INSTITUTO DE ALTA INVESTIGACIÓN

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STAR

# Collective properties of the nuclear matter from the STAR experiment at RHIC

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New Trends in High-Energy and Low-x Physics

Sfantu Gheorghe, Romania
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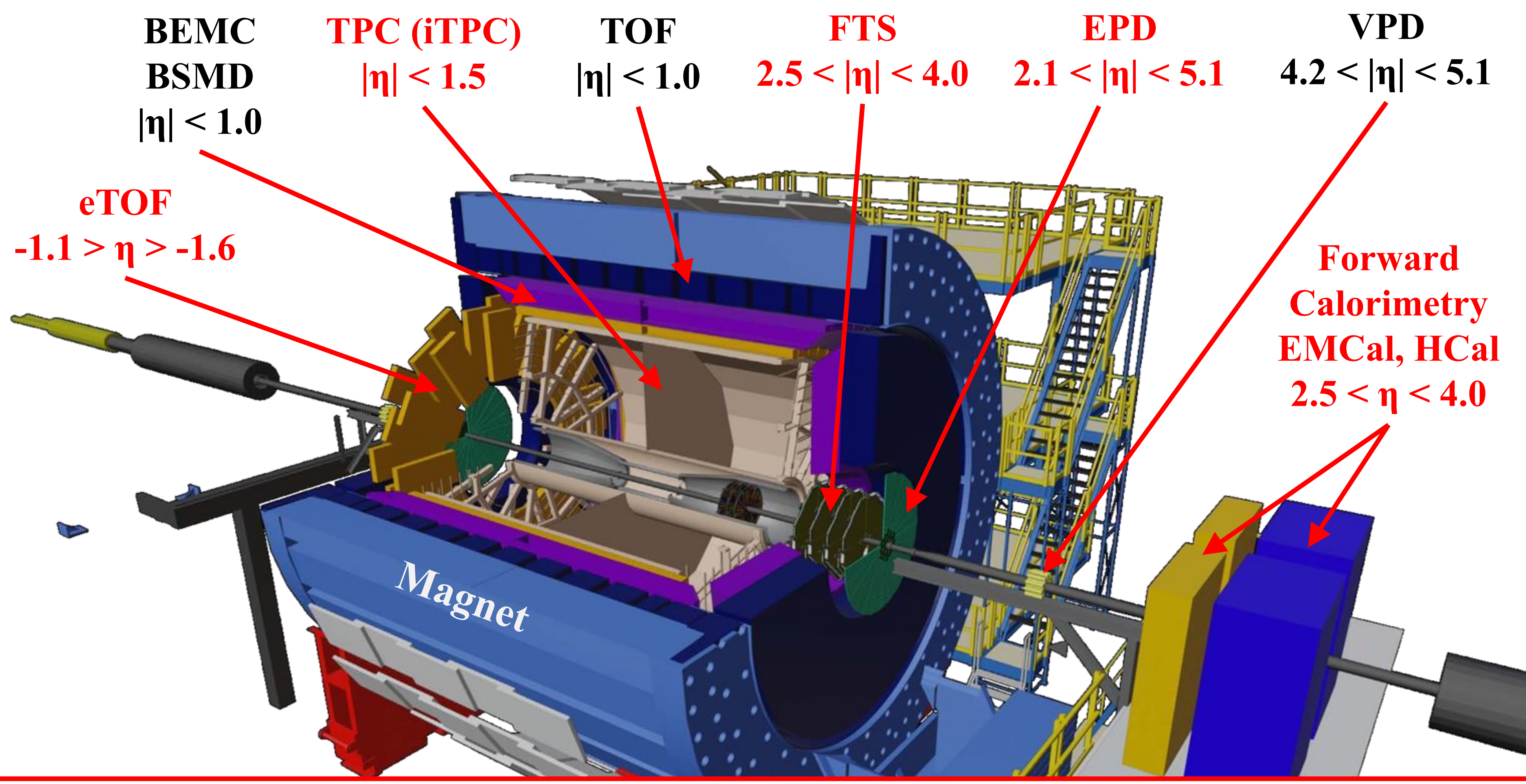
# Outline

- Introduction: STAR Experiment at RHIC
- Motivation
- Collective flow
  - Directed Flow ($v_1$)
  - Elliptic Flow ($v_2$)
  - Triangular Flow ($v_3$)
- Nuclear size and deformation
- Summary

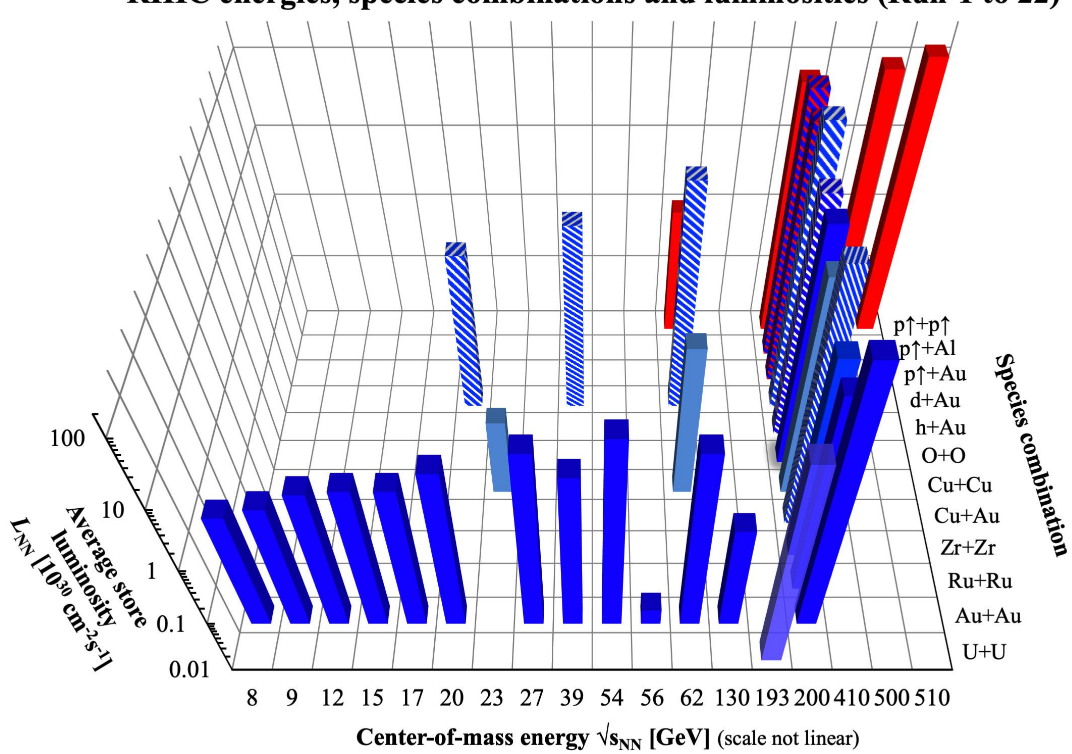
# STAR experiment at RHIC

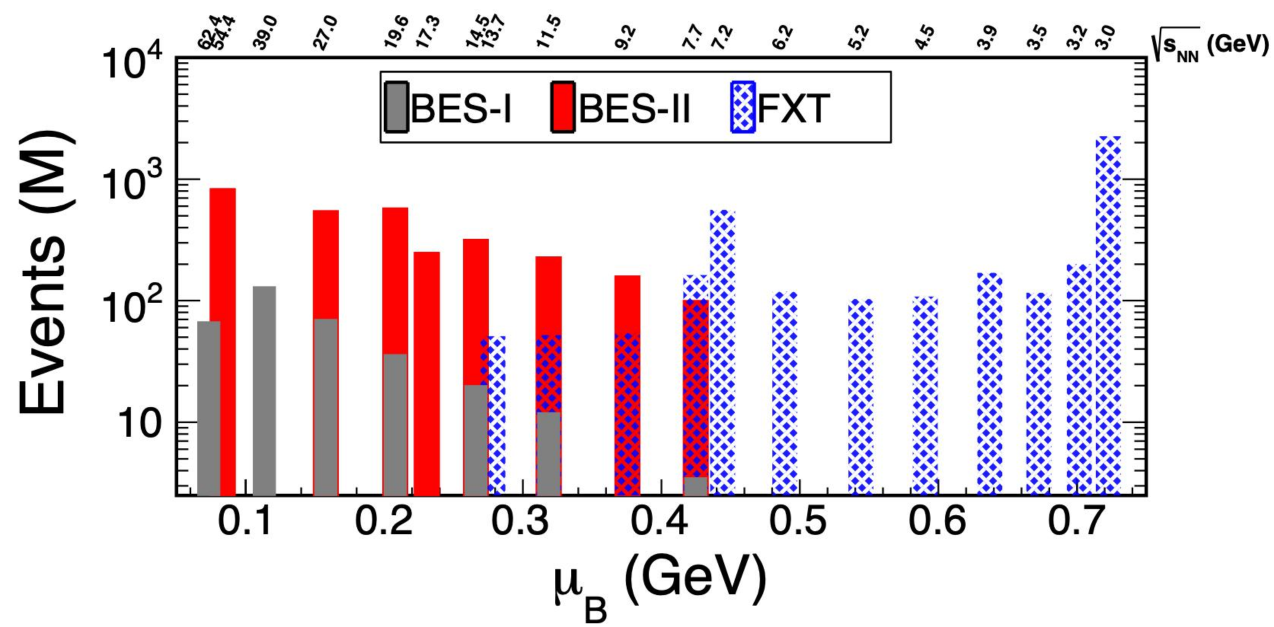



- iTPC: Improved tracking, extended acceptance to $|\eta| < 1.5$, better dE/dx and momentum resolution
- eTOF: Extended PID in the forward region
- EPD: Independent centrality detector, Improved EP resolution, Trigger
- Recent forward upgrades: FCS, FTS, EMcal & HCal

# Beam energies and colliding systems at STAR

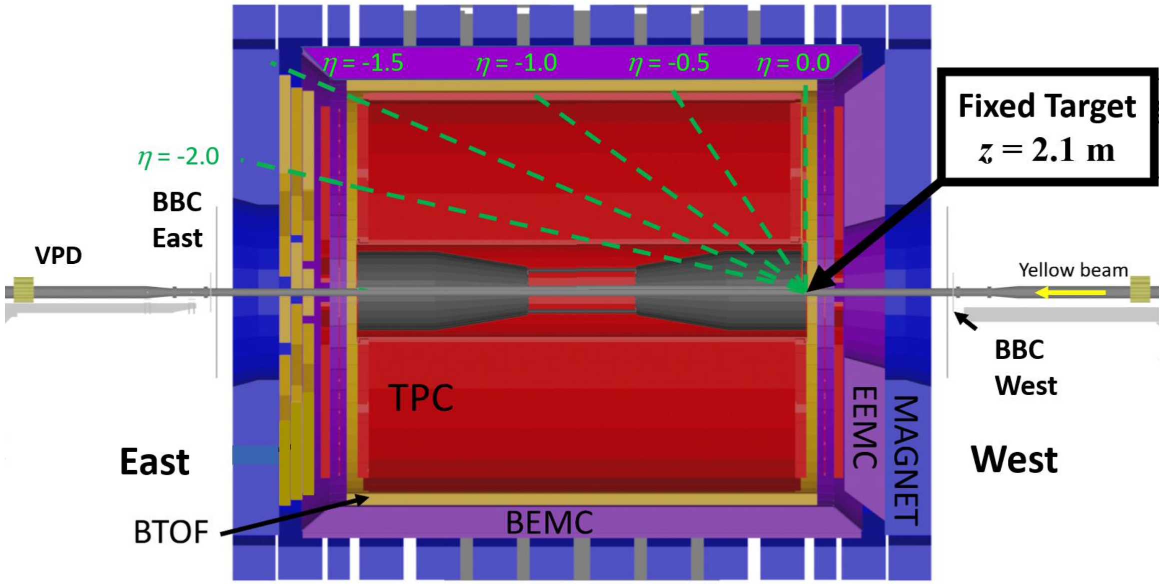
- Wide range of collision beam energies to explore QCD phase diagram
  - Beam Energy Scan Phase II (BES-II): $\sqrt{s_{NN}}$ = 7.7 – 54.4 GeV
  - Fixed Target (FXT): $\sqrt{s_{NN}}$ = 3.0 – 7.7 GeV
- Different collision species to study the QCD medium at top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV
  - 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



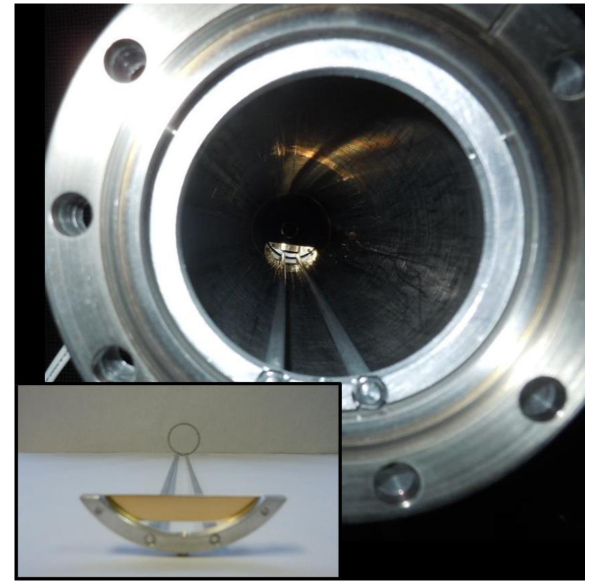




https://www.agsrhichome.bnl.gov/RHIC/Runs/

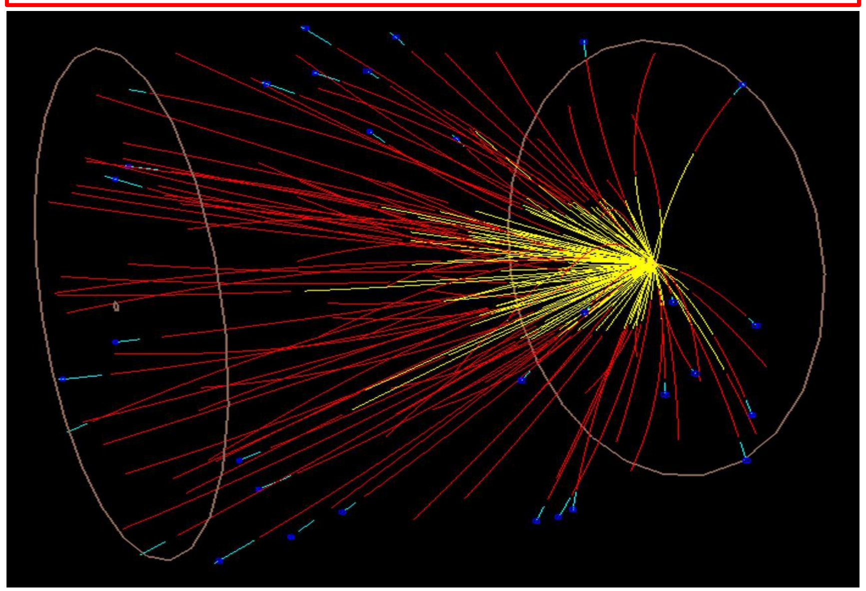
# STAR Fixed Target (FXT) Setup




**Gold target:**
- **2 cm below nominal beam axis**
- **2.1 m from center of STAR**
- **0.25 mm foil**



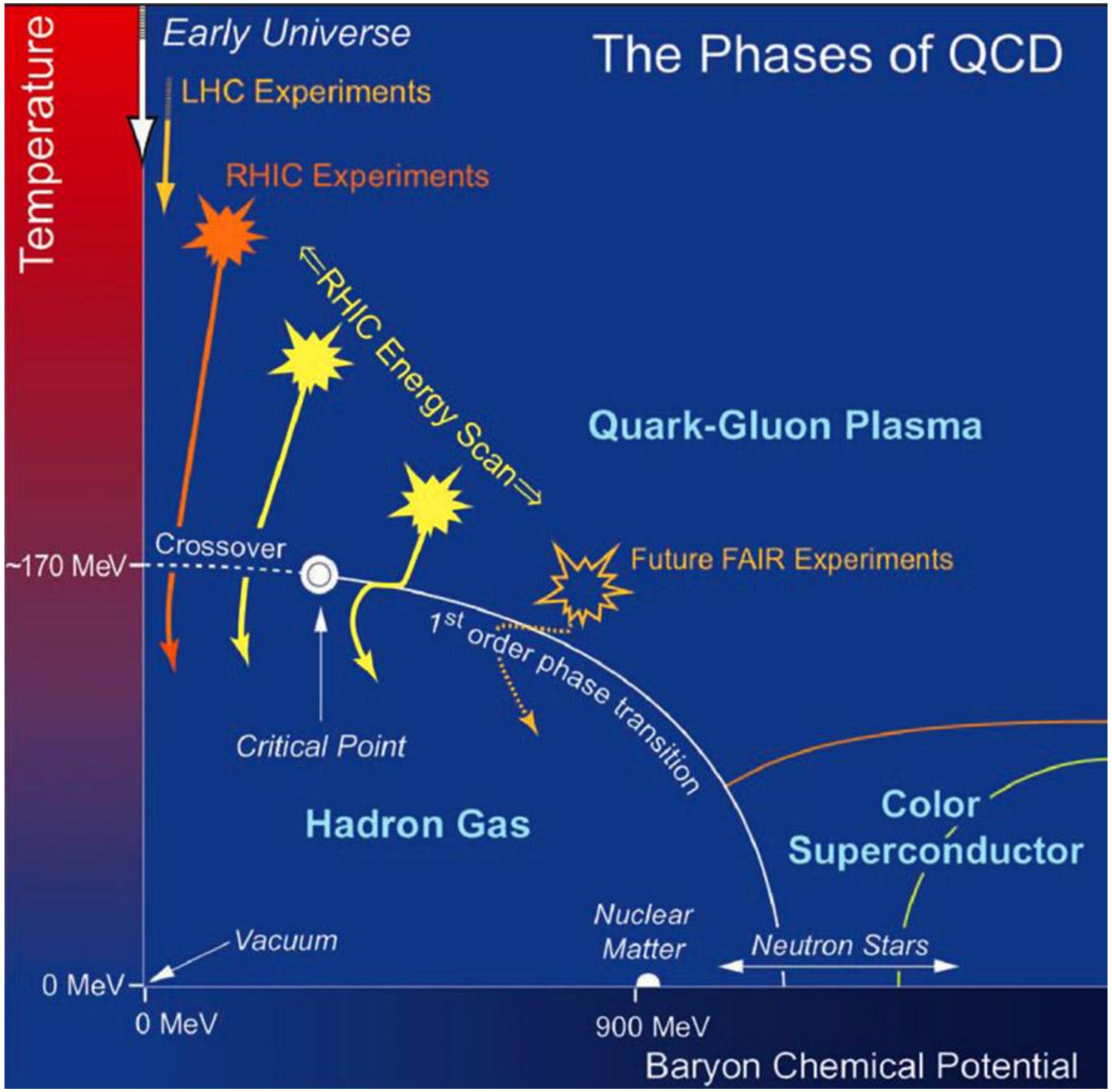
Au+Au at $\sqrt{s_{NN}}$ = 4.5 GeV event



| Beam Energy (GeV/nucleon) | $\sqrt{s_{NN}}$ (GeV) | $\mu_B$ (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** |

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

# Exploring phase structure of QCD matter

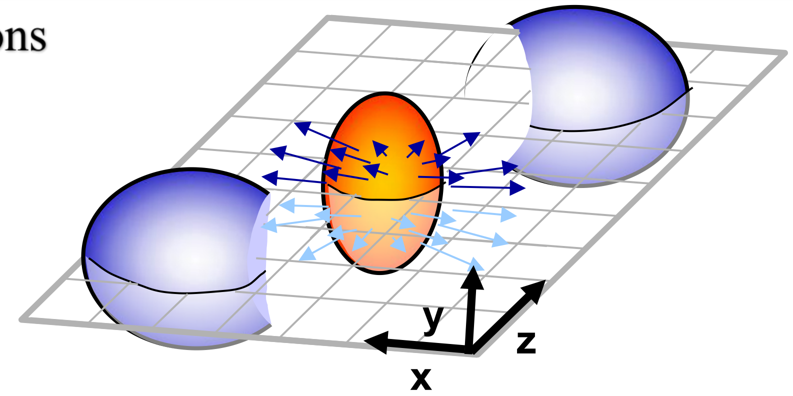



**Conjectured QCD Phase diagram**

- 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 $\mu_B$
- 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*

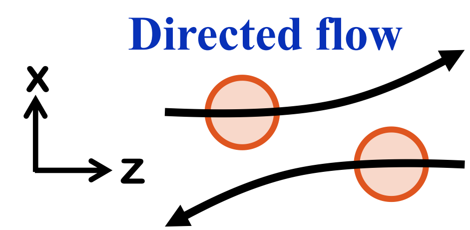
# Collective Flow

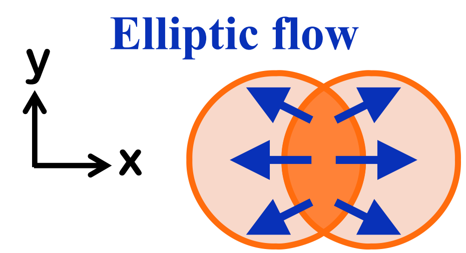


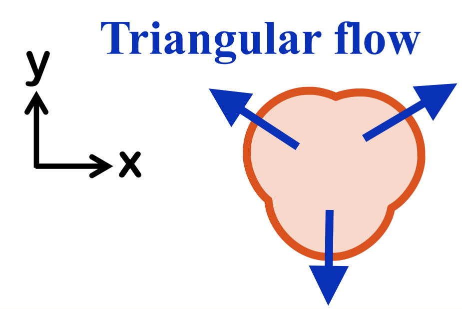

- Collective flow describe the response of the medium produced in heavy-ion collisions
- Collective flow can be quantified using the Fourier expansion:

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

- 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



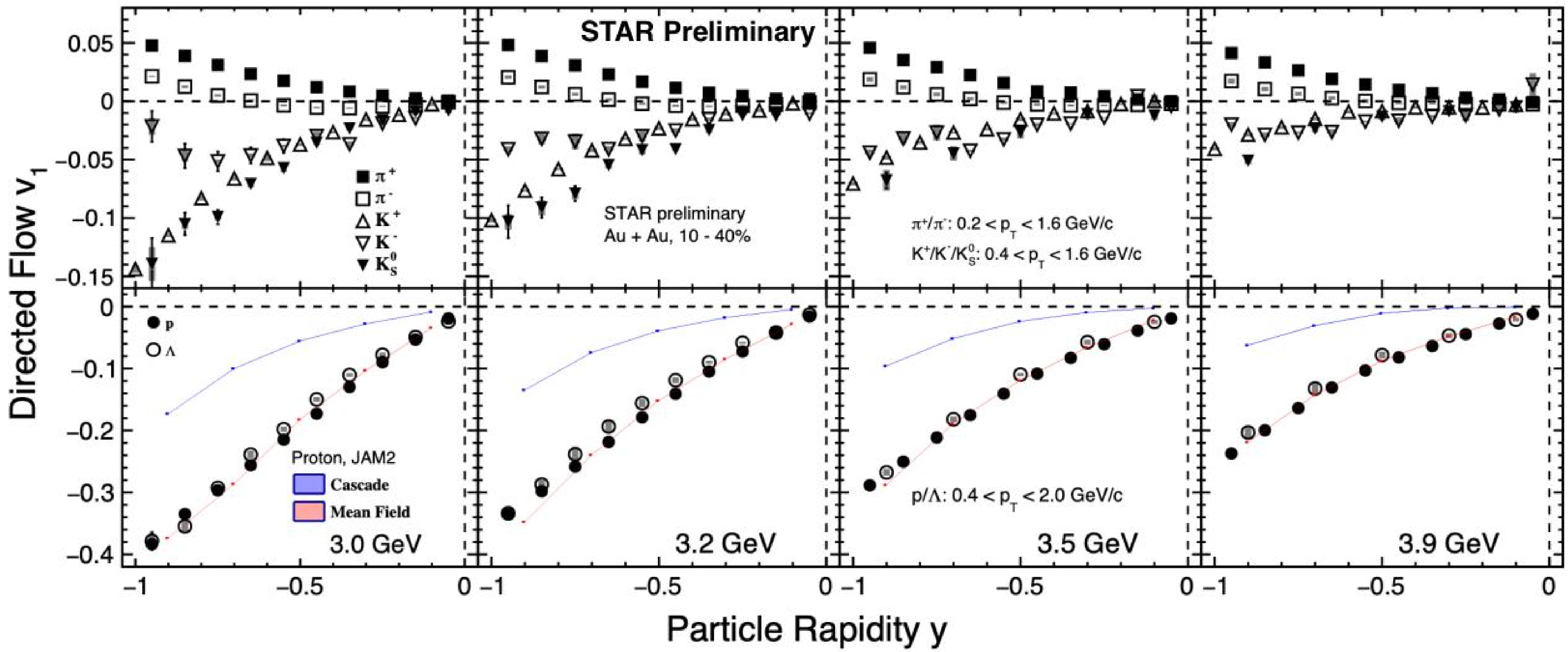




- **Sensitive to initial conditions, equation of state, transport properties (η/s) of system, and initial state fluctuations**
- **Probe for the particle production mechanism (e.g. quark coalescence)**


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

# Directed flow at high $\mu_B$



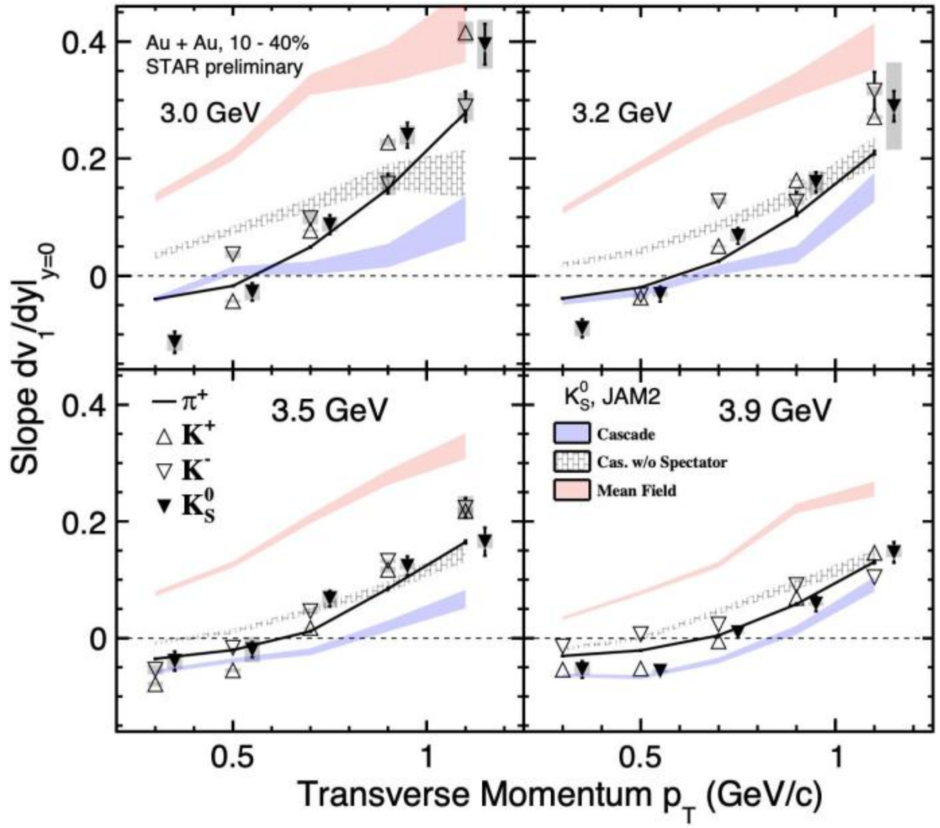

- Directed flow $v_1(y)$ of π, K, p, and Λ measured across various beam energies with high $\mu_B$
- JAM model with momentum dependent baryonic mean-field describes baryon flow compared to cascade model

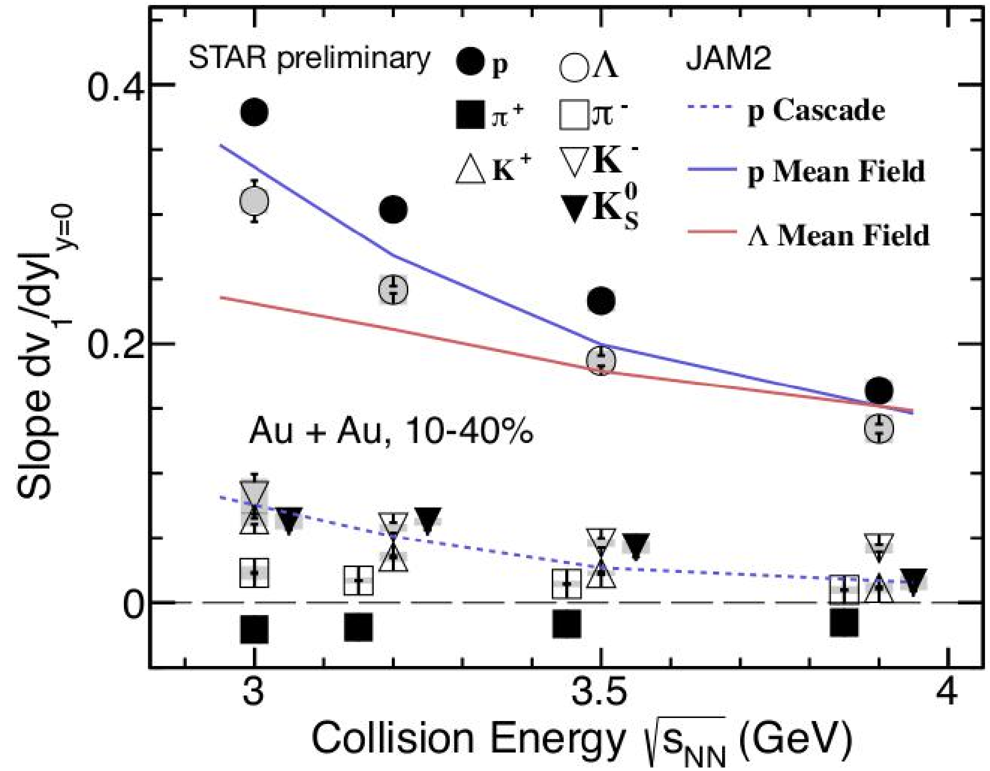
JET AA Microscopic Transport Model

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

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

# Directed flow at high $\mu_B$

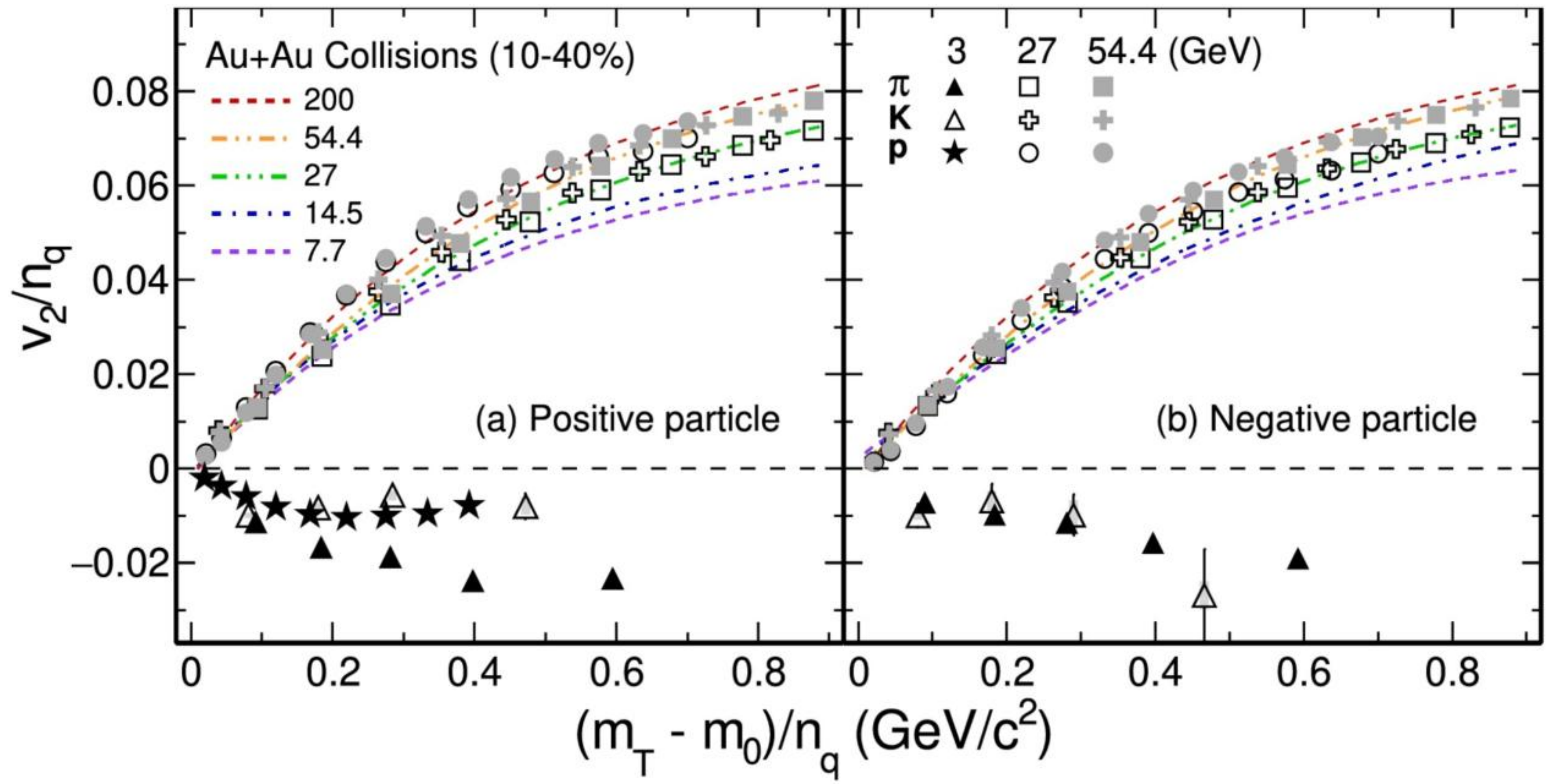



- Anti-flow of $\pi^+$, $K^\pm$, $K_s$ at low $p_T$ is observed in beam energy range of 3-3.9 GeV.
- Shadowing effect of spectators could be responsible for anti-flow of these particles at high $\mu_B$.
- Baryons $v_1$ slope decreases with increase in collision energy.
- JAM with baryonic mean field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


[1] M. S. Abdallah et al. (STAR Collaboration) Phys. Lett. B 827, 137003 (2022)
[2] Yasushi Nara, Akira Ohnishi. Phys. Rev. C 105, 014911 (2022)

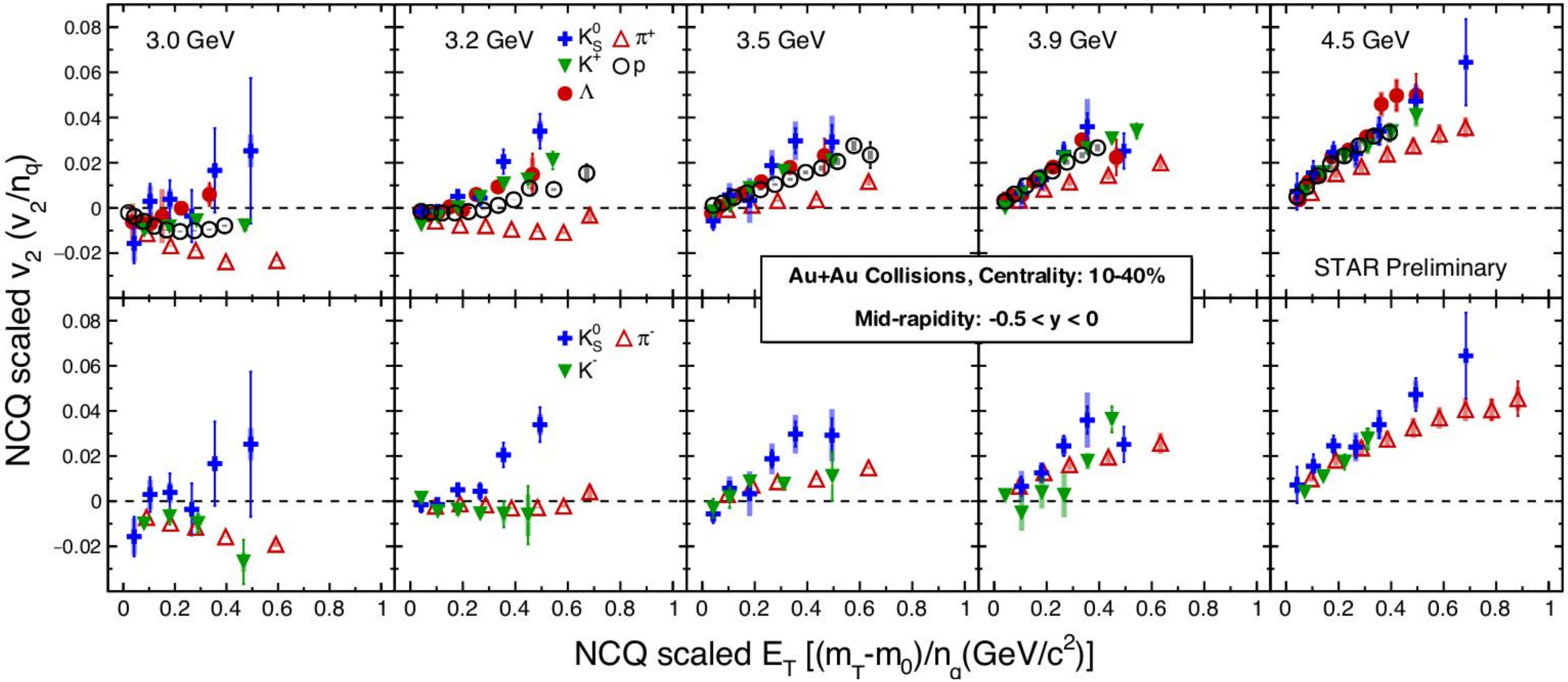
# Elliptic flow and partonic collectivity




- 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] 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)

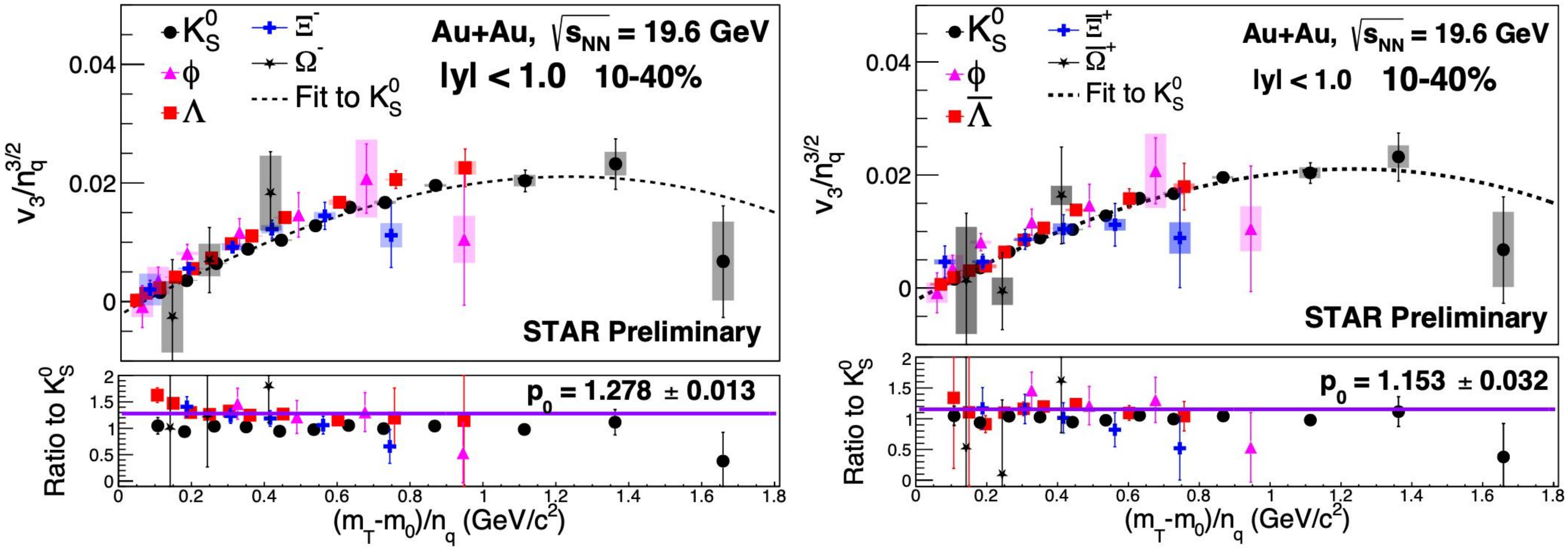
# Onset of partonic collectivity




- 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

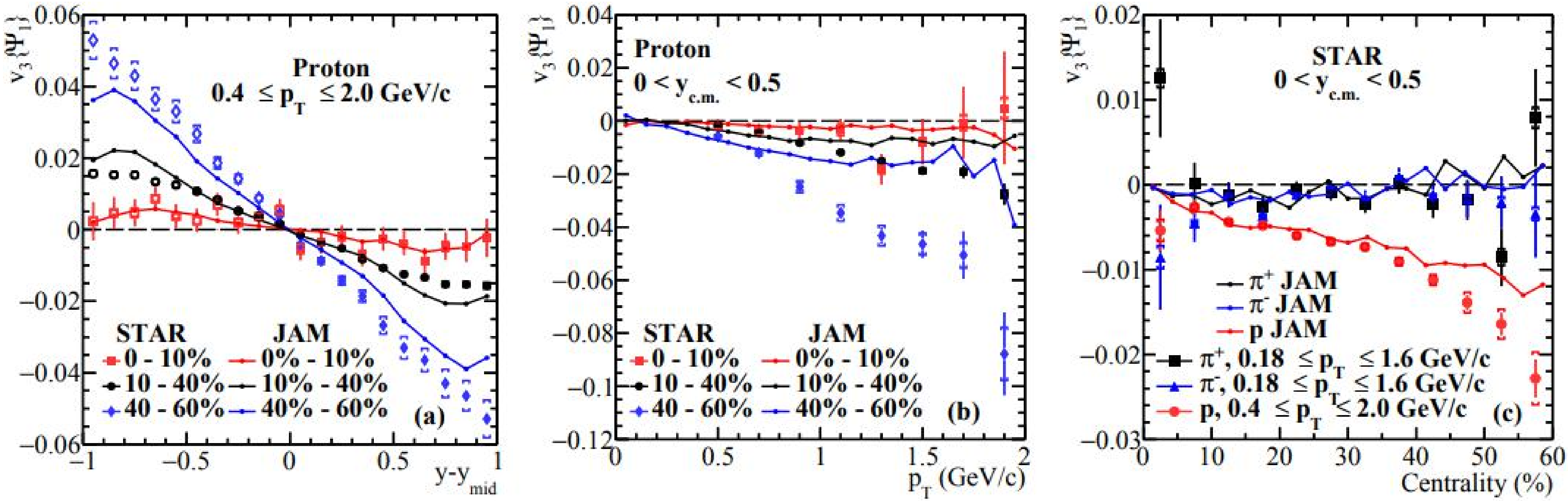
→ Indication of transition from hardonic dominated medium to partonic medium

# Triangular flow ($v_3$)




- Strange and multi-strange $v_3$ studied systematically in Au+Au collisions at BES-II energy $\sqrt{s_{NN}} = 19.6$ GeV.
- NCQ scaling of $v_3$ holds better for anti-particles (~15%) than the particles (~30%).

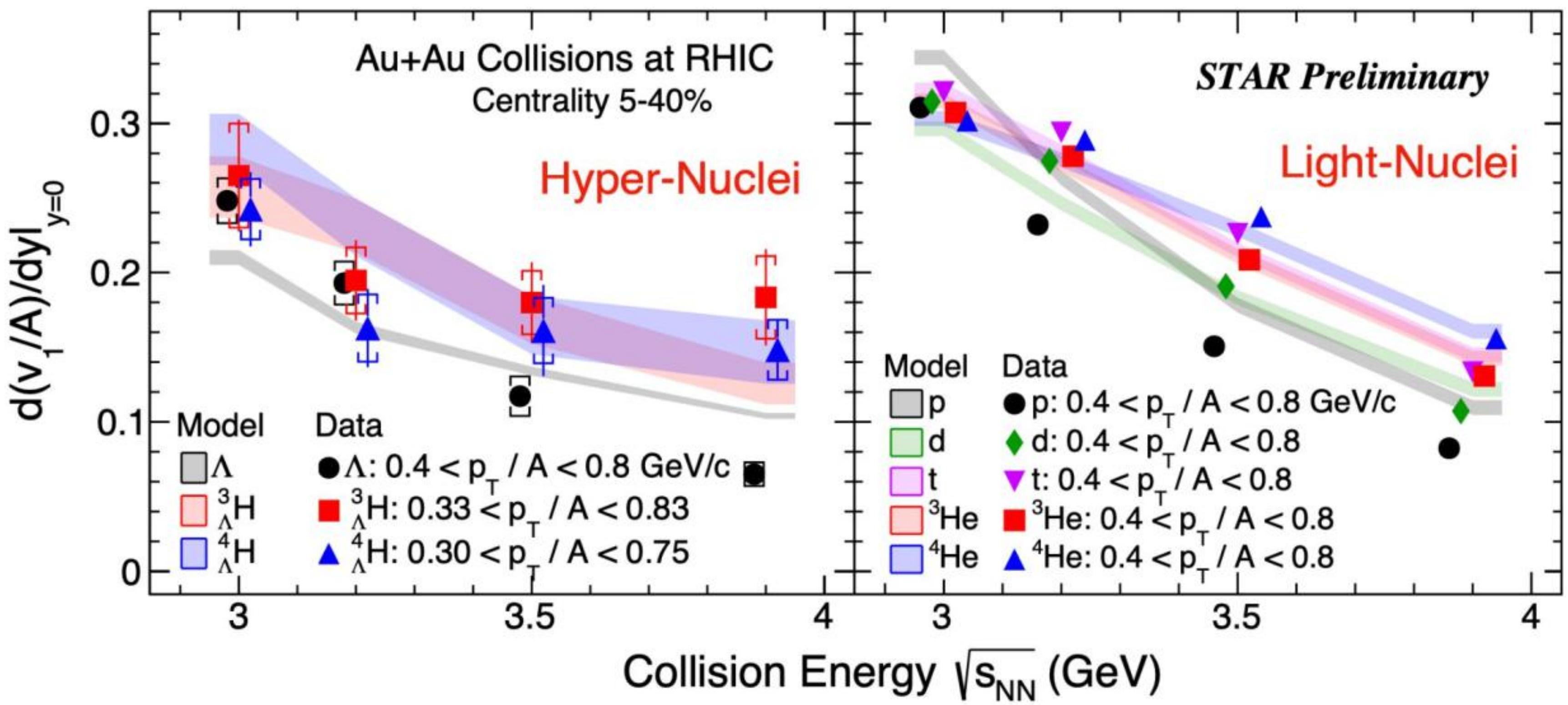
# Triangular flow ($v_3$)




- Proton $v_3\{\psi_1\}$ measured as function of rapidity and $p_T$ in Au+Au collisions $\sqrt{s_{NN}} = 3.0$ GeV.
- Magnitude of $v_3$ increases from central to peripheral collisions showing strong geometric effect.
- JAM model with mean-field describes the data well suggesting nuclear potential is essential for the development of $v_3\{\psi_1\}$ in Au+Au collisions $\sqrt{s_{NN}} = 3.0$ GeV.

[1] M. I. Abdulhamid et al. (STAR Collaboration ) Phys. Rev. C 109, 044914 (2024)

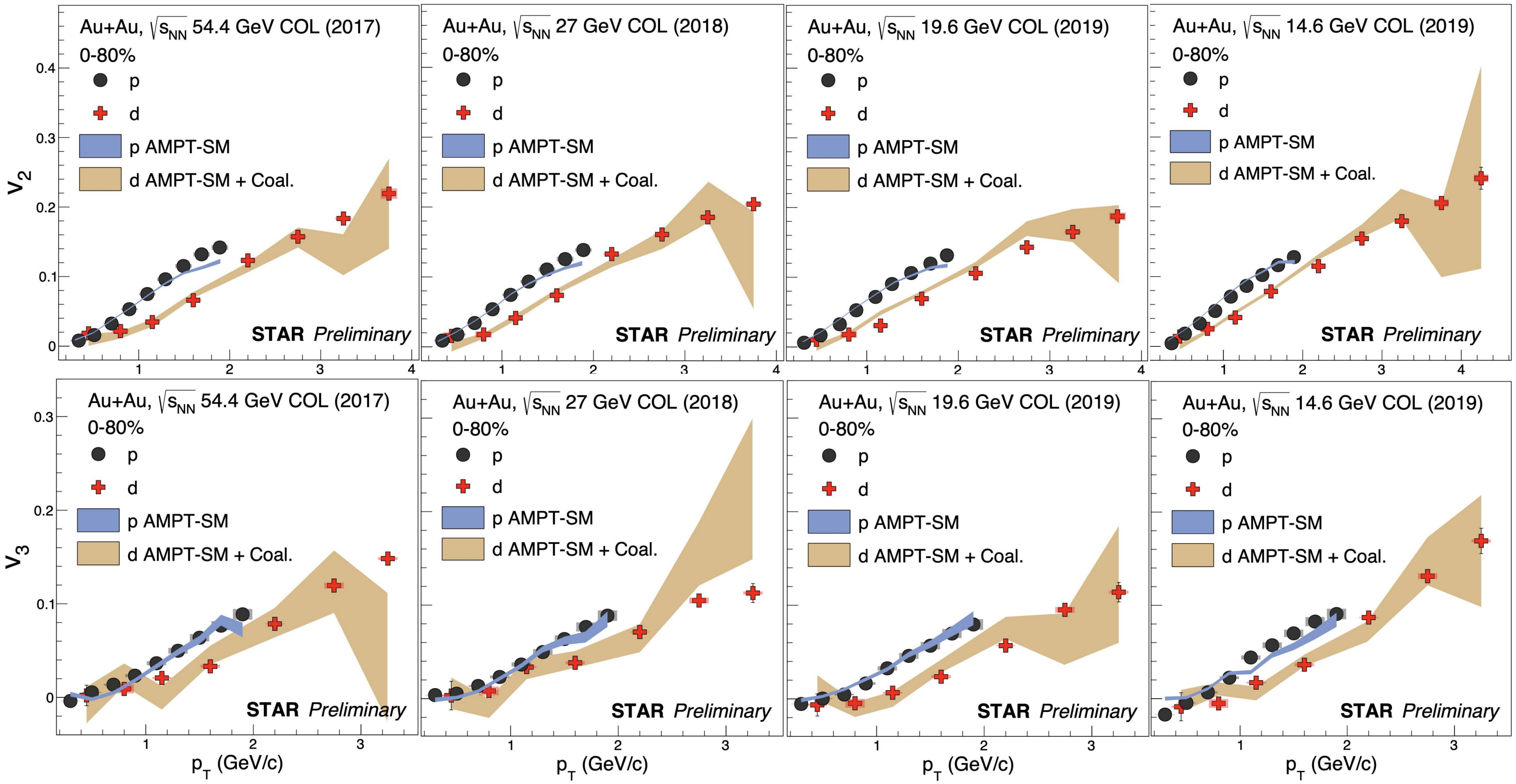
# Light and Hyper nuclei $v_1$ at high $\mu_B$




- 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, indicating coalescence as their production mechanism at high $\mu_B$.


[1] M. S. Abdallah et al. (STAR Collaboration) Phys. Lett. B 827, 137003 (2022)
[2] B. E. Aboona et al., (STAR Collaboration), Phys. Rev. Lett. 130, 211301 (2023)
[3] Yasushi Nara, Akira Ohnishi. Phys. Rev. C 105, 014911 (2022)

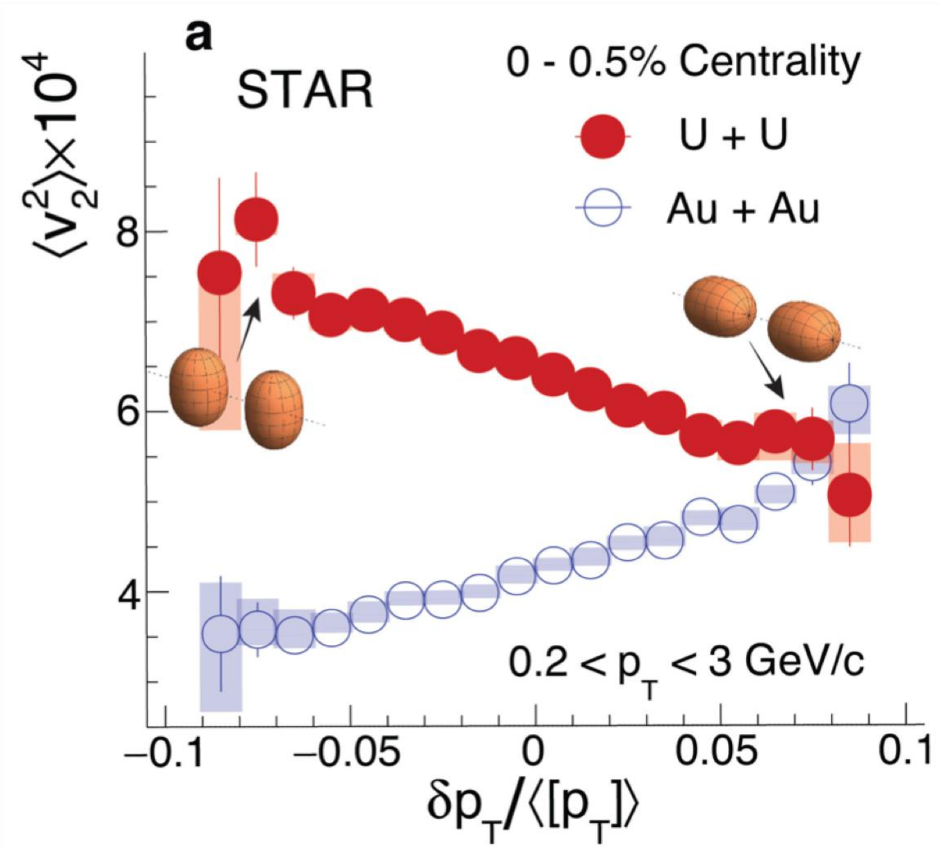
# Light nuclei collectivity

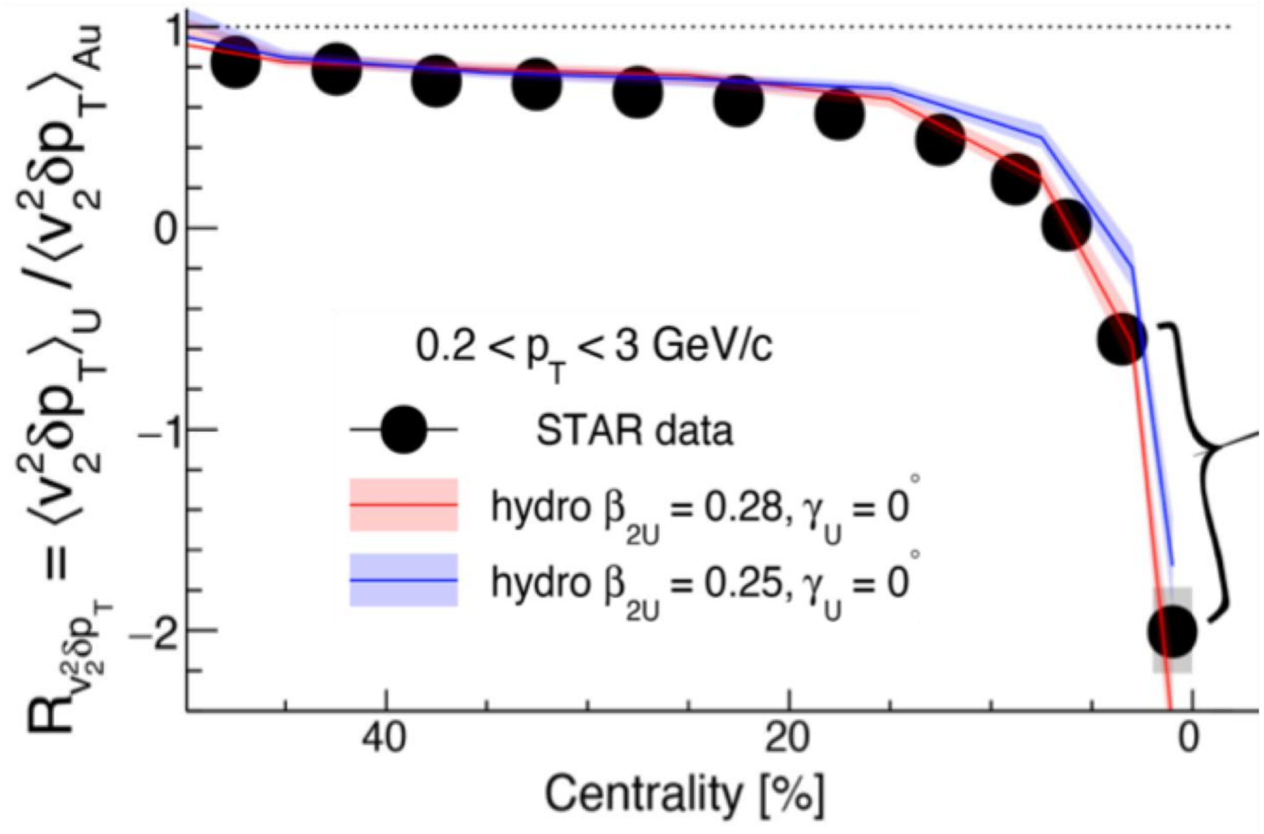



- AMPT(SM) model with coalescence describes deuteron $v_2$ and $v_3$
  → Insights to light nuclei production mechanism in heavy-ion collisions


[1] 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)

# Nuclear size and deformation

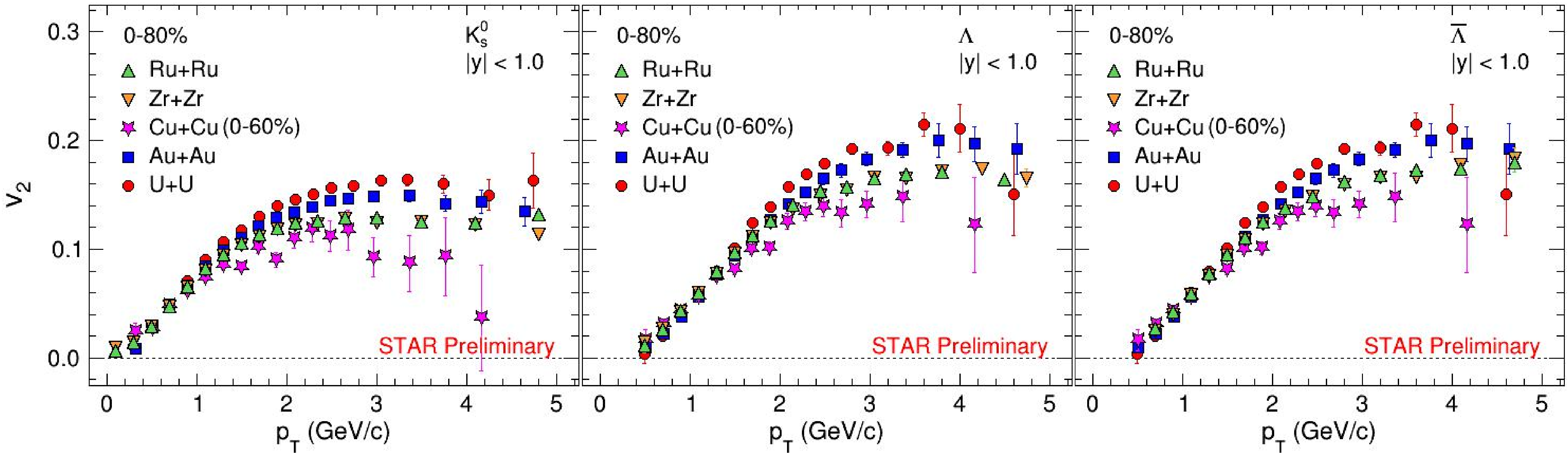



- Elliptic flow $v_2$ of charged hadrons enhanced in central U+U collisions compared to Au+Au colisions
- Average $v_2$ ratio and $v_2$-$p_T$ correlations can be use to constrain initial conditions and nuclear structure in U+U collisions

[1] STAR, arXiv:2401.06625 [nucl-ex] (2024)
[2] G. Giacalone et al., Phys. Rev. Lett. 127, 242301 (2021)
[3] B. Schenke et al., Phys. Rev. C 102, 034905 (2020)

# Nuclear size and deformation

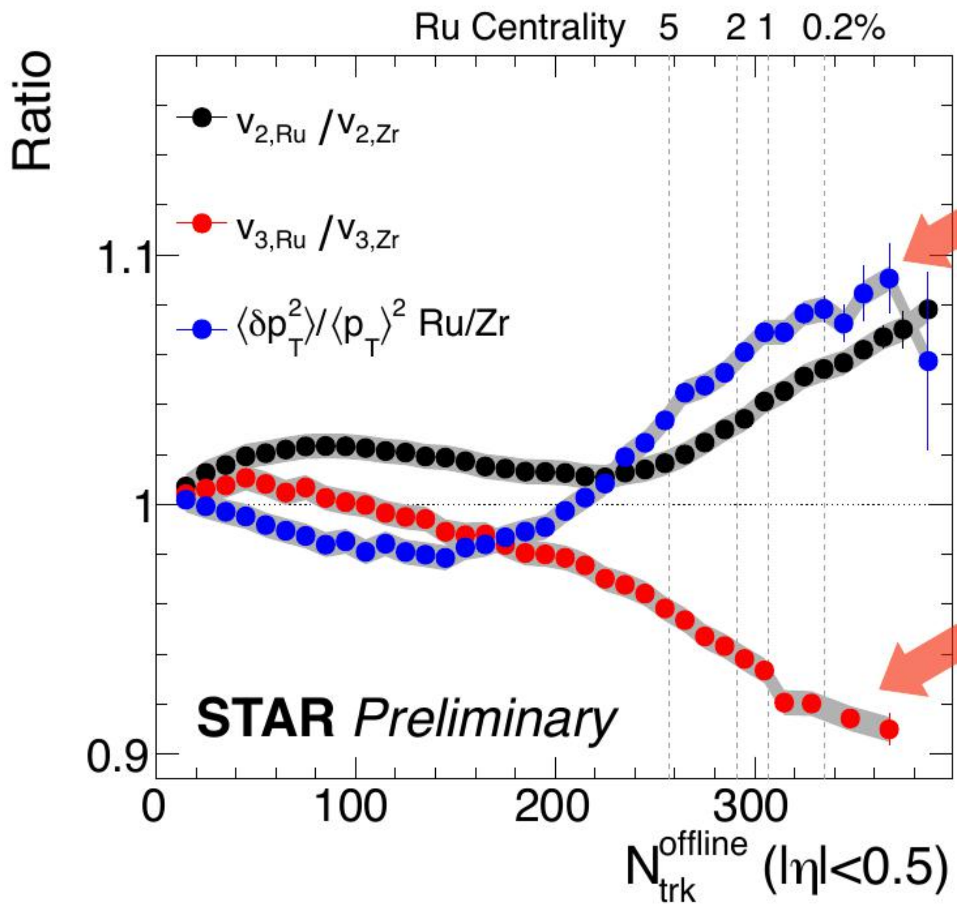


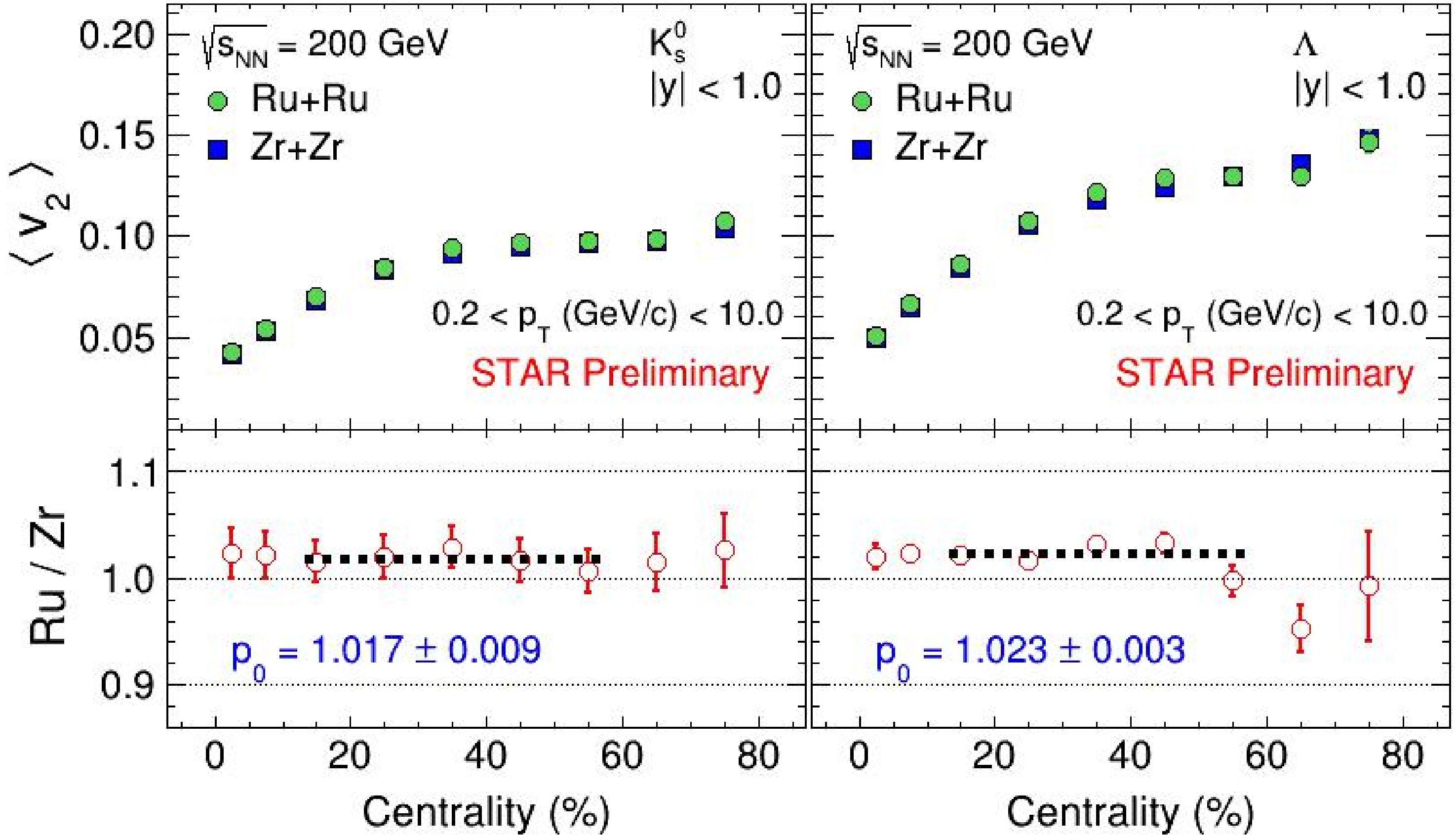

- Elliptic flow at high $p_T$ increasases with atomic mass number of nuclei.

→ Indicating a nuclear size dependence

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

# Nuclear size and deformation



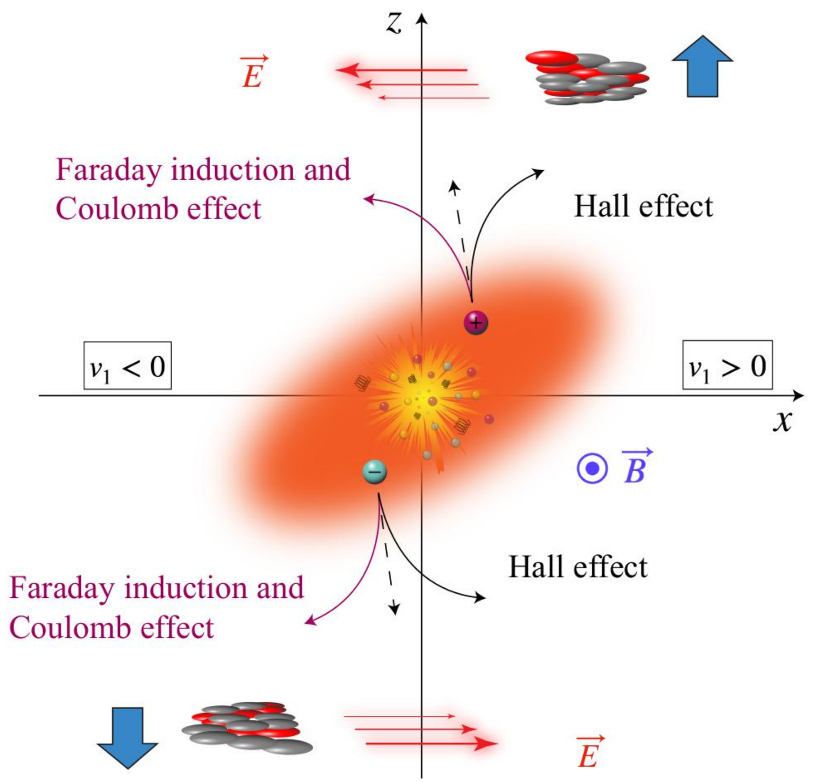



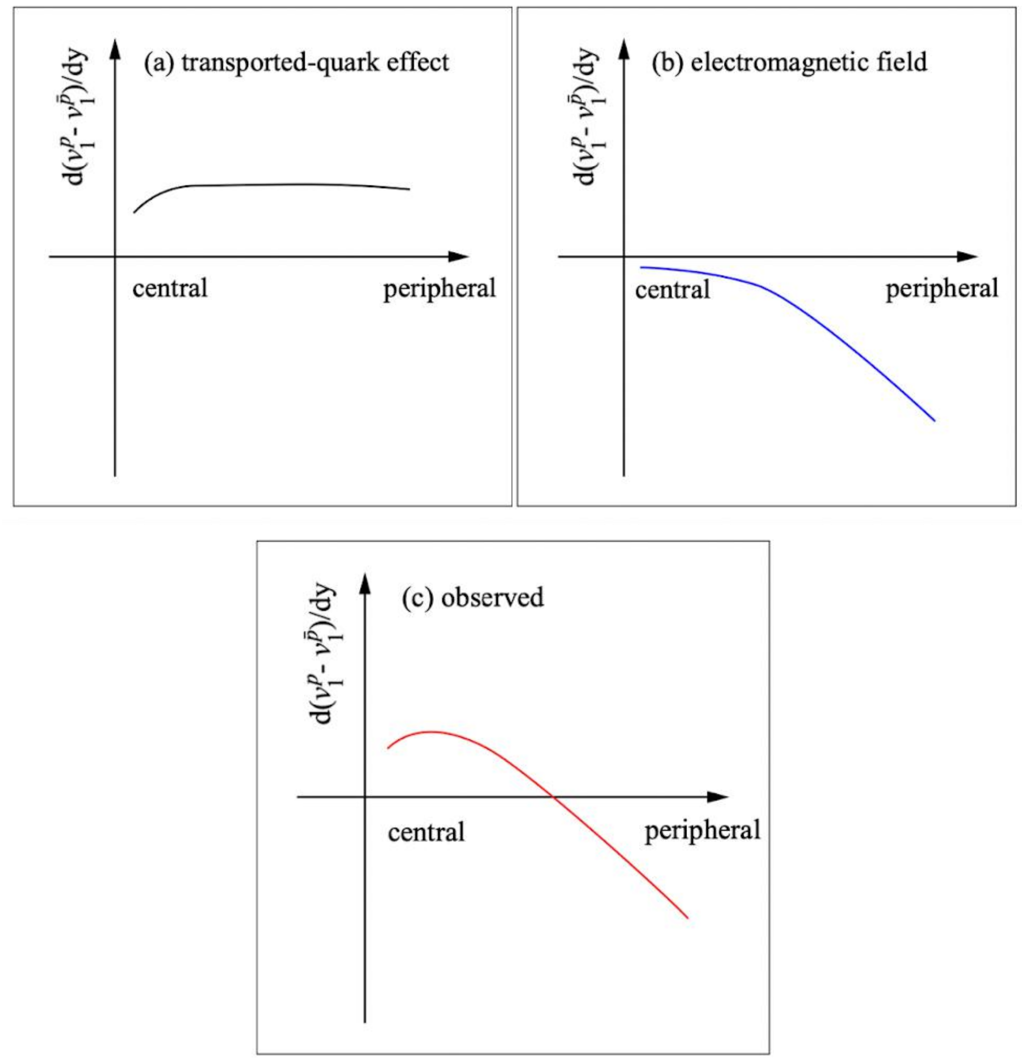

- Ratio of integrated $v_2$ between Ru+Ru and Zr+Zr collisions differs from unity
  → Indication of larger quadruple deformity in Ru nuclei than in the Zr nuclei

# Directed flow and EM-field effects

Quarks experience forces in the medium due to:

- **Hall Effect:** $\vec{F} = q(\vec{v} \times \vec{B})$
- **Coulomb Effect** ($\vec{E}$ generated by spectators) and
- **Faraday Induction** ($\vec{E}$ generated by decreasing magnetic field)



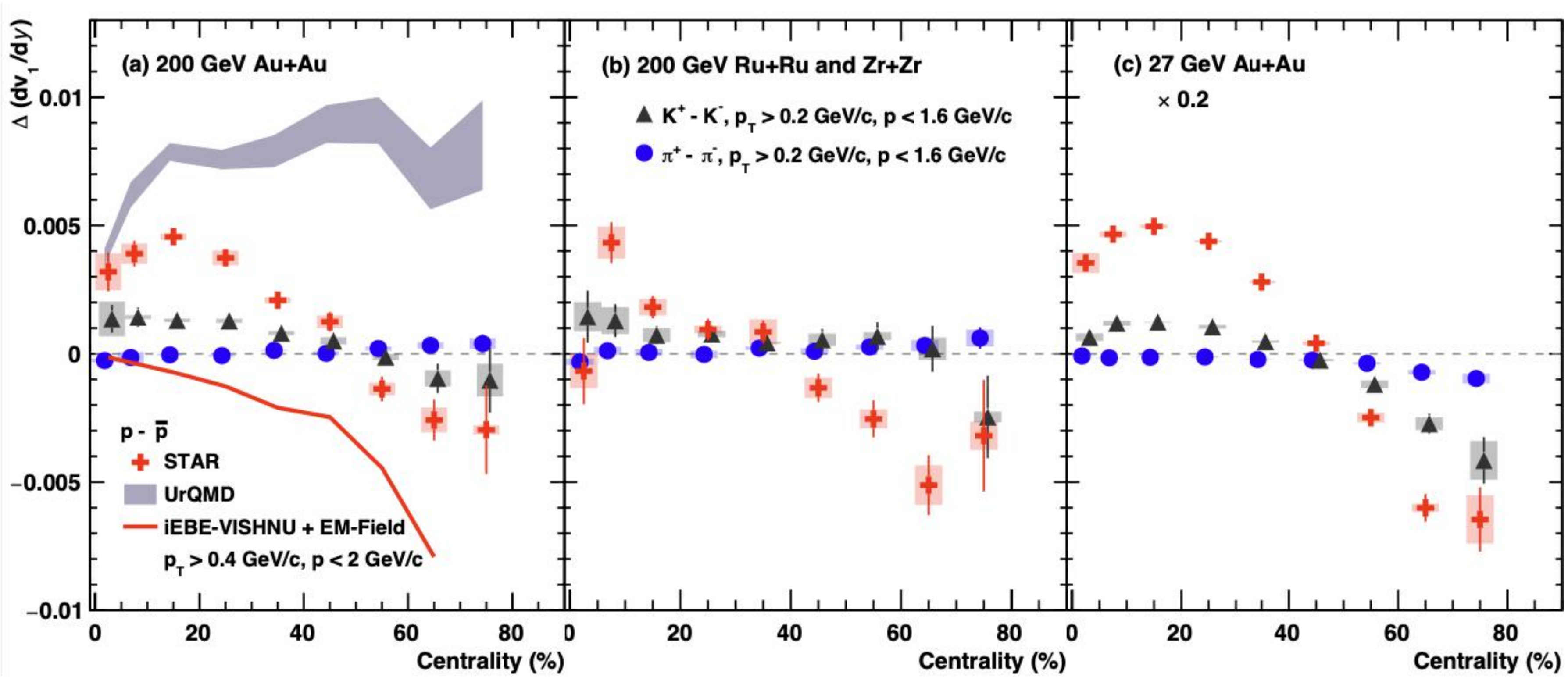




- Theory predict positive $\Delta dv_1/dy$ from transported quarks and negative $\Delta dv_1/dy$ from electromagnetic fields in QGP


[1] U. Gursoy el. al. Phys. Rev. C 98, 055201 (2018); Phys. Rev. C 89, 054905 (2014)

[2] M. I. Abdulhamid et al. (STAR Collaboration) Phys. Rev. X 14, 011028 (2024)

# Directed flow and EM-field effects




- Negative $\Delta(dv_1/dy)$ in peripheral collisions consistent with expectation from electromagnetic field effects
  → Dominance of Faraday effect in peripheral collisions
- Positive $\Delta(dv_1/dy)$ for protons in (mid)central collisions shows transported quark effect

M. I. Abdulhamid et al. (STAR Collaboration) Phys. Rev. X 14, 011028 (2024)

# Summary & Outlook

### Collectivity in high $\mu_B$ 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 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

### System size dependence

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

### Electromagnetic field effects in HIC

- Charge dependent $v_1$ results indicate dominance of Faraday effect in peripheral collisions

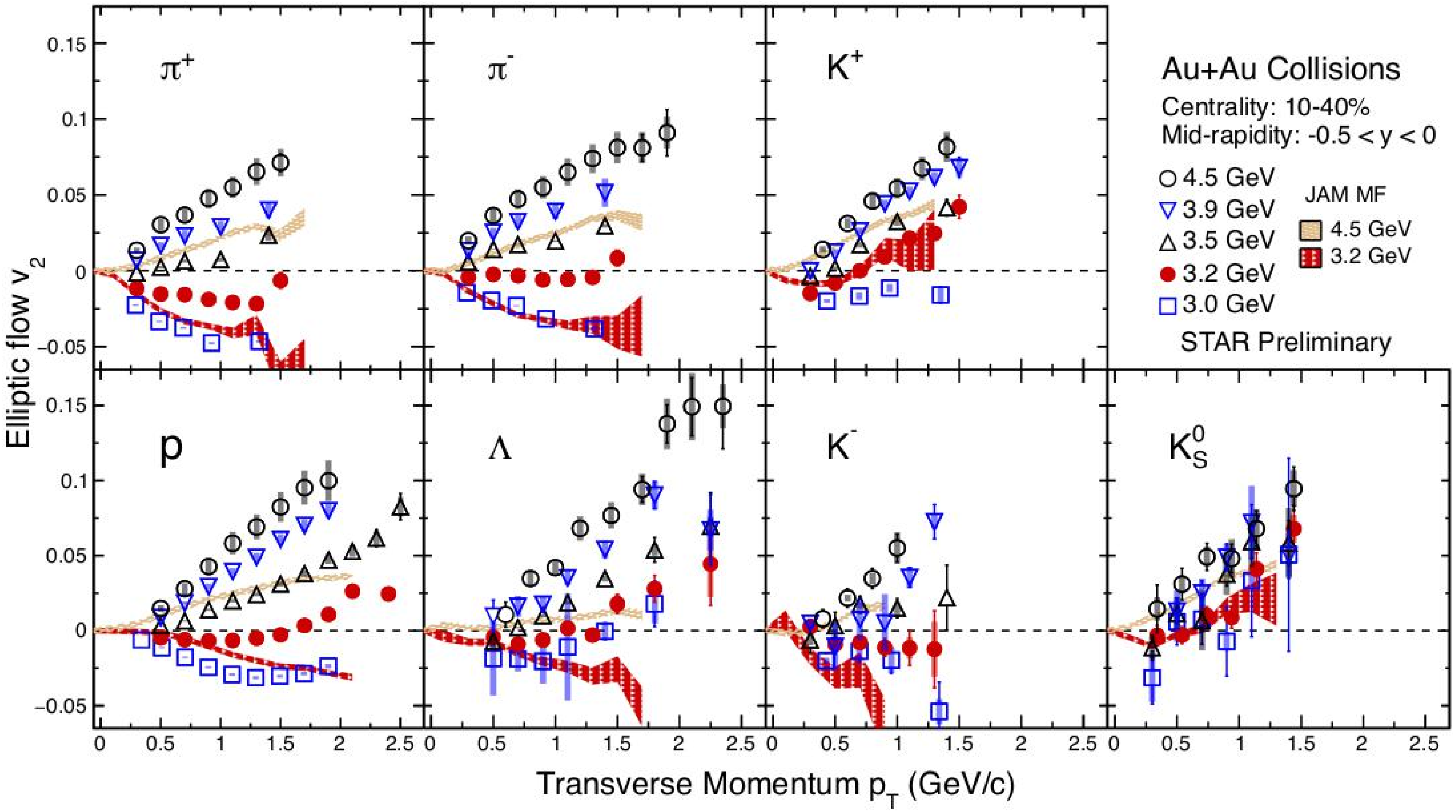
More exciting results to come from the high statistics data of BES and FXT program at STAR. Collectivity from small to large systems and measurements in wider rapidity ranges using forward detectors enable us to explore the QGP properties, phase transtiton and more....

# Thank you for your attention!

# Backup

# Ellitpic flow $v_2$ at high $\mu_B$

FXT

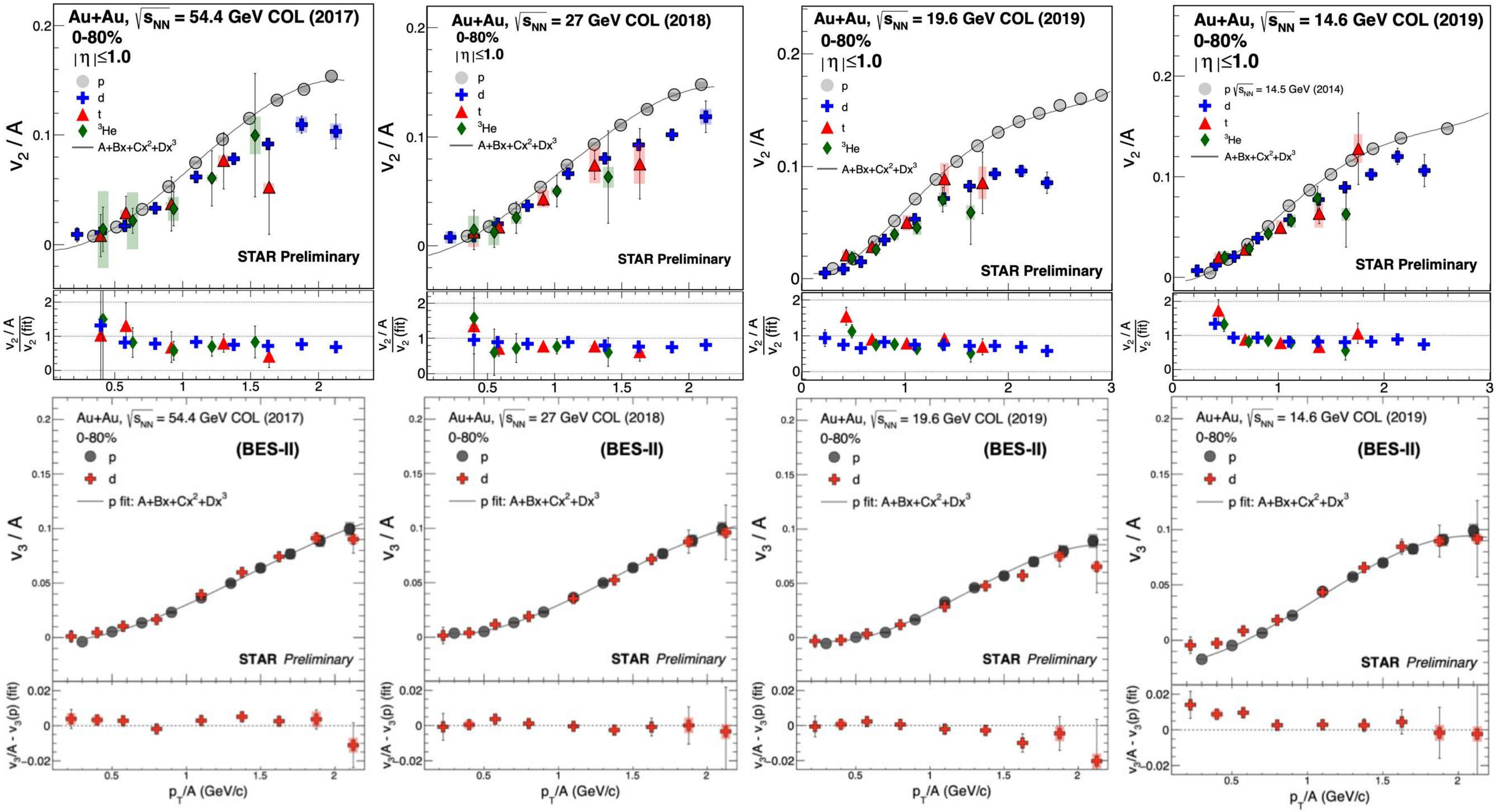



JET AA Microscopic Transport Model

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

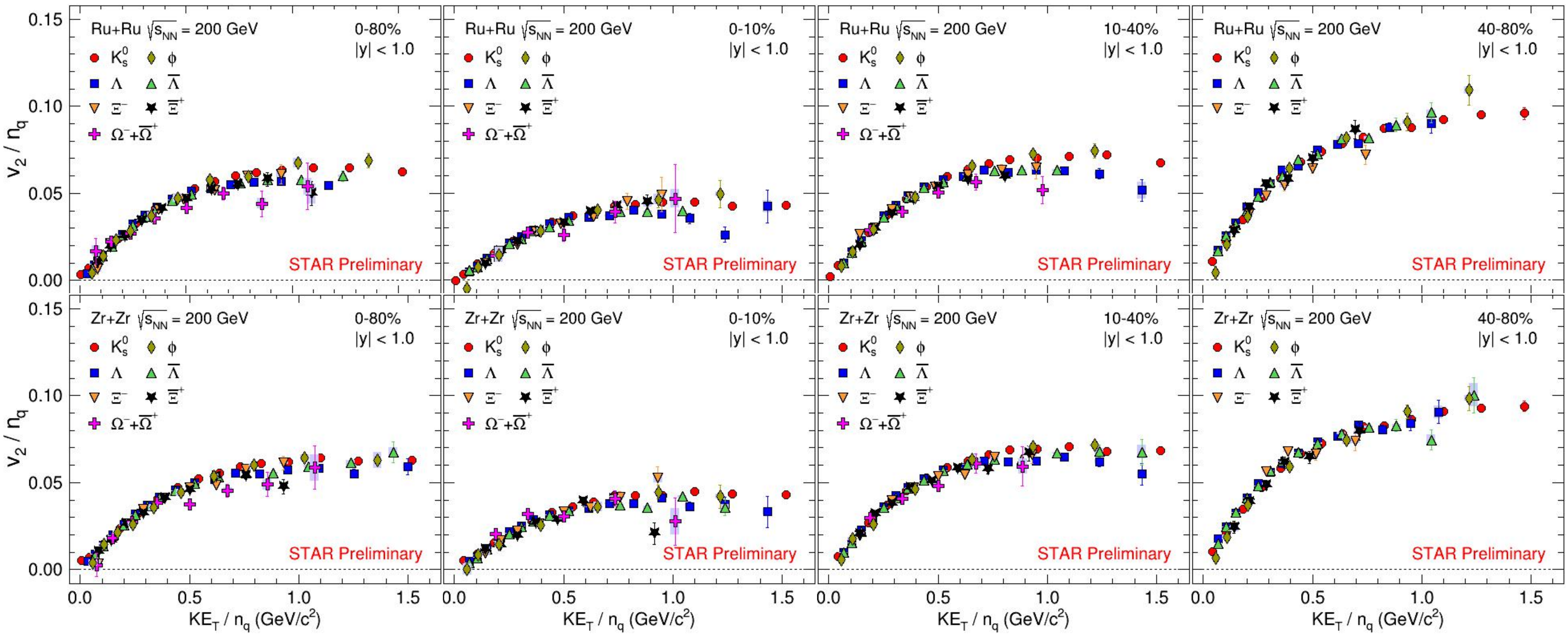
- Energy dependence of $v_2(p_T)$: transition from negative to positive values indicate shadowing effect.
- JAM model with baryonic mean field describe 3.2 GeV data well while underestimating 4.5 GeV data, suggest baryonic dominated medium.

# 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.