Collective properties of the nuclear matter at RHIC

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Diffraction and Low-x

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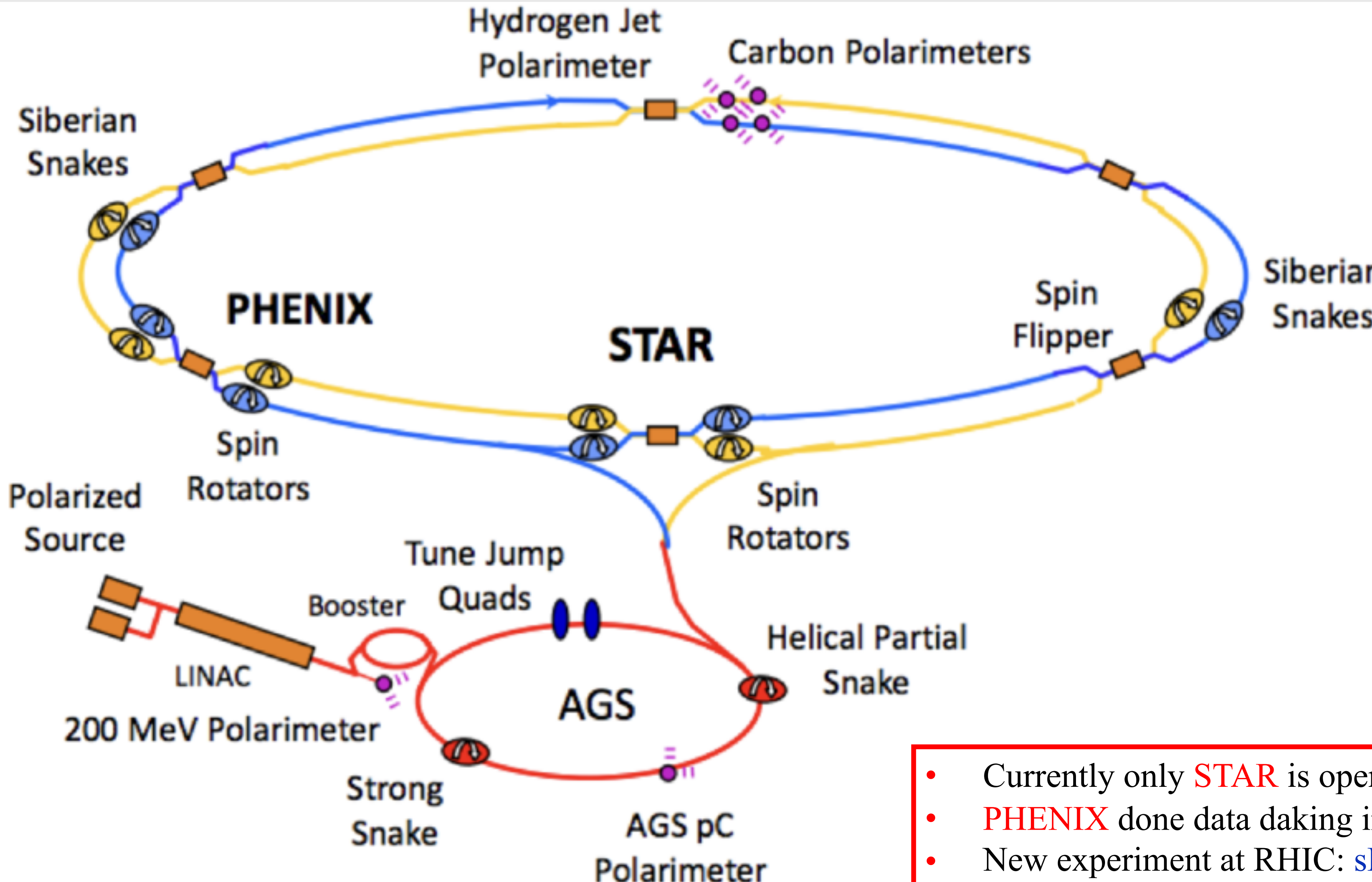
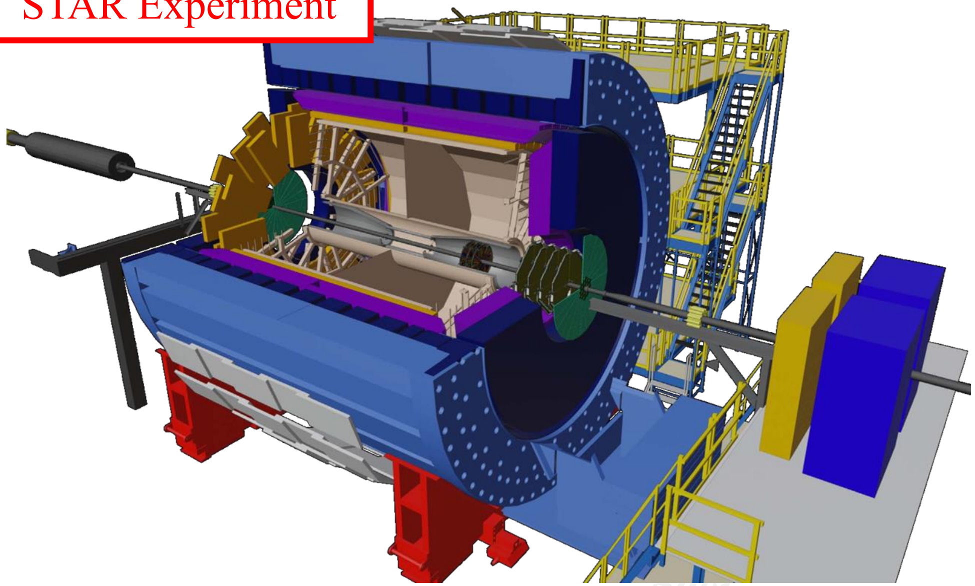
Relativistic Heavy-Ion Collider



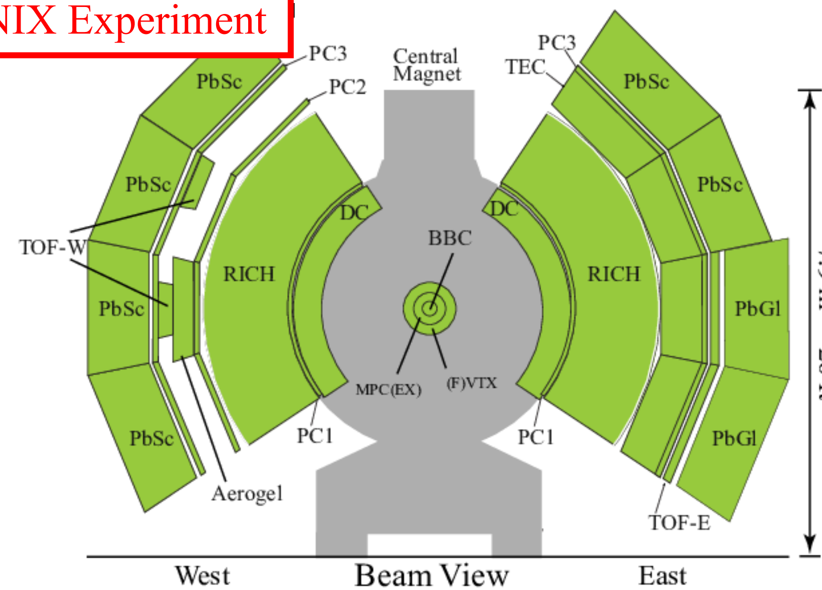
- Currently only STAR is operational.
- PHENIX done data daking in 2016
- New experiment at RHIC: sPHENIX

STAR and PHENIX experiments

STAR Experiment



PHENIX Experiment

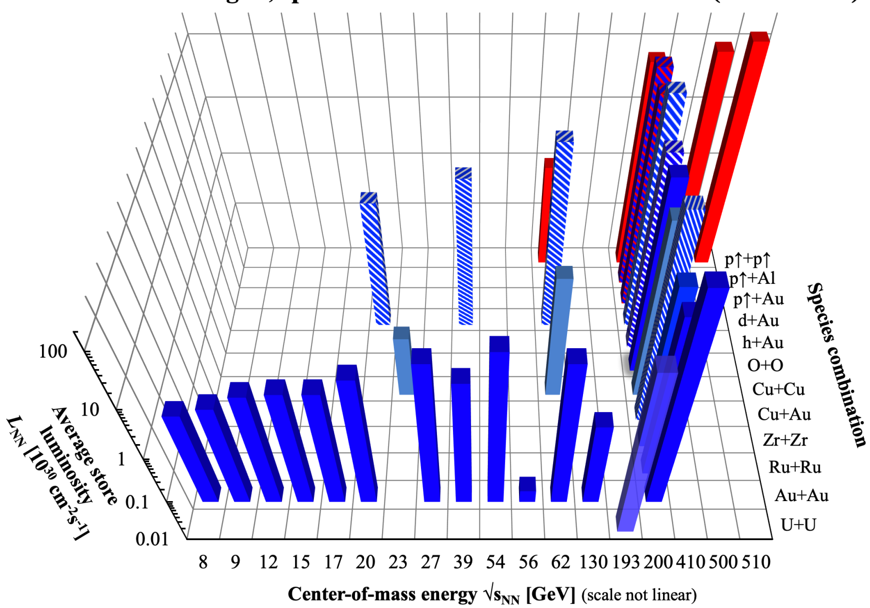


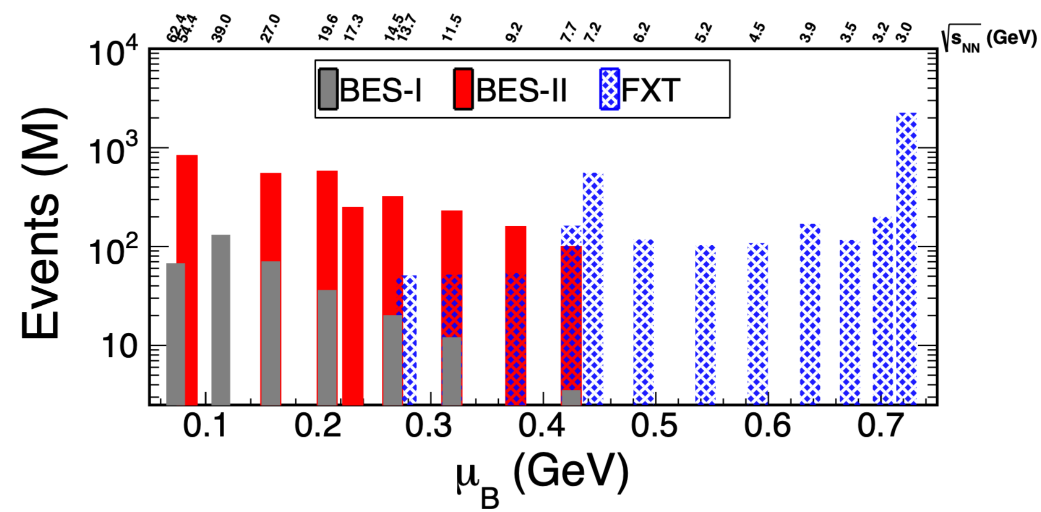
- TPC: Tracking and particle identification
- TOF: Extended PID
- EPD: Independent centrality detector, improved EP resolution, trigger
- Recent upgrades: FCS, FTS, EMcal & HCal, iTPC, eTOF

- Central and Muon Arms: Tracking and particle idenfication
- TOF east and west: PID in the forward region
- BBC, ZDC: Event characterization, centrality and trigger
- Recent upgrades: sPHENIX

Beam energies and colliding systems RHIC

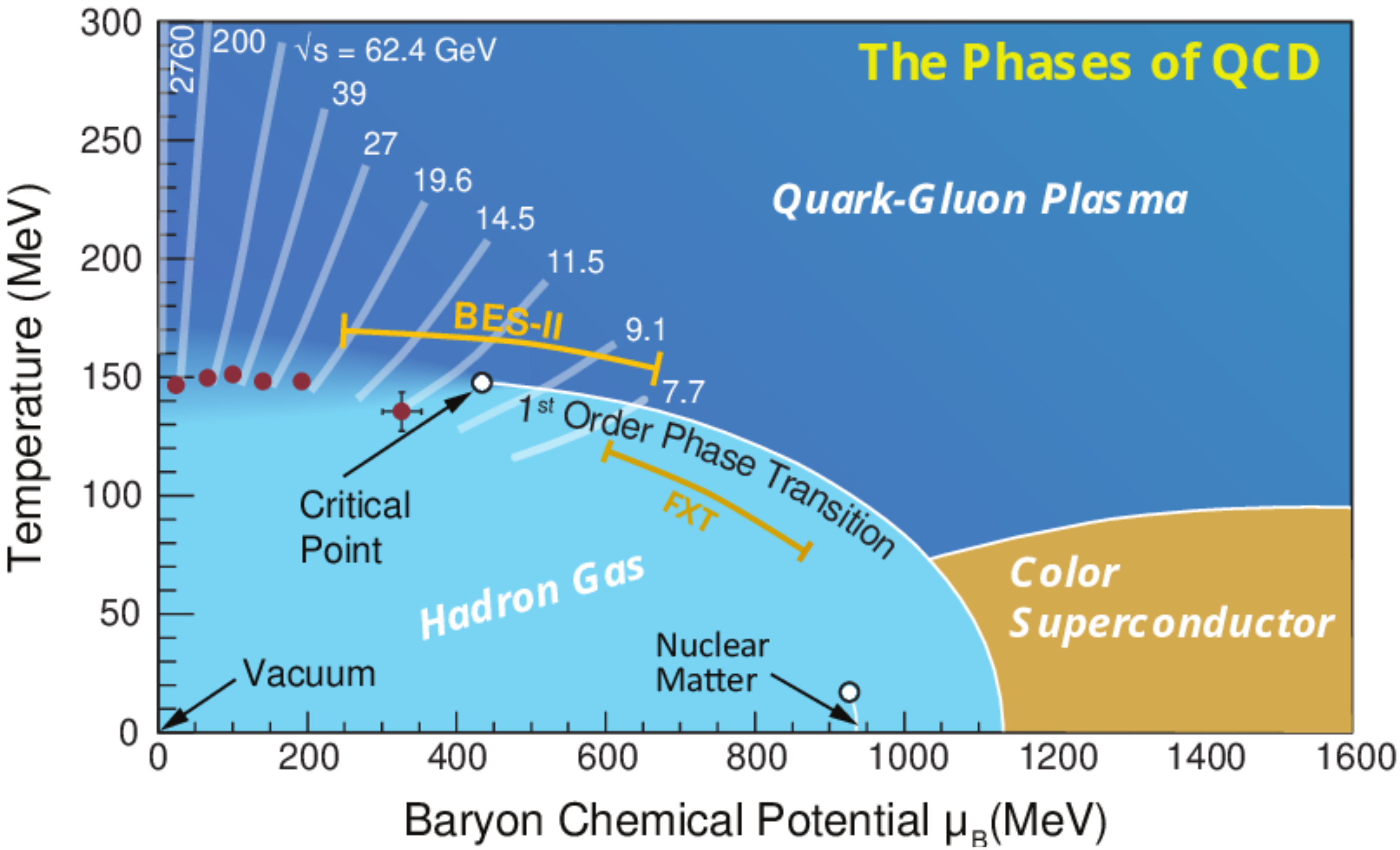
- Wide range of collision beam energies to explore QCD phase diagram
  - Beam Energy Scan Phase II (BES-II): $\sqrt{s_{NN}}$ = 7.7 – 54.4 GeV
  - Fixed Target (FXT): $\sqrt{s_{NN}}$ = 3.0 – 7.7 GeV
- Different collision species to study the QCD medium at top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV
  - U+U, Au+Au, Ru+Ru, Zr+Zr, Cu+Cu, O+O, Cu+Au, *He*³+Au, *d*+Au, *p*+Au etc
- Increase in statistics over the years for precision measurement





https://www.agsrhichome.bnl.gov/RHIC/Runs/

Phase structure of QCD matter

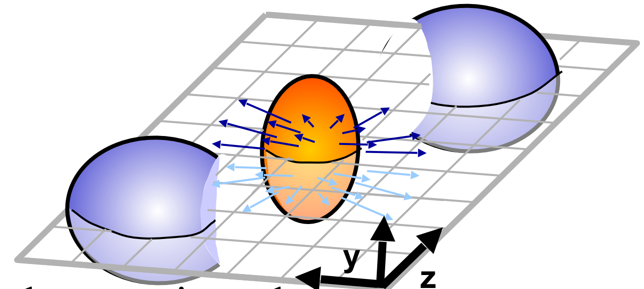


Conjectured QCD phase diagram can be explored by beam energy scan in heavy-ion collisions

Collective Flow

- Collective flow describe the response of the medium produced in heavy-ion collisions
- Collective flow can be quantified using the Fourier expansion:

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum 2v_n \cos n(\phi - \Psi_n^{EP})\right)$$



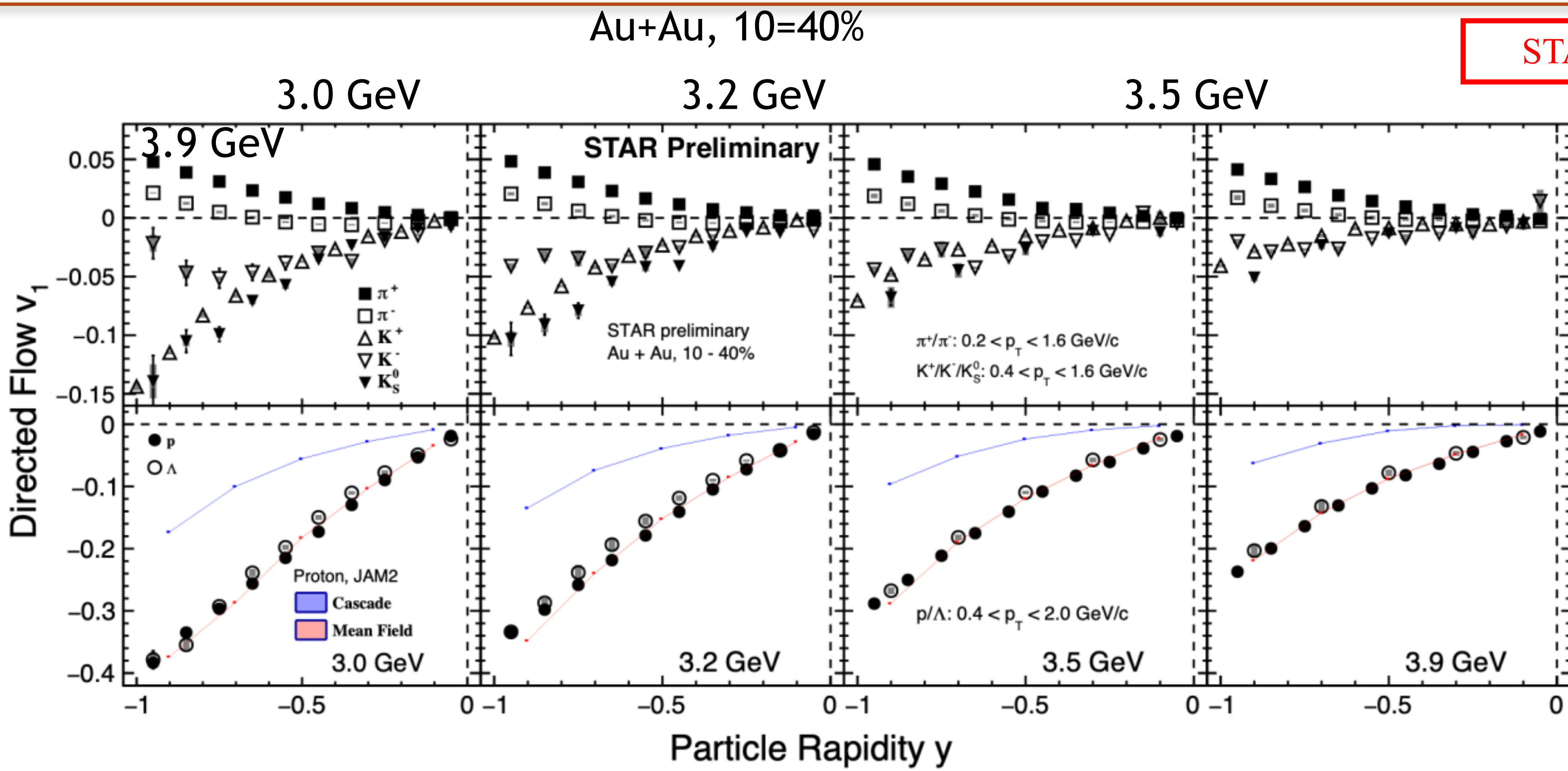
- Different flow coefficients:
  - → Directed Flow (v_1): Sideward deflection of produced particles in the reaction plane
  - → Elliptic Flow (v_2): Result of pressure gradients caused by the initial overlap geometry
  - → Triangular Flow (v_3): Produced by event-by-event fluctuations in the initial shape

- **Sensitive to initial conditions, equation of state, transport properties (η/s) of system, and initial state fluctuations**
- **Probe for the particle production mechanism (e.g. quark coalescence)**

[1] A. M. Poskanzer & S.A. Voloshin, Phys. Rev. C 58, 1671 (1998).
[2] S. A. Voloshin, A. M. Poskanzer & R. Snellings, Landolt-Bornstein 23, 293-333 (2010).

Collectivity at high μ_B

STAR



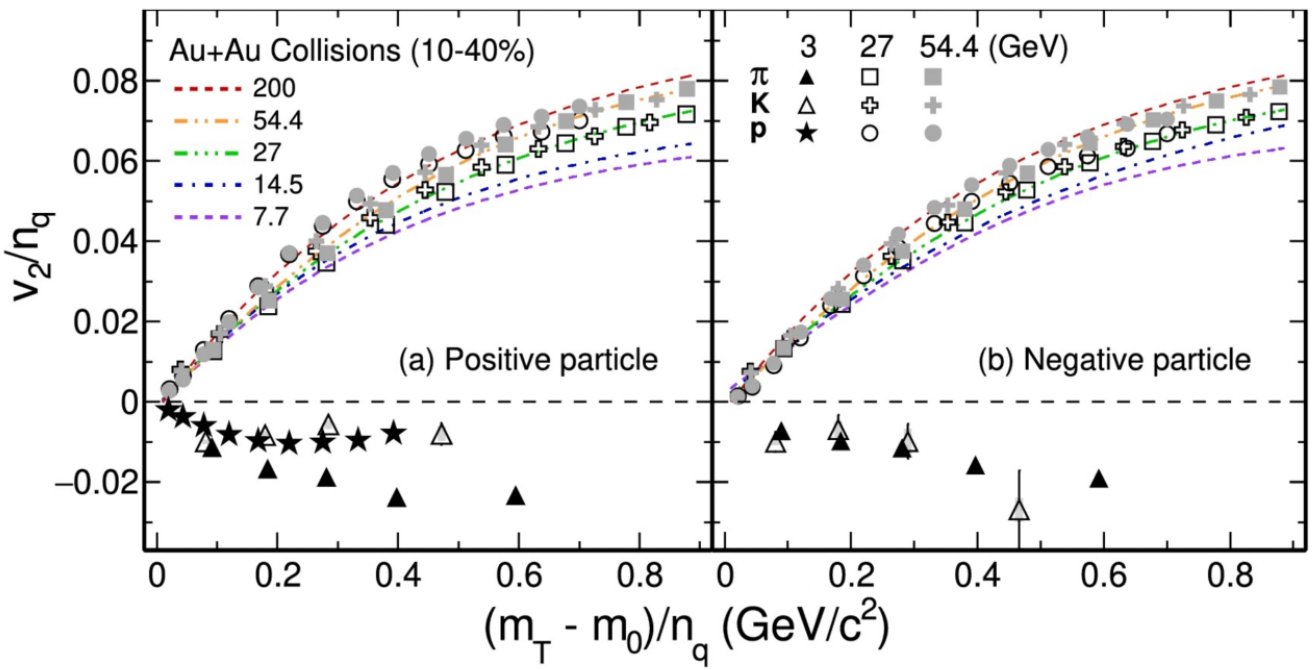
Directed flow $v_1(y)$ of hadrons across various beam energies with high μ_B

JAM model with momentum dependent baryonic mean-field describes baryon flow

M. S. Abdallah et al. (STAR Collaboration) Phys. Lett. B 827, 137003 (2022)

Collectivity at high μ_B

STAR



NCQ scaling holds in Au+Au collisions from top RHIC energy $\sqrt{s_{NN}}$ = 200 to 7.7 GeV

Partonic collectivity

Negative v_2 values and breaking of NCQ scaling at $\sqrt{s_{NN}}$ = 3 GeV

Indicative of medium dominated by hadronic interactions

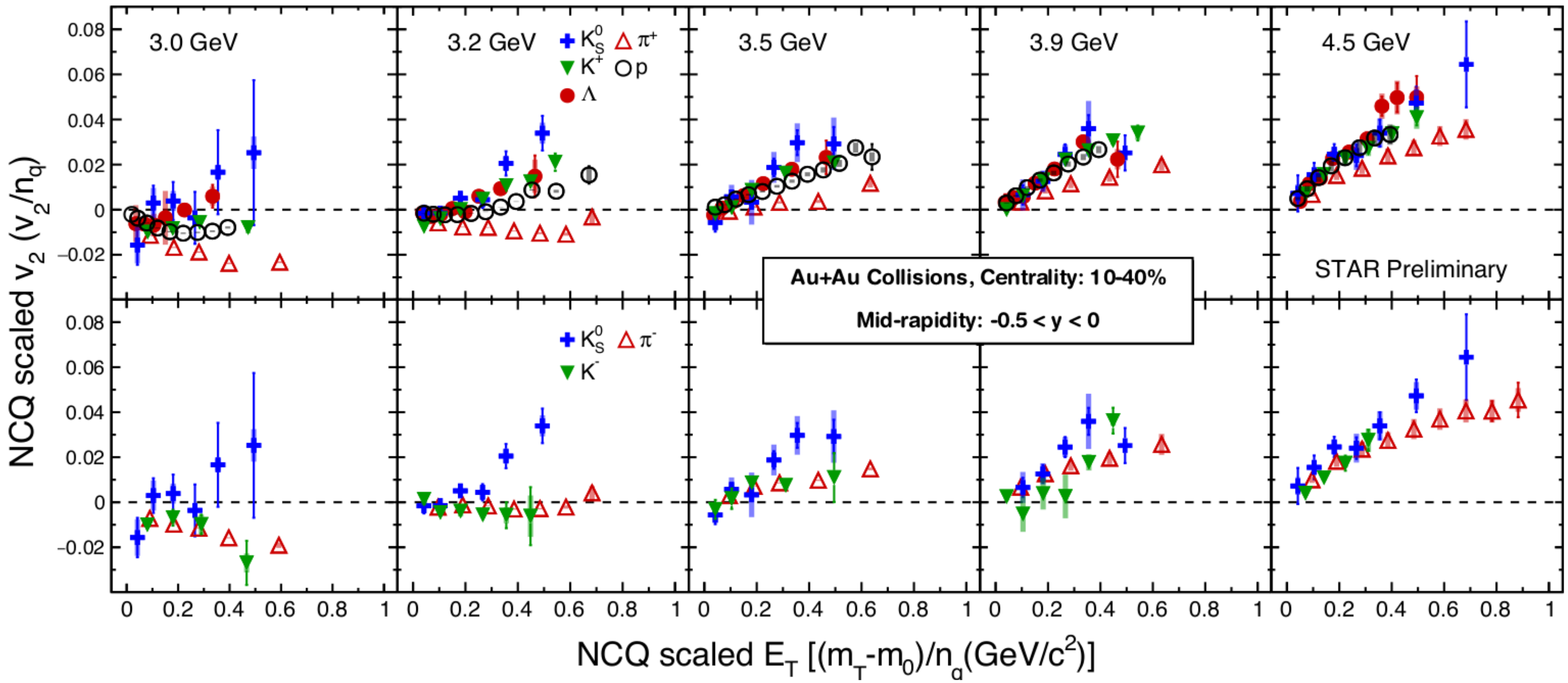
[1] L. Adamczyk et al. (STAR Collaboration) Phys. Rev. C 88, 014902 (2013)
[2] M. S. Abdallah et al. (STAR Collaboration), Phys. Rev. C 103, 034908 (2021); Phys. Lett. B. 827 137003 (2022)

Collectivity at high μ_B

Au+Au, 10=40%

STAR

3.0 GeV, 3.2 GeV, 3.5 GeV, 3.9 GeV, 4.5 GeV



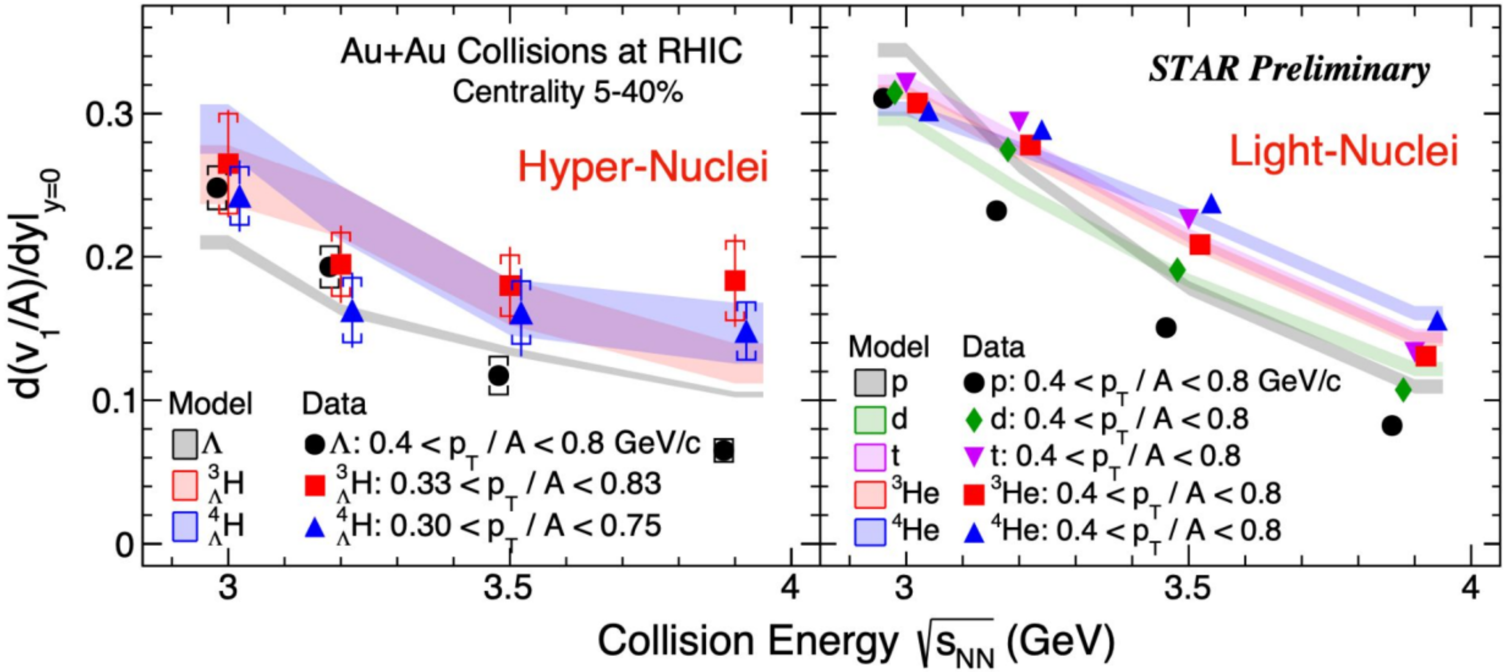
NCQ scaling is broken in Au+Au collisions below 3.2 GeV and gradually improves in Au+Au collisions from 3.2 to 4.5 GeV

Indication of transition from hadronic dominated medium to partonic medium

B. Trzerziak et al (STAR) ICNFP 2024

Collectivity at high μ_B

STAR



The mid-rapidity v_1 slope of light and hyper-nuclei decreases with increasing collision energy

JAM2 model with mean field + Coalescence is consistent with observed energy dependence

Indicating coalescence as production mechanism at high μ_B

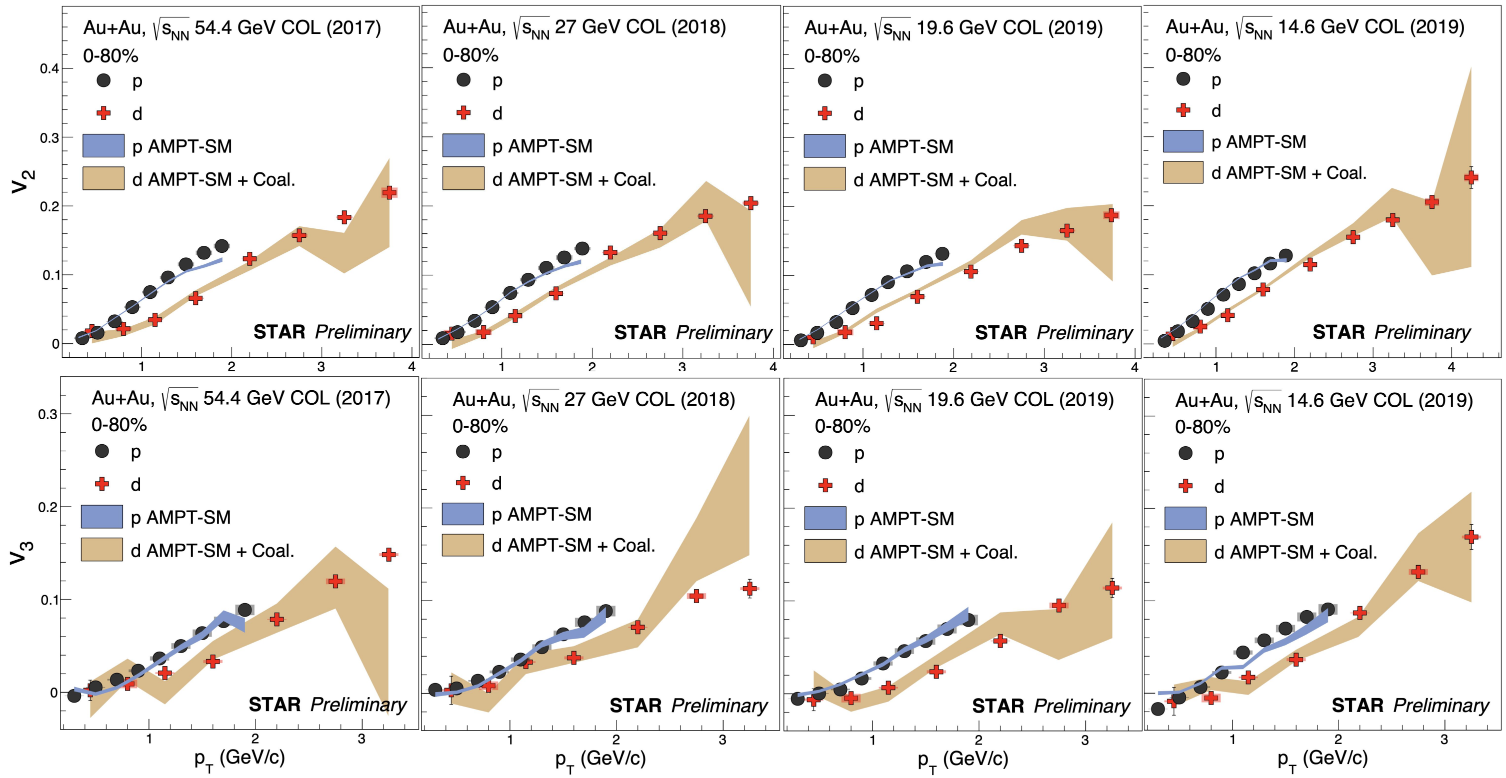
[3] Yasushi Nara, Akira Ohnishi. Phys. Rev. C 105, 014911 (2022)

Collectivity at high μ_B

STAR

v2

v3



Au+Au, 0-80%, 54.4, 27, 19.6, 14.6 GeV

AMPT(SM) model with coalescence describes deuteron v_2 and v_3

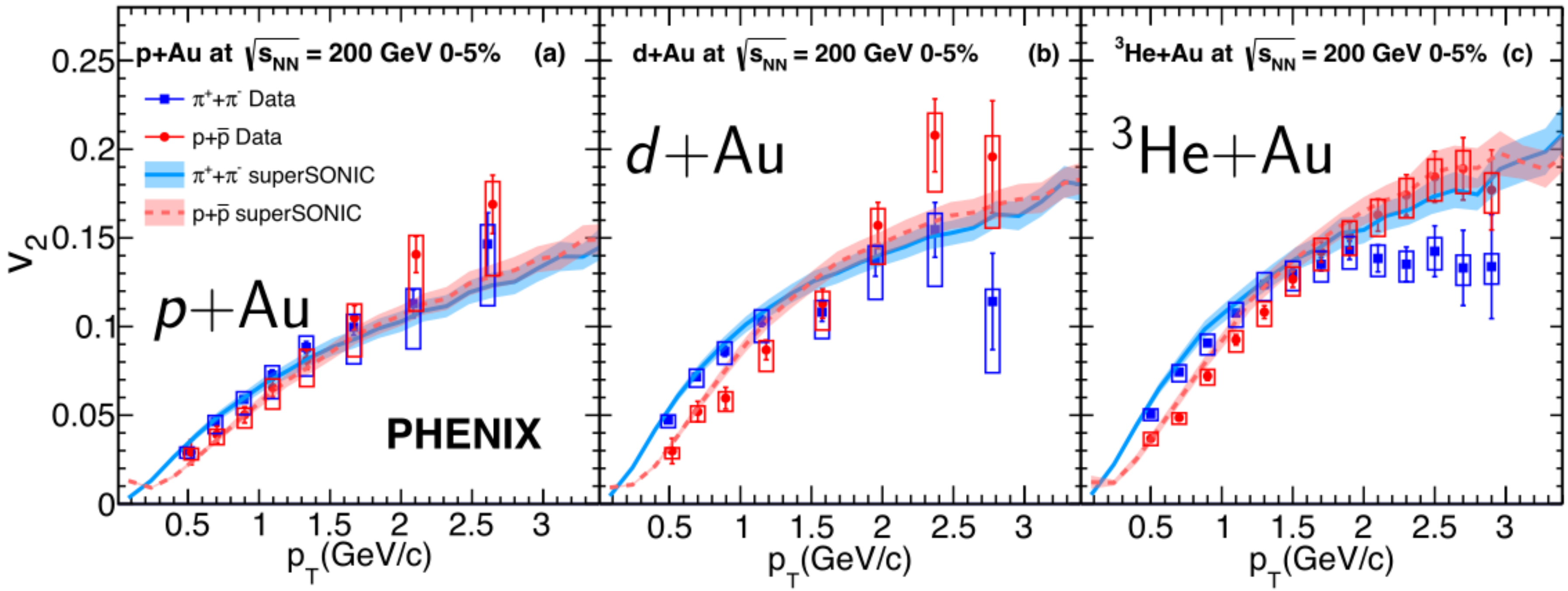
Insights to light nuclei production mechanism in heavy-ion collisions

[1] L. Adamczyk et al. (STAR Collaboration) Phys. Rev. C 88, 014902 (2013) [2] M. S. Abdallah et al. (STAR Collaboration), Phys. Rev. C 103, 034908 (2021)
[3] M. S. Abdallah et al. (STAR Collaboration) Phys. Lett. B. 827 137003 (2022) [4] Z.-W. Lin et al., Phys. Rev. C 72, 064901 (2005)

Collectivity in small systems

PHENIX

v2, p+Au, d+Au, 3He+Au, 200 GeV 0=5%

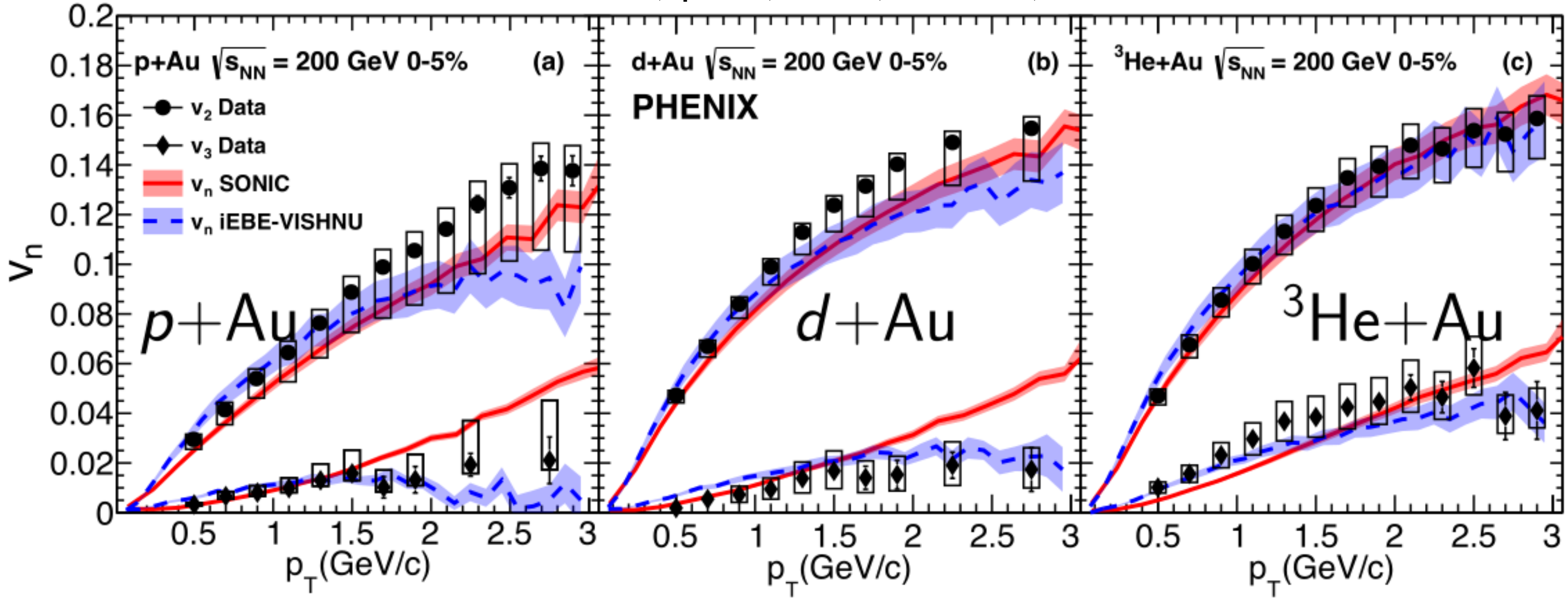


Mass ordering of identified hadrons $v_2(p_T)$ is well-described by hydrodynamics in small systems

Collectivity in small systems

PHENIX

v2 and v3, p+Au, d+Au, 3He+Au, 200 GeV 0=5%



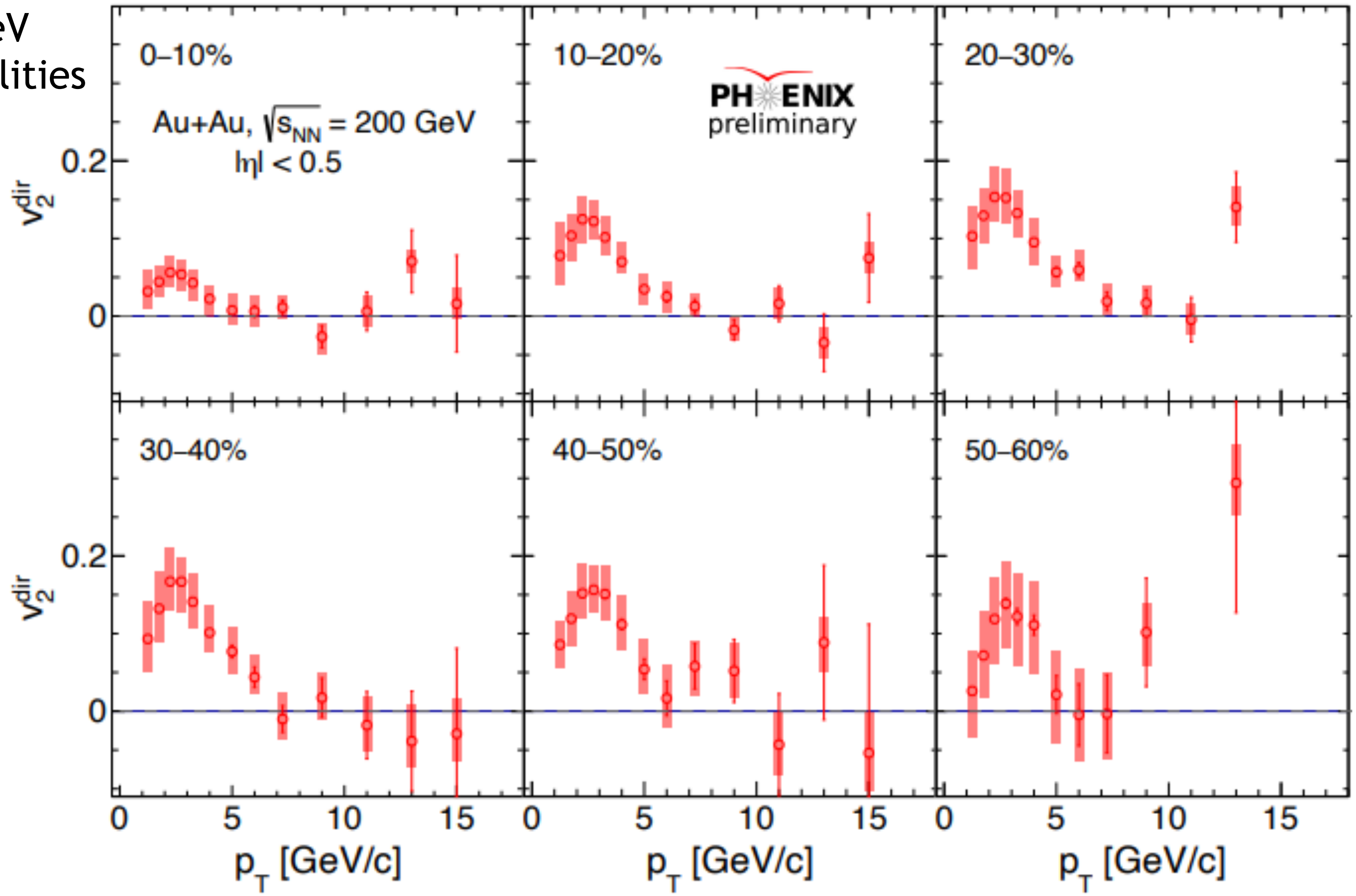
Charged hadron v_2 and v_3 are well-described by hydrodynamics in small systems

Strong indication of QGP formation in small systems

Direct Photon Flow at PHENIX

PHENIX

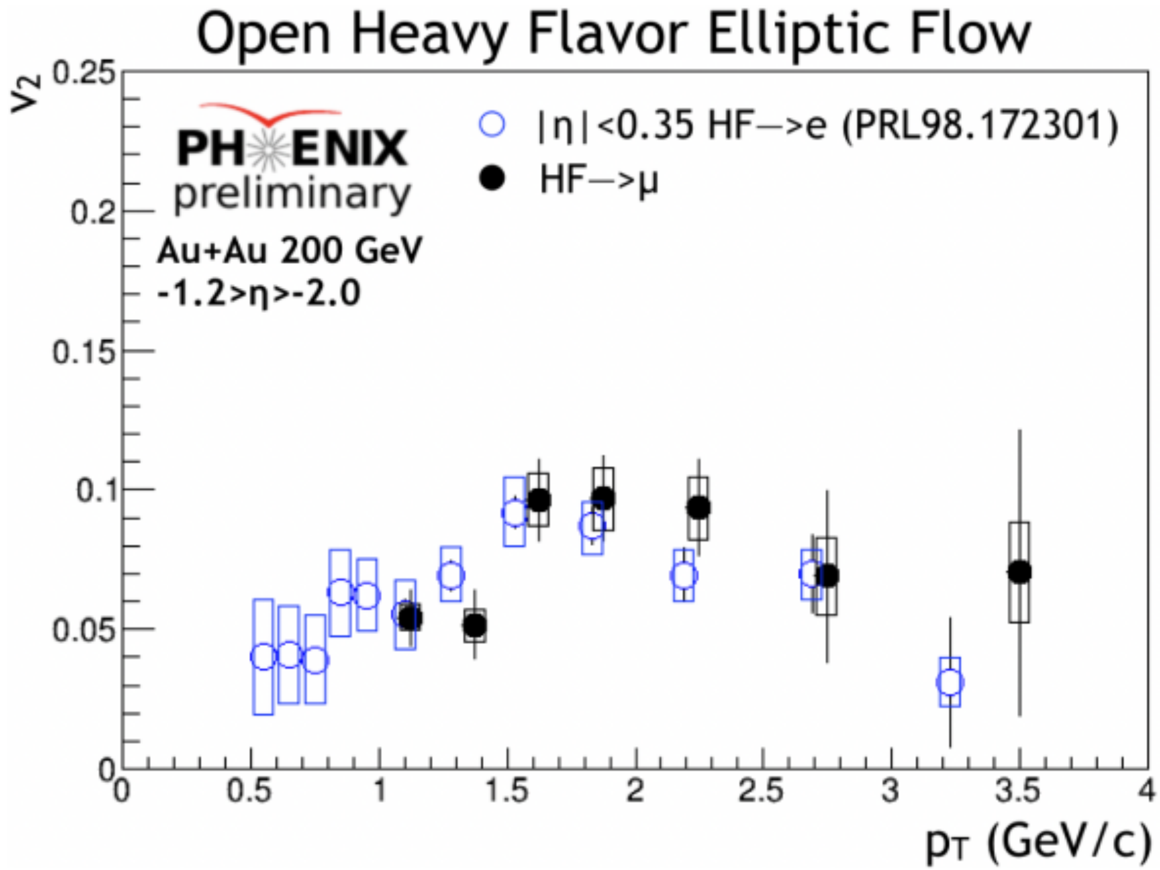
Au+Au, 200 GeV
various centralities



Direct photons v_2 in the high p_T region is diminishing

Open Heavy Flavor Flow at PHENIX

PHENIX



First-ever RHIC measurement of open heavy flavor elliptic flow at forward rapidity

Open heavy flavor v_2 consistent with PHENIX mid-rapidity results

Summary & Outlook

Collectivity in high μ_B region

- Absence of NCQ scaling at $\sqrt{s_{NN}}$ = 3 and 3.2 GeV indicate baryonic interactions dominating nulcear EoS
- NCQ scaling gradully improves from 3.2 to 4.5 GeV, indicating dominance of partonic interactions for $\sqrt{s_{NN}} >=$ 4.5 GeV

Light nuclei collectivity

- Hadronic transport model (JAM + Coalescence) indiacates coalescence to be the dominant mechanism of light and hyper nuclei production in heavy-ion collisions

Direct photon collectivity

- Elliptic flow of direct photons in high p_T region is consistent with zero

Open Heavy-Flavor flow

- Open heavy flavor v_2 first-ever RHIC measurement in mid and forward rapidity

More exciting results to come from the high statistics data of BES and FXT program RHIC
Collectivity from small to large systems and measurements in wider rapidity ranges using forward detectors enable us to explore the QGP properties, phase transition and more....