Recent flow measurements in the high baryon density region

Shusu Shi

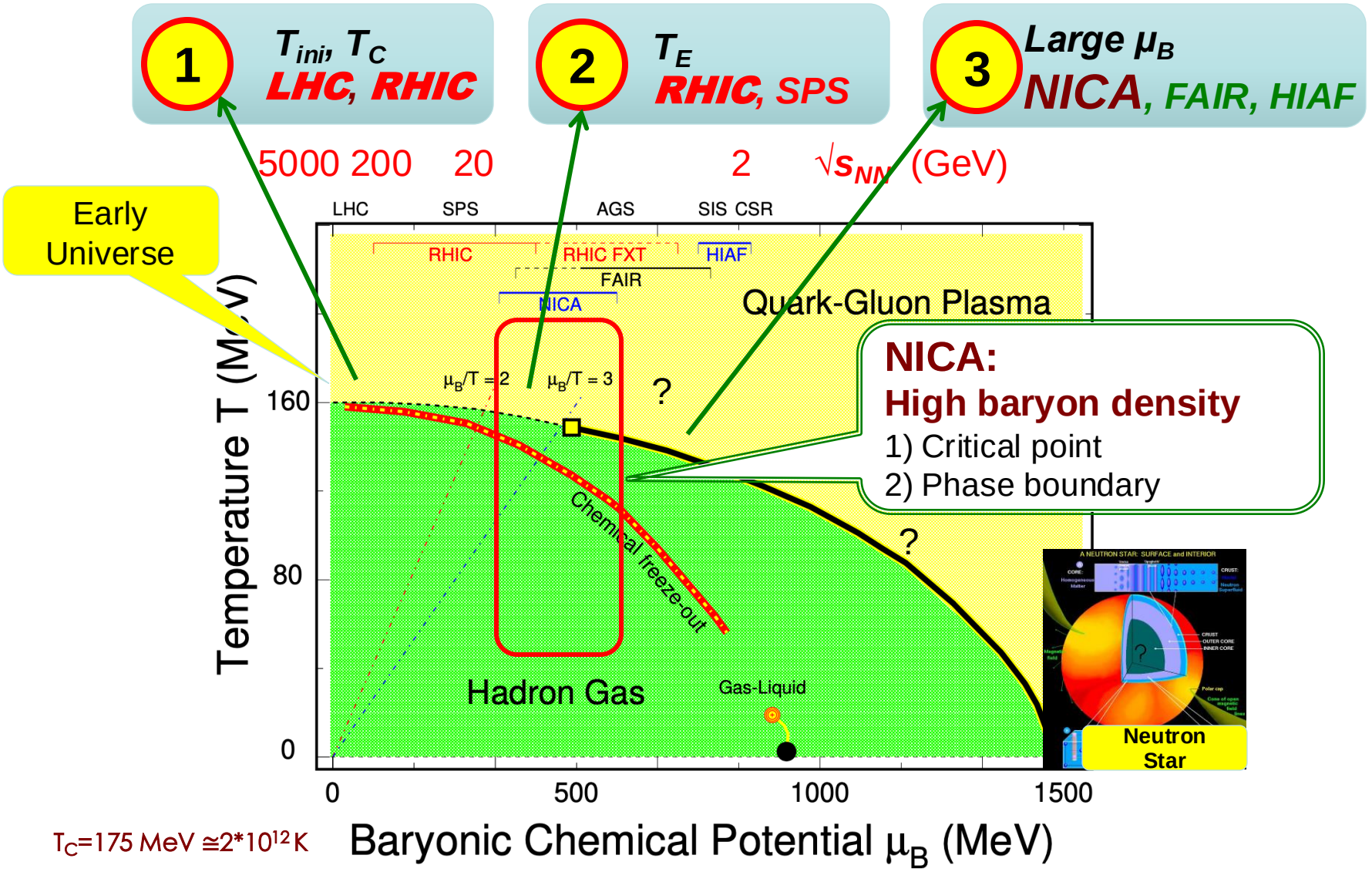
Central China Normal University

The 2nd China-Russia Joint Workshop on NICA Facility

Outline

- **Motivation**
- **Experimental Setup**
- **Results and Discussions**
- **Summary**

Motivation

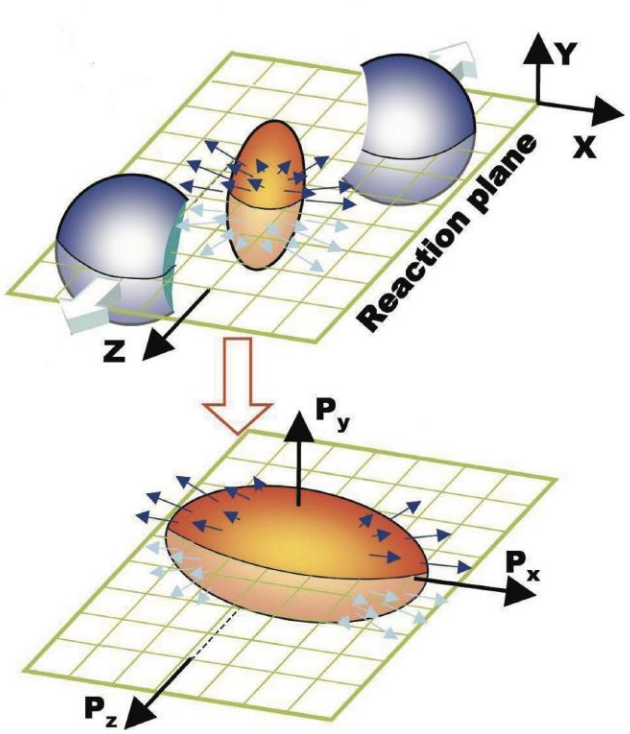


A. Bzdak et al. Phys. Rept. 853, 1 (2010); X. Luo, S. Shi, Nu Xu and Y. Zhang. Particle 3, 278 (2020)

Anisotropic Flow

Anisotropies in particle momentum distributions relative to the reaction plane

Initial spatial anisotropy → Pressure gradient → Momentum space anisotropy



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

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

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

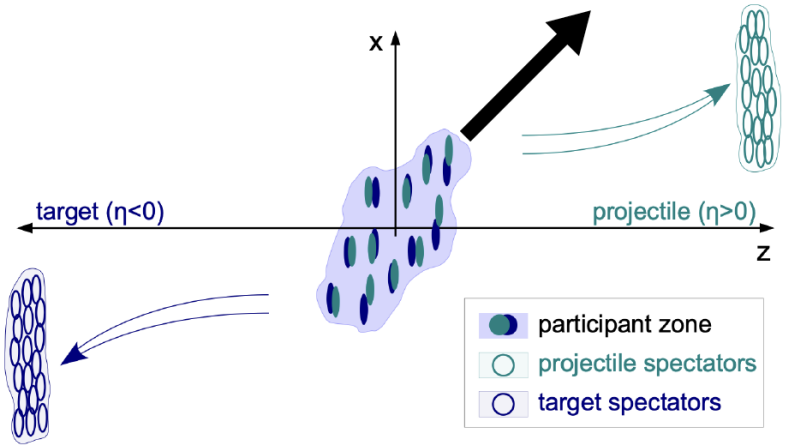
- **Equation of State**
- **Degree of Freedom**

A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998)

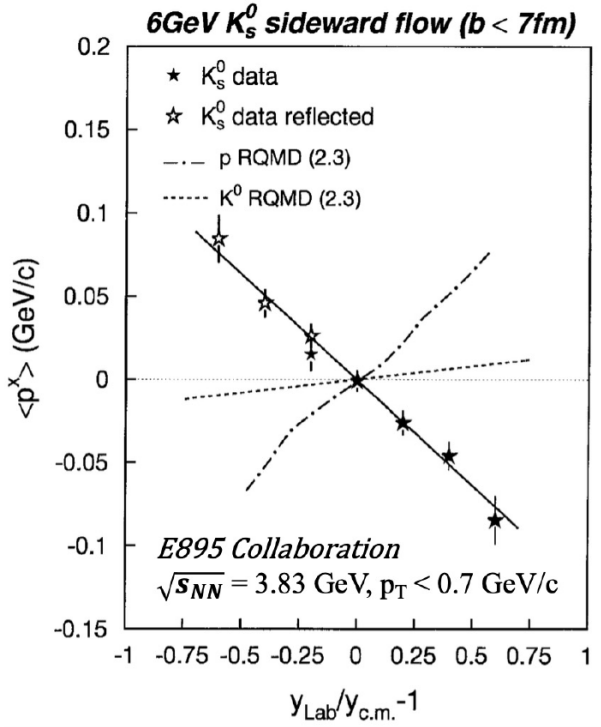
P. Danielewicz, R. Lacey, Science 298 (2002)
STAR, Phys. Rev. Lett. 118, 212301 (2017)

Motivation: Anti-flow of v_1

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



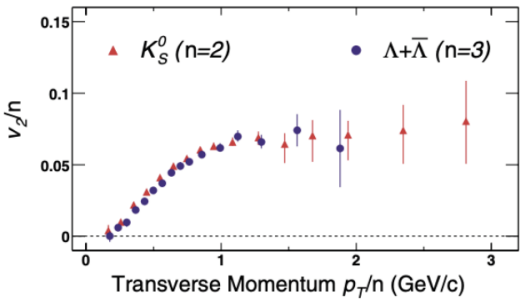
E895, Phys. Rev. Lett. 85, 940 (2000)



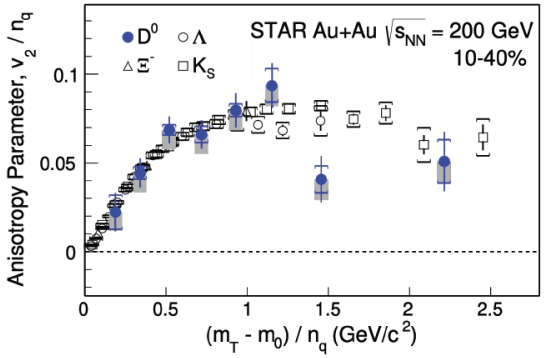
- Bounce-off: Positive flow in positive rapidity
- Au+Au 3.83 GeV: Anti-flow of kaon at low p_T (< 0.7 GeV/c) → Kaon potential?

Motivation: Elliptic Flow

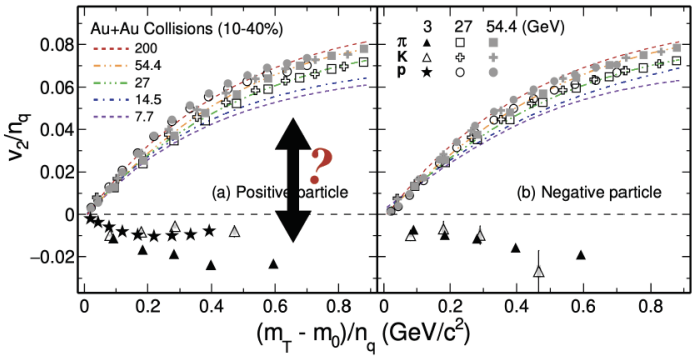
STAR, Phys. Rev. Lett. 92, 052302 (2004)



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

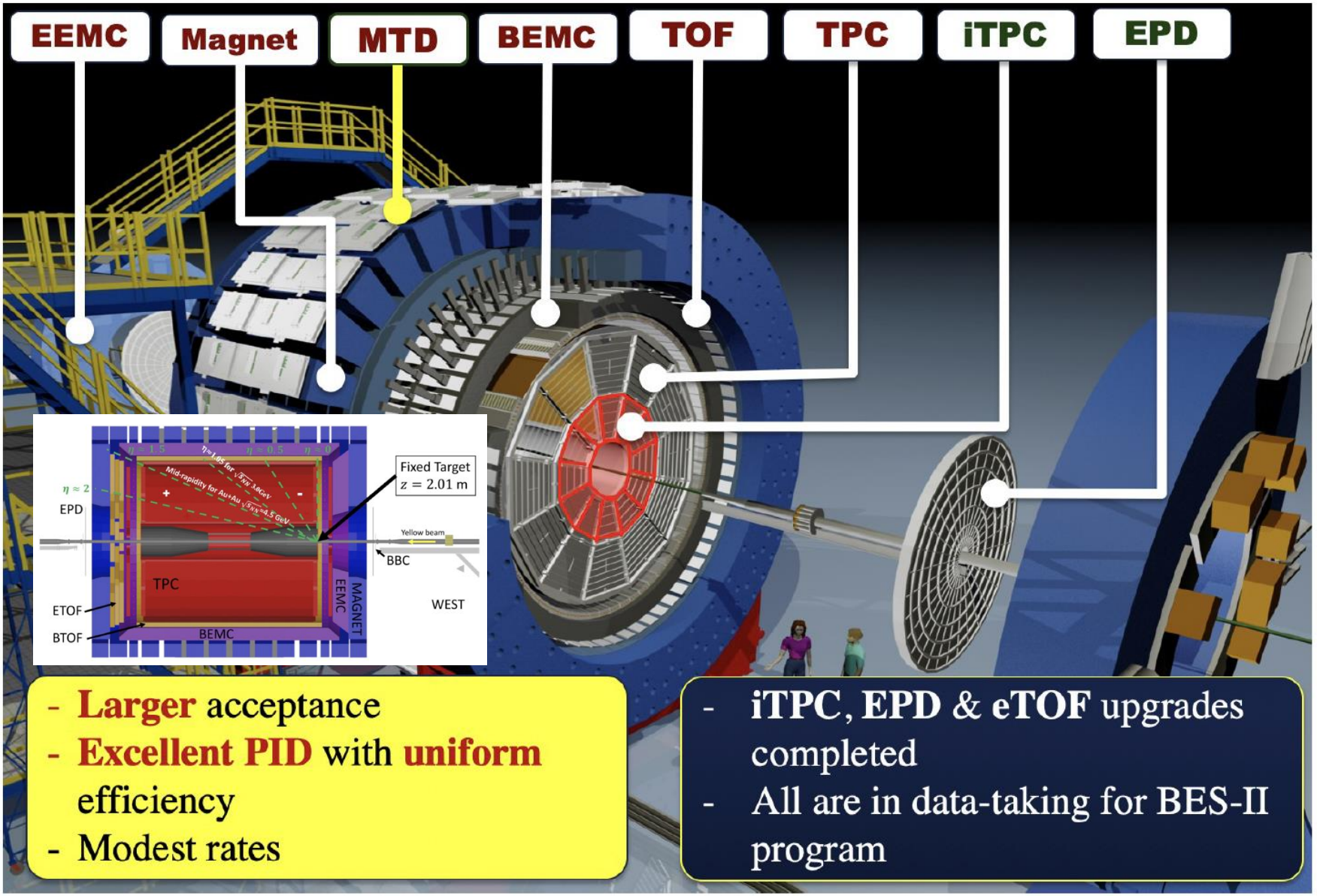


STAR, Phys. Rev. Lett. 110, 142301 (2013)
Phys. Rev. C 93, 14907 (2016), Phys. Lett. B 827, 137003 (2022)



- 200 GeV: Partonic collectivity
- 3.0 GeV: Hadronic interaction dominates
- Transition in degree of freedom: 3.0 → 7.7 GeV?

Experimental Setup



STAR Beam Energy Scan

CENTRAL CHINA NORMAL UNIVERSITY

Au+Au Collisions at RHIC

Collider Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19
2	62.4	46 M	75 MeV		Run-10
3	54.4	1200 M	85 MeV		Run-17
4	39	86 M	112 MeV		Run-10
5	27	585 M	156 MeV	3.36	Run-11, 18
6	19.6	595 M	206 MeV	3.1	Run-11, 19
7	17.3	256 M	230 MeV		Run-21
8	14.6	340 M	262 MeV		Run-14, 19
9	11.5	57 M	316 MeV		Run-10, 20
10	9.2	160 M	372 MeV		Run-10, 20
11	7.7	104 M	420 MeV		Run-21

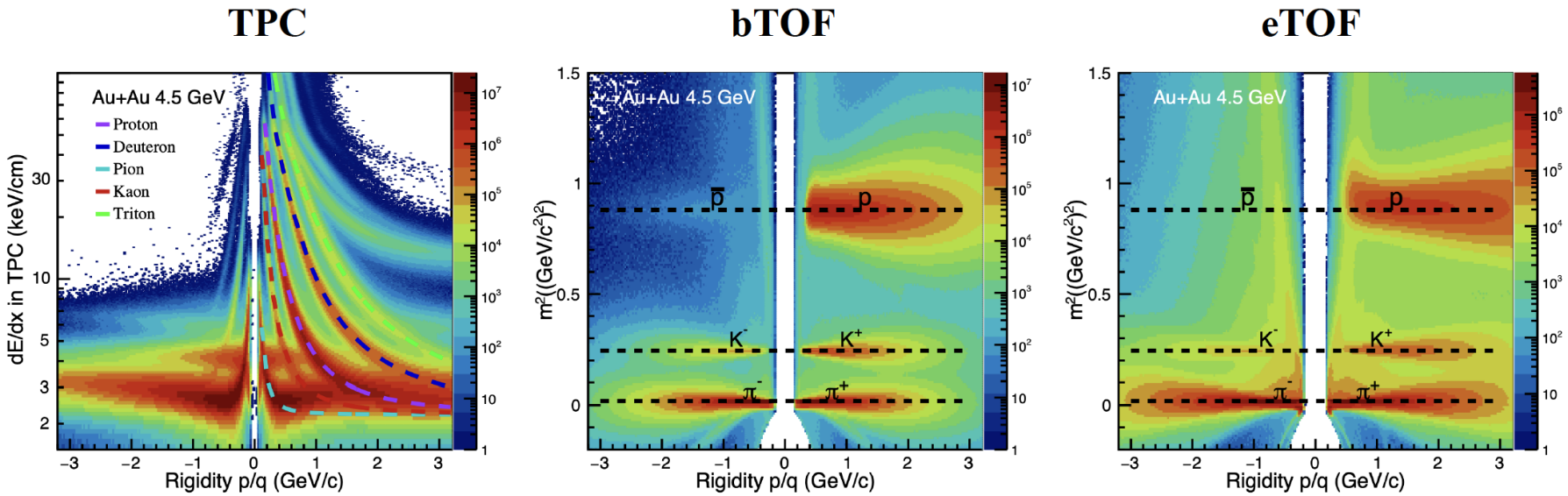
Fixed-Target Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
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

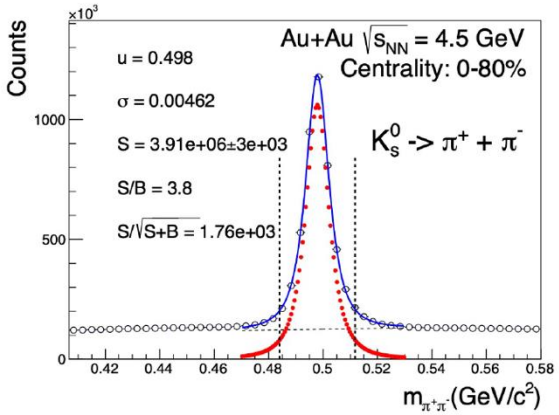
Particle Identification

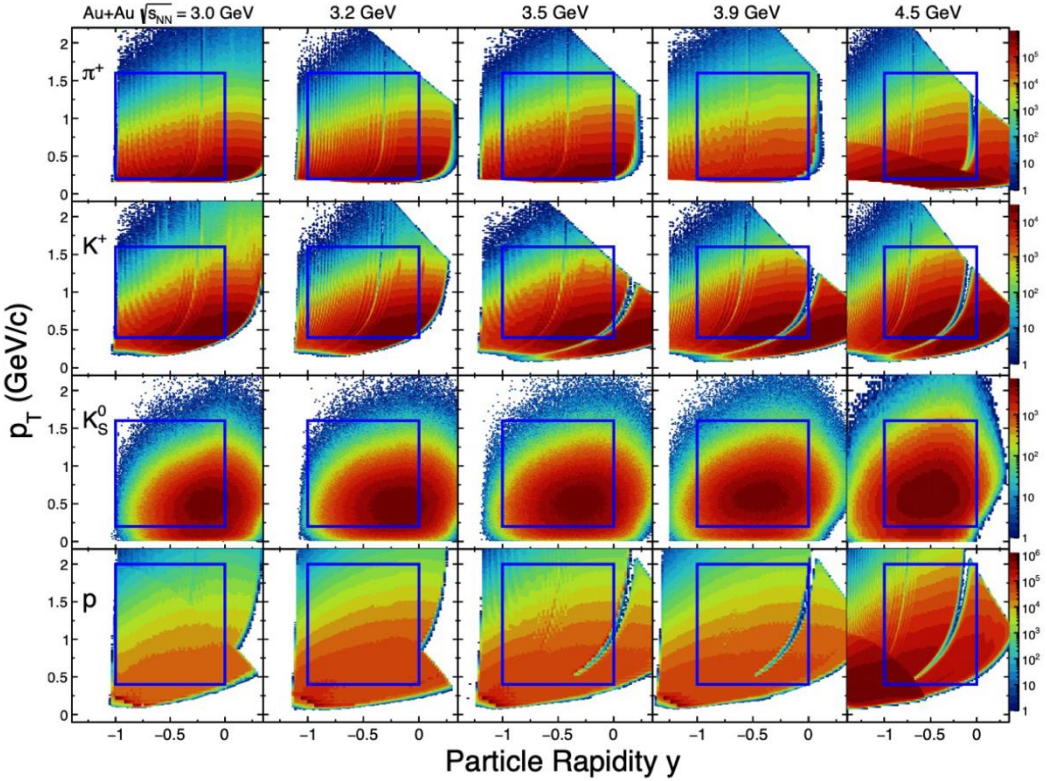


Au+Au (GeV)	3.0	3.2	3.5	3.9	4.5
Baryon chemical potential (~MeV)	750	700	670	635	590
Events analyzed (M)	260	206	107	94	128

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

Particle Acceptance



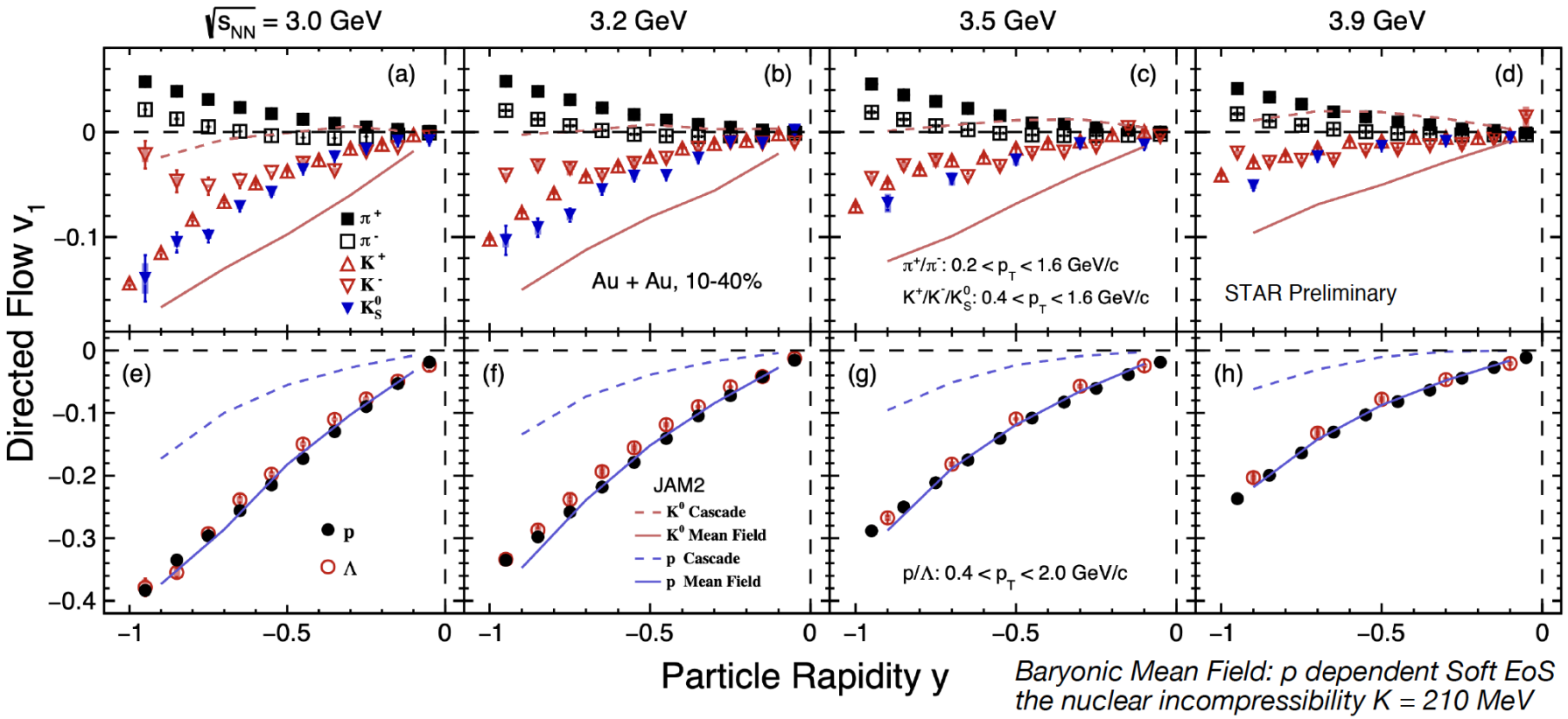


- K_s^0, Λ are reconstructed by invariant mass method (KF particle package)
- Particle rapidity coverage from -1 to 0 (blue boxes)

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

Rapidity Dependence of v_1

STAR: CPOD2024, SQM2024

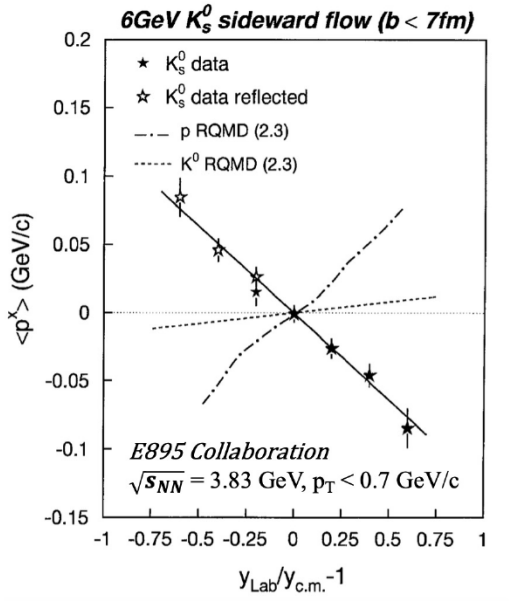


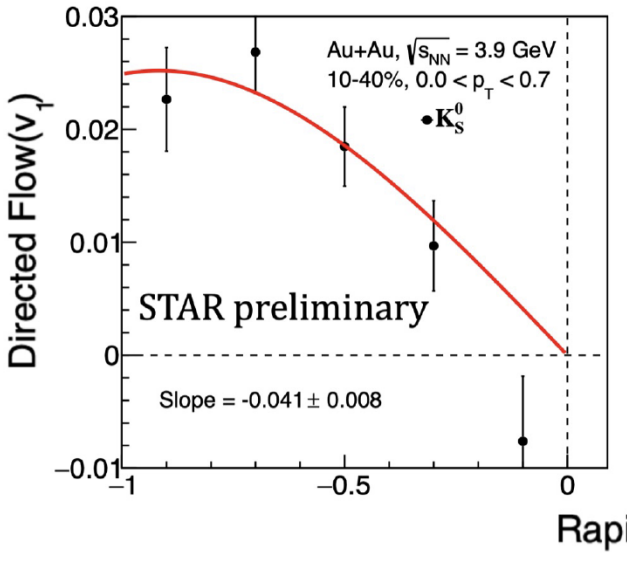
Measurements of v_1 vs. rapidity for $\pi^{\pm}, K^{\pm}, K^0_S, p, \Lambda$ at 3.0, 3.2, 3.5, and 3.9 GeV

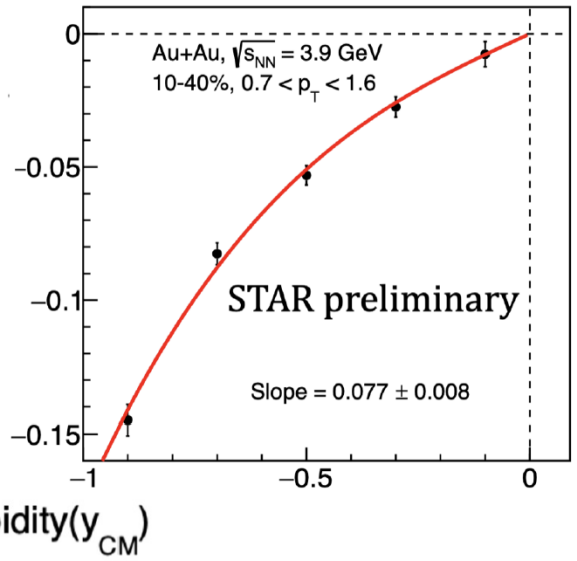
Anti-flow of Kaons

STAR: CPOD2024, SQM2024

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





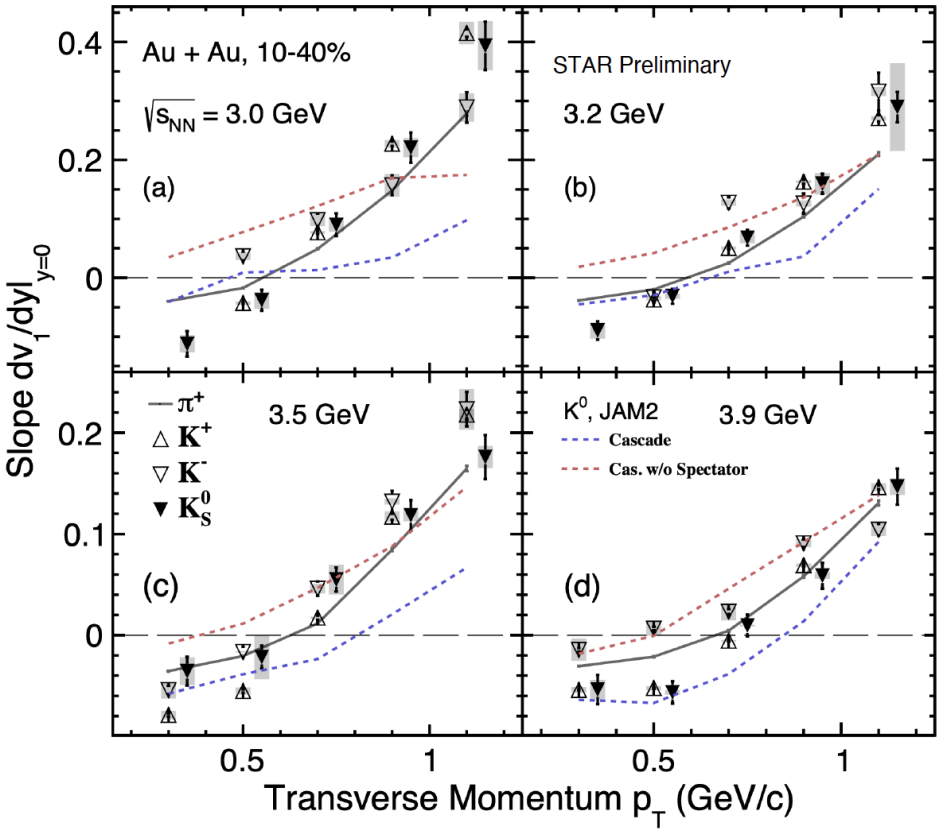


- 3.9 GeV: anti-flow observed for K^0_S at $p_T < 0.7$ GeV/c
- Positive directed flow slope of K^0_S at $p_T > 0.7$ GeV/c

Strong p_T dependence of K^0_S v_1 slope

p_T Dependence of v_1 Slope

STAR: CPOD2024, SQM2024

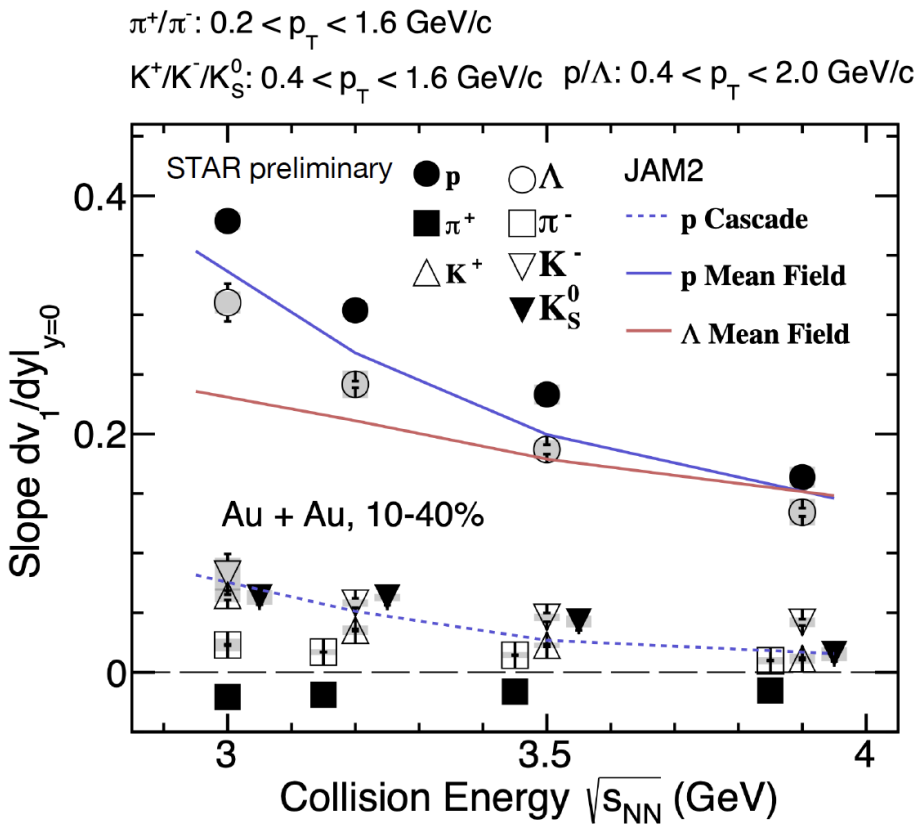


- Anti-flow of π^+ and $K^0_S, K^{\pm}$ at low p_T
- Anti-flow could be explained by shadowing effect from spectators

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

Energy Dependence of v_1 Slope

STAR: CPOD2024, SQM2024

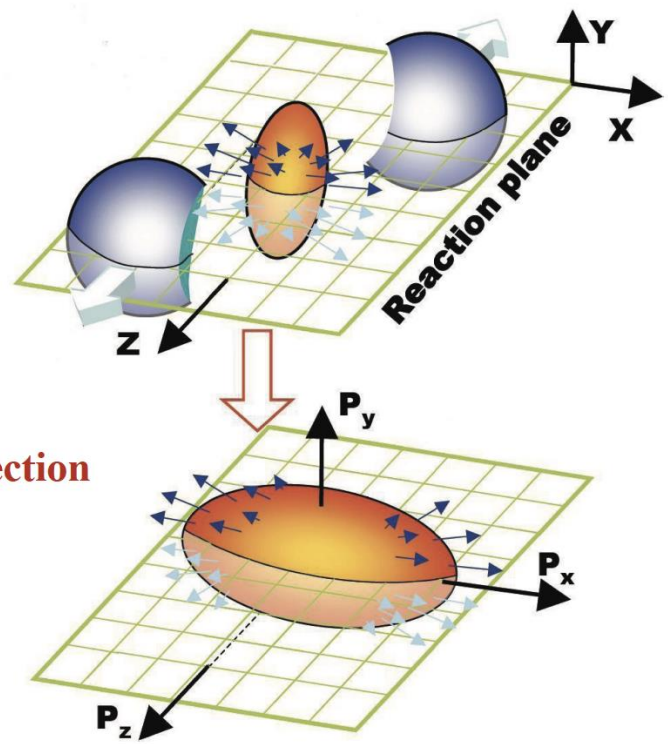


- v_1 slope of baryons drops as collision energy increases
- JAM with baryonic Mean Field better describes data

  Mean field potential plays important role

Anisotropic Flow

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



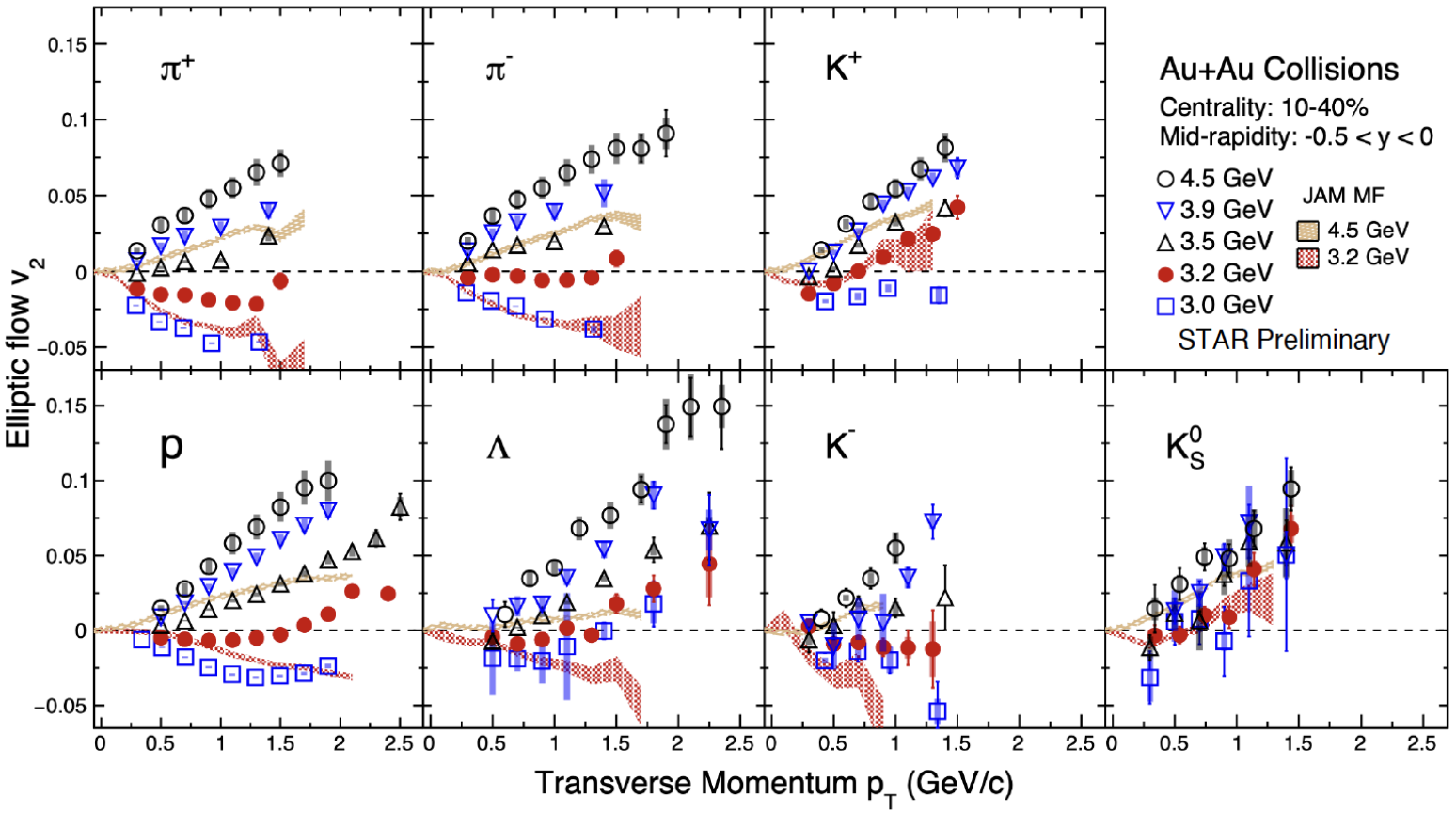
$$v_2 = \cos[2(\phi - \psi_r)] = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle$$

v_1 reflect asymmetry along X direction

v_2 reflect asymmetry on X-Y plane

p_T Dependence of v_2 at 3 - 4.5 GeV

STAR: CPOD2024, SQM2024



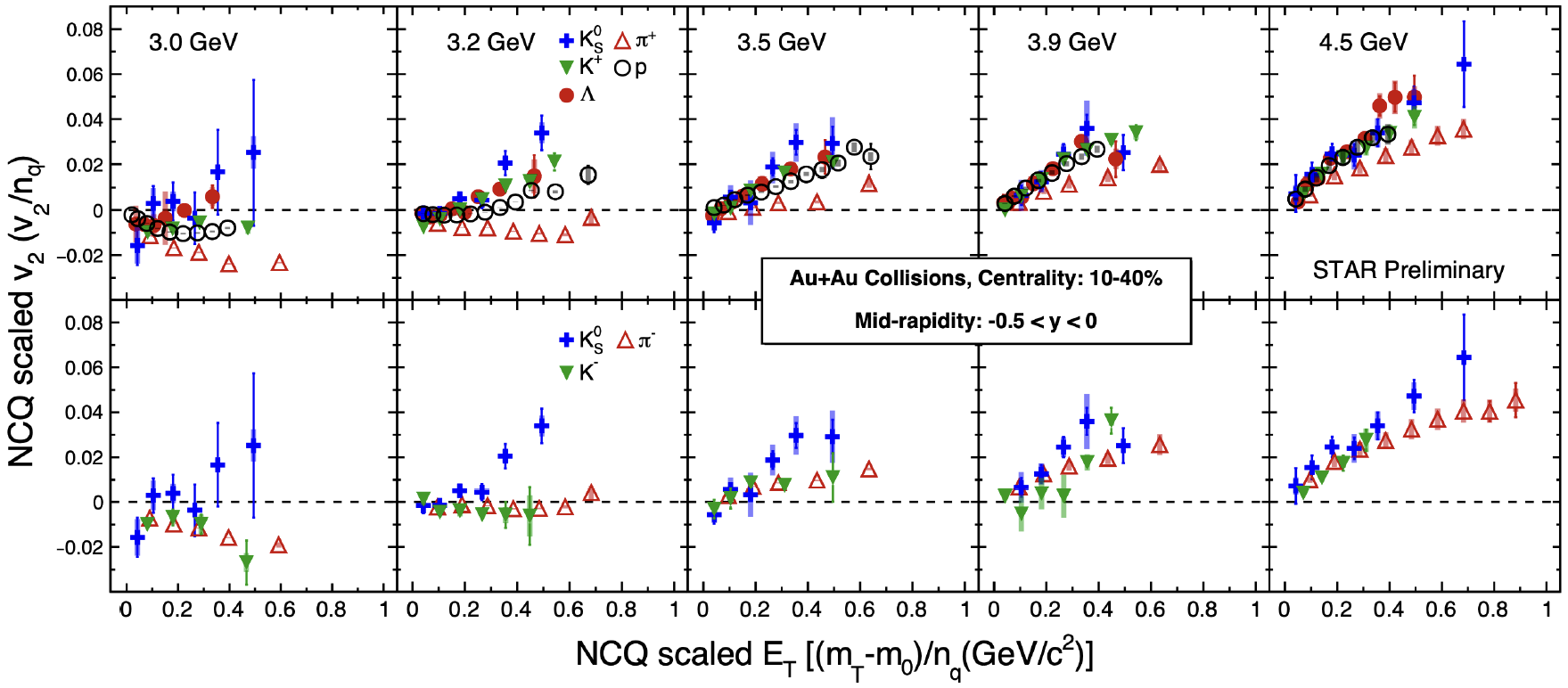
- Clear energy dependence for $v_2(p_T)$ from negative to positive: **Shadowing effect**
- JAM + baryonic Mean Field better describe the 3.2 GeV while underestimate 4.5 GeV data

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

NCQ scaling of v_2 at 3 - 4.5 GeV

Hadronic interaction

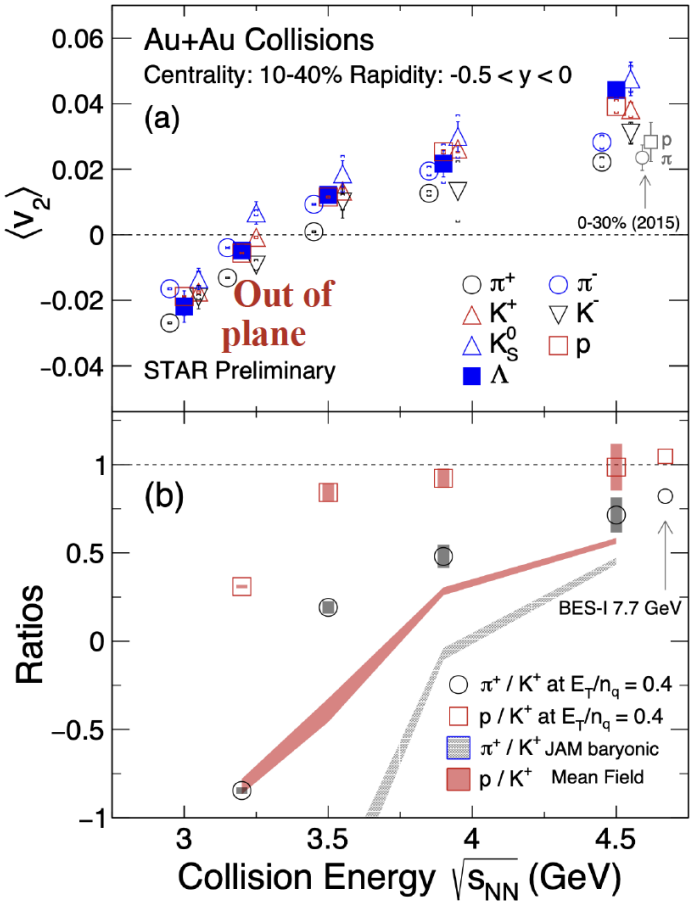
Partonic collectivity



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

Energy dependence of $\langle v_2 \rangle$

STAR: CPOD2024, SQM2024



In-plane expansion

- 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

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

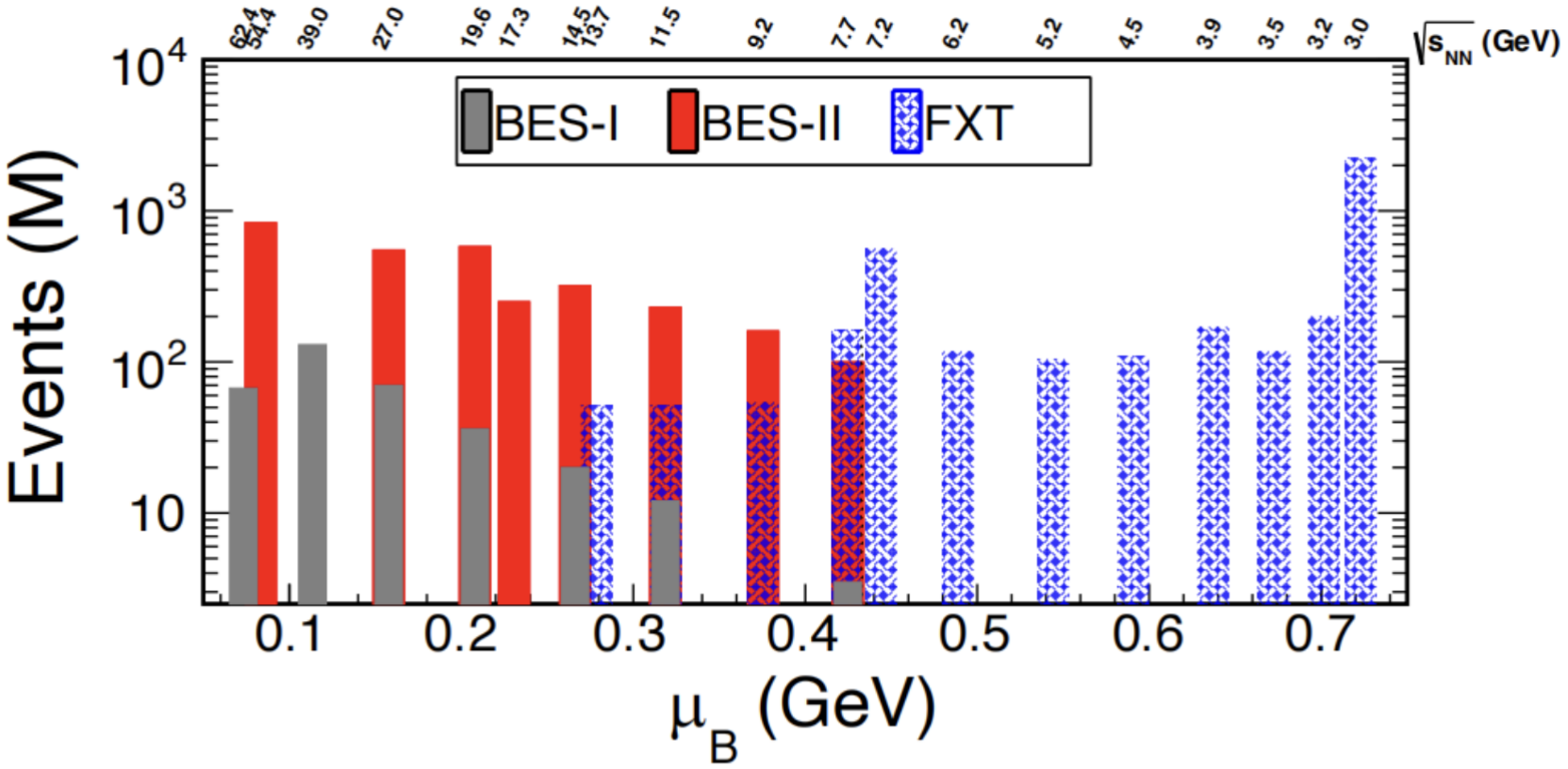
Summary

- 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!