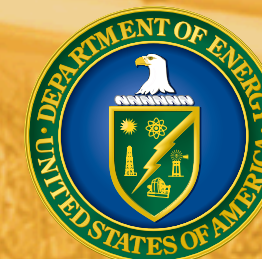


HYDRODYNAMICS IN SMALL SYSTEMS

Björn Schenke, Brookhaven National Laboratory

RHIC-AGS Users' Meeting
Brookhaven National Laboratory
May 21 2025



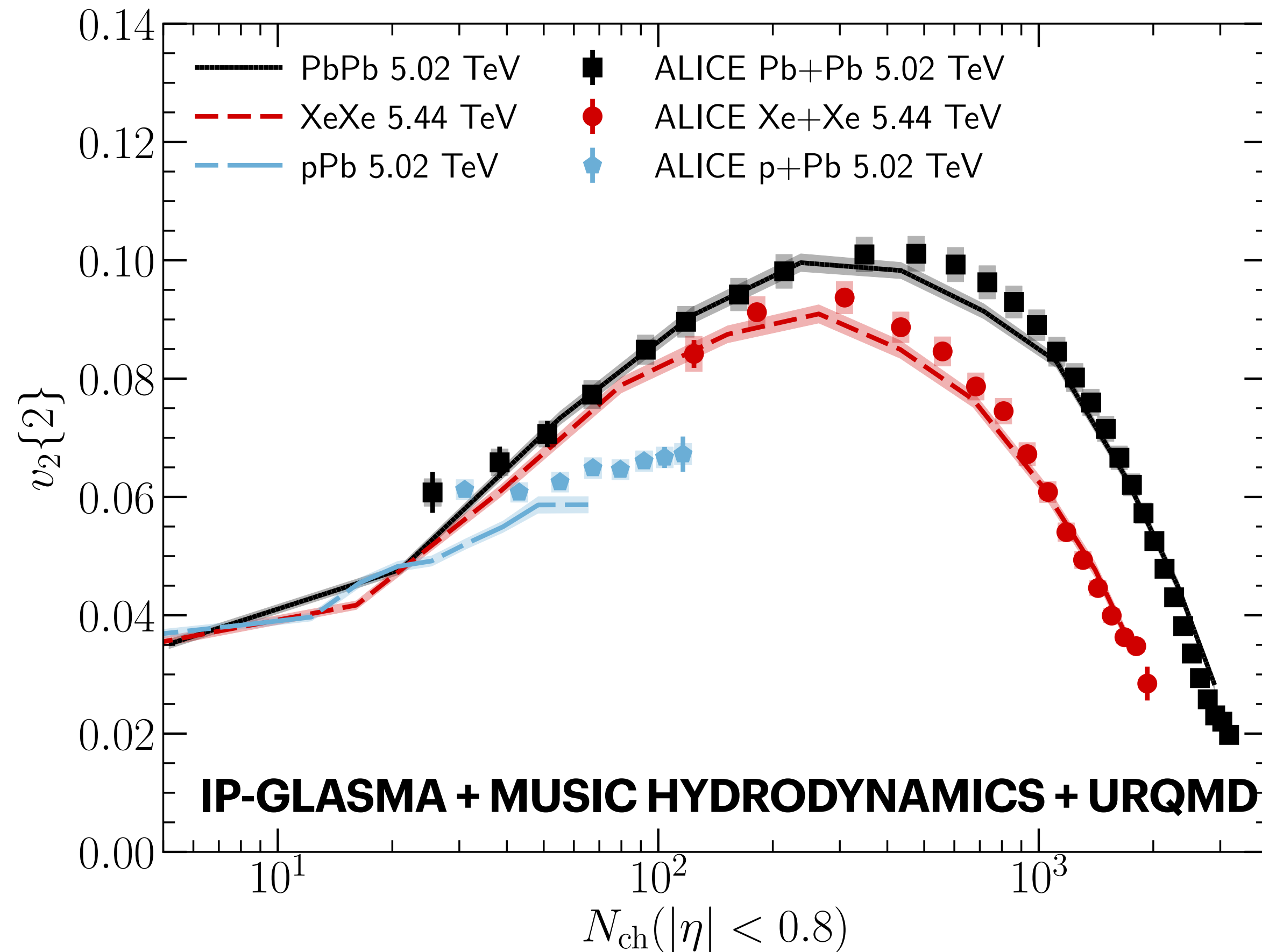
U.S. DEPARTMENT OF
ENERGY

Office of
Science



Brookhaven[™]
National Laboratory

FLOW IN SMALL SYSTEMS



Anisotropic flow in heavy ion collisions is driven by **final state response to the initial geometry**

There is evidence that the same is true in high multiplicity small systems

B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905
ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301

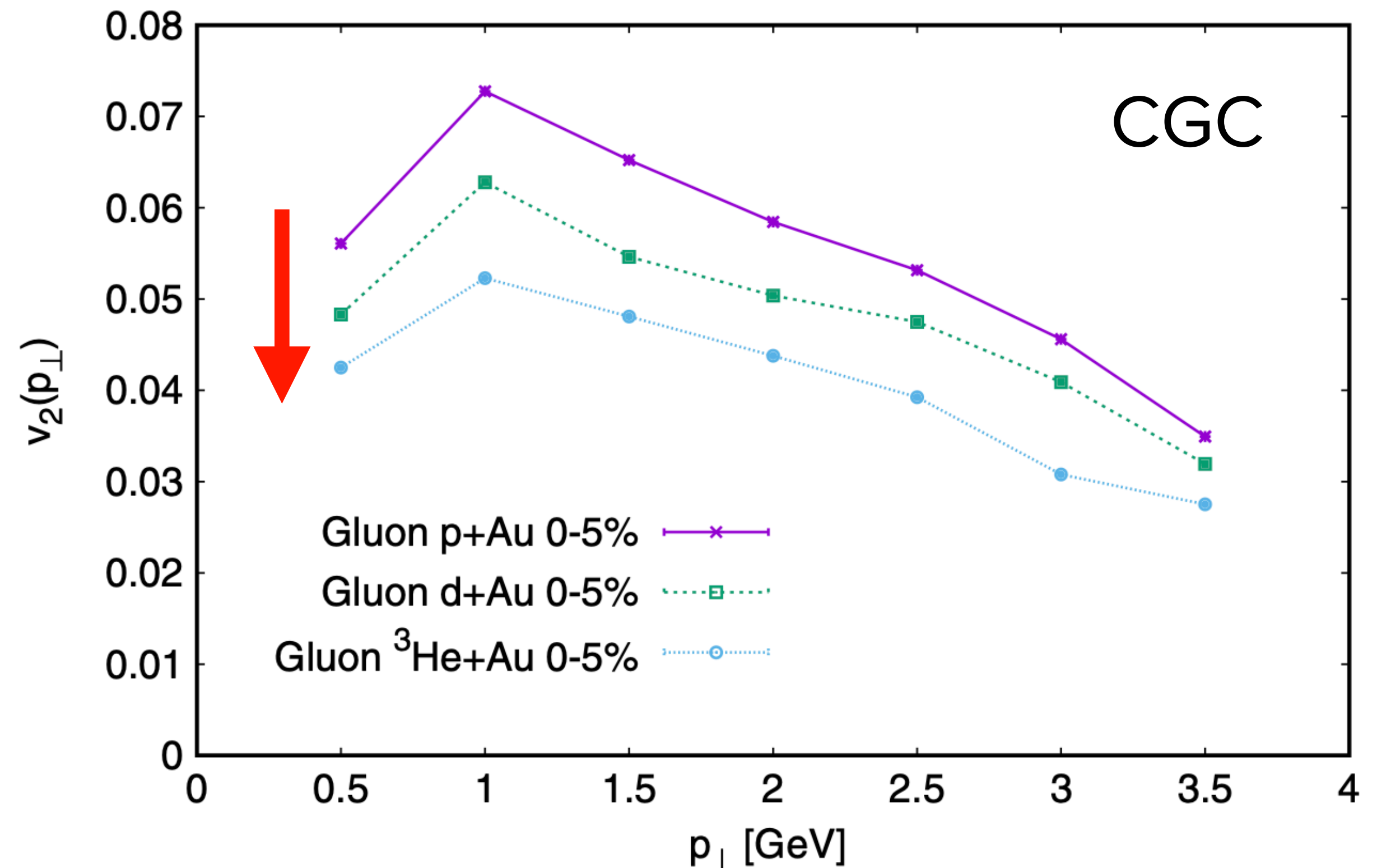
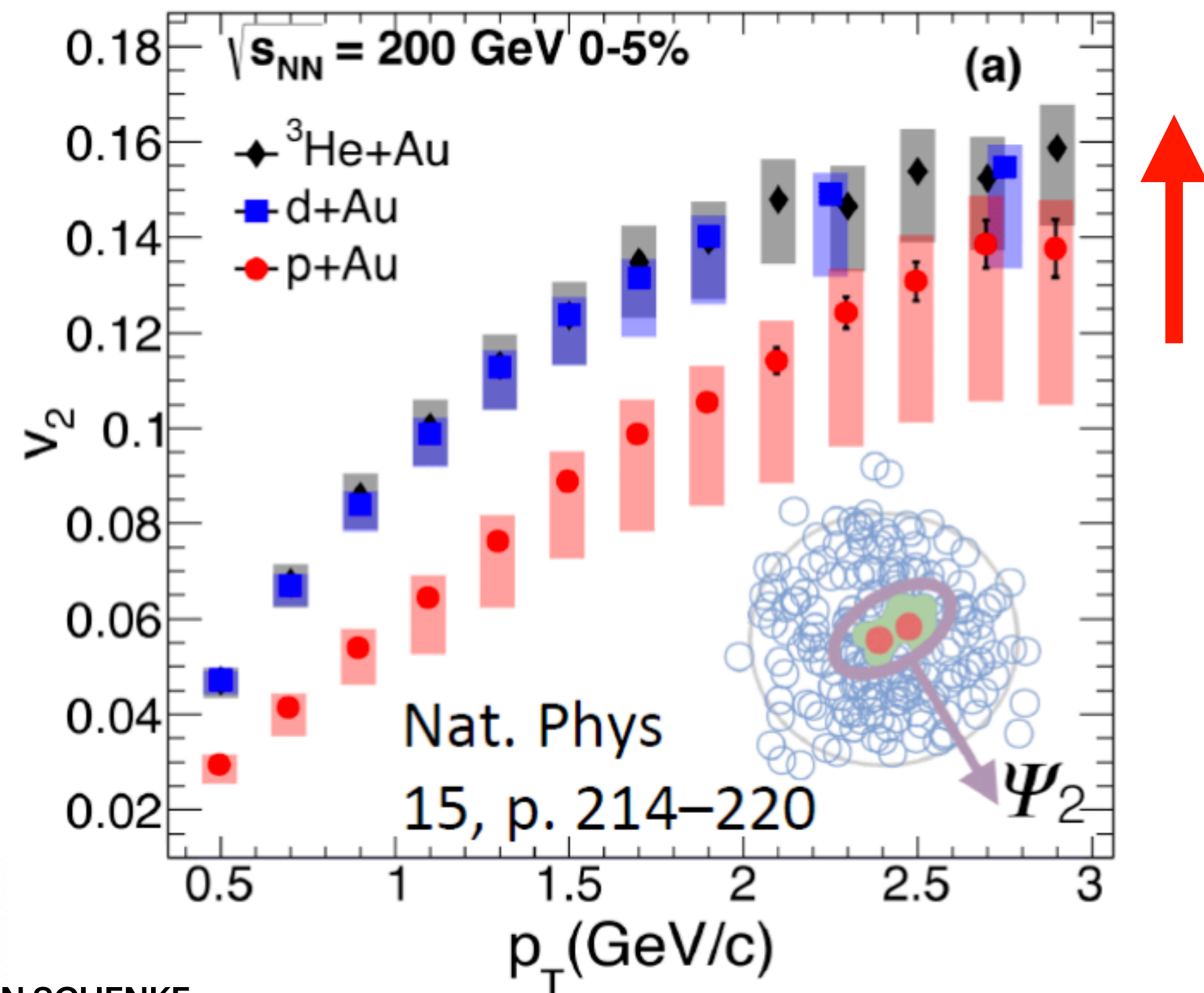
INITIAL STATE EFFECTS?

PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)

B. Schenke, S. Schlichting, R. Venugopalan, Phys.Lett.B 747 (2015) 76-82, 1502.01331

M. Mace, V. V. Skokov, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 121, 052301 (2018), PRL123, 039901(E) (2019)

Initial state momentum anisotropy, for example from the Color Glass Condensate:
Cannot get all systematics right:



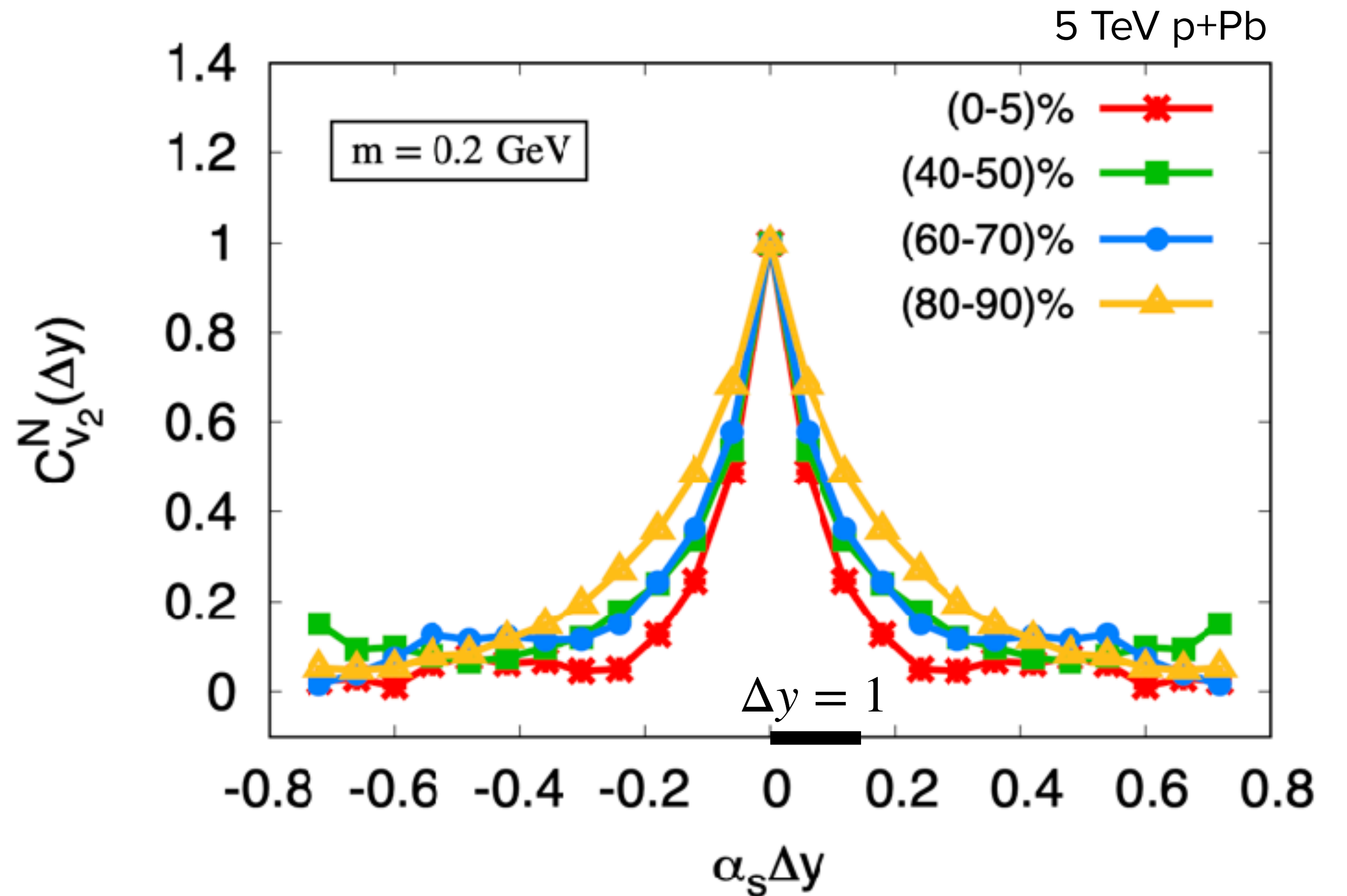
RAPIDITY DEPENDENCE OF INITIAL ANISOTROPY

B.Schenke, S. Schlichting, and Pragma Singh, Phys.Rev.D 105 (2022) 9, 094023

CGC based IP-Glasma
+ rapidity evolution (JIMWLK)

$$C_{\mathcal{O}}^N(\eta_1, \eta_2) = \frac{\langle \text{Re}(\mathcal{O}(\eta_1)\mathcal{O}^*(\eta_2)) \rangle}{\sqrt{\langle |\mathcal{O}(\eta_1)|^2 \rangle \langle |\mathcal{O}(\eta_2)|^2 \rangle}}$$

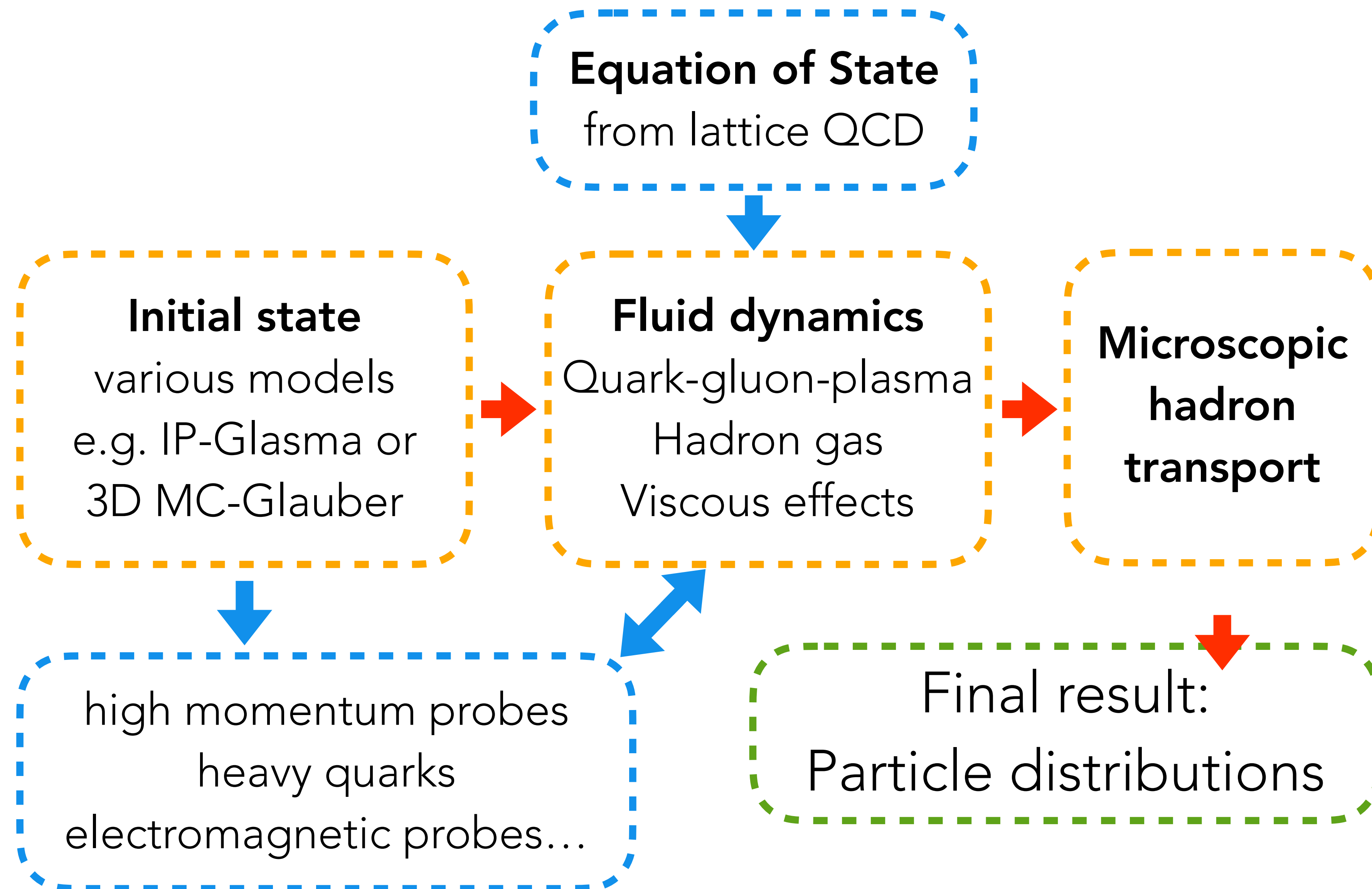
Initial momentum anisotropy
decorrelates quickly
with rapidity difference



further evidence: Observed Baryon/meson v_2 grouping and splitting

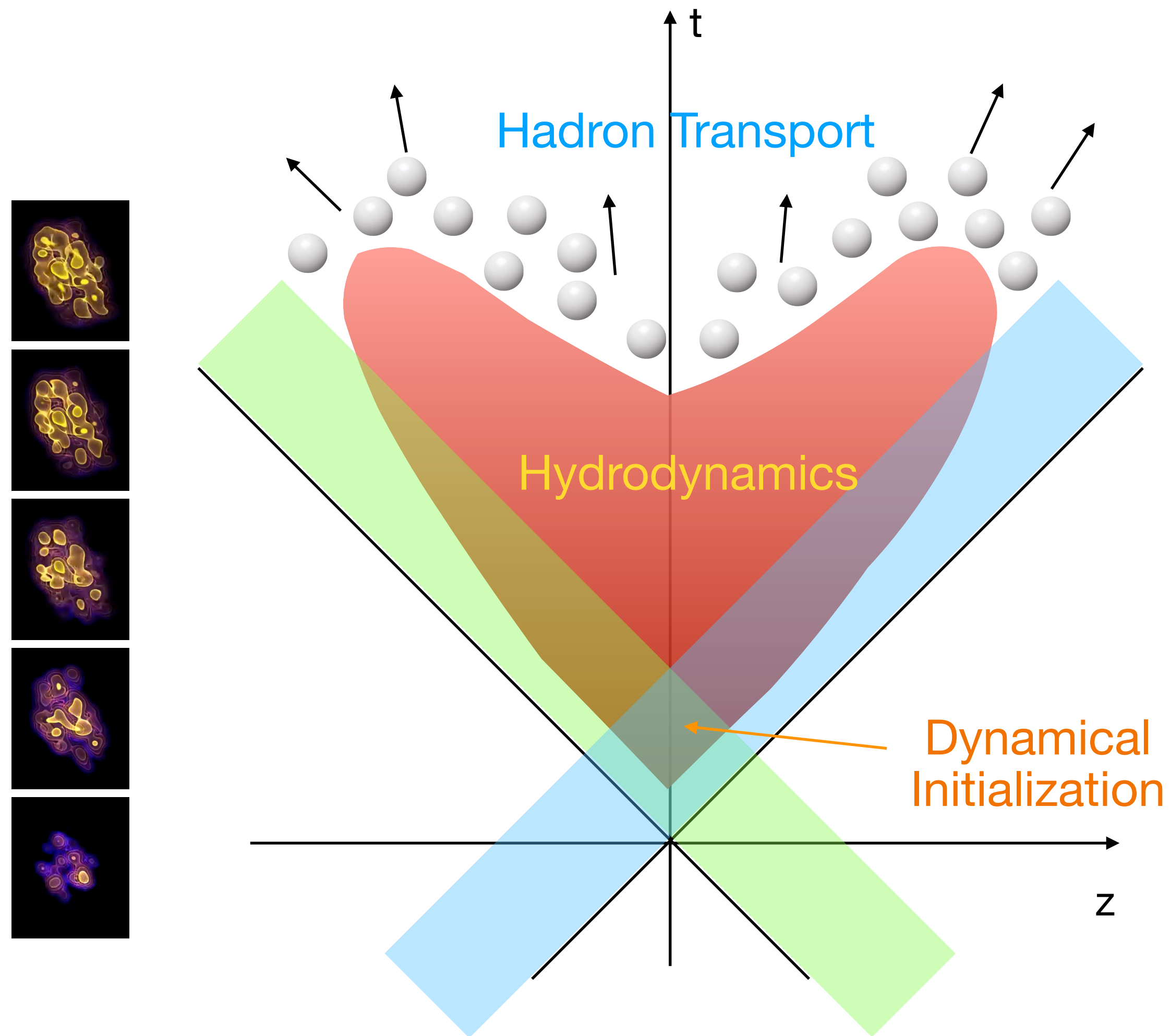
→ **Strong final state interactions needed to describe data**

GENERAL SIMULATION FRAMEWORK

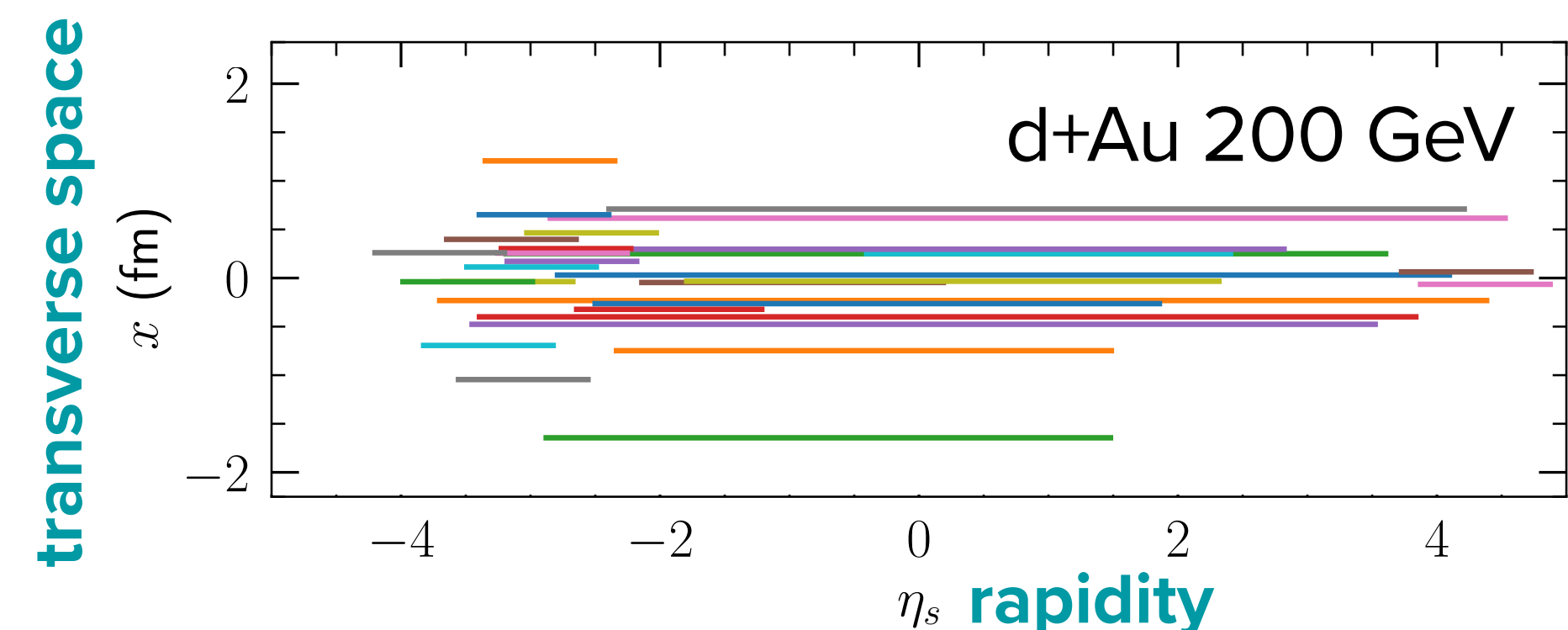


DYNAMIC 3+1D SIMULATION

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907; Phys. Rev. C 105, 064905 (2022)

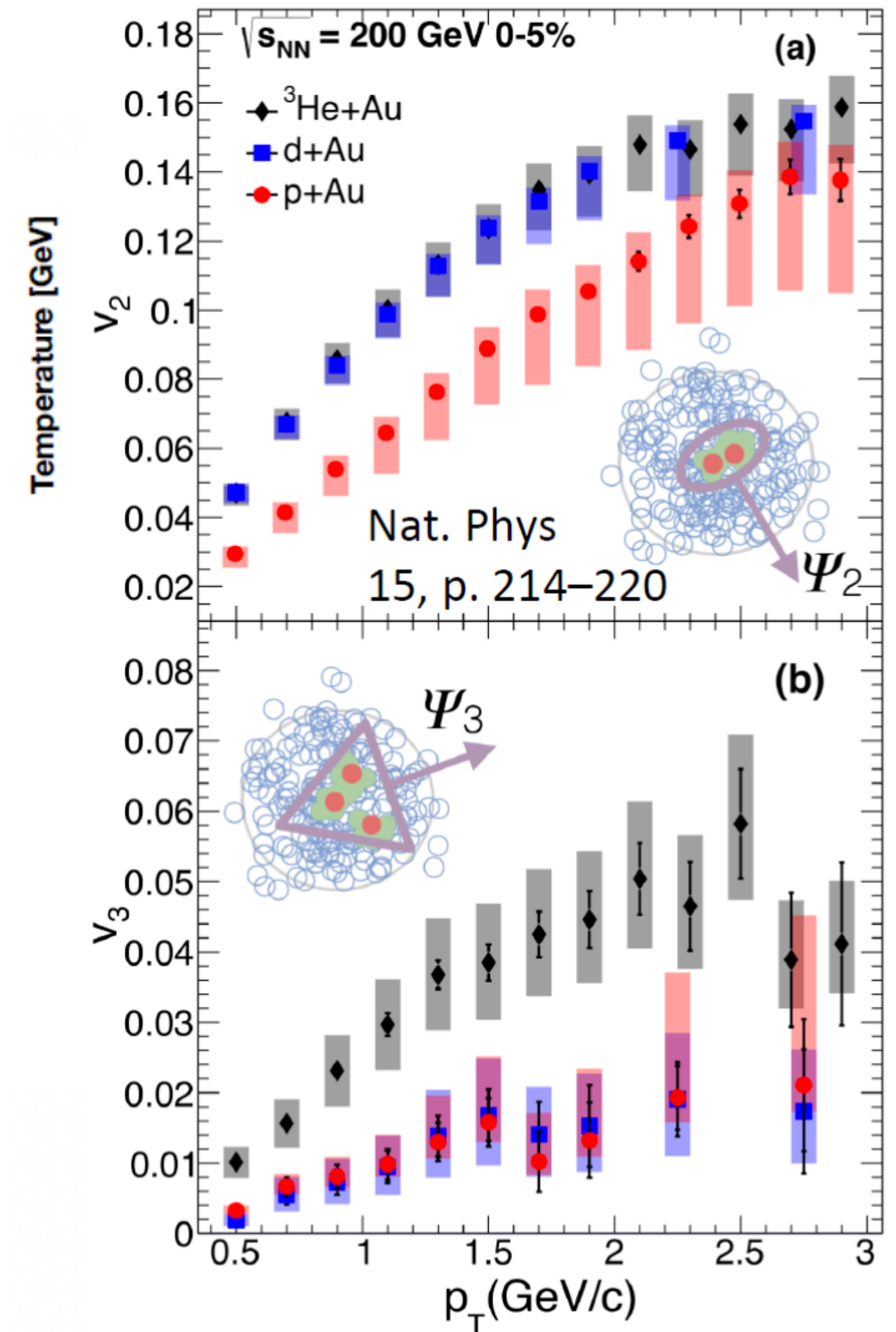
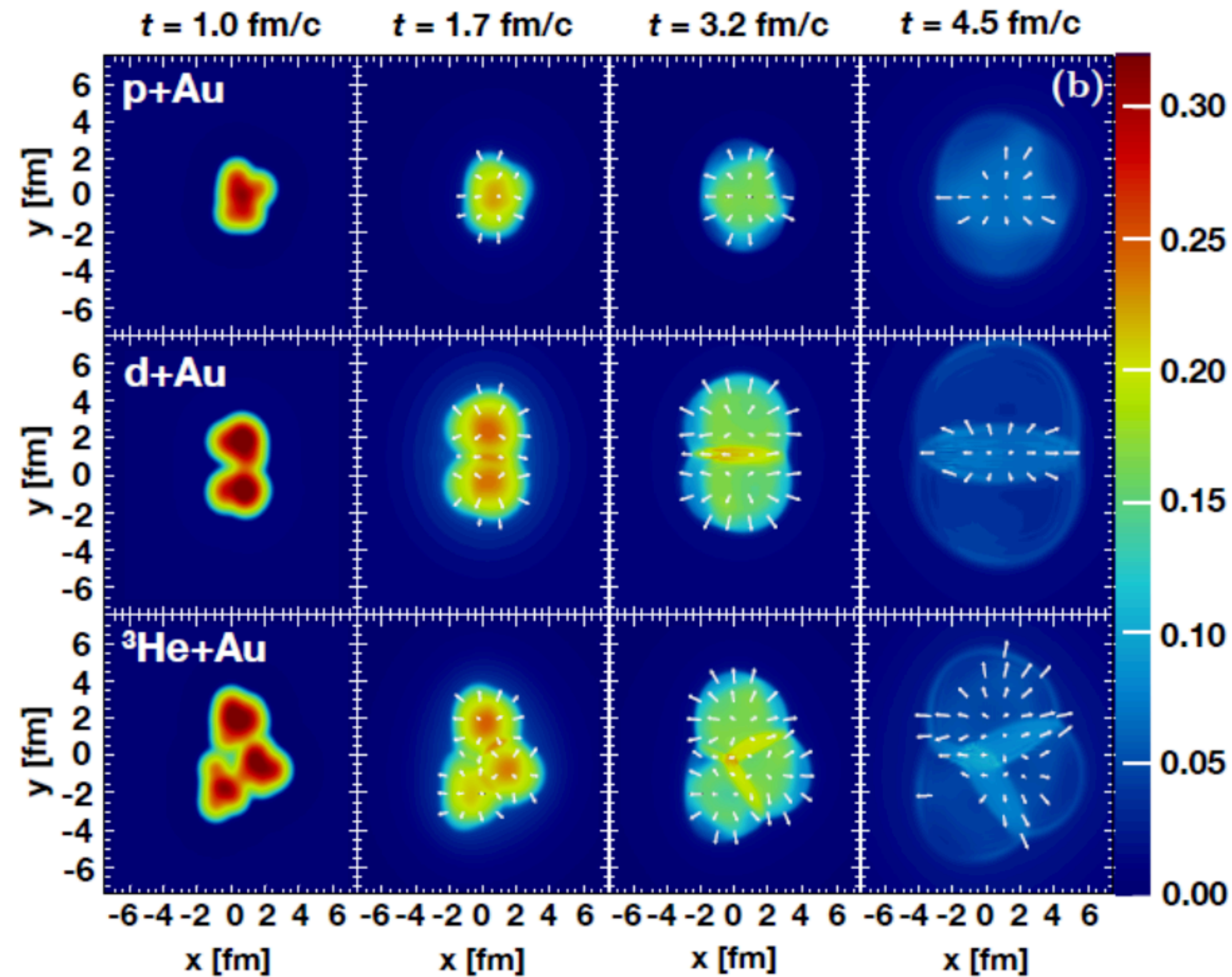


- Simulate small systems dynamically in 3+1D
- Initialize using MC-Glauber + string deceleration model with source terms in hydro
- Provides fluctuating transverse+longitudinal geometry



SMALL SYSTEM SCAN AT RHIC

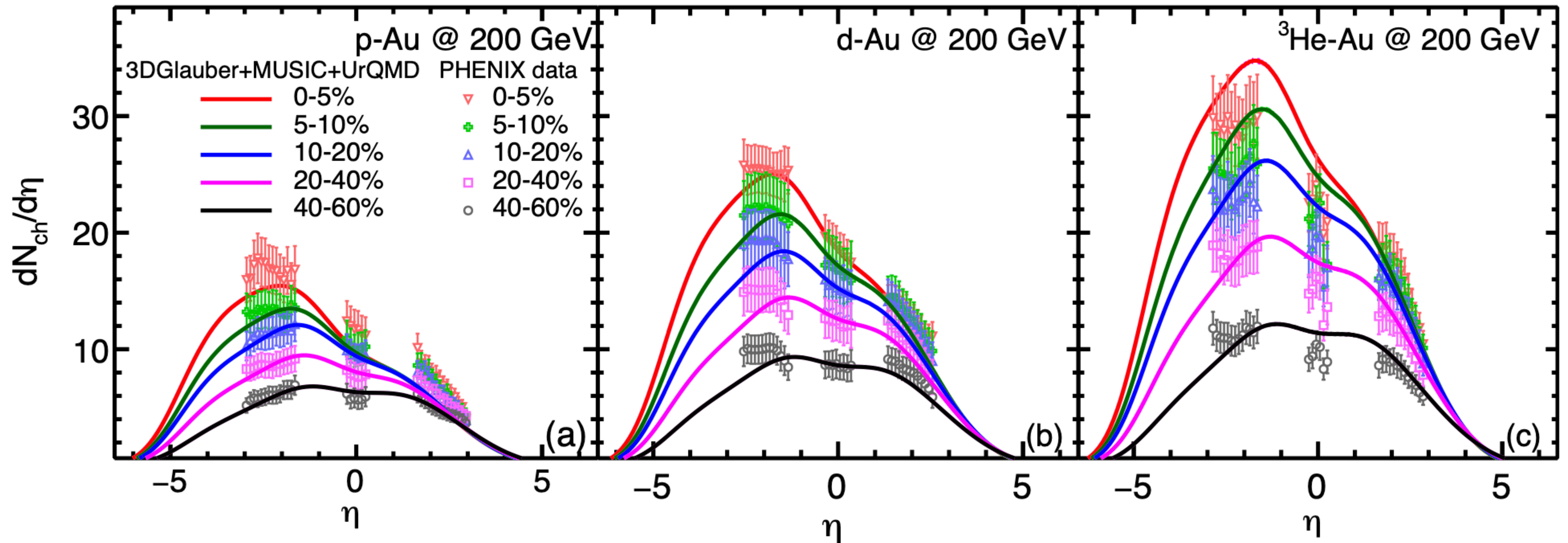
PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)



MULTIPLICITY VS. RAPIDITY

W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904

Data: PHENIX Collaboration, Phys. Rev. Lett. 121, 222301 (2018)

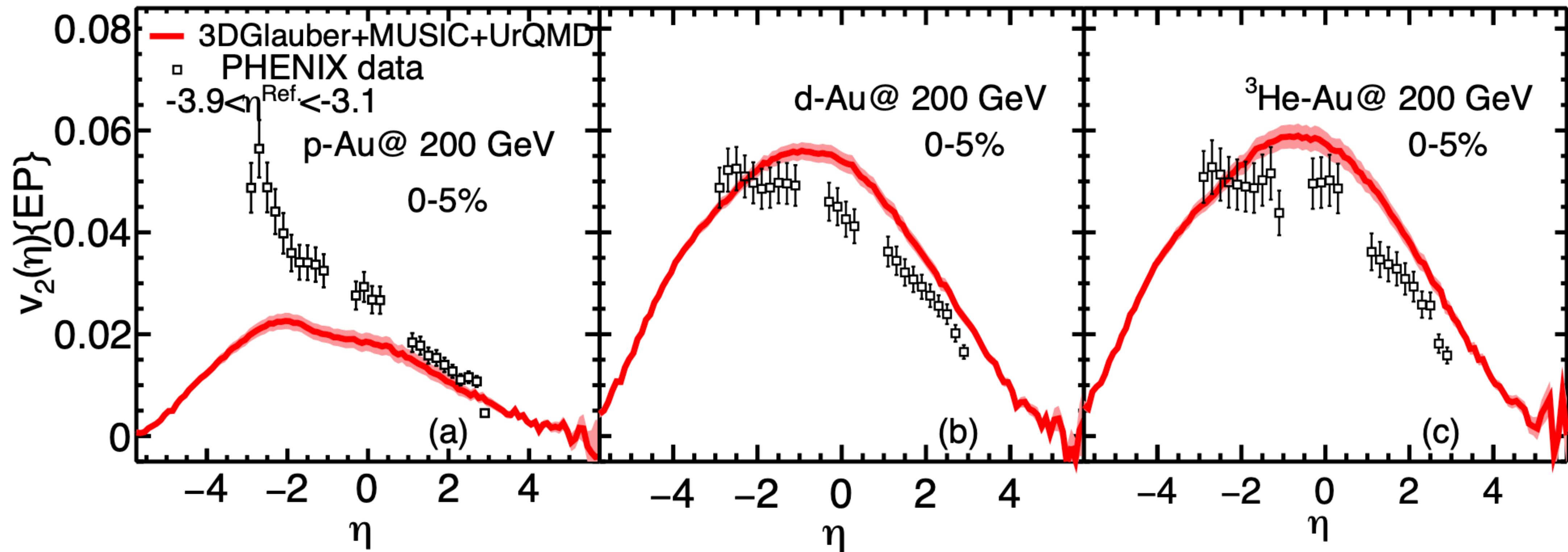


The (3+1)D hybrid model captures the rapidity and centrality dependence of $dN^{ch}/d\eta$ for all asymmetric systems

ANISOTROPIC FLOW VS RAPIDITY

W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904

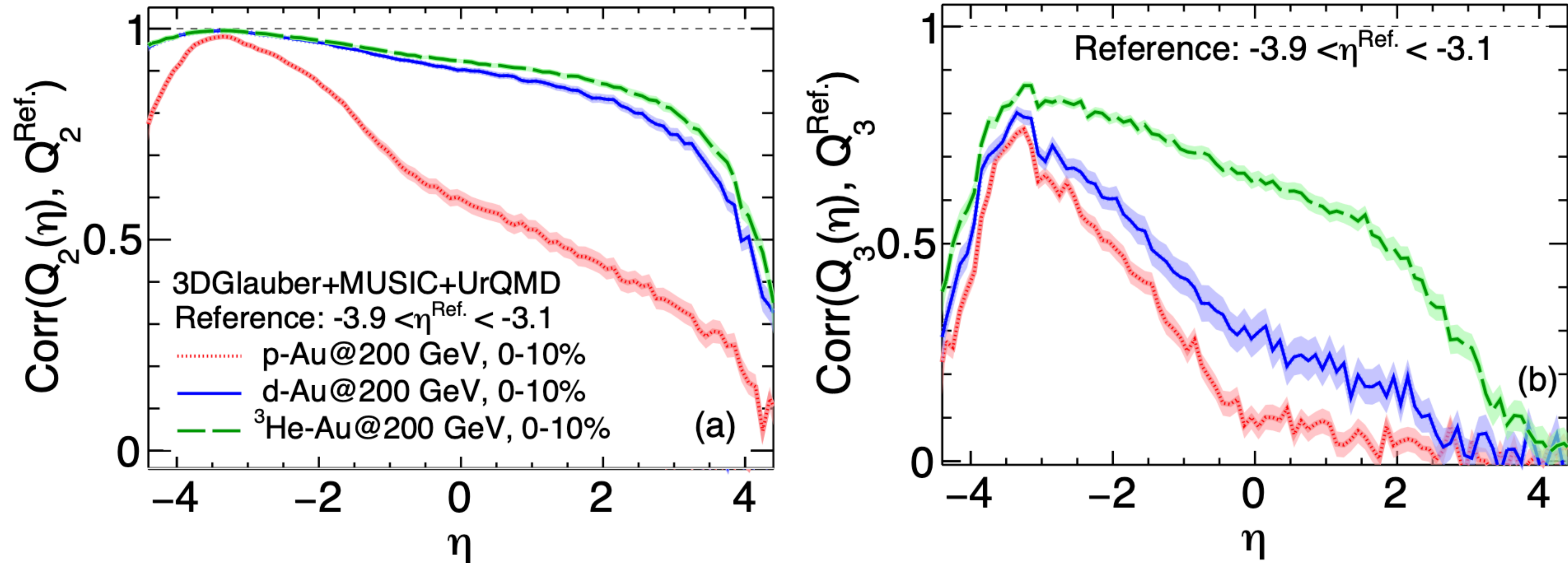
Data: PHENIX Collaboration, Phys. Rev. Lett. 121, 222301 (2018)



- Pseudo-rapidity dependence of $v_2\{EP\}$ reproduced for d+Au and ^3He +Au
- The elliptic flow in $\eta < 1$ in p+Au collisions is underestimated because of the strong longitudinal flow decorrelation in our model + potential non-flow

FLOW VECTOR DECORRELATION

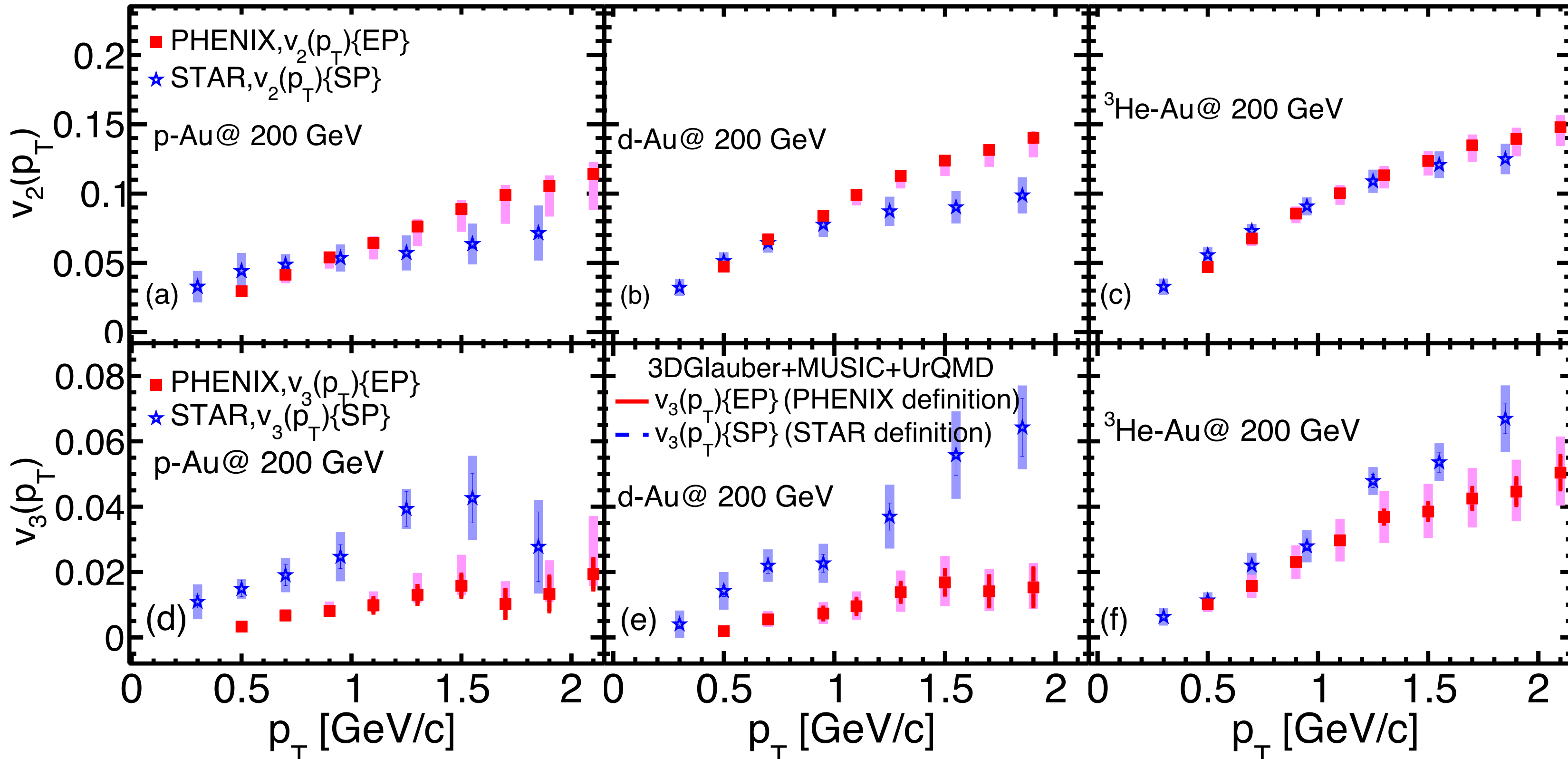
W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904



- Decorrelation is much stronger in the smaller p+Au system
- Decorrelations of v_3 flow vectors are much stronger than v_2
- **Hierarchy between v_n and between systems is driven by decorrelation in this model**

COMPARING PHENIX WITH STAR DATA

PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019) STAR Collaboration, Phys.Rev.Lett. 130 (2023) 24, 242301



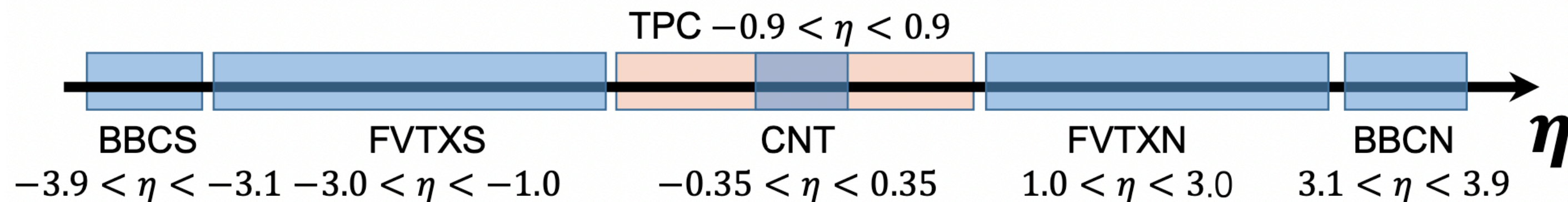
PHENIX:

(p, d)+Au: $\eta_1 \in [-3.9, -3.1]$,
 $\eta_2 \in [-0.35, 0.35]$

$^3\text{He+Au}$: $\eta_1 \in [-3, -1]$,
 $\eta_2 \in [-0.35, 0.35]$

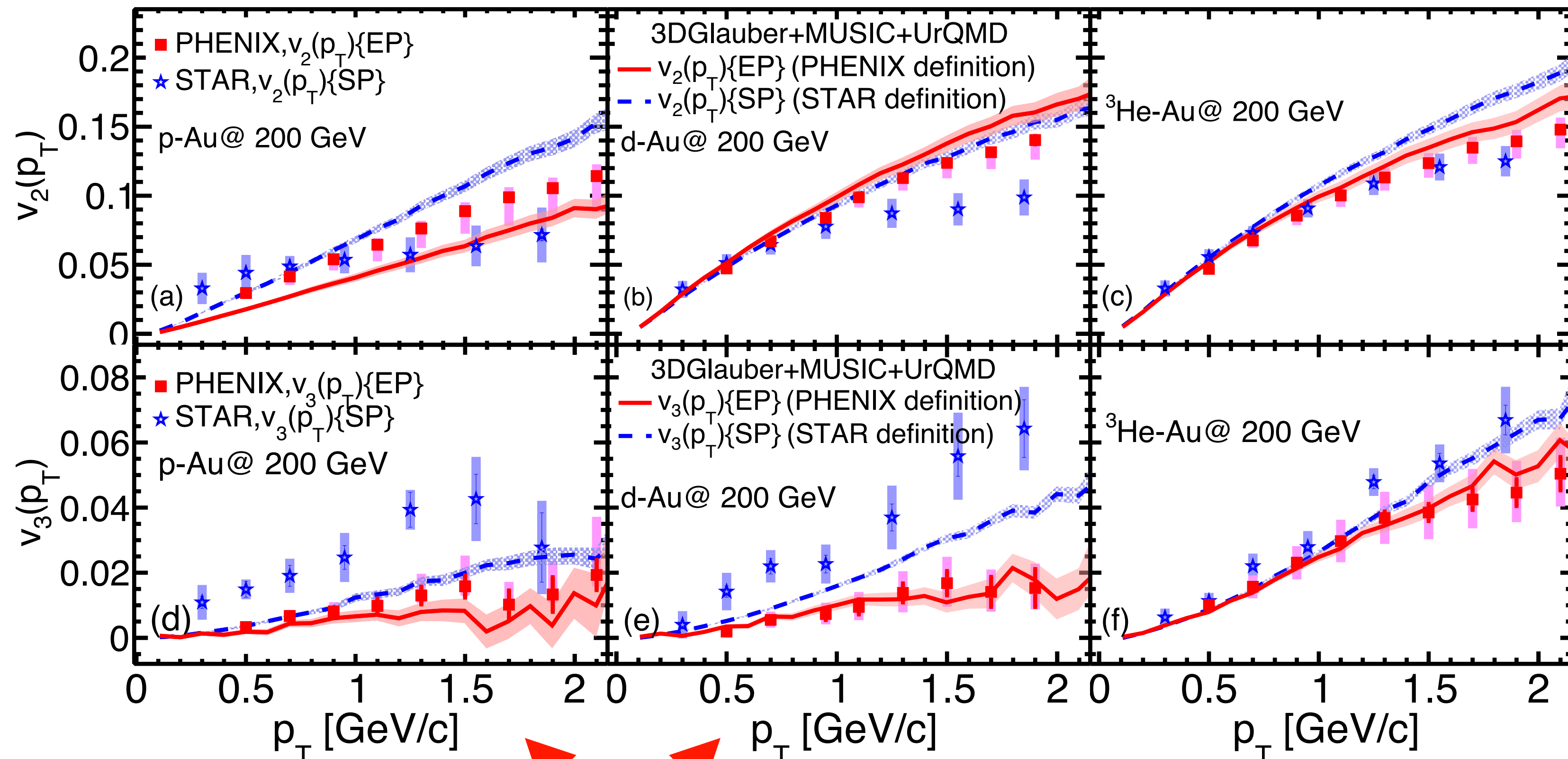
STAR:

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



DIFFERENT RAPIDITY BINS, DIFFERENT RESULTS

W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904



PHENIX:

(p, d)+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:

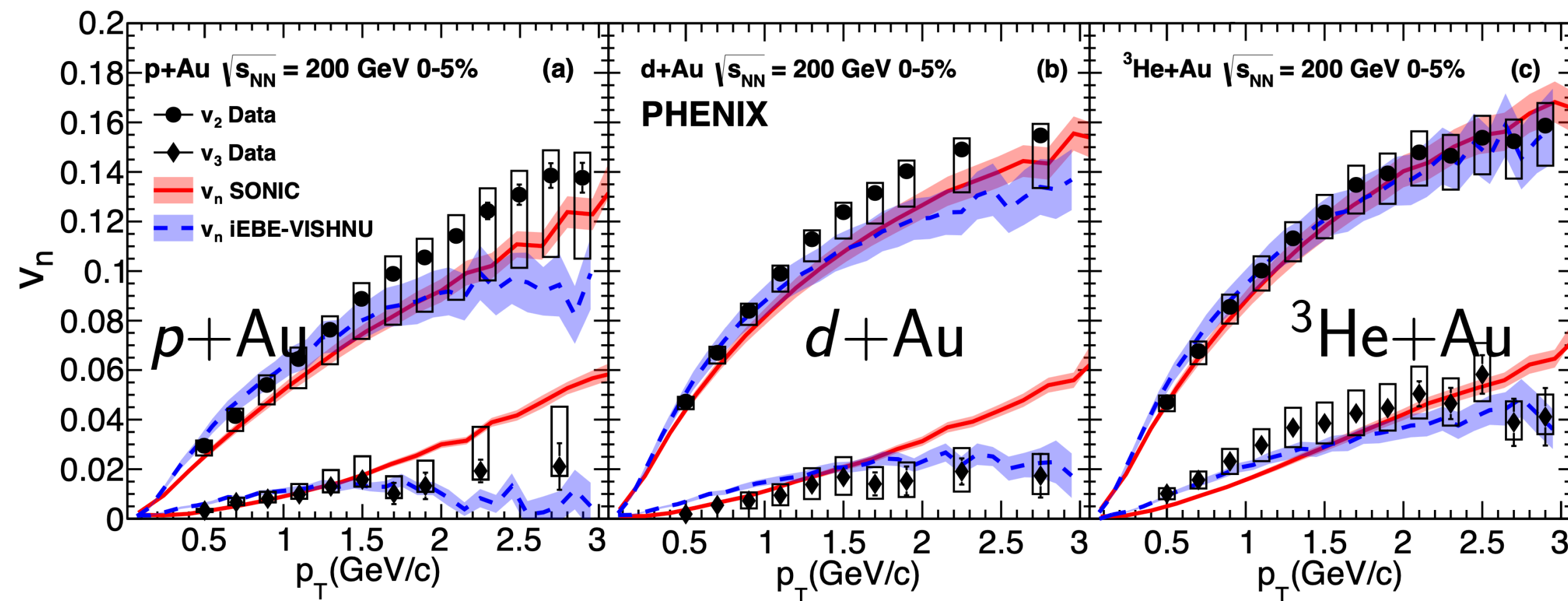
$\eta \in [-0.9, 0.9]$ with $|\Delta\eta| > 1$

Tune to $^3\text{He}+\text{Au}$:
 PHENIX $v_n(p_T)$ in
 (d, ^3He)+Au collisions
 well described

Longitudinal flow decorrelations lead to smaller $v_3(p_T)$ for PHENIX,
 explaining ~50% of the difference between the two measurements

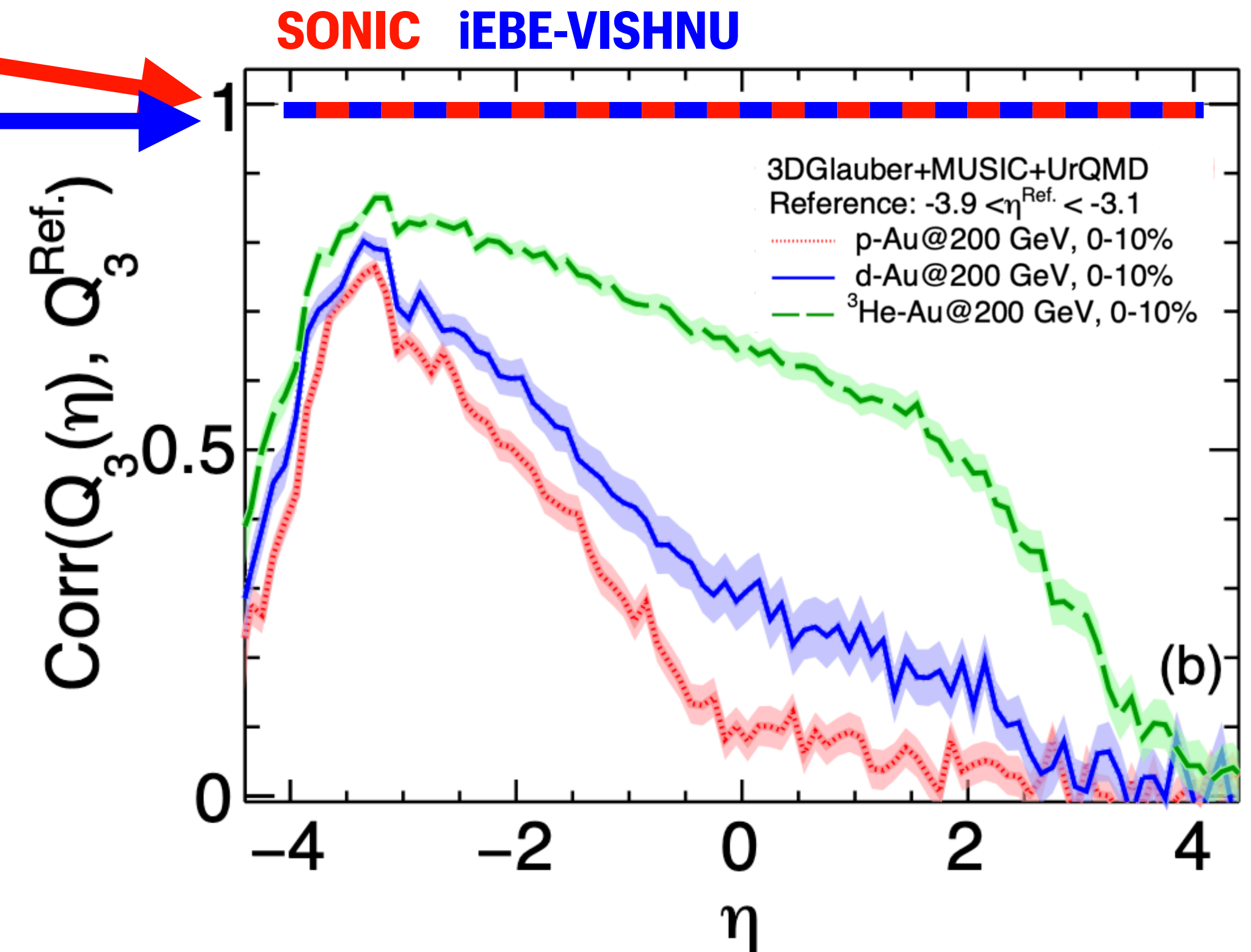
COMPARISON WITH BOOST INVARIANT MODELS

W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904



PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)

- Meaningful comparison?
- Assuming boost invariance and ignoring decorrelation can cause large errors
- Same problem for all boost invariant models



APPLICABILITY OF HYDRODYNAMICS

- Initial transverse volume in small systems **50 × smaller** than in central Pb+Pb
- Locally **large** Knudsen (macroscopic scale / microscopic scale) and inverse Reynolds numbers (ratio of viscous forces to inertial forces)
- Could lead to inaccurate results
- **Use non-equilibrium component:** Early time free streaming, effective kinetic theory, or core-corona models
- Far from equilibrium, causality could be violated
- Alternative to Israel-Stewart like theories, BDNK, can be shown to be causal

G. Inghirami, H. Elfner, Eur.Phys.J.C 82 (2022) 9, 796

A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, and D. Teaney
Phys. Rev. Lett. 122(12), 122302

BDNK:

F. S. Bemfica, M. M. Disconzi, and J. Noronha, Phys. Rev. X. 12(2), 021044 (2022)

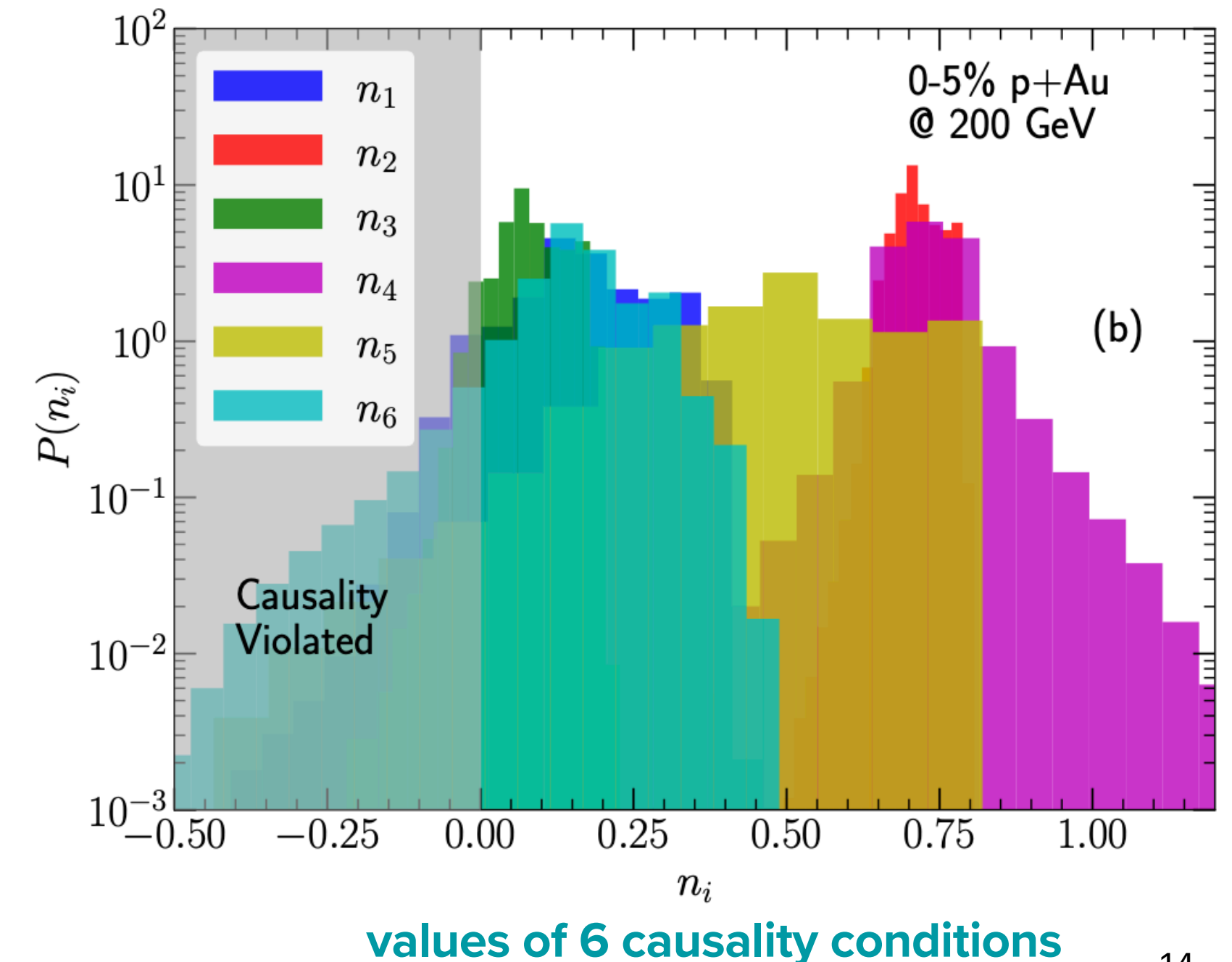
P. Kovtun, JHEP 10 (2019) 034

Causality:

C. Plumberg, D. Almaalol, T. Dore, J. Noronha, J. Noronha-Hostler, Phys. Rev. C. 105(6), L061901 (2022)

C. Chiu and C. Shen, Phys. Rev. C. 103(6), 064901 (2021)

ExTrEMe Collaboration, R. Krupczak et al., Phys.Rev.C 109 (2024) 3, 034908



EFFECTS OF ENFORCING CAUSALITY

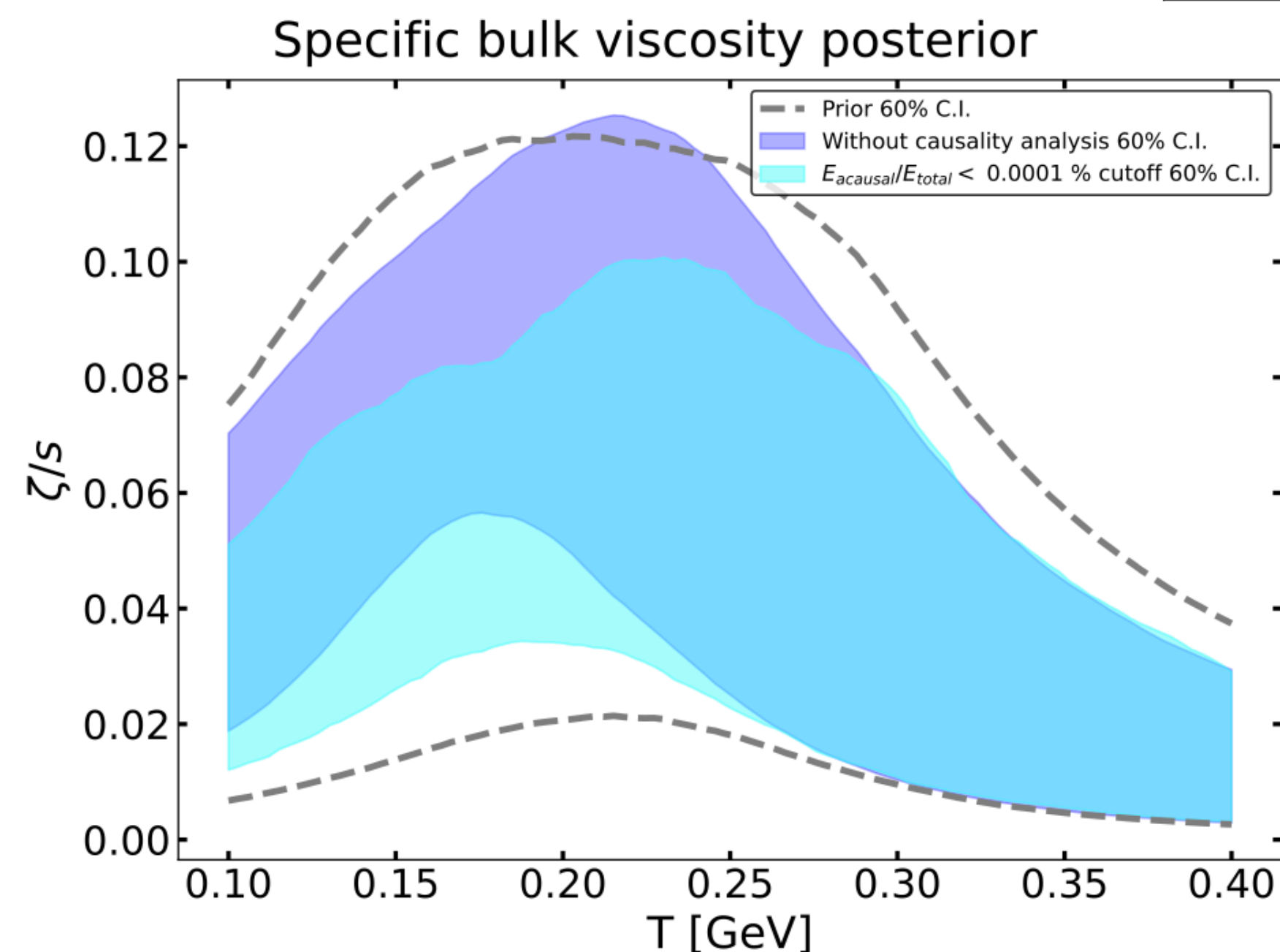
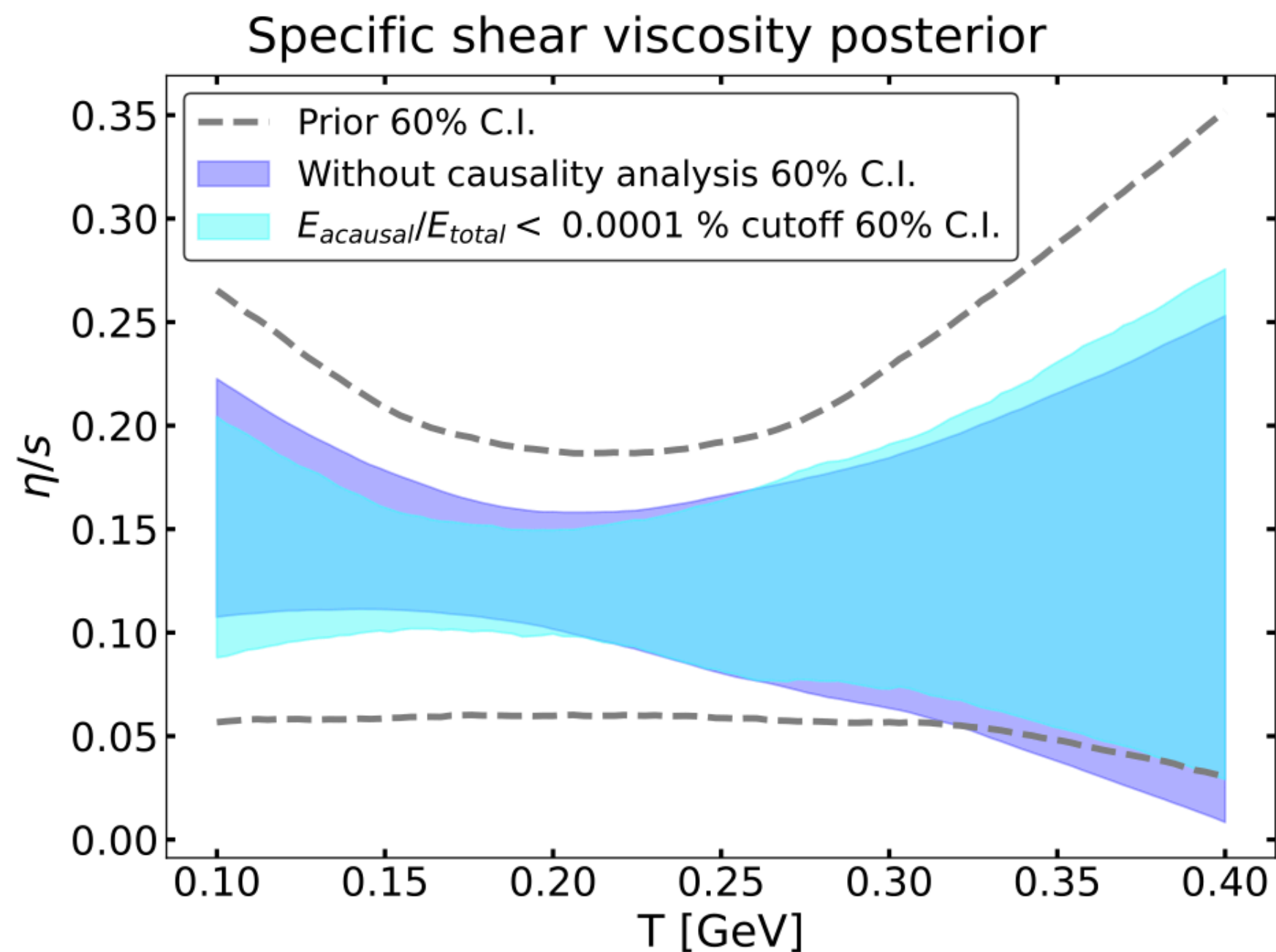
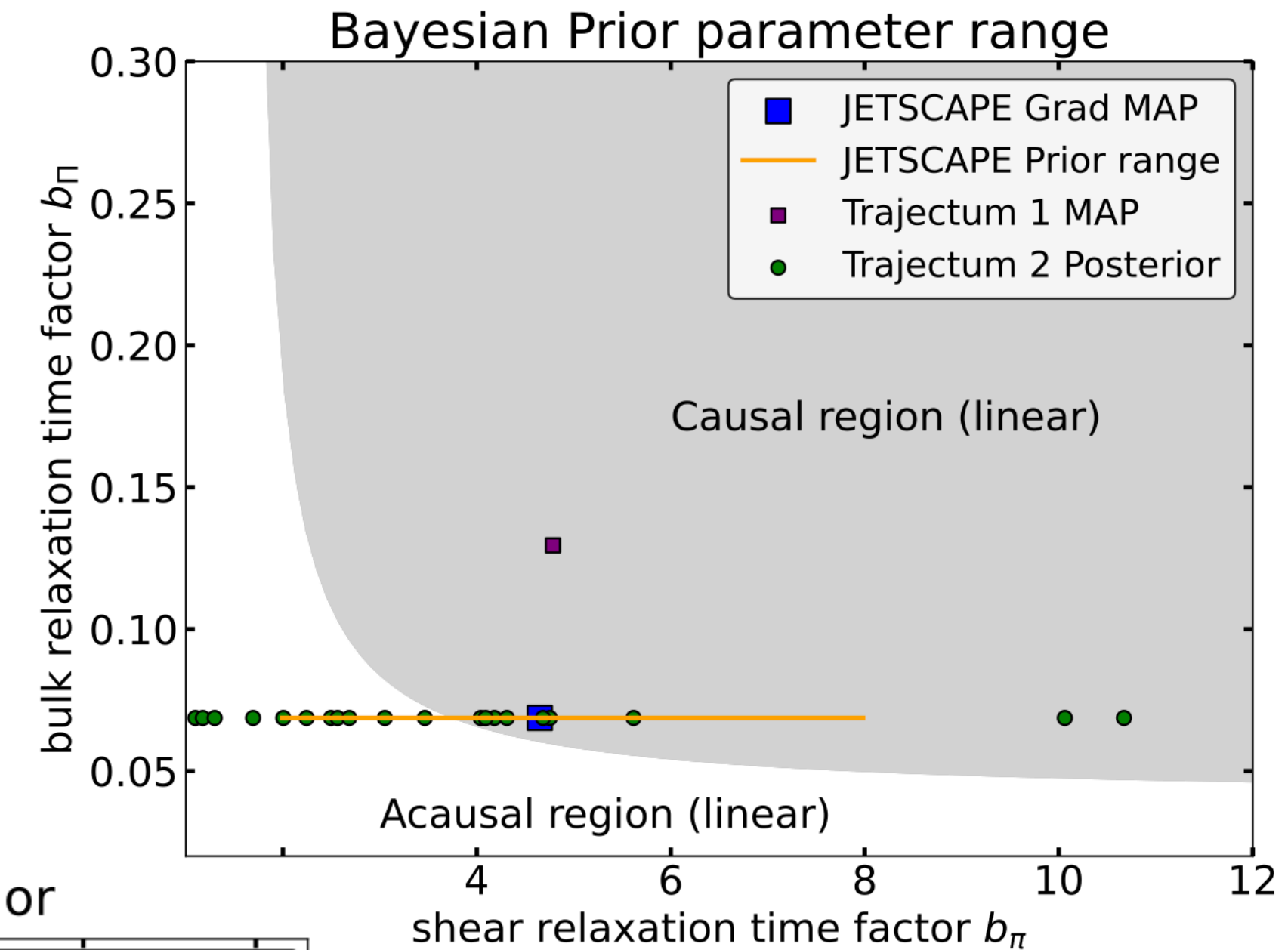
There are necessary and sufficient causality conditions

F. S. Bemfica, M. M. Disconzi, V. Hoang, J. Noronha, and M. Radosz, *Phys. Rev. Lett.* **126**, 222301 (2021)

For certain parameter values, the conditions can be violated

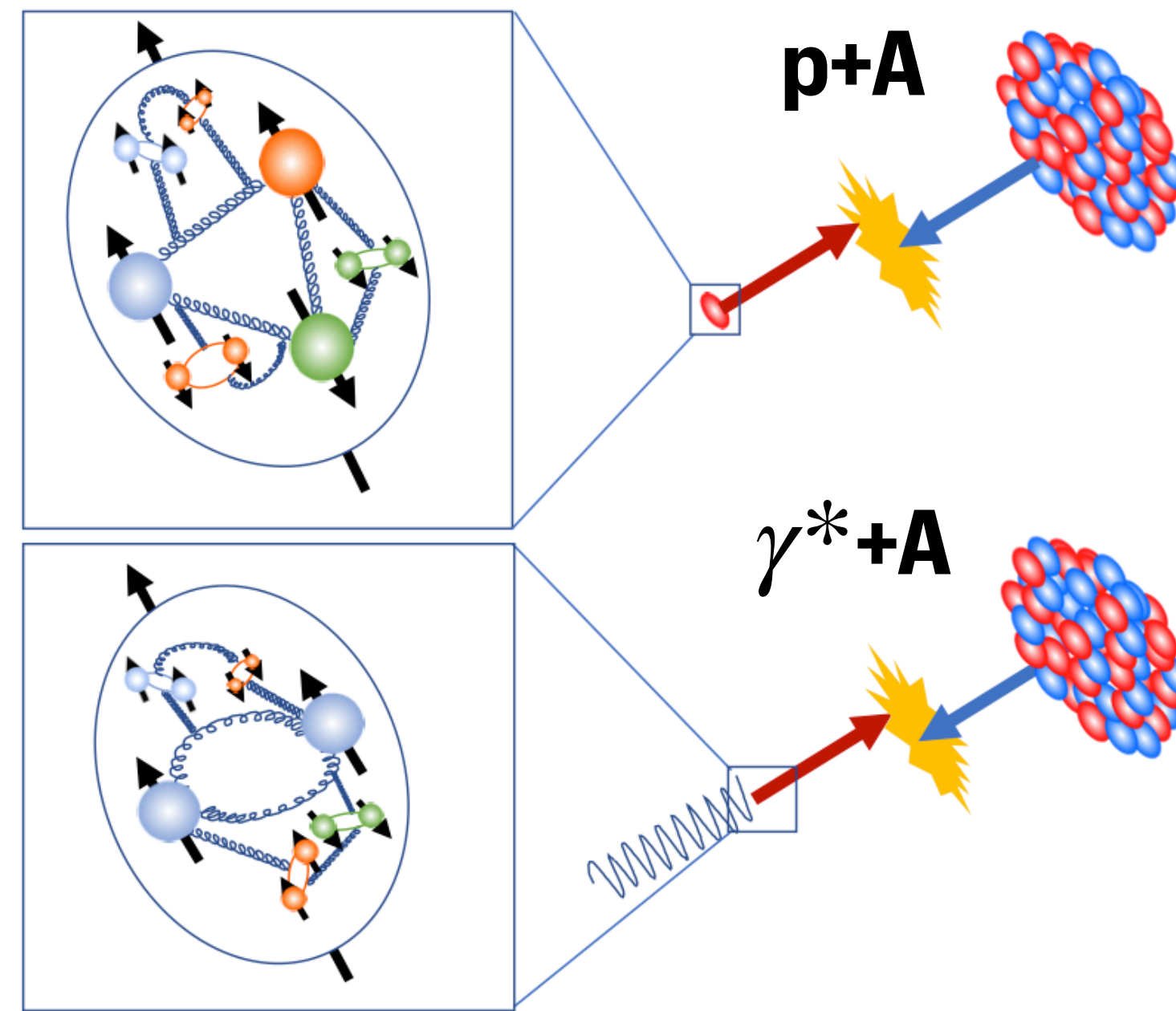
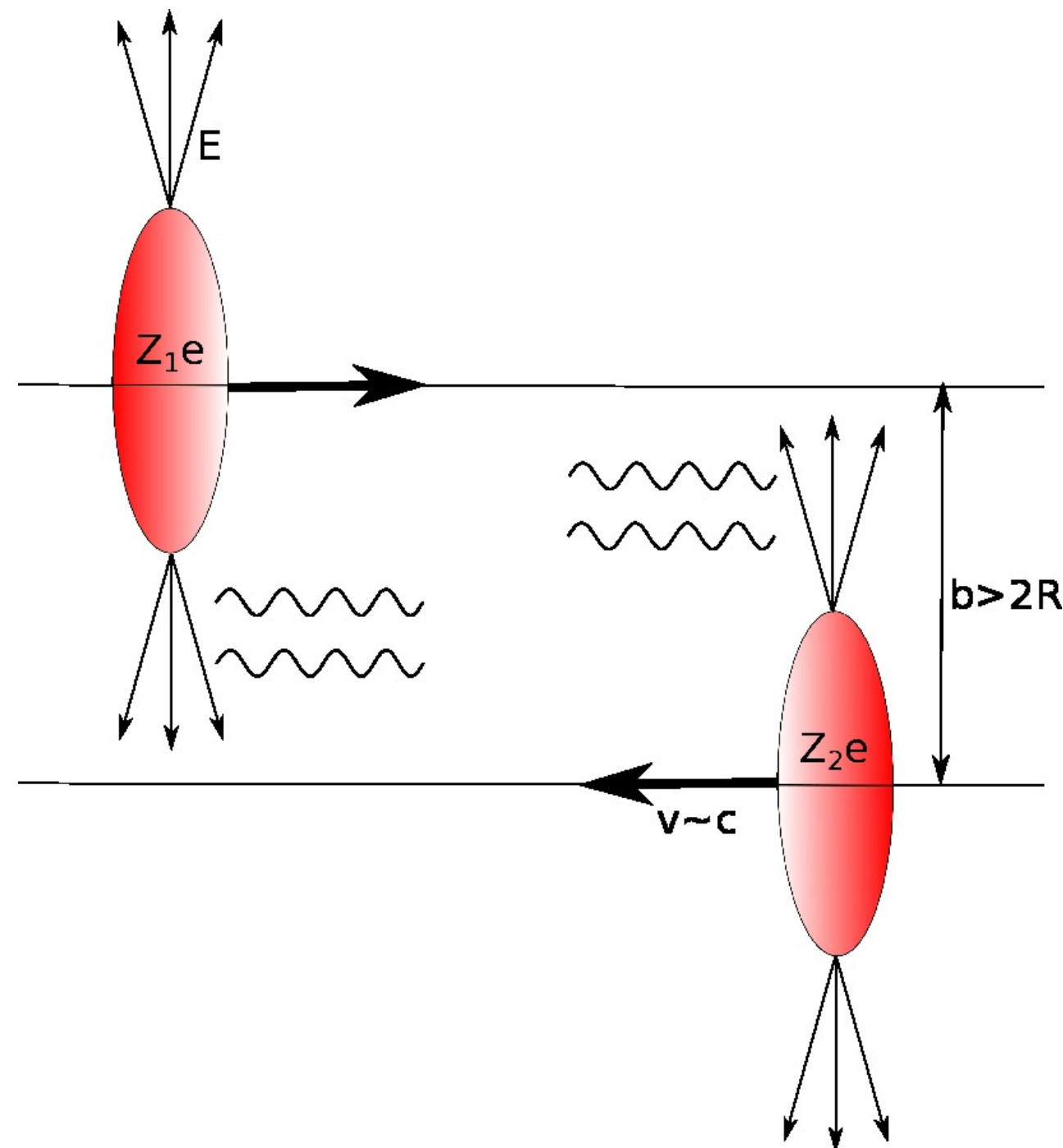
What happens when necessary conditions are enforced in a Bayesian analysis with a hydrodynamic model?

T. S. Domingues, R. Krupczak, J. Noronha, T. Nunes da Silva, J.-F. Paquet, M. Luzum
Phys.Rev.C **110** (2024) **6**, 064904



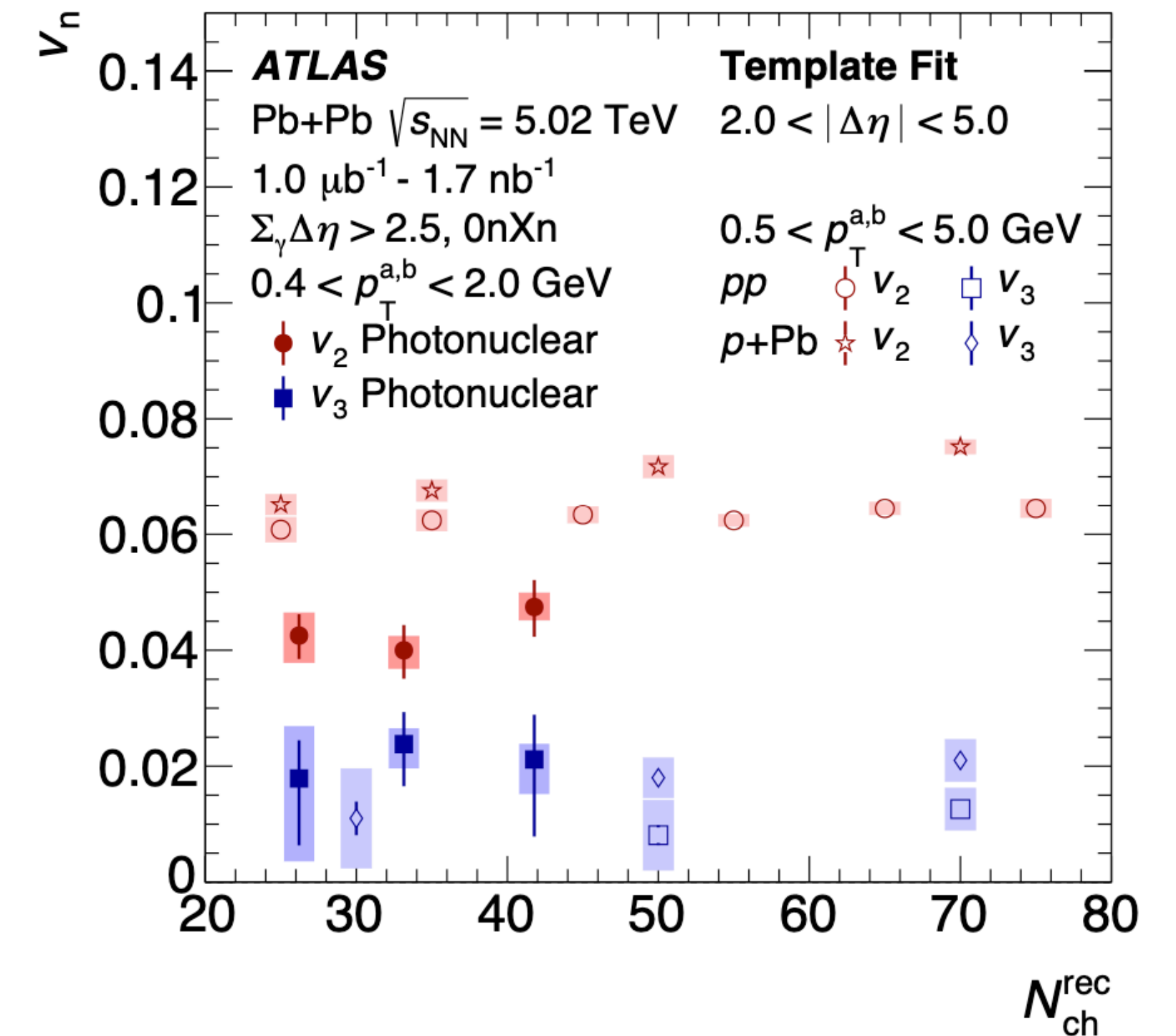
ULTRAPERIPHERAL COLLISIONS

W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302



Phys. Rev. D 103, 054017 (2021)

ATLAS Phys. Rev. C 104, 014903 (2021)

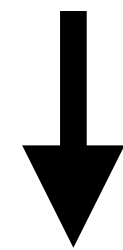


- Long range two-particle correlations were observed in photo-nuclear processes in ultra-peripheral Pb+Pb collisions (UPC) at the LHC
- The magnitudes of v_n in UPCs are comparable with those in p+Pb collisions

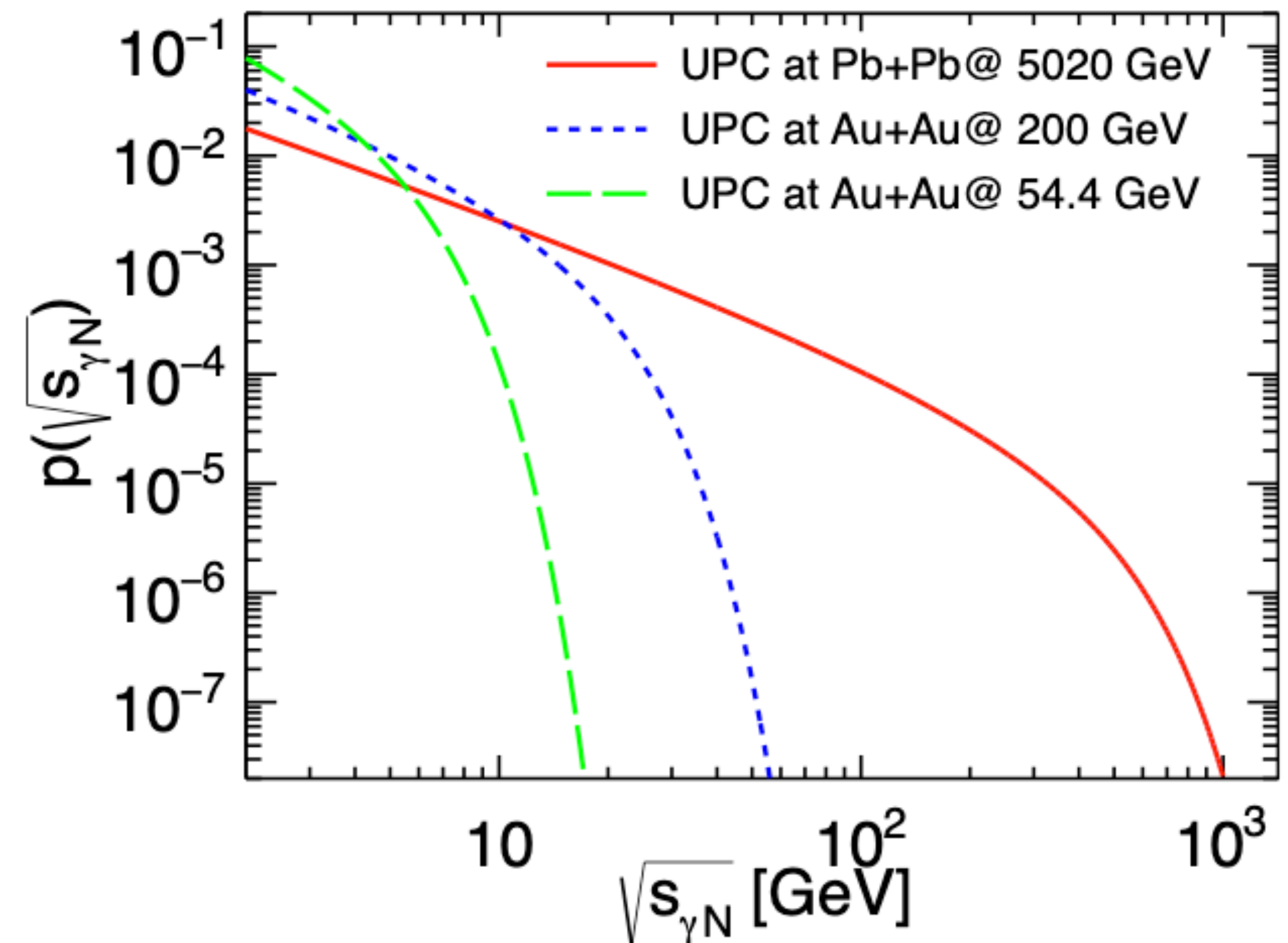
MODELING $\gamma^* + \text{Pb}$

A. J. Baltz *et al.* Phys. Rept. 458, 1-171 (2008); W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302

- Same 3+1D hydrodynamic model
- Virtual photon described as vector meson: quark-antiquark pair plus soft cloud
- Energy of the incoming photon fluctuates event by event

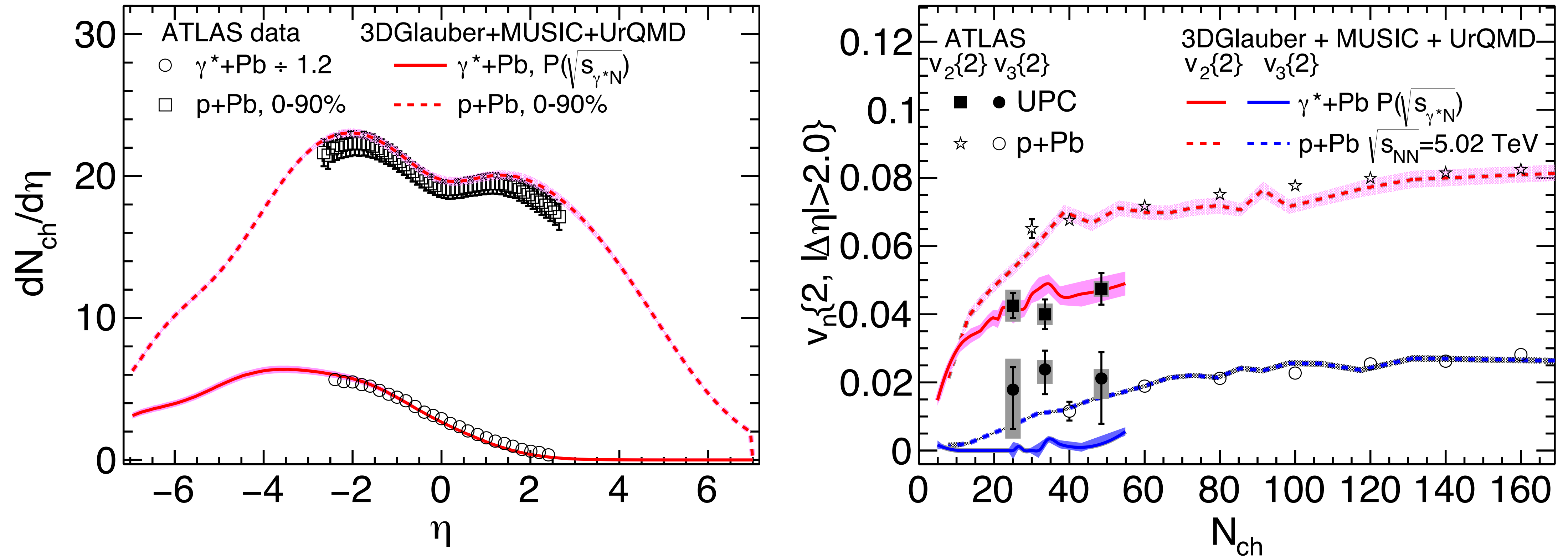


- Center of mass collision energy for the $\gamma^* + A$ system fluctuates
- Center of mass rapidity of $\gamma^* + A$ collision fluctuates in the lab frame



PARTICLE PRODUCTION AND FLOW IN p+A AND γ^*+A

W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302

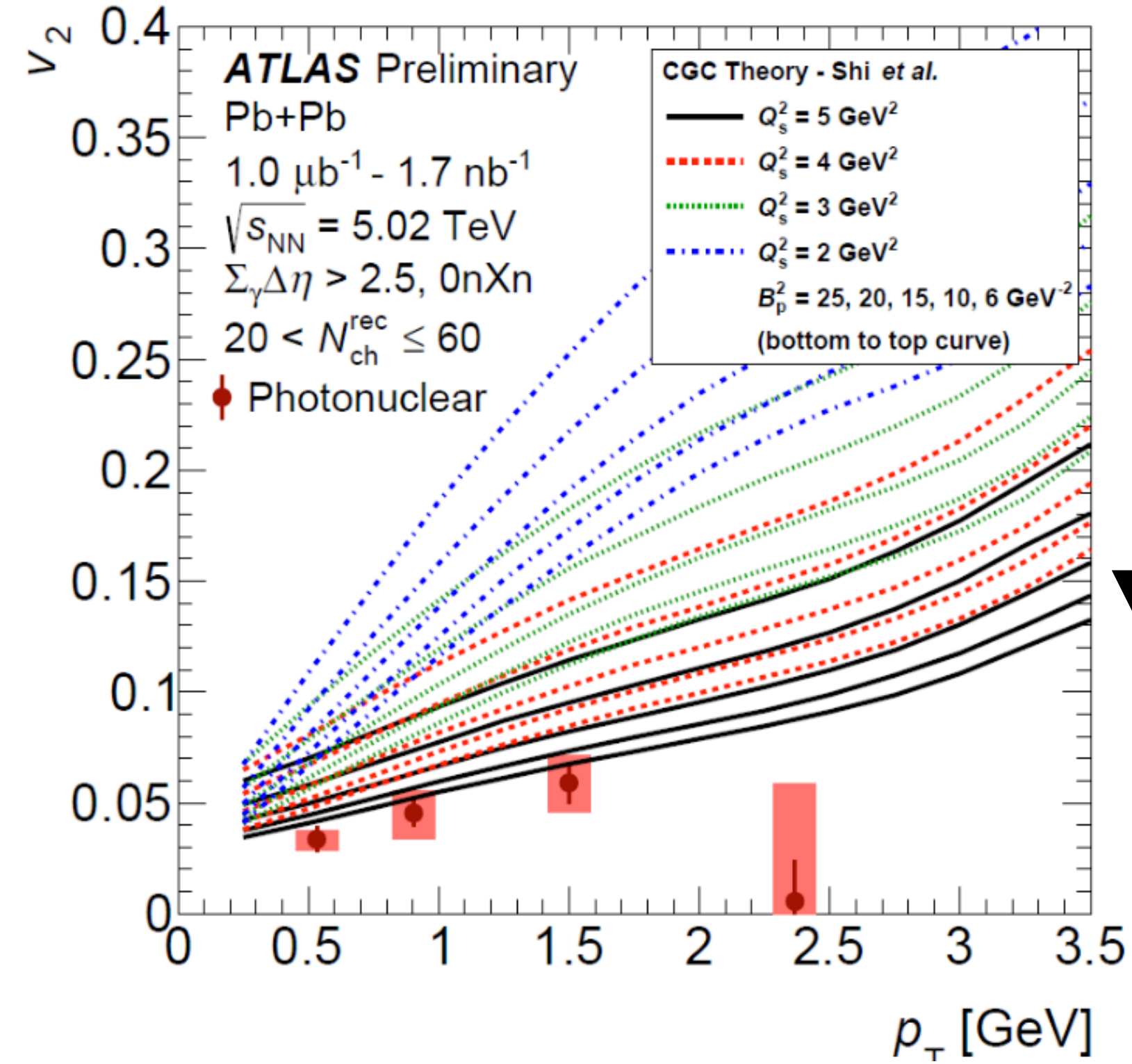
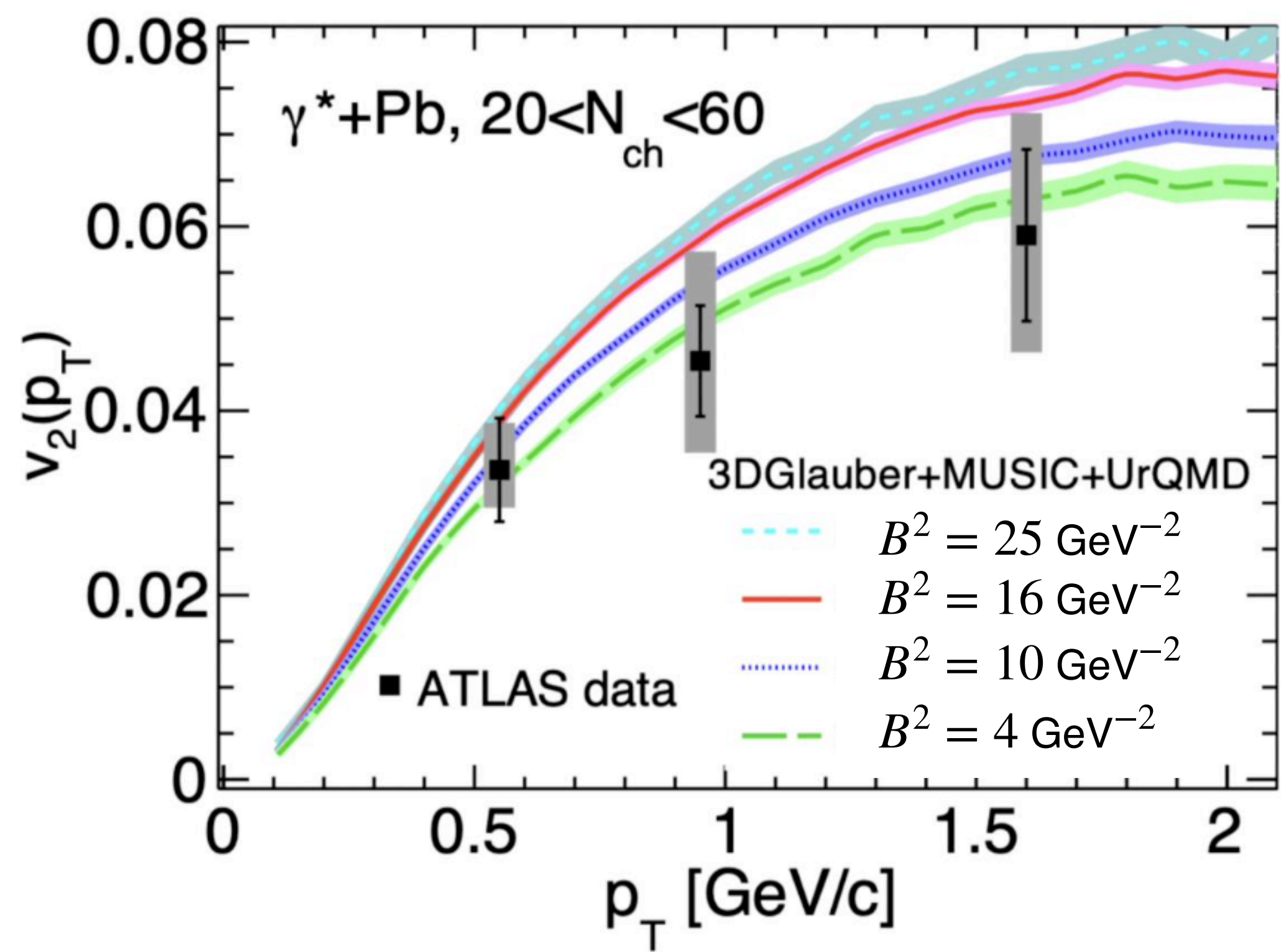


- Shapes of $dN_{ch}/d\eta$ reproduced for p+Pb and γ^*+Pb collisions
- Elliptic flow difference between p+Pb and γ^*+Pb collisions reproduced
- Driven by different amount of longitudinal flow decorrelation

DISTINGUISH MODELS IN e+A COLLISIONS AT EIC

W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302

Y. Shi, L. Wang, S. Y. Wei, B. W. Xiao and L. Zheng, Phys. Rev. D 103, 054017 (2021)

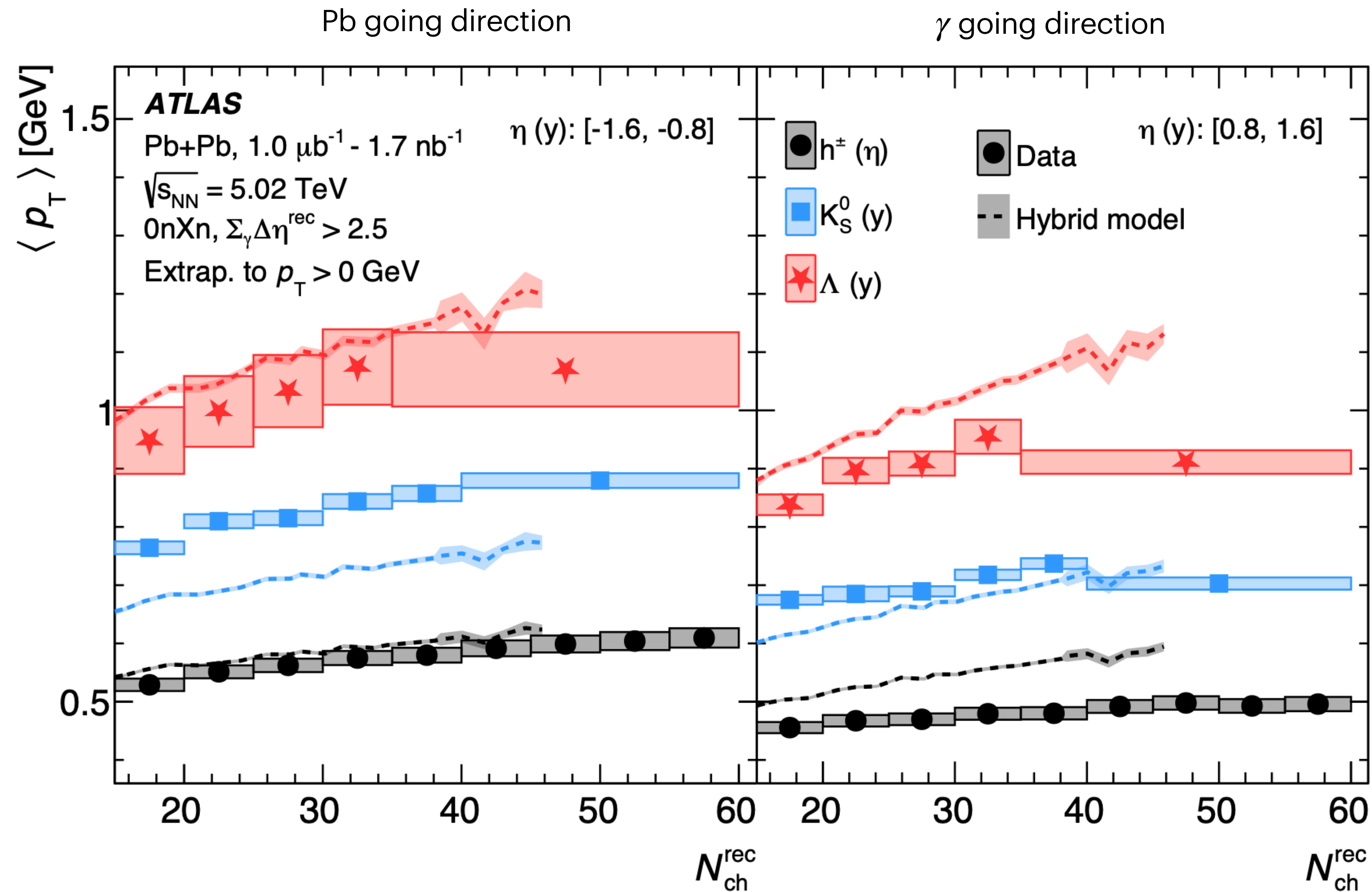


increasing
transverse size
 $\propto B^2$
($\sim 1/Q^2$)

- Hydro: Larger B^2 means larger transverse area for geometry to fluctuate $v_2 \propto B^2$
- CGC: Larger B^2 leads to a larger number of independent color domains $v_2 \propto 1/B^2$

$\langle p_T \rangle$ IN $\gamma + \text{Pb}$

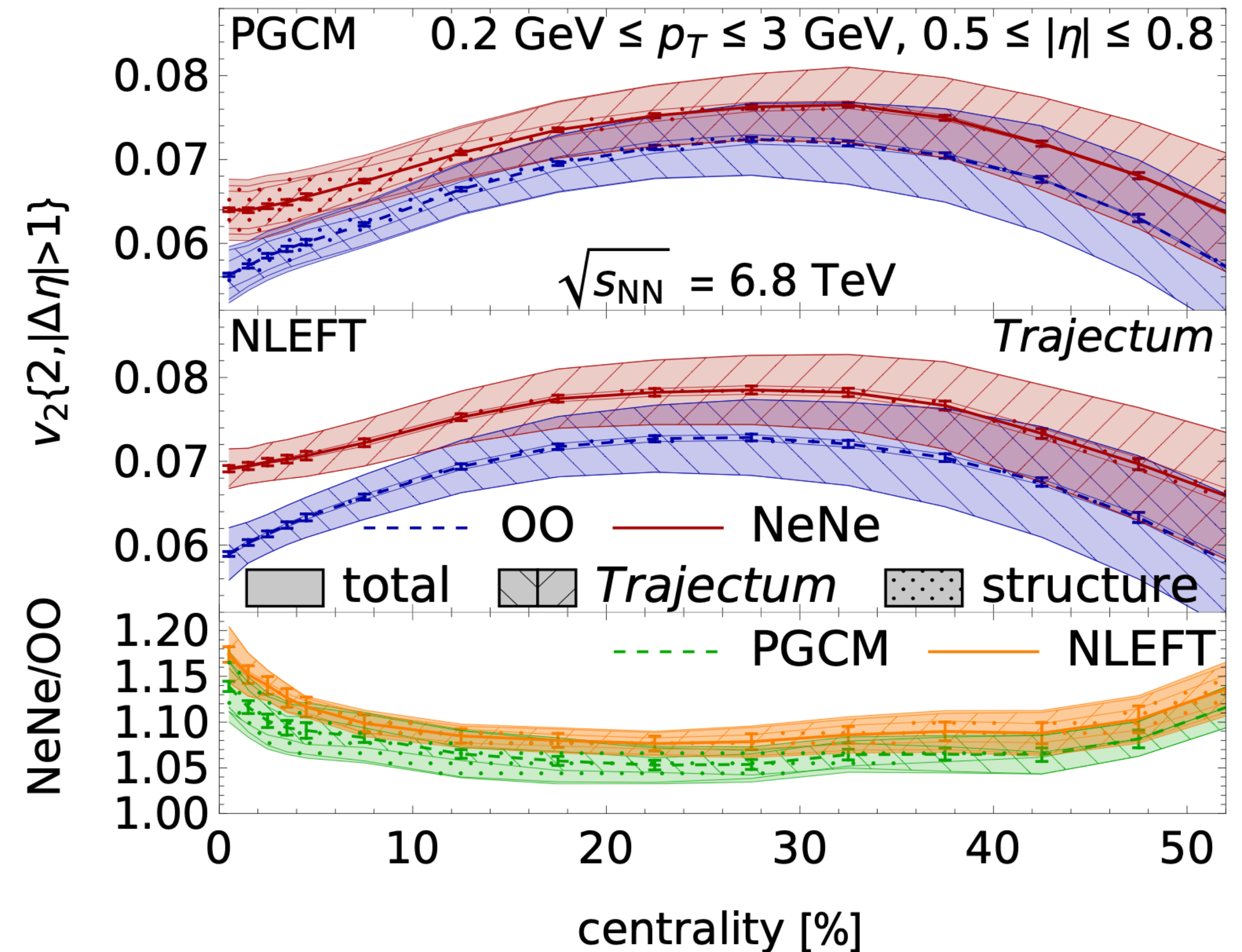
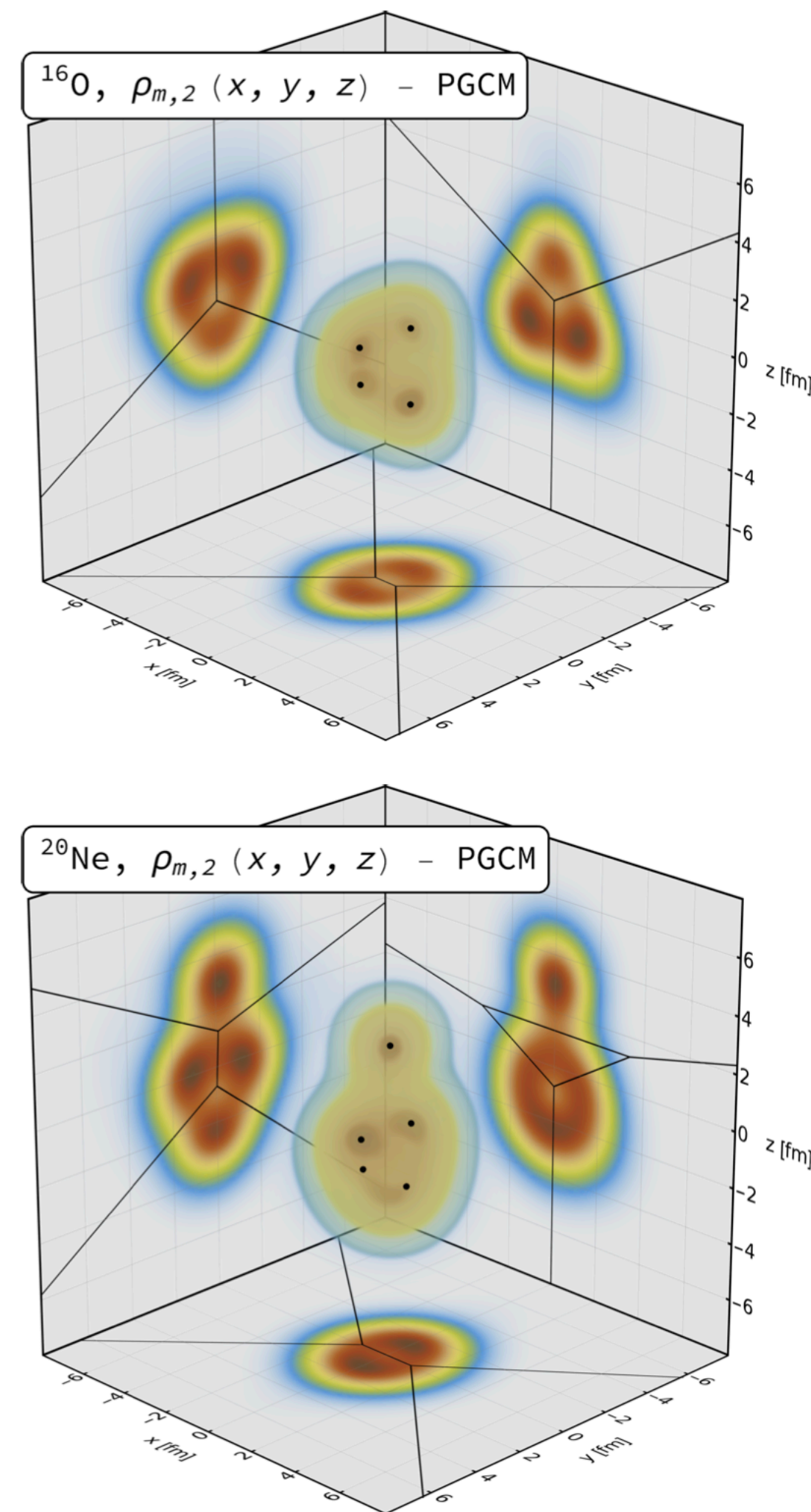
ATLAS Collaboration, arXiv:2503.08181



O+O and Ne+Ne

G.Giacalone et al, e-Print: 2402.05995

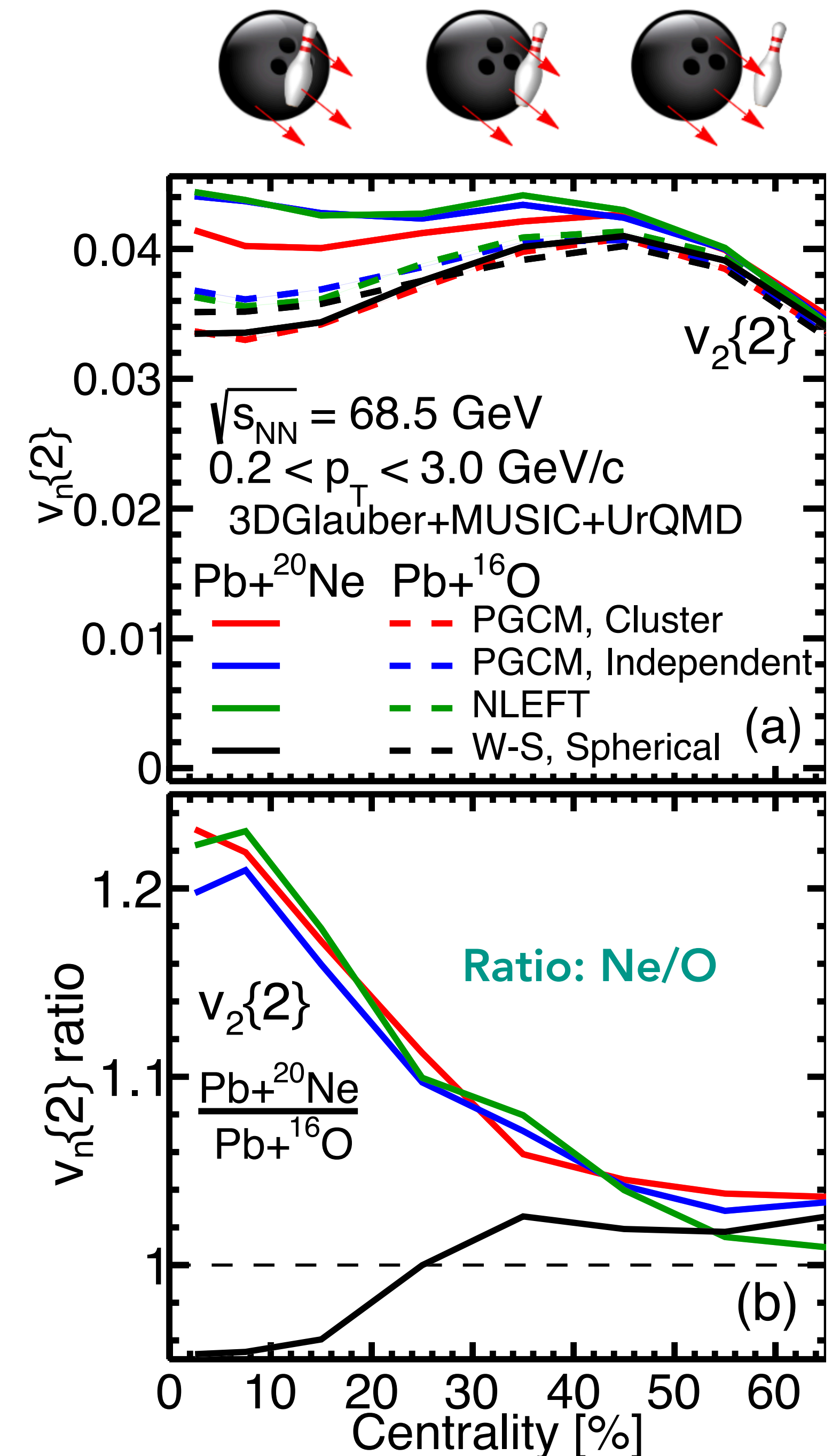
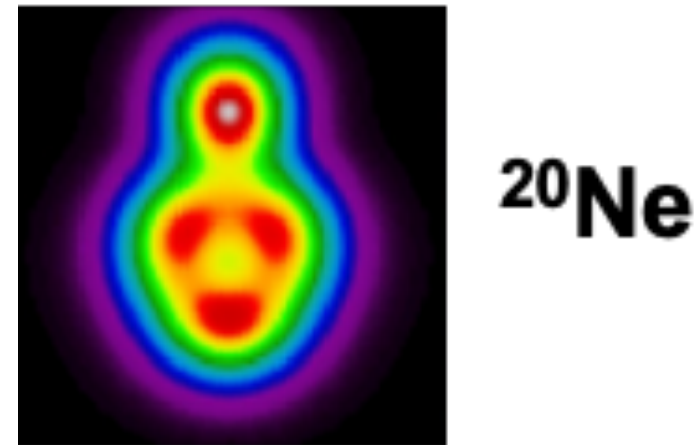
Elliptic flow is enhanced in Ne+Ne collisions compared to O+O because of neon's characteristic shape



Pb+Ne and Pb+O

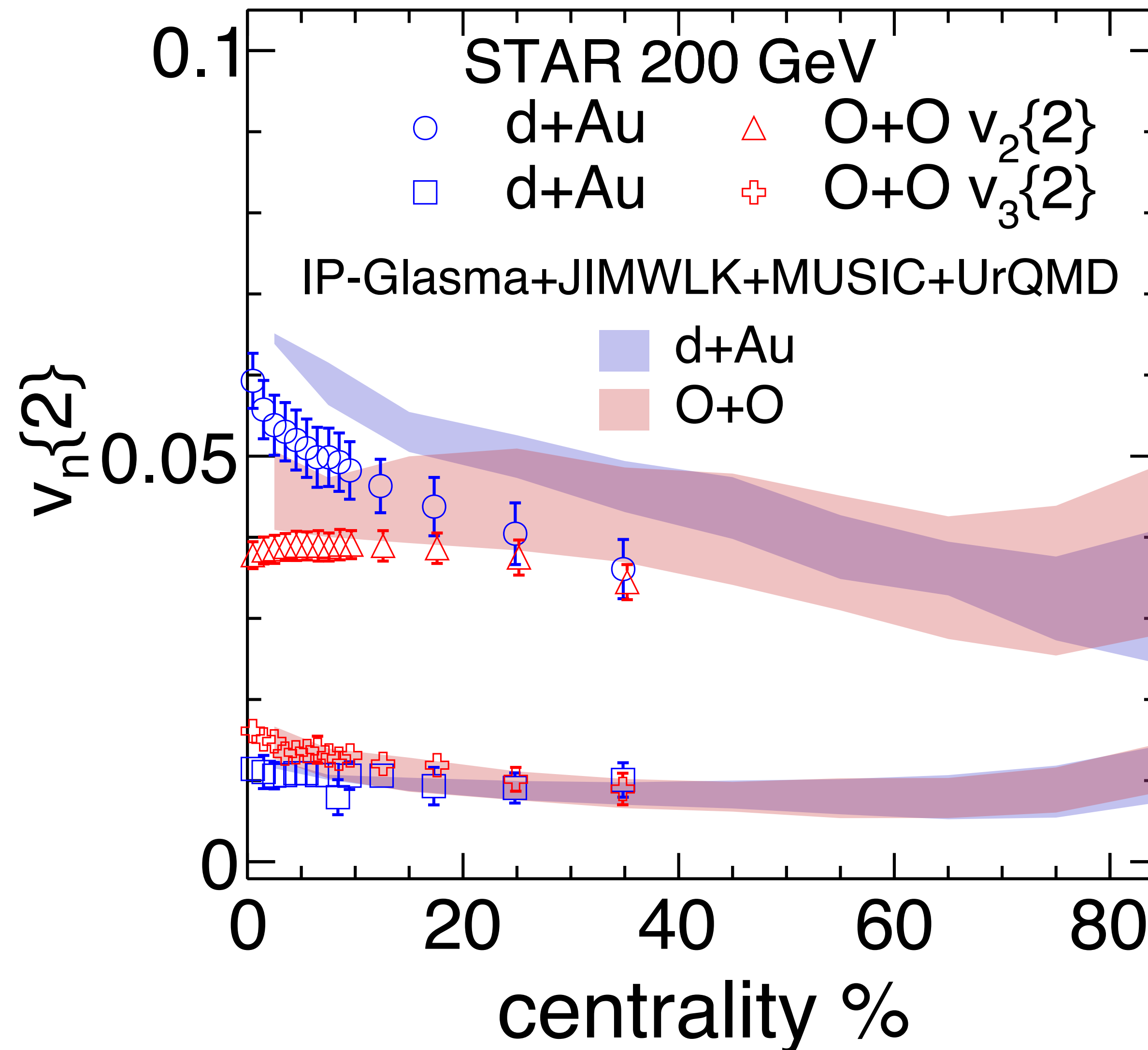
G. Giacalone et al, Phys.Rev.Lett. 134 (2025) 8, 082301

- Flow sensitive to shapes of Ne and O
- Clear predictions from fluid dynamics with input from ab initio calculations of the structure of ^{16}O and ^{20}Ne
- Further test hydrodynamic picture at LHC using fixed target collisions at LHCb's SMOG2



O+O and d+Au

W. Zhao, H. Mäntysaari, B. Schenke, C. Shen, et al., in preparation



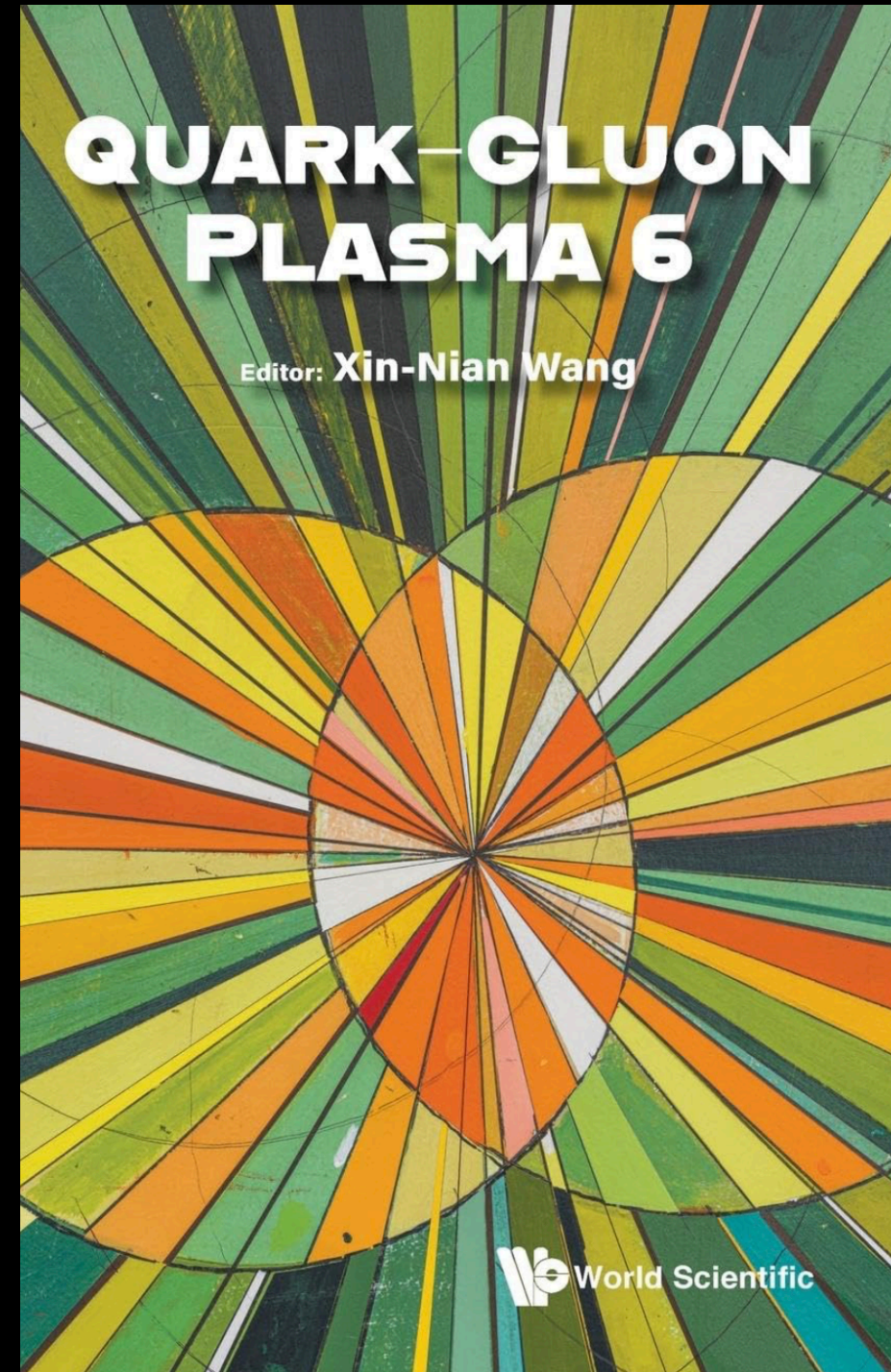
Trends are well described in IP-Glasma+MUSIC+UrQMD model - yet uncertainties from early time dynamics and matching to hydrodynamics are large in small systems (bands)

SUMMARY

- Hydrodynamics has been very successful in describing heavy ion and also smaller system collision data
- Small system collisions feature strong final state effects that are at least qualitatively well described by fluid dynamics
- Fluid dynamics is used at the limits of its applicability, and more progress is needed to understand quantitative limitations
- We are going to more extreme small systems, including photon-nucleus collisions and flow inside of jets
- We are sensitive to nuclear structure - in small nuclei we can test low-energy ab-initio model predictions for deformations and clustering at high energy

SUMMARY

- Hydrodynamic description and also smaller systems
 - Small systems: qualitative progress is
 - Fluid dynamics needed to progress is
 - We are going to nucleus
- We are sensitive to nuclear structure - in small nuclei we can test low-energy ab-initio model predictions for deformations and clustering at high energy



See contribution to Quark-Gluon Plasma 6 (World Scientific):

Progress and Challenges in Small Systems

Jorge Noronha, Björn Schenke, Chun Shen, Wenbin Zhao

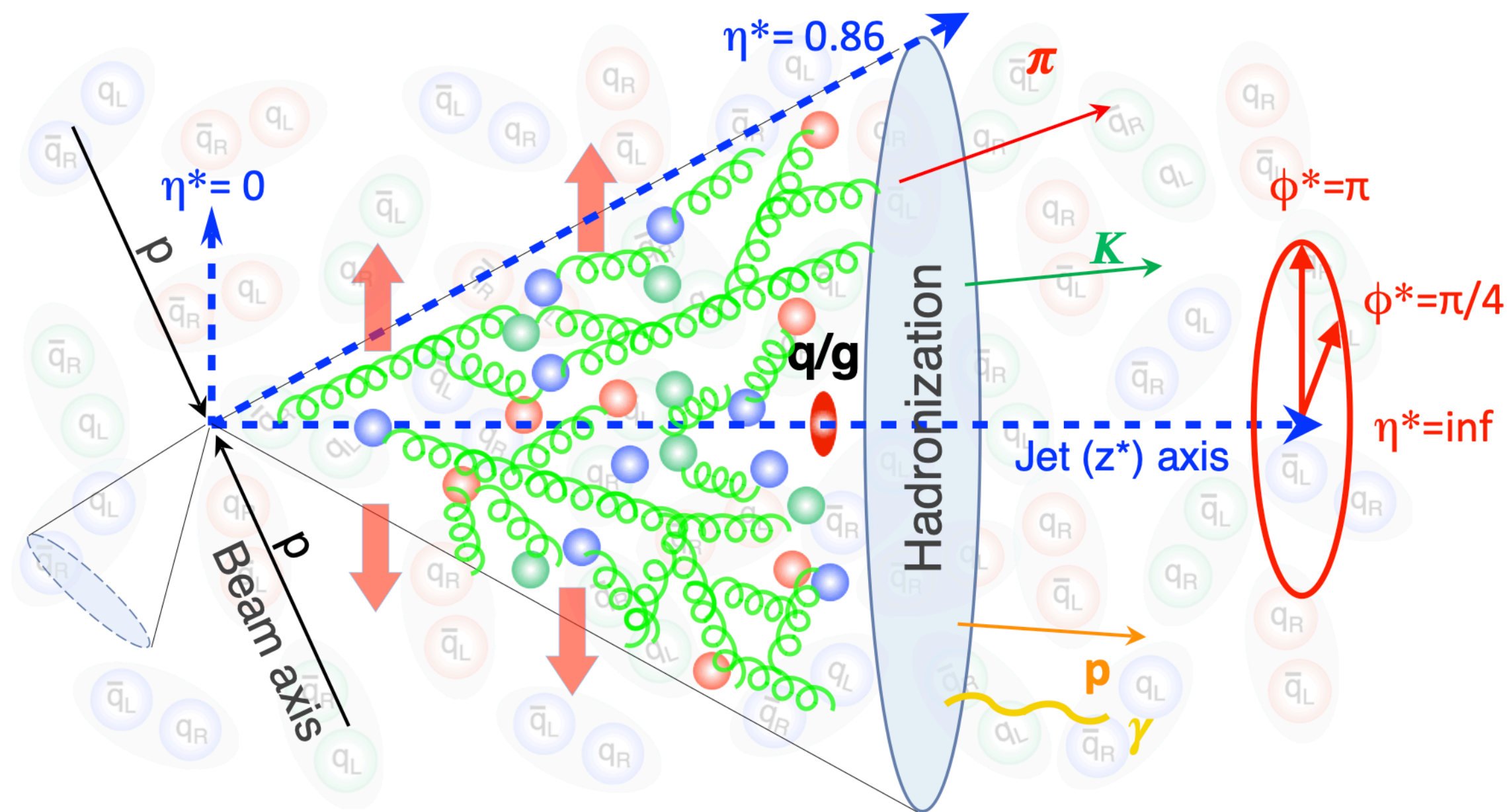
e-Print: 2401.09208 [nucl-th]

BACKUP

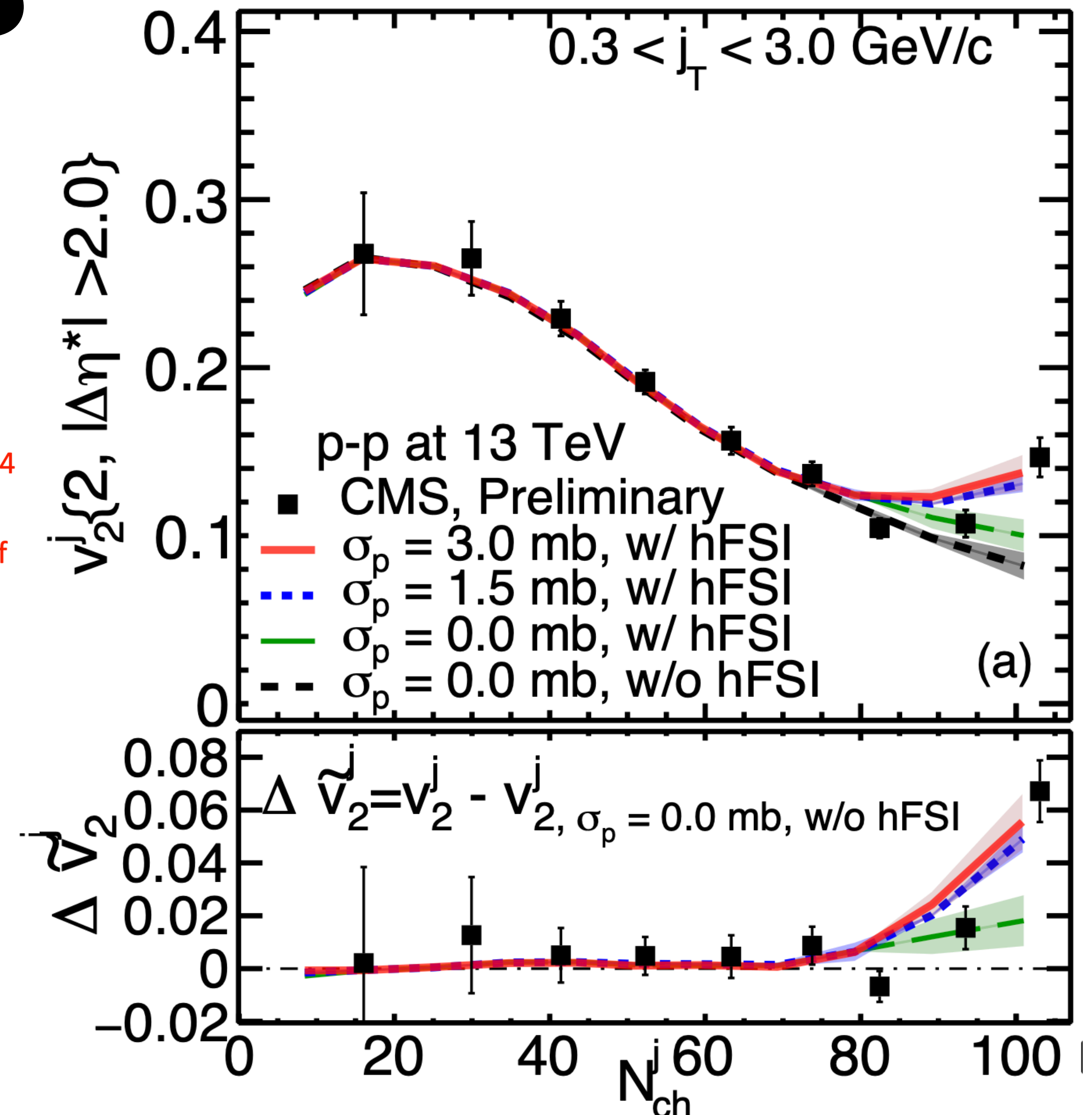
FLOW INSIDE JETS

CMS Collaboration, arXiv:2312.17103

W. Zhao, Z.-W. Lin, X.-N. Wang, arXiv:2401.13137



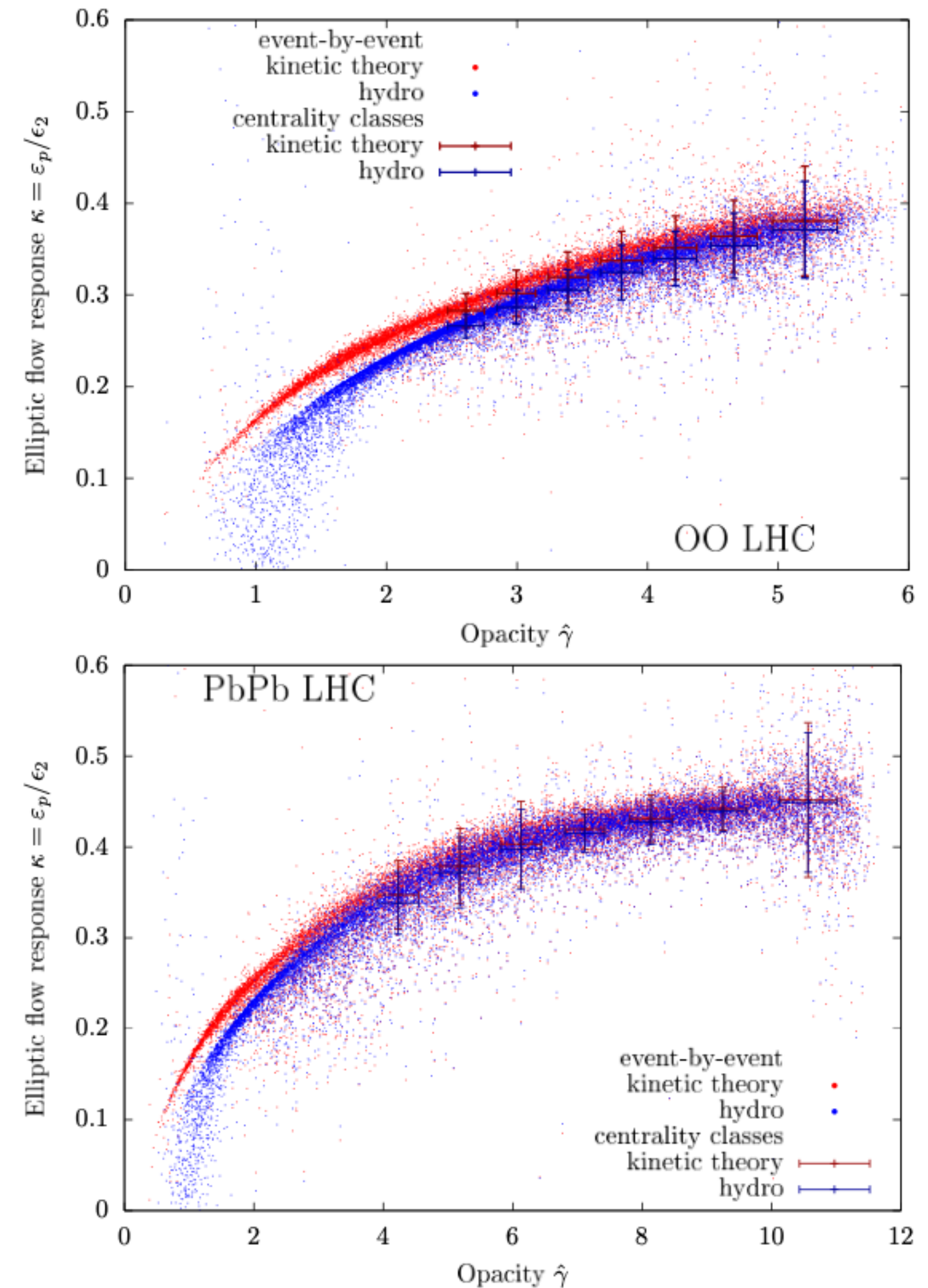
Final state effects can explain increase of v_2 at high multiplicity



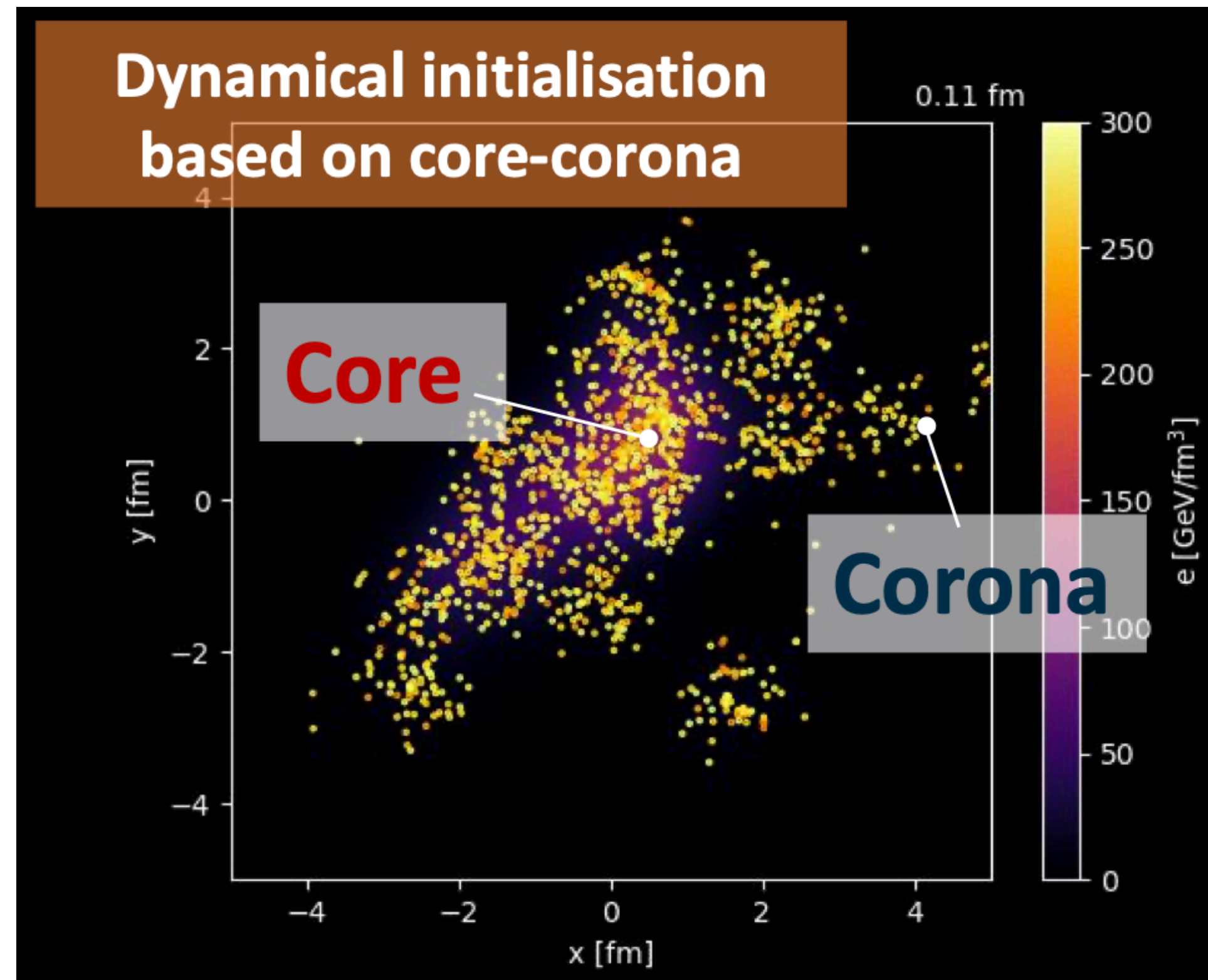
Kinetic theory vs. hydrodynamics

V. E. Ambrus,, S. Schlichting, C. Werthmann
Phys.Rev.D 111 (2025) 5, 054024

- Compare **kinetic theory** to **Israel-Stewart hydrodynamics**
- Hydro aspects are chosen to be the same
- Opacity measures total interaction rate, depends on viscosity, transverse size and energy scale
- They differ at low opacity where the system is not fully described by just the hydrodynamic modes

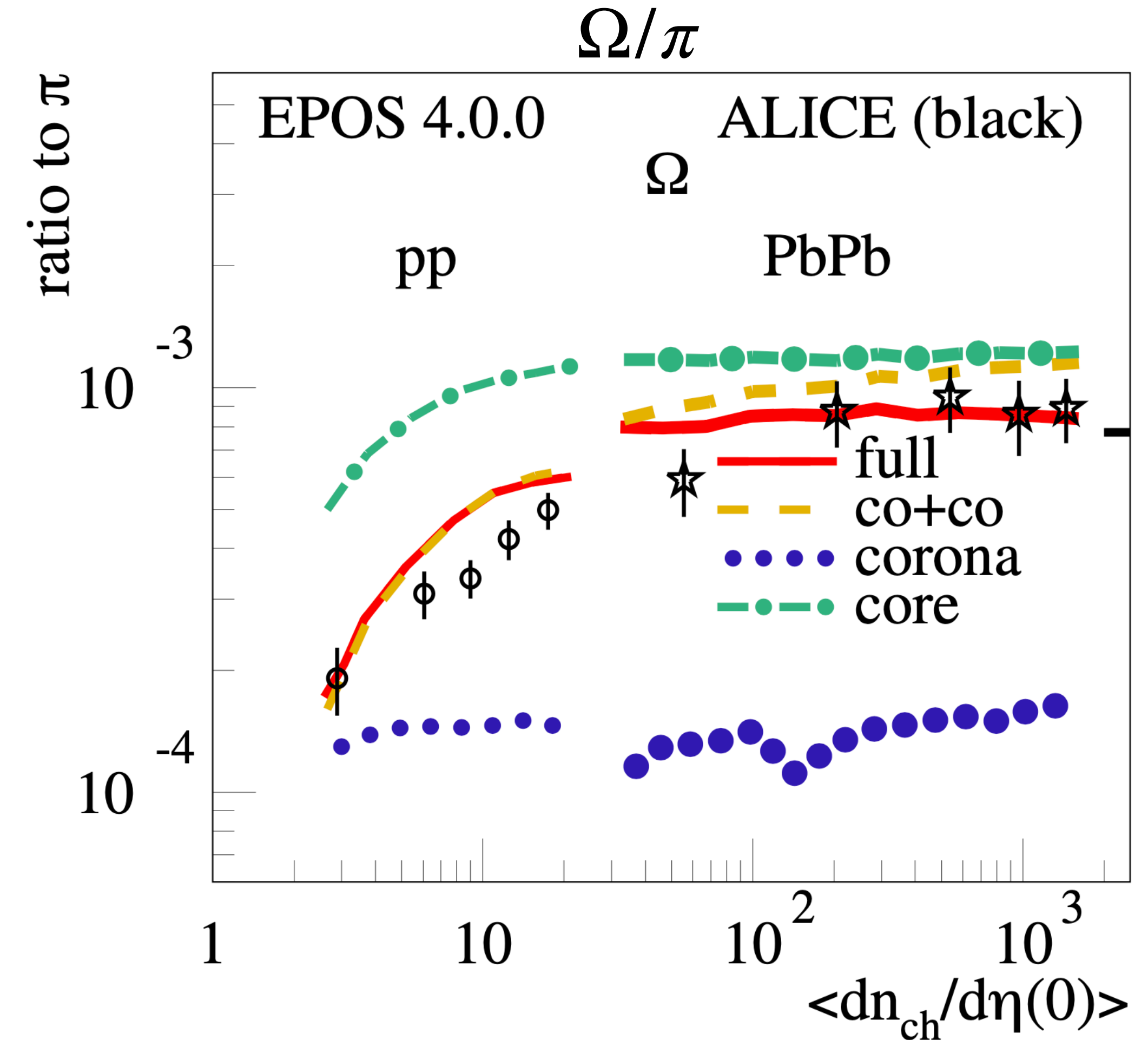


CORE+CORONA PICTURE



Y. Kanakubo, Quark Matter 2023

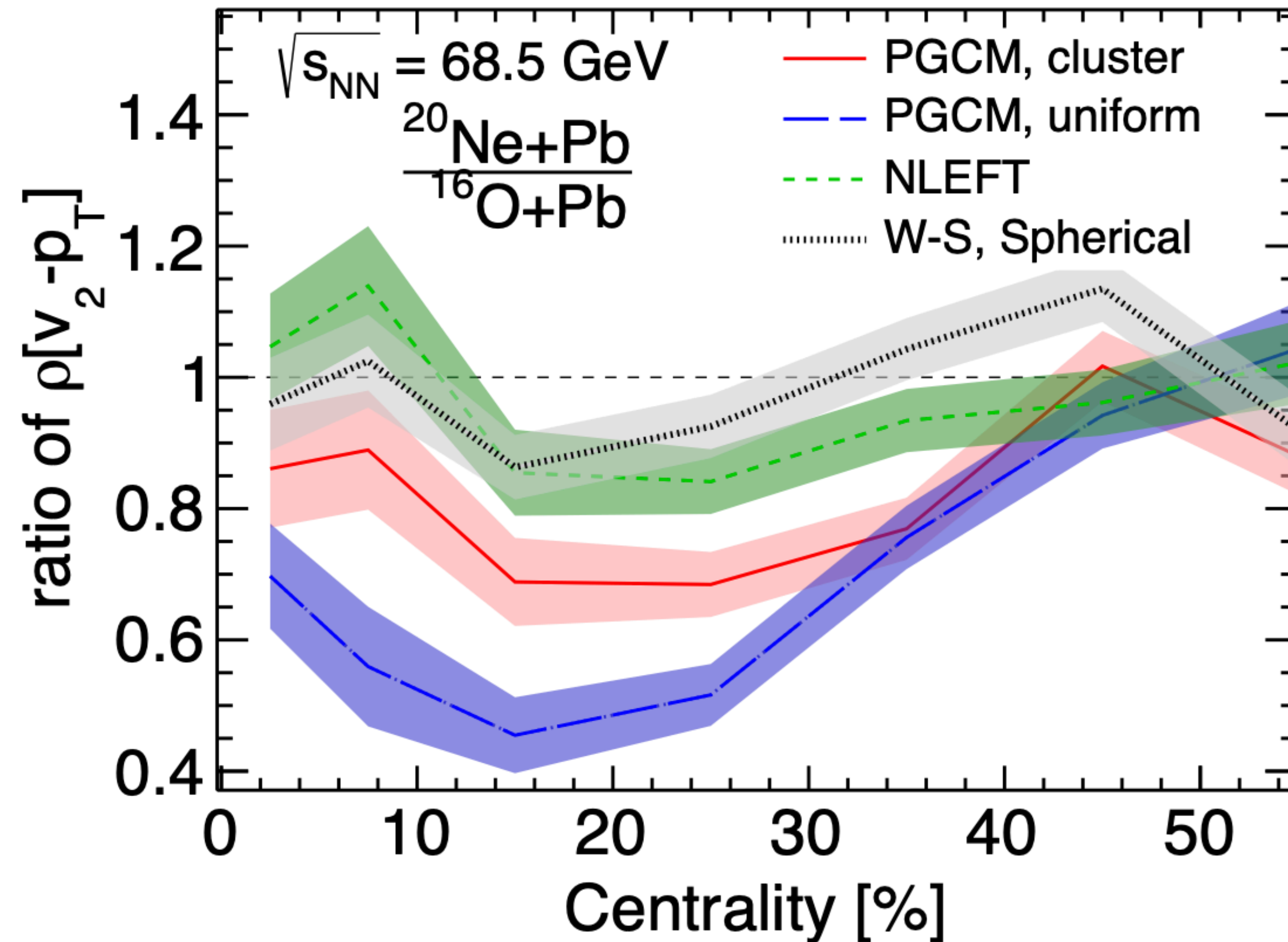
Hydro-like core begins to dominate
for $dN_{\text{ch}}/d\eta \approx 10 - 20$



K. Werner, Phys.Rev.C 108 (2023) 6, 064903

Pb+Ne and Pb+O

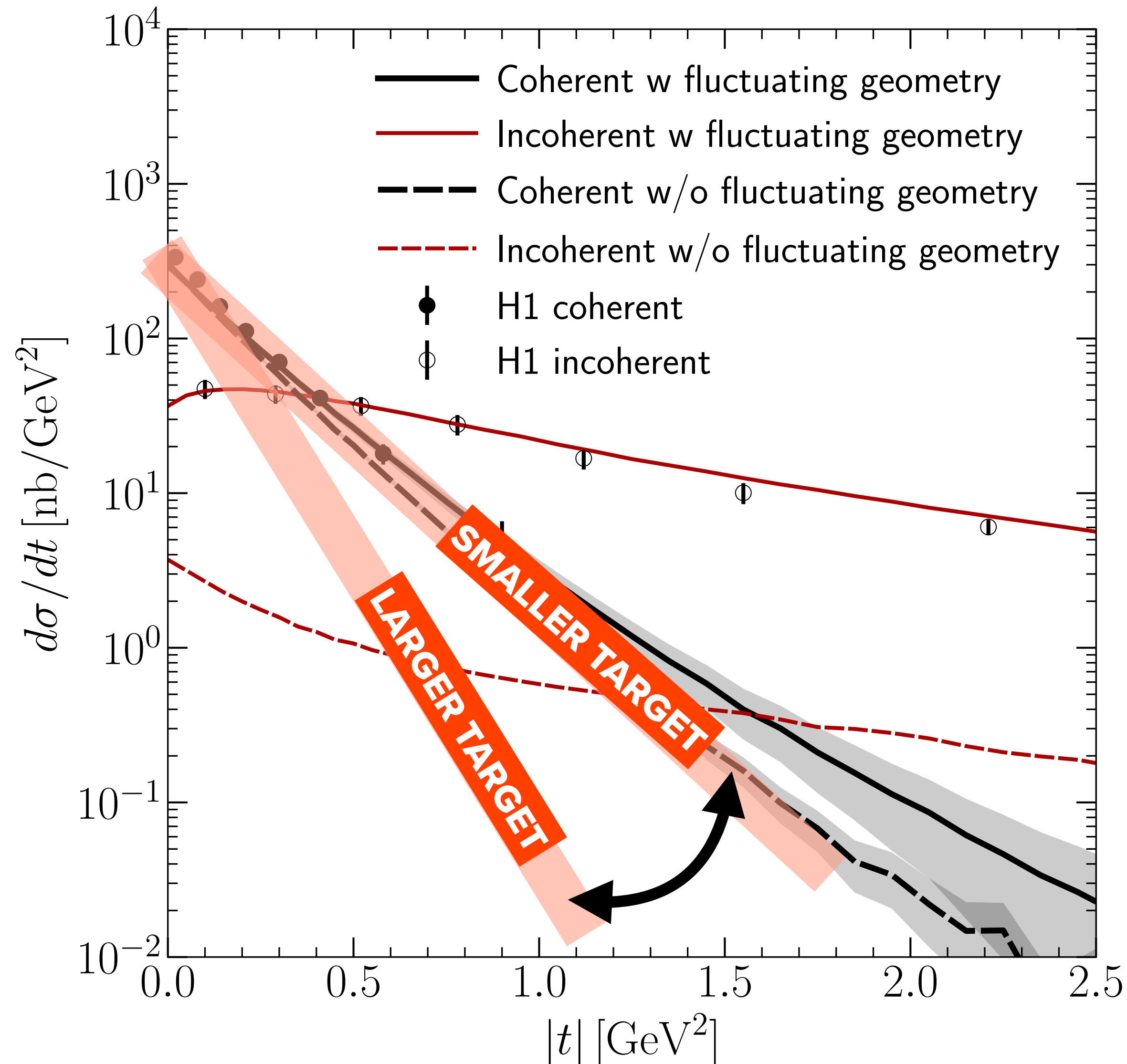
G. Giacalone, W. Zhao, B. Schenke, C. Shen, et al., in preparation



$$\rho(v_n^2, \langle p_T \rangle) = \frac{\langle \hat{\delta} v_n^2 \hat{\delta} \langle p_T \rangle \rangle}{\sqrt{\langle (\hat{\delta} v_n^2)^2 \rangle \langle (\hat{\delta} \langle p_T \rangle)^2 \rangle}}$$

The ratios of the $v_2 - p_T$ correlation show strong sensitivity to nuclear configurations from different low-energy nuclear theory calculations

PROTON RADIUS MEASUREMENT



H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

Slope of coherent cross section constrains **gluonic radius** of the proton

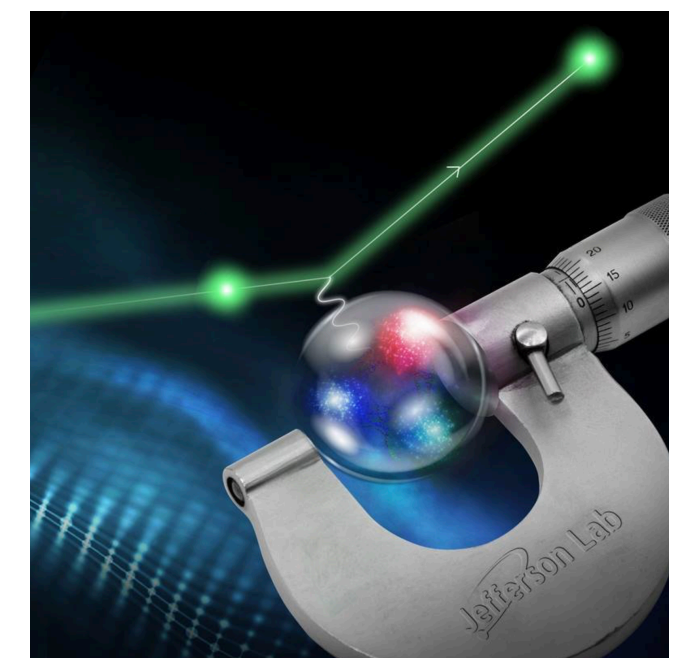
Extracted value for $r_p^g \approx 0.6$ fm

Compare to proton mass rms radius
 $r_p^M = 0.52 \pm 0.03$ fm determined at JLab via
 threshold production of J/ψ

[J/ψ-007 Collaboration, Nature 615, 813–816 \(2023\)](#)

Smaller than charge radius:

$r_p = 0.84$ fm



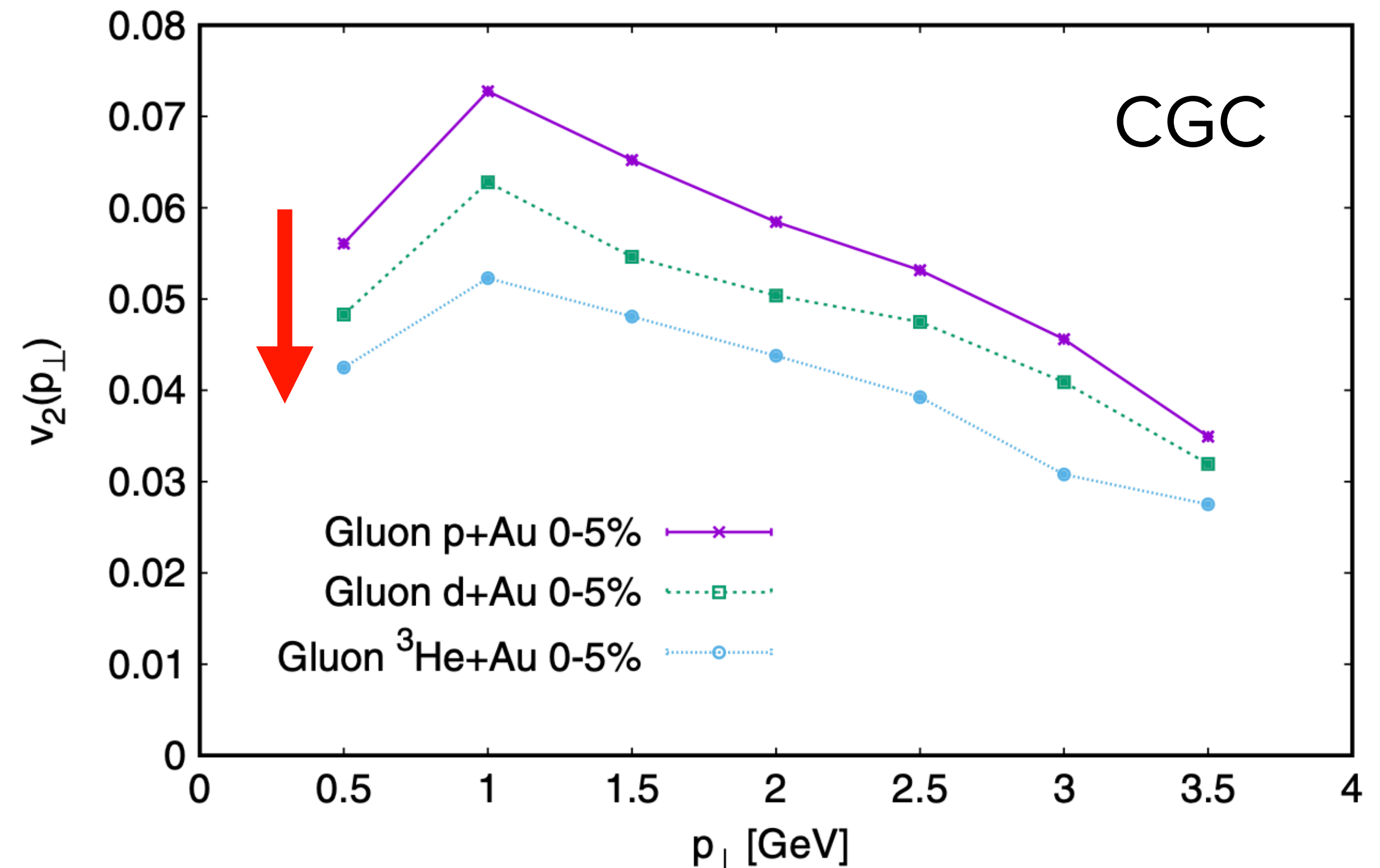
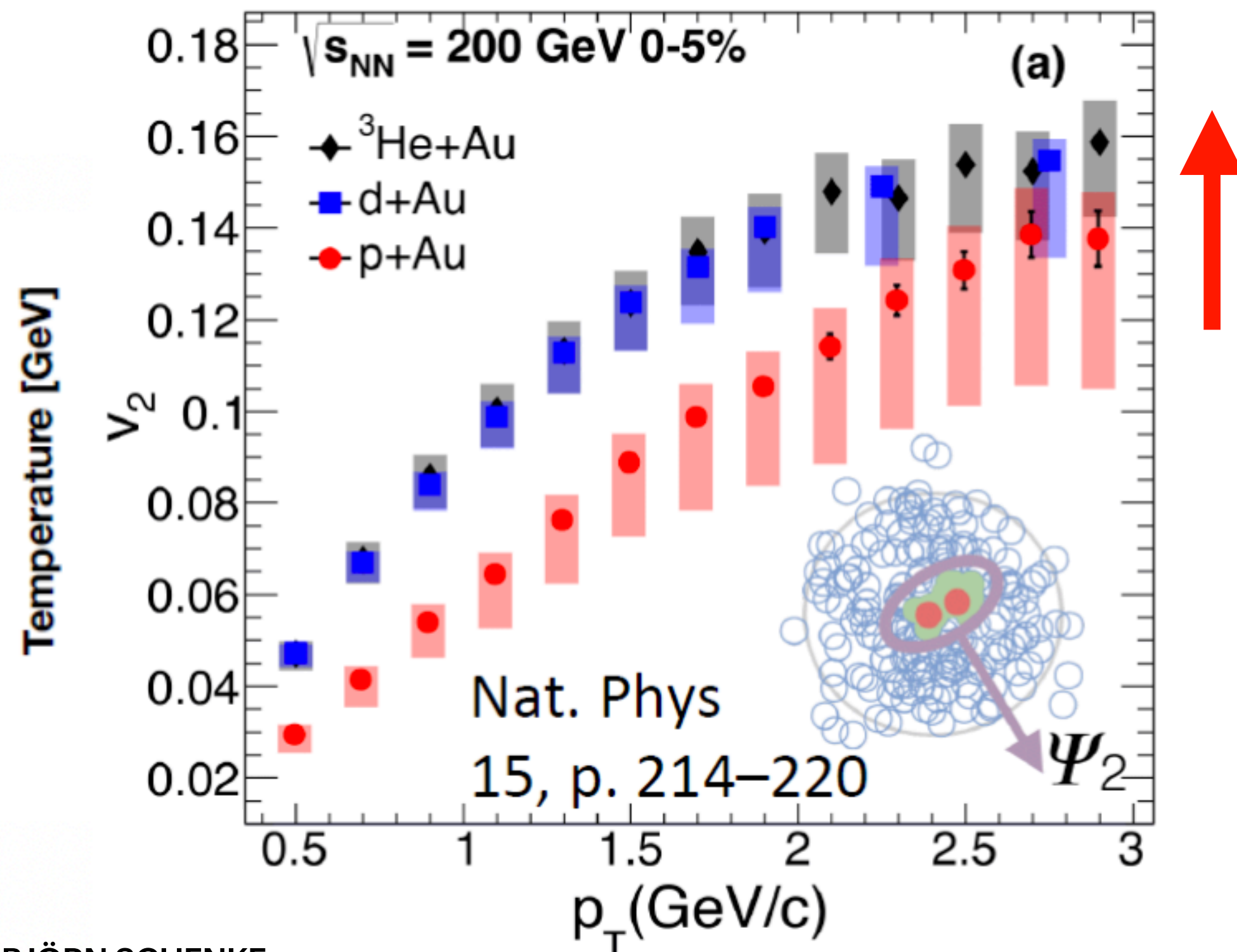
INITIAL STATE EFFECTS?

PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)

B. Schenke, S. Schlichting, R. Venugopalan, Phys.Lett.B 747 (2015) 76-82, 1502.01331

M. Mace, V. V. Skokov, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 121, 052301 (2018), PRL123, 039901(E) (2019)

Initial state momentum anisotropy, for example from the Color Glass Condensate:
Cannot get all systematics right:



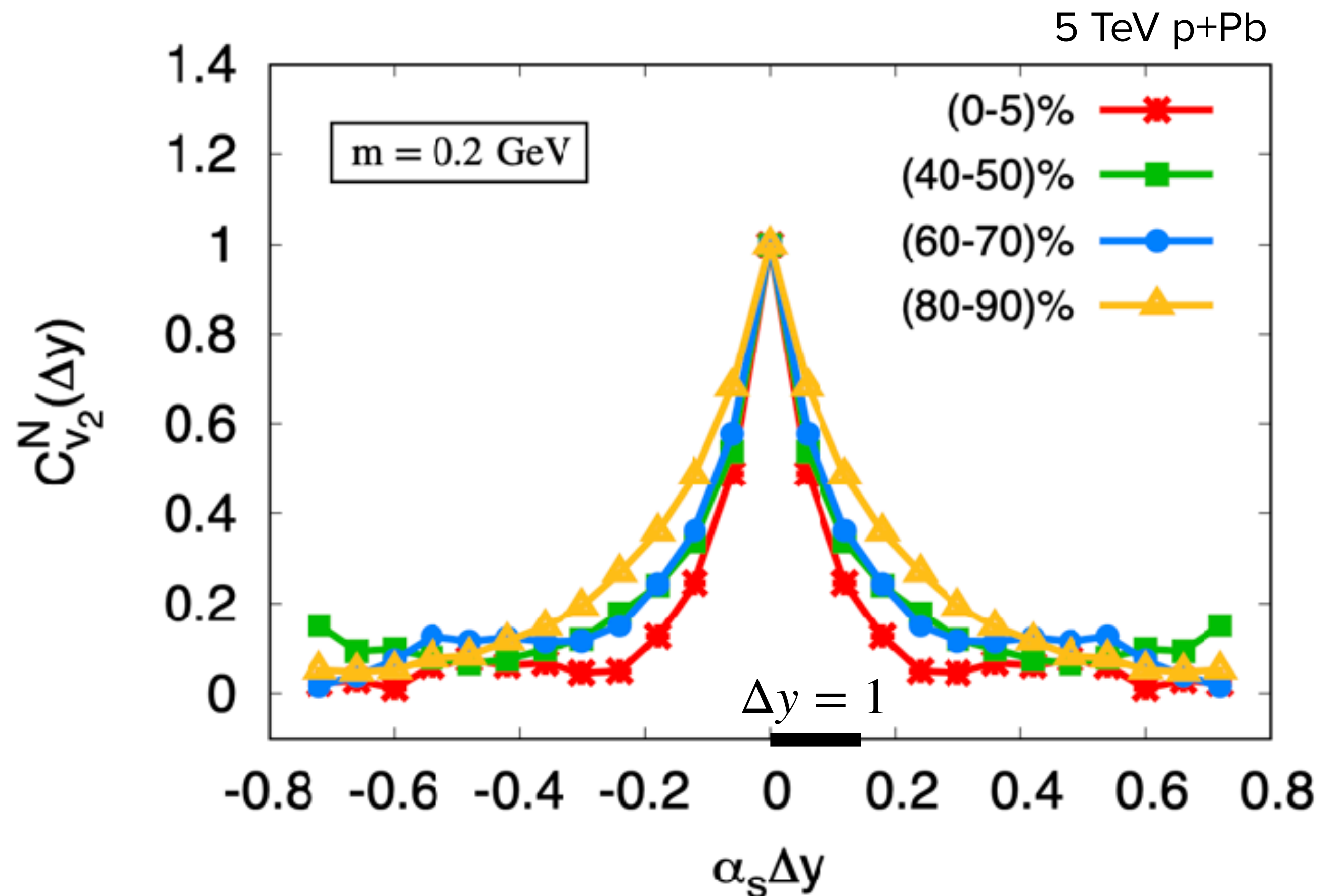
RAPIDITY DEPENDENCE OF INITIAL ANISOTROPY

B.Schenke, S. Schlichting, and Pragma Singh, Phys.Rev.D 105 (2022) 9, 094023

CGC based IP-Glasma
+ rapidity evolution (JIMWLK)

$$C_{\mathcal{O}}^N(\eta_1, \eta_2) = \frac{\langle \text{Re}(\mathcal{O}(\eta_1)\mathcal{O}^*(\eta_2)) \rangle}{\sqrt{\langle |\mathcal{O}(\eta_1)|^2 \rangle \langle |\mathcal{O}(\eta_2)|^2 \rangle}}$$

Initial momentum anisotropy
decorrelates quickly
with rapidity difference



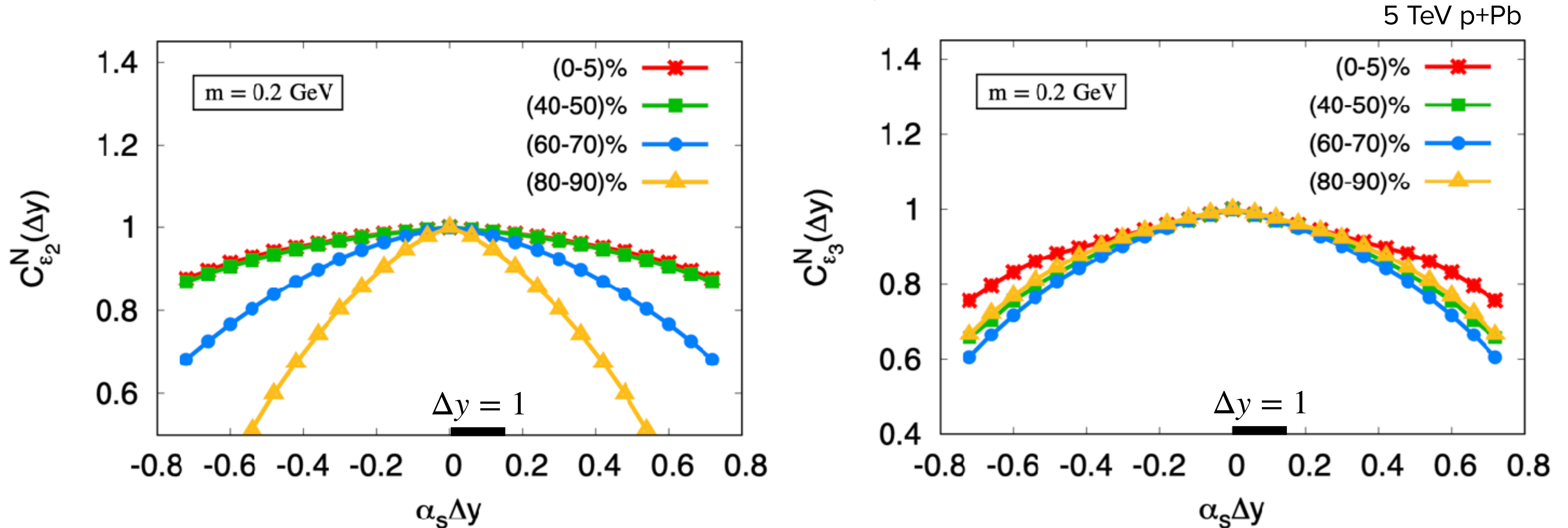
further evidence: Observed Baryon/meson v_2 grouping and splitting (see You Zhou's talk)

→ **Strong final state interactions needed to describe data**

RAPIDITY DEPENDENCE OF GEOMETRY

B.Schenke, S. Schlichting, and Pragma Singh, Phys.Rev.D 105 (2022) 9, 094023

The geometry, quantified here with ε_2 and ε_3 , decorrelates slowly



but rapidity dependence is not insignificant

$$C^N_{\mathcal{O}}(\eta_1, \eta_2) = \frac{\langle \text{Re}(\mathcal{O}(\eta_1) \mathcal{O}^*(\eta_2)) \rangle}{\sqrt{\langle |\mathcal{O}(\eta_1)|^2 \rangle \langle |\mathcal{O}(\eta_2)|^2 \rangle}}$$

EQUATION OF STATE AT FINITE CONSERVED CHARGES

M. Albright, J. Kapusta and C. Young, Phys. Rev. C90, 024915 (2014)

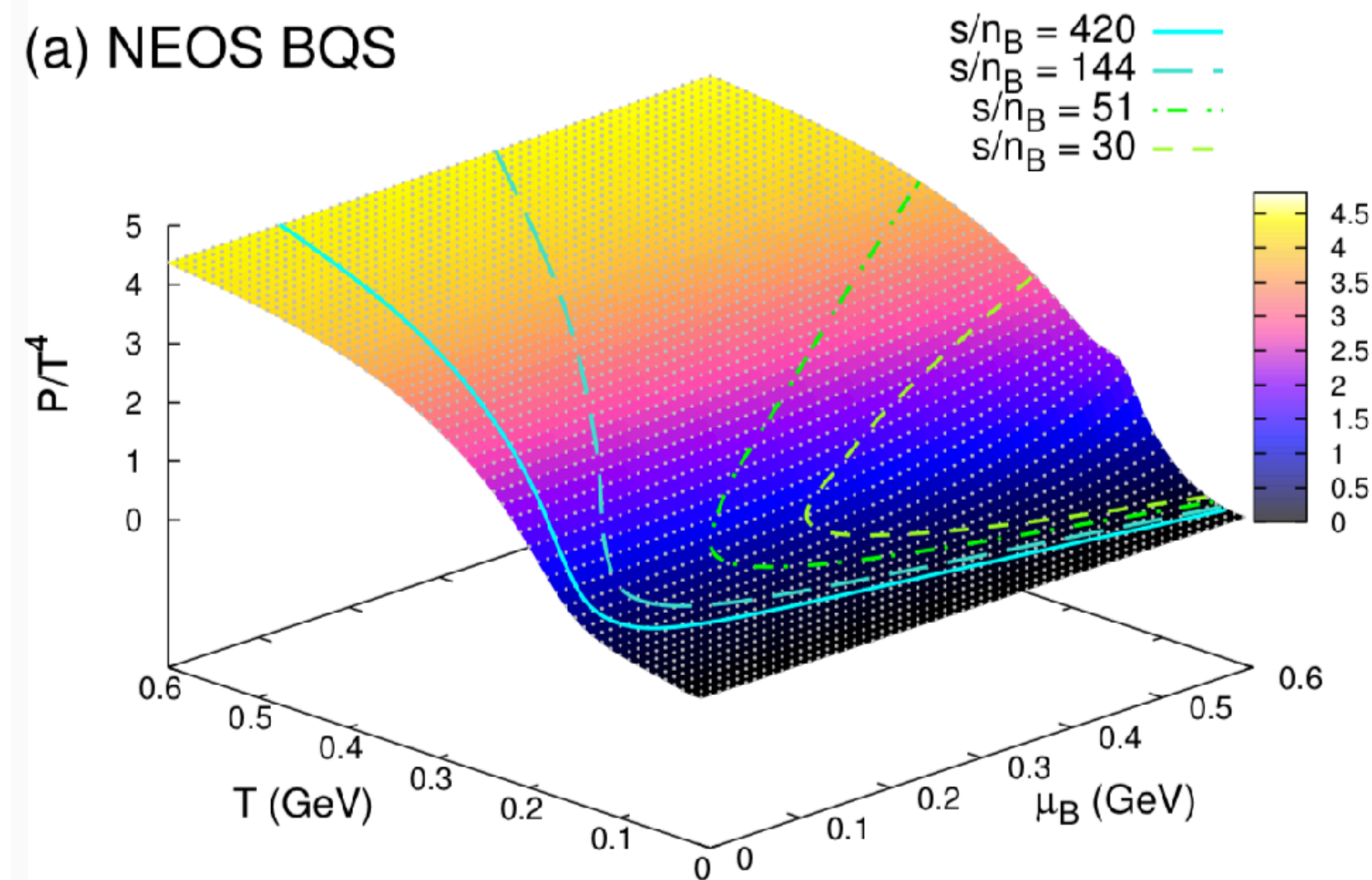
A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)

J. Noronha-Hostler, P. Parotto, C. Ratti and J. M. Stafford, Phys. Rev. C100, 064910 (2019)

J. M. Karthein et. al, Eur. Phys. J. Plus 136 (2021) 6, 621

$$n_s = 0 \quad n_Q = 0.4n_B$$

(a) NEOS BQS



Lattice QCD: Taylor expansion up to the 4th order

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi_{l,m,n}^{B,Q,S}}{l!m!n!} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

Match to Hadron Resonance Gas model at low T

$$\frac{P}{T^4} = \frac{1}{2}[1 - f(T, \mu_J)] \frac{P_{\text{had}}(T, \mu_J)}{T^4} + \frac{1}{2}[1 + f(T, \mu_J)] \frac{P_{\text{lat}}(T, \mu_J)}{T^4}$$

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C100, 024907 (2019)

Being extended to fully 4D EOS $P(\varepsilon, n_B, n_Q, n_S)$