradually restores from 3 to 4.5 GeV

- **As collision energy increases, passing time decreases, and shadowing effect diminishes**
- **Partonic interactions become more important at 4.5 GeV**

Outlook



- BES-II: enhanced statistics, upgraded detectors, precise measurements
- Explore the QCD phase diagram

Results from more datasets will presented in QM2025