Recent Collective Flow Results from STAR Beam Energy Scan II

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Workshop on High Baryon Density Physics in High-Energy Nuclear Collisions, Berkely, Mar. 19th – 20th

Outline

- **QCD Phase Diagram**
- **Collective Flow**
- **Results and Discussion**
- **Summary and Outlook**

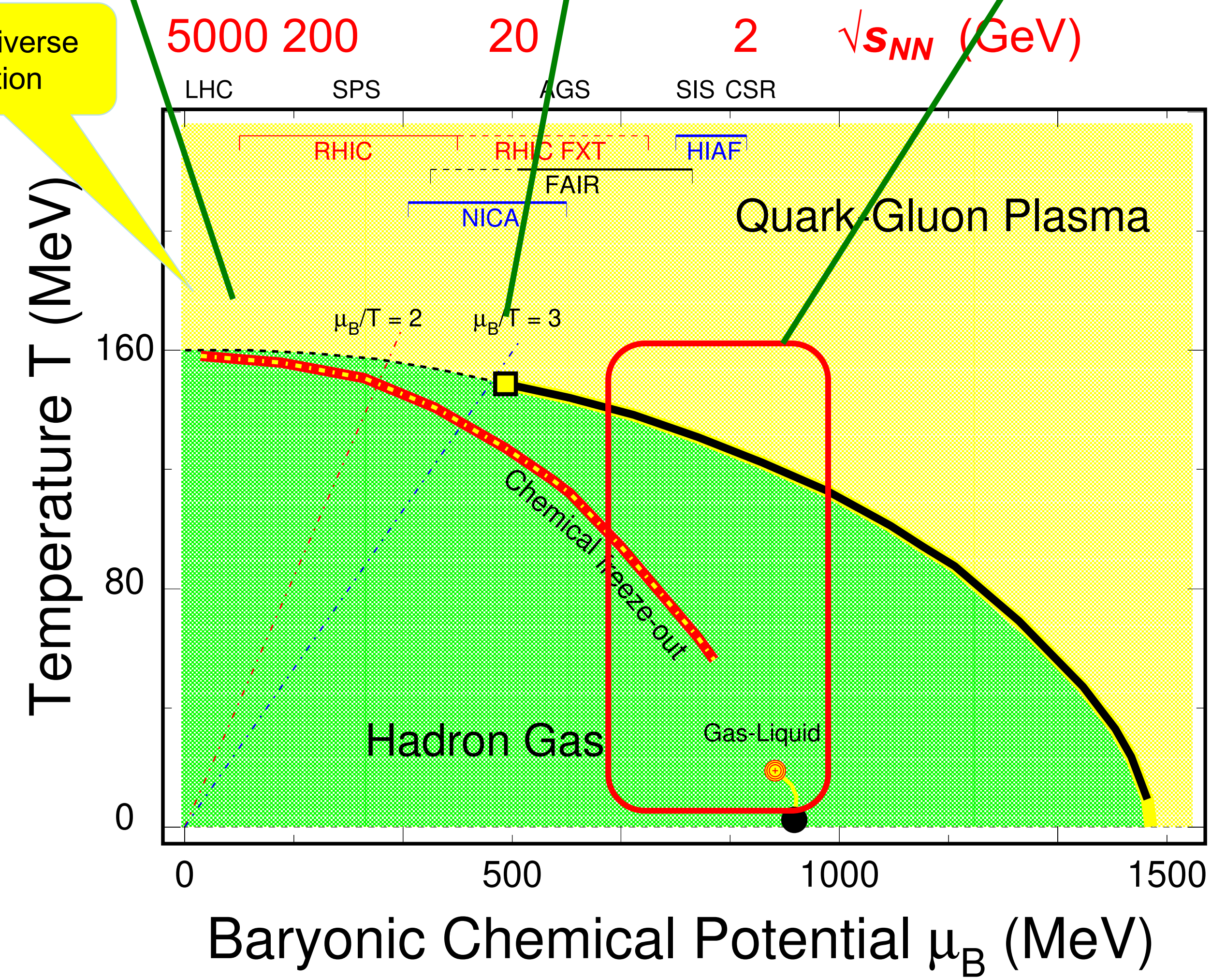
QCD Phase Diagram

1 — ***T_{ini}, T_C*** — ***LHC, RHIC***

2 — ***T_E*** — ***RHIC, SPS***

3 — ***Large μ_B*** — ***FAIR, NICA, CSR***

Early universe evolution

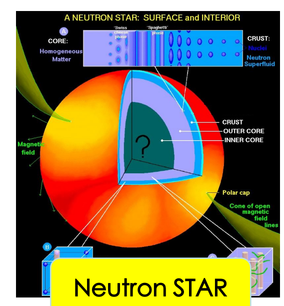


- Low Baryon Density (High energy):

The properties of QGP

- High Baryon Density (BES)：

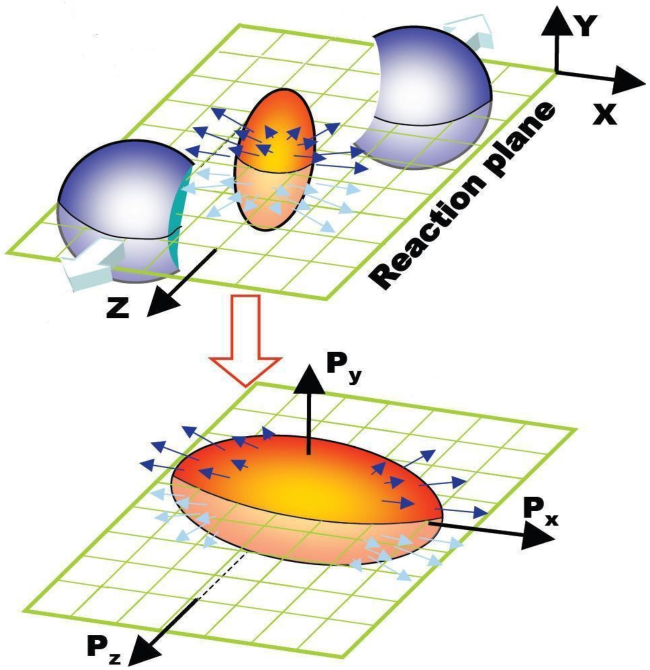
QCD Phase transition



High Baryon Density

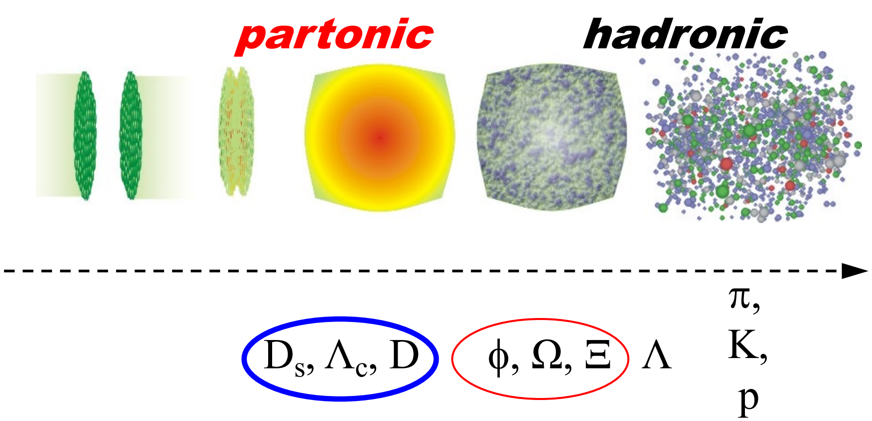
X. Luo, S. Shi, N. Xu and Y. Zhang, Particle 3, 278 (2020)

Collective Flow



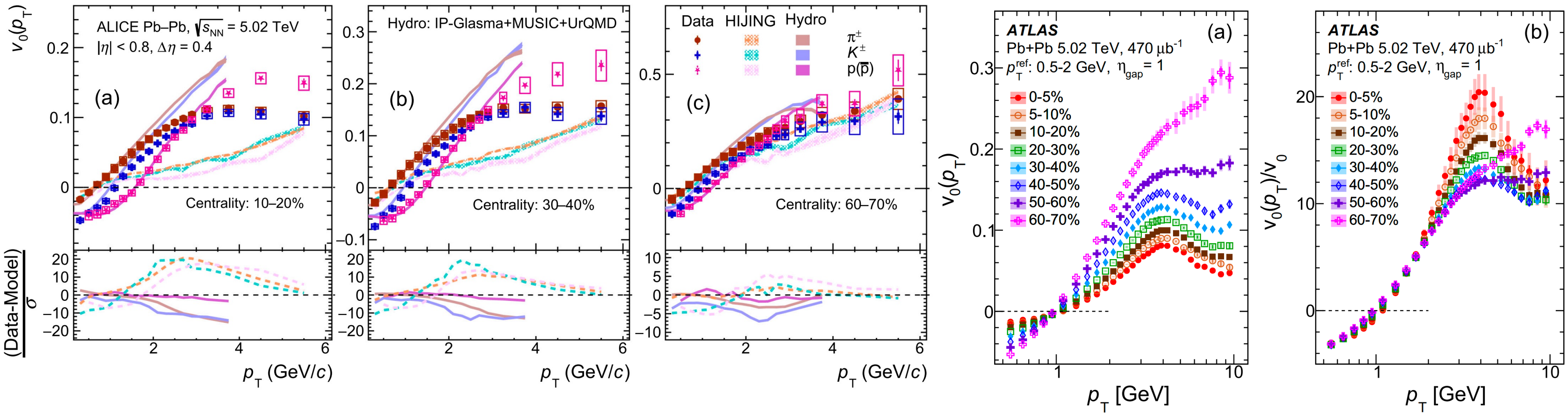
$$\frac{d^2N}{d\phi dp_T} = N(p_T)\,\left(1 + 2\sum_{n\geq 1} v_n \cos(n(\phi - \psi_n))\right)$$

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

New Probe: $v_0(p_T)$



ALICE, Phys. Rev. Lett. 136, 032302 (2026)
ATLAS, Phys. Rev. Lett. 136, 032301 (2026)

$$v_0(p_T) \equiv \frac{\langle \delta n_A(p_T)\delta[p_T]_B \rangle}{\langle n_A(p_T)\rangle \sigma_{p_T}}$$

- Mass ordering observed for $v_0(p_T)$ at low p_T
- Baryon-meson splitting at intermediate p_T

$v_0(p_T)$: System-size Dependence

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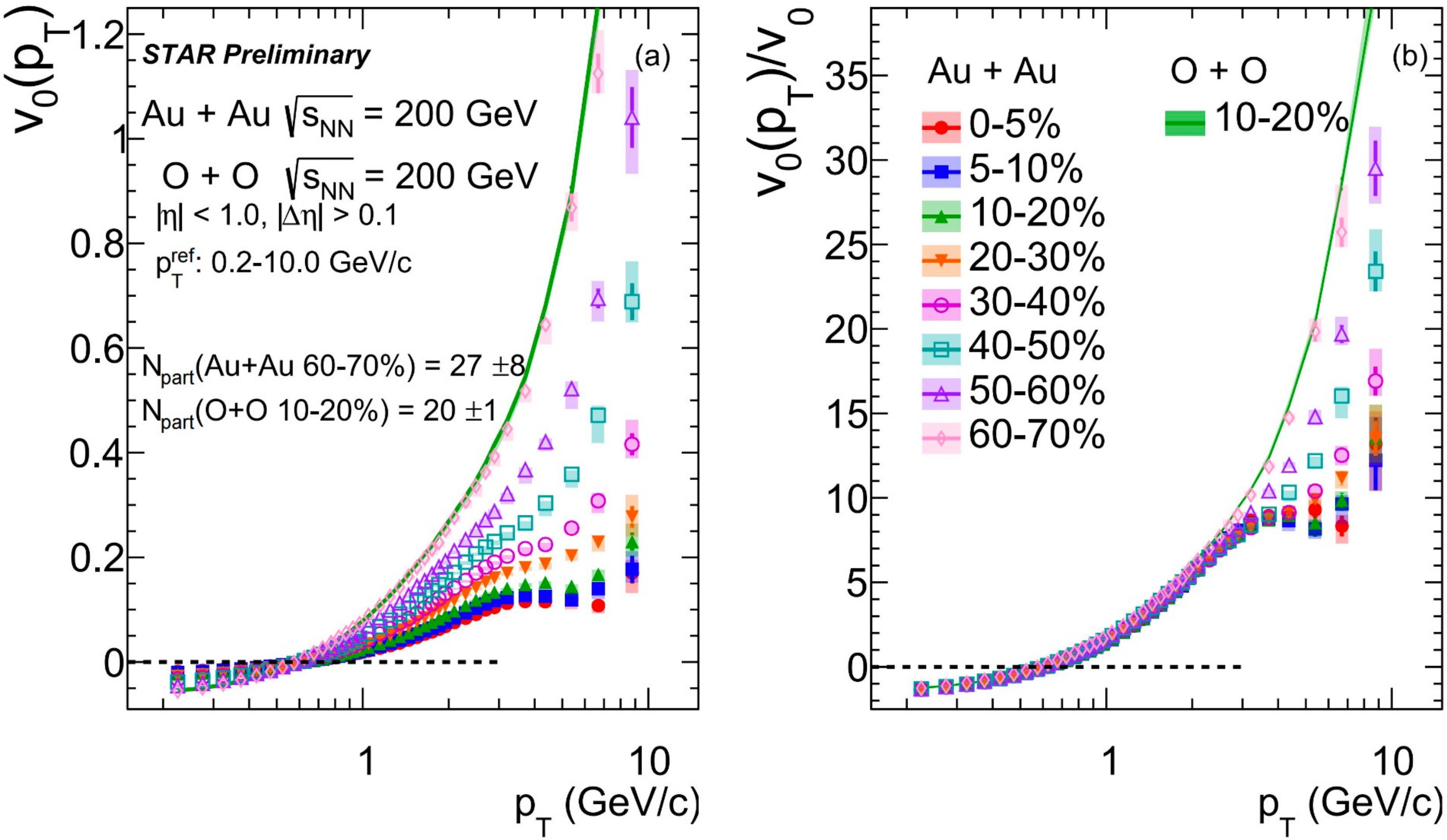
Zaining Wang for STAR, SQM2026



- $v_0(p_T)$ captures system-size dependent radial flow fluctuations with coherent hydrodynamic response

$v_0(p_T)$: Sensitive to Bulk Viscosity

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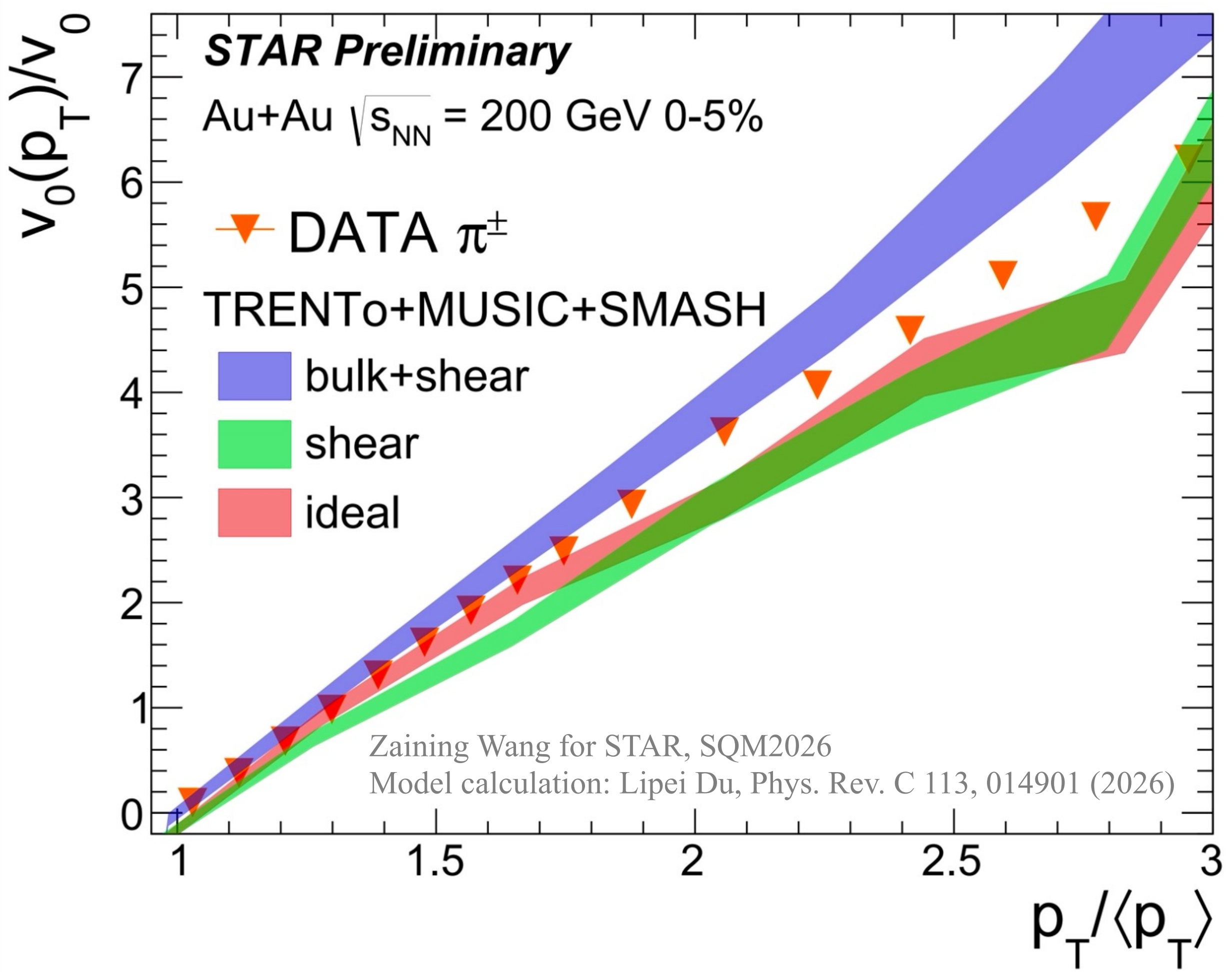
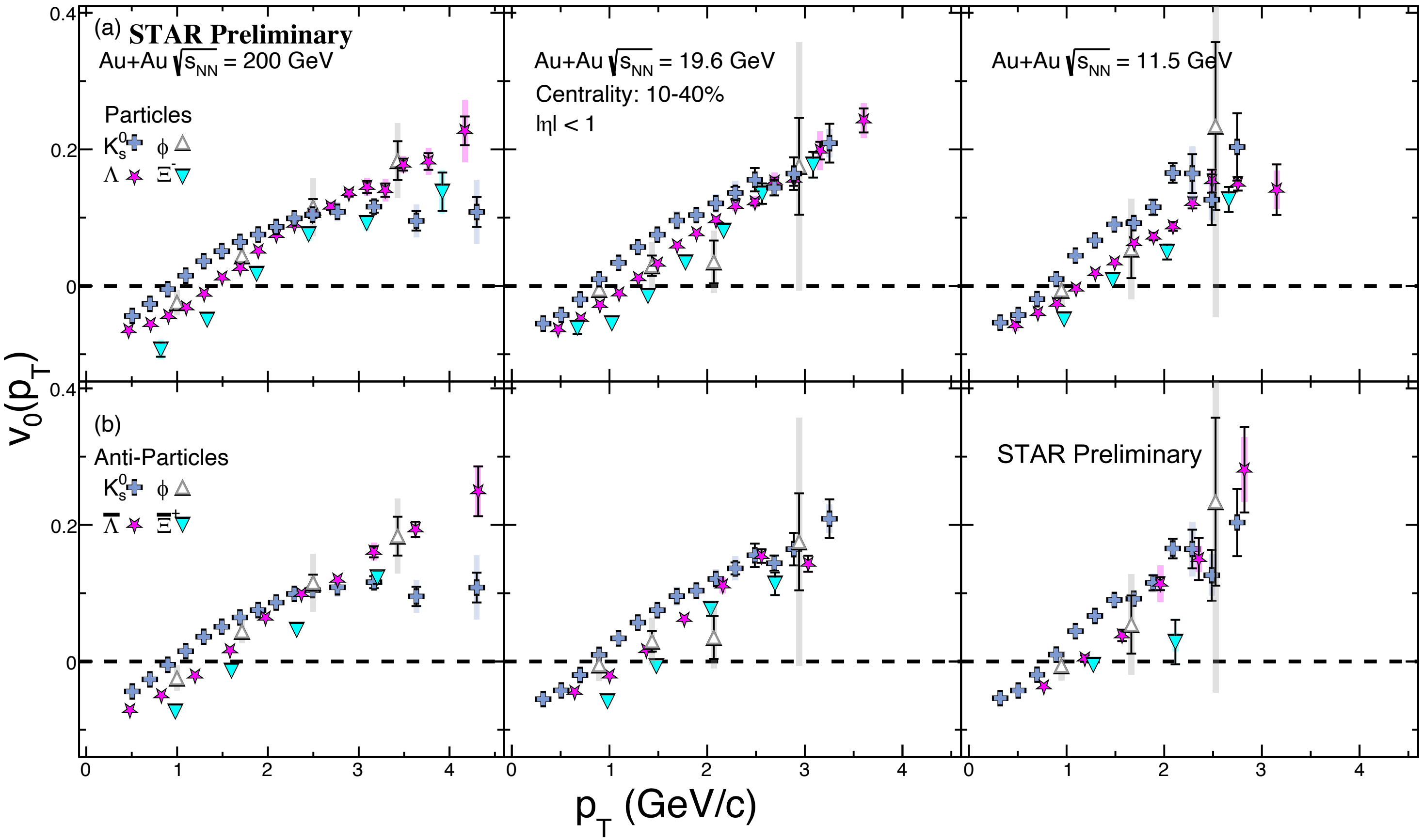


➢ $v_0(p_T)$ sensitive to bulk viscosity, weakly influenced by shear viscosity

$v_0(p_T)$: (Multi)strange Hadrons

Yuli Kong for STAR, SQM2026



- 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 at 200 GeV

  limited by statistical precision at 19.6 and 11.5 GeV

$v_0(p_T)$: NCQ Scaling Test

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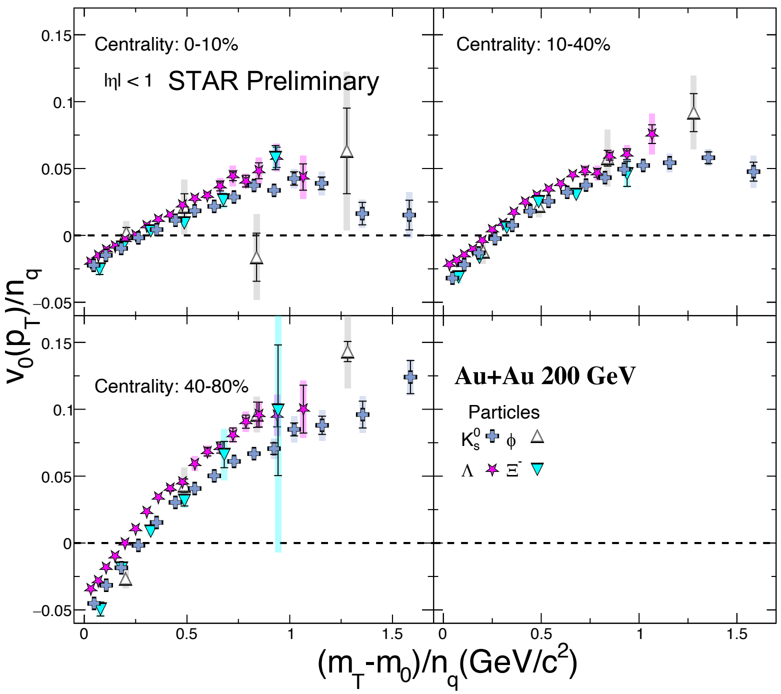
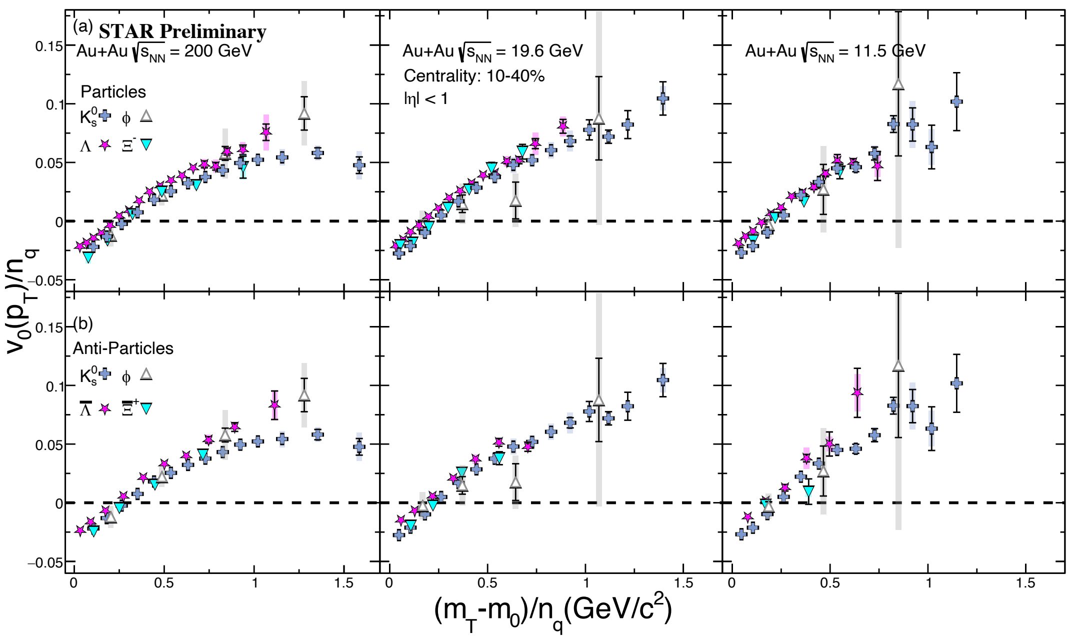
Yuli Kong for STAR, SQM2026





➢ Better NCQ scaling in more central collisions at 200 GeV

v_2: Onset of NCQ Scaling

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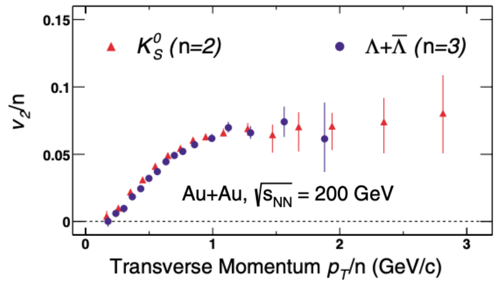
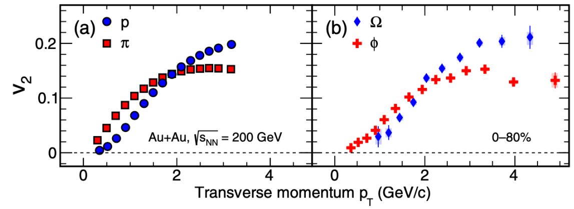
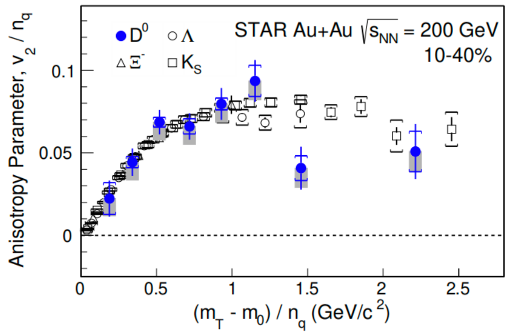
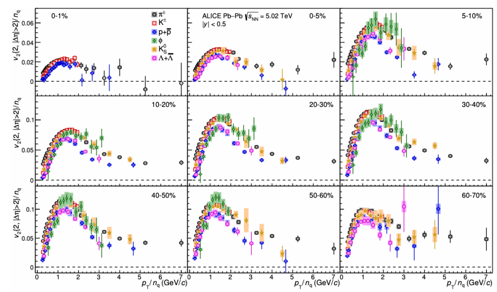
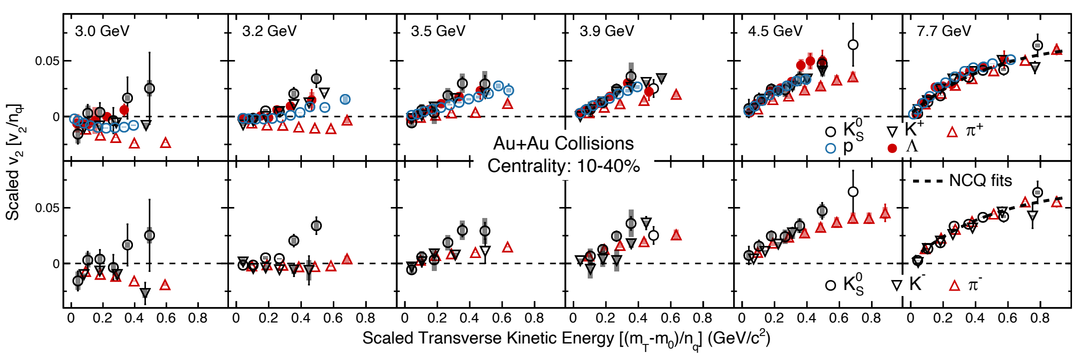










- First observation of NCQ scaling at 200 GeV

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

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

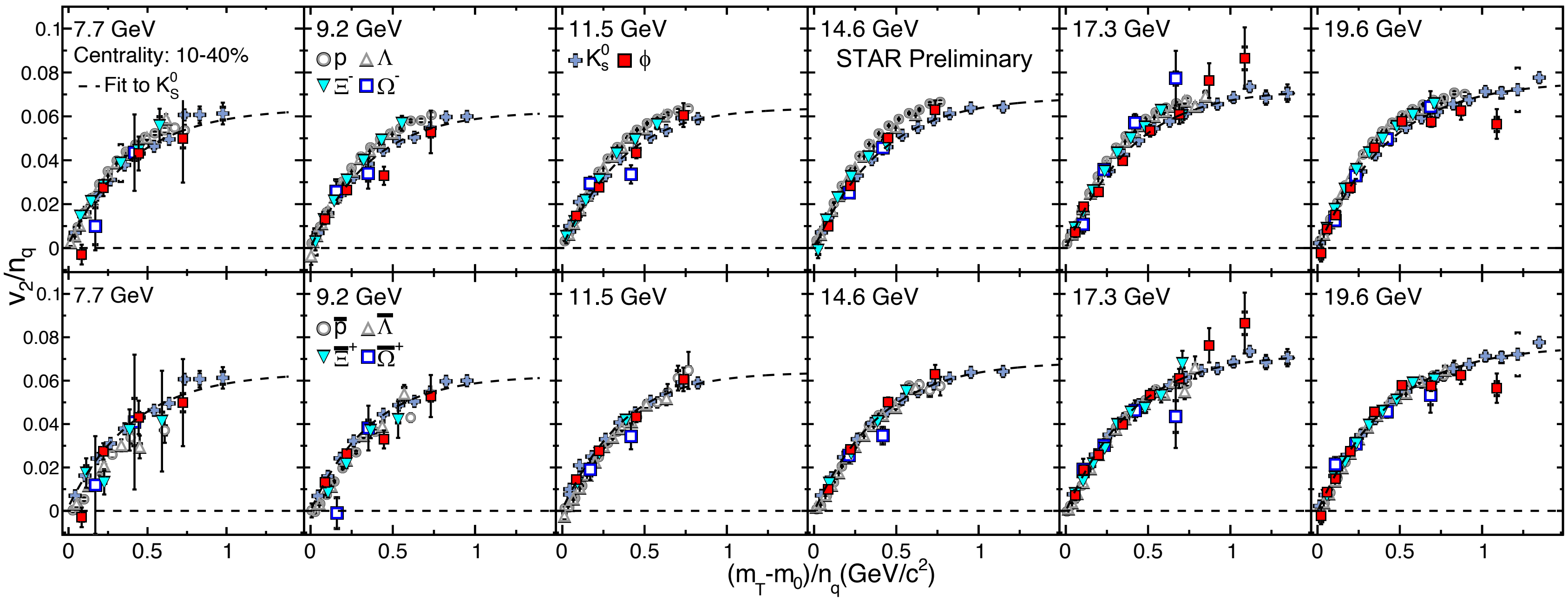
Partonic collectivity

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)

v_2: Multi-strange Hadrons

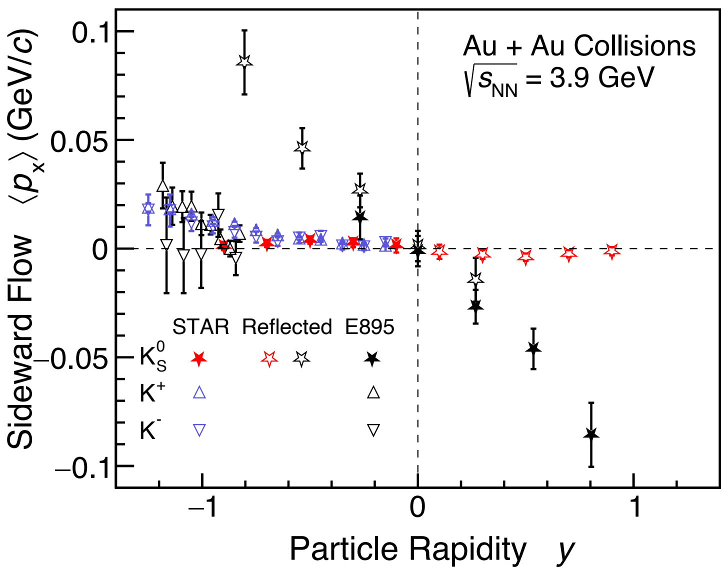


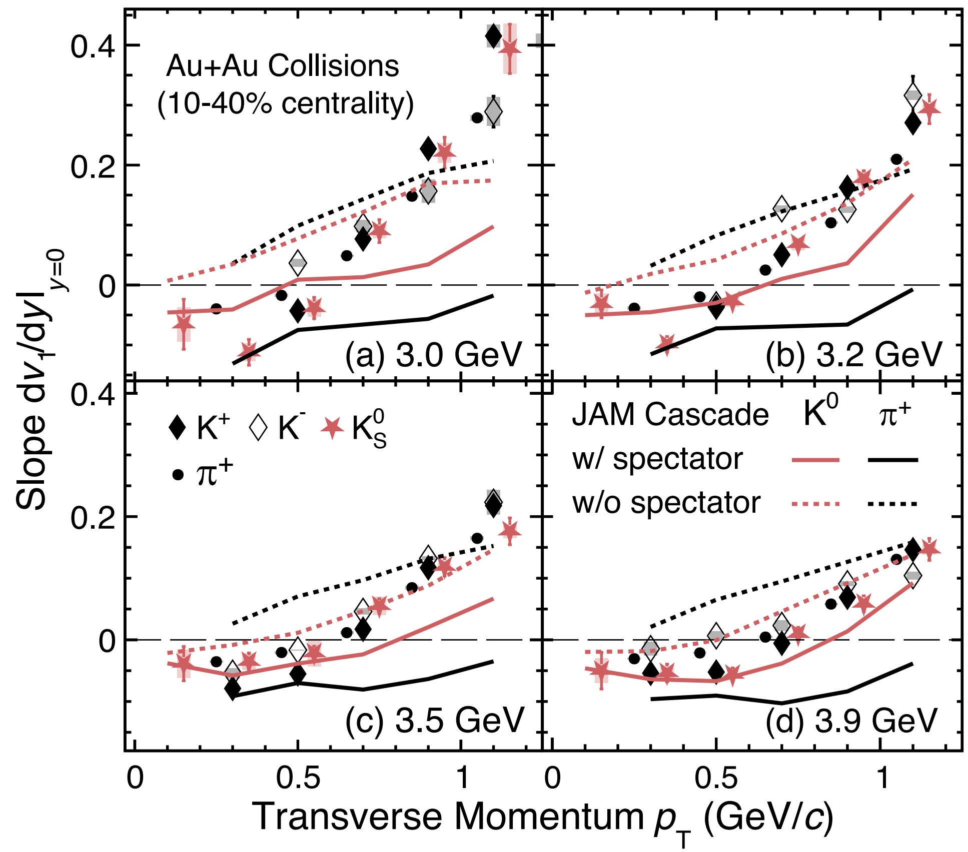
➢ Precision measurements of multi-strange hadrons and φ mesons at $\sqrt{s_{NN}} \geq 7.7$ GeV

Partonic collectivity

Kaon v_1 in the High Baryon Density

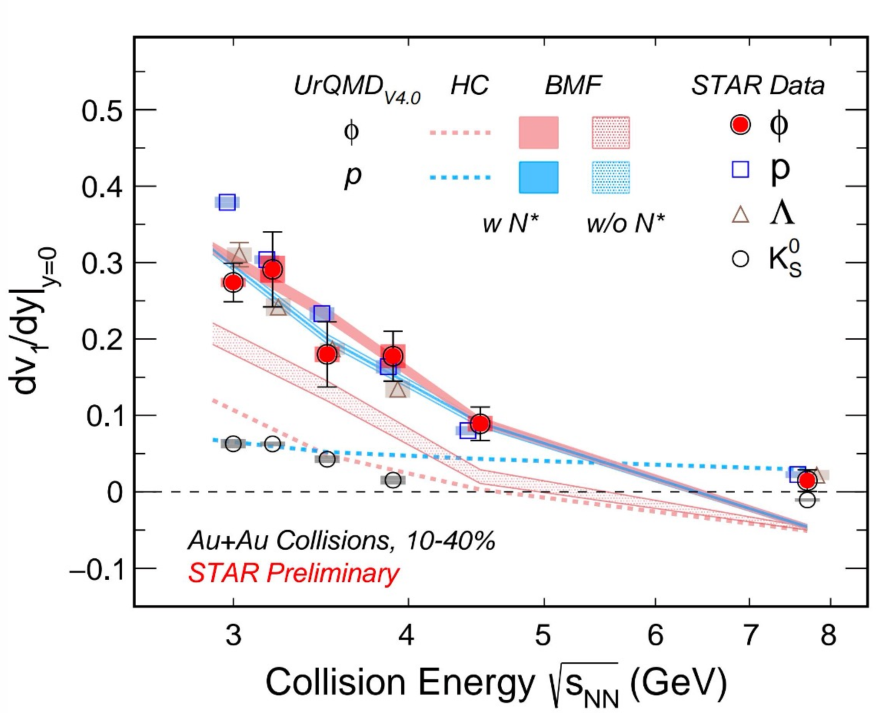
STAR: arxiv: 2503.23665, accepted by PLB
E895, Phys. Rev. Lett. 85, 940 (2000)





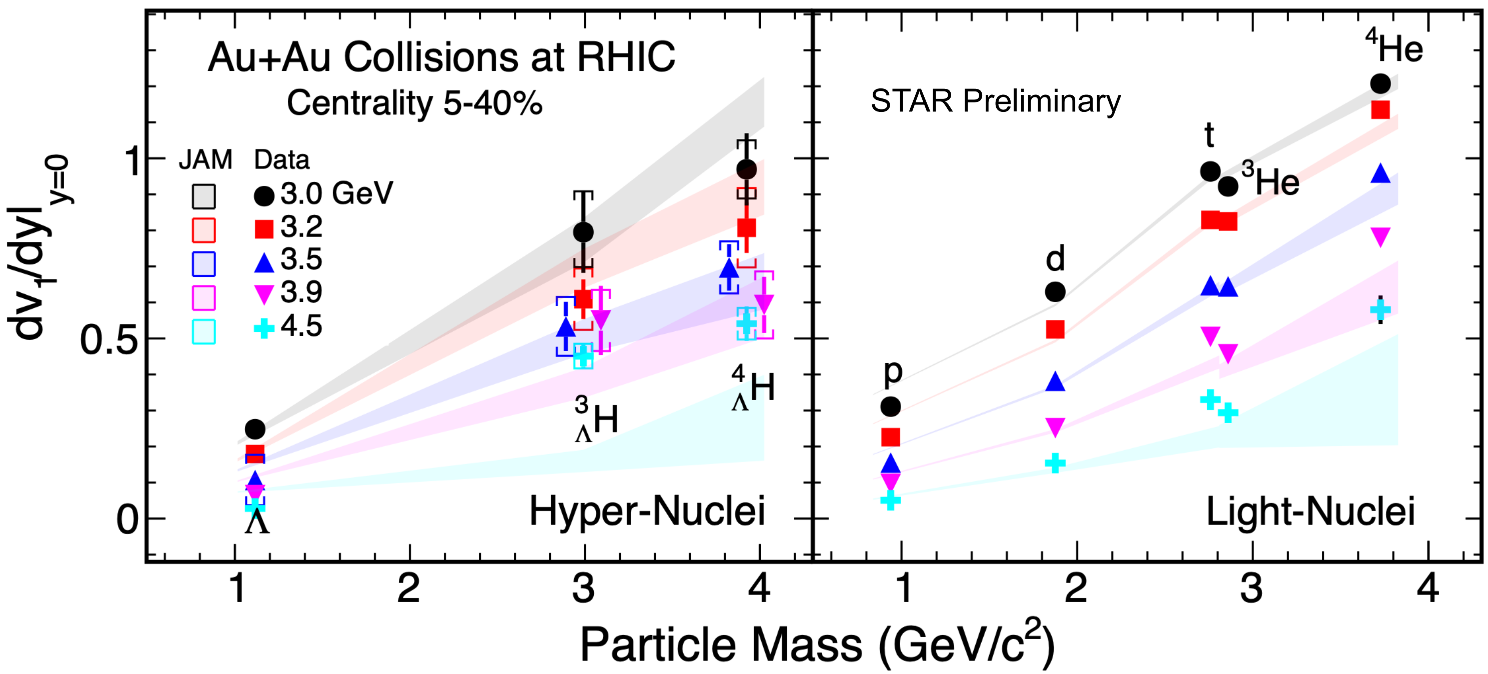
- ➢K_S^0 anti-flow: STAR measurement 8 times smaller than E895
- ➢20 years of kaon potential theories need re-examination

φ v_1 in the High Baryon Density



- φ v_1 at 3-4.5 GeV – 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
- Why φ shows strong flow but other mesons don't?
  → Possibly due to φ–N cross section

v_1 of (Hyper)nuclei



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

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

JAM + afterburner reproduces data

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

Possible signature of different NY vs. NN interactions

Summary

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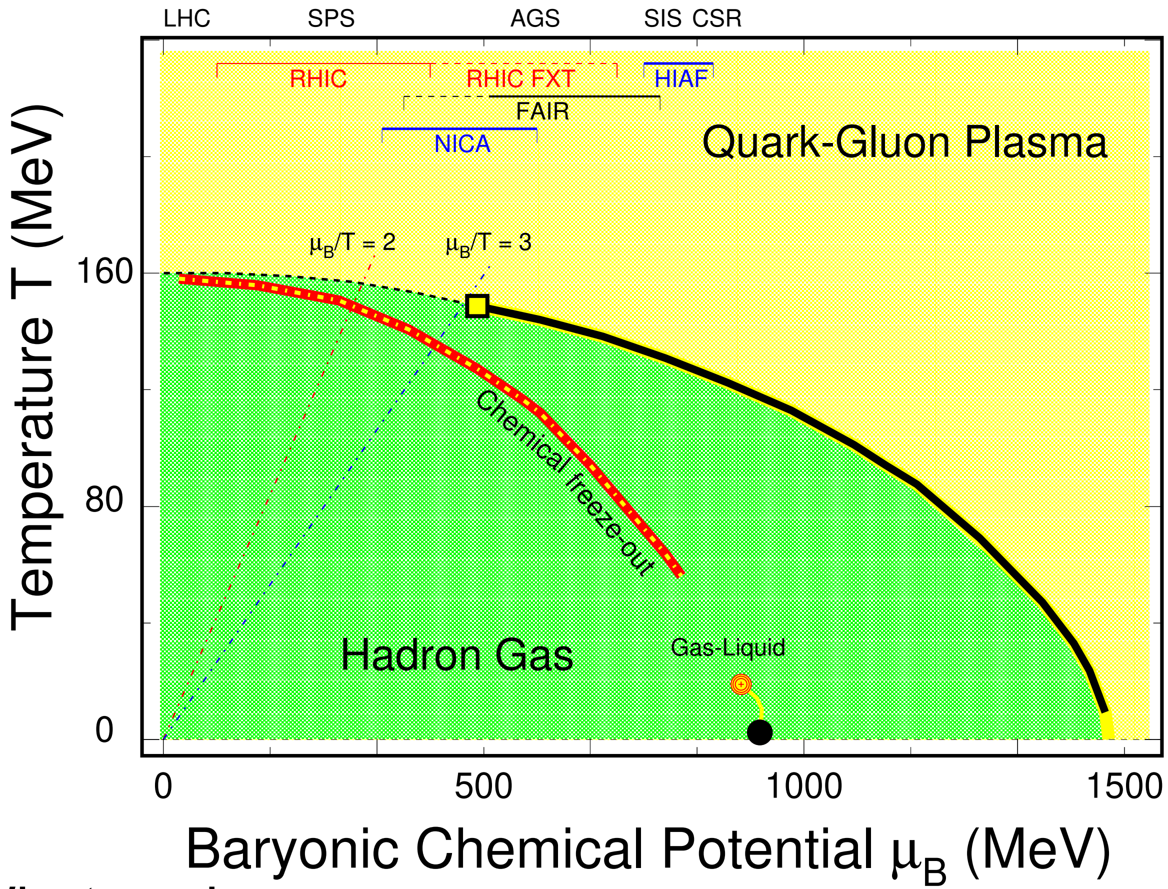
Probing Degrees of Freedom

- **$v_0(p_T)$:** probes radial collectivity and transport coefficients
- **NCQ scaling on v_2:** onset at ~4.5 GeV

High Baryon Density Region

- **Kaon anti-flow:** spectator shadowing, kaon potential theories need re-examination
- **φ flow:** driven by high-mass baryon resonances
- **(Hyper)nuclei flow:** supports nucleon coalescence, constrains YN interaction

Outlook



➢What we know:

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

➢What's next (CBM/MPD/CEE):

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)

Thank you!