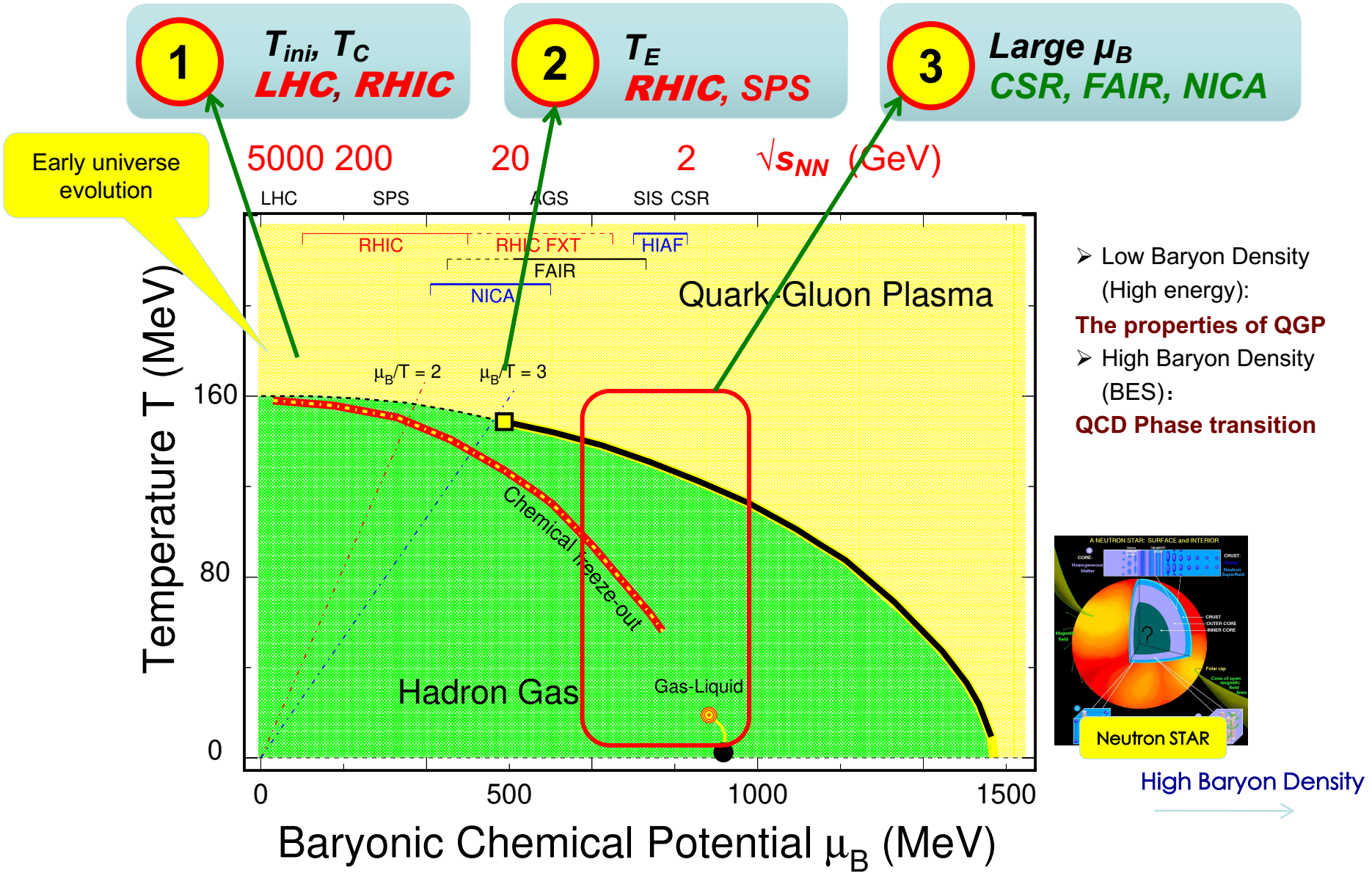
高重子密度区核物理相结构的实验研究

施梳苏

华中师范大学

极端核物质前沿研讨会，2026年4月24-28日

QCD Phase Diagram



- Low Baryon Density (High energy):

The properties of QGP

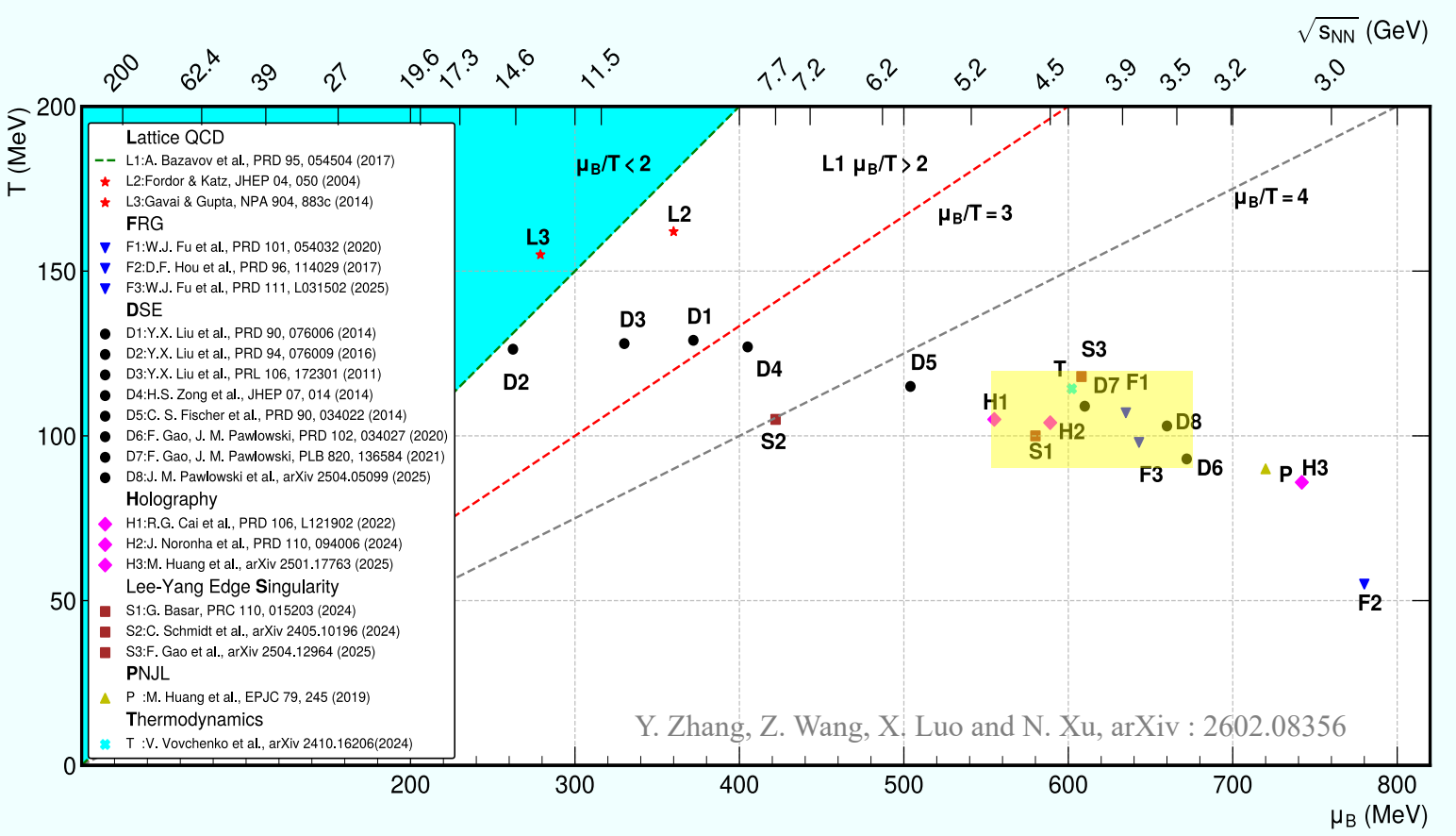
- High Baryon Density (BES):

QCD Phase transition

High Baryon Density

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

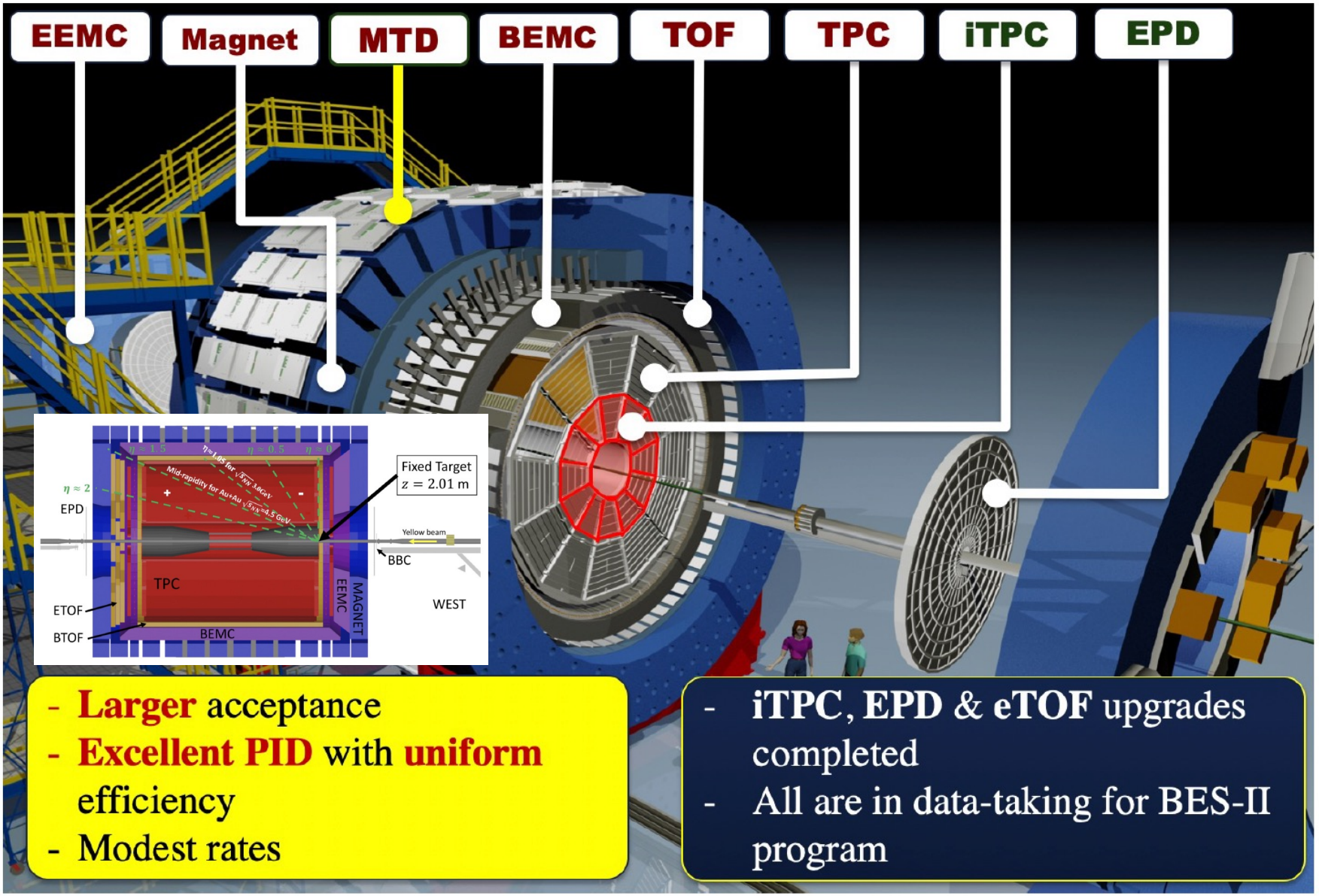
CP Estimation



μ_B^{CEP}: ~ **550 – 700 MeV**
T^{CEP}: ~ **90 – 118 MeV**

High Baryon Density Region

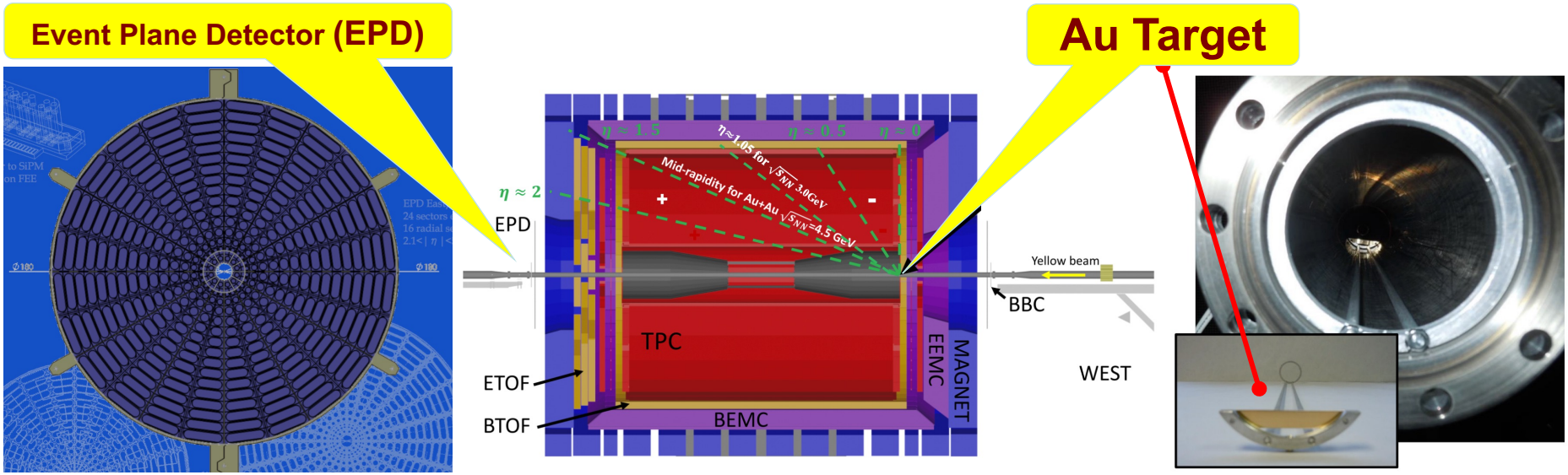
Experimental Setup



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

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

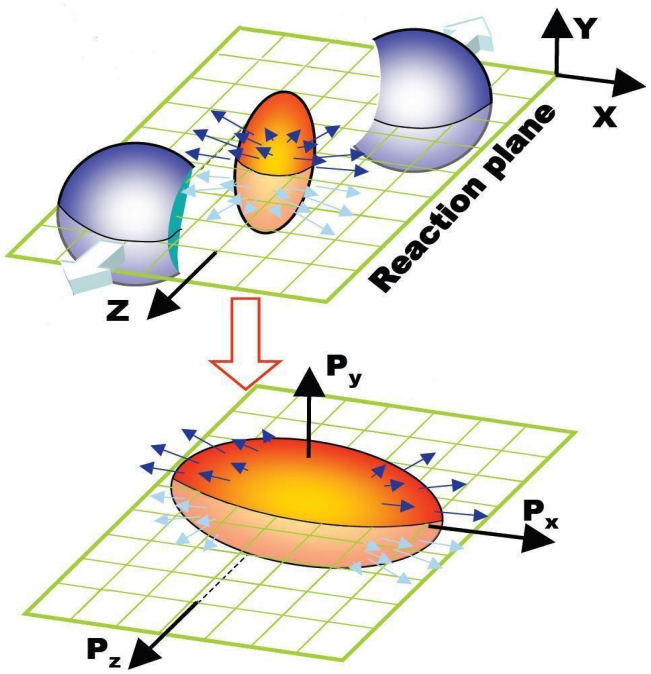
STAR Fixed Target Setup



➢ Good mid-rapidity coverage for FXT 3 – 4.5 GeV collisions

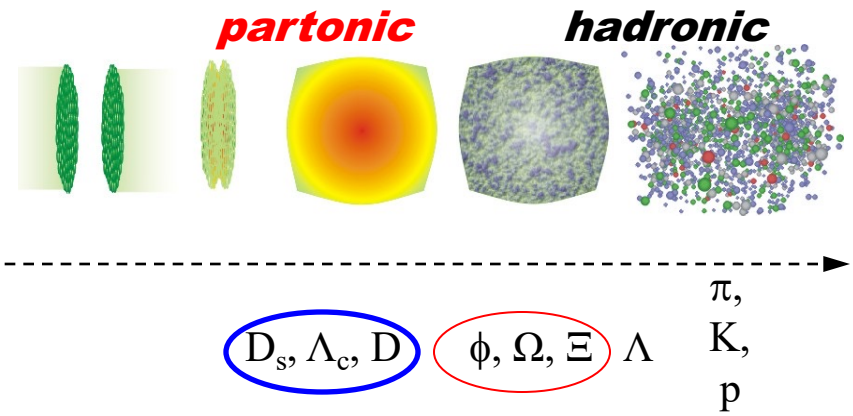
Conventions: beam-going direction is the positive rapidity direction (Yellow beam)

Collective Flow



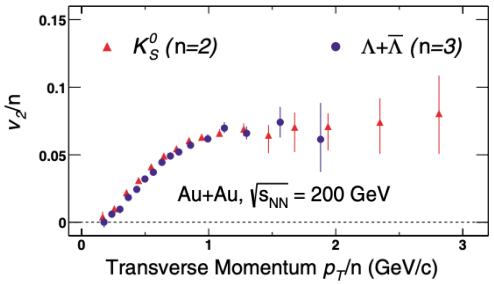
$$\frac{d^2N}{d\phi dp_T} = N(p_T)\,(1 + 2\sum_{n\geq 1} v_n \cos(n(\phi - \psi_n))$$

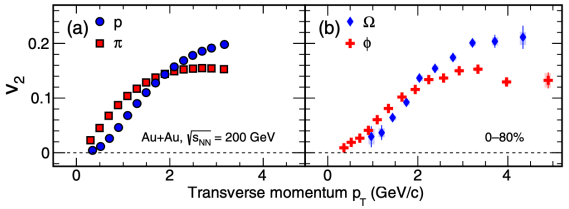
v_0: radial flow; v_1: directed flow;
v_2: elliptic flow; v_3: triangular flow
……

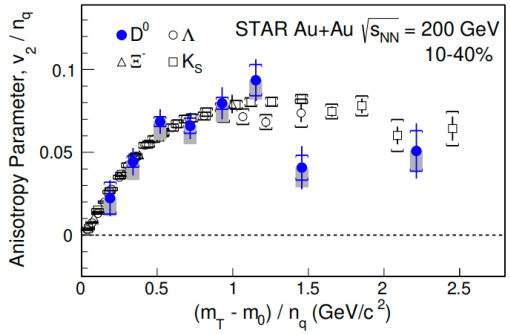


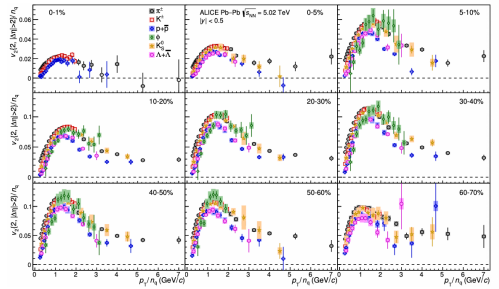
- **Anisotropic flow**:
  Sensitive to the early stage of the collision
- **Heavy flavor flow**
  Study medium properties from motion of heavy quarks in medium
- **Multi-strange hadrons and ϕ meson**:
  Less sensitive to late hadronic rescatterings

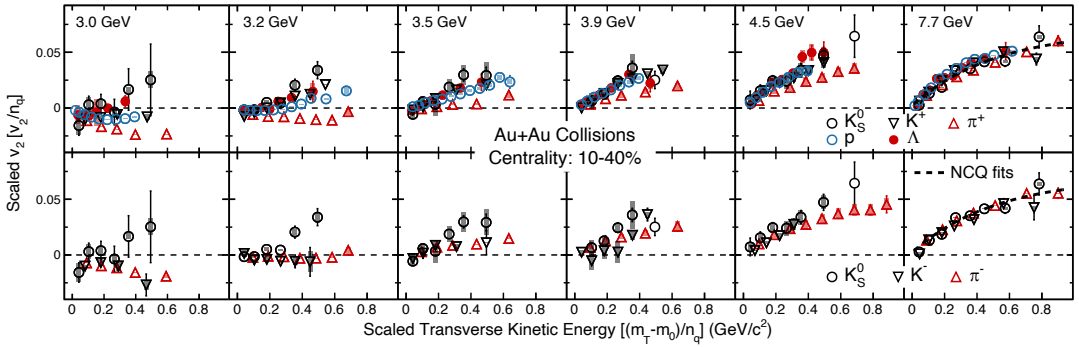
Onset of v_2 NCQ scaling









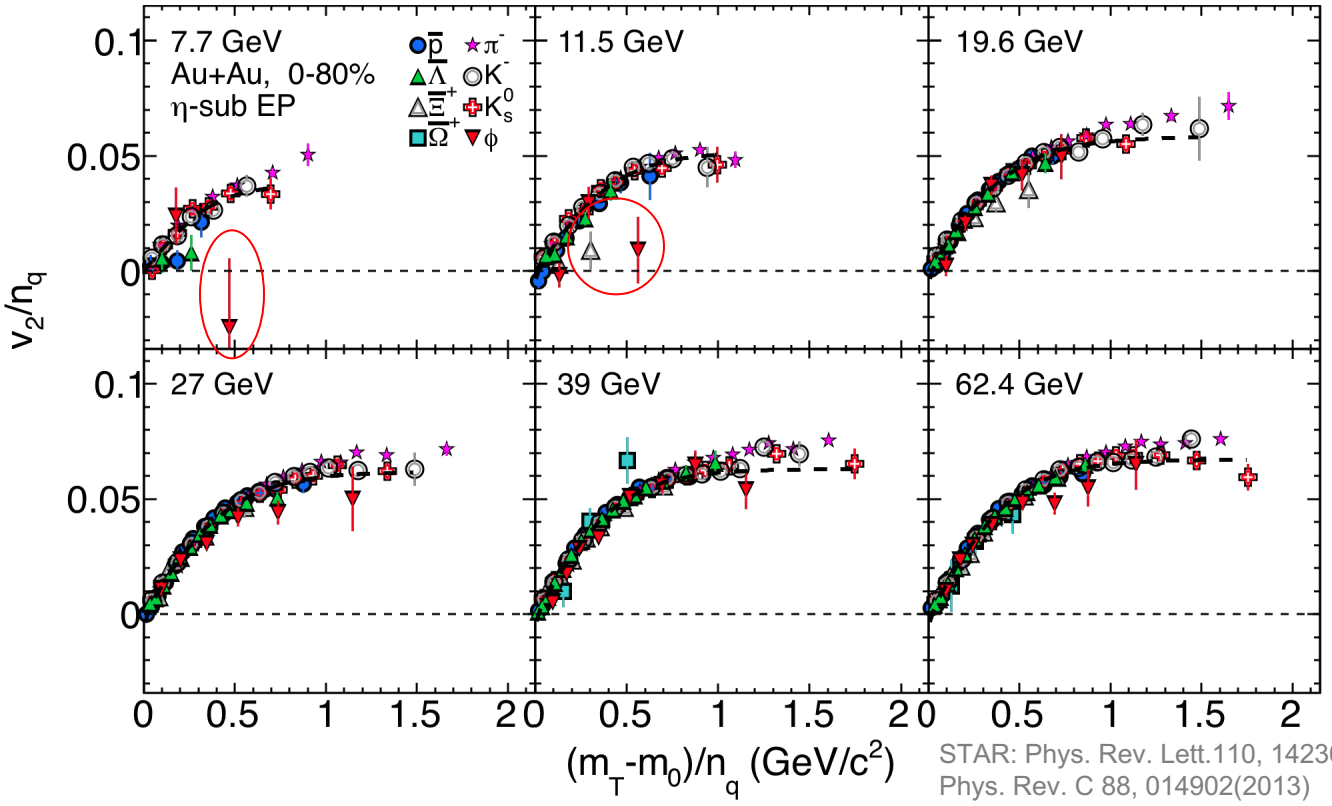


- First observation of NCQ scaling at 200 GeV
  STAR, Phys. Rev. Lett. 92, 052302 (2004)

- NCQ scaling for the multi-strange hadrons and D meson at 200 GeV and LHC energy
  Partonic collectivity
  STAR, Phys. Rev. Lett.116, 062301 (2016)
  Phys. Rev. Lett.118, 212301 (2017)
  ALICE, JHEP 09, 006 (2018)

- NCQ scaling gradually restores from 3.2-4.5 GeV
  STAR, Phys. Rev. Lett.110, 142301 (2013)
  Phys. Lett. B 827 (2022) 137003
  Phys. Rev. Lett.135, 072301 (2025)

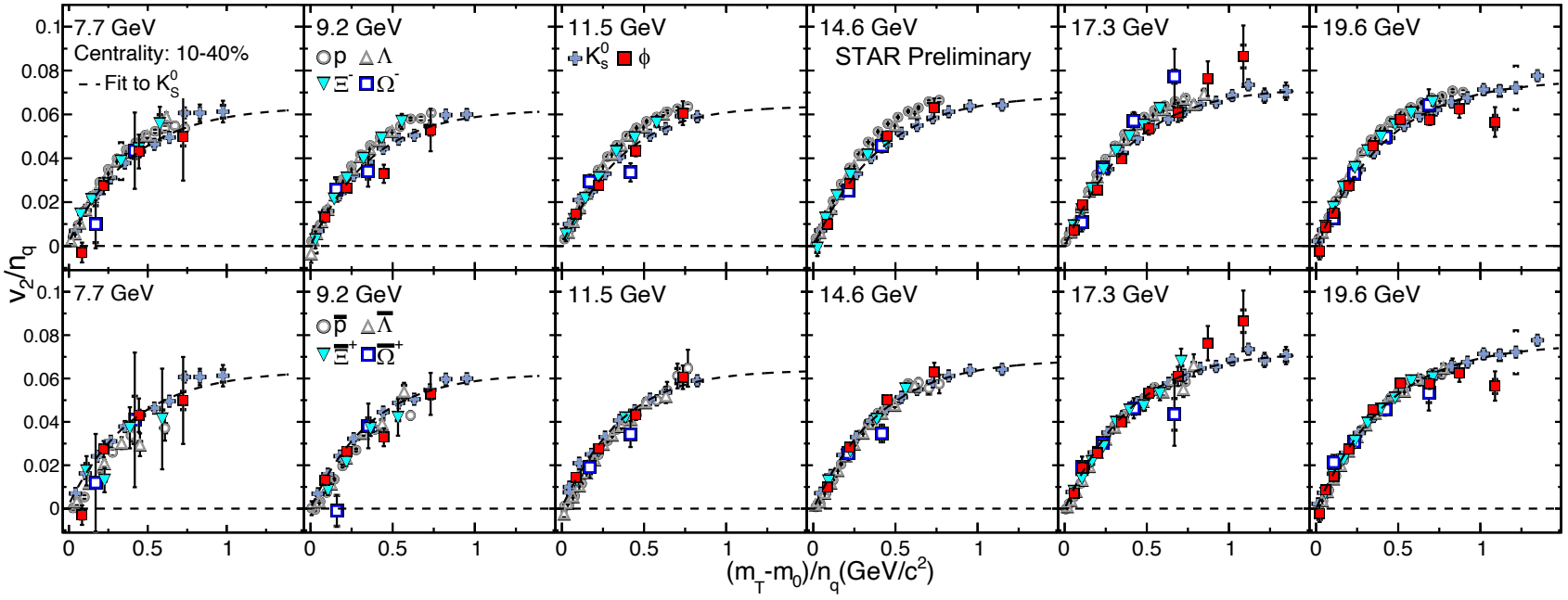
Multi-strange Hadron v_2: BESI



STAR: Phys. Rev. Lett.110, 142301(2013)
Phys. Rev. C 88, 014902(2013)
Phys. Rev. C 93, 014907(2016)

- Multi-strange hadron and φ v_2 seems lower than others, but with large uncertainties

Multi-strange Hadron v_2: BESII



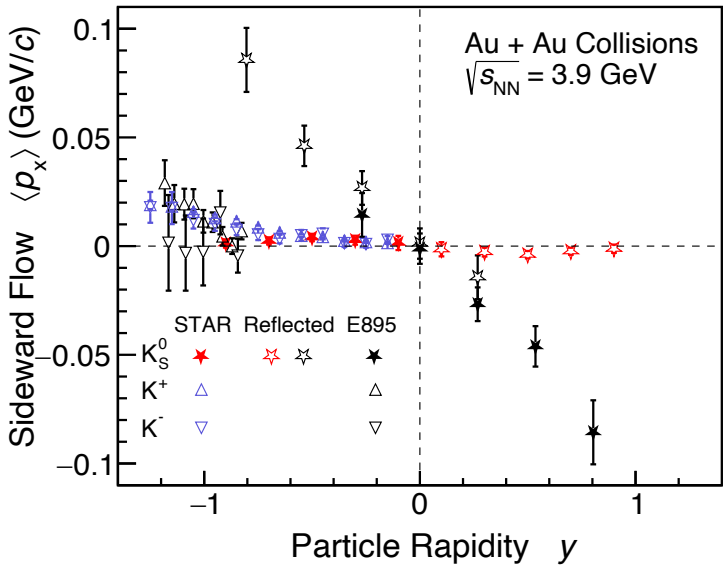
- Precision measurements of multi-strange hadrons and φ mesons at $\sqrt{s_{NN}} \geq 7.7$ GeV

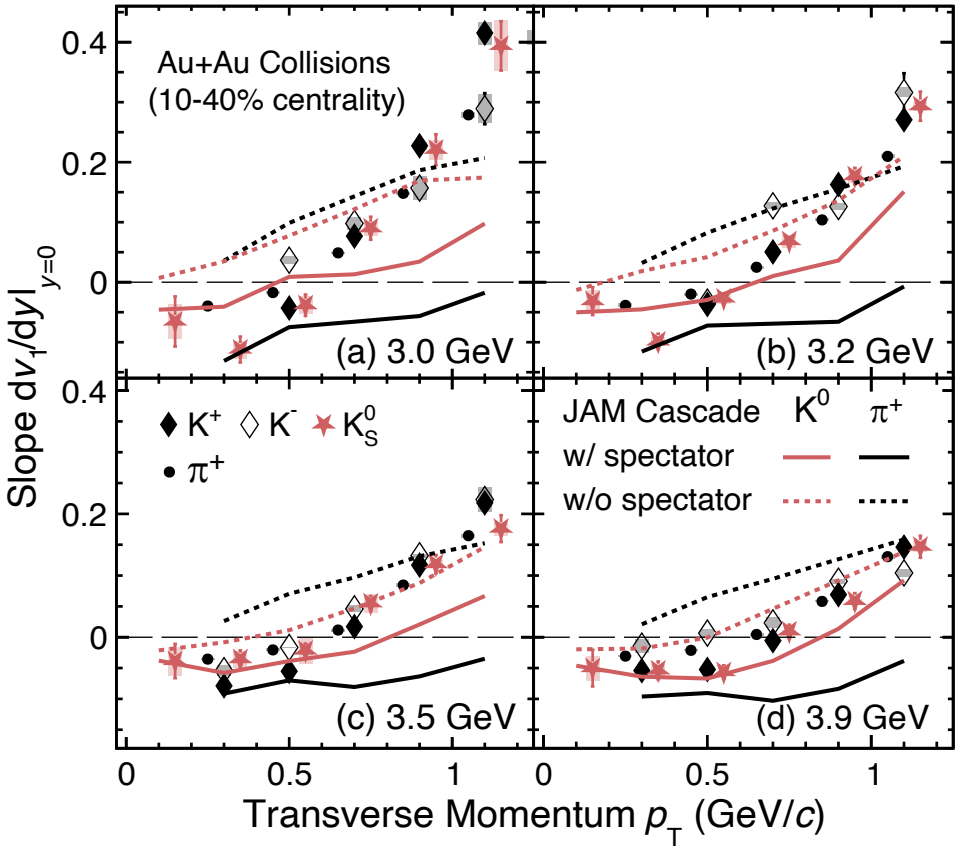
Partonic collectivity

A missing piece in the 7.7–20 GeV energy range:
completed with the BESII dataset

Kaon v_1 in high baryon density

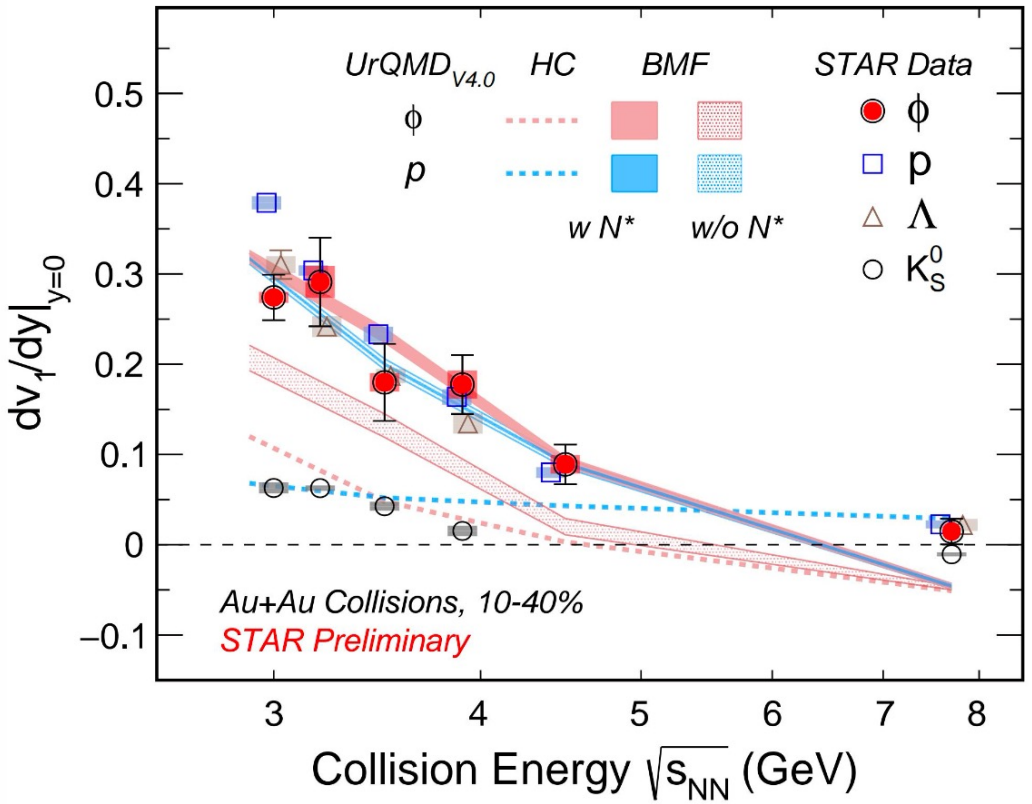
STAR: Phys. Lett. B 875, 140353 (2026)
E895, Phys. Rev. Lett. 85, 940 (2000)





- K^0_S anti-flow: STAR measurement 8 times smaller than E895
- 20 years of kaon potential theories need re-examination

φ v_1 in high baryon density



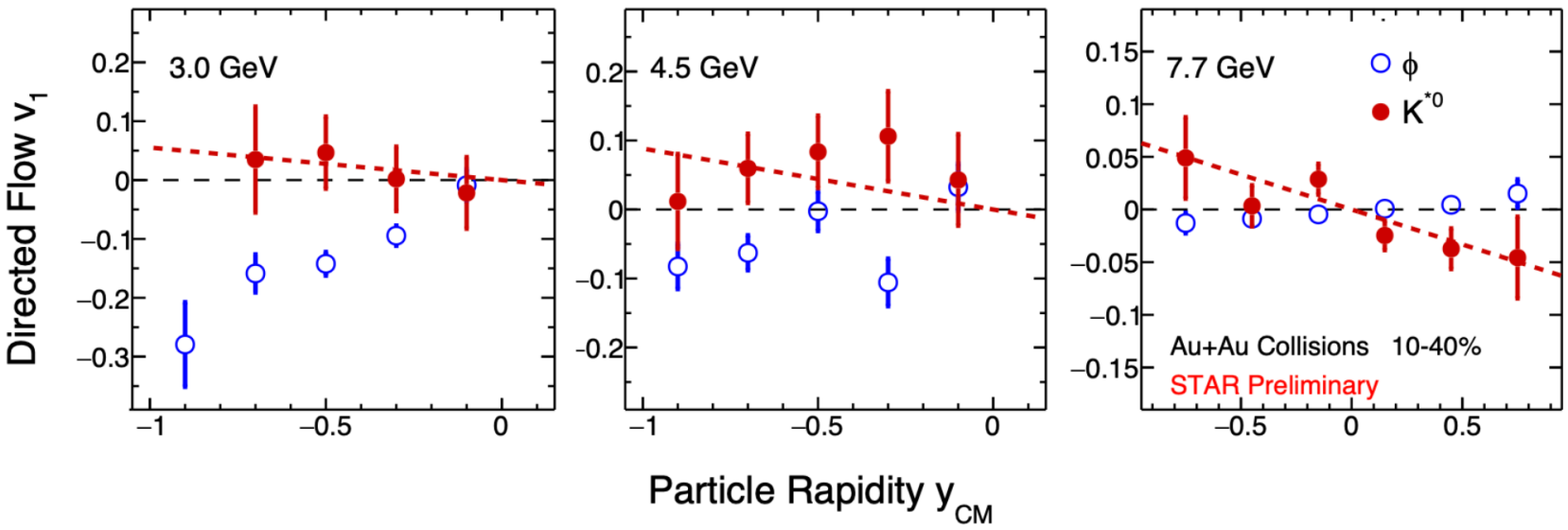
- UrQMD with mean-field:
  - Proton data: reproduced
  - φ data: not reproduced (fails without high-mass resonances)
- Key implication:

  High-mass baryon resonances (N*) may drive φ production & its baryon-like flow

  $N + N \rightarrow N^* + N \rightarrow N + \phi + N$

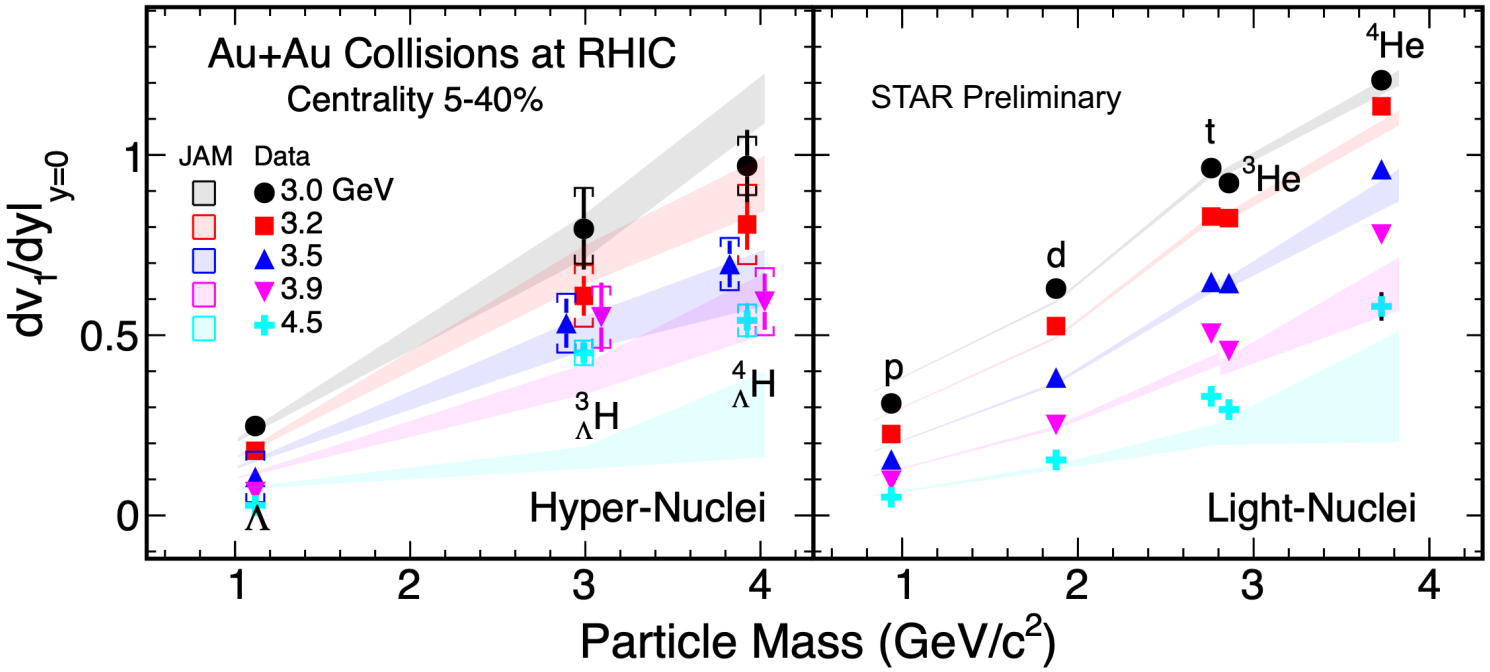
φ meson production mechanism changes from low to high baryon density regions.

K* v_1 in high baryon density



- The short-lived K^{*0} ($c\tau$ ~ 1 fm) undergoes strong hadronic re-scattering, causing v_1 signal loss.
- The v_1 slope of K^{*0} is negative, opposite to other mesons.

v_1 of (Hyper)nuclei in high baryon density



3.0 GeV: STAR, PLB827, 136941 (2022); PRL130, 212301(2023)

- v_1 slope scaling: scales with A → supports nucleon coalescence

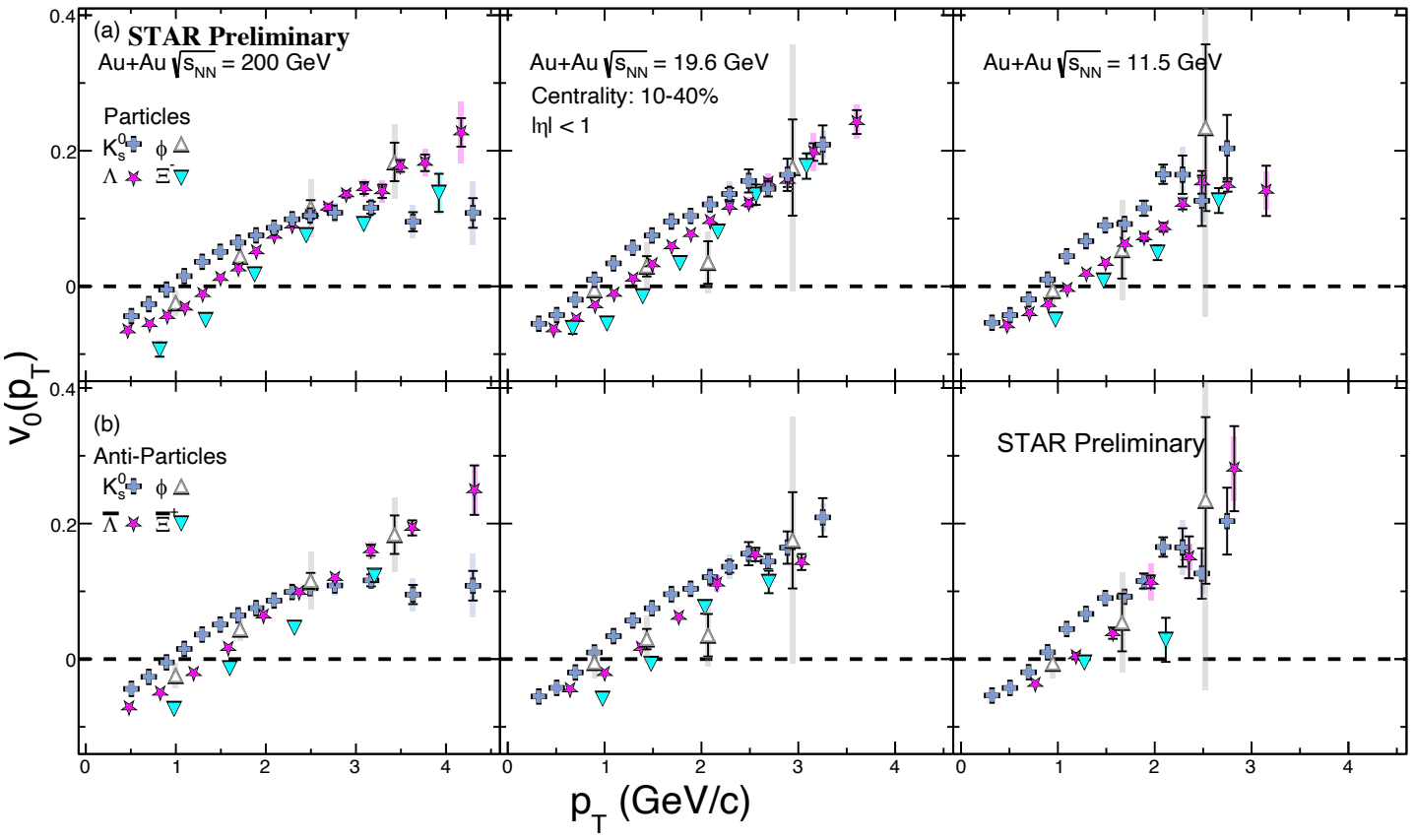
  JAM + afterburner reproduces data

  Nucleon coalescence first proposed by T. Yan, Y. Ma et al., PLB638, 50 (2006)

- NY vs. NN: hyper-nuclei slope < light nuclei

  Possible signature of different NY vs. NN interactions

$v_0(p_T)$: (Multi-)strange hadrons at RHIC

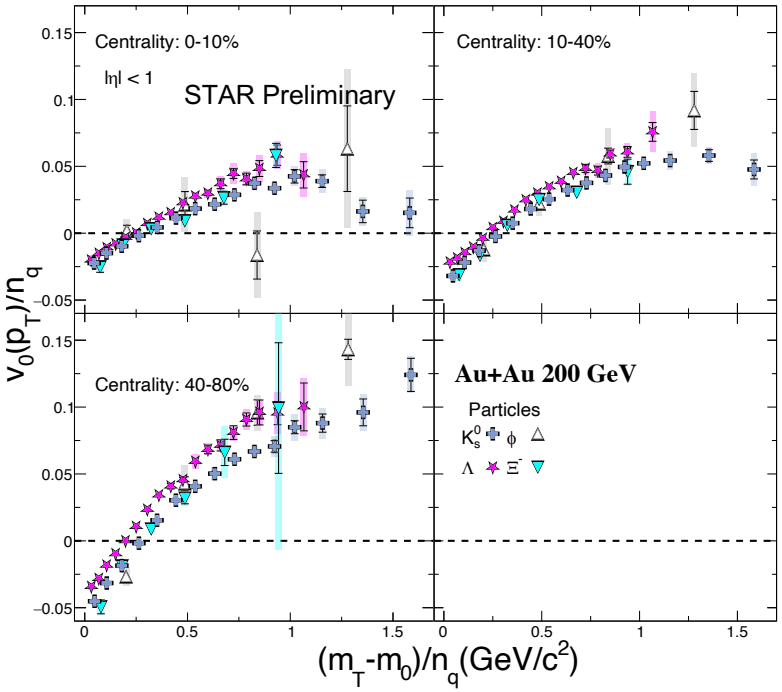


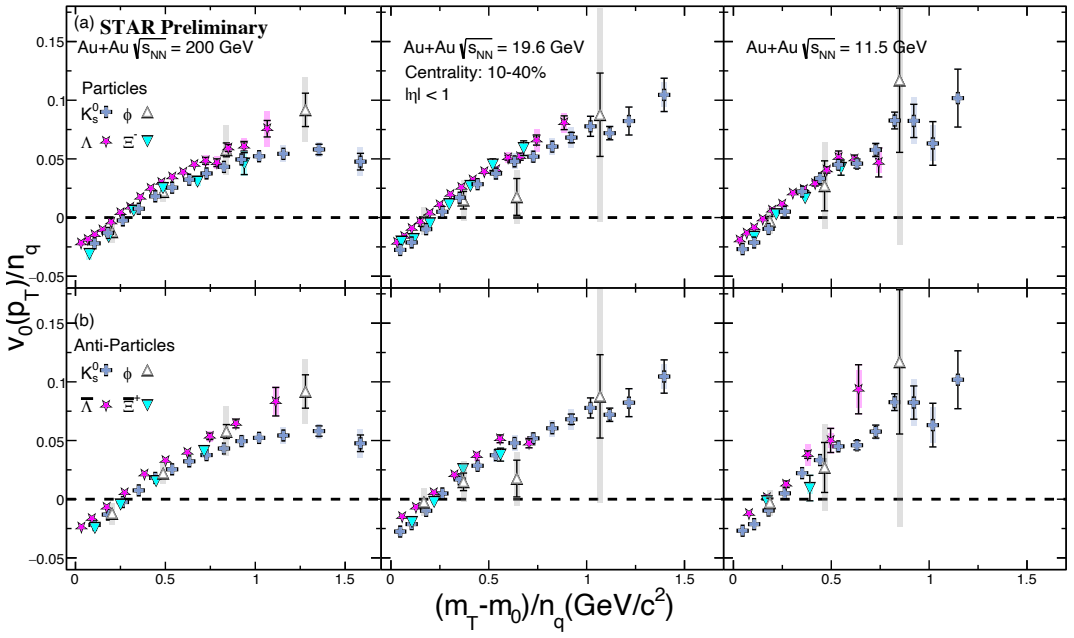
- At low p_T (< 2 GeV/c): mass ordering
- At intermediate p_T (2 - 4 GeV/c):

  baryon-meson splitting between Λ and K_S^0

See also: Chunjian Zhang's talk, 16:30–17:00, Apr. 26th

$v_0(p_T)$: NCQ scaling test at RHIC

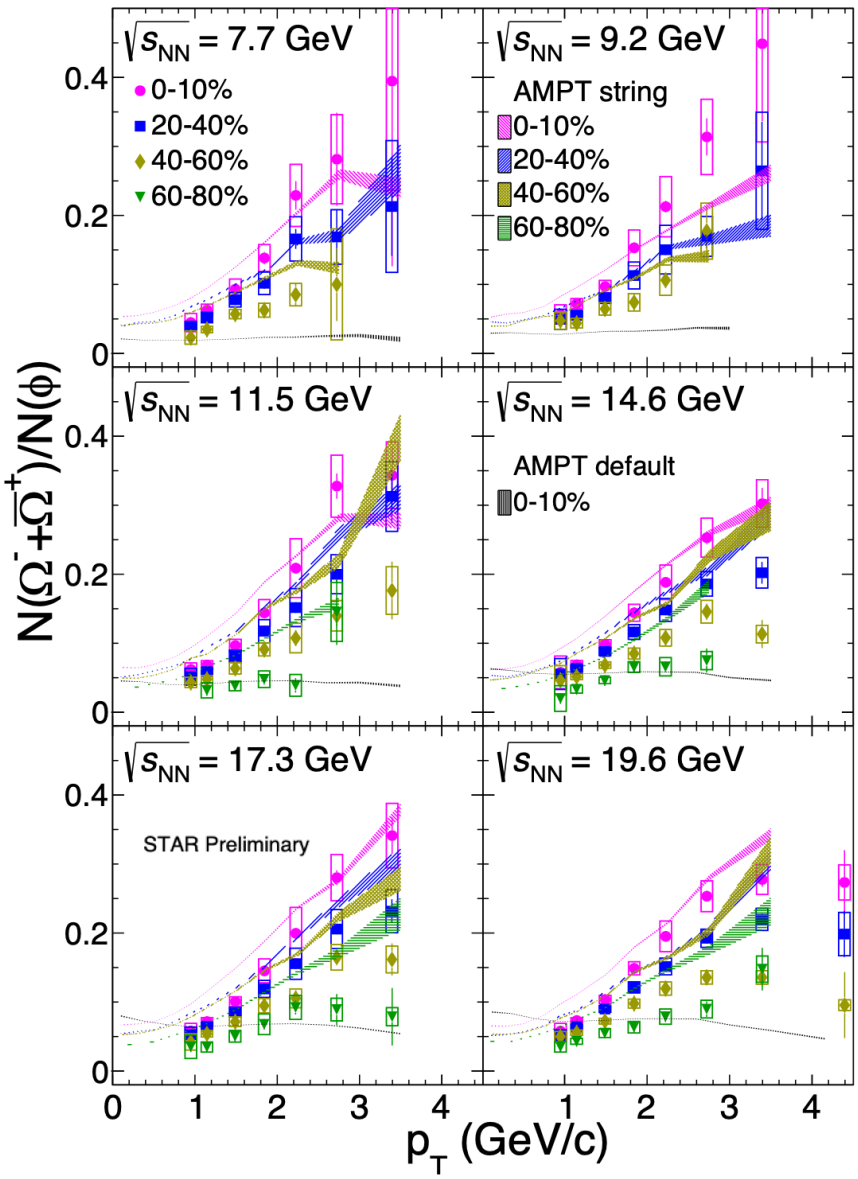




- Better NCQ scaling in more central collisions at 200 GeV

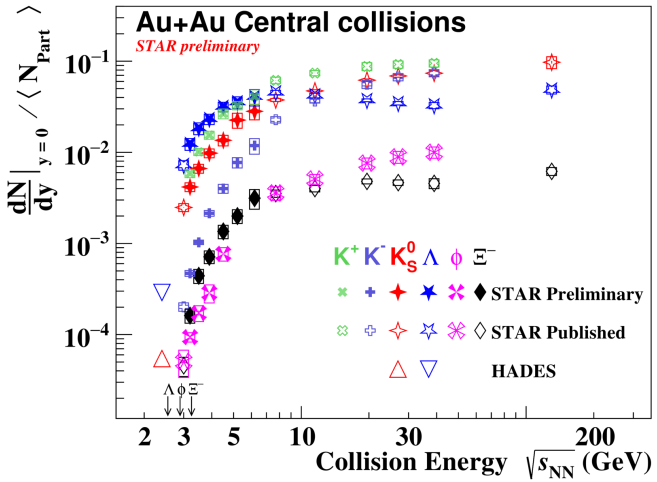
$v_0(p_T)$ will be measured in the high baryon density region, extending flow studies from anisotropic to radial flow.

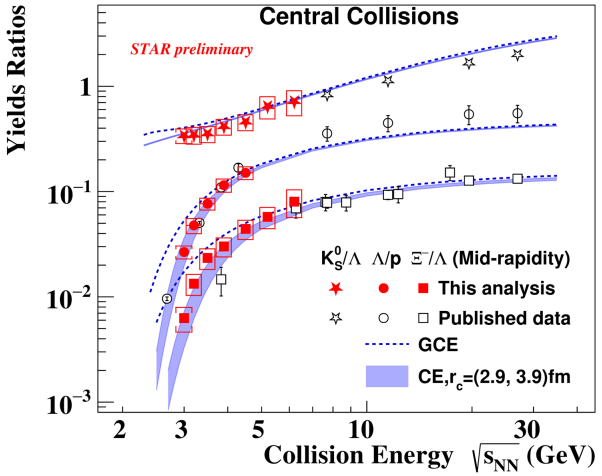
Ω/ϕ ratio in BESII

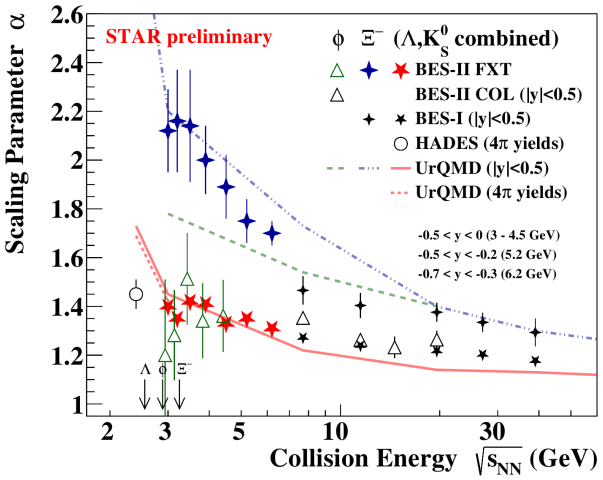


- Clean probe of deconfinement
- Strong Ω enhancement over ϕ at intermediate p_T, across all energies and centralities
- String-melting AMPT (strange quark coalescence) reproduces data; hadronic AMPT fails
- Data–model agreement supports deconfinement in central AA collisions at $\sqrt{s_{NN}} \geq 7.7$ GeV

Strangeness in high baryon density







STAR: PLB 831, 137152 (2022); JHEP 10 (2024) 139

α: Centrality scaling parameter of particle yields Yields = kN_{part}^{α}

- First measurement of Ξ^- yield near threshold in Au+Au collisions

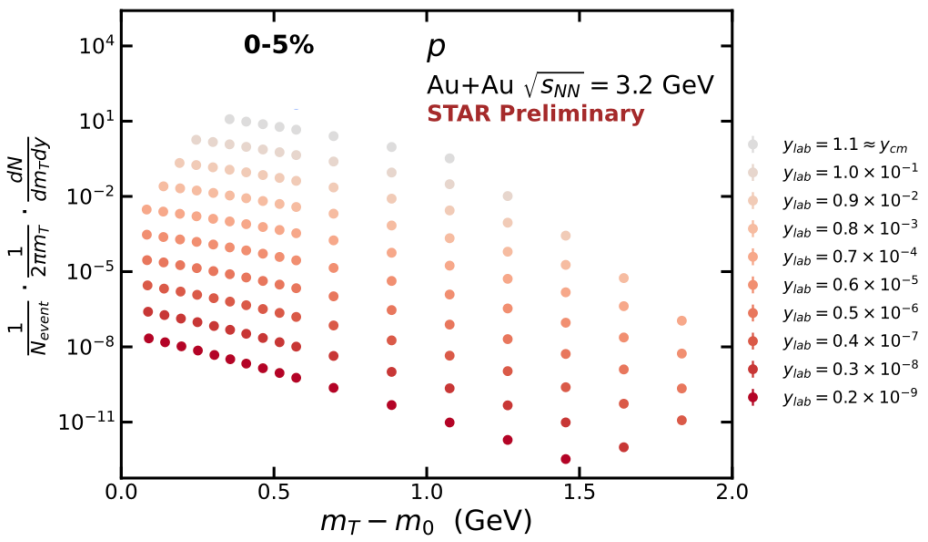
α value for Ξ^- in high baryon density region significantly larger than for Λ, K_S^0, φ

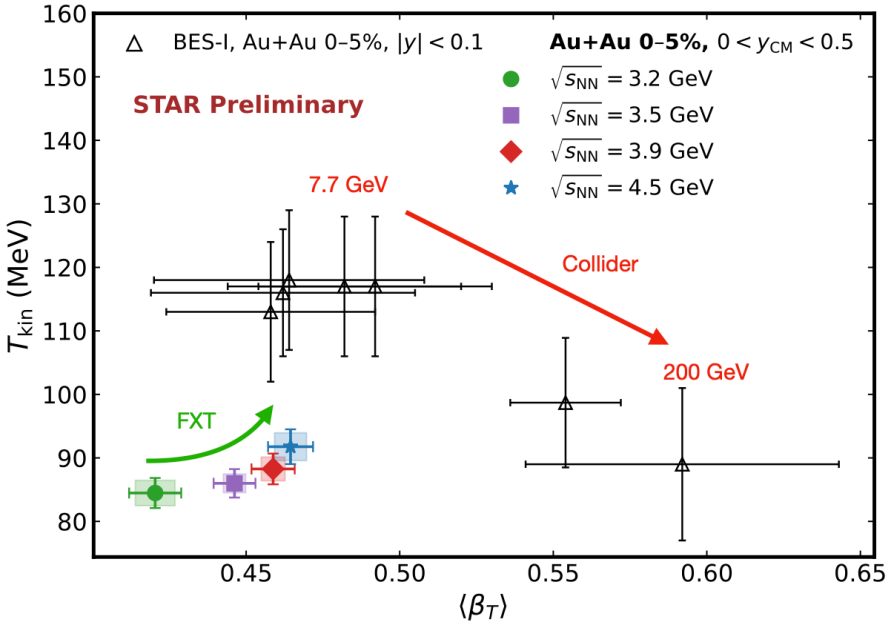
- Strange hadron yields in high baryon density region:

Canonical ensemble describes data better than Grand-Canonical ensemble

Nuclear matter property in HBDR: hadronic interactions dominate

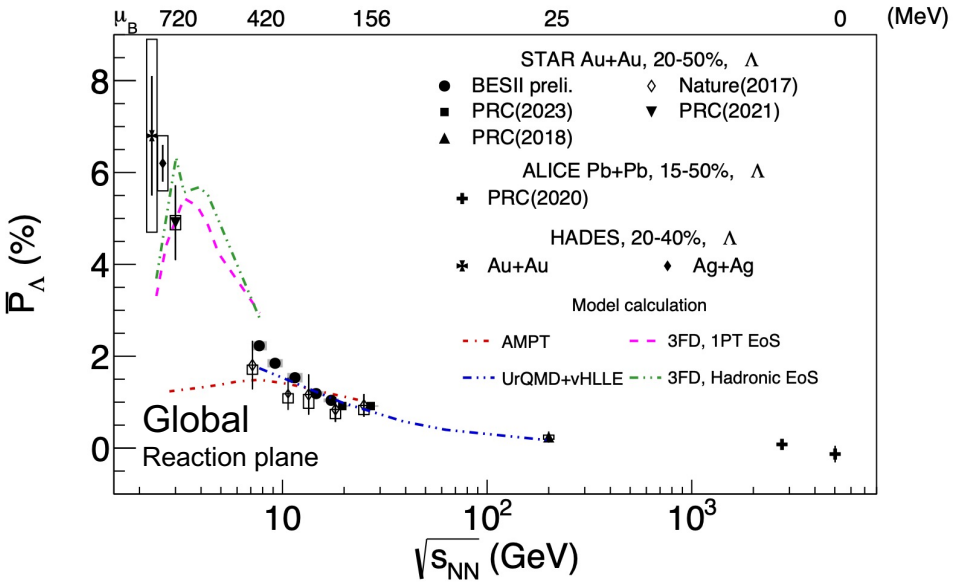
Kinetic freeze-out in high baryon density

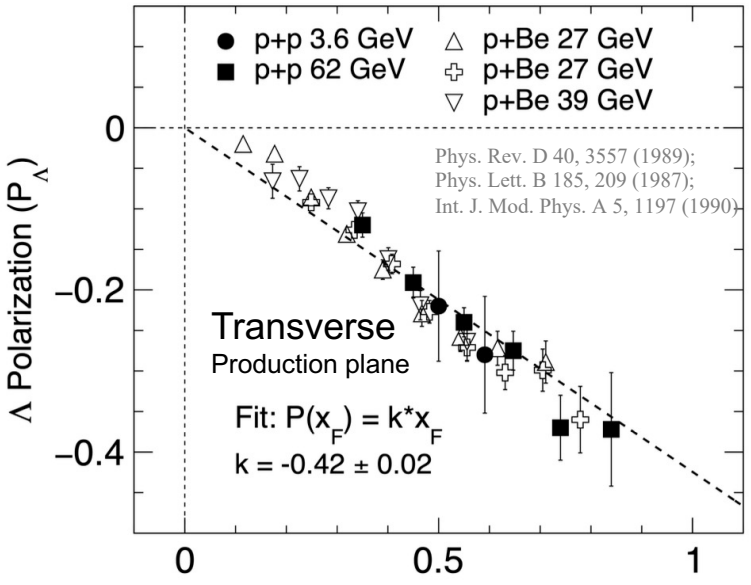


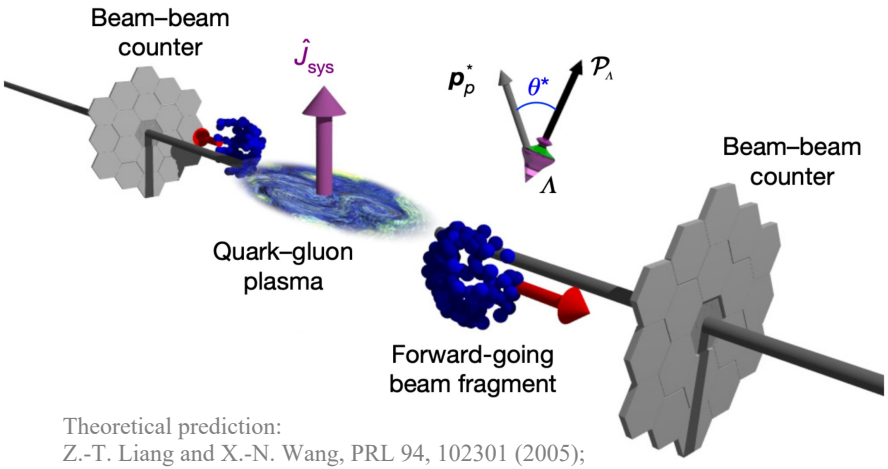


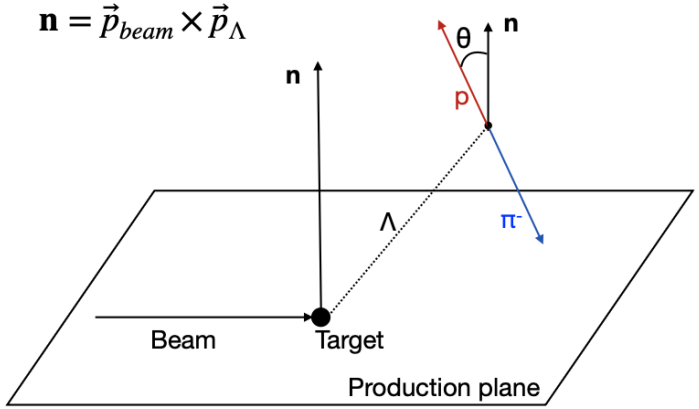
- Fit π, K, p simultaneously with a blast wave function to extract kinetic freeze-out parameters
- Both T_{kin} and $\langle \beta_T \rangle$ increases with energy in FXT energy range

Polarization









Theoretical prediction:
Z.-T. Liang and X.-N. Wang, PRL 94, 102301 (2005);
PLB 629, 20 (2005)

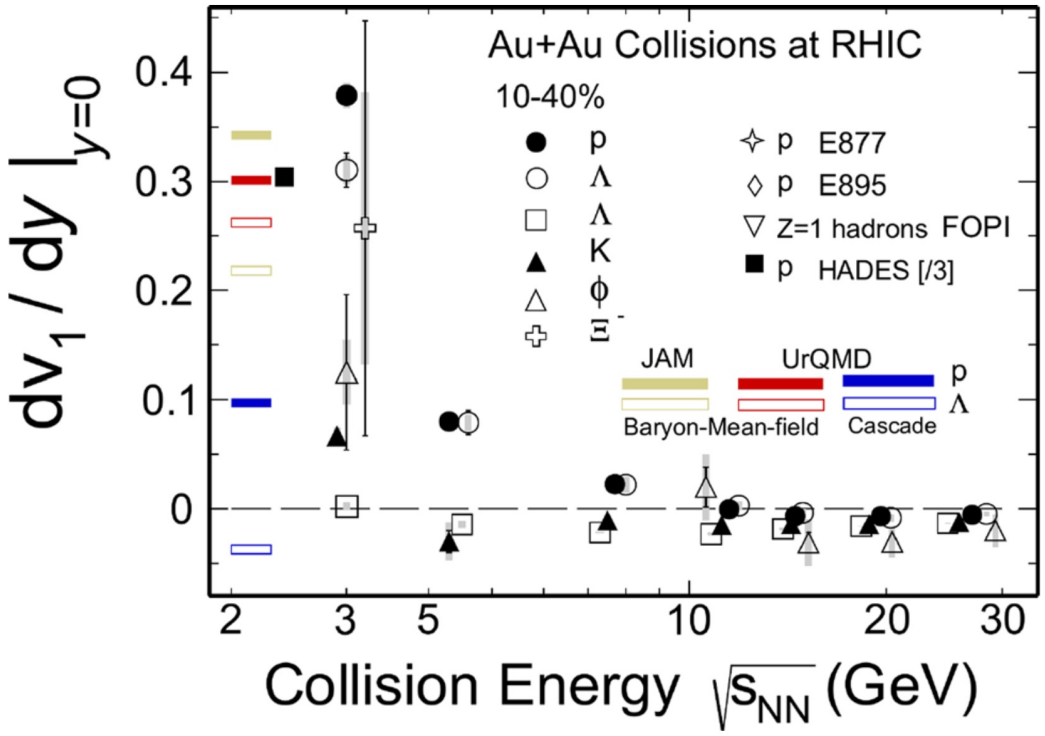
Transverse polarization + v_1 → contribution to global polarization

F Liu and Z. Tu: arXiv: 2603.19581

Polarization Decomposition

$$P_H = P_\omega + v_1 * P_T$$

P_ω: Polarization from vorticity; P_T: Polarization from production plane



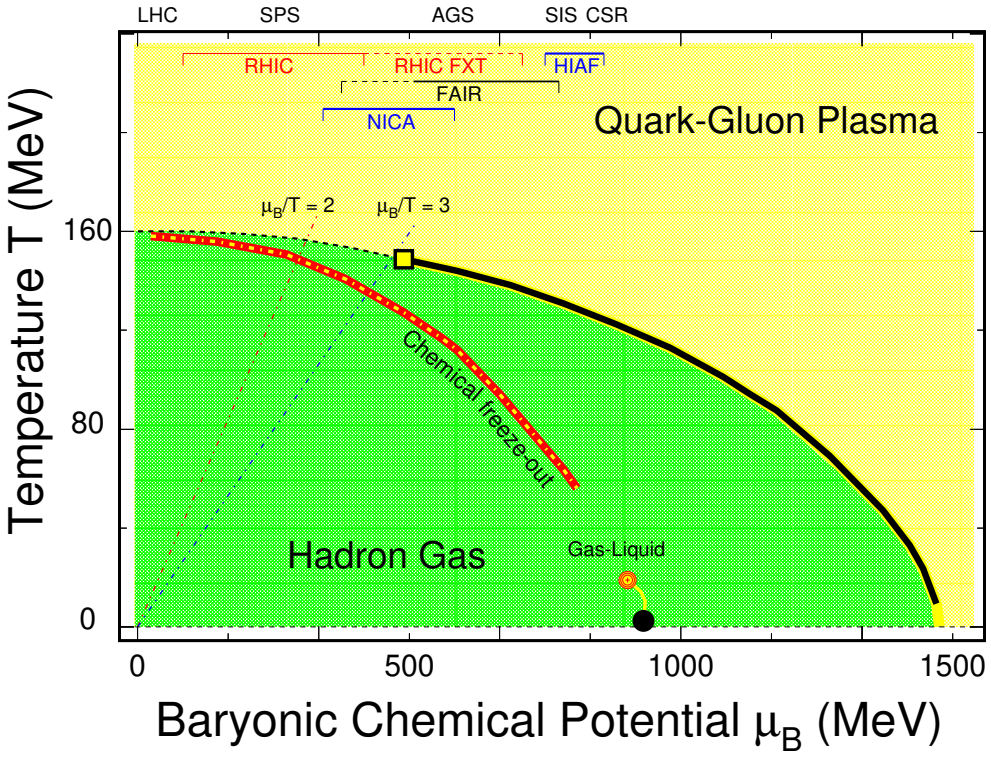
v_1 is large in the high baryon density region

Summary

- **Ω/ϕ and multi-strange v_2: QGP at ≥ 7.7 GeV**
- **$v_0(p_T)$: a new radial flow probe**
- **High baryon density:**
  - NCQ scaling on v_2: onset at ~4.5 GeV
  - Kaon anti-flow: kaon potential theories need re-examination
  - Strong ϕ v_1: hadronic production mechanism
  - Hyper(nuclei) v_1: nucleon coalescence; NN vs. NY interactions
  - Strangeness production: hadronic interaction dominate

Polarization: QCD phase diagram with spin degrees of freedom

Outlook



➢What we know:

≤ 3.2 GeV: Hadronic interactions dominate; ≥ 7.7 GeV: Partonic collectivity

➢What's next (CEE/CBM/MPD/):

Phase structure including spin degrees of freedom

Probe nuclear matter properties in HBDR; Search for gas-liquid phase transition

N. Kaiser and W. Weise, Liquid-gas phase transition of nuclear matter, arxiv:2602.09916
P. Siemens, Liquid–gas phase transition in nuclear matter, Nature 305, 410 (1983)