Collective flow measurements in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 - 19.6 GeV

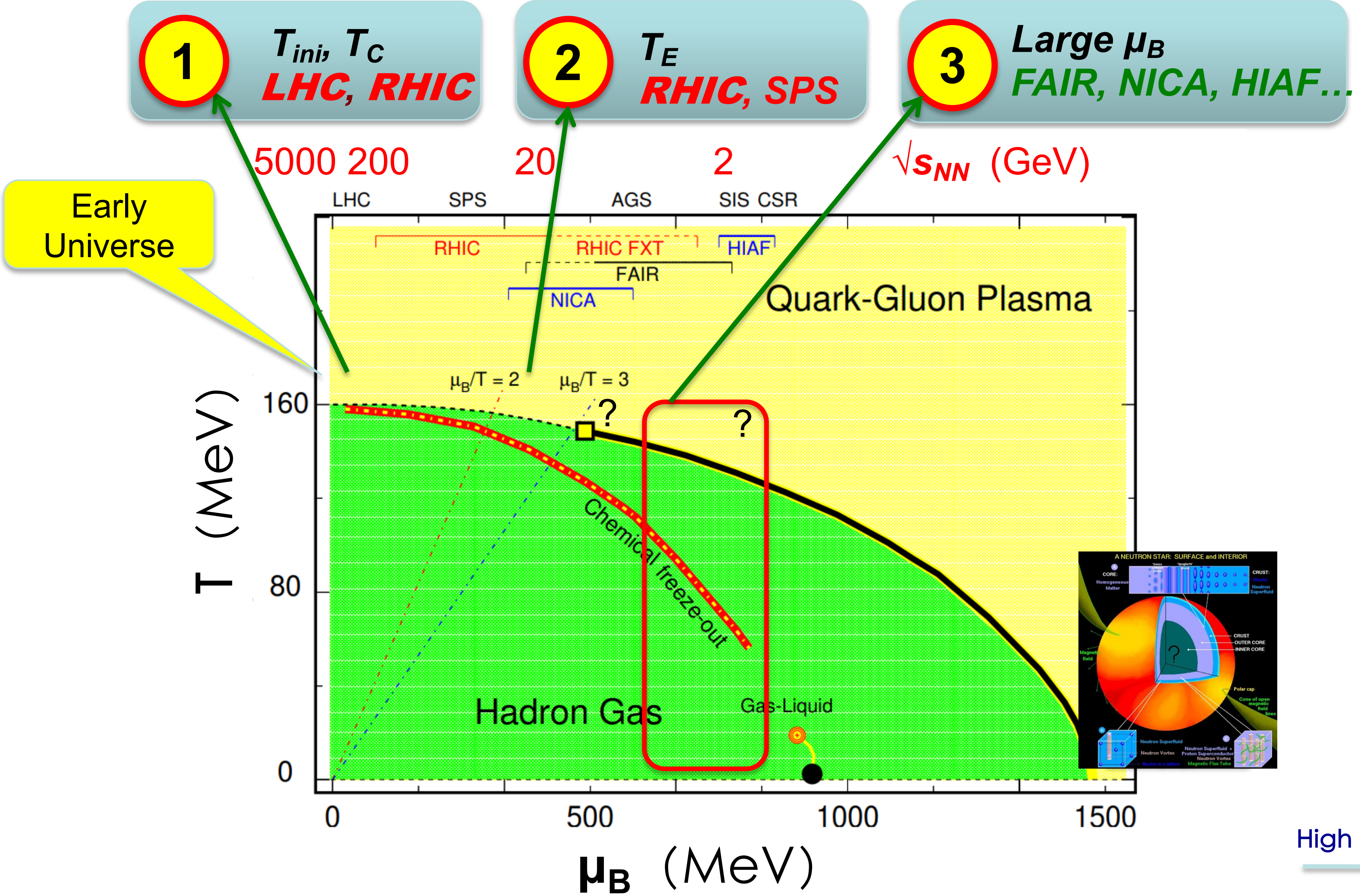
Shusu Shi

Central China Normal University

Outline

- Motivation
- Elliptic Flow
  - Degree of Freedom: Partonic or Hadronic
- Directed Flow
  - Anti-flow of Mesons
- Summary and Outlook

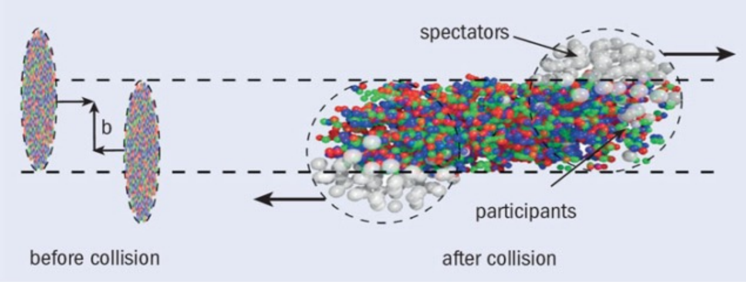
QCD Phase Diagram



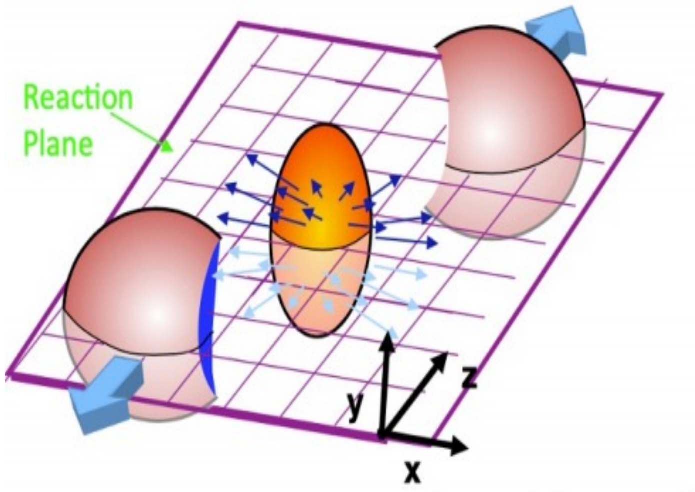
High Baryon Density

X. Luo, S. Shi, Nu Xu and Y. Zhang. Particle 3, 278 (2020)

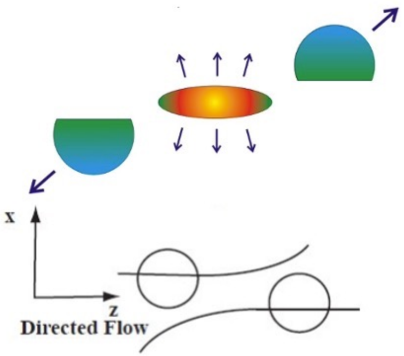
Anisotropic Flow

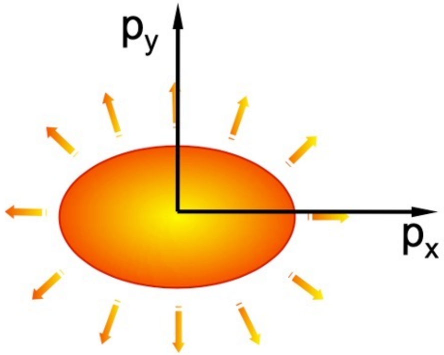


$$\frac{dN}{d(\phi - \Psi)} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi))$$



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

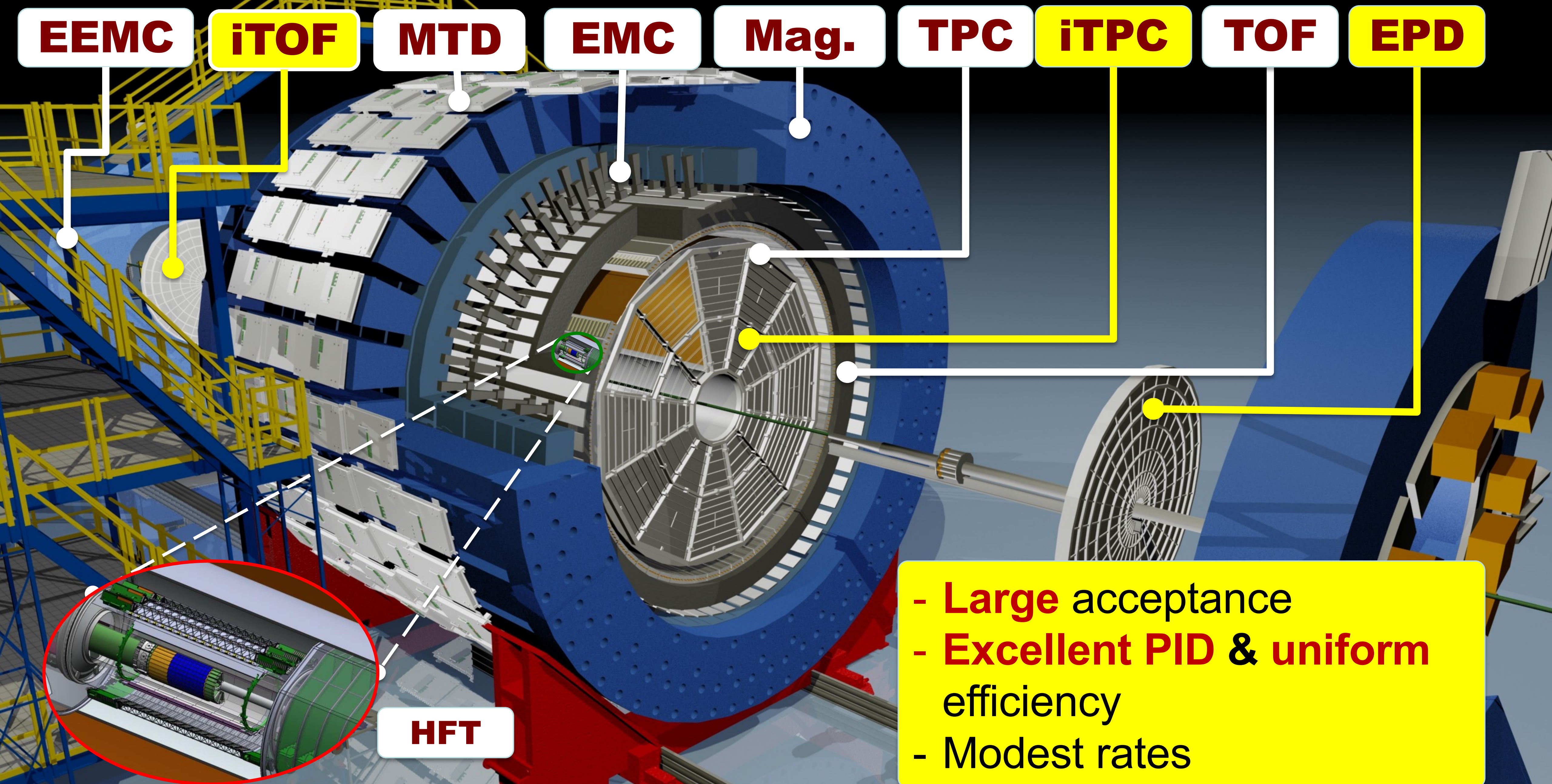




- v_1 is sensitive to the Equation-of-State (EoS)
- v_2 is sensitive the degree of freedom: partonic vs. hadronic

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

STAR DETECTOR SYSTEM



- **Large** acceptance
- **Excellent PID** & **uniform** efficiency
- Modest rates

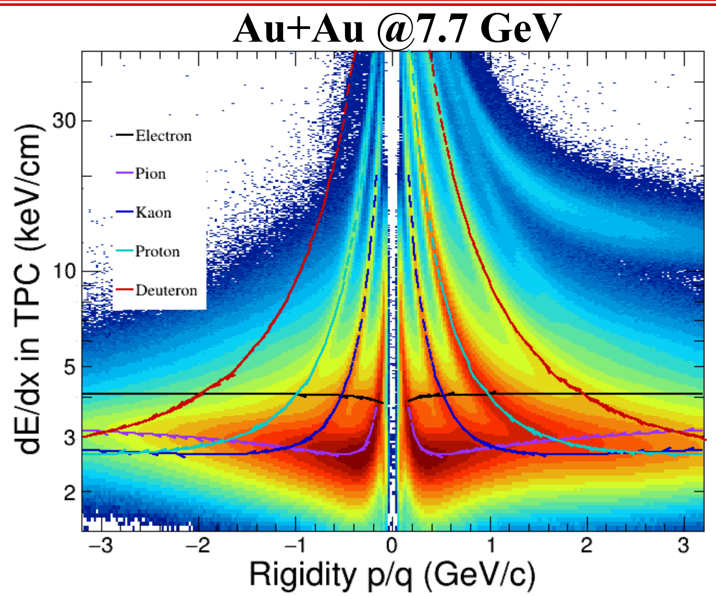
STAR Beam Energy Scan

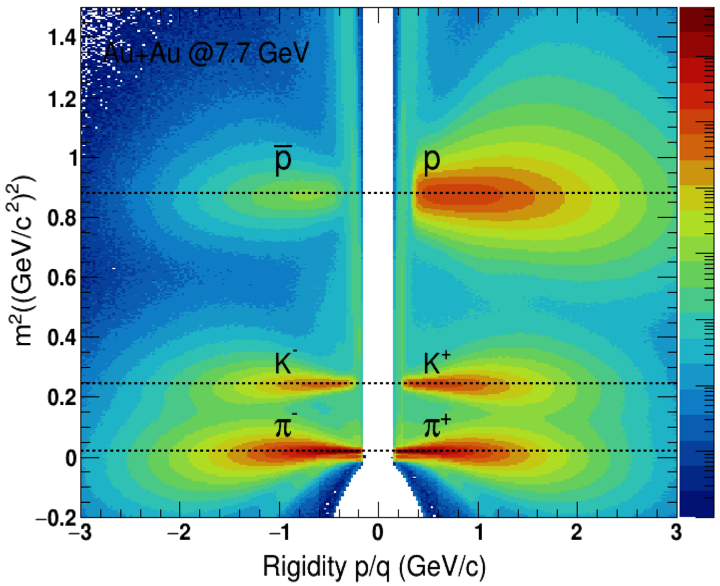
Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	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

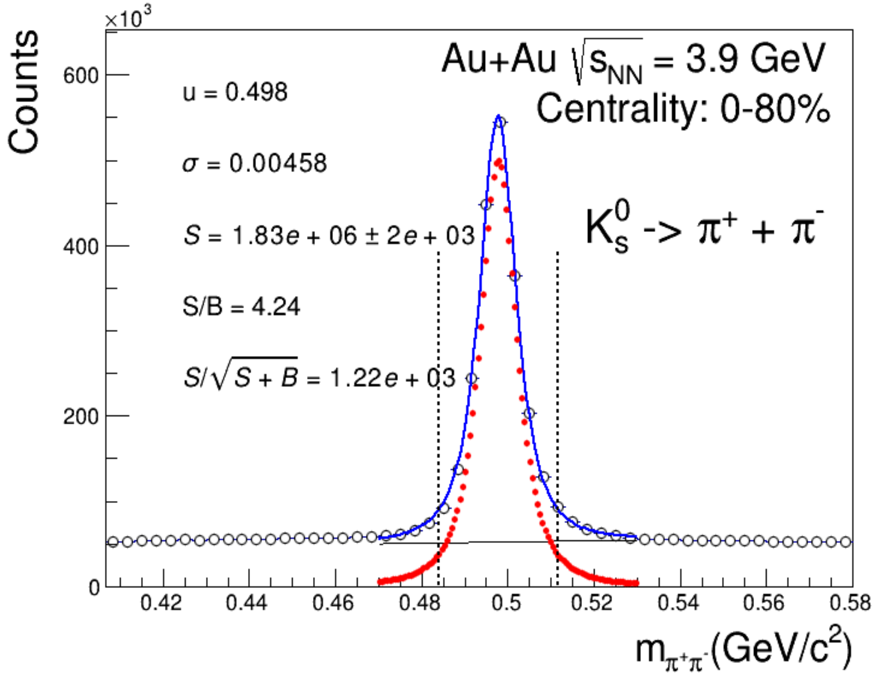
Most precise data to map the QCD phase diagram

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

Particle Identification



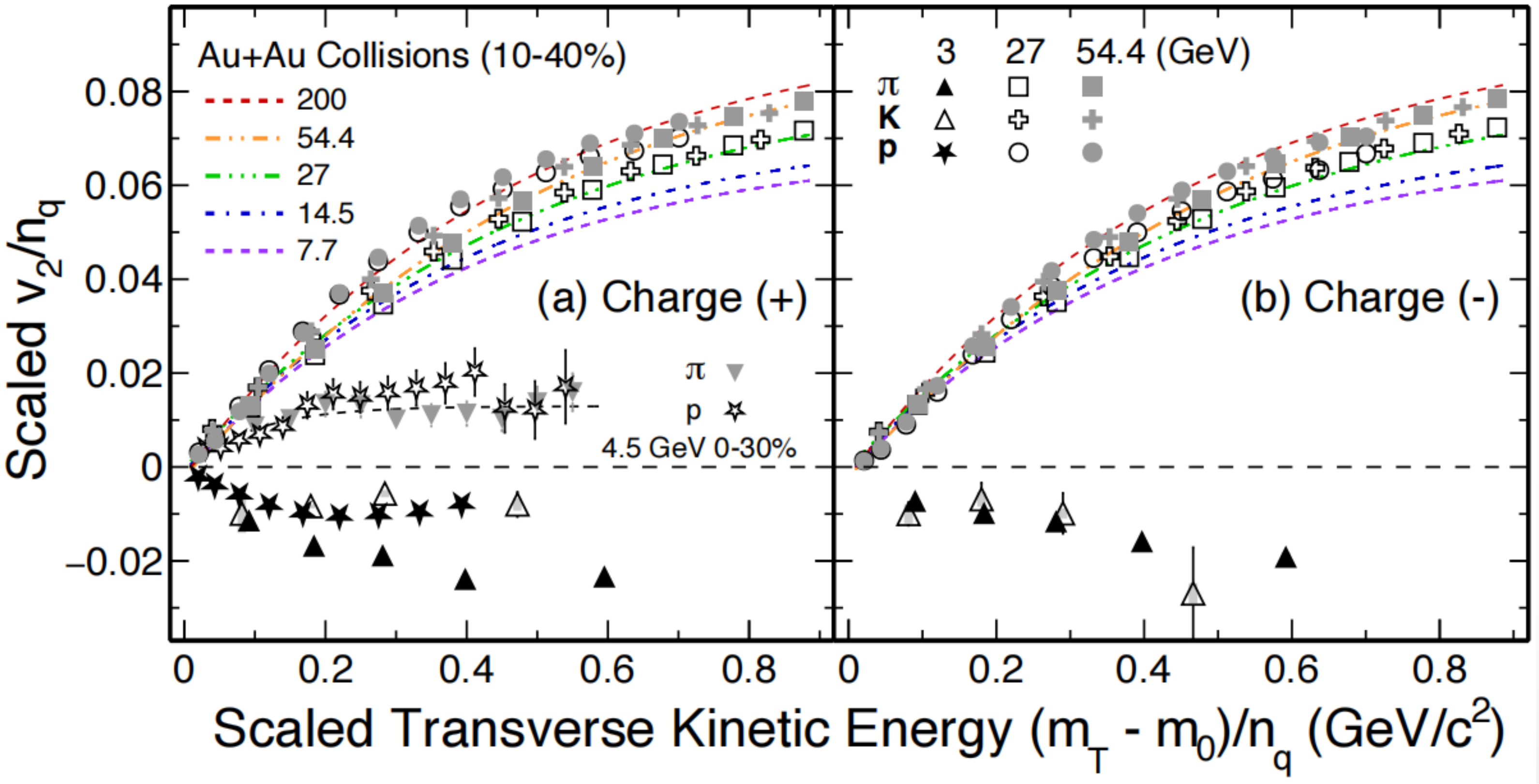




- Good capability of particle identification (PID) based on TPC and TOF
- Decayed particles reconstructed by KF(Kalman Filter) particle package

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

NCQ Scaling of v_2 at 3 GeV

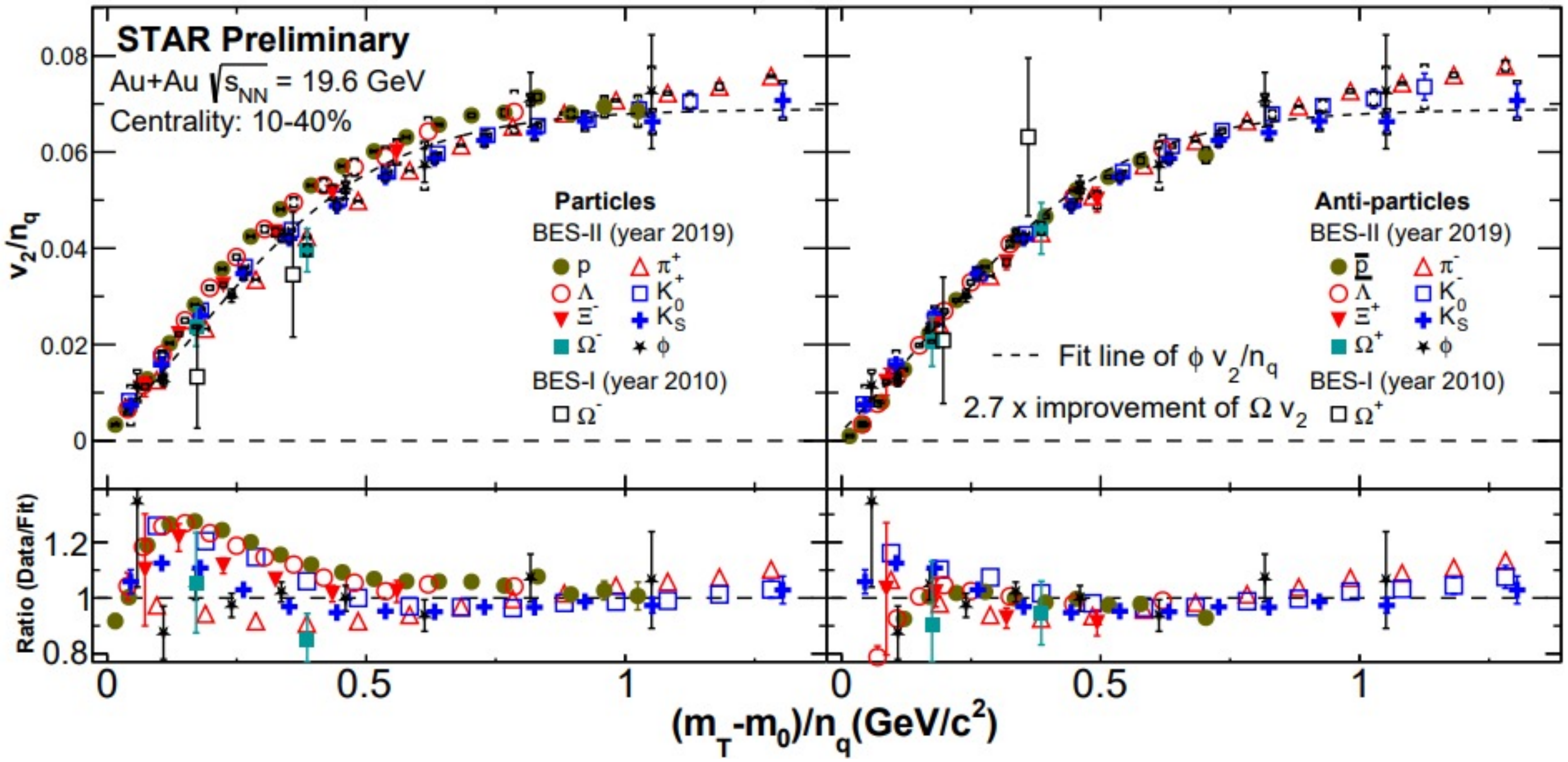


STAR: Phys. Lett. B 827 (2022) 137003; Phys. Rev. C.107 (2023) 024912

- 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

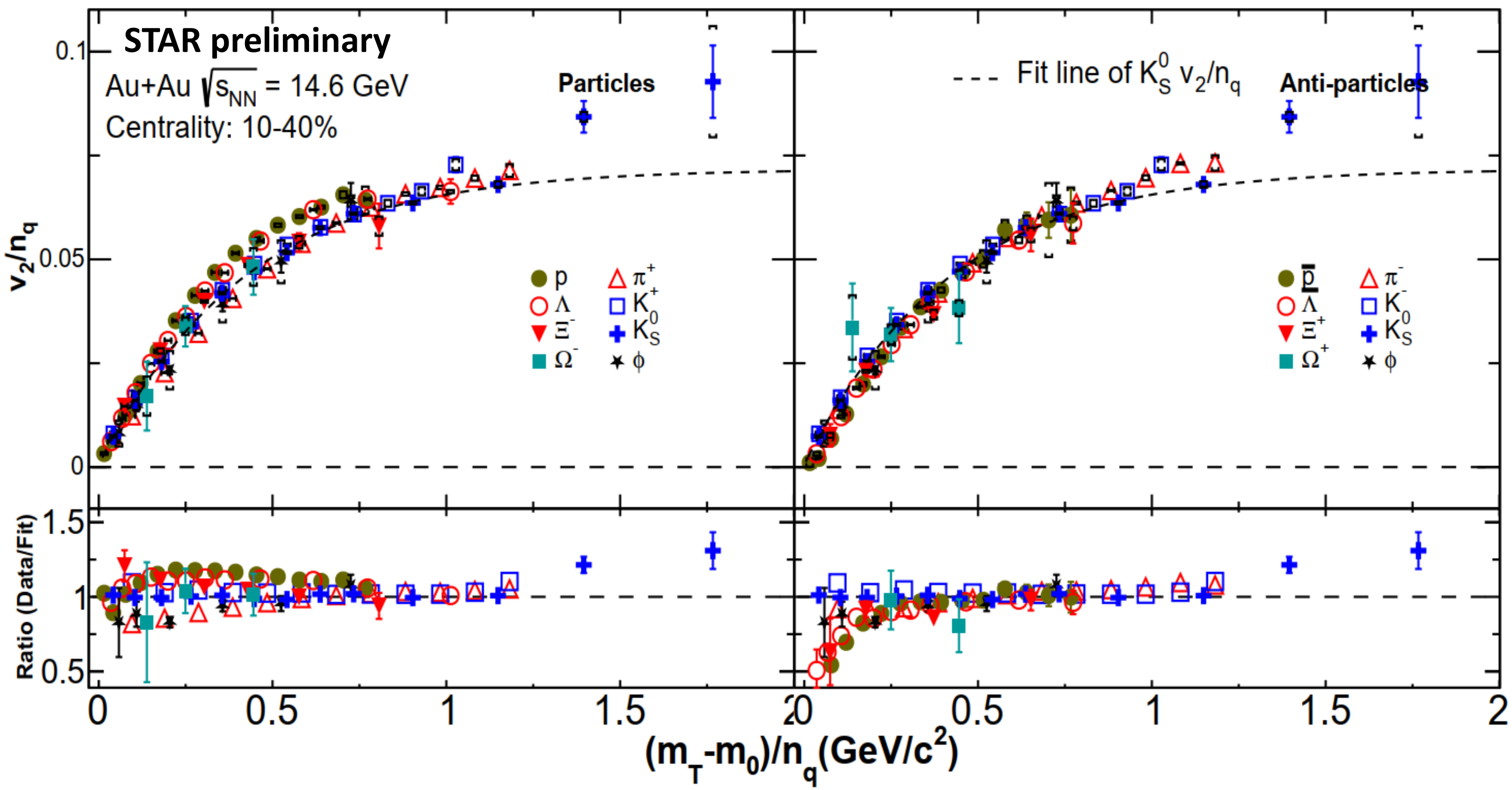
NCQ Scaling of v_2 at 19.6 GeV



- The NCQ scaling holds within 20% for particles and within 10% for anti-particles
- The NCQ scaling of anti-particles is better than particles: produced vs. transported quarks

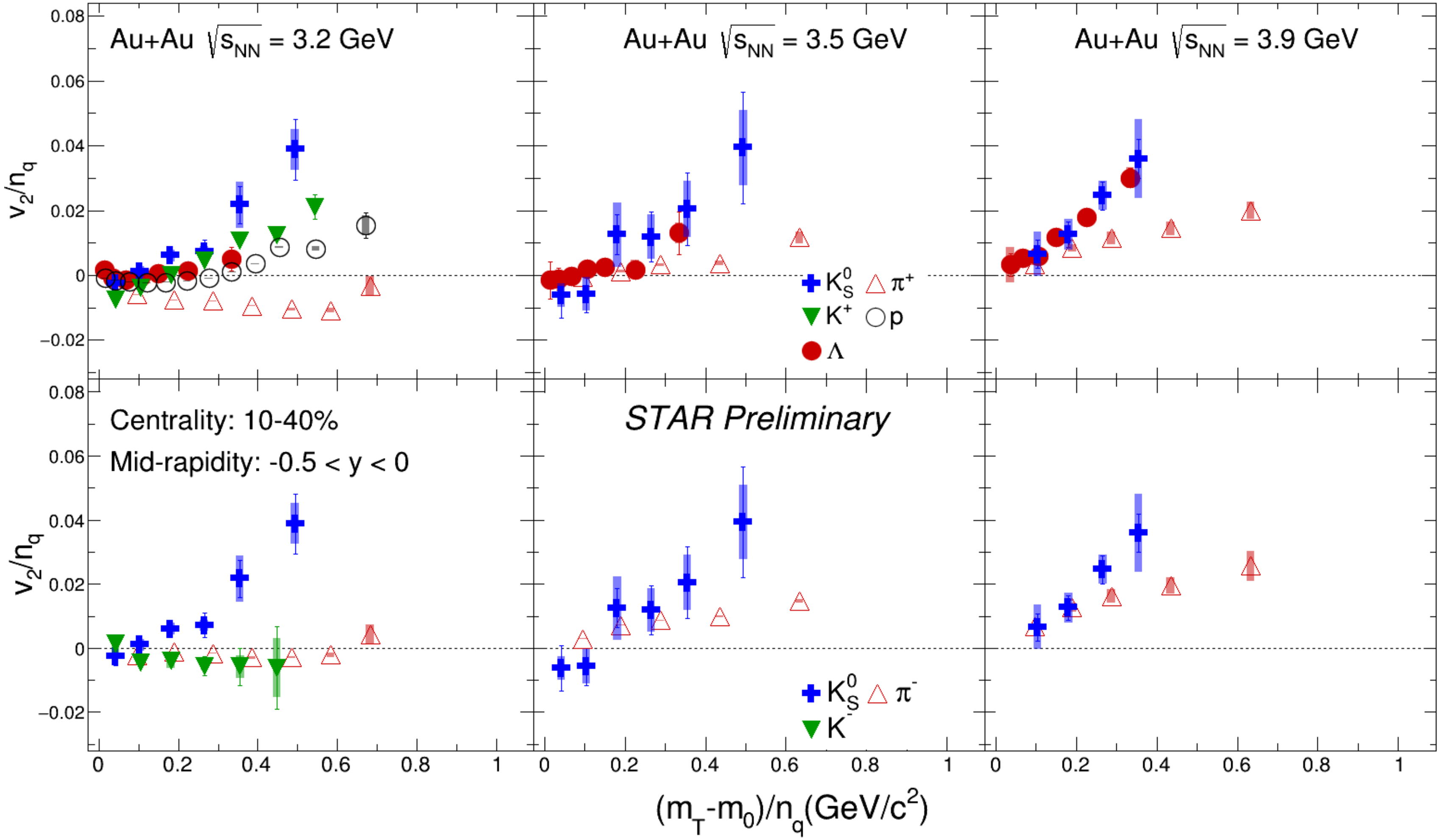
→ The collectivity has been built up in the partonic stage at 19.6 GeV

NCQ Scaling of v_2 at 14.6 GeV



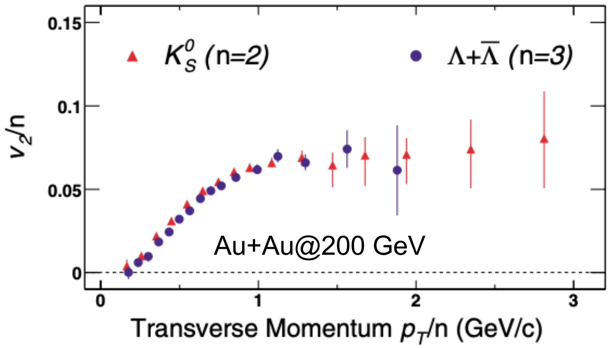
➢ The NCQ scaling holds within 15% for anti-particles and within 25% for particles
→ Partonic collectivity at 14.6 GeV

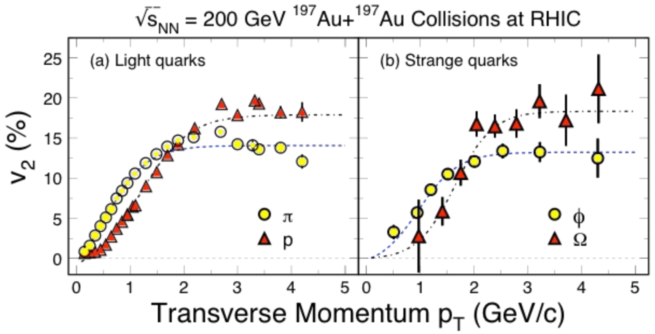
NCQ Scaling of v_2 at 3.2 - 3.9 GeV

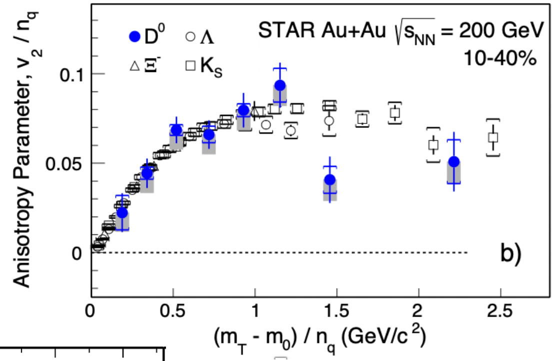


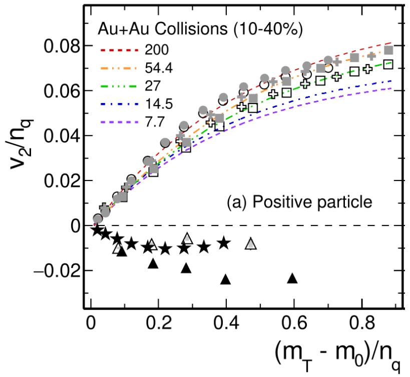
➢ The NCQ scaling totally breaks at 3.2 GeV
→ Hadronic interaction dominates

NCQ Scaling: 20 Years









- First observation of NCQ scaling at 200 GeV

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

- NCQ scaling for the multi-strange hadrons and D meson at 200 GeV

  Partonic collectivity

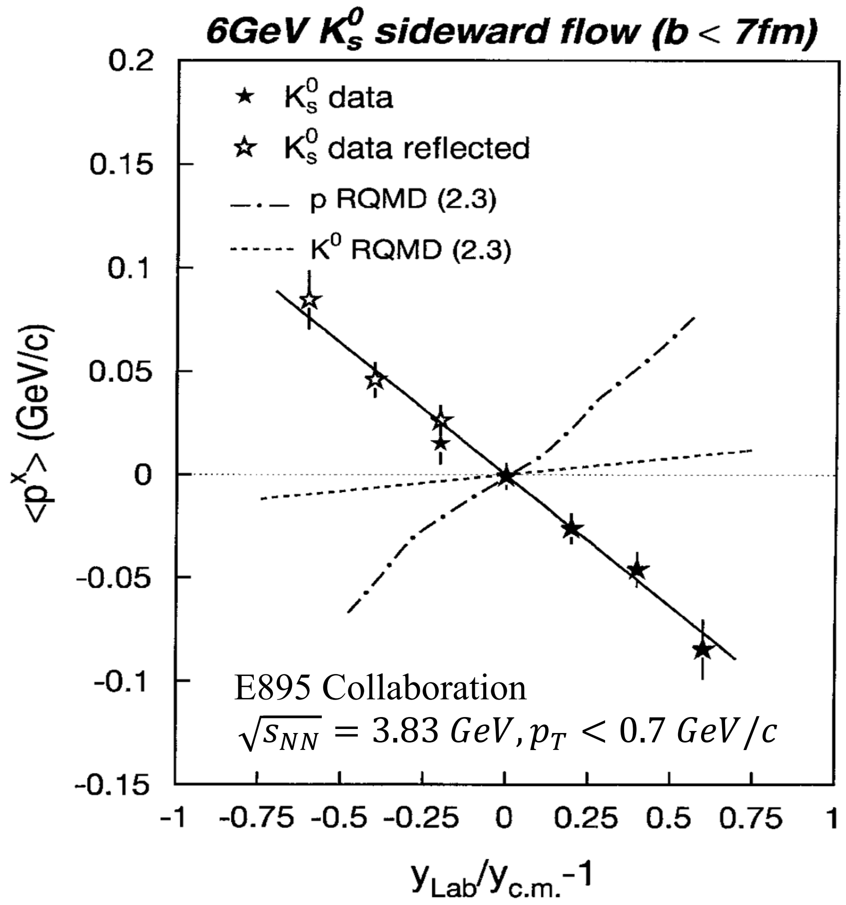
  STAR, Phys. Rev. Lett.116, 062301 (2016)
  Phys. Rev. Lett.118, 212301 (2017)

- NCQ scaling breaks at 3.0 GeV

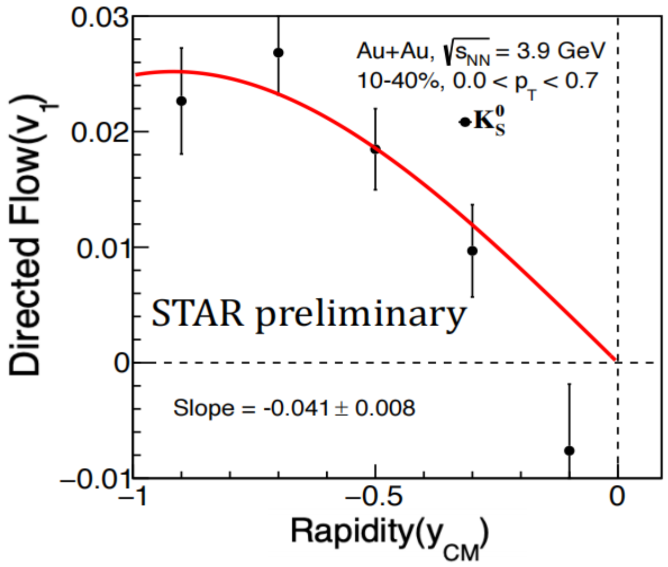
  Disappearance of partonic collectivity

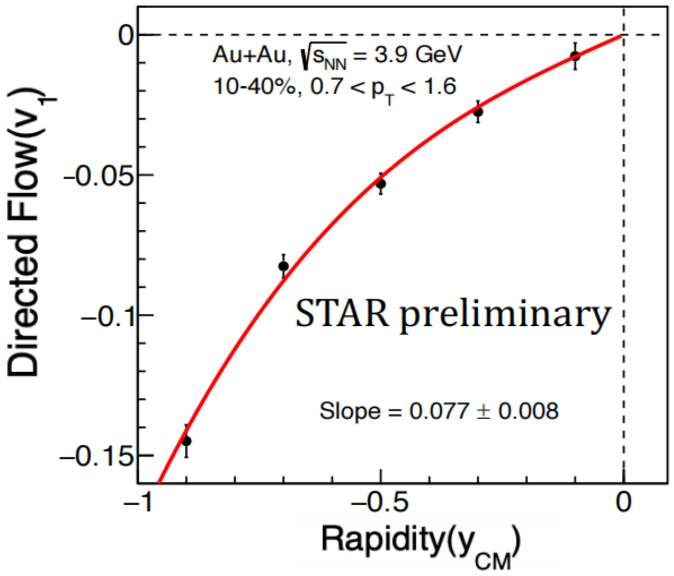
  STAR, Phys. Lett. B 827 (2022) 137003

Anti-flow of K_s^0



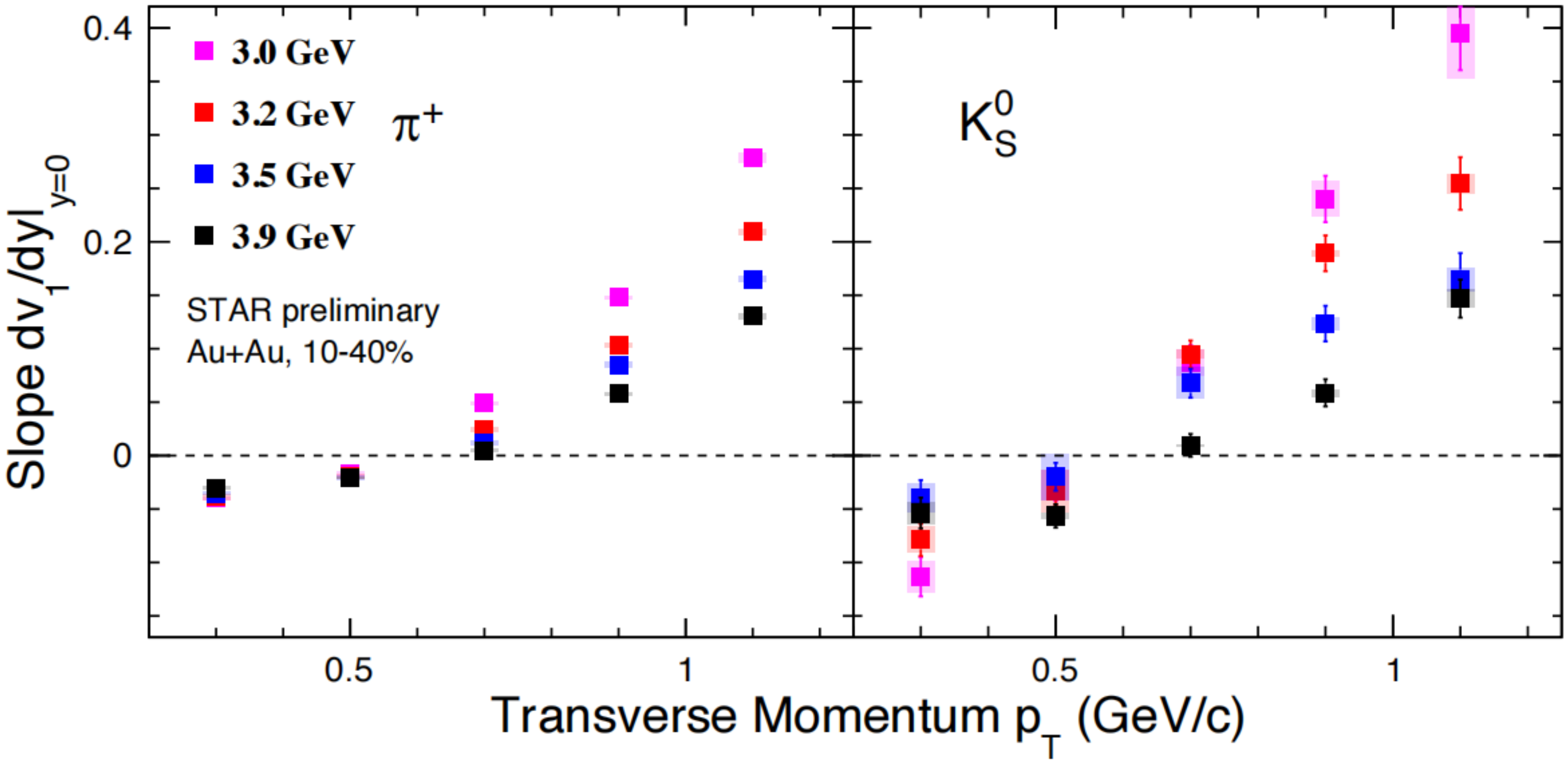
E895: Phys. Rev. Lett. 85, 940 (2000)





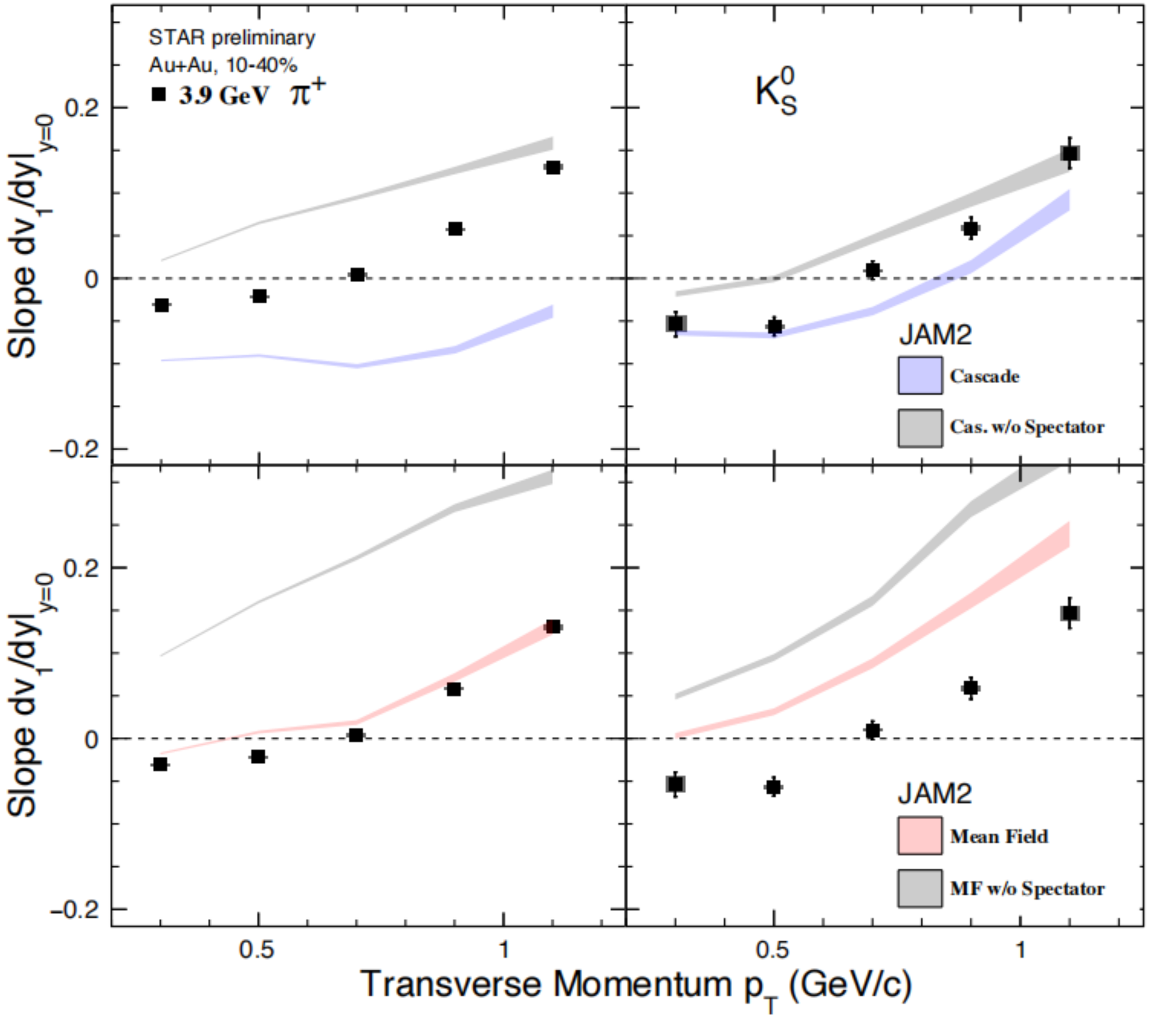
- E895: Kaon vector potential plays an important role in high density nuclear matter
- Anti-flow of K_s^0 is observed at 3.9 GeV ($p_T < 0.7$ GeV)

Anti-flow of Mesons



- v_1 slope of $\pi^+$and K_s^0 as a function of p_{T} measured for 10-40% centrality
- The v_1 slope decreases as the collision energy increasing
- Anti-flow of $\pi^+$and K_s^0 are observed in low p_T region at 3.0 - 3.9 GeV

Anti-flow of Mesons



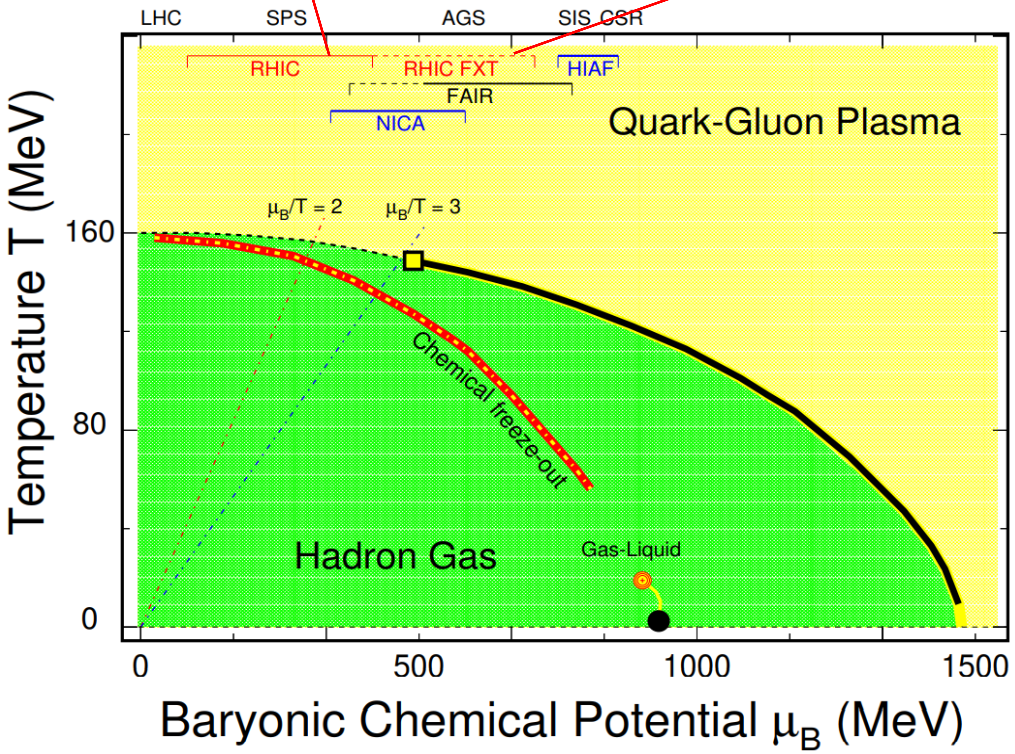
- JAM2 cascade mode and mean-field mode calculation of v_1 slope at 3.9 GeV
- Shadowing effect from spectator may lead to anti-flow at low p_T

Summary

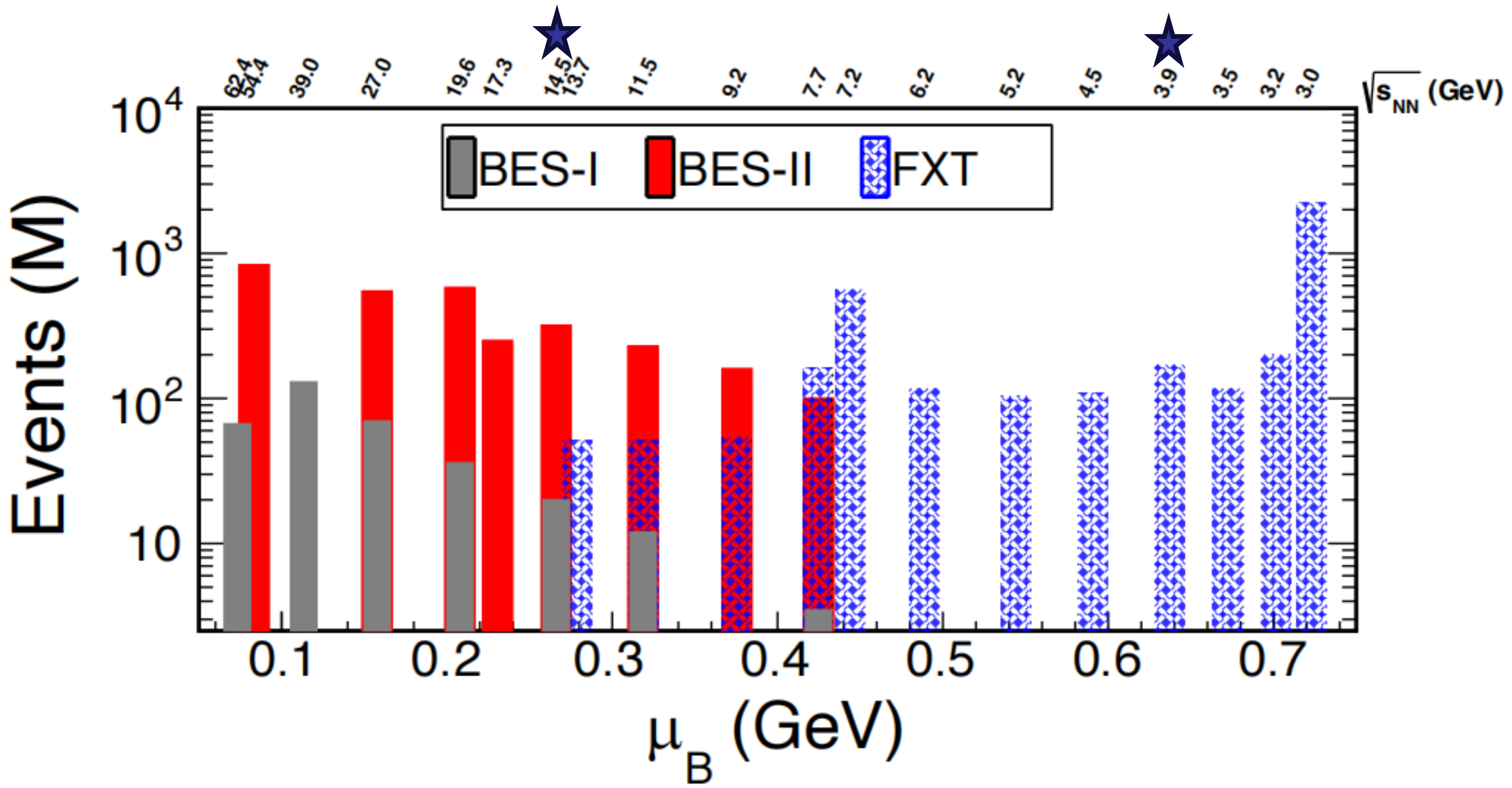
- Anti-flow of K_s^0 is observed at 3.0 - 3.9 GeV → Shadowing effect by spectators
- NCQ Scaling holds at 14.6 GeV and above → Partonic interaction dominates
- NCQ Scaling breaks at 3.2 GeV and below → Hadronic interaction dominates

Partonic interaction: $\sqrt{s_{NN}}$ = 14.6 GeV and above

Hadronic interaction: $\sqrt{s_{NN}}$ = 3.2 GeV and below



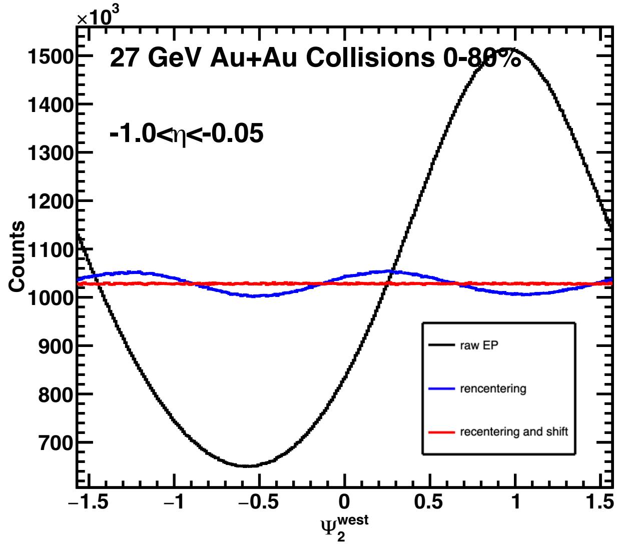
Outlook

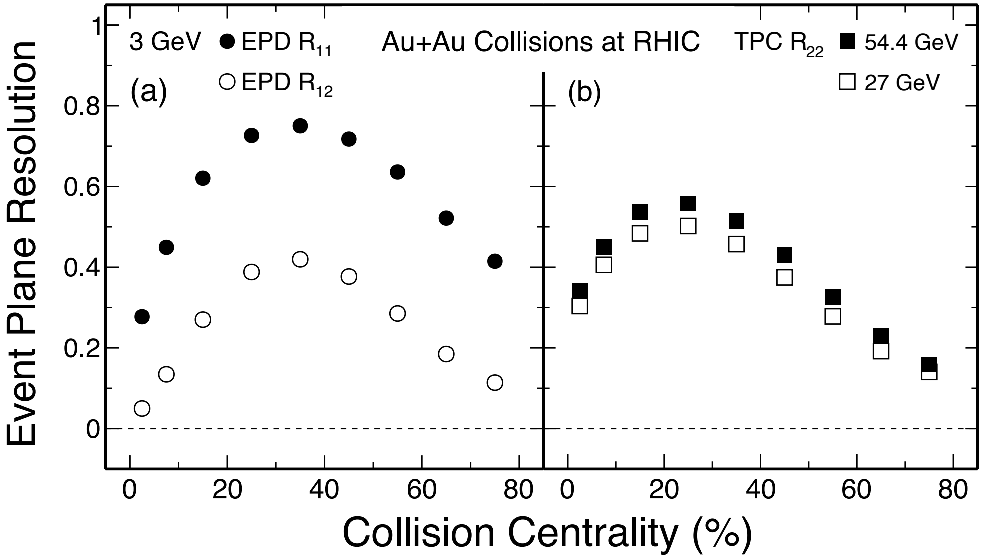


- Higher statistics, better detector performance and more energy points in BES-II
- Explore the QCD phase diagram

Stay tuned for more new results!

Event Plane Determination



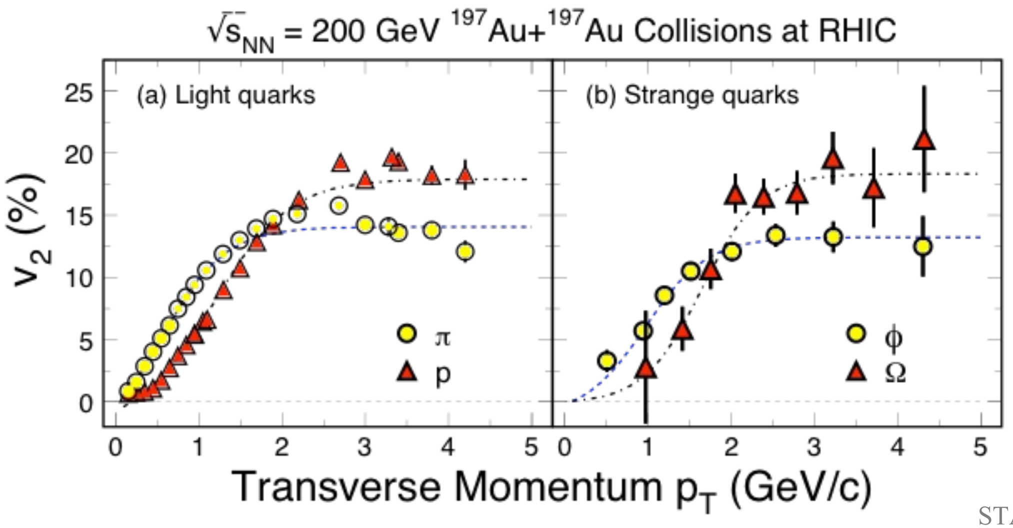


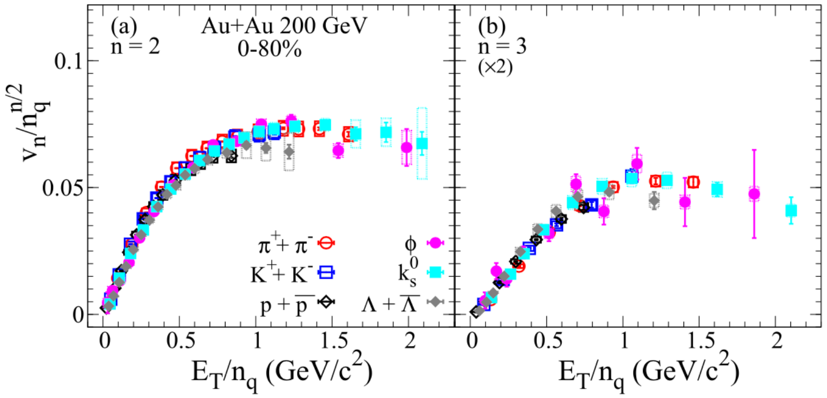
A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998)

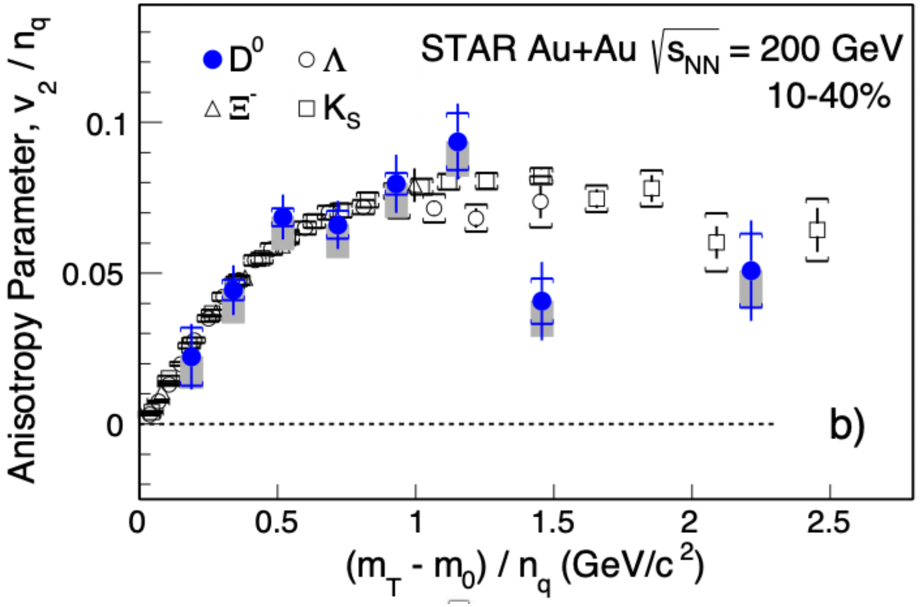
- TPC 2nd order event plane
  - EP resolution (R_{22}) is calculated by two sub-event method

- The 1st order event plane from east side EPD at 3 GeV
  - The 1st order EP resolution (R_{11}) is calculated by three sub-event method
  - R_{12} is for v_2 measurement

RHIC Top Energy

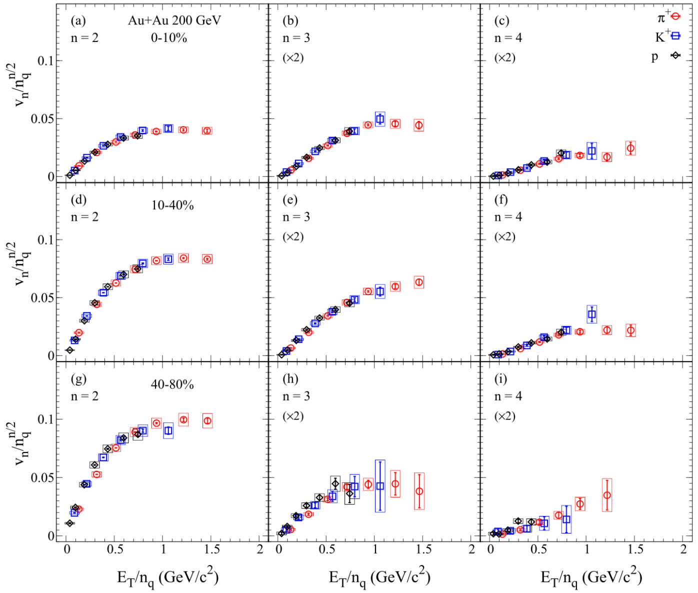






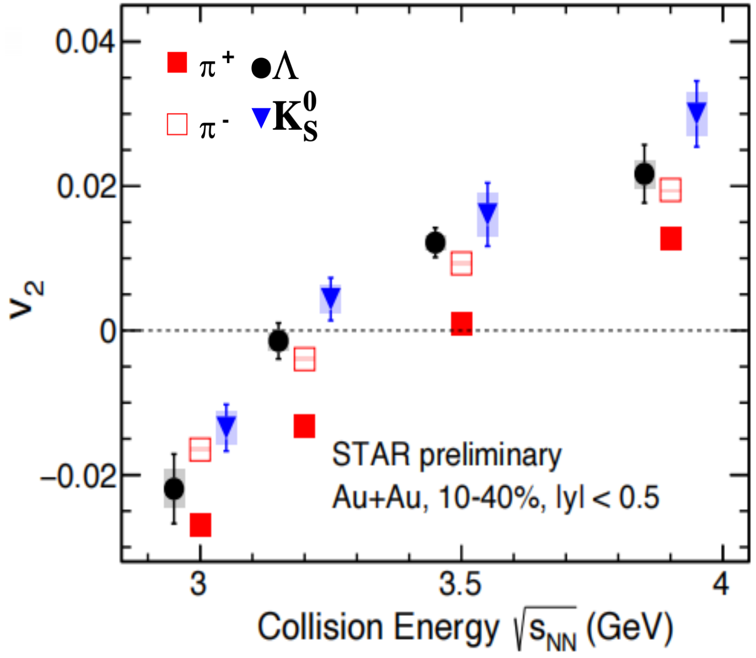
STAR:
Phys. Rev. Lett.116, 062301 (2016)
Phys. Rev. Lett.118, 212301 (2017)
Phys. Rev. C.105, 064911 (2022)

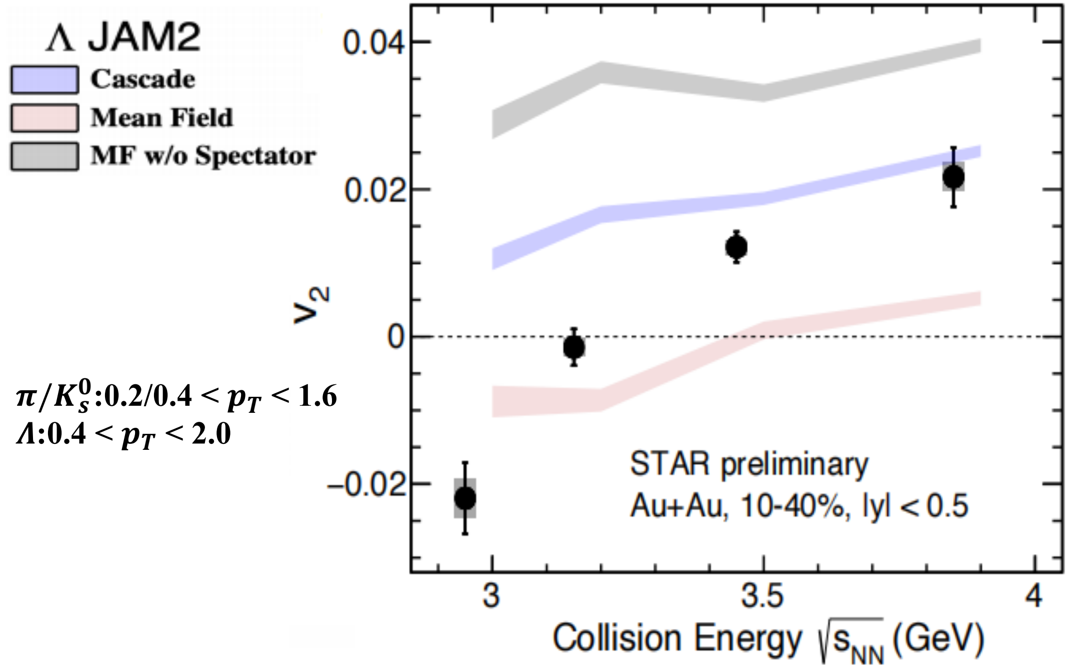
- **Light, strange and charm flow**
- **NCQ scaling up to v_4**

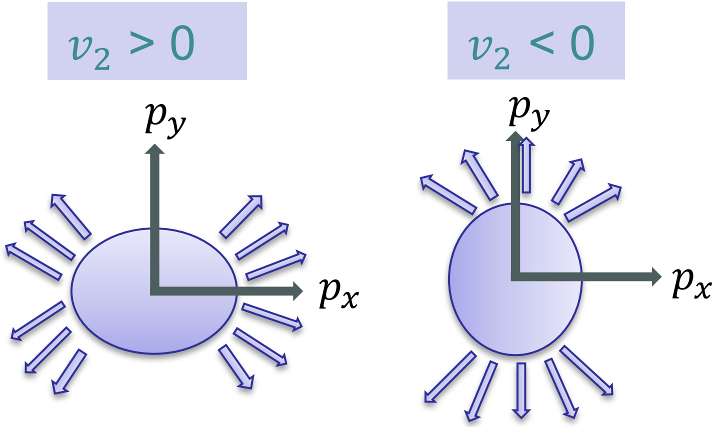


Partonic collectivity

Energy Dependence of v_2







In-Plane expansion   Out-of-Plane expansion

- Negative v_2 of all particles goes to positive value from 3 GeV to 3.9 GeV
- Squeeze-out effect from spectator result in sign change of v_2
- JAM2 calculations of mean-field with spectator reproduce sign change of v_2