Onset of Constituent Quark Number Scaling in Heavy-Ion Collisions at RHIC

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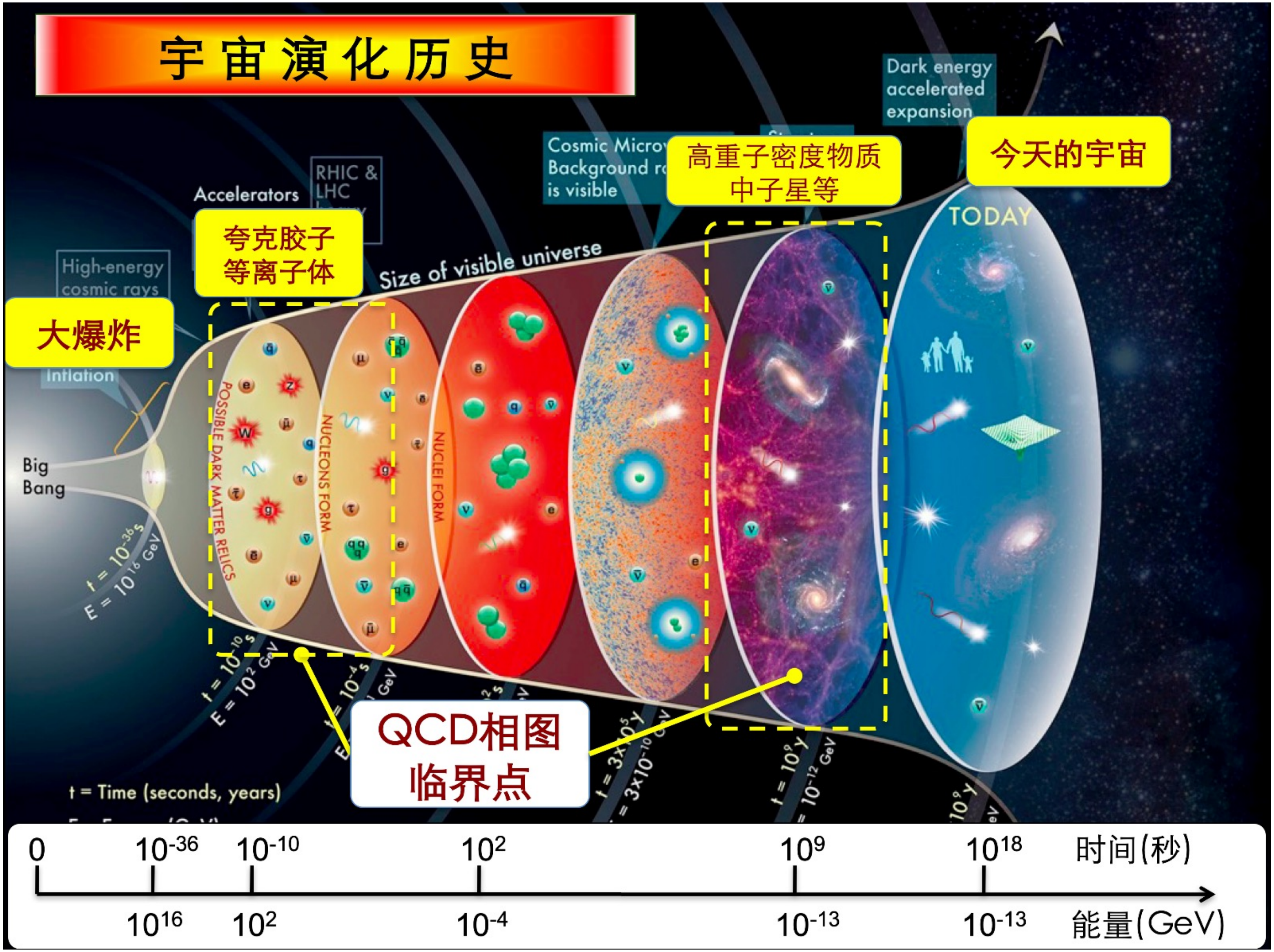
Outline

- Heavy-ion Collisions
- STAR Experiment
- Results and Discussions
- Summary

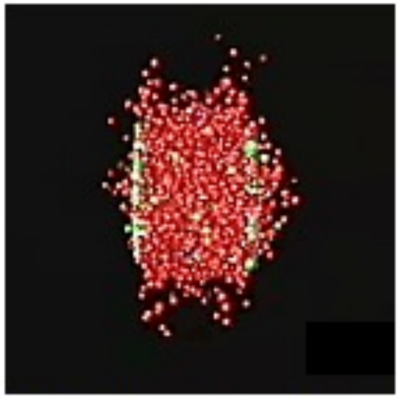
The Evolution of Universe



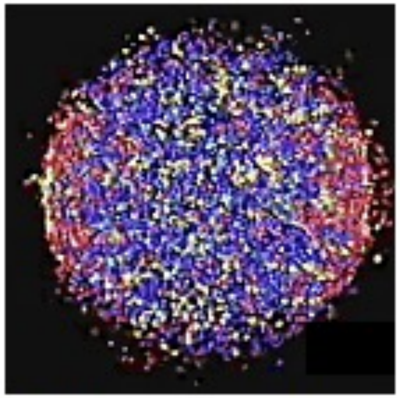
Why Heavy-ion Collisions

1. Ions about to collide*

2. Ion collision



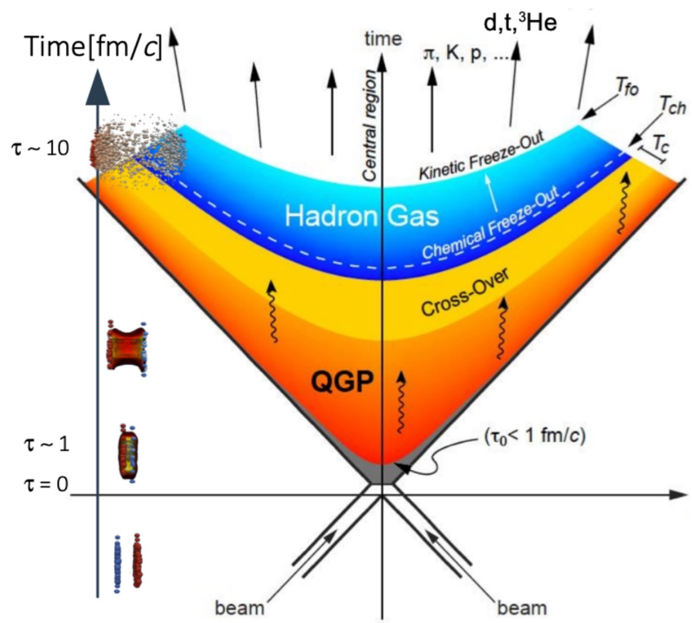
3. Quarks, gluons freed

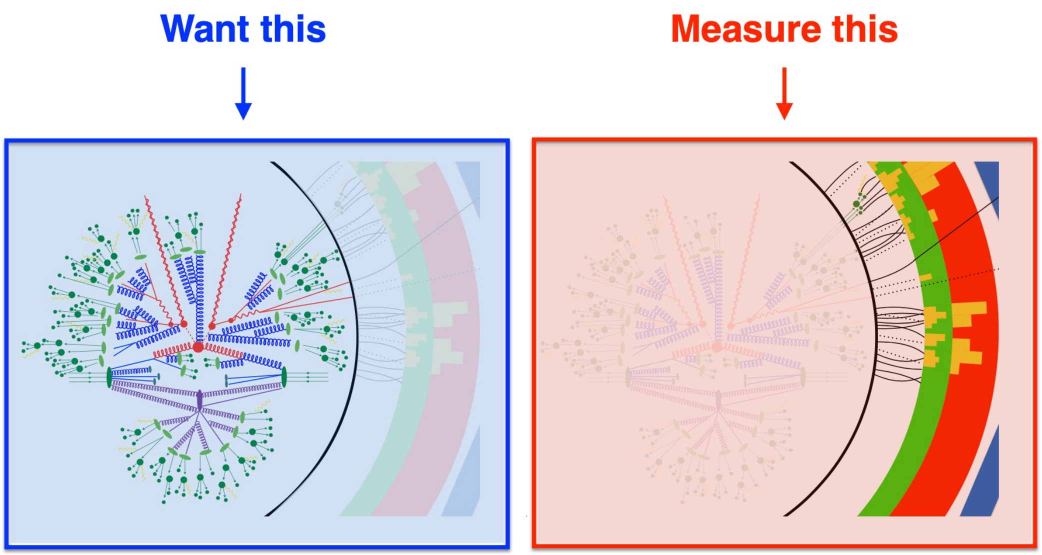


4. Plasma created

If conditions are right, the collision "melts" the protons and neutrons and, for a brief instant, liberates their constituent quarks and gluons. Just after the collision, thousands more particles form as the area cools off. Each of these particles provides a clue as to what occurred inside the collision zone. Physicists sift through those clues for interesting information.

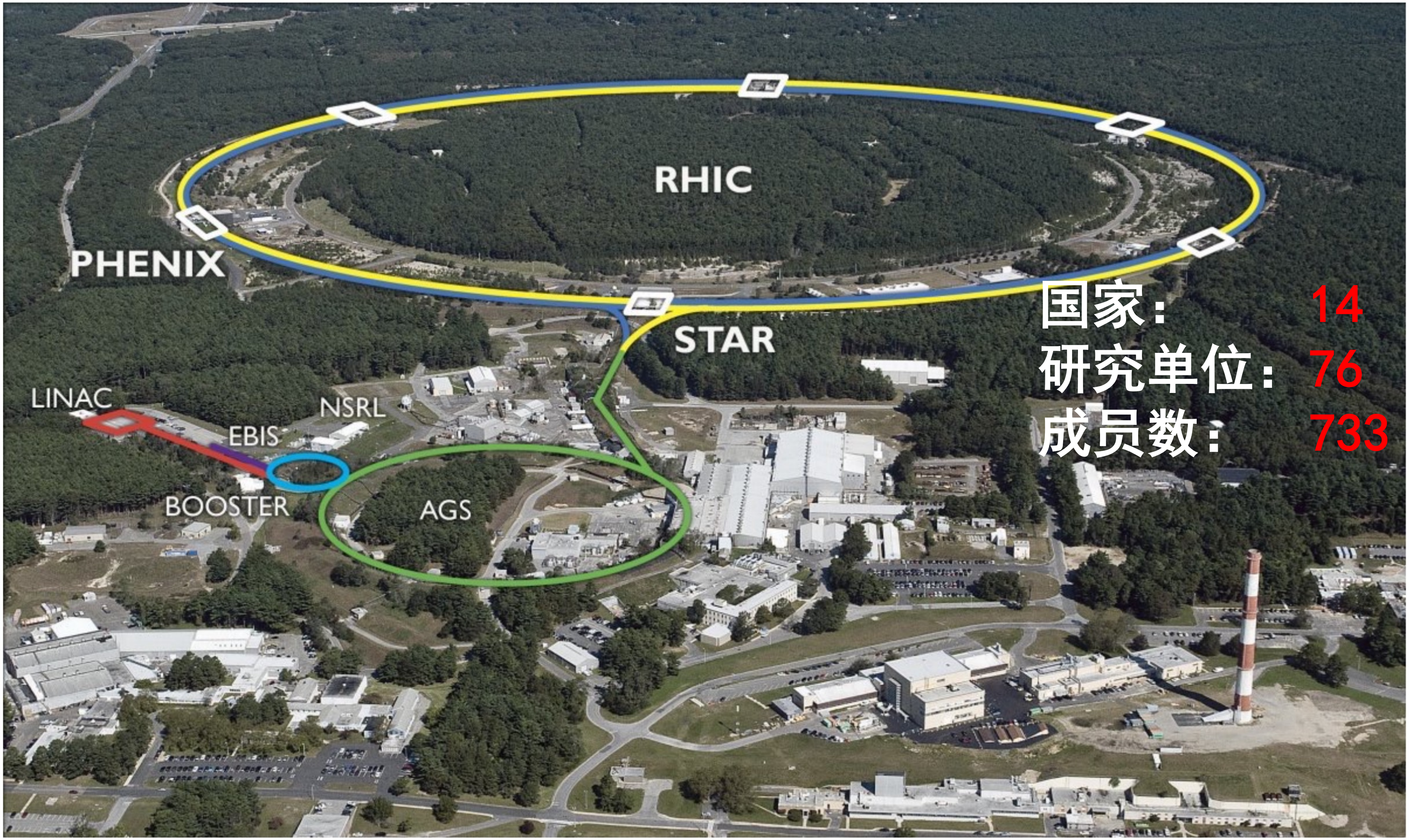
HIC: Time Evolution





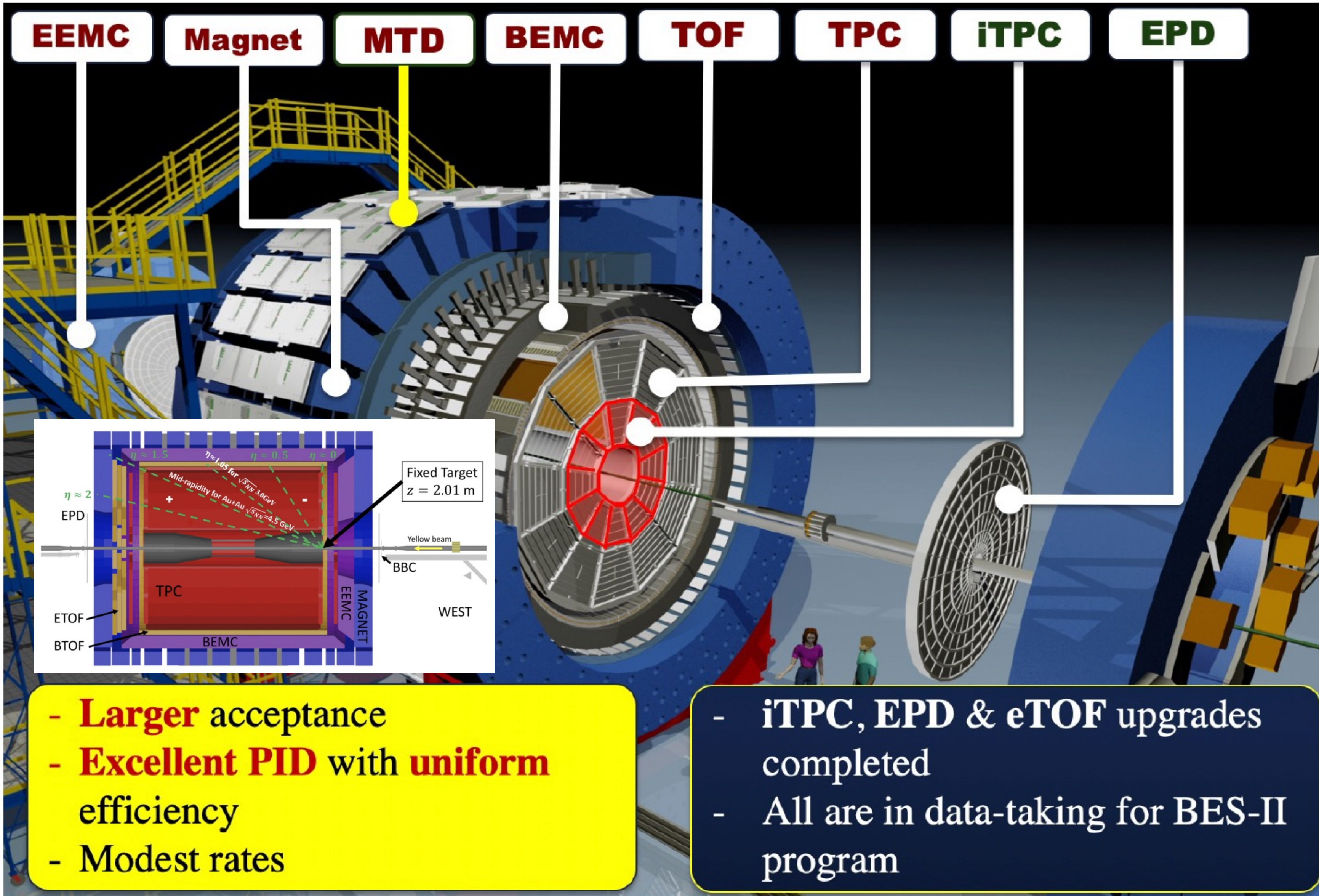
- Chemical freeze-out: Inelastic collisions cease, the chemical composition of particle yield get fixed
- Kinetic freeze-out: Elastic collisions cease, particle momentum distribution get fixed
- Decode the kinematics information of the QCD matter

RHIC-STAR



Heavy ion collisions: 3 - 200 GeV

Experimental Setup

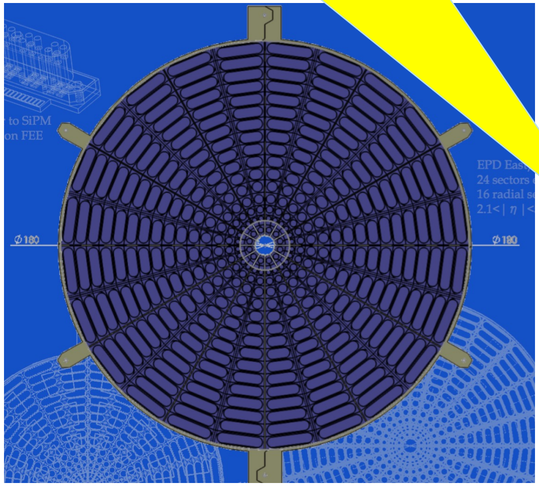


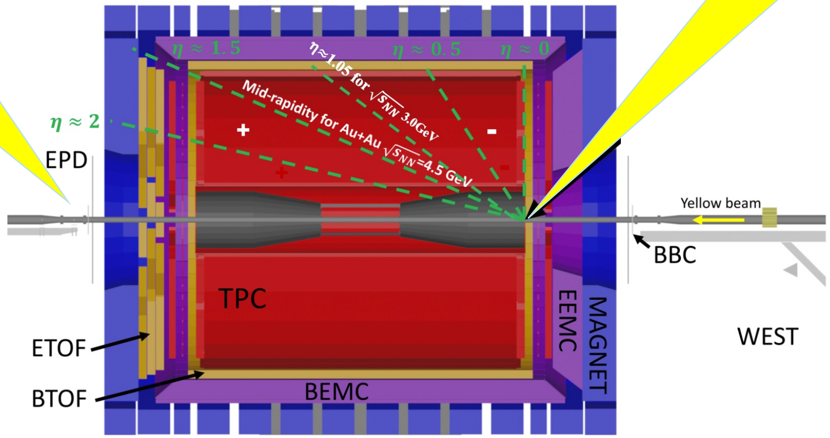
- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

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

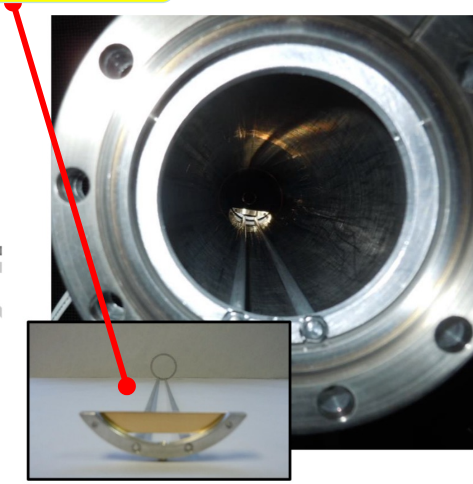
STAR Fixed Target Setup

Event Plane Detector (EPD)





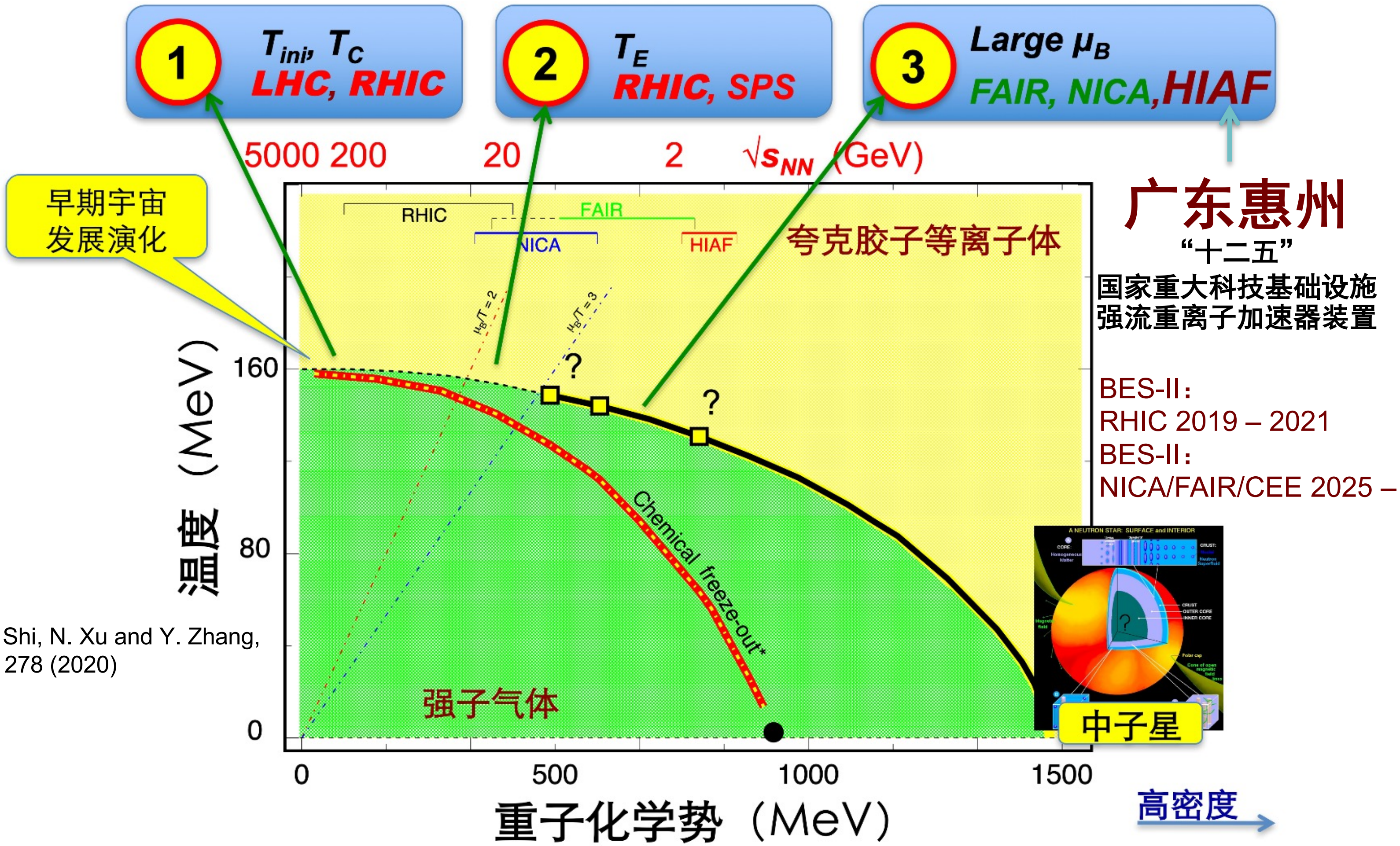
Au Target



➢ **Good mid-rapidity coverage for FXT 3 GeV collisions**

Conventions: beam-going direction is the positive rapidity direction (Yellow beam)

QCD Phase Diagram

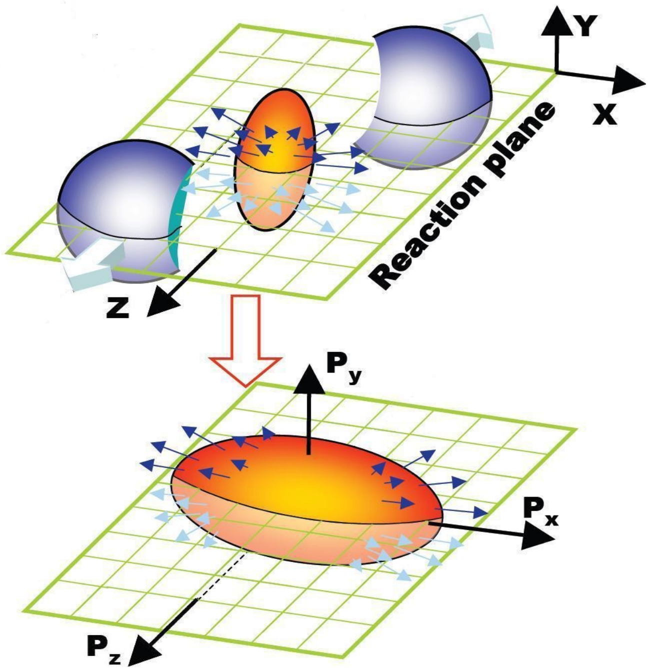


X. Luo, S. Shi, N. Xu and Y. Zhang, Particle 3, 278 (2020)

Experimental Studies on the QCD Phase Structure

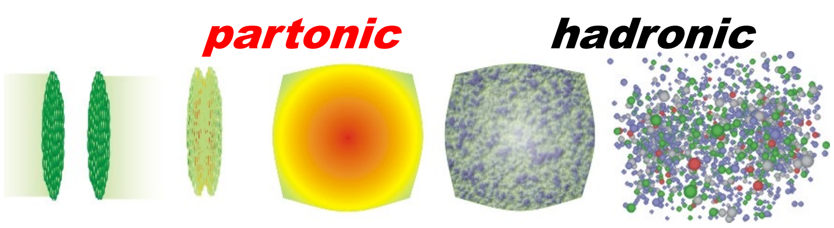
- Low Baryon Density (High energy): **The properties of QGP**
- High Baryon Density (BES)：**QCD Phase transition signals**

Anisotropic Flow



$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]$$

v_1: directed flow; v_2: elliptic flow;
v_3: triangular flow



D_s, Λ_c, D ϕ, Ω, Ξ Λ π, K, p

- **Anisotropic flow**:
  Sensitive to the early stage of the collision
- **Heavy flavor flow**
  Study medium properties from motion of heavy quarks in medium
- **Multi-strange hadrons and ϕ meson**:
  Less sensitive to late hadronic rescatterings

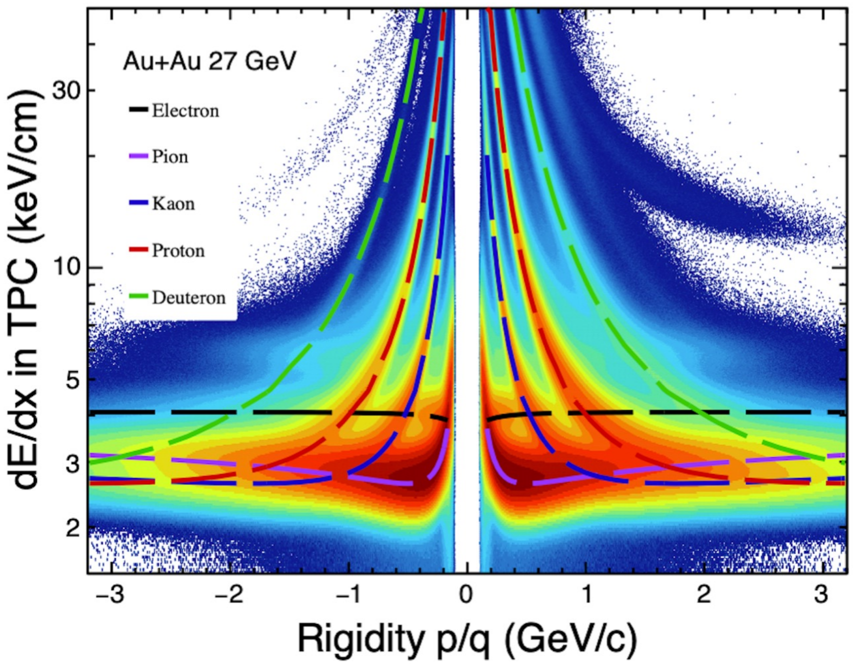
STAR Dataset

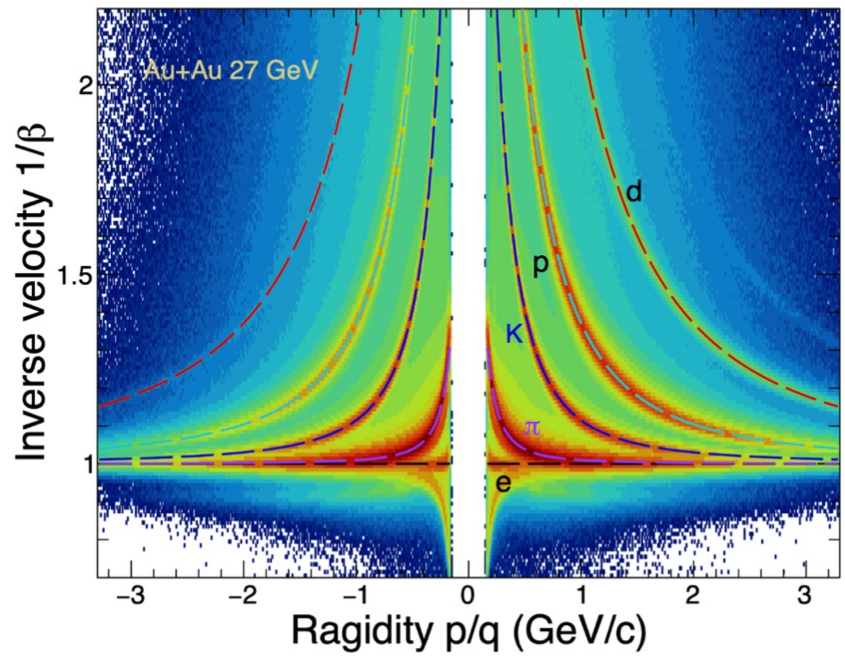
Au+Au Collisions at RHIC											
Collider Runs						**Fixed-Target Runs**					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50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

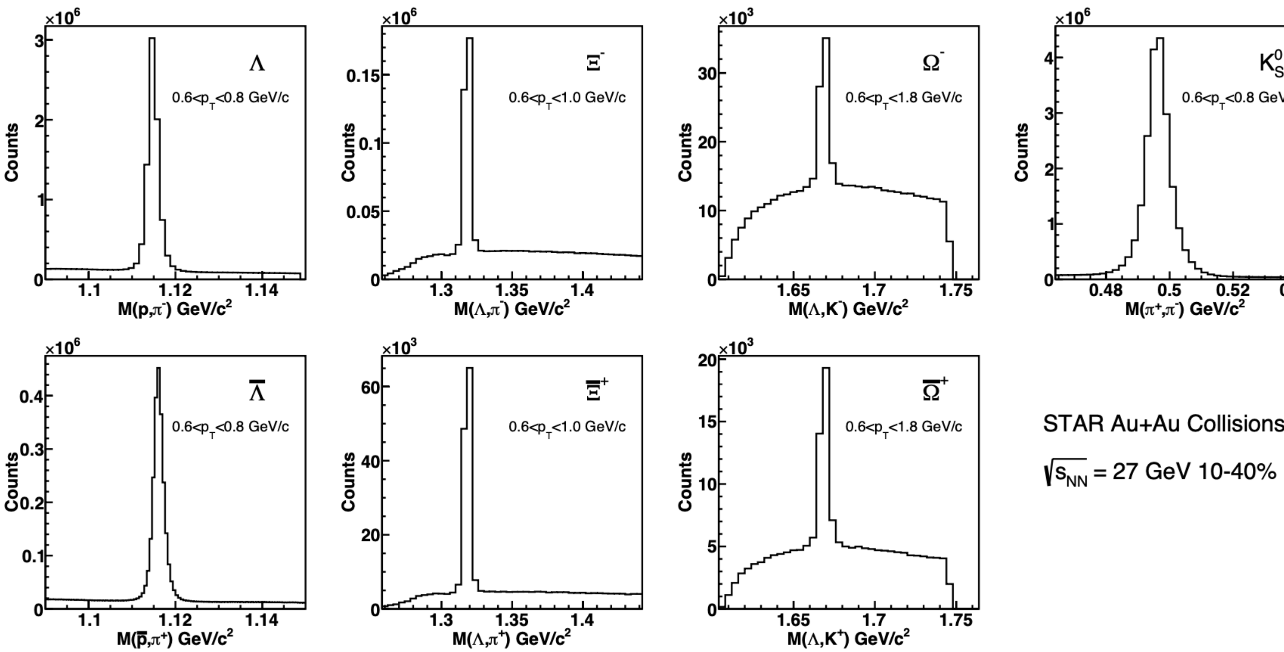
Particle Identification

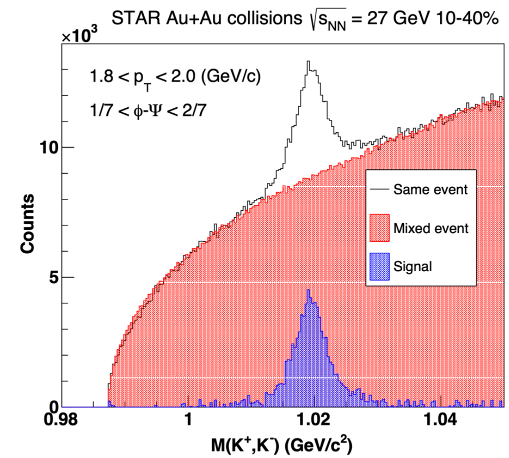




- ➢ Good capability of particle identification (PID) with TPC and TOF
- ➢ Extend the phase space coverage by TOF

Short Lived Particles

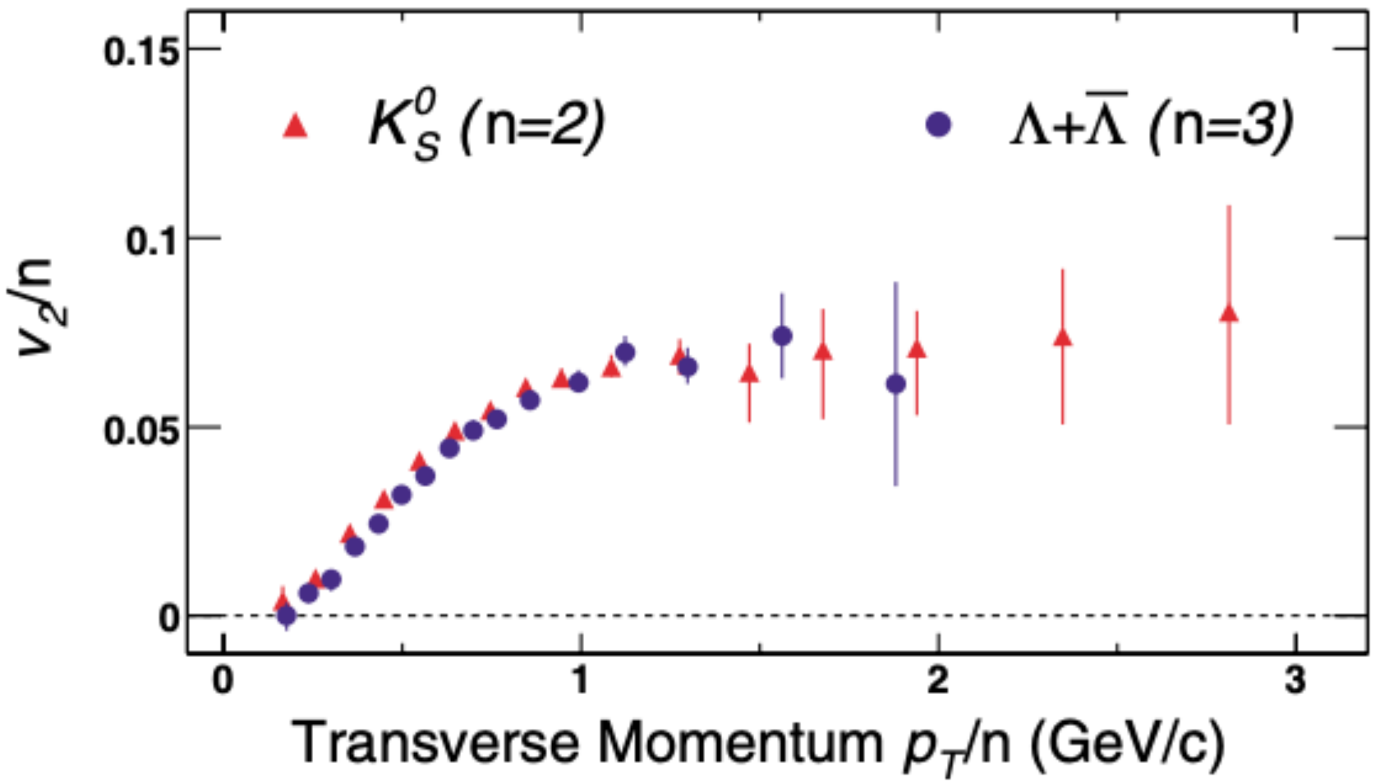




- The weak decay particles ($K_S^0, \Lambda, \Xi, \Omega$) are through their hadronic decay channel
  - The additional optimized decay topology cuts can effectively suppress the background
- ϕ-mesons are reconstructed in K^+K^- channel with primary tracks
  - Background is obtained by using mixed event

The 21-year journey of v_2 NCQ scaling 2004 - 2025

NCQ Scaling



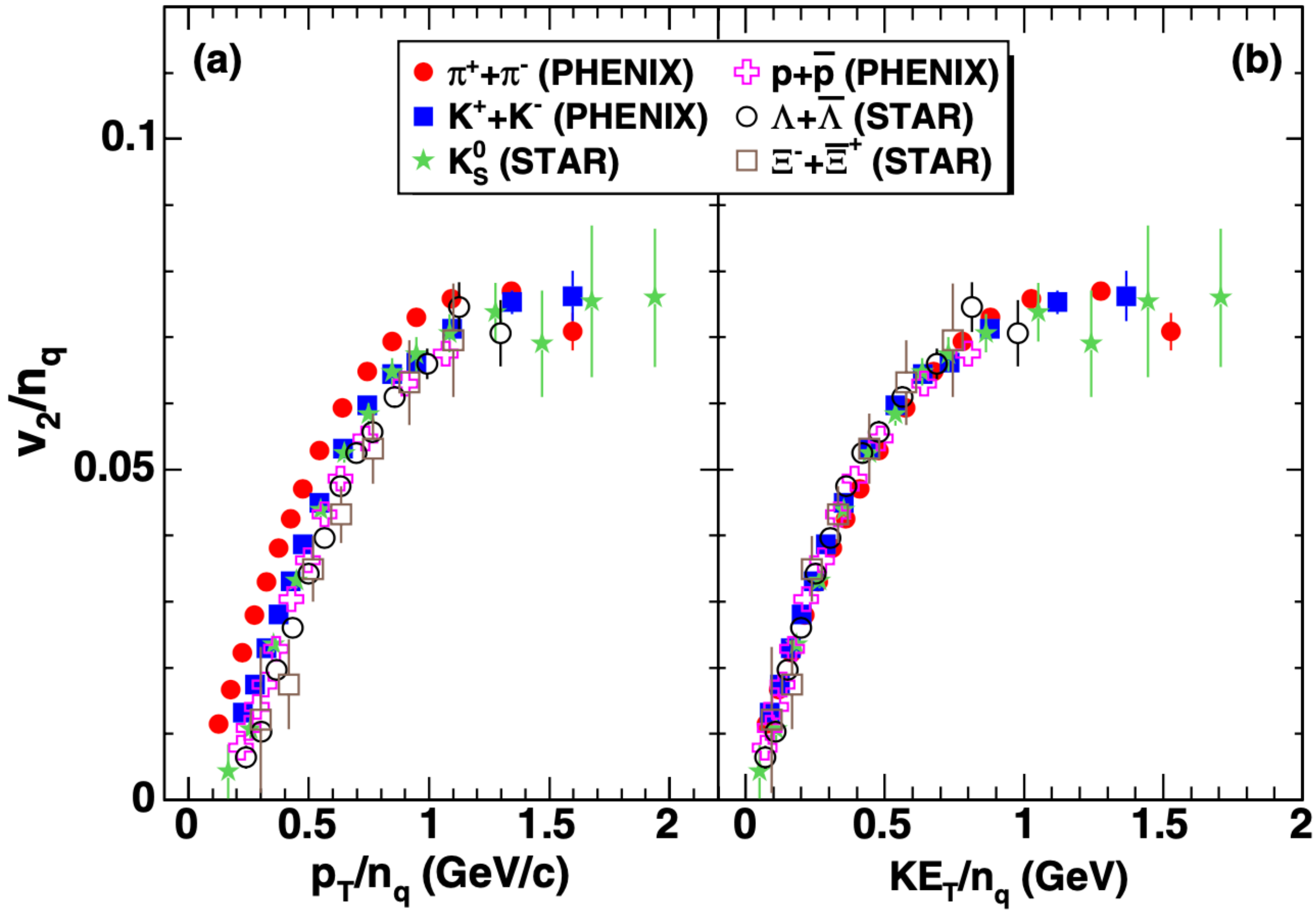
Paul Sorensen, Hui Long, Ben Norman, Jinghua Fu (CCNU), Huan Huang, Nu Xu, Matt Lamont, STAR

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

1.6 M minimum bias events

First observation on v_2 NCQ scaling

NCQ Scaling: STAR and PHENIX

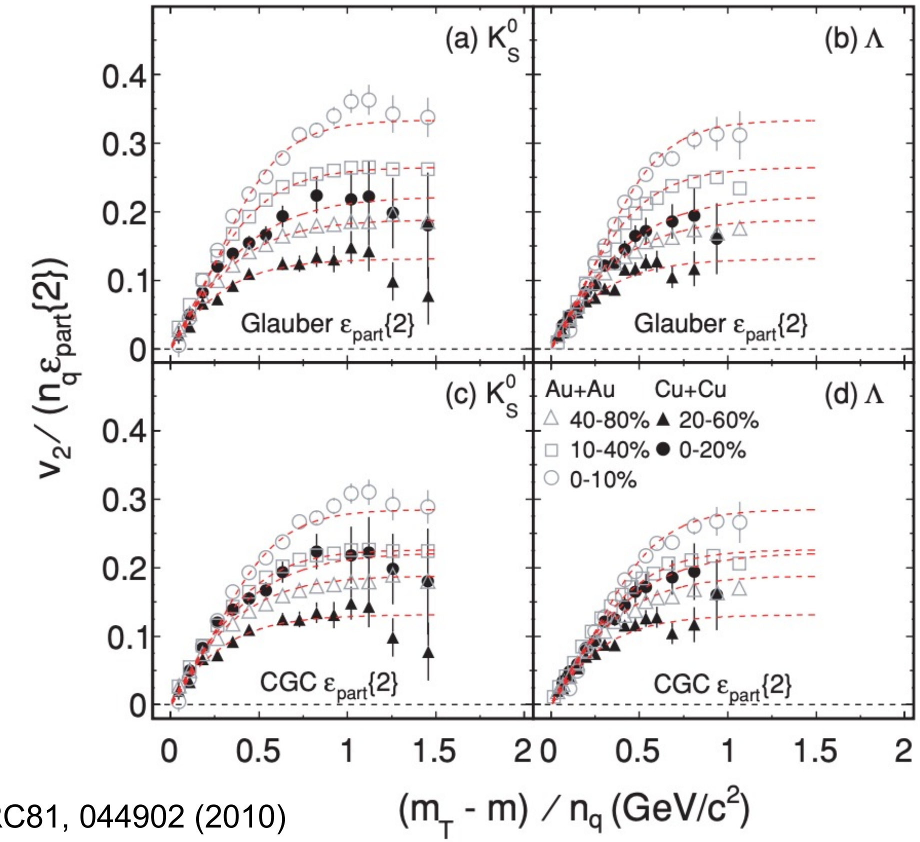


PHENIX, Phys. Rev. Lett. 98, 162301 (2007)

- Au+Au 200 GeV: two RHIC experiments STAR and PHENIX

NCQ Scaling: System Size

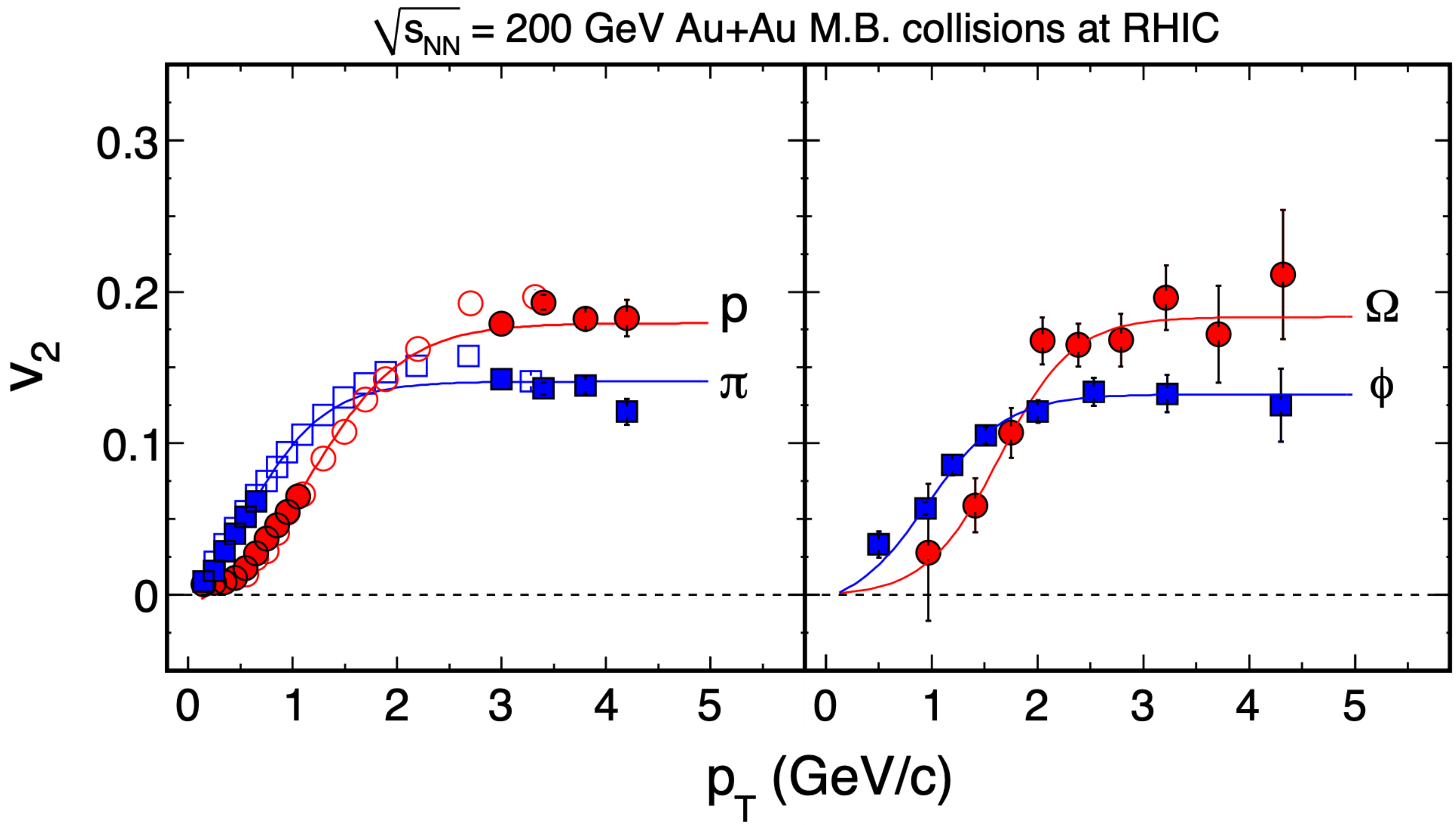
200 GeV collisions: Au+Au and Cu+Cu



STAR, PRC81, 044902 (2010)

- Divided by eccentricity: remove the initial geometry
- Stronger collectivity observed in collisions with larger N_{part}

STAR Run 2007

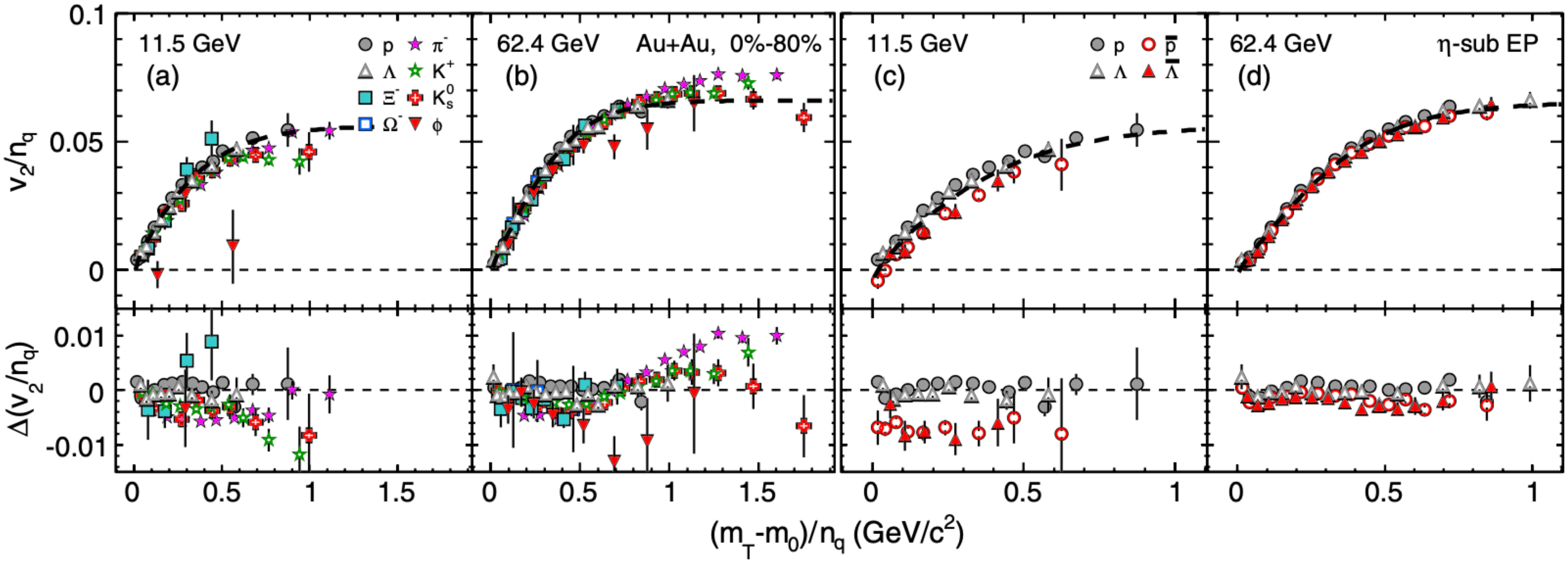


66 M minimum bias events
QM 2009, Shusu Shi for STAR and PhD thesis

First evidence: Ω baryon follows NCQ scaling

STAR Run 2010 and 2011

BES-I



STAR, Phys. Rev. Lett. 110, 142301 (2013)

SQM 2011, Shusu Shi for STAR:
https://cerncourier.com/a/strangeness-and-heavy-flavours-in-

Using the Beam Energy Scan at RHIC, the STAR collaboration has progressed significantly with tackling the evolution of the collective effects observed in heavy-ion (Au–Au) collisions between $\sqrt{s_{NN}}$=7.7 GeV and 62.4 GeV, as Shusu Shi of Central China Normal University showed. While studying the excitation function of the second harmonic v_2 in the azimuthal distribution of particle (π, K, p and Λ) production, the collaboration identified a significant difference in the behaviour of particles and antiparticles for 0–80% central Au–Au reactions (figure 2). The increasing deviation in v_2 between particles and antiparticles, observed with decreasing $\sqrt{s_{NN}}$, is more pronounced for baryons, such as protons and Λs, than for mesons (charged π and K). However, it must be noted that above 39 GeV, the difference in v_2 between particles and antiparticles remains almost constant to higher energies at about 5–10%. The

STAR Run 2010 and 2011

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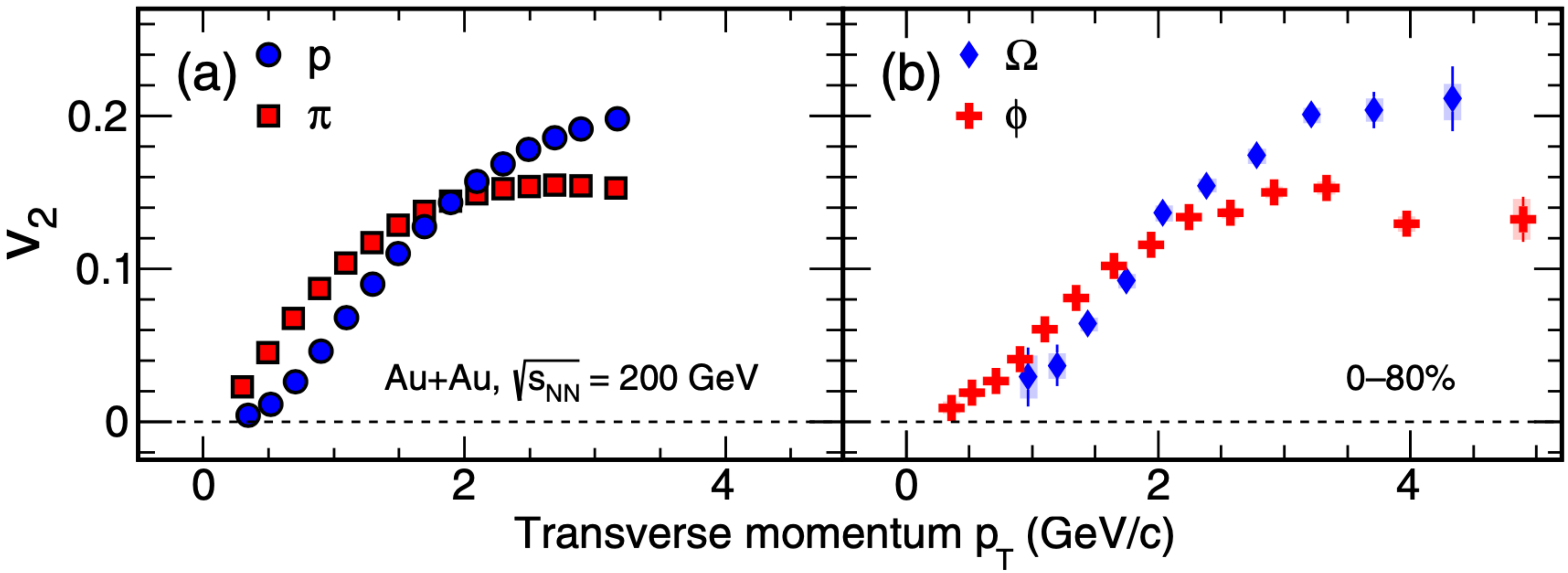
STAR, Phys. Rev. Lett. 116, 062301 (2016)

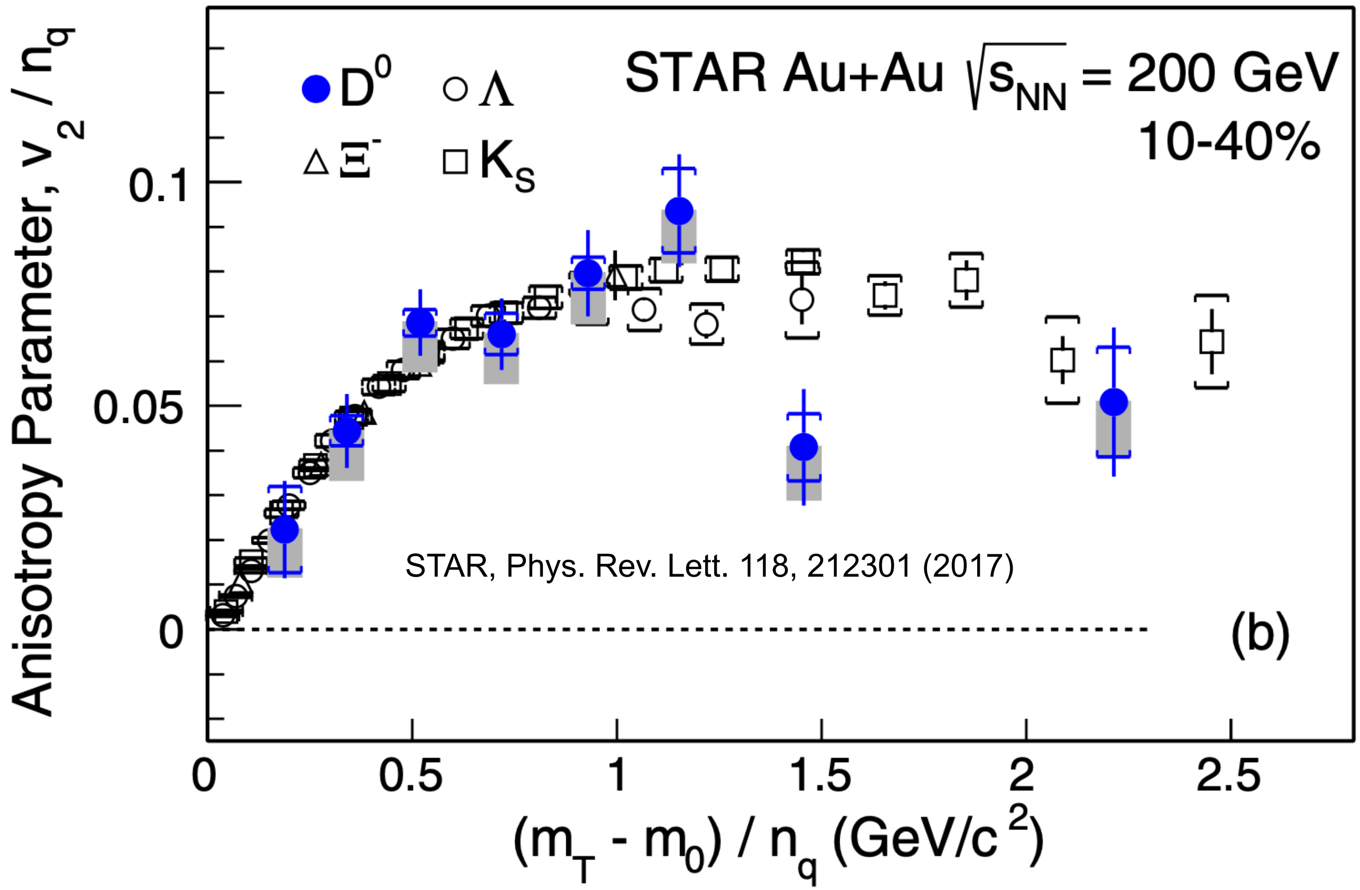


730 M minimum bias events

Partonic collectivity

u, d and s quarks

STAR Run 2014

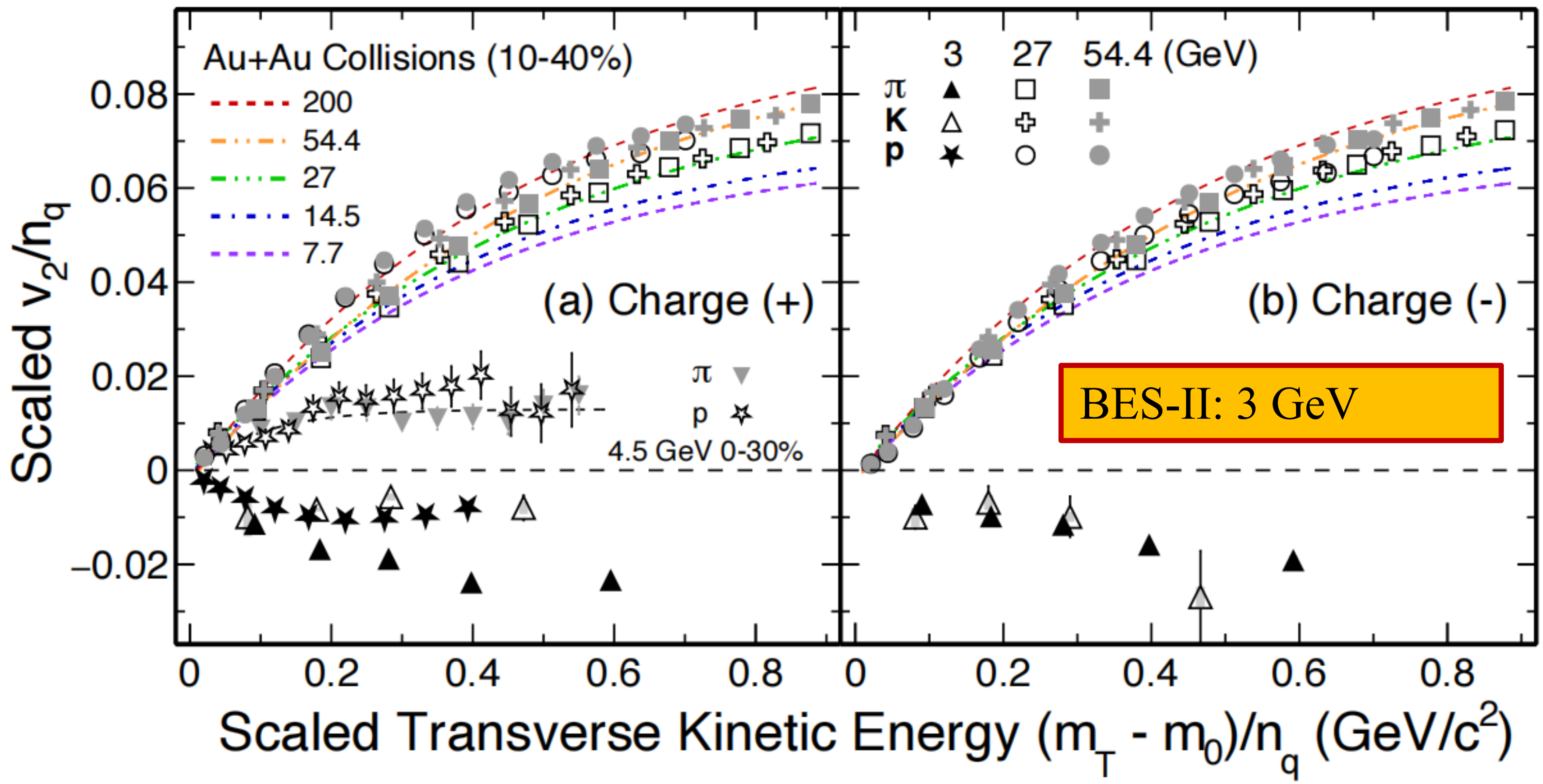


1100 M minimum bias events with Heavy Flavor Tracker

Partonic collectivity

light (u, d and s) quarks to charm quarks

Disappearance of NCQ Scaling



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

- 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

p_T Dependence of v_2 at 3 - 4.5 GeV

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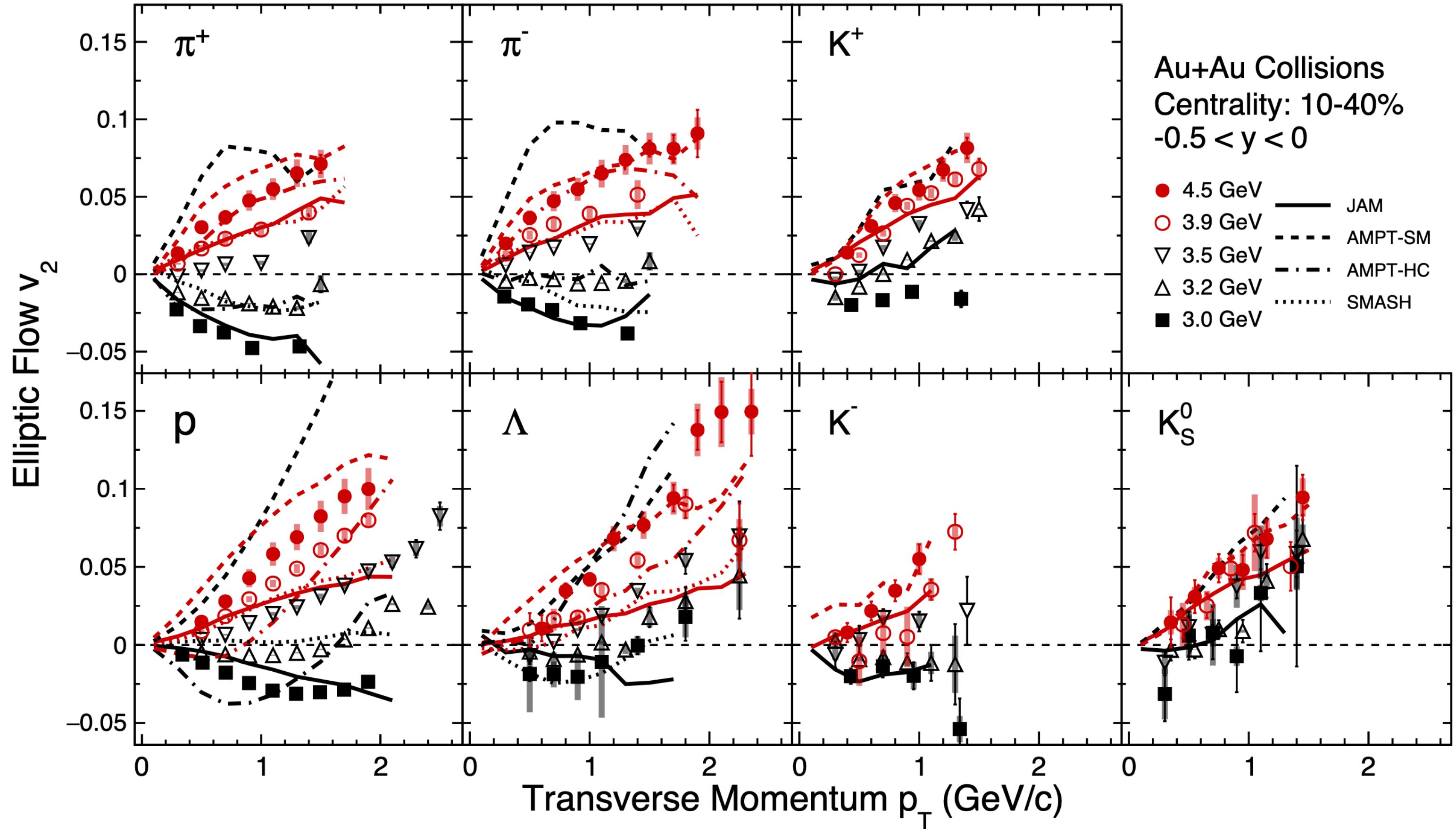
STAR, Phys. Rev. Lett. 135, 072301 (2025)

BES-II



- 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

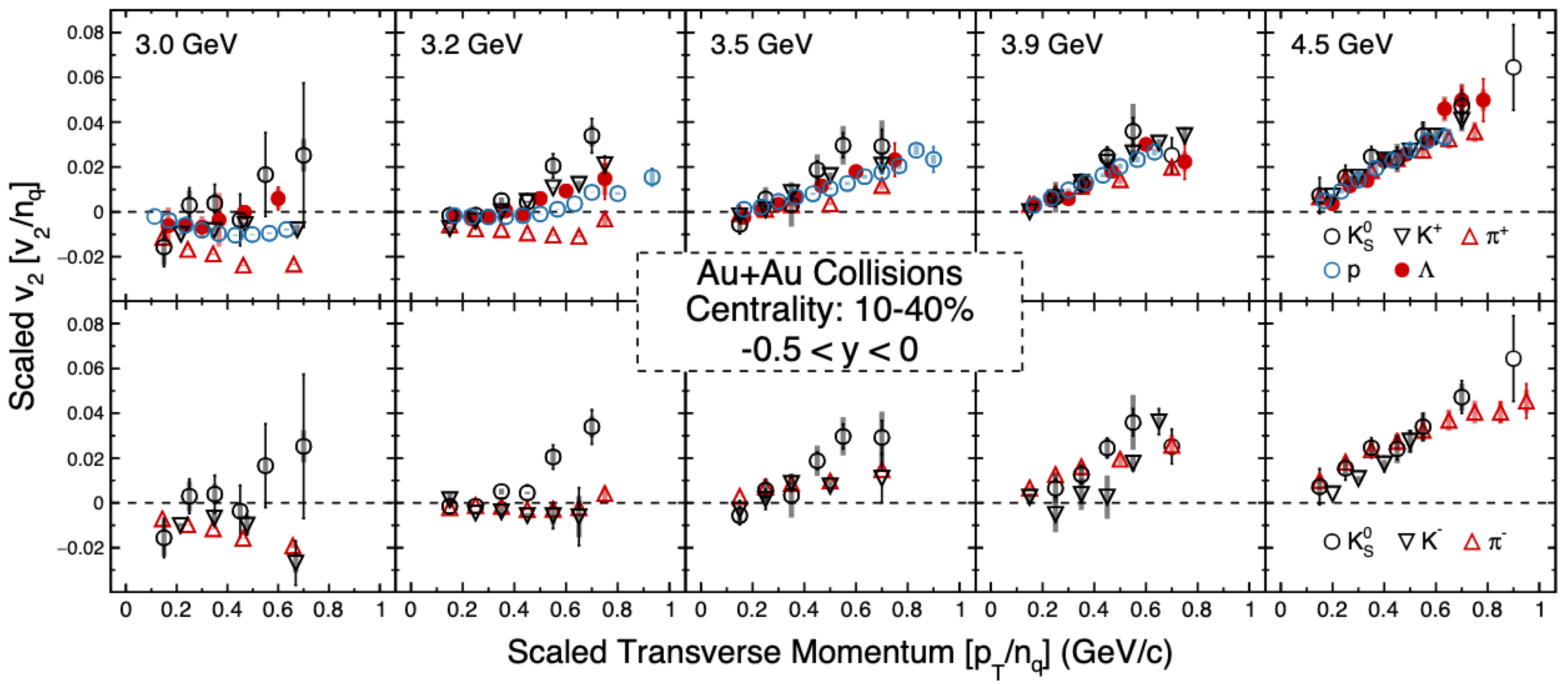
Baryonic Mean Field: p dependent Soft EoS, the nuclear incompressibility K = 210 MeV

NCQ scaling of v_2 at 3 - 4.5 GeV

STAR, Phys. Rev. Lett. 135, 072301 (2025)

Hadronic interaction

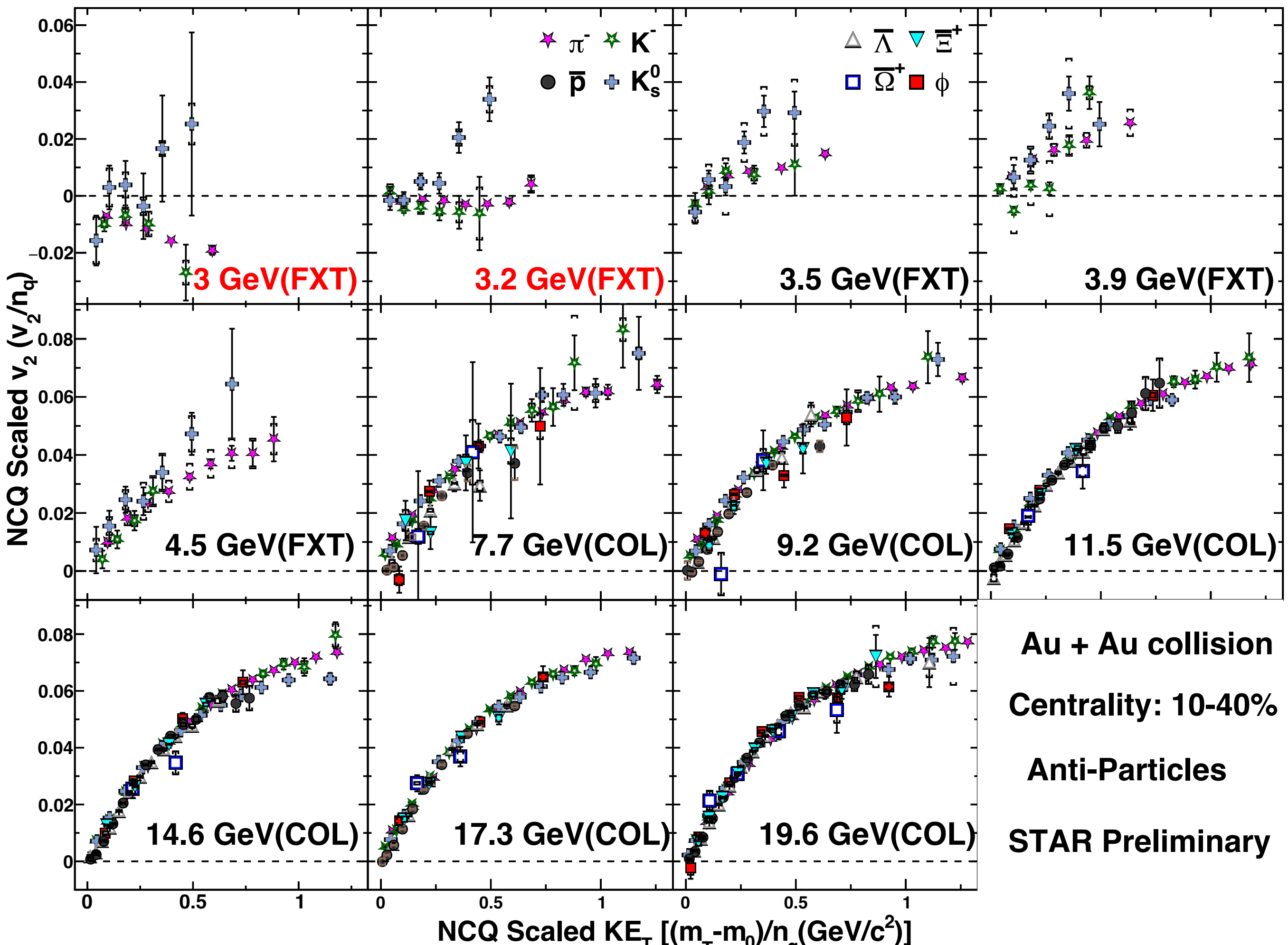
Partonic collectivity



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

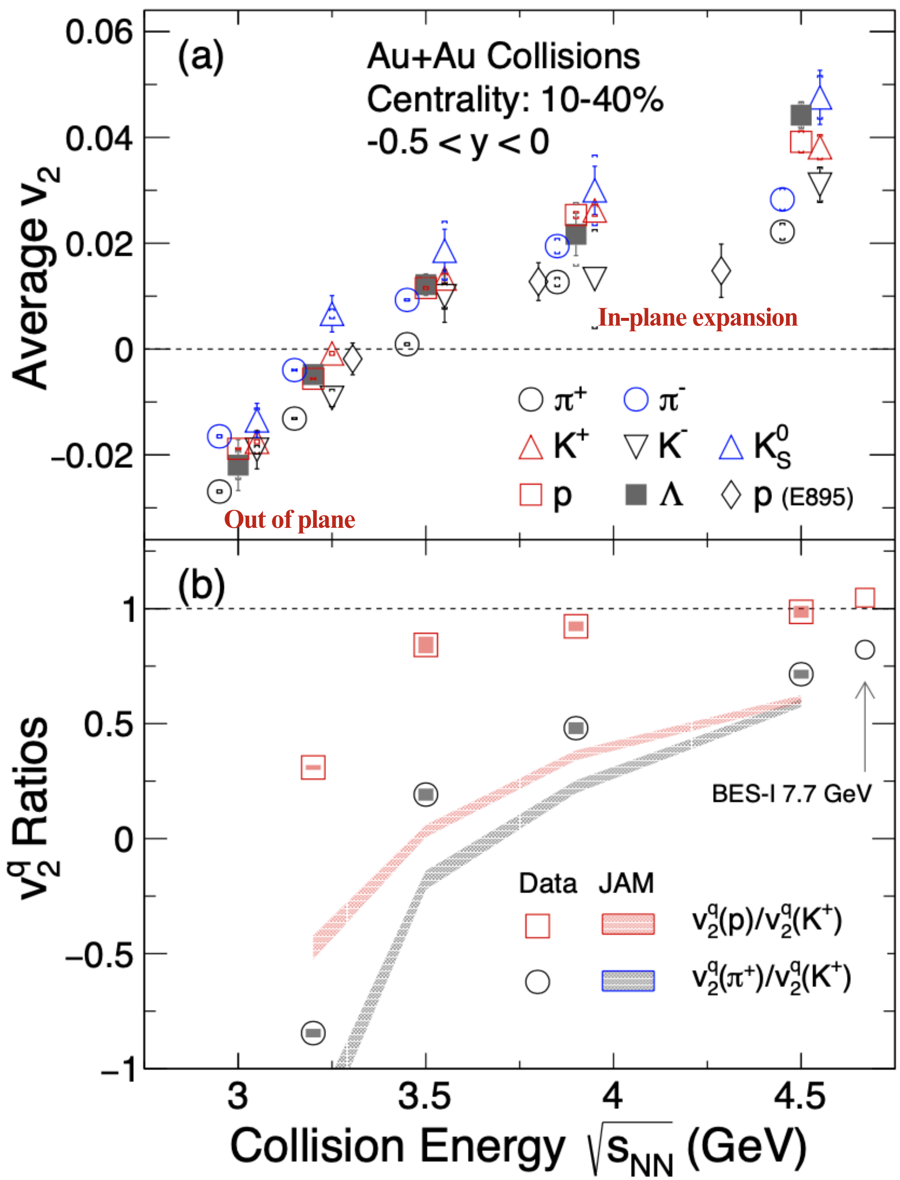
Onset of NCQ Scaling

STAR, Phys. Rev. Lett. 135, 072301 (2025), QM2025



Multi-strange and ϕ meson v_2: partonic collectivity in 7.7 – 19.6 GeV

Energy dependence of $<v_2>$



STAR, Phys. Rev. Lett. 135, 072301 (2025)

- ➢Negative to positive flow: 3 to 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

- **Top 200 GeV Collisions**
  - Partonic collectivity: *light flavor to charm*

- **Beam Energy Scan**
  - Onset of NCQ scaling: *3.2 to 4.5 GeV*
  - Multi-strange and ϕ v_n: *Partonic vs. hadronic*

Collective flow is a powerful tool for studying the nuclear matter created in HIC

Thank you!