Supported in part by the U.S. DEPARTMENT OF ENERGY Office of Science

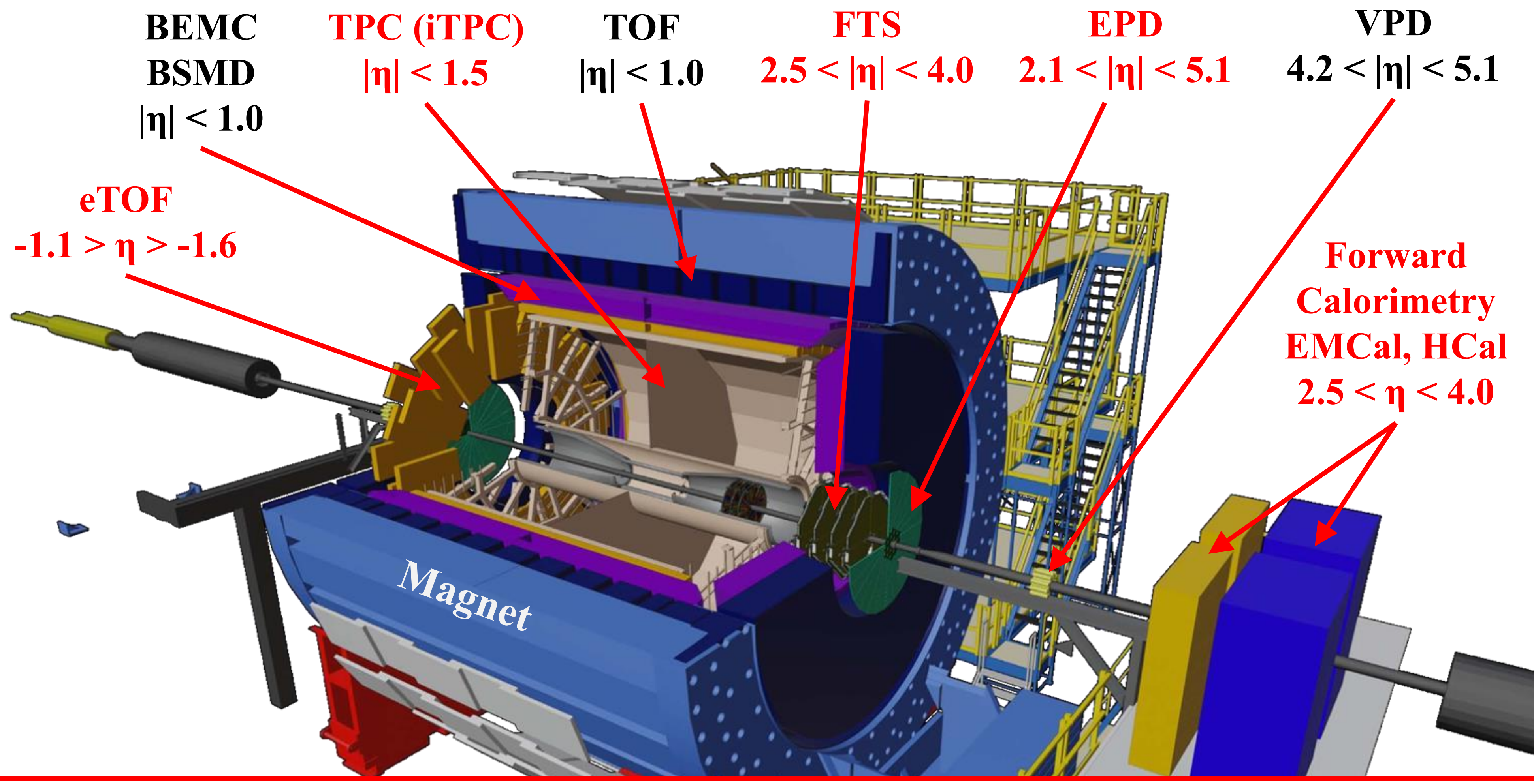
Collective dynamics of the nuclear matter from the STAR experiment at RHIC

Vipul Bairathi *(for the STAR Collaboration)*
Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile

Outline

- Introduction: STAR Experiment at RHIC
- Motivation
- Collective flow
  - Collectivity at high μ_B
  - Collectivity in small systems
  - System size and shape dependence
- Summary

STAR experiment at RHIC

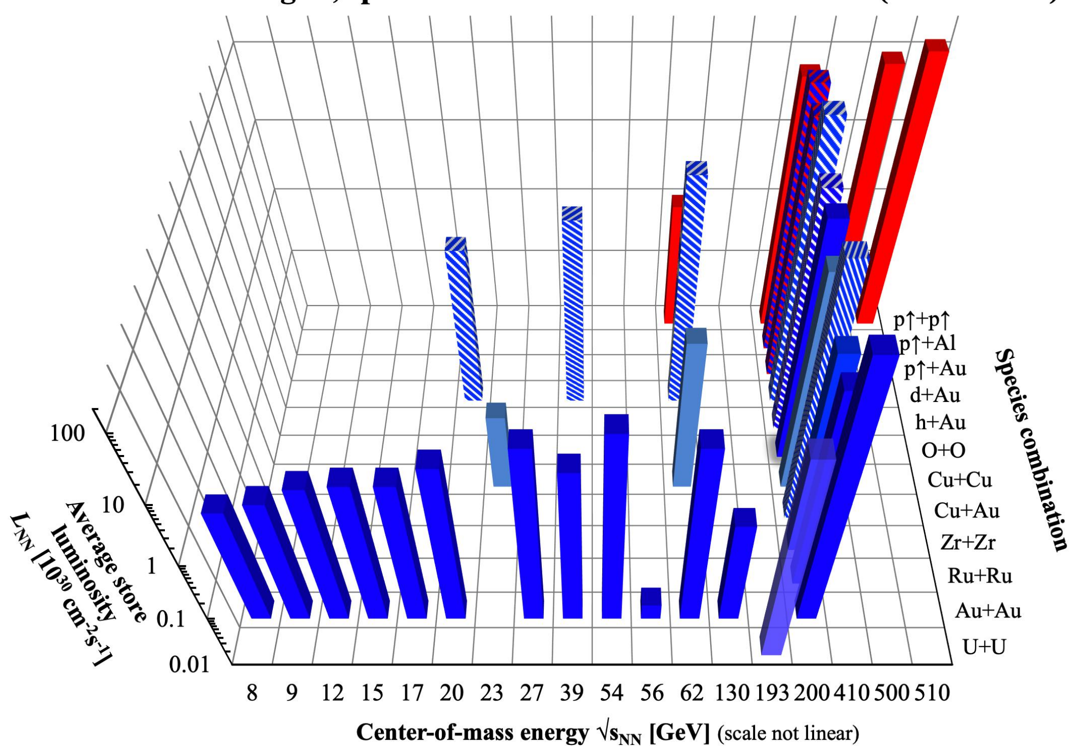


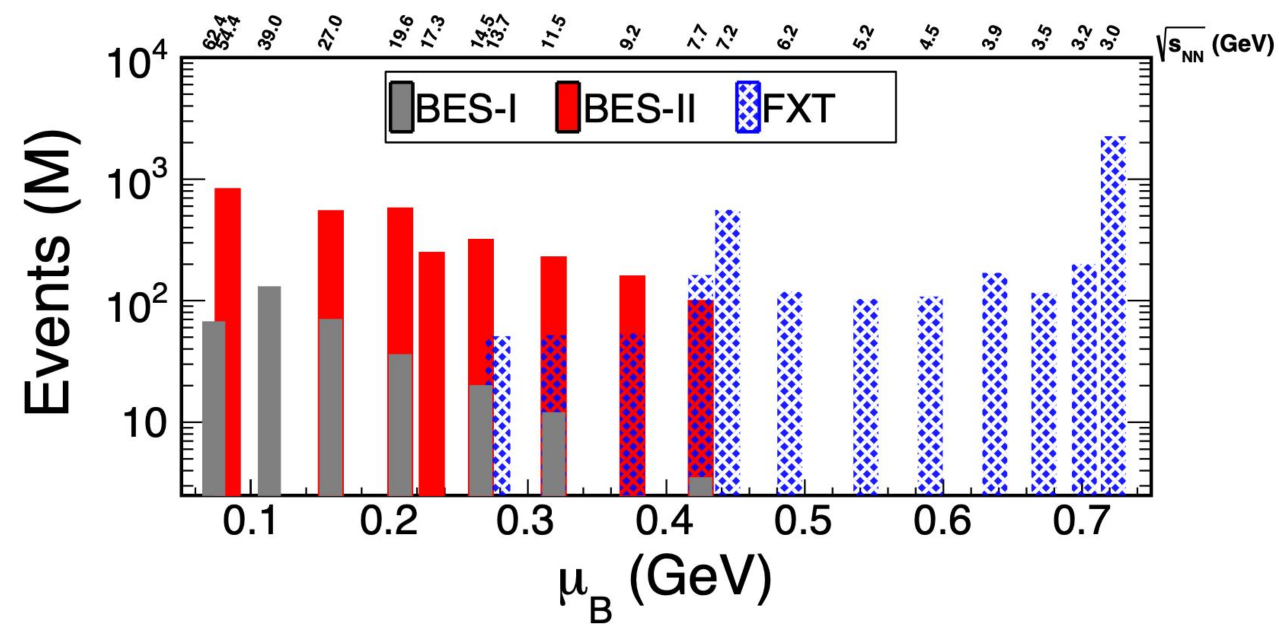
- iTPC: Improved tracking, extended acceptance to $|\eta| < 1.5$, better dE/dx and momentum resolution
- eTOF: Extended PID in the forward region
- EPD: Independent centrality detector, Improved EP resolution, Trigger
- Recent forward upgrades: FCS, FTS, EMcal & HCal

Beam energies and colliding systems at STAR

- 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 – 13.7 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, ^{3}He+Au, d+Au, p+Au
- Increase in statistics over the years for precision measurement

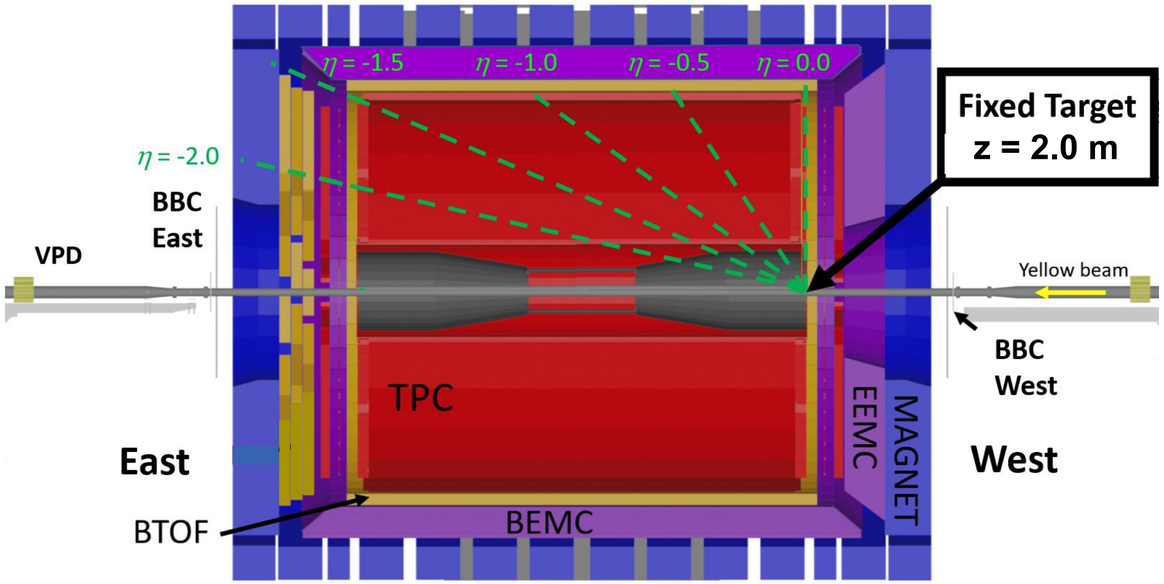
RHIC energies, species combinations and luminosities (Run-1 to 22)





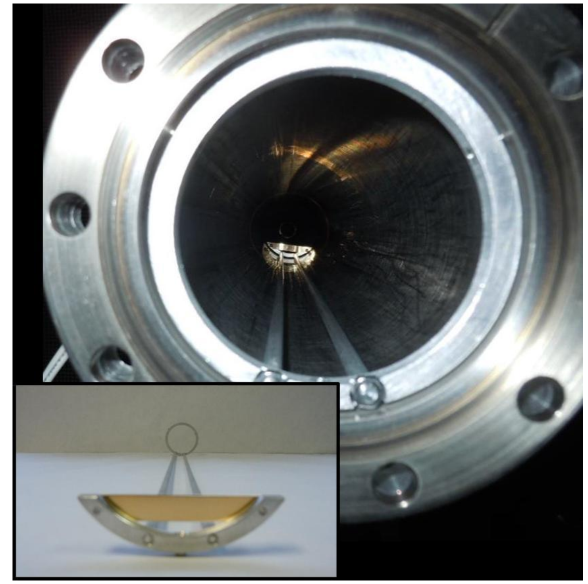
https://www.agsrhichome.bnl.gov/RHIC/Runs/

STAR Fixed Target (FXT) Setup

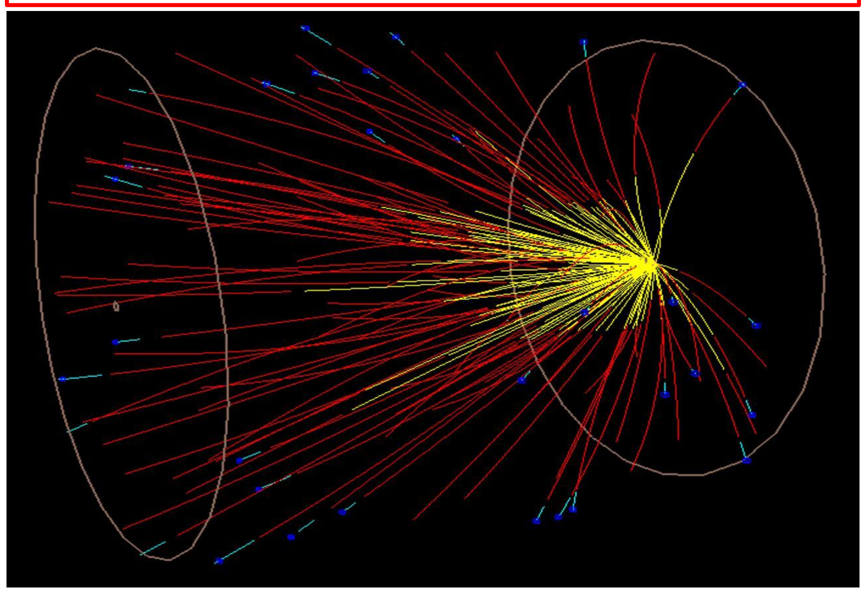


Gold target:

- 2 cm below nominal beam axis
- 2.0 m from center of STAR
- 0.25 mm foil



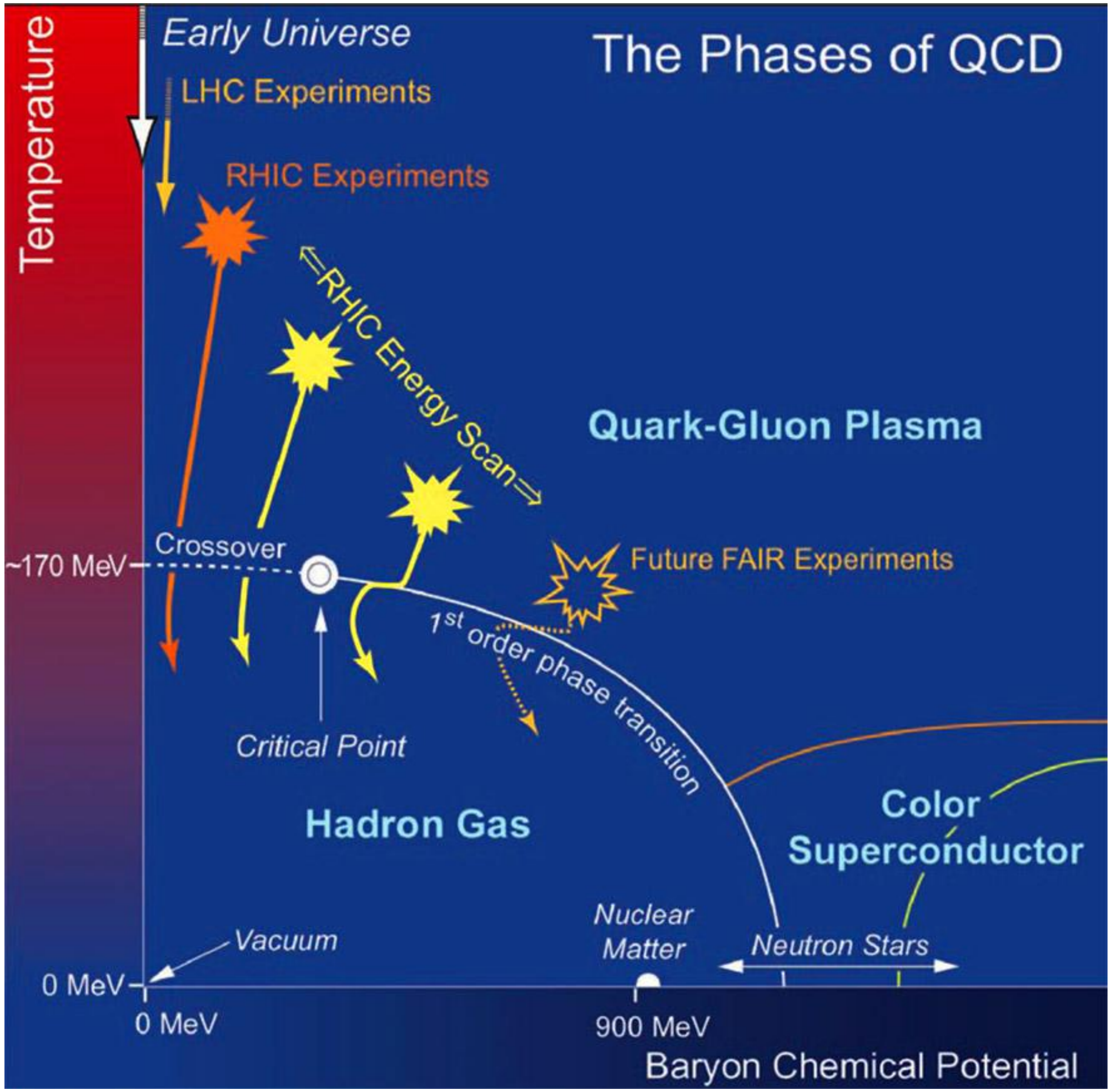
Au+Au at $\sqrt{s_{NN}}$ = 4.5 GeV event



Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18
3.85	3.0 (FXT)	721	13.7 days	(1.7 B)	Run-21

STAR: M. S. Abdallah et al. Phys. Rev. C 103 (2021) 034908

Exploring phase structure of QCD matter



Conjectured QCD Phase diagram

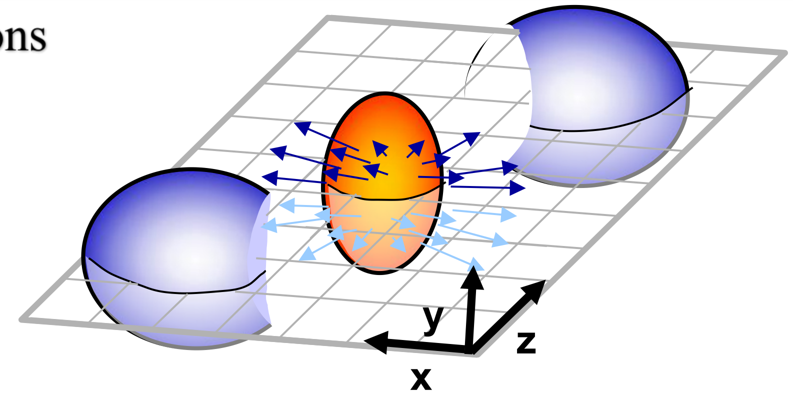
- Explore QCD phase diagram by varying baryon chemical potential and temperature via beam energy scan (BES)
- BES program at RHIC provide an experimental way to study nuclear matter at finite μ_B
- Properties of the QCD matter can be probed through bulk observables such as collective flow
- Provide a chance to study phase transition and to constrain initial conditions and geometry by studying fluctuations

STAR White Paper II
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Collective Flow

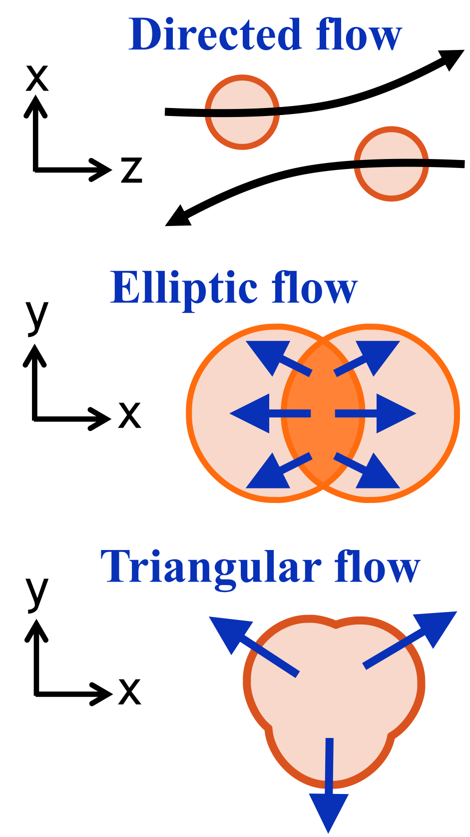
- Collective flow describe the response of the medium produced in heavy-ion collisions

- 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

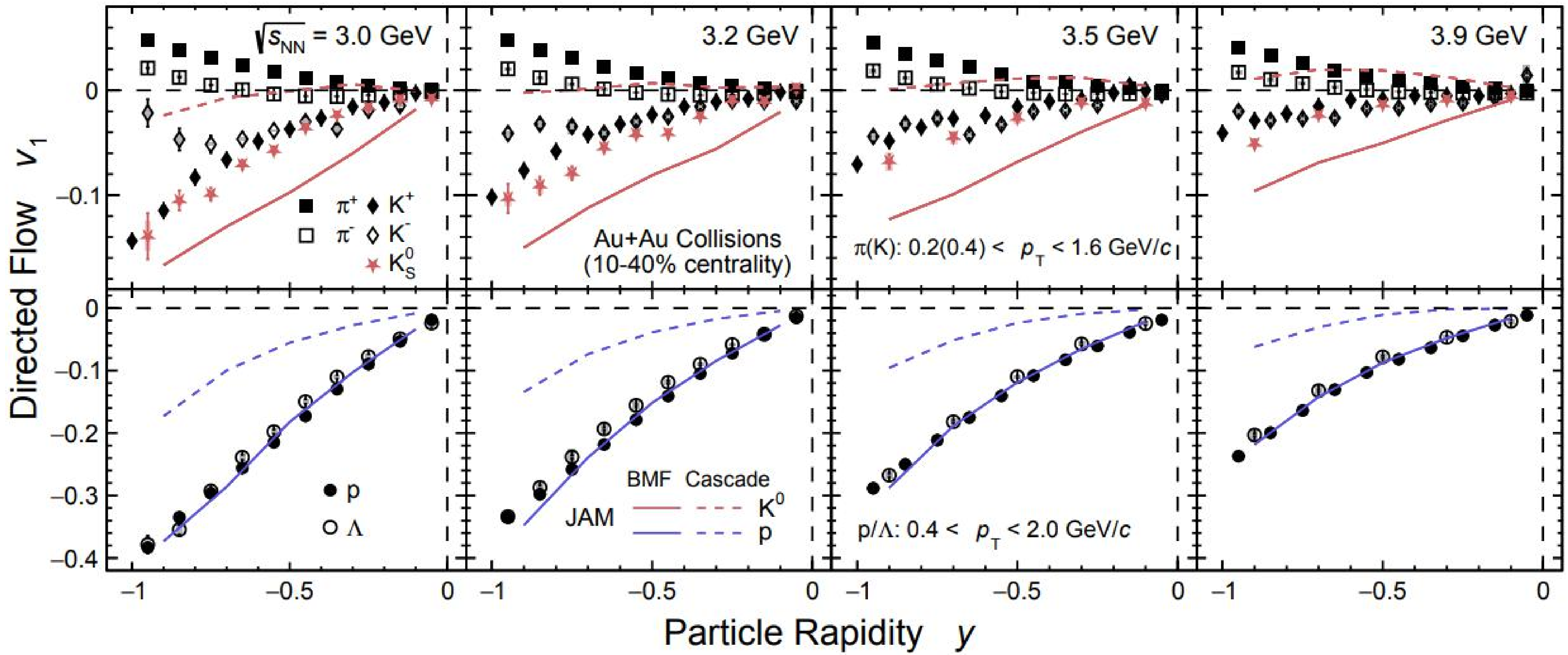


- **Sensitive to initial conditions, equation of state, transport properties (η/s) of system, and initial state fluctuations**
- **Probe for the particle production mechanism (e.g. quark coalescence)**

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

Collectivity at high μ_B

Directed flow at high μ_B



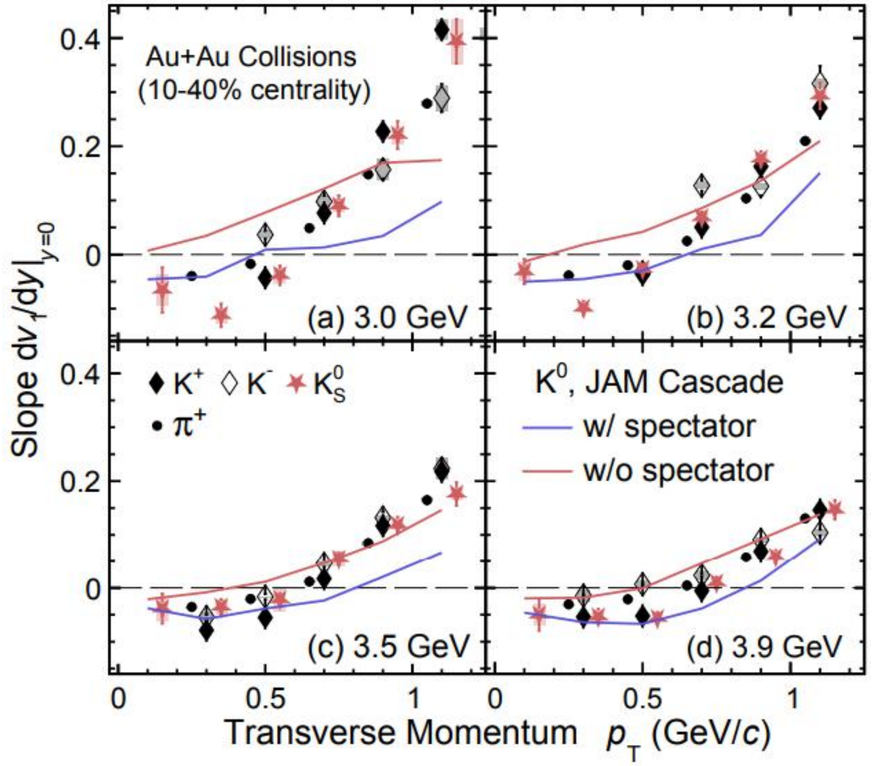
- Directed flow $v_1(y)$ of π, K, p, and Λ measured across various beam energies with high μ_B
- JAM model with momentum dependent baryonic mean-field describes baryon flow compared to cascade model without the mean-field potential

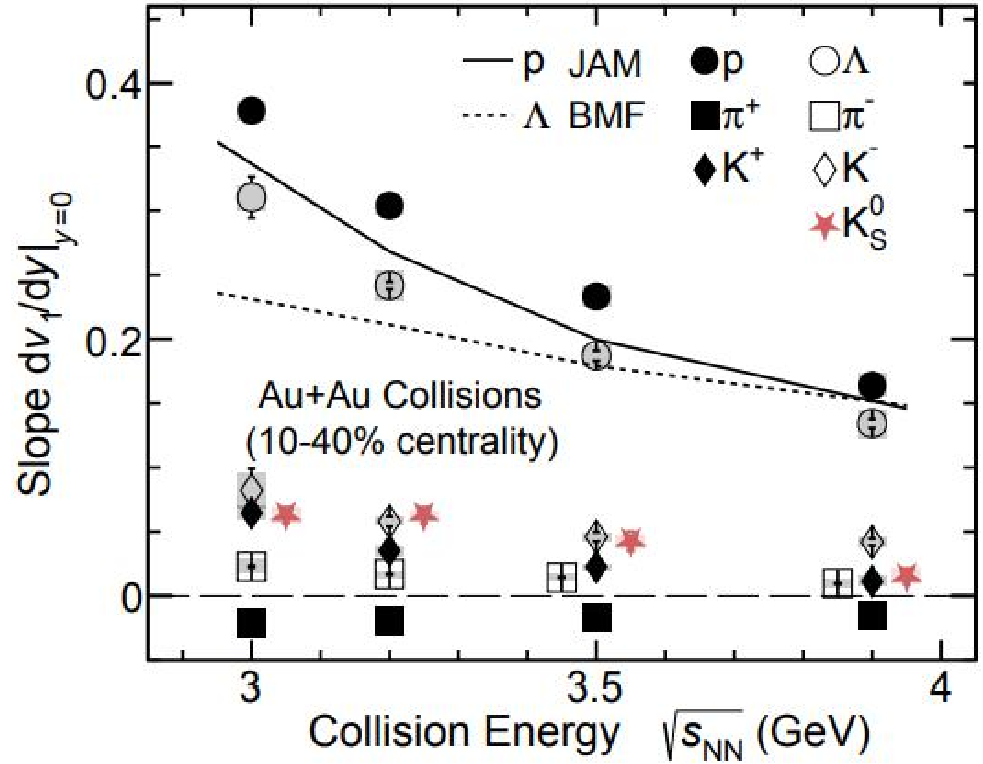
JET AA Microscopic Transport Model

- MS2: momentum dependent mean-field potential
- Incompressibility constant κ = 210 MeV

STAR: arXiv:2503.23665 [nucl-ex] (2025)

Directed flow at high μ_B

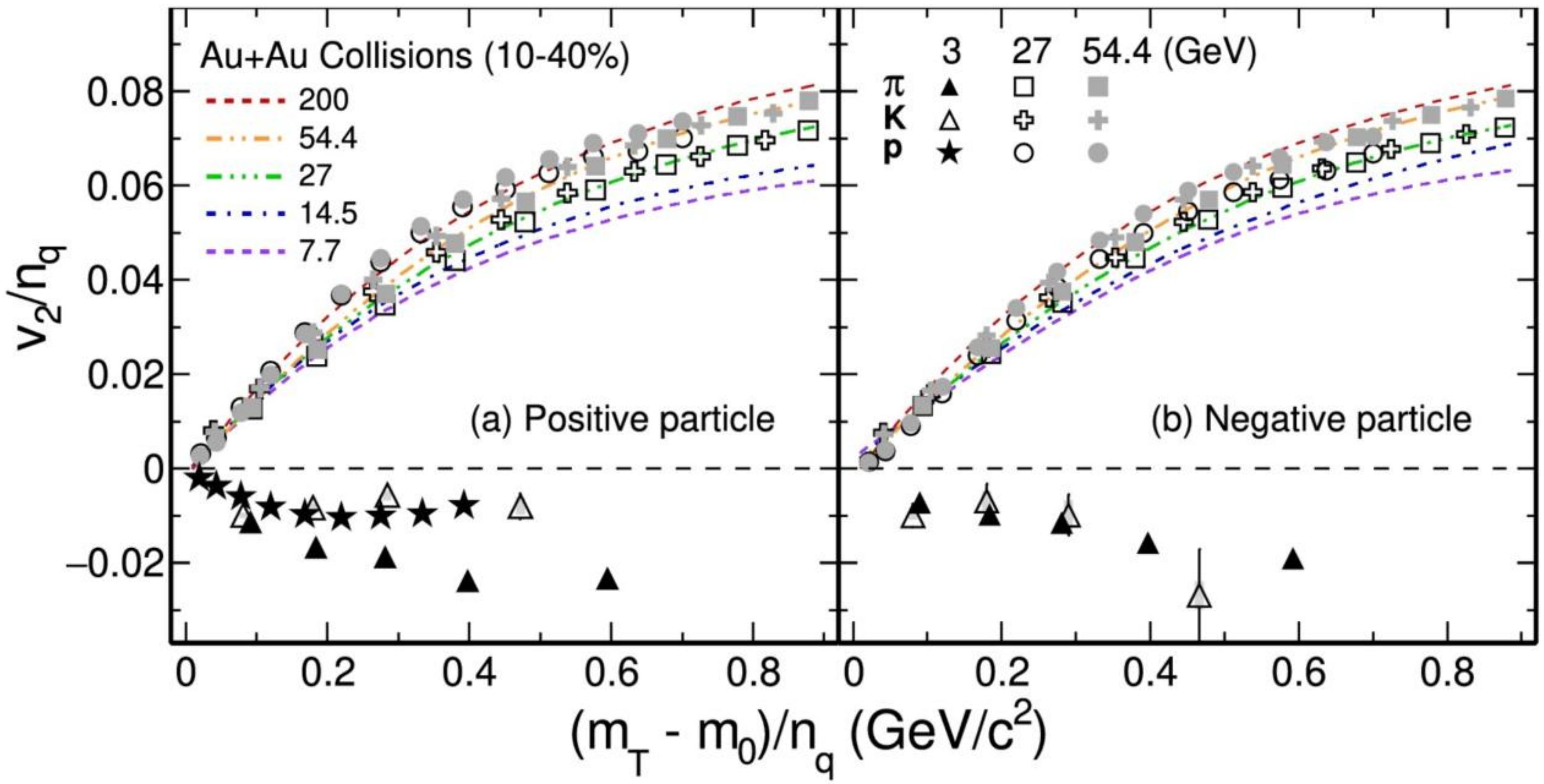




- Anti-flow of π^+, $K^\pm$, K_s at low p_T is observed in beam energy range of 3-3.9 GeV
- Shadowing effect of spectators could be responsible for anti-flow of these particles at high μ_B
- Baryons v_1 slope decreases with increase in collision energy
- JAM with baryonic mean field suggest a strong mean field at high baryon density region

[1] STAR: arXiv:2503.23665 [nucl-ex] (2025)
[2] Yasushi Nara, Akira Ohnishi. Phys. Rev. C 105 (2022) 014911

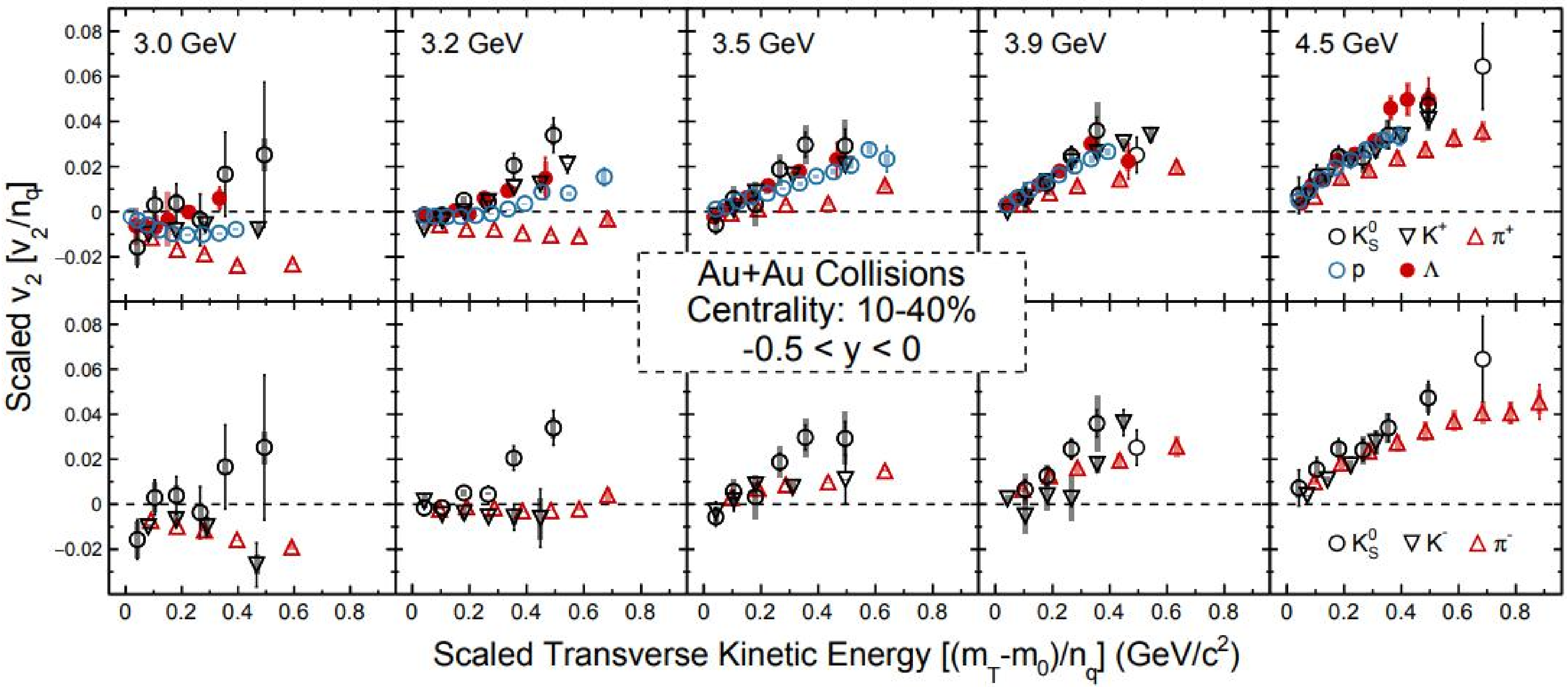
Elliptic flow and partonic collectivity



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

Onset of partonic collectivity

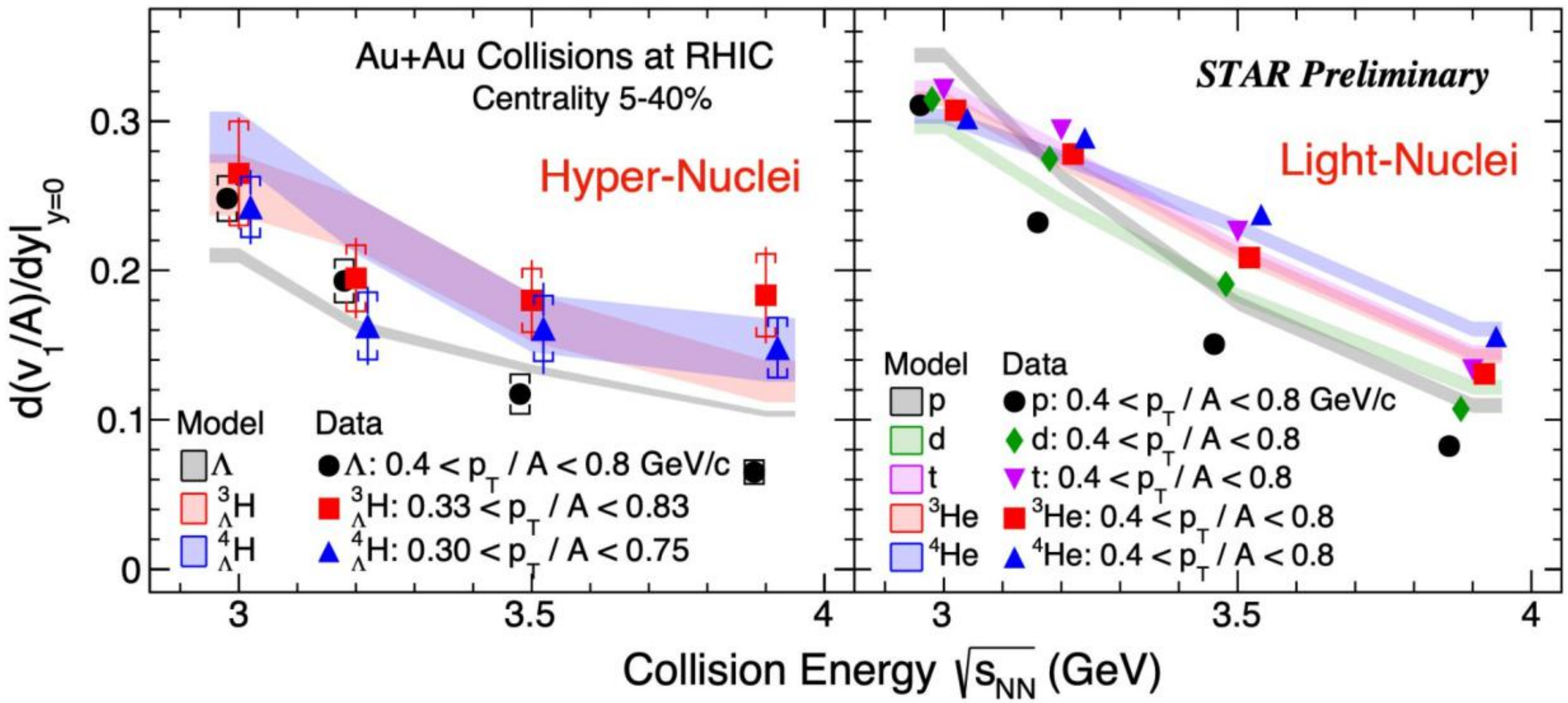


- NCQ scaling is broken in Au+Au collisions below 3.2 GeV
- NCQ scaling gradually improves in Au+Au collisions from 3.2 to 4.5 GeV

→ Indication of transition from hardonic dominated medium to partonic medium

STAR: arXiv:2504.02531 [nucl-ex] (2025)

Light and Hyper nuclei v_1 at high μ_B

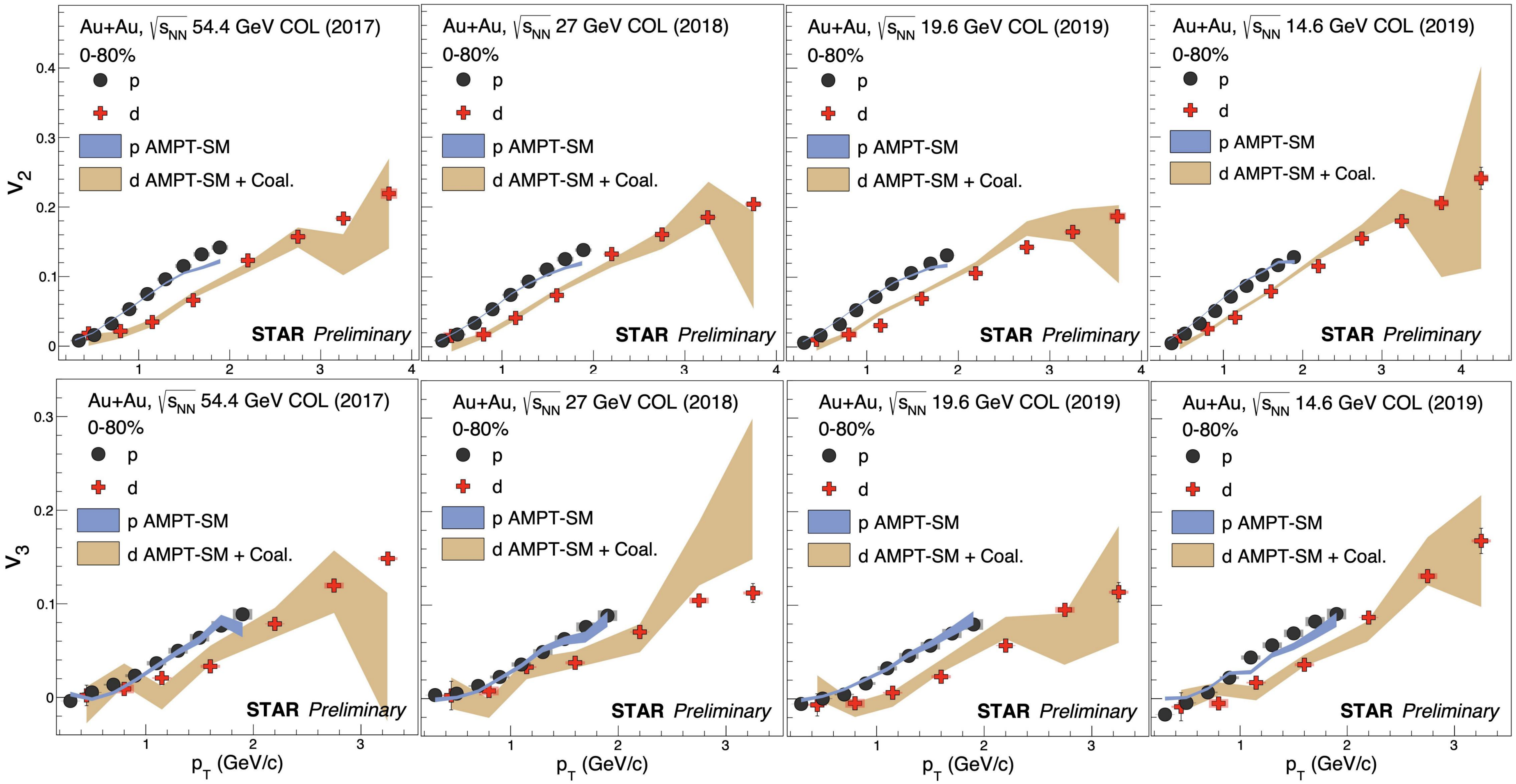


- The mid-rapidity v_1 slope of light and hyper-nuclei decreases with increasing collision energy
- The slopes seems to scale with atomic mass number (A) at a given energy for both light and hyper-nuclei
- Hadronic transport model (JAM2 mean field + coalescence) is consistent with observed energy dependence
- Mass dependence of light and hyper-nuclei v_1 slope is reproduced by JAM + coalescence model

[1] STAR: M.S. Abdallah et al. Phys. Lett. B 827 (2022) 137003; B. E. Aboona et al. Phys. Rev. Lett. 130 (2023) 211301

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

Light nuclei collectivity



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

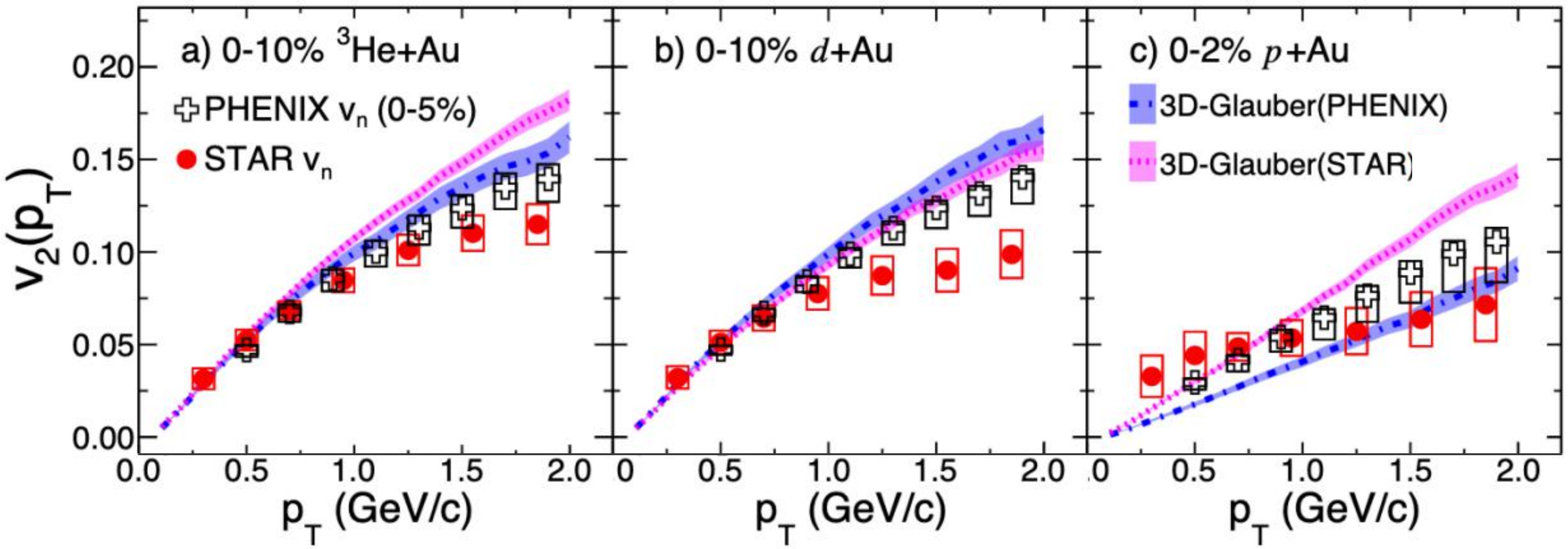
  → Insights to light nuclei production mechanism in heavy-ion collisions

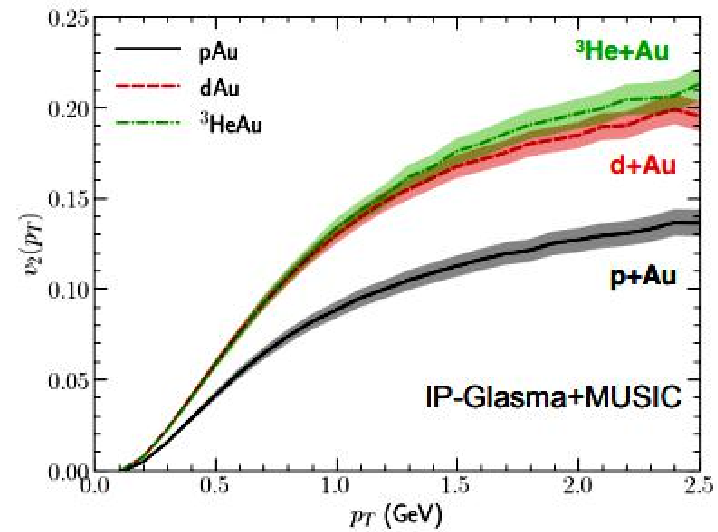
[1] STAR: L. Adamczyk et al., Phys. Rev. C 88 (2013) 014902; M. S. Abdallah et al., Phys. Rev. C 103 (2021) 034908; Phys. Lett. B. 827 (2022) 137003

[2] Z.-W. Lin et al., Phys. Rev. C 72 (2005) 064901

Collectivity in small systems

Collectivity in p+Au, d+Au, ^{3}He+Au



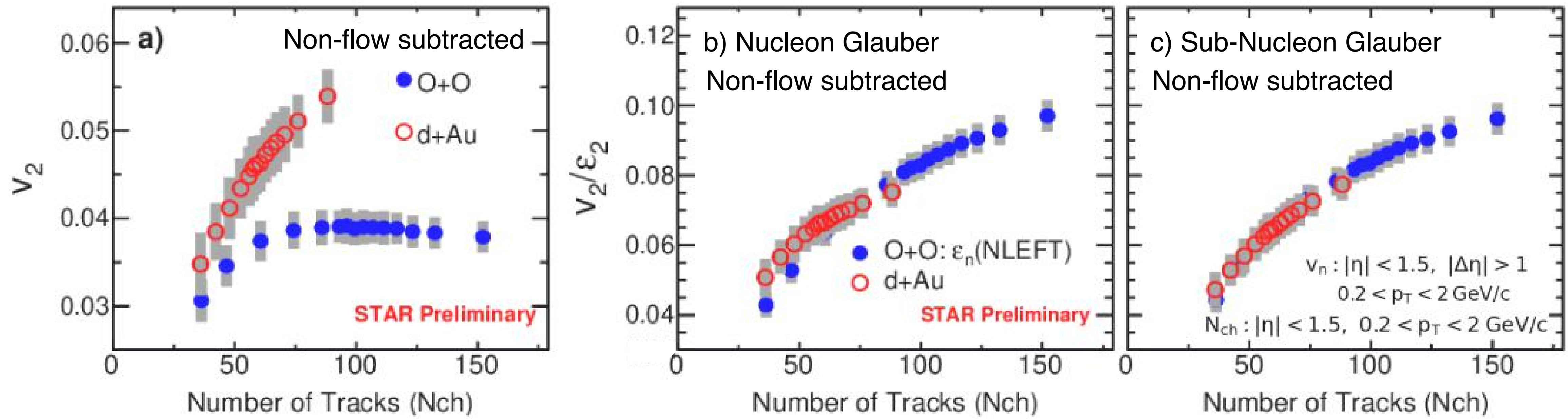


- Relativistic Hydrodynamics prediction: $v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$
- Experimental results: $v_2(^3He+Au) \sim v_2(d+Au) > v_2(p+Au)$,
  - → Ordering consistent with Hydrodynamics, indicates dominance of final state effect
  - → 3D-Glauber model with sub-nucleonic geometry and fluctuations predicts smaller difference between d+Au and ^{3}He+Au results

[1] STAR: M. I. Abdulhamid et al. Phys. Rev. C 110 (2024) 64902; Phys. Rev. Lett. 130 (2023) 242301
[2] PHENIX: Nat. Phys. 15 (2019) 214-220, Phys. Rev. C 107 (2023) 024907

Figs: P. Tribedy, APS GHP meeting (2025)

Collectivity in O+O

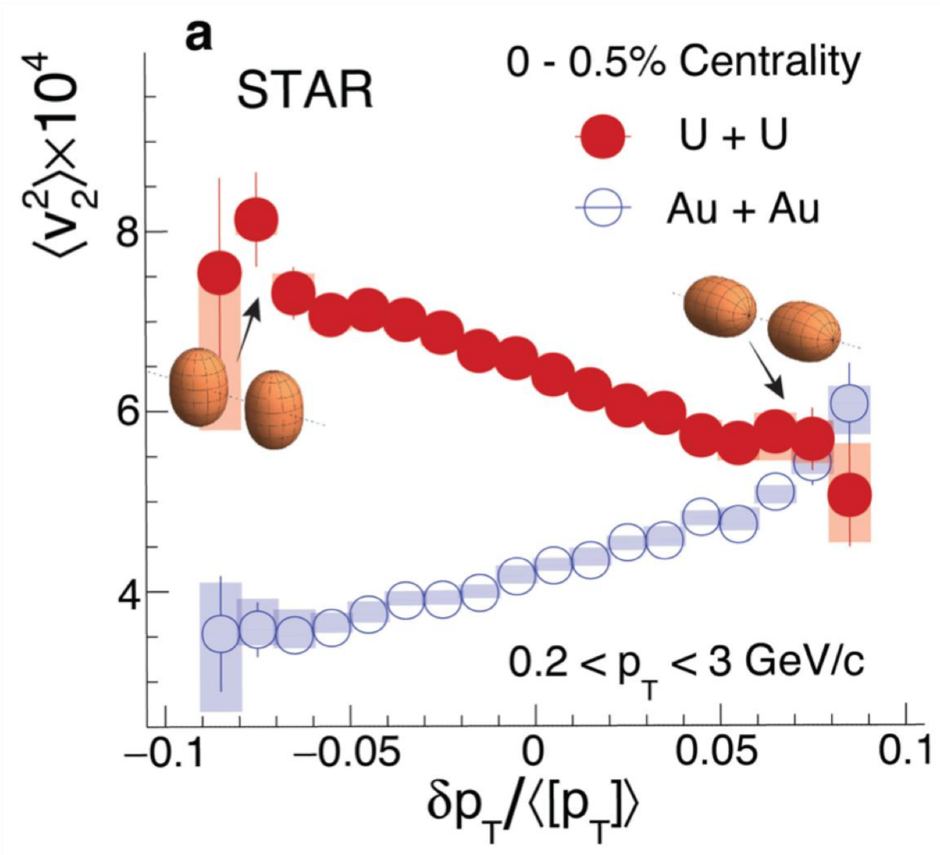


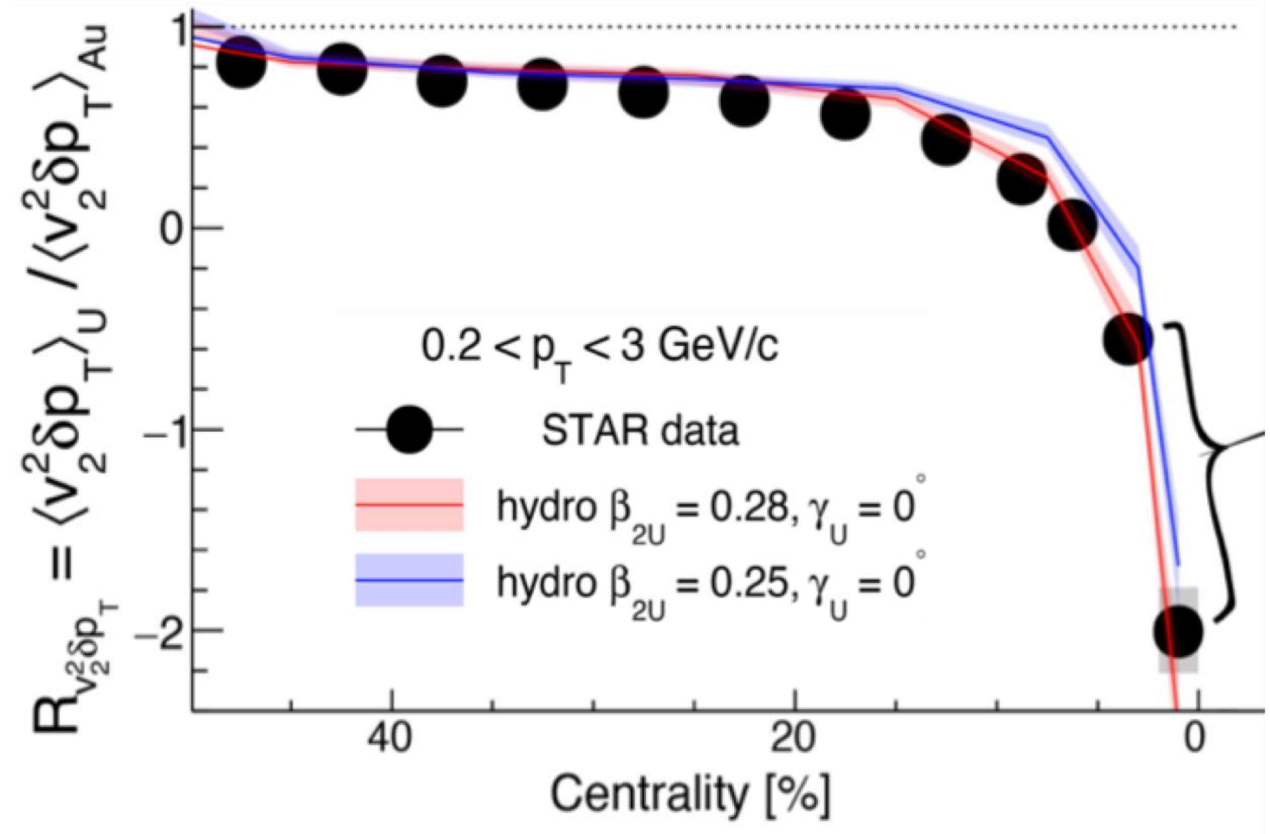
- Experimental results: v_2(d+Au) > v_2(O+O) at large charged particle multiplicity (N_{ch})
  - → Ordering consistent with v_2 arising from medium response to initial eccentricity (ε_2)
  - → Eccentricity scaled v_2 values consistent between the two systems

[1] STAR: M. I. Abdulhamid et al. Phys. Rev. C 110 (2024) 64902; Phys. Rev. Lett. 130 (2023) 242301
[2] NLEFT: Lu et al., PLB 797 (2019) 134863, Glauber: Loizides, PRC 94, 024914 (2016)

System size and shape dependence

Nuclear size and deformation

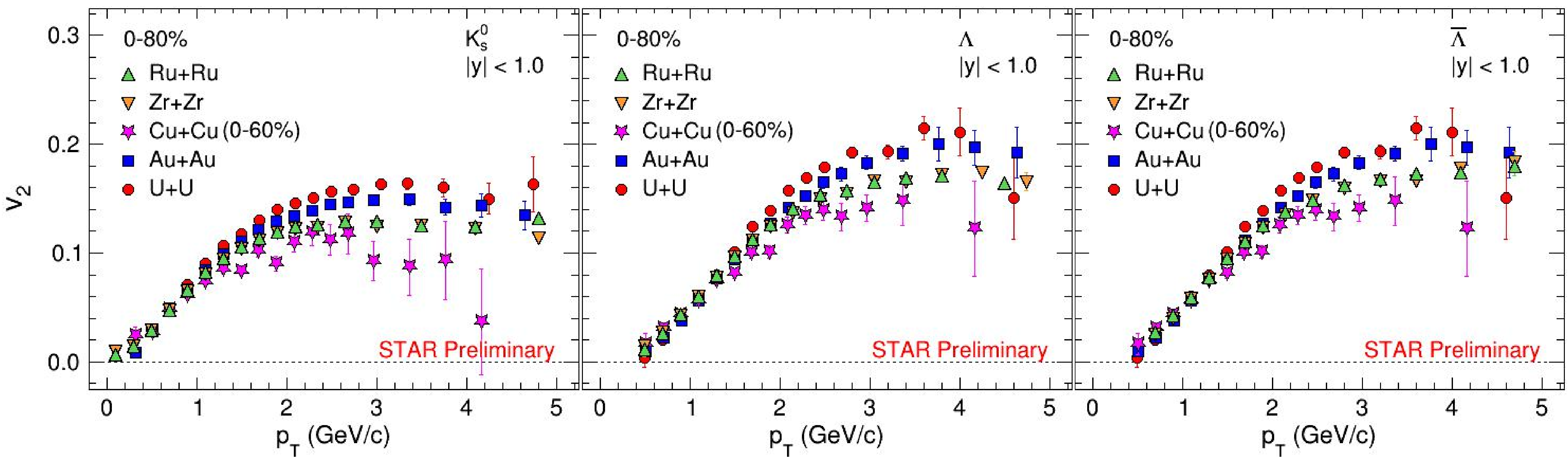




- Flow fluctuations (v_2^2) of charged hadrons enhanced in central U+U collisions compared to Au+Au collisions
- Average v_2 ratio and v_2-p_T correlations can be use to constrain initial conditions and nuclear structure in U+U collisions

[1] STAR, Nature 635 (2024) 8037, 67-72
[2] G. Giacalone et al., Phys. Rev. Lett. 127 (2021) 242301
[3] B. Schenke et al., Phys. Rev. C 102 (2010) 034905

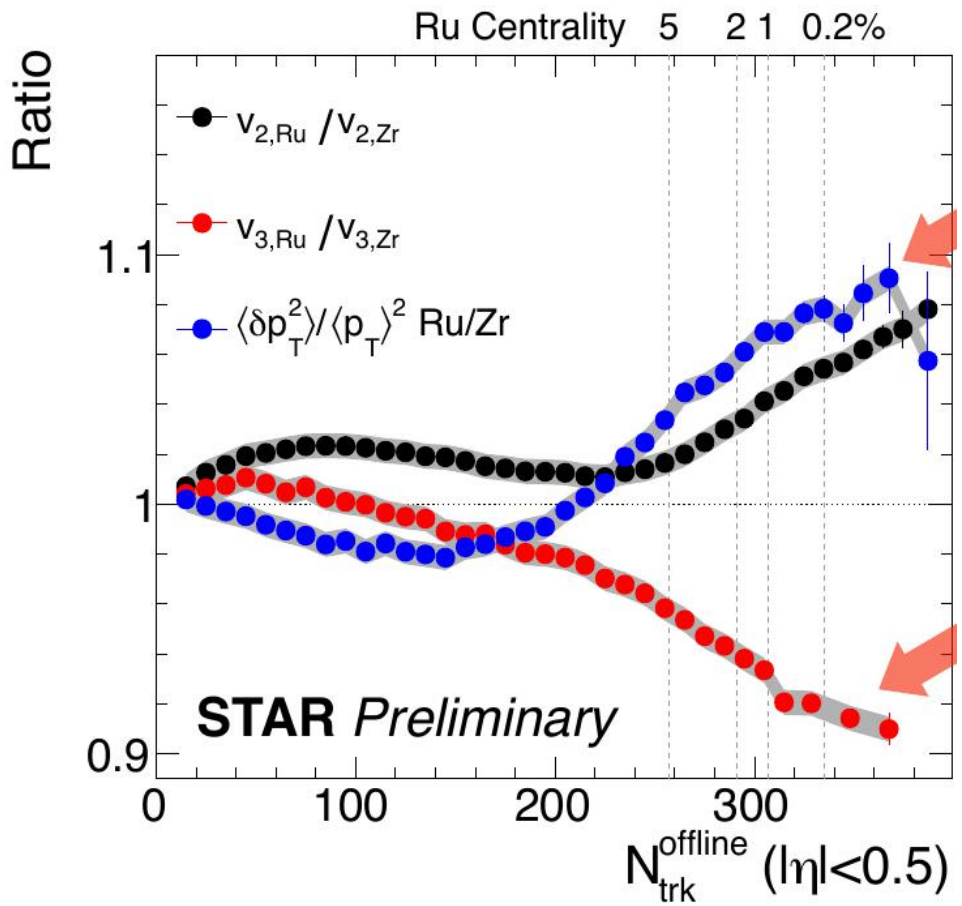
Nuclear size and deformation

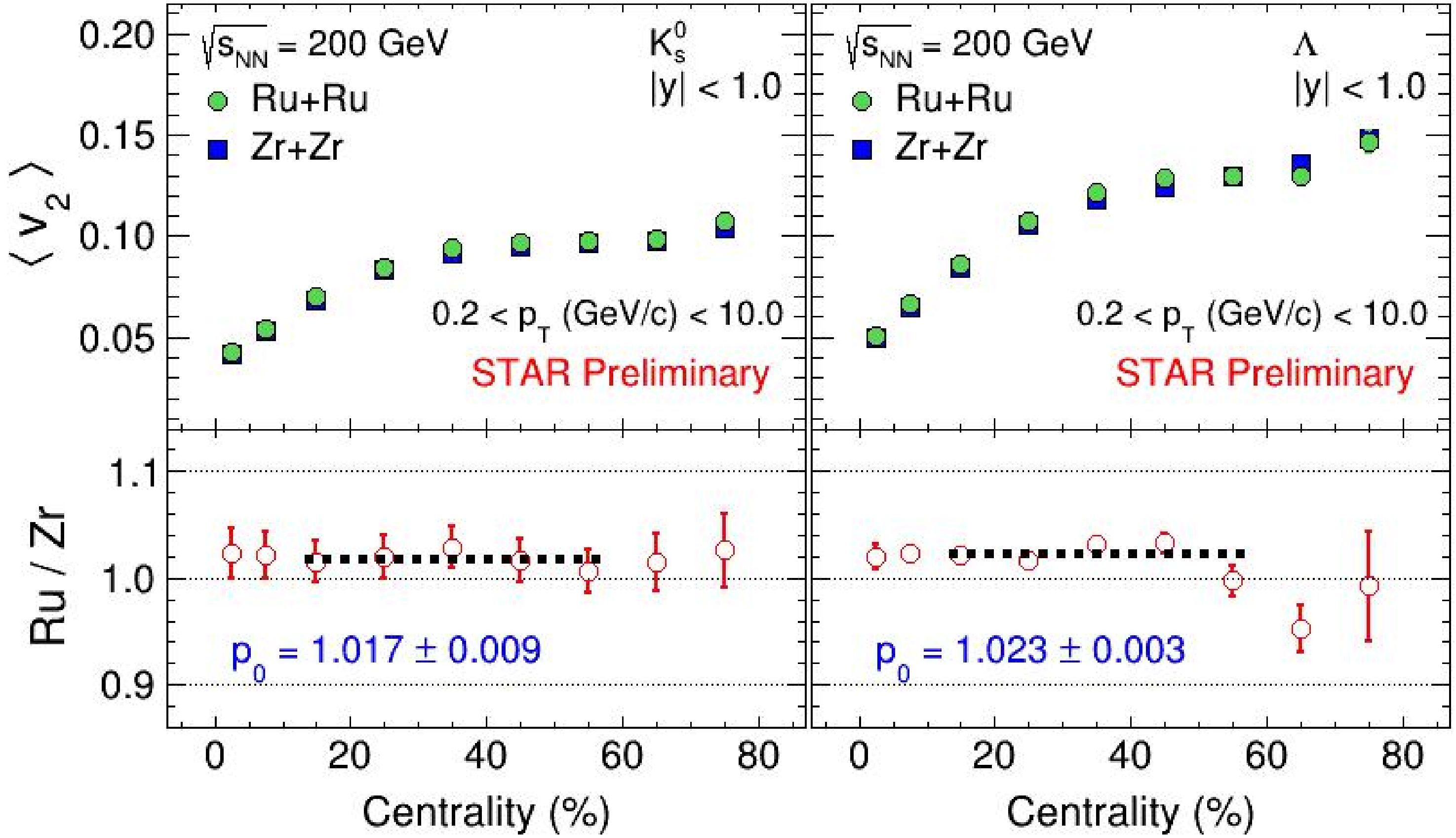


- Elliptic flow at high p_T increases with atomic mass number of nuclei
  → Shows an ordering with increasing system size

[1] STAR: B. I. Abelev et al. Phys. Rev. C 77 (2008) 054901; Phys. Rev. C 81 (2010) 044902
[2] STAR: M. S. Abdallah et al. Phys. Rev. C 103 (2021) 064907

Nuclear size and deformation





- Ratio of integrated v_2 for different particles between Ru+Ru and Zr+Zr collisions differs from unity

  → Indication of larger quadruple deformity in Ru nuclei than in the Zr nuclei

Summary & Outlook

Collectivity in high μ_B region

- Anti-flow of mesons at low p_T suggest shadowing effect from spectators
- Absence of NCQ scaling at $\sqrt{s_{NN}}$ = 3 and 3.2 GeV indicate baryonic interactions dominating nuclear EoS
- NCQ scaling gradually improves from 3.2 to 4.5 GeV → dominance of partonic interactions at $\sqrt{s_{NN}}$ >= 4.5 GeV
- Hadronic transport model (JAM + Coalescence) describes light and hyper nuclei flow in heavy-ion collisions

Collectivity in small systems

- Elliptic flow v_2 ordering aligns with initial geometry-driven collectivity in p/d/^{3}He+Au
- O+O vs. d+Au: clear v_2 ordering driven by collision geometry

System size dependence

- Elliptic flow at high p_T increases with atomic mass number of nuclei indicating nuclear size dependence.
- Ratio of $\langle v_2 \rangle$ and v_2-p_T correlation between different collision system provide access to nuclei deformation

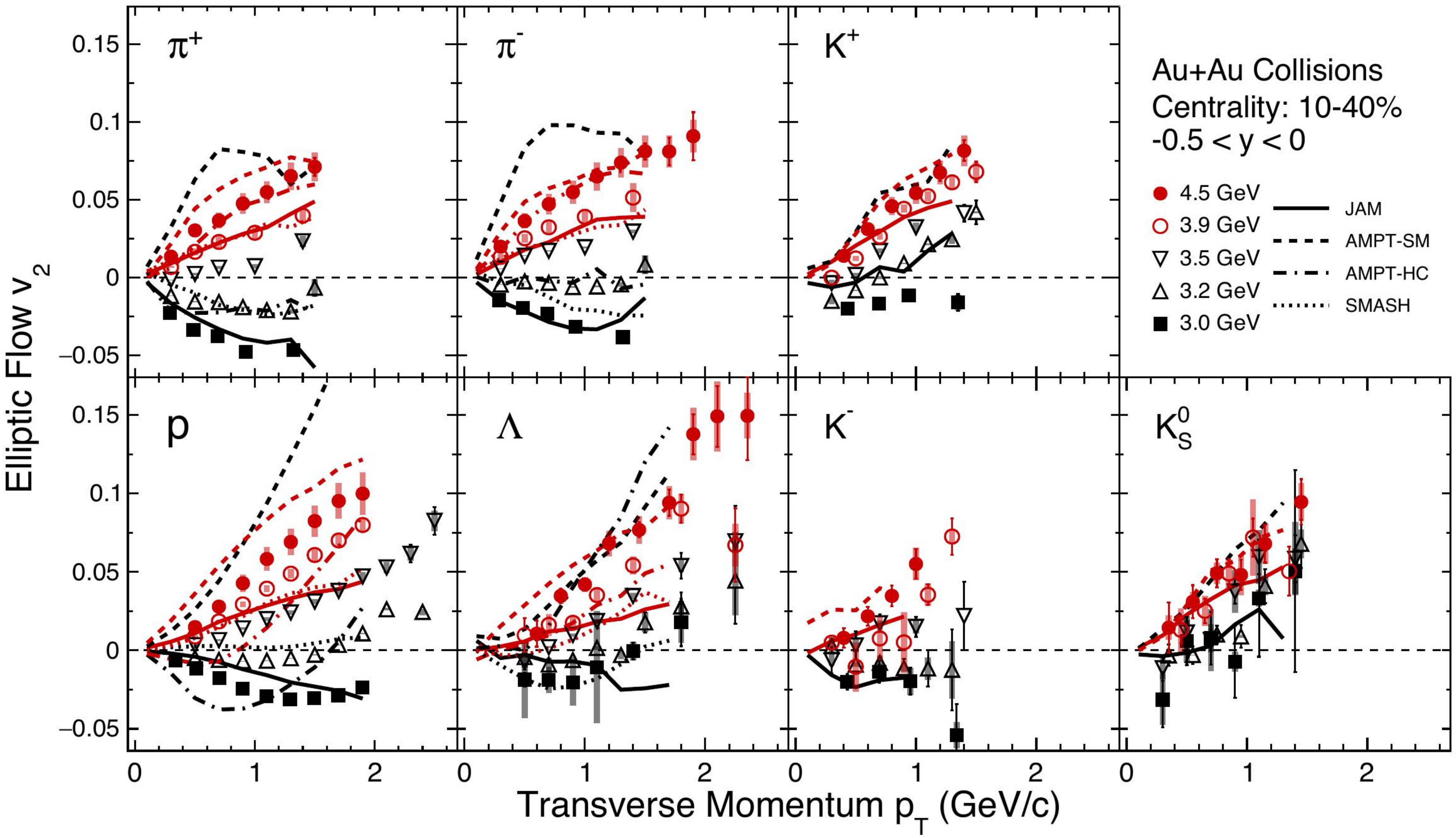
More exciting results to come from the high statistics data of BES and FXT program at STAR. Collectivity from small to large systems and measurements in wider rapidity ranges using forward detectors enable us to explore the QGP properties, phase transition and more....

Thank you for your attention!

Backup

Elliptic flow v_2 at high μ_B

FXT



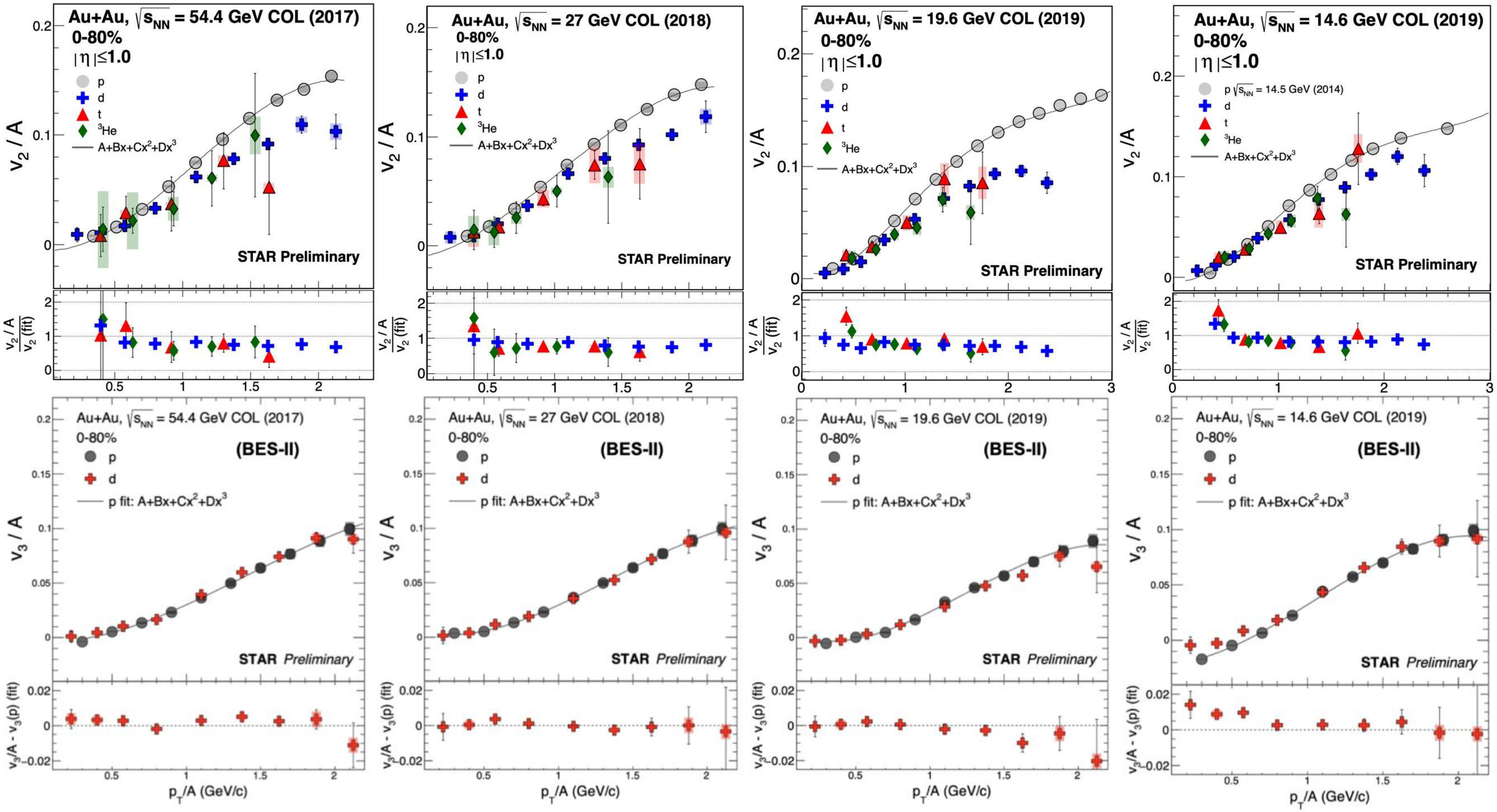
JET AA Microscopic Transport Model

- Momentum dependent mean-field potential
- Incompressibility constant κ = 210 MeV

- Energy dependence of $v_2(p_T)$: transition from negative to positive values indicate shadowing effect.
- JAM model with baryonic mean field describe 3.2 GeV data well while underestimating 4.5 GeV data, suggest baryonic dominated medium.

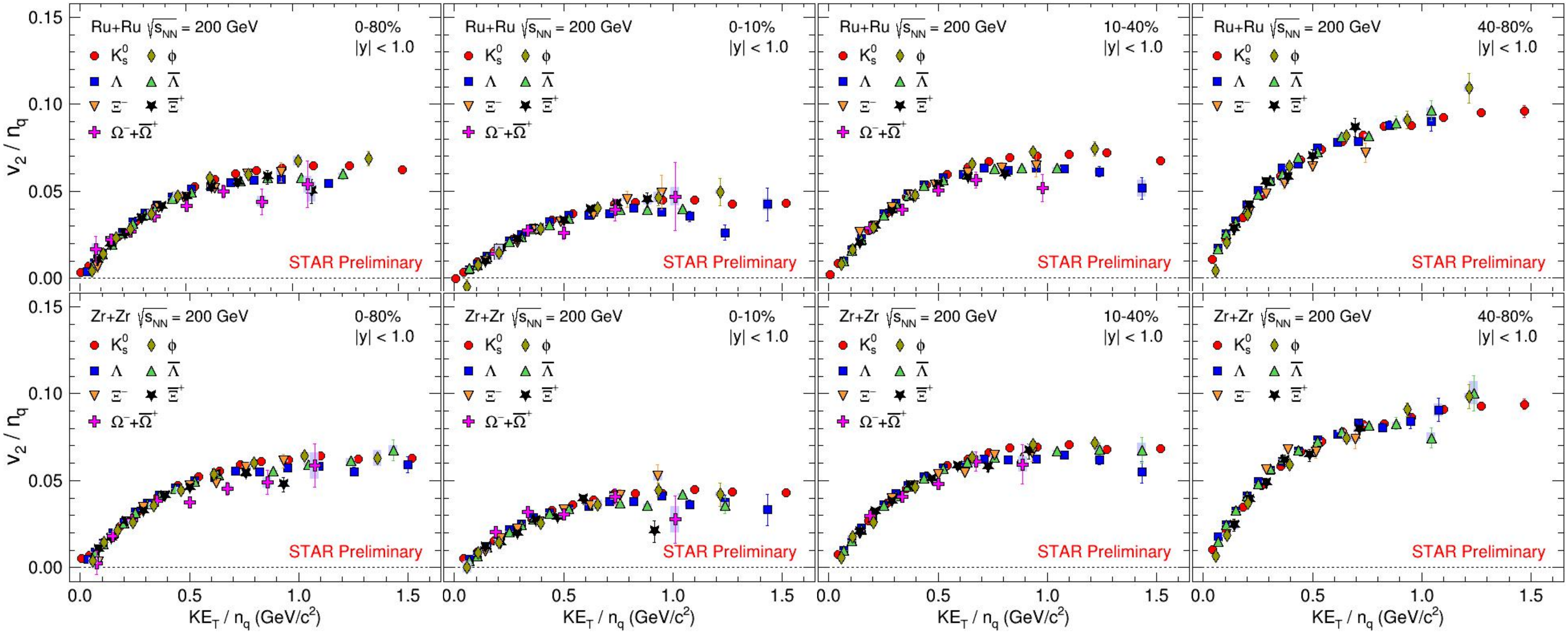
STAR: arXiv:2504.02531 [nucl-ex] (2025)

Light nuclei flow



- Light nuclei v_2 and v_3 obey mass number scaling at ~30% level in BES energies

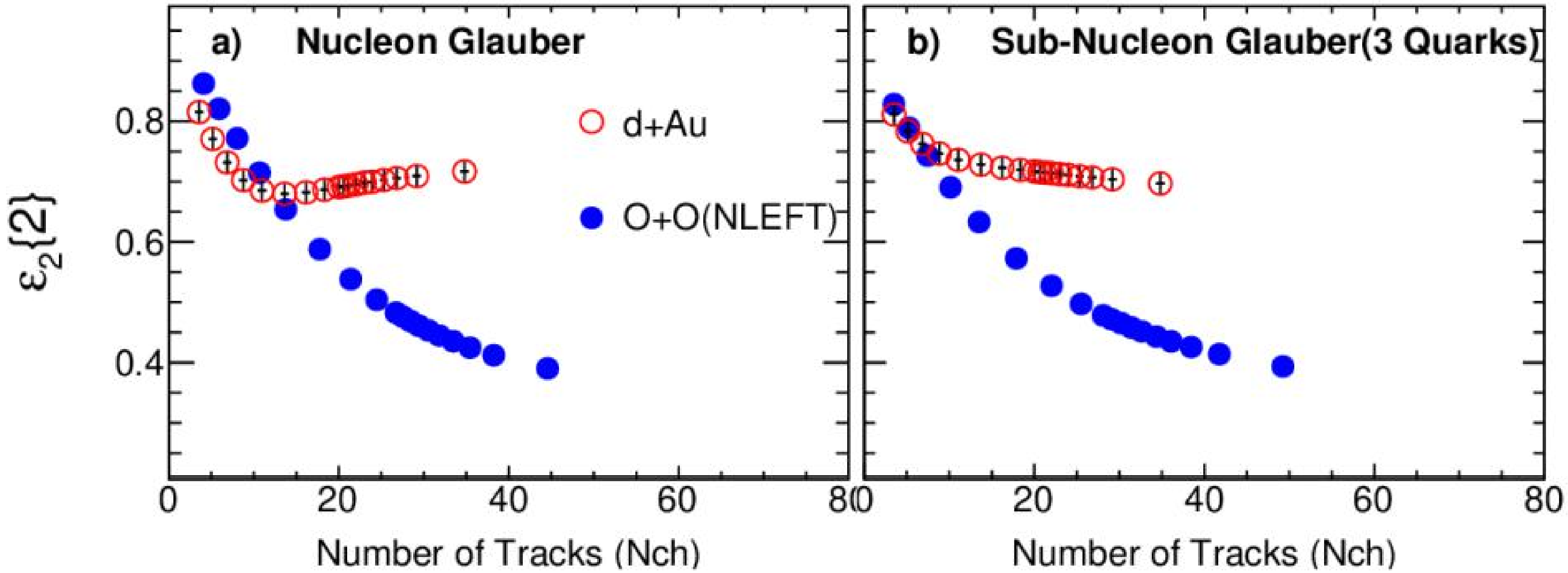
NCQ scaling in isobar collisions



n_q = Number of constituent quarks (3 for baryons and 2 for mesons); Transverse kinetic energy (KE_T) = $m_T - m_0$

- NCQ scaling hold good to ±10% within uncertainties in both Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200 GeV.
- Elliptic flow (v_2) scaled by number of constituent quarks falling on a universal curve, indicating partonic collectivity.

Origin of collectivity in small systems



- ε_2(d+Au) > ε_2(O+O) at large charged particle multiplicity (N_{ch})

NLEFT: Lu et al., PLB 797 (2019) 134863, Glauber: Loizides, PRC 94, 024914 (2016)