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Collectivity from the STAR BES program

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Workshop on Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics, Oct. 19-24, 2024

Outline

- Motivation
- Experimental Setup
- Results and Discussions
- Summary

Motivation

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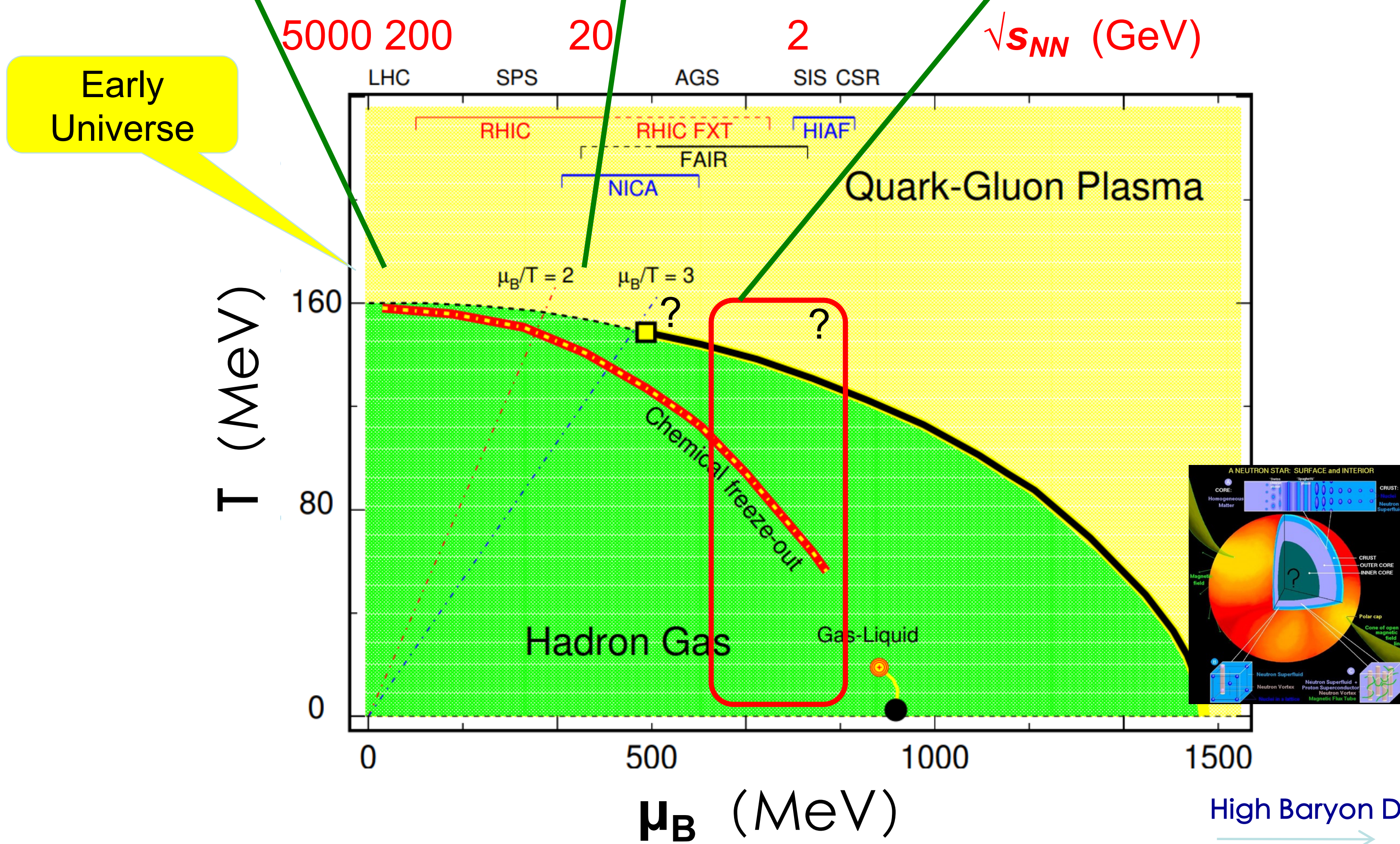
1 T_{ini}, T_C
LHC, RHIC

2 T_E
RHIC, SPS

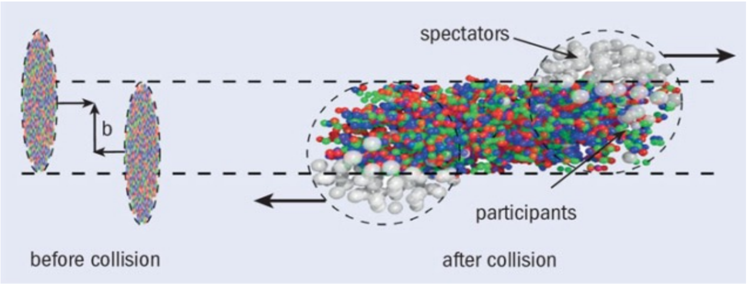
3 Large μ_B
FAIR, NICA, HIAF…



High Baryon Density

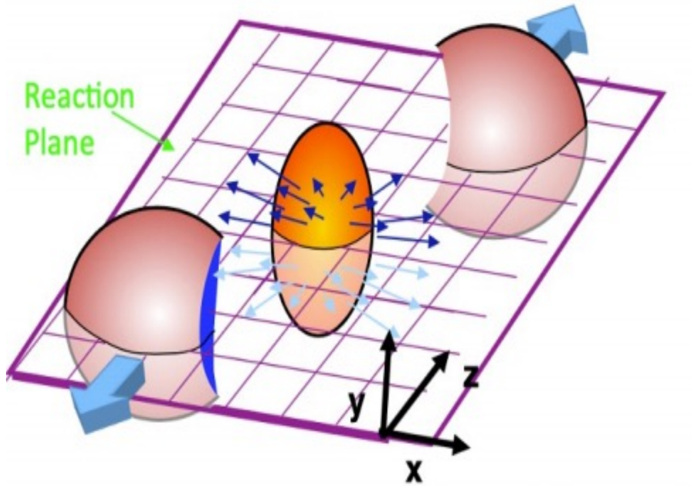
A. Bzdak et al. Phys. Rept. 853, 1 (2010); X. Luo, S. Shi, Nu Xu and Y. Zhang. Particle 3, 278 (2020)

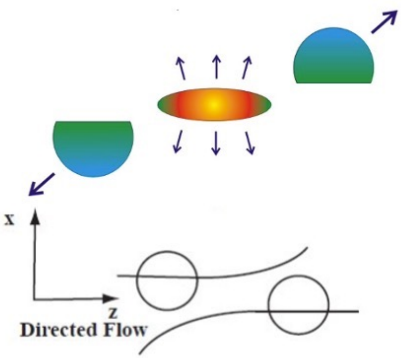
Anisotropic Flow

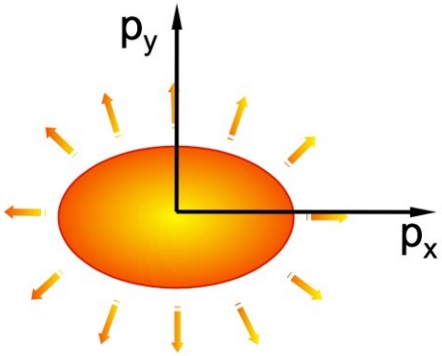


$$\frac{dN}{d(\phi-\Psi)} \sim 1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi))$$

- Directed flow: $v_1 = \langle \cos(\phi-\Psi) \rangle$
- Elliptic flow: $v_2 = \langle \cos 2(\phi-\Psi) \rangle$





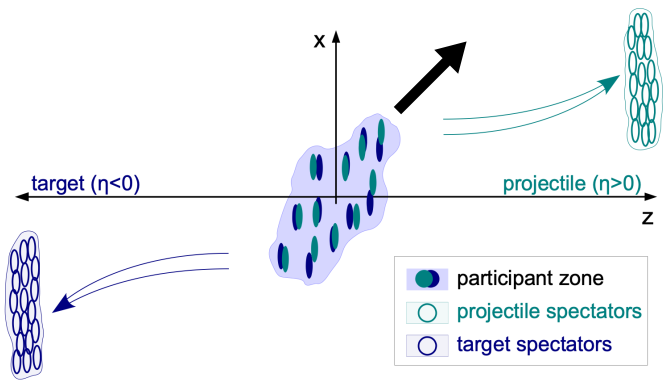


- v_1 is sensitive to the Equation-of-State (EoS)
- v_2 is sensitive the degree of freedom: partonic vs. hadronic

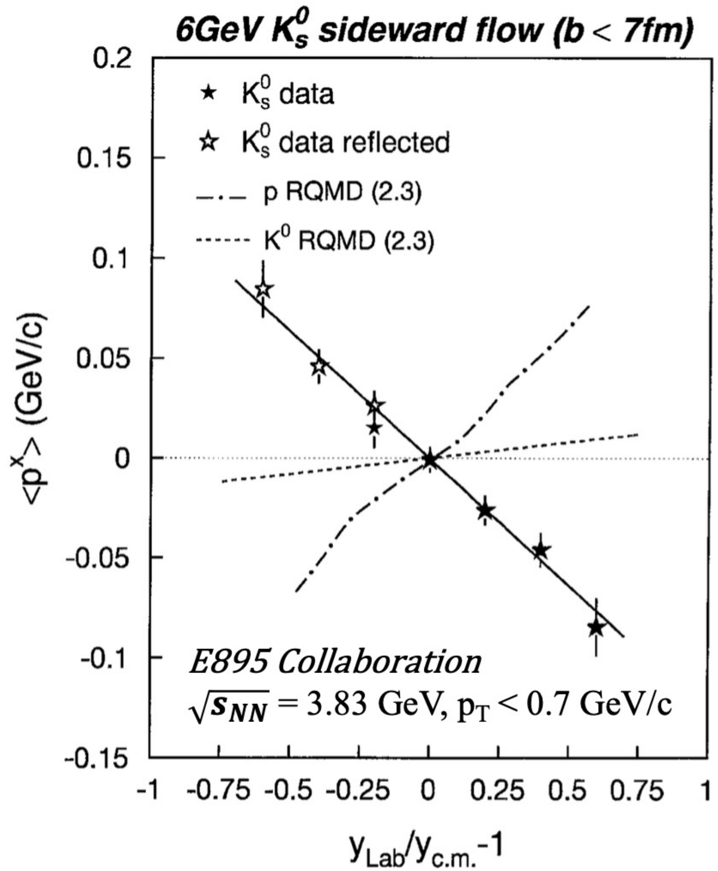
S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998)

Motivation: Anti-flow of v_1

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



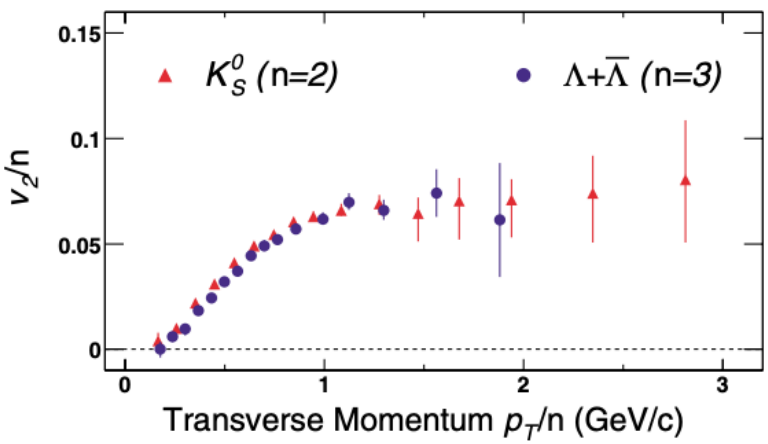
E895, Phys. Rev. Lett. 85, 940 (2000)



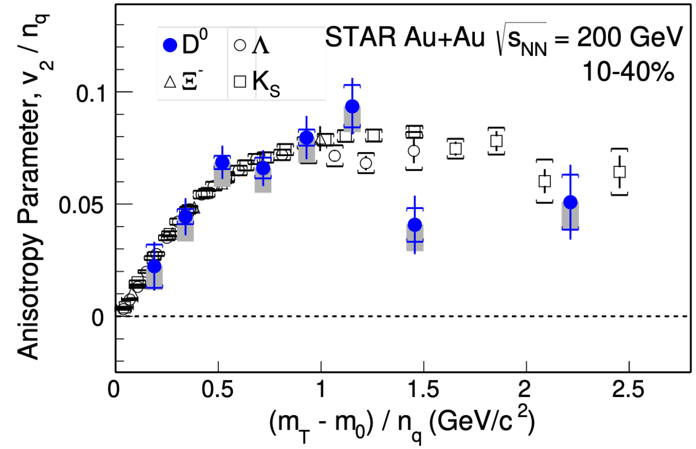
- **Bounce-off: Positive flow in positive rapidity**
- **Au+Au 3.83 GeV: Anti-flow of kaon at low p_T (< 0.7 GeV/c) → Kaon potential?**

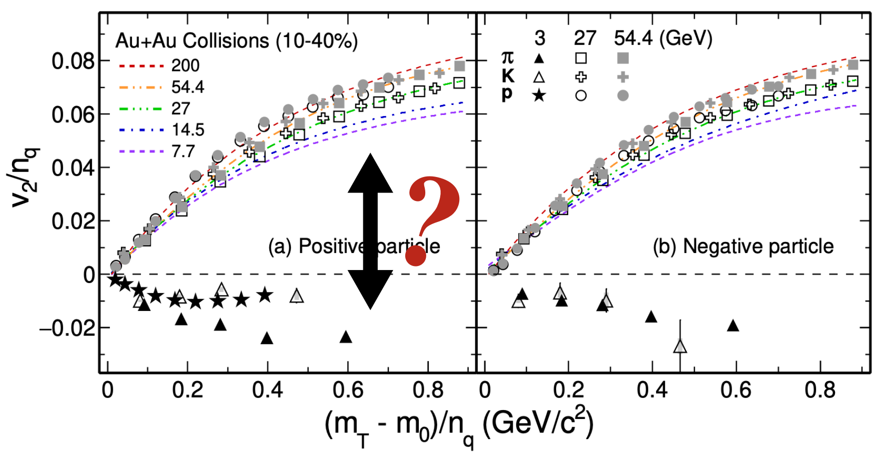
Motivation: Elliptic Flow

STAR, Phys. Rev. Lett. 92, 052302 (2004)



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



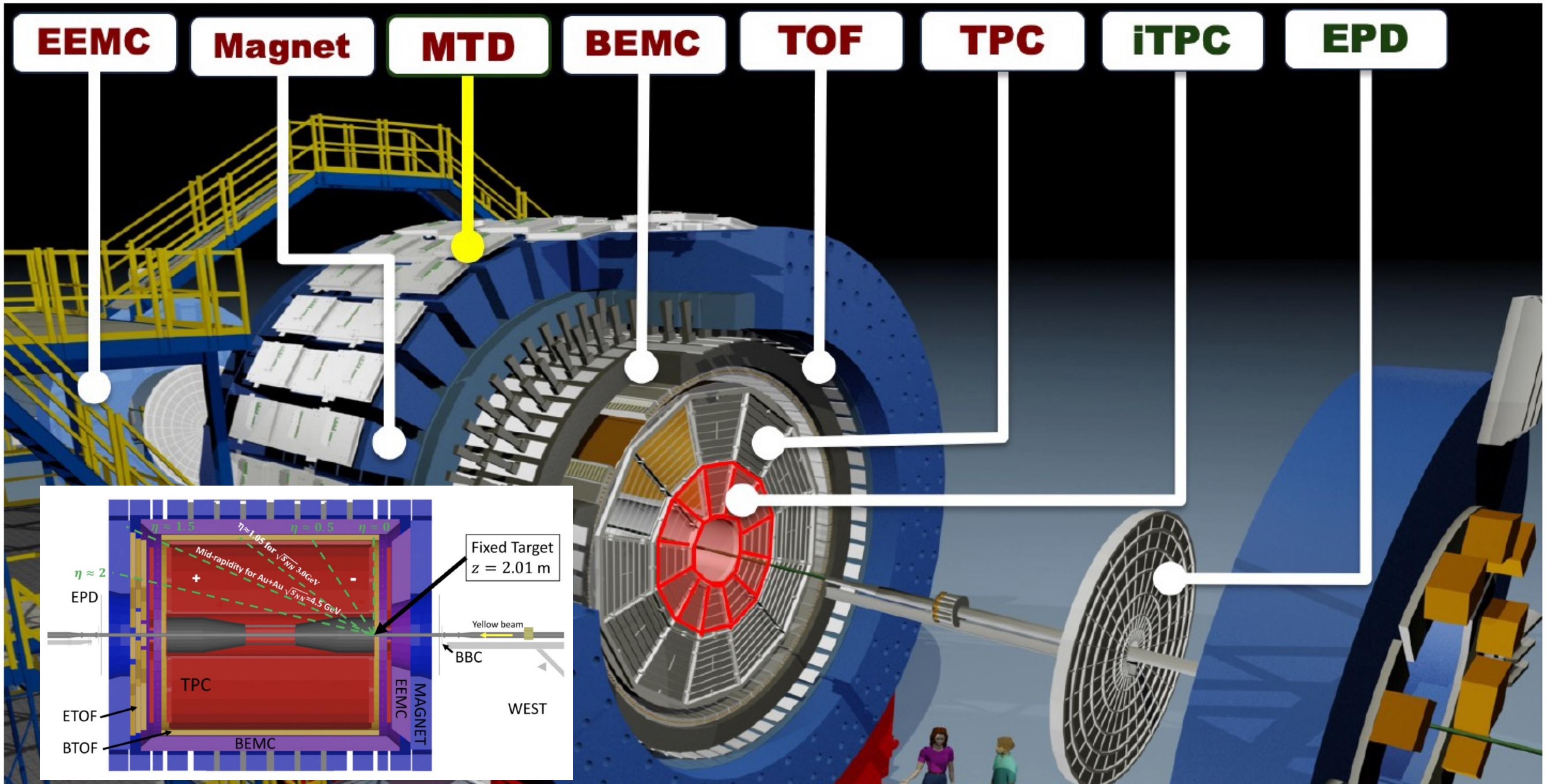


STAR, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)

- **200 GeV: Partonic collectivity**
- **3.0 GeV: Hadronic interaction dominates**
- **Transition in 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 Bean Energy Scan

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Au+Au Collisions at RHIC

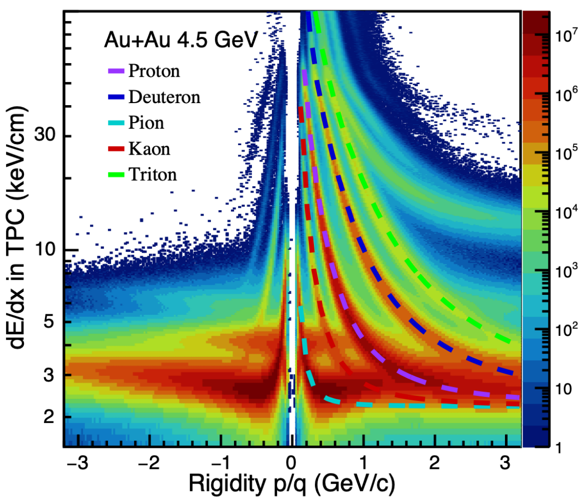
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 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	57 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)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

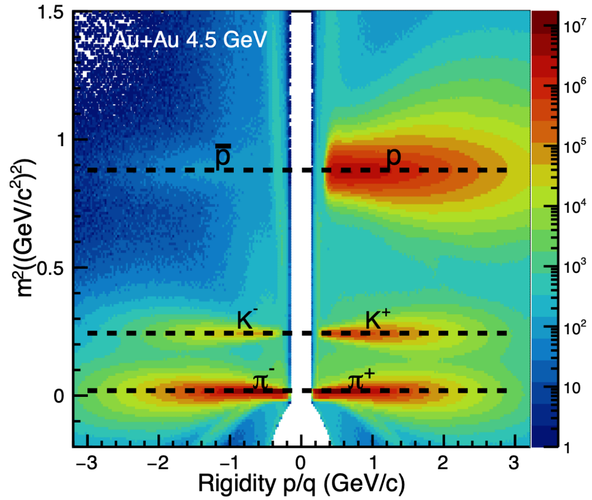
$3 < \sqrt{s_{NN}} < 200$ GeV; $760 > \mu_B > 25$ MeV

Particle Identification

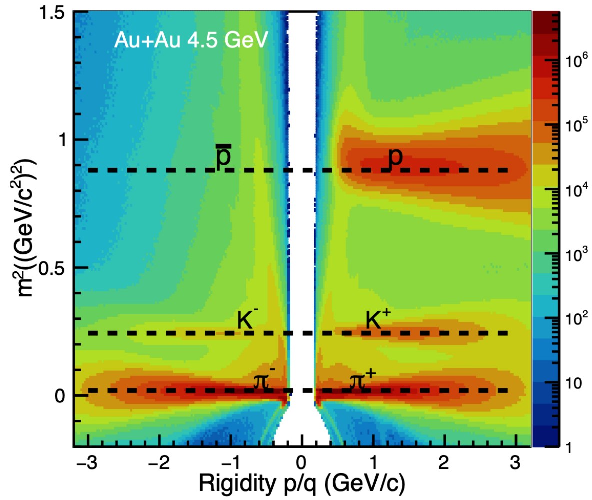
TPC



bTOF



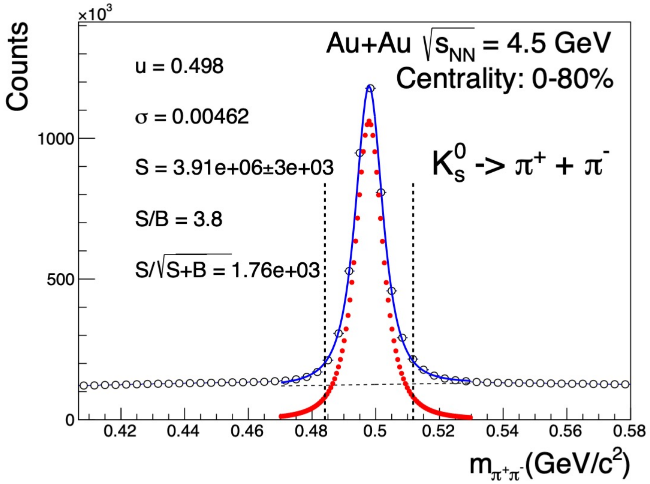
eTOF

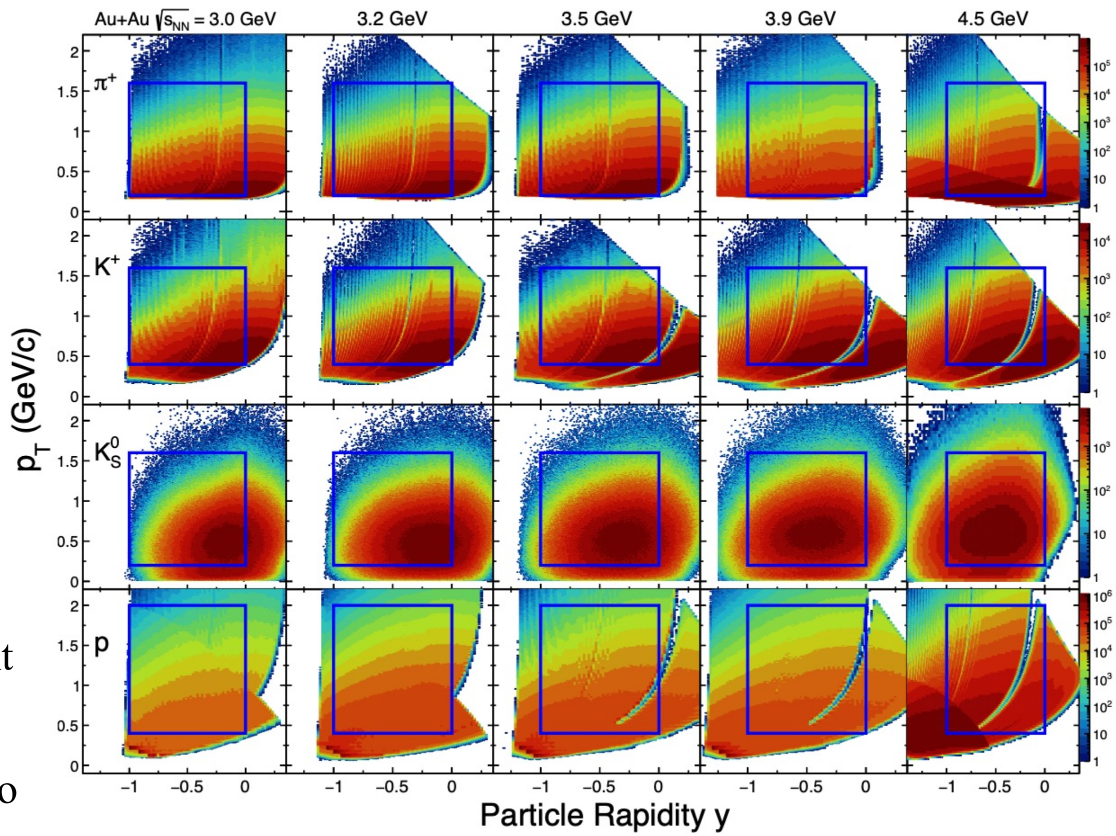


Au+Au (GeV)	3.0	3.2	3.5	3.9	4.5
Baryon chemical potential (~MeV)	750	700	670	635	590
Events analyzed (M)	260	206	107	94	128

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

Particle Acceptance



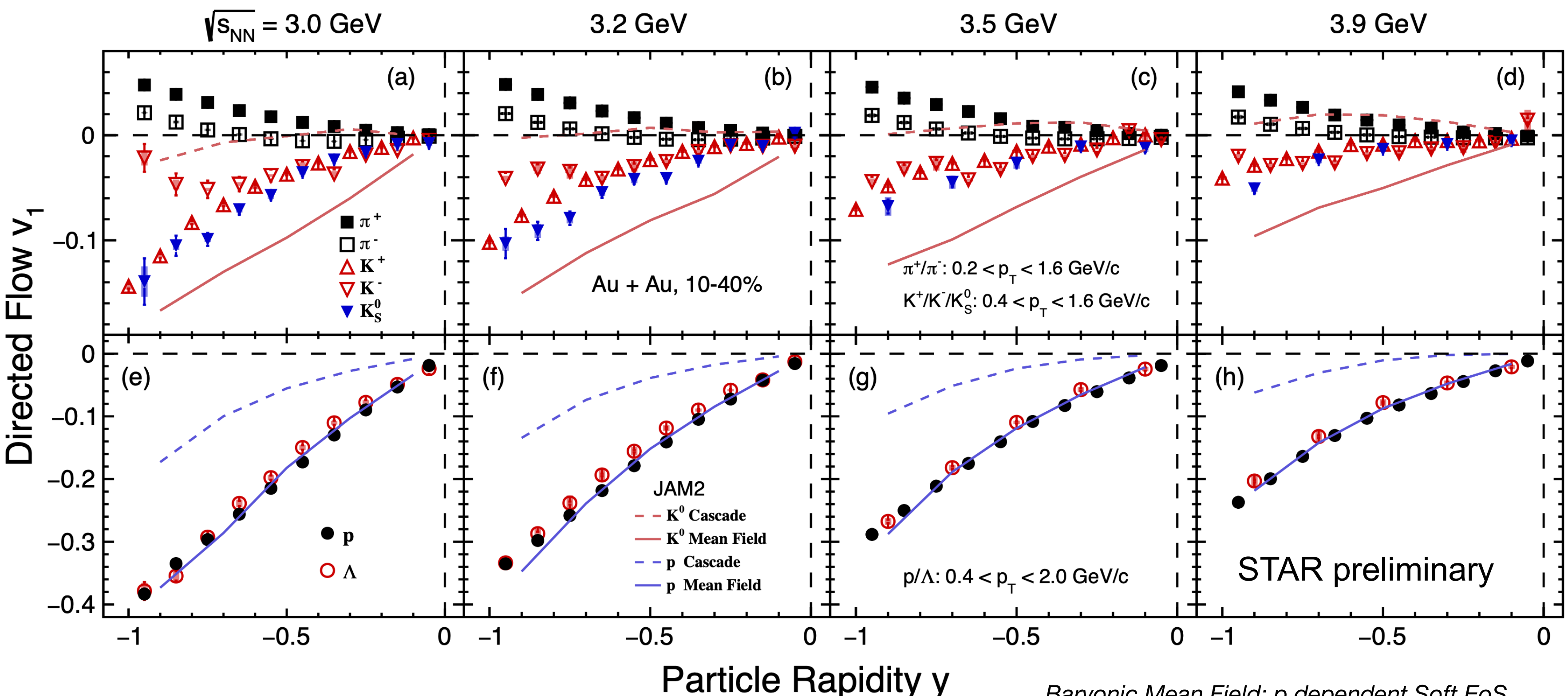


- ➢ K_S^0, Λ are reconstructed by invariant mass method (KF particle package)
- ➢ Particle rapidity coverage from -1 to 0 (blue boxes)

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

Rapidity Dependence of v_1

STAR: CPOD2024, SQM2024

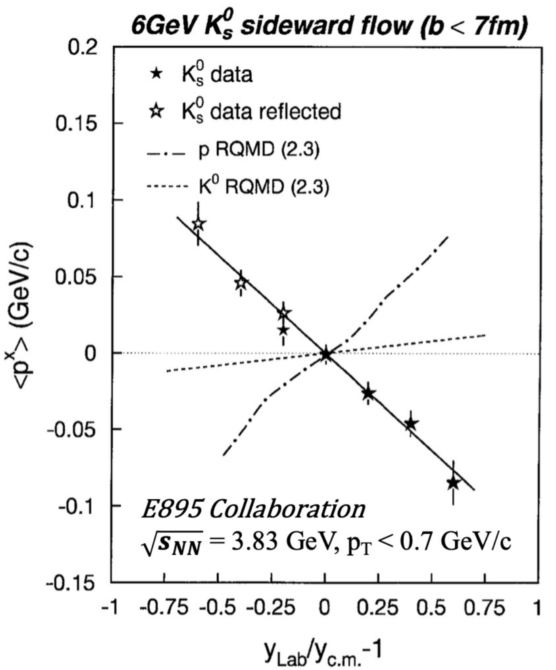


Baryonic Mean Field: p dependent Soft EoS
the nuclear incompressibility K = 210 MeV

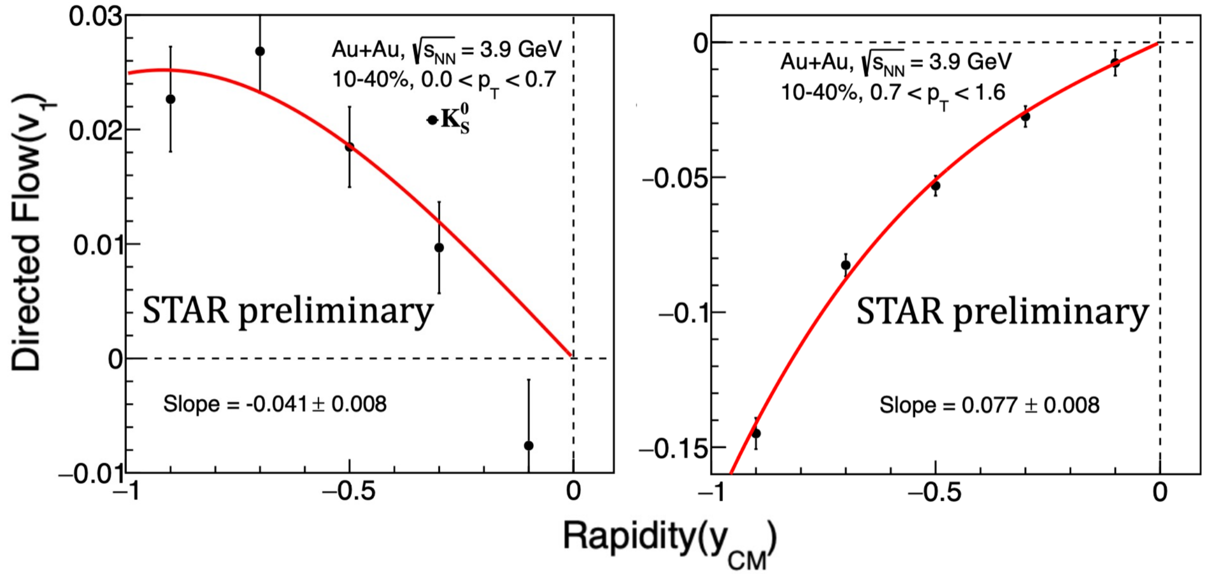
Measurements of v_1 vs. rapidity for $\pi^\pm, K^\pm, K_S^0, p, \Lambda$ at 3.0, 3.2, 3.5, and 3.9 GeV

Anti-flow of Kaons

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



STAR: CPOD2024, SQM2024

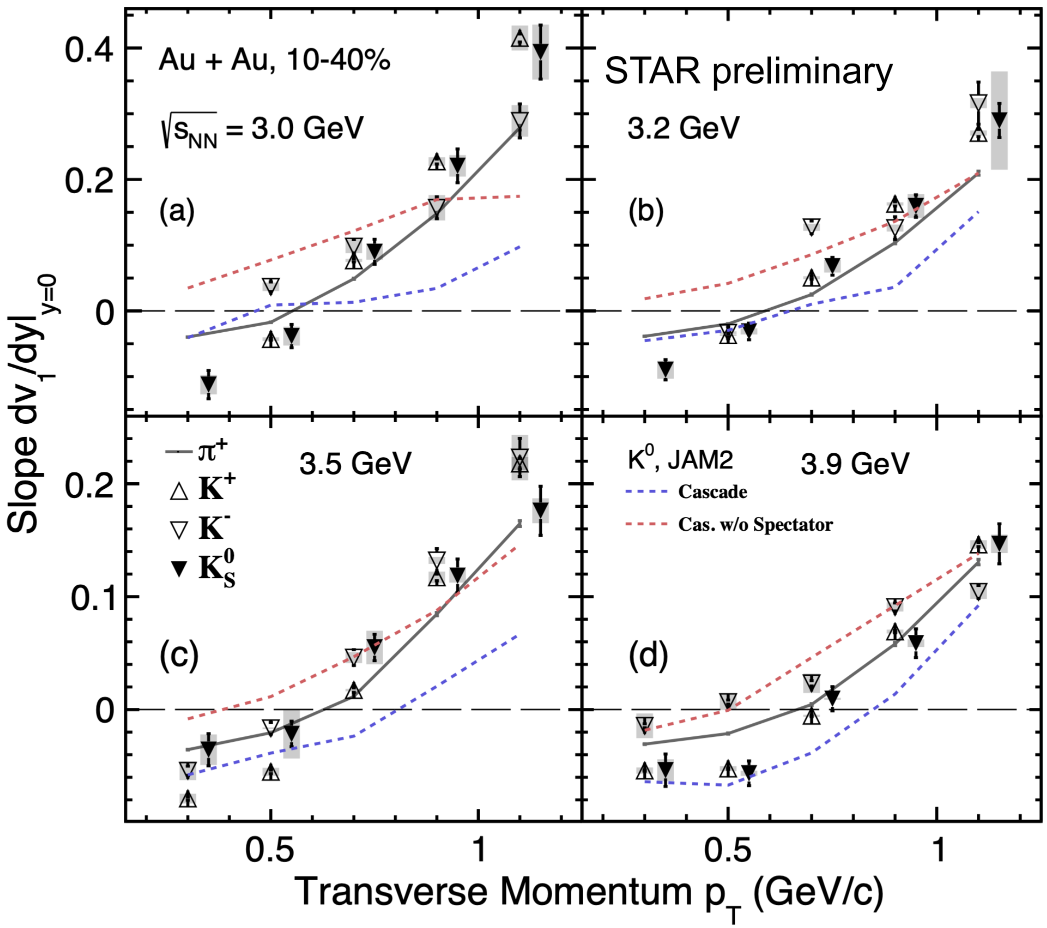


- 3.9 GeV: anti-flow observed for K_S^0 at p_T < 0.7 GeV/c
- Positive directed flow slope of K_S^0 at p_T > 0.7 GeV/c

  Strong p_T dependence of K_S^0 v_1 slope

p_T Dependence of v_1 Slope

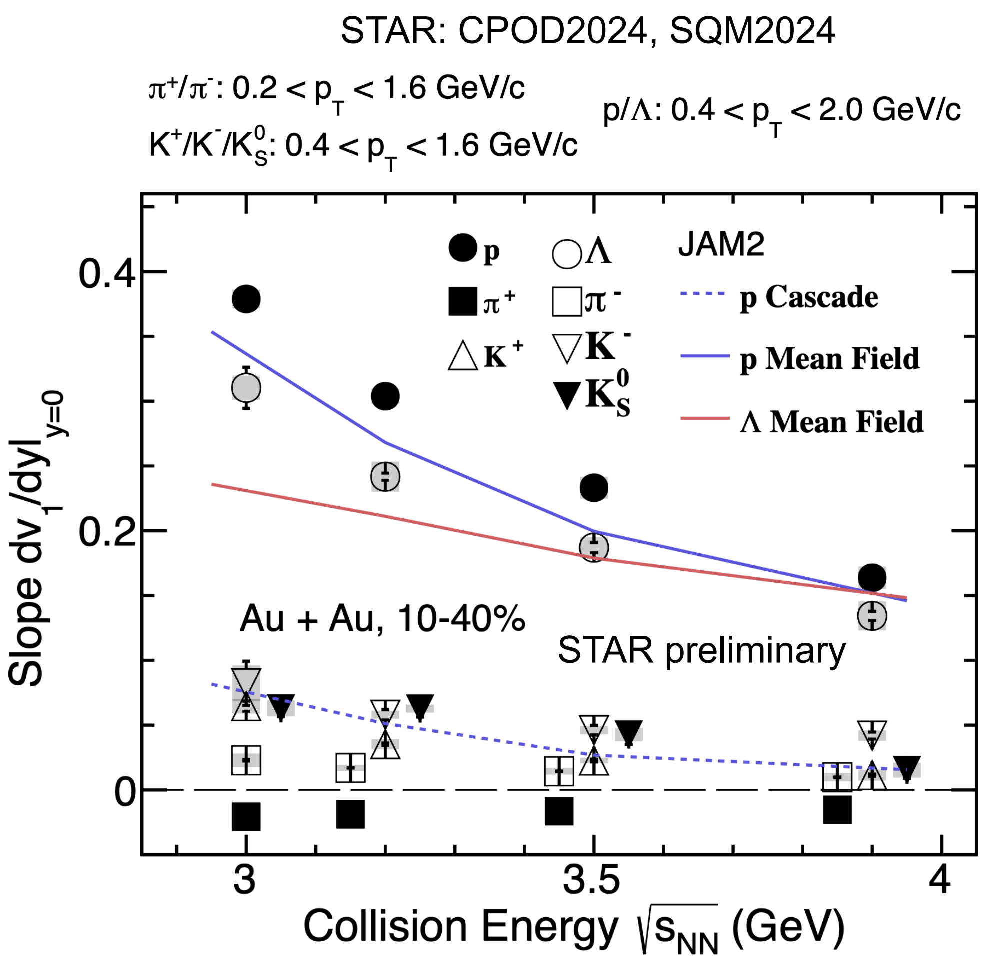
STAR: CPOD2024, SQM2024



- ➢Anti-flow of π^+ and $K_S^0, K^\pm$ at low pT
- ➢Anti-flow could be explained by shadowing effect from spectators

Model study:
Z. Liu and S. Shi, Phys. Rev. C 110, 034903 (2024)

Energy Dependence of v_1 Slope



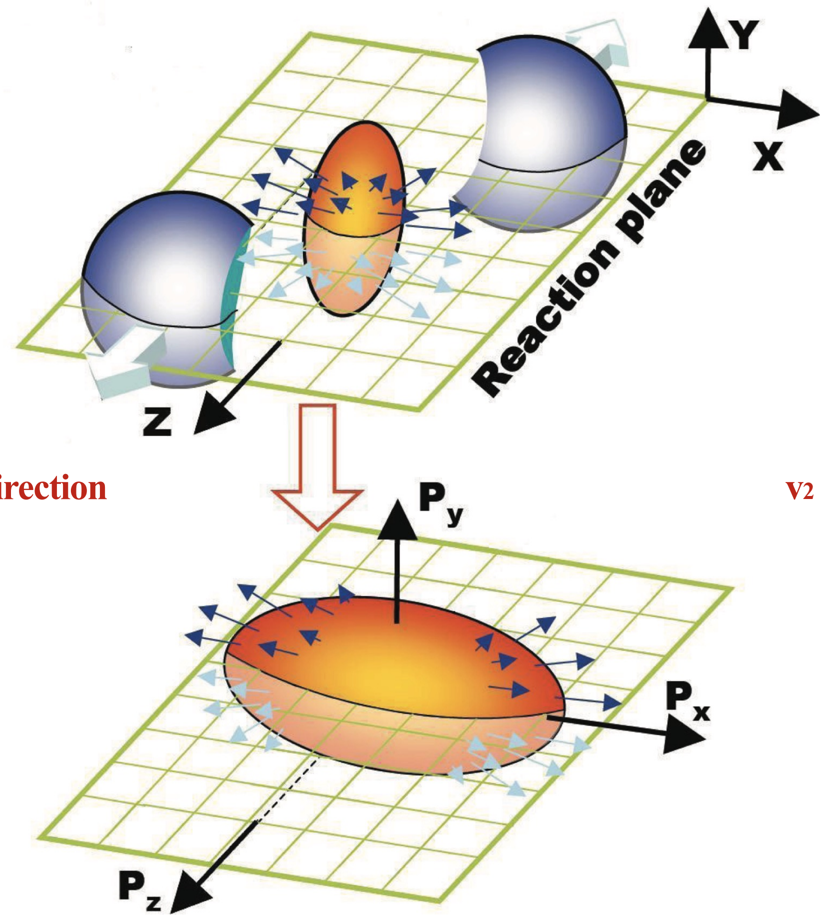
- ➢v_1 slope of baryons drops as collision energy increases
- ➢JAM with baryonic Mean Field better describes data

  Mean field potential plays important role

Anisotropic Flow

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

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



v1 reflect asymmetry along X direction

v2 reflect asymmetry on X-Y plane

p_T Dependence of v_2 at 3 - 4.5 GeV

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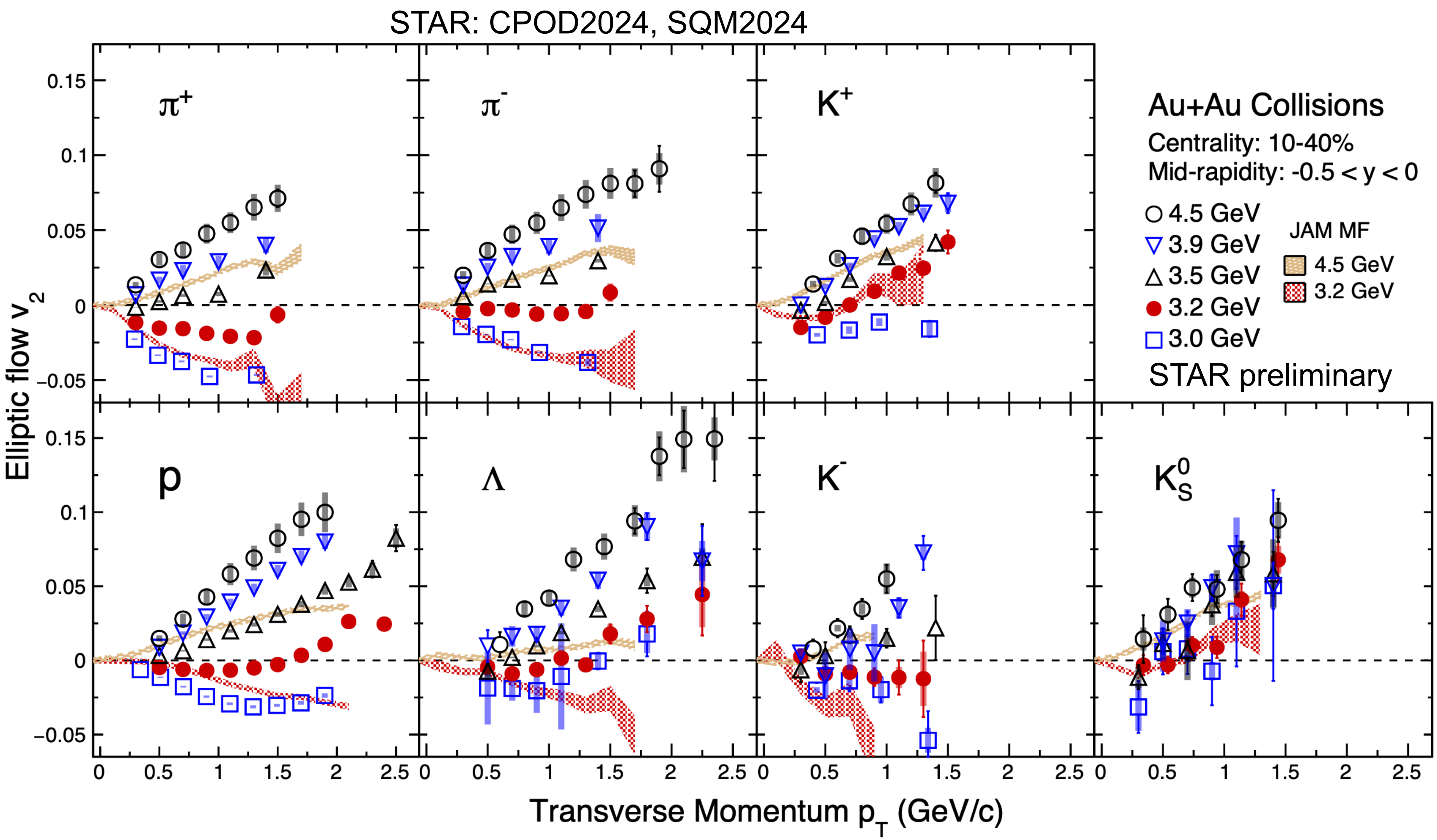
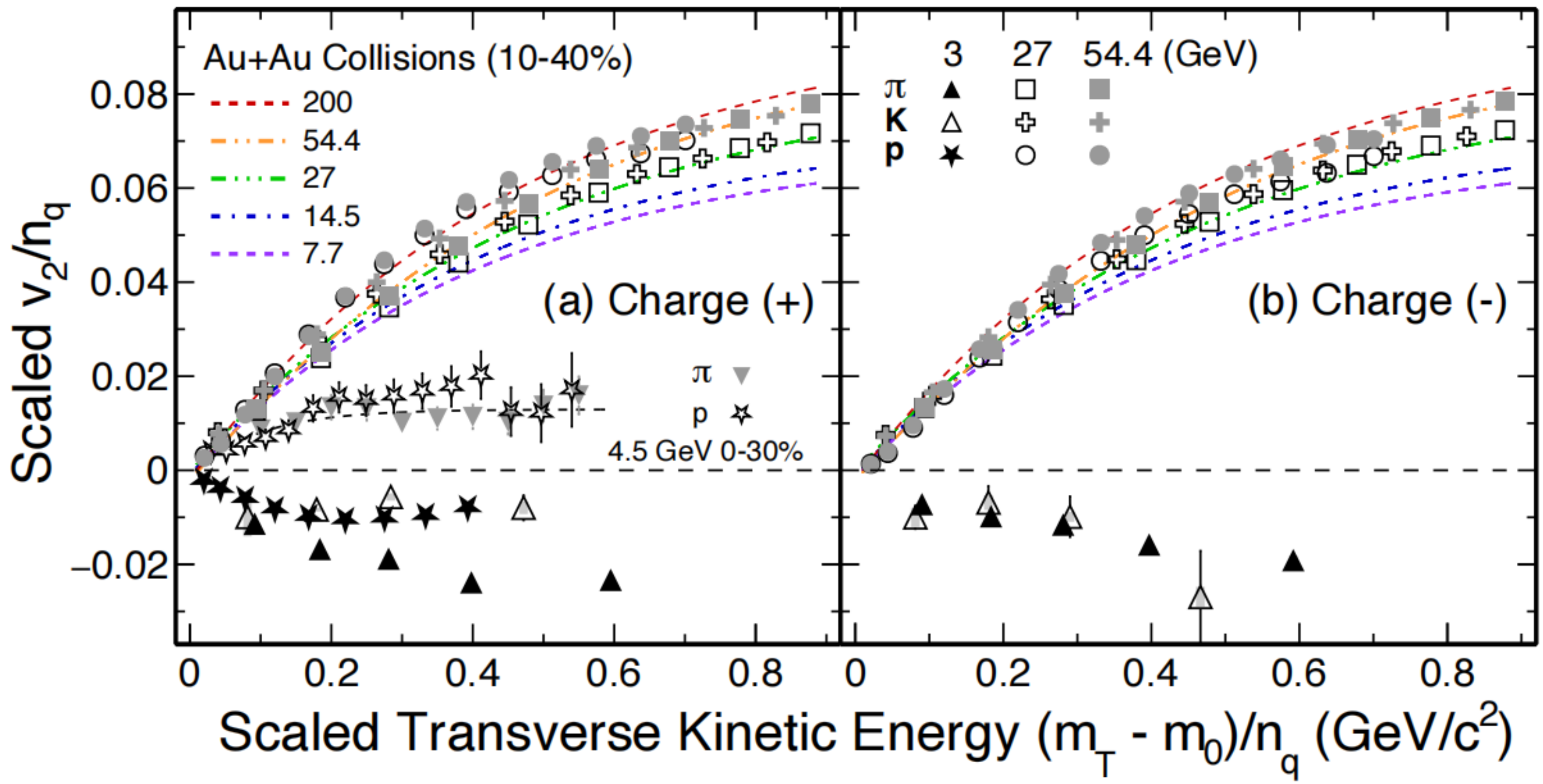


- Clear energy dependence for $v_2(p_T)$ from negative to positive: **Shadowing effect**
- JAM + baryonic Mean Field better describe the 3.2 GeV while underestimate 4.5 GeV data

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

NCQ scaling at 3 GeV



STAR: Phys. Lett. B 827 (2022) 137003; Phys. Rev. C.107 (2023) 024912

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

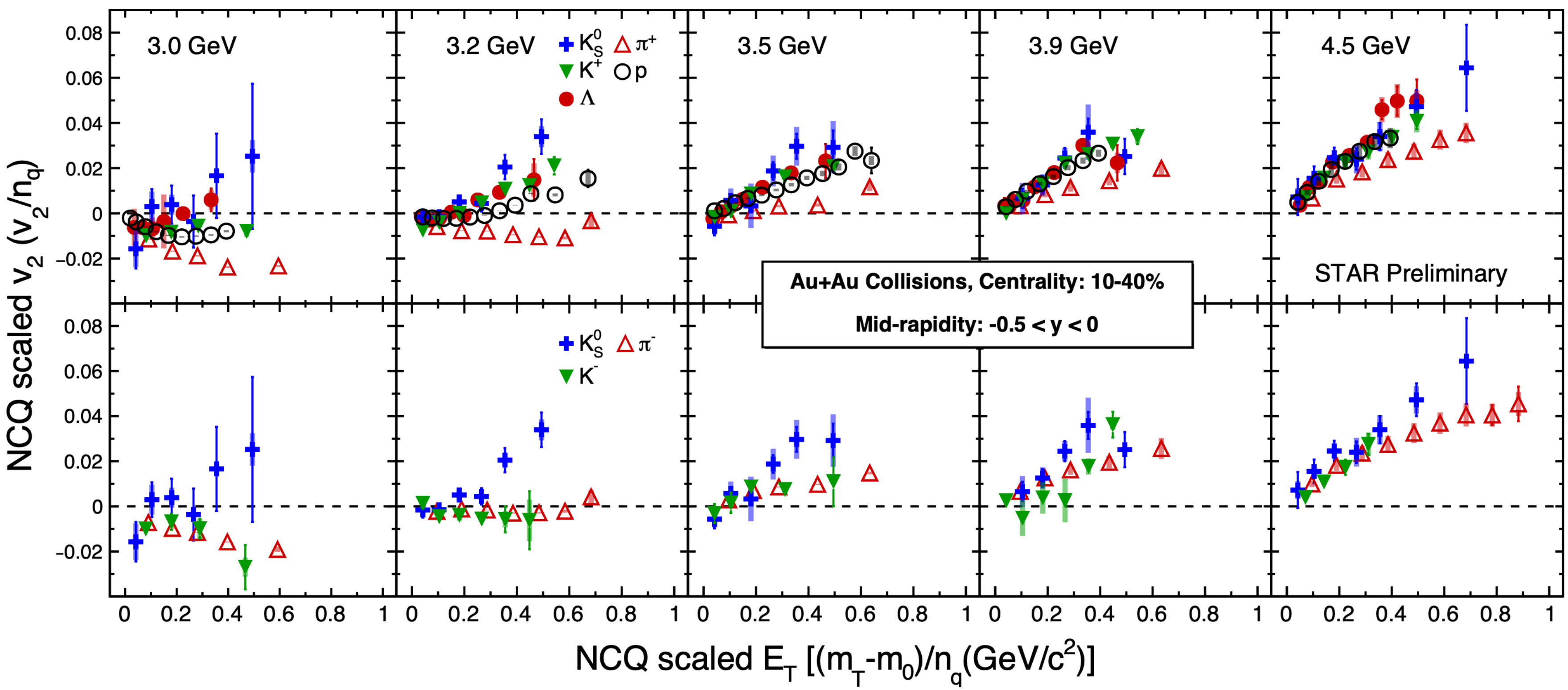
  → The hadronic degree of freedom dominates

NCQ scaling of v_2 at 3 - 4.5 GeV

Hadronic interaction

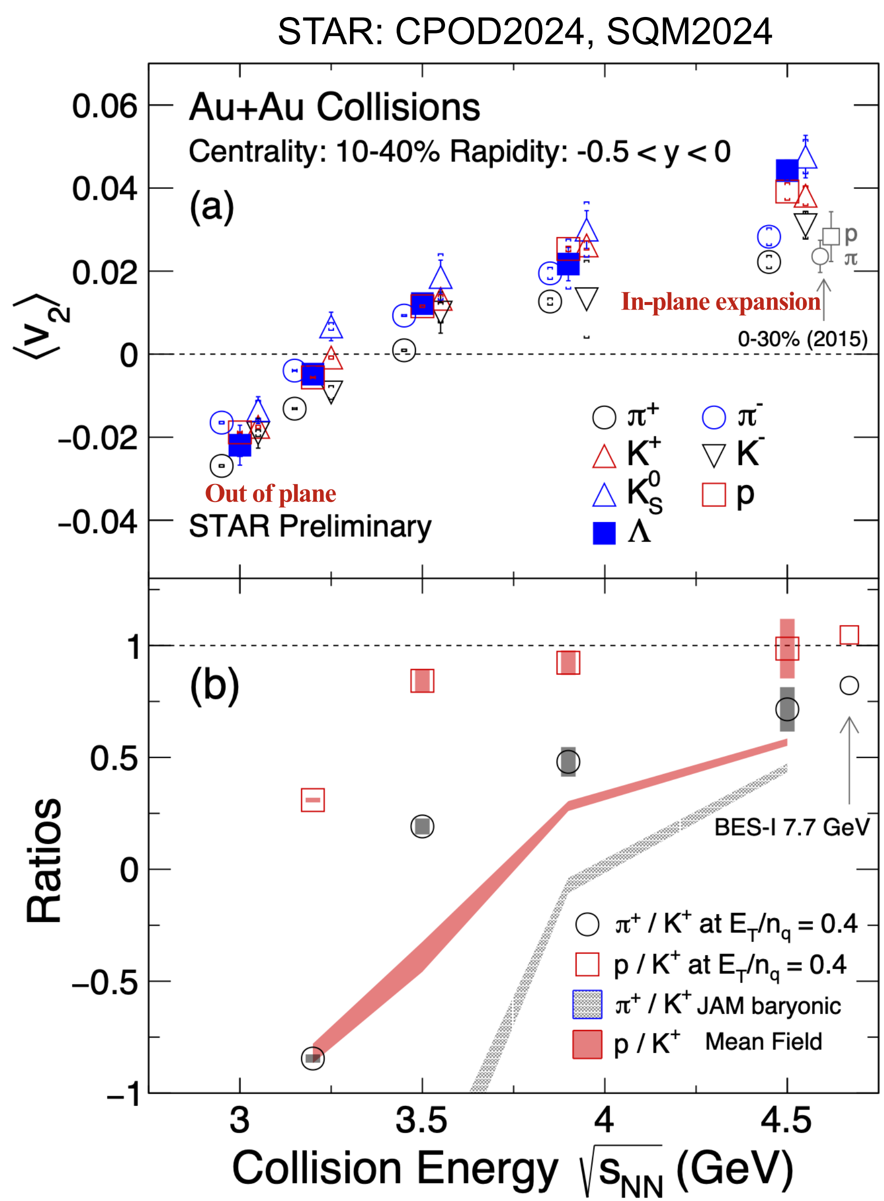
STAR: CPOD2024, SQM2024

Partonic collectivity



- NCQ scaling completely breaks below 3.2 GeV
- NCQ scaling becomes better gradually from 3 .2 to 4.5 GeV

Energy dependence of $\langle v_2 \rangle$



- Negative to positive flow: 3 → 4.5 GeV
- The NCQ-scaled v_2 ratio of p/K^+ is close to 1 at 3.9 and 4.5 GeV, while it deviates largely from 1 at 3.2 GeV

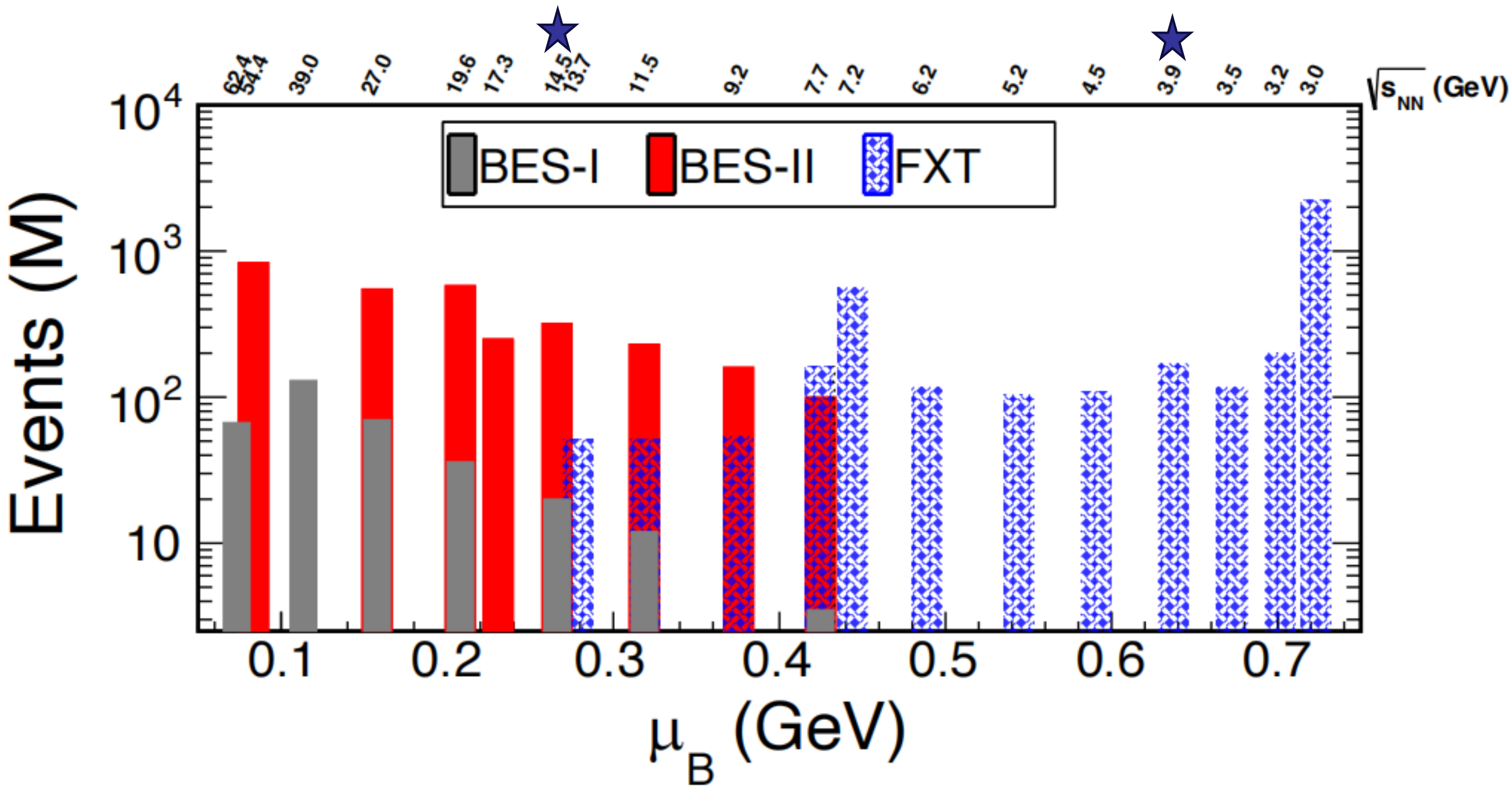
Summary

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

    anti-flow is not unique to the presence of a kaon potential

- **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**

Outlook



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

Stay tuned for more new results!

Thank you!