Highlights on flow measurements from the STAR experiment

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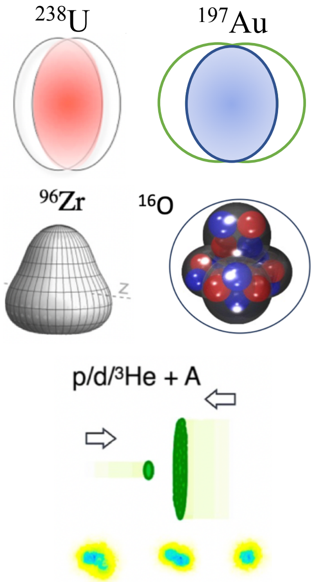
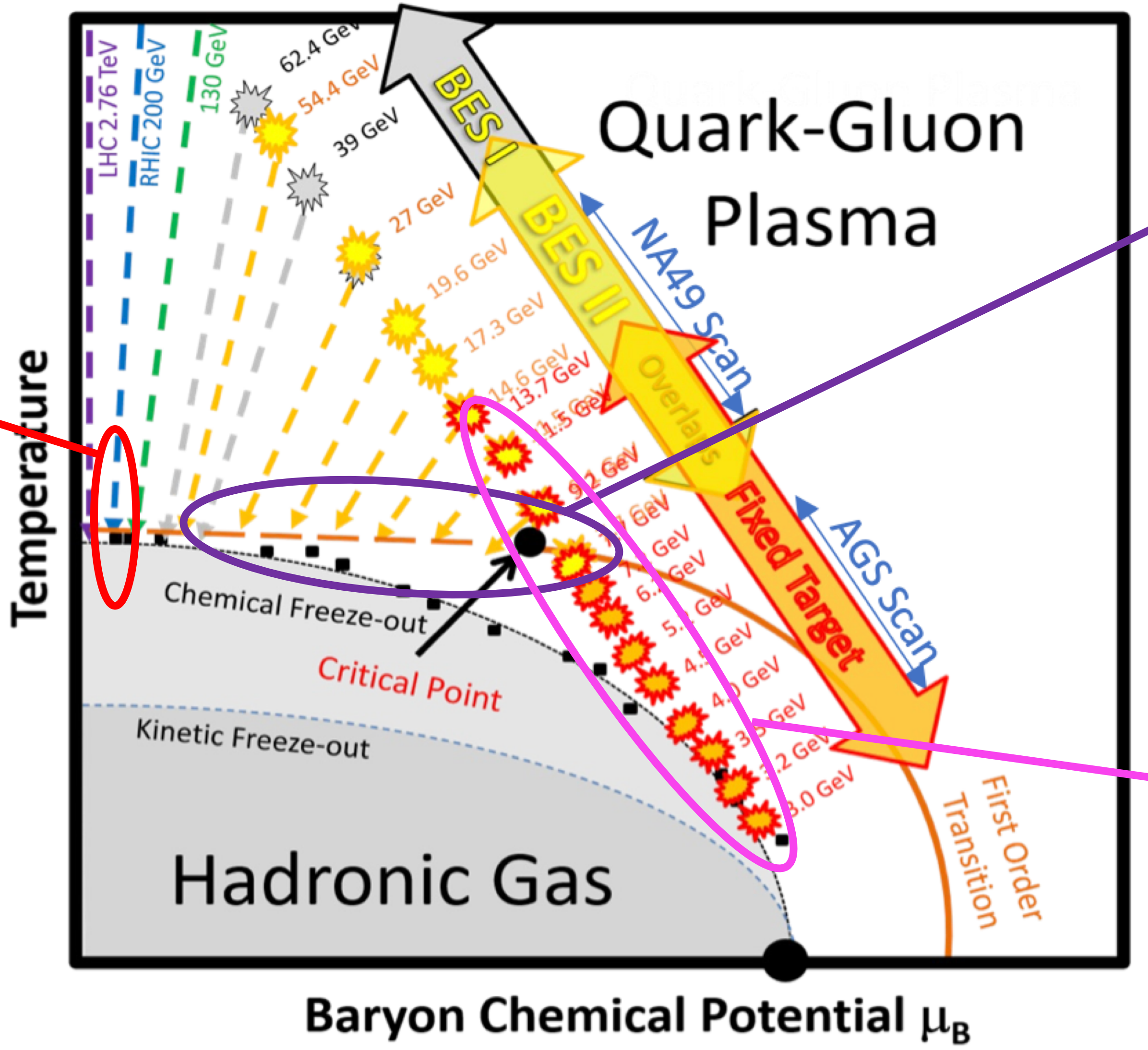
RHIC-AGS Annual Users' Meeting

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

Beam energy and system scan at STAR

3) System scan at RHIC top energy $\sqrt{s_{NN}} = 200$ GeV





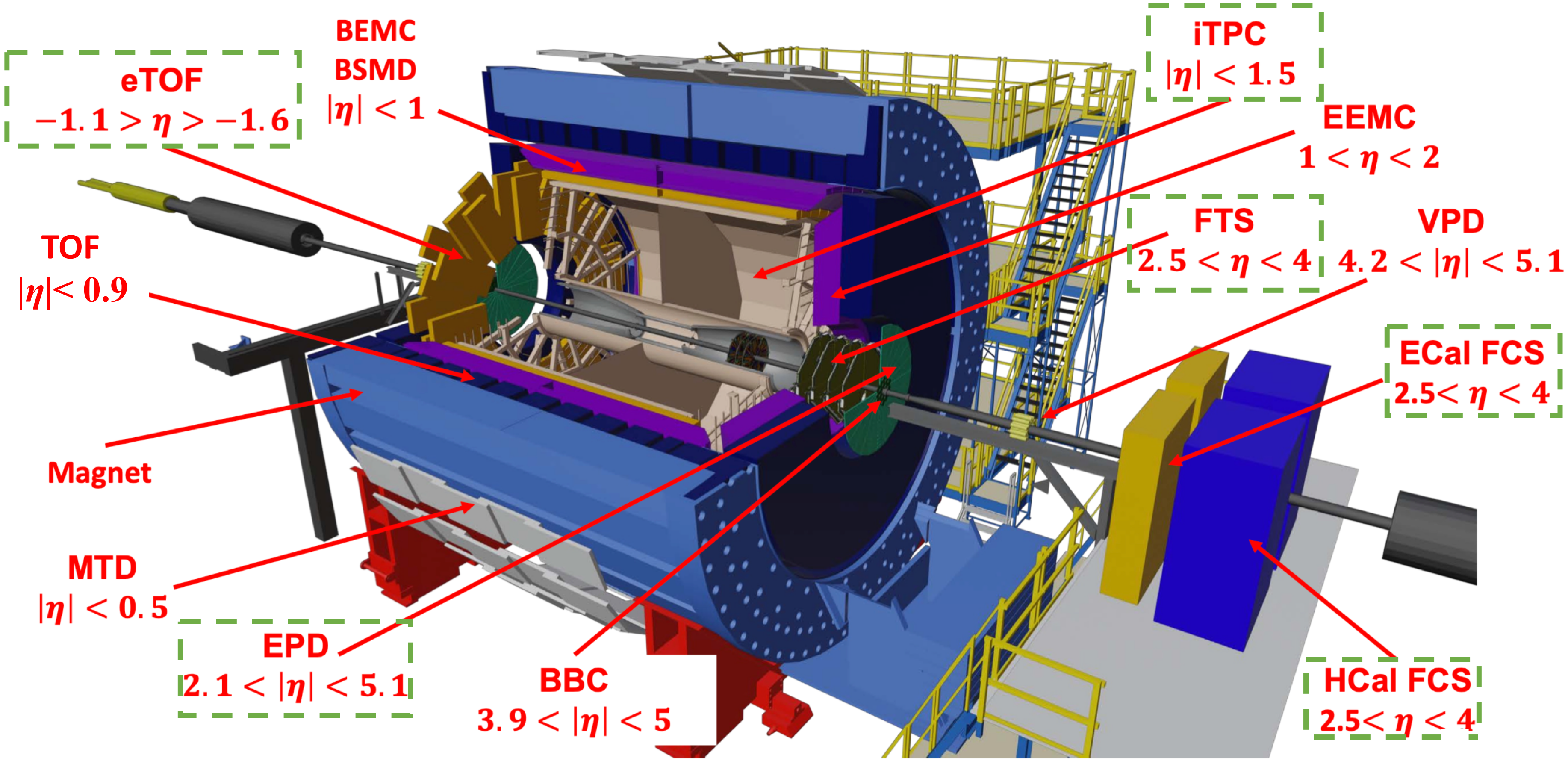
1) BES-II collider energies $\sqrt{s_{NN}} = 7.7 – 54.4$ GeV

- Onset of deconfinement
- Nature of the phase transition
- Critical Point
- Study of QGP properties

2) FXT energies $\sqrt{s_{NN}} = 3.0 – 13.7$ GeV

K Meehan, Nuclear Physics A. 967 (2017) 10.1016

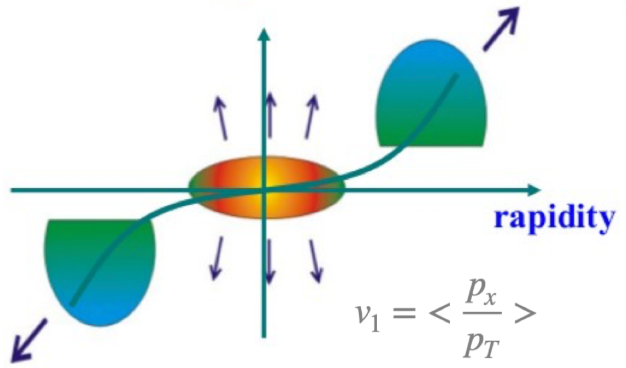
Solenoidal Tracker at RHIC (STAR)



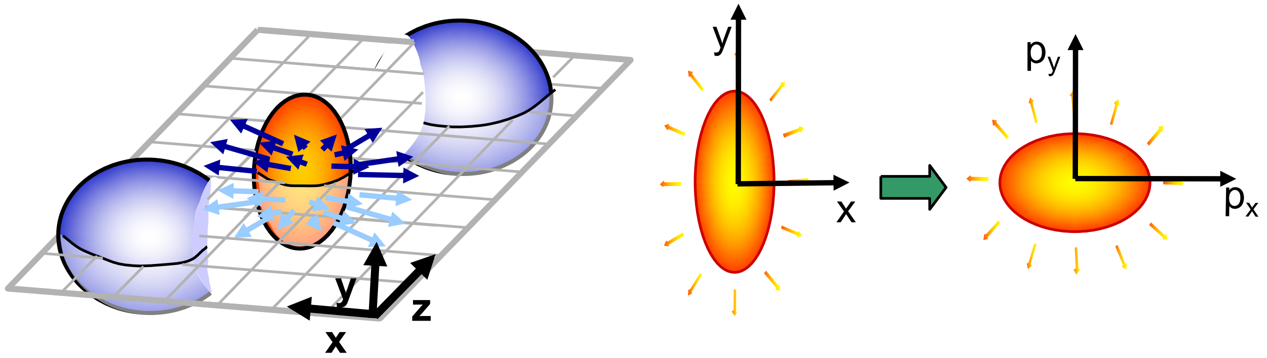
- Enlarged rapidity acceptance
- Improved particle identification
- Enhanced event plane resolution

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/. public/sn0619.
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102.
EPD: J. Adams, et al. NIM A968, 163970 (2020)

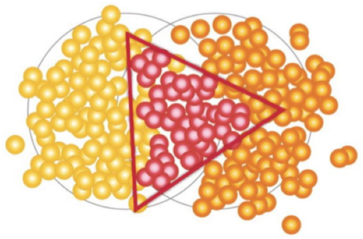
Anisotropic flow



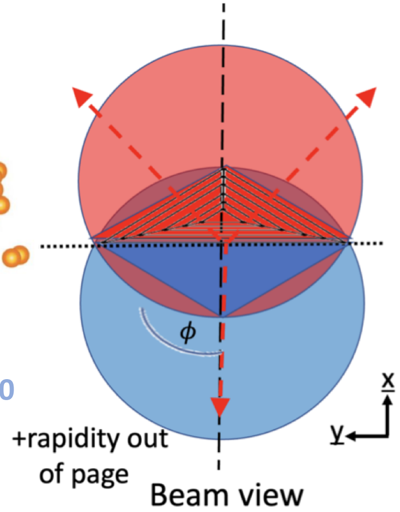
Directed flow (v_1): Sideward collective motion of produced particles



Elliptic flow (v_2): Initial spatial anisotropy leading to final momentum asymmetry of produced particles



Science 337 (2012) , 310



STAR, PRC 109 (2024), 044914

Triangular flow (v_3): Higher energy: Sensitive to initial state event-by-event fluctuations
Lower energy: Result of shadowing and baryon stopping; sensitive to medium potential

Reaction plane: z-x plane

$$\frac{dN}{d\phi} \propto [1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_R))]$$

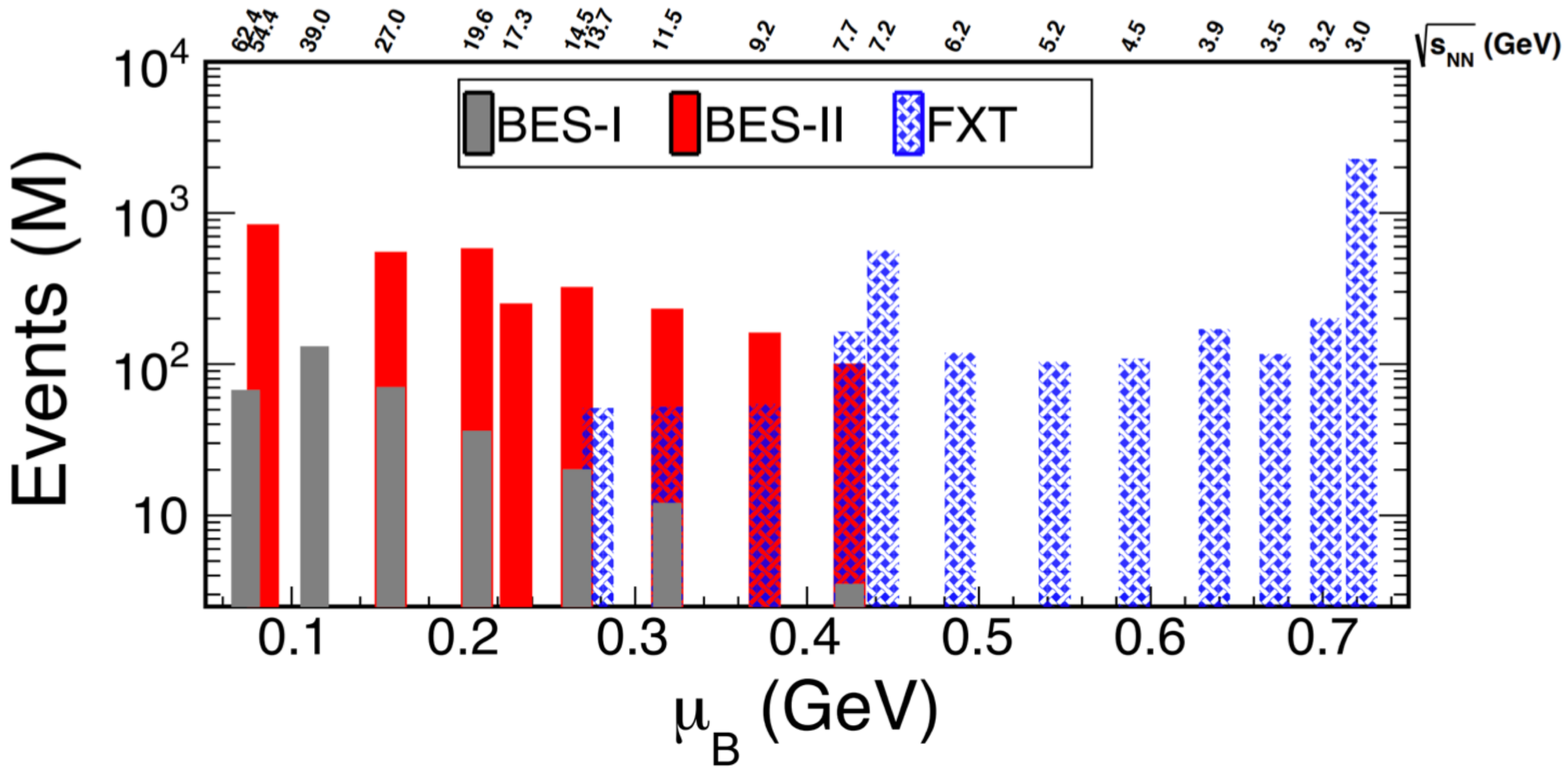
$$v_n = < \cos(n(\phi - \Psi_R)) >$$

→ Equation of State of the medium
→ Early stage dynamics

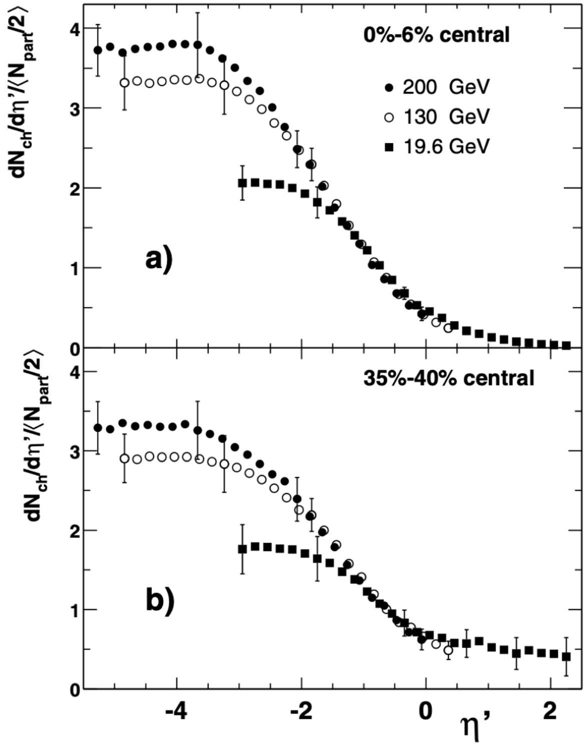
A.M. Poskanzer & S.A. Voloshin, PRC 58 (1998), 1671
STAR, PRL 118 (2017), 212301

Emilie Duckworth
Wednesday 3:00 PM

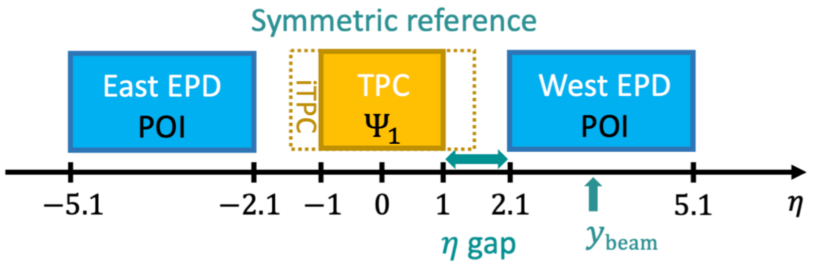
Beam Energy Scan

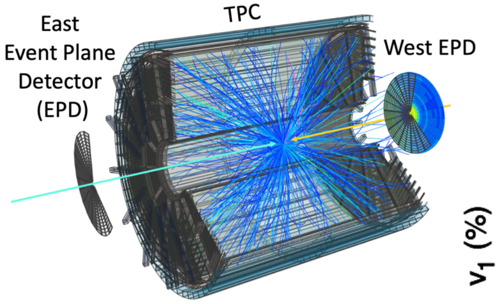


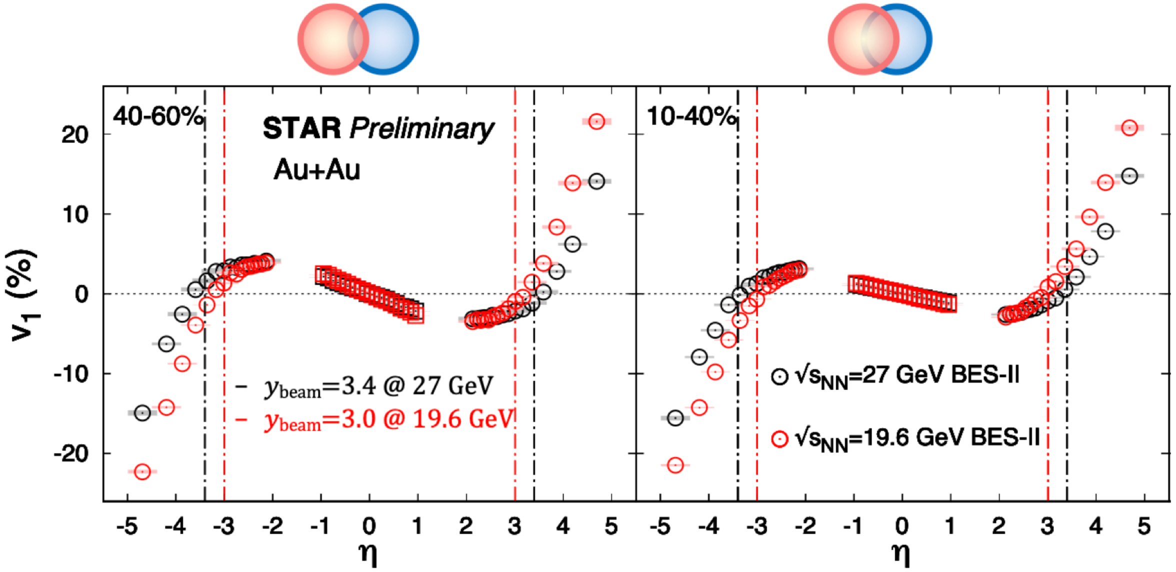
Limiting fragmentation of v_1

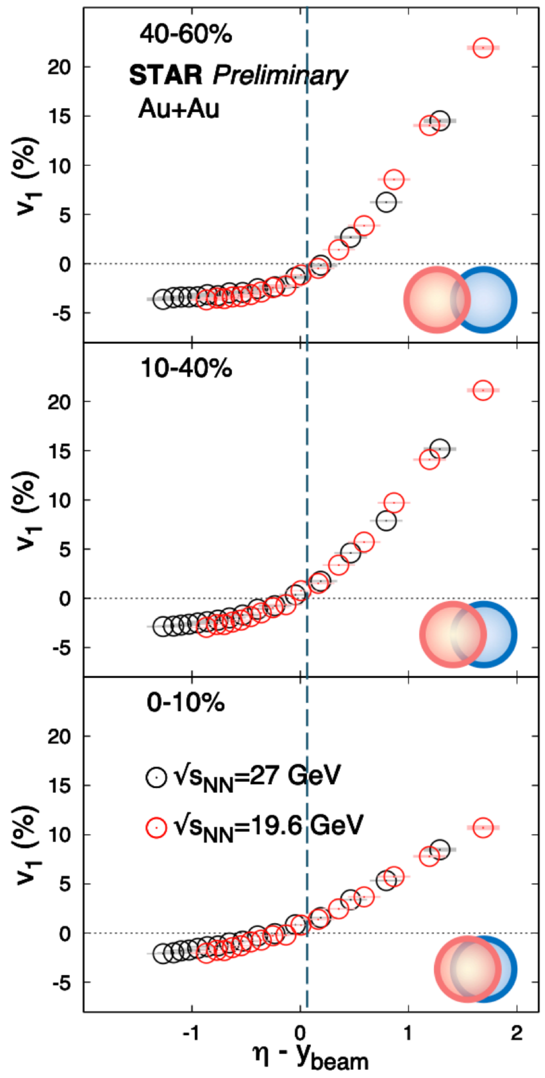


PHOBOS. PRL 91 (2003), 052303
PHOBOS. PRL 97 (2006), 012301



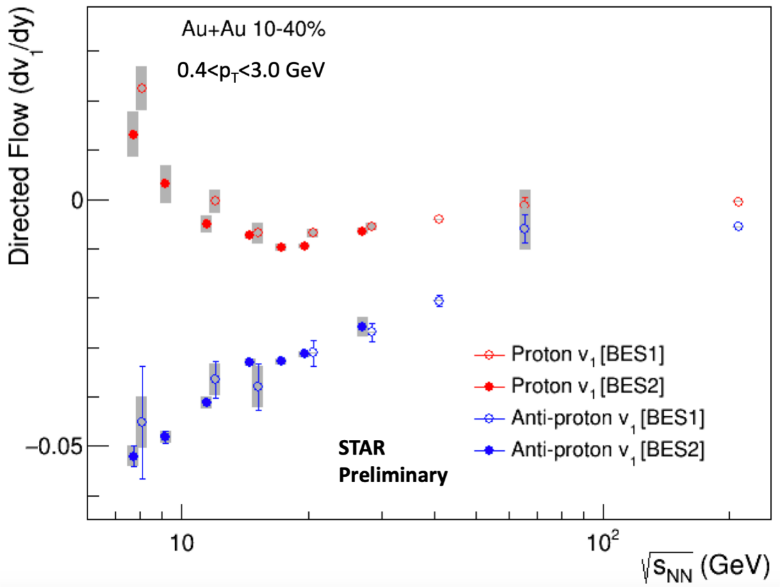




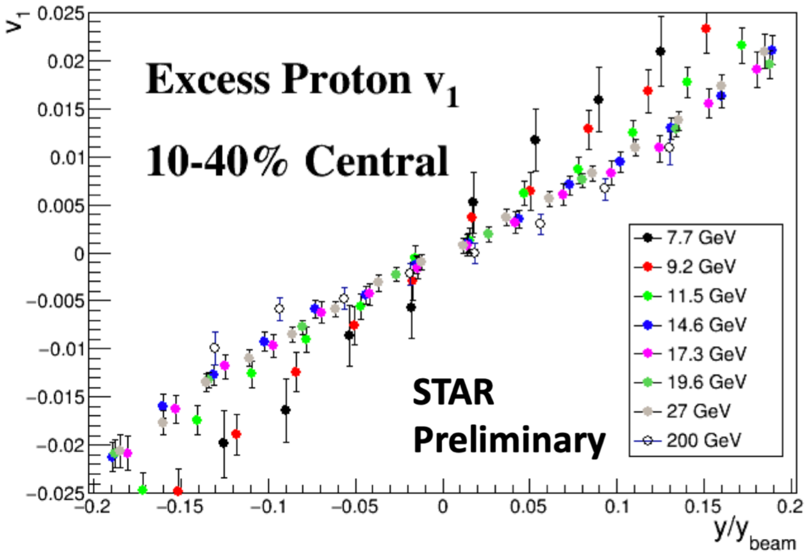


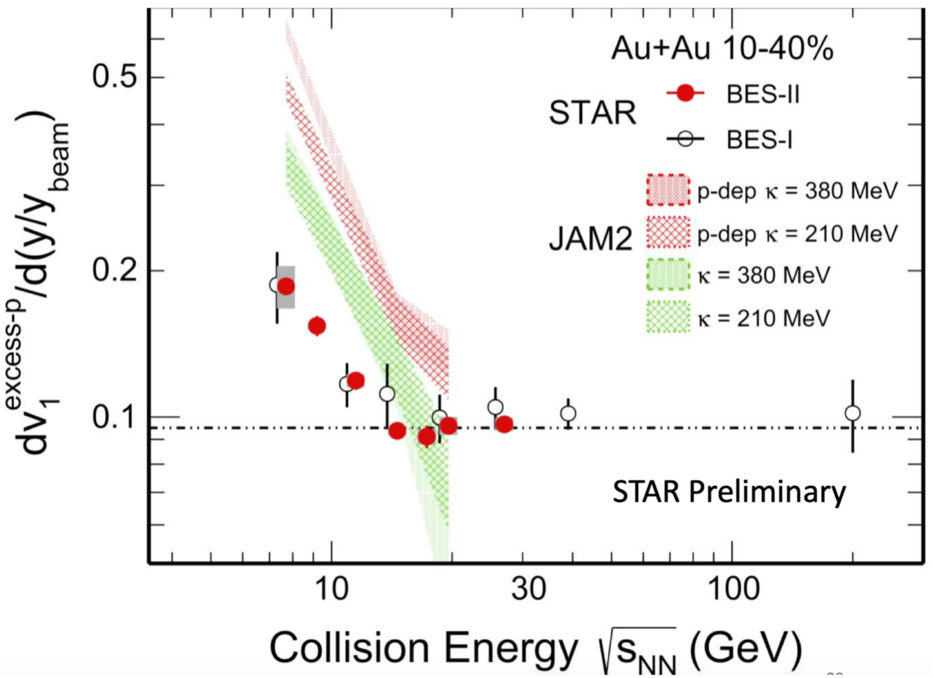
- ➢ Measurement of flow over nine units of pseudorapidity (η)
- ➢ Precision measurement of v_1 enables observation of limiting fragmentation
- ➢ The phenomenon extends for various centralities at BES-II energies

Excess proton v_1 in BES-II



- Precision measurement of $\bar{p}$ and p from 7.7 to 200 GeV





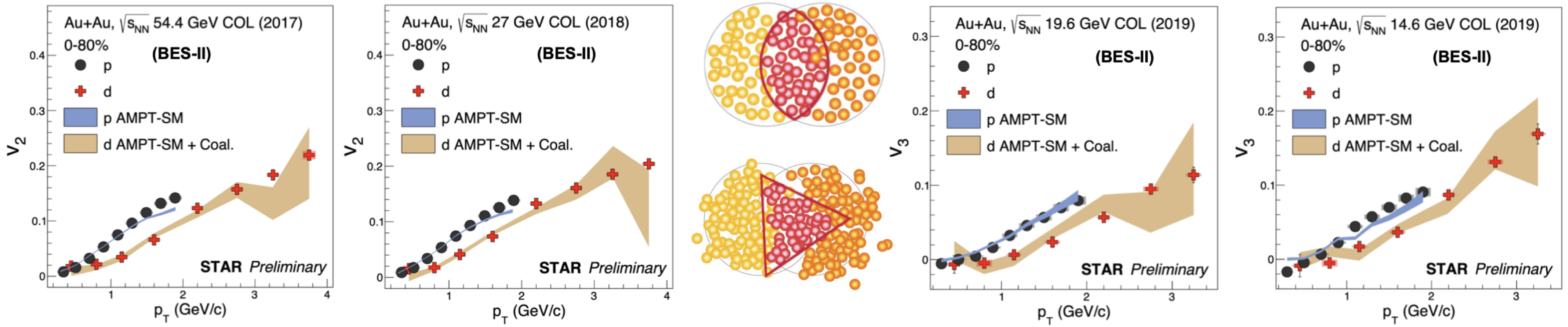
$$v_{1,excess} = \frac{(v_{1,p} - v_{1\bar{p}})}{1-r}$$

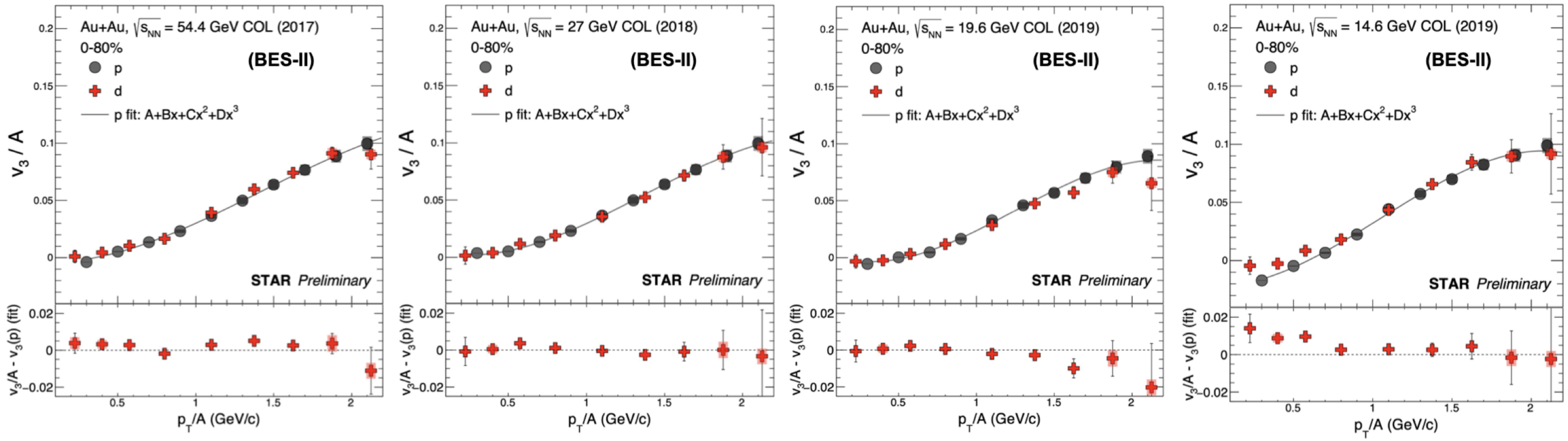
$$r = \frac{yield\ of\ \bar{p}}{yield\ of\ p}$$

- Scaling of excess proton flow with collision energy
- Indication of scale breaking at 11.5 GeV → change in medium and collision dynamics
- Mean field calculations overpredict the $v_{1,excess}$ data below 14.6 GeV

Nucl. Instrum. Meth. A 968 (2020), 163970
STAR, PRL 120 (2018), 62301
Y. Nara et al., PRC 100 (2019), 054902

v_n of light nuclei in BES-II

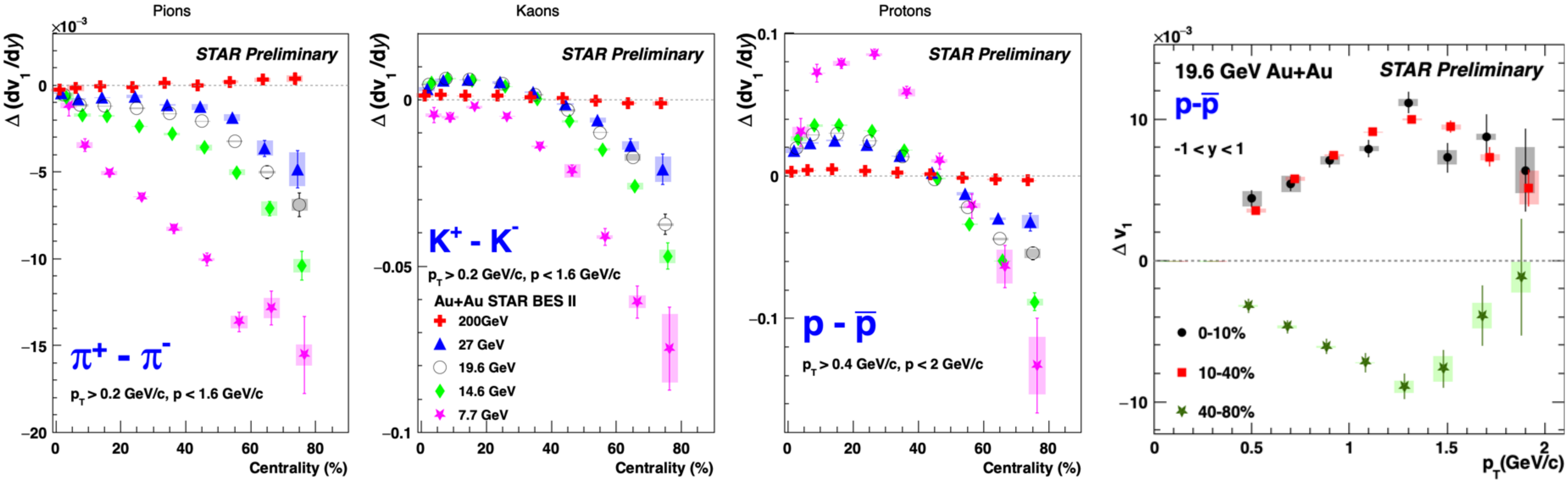




PRC 72 (2005), 064901
PRC 93 (2016), 014907
PRC 88 (2013), 014902
PLB 827 (2022), 137003
Nucl. Phys. A 729 (2003) 809–834

- First measurement of v_3 of light nuclei at collider energies
- Suggests coalescence to be the dominant mechanism of light nuclei production

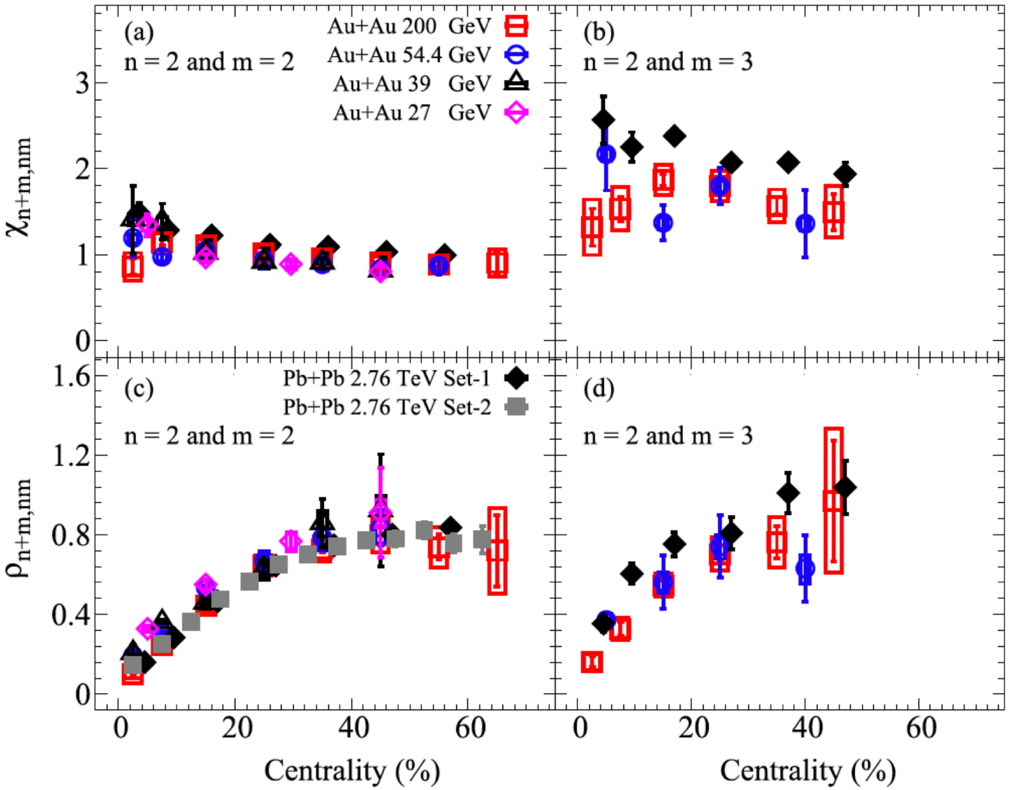
Beam energy dependence of Δv_1 slope



- Δv_1 slope is more negative at lower collision energies
  - → Could be due to EM-field effect, longer-lived field and shorter lifetime of fireball
- Indication of strong p_T dependence of splitting

STAR, PRX 14 (2024), 011028
U. Gürsoy et al. PRC 98 (2018) ,055201; PRC 89 (2014), 054905

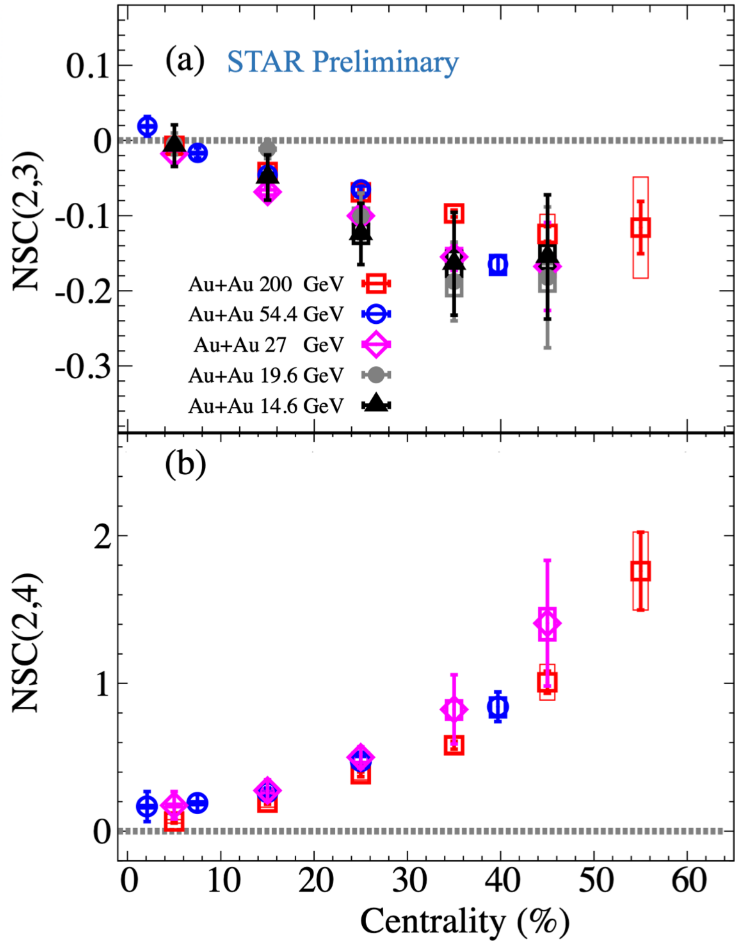
Beam energy dependence of flow cumulants



$$V_4 = v_4 e^{i4\psi_4} = \kappa_4 \varepsilon_4 e^{4i\Phi_4} + \kappa'_4 \varepsilon_2^2 e^{4i\Phi_2}$$
$$= V_4^{\rm Linear} + \chi_{4,22} V_4^{\rm MC},$$

Mode-coupling

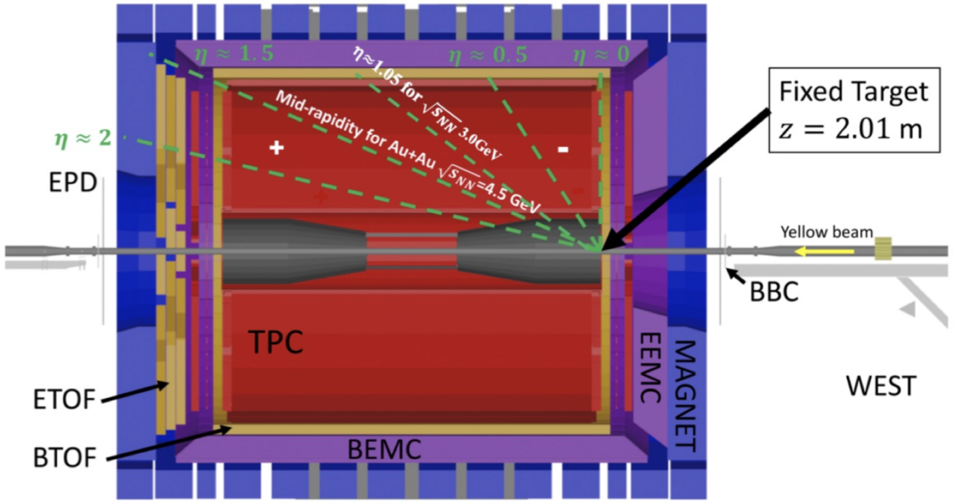
- Anti-correlation between v_2 and v_3
  → Anti-correlation b/w ε_2 and ε_3
- Mode coupling between v_2 and v_4

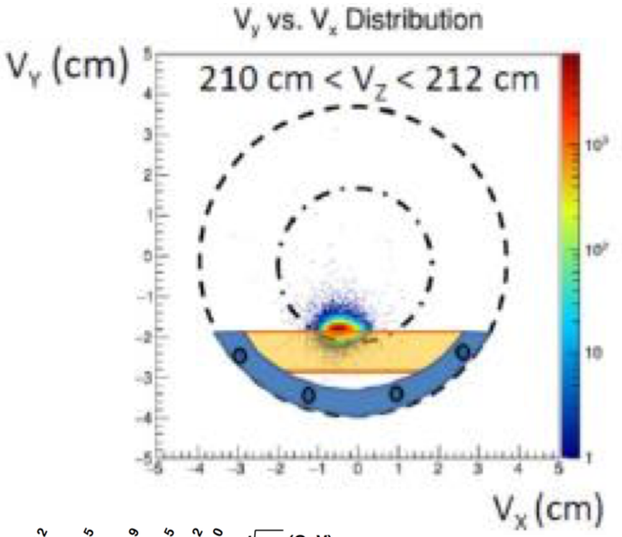


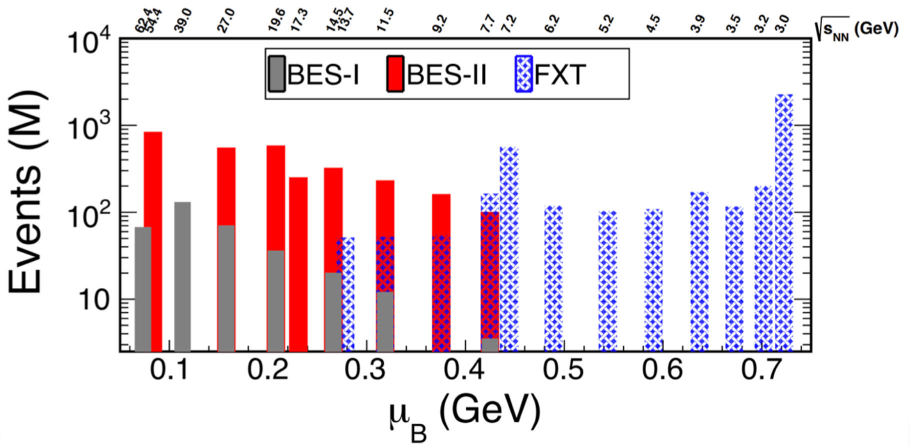
- Weak dependence on beam energy
  → Weakly sensitive to the viscous effects (η/s) ; more sensitive to the initial-state effects

STAR, PLB 839 (2023) 137755; A. Bilandzic et al. PRC 89, 064904, R.A. Lacey et al. arXiv:1311.1728, N. Magdy Universe 2023, 9(2) 107

Fixed–target (FXT) energies

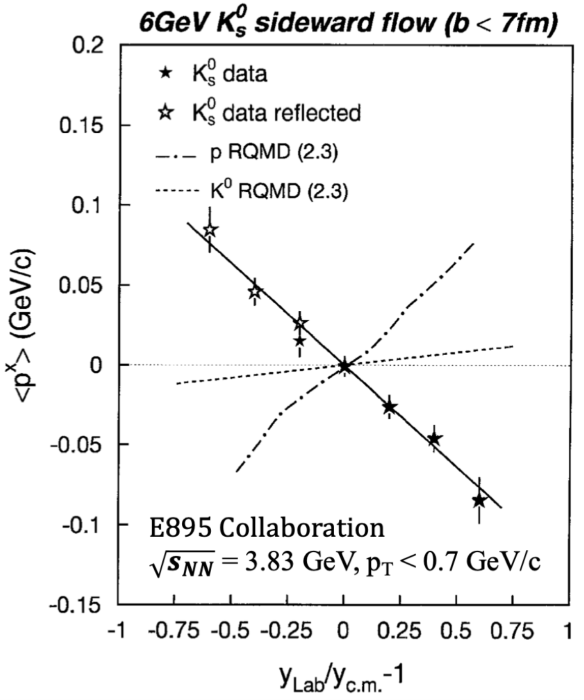




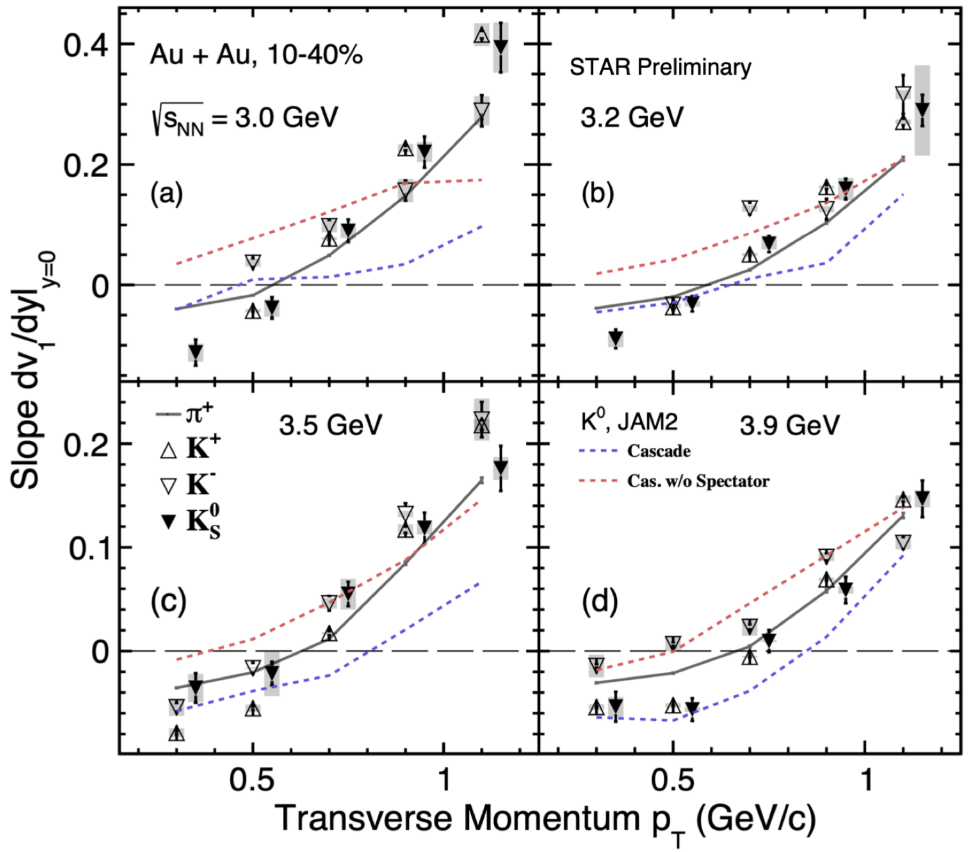


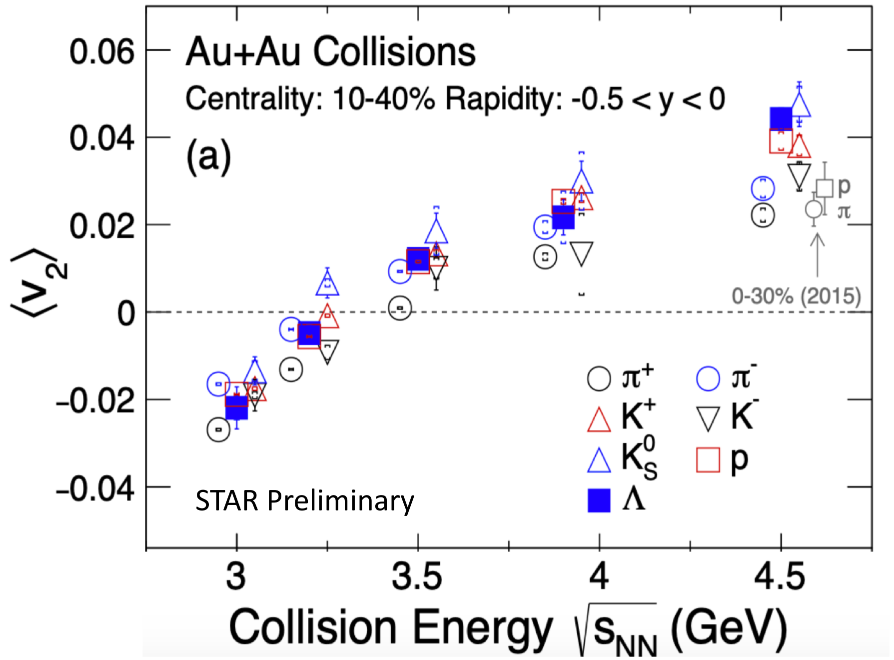
STAR, PRC 109 (2024), 044914
Nucl. Phy A (2017) 808-811

Energy dependence of v_1, v_2 at FXT energies



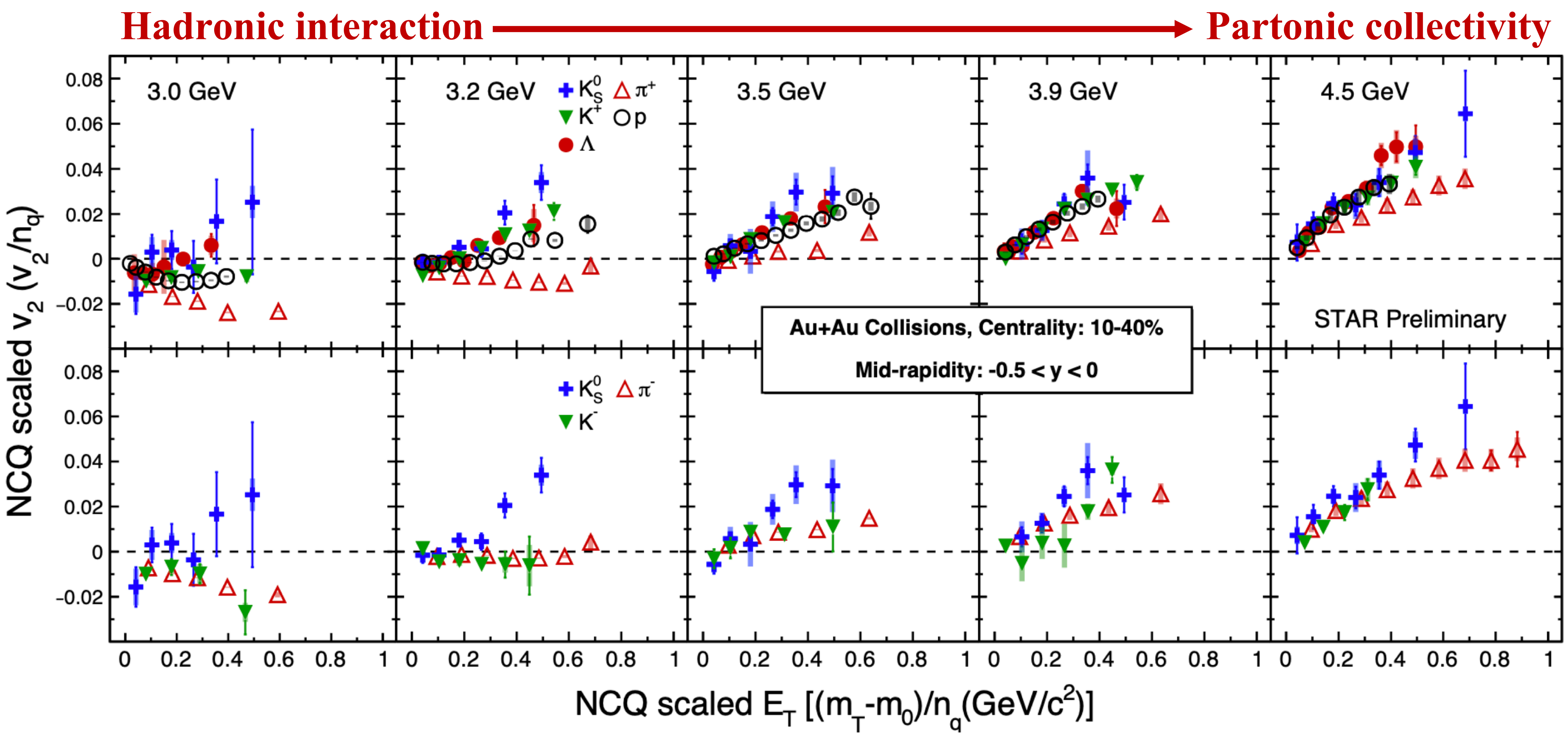
E895, PRL 85 (2000), 940





- Anti-flow only of kaon at low p_T at 3.83 GeV
- Anti-flow observed at 3 – 3.9 GeV for π^+ $K^\pm$ and K_s^0, at low p_T
  → Shadowing effect from spectators
- Out-of-plane → In-plane expansion b/w 3 - 4.5 GeV

NCQ scaling of v_2 at 3 - 4.5 GeV

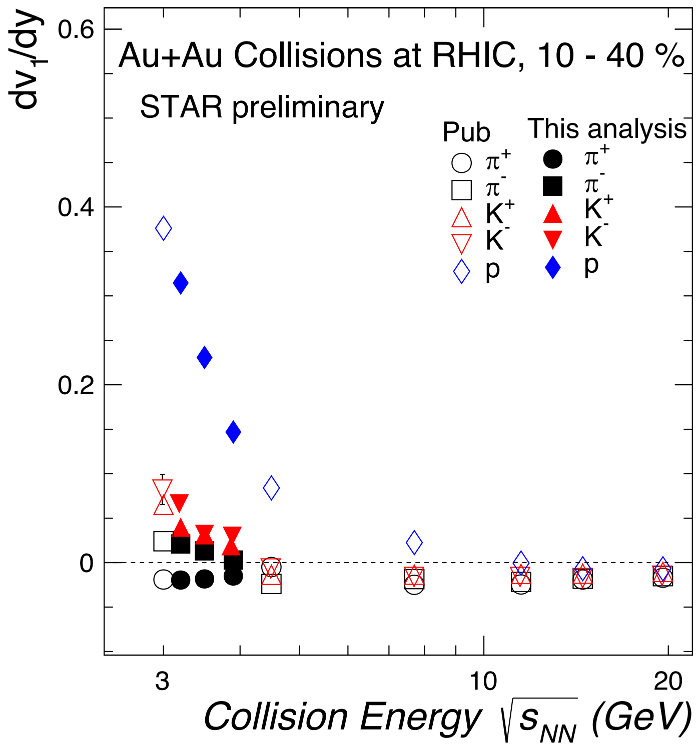


- NCQ scaling completely breaks below 3.2 GeV
- Scaling becomes gradually better above 3.2 GeV

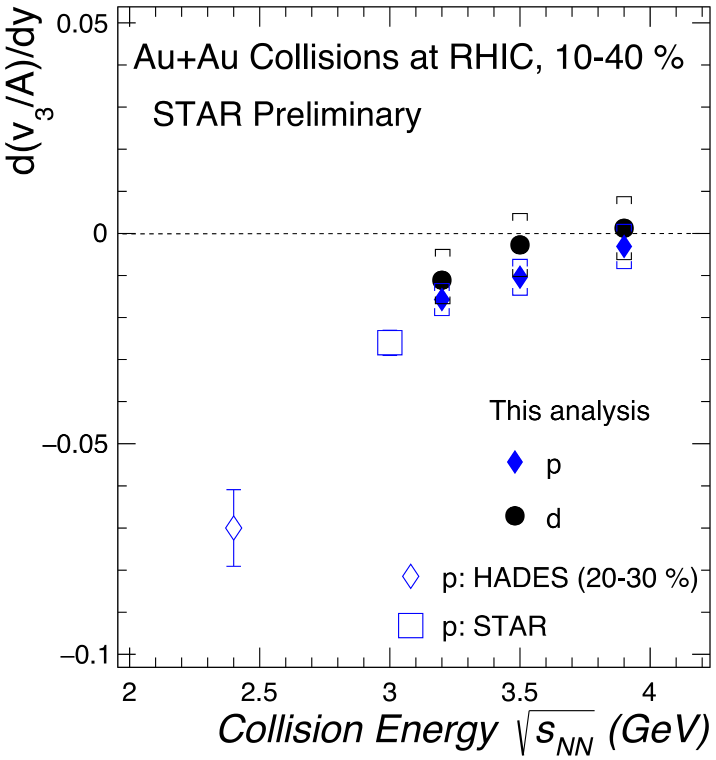
STAR, PLB 827 (2022) 137003

v_1, v_3 at FXT energies

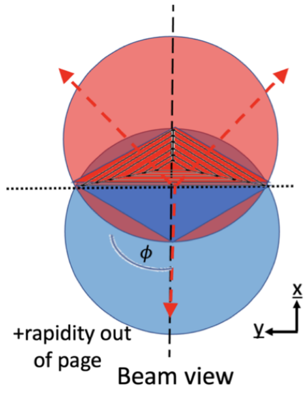
- Increasing collision energy → decreasing v_1 slope; v_3 slope approach zero
- Trend consistent with HADES results at 2.4 GeV
- Non-zero $|v_3\{\Psi_1\}|$, increase towards peripheral collisions
  - → Geometry driven v_3 at lower energy
  - → JAM describes the data implying importance of nuclear potential

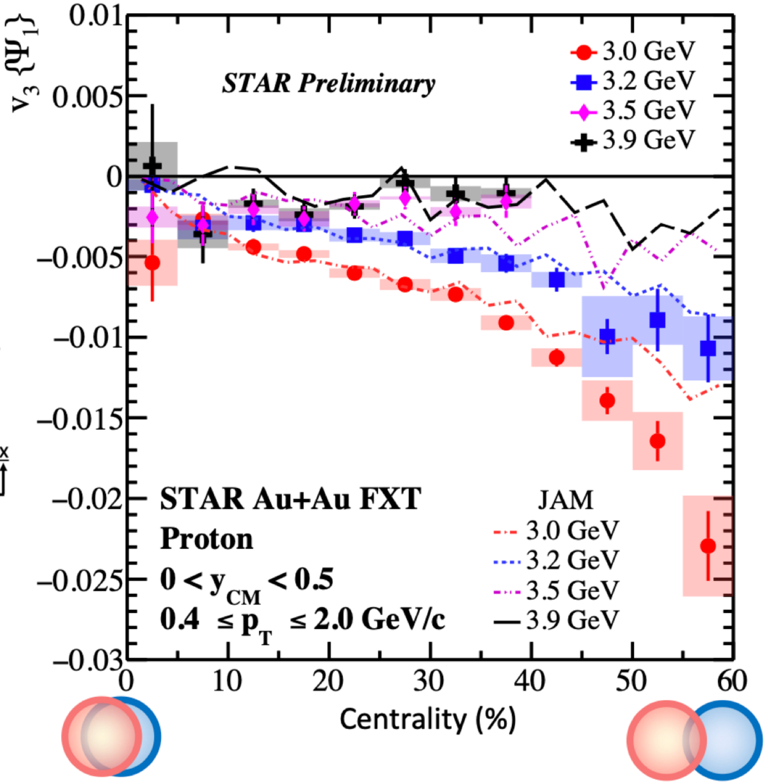


PRL 120 (2018), 062301; PLB 827 (2022), 137003



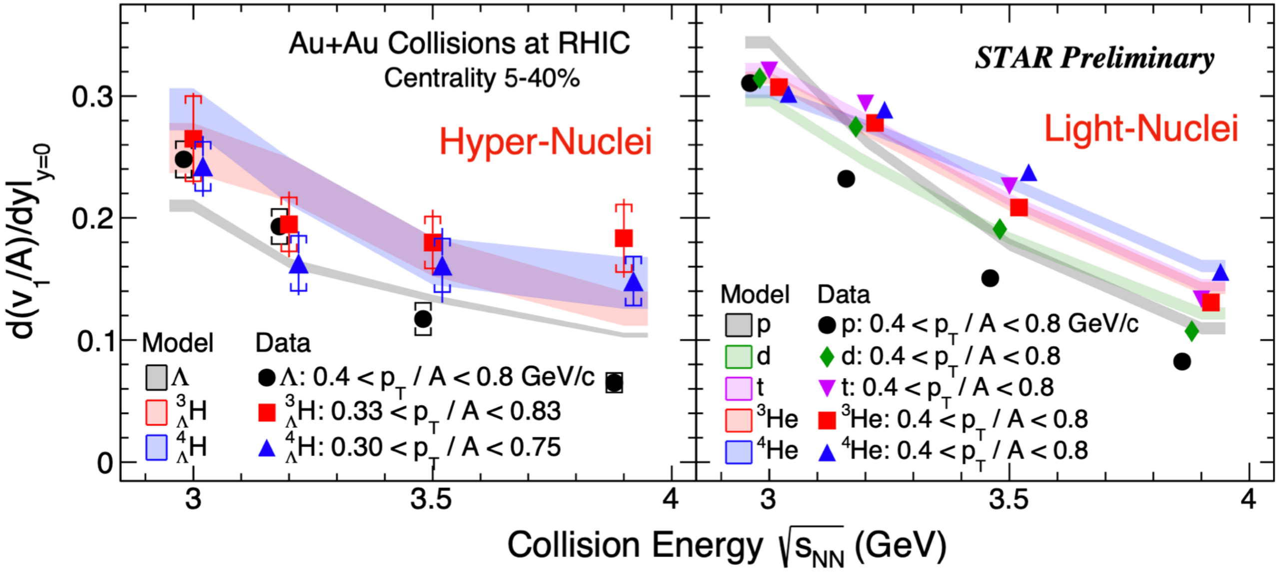
HADES, PRL 125 (2020), 262301; STAR, PRC 109 (2024) 44914

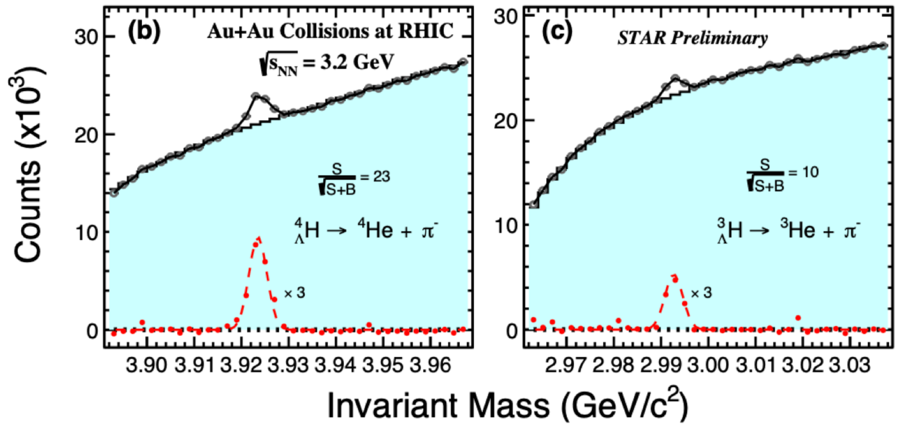


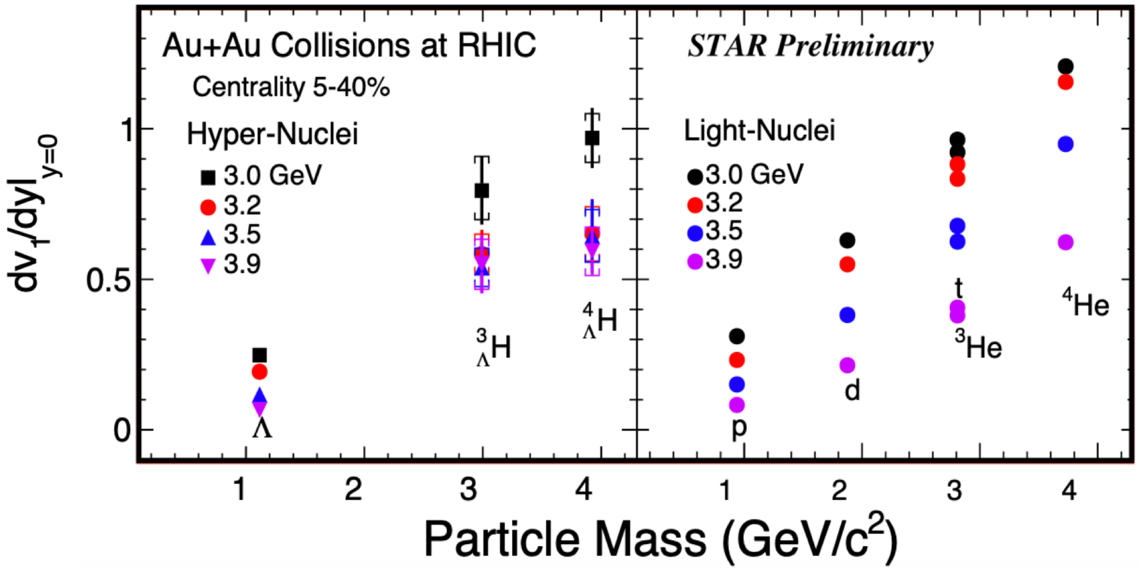


Flow of light and hyper nuclei at FXT

- Light- and Hyper-Nuclei production are enhanced at high μ_B
- Understanding production mechanism of light/hyper nuclei
- Hyper-nuclei probes Y-N interactions → inner core of neutron stars



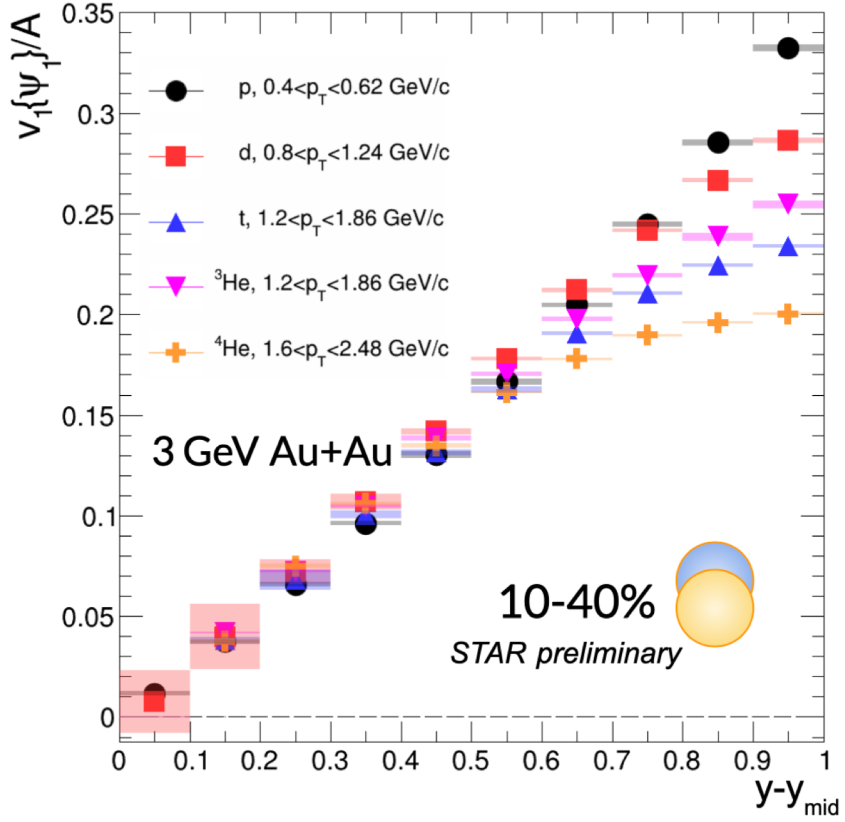


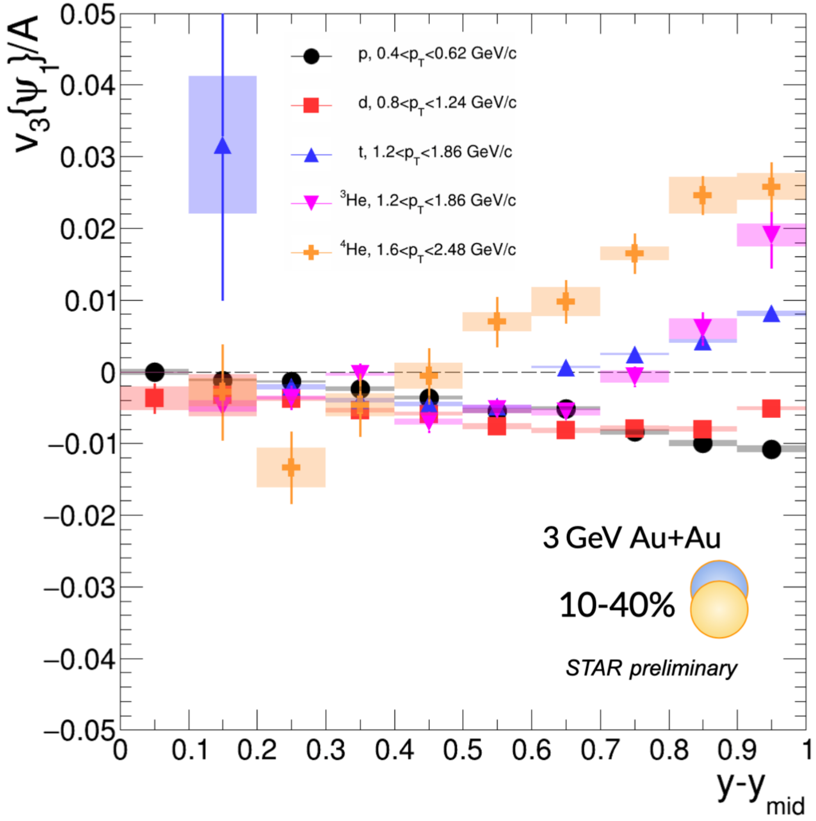


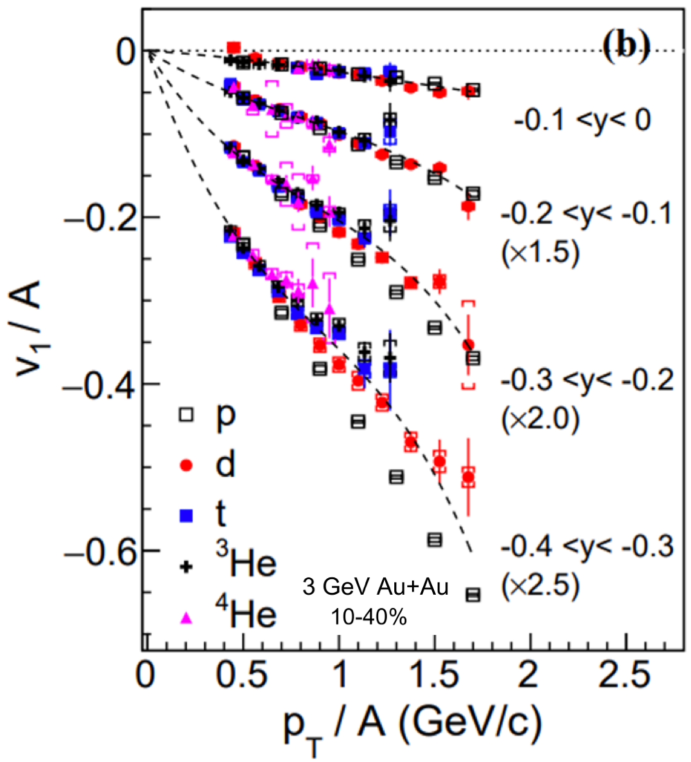
- Collision energy increases → the v_1 slope of light- and hyper-nuclei decreases
- v_1 slope scales with mass number A or/and particle mass
- JAM2 mean field + coalescence calculations explains the energy dependence

STAR, PRL 130 (2023), 211301
Y. Nara et al., PRC 106 (2022) , 044902
Gorbunov and I. Kisel, CBM-SOFT-note-2007-003, 2007

v_1, v_3 of light nuclei at 3 GeV



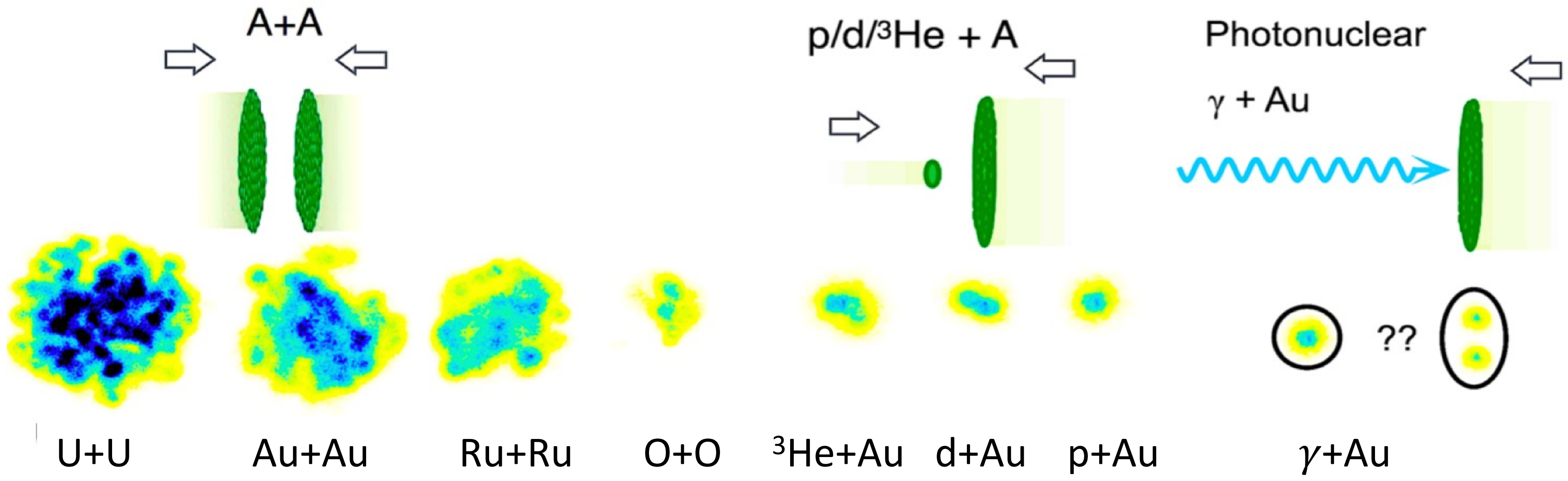




STAR, PLB 827 (2022) 136941

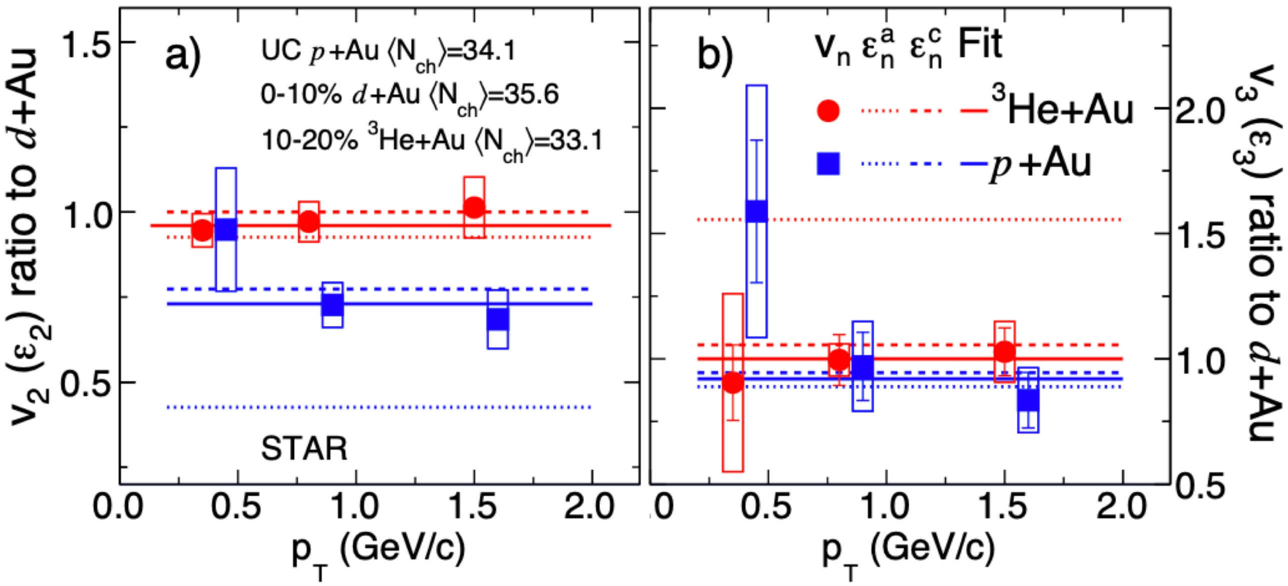
- A-scaling for v_1 and v_3 breaks above rapidity ~0.5 in 10-40% centrality → Coalescence production at mid-rapidity and indication of different production mechanism at forward rapidity
- To explore the measurement to the target rapidity

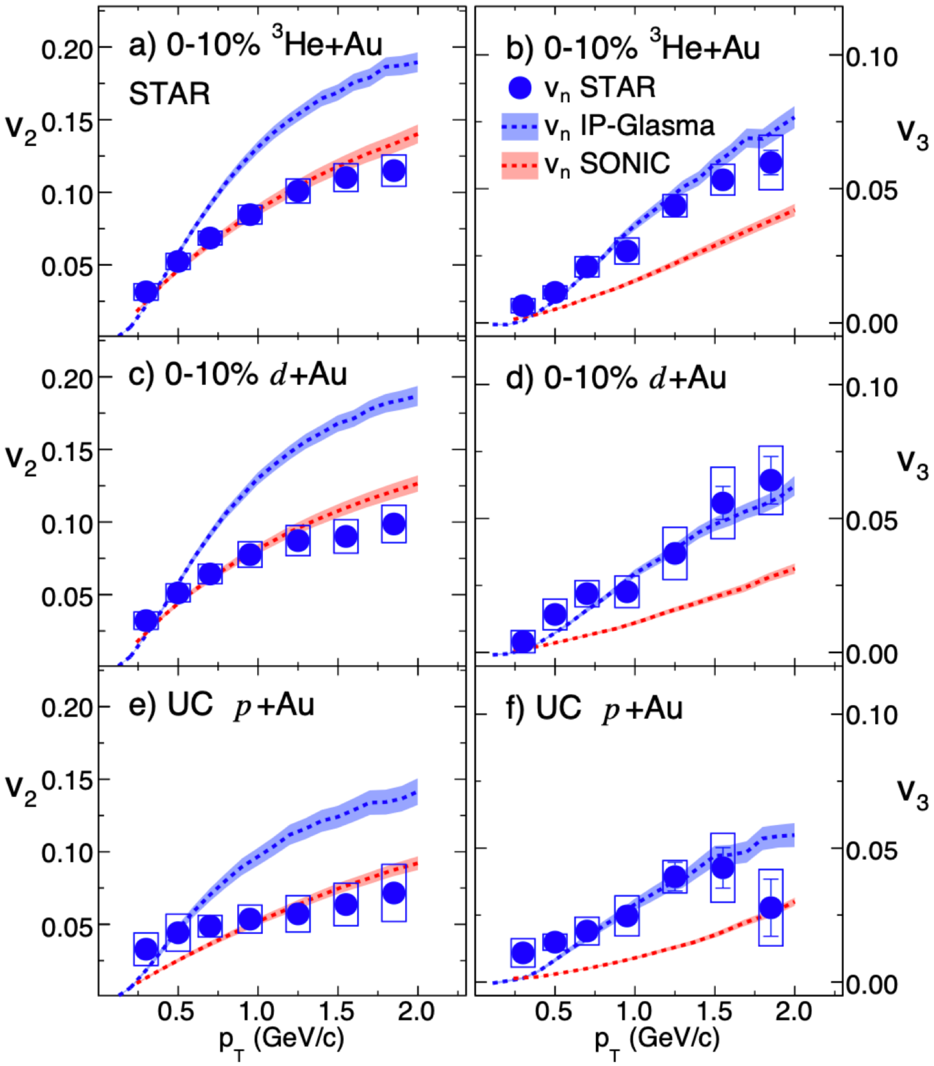
System size scan of collectivity



Small system flow at STAR

Zhengxi Yan : Tuesday 1:00 PM



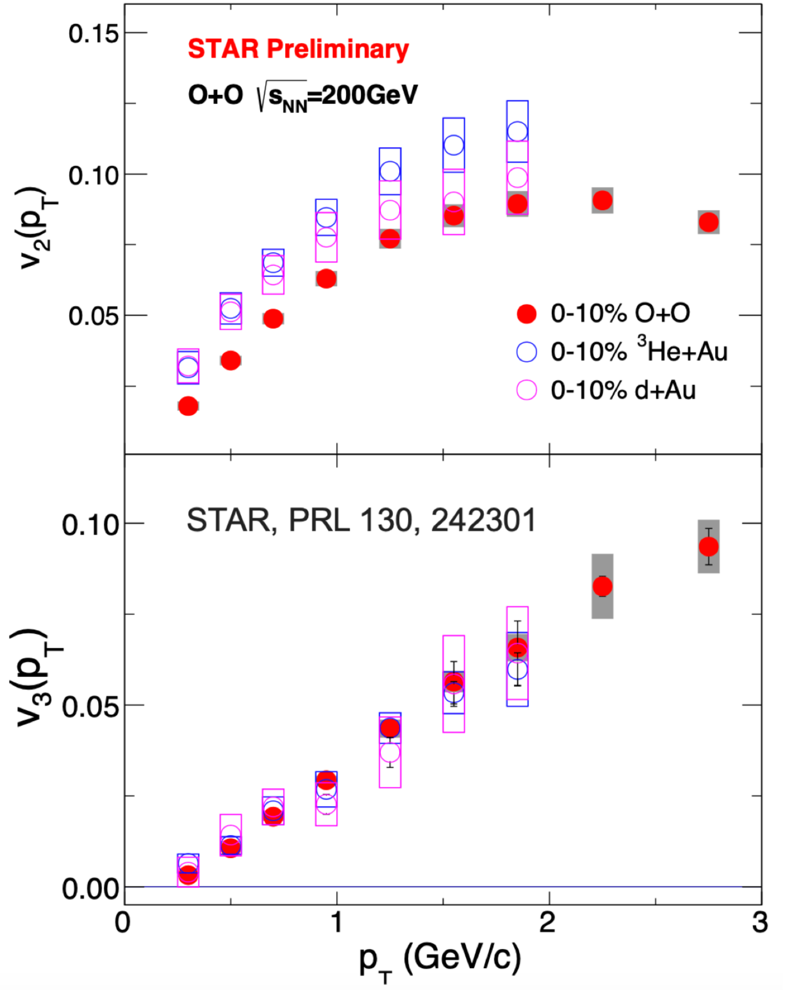


- $v_2(p_T)$ values depend on the colliding systems
- v_3 (p+Au) ~ v_3(d+Au) ~ v_3(^{3}He+Au)
  - → IP-Glasma+MUSIC including subnucleonic fluctuations shows good agreement with $v_3(p_T)$

STAR, PRL 130 (2023) 242301

Flow in O+O collisions

Zhengxi Yan : Tues 1 PM



- v_2 (O+O) < v_2(d+Au) ≈ v_2(^{3}He+Au)
- v_3 (O+O) ≈ v_3(d+Au) ≈ v_3(^{3}He+Au)

- Gluon fluctuation around quark model:

  ε_n(d+Au) ≈ ε_n(^{3}He+Au); n=2,3

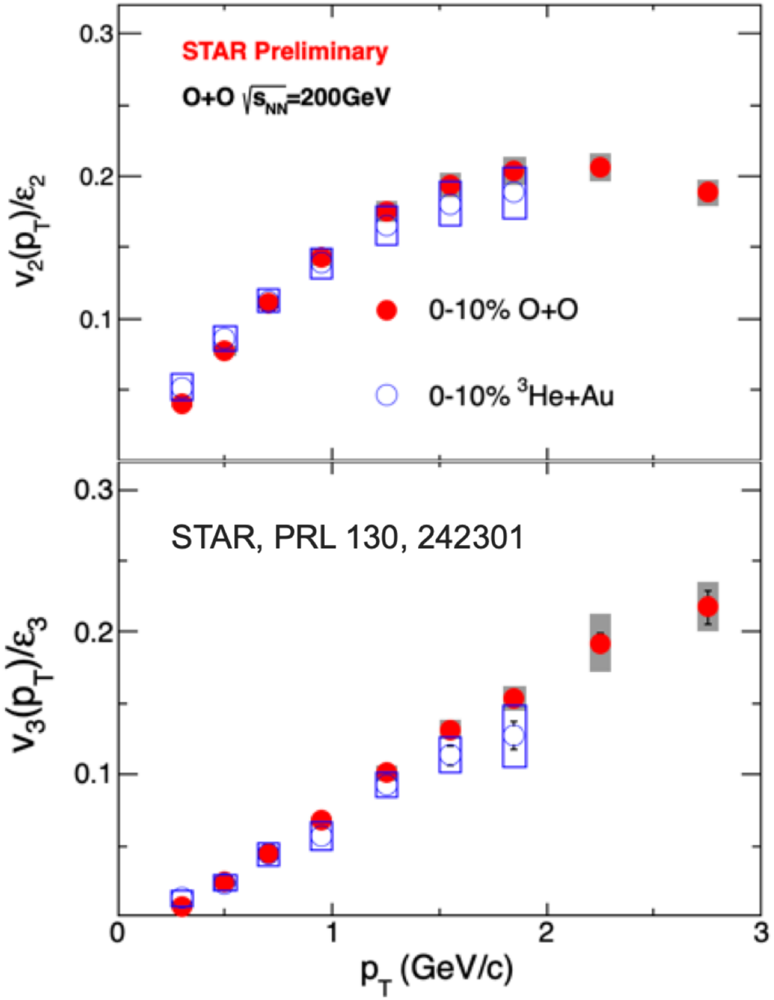
  Gluon field: PRC 94 (2016), 024919

- ε_2(O+O) < ε_2(^{3}He+Au)

  ε_3(O+O) ≈ ε_3(^{3}He+Au)

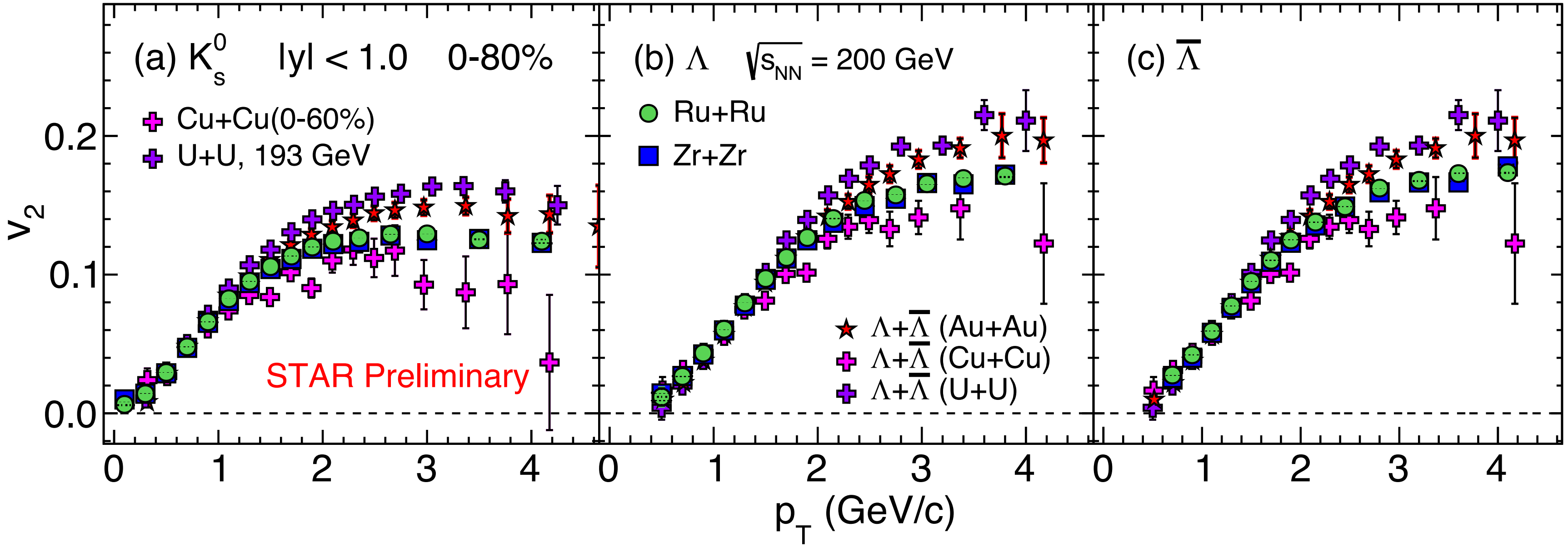
  → v_n/ε_n similar between O+O and ^{3}He+Au, within a quark Glauber model

  arXiv:2312.12167 [nucl-ex]
  Phys. Rev. Lett. 111 (2013) 032501
  Phys. Rev. Lett. 119 (2017) 222505



STAR, PRL 130 (2023) 242301

Strange hadrons' flow



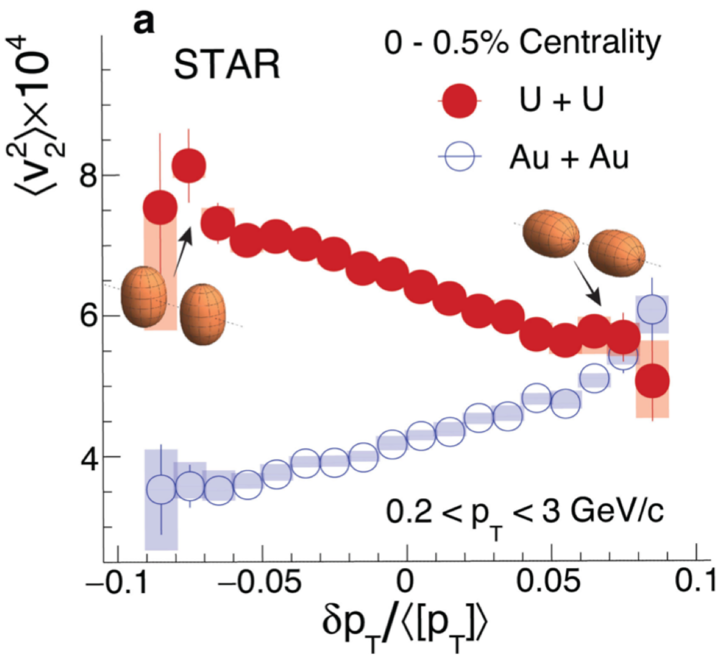
- v_2 of K_s^0, Λ, and $\overline{Λ}$ in isobar collisions (Ru+Ru and Zr+Zr) is smaller than in ^{197}Au+^{197}Au and ^{238}U+^{238}U collisions at p_T > 1.5 GeV/c
- v_2 in Ru+Ru and Zr+Zr collisions is larger as compared to ^{63}Cu+^{63}Cu collisions at higher p_T

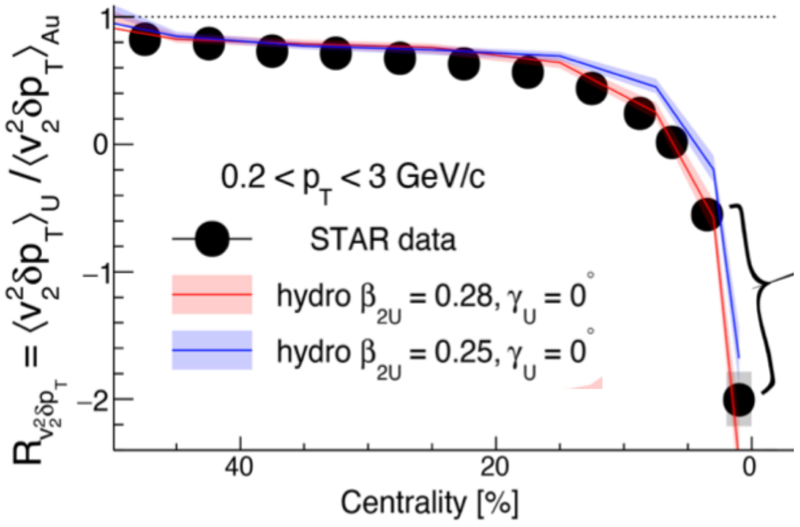
$^{238}_{92}U,\ ^{197}_{79}Au,\ ^{96}_{44}Ru,\ ^{96}_{40}Zr,\ ^{63}_{29}Cu$

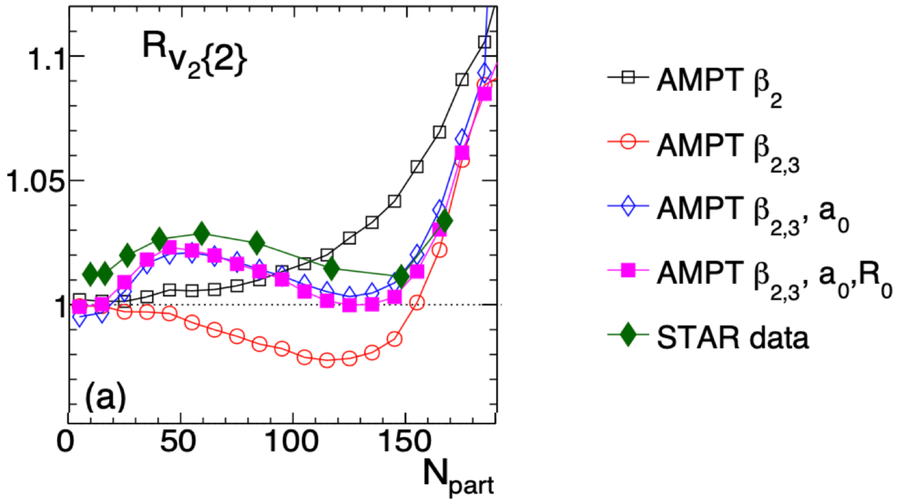
STAR, PRC 77 (2008) 054901; PRC 81 (2010) 044902; PRC 103 (2021) 064907

Imaging Shapes of Atomic Nuclei

- Snapshot of the spatial matter distribution $\xrightarrow{\text{hydrodynamics}}$ imprints on the particle momentum distribution







$\beta_2^{U} = 0.286 \pm 0.025$

$\beta_2^{Ru} = 0.16 \pm 0.02 \quad \beta_3^{Zr} = 0.20 \pm 0.02$

C. Zhang and J. Jia, PRL 131 (2022), 022301

STAR, arXiv:2401.06625 [nucl-ex]
B Schenke, PRC 102 (2020), 034905
J. Jia, PRC 105 (2022), 014905
G. Giacalone et al, PRL 127 (2021), 242301
P. Sinha et al, Phys. Rev. C 108 (2023) 024911

- Enhanced v_2 particularly in central U+U collisions
  → Nuclear deformation influences collisions over a wide centrality range
- Mean v_2 ratios and v_2-p_T correlations are used to constrain initial conditions and nuclear structure in U+U and isobar collisions

Summary

- ✓ More negative Δv_1 slope at lower energies : Qualitatively consistent with influence of EM-field and shorter lifetime of fireball
- ✓ Explored particle production in the fragmentation region and of light/hyper nuclei at wide range of rapidity
  - ➢ a probe for medium dynamics
- ✓ Anti-flow of mesons observation showing hints of nuclear shadowing effect
- ✓ Hadronic interaction —— from 3.2 GeV towards 4.5 GeV ——→ Partonic collectivity
- ✓ JAM calculations suggest potential is essential for development of geometry driven $v_3\{\Psi_1\}$ at lower energies, whereas JAM overpredicts the excess v_1 below 14.6 GeV → Better constraint on EoS
- ✓ Significance of sub-nucleonic fluctuations in small systems
- ✓ Exploring anisotropic flow as a new means to imaging of nuclear structure

Outlook

- Stay tuned for more exciting results covering the entire BES-II collider and FXT energies
- γ+Au@2023, d+Au@2021 and O+O@2021 will provide more information for collectivity in small systems
- Forward detectors enables the flow measurements in wider rapidity ranges, opening new windows to explore the QGP properties

This precision era takes us closer to uncover the secrets of QGP phase, its transitions and much more…

Thank you for your attention!