

RBRC
RIKEN BNL Research Center

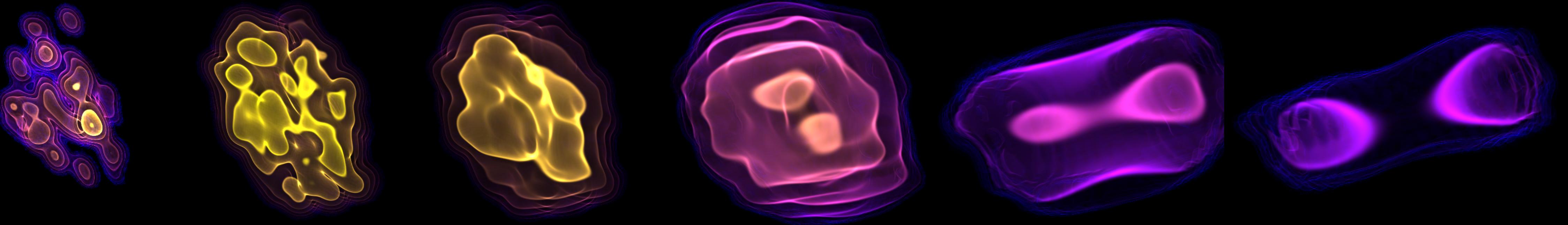


BEST
COLLABORATION

JETSCAPE

NUCLEAR AND NUCLEON STRUCTURE IMPACT ON SMALL-X EVOLUTION AND RAPIDITY DEPENDENCE

CHUN SHEN

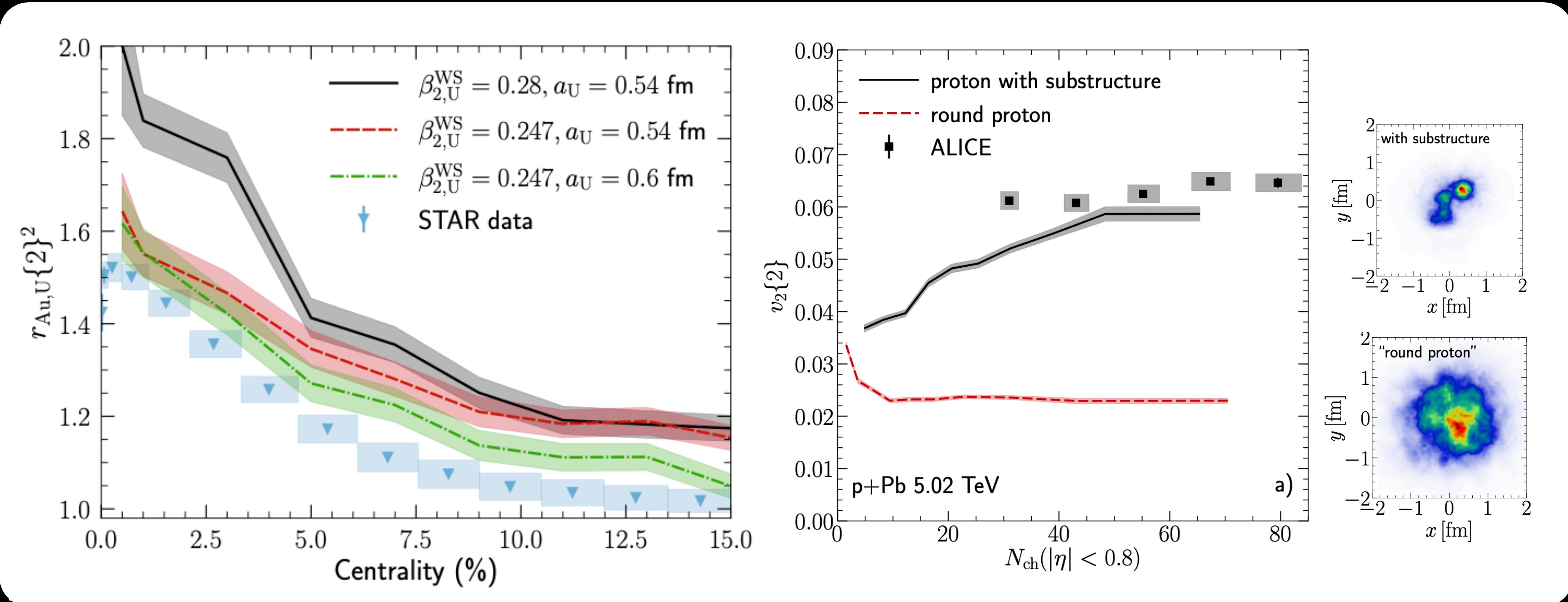


June 21, 2023

NUCLEAR STRUCTURE IS IMPORTANT

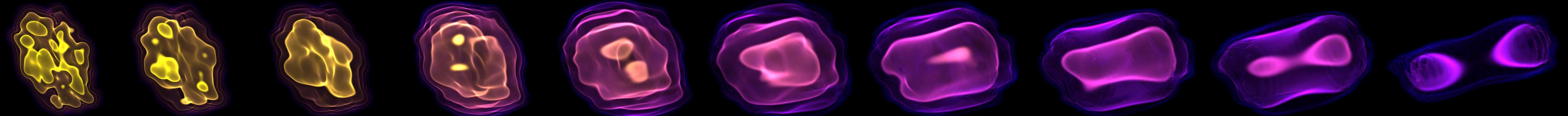
W. Ryssens, G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 130, 212302 (2023)

B. Schenke, Rept. Prog. Phys. 84, 082301 (2021)

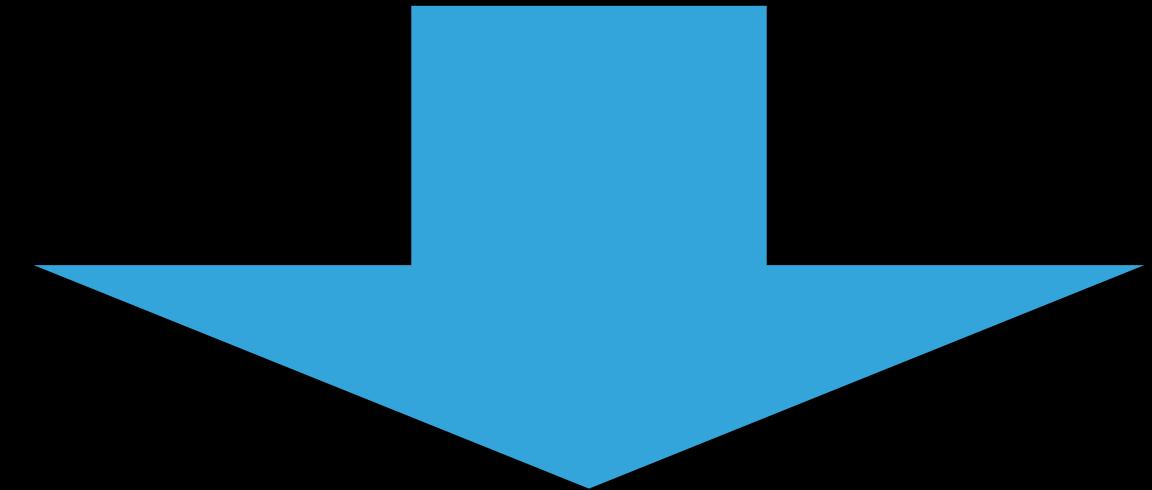


- The structure of nuclei plays a crucial role in precision heavy-ion physics
- Proton's sub-nucleonic structure is essential to understand the collectivity in small collision systems

ENTERING THE FULL (3+1)D ERA

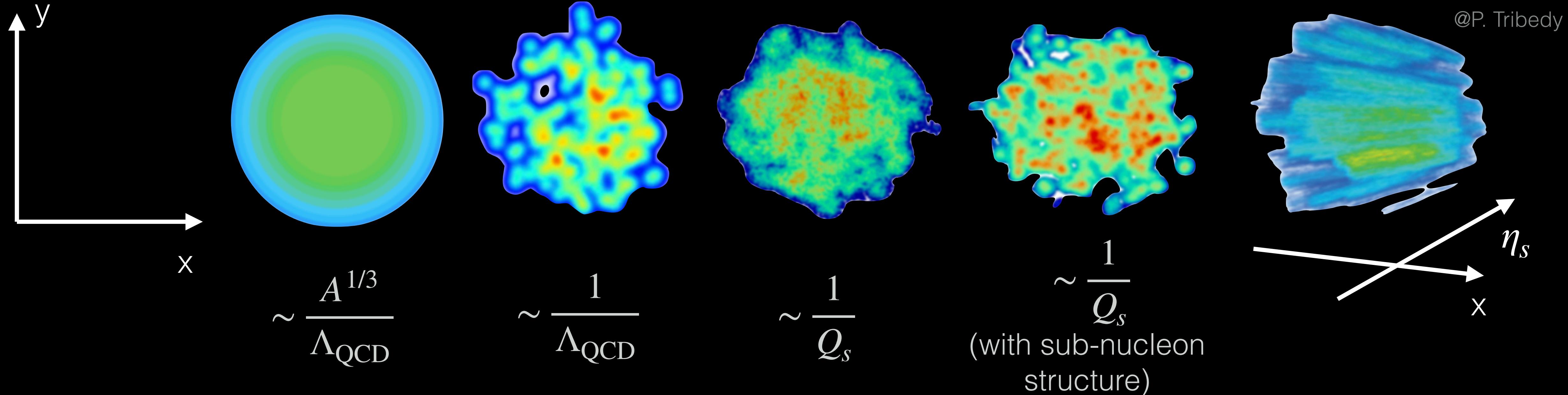


- Probes the **inner working of QGP** at multi-resolution scales with jets and heavy-quarks
- What is the **smallest QGP droplet?**
- What is the structure of **QCD phase diagram?**



How does the strongly coupled liquid emerge from fundamental QCD interactions?

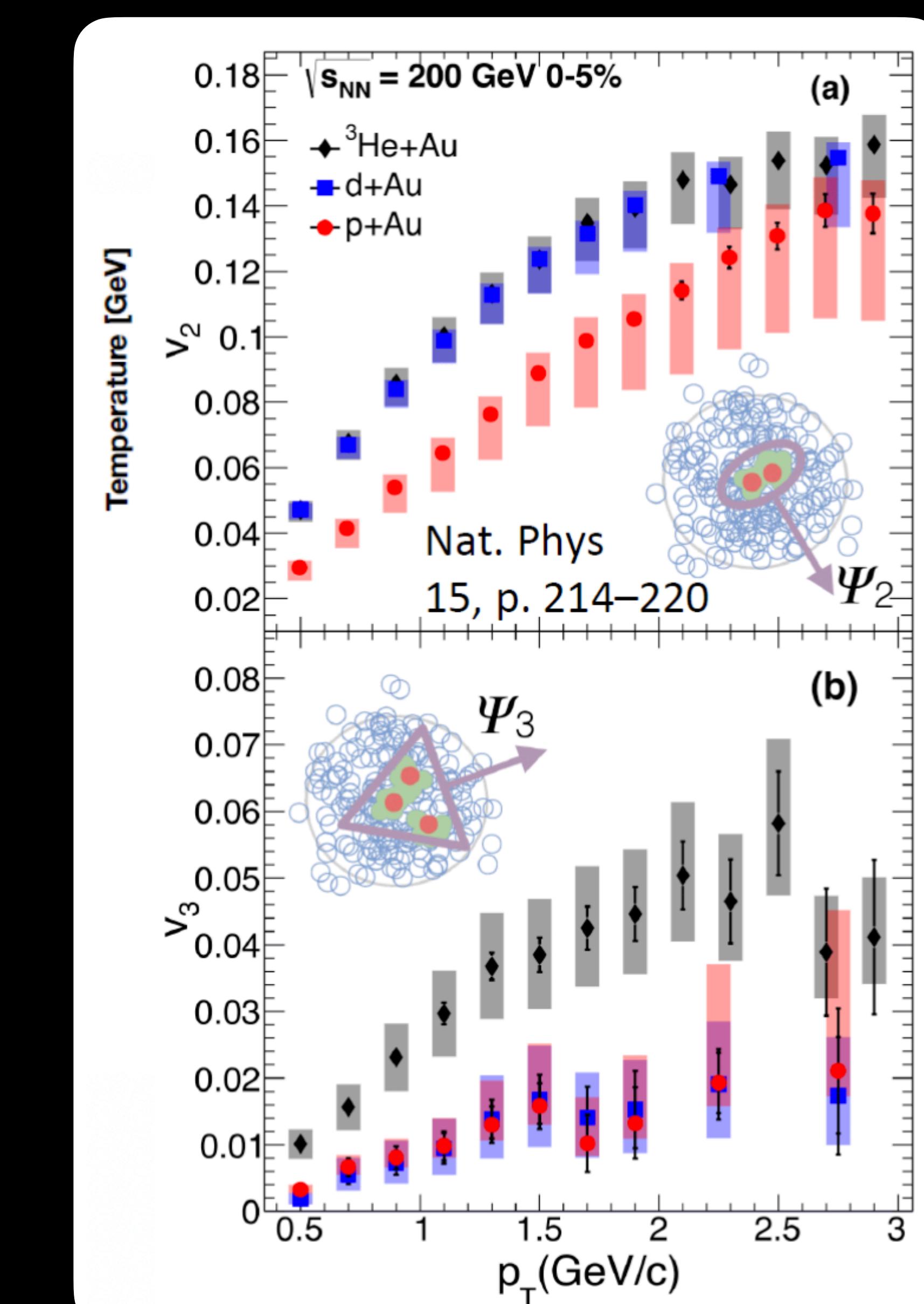
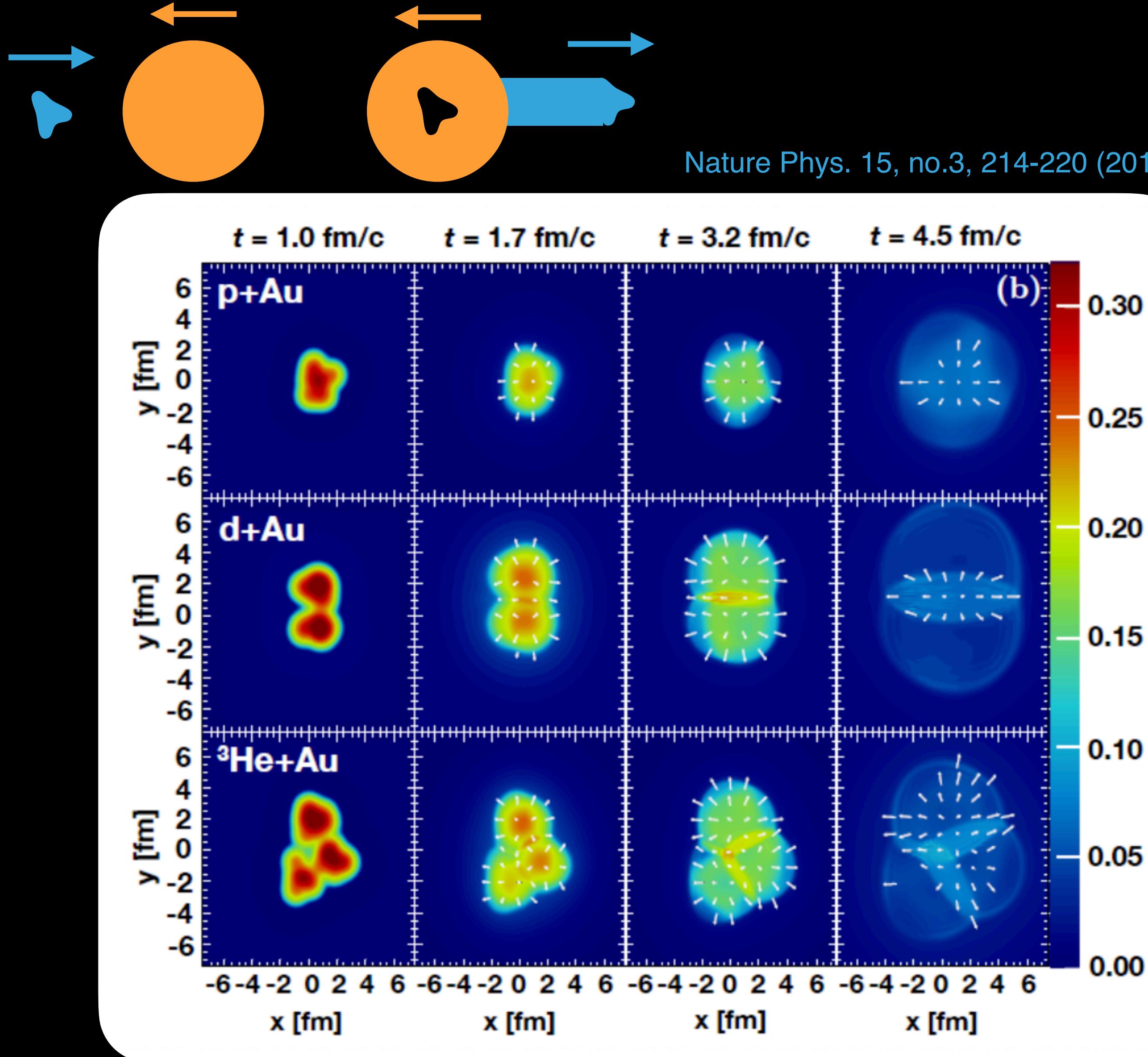
THEORETICAL EVOLUTION OF INITIAL CONDITIONS



- The spatial structures of nuclei and nucleons play a crucial role in the initial conditions for relativistic heavy-ion collisions
- The longitudinal distribution opens a new dimension to understanding the dynamics of heavy-ion collisions at different collision energies

SEE TALKS BY P. SINGH, D. SOEDER, O. GARCIA-MONTERO, P. CARZON

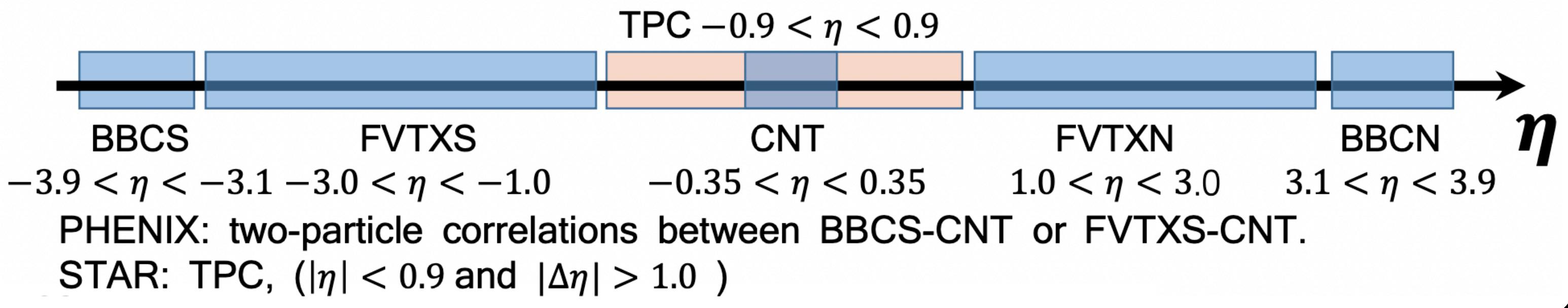
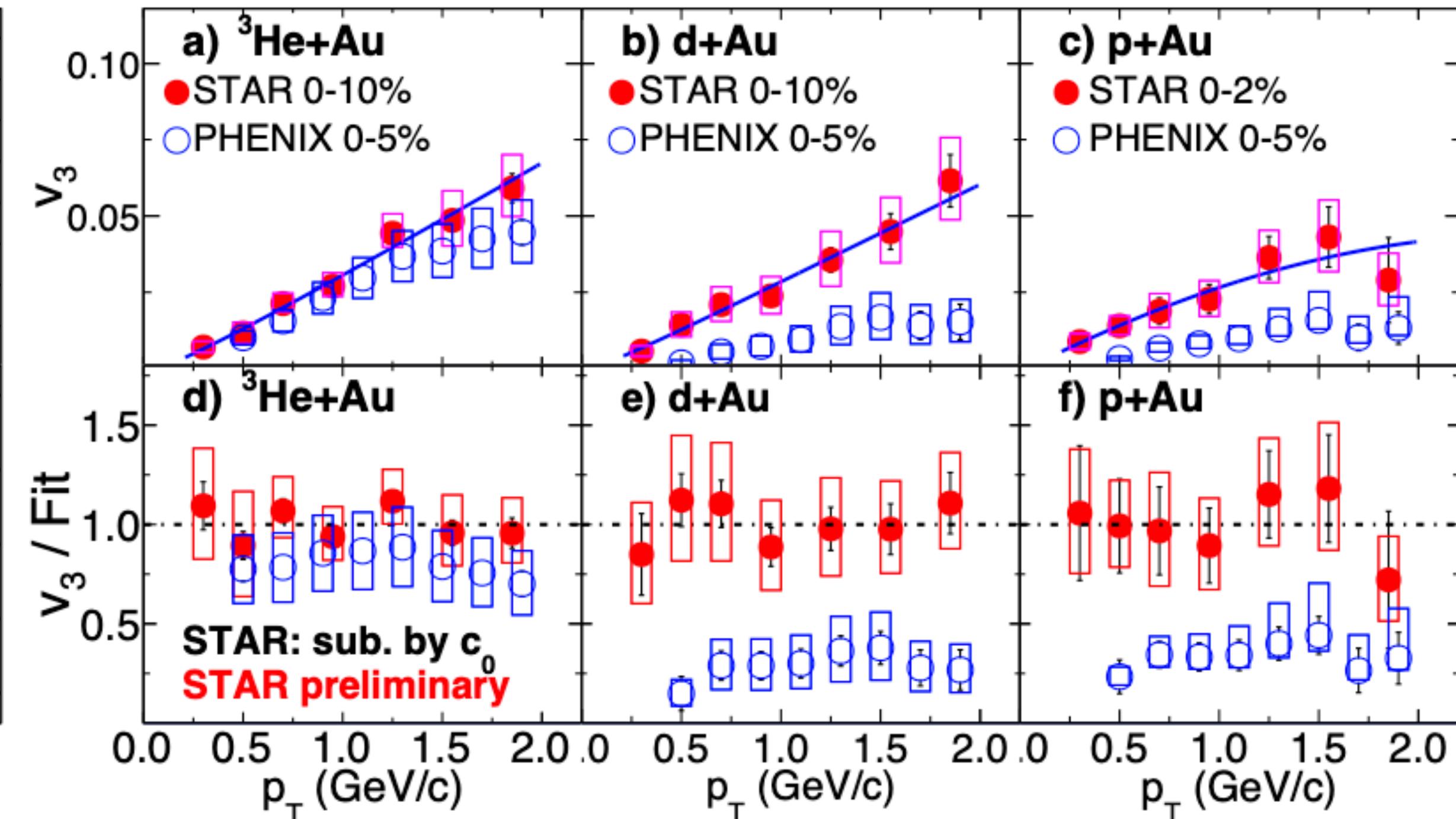
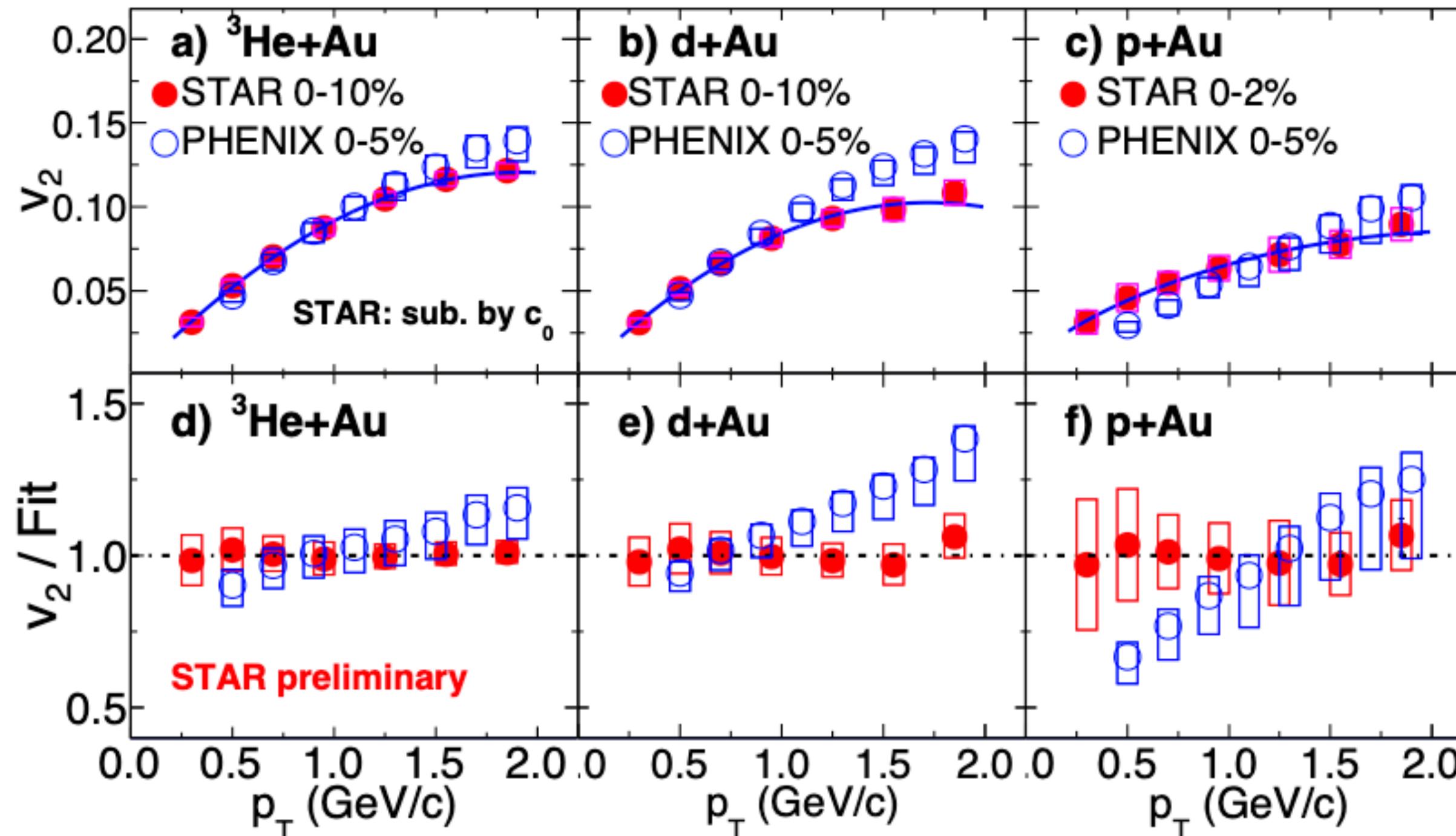
TEST HYDRODYNAMIC RESPONSE TO GEOMETRY



SMALL SYSTEM SCAN AT RHIC

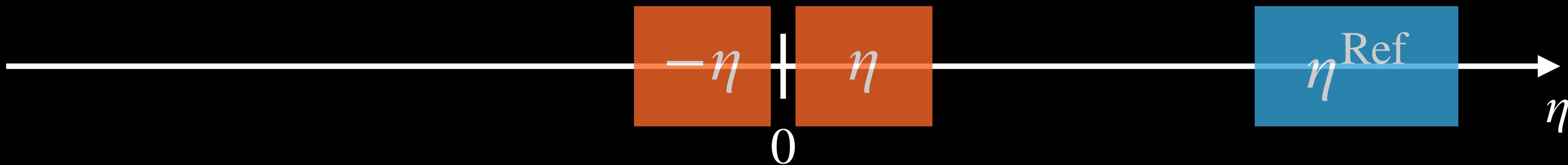
STAR Collaboration, arXiv:2210.11352 [nucl-ex]

R. A. Lacey [STAR], Nucl. Phys. A1005, 122041 (2021)



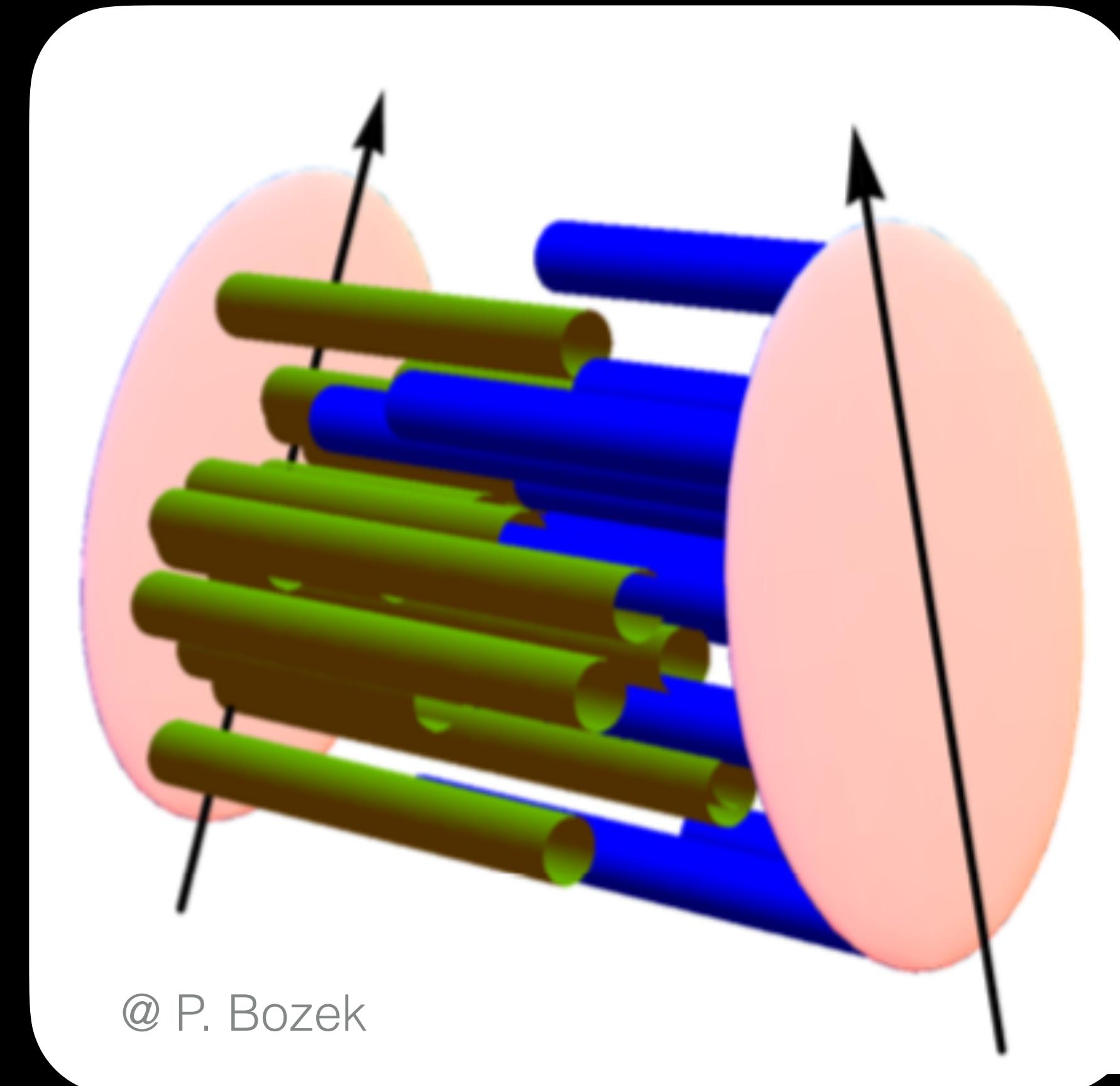
- (3+1)D simulations are essential to understand the difference between PHENIX and STAR measurements

LONGITUDINAL FLOW DECORRELATION



$$r_n = \frac{\langle Q_n(-\eta) Q_n(\eta^{\text{ref}})^* \rangle}{\langle Q_n(\eta) Q_n(\eta^{\text{ref}})^* \rangle}$$

$$r_n^\epsilon = \frac{\langle \mathcal{E}_n(-\eta_s) \mathcal{E}_n(\eta_s^{\text{ref}})^* \rangle}{\langle \mathcal{E}_n(\eta_s) \mathcal{E}_n(\eta_s^{\text{ref}})^* \rangle}$$

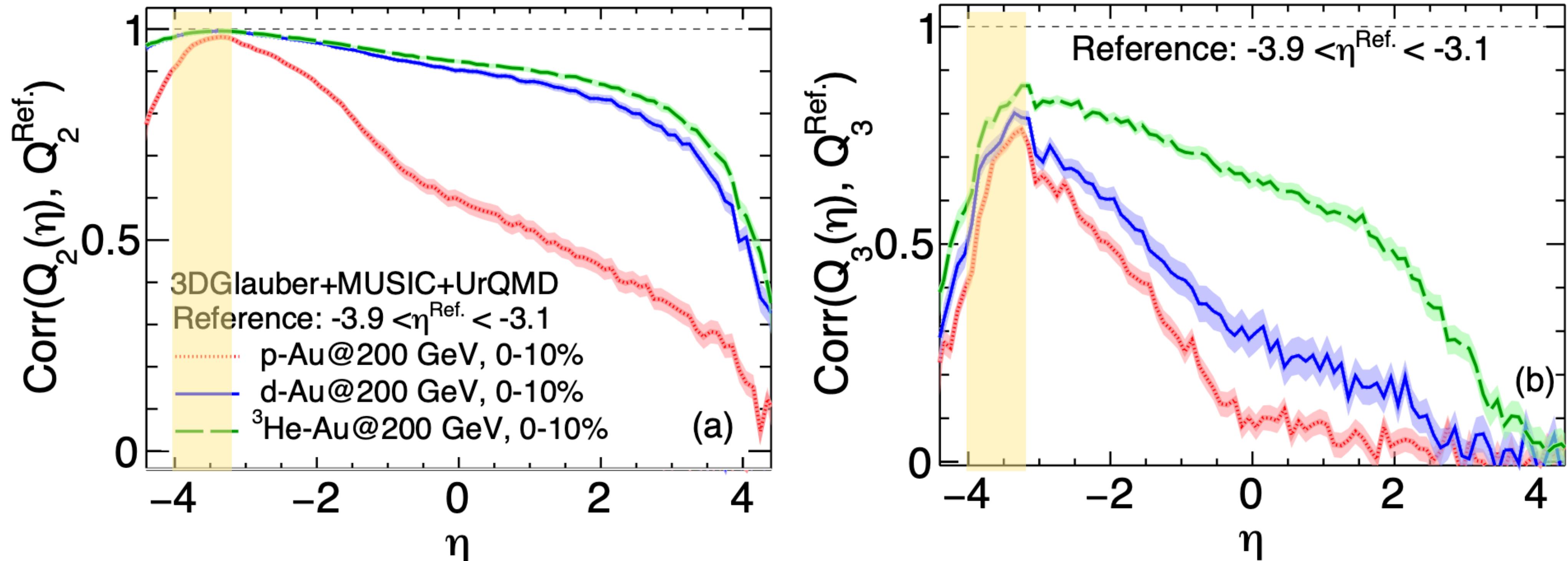


@ P. Bozek

FLOW CORRELATION IN PHENIX KINEMATICS

W. Zhao, S. Ryu, C. Shen, and B. Schenke, Phys. Rev. C 107 014904 (2023)

$$r_n = \frac{\langle Q_n(-\eta)Q_n(\eta^{\text{ref}})^* \rangle}{\langle Q_n(\eta)Q_n(\eta^{\text{ref}})^* \rangle}$$



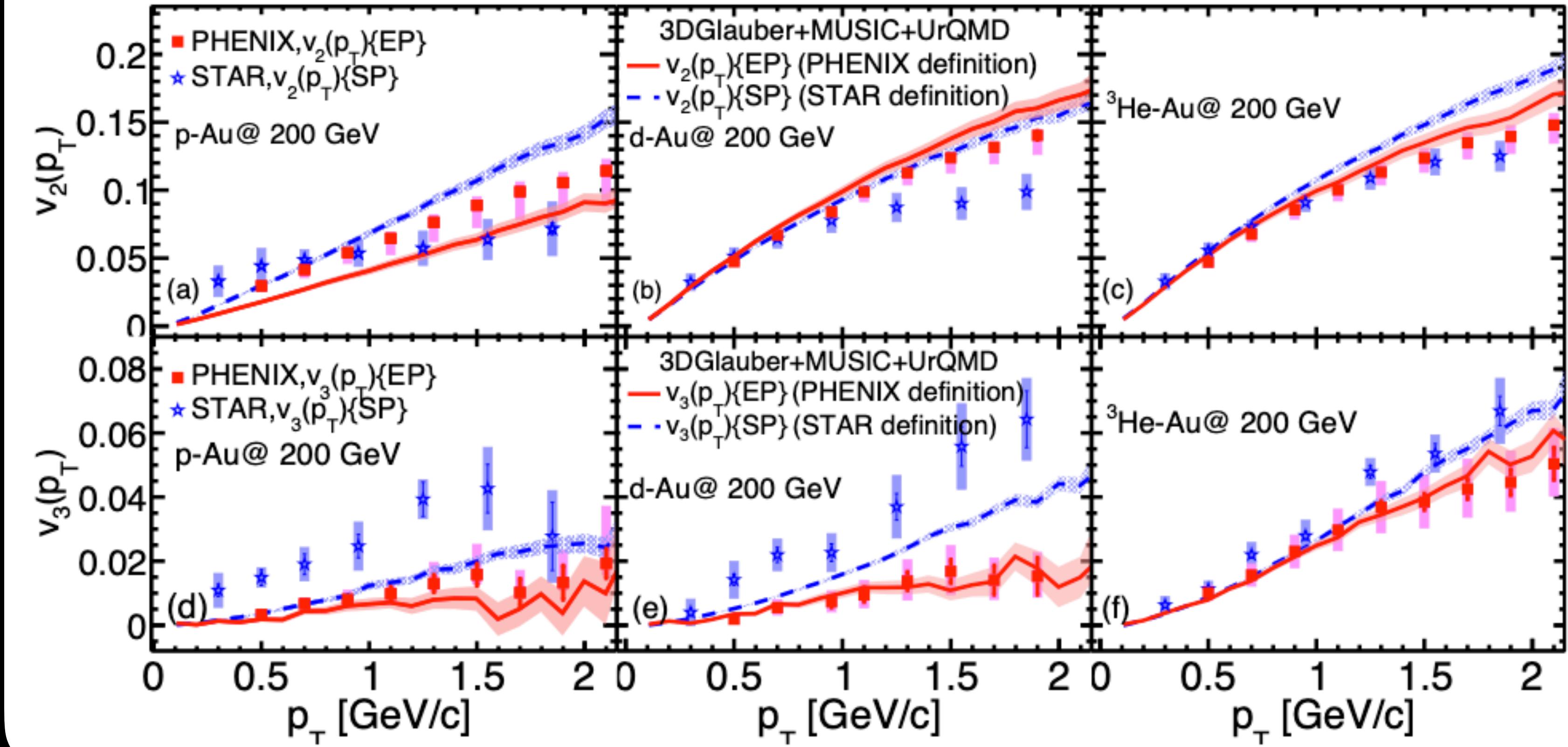
- The elliptic flow correlations in (d, ${}^3\text{He}$)+Au remain strong with an increasing η difference, which ensures a strong geometric response in the PHENIX measurements
- Flow correlations of v_3 in all systems are significantly below 1, indicating that the choice of reference flow angle is crucial for the two-particle flow measurements

PHENIX VS. STAR

W. Zhao, S. Ryu, C. Shen, and B. Schenke, Phys. Rev. C 107 014904 (2023)

PHENIX:
 $(p, d) + \text{Au}$: $\eta_1 \in [-3.9, -3.1]$,
 $\eta_2 \in [-0.35, 0.35]$
 ${}^3\text{He} + \text{Au}$: $\eta_1 \in [-3, -1]$,
 $\eta_2 \in [-0.35, 0.35]$

STAR:
 $\eta \in [-0.9, 0.9]$ with $|\Delta\eta| > 1$

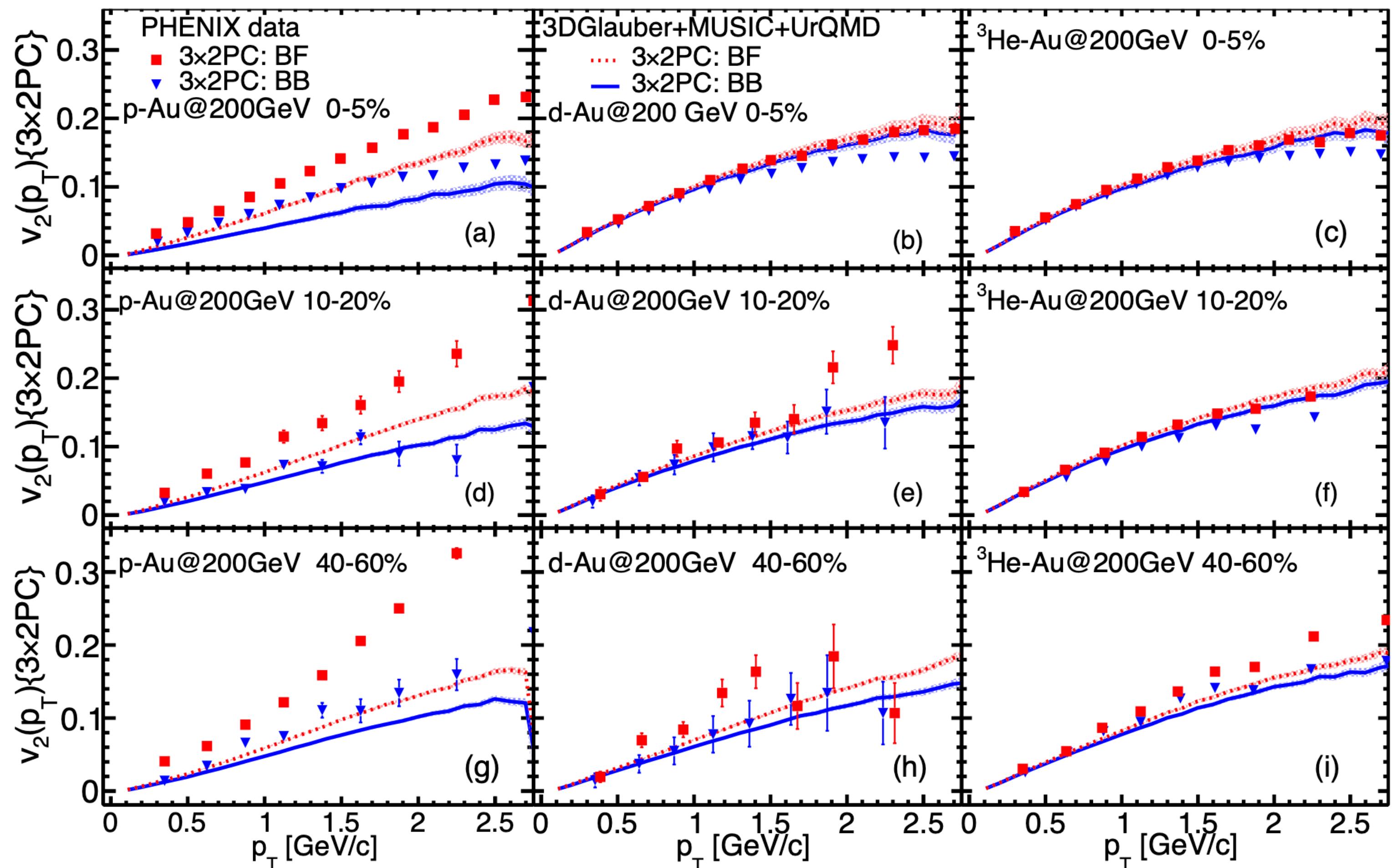
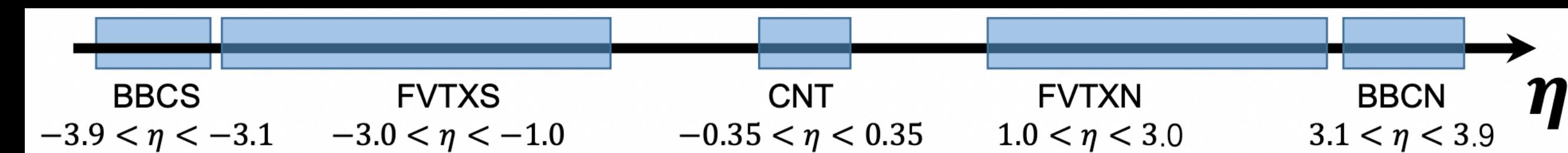


- Our (3+1)D model reproduces the PHENIX $v_n(p_T)$ in (d, ${}^3\text{He}$)+Au collisions
- Longitudinal flow decorrelation results in a larger $v_3(p_T)$ with the STAR definition than those from PHENIX, explaining part of the difference between the two measurements

FLOW RAPIDITY CORRELATION IN THE 3X2PC MEASUREMENTS

N. J. Abdulameer *et al.* [PHENIX], Phys. Rev. C 107, 024907 (2023)

W. Zhao, S. Ryu, C. Shen, and B. Schenke, Phys. Rev. C 107 014904 (2023)



3 × 2PC

$$C_n^{AB} = \langle Q_{nA} Q_{nB}^* \rangle,$$

$$c_n^{AC}(p_T) = \langle Q_{nA} q_{nC}^*(p_T) \rangle,$$

$$c_n^{BC}(p_T) = \langle Q_{nB} q_{nC}^*(p_T) \rangle.$$

$$v_n^C(p_T) = \sqrt{\frac{c_n^{AC}(p_T) c_n^{BC}(p_T)}{C_n^{AB}}}.$$

BB: BBCS-FVTXS-CNT
BF: FVTXS-CNT-FVTXN

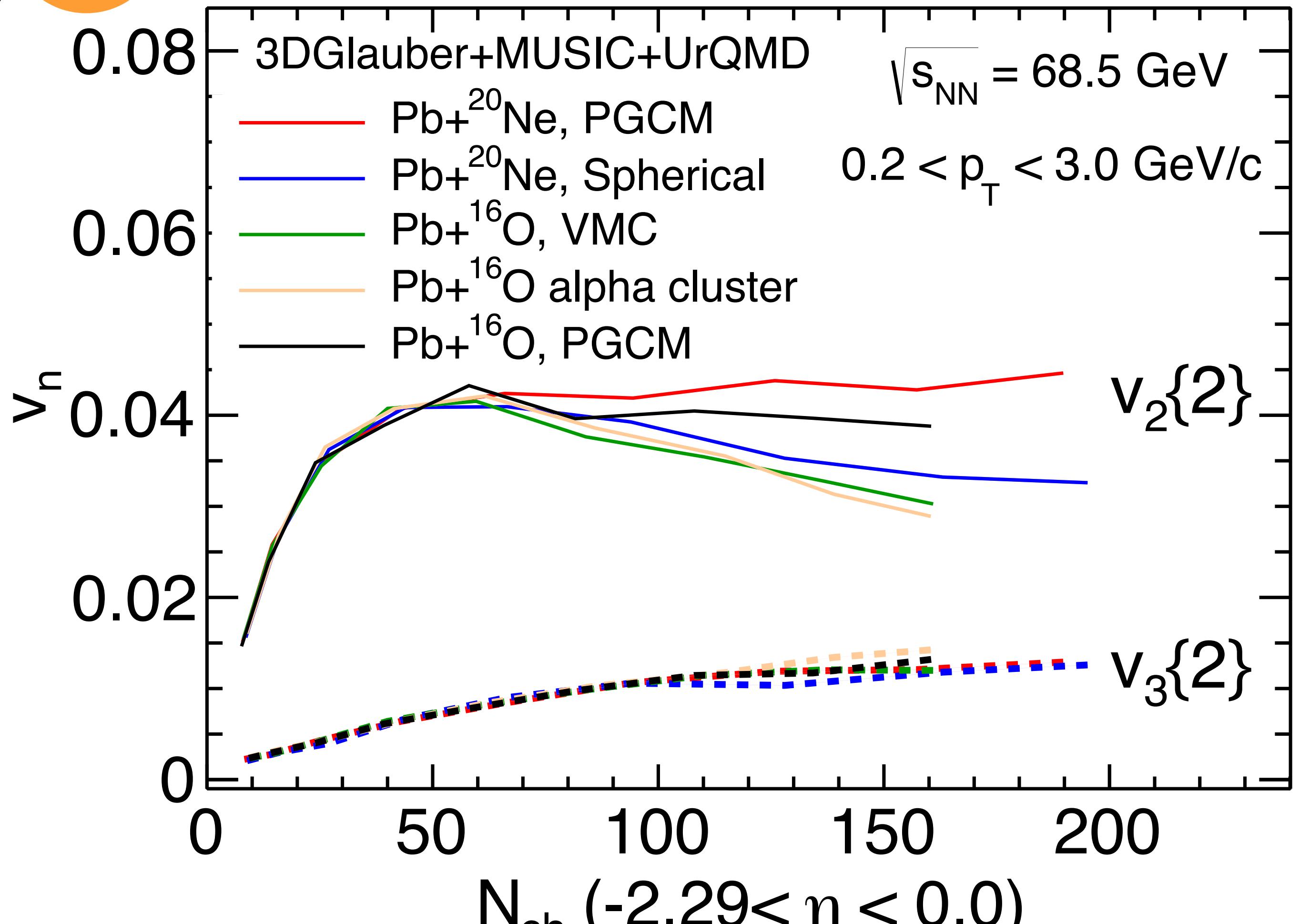
- The longitudinal flow decorrelation quantitatively reproduces the differences in the BB and BF measurements.

NUCLEAR STRUCTURE IN THE LHCb SMOG EXPERIMENT



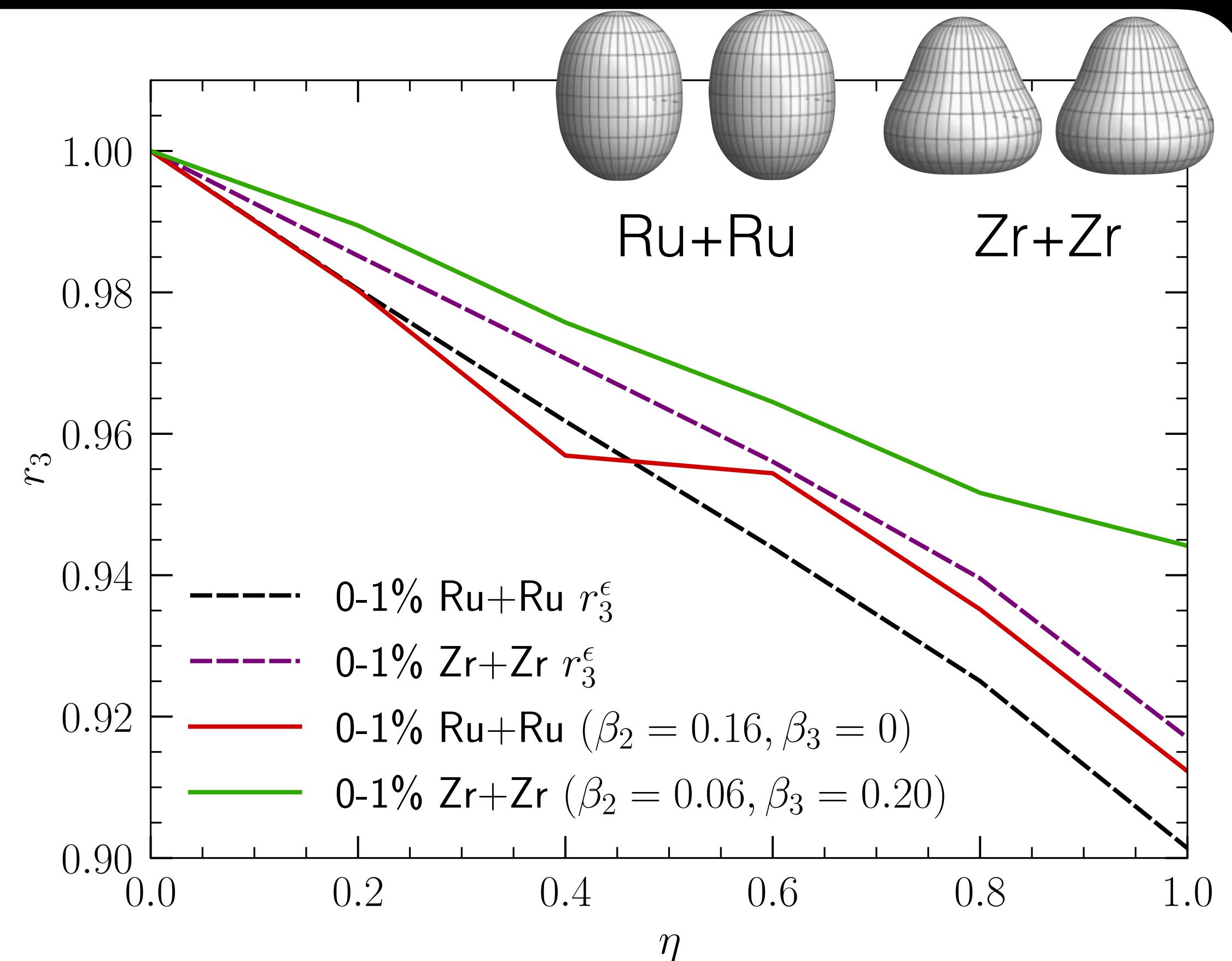
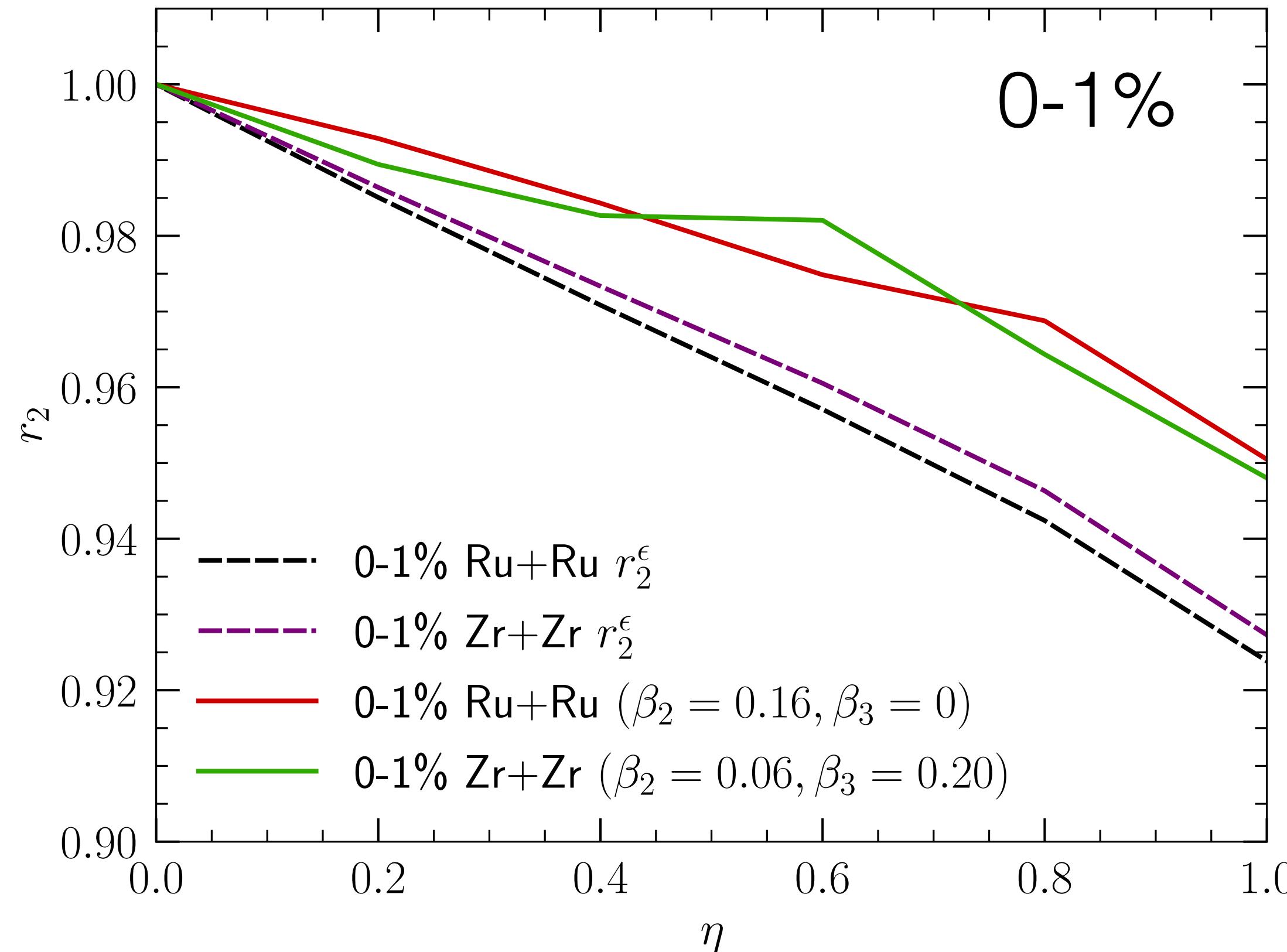
M. Rybczynski, M. Piotrowska and W. Broniowski, Phys. Rev. C97, 034912 (2018)

W. Zhao, G. Giacalone, B. Schenke, and C. Shen, in preparation



- Anisotropic flow in central light + Pb collisions shows strong sensitivity to light nuclei's nuclear structure
- Within the PGCM framework, central Ne+Pb collisions have 10% more $v_2\{2\}$ than that of O+Pb collisions at the same multiplicity
- Complementary to O+O and Ne+Ne collisions at top RHIC and LHC energies

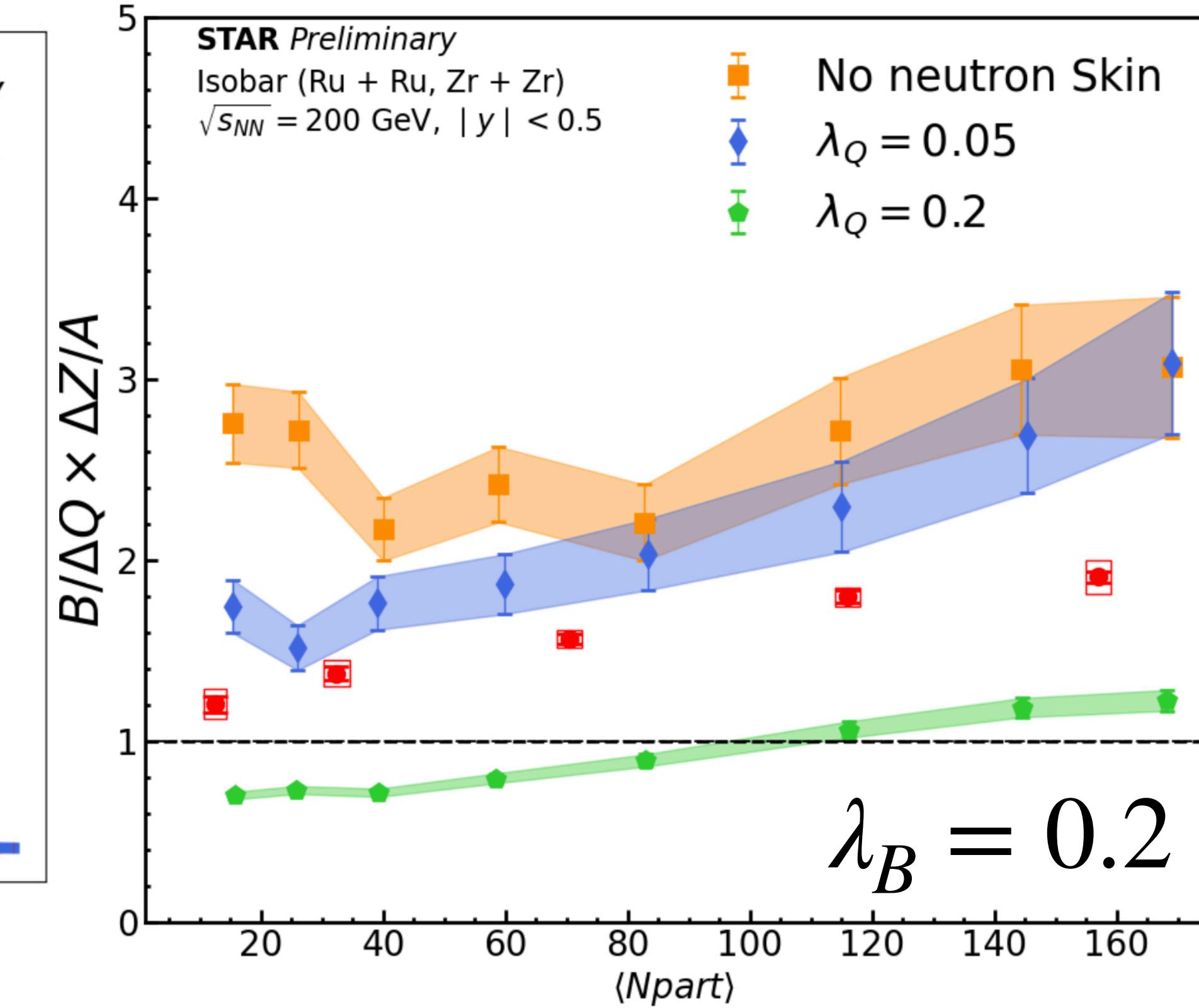
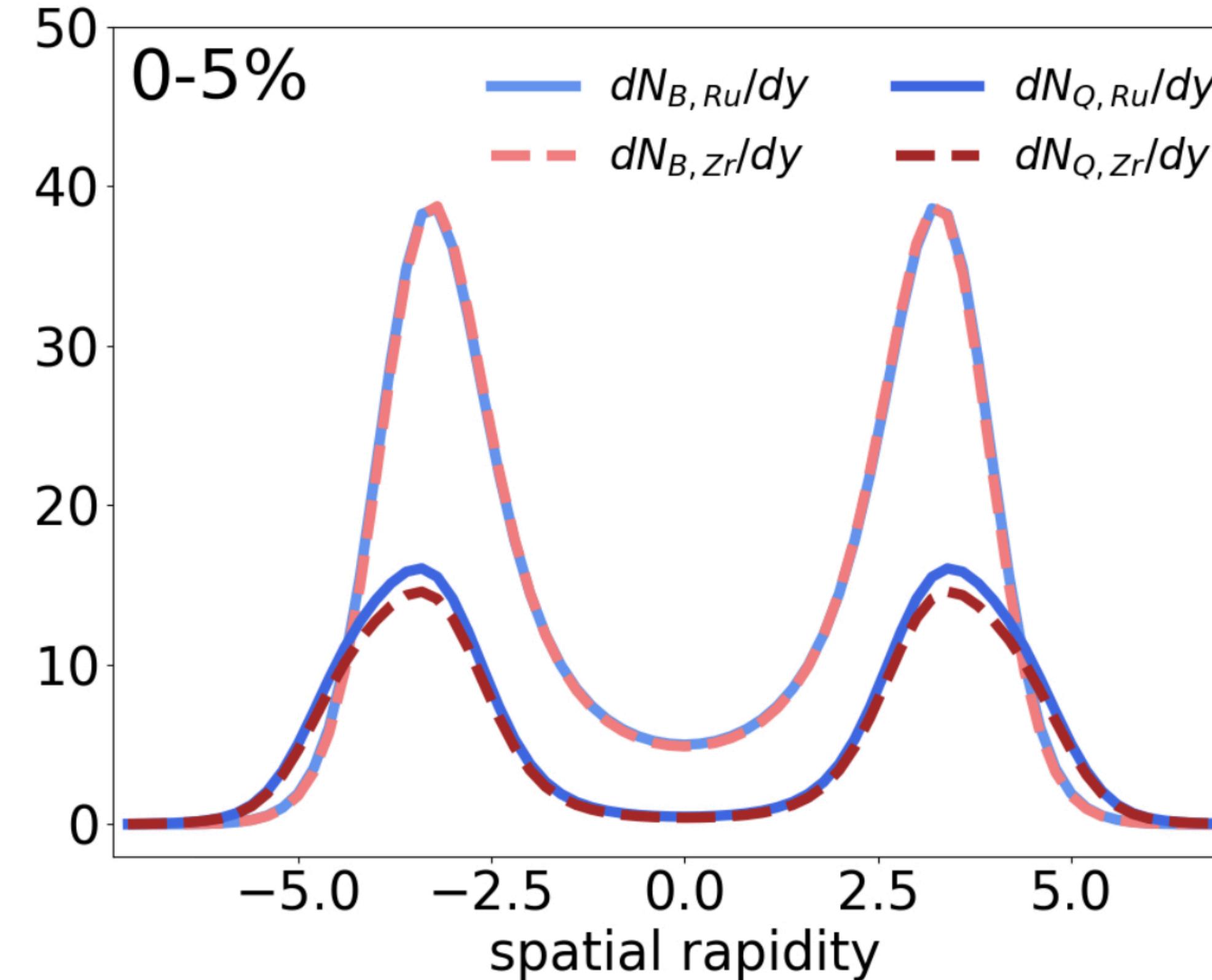
NUCLEAR STRUCTURE EFFECTS ON r_n AT RHIC ISOBAR



- The non-zero β_3 in central Zr+Zr collisions results in a larger r_3 than those in Ru+Ru collisions in central isobar collisions

BARYON AND ELECTRIC CHARGE STOPPING AT RHIC

G. Pihan, A. Monnai, B. Schenke, C. Shen, in preparation

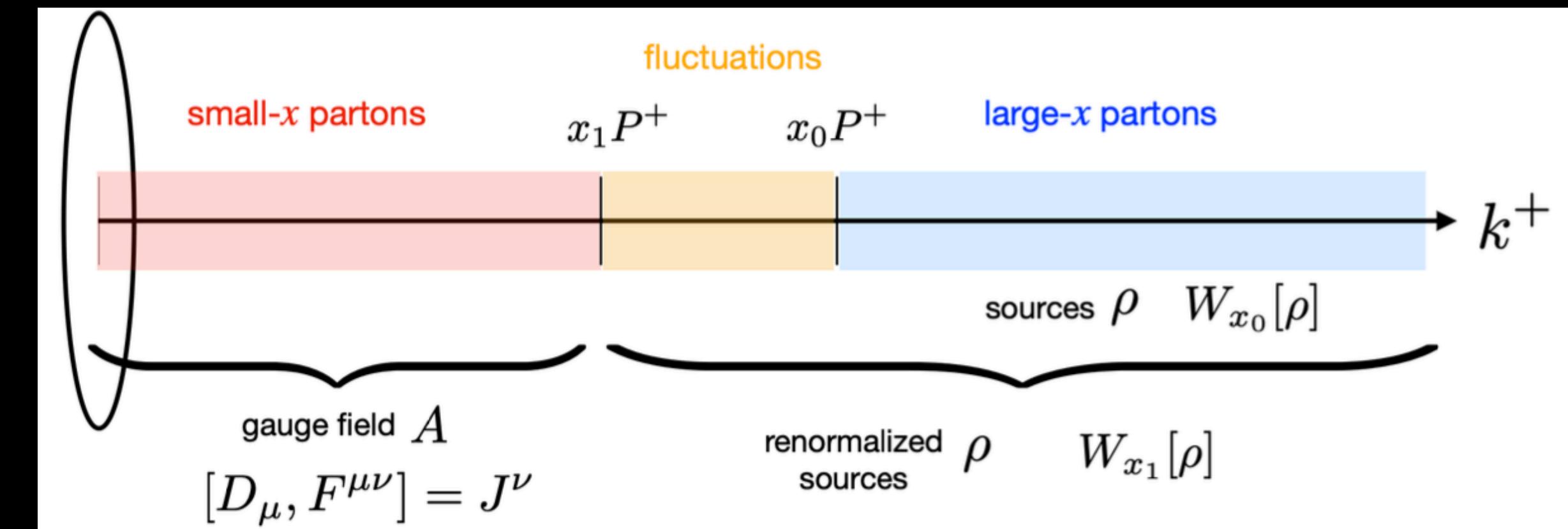
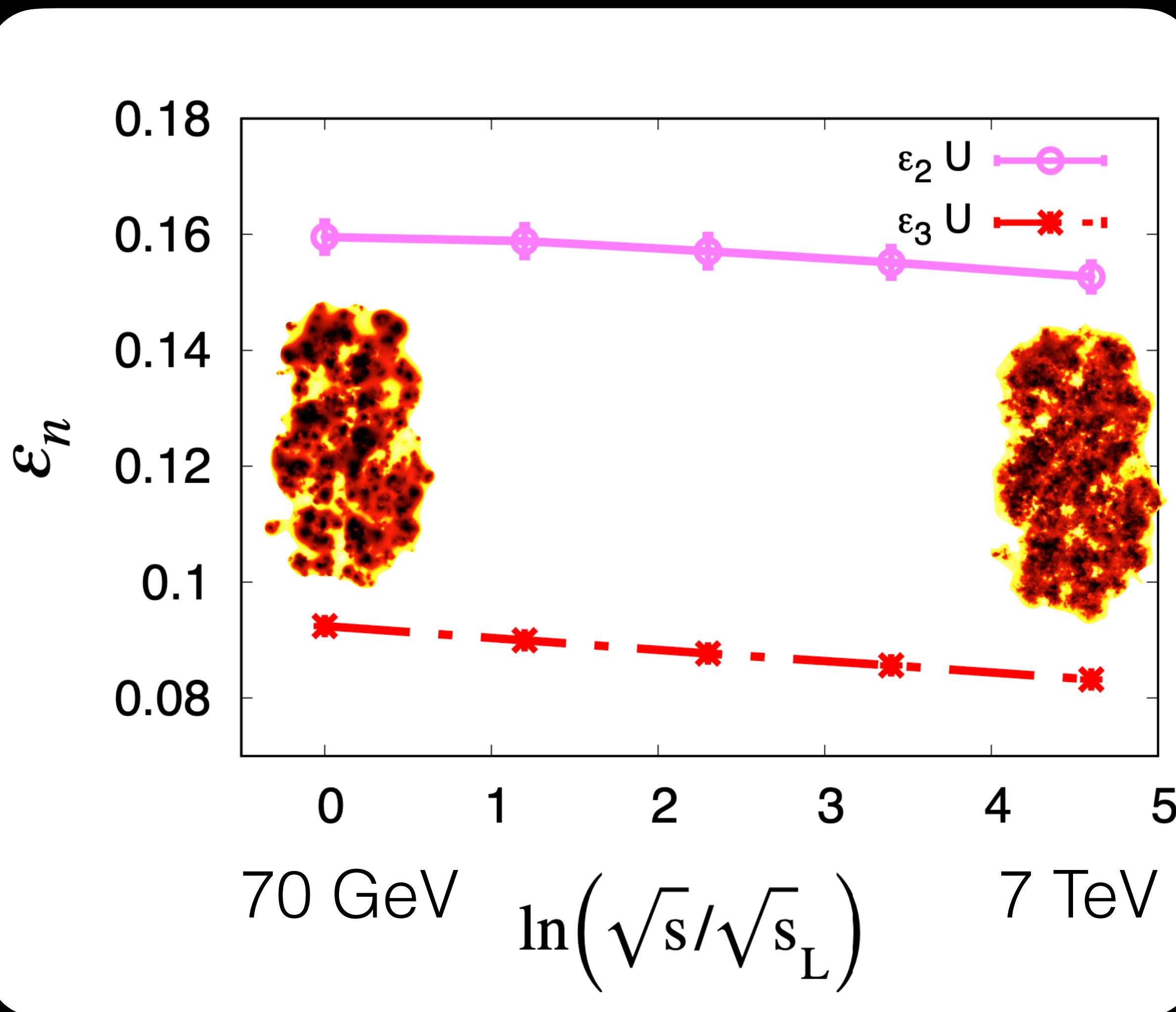


- The ratios of net baryon over net electric charges in the RHIC isobar collisions show strong sensitivity to longitudinal charge transport and neutron skin of the colliding nuclei

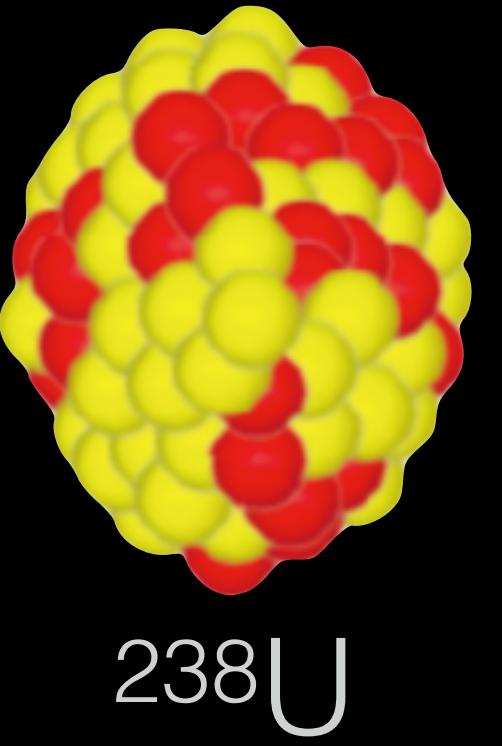
SEE N. LEWIS' TALK & G. PIHAN'S POSTER

NUCLEAR STRUCTURE WITH SMALL-X EVOLUTION

P. Singh, G. Giacalone, B. Schenke, and S. Schlichting



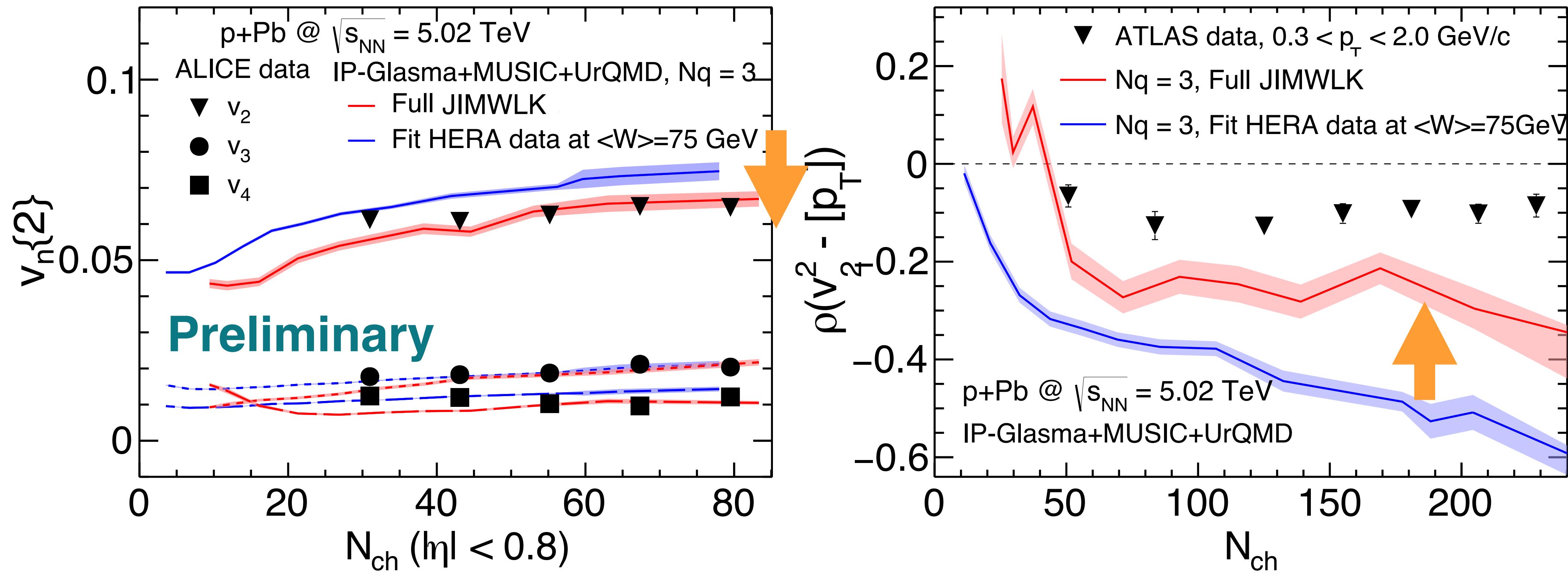
- JIMWLK evolution leads to smoothening of geometric profile and growth in impact parameter space
- The initial spatial eccentricities reduce by ~5% (ϵ_2) and ~10% (ϵ_3)



SEE TALK BY P. SINGH

JIMWLK IN HEAVY-ION PHENOMENOLOGY

H. Mantysaari, B. Schenke, C. Shen, and W. Zhao, in preparation



- The small- x (JIMWLK) evolution smoothens the sub-nucleon structure at high energy and improves the description of anisotropic flow and $v_2 - \langle p_T \rangle$ correlation in $p+Pb$ collisions at 5 TeV

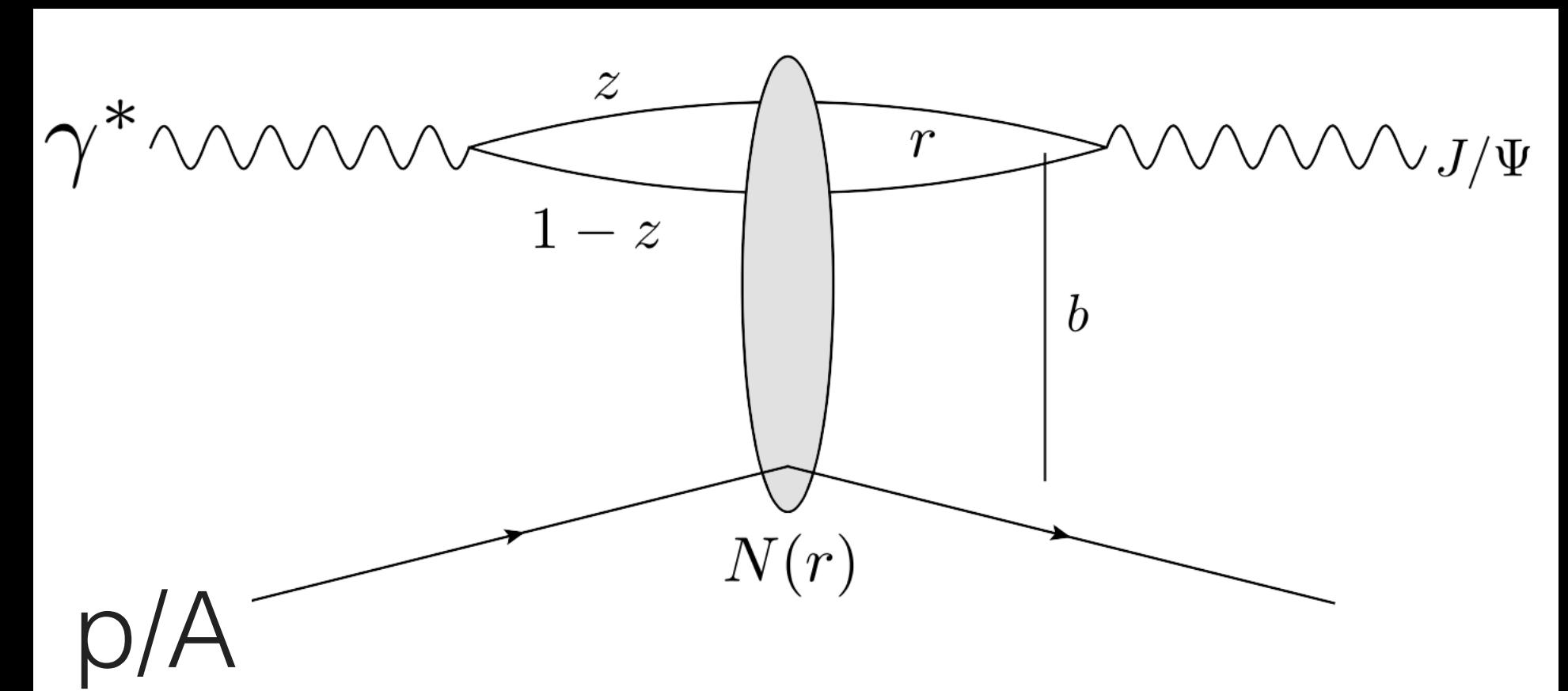
IMAGING NUCLEI AND NUCLEON SHAPES AT HIGH-ENERGY e^+ (P/A) COLLISIONS

CONSTRAIN FLUCTUATING PROTON/NUCLEI SHAPE

- Diffractive processes in $e+(p/A)$ collisions offer a precision tool to constrain the event-by-event configuration of proton shape

$$\mathcal{A} \sim \int d^2b dz d^2r \Psi^* \Psi^V(r, Q^2, z) e^{-ib \cdot \Delta} N(r, x, b, \Omega)$$

- Dipole amplitude $N_\Omega = 1 - \exp[-r^2 F(x, r) T_{p/A}^\Omega(b)]$; $T_{p/A}^\Omega(b)$ encodes proton/nucleus's shape



Coherent processes:

Proton stays intact

$$\sigma_{\text{coherent}} \sim |\langle \mathcal{A} \rangle_\Omega|^2$$

Probes the average shape

Incoherent processes:

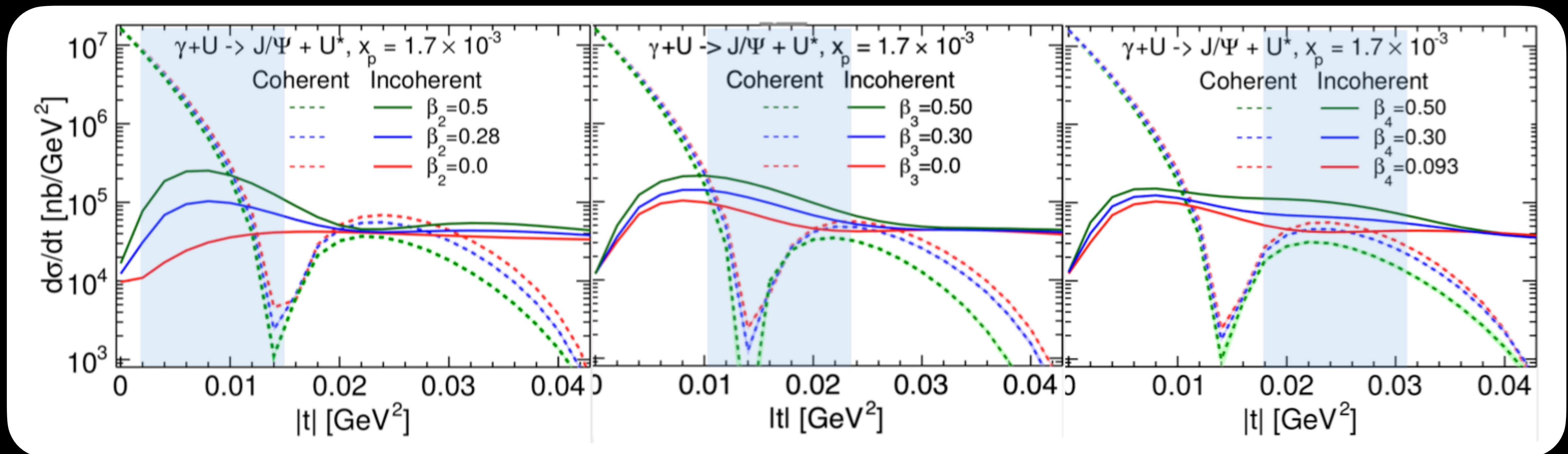
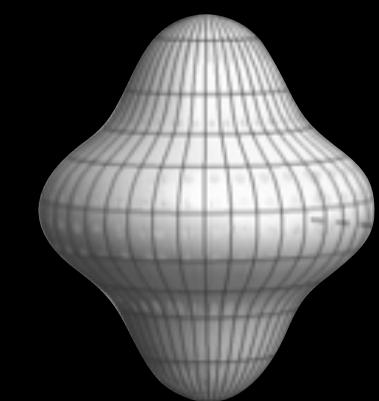
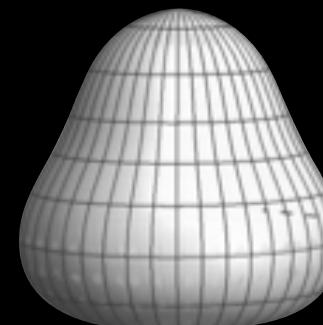
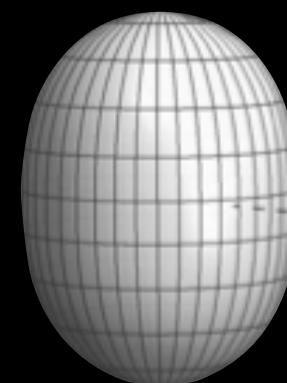
Proton breaks apart

$$\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle_\Omega - |\langle \mathcal{A} \rangle_\Omega|^2$$

Probes the variance of event-by-event fluctuations in proton structure

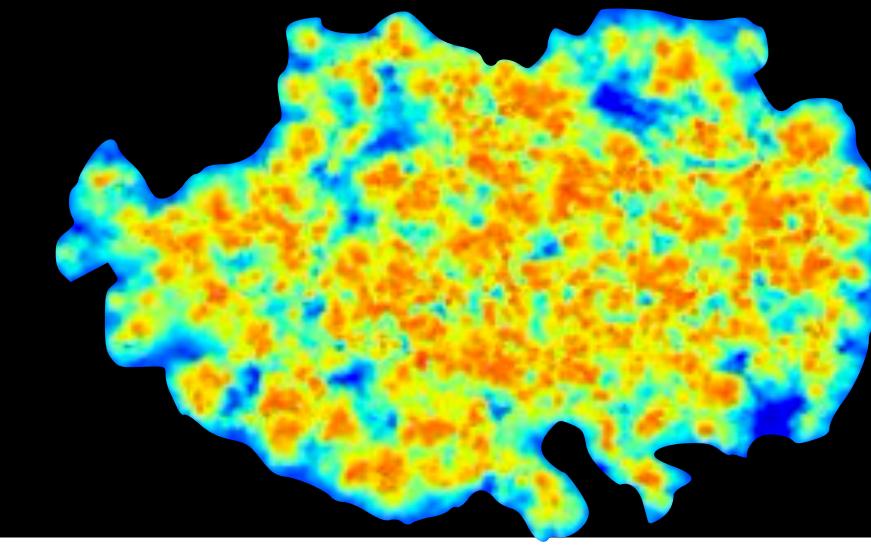
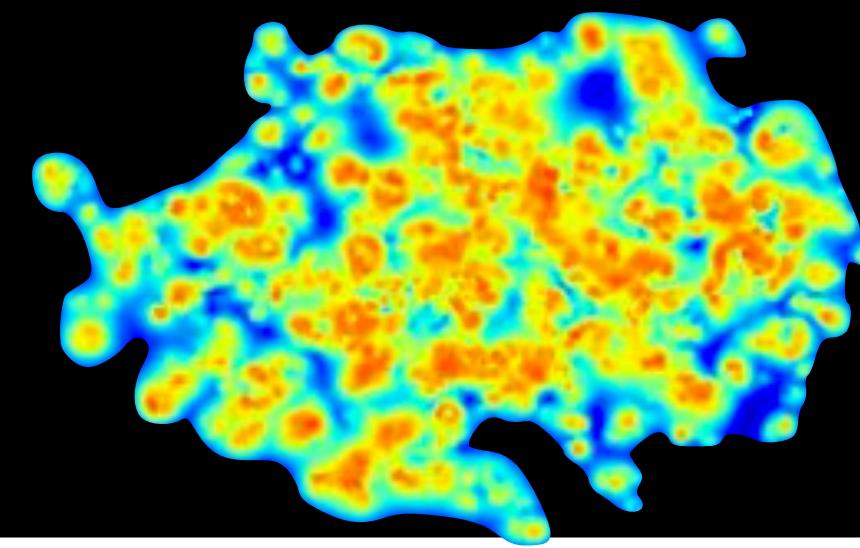
EFFECTS OF DEFORMATION ON DIFFRACTIVE CROSS SECTION

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, arXiv:2303.04866 [nucl-th]

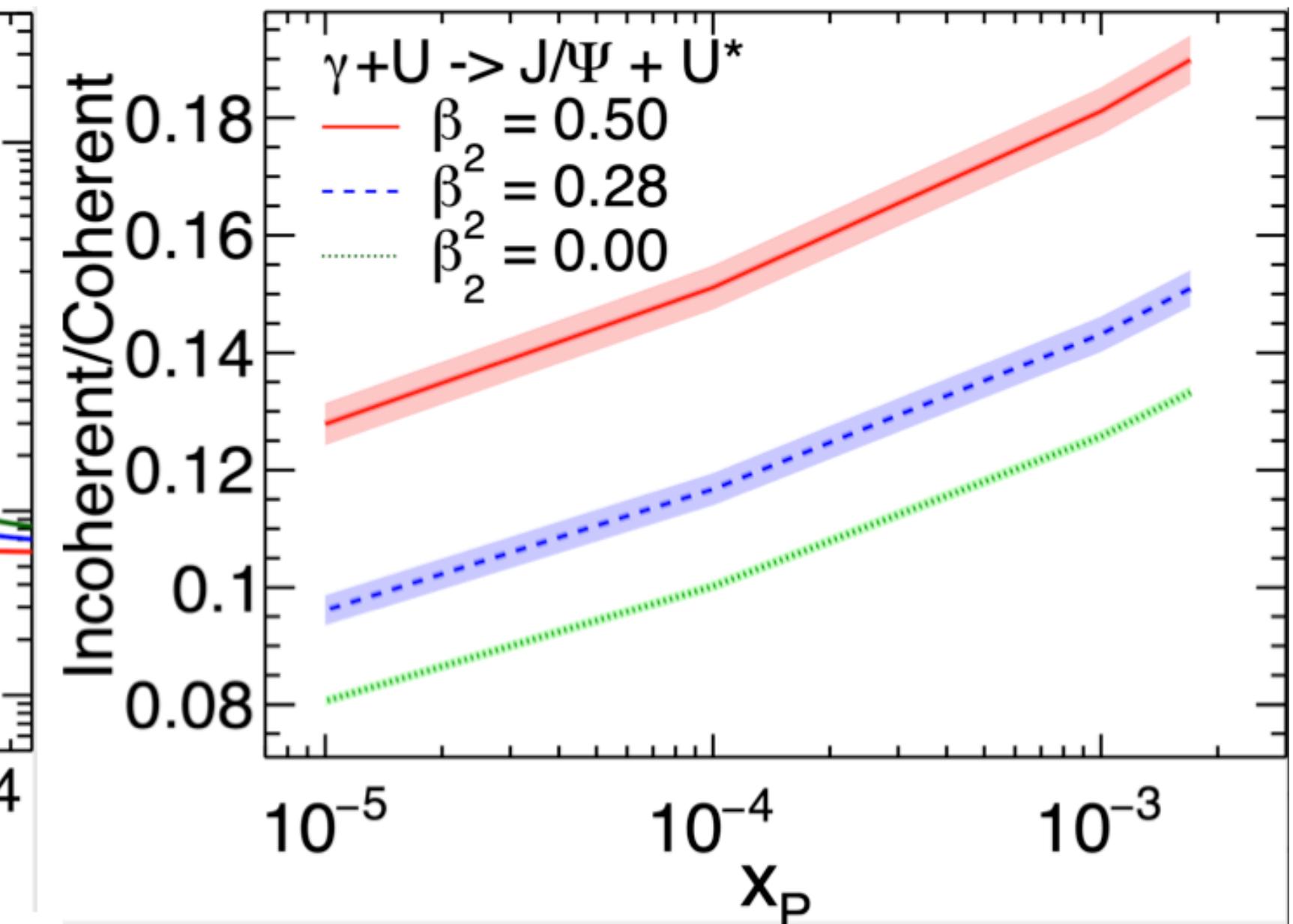
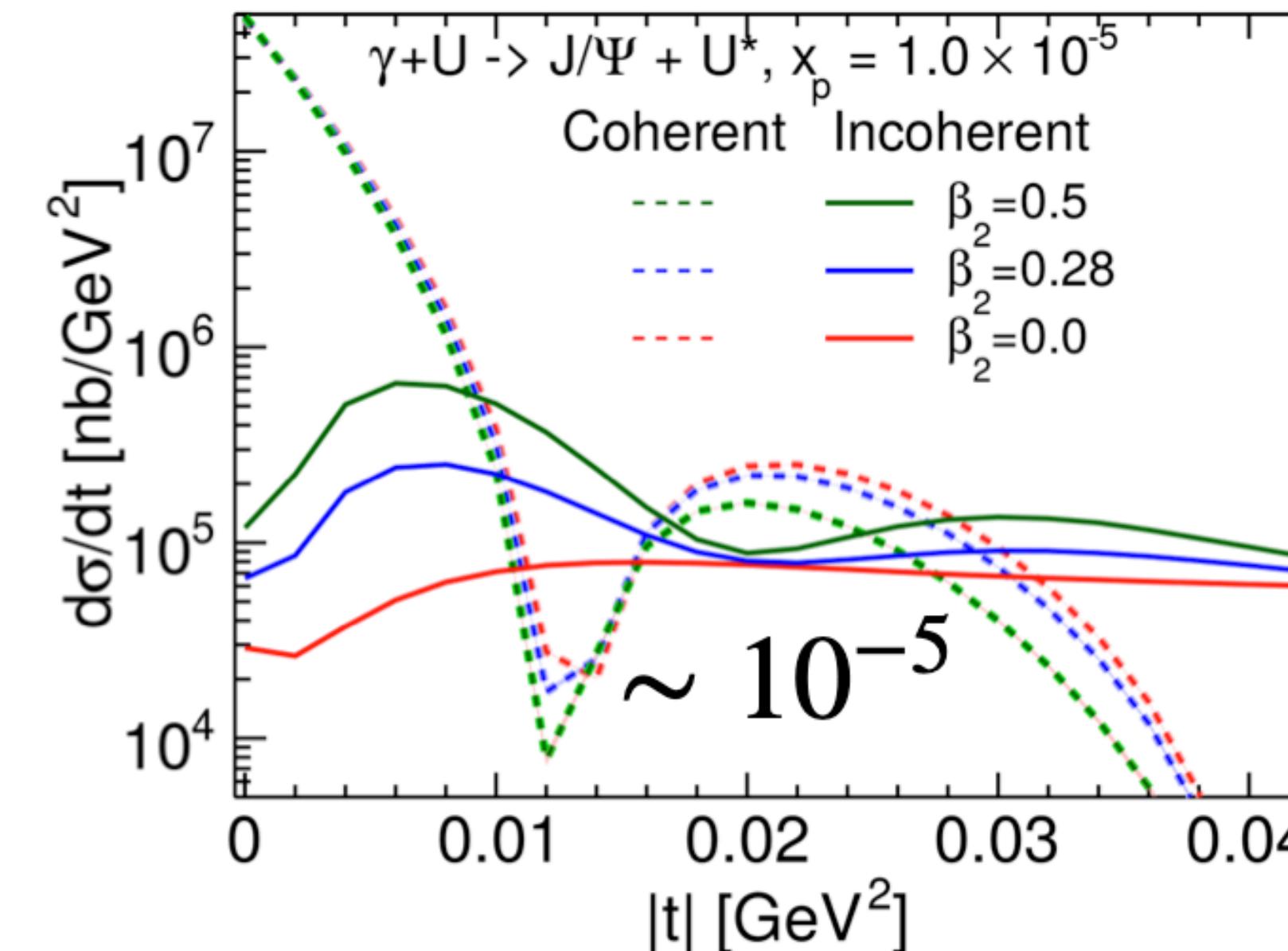
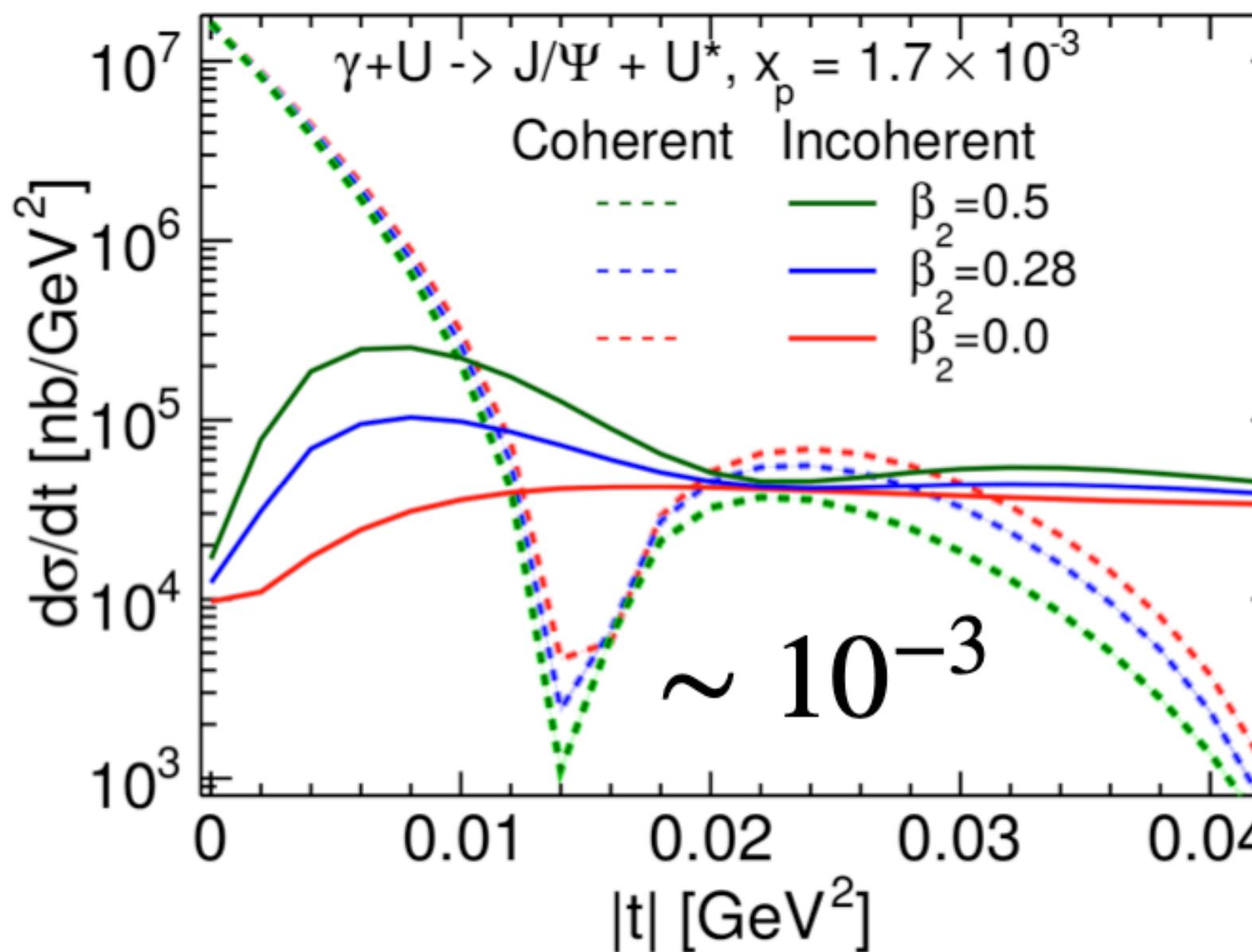


- The β_2 , β_3 , and β_4 modify fluctuations at different length scales (different $|t|$ regions in the incoherent spectra); They do not affect the average size of the nucleus (first minimum of coherent cross-section)

NUCLEAR DEFORMATION SURVIVE AT HIGH ENERGY



H. Mantysaari, B. Schenke, C. Shen and W. Zhao,
arXiv:2303.04866 [nucl-th]



- Both coherent and incoherent cross section grows for smaller x
- Because fluctuations are reduced, the incoherent/coherent ratio decreases
- Effects of deformation **remain** qualitatively the same at small x

SUMMARY

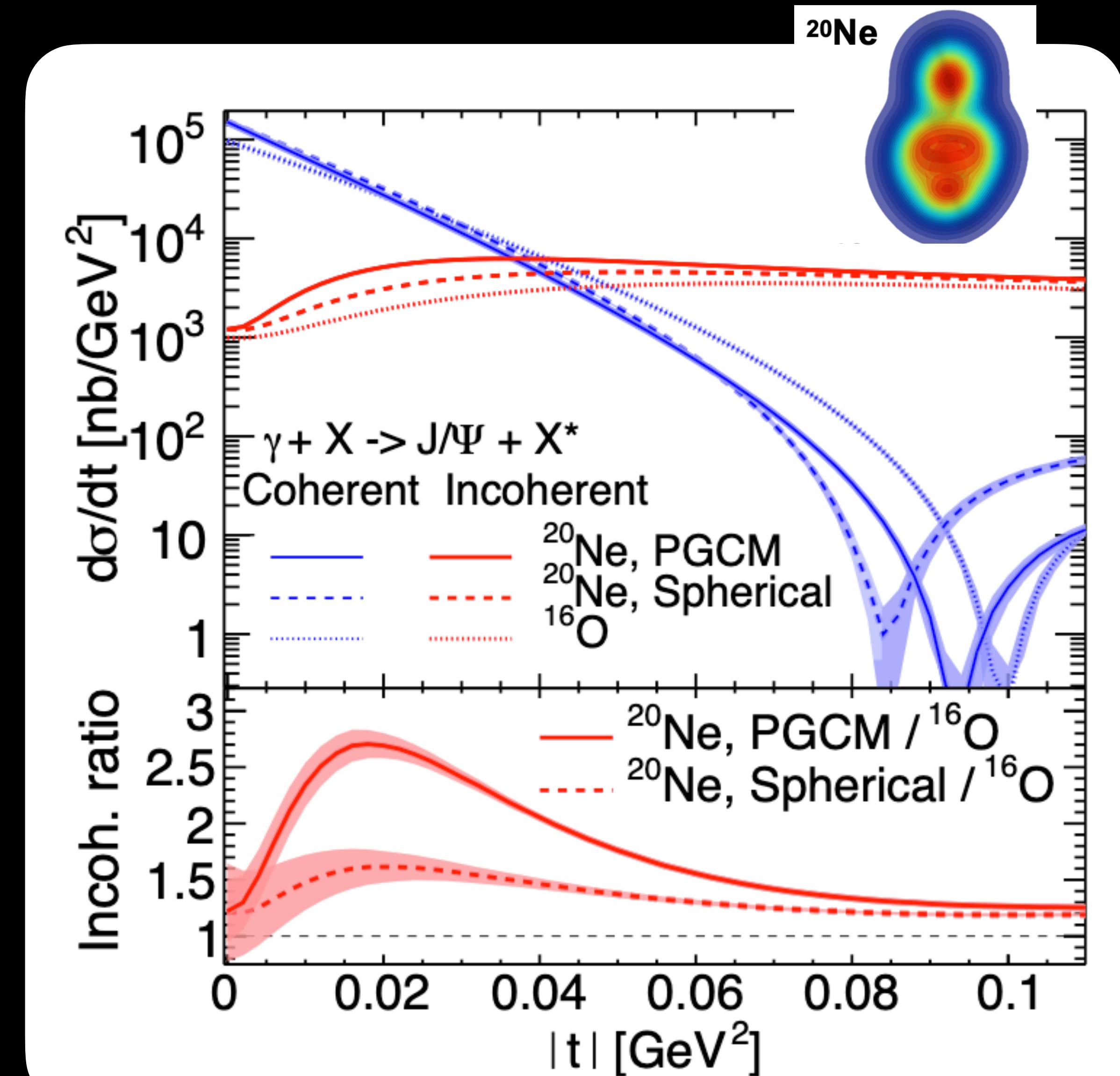
- As relativistic heavy-ion physics enters a **precision era**, the structure of nuclei and nucleons provide crucial inputs for characterizing the QGP properties with experimental measurements
- **Rapidity dependence** of observables can unravel the system's longitudinal dynamics and small-x evolution in the initial states
- Full (3+1)D hybrid simulations are essential to make quantitative comparisons for the asymmetric **light+heavy collisions** — a new way to infer the nuclear shape of light ions at high energy
- Diffractive processes in e+p/nucleus collisions **image the target's geometric shape** at multiple scales — nuclear structure plays an important role in the current UPC and future EIC physics



DEFORMATION IN LIGHT NUCLEI: NEON VS OXYGEN

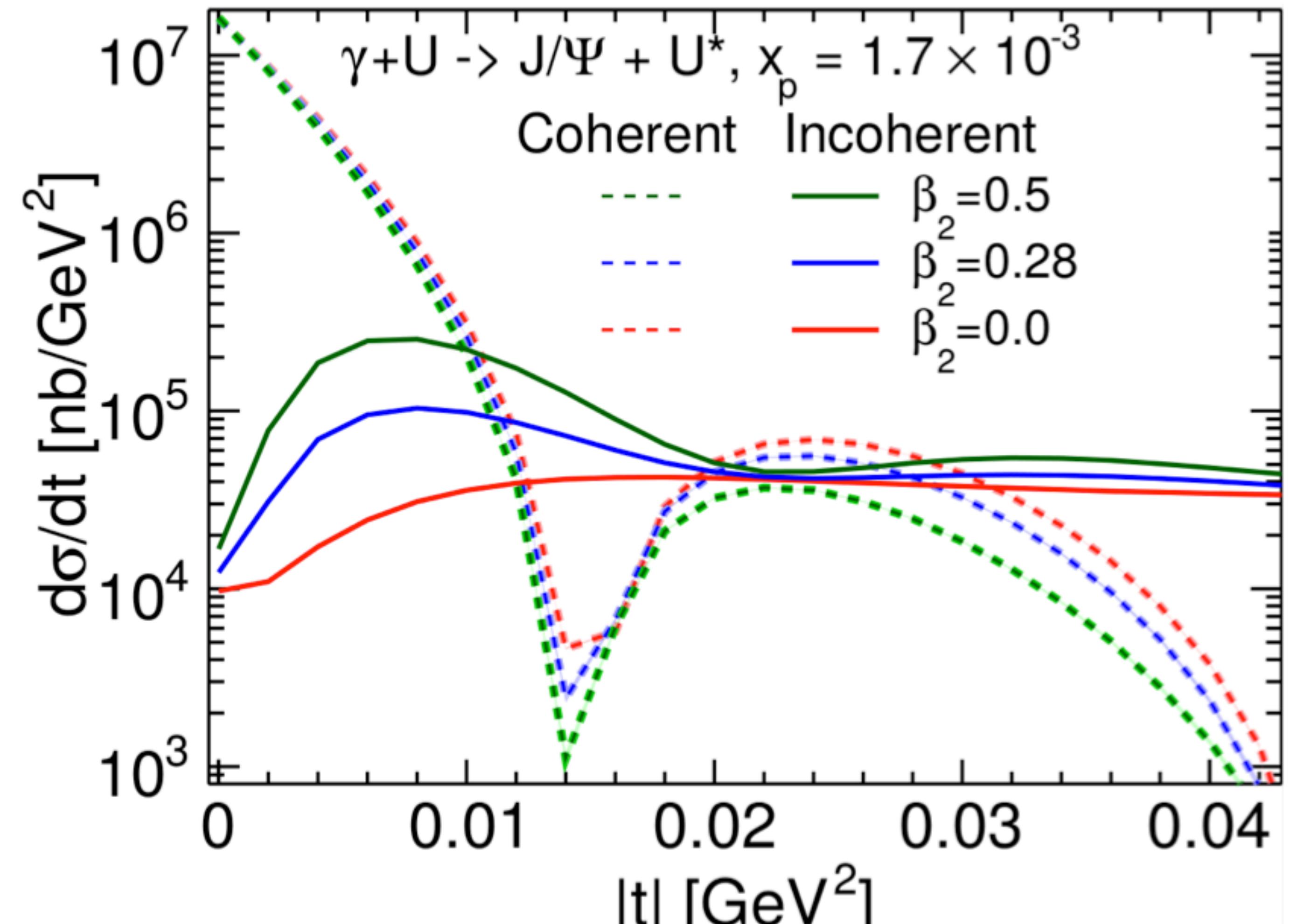
H. Mantysaari, B. Schenke, C. Shen and W. Zhao, arXiv:2303.04866 [nucl-th]

- Incoherent cross section at small $|t|$ (enhanced by 67%) captures the deformation of ^{20}Ne
- Significant difference between ^{20}Ne and ^{16}O diffractive cross sections

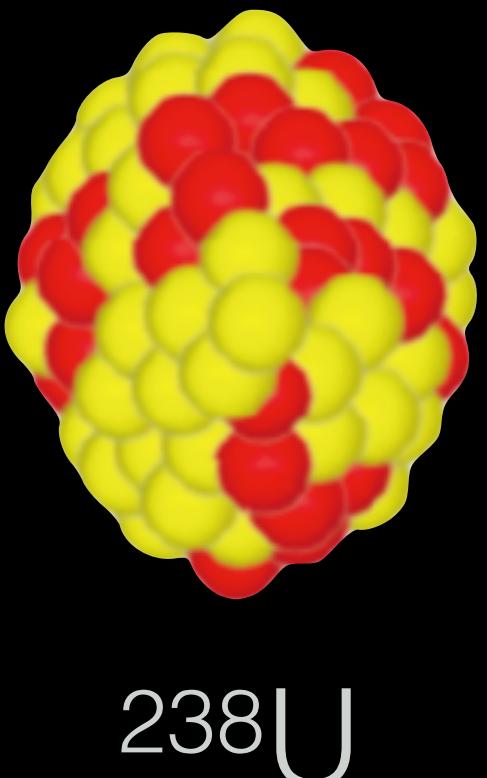


EFFECTS OF DEFORMATION ON DIFFRACTIVE CROSS SECTION

H. Mantysaari, B. Schenke, C. Shen and W. Zhao, arXiv:2303.04866 [nucl-th]



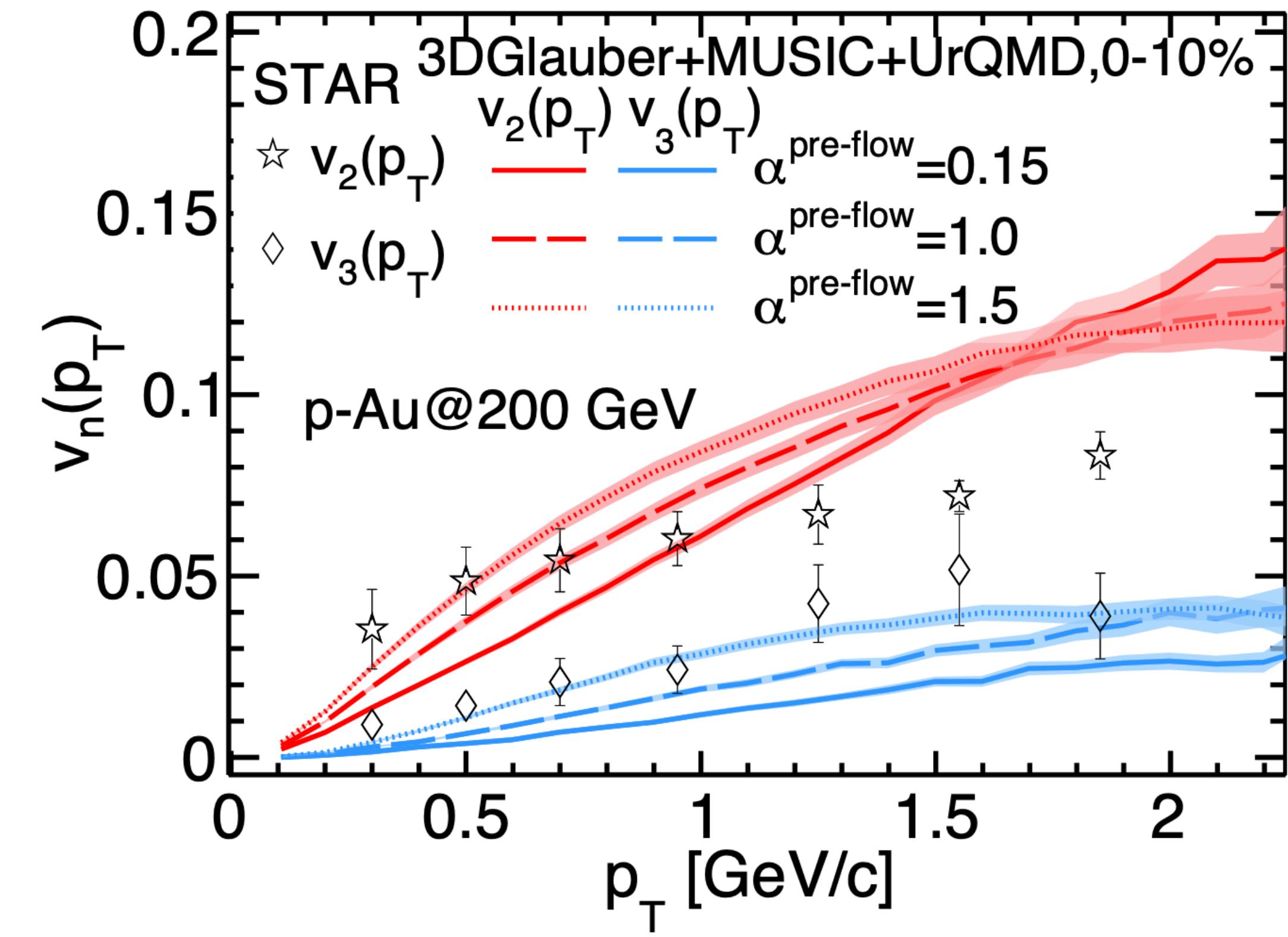
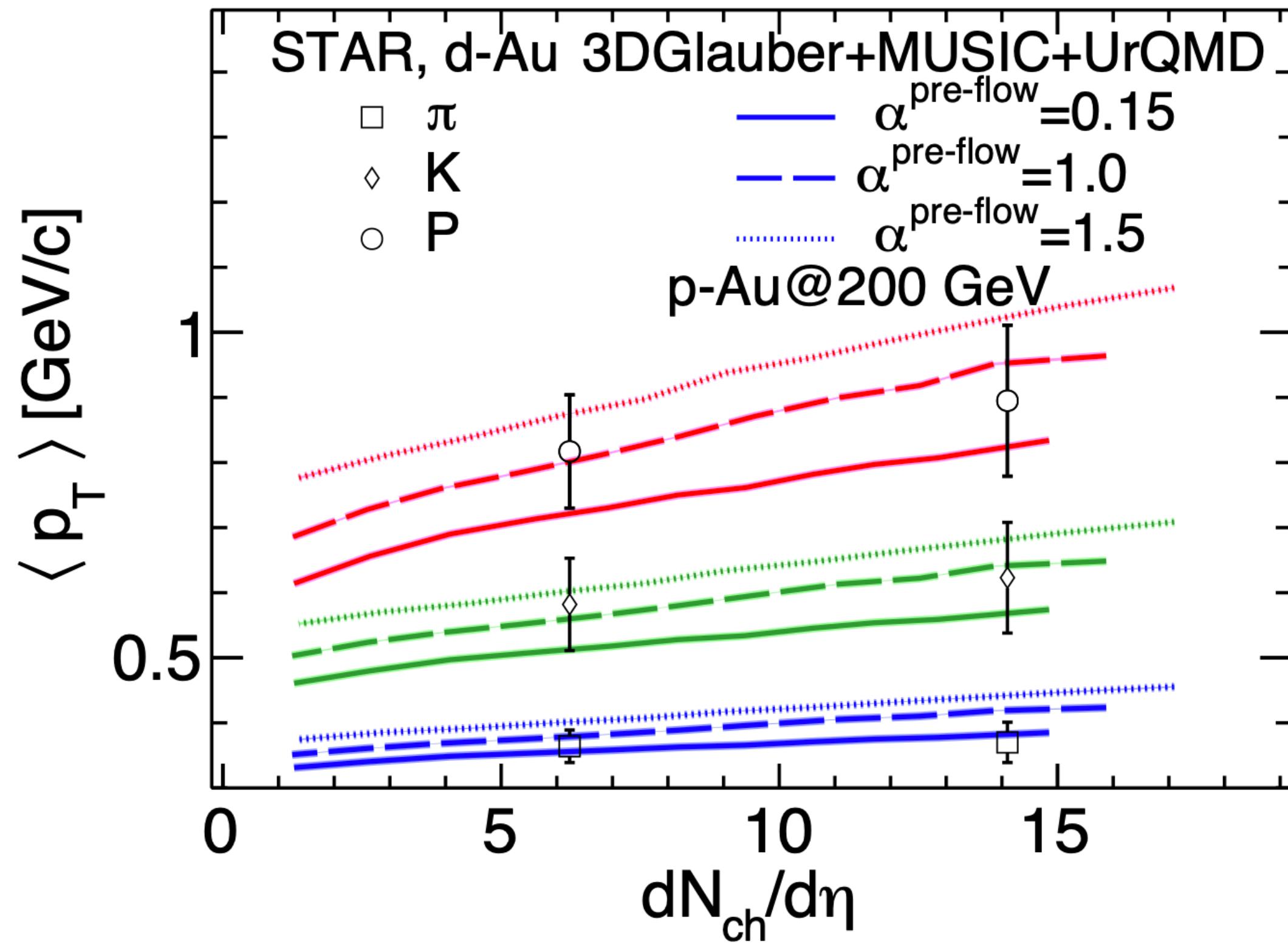
Nucleus deformation affects incoherent cross section at small $|t|$ (large length scales)



This observable provides direct information on small x structure

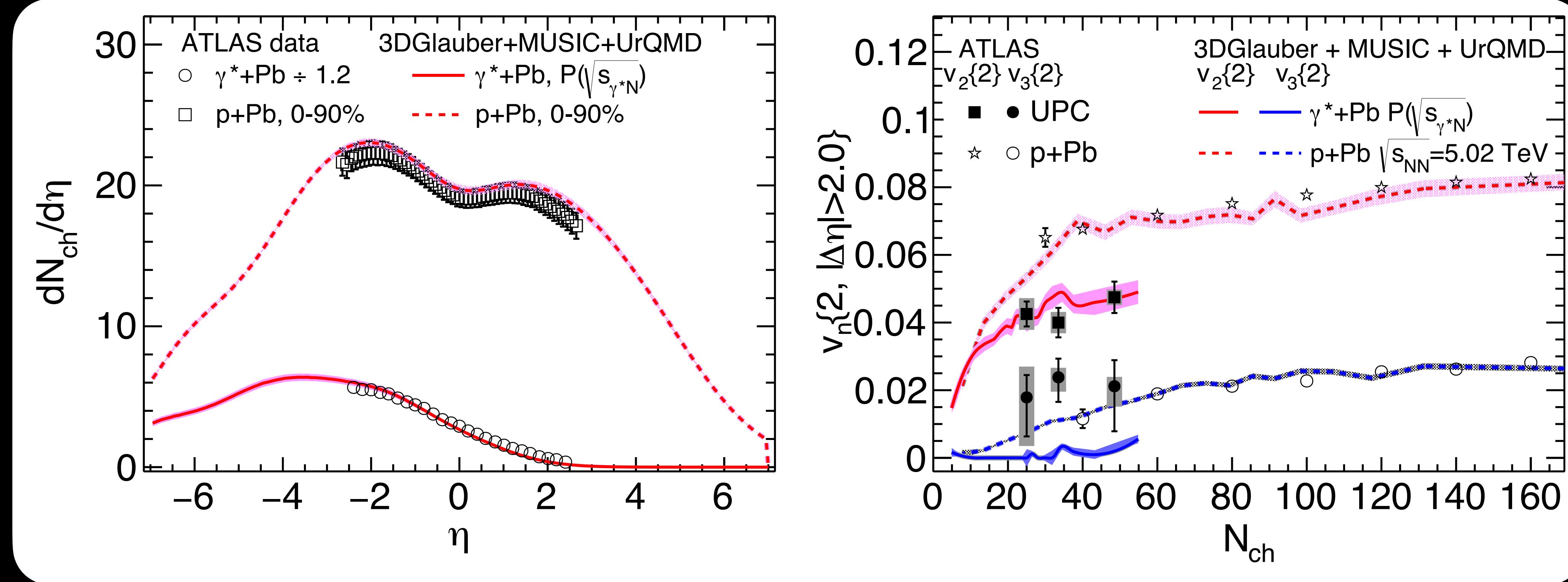
EFFECTS OF PRE-EQUILIBRIUM FLOW IN P+AU

W. Zhao, S. Ryu, C. Shen, and B. Schenke, Phys. Rev. C 107 014904 (2023)



PARTICLE PRODUCTION AND FLOW IN pA AND γA

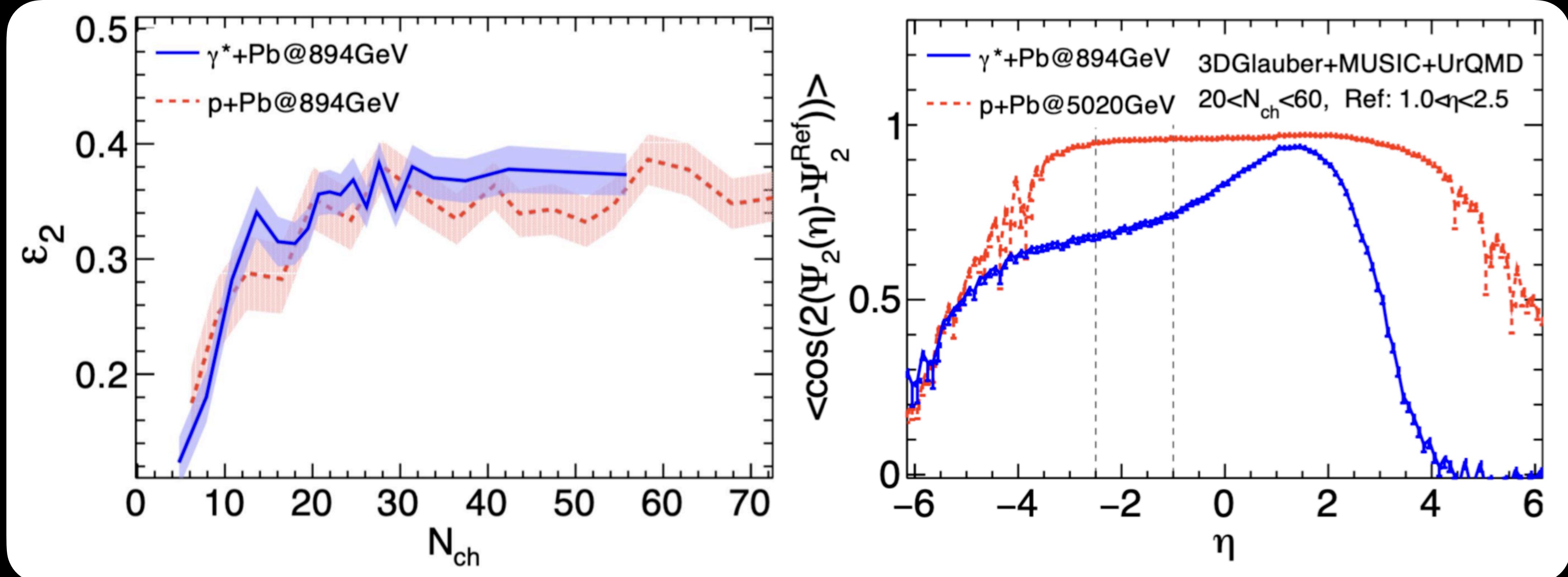
W. Zhao, C. Shen and B. Schenke, Phys. Rev. Lett. 129, 252302 (2022)



- Our model reproduces the shapes of $dN_{ch}/d\eta$ for $p+Pb$ and γ^*+Pb collisions
- The elliptical flow hierarchy between $p+Pb$ and γ^*+Pb collisions are reproduced by the different amount of longitudinal flow decorrelations

UNDERSTAND THE ν_2 HIERARCHY BETWEEN pA AND γ^*A

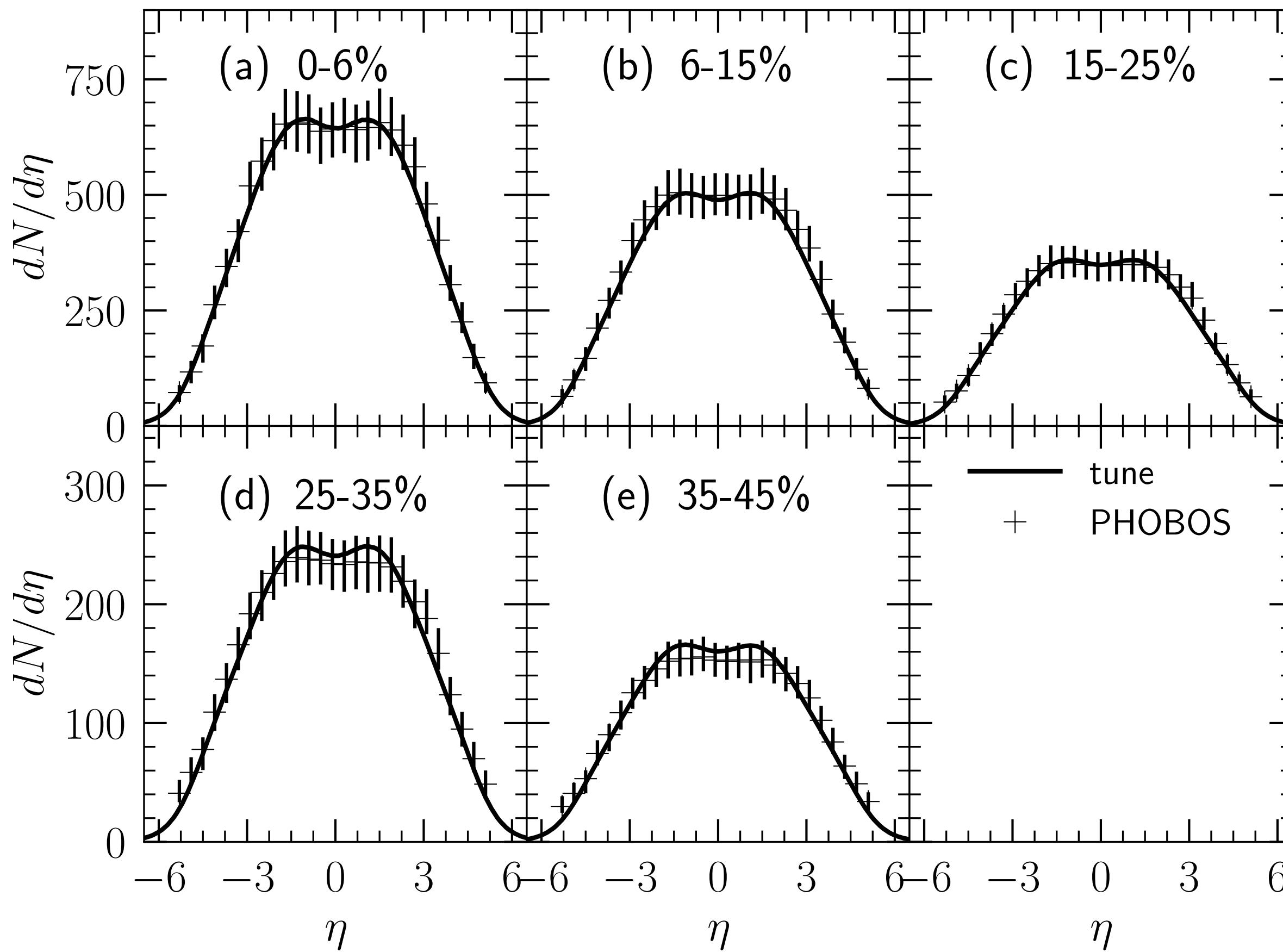
W. Zhao, C. Shen and B. Schenke, arXiv:2203.06094 [nucl-th]



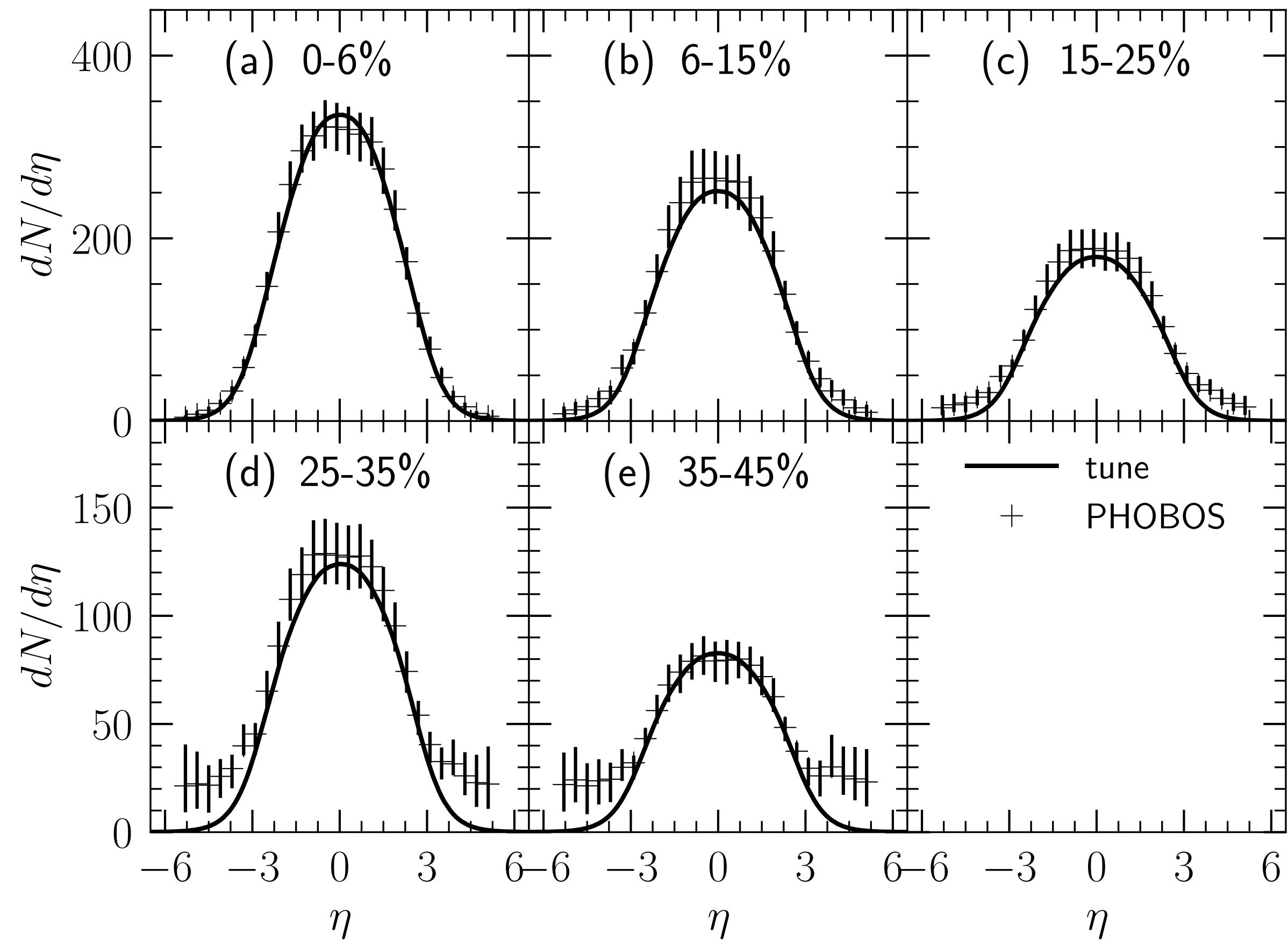
- Initial eccentricities are comparable between $p+Pb$ and γ^*+Pb systems
- The lower $\sqrt{s_{\gamma N}}$ leads to a larger event-plane decorrelation and results in smaller $\nu_2\{2\}$ than that in $p+Pb$ collisions at the same N_{ch}

PARTICLE PRODUCTION IN AA COLLISIONS

Au+Au @ 200 GeV

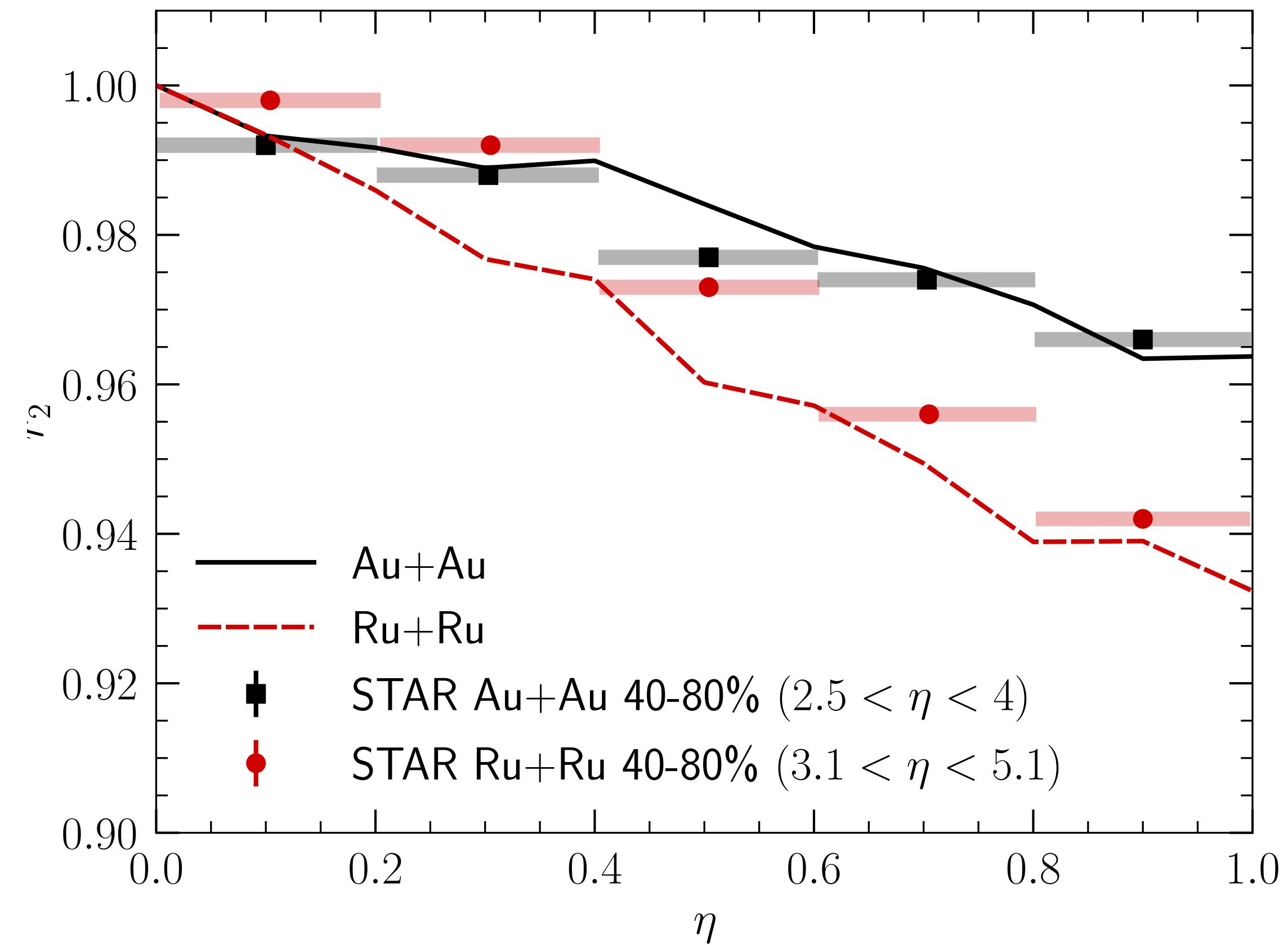
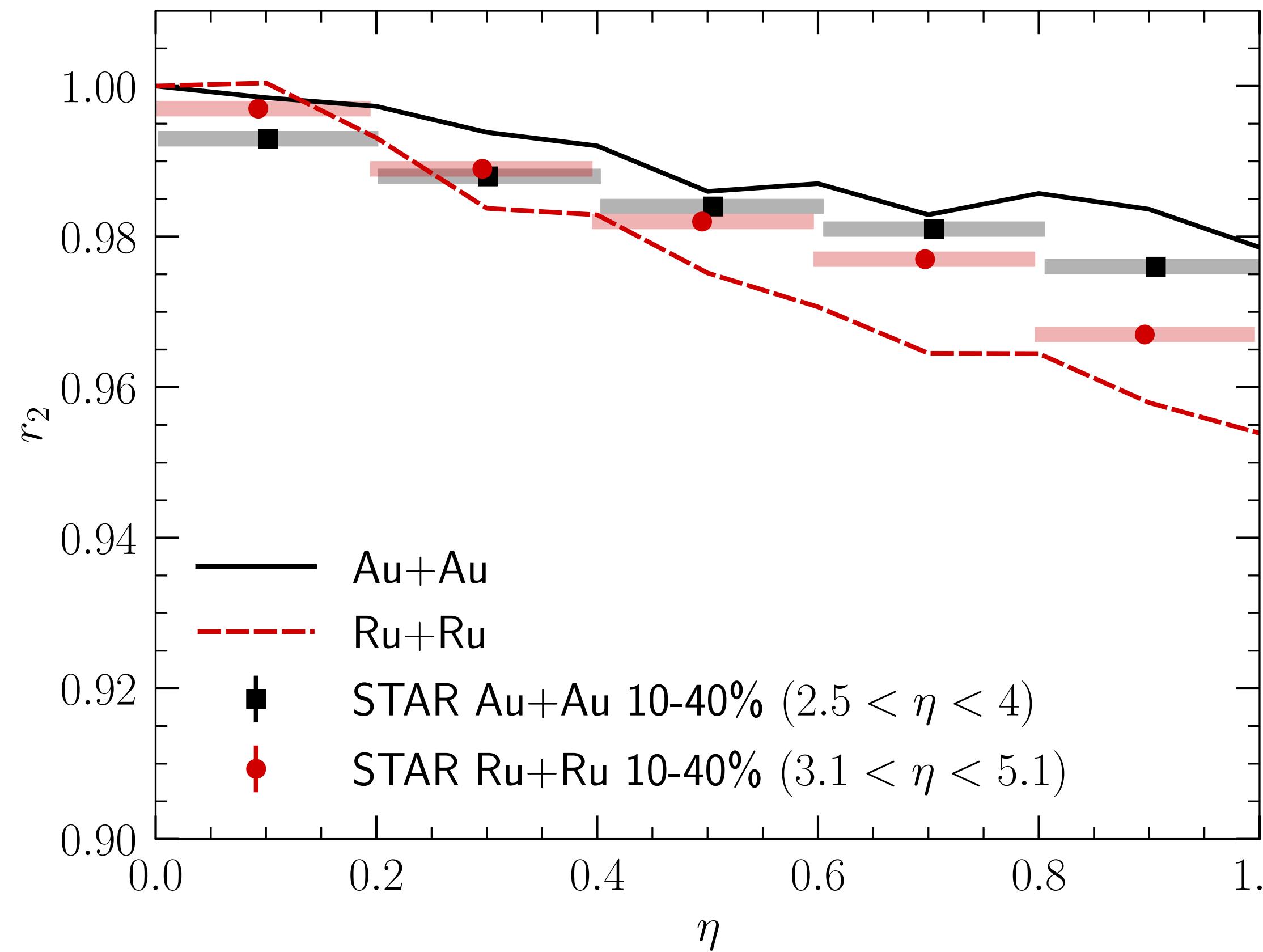


Au+Au @ 19.6 GeV



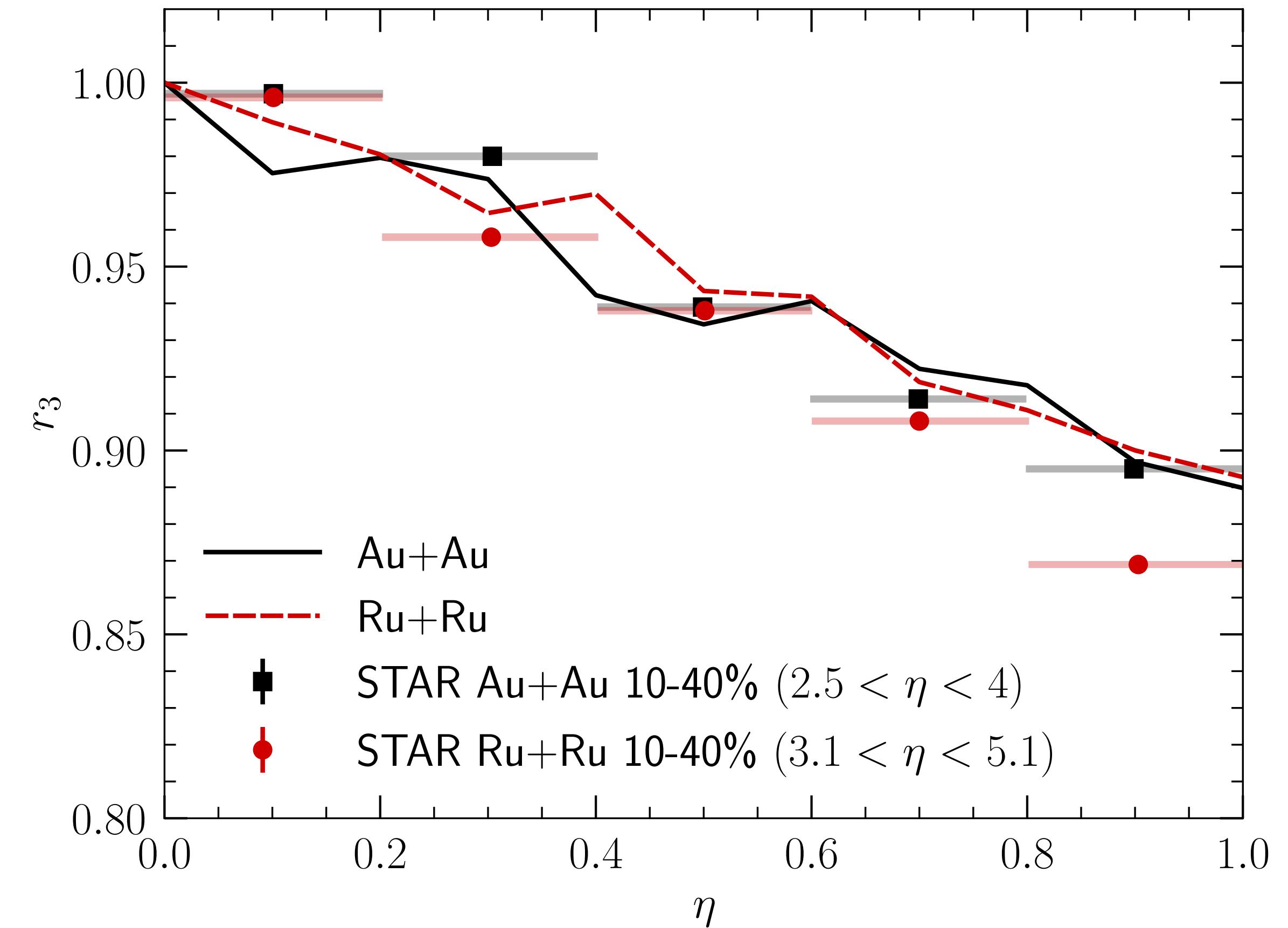
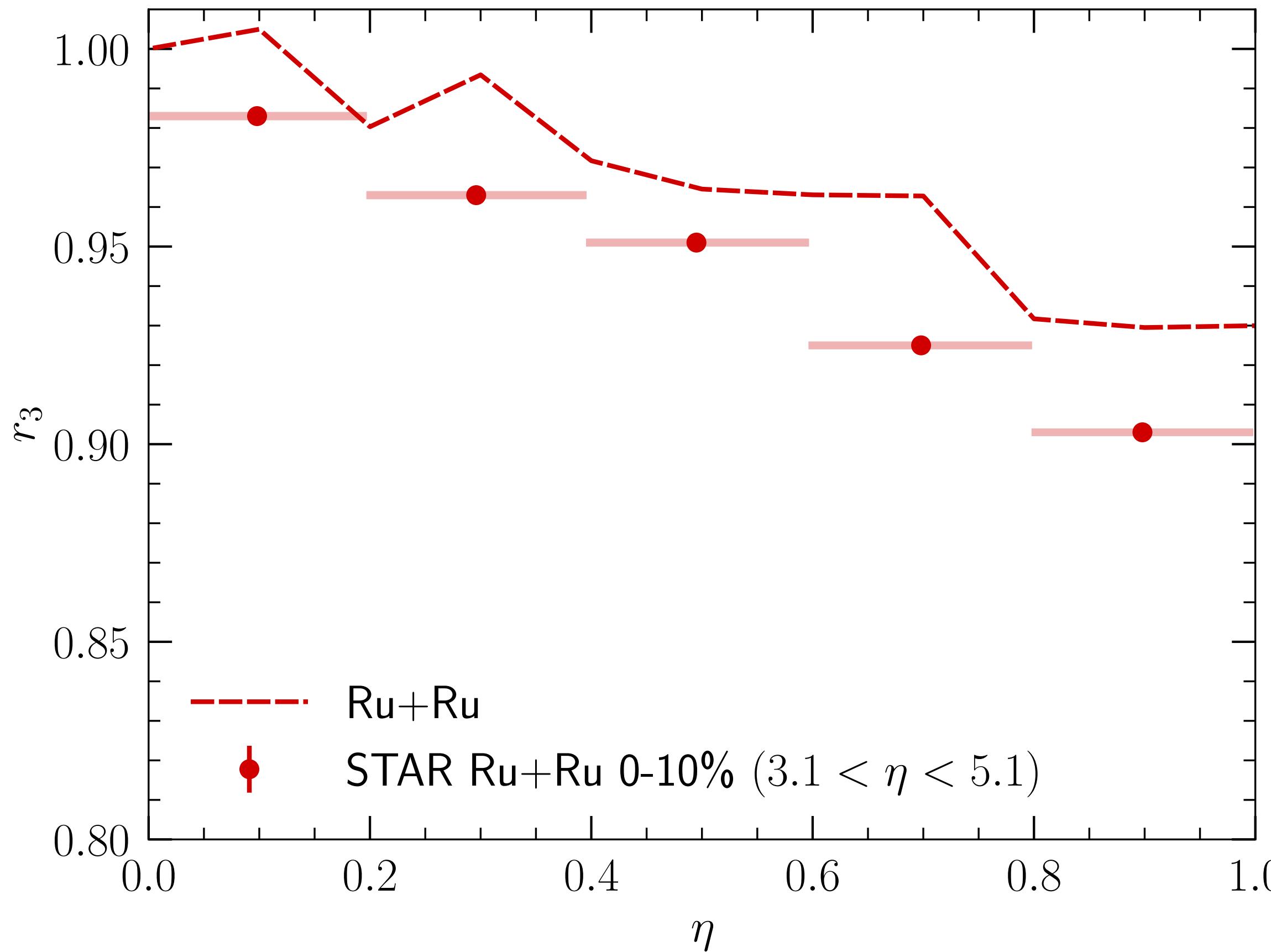
- Extension to AA collisions gives a reasonable description of the PHOBOS data

SYSTEM SIZE DEPENDENCE OF r_n



- The smaller Ru+Ru collisions have larger flow decorrelation with those in Au+Au collisions

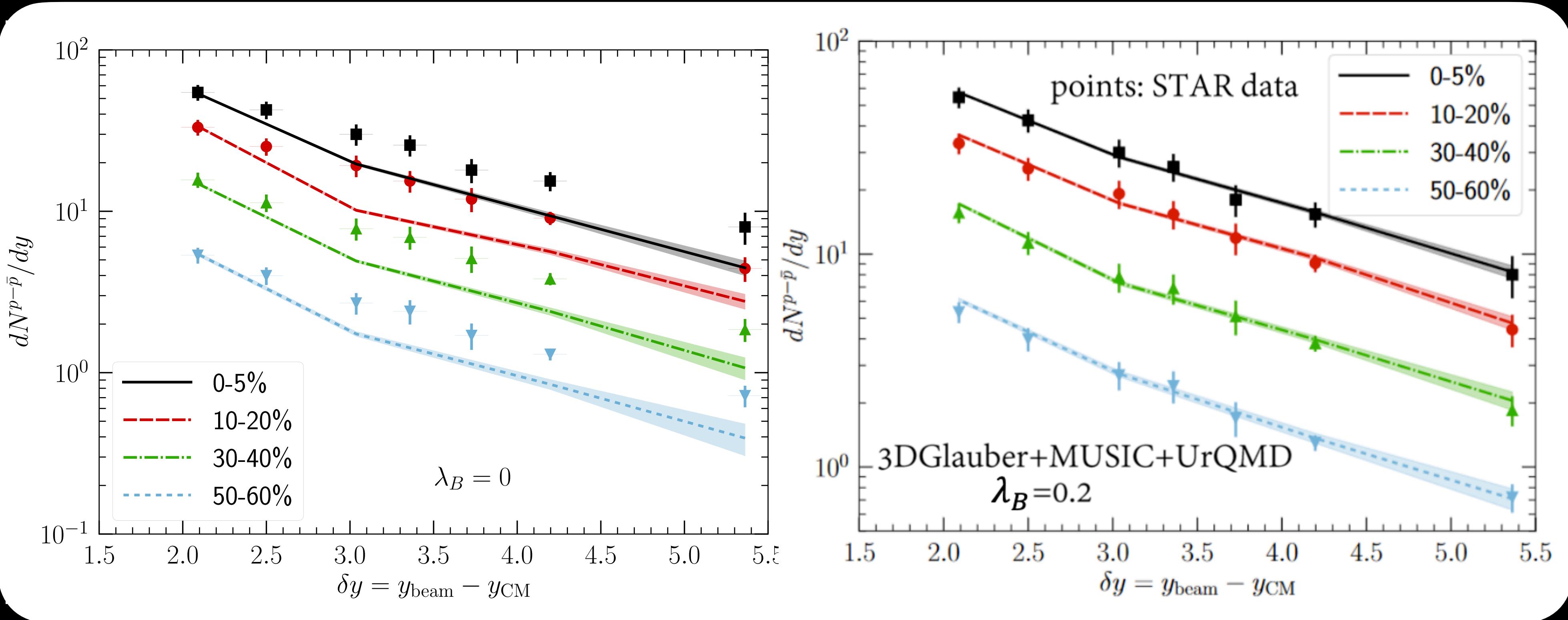
SYSTEM SIZE DEPENDENCE OF r_n



- Our model underestimated the r_3 compared to the STAR measurements

CALIBRATE BARYON JUNCTION IN AA COLLISIONS

C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)

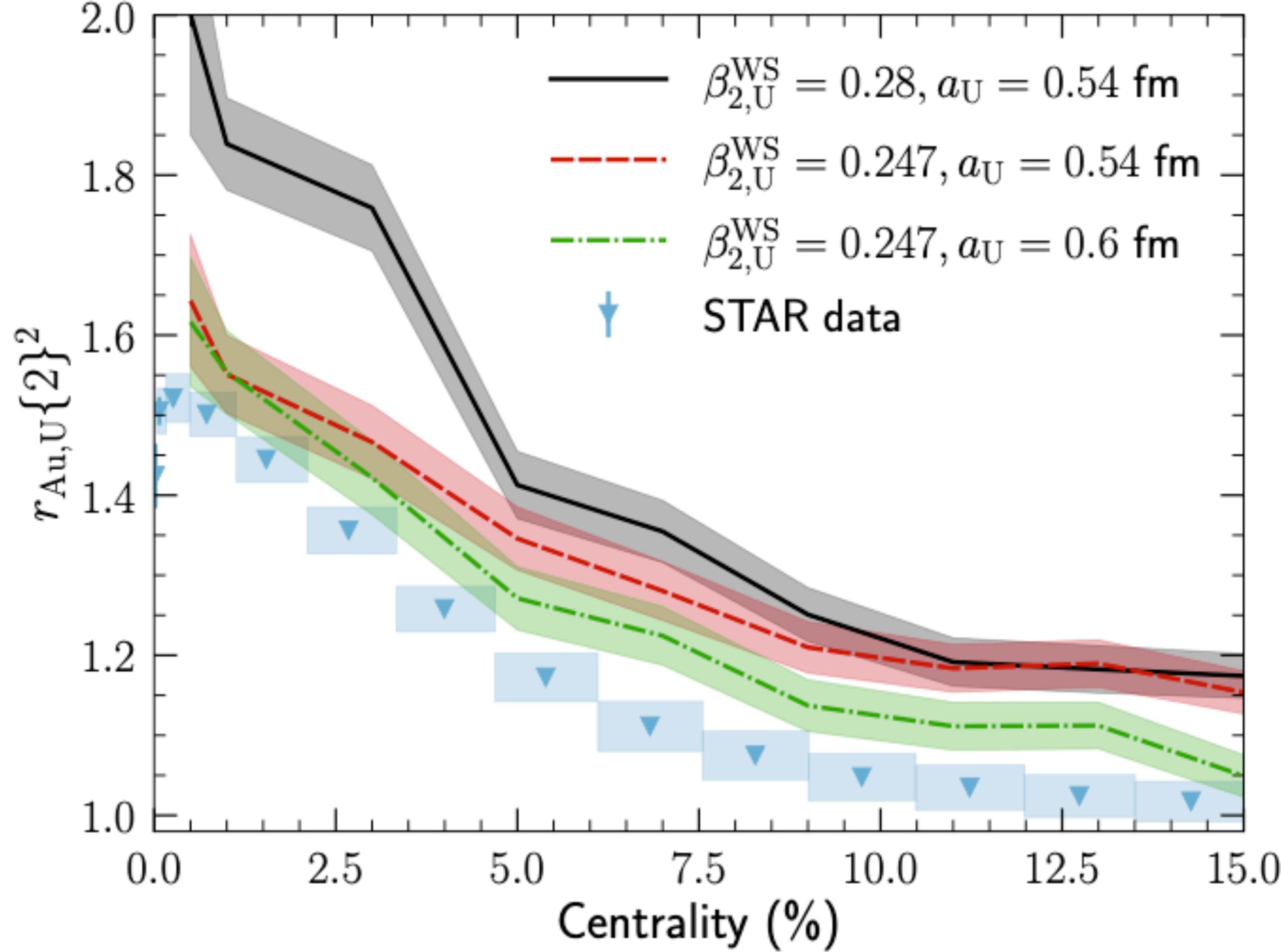


$$P(y_{P/T}^B) = (1 - \lambda_B)y_{P/T} + \frac{e^{(y_{P/T}^B - (y_P + y_T)/2)/2}}{\lambda_B 4 \sinh((y_P - y_T)/4)}$$

- Au+Au collisions at RHIC BES energies prefer 20% of baryon charges ($\lambda_B = 0.2$) to fluctuate to the string junctions in the initial state

NUCLEAR STRUCTURE IS IMPORTANT

W. Ryssens, G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 130, 212302 (2023)



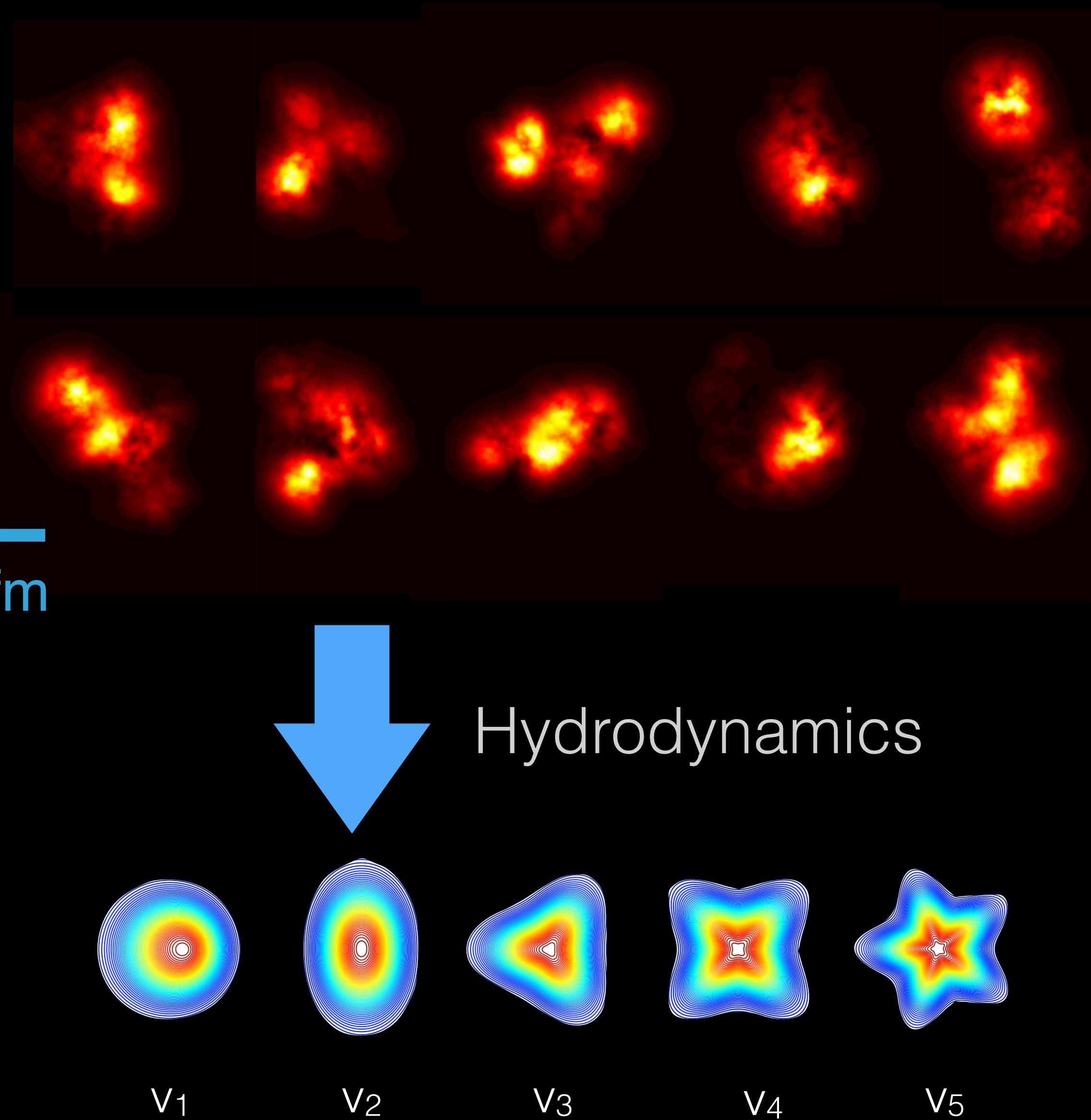
$$r_{Au,U}^2\{2\} = \frac{v_2^U\{2\}^2}{v_2^{Au}\{2\}^2}$$

The ratio of elliptic flow in central U+U and Au+Au favors $\beta_{2,U}^{WS} = 0.247$ over $\beta_{2,U}^{WS} = 0.28$

The ratio of elliptic flow in for semi-peripheral U+U and Au+Au is sensitive to the nuclei's skin

The structure of nuclei plays a crucial role in precision heavy-ion physics

SUB-NUCLEON STRUCTURE IN SMALL SYSTEMS



- Proton's sub-nucleonic structure is crucial to understand the collectivity in small collision systems

