PROGRESS TOWARDS UNDERSTANDING FLOW IN SMALL SYSTEMS

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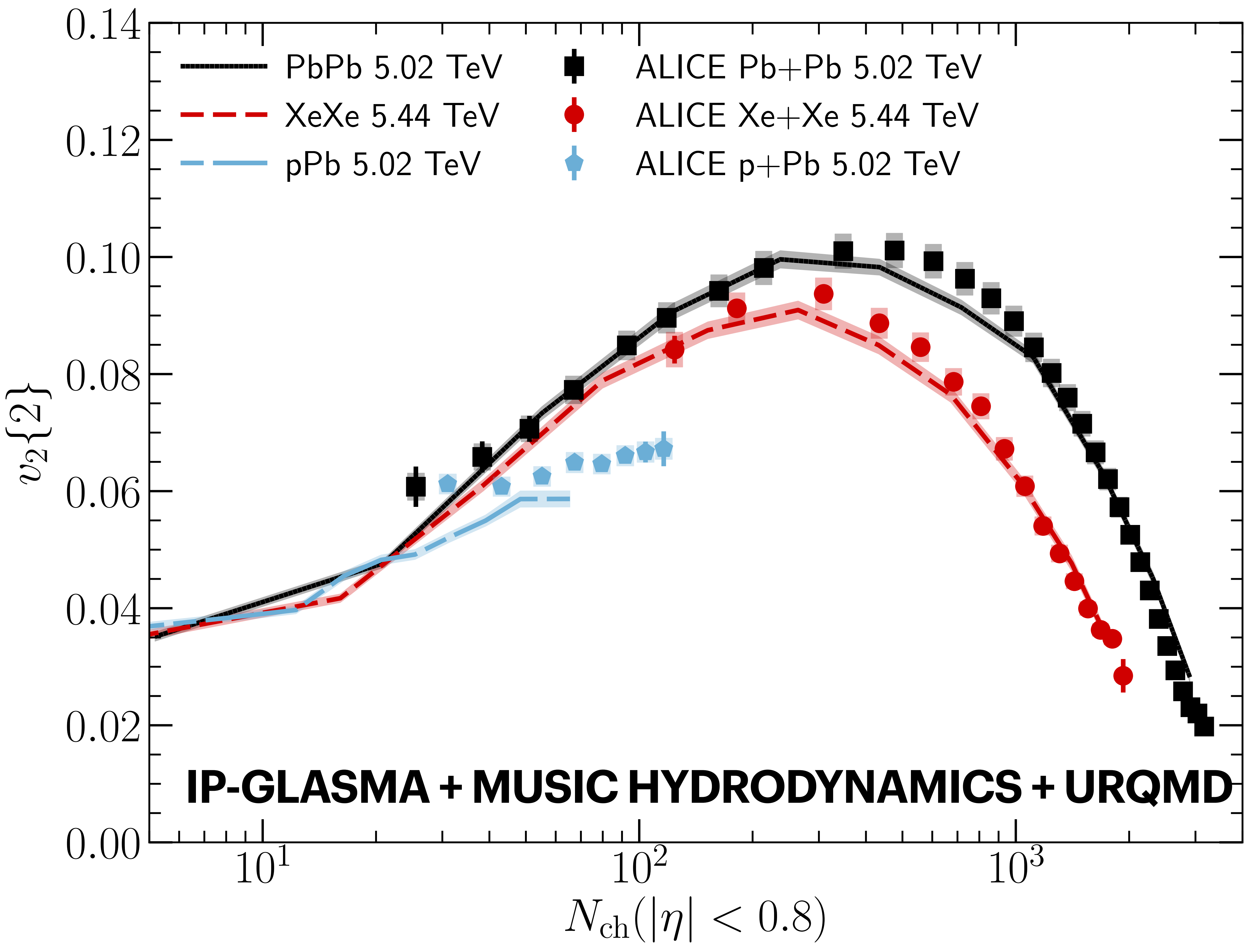
JUNE 7 2024

STRANGE QUARK MATTER 2024
STRASBOURG, FRANCE

SQM 2024

FLOW IN SMALL SYSTEMS



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

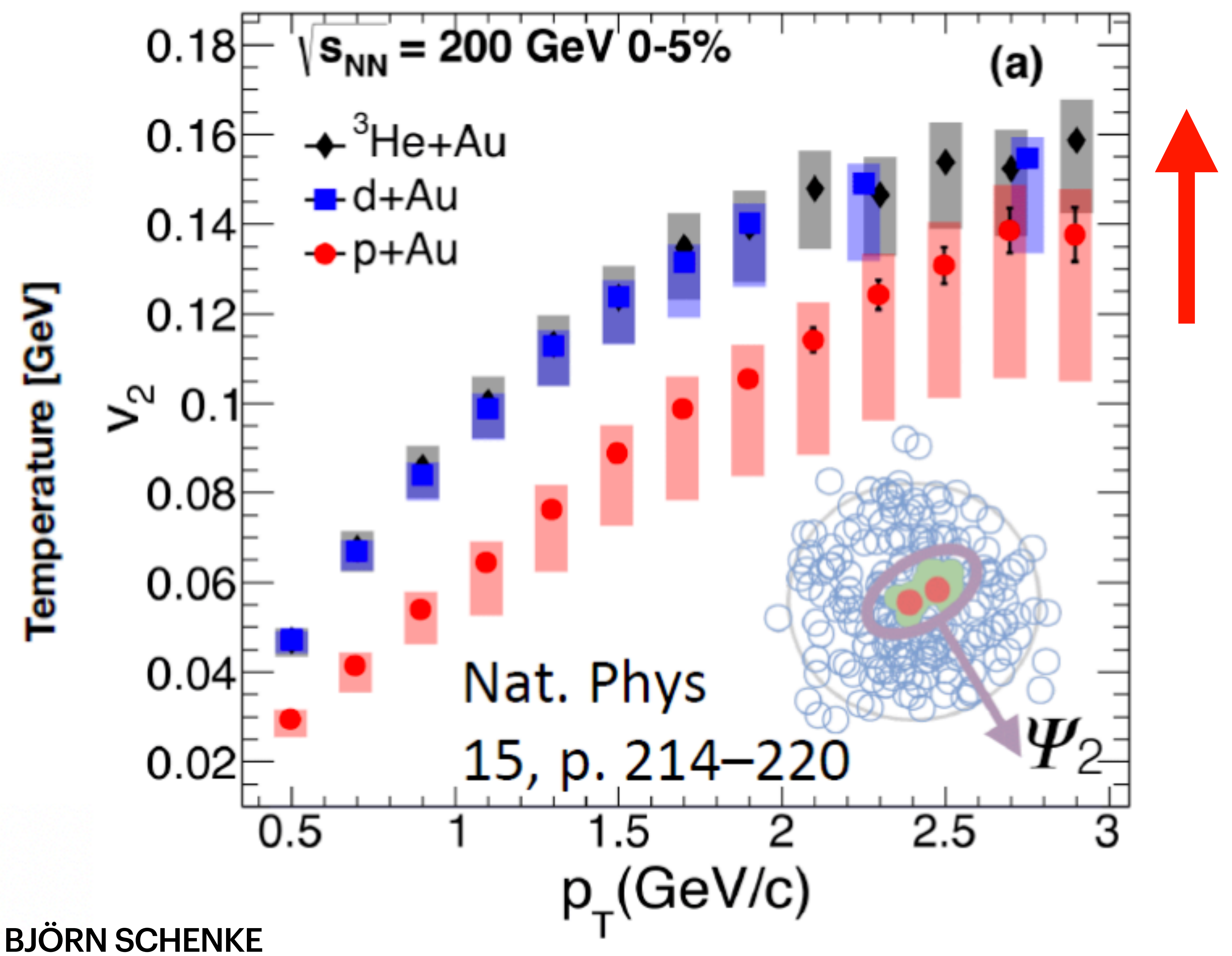
There is evidence that the same is true in high multiplicity small systems

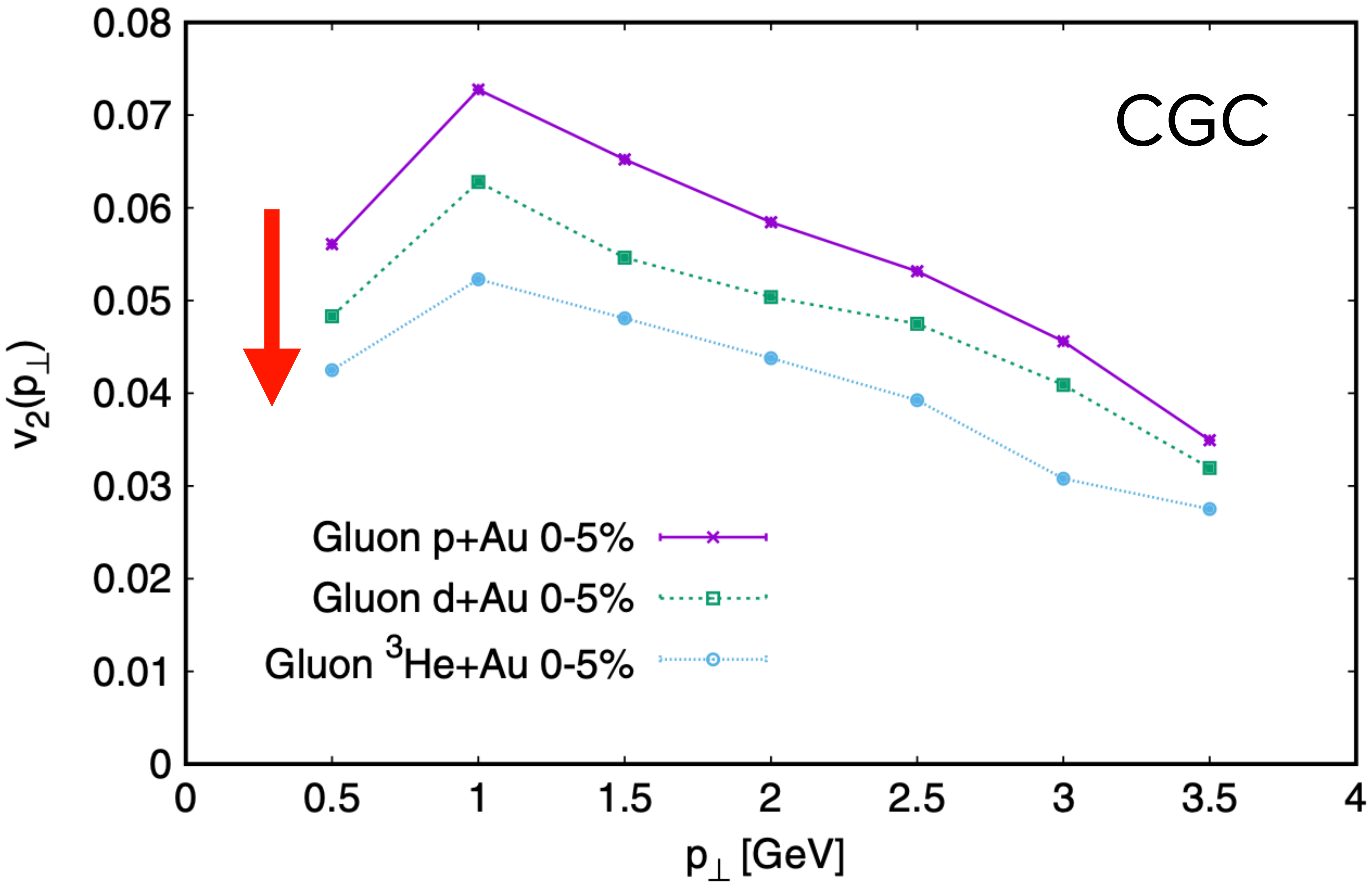
B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905
ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301

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:





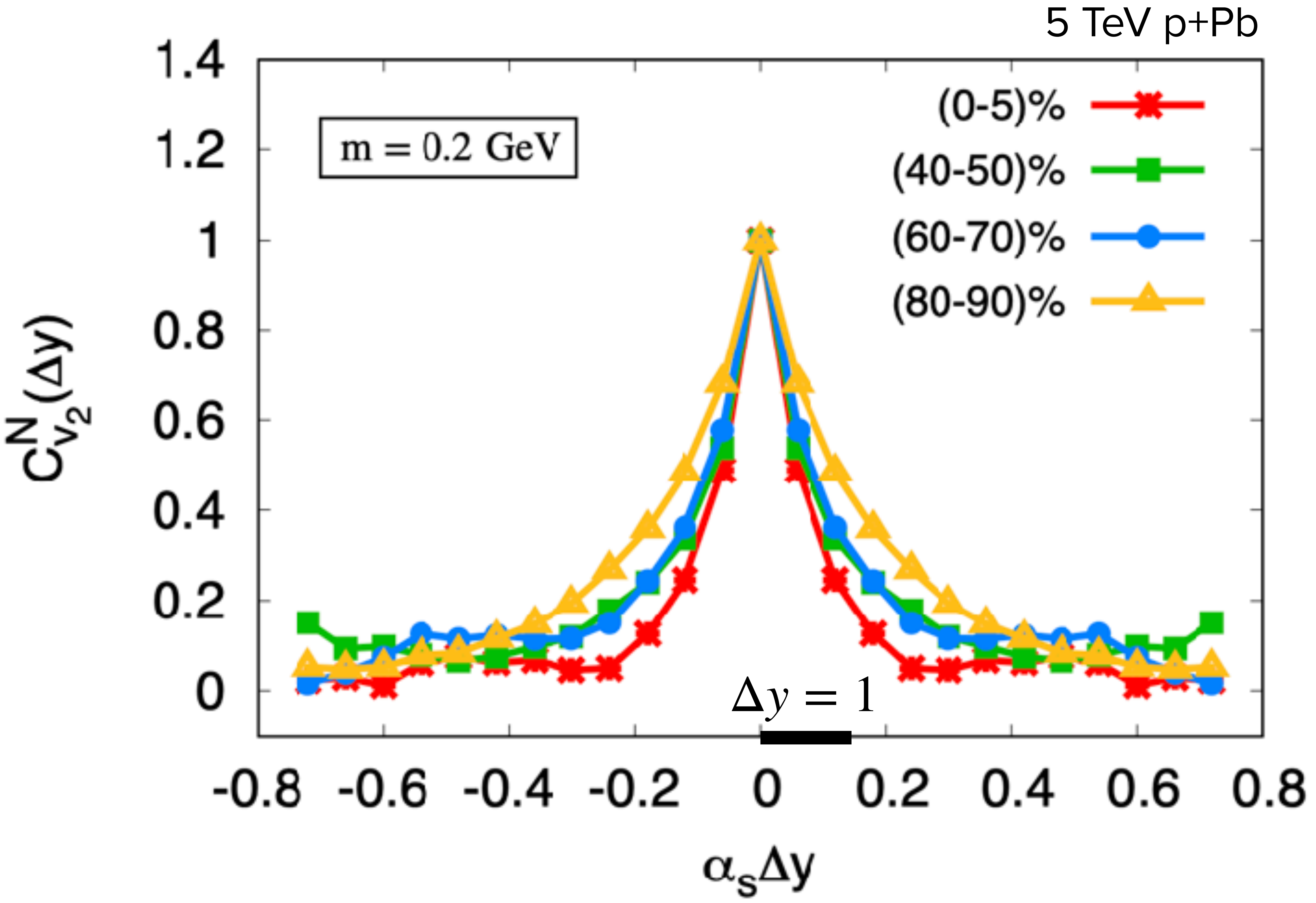
RAPIDITY DEPENDENCE OF INITIAL ANISOTROPY

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

CGC based IP-Glasma
+ rapidity evolution (JIMWLK)

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

Initial momentum anisotropy
decorrelates quickly
with rapidity difference



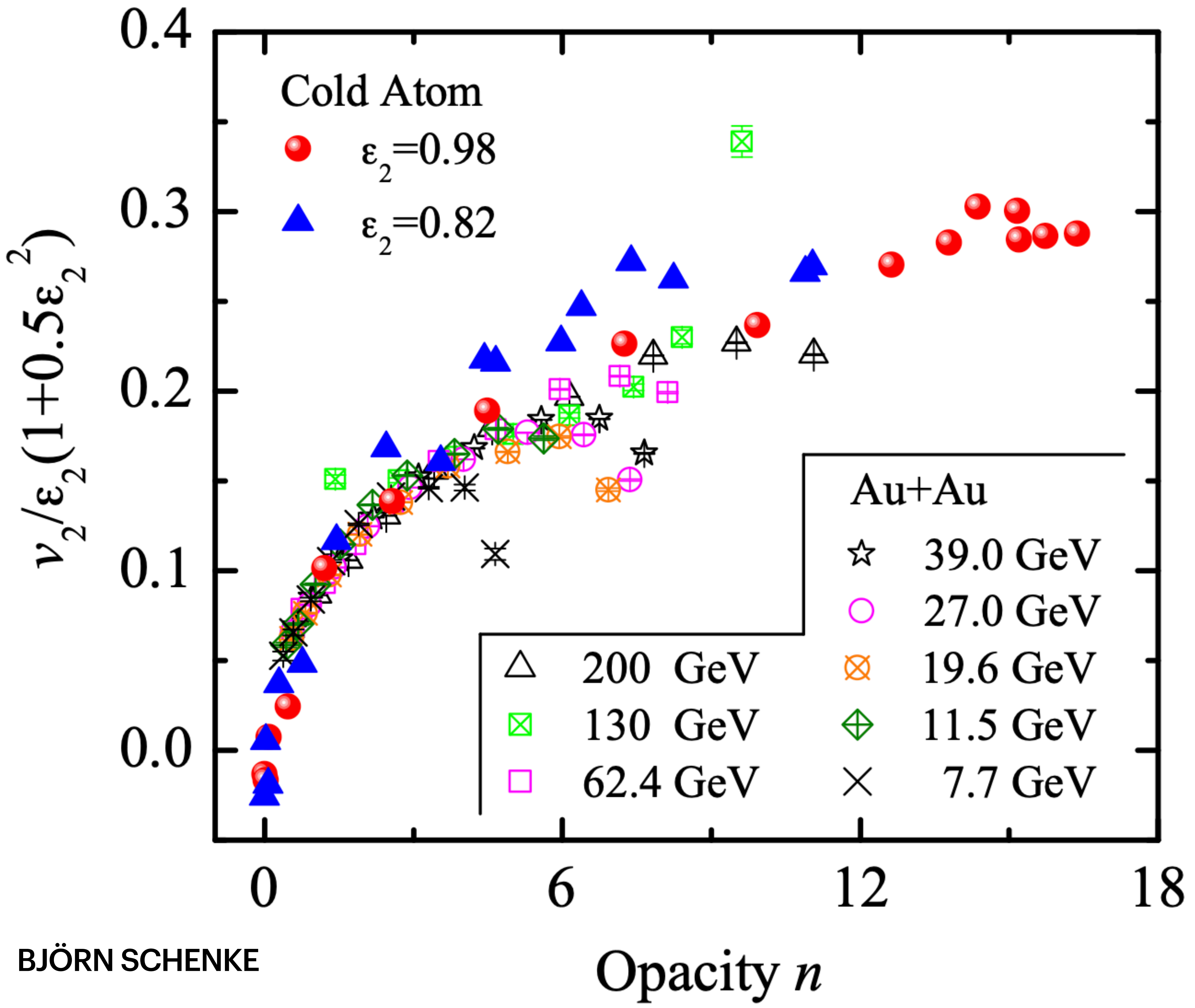
further evidence: Observed Baryon/meson v_2 grouping and splitting (see You Zhou’s talk)

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

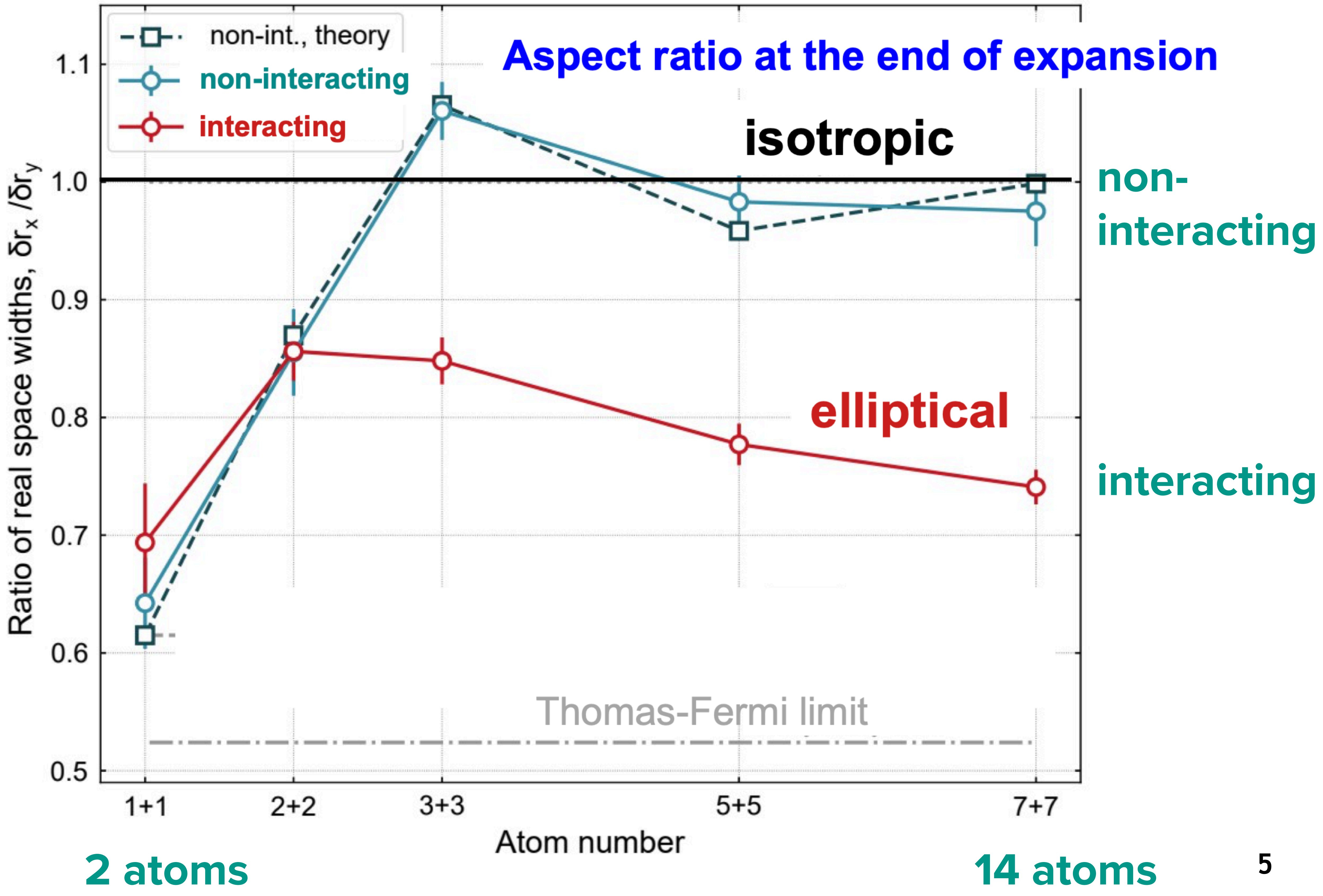
INSIGHTS FROM COLD ATOMS

K. Li, H.-F. Song, Y.-L. Sun, H.-J. Xu, F. Wang, arXiv:2405.02847
Bandstetter, Lunt, Heintze, Giacalone, Heyen, Gałka, Subramanian, Holten, Preiss, Floerchinger, Jochim arXiv:2308.09699

Heavy ions vs. cold ^{6}Li ions with varying interaction strength: v_2/ε_2 agree



Very few particles: interaction drives elliptic flow for $N_{\text{atoms}} \geq 6$ see talk by Lars Heyen

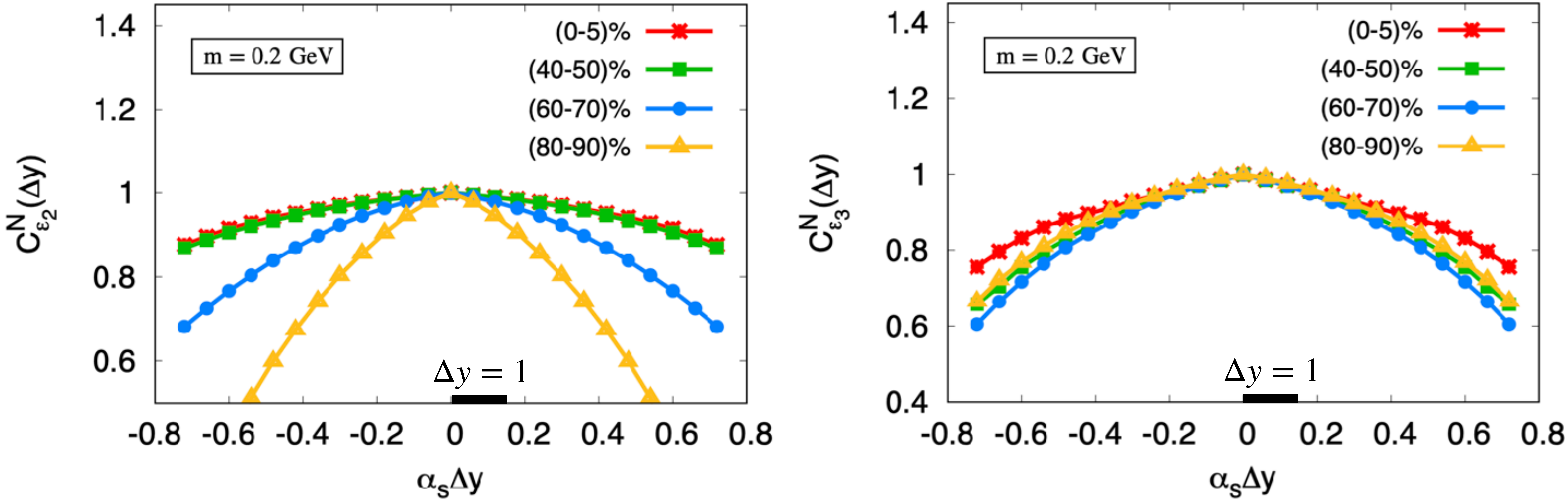


RAPIDITY DEPENDENCE OF GEOMETRY

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

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

5 TeV p+Pb

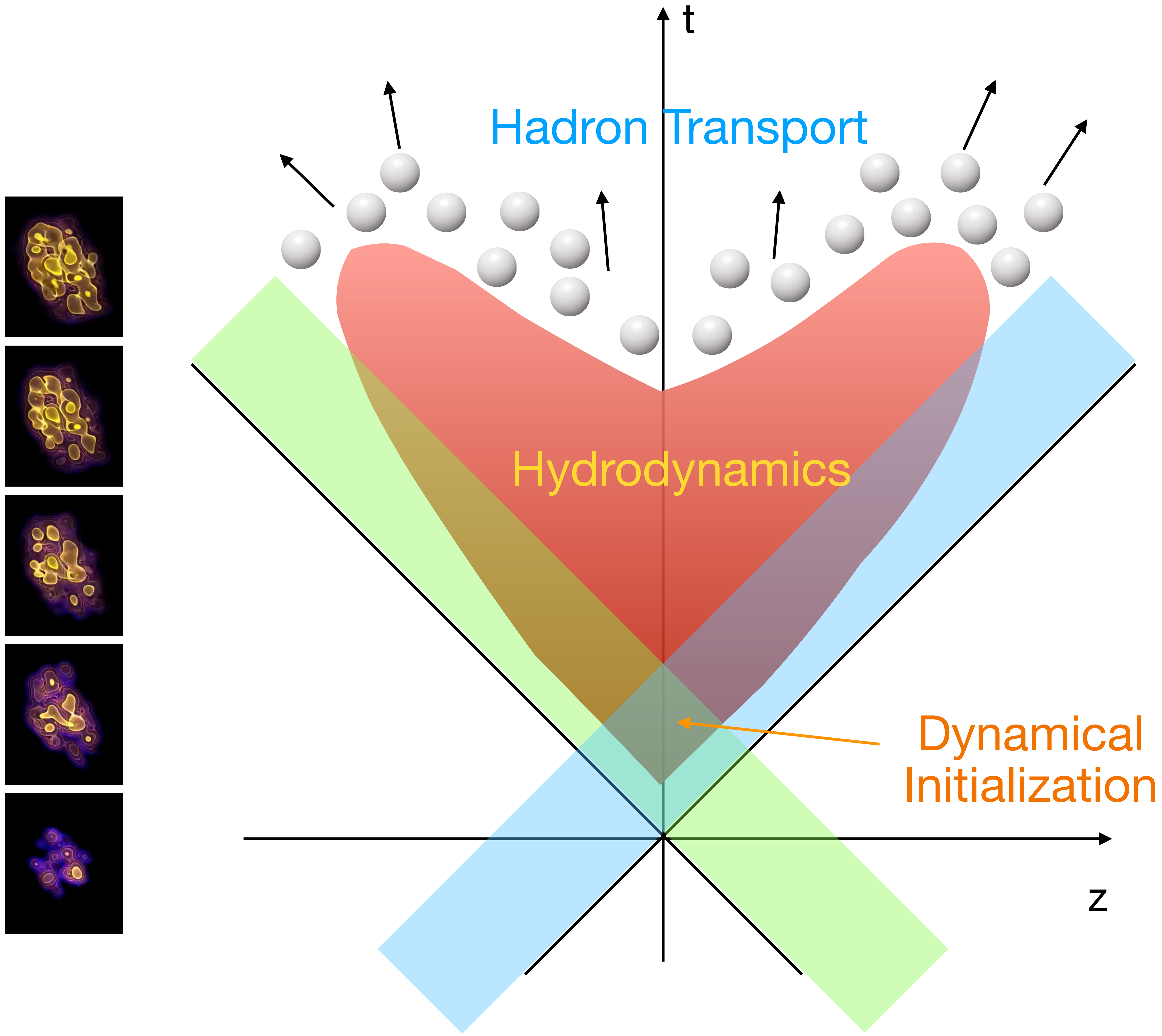


but rapidity dependence is not insignificant

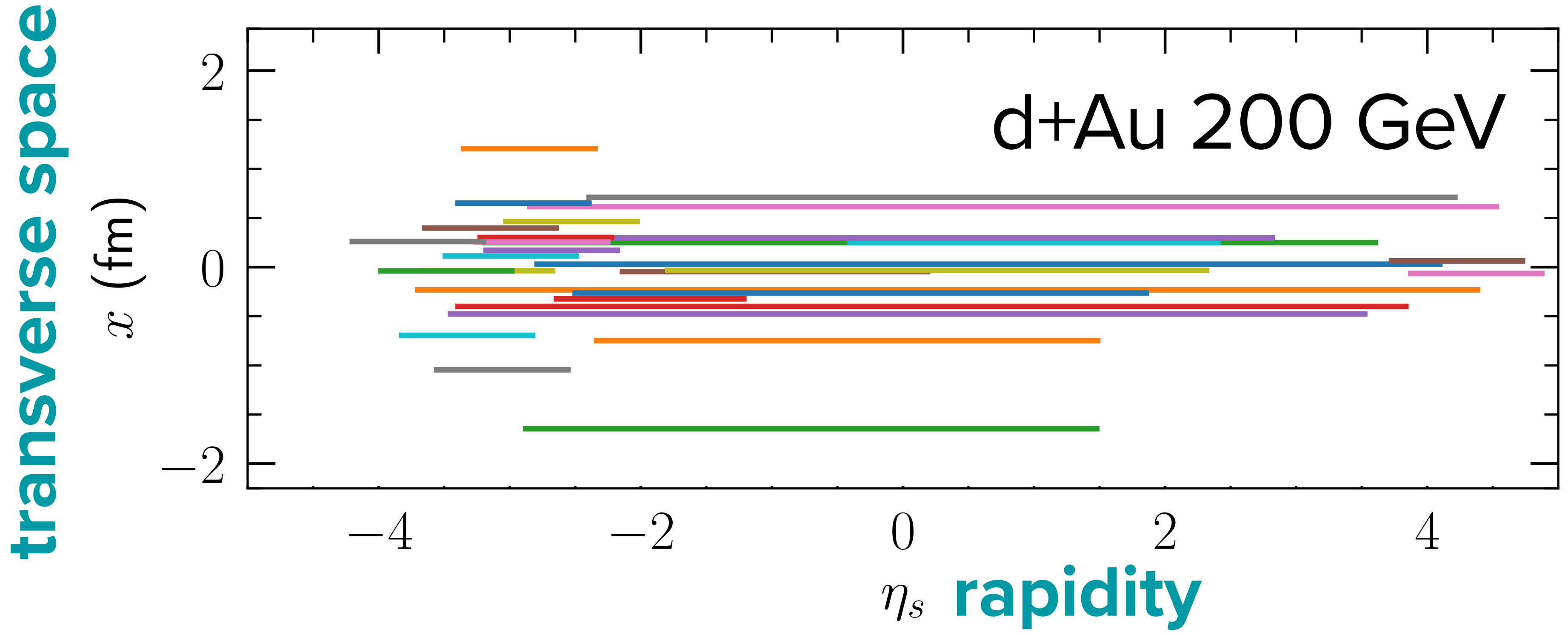
$$C^N_{\mathcal{O}}(\eta_1, \eta_2) = \frac{\left\langle \mathrm{Re}\left(\mathcal{O}(\eta_1)\mathcal{O}^*(\eta_2)\right) \right\rangle}{\sqrt{\langle |\mathcal{O}(\eta_1)|^2 \rangle \langle |\mathcal{O}(\eta_2)|^2 \rangle}}$$

DYNAMIC 3+1D SIMULATION

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

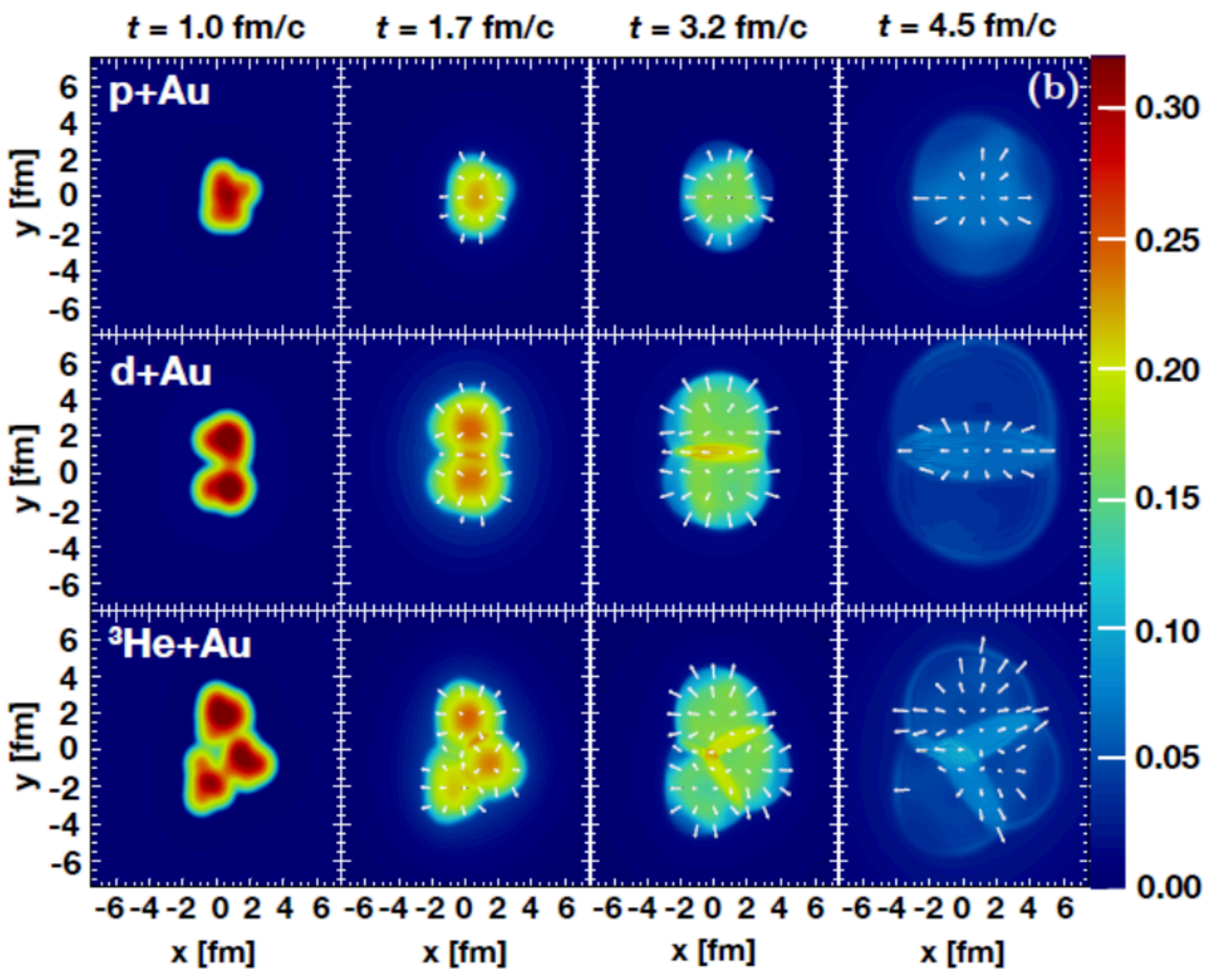


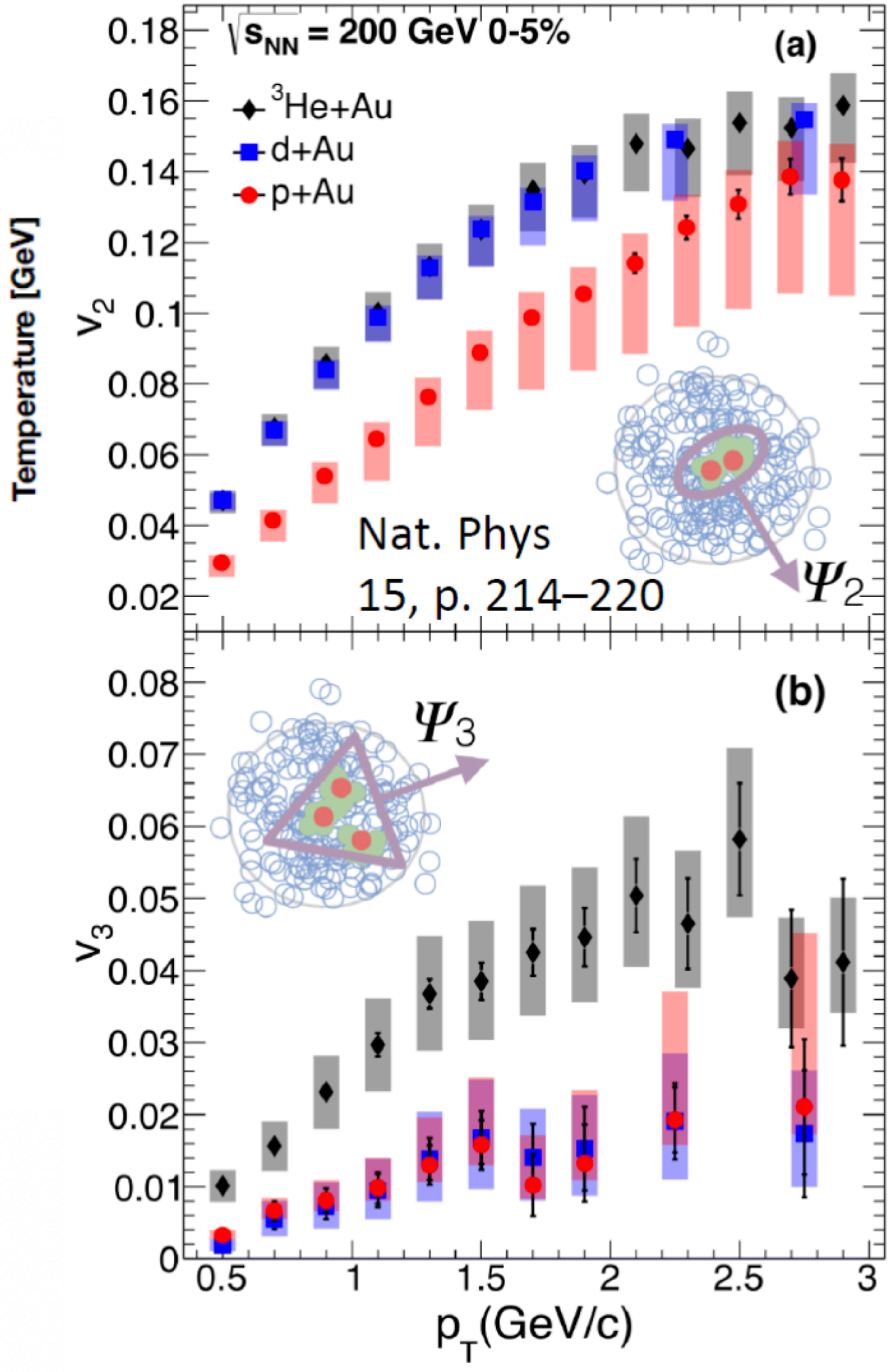
- Simulate small systems dynamically in 3+1D
- Initialize using MC-Glauber + string deceleration model with source terms in hydro
- Provides fluctuating transverse+longitudinal geometry



SMALL SYSTEM SCAN AT RHIC

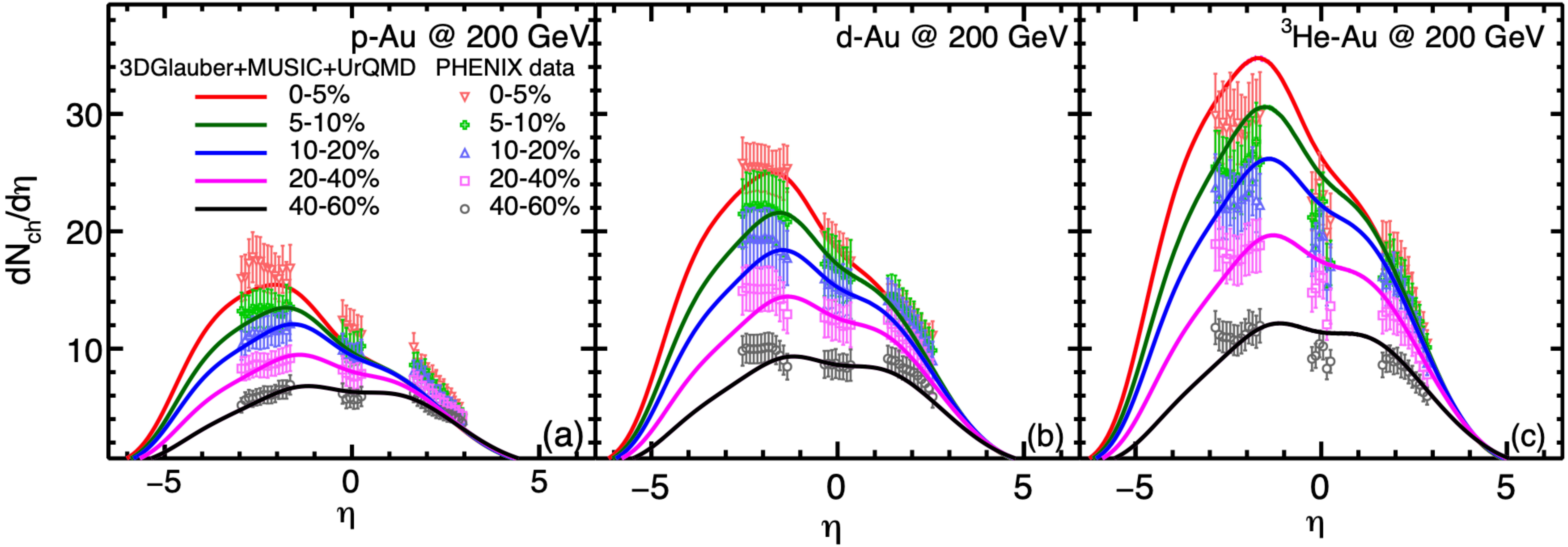
PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)





MULTIPLICITY VS. RAPIDITY

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

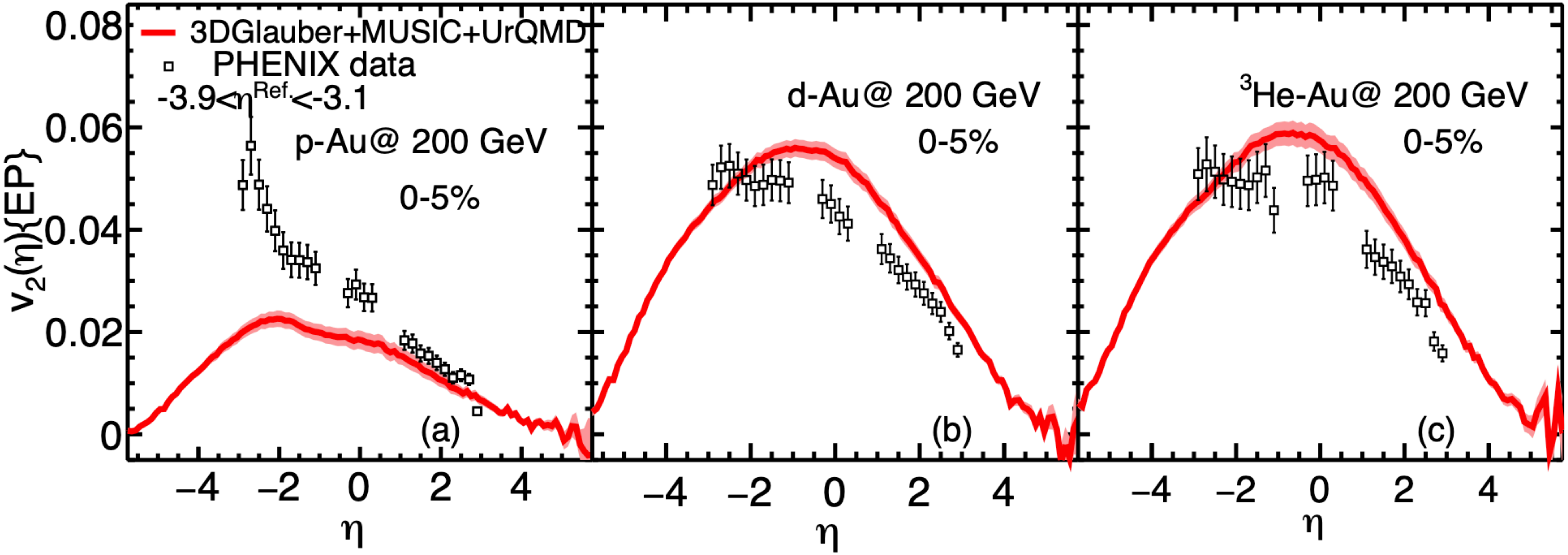


The (3+1)D hybrid model captures the rapidity and centrality dependence of $dN^{\rm ch}/d\eta$ for all asymmetric systems

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

ANISOTROPIC FLOW VS RAPIDITY

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

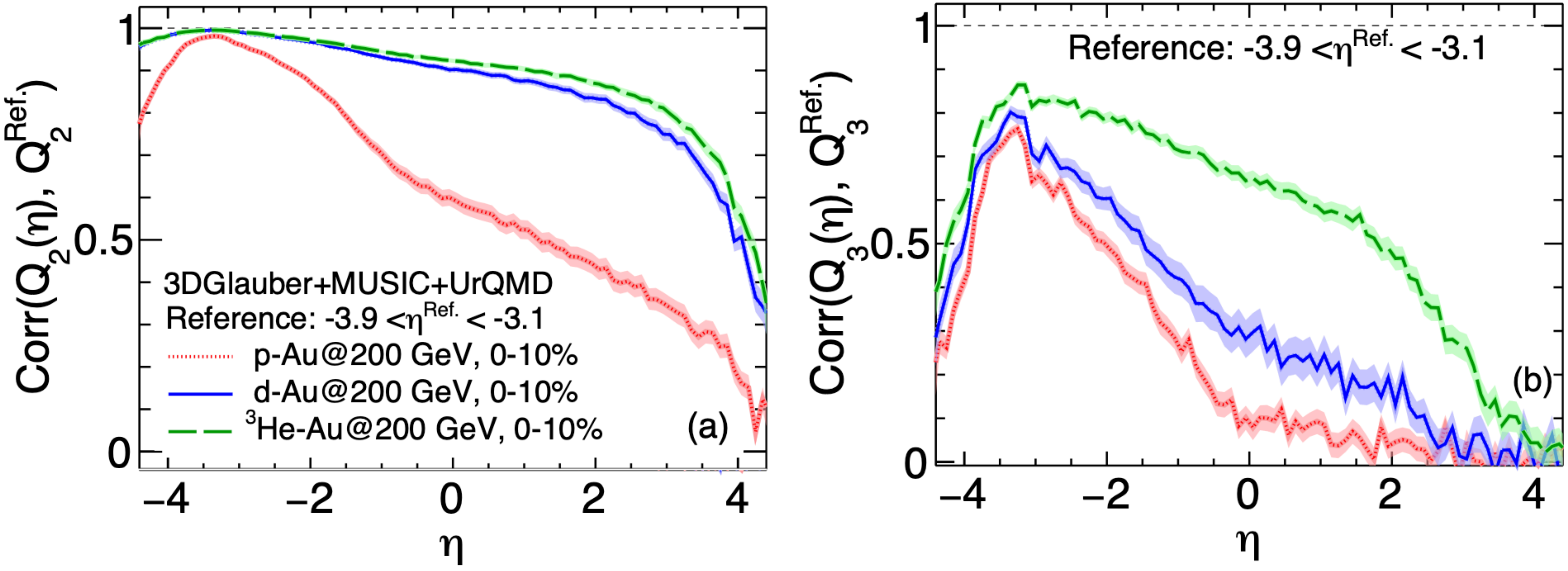


- Pseudo-rapidity dependence of $v_2\{EP\}$ reproduced for d+Au and ^{3}He+Au
- The elliptic flow in $\eta < 1$ in p+Au collisions is underestimated because of the strong longitudinal flow decorrelation in our model + potential non-flow

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

FLOW VECTOR DECORRELATION

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

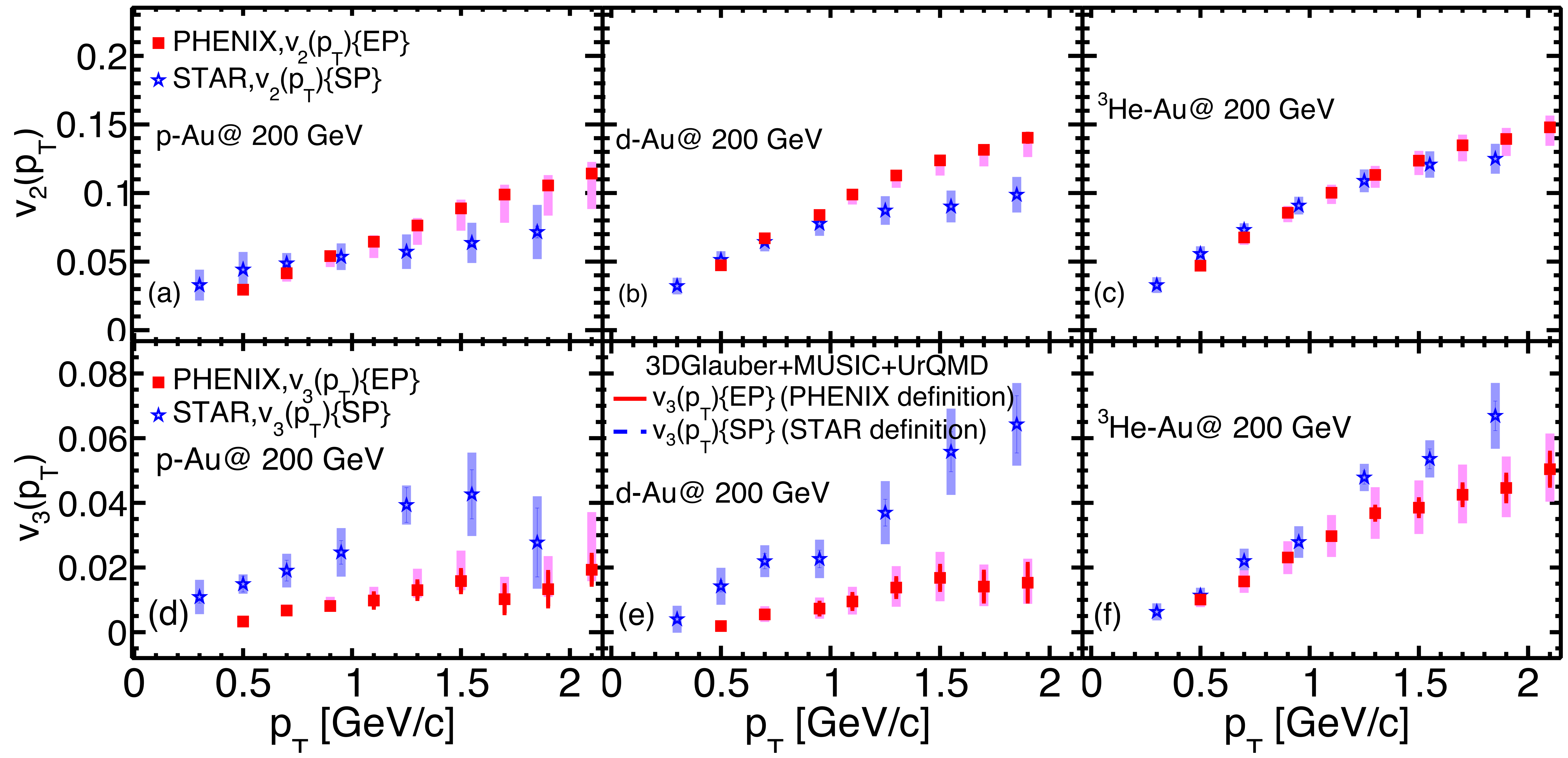


- Decorrelation is much stronger in the smaller p+Au system
- Decorrelations of v_3 flow vectors are much stronger than v_2
- **Hierarchy between v_n and systems driven by decorrelation in this model**

see talk by B. Seidlitz on measurement of decorrelation in p+p and Xe+Xe with ATLAS

COMPARING PHENIX WITH STAR DATA

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



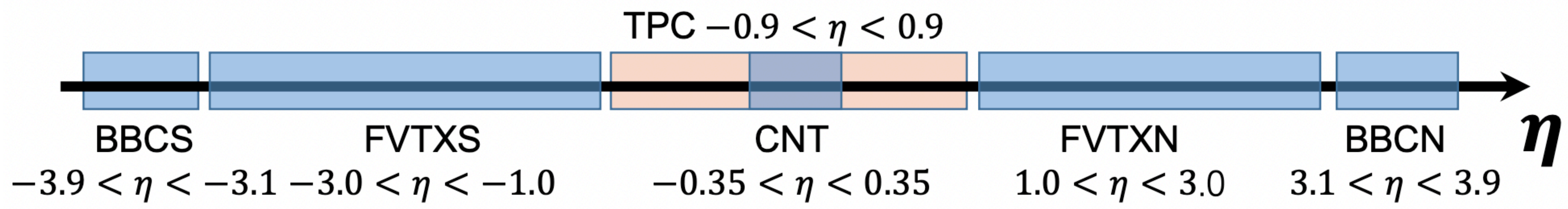
PHENIX:

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

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

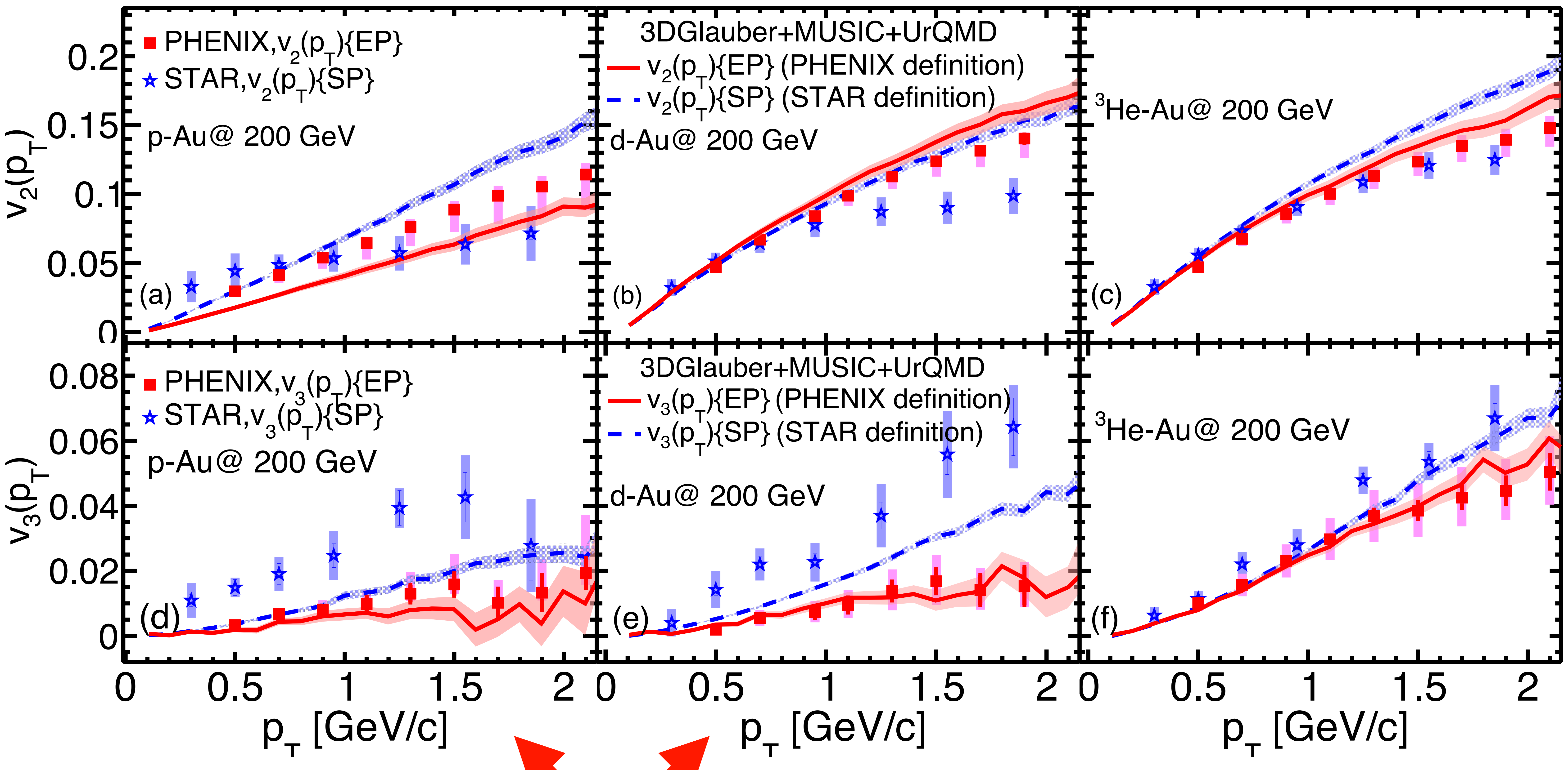
STAR:

$\eta \in [-0.9, 0.9]$ 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}He+Au: $\eta_1 \in [-3, -1]$,
$\eta_2 \in [-0.35, 0.35]$

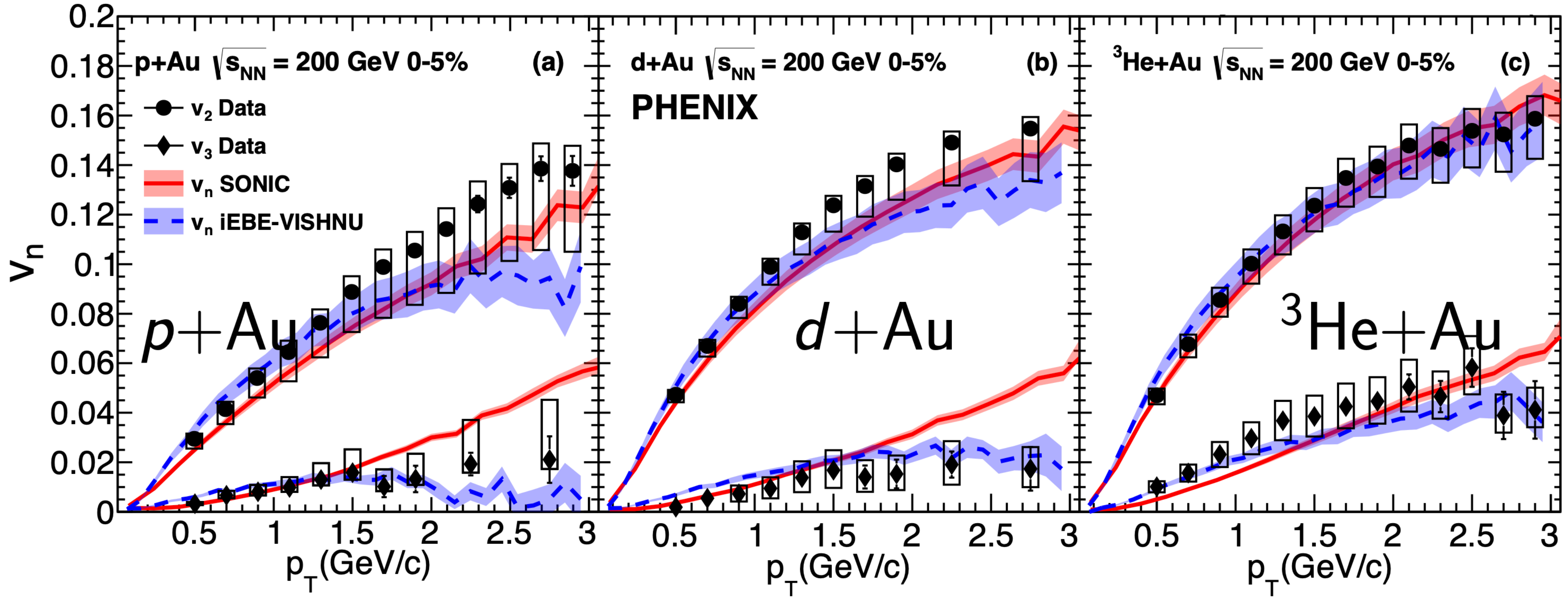
STAR:
$\eta \in [-0.9, 0.9]$ with $|\Delta\eta| > 1$

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

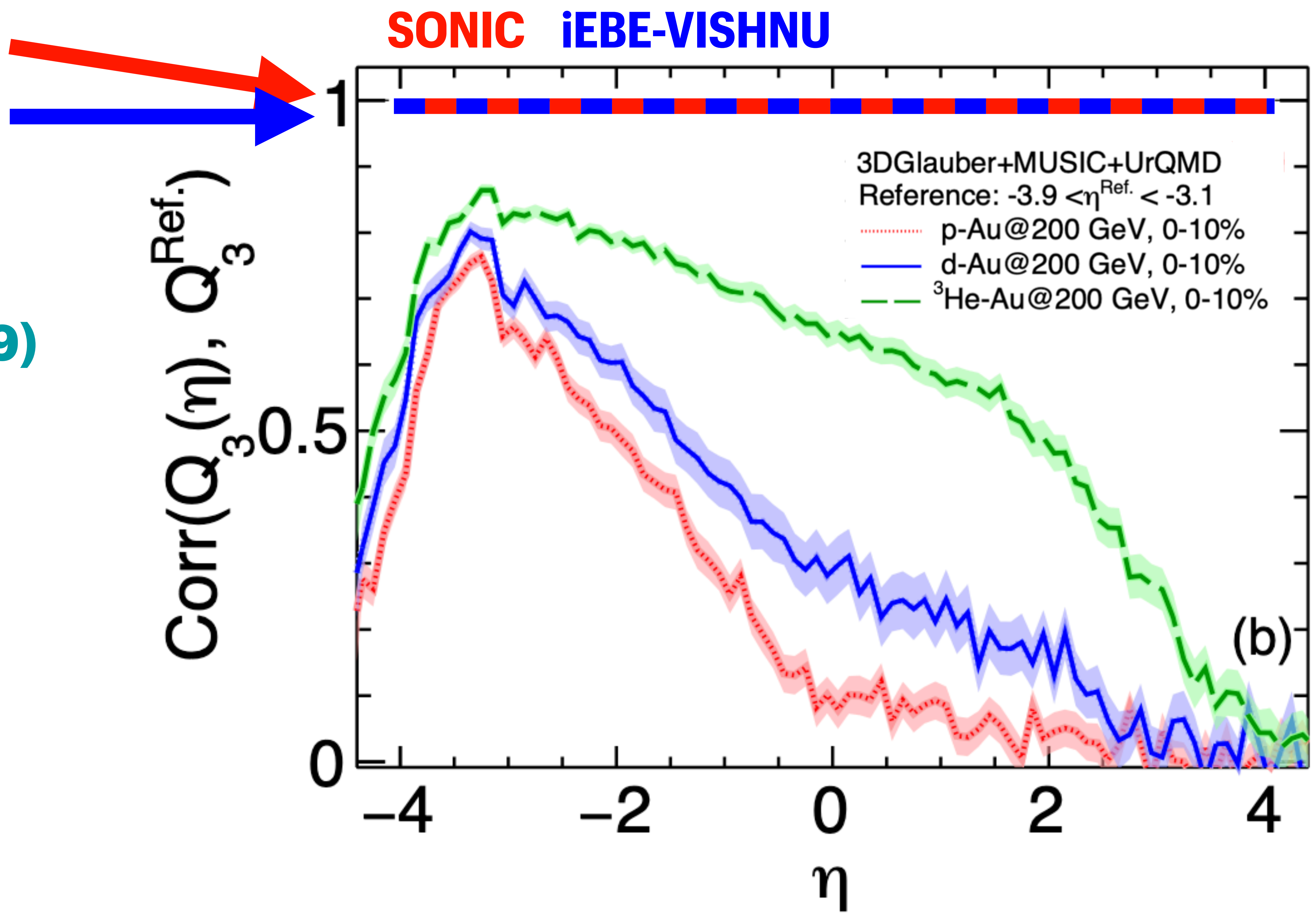
Longitudinal flow decorrelations lead to smaller $v_3(p_T)$ for PHENIX, explaining ~50% of the difference between the two measurements

COMPARISON WITH BOOST INVARIANT MODELS

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



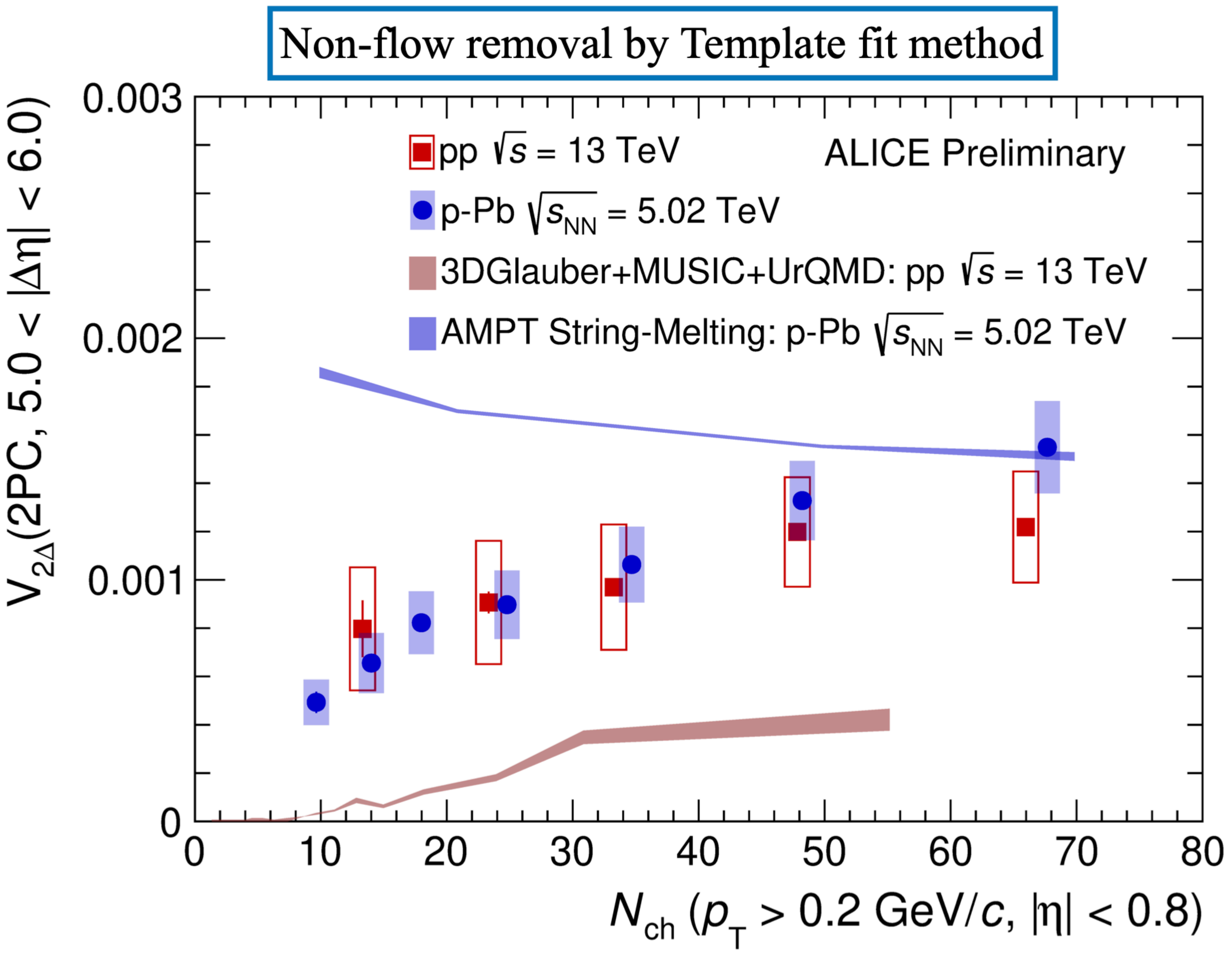
PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)



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

VERY LONG RANGE CORRELATIONS

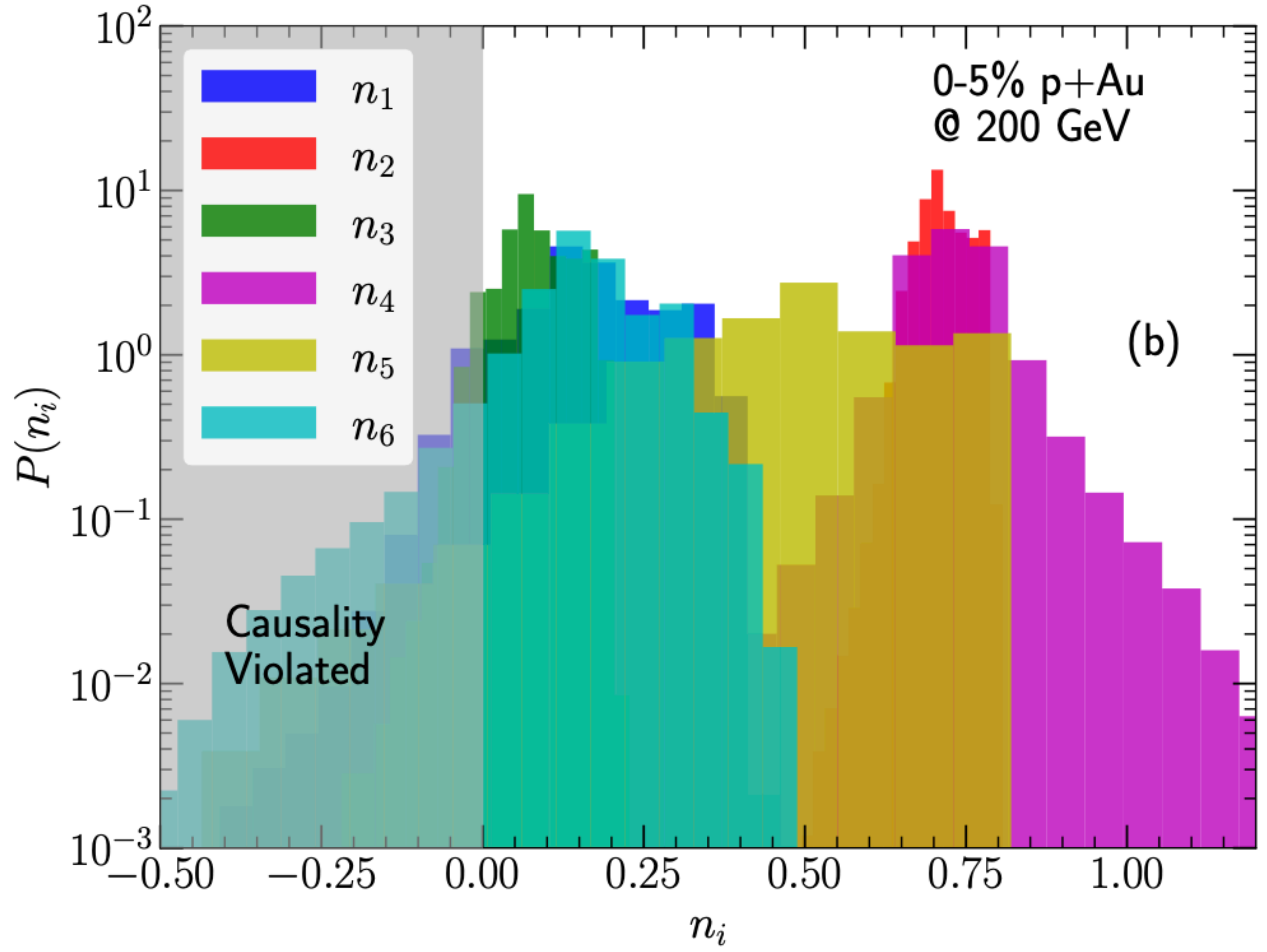
ALICE Collaboration, ALI-PREL-573662, talk by Debojit Sarkar



- p+p collisions at 13 TeV
- $5 < |\Delta\eta| < 6$
- Models do not describe the data
- Need better description of 3D geometry
- Applicability of hydrodynamics?

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



values of 6 causality conditions

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

APPLICABILITY OF HYDRODYNAMICS

- Initial transv ... ntral Pb+Pb
- Locally lar ... nverse Reynolds
- Could lea
- Use non-e ... kinetic theory, or
- Far from e
- Alternativ BDNK, ca

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

Progress and Challenges in Small Systems

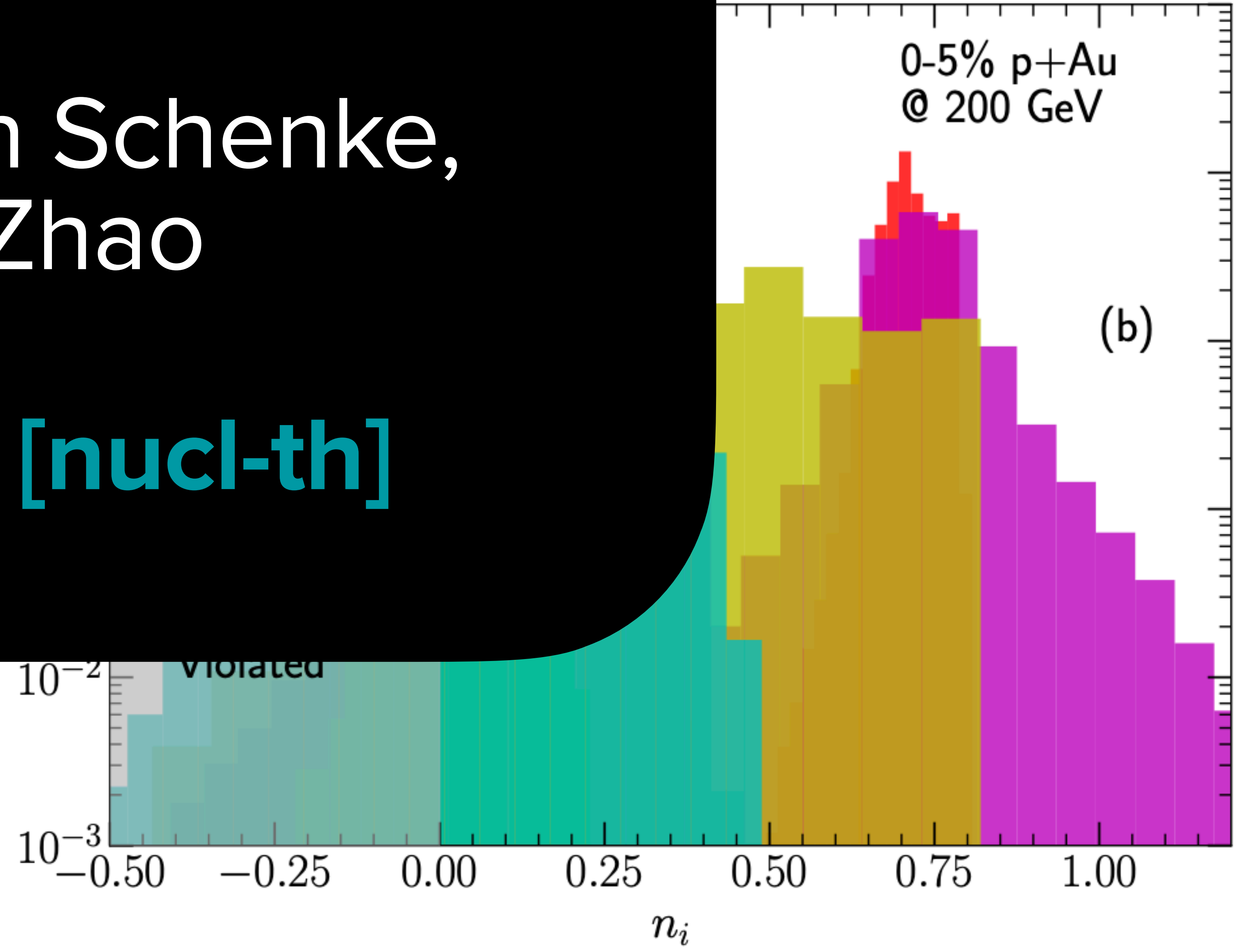
Jorge Noronha, Björn Schenke, Chun Shen, Wenbin Zhao

e-Print: 2401.09208 [nucl-th]

G. Inghirami, H. Elfner
A. Kurkela, A. Mazelia
Phys. Rev. Lett. 122(12

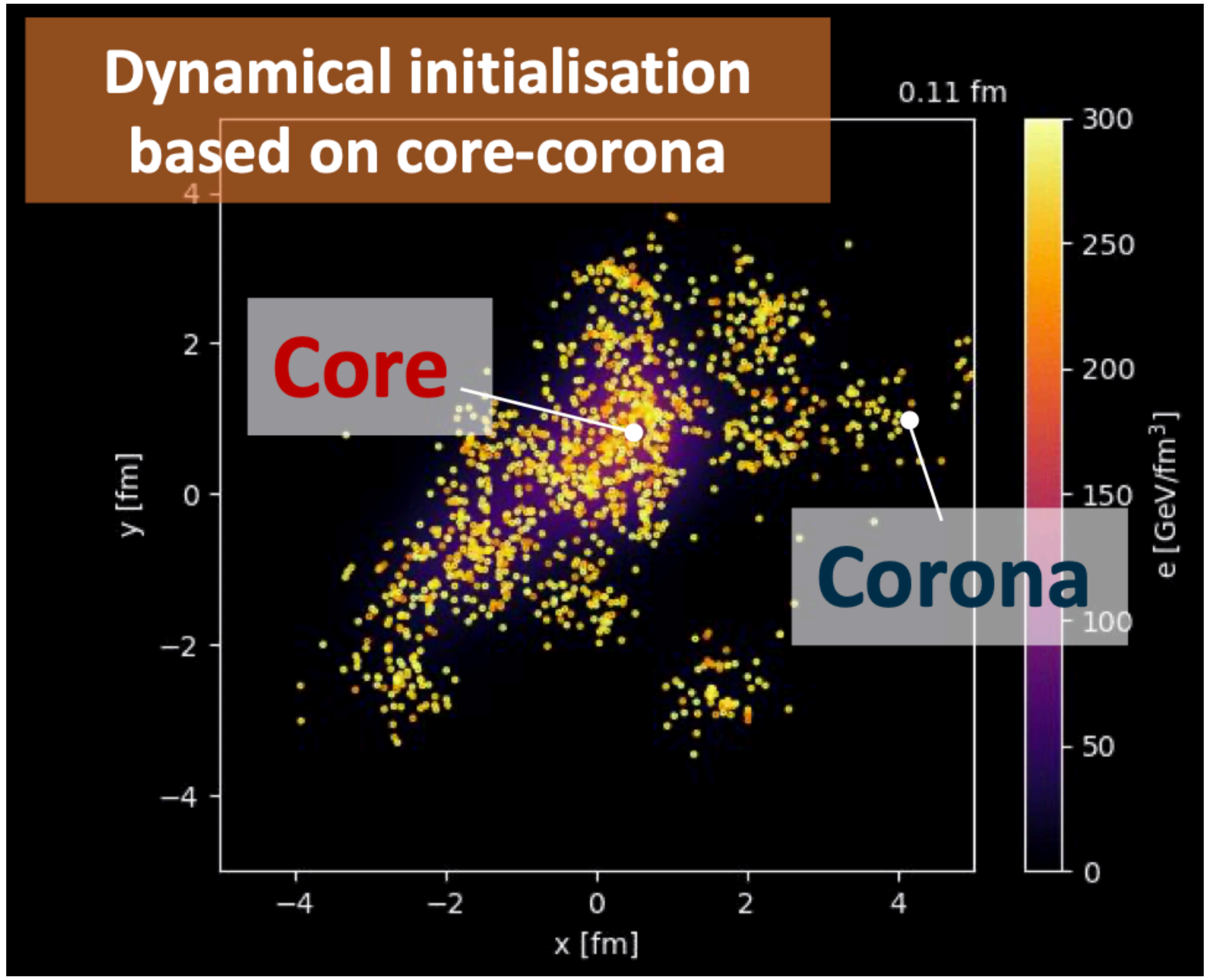
BDNK:
F. S. Bemfica, M. M. Di
P. Kovtun, JHEP 10 (2019

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



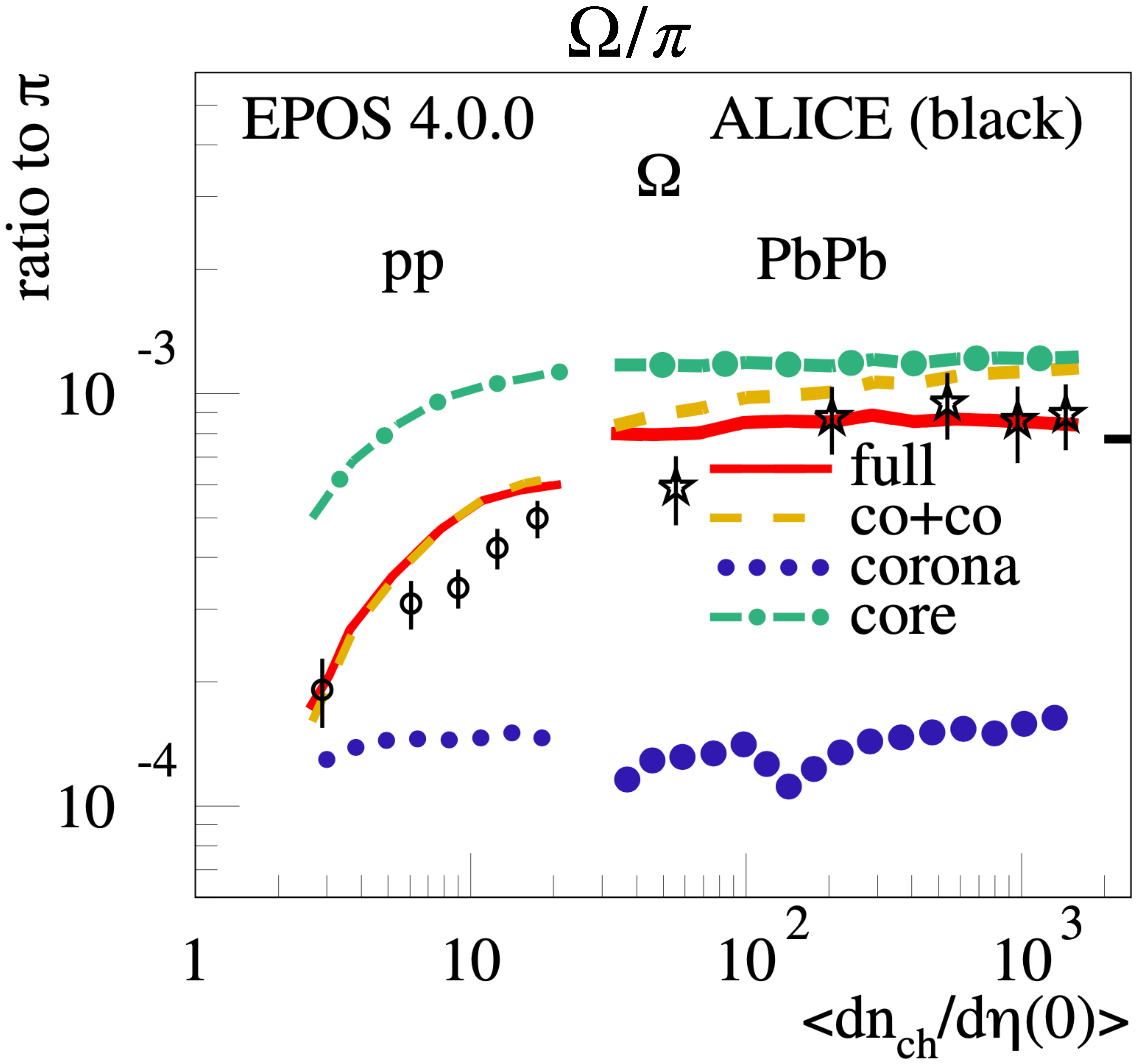
values of 6 causality conditions

CORE+CORONA PICTURE



Y. Kanakubo, Quark Matter 2023

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



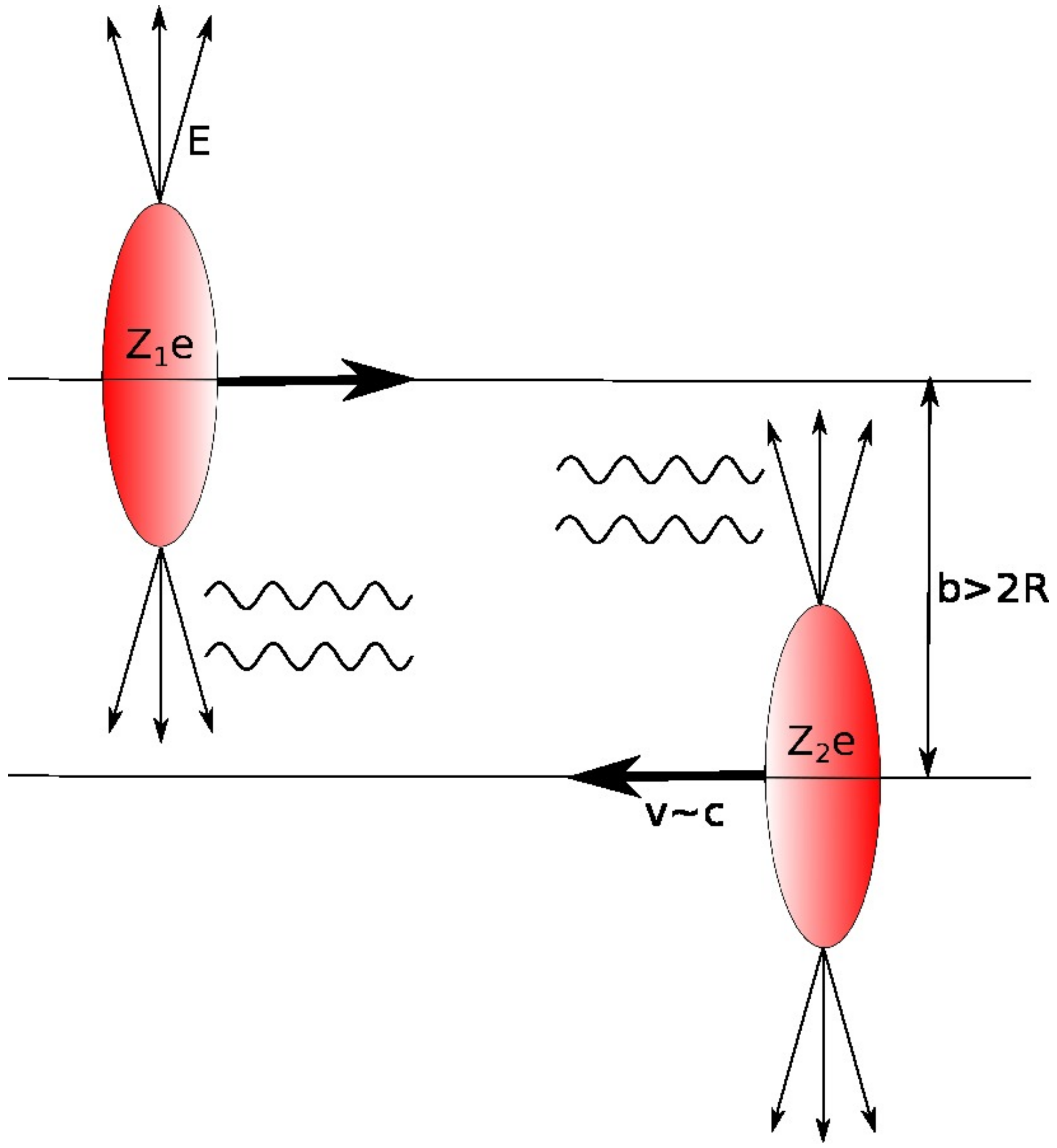
K. Werner, Phys.Rev.C 108 (2023) 6, 064903

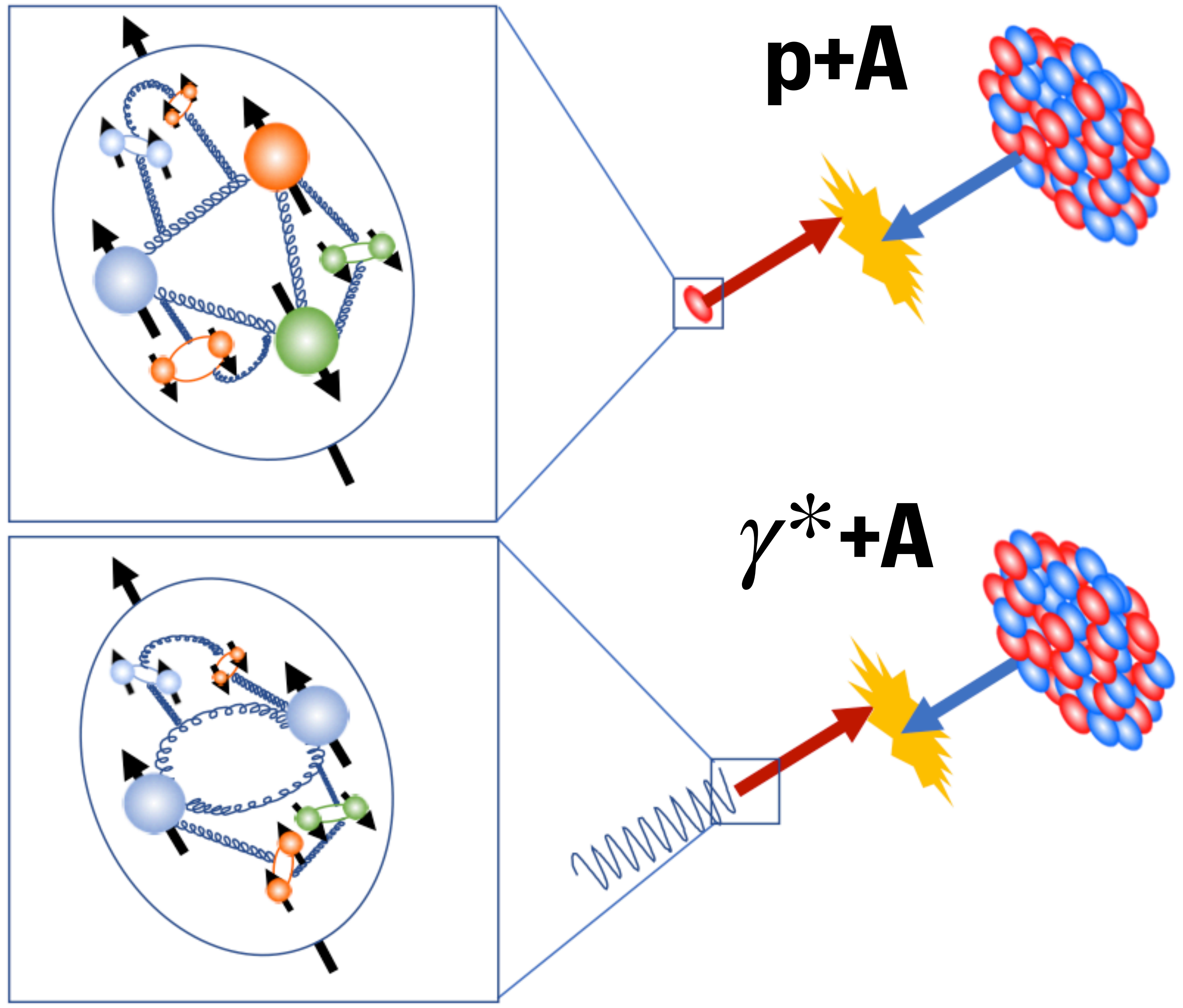
see talk by P.B. Gossiaux

see talk by Ishu Aggarwal on new measurements in d+Au by STAR

SMALLER: ULTRAPERIPHERAL COLLISIONS

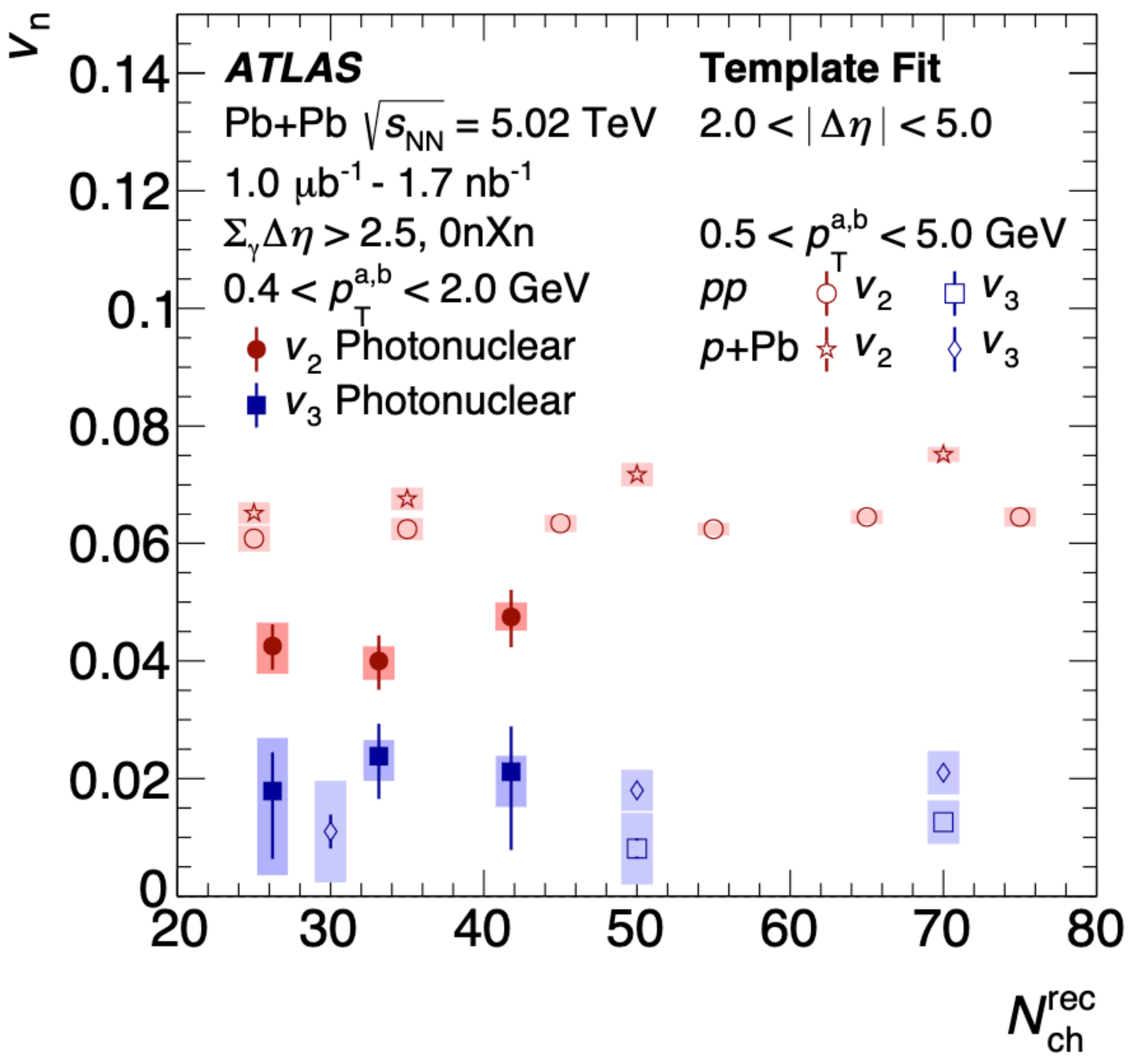
W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302





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

see talk by A. Baty for another really small system: $e^+ + e^-$ at the highest multiplicity

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

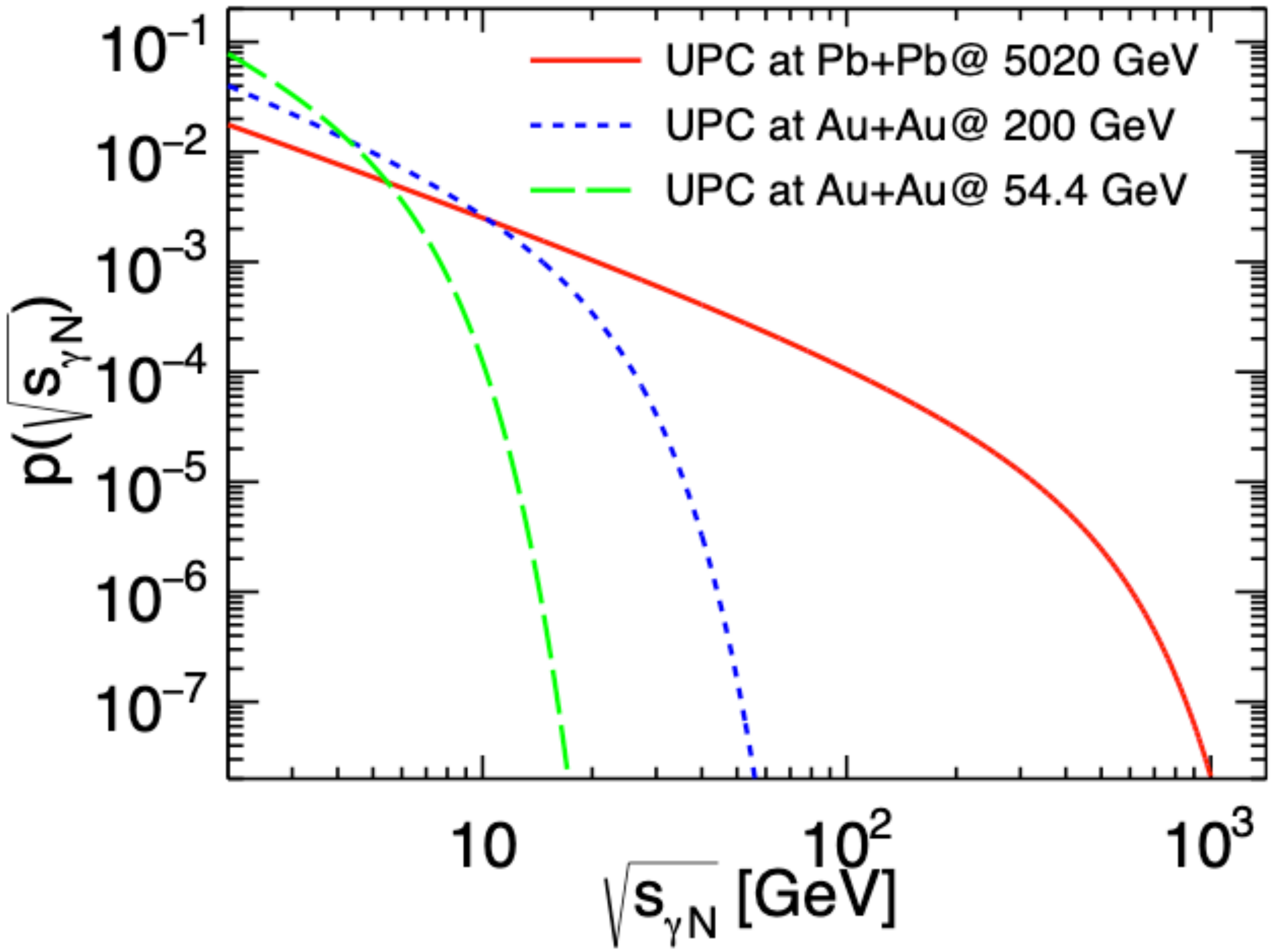
A. J. Baltz *et al.* Phys. Rept. 458, 1-171 (2008); W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302

- 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

↓

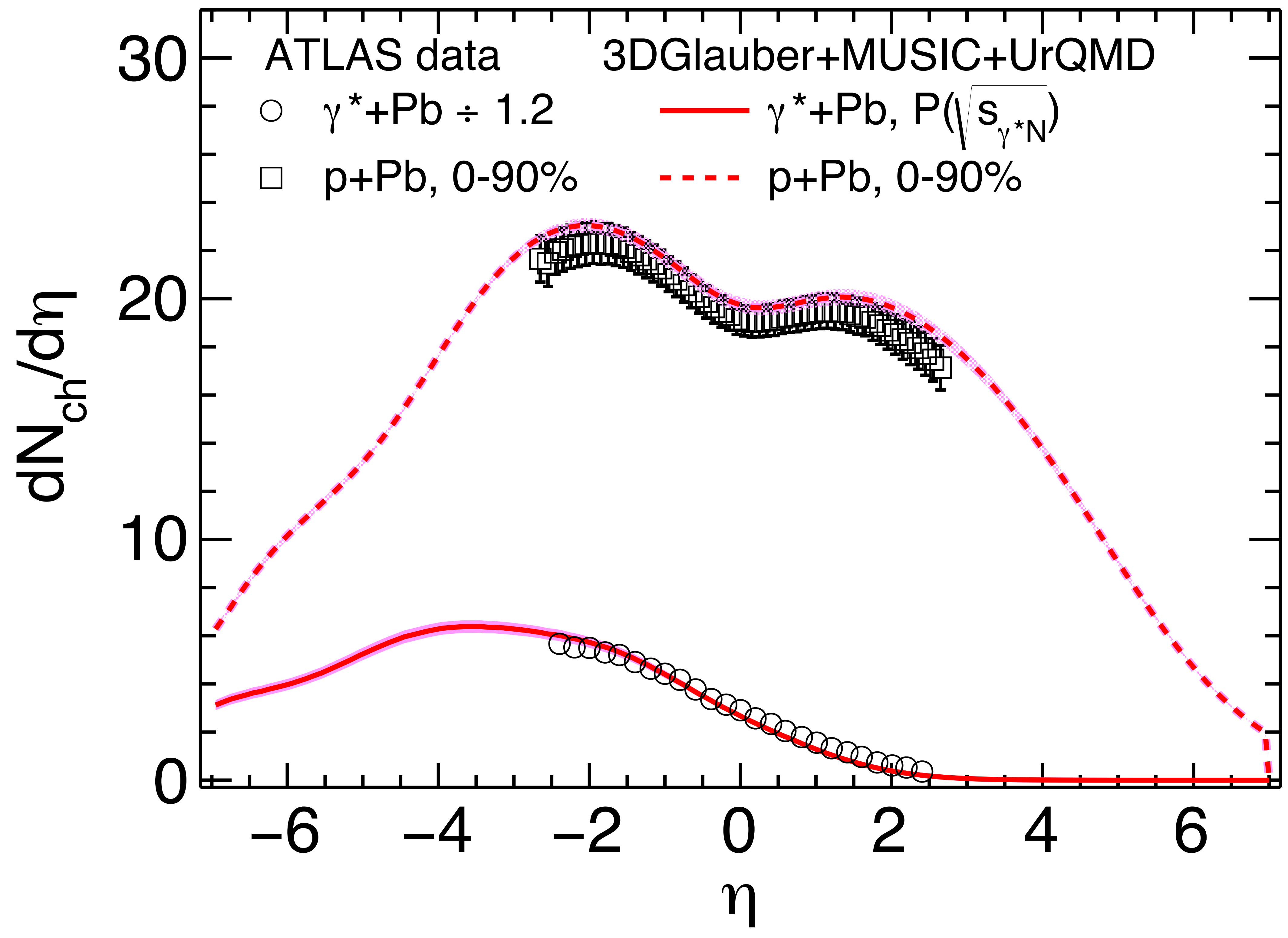
- Center of mass collision energy for the $\gamma^* + A$ system fluctuates

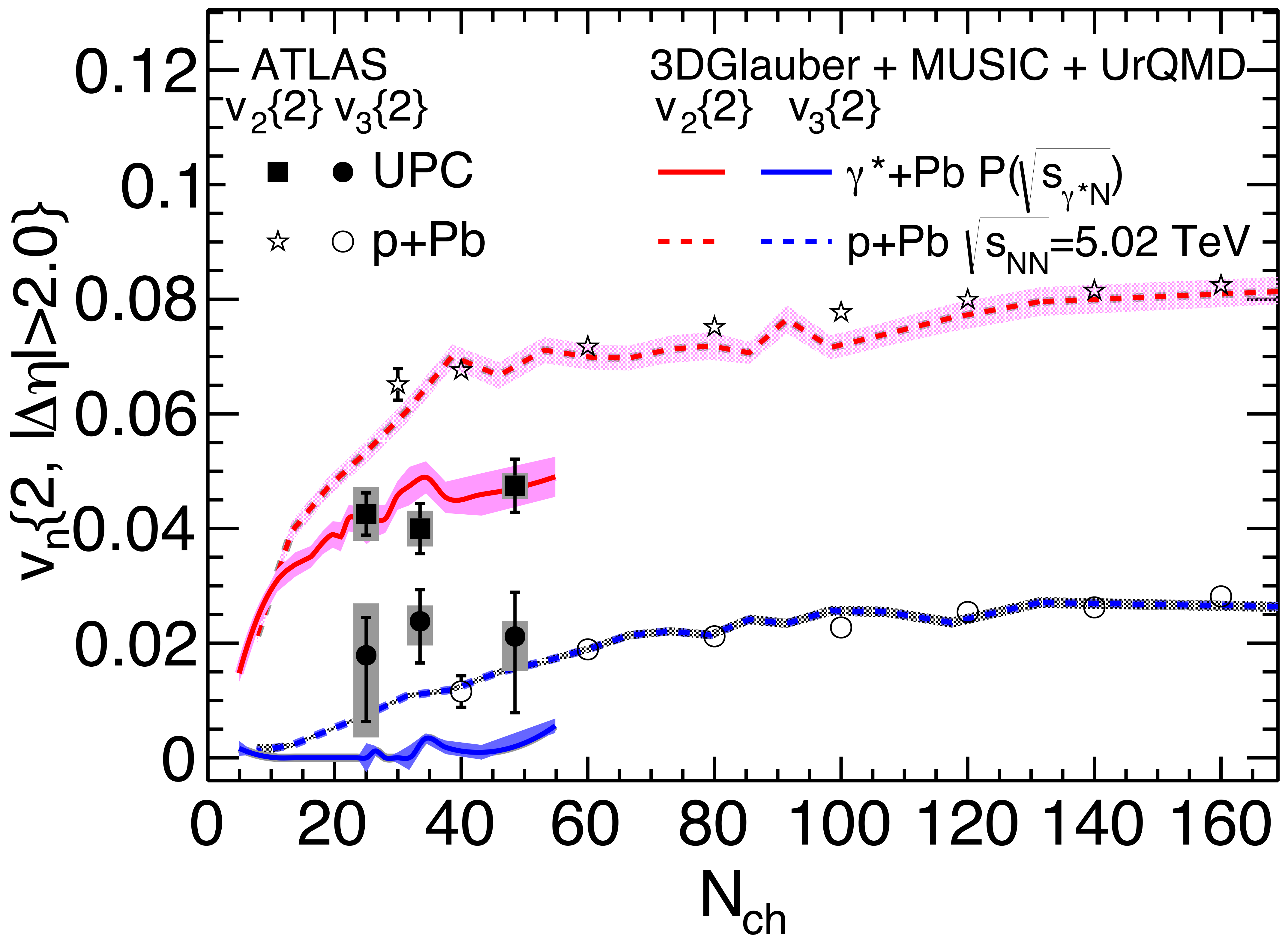
- Center of mass rapidity of $\gamma^* + A$ collision fluctuates in the lab frame



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

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



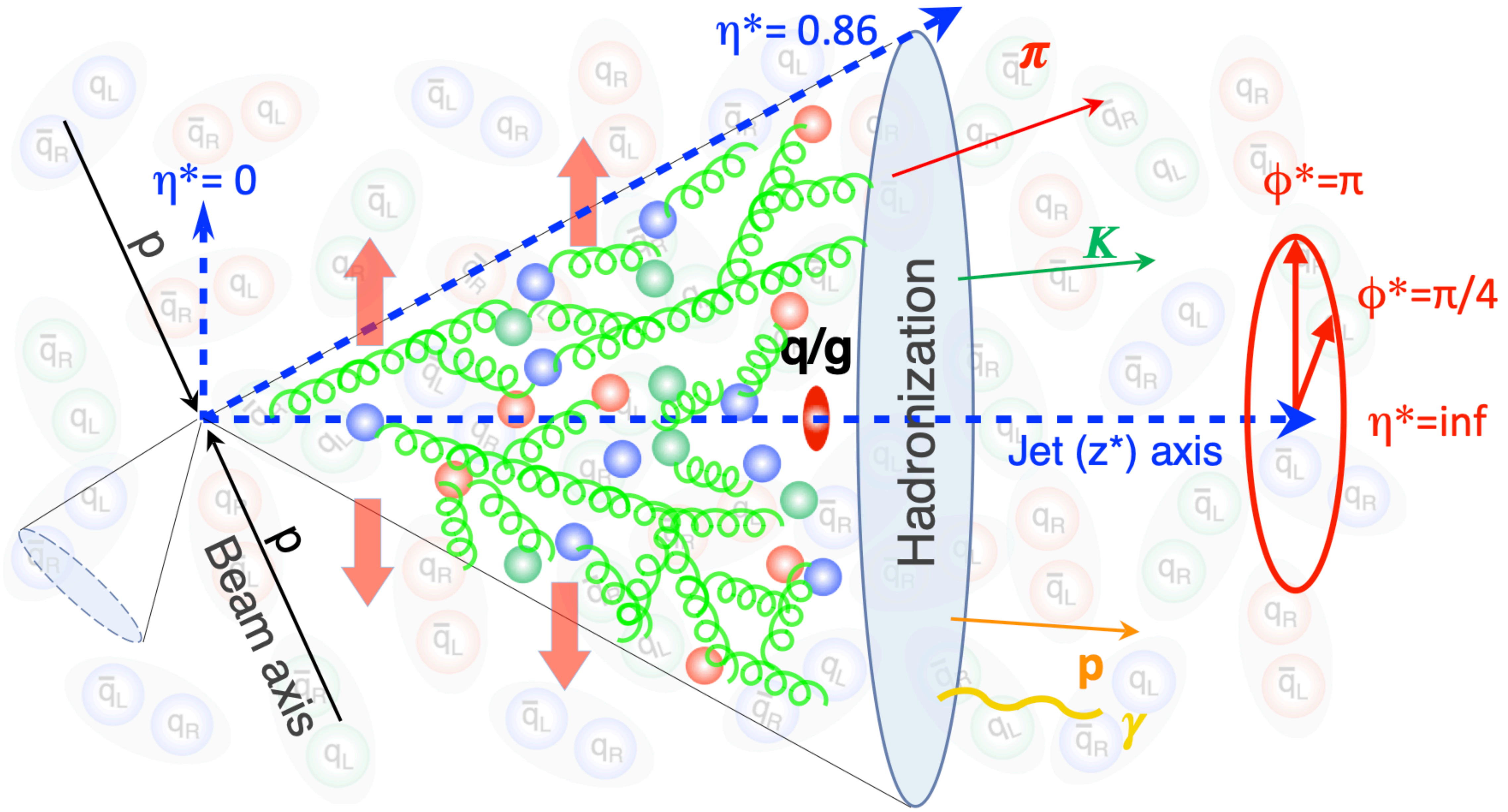


- Shapes of $dN_{ch}/d\eta$ reproduced for p+Pb and γ^*+Pb collisions
- Elliptic flow difference between p+Pb and γ^*+Pb collisions reproduced
  Driven by different amount of longitudinal flow decorrelation

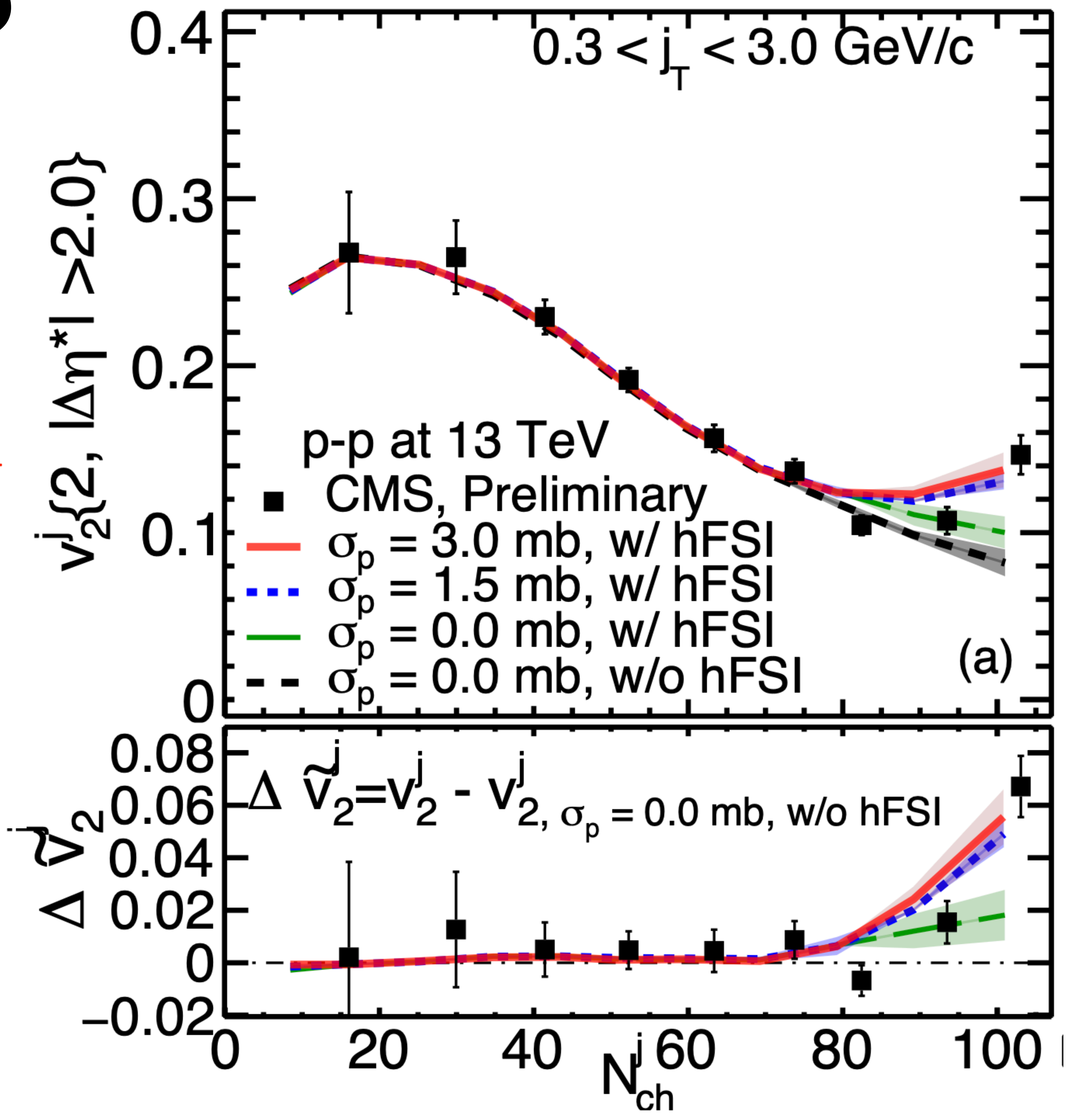
FLOW INSIDE JETS

CMS Collaboration, arXiv:2312.17103

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

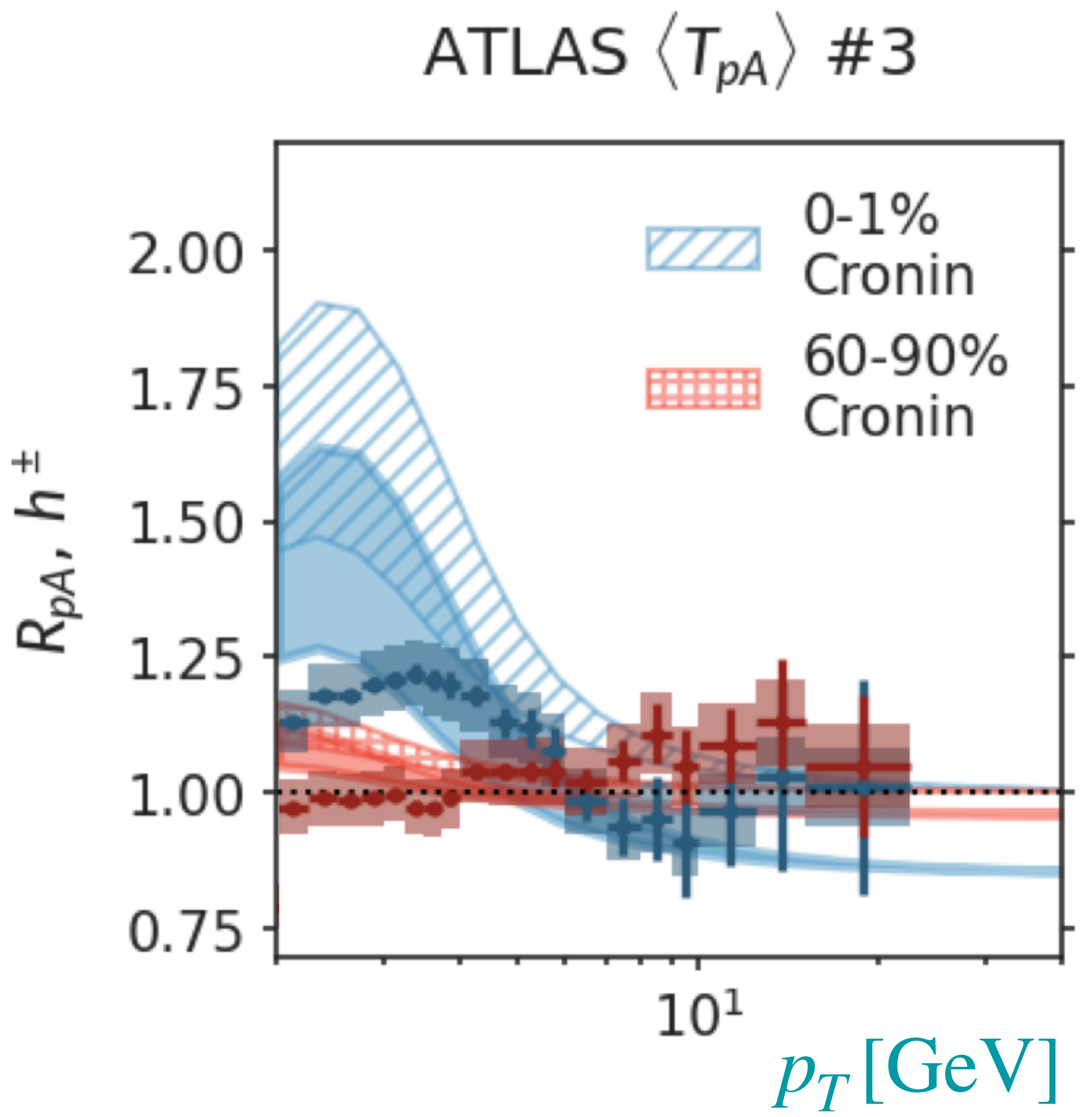


Final state effects can explain increase of v_2 at high multiplicity

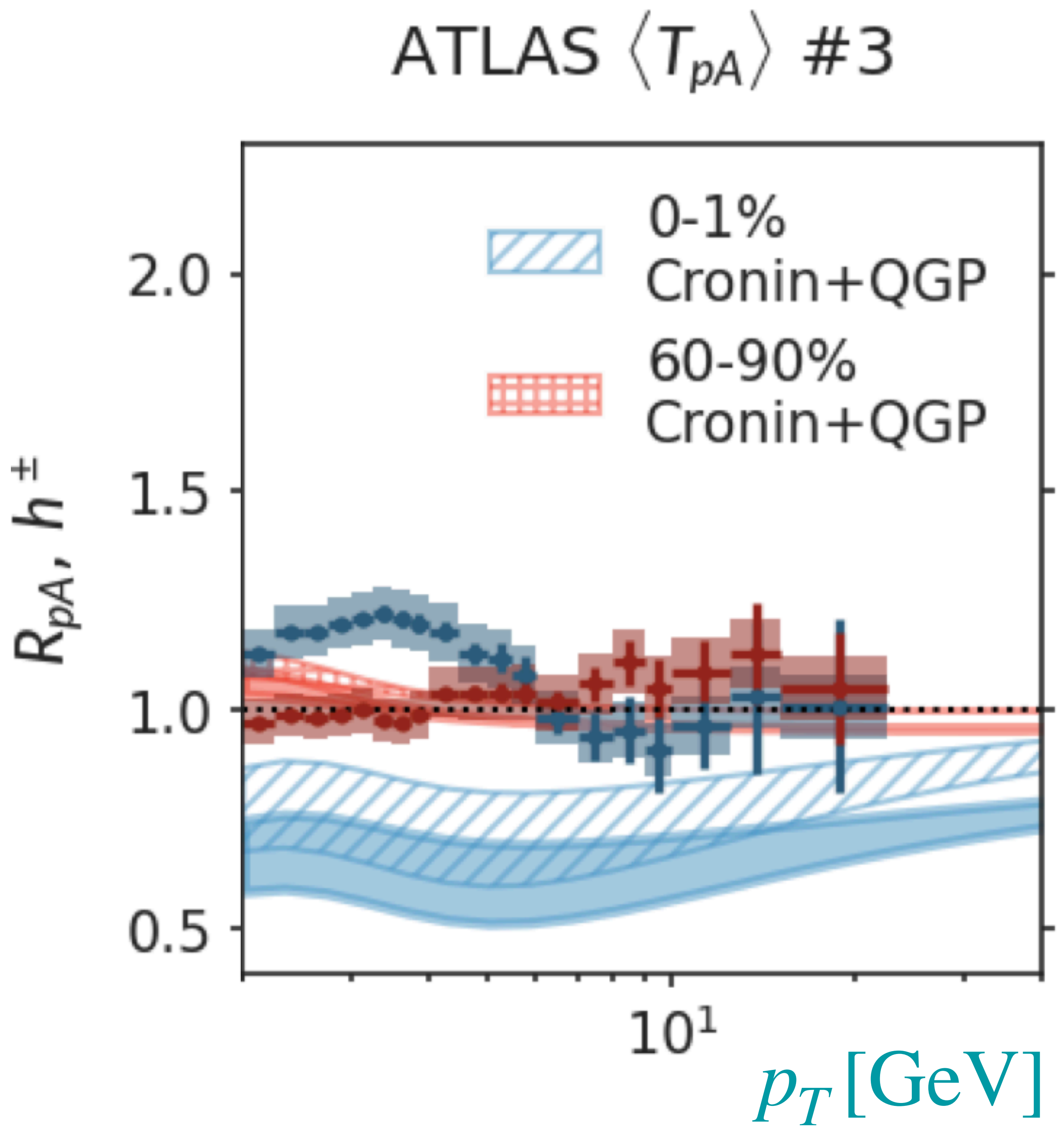


HARD PROBES

W. Ke, I. Vitev, Phys.Rev.C 107 (2023) 6, 064903



Calculation including cold nuclear matter effects



Same + QGP energy loss using SCET

Model of QGP formation in p+A as described by hydrodynamics leads to quenching of hadron spectra that is inconsistent with the p+Pb data

Agreement in d+Au collisions is better! (data has opposite high p_T behavior with centrality) → **Centrality determination is critical**

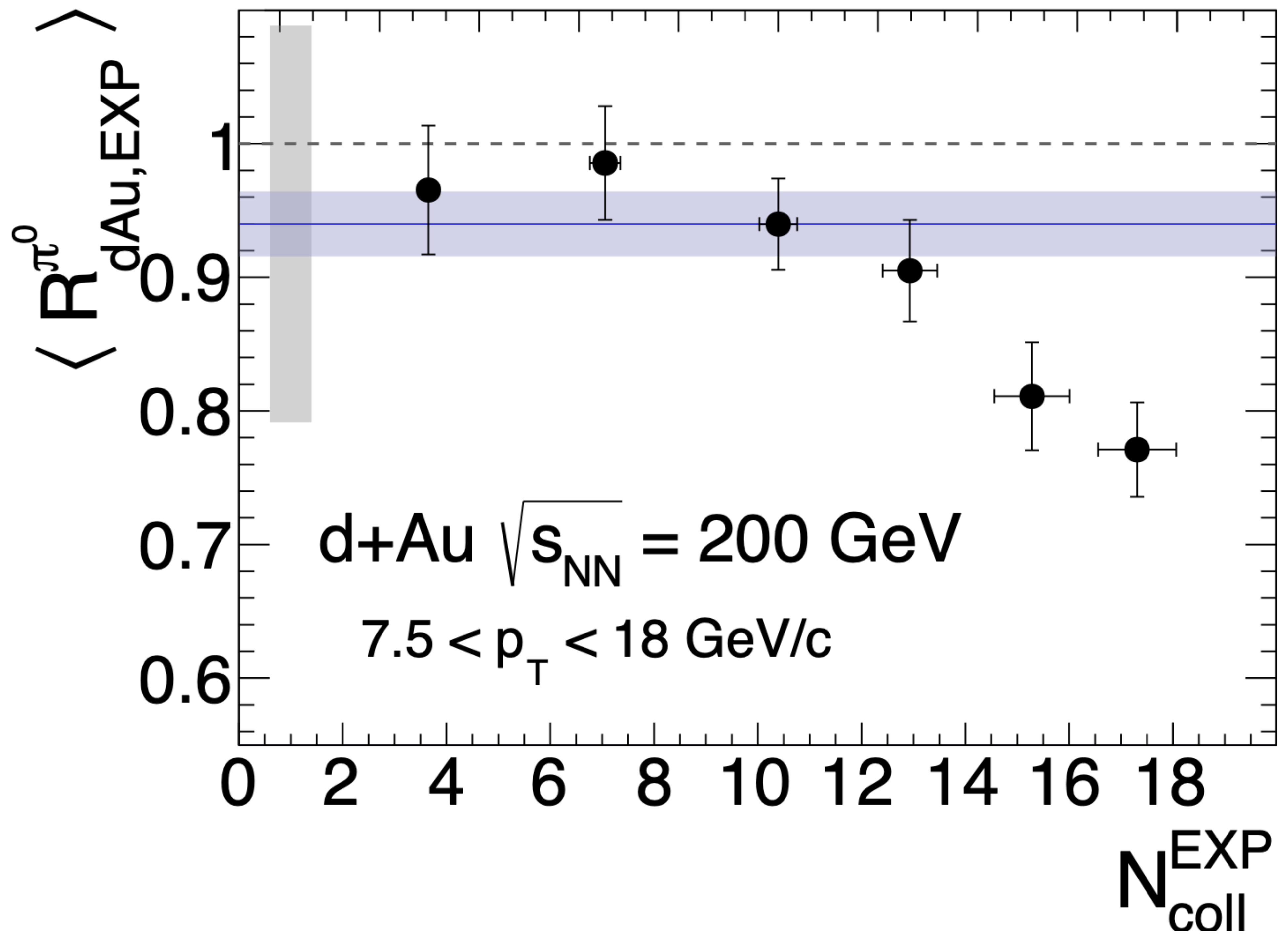
Correlation between hard and soft degrees of freedom important
A. Majumder for JETSCAPE, arXiv:2308.02650

 Data: ATLAS Collaboration, Phys. Lett. B 763 (2016) 313

HARD PROBES - EXPERIMENTAL N_{coll}

Removing centrality selection bias in π^0 suppression in d+Au collisions:

PHENIX Collaboration, arXiv:2303.12899



event activity from direct photons

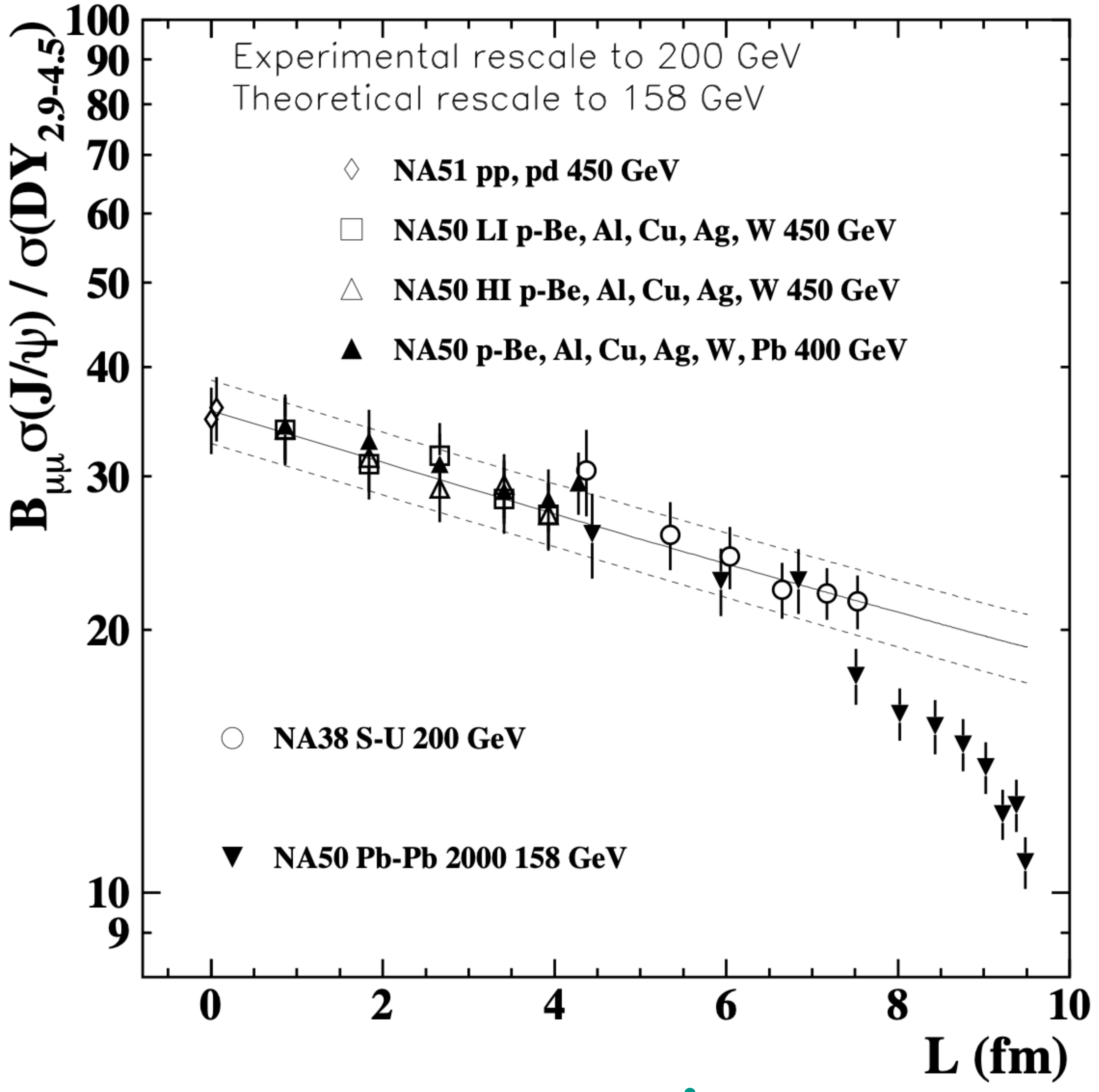
- Direct photons as benchmark for particle production from hard-scattering processes

$$N^{\text{EXP}}_{\text{coll}} = Y^{\gamma^{\text{dir}}}_{d\text{Au}} / Y^{\gamma^{\text{dir}}}_{pp}$$

- Using a Glauber model N_{coll} led to enhancement at low N_{coll} → now removed
- Suppression at large N_{coll} remains

J/PSI SUPPRESSION IN SMALL SYSTEMS

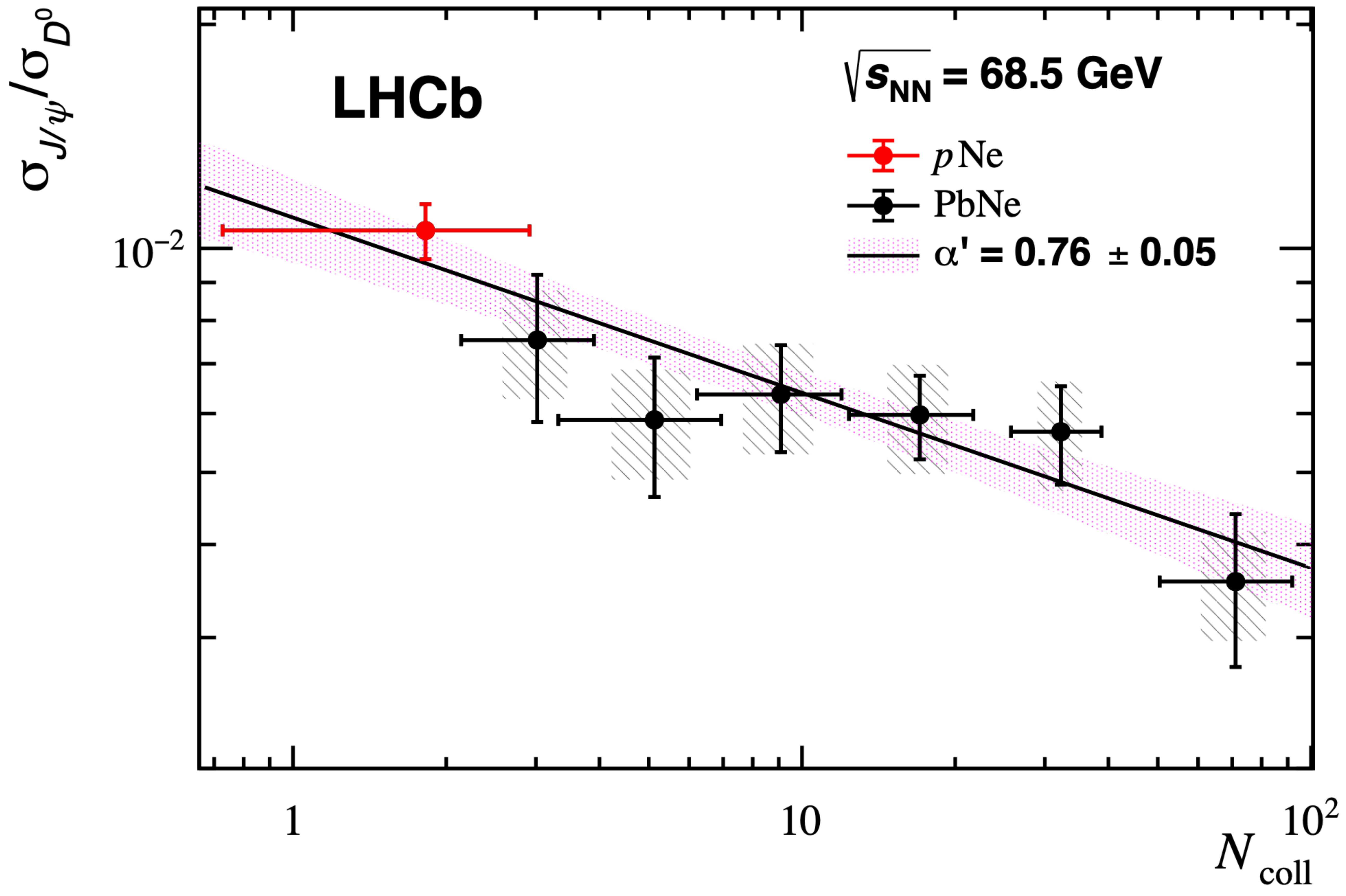
NA50 Collaboration
Eur.Phys.J.C 39 (2005) 335-345



system size →

No QGP-like J/ψ suppression in Pb+Ne

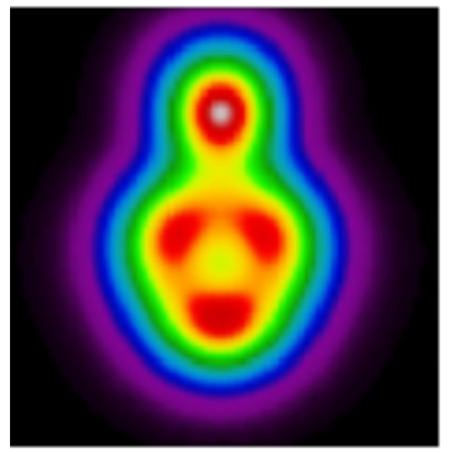
LHCb Collaboration, Eur.Phys.J.C 83 (2023) 7, 658



Pb+Ne and Pb+O

G. Giacalone et al, arXiv:2405.20210

- Flow sensitive to shapes of Ne and O

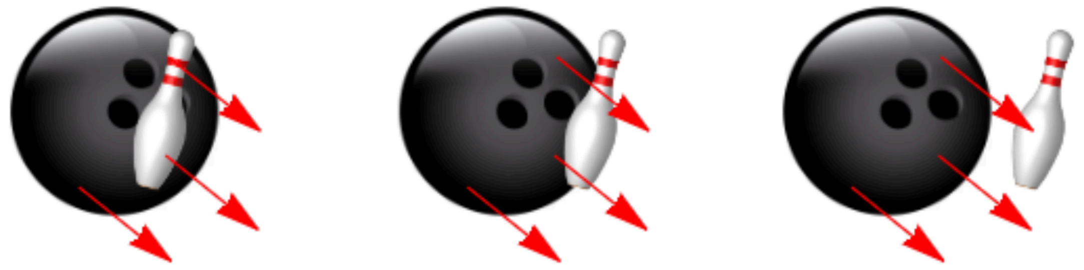


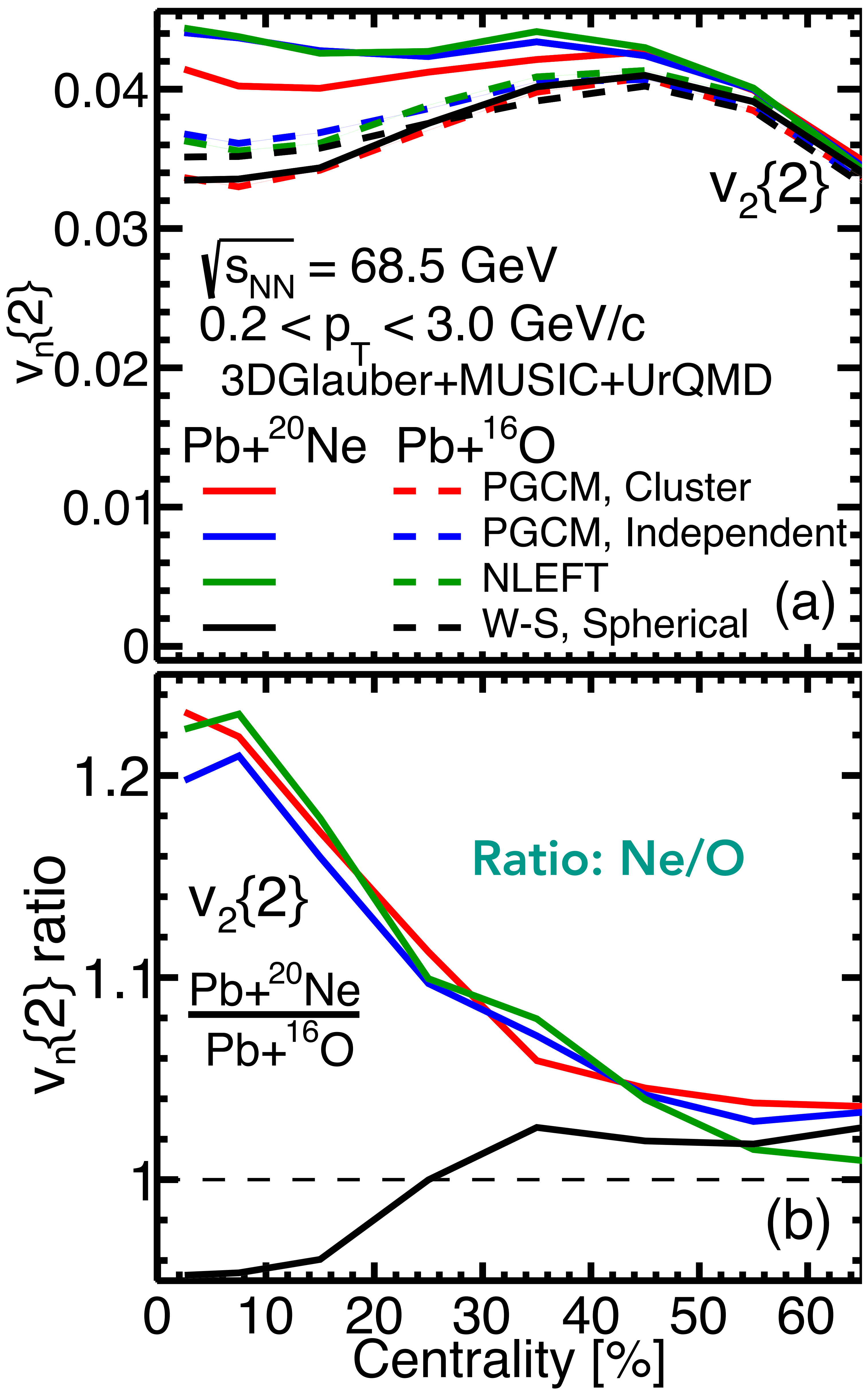
^{20}Ne

- 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

see talk by G. Giacalone





SUMMARY

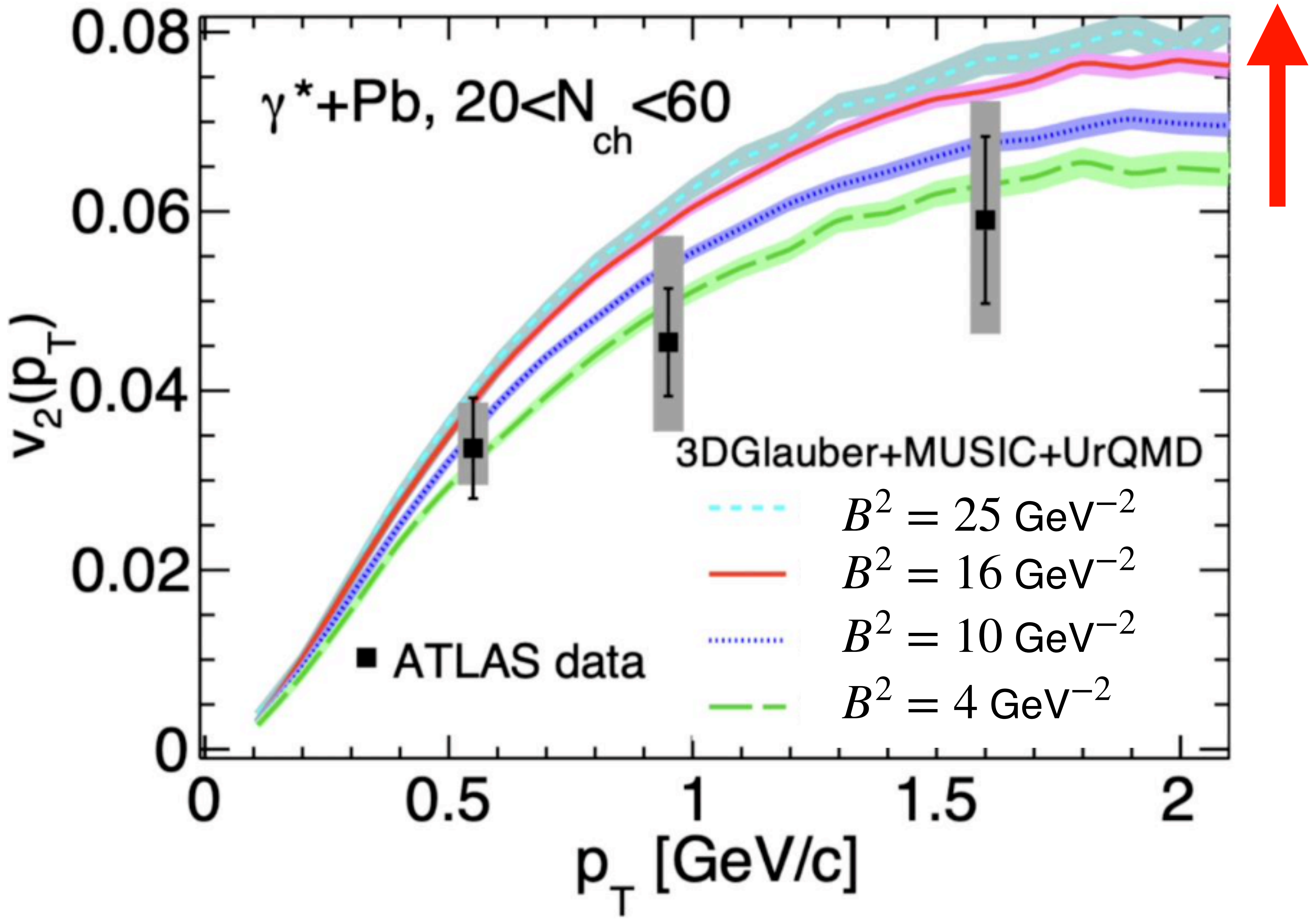
- Strong final state effects provide most consistent description of small systems
- Differences between v_n from STAR and PHENIX from different rapidity ranges
- Elliptic flow in photo-nuclear events well described by same framework used in p+A
- Applicability of hydrodynamics:
  Issues of accuracy, causality, stability
- Frameworks with non-equilibrium transport component possible way to go
- Studies of hard probes in small systems plagued by biases from centrality selection

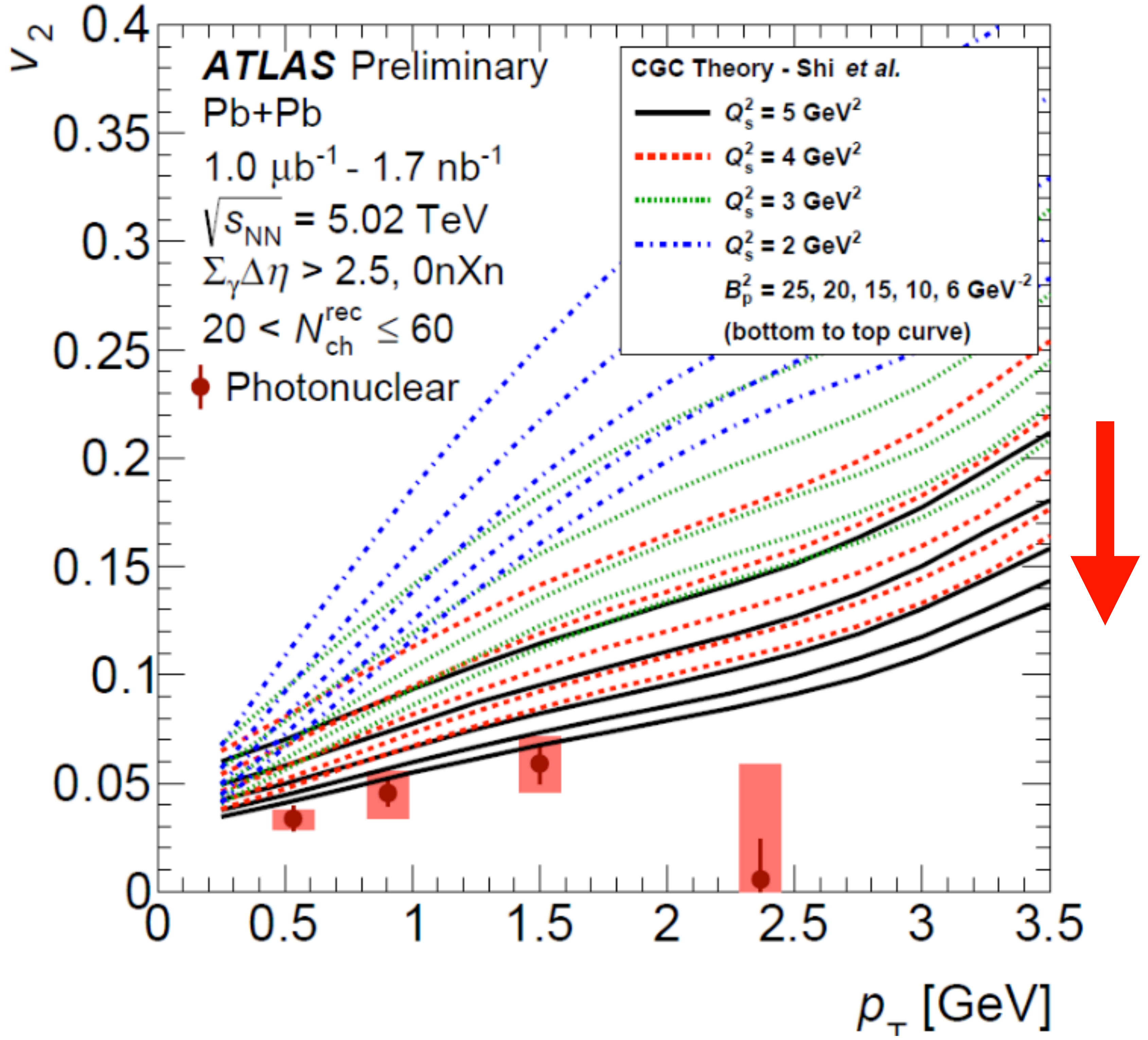
SQM
Strasbourg 2024
Strangeness in Quark Matter

BACKUP

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)





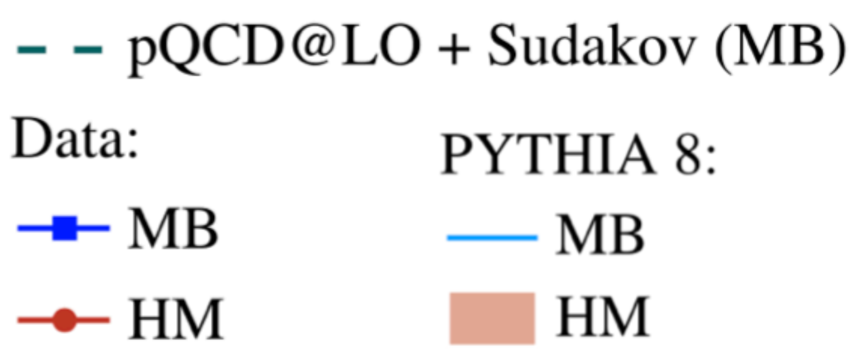
increasing transverse size $\propto B^2$

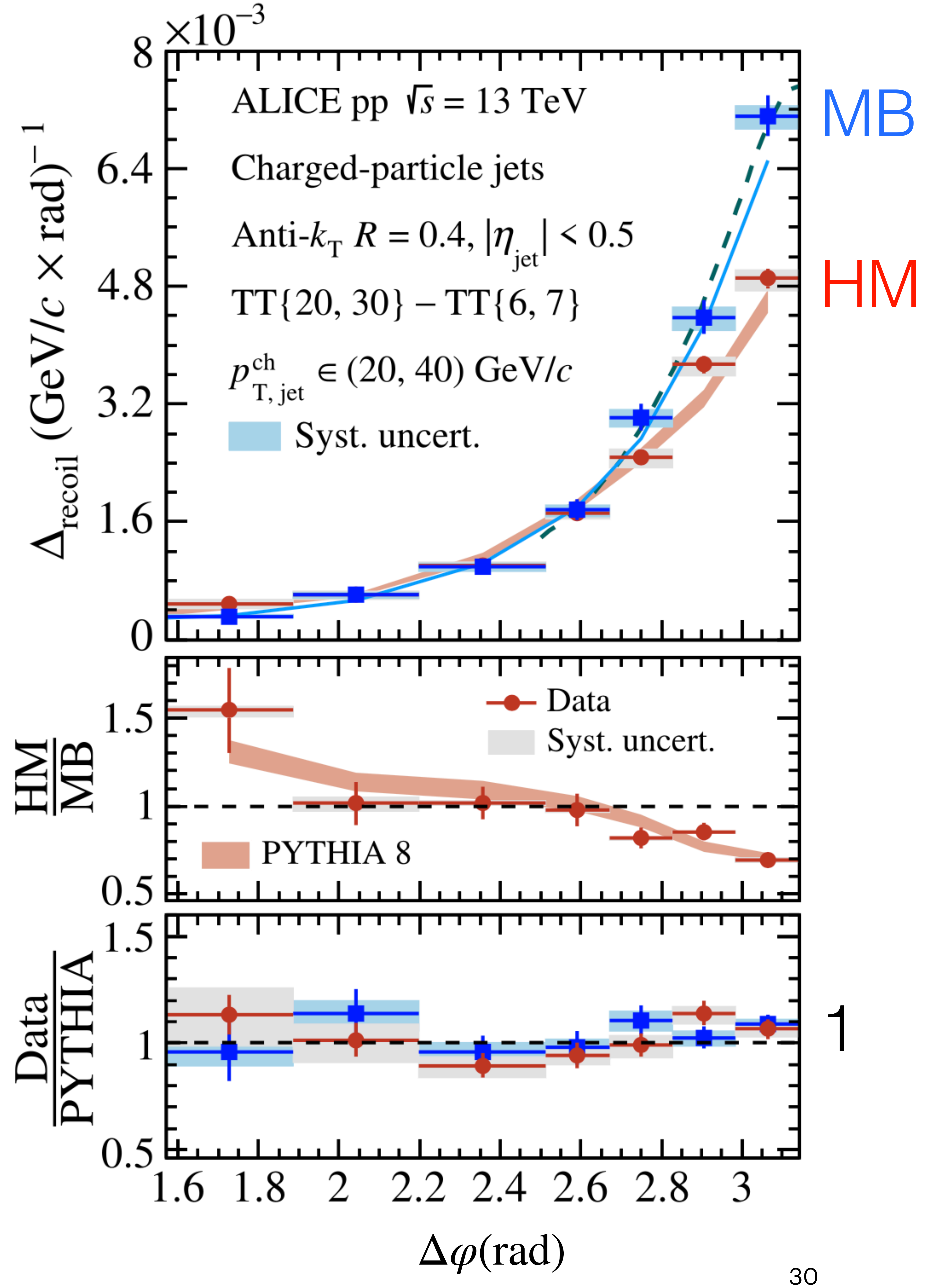
- Hydro: Larger B^2 means larger transverse area for geometry to fluctuate $v_2 \propto B^2$
- CGC: Larger B^2 leads to a larger number of independent domains $v_2 \propto 1/B^2$
- Study Q^2 dependence at the Electron Ion Collider (EIC) to test this

JET QUENCHING

ALICE Collaboration, arXiv:2309.03788

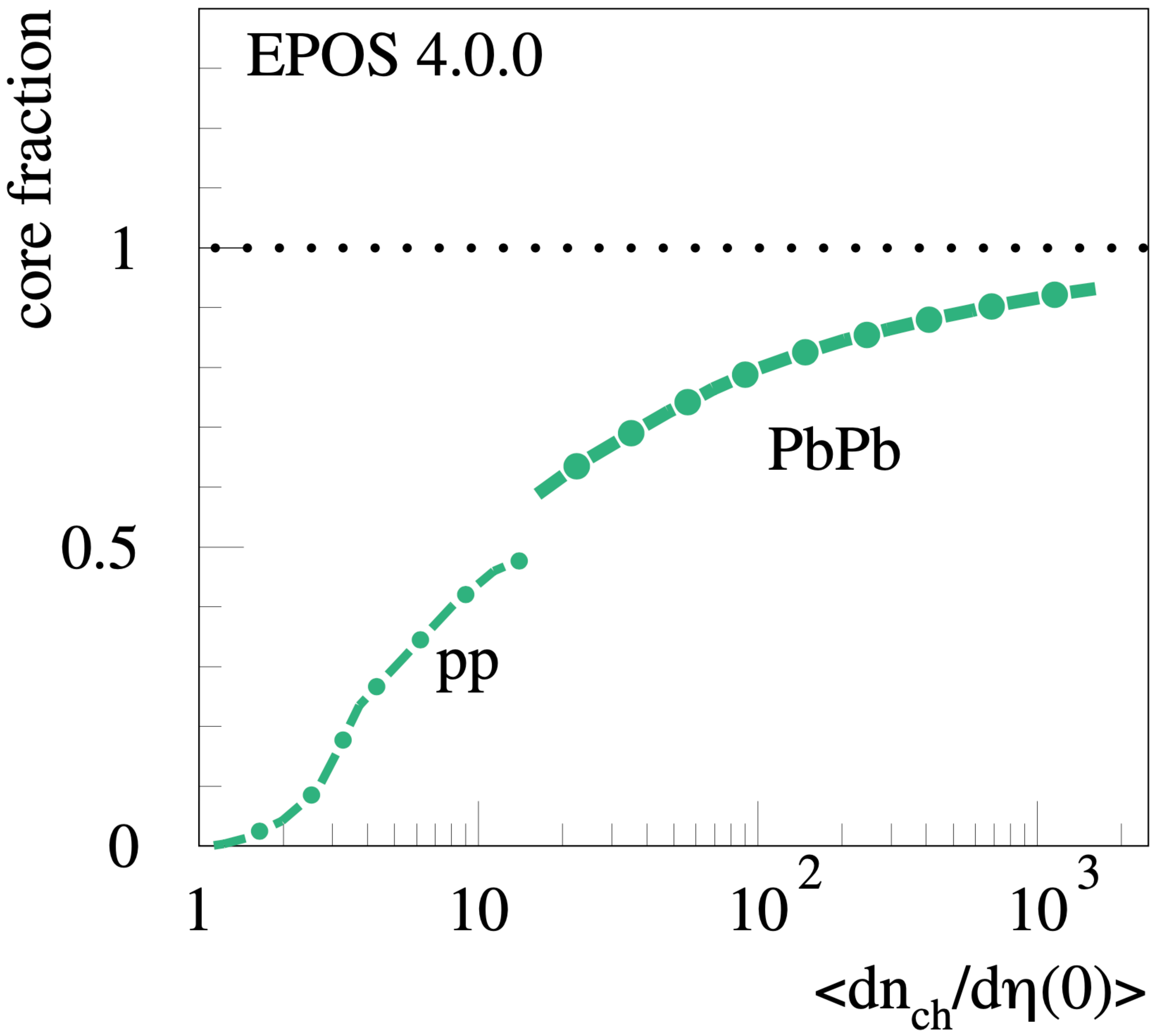
- Recoil jet distribution widens in High Multiplicity (HM) events
- PYTHIA8 (no jet quenching) reproduces effect
- Effect is bias from HM event selection
  - Preference for events with recoil jet at forward rapidity where multiplicity is determined, depletes recoil jets at mid rapidity, bias towards multi-jet states



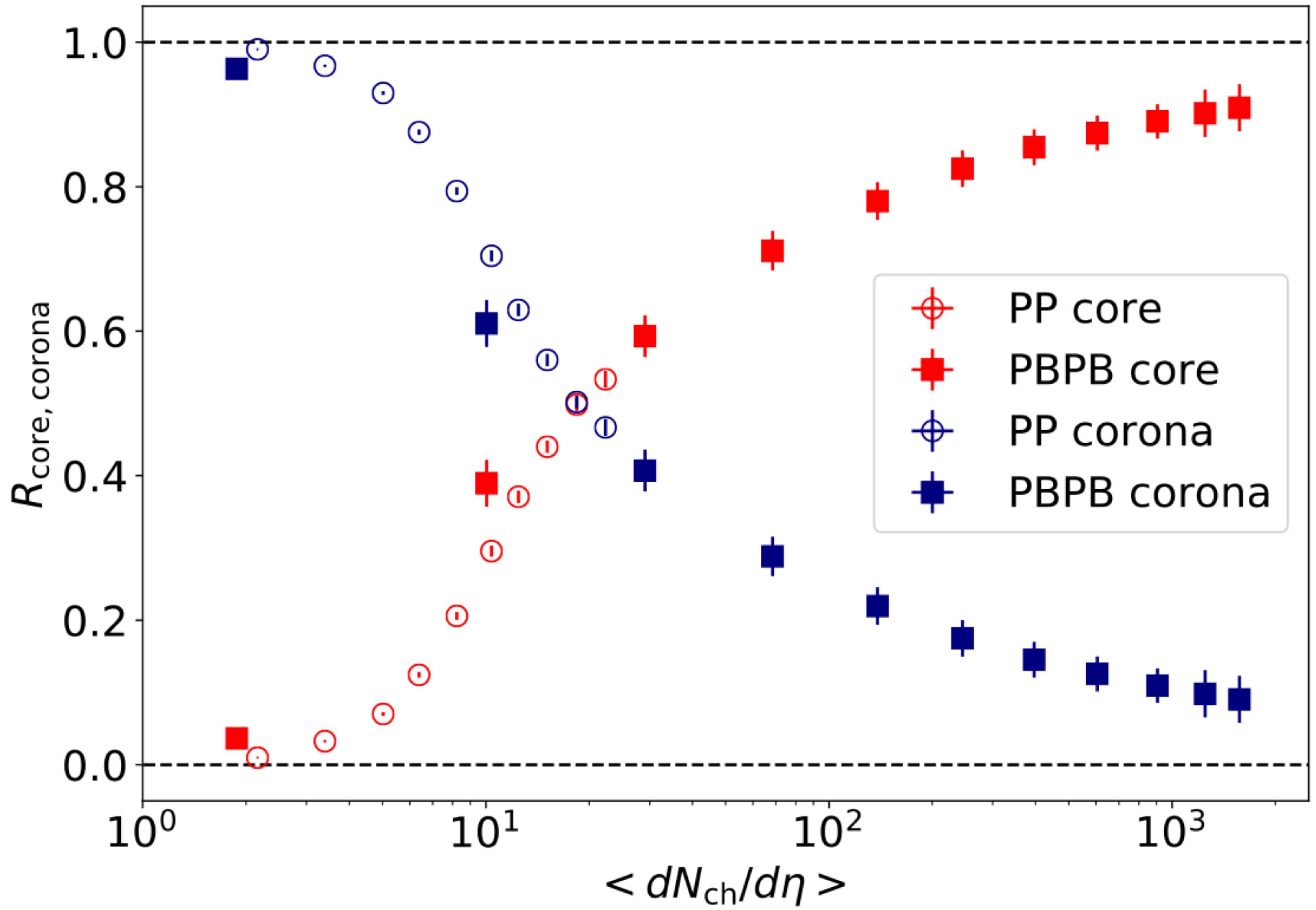


CORE+CORONA PICTURE

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

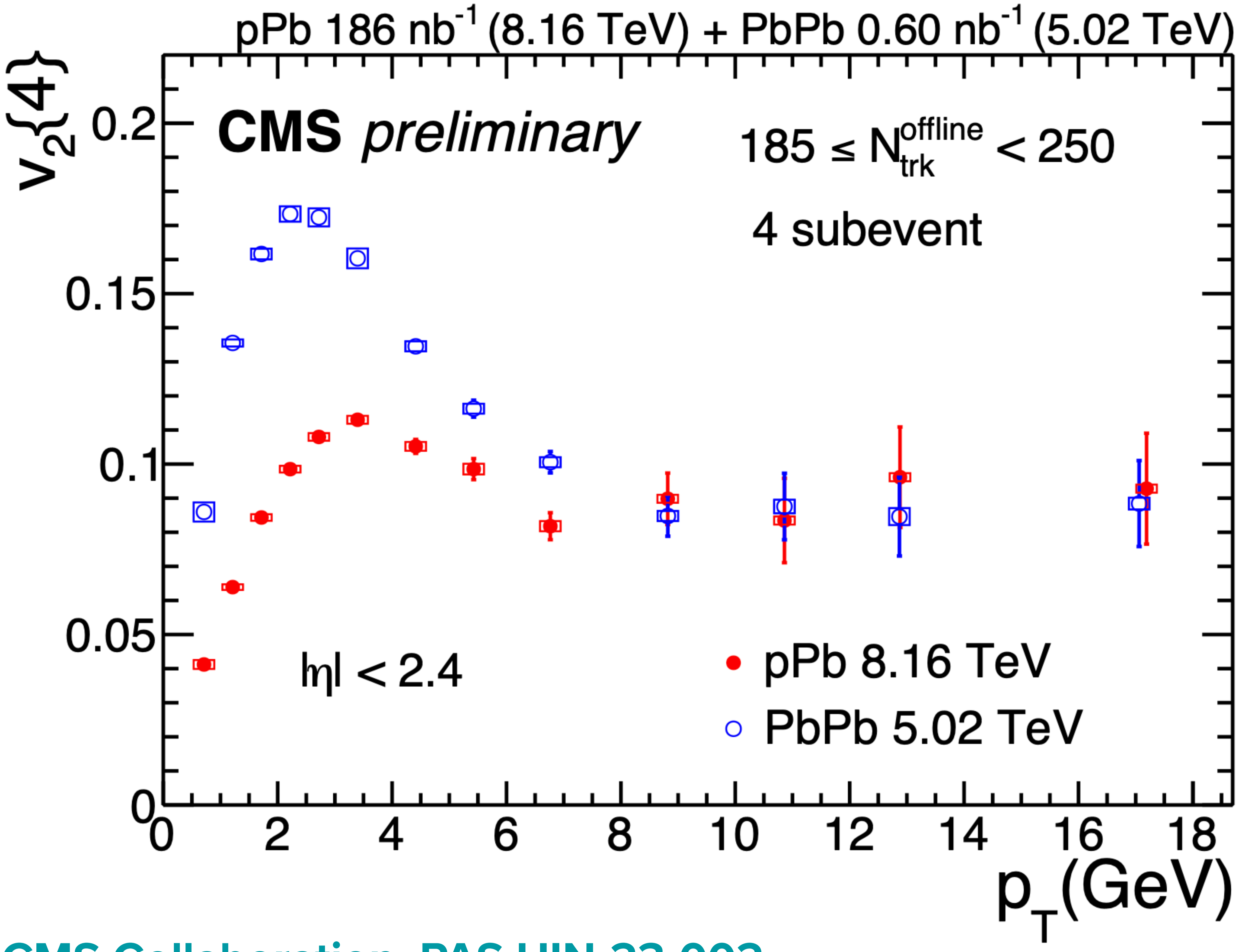


K. Werner, Phys.Rev.C 108 (2023) 6, 064903



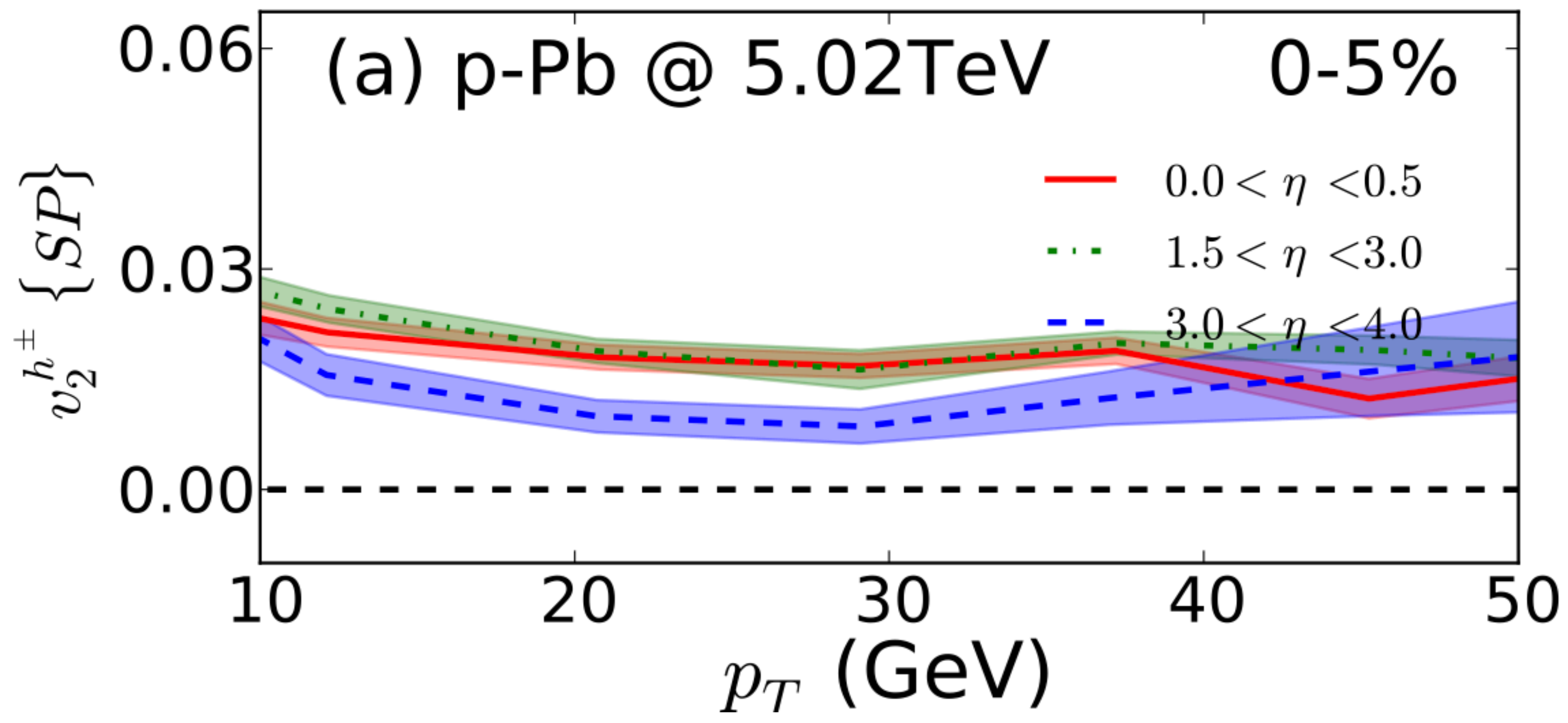
Y. Kanakubo et al., Phys. Rev. C 105 (2022) 2, 024905

HIGH p_T AZIMUTHAL ANISOTROPY



CMS Collaboration, PAS HIN-23-002,
Rohit Kumar Singh's poster; also see
ATLAS Collaboration, Eur.Phys.J.C 80 (2020) 1, 73

Path-length dependent energy loss in p+Pb? C. Park, S. Jeon, C. Gale Nucl.Part.Phys.Proc. 289-290 (2017)



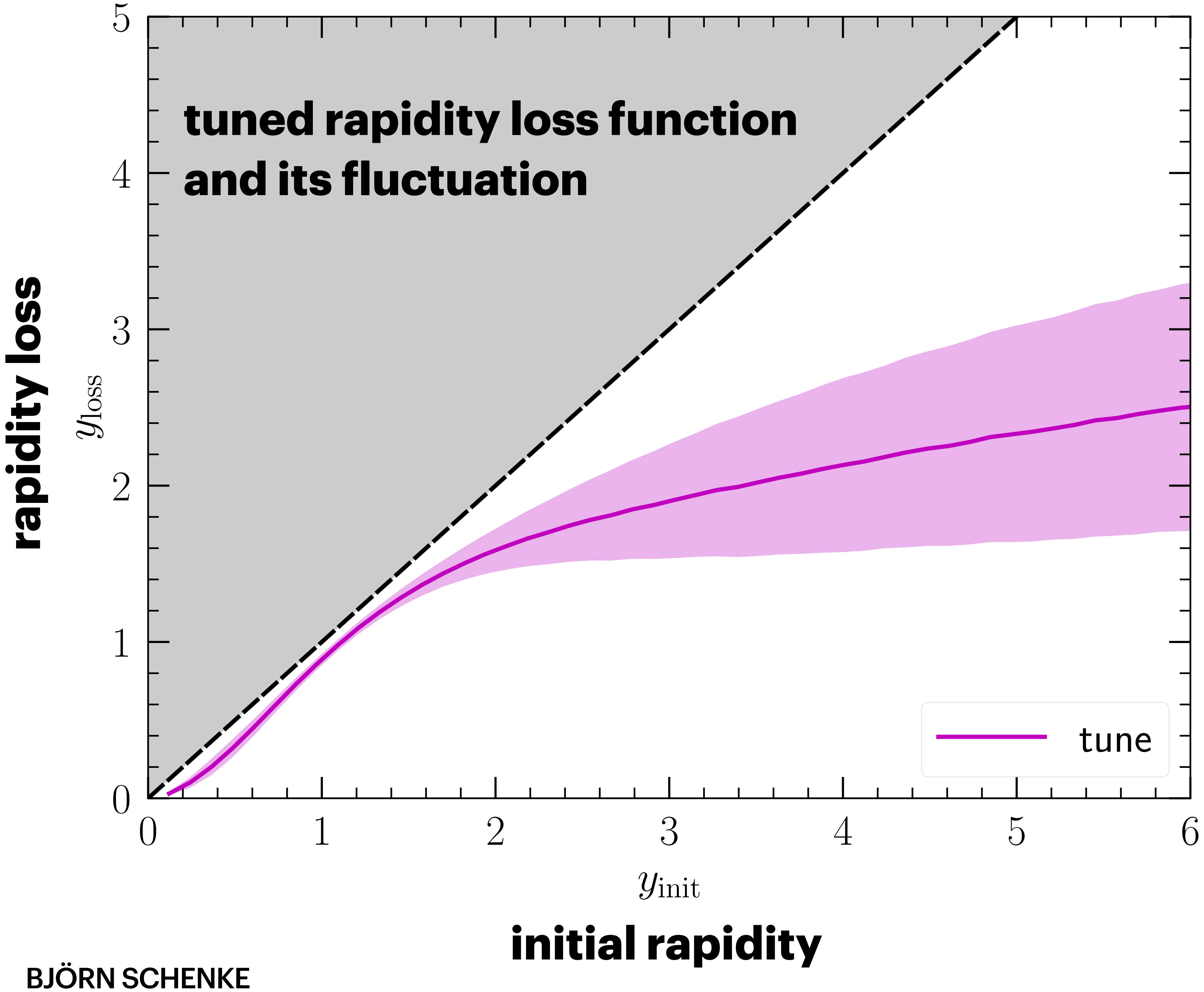
Alternative: Anisotropy from transverse momentum of incoming partons; Contribution from $gg \to gg$ with one gluon linearly polarized gives largest contribution to v_2

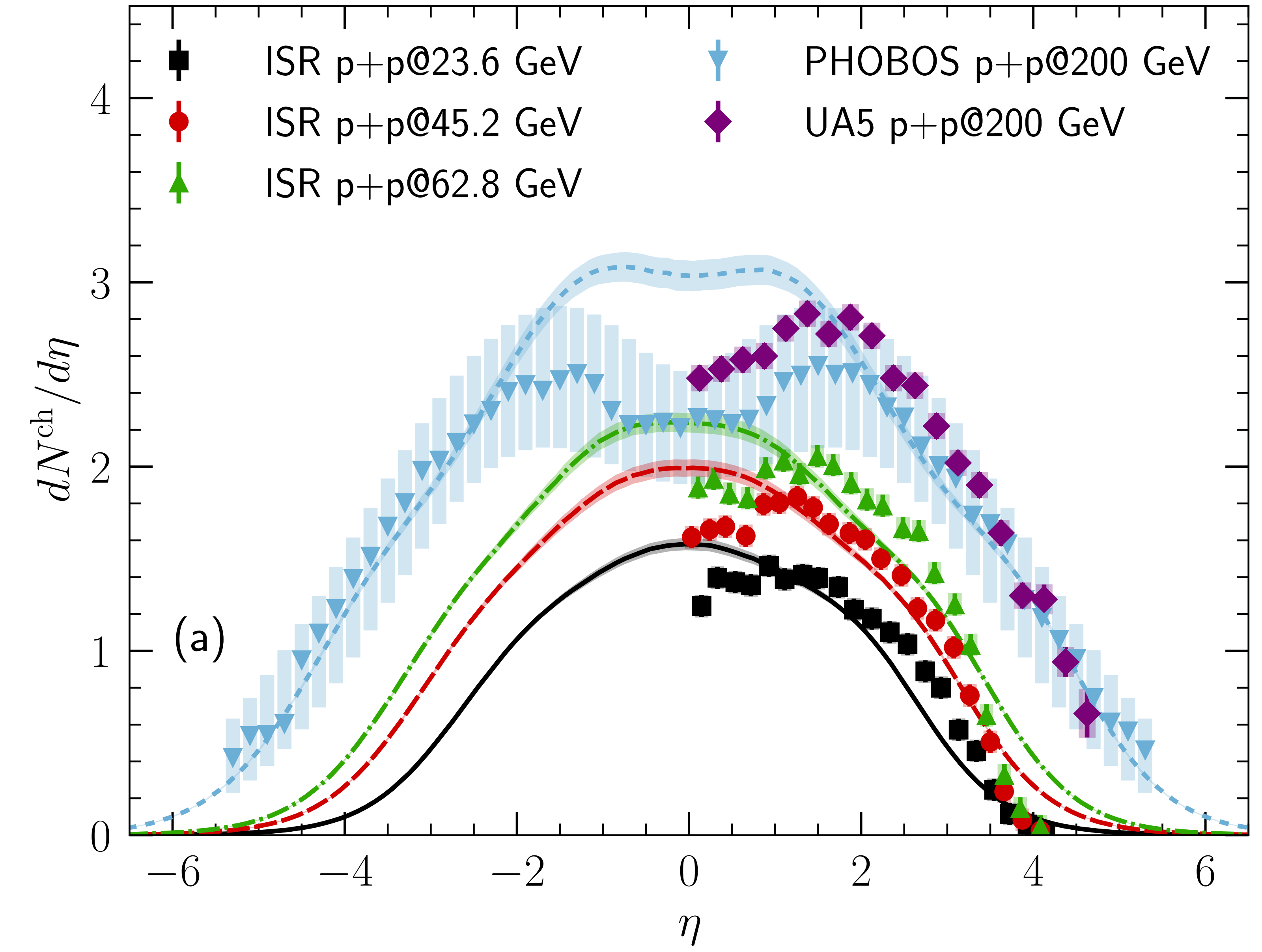
I. Soudi, A. Majumder, arXiv:2308.14702, 2404.05287

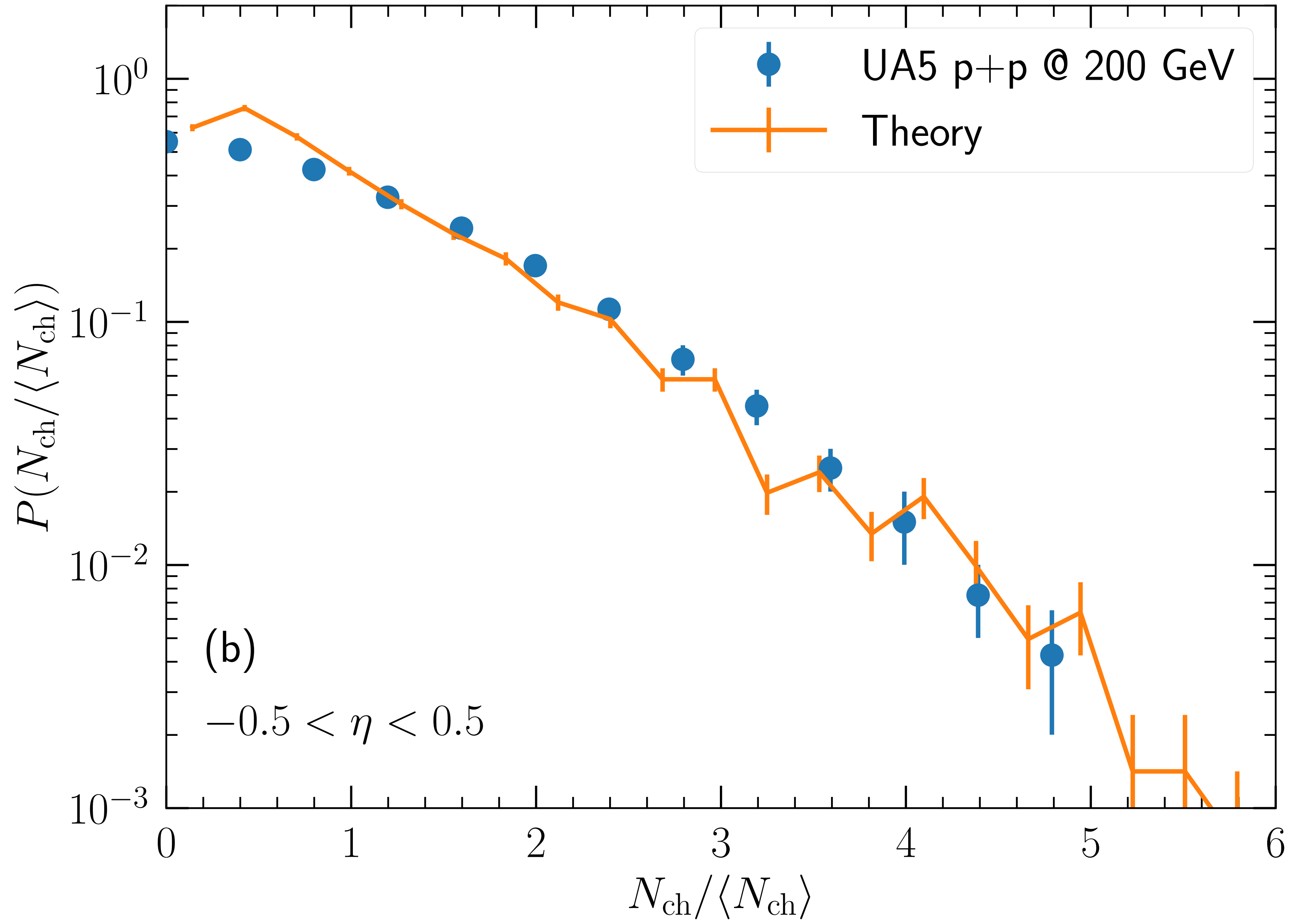
CALIBRATION IN p+p COLLISIONS

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

How much rapidity does a valence quark lose in a collision?

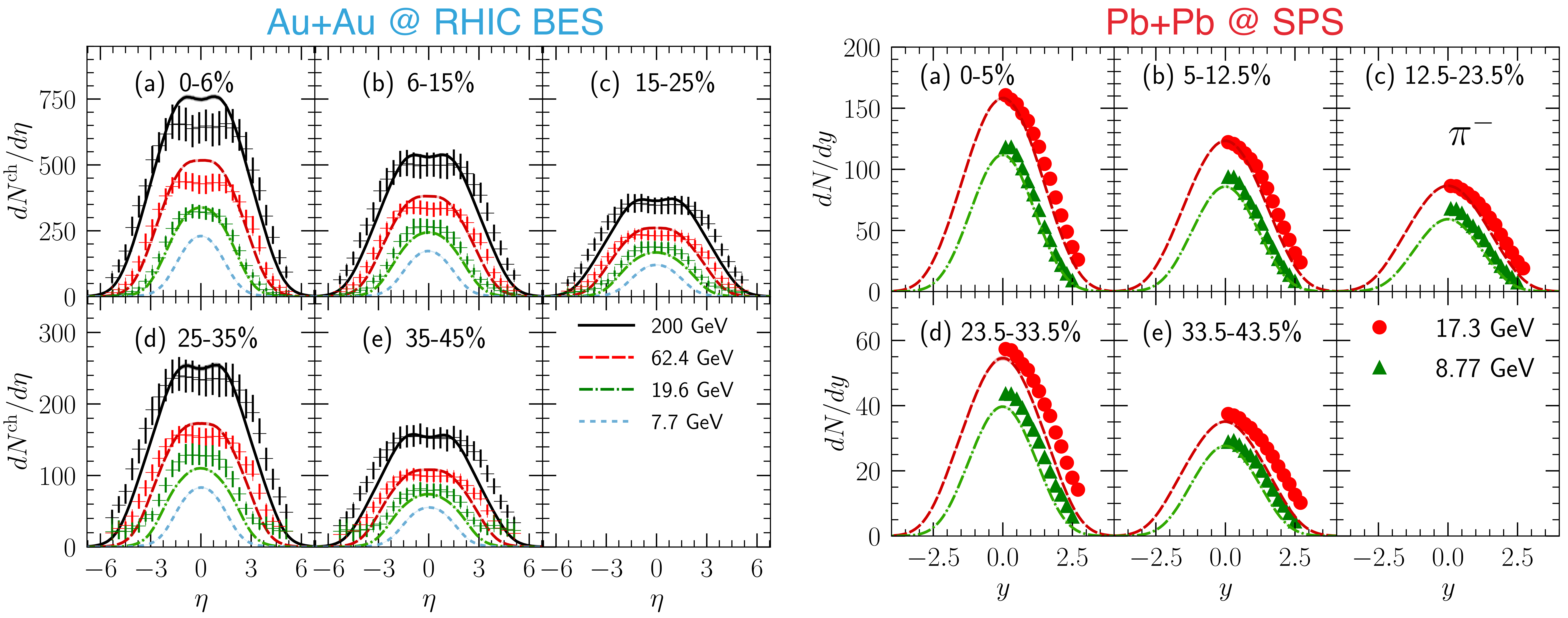






COMPARISON TO A+A DATA

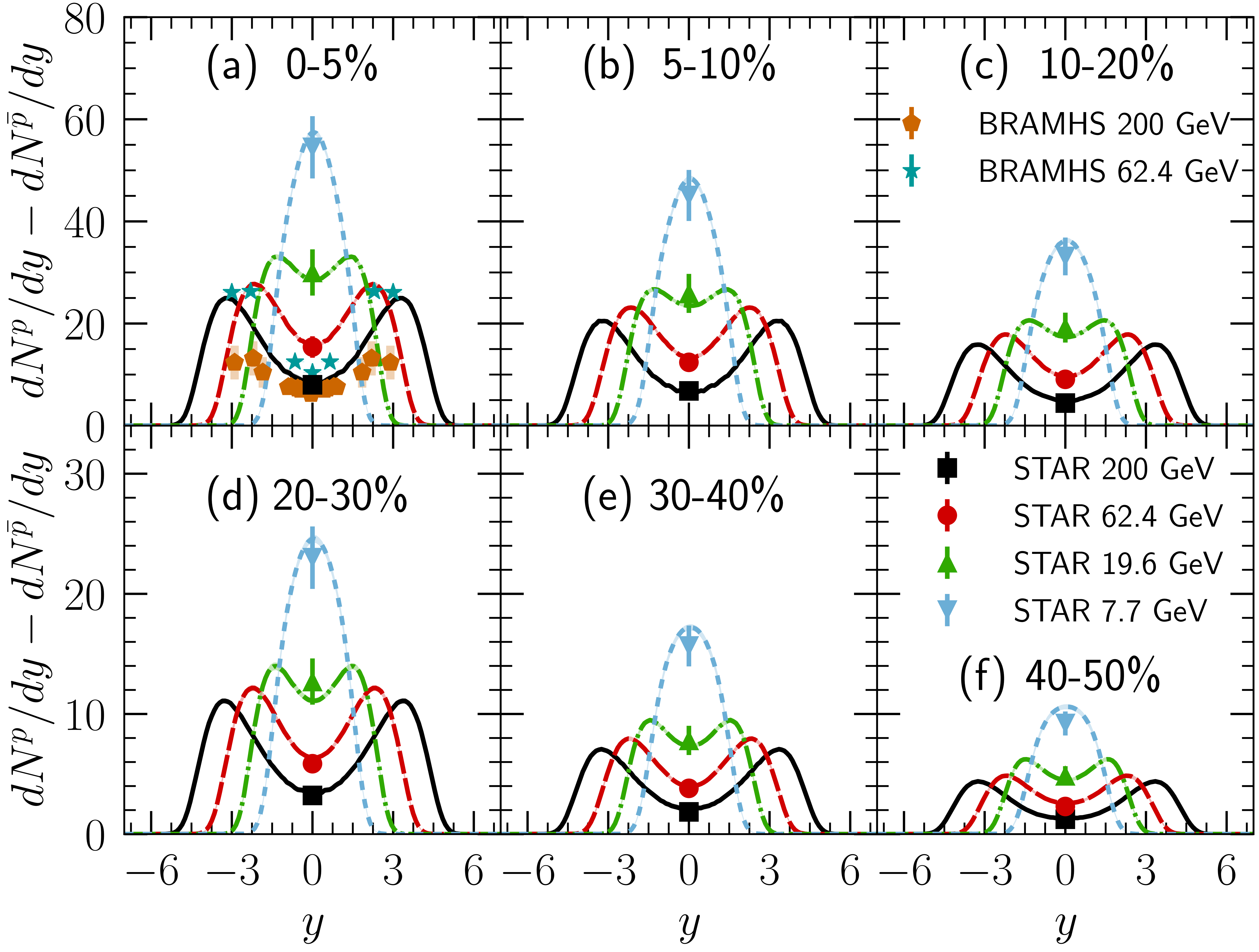
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)



- **Reasonable description of A+A experimental data**

NET-PROTON PRODUCTION

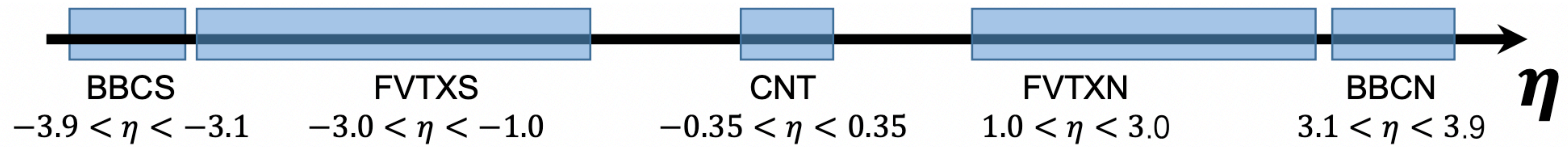
C. Shen and B. Schenke, Phys. Rev. C 105, 064905 (2022)

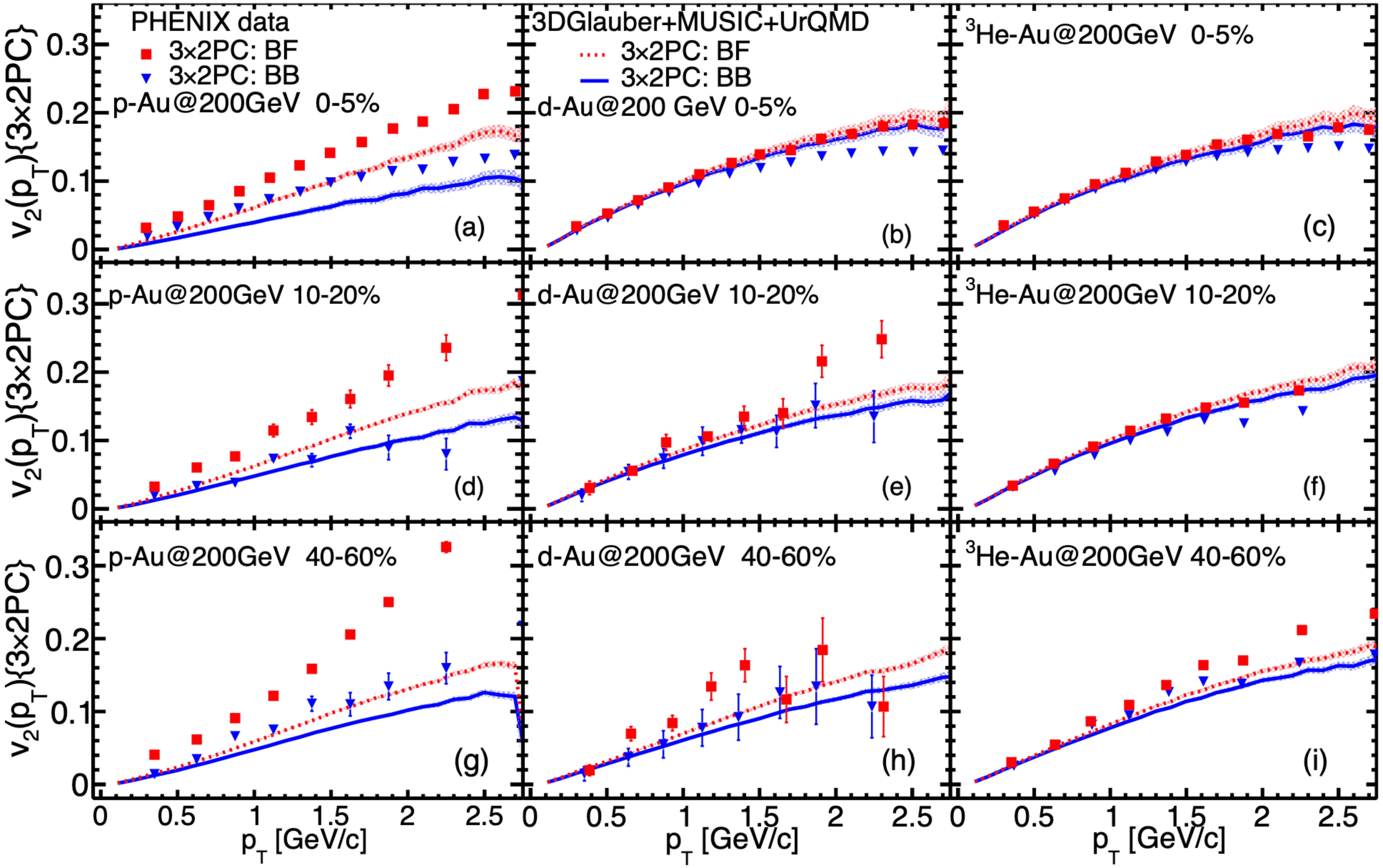


- Predictions for the net proton rapidity and centrality dependence at RHIC BES energies
- Our results at mid-rapidity are consistent with the STAR measurements
- Measurements of the rapidity dependence can further constrain the distributions of initial baryon charges

PHENIX 3X2PC STUDY

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





$3\times\ 2PC$

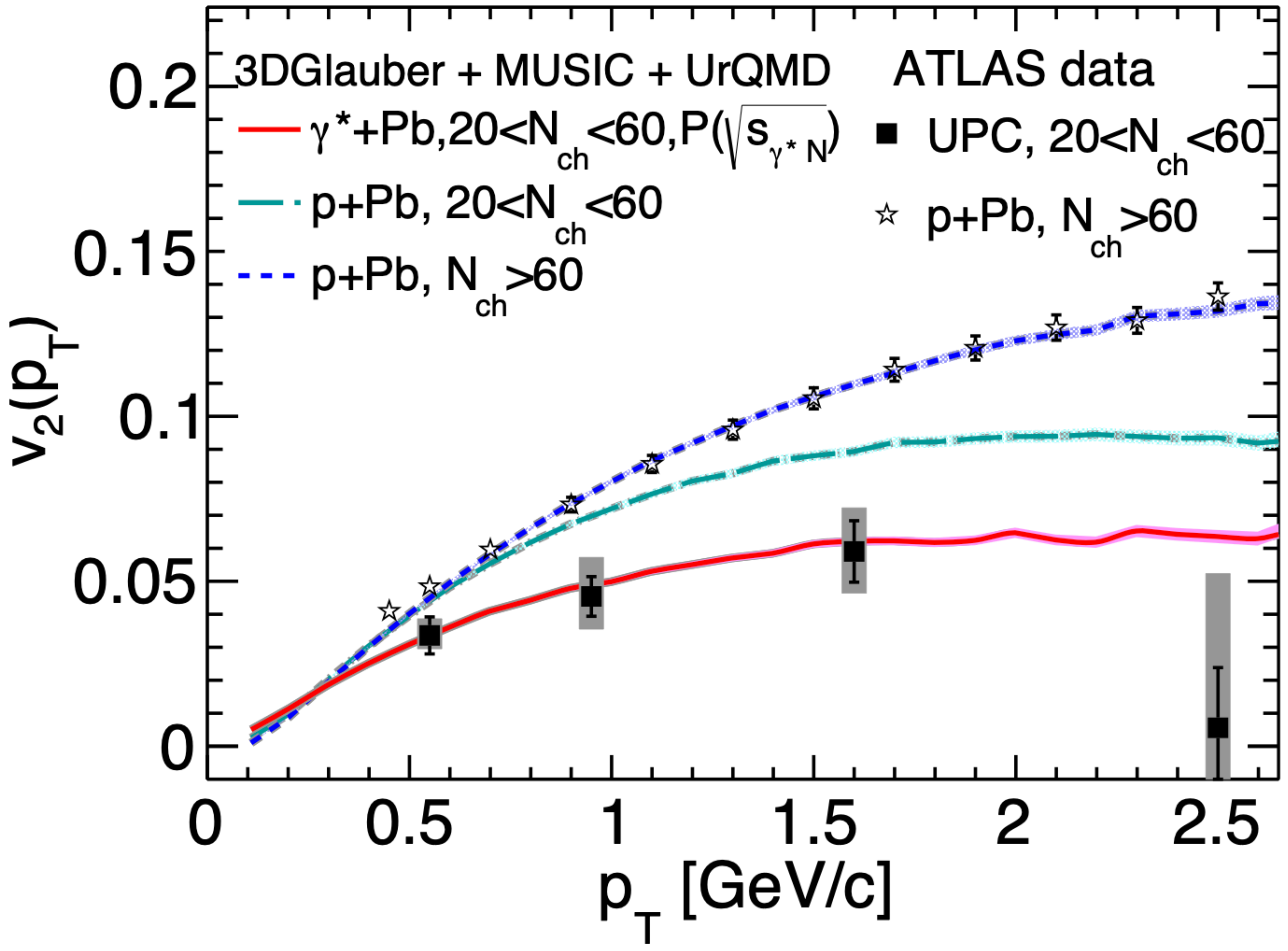
$$C_n^{AB} = \langle Q_{nA} Q_{nB}^* \rangle\,,$$
$$c_n^{AC}(p_T) = \langle Q_{nA} q_{nC}^*(p_T) \rangle\,,$$
$$c_n^{BC}(p_T) = \langle Q_{nB} q_{nC}^*(p_T) \rangle\,.$$

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

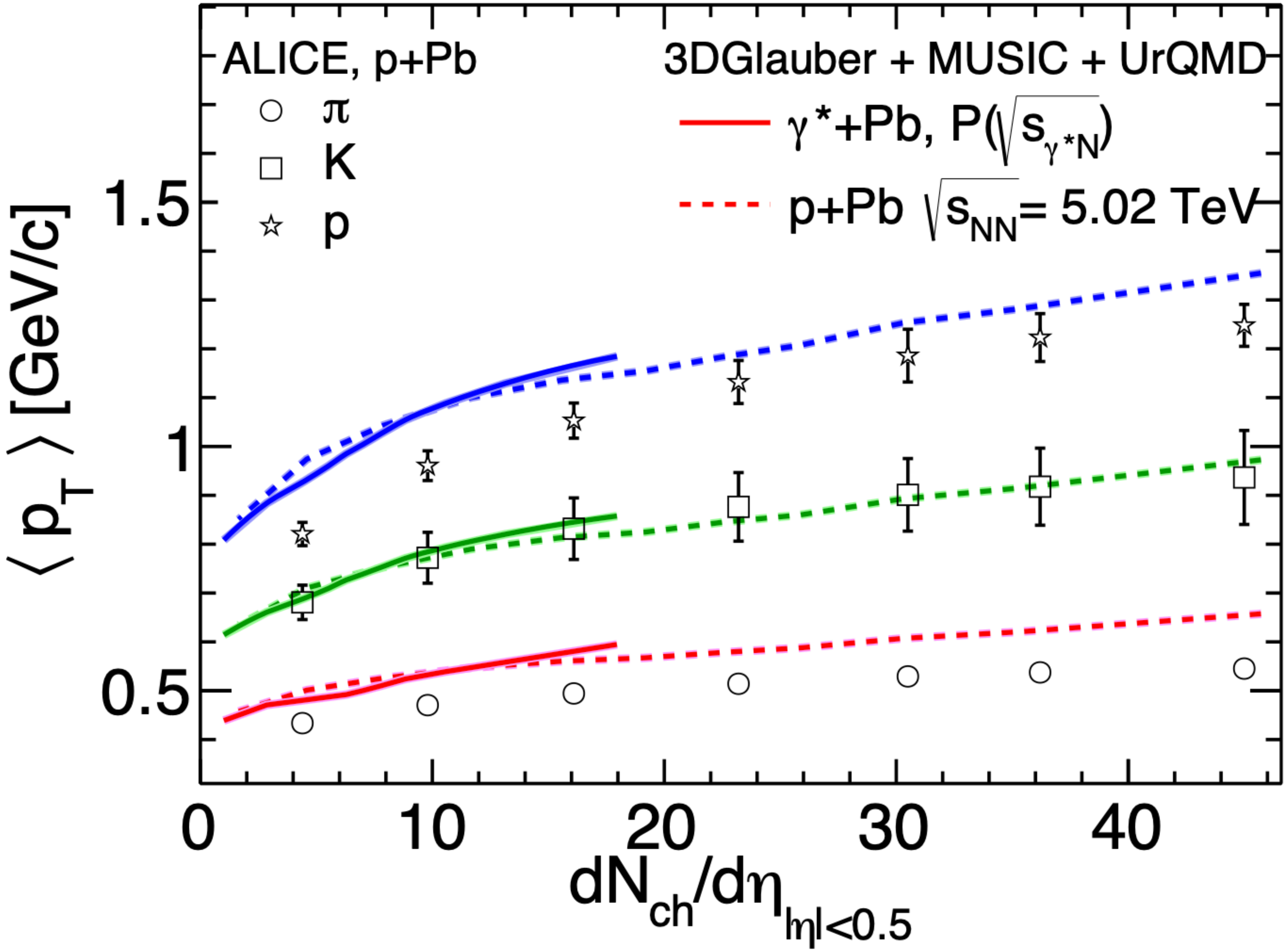
BB: BBCS-FVTXS-CNT
BF: FVTXS-CNT-FVTXT

Longitudinal flow decorrelation reproduces some differences between BB and BF measurements

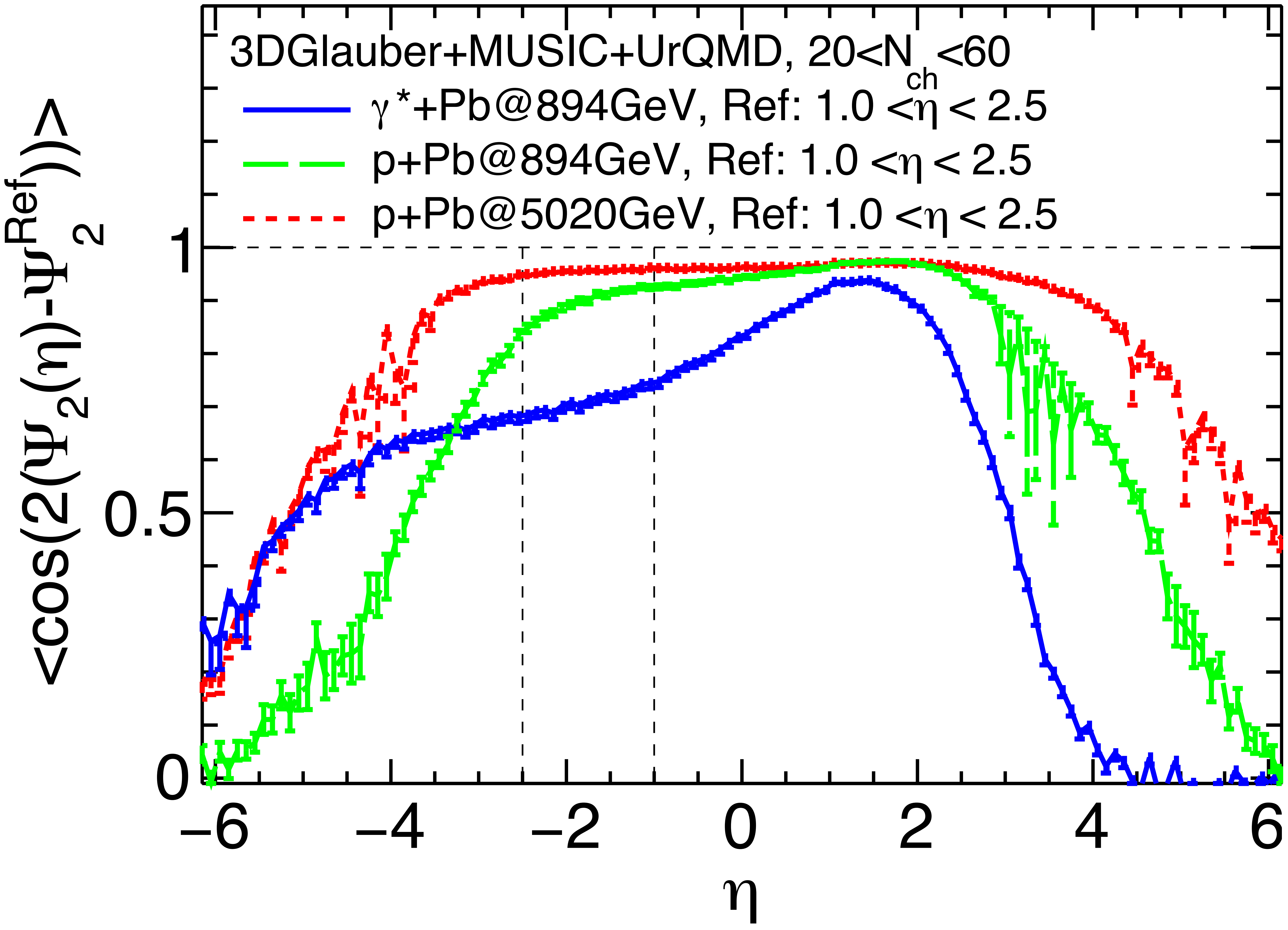
DIFFERENTIAL v_2 IN UPC Pb+Pb



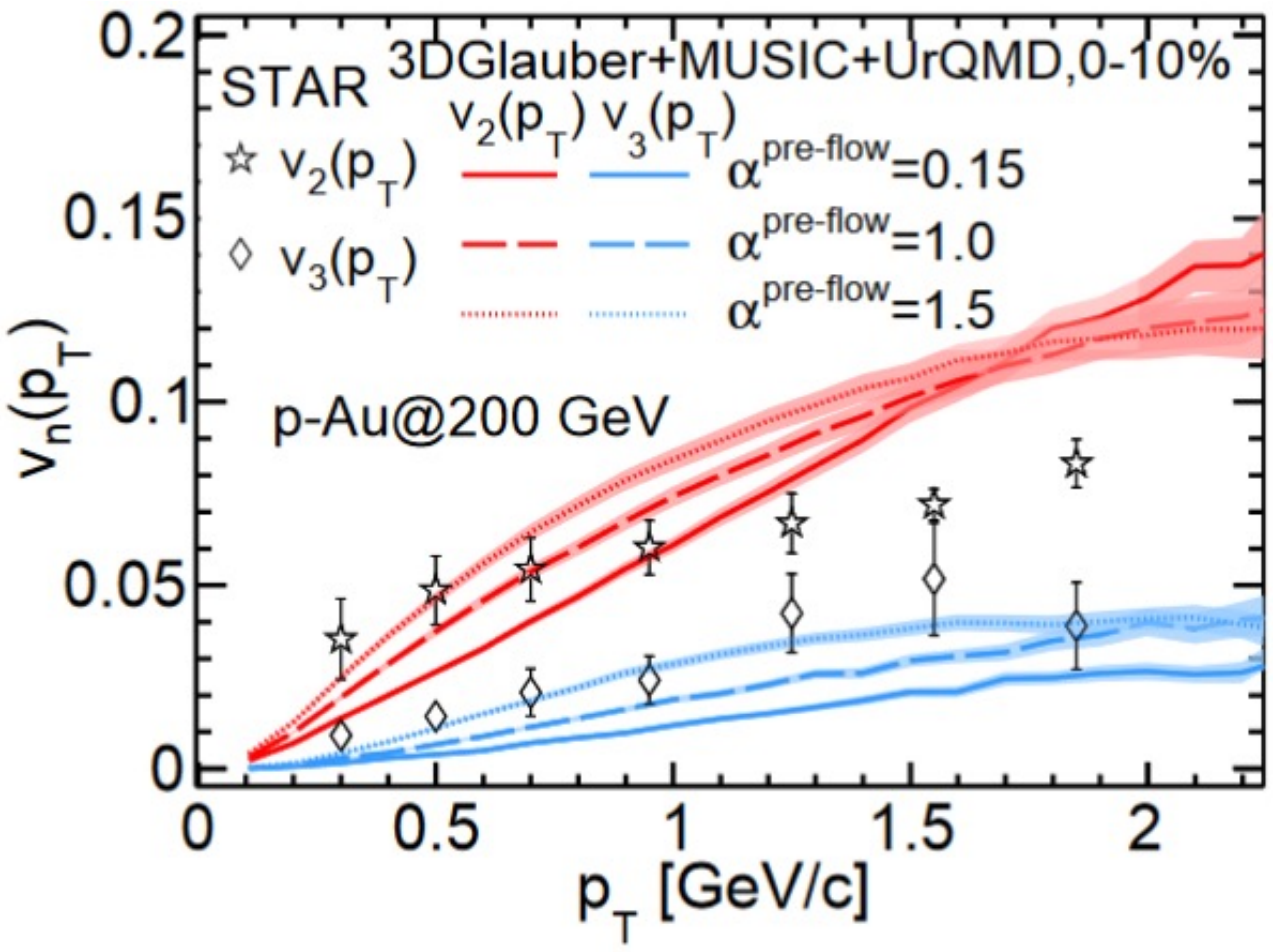
MEAN p_T IN UPC Pb+Pb

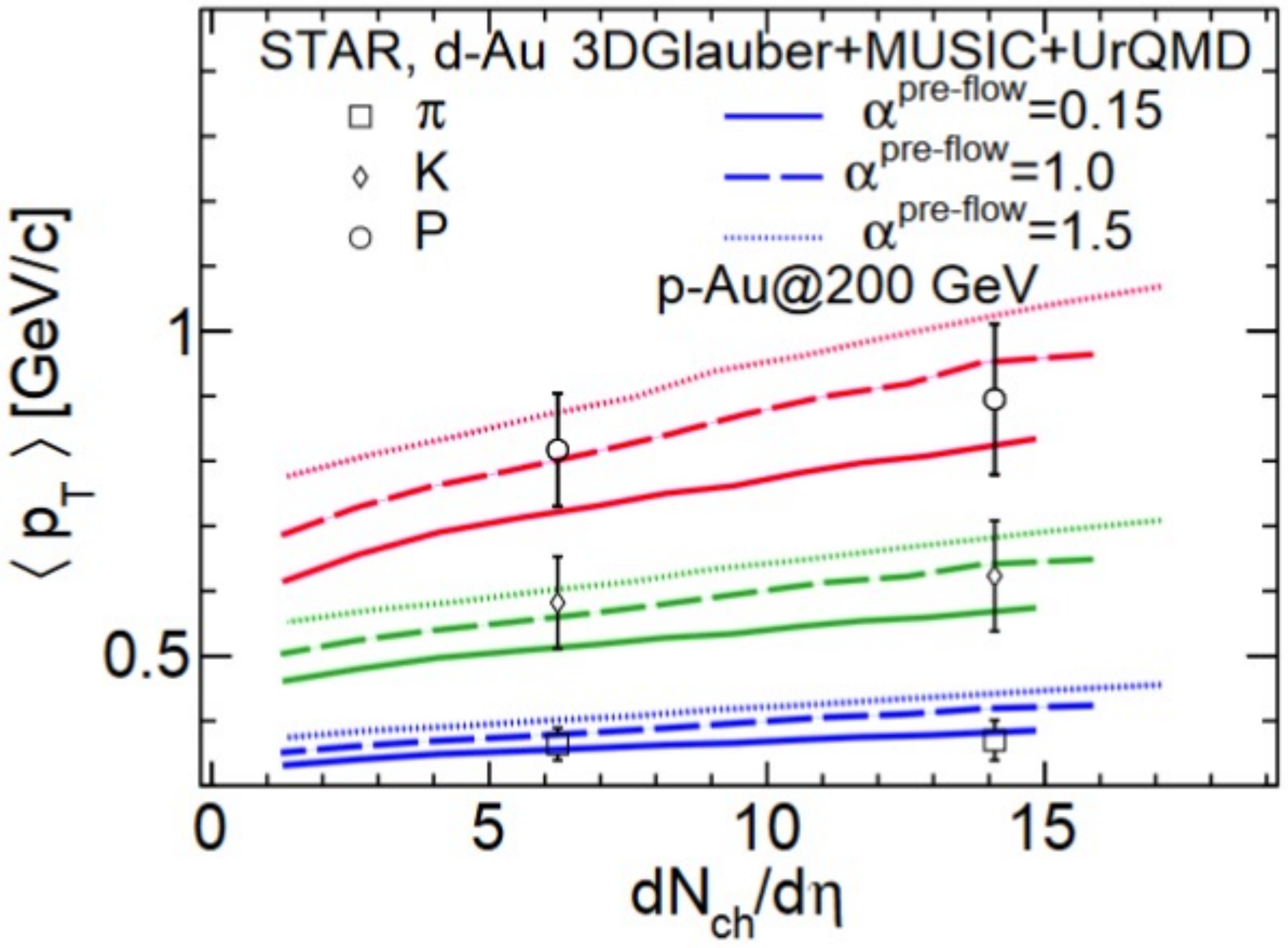


DECORRELATION IN UPC



Importance of Pre-Hydrodynamic Evolution





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

A blast-wave like pre-hydrodynamic flow: $\eta_\perp = \alpha^{\mathrm{pre-flow}} r,$

$\eta_\perp$ is transverse flow rapidity, r is the distance from the point to the string center. The $\alpha^{pre-flow}$ controls the strength of the pre-hydrodynamic flow.

- Stronger pre-hydrodynamic flow leads to larger mean p_T and anisotropic coefficients.
- A systematic calibration including pre-hydrodynamic flow is important.

HYDRODYNAMICS AND EOS

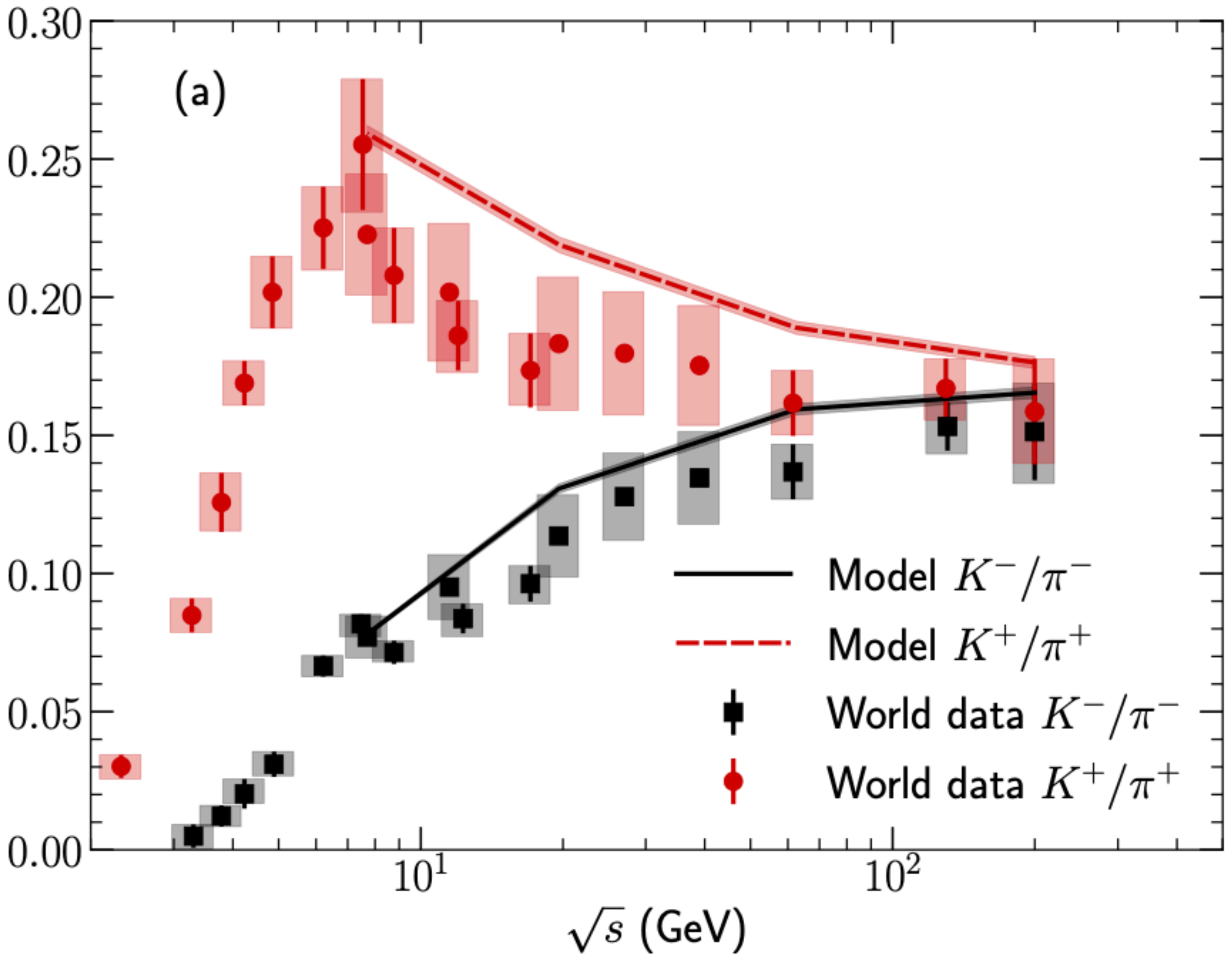
- **For the equation of state we use NEOS with finite μ_B, μ_S, μ_Q**

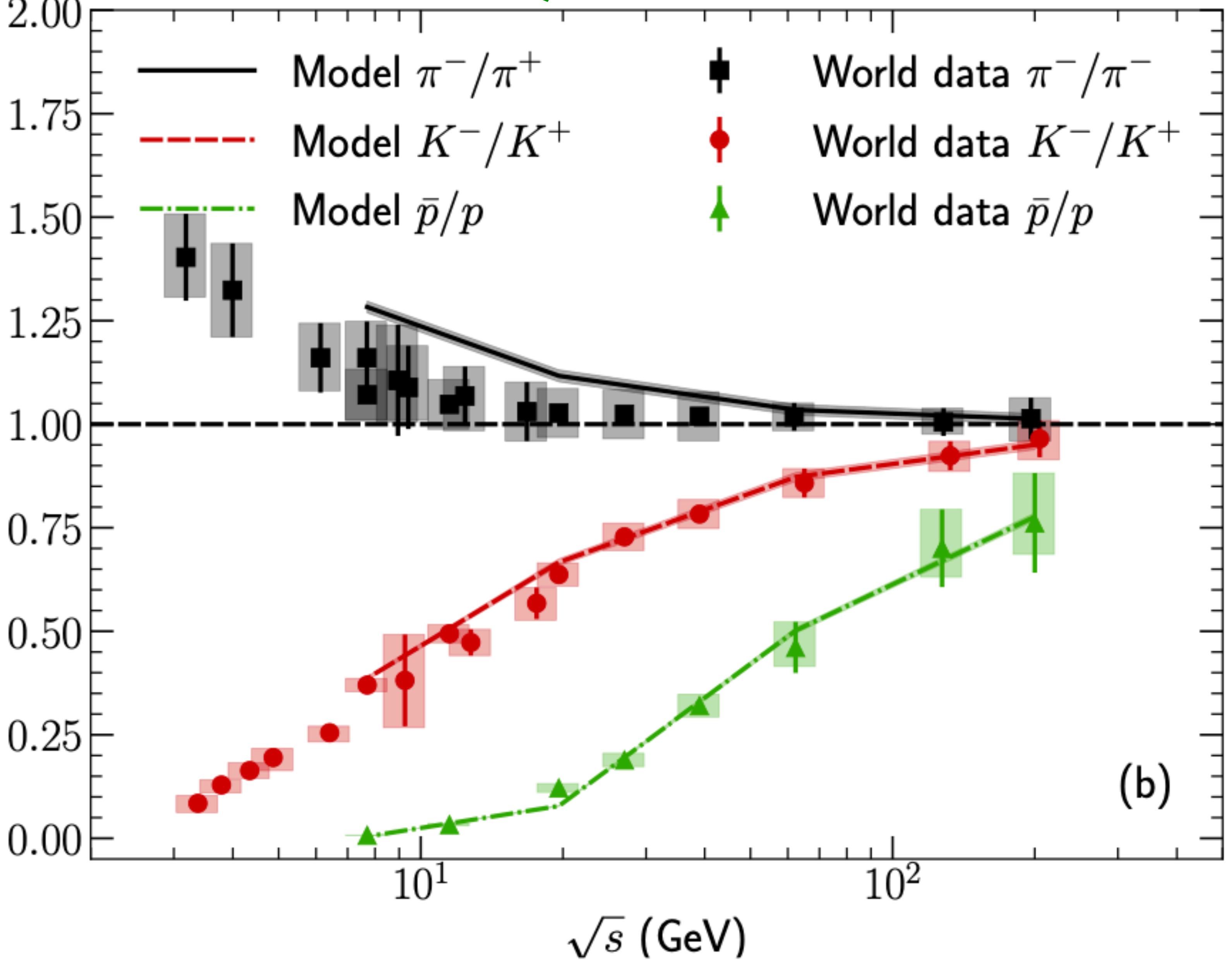
  A. Monnai, B. Schenke, C. Shen, Phys. Rev. C 100, 024907 (2019)

  A. Monnai, B. Schenke, C. Shen, Int.J.Mod.Phys.A 36 (2021) 07, 2130007

  And choose $n_S = 0$ and $n_Q = 0.4 n_B$ for Au+Au collisions:

C. Shen, e-Print: 2108.04987

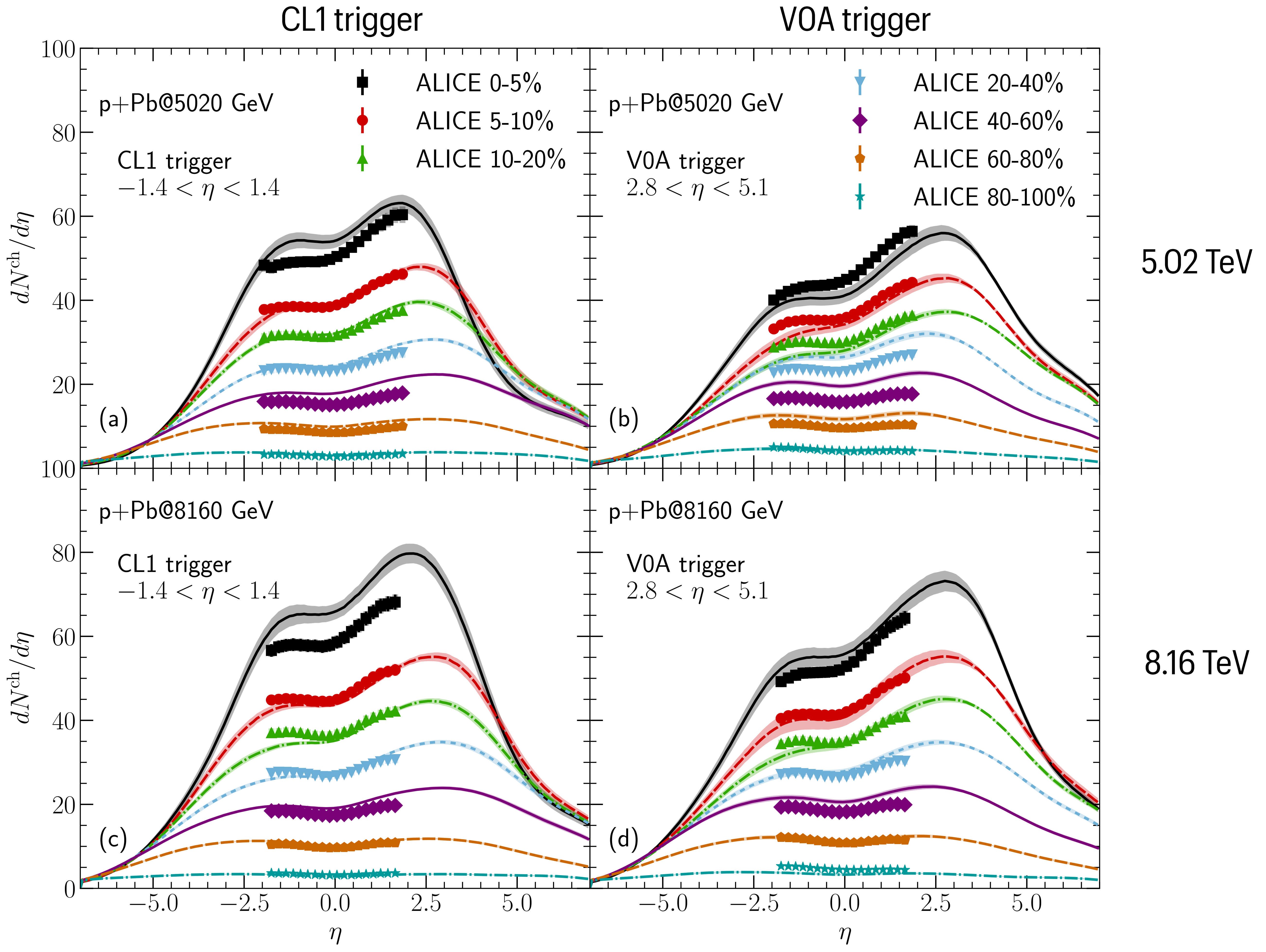




CENTRALITY DEFINITION

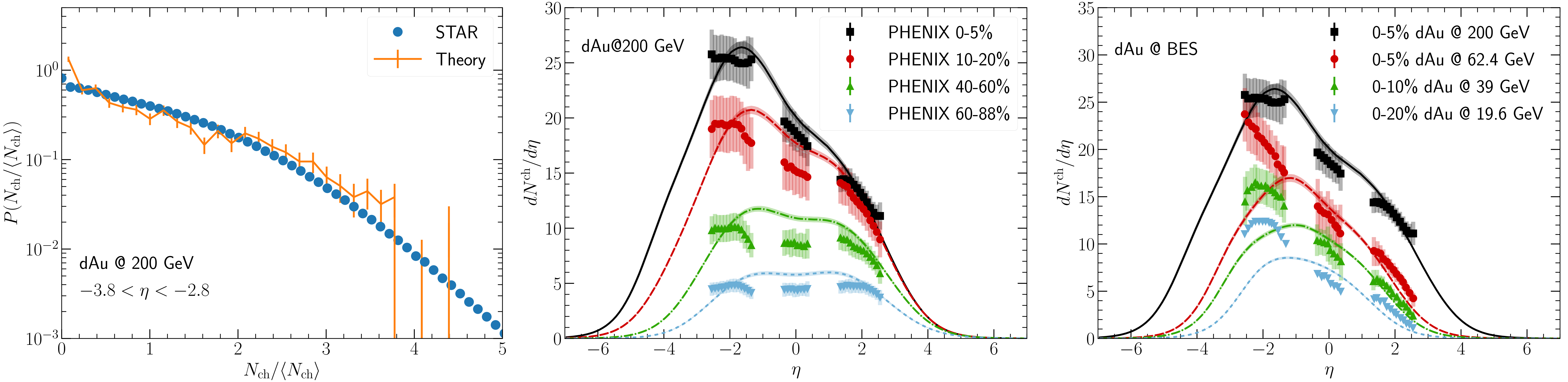
C. Shen and B. Schenke, in preparation

- **We can now determine centrality in the same rapidity bins as the experiments**
- **It does make a difference for the shape of the rapidity distribution**



MULTIPLICITY DISTRIBUTIONS

C. Shen and B. Schenke, in preparation

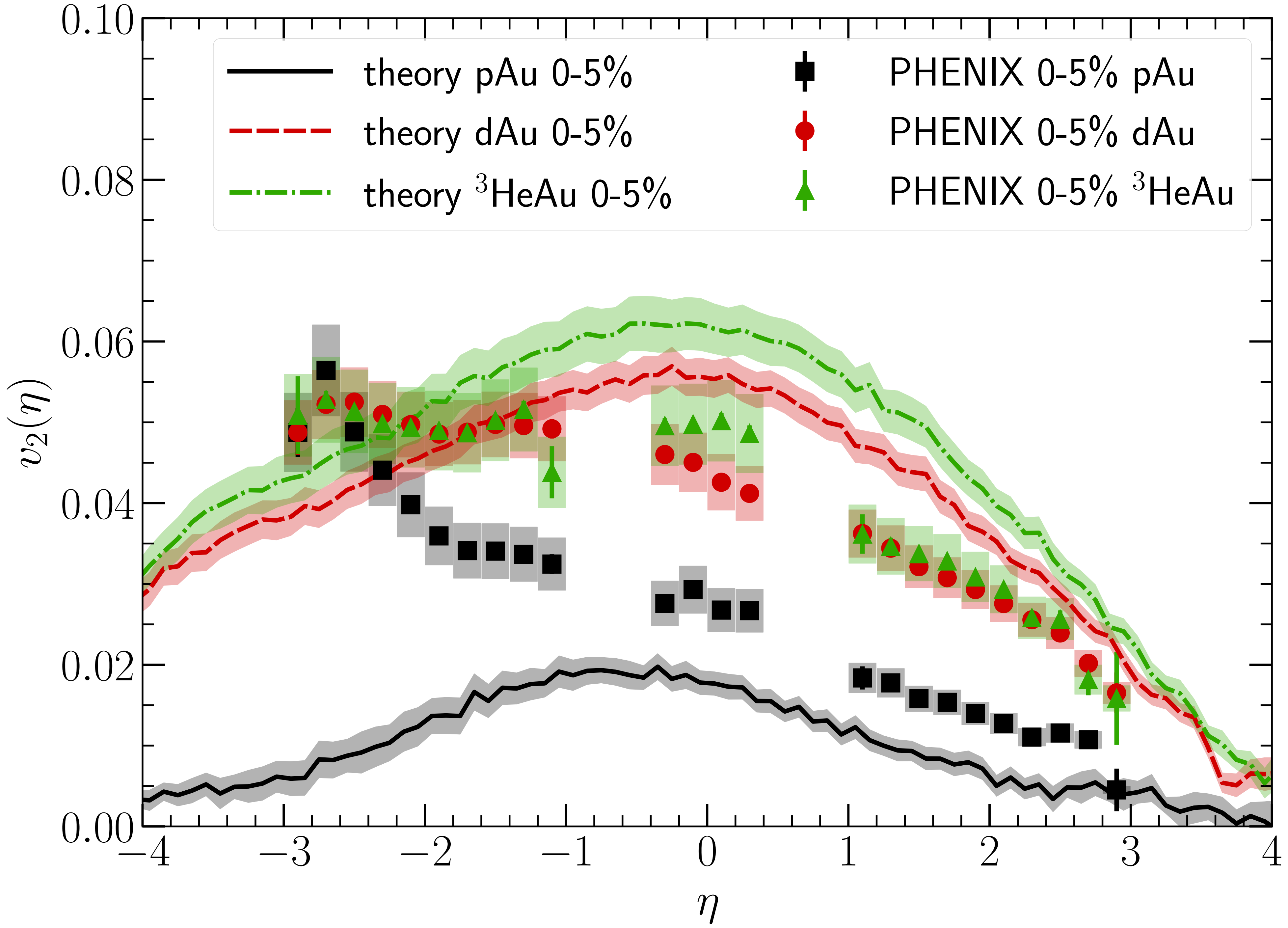


- **Model reproduces the STAR multiplicity distribution in d+Au collisions at 200 GeV**
- **The predicted charged hadron rapidity distribution agrees well with the PHENIX measurements from central to peripheral collisions**
- **The role of spectators at forward rapidity needs further investigation**

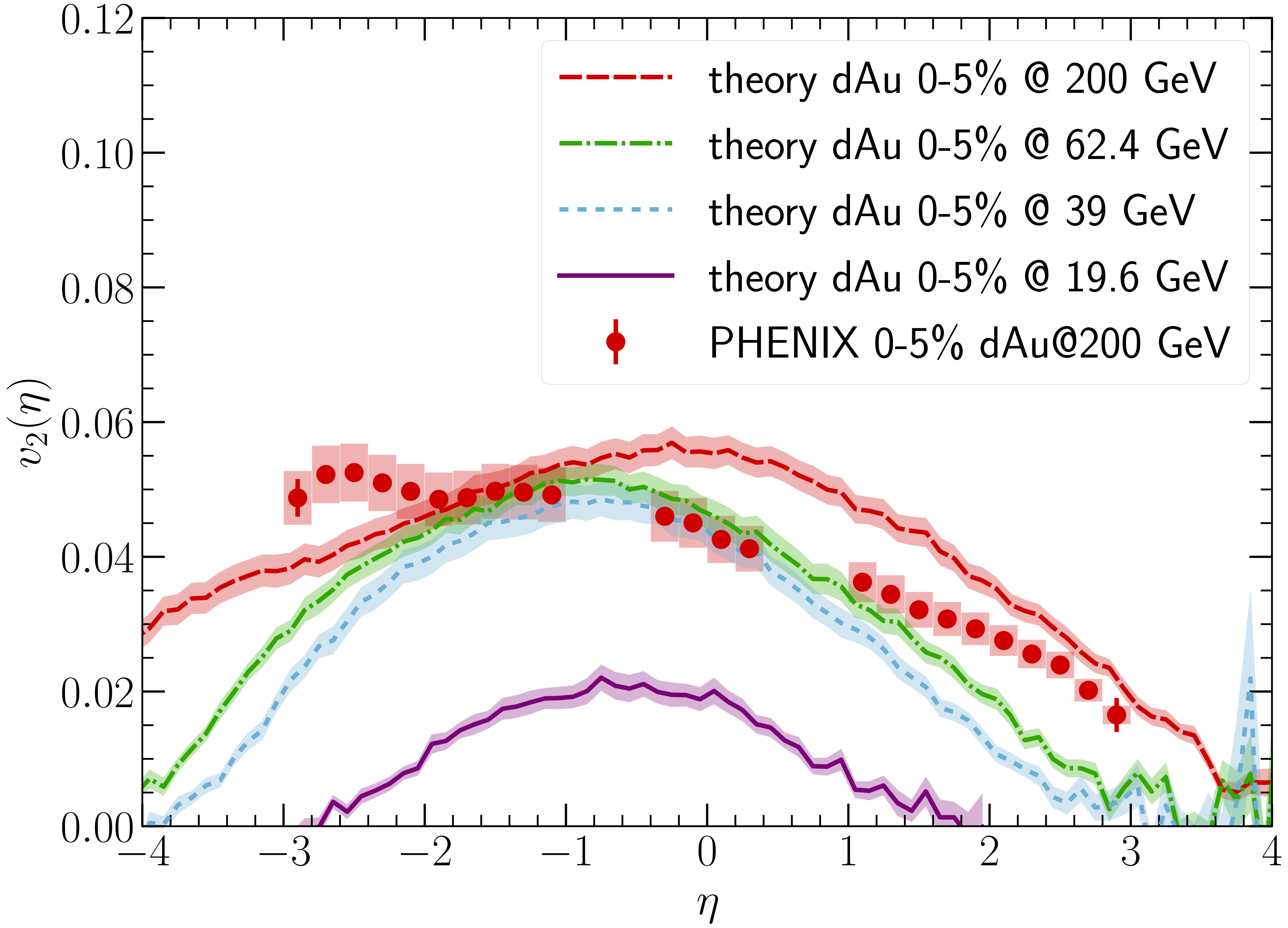
ANISOTROPIC FLOW

C. Shen and B. Schenke, in preparation

System dependence



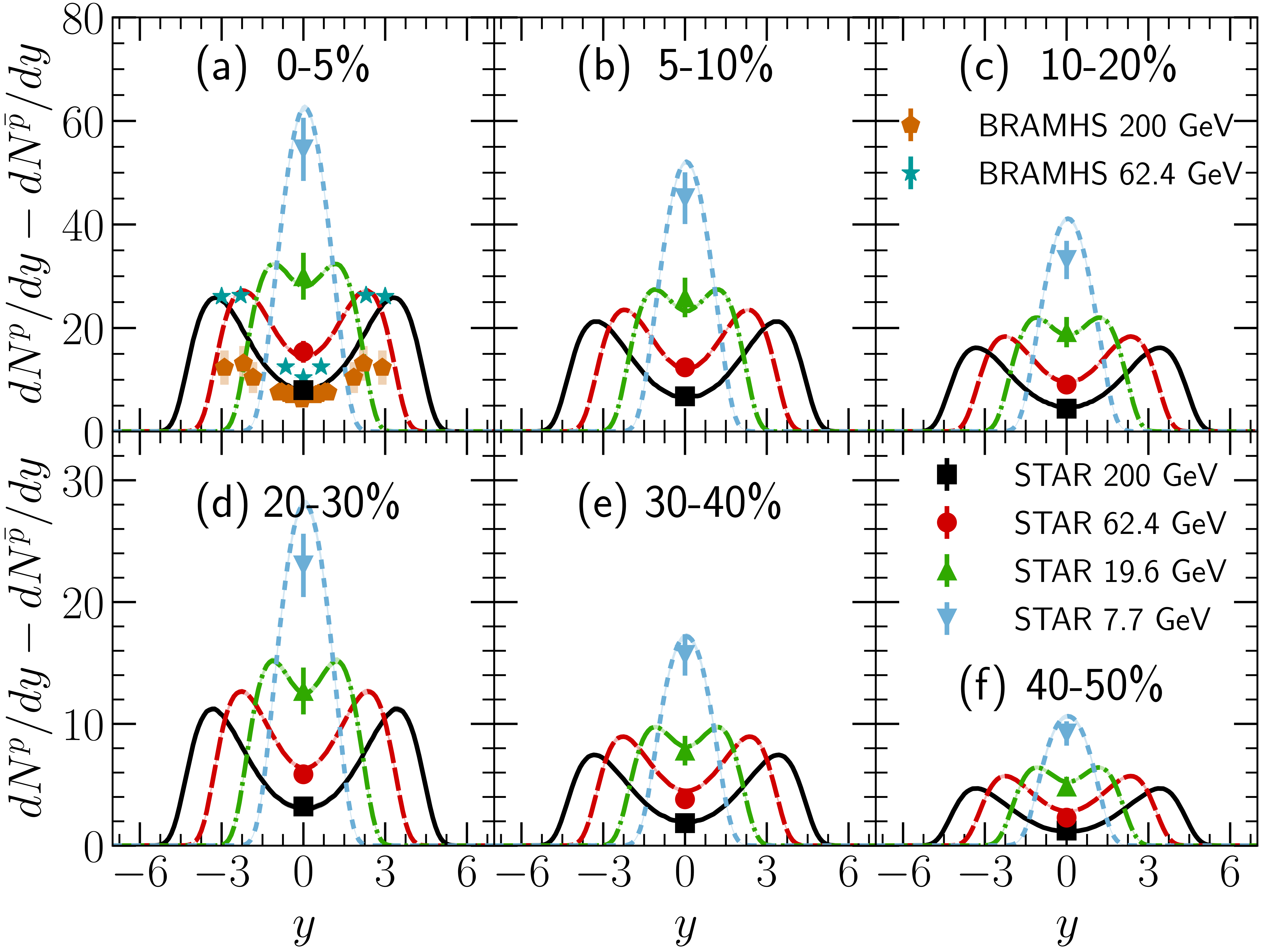
Energy dependence



- **Discrepancies could come from different method being used in the experiment**
- **Biggest deviation from the data in p+Au in the Au going direction (non-flow?)**
- **PHENIX event plane method with event plane at *y* in [-3.9, -3.1]**

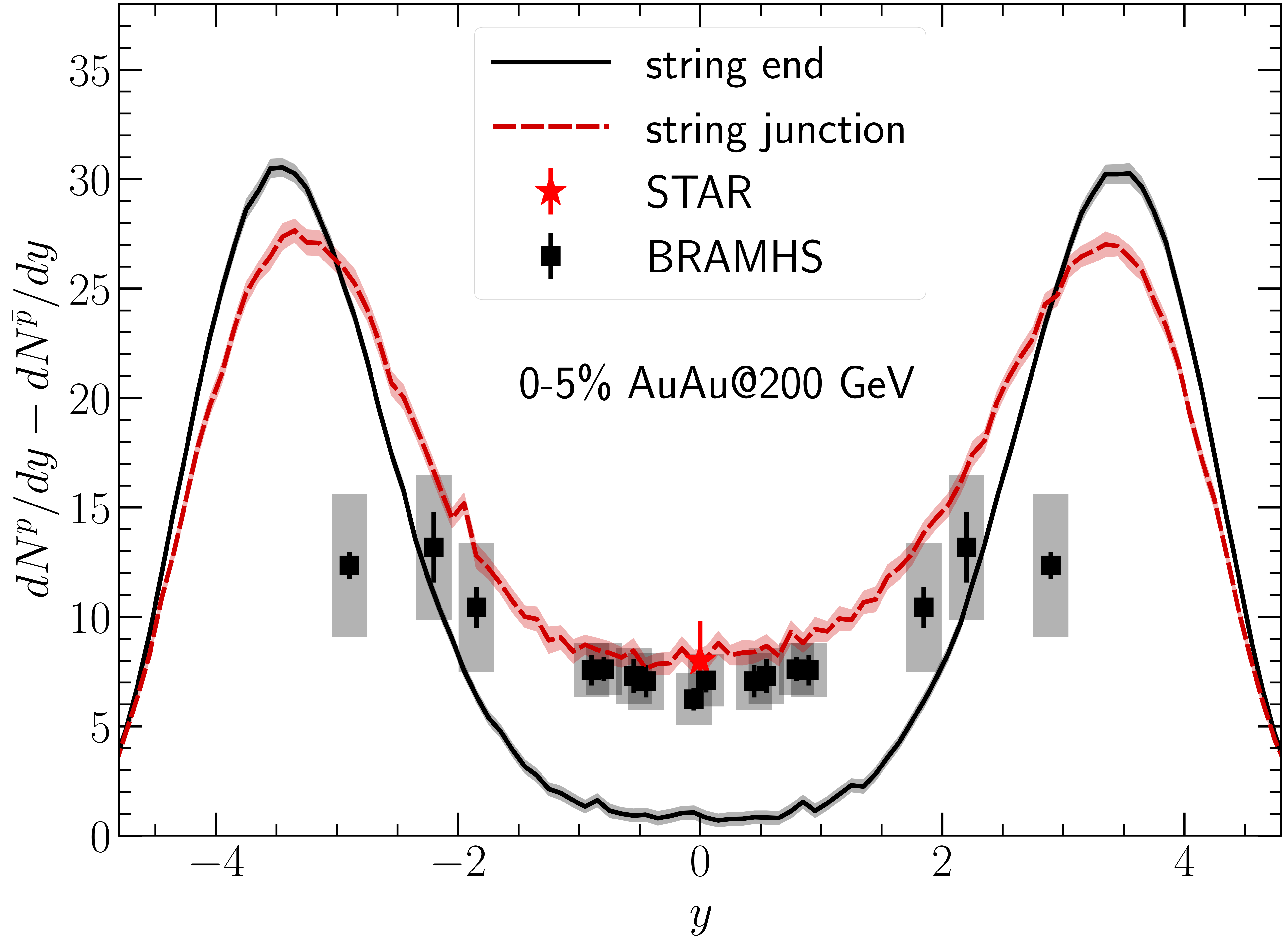
NET-BARYON DISTRIBUTIONS

C. Shen and B. Schenke, in preparation



NET-BARYON DISTRIBUTIONS

C. Shen and B. Schenke, in preparation



Effect of baryon junctions