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STAR

Recent flow results from STAR experiment at RHIC

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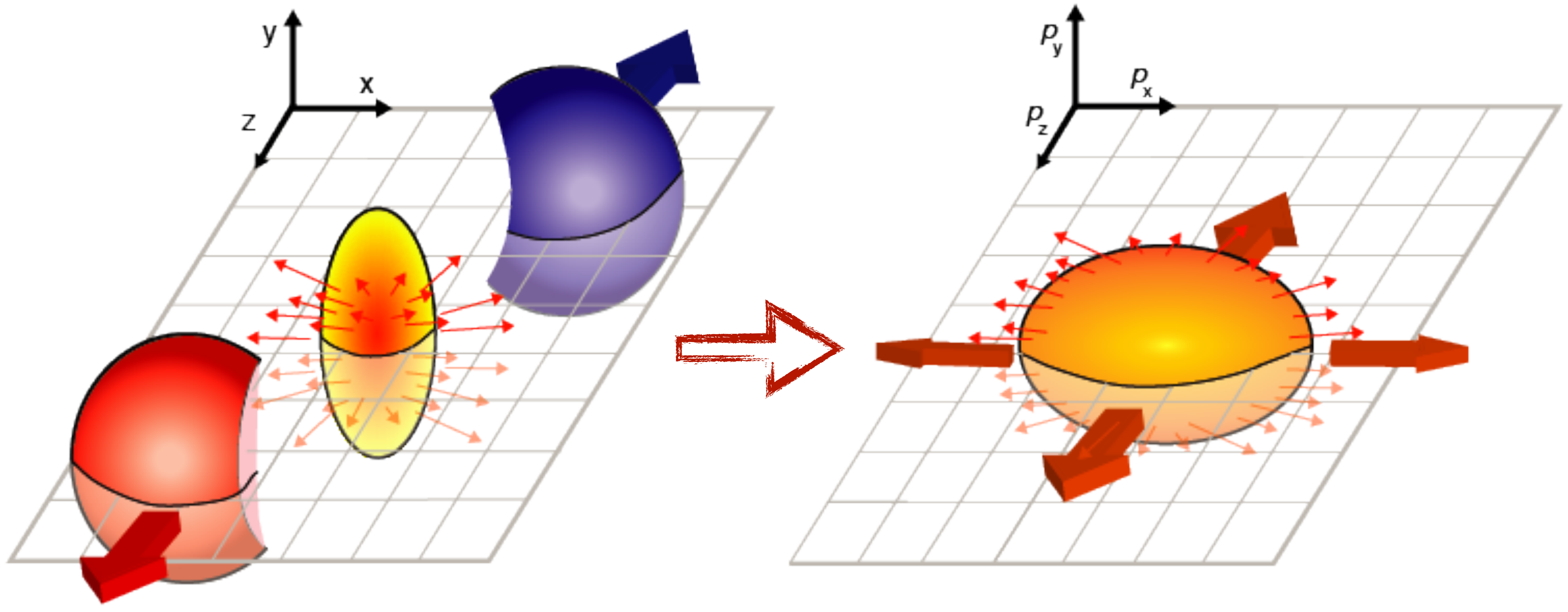
Joint Institute for Nuclear Research

52nd International Symposium on Multiparticle Dynamics
Gyöngyös, Hungary, 21–26 August 2023

Azimuthal anisotropic flow



- Anisotropy of initial spacial geometry transfers to anisotropy of particles in momentum space via medium created in collisions
  - sensitive to early stages of the collisions
  - useful probe to study initial state, viscosity, equation of state (EoS), etc.

S. Voloshin, Y. Zhang, Z.Phys.C **70** (1996) 665

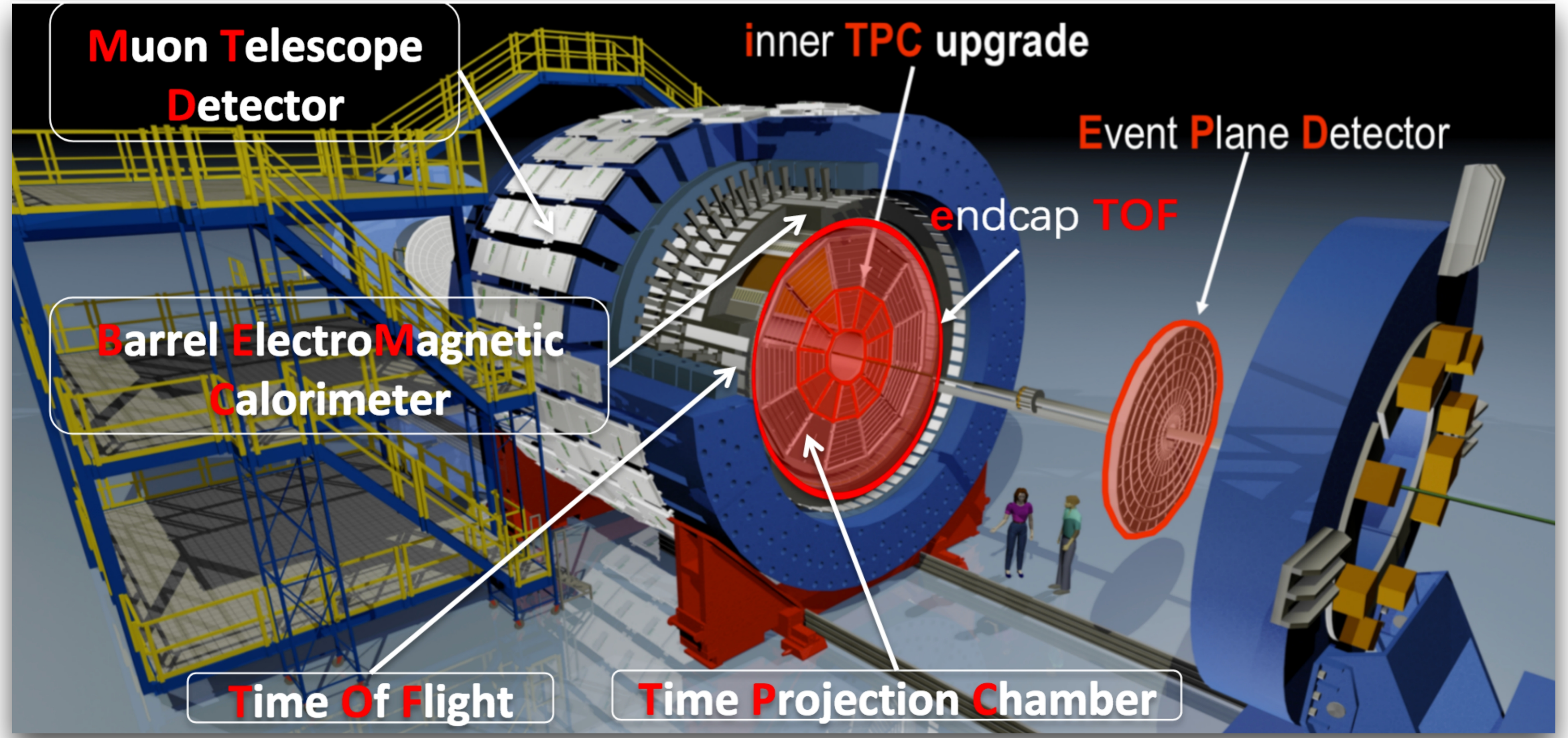
- Fourier series decomposition of azimuthal distribution of emitted particles:

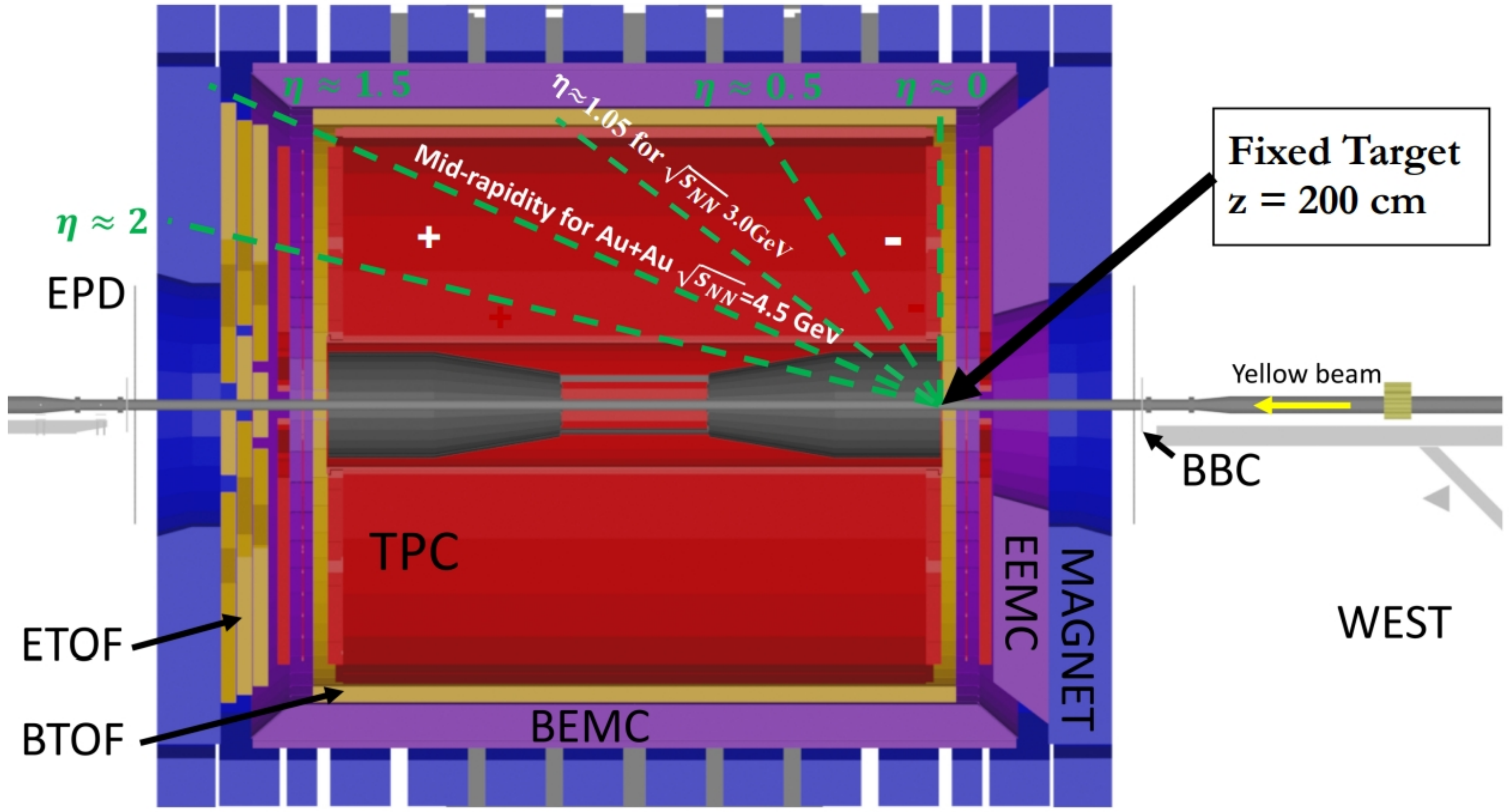
$$\frac{dN}{d(\phi - \Psi_n)} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_n)\right]$$

$$v_n = \langle \cos\left[n(\phi - \Psi_n)\right] \rangle$$

- Ψ_n — event plane (EP)
- v_n — flow coefficients
  - v_1 — directed flow
  - v_2 — elliptic flow
  - v_3 — triangle flow

STAR detector



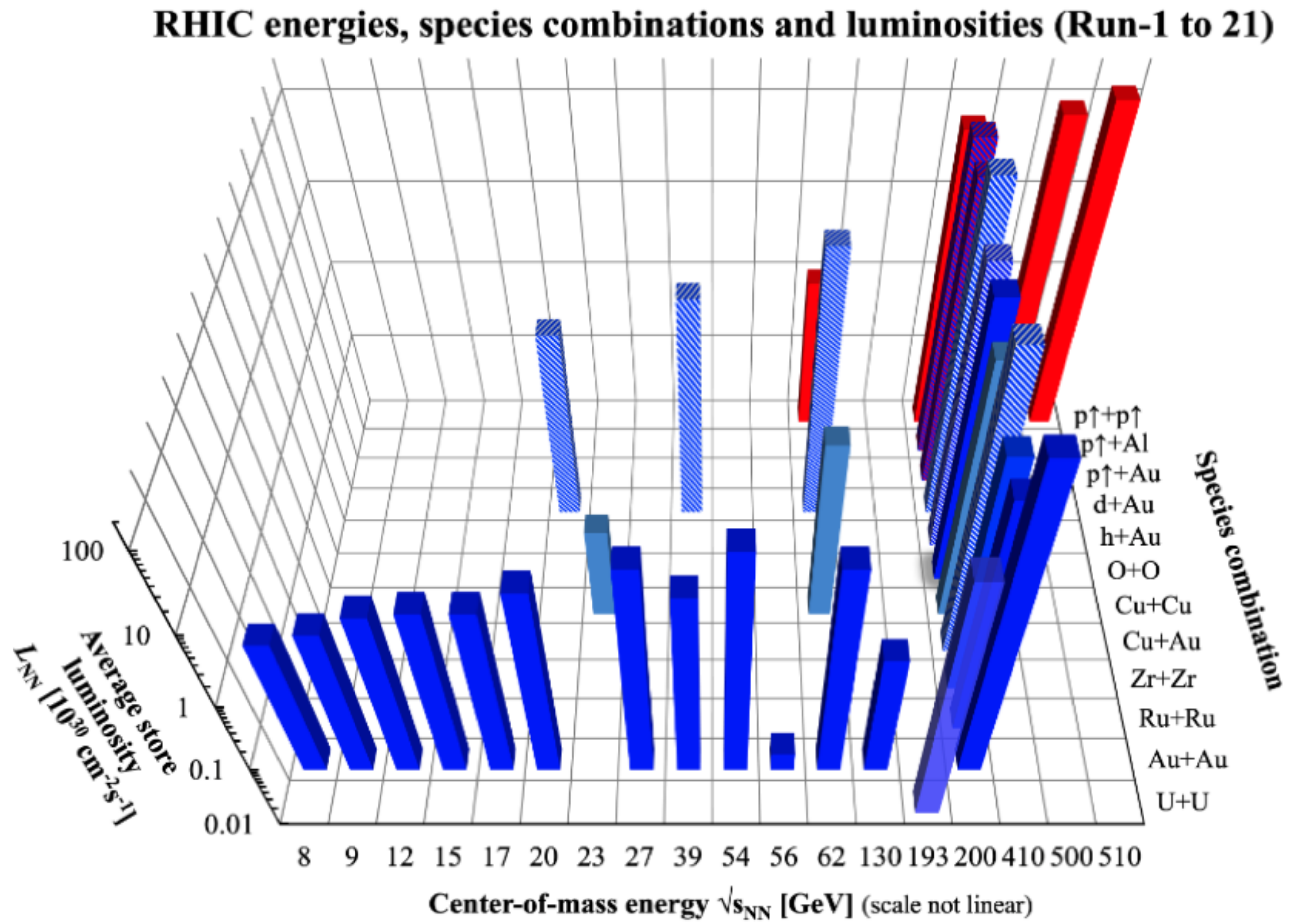


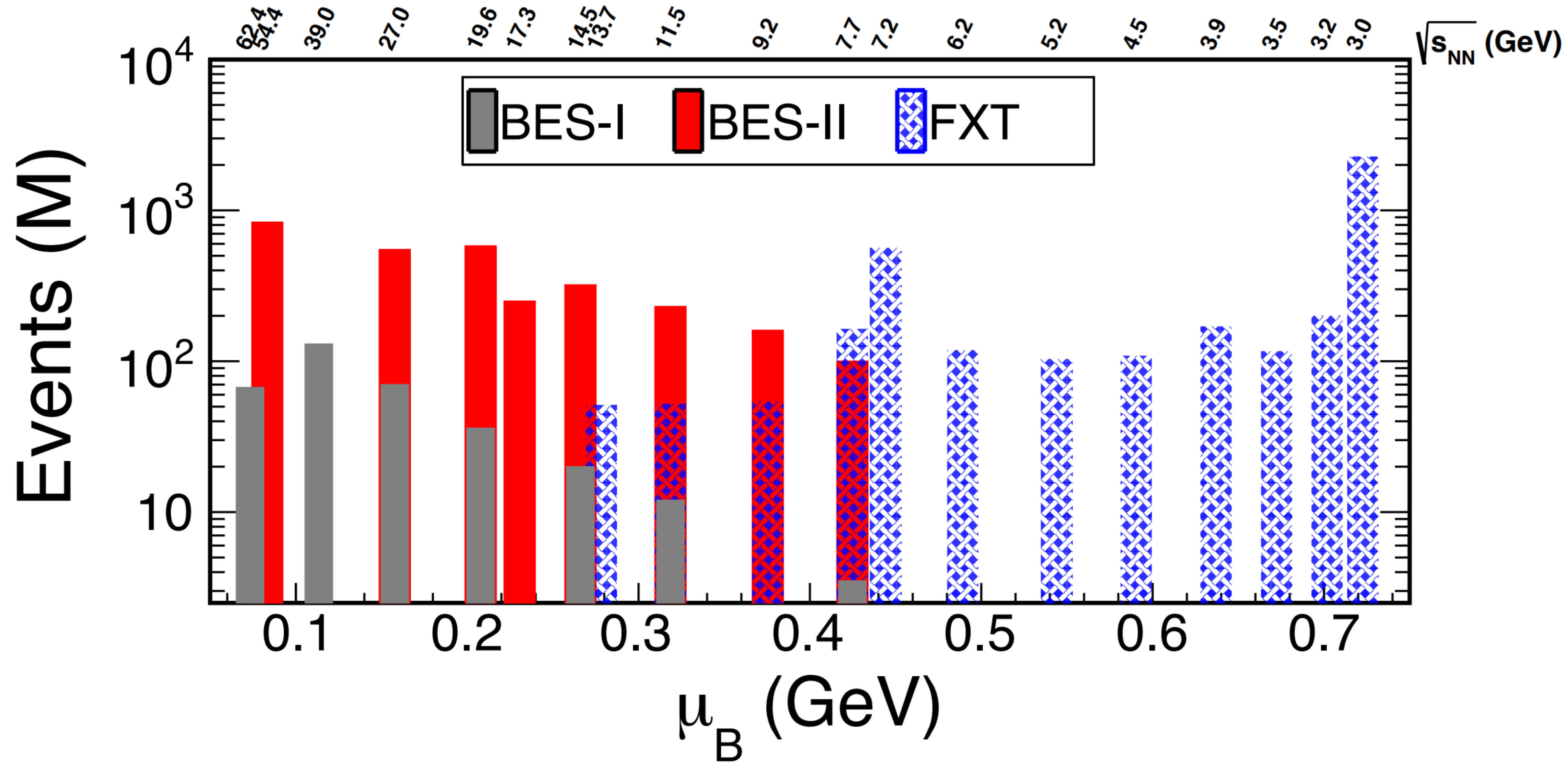
- Beam energy scan II (BES-II) upgrades
  - iTPC (2019+): extended η acceptance and improved tracking, dE/dx resolution
  - eTOF (2019+): extended PID coverage
  - EPD (2018+): EP determination away from mid-rapidity, improved EP resolution compared to BBC

- Fixed-target (FXT) setup
  - Access to energies $\sqrt{s_{NN}} < 7.7$ GeV

Colliding systems and energies at STAR

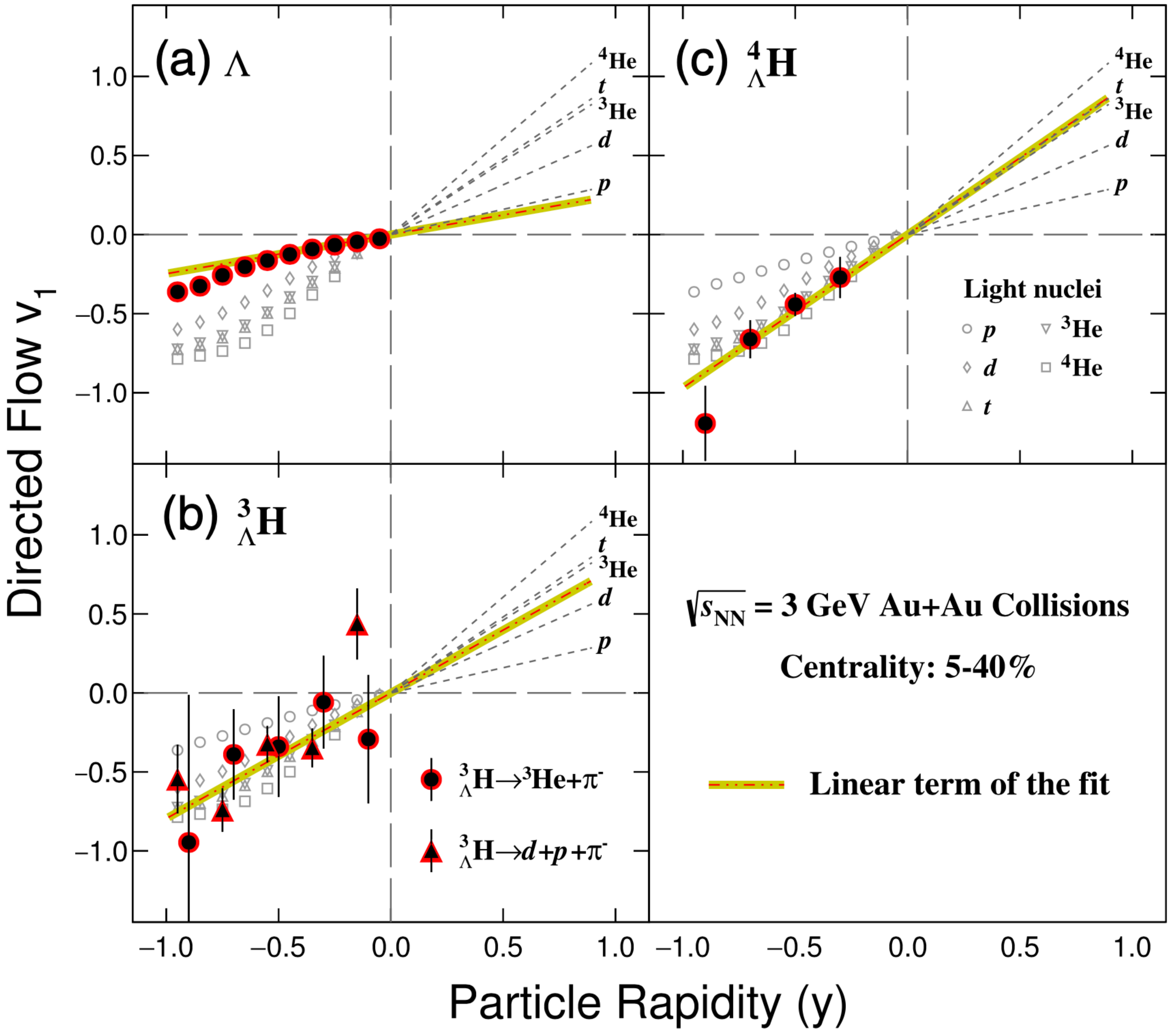
- BES-II and FXT program: Au+Au collisions at $\sqrt{s_{NN}}$ = 3.0 — 54.4 GeV
- Top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV:, Au+Au, Zr+Zr, Ru+Ru, p+Au, d+Au, t+Au, O+O etc.





Hypernuclei v_1 at $\sqrt{s_{NN}}$ = 3 GeV

STAR, PRL **130** (2023) 212301



- $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H hypernuclei v_1 slopes are lower than ones of light nuclei

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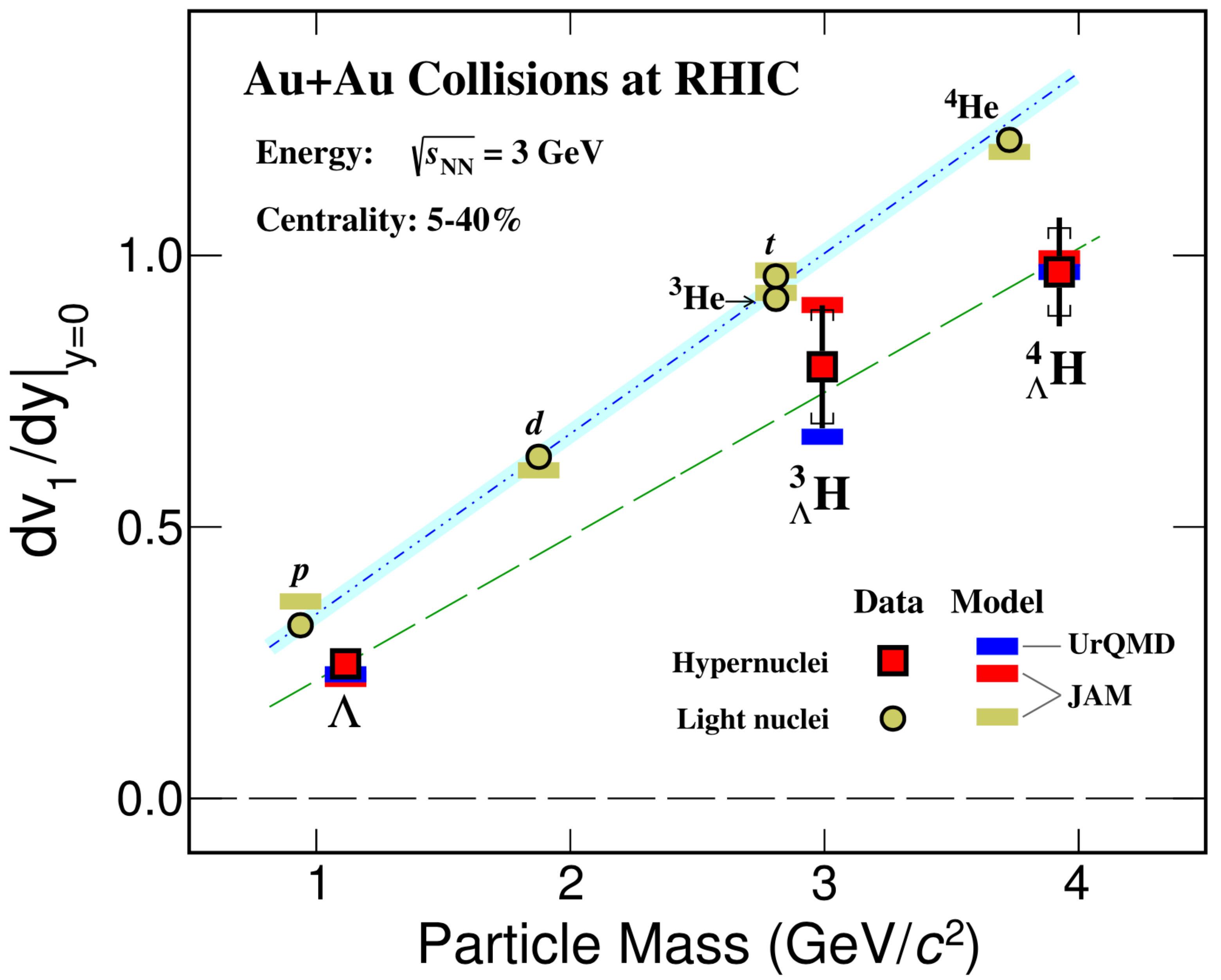
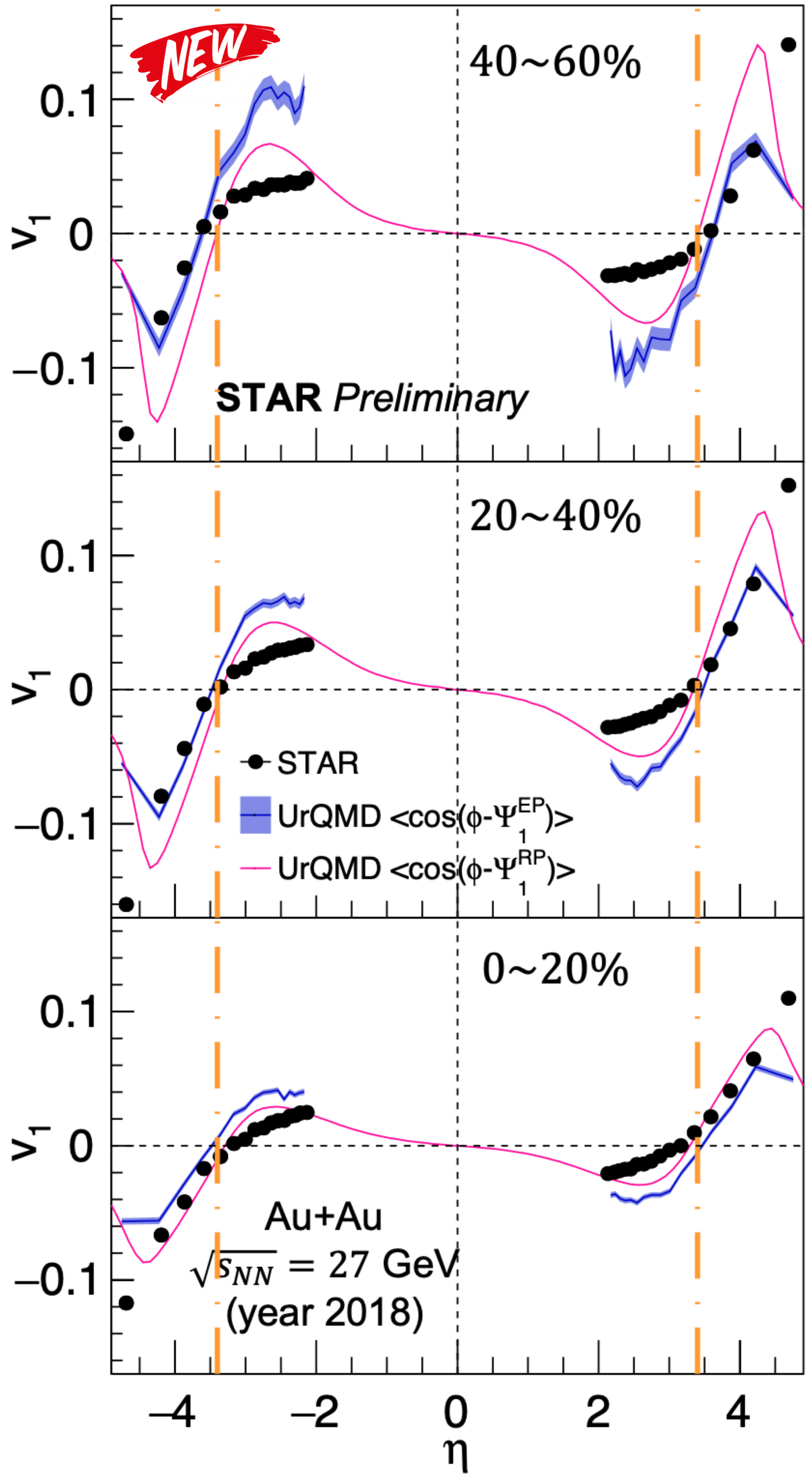
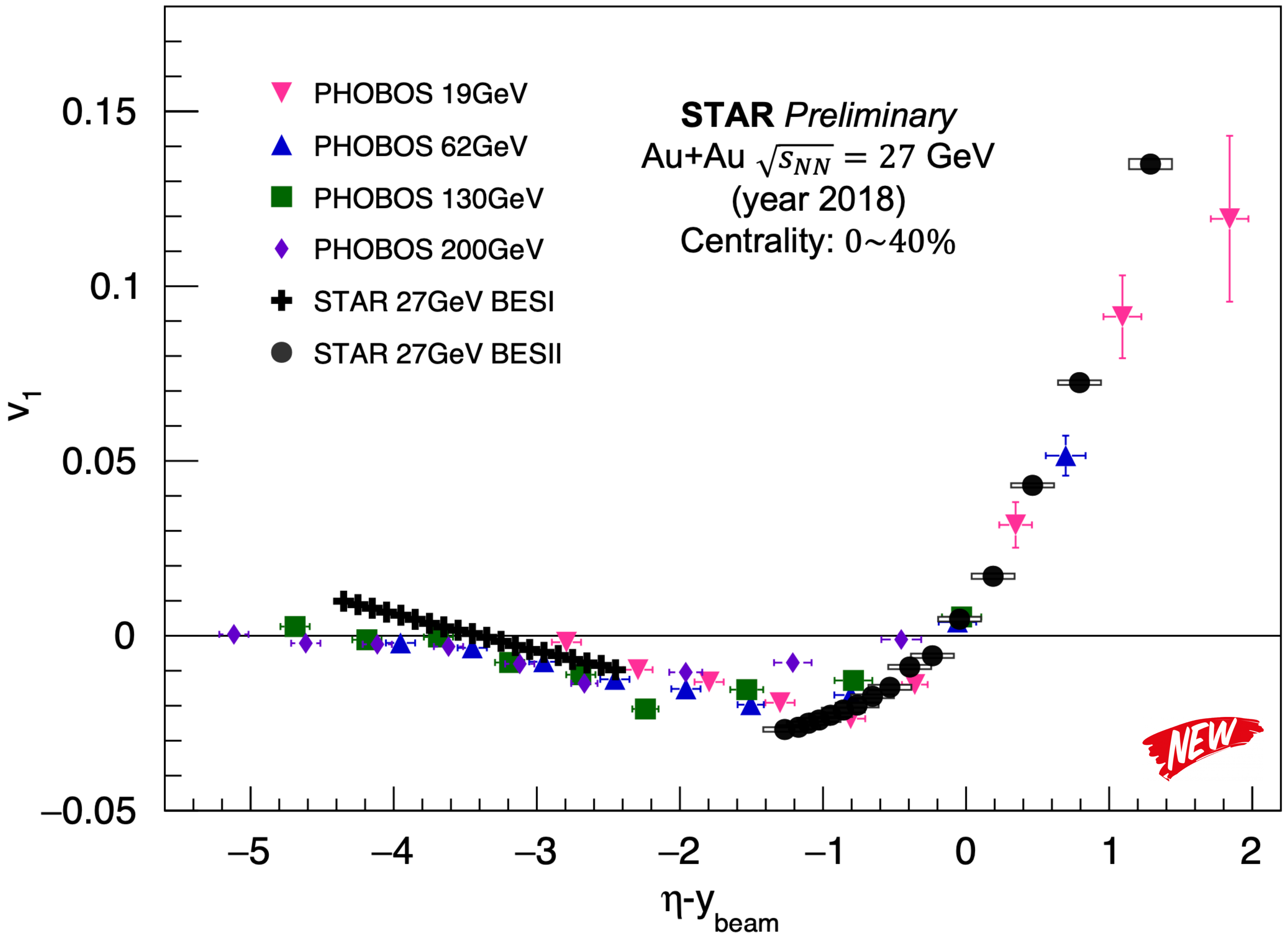


- Midrapidity v_1 slope of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H follow baryon number scaling
  - Coalescence is the dominant mechanism for hypernuclei production

v_1 at forward and backward pseudorapidity

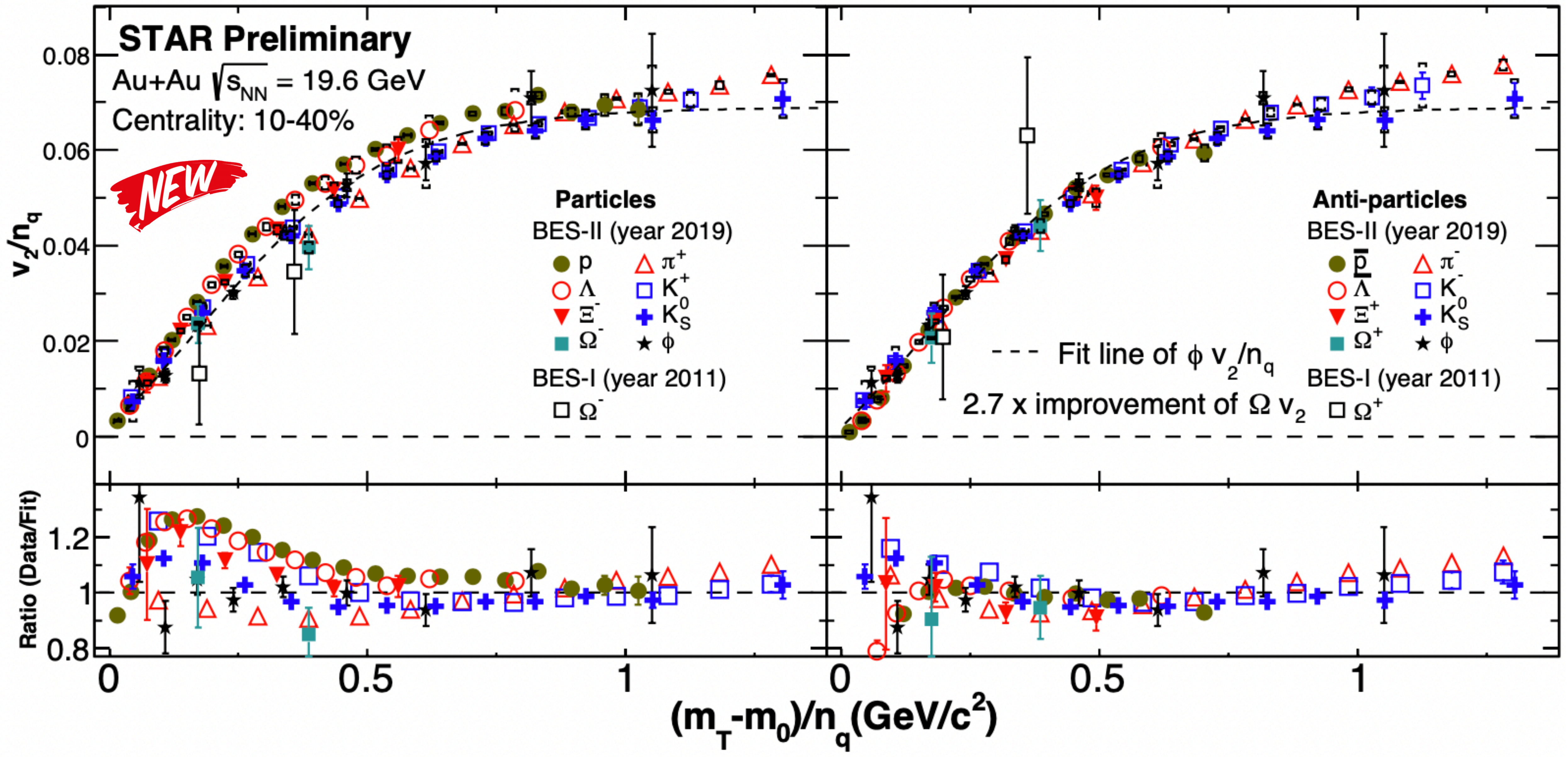


- $v_1(\eta)$ changes sign near beam rapidity at all centralities
- UrQMD fails to describe the measurements
- Can be used to constrain T-dependence of medium viscosity

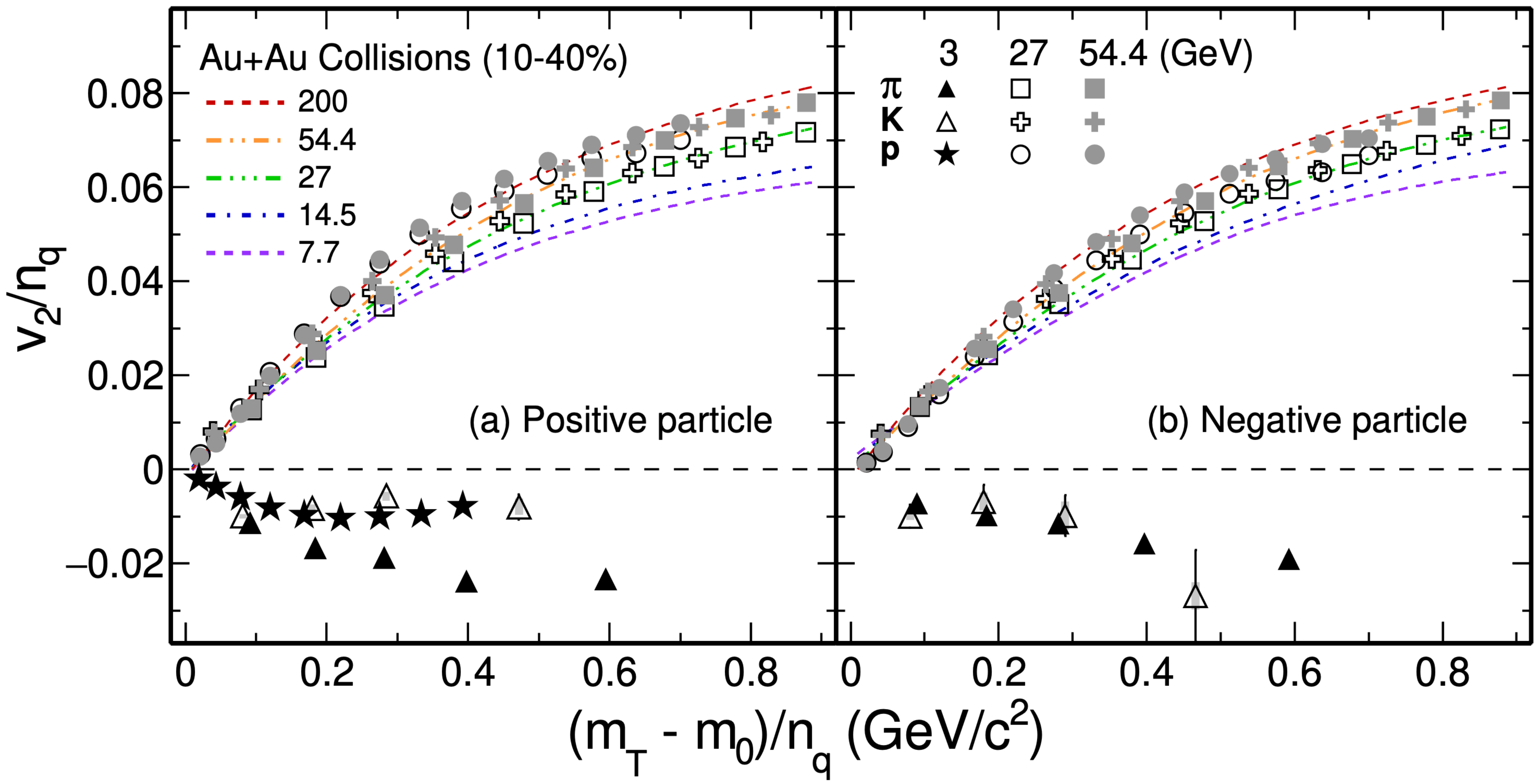


- Test of limiting fragmentation: v_1 collapse to a common curve with other energies in a region of $\eta - y_{\rm beam}$

Number-of-constituent-quark (NCQ) scaling



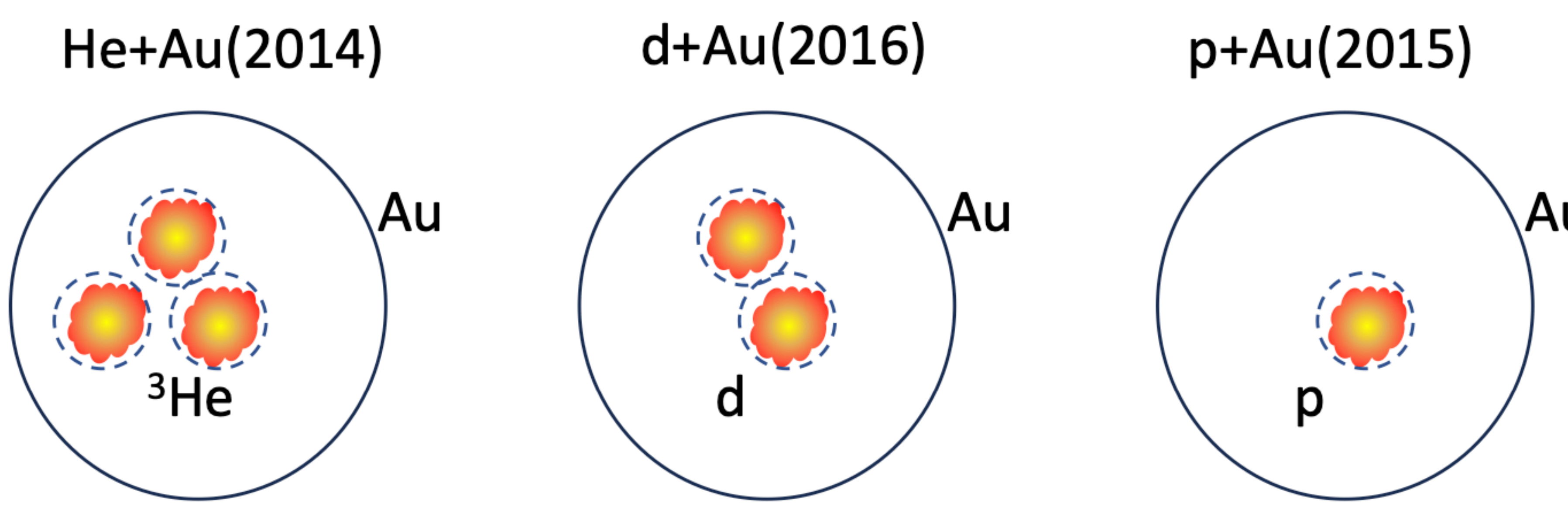
STAR, PLB **827** (2022) 137003



- At $\sqrt{s_{NN}}$ = 19.6 GeV (BES-II), NCQ scaling holds within 10% for $(m_T - m_0)/n_q > 0.5$ GeV/c^2
  - Dominance of partonic interactions

- At $\sqrt{s_{NN}}$ = 3 GeV, the NCQ scaling is absent
  - Dominance of baryonic interactions

Flow in small systems



	Nucleon Glauber $\varepsilon_2(\varepsilon_3)$	Sub-Nucleon Glauber $\varepsilon_2(\varepsilon_3)$
0-5% pAu	0.23(0.16)	0.38(0.30)
0-5% dAu	0.54(0.18)	0.51(0.31)
0-5% ^{3}He+Au	0.50(0.28)	0.52(0.35)

Nucleon Glauber: J. L. Nagle, et. al., PRL 113 (2014) 112301

Sub-nucleon: K. Welsh, et. al., PRC 94 (2016) 024919

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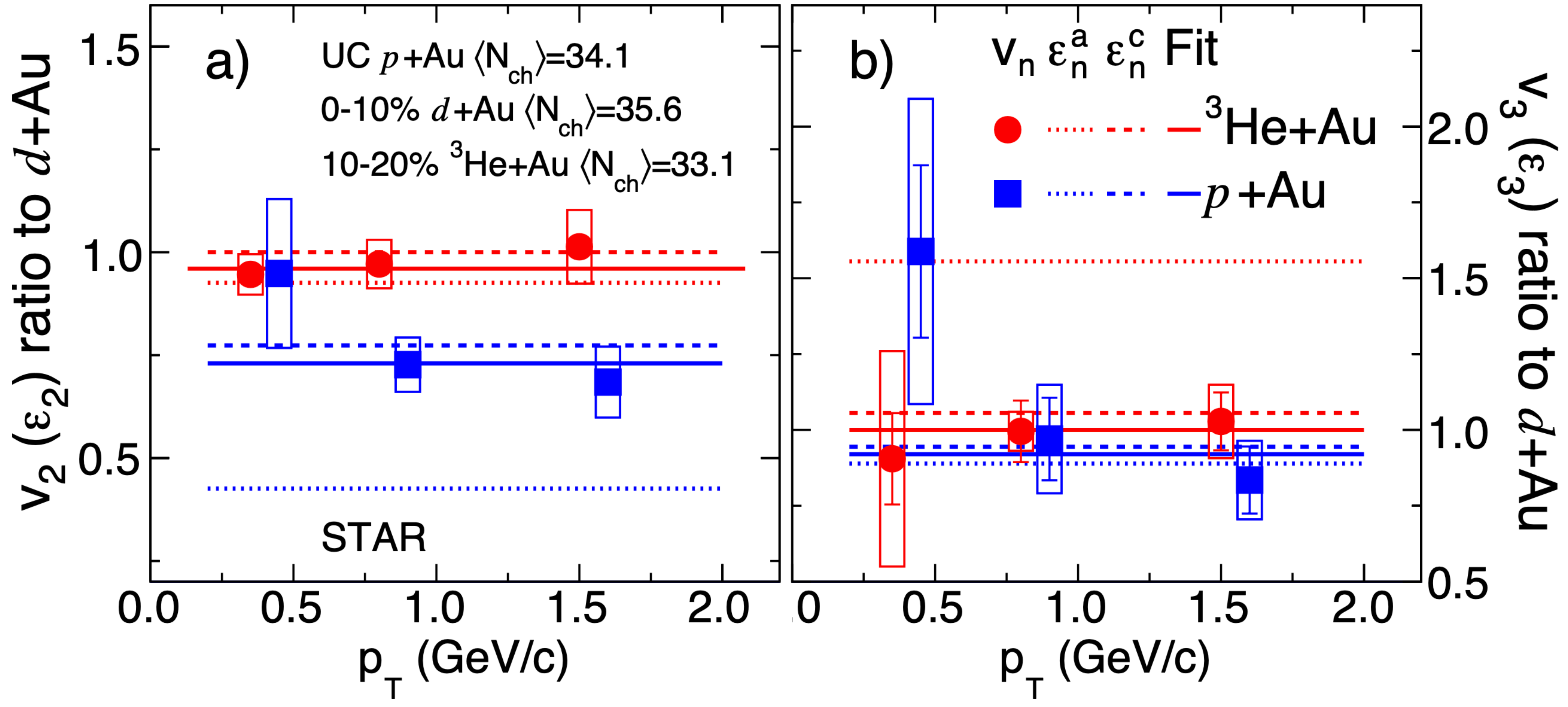
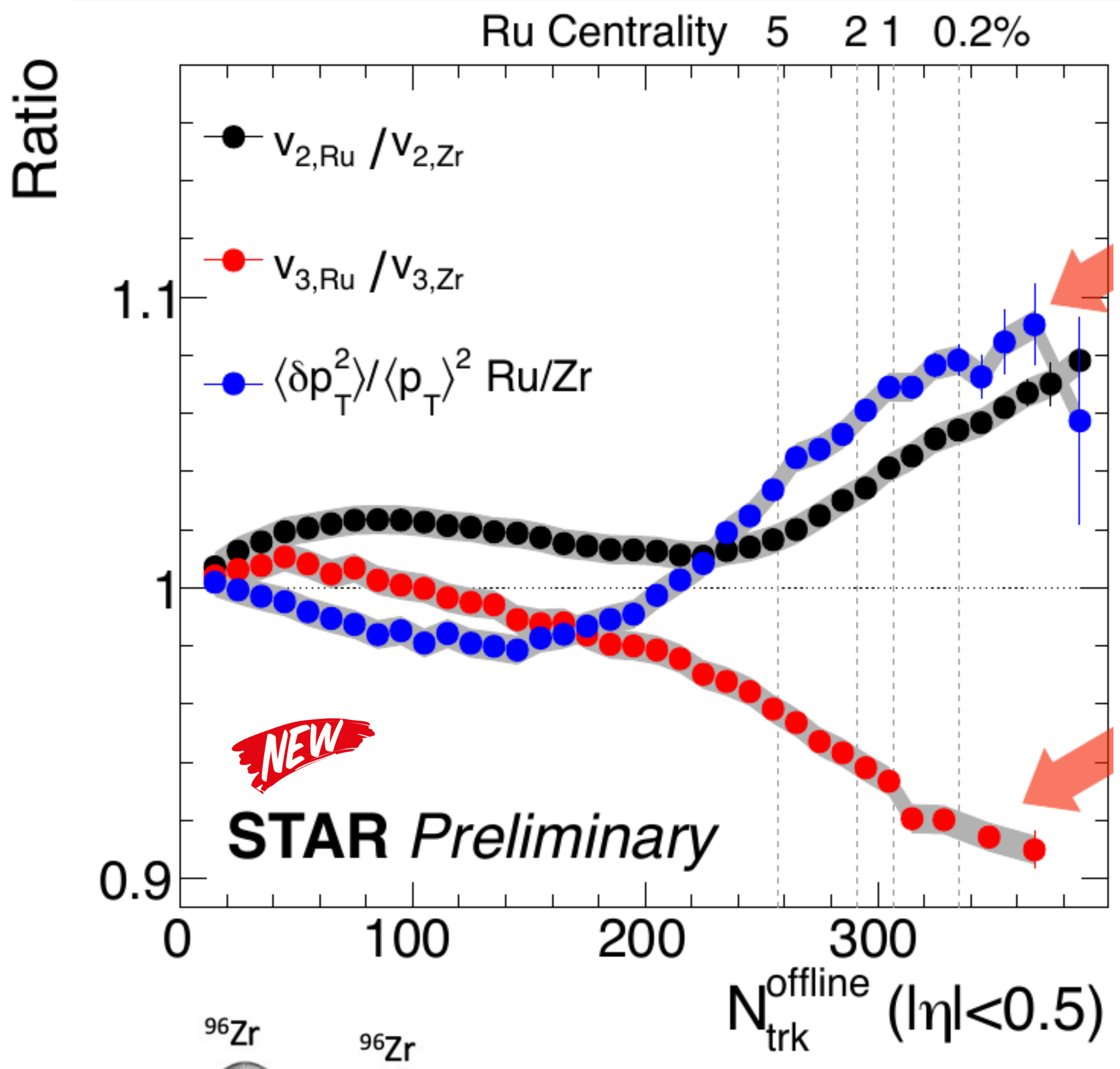
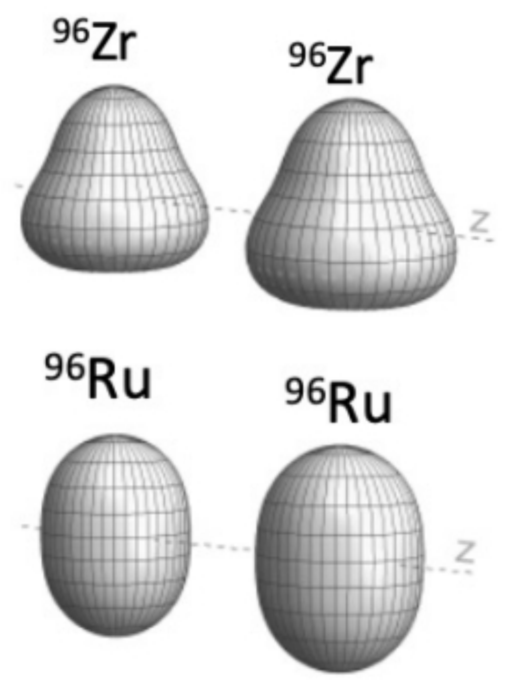


- $v_2^{\mathrm{He+Au}} \approx v_2^{d\mathrm{+Au}} > v_2^{p\mathrm{+Au}}$
- $v_3^{\mathrm{He+Au}} \approx v_3^{d\mathrm{+Au}} \approx v_3^{p\mathrm{+Au}}$
  - Suggests significant influence of sub-nucleonic fluctuations
  - Need to study pre-flow

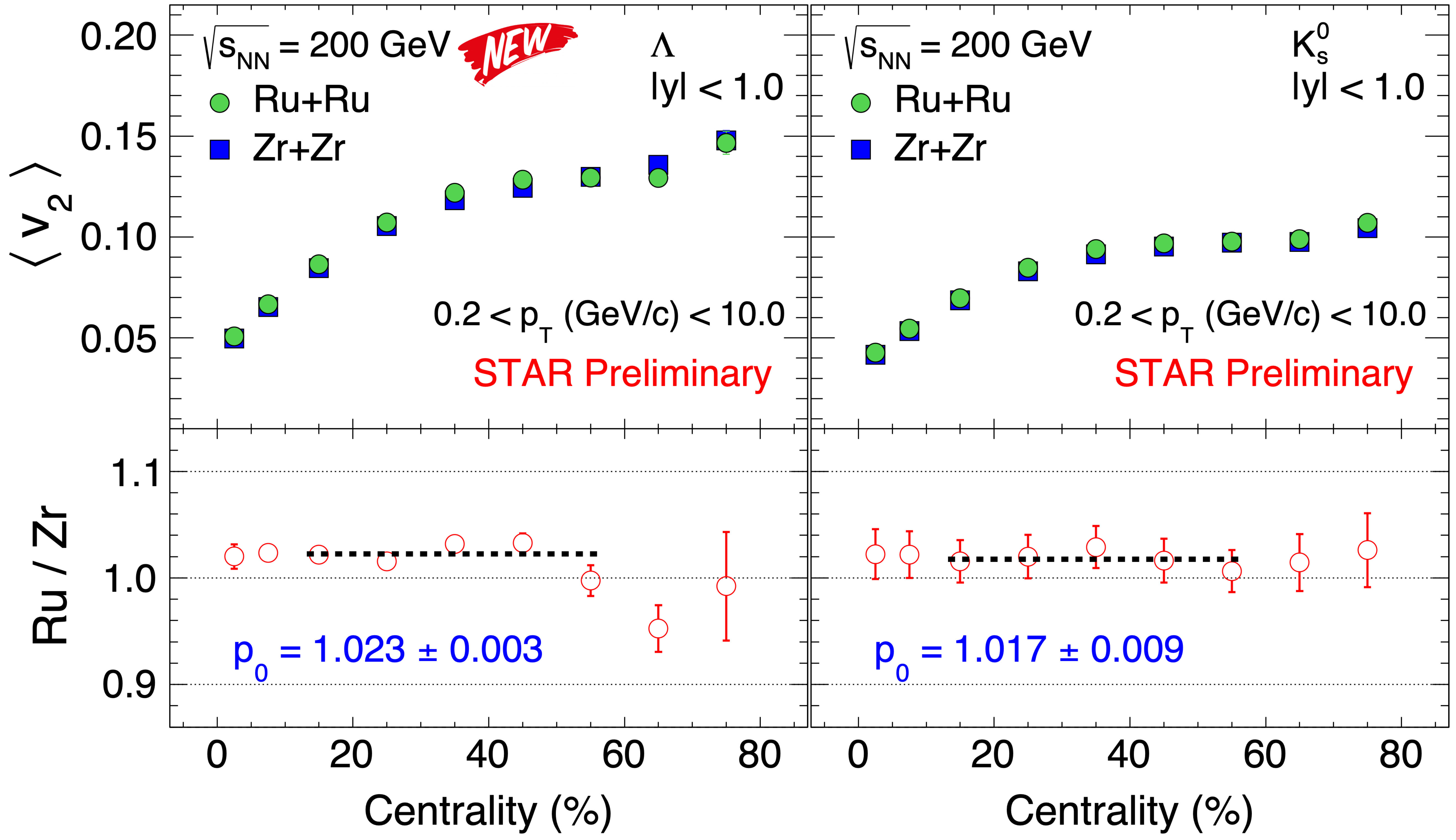
Nuclear deformation from isobar collision





$\beta_2(\mathrm{Ru}) > \beta_2(\mathrm{Zr})$

$\beta_3(\mathrm{Ru}) < \beta_3(\mathrm{Zr})$

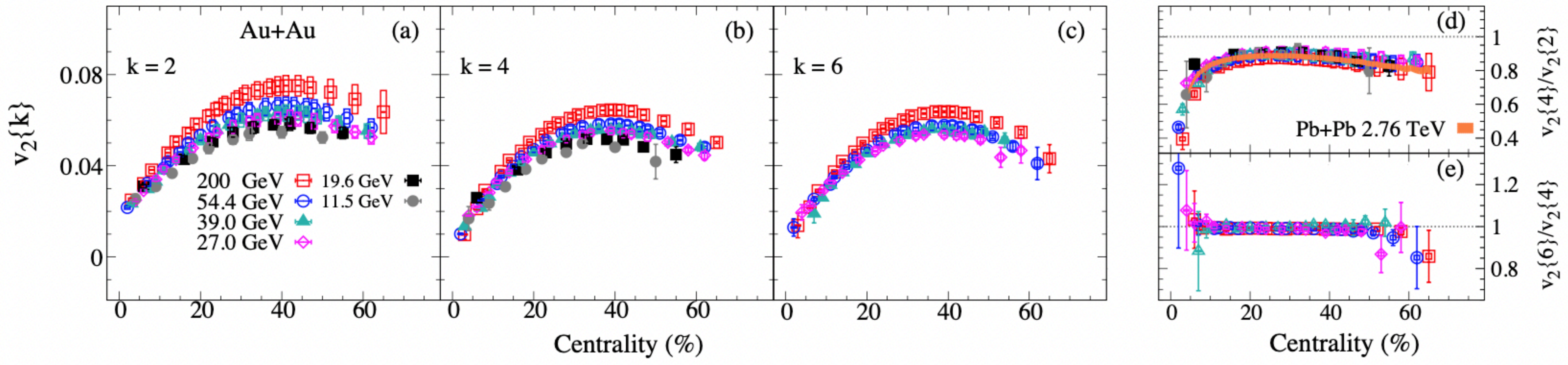


Vipul Bairathi, *Mon. 9:20 AM*

- Ratio of integrated v_2 between Ru+Ru and Zr+Zr collisions differs from 1
  - Indication of larger nuclear deformity in Ru nuclei than in the Zr nuclei

Flow fluctuations via multiparticle flow cumulants

STAR, PRL **129** (2022) 252301



- Assuming a Gaussian distribution of v_2
  - $v_2\{2\} \approx \langle v_2 \rangle + \sigma^2/(2\langle v_2 \rangle)$
  - $v_2\{4\} \approx v_2\{6\} \approx \langle v_2 \rangle - \sigma^2/(2\langle v_2 \rangle)$
  - $v_2\{4\}/v_2\{2\}$ ratio serves as a metric for v_2 fluctuations

- $v_2\{k\}$ increasing with increasing colliding energy
- $v_2\{4\}/v_2\{2\}$ show a weak colliding energy dependence
  - Weak energy dependence of flow fluctuations
- $v_2\{6\}/v_2\{4\}$ are consistent with unity within uncertainties

Constraints on initial conditions

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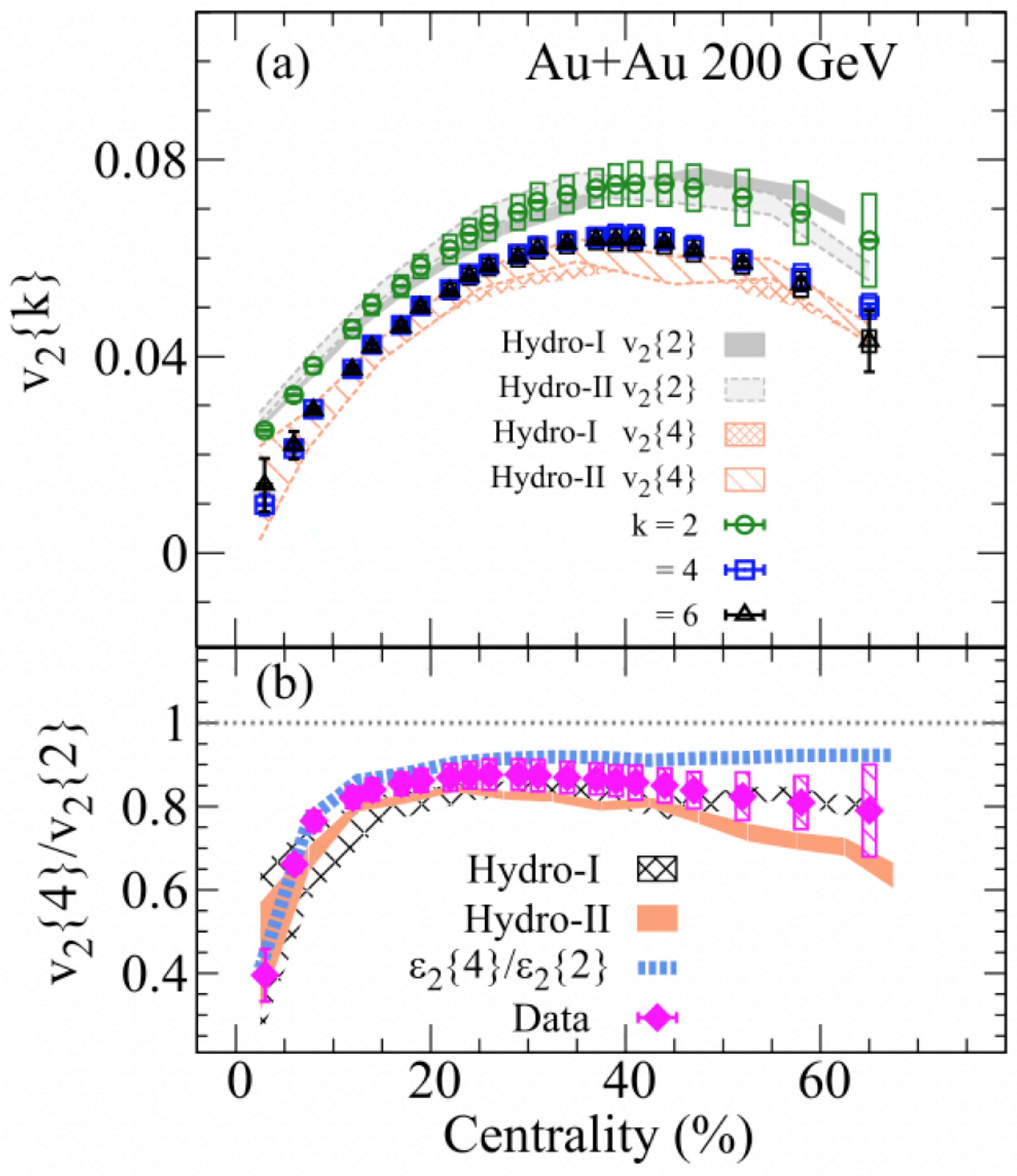
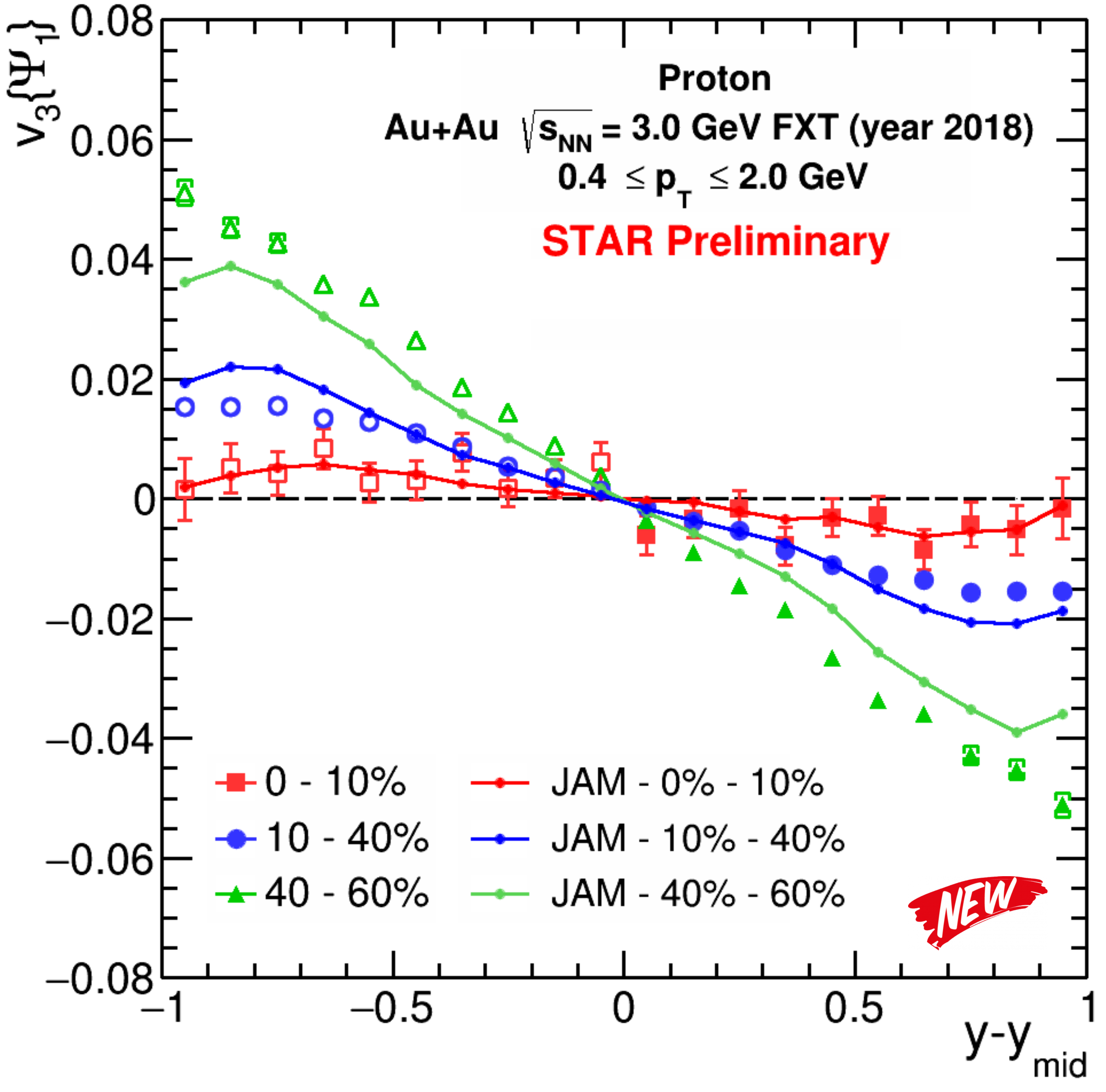
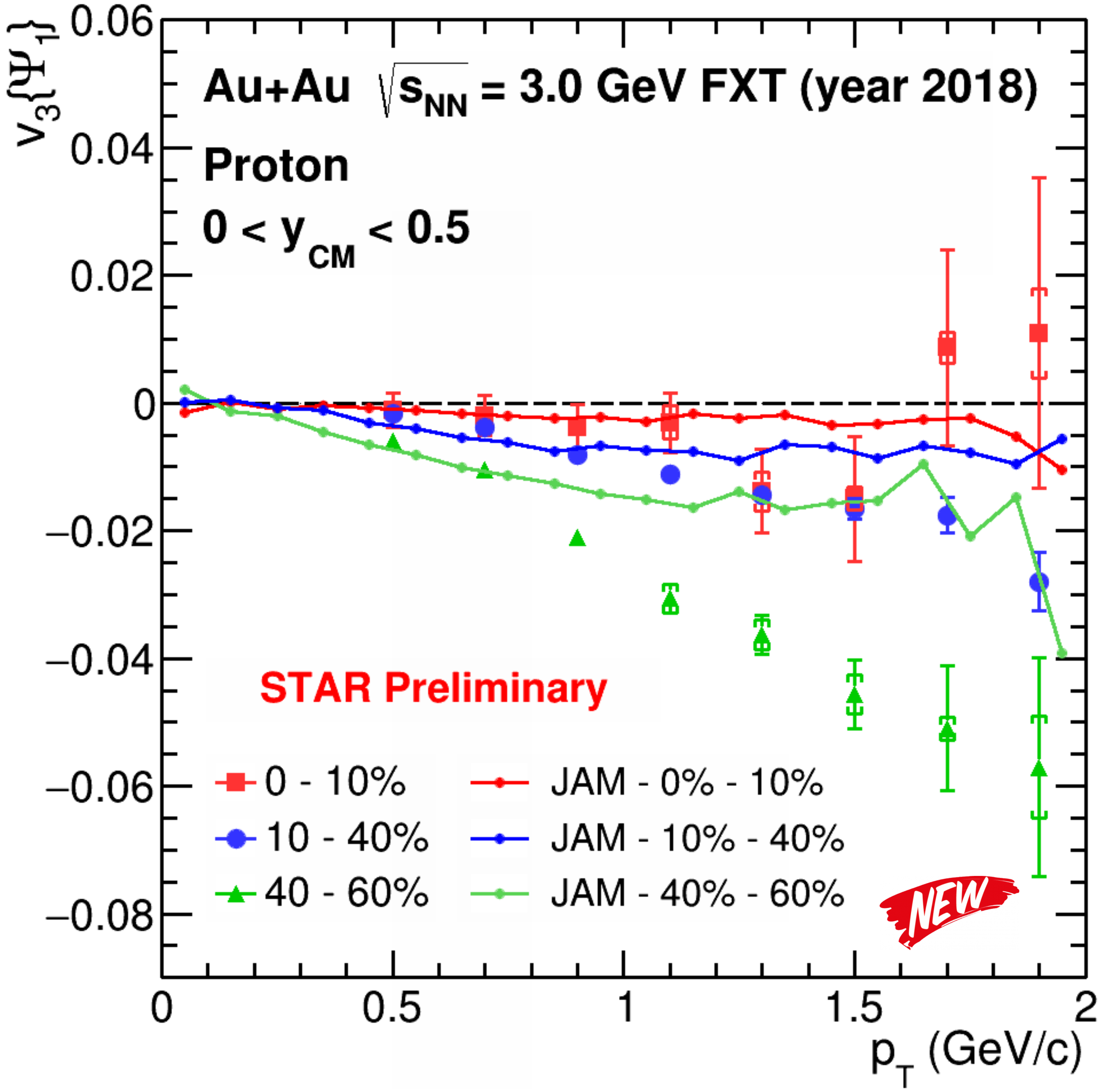


	Hydro-I	Hydro-II
η/s	0.12	0.05
Initial conditions	IP-Glasma	TRENTO
Contributions	Hydro + Hadronic cascade	Hydro + Direct decays

- Both models describe $v_2\{k\}$ well
- $\varepsilon_2\{4\}/\varepsilon_2\{2\} \approx v_2\{4\}/v_2\{2\}$ for central collisions
  - Initial-state eccentricity fluctuations dominate v_2 fluctuations
- $v_2\{4\}/v_2\{2\}$ from Hydro-I agrees well with the data
  - Feasible constraints on the initial stages

$v_3\{\Psi_1\}$ at $\sqrt{s_{NN}}$ = 3 GeV





- $v_3\{\Psi_1\}$ measured at 3 GeV with STAR is much weaker than one observed at 2.4 GeV*, further decreases at $\sqrt{s_{NN}}$ = 3.2—3.9 GeV**
- Signal could only be reproduced with including mean field potential
- Can be used to constrain EoS

*HADES, PRL **125** (2020) 262301

**Sharang Rav Sharma, Mon. 10:20

Summary

- v_1 of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$
  - Measured for the first time
  - v_1 slope follows baryon number scaling
- $v_1^{\mathrm{EPD}}(\eta)$
  - Limited fragmentation check
  - Useful to constrain T-dependent shear viscosity
- Number-of-constituent-quark scaling
  - Holds at $\sqrt{s_{\mathrm{NN}}}$ = 19.6 GeV
  - Absent at $\sqrt{s_{\mathrm{NN}}}$ = 3 GeV
- v_2, v_3 in $\mathrm{He+Au}$, $d\mathrm{+Au}$, $p\mathrm{+Au}$ collisions
  - Suggests significant influence of sub-nucleonic fluctuations
- Strange hadron v_2 from isobar collisions
  - Give access to nuclei deformation
- $v_2\{4\}/v_2\{2\}$
  - Flow fluctuations show weak energy dependence
  - Provide constraints for initial conditions
- $v_3\{\Psi_1\}$ at $\sqrt{s_{\mathrm{NN}}}$ = 3 GeV
  - Useful to constrain EoS

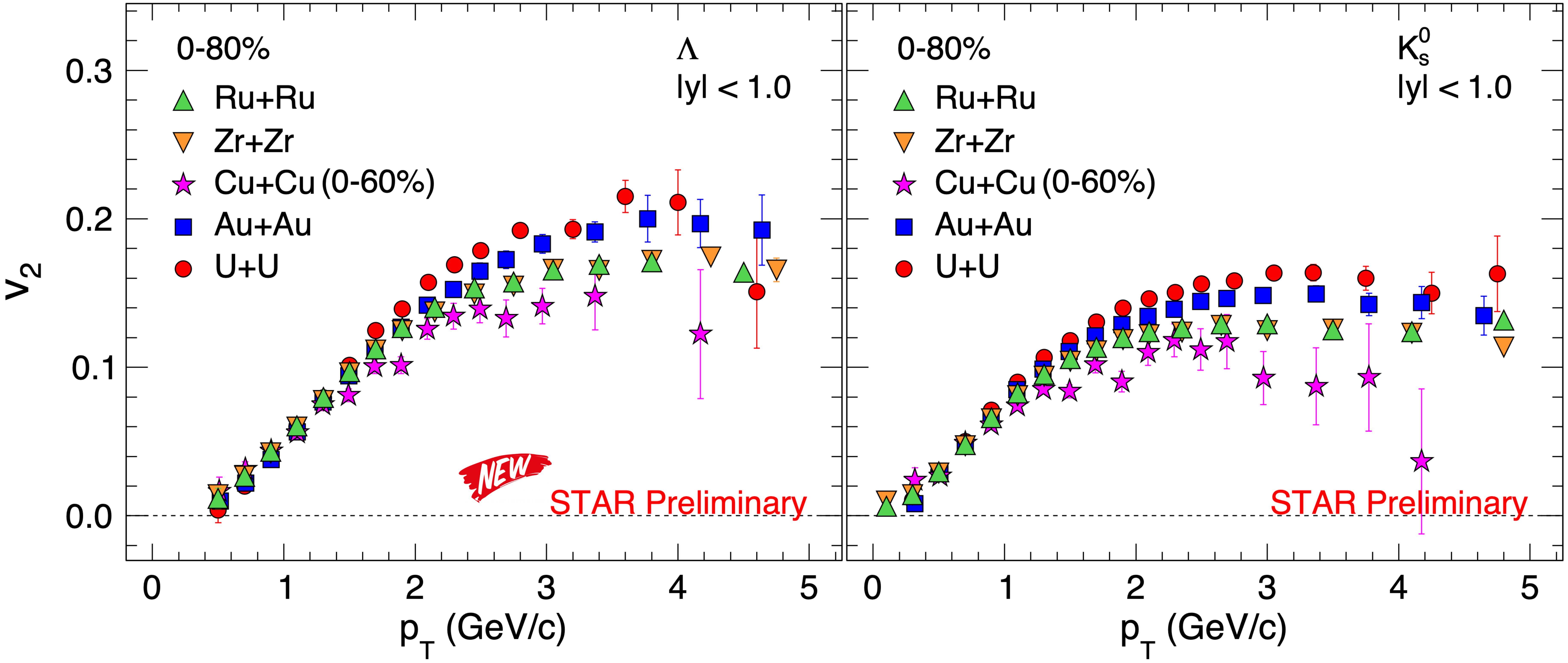
Stay tuned for more flow results from BES-II and FXT programs!

Köszönöm!

Back-up

System size dependence

Vipul Bairathi, *Mon. 9:20 AM*



- v_2 at high p_T incresases with atomic mass number of colliding nuclei
  - Indicating a nuclear size dependence