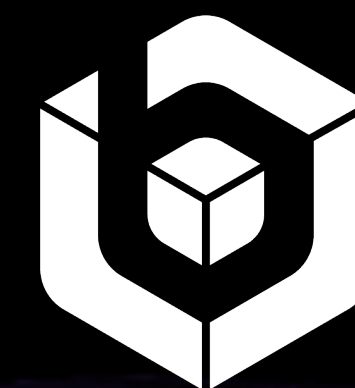




U.S. DEPARTMENT OF
ENERGY

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Brookhaven[™]
National Laboratory

HEAVY-ION COLLISIONS AS A PRECISION LABORATORY FOR HOT AND COLD QCD

Björn Schenke, Brookhaven National Laboratory

EINN 2025

Paphos, Cyprus

October 31, 2025

50 YEARS OF QUARK-GLUON PLASMA

1973: Birth of Quantum Chromo Dynamics

1974: The Bear Mountain Workshop, 11/29 - 12/1, 1974

1980: Shuryak coins a phrase: QGP

1983: Foundational Year: convergence of experimental and theoretical efforts in understanding the expected reaction dynamics, funding decisions

2000: RHIC begins operation: BRAHMS, PHOBOS, STAR, PHENIX experiments

2001: Major results from all 4 collaborations

Discovery of strong “elliptic” flow

Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV, STAR Collaboration, Phys.Rev.Lett.86:402-407,2001

Discovery of strong “jet quenching”

Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV, PHENIX Collaboration, Phys.Rev.Lett.88:022301, 2002

2002: First full-energy Au+Au run

2005: BNL press release: RHIC Scientists Serve Up “Perfect” Liquid

2010: LHC comes online: discovers elliptic flow in p+p and p+Pb collisions, delivers highest energy heavy ion collisions

2011: RHIC Beam Energy Scan

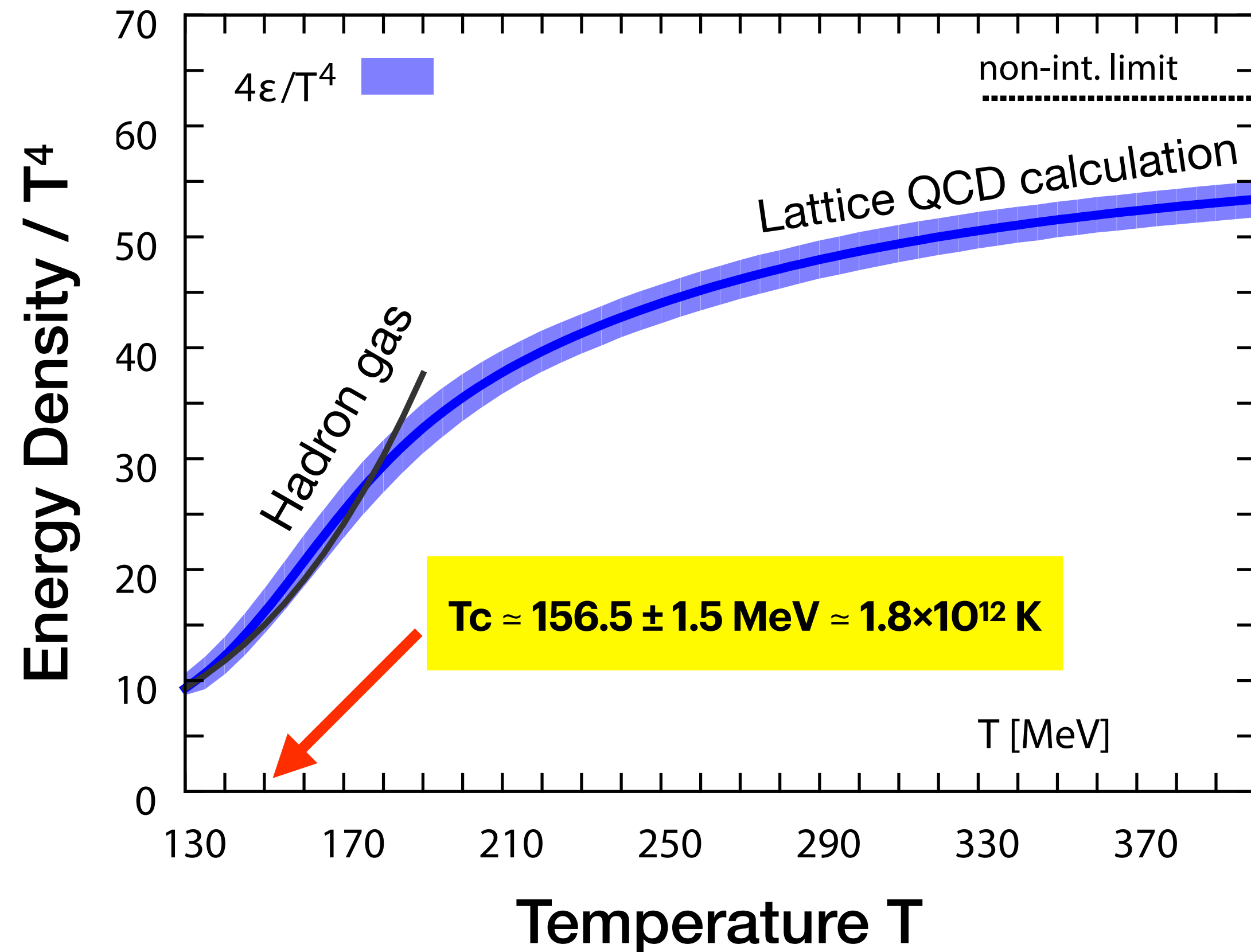
2015: RHIC small system scan

2021: RHIC Beam Energy II

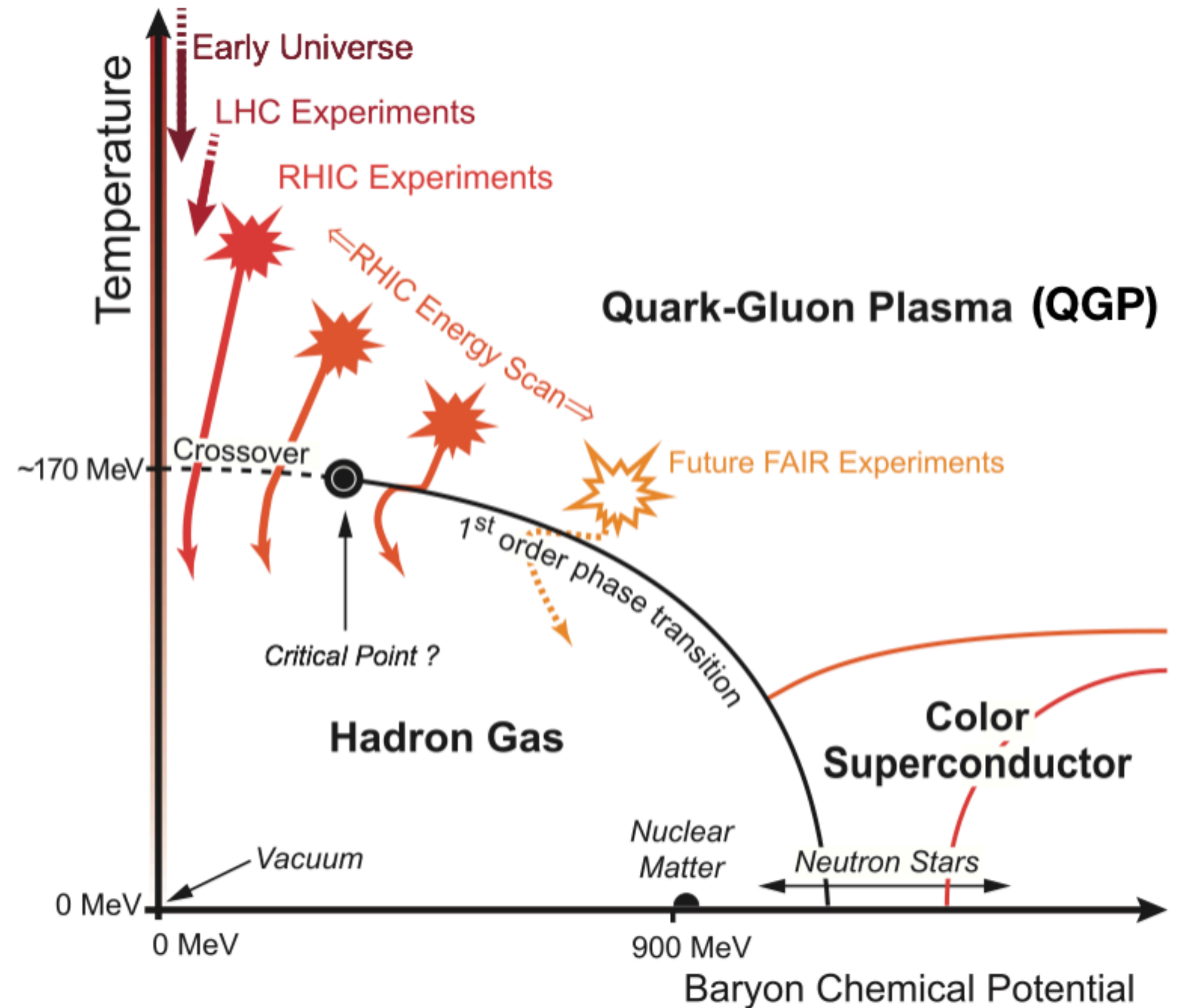
!! this list is very incomplete !!



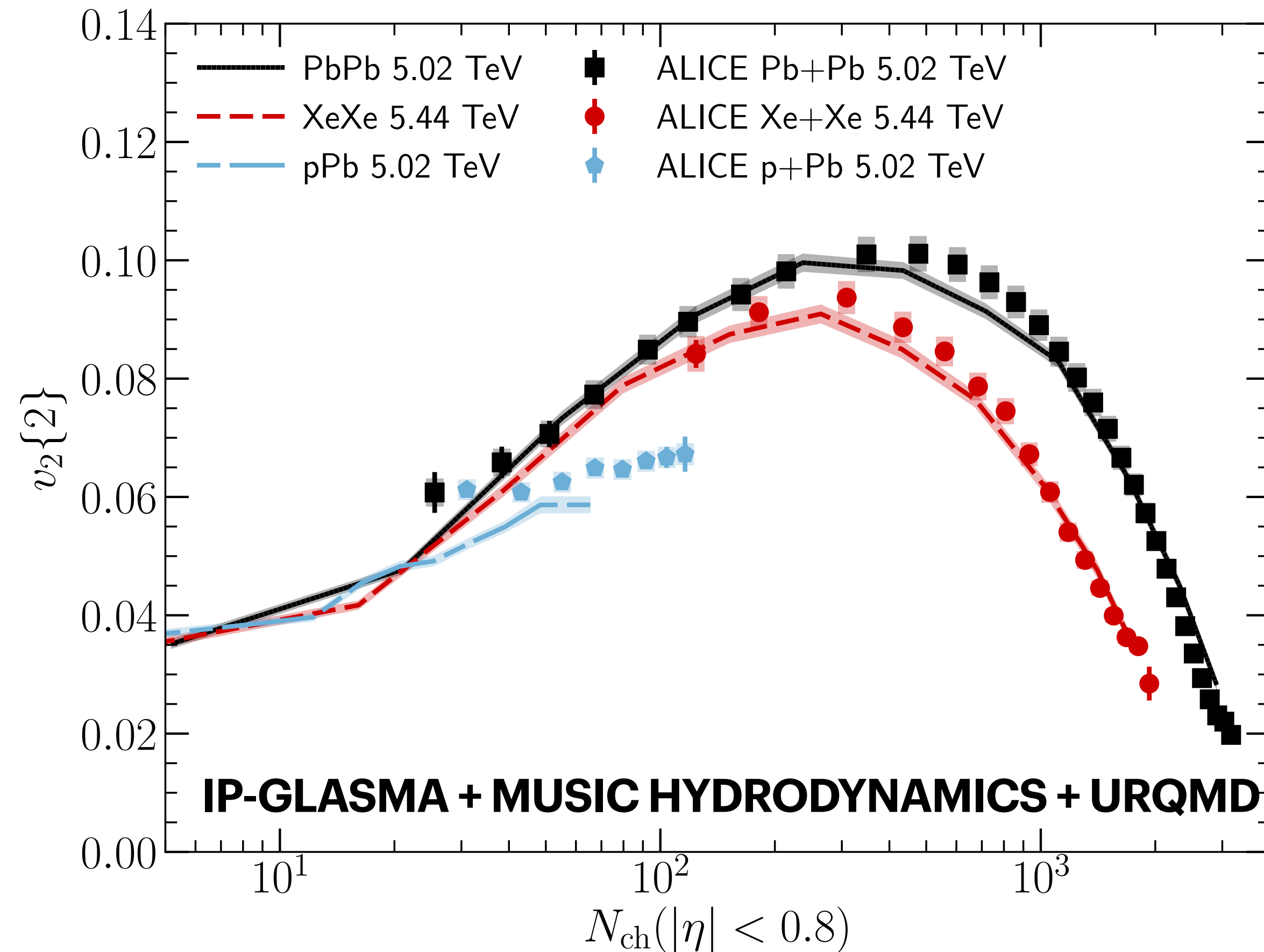
QUARK-GLUON PLASMA



HotQCD Collaboration: Phys.Lett. B795 (2019) 15-21
(chiral crossover temperature)



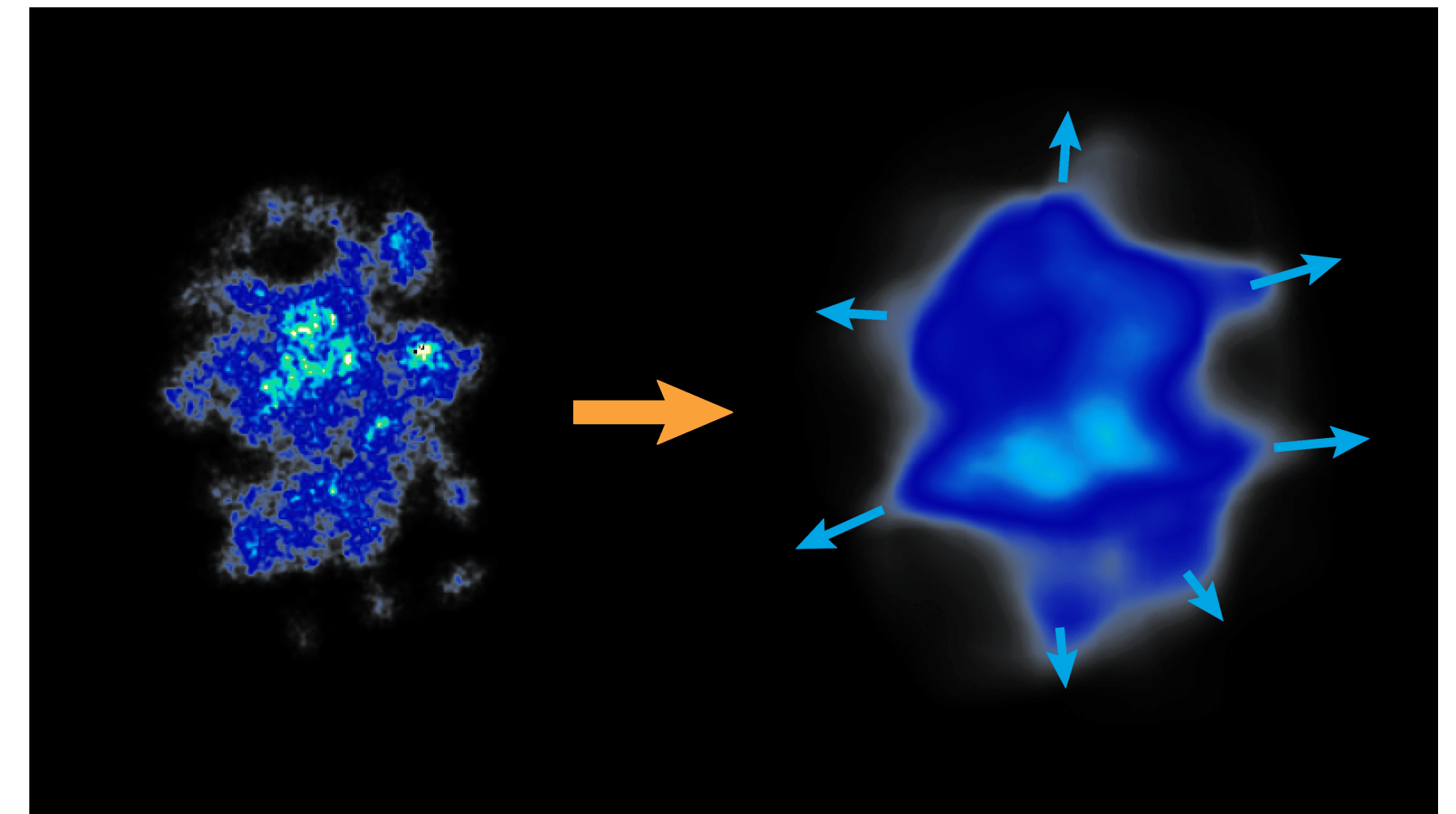
ANISOTROPIC FLOW



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

Initial energy density distribution

Hydrodynamic expansion



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

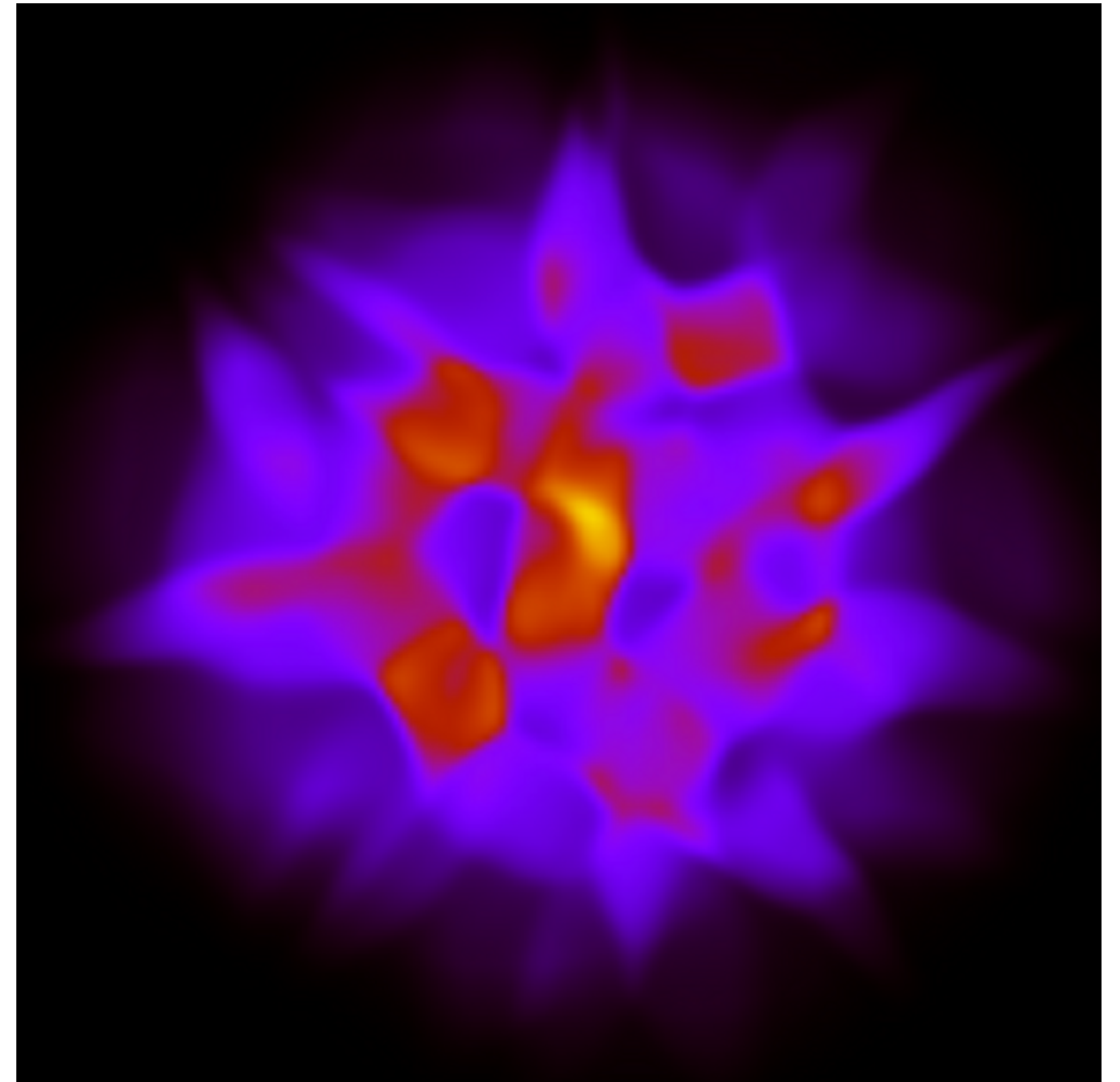
There is evidence that the same is true in high multiplicity small systems

FLOW: INCREDIBLY POWERFUL

Producing a nearly perfect liquid is interesting in itself.
But it has also **enabled many new developments**.

Focus on several recent topics of interest:

- Imaging of spatial nucleon structure
- Limits of collectivity and relativistic fluid dynamics
- Nuclear structure measurements at high energy
- Charge carriers in the proton
- Ultra-peripheral collisions

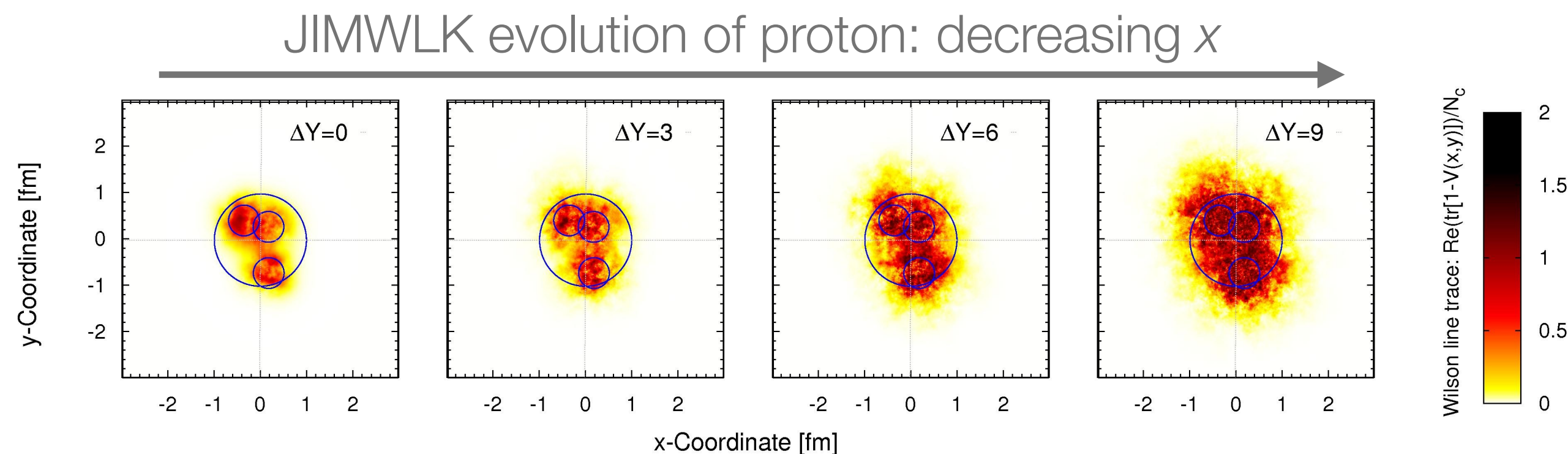


INITIAL STATE - LATEST DEVELOPMENTS

High energy collisions: **Color Glass Condensate** framework

Apply to both **diffractive DIS** and **heavy ion collisions**

- Describe proton or nucleus using color charges and Wilson lines (gluon fields)
- Energy dependence from JIMWLK small-x evolution



S. Schlichting, B. Schenke, *Phys. Lett. B* **739**, 313-319 (2014)

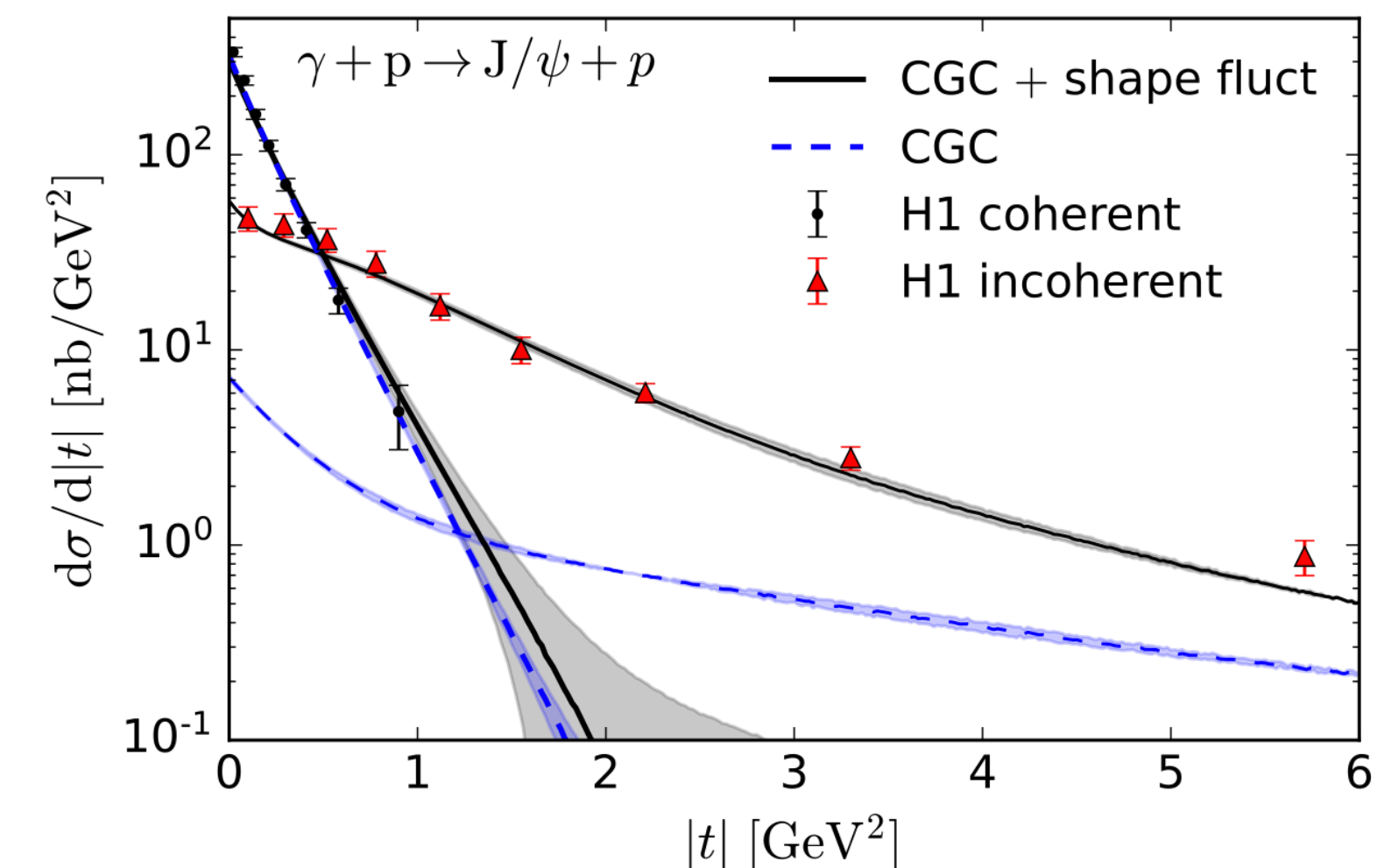
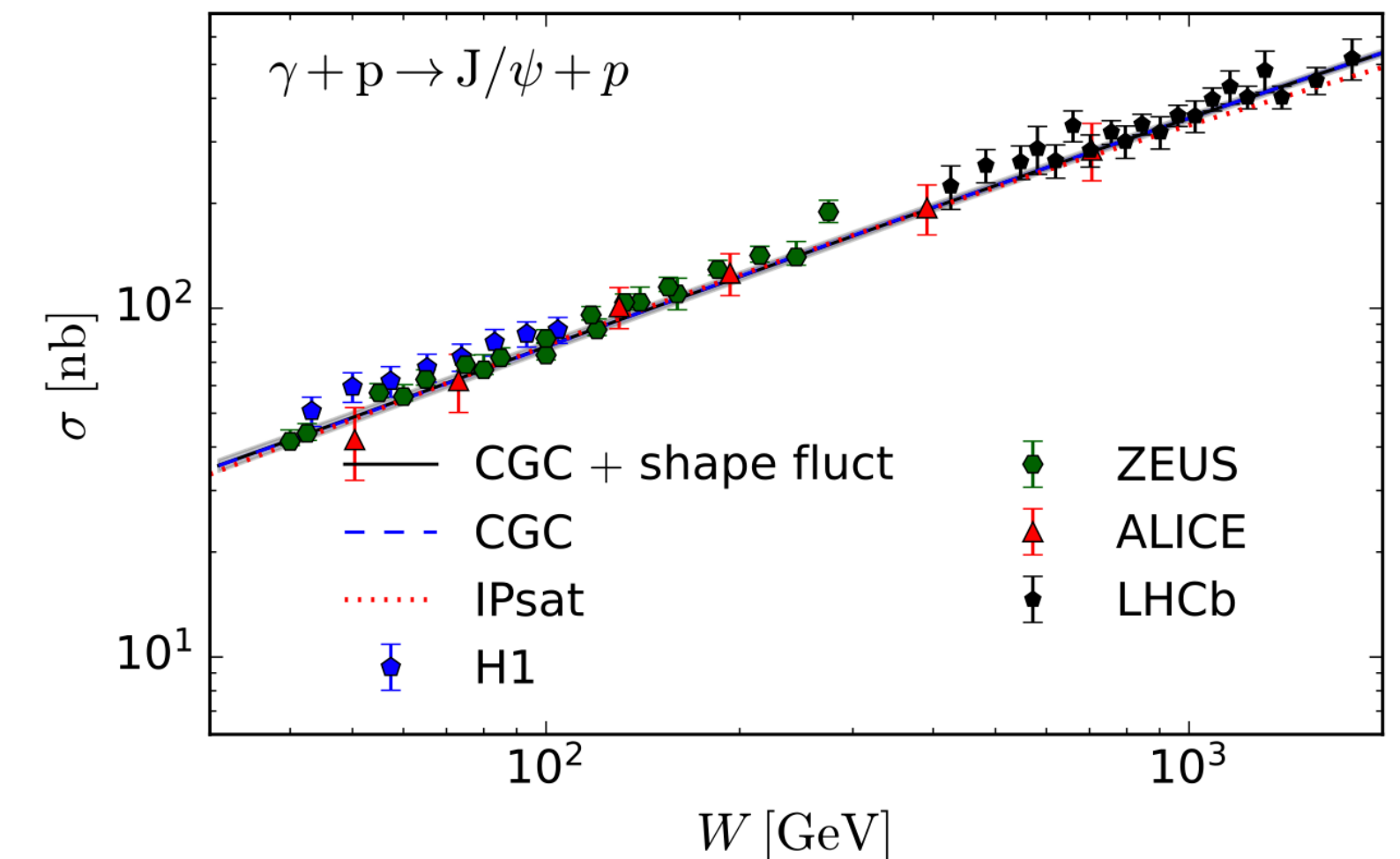
- Compute coherent and incoherent vector meson production in $e+p$ collisions at HERA
- Constrain proton average size and fluctuations

H. Mäntysaari, B. Schenke, *Phys. Rev. Lett.* **117** (2016) 052301

Phys. Rev. D **94** (2016) 034042; H. Mäntysaari, *Rep. Prog. Phys.* **83** 082201 (2020)

B. Schenke, *Rep. Prog. Phys.* **84** 082301 (2021)

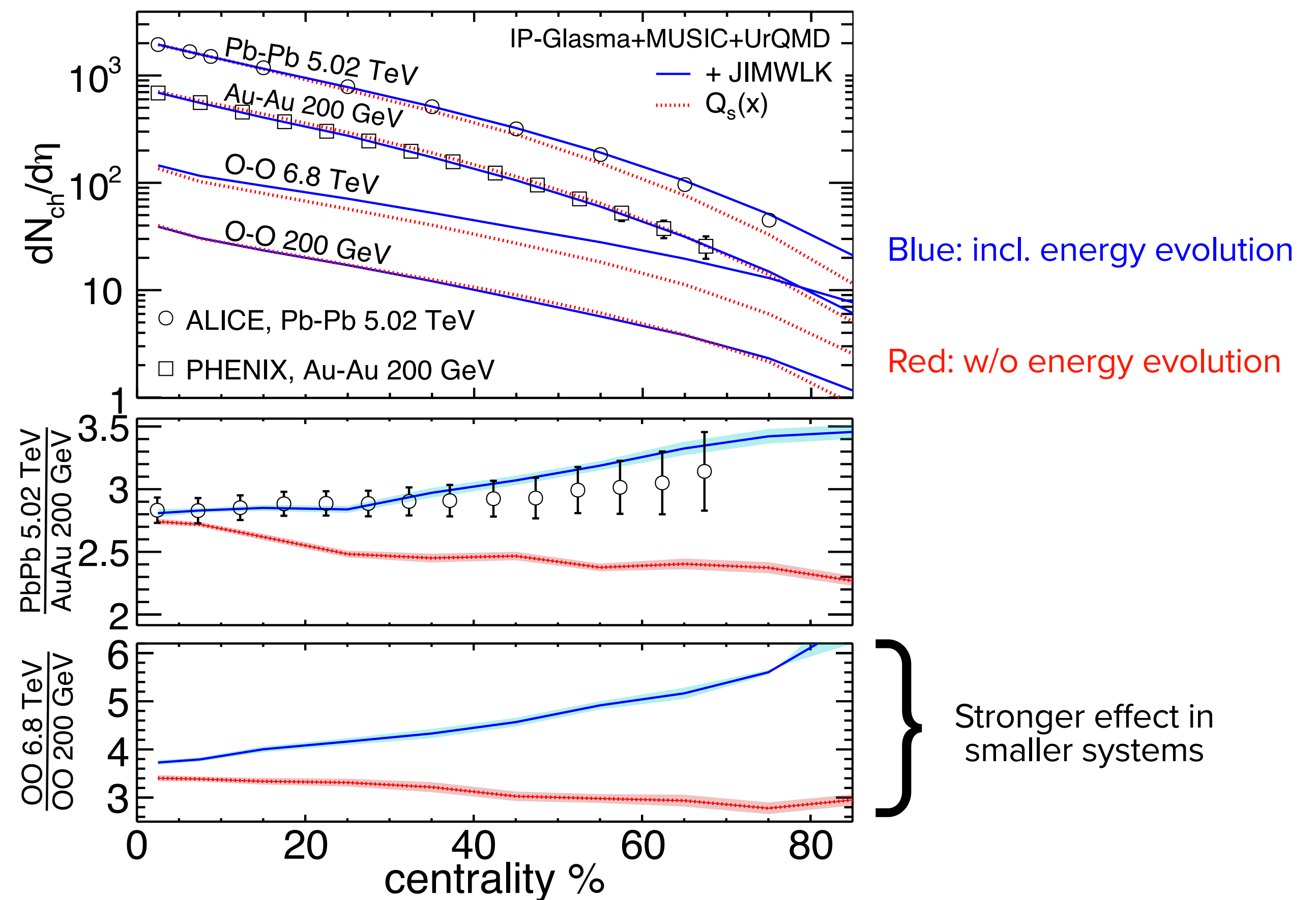
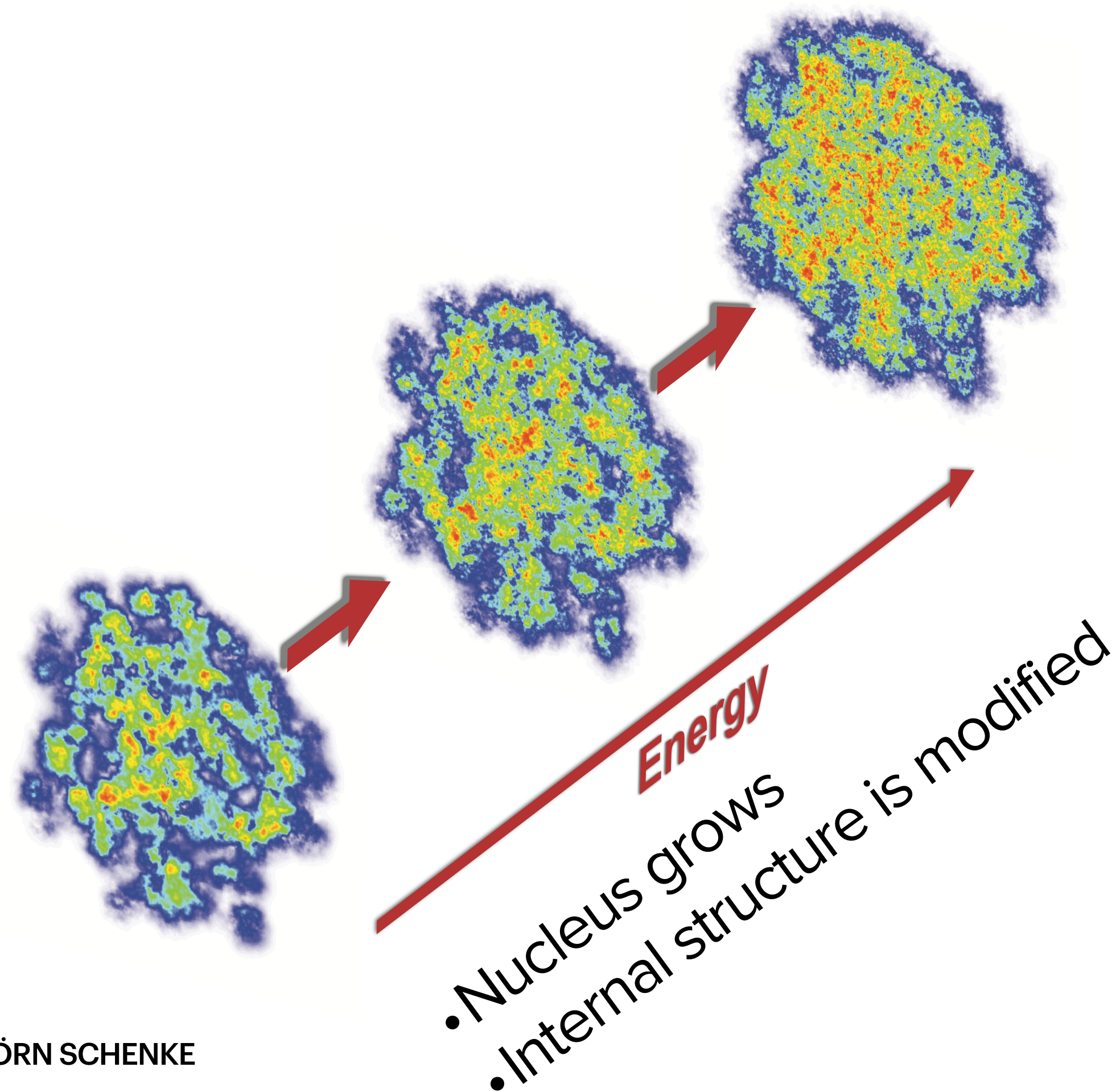
For Bayesian analysis see: H. Mäntysaari, H. Roch, F. Salazar, B. Schenke, C. Shen, W. Zhao, [arXiv:2507.14087](https://arxiv.org/abs/2507.14087)



INCLUDING NON-LINEAR QCD EVOLUTION

- Now employ constrained nucleons to construct nuclei and the initial state for heavy ion collisions
- For the first time include JIMWLK evolution to describe the energy dependence of heavy-ion collisions

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, *Phys.Rev.Lett.* **135** (2025) **2**, 022302, and forthcoming

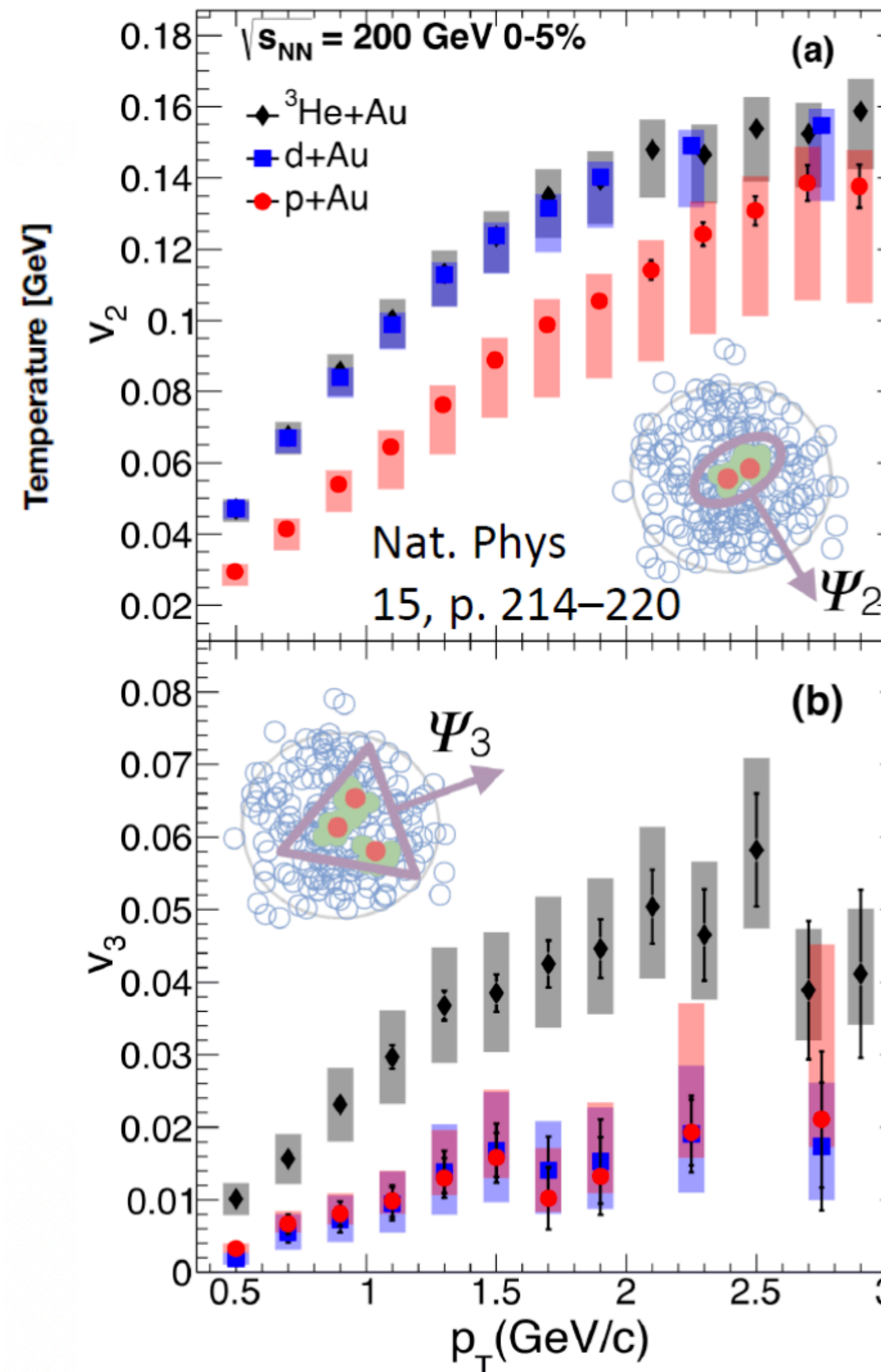
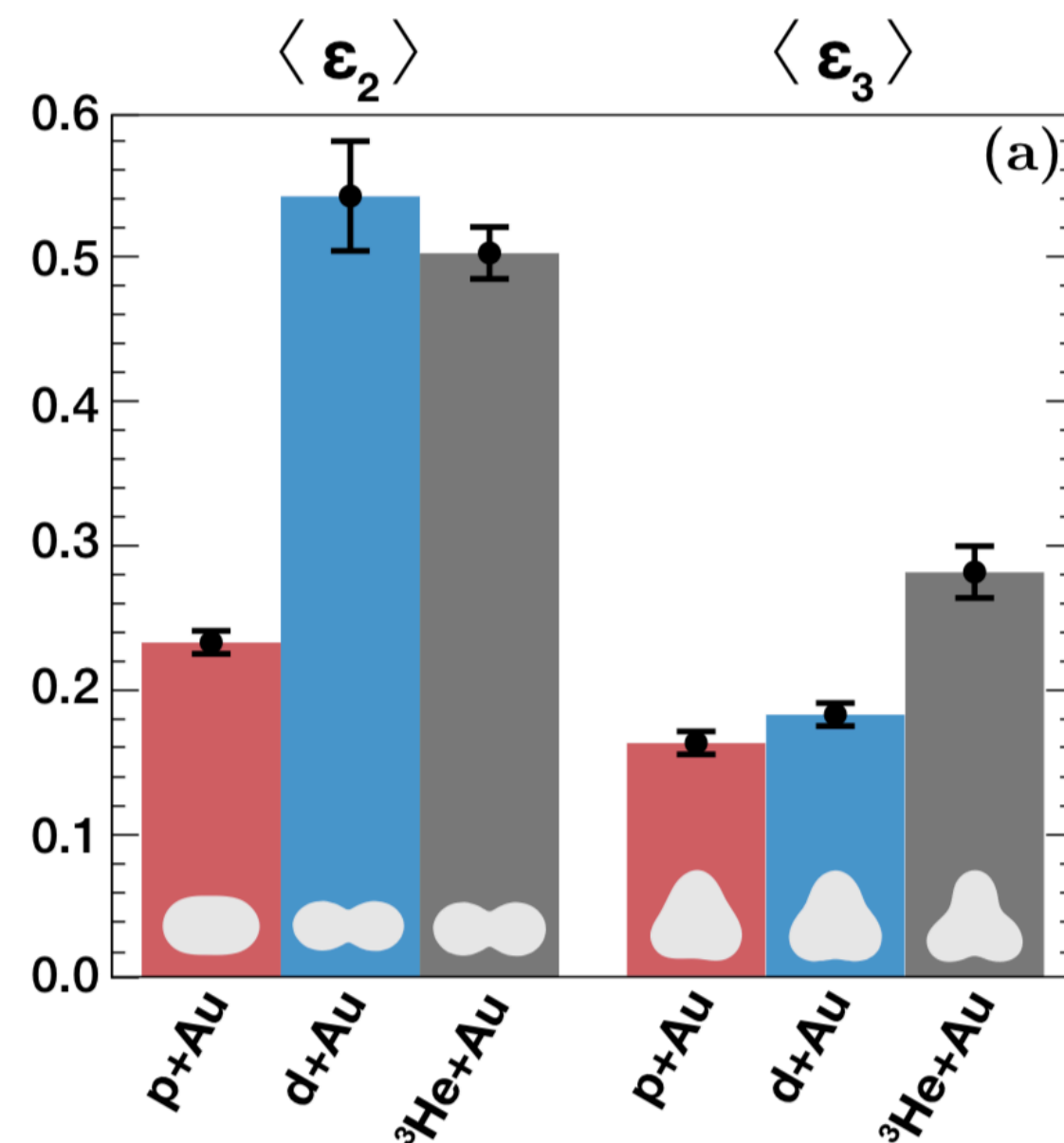


HOW SMALL A QGP CAN WE MAKE?

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

- Small system: Is the anisotropic flow due to final state response to the geometry?
- To answer: Engineer the geometry using different projectiles: p, d, ^3He on Au

Simple model expectation:
(using nucleon degrees of freedom)

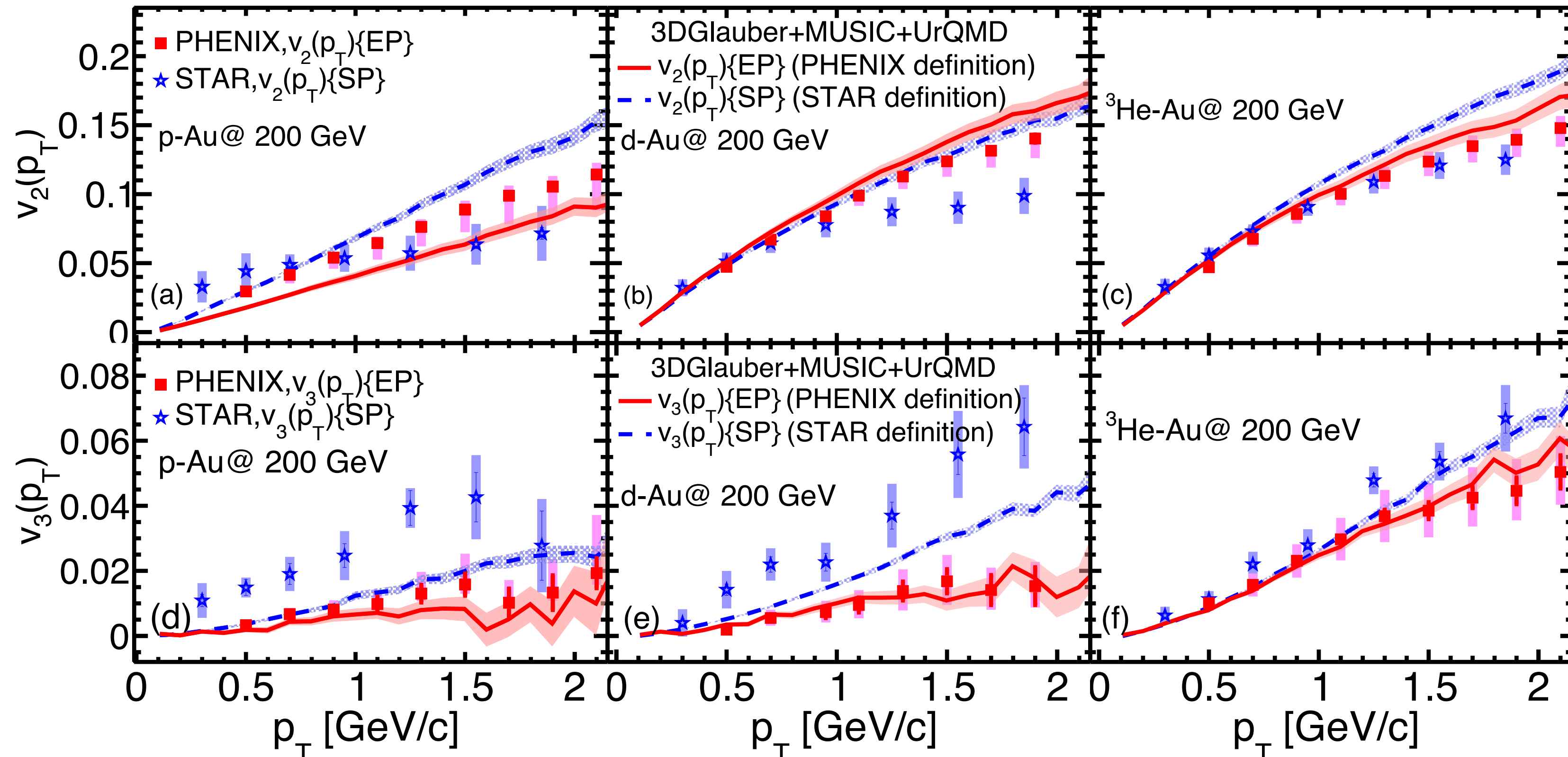


As predicted:
Large v_2 for d+Au and ^3He +Au

Large v_3 for ^3He +Au

COMPARING STAR AND PHENIX

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 $|\Delta\eta| > 1$

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

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

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
- Far from equilibrium, causality could be violated
- Alternative to Israel-Stewart like theories, BDNK, can be shown to be causal

Small systems have been major driver for developments in relativistic viscous fluid dynamics

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:

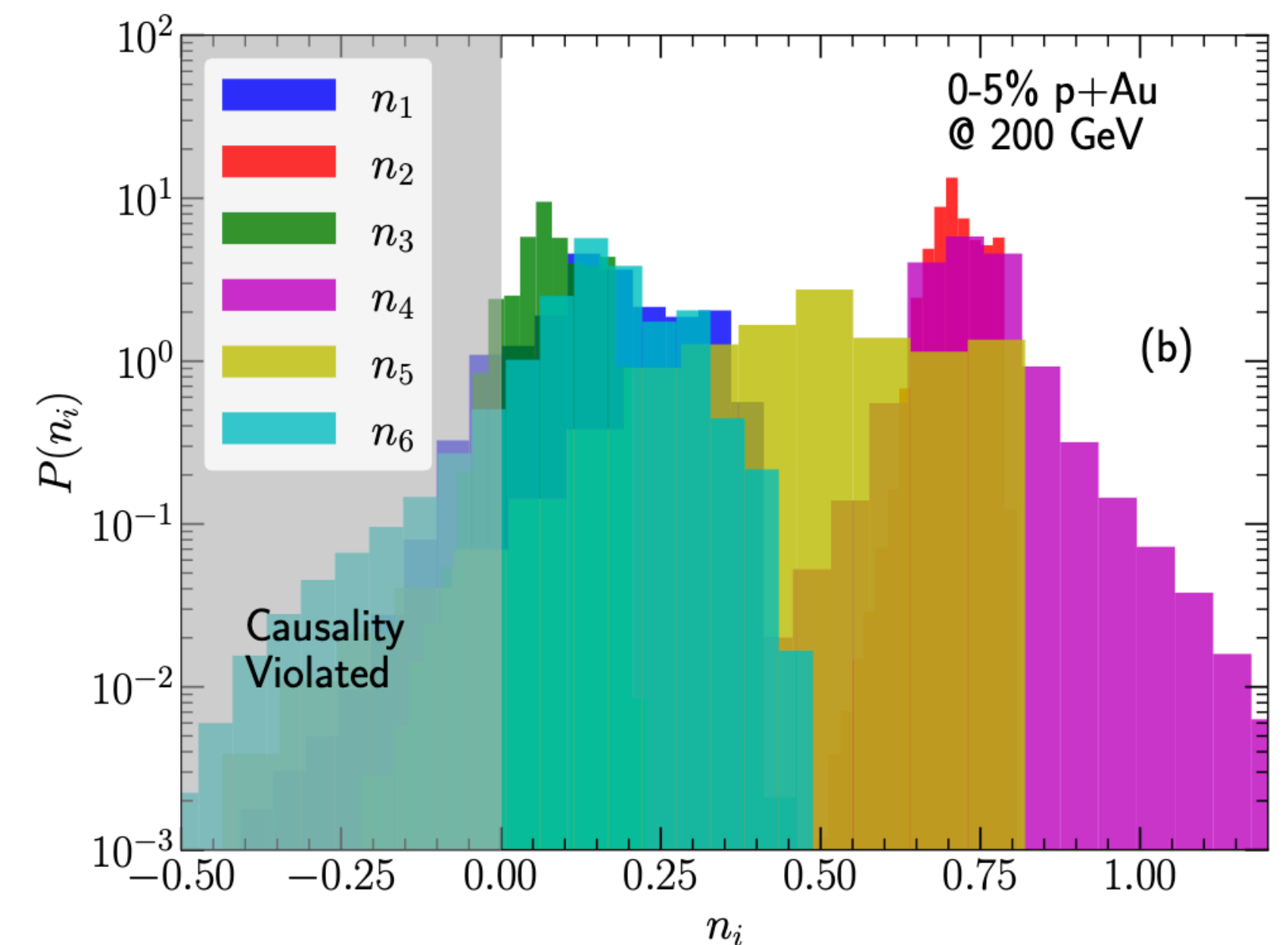
C. Plumberg, D. Almaalol, T. Dore, J. Noronha, J. Noronha-Hostler, Phys. Rev. C. 105(6), L061901 (2022)

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

T. S. Domingues, R. Krupczak, J. Noronha, T. Nunes da Silva, J.-F. Paquet, M. Luzum

Phys.Rev.C 110 (2024) 6, 064904



APPLICABILITY OF HYDRODYNAMICS

Validity of hydrodynamics may not require thermalization or even isotropization, but merely “hydrodynamization”, which is achieved when the hydrodynamic modes dominate

Hydrodynamic attractors are reached at times $\mathcal{O}(1\text{fm})$
Largely independent of the underlying microscopic theory

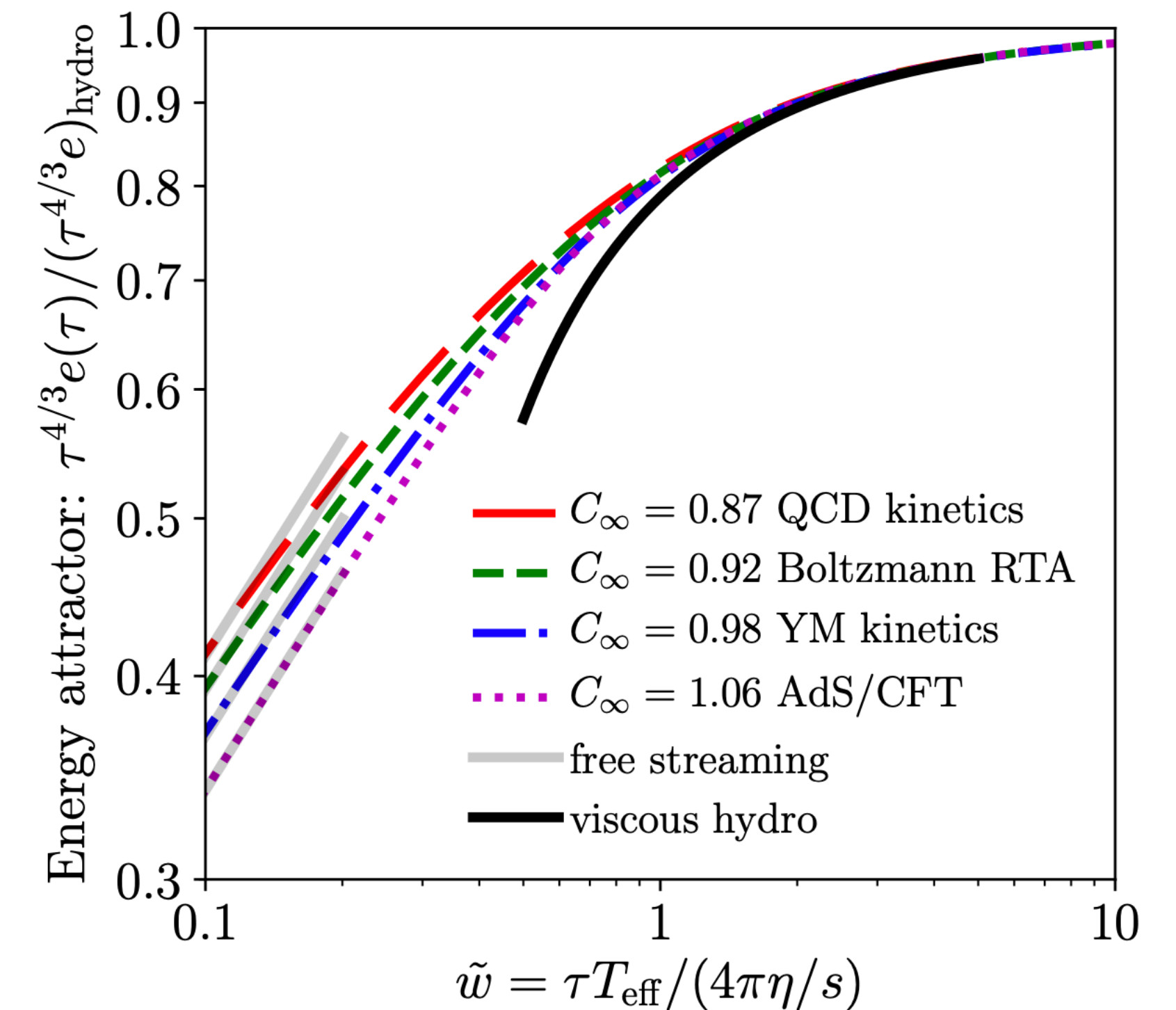
In practice smoothly connect initial state model to hydrodynamics using effective kinetic theory

A. Kurkela, Mazeliauskas, J.-F. Paquet, S. Schlichting, D. Teaney 2019 Phys. Rev. Lett. 122 122302;
The ExTrEMe Collaboration, Phys.Rev.C 103 (2021) 054906
Gale, Paquet, Schenke, Shen, Phys.Rev.C 105 (2022) 1, 014909

Also core-corona models

T. Pierog, Iu. Karpenko, J.M. Katzy, E. Yatsenko, K. Werner, Phys.Rev.C 92 (2015) 3, 034906
Y. Kanakubo, Y. Tachibana, T. Hirano, Phys.Rev.C 101 (2020) 2, 024912

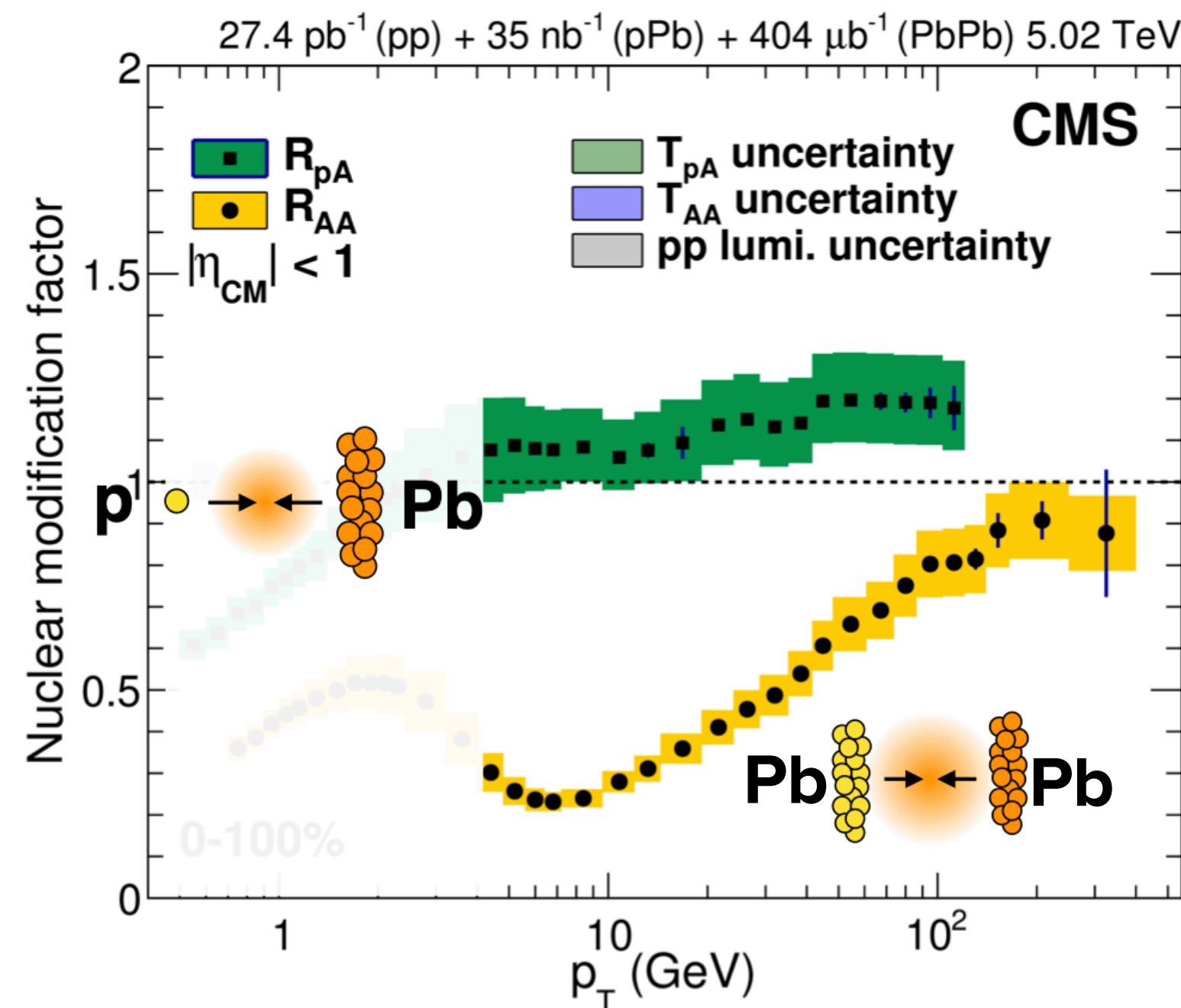
See reviews Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299
Romatschke, Romatschke, 1712.05815
Noronha, Schenke, Shen, Zhao, 2401.09208



Giacalone, Mazeliauskas, Schlichting, Phys.Rev.Lett. 123 (2019) 26, 262301
S. Kamata, M. Martinez, P. Plaschke, S. Ochsenfeld, S. Schlichting Phys.Rev.D 102 (2020) 5, 056003 (2004.06751)

JET QUENCHING IN SMALL SYSTEMS?

- If strongly interacting (and flowing) matter is formed in small systems, are jets quenched like in A+A?



- No unambiguous evidence for quenching in high-multiplicity pPb (or very peripheral PbPb collisions)

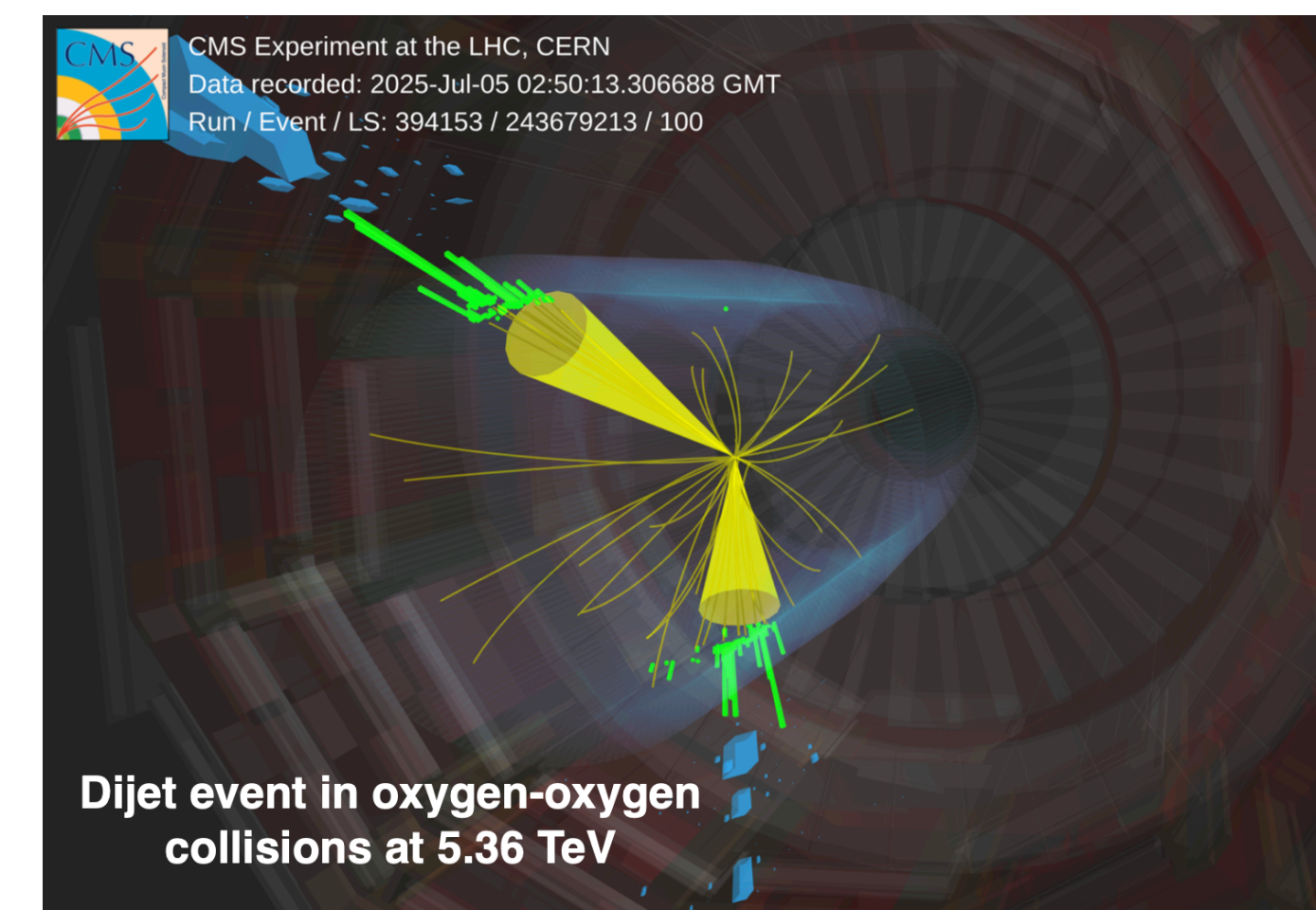
CMS Collaboration, JHEP 04 (2017) 039

- Motivates study of small symmetric collision systems with better controlled geometry: **New O+O and Ne+Ne runs**

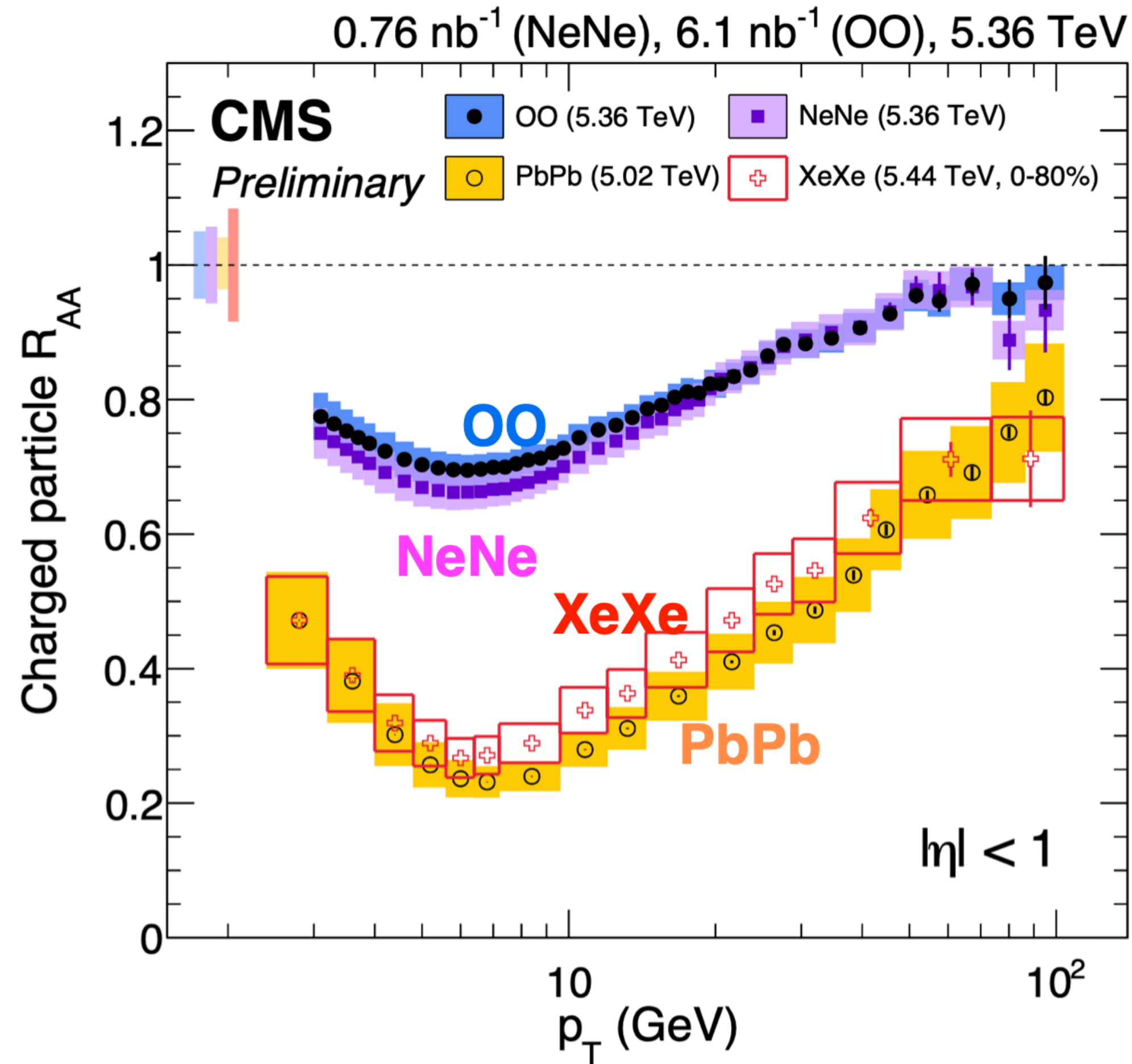
- Consistent with energy loss calculations in p+Pb

JETSCAPE Collaboration, Phys.Rev.C 112 (2025) 1, 014905

- Significant centrality selection bias



NEW O+O AND Ne+Ne RESULTS FROM LHC



- There is quenching in O+O and Ne+Ne

[CMS, CMS-PAS-HIN-25-014](#); [ALICE, ALI-PREL-609795](#); [ATLAS, ATLAS-CONF-2025-010](#)

- Results from ATLAS and ALICE also show quenching signals
- O+O is the smallest ion system where jet quenching has been seen
- Helps pinpoint the system size at which QGP begins to affect high-energy jets

O+O AND Ne+Ne COLLISIONS

- Additional motivation: Precision data should be sensitive to the nuclear structure of the O and Ne nuclei

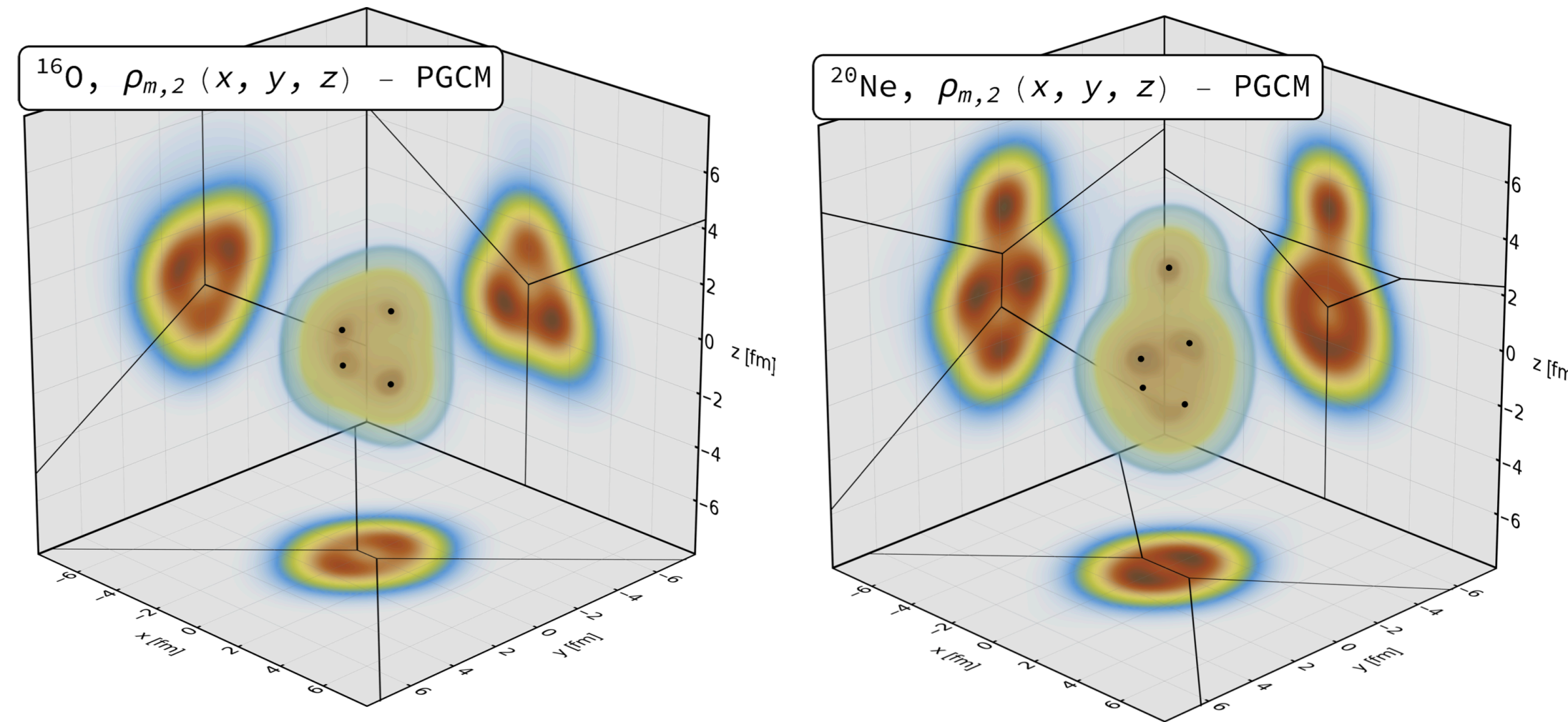
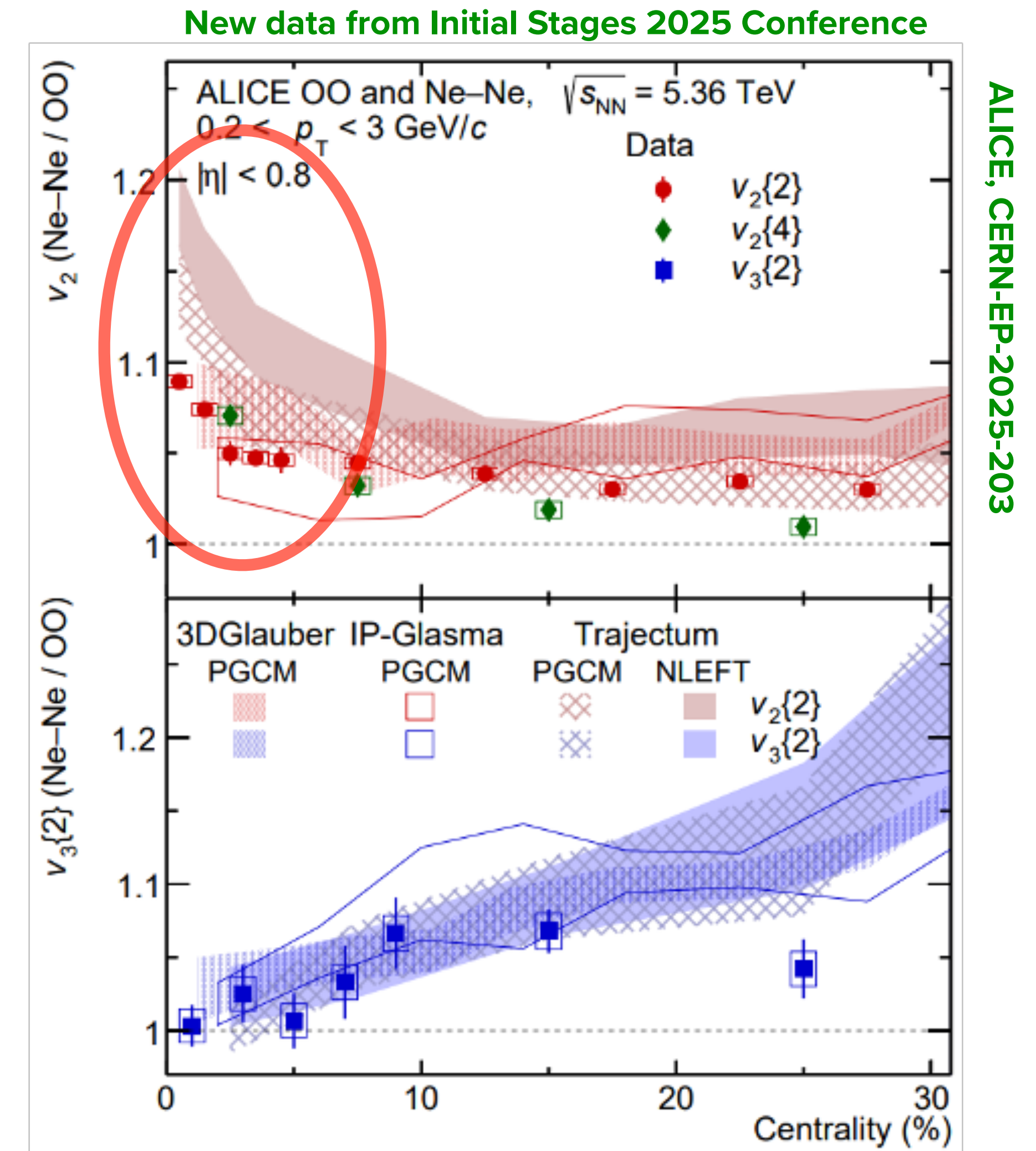
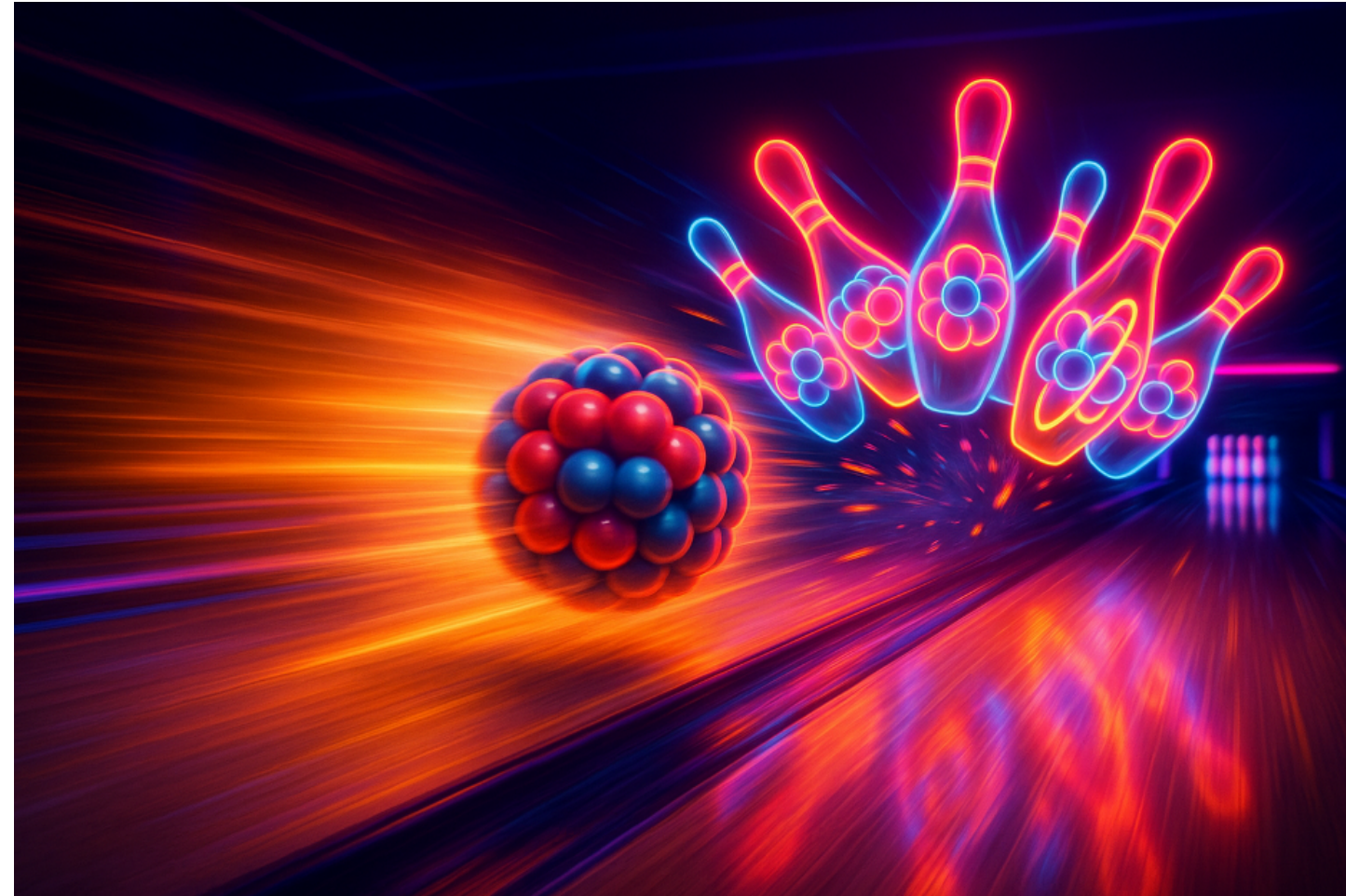


Figure. from G. Giacalone et al, Phys.Rev.Lett. 135 (2025) 1, 012302
using ab-initio Projected Generator Coordinate Method

- Predictions of the ratio of anisotropic flow in Ne+Ne/O+O agree rather well with the data
- More deformed shape of neon-20 nucleus shows effect in central collisions:
More shape fluctuations lead to larger v_2



Pb+smaller nucleus

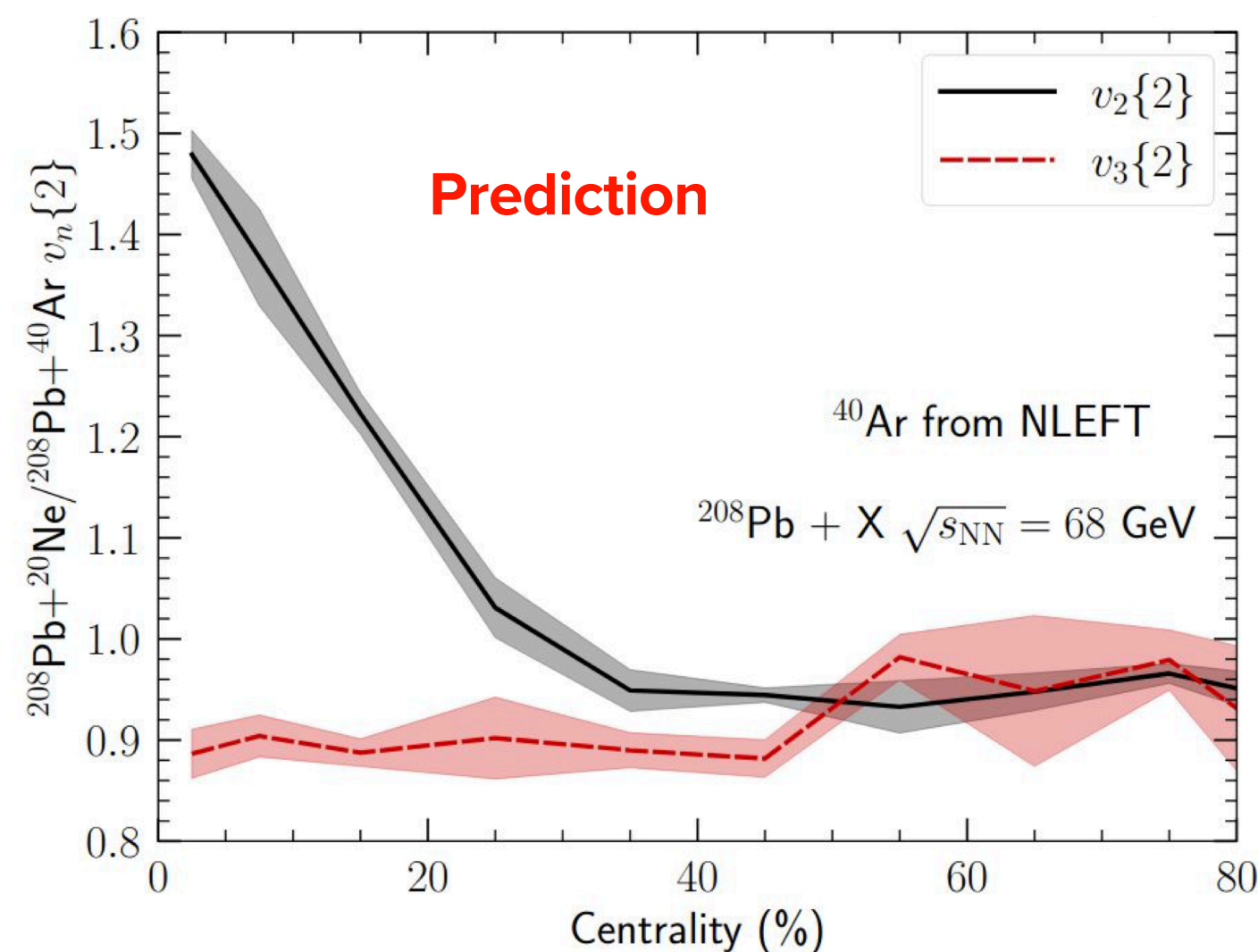


- Colliding large Pb nuclei with small Ne, O, or Ar nuclei allows to image the smaller nuclei
- The initial overlap area is sensitive to the nuclear structure of the smaller nucleus
- Flow translates the shape to measurable particle distributions



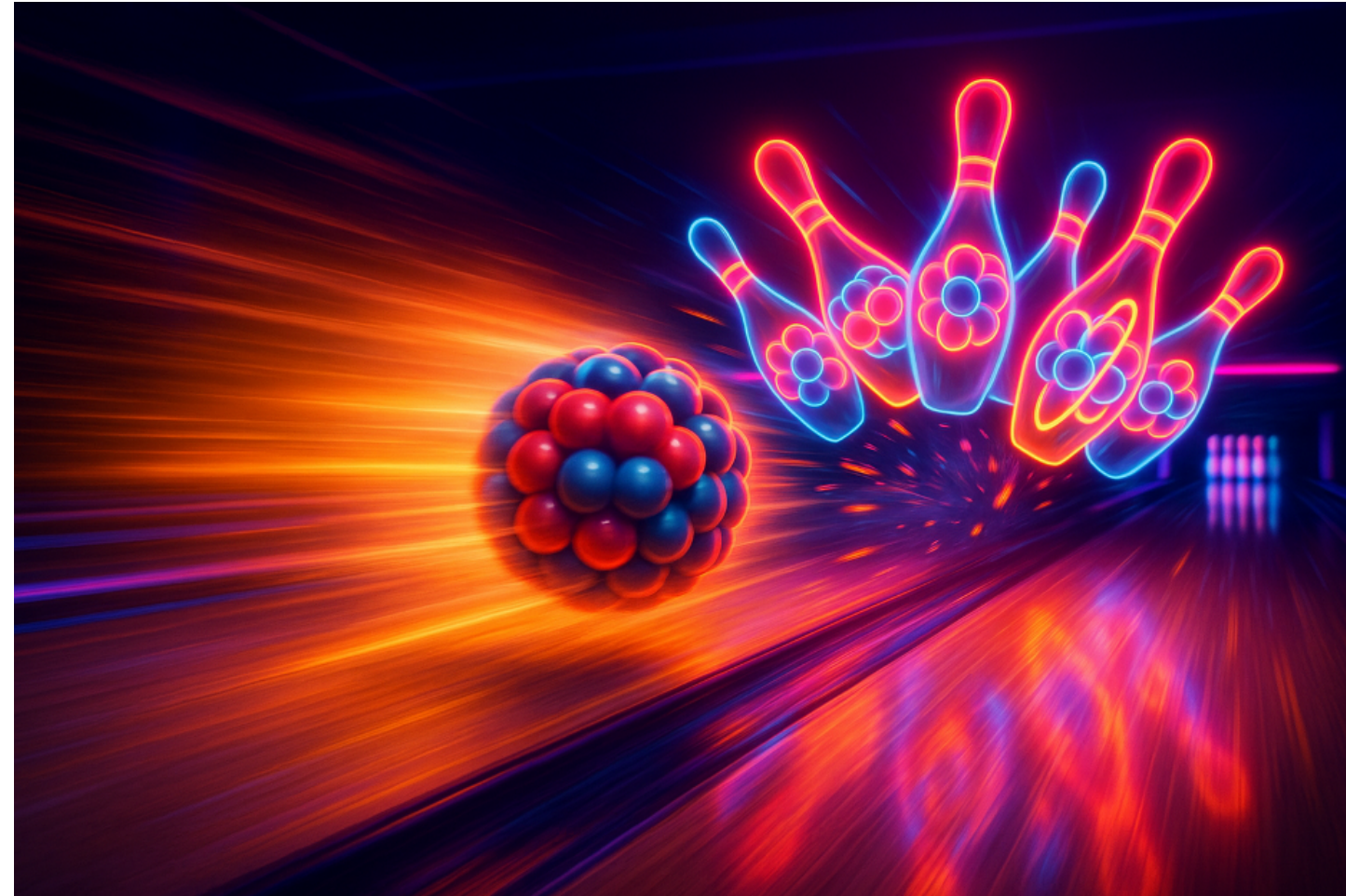
Initial overlap region of Pb nucleus
with Wile E. Coyote shaped nucleus

- Elliptic flow ratio between **deformed** (Ne) and **round** (Ar) target



Prediction: Quark Matter 2025:
<https://indico.cern.ch/event/1334113/contributions/6289808/> (B. Schenke, C. Shen, H. Mäntysaari and W. Zhao)

Pb+smaller nucleus

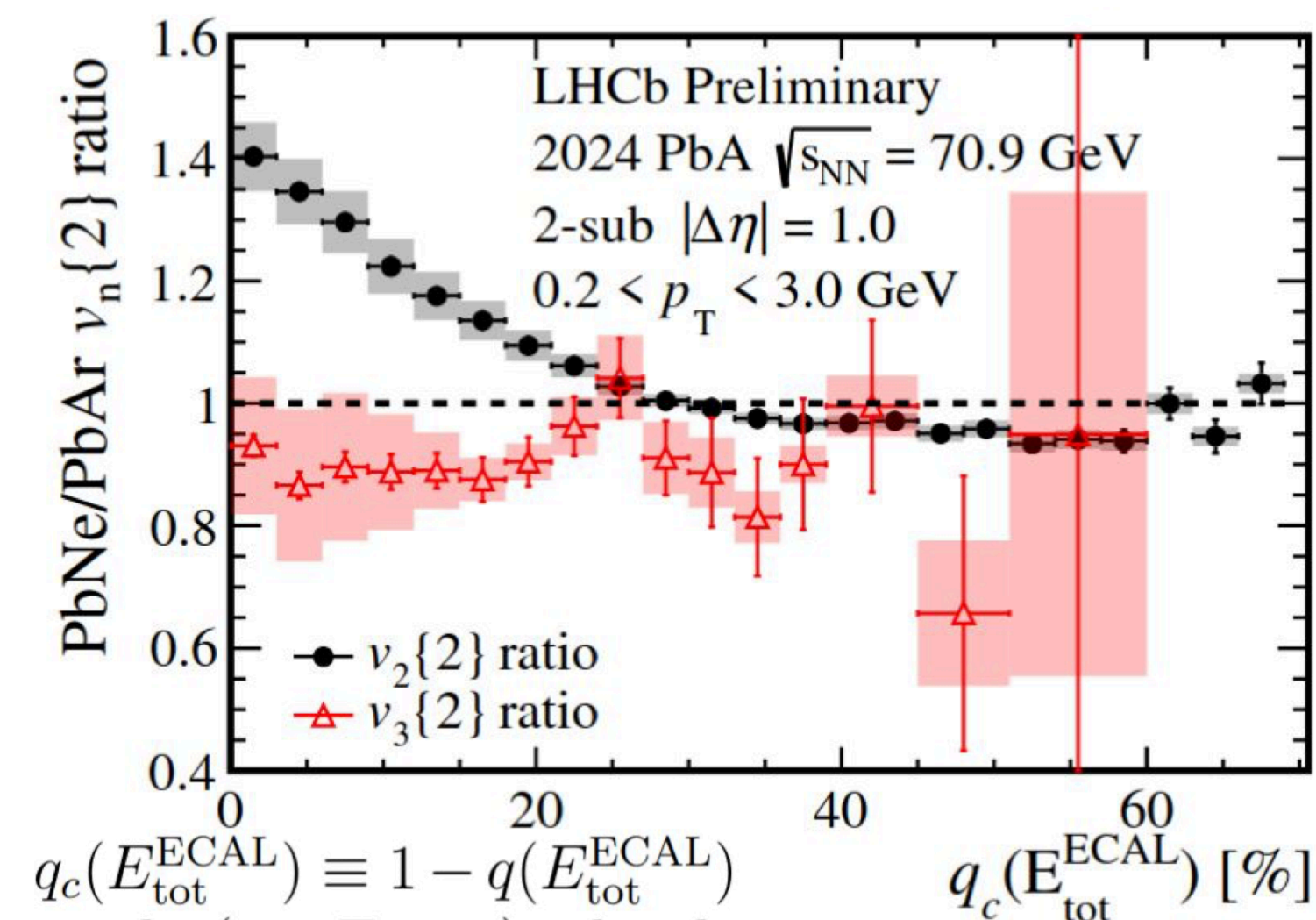
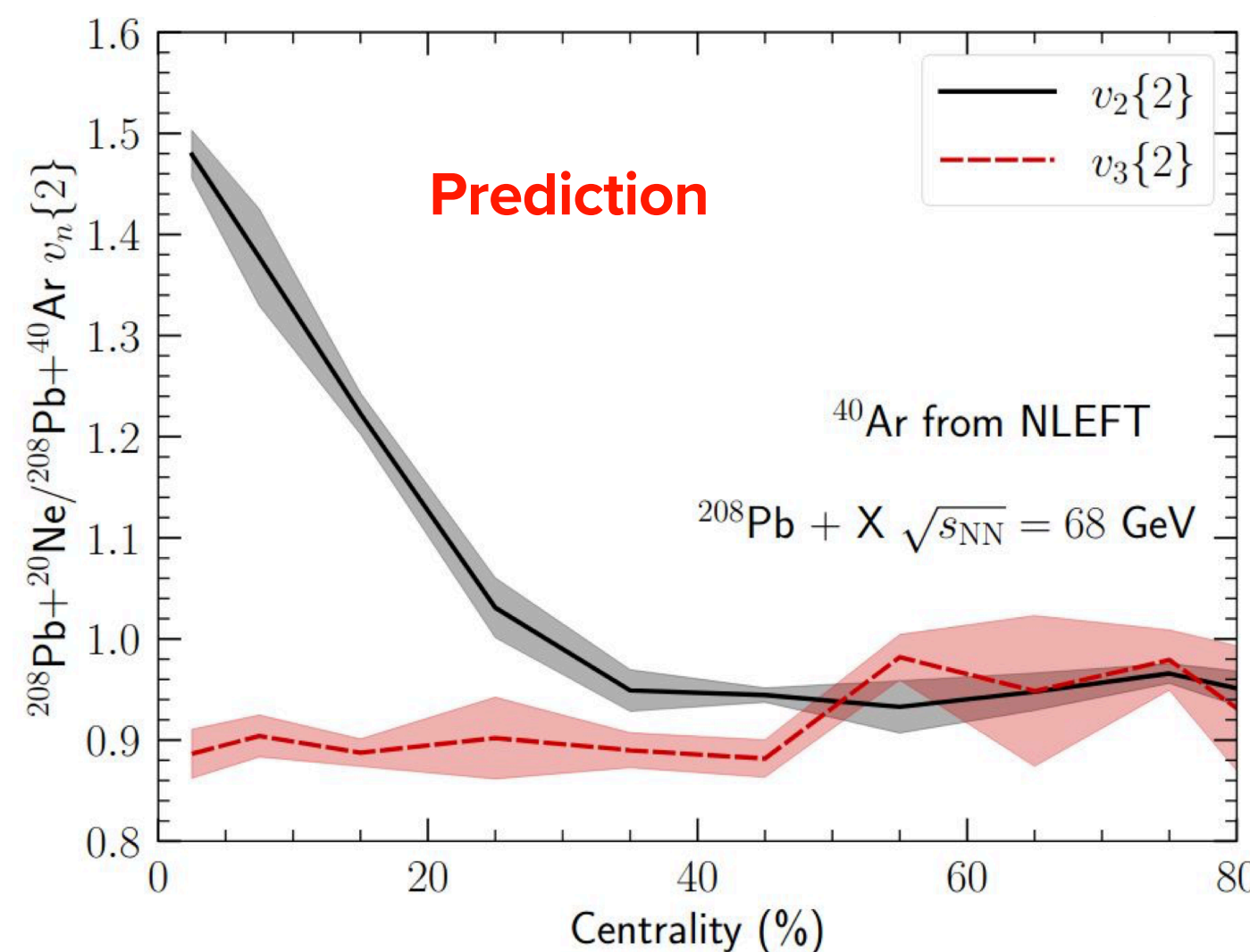


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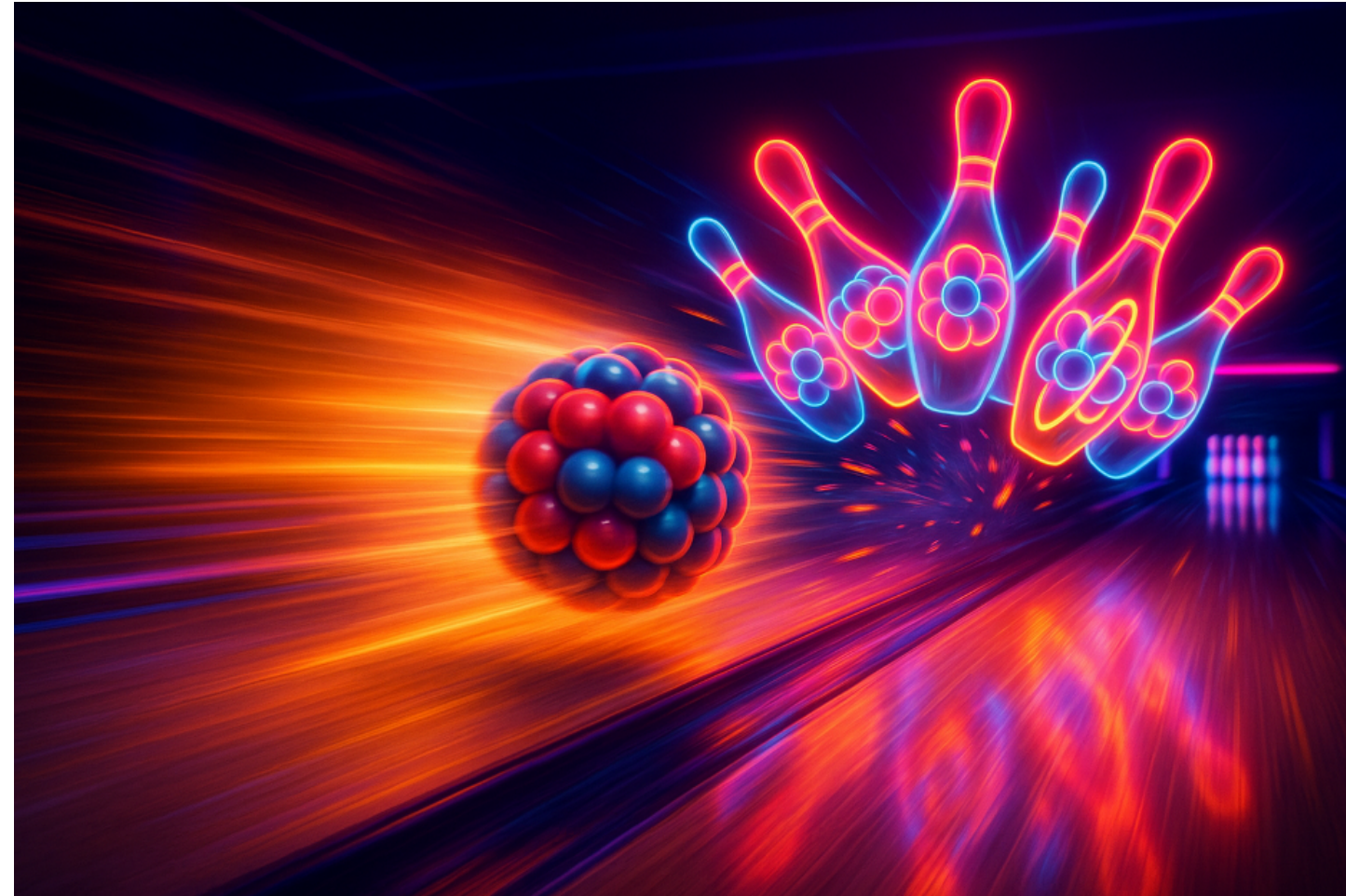
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<https://indico.cern.ch/event/1479384/contributions/6663093/attachments/3132588/5557527/IS25.pdf> (SMOG2)
LHCb-CONF-2025-001, in preparation

Prediction: Quark Matter 2025:
<https://indico.cern.ch/event/1334113/contributions/6289808/> (B. Schenke, C. Shen, H. Mäntysaari and W. Zhao)

Pb+smaller nucleus

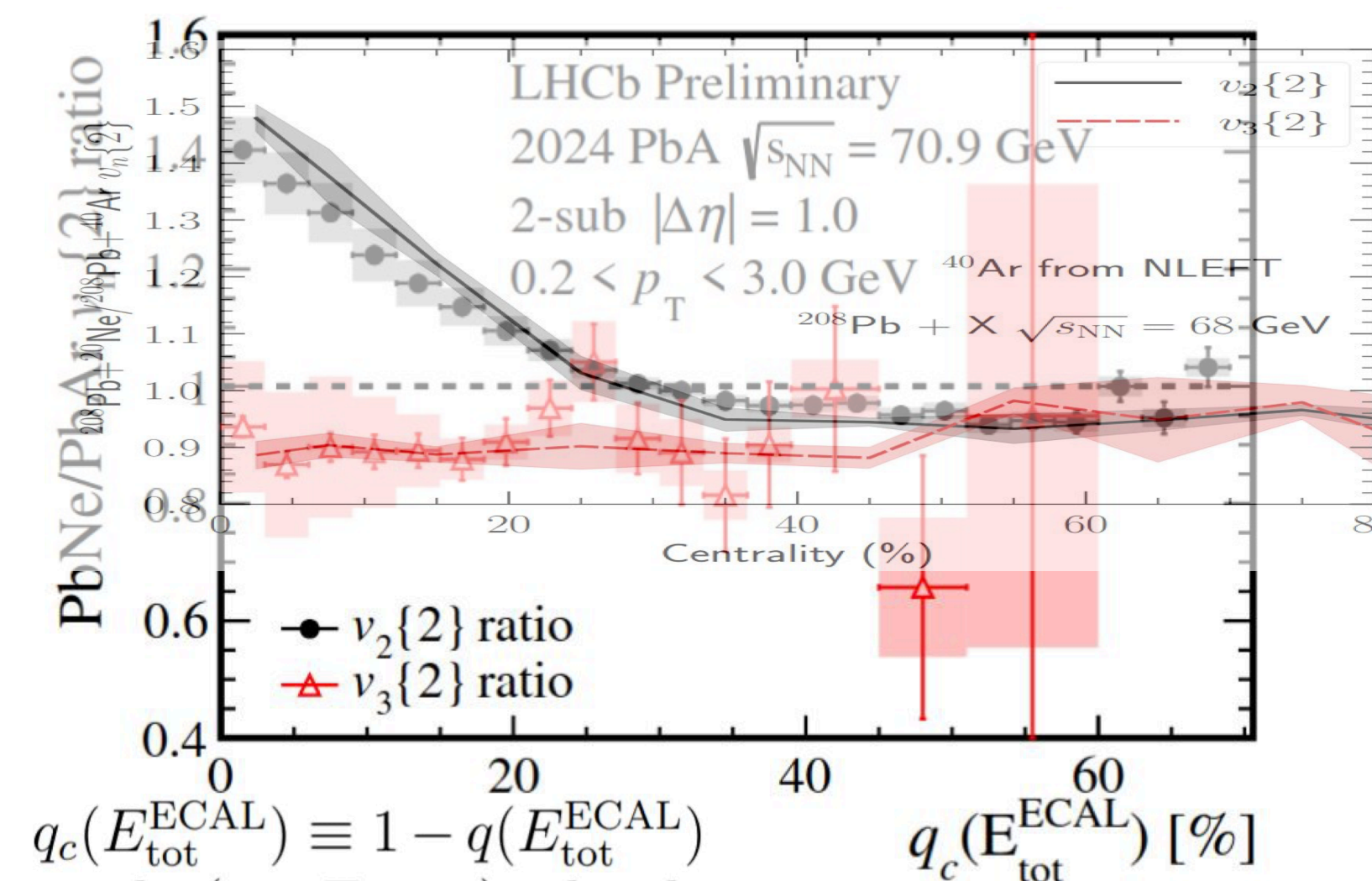
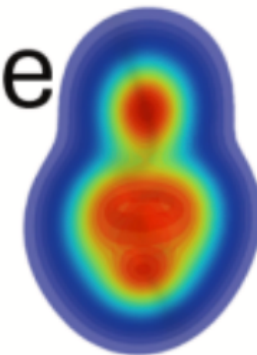


- Colliding large Pb nuclei with small Ne, O or Ar nuclei allows to image the smaller nuclei
- The initial overlap area is sensitive to the nuclear structure of the smaller nucleus
- Flow translates the shape to measurable particle distributions



Initial overlap region of Pb nucleus with Wile E. Coyote shaped nucleus

- Elliptic flow ratio between **deformed** (Ne) and **round** (Ar) target
- Excellent agreement between prediction and experimental data from LHCb
- Consistent with “bowling pin shape” of ^{20}Ne



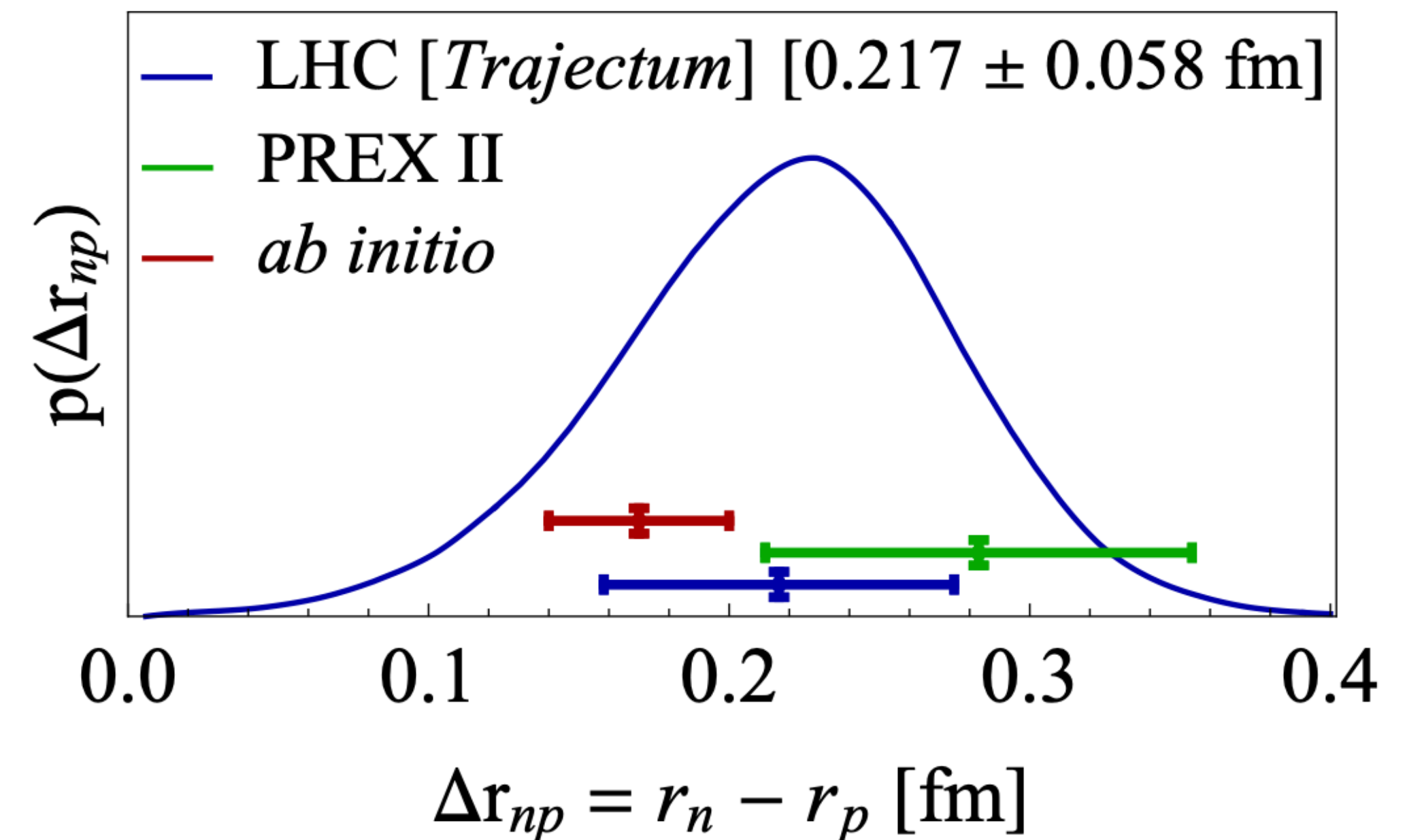
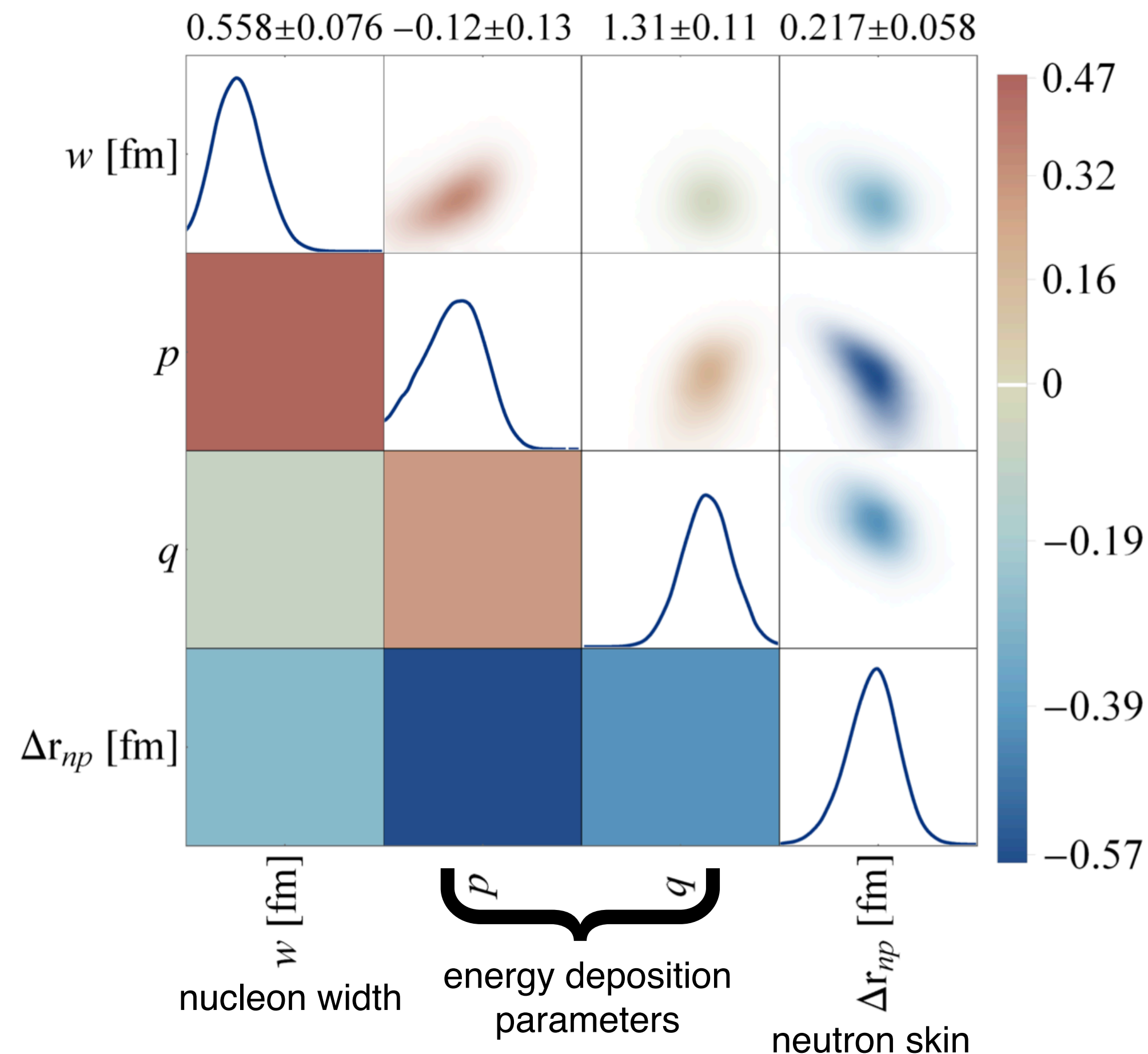
<https://indico.cern.ch/event/1479384/contributions/6663093/attachments/3132588/5557527/IS25.pdf> (SMOG2)
LHCb-CONF-2025-001, in preparation

Prediction: Quark Matter 2025:
<https://indico.cern.ch/event/1334113/contributions/6289808/> (B. Schenke, C. Shen, H. Mäntysaari and W. Zhao)

NEUTRON SKIN

Giuliano Giacalone, Govert Nijs, Wilke van der Schee, *Phys.Rev.Lett.* **131** (2023) 20, 20

- Bayesian analysis of Pb+Pb data from LHC allows to extract the neutron skin
- Neutron skin affects diffuseness of the Pb nuclei, which affects centrality dependence of particle production and flow observables



D. Adhikari et al. (PREX), *Phys. Rev. Lett.* **126**, 172502 (2021)
 B. Hu et al., *Nature Phys.* **18**, 1196 (2022)

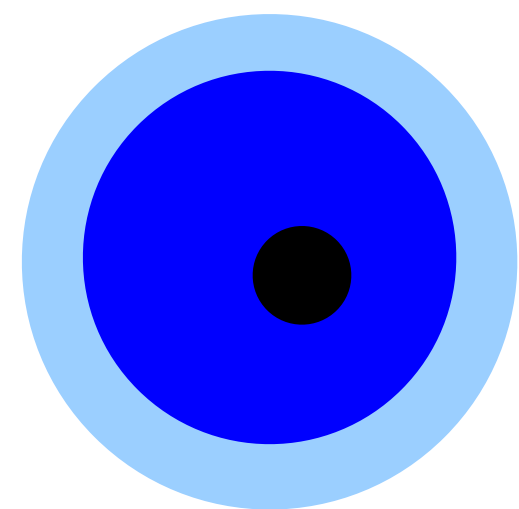
NEUTRON SKIN

Grégoire Pihan, Akihiko Monnai, Björn Schenke, Chun Shen, arXiv:2509.21644

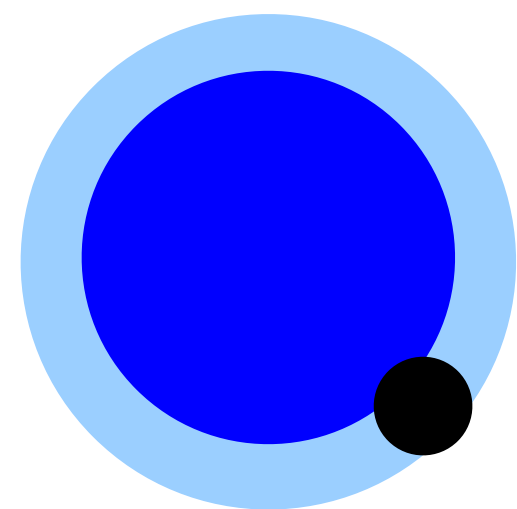
- Measurements of electric vs. baryon charge as function of centrality is also sensitive to neutron skin
- LHCb could measure the double ratio in p+Pb collisions:

$$\mathcal{R}_{c_1, c_2}^{Q, B}(y_1, y_2) = \frac{N_Q(y_1, y_2, c_1)}{N_B(y_1, y_2, c_1)} \bigg/ \frac{N_Q(y_1, y_2, c_2)}{N_B(y_1, y_2, c_2)},$$

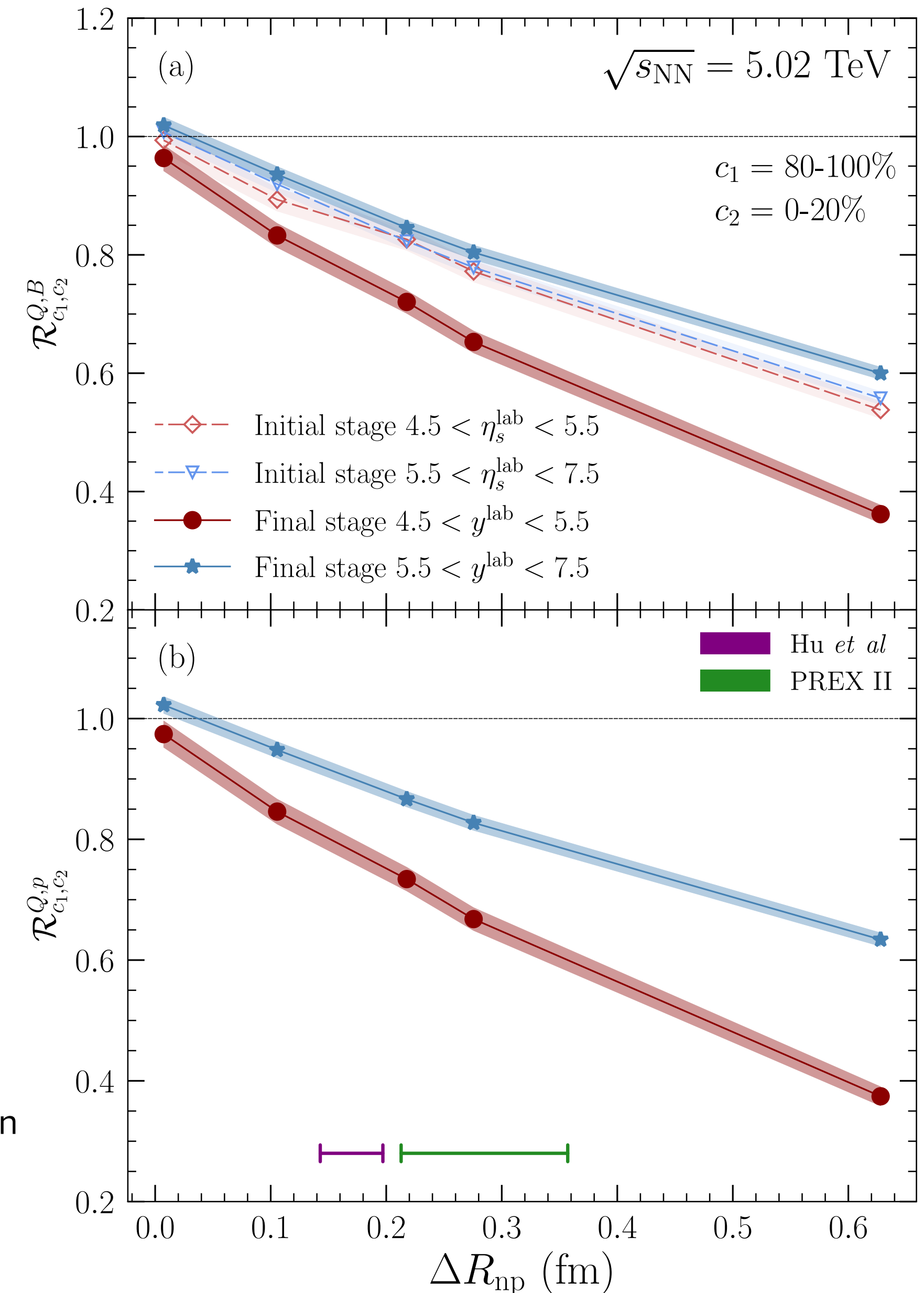
c_1 and c_2 : peripheral and central centrality class, resp.
Q and B: electric and baryon charge, respectively



central collision:
proton hits $n \approx p$
transport $Q \approx B$
towards mid rapidity



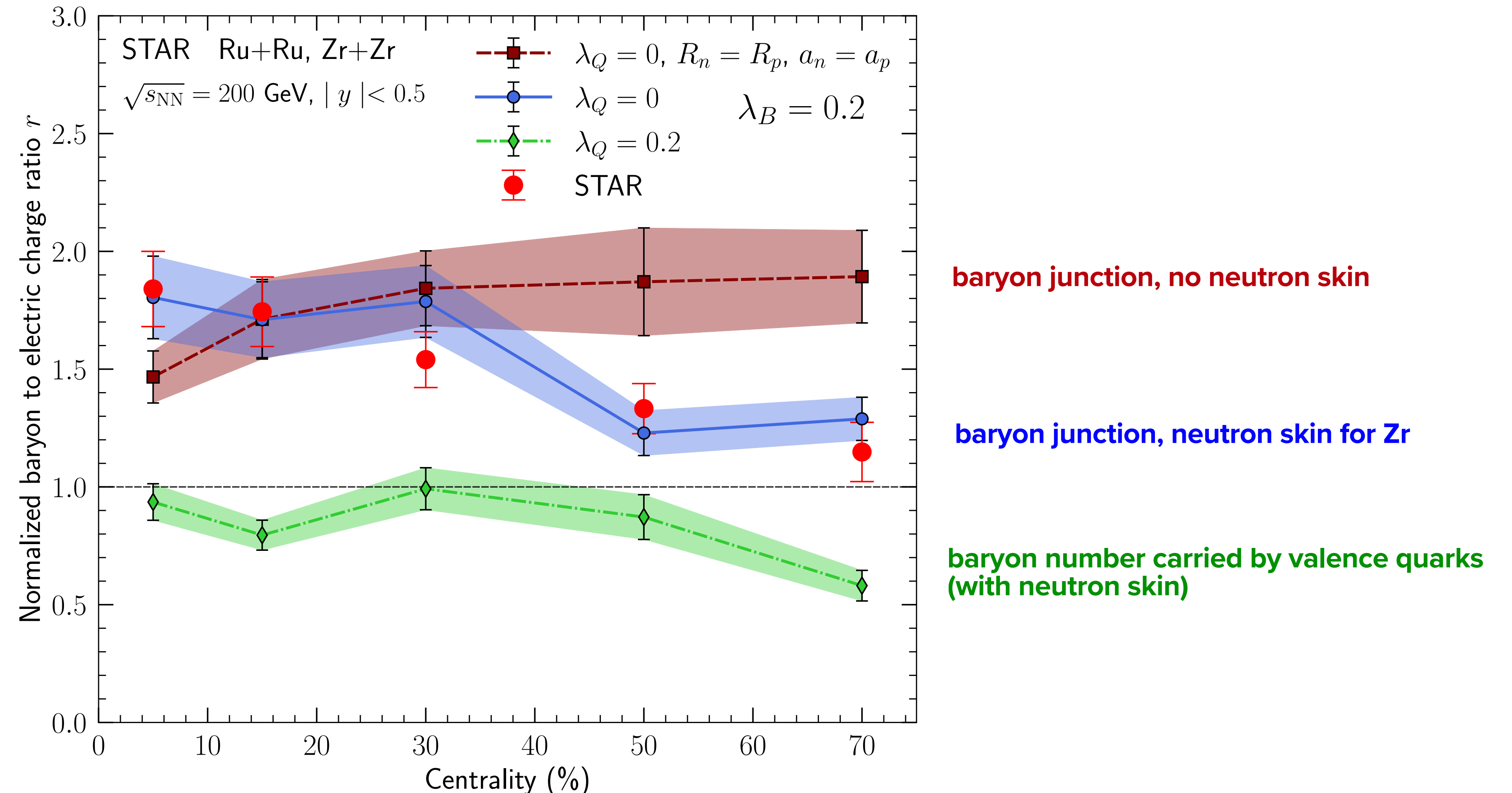
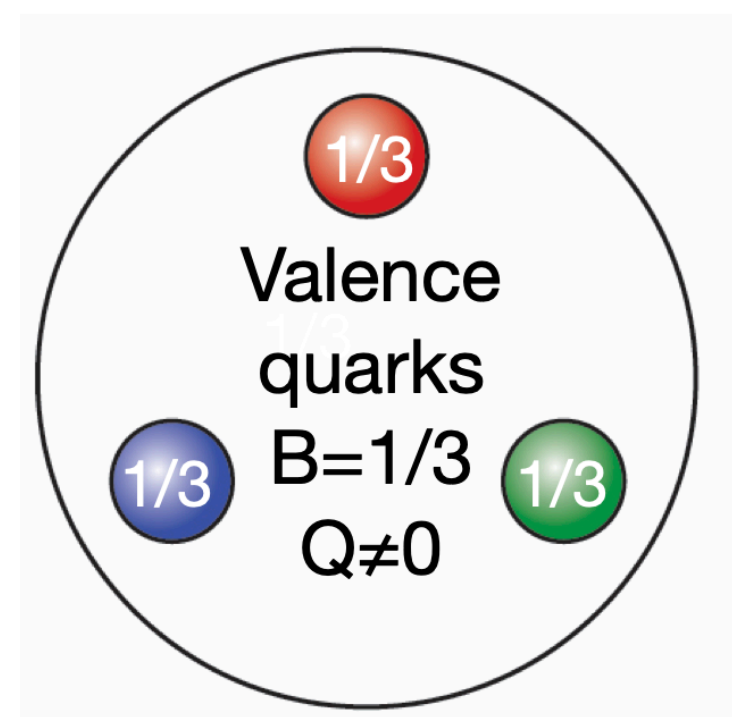
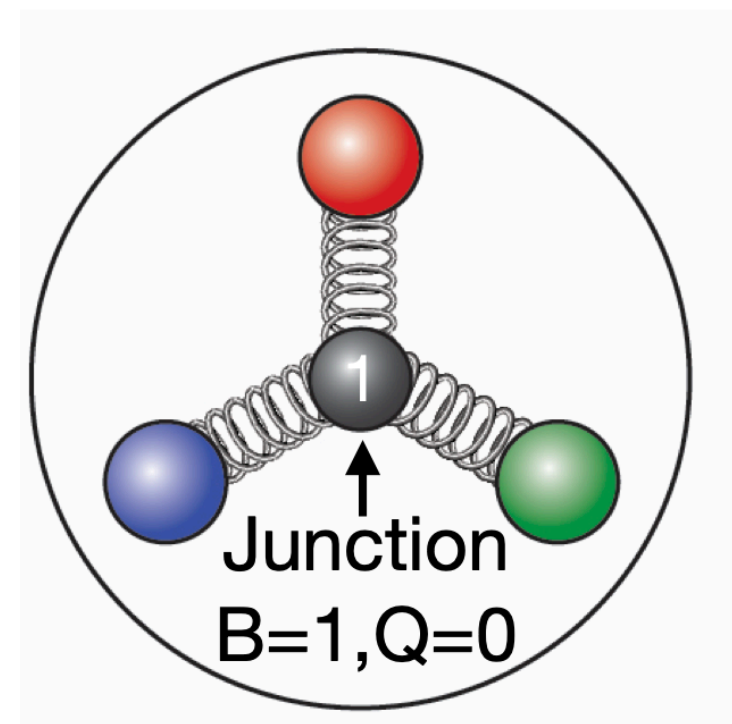
peripheral collision:
proton hits $n > p$
depending on neutron skin
transport $Q < B$
towards mid rapidity



WHAT CARRIES BARYON NUMBER?

D. Kharzeev, Phys. Lett. B 378, 238–246 (1996), G. Rossi, G. Veneziano, Nucl. Phys. B 123, 507–545 (1977), STAR Collaboration, [arXiv:2408.15441](https://arxiv.org/abs/2408.15441)

Grégoire Pihan, Akihiko Monnai, Björn Schenke, Chun Shen, Phys. Rev. Lett. 133 (2024) 18, 182301



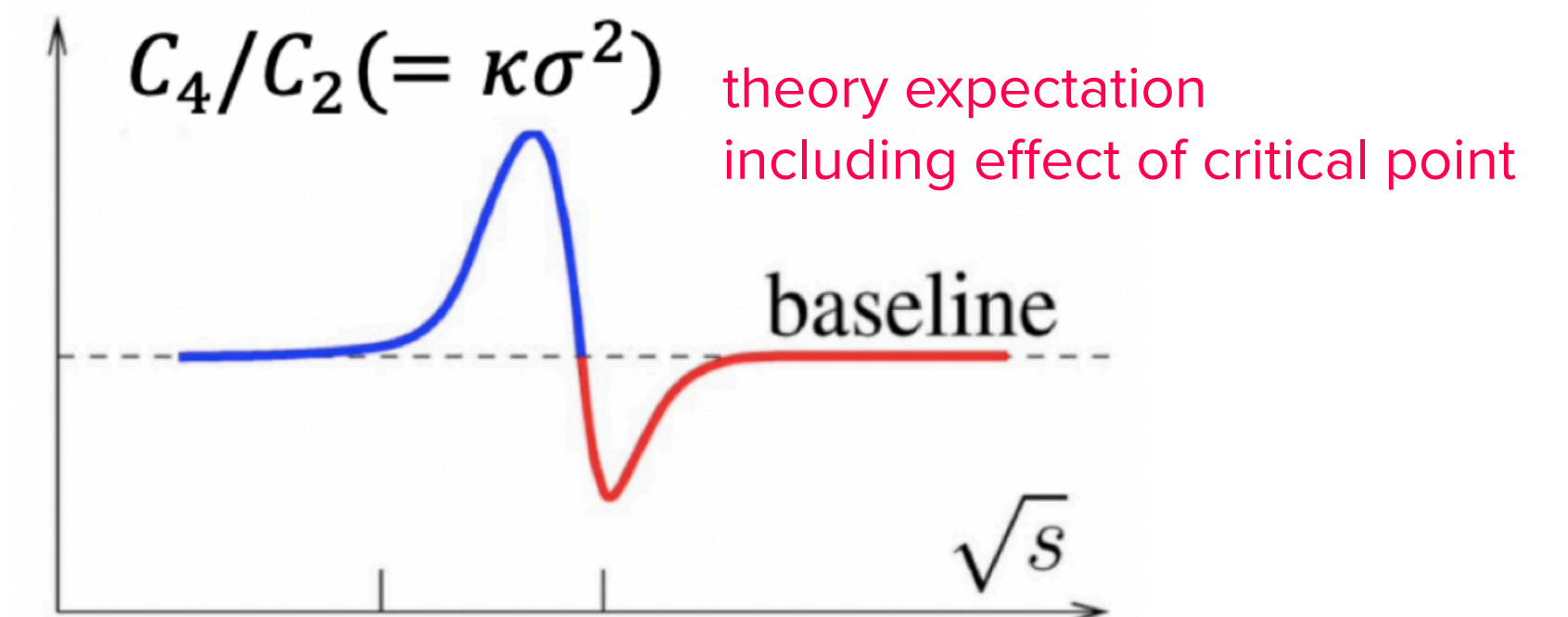
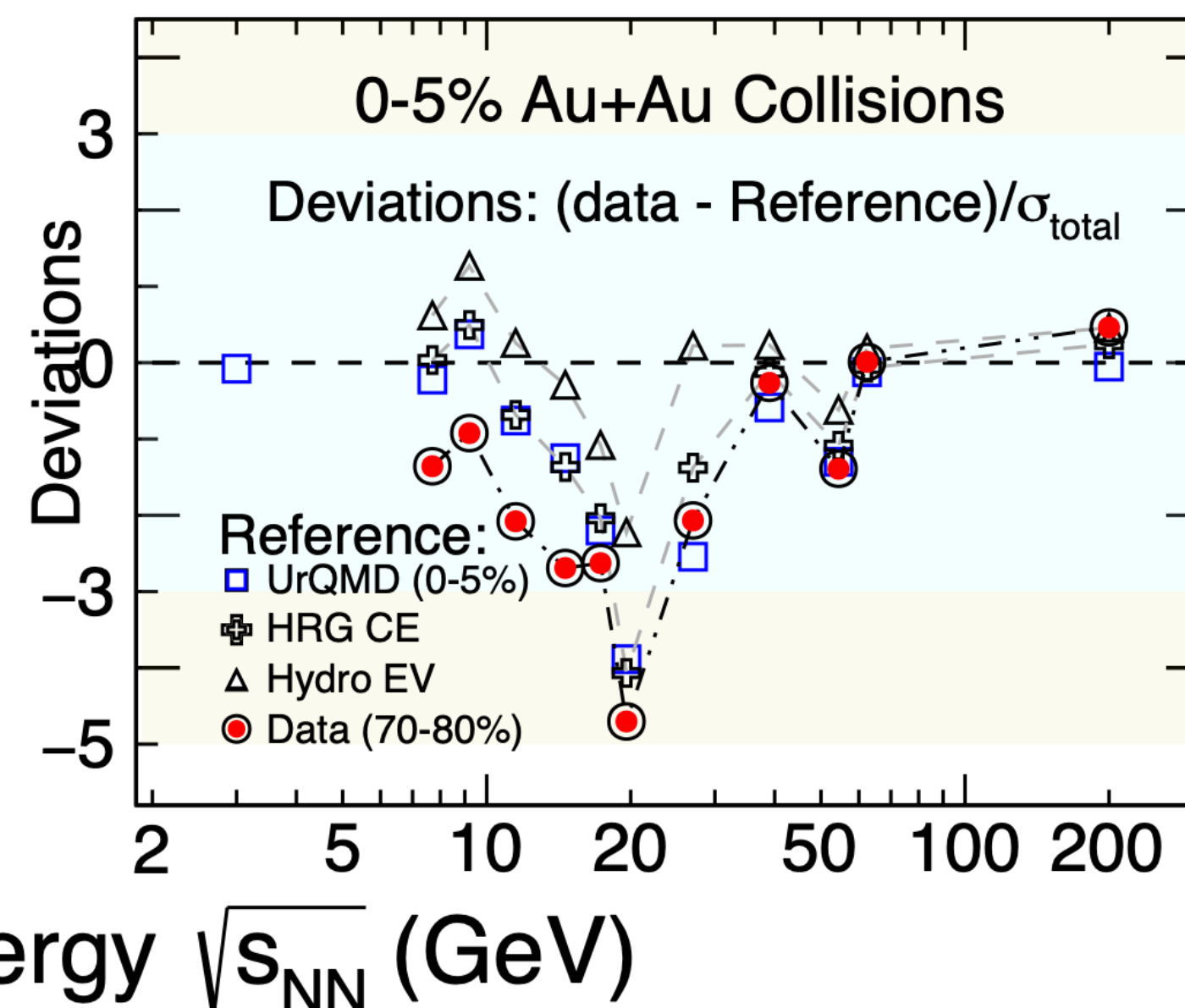
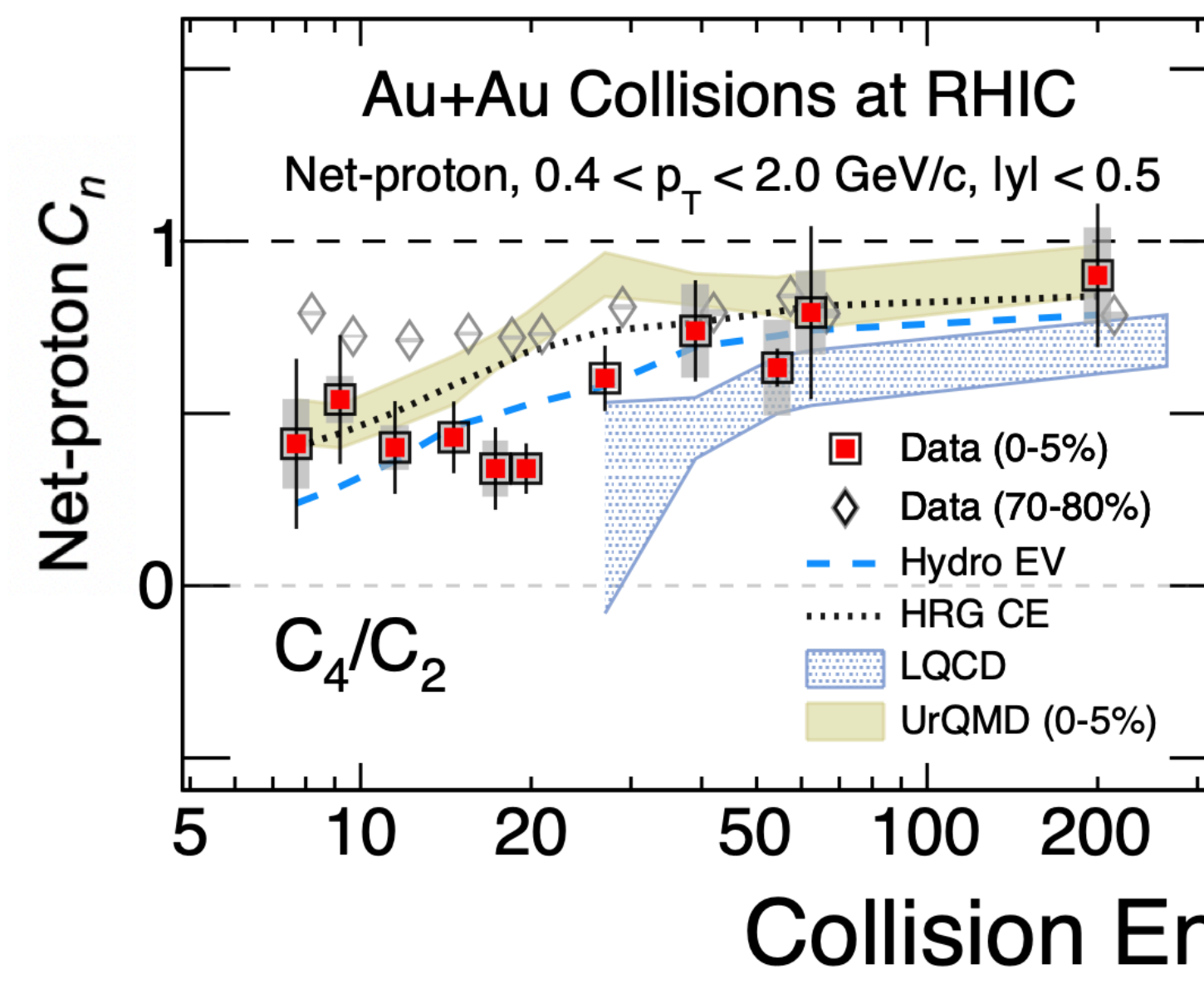
The ratio of the mean net-baryon number ($\langle B \rangle$) to the net-charge difference between Ru+Ru and Zr+Zr collisions (ΔQ), scaled by $\Delta Z/A = 4/96$, as a function of centrality

BEAM ENERGY SCAN - II

STAR Collaboration, Phys.Rev.Lett. 135 (2025) 14, 142301

• QCD Critical Point search

- Net-Proton fluctuations to expose critical fluctuations (divergence of correlation length near critical point)
- Different collision energies scan different baryon chemical potentials (and temperatures)
- There seems to be several hints, we will continue in STAR, including programs at LHC/SPS, RHIC/AGS, FAIR/SIS, HIAF, J-PARC, and going to fully net-baryon (neutrons etc) measurements

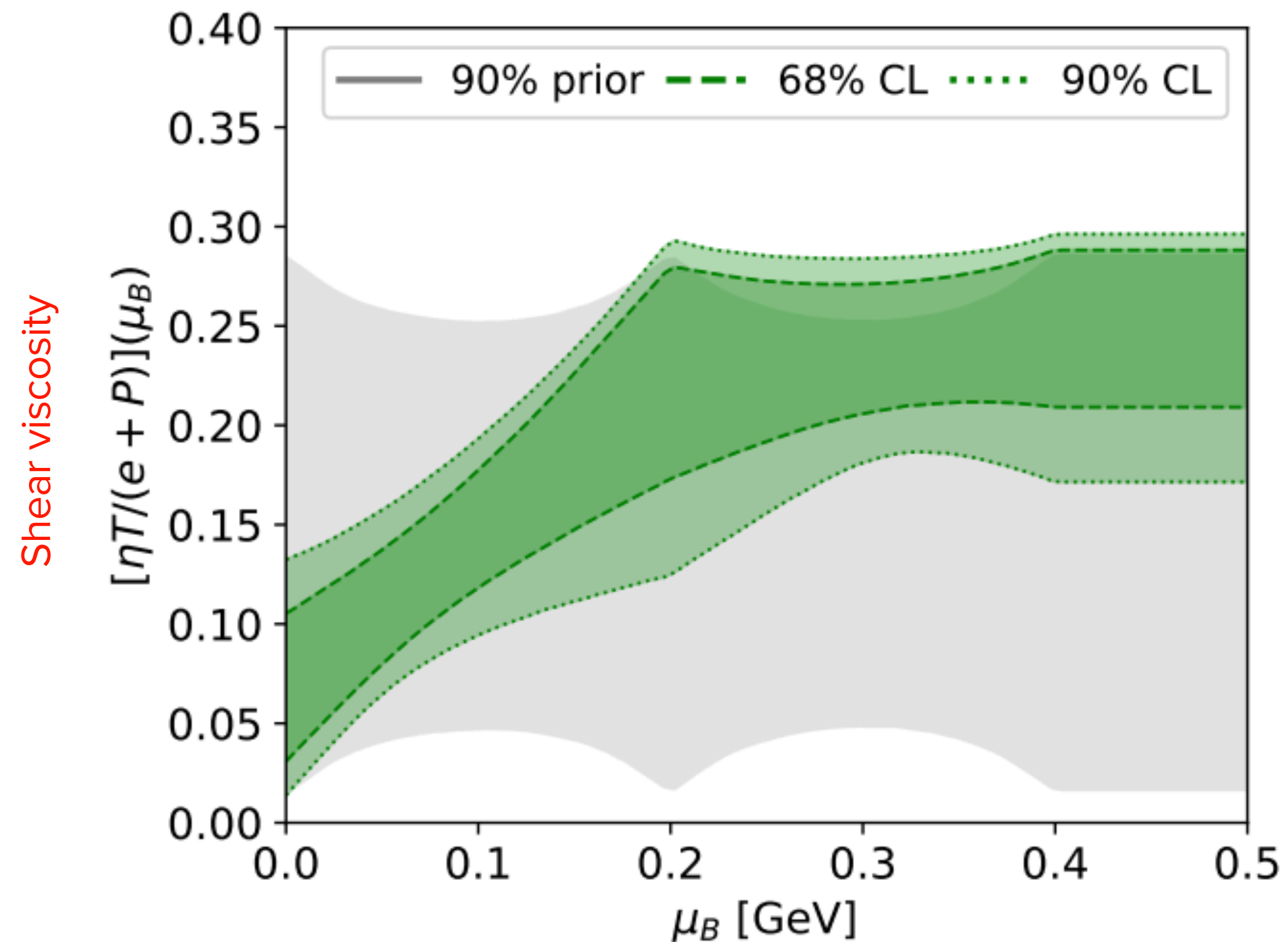


2 - 5 σ deviation
from calculations
without CP, peripheral data

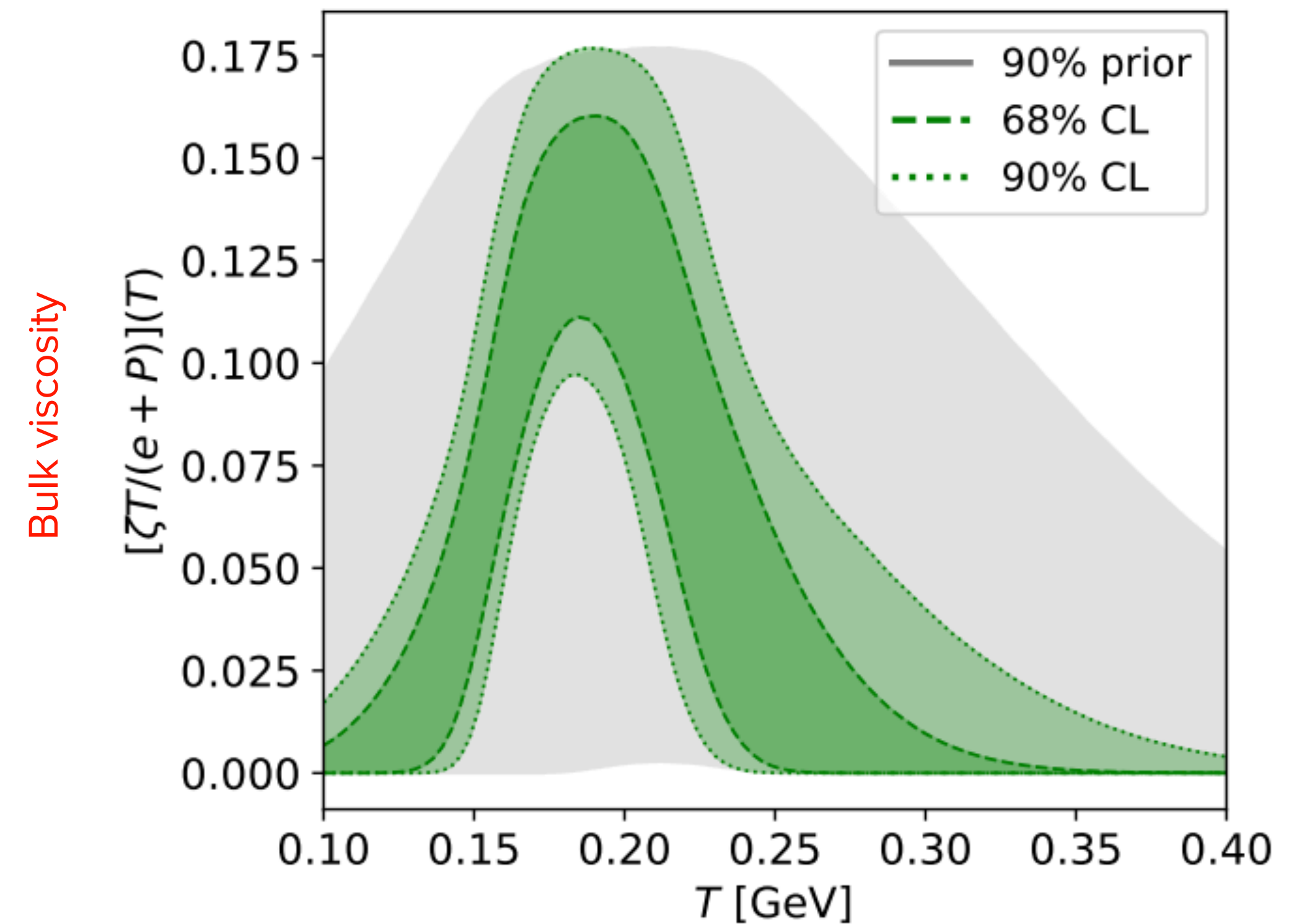
BEAM ENERGY SCAN - II

C. Shen, B. Schenke, W. Zhao, Phys.Rev.Lett. 132 (2024) 7, 072301, S. A. Jahan, H. Roch and C. Shen, Phys. Rev. C 110, 054905

- Properties of the medium across the phase diagram
 - Bayesian analysis using beam energy scan data on particle spectra and correlations



Baryon chemical potential

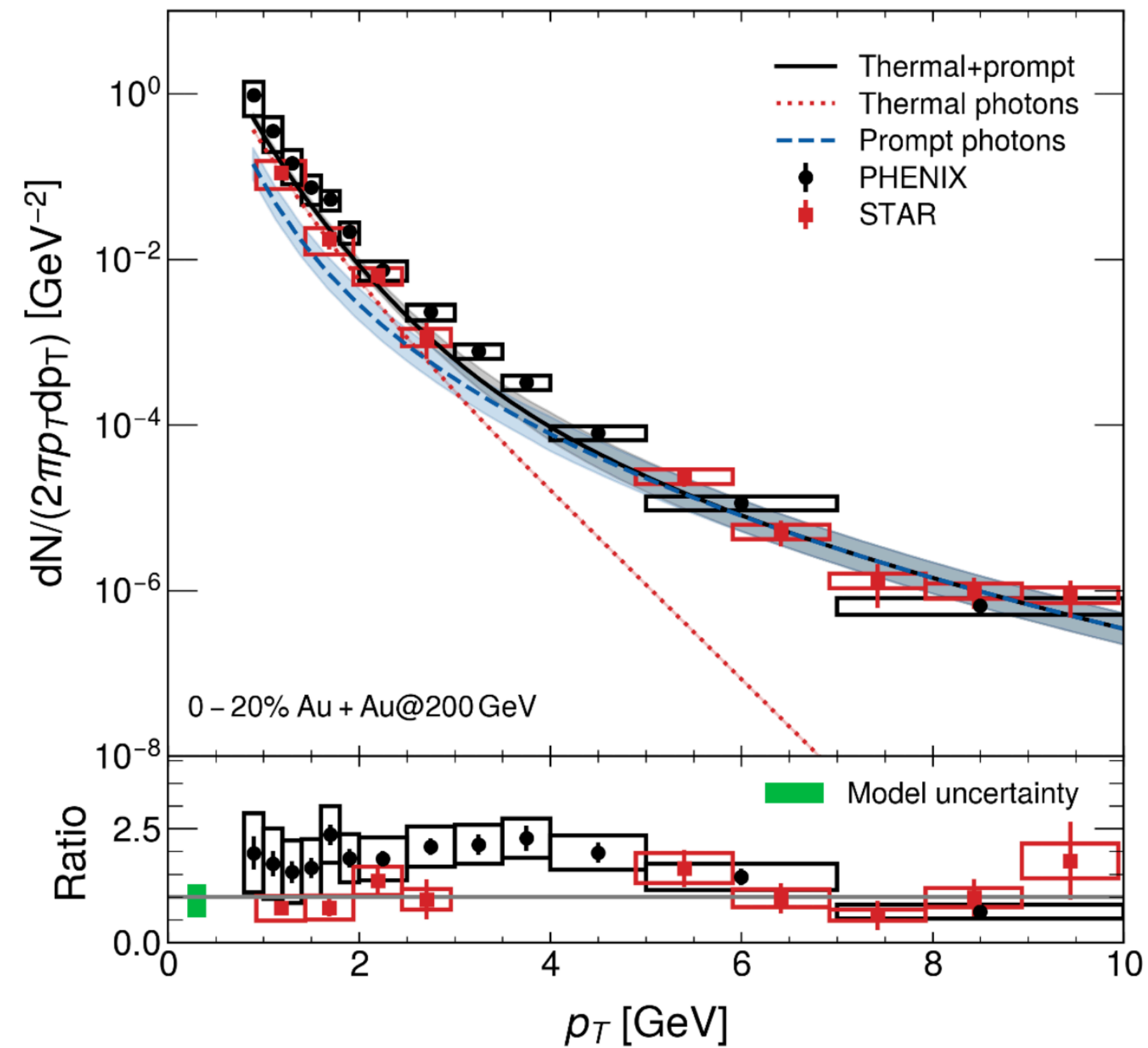


temperature

ELECTROMAGNETIC PROBES

Xiang-Yu Wu, Charles Gale, Sangyong Jeon, Jean-Francois Paquet, Bjoern Schenke, Chun Shen, forthcoming

Photon spectrum: prompt+thermal contribution
using fluid dynamic simulation for the medium:

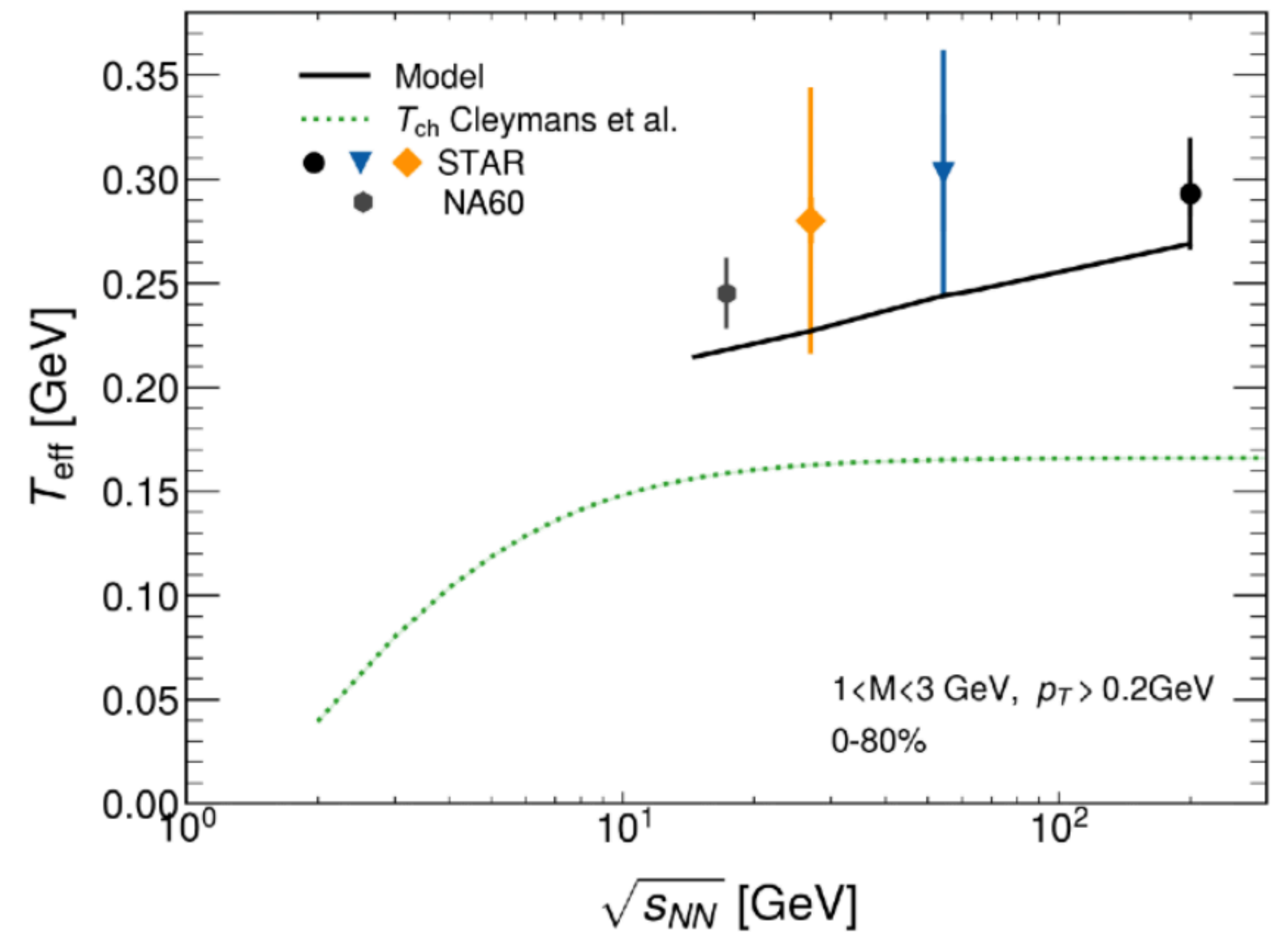


PHENIX Collaboration, Phys. Rev. C 91, 064904 (2015)

STAR Collaboration, Phys. Lett. B 770, 451–458 (2017)

BJÖRN SCHENKE

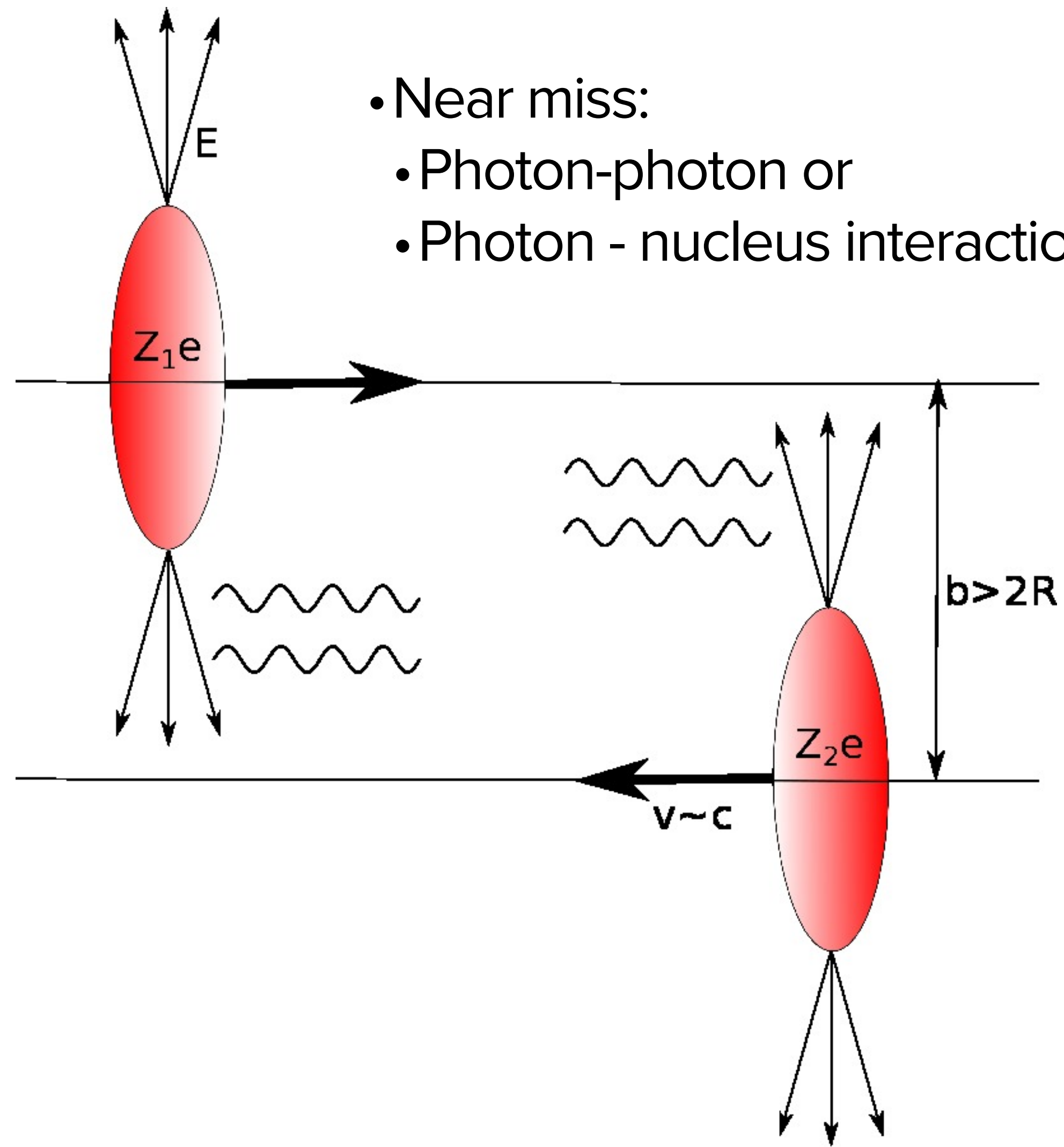
QGP temperature from high invariant mass dileptons



STAR Collaboration, arXiv:2505.06361 [nucl-ex].

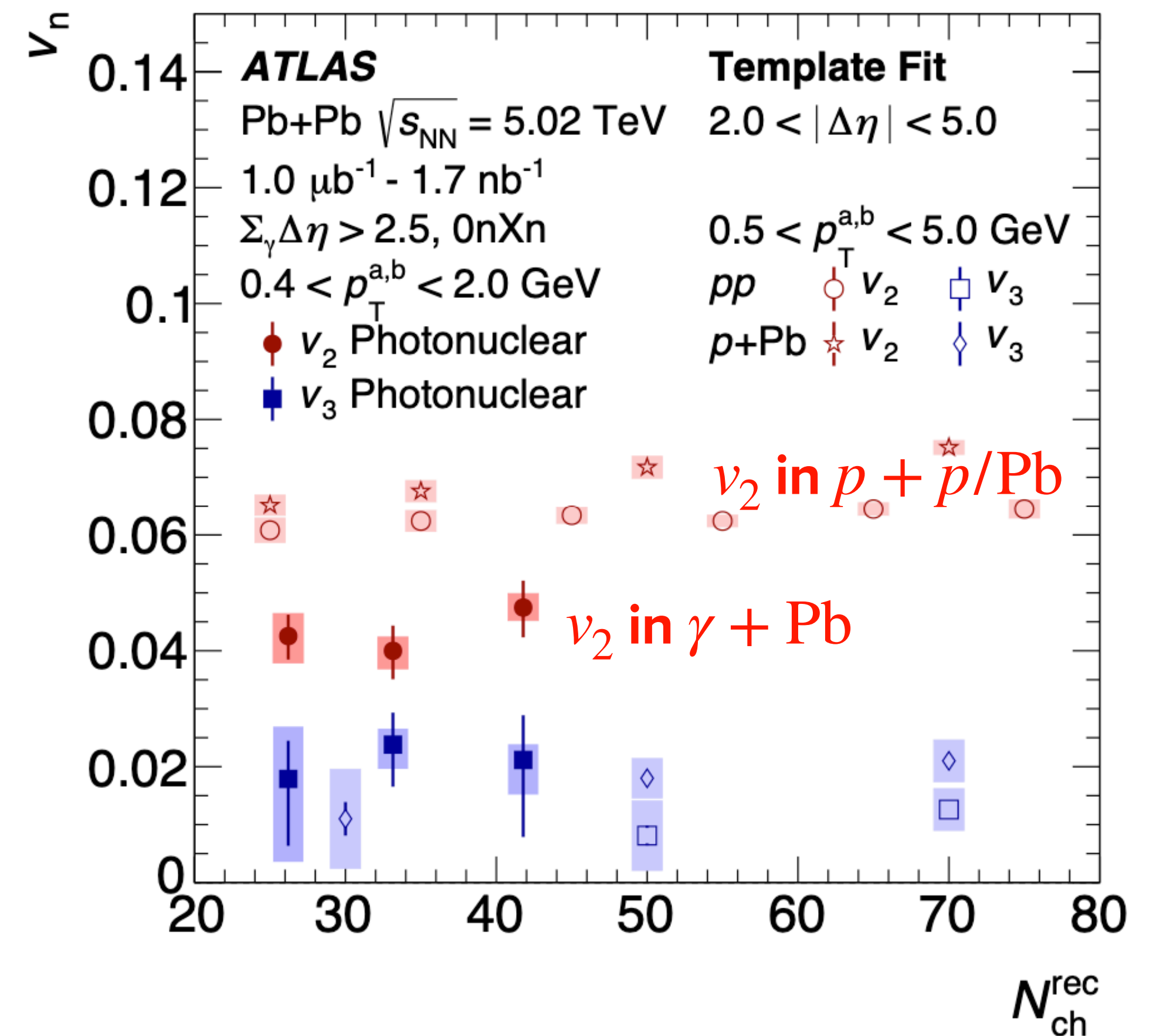
NA60 Collaboration, Eur. Phys. J. C 59, 607–623 (2009)

ULTRA-PERIPHERAL COLLISIONS



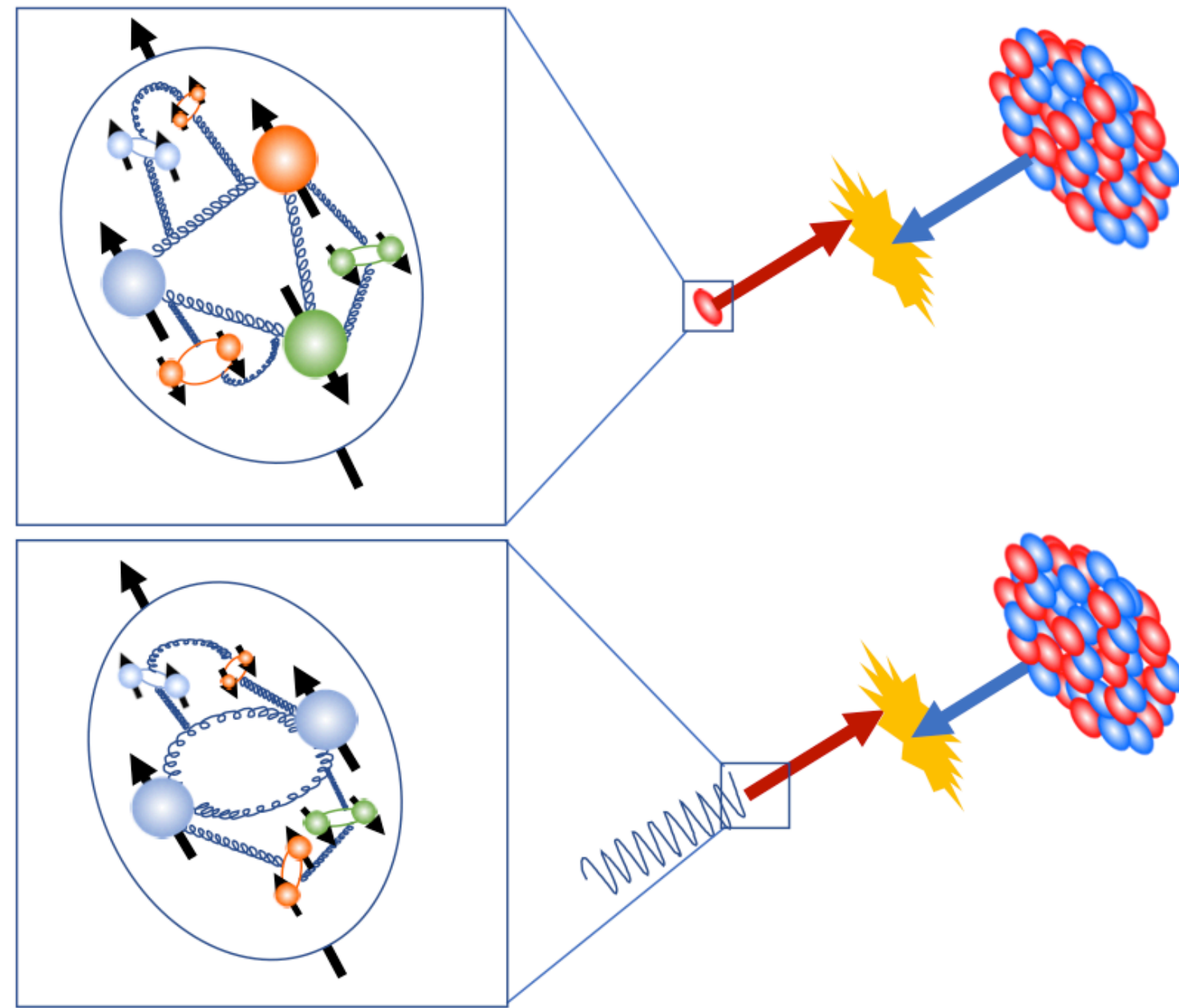
- Near miss:
 - Photon-photon or
 - Photon - nucleus interactions

- Again: Collectivity when many particles are produced?

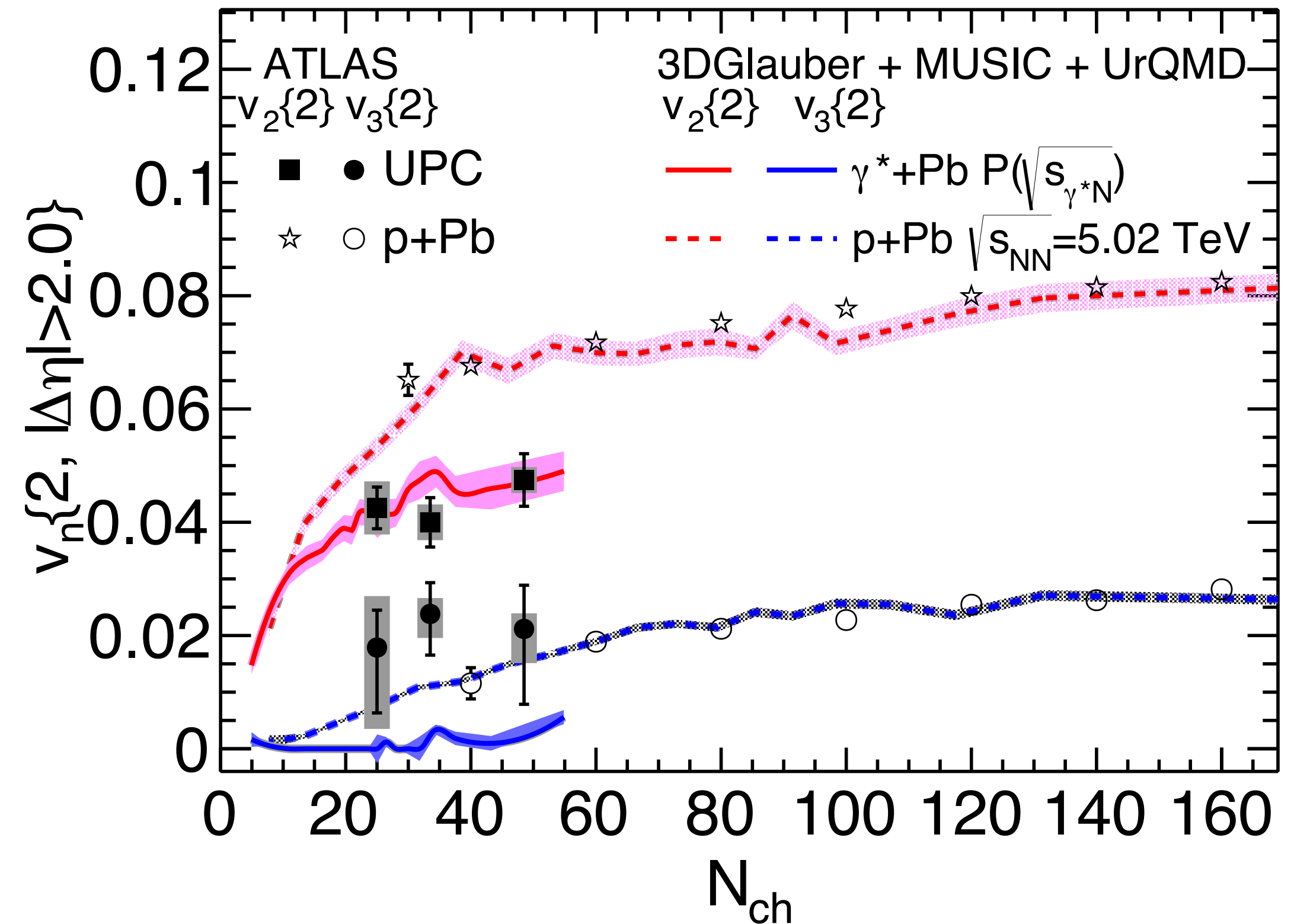


COLLECTIVITY IN UPCs?

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



Phys. Rev. D 103, 054017 (2021)



- 3+1D hydrodynamic model for γ^* +Pb (vector meson + Pb) collisions
- Elliptic flow difference between p+Pb and γ^* +Pb collisions reproduced - driven by different amount of longitudinal flow decorrelation

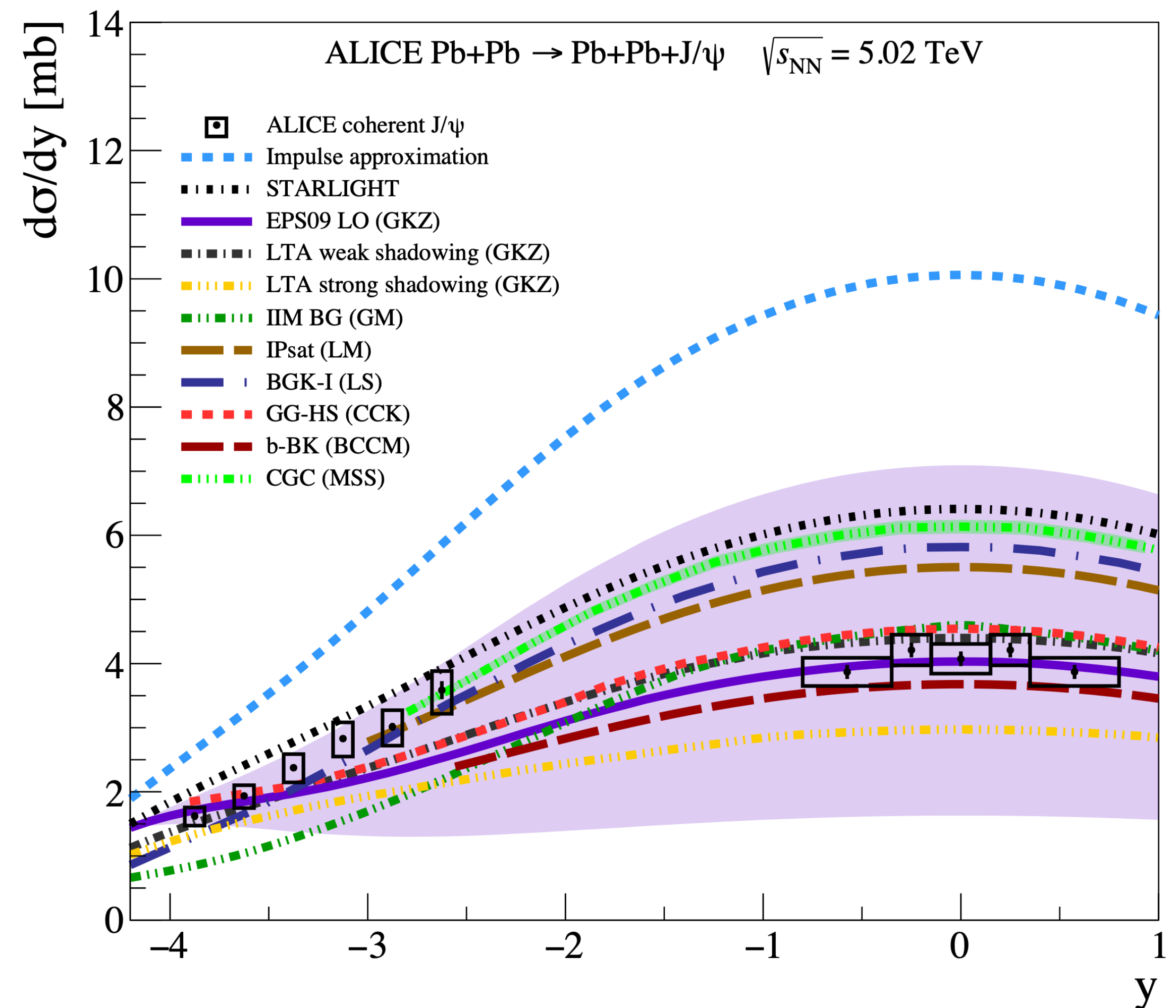
EXCLUSIVE PROCESSES: PREVIEW TO EIC

B. Schenke, H. Mäntysaari, F. Salazar, C. Shen, W. Zhao, Phys.Proc.UPC 1 (2024) 2

- Consider exclusive J/ψ production in $\gamma + p$ and $\gamma + \text{Pb}$ collisions
- Nuclear suppression can reveal shadowing or saturation effects
- Saturation models overestimate midrapidity cross section

Experimental data: ALICE Collaboration, Phys. Lett. B, 798:134926 (2019)
Eur. Phys. J. C, 81(8):712 (2021)

- Many other observables:
 - Dijets, dihadrons (inclusive/exclusive)
 - Angular correlations of vector-meson decay products: Extract quantum interference effects
 - Inclusive charm production, ...

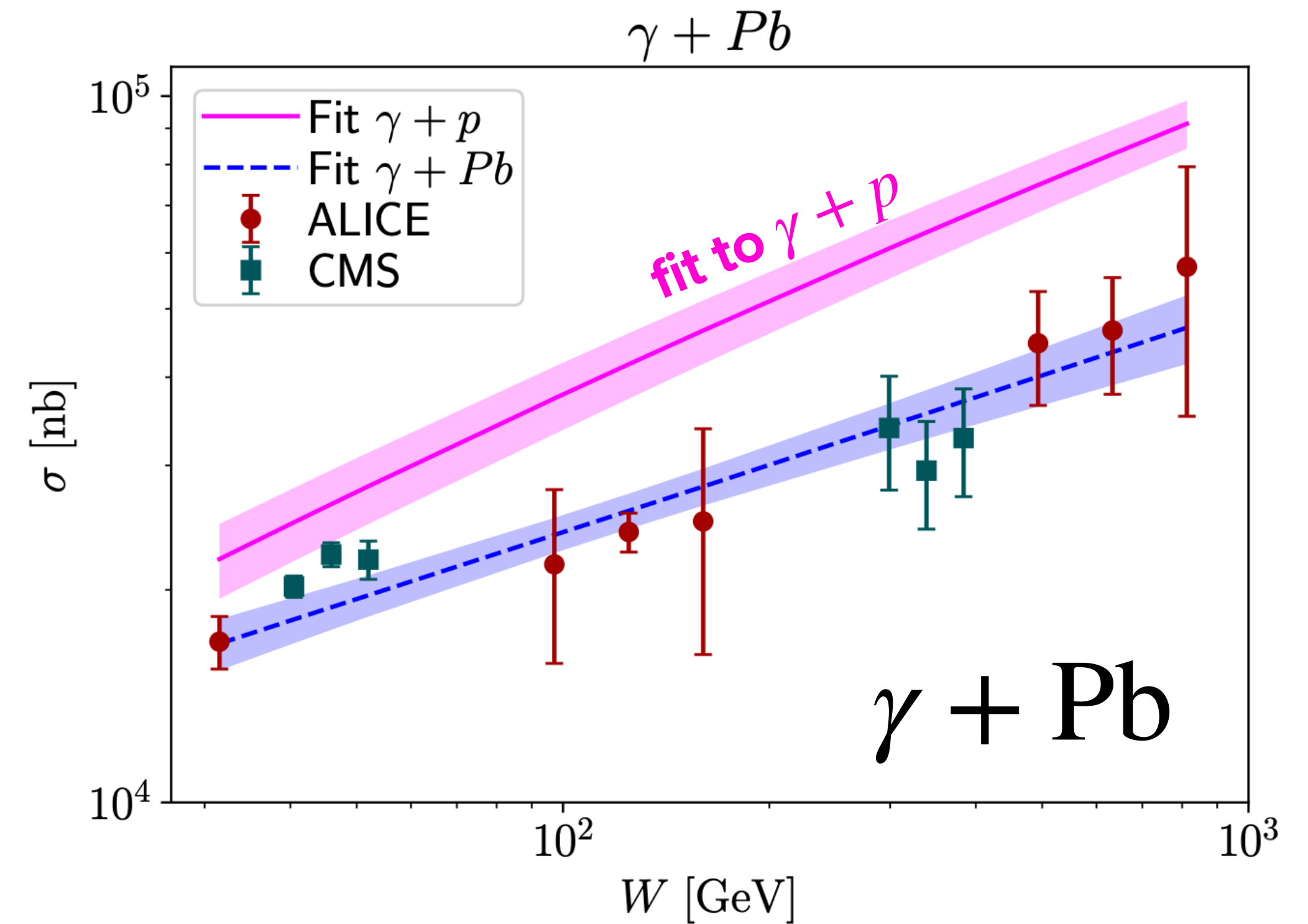
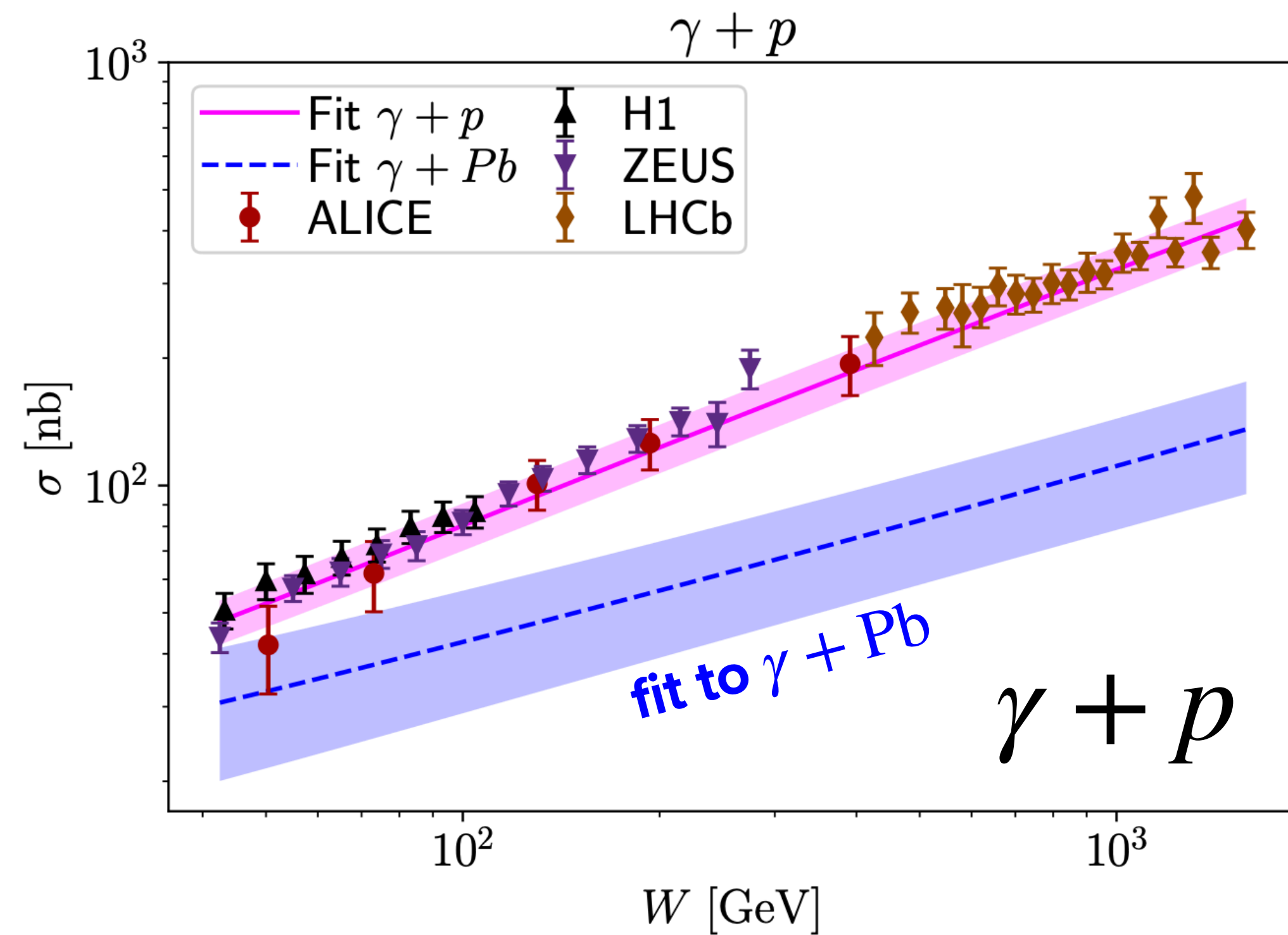


EXCLUSIVE PROCESSES: PREVIEW TO EIC

H. Mäntysaari, H. Roch, F. Salazar, B. Schenke, C. Shen, W. Zhao, e-Print: 2507.14087

Global Bayesian Analysis of J/ψ Photoproduction on Proton and Lead Targets

Challenging to describe $\gamma + p$ and $\gamma + \text{Pb}$ data at the same time (here within the CGC):



Bayesian analysis using Gaussian Process Emulator.

Simultaneous description of $\gamma + p$ and $\gamma + \text{Pb}$ data requires a rescaling of the cross section (absorbing uncertainties in e.g. the VM wave function)

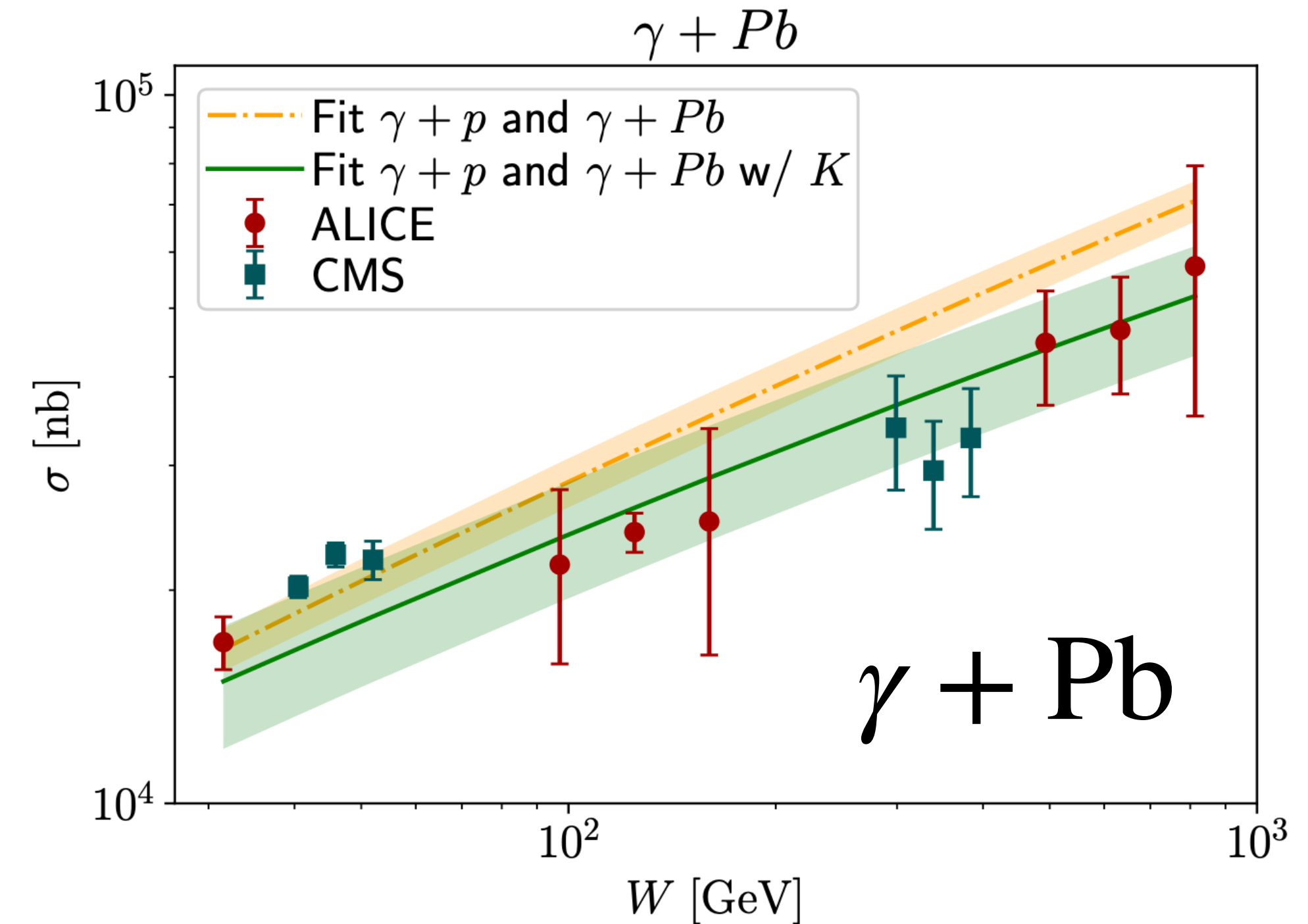
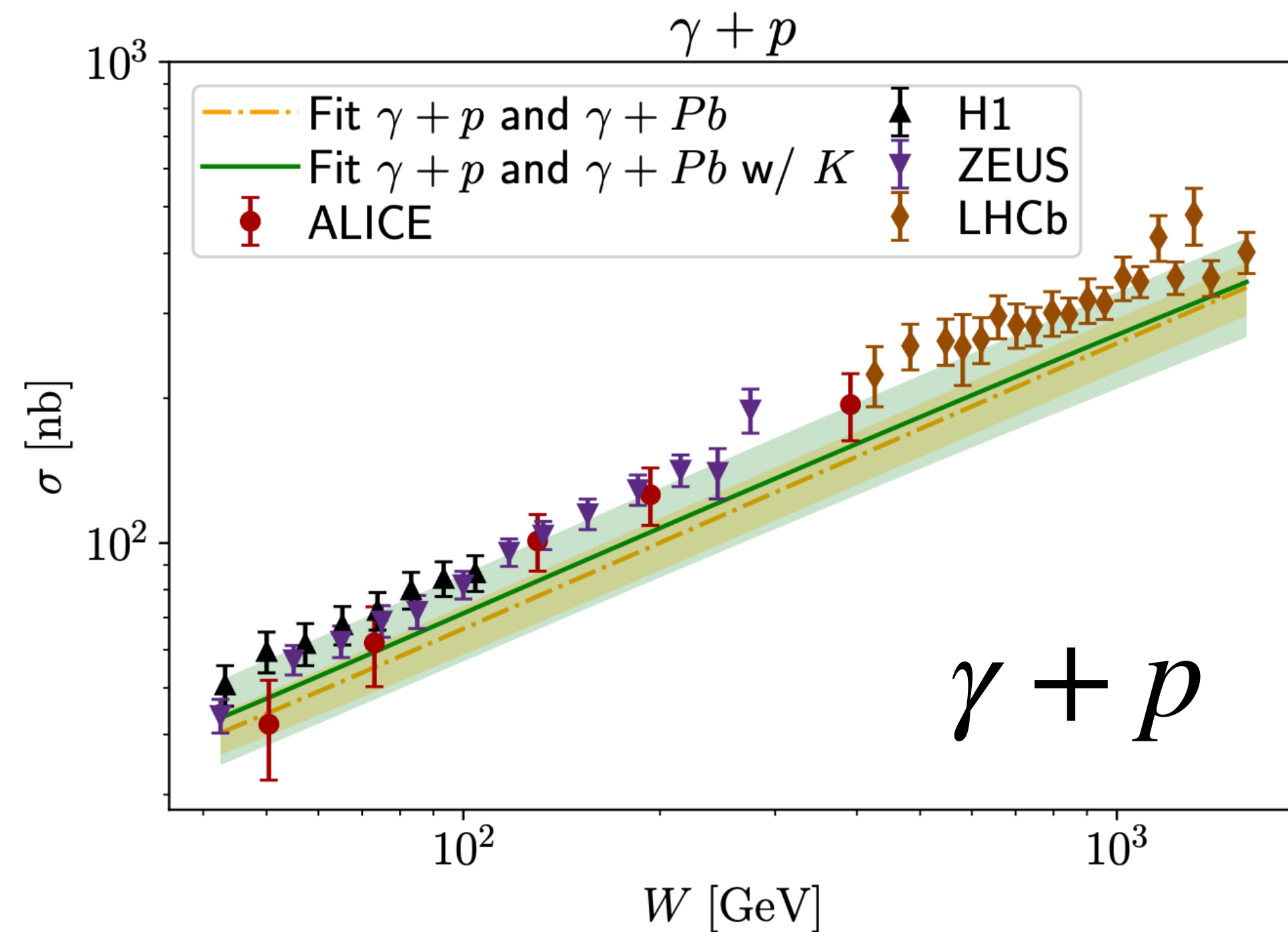
ALICE Collaboration, Phys. Rev. Lett. 113 (2014) 232504,
Eur. Phys. J. C 79 (2019) 5 402,
JHEP 10 (2023) 119
H1 Collaboration, Eur. Phys. J. C 46 (2006) 585,
Eur. Phys. J. C 73 (2013) 6 2466
ZEUS Collaboration, Eur. Phys. J. C 24 (2002) 345
LHCb Collaboration, JHEP 10 (2018) 167
CMS Collaboration, Phys. Rev. Lett. 131 (2023) 26 262301

EXCLUSIVE PROCESSES: PREVIEW TO EIC

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ALICE Collaboration, Phys. Rev. Lett. 113 (2014) 232504,
Eur. Phys. J. C 79 (2019) 5 402,
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ZEUS Collaboration, Eur. Phys. J. C 24 (2002) 345
LHCb Collaboration, JHEP 10 (2018) 167
CMS Collaboration, Phys. Rev. Lett. 131 (2023) 26 262301

SUMMARY

- **Heavy-ion collisions:** a versatile QCD lab
- **Near-perfect fluid + precision data** → broad measurement reach
- **Access to:** nucleon/nuclear structure, QCD phase diagram, viscosities, energy evolution, ...
- **Small systems:** strong collective behavior
- **Ultra-peripheral collisions:** Cold-QCD - shadowing & gluon saturation - precursor to the EIC

“QGP at Fifty - A Commemorative Journey” (Springer Nature):

The Early History of the Quark-Gluon Plasma [W. Busza](#), [W.A. Zajc](#) e-Print: [2504.08720](#)

What is the Quark-Gluon Plasma made of? [Berndt Müller](#) e-Print: [2506.07181](#) [nucl-th]

The quark-gluon plasma: diagnosis with thermal hadron production from the early history until detailed characterization at high energy colliders [Peter Braun-Munzinger](#), [Krzysztof Redlich](#), [Johanna Stachel](#) e-Print: [2506.04733](#) [nucl-th]

Hydrodynamic Description of the Quark-Gluon Plasma [Ulrich Heinz](#), [Björn Schenke](#) e-Print: [2412.19393](#) [nucl-th]

Electromagnetic Radiation from High-Energy Nuclear Collisions [Charles Gale](#) e-Print: [2502.13938](#) [nucl-th]

QGP@50: More than Four Decades of Jet Quenching [Xin-Nian Wang](#), [Urs Achim Wiedemann](#) e-Print: [2508.18794](#) [hep-ph]

Quark Recombination [Rainer J. Fries](#), [Vincenzo Greco](#), [Ralf Rapp](#) e-Print: [2506.24023](#) [hep-ph]

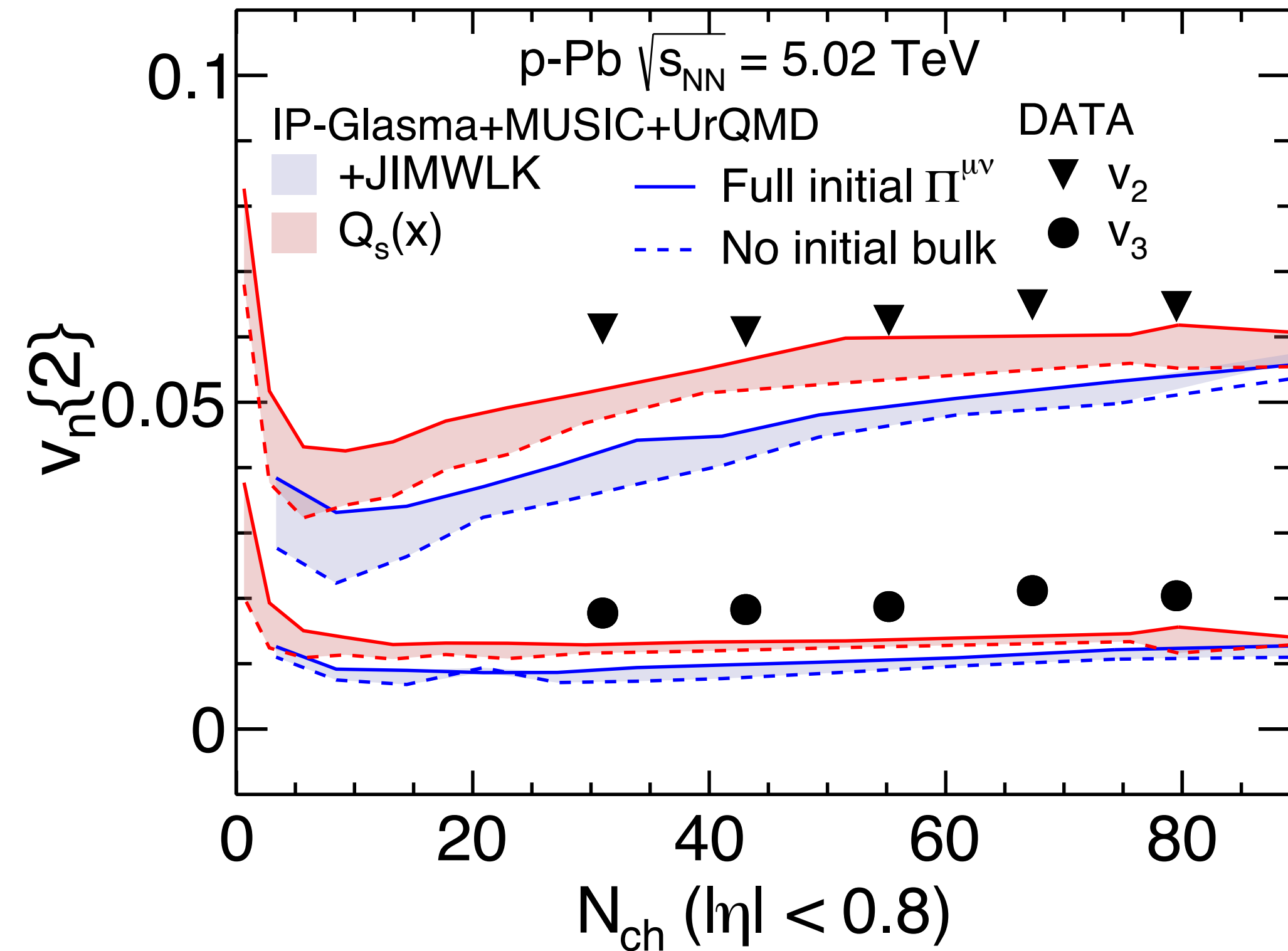
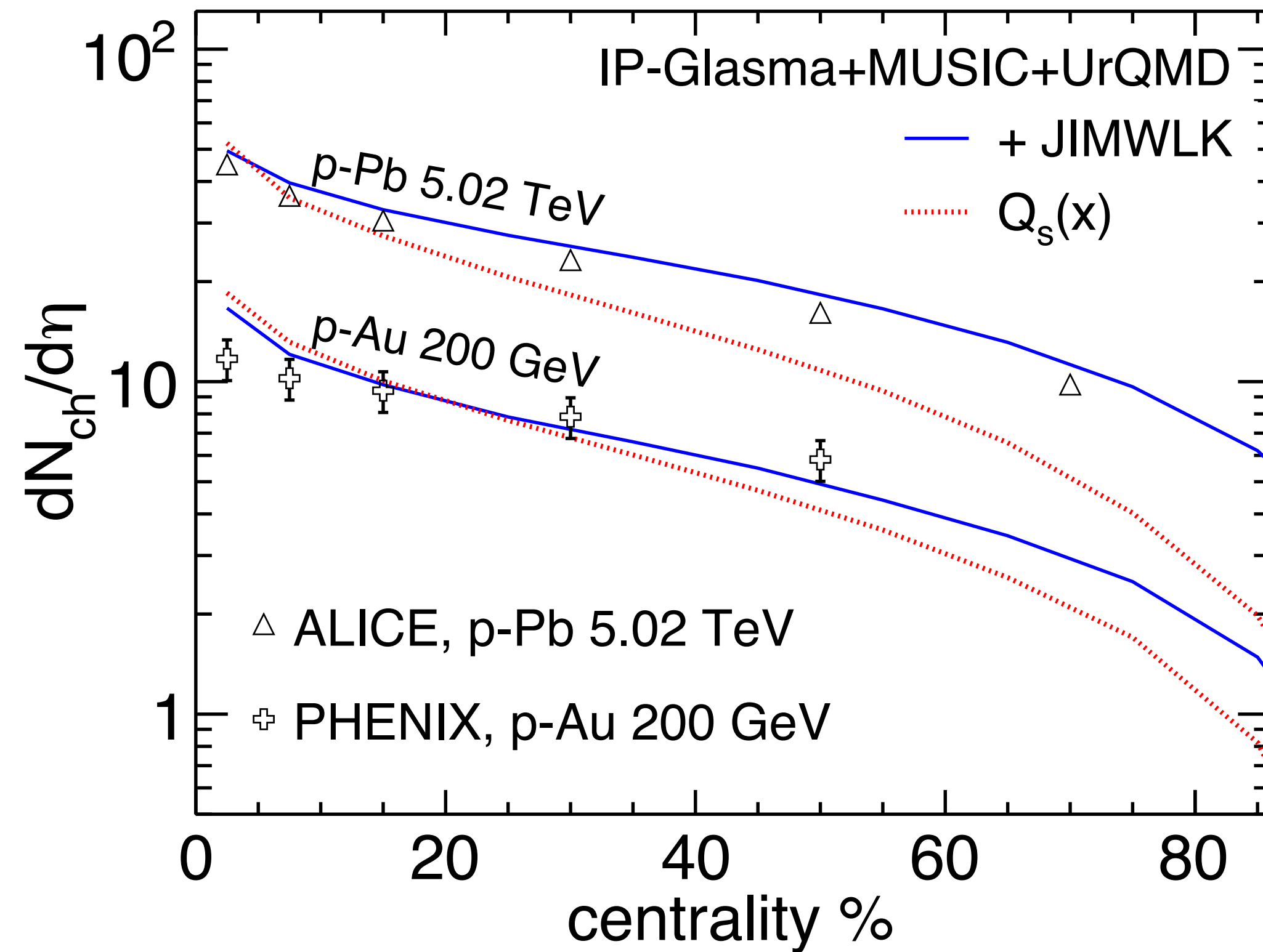
Advertisement

BACKUP

SMALLER SYSTEMS

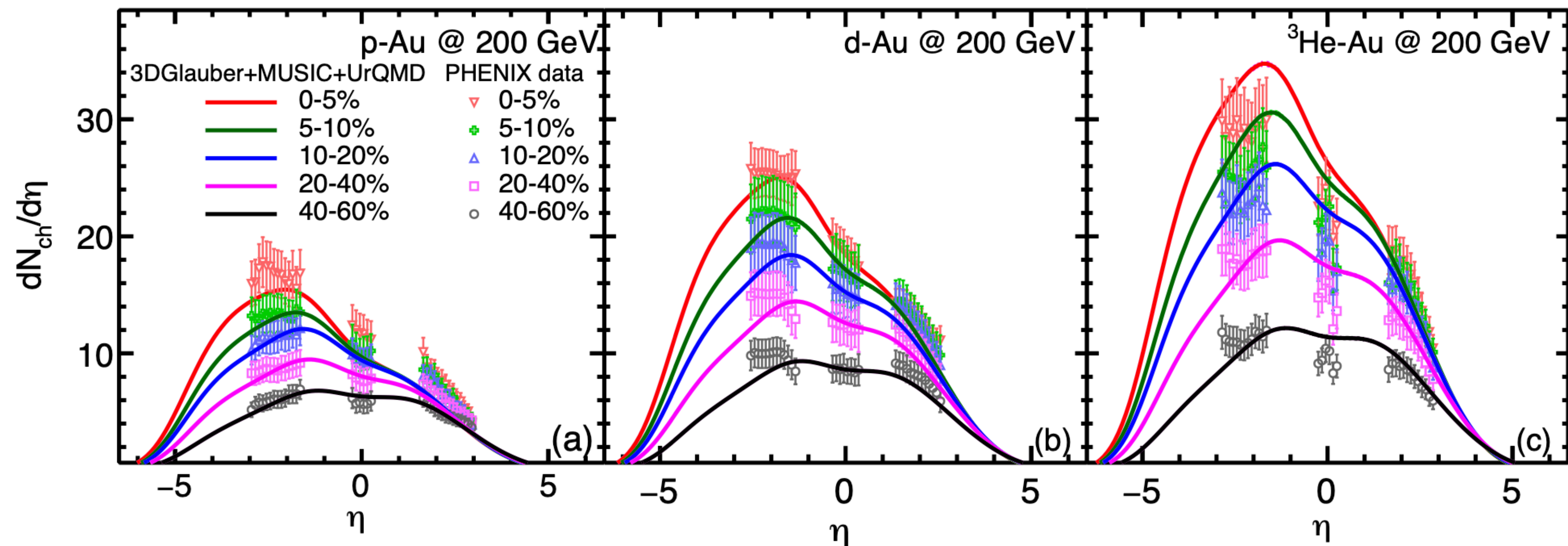
- Larger effects in smaller systems - flow harmonics v_n in p+Pb are underestimated

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys.Rev.Lett. 135 (2025) 2, 022302, and forthcoming



COMPUTING RHIC SMALL SYSTEMS

Asymmetric systems, measurements over large range in rapidity:
Need 3D initial state + 3+1D hydrodynamic simulations

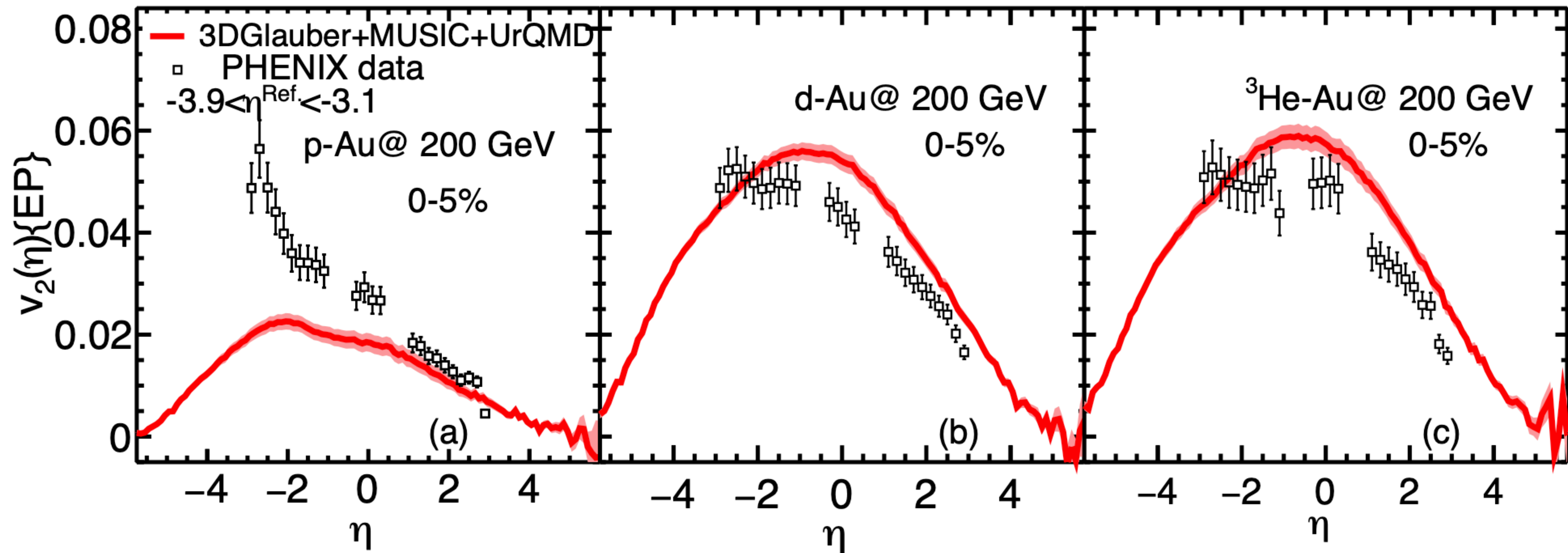


Dynamic 3D initial state (string deceleration with dynamic energy deposition) + hydrodynamics captures the rapidity and centrality dependence of $dN^{ch}/d\eta$ for all asymmetric systems

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 ^3He +Au
- Longitudinal decorrelation is important!
- The elliptic flow in $\eta < 1$ in p+Au collisions is underestimated because potential non-flow

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

EFFECTS OF ENFORCING CAUSALITY

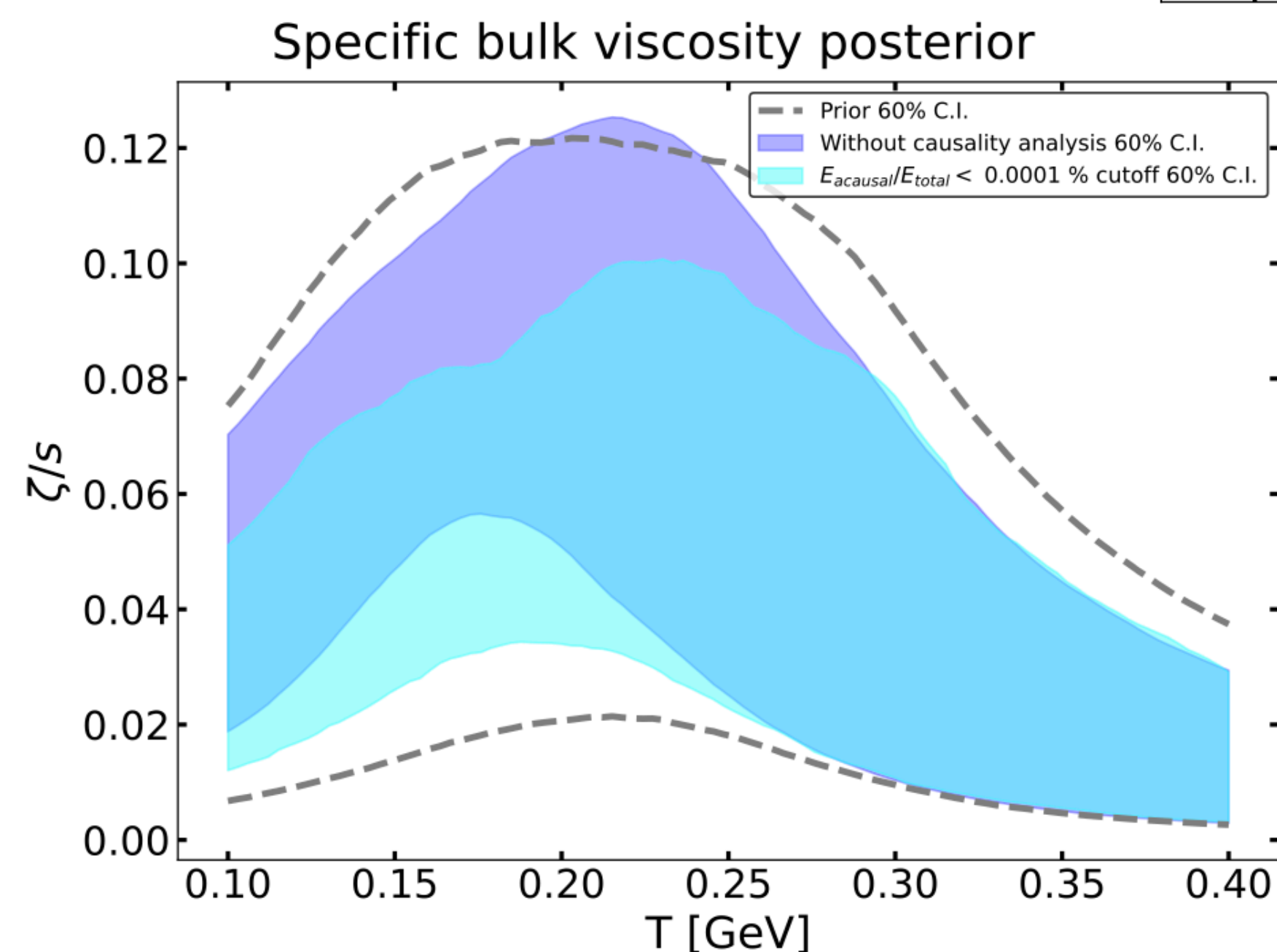
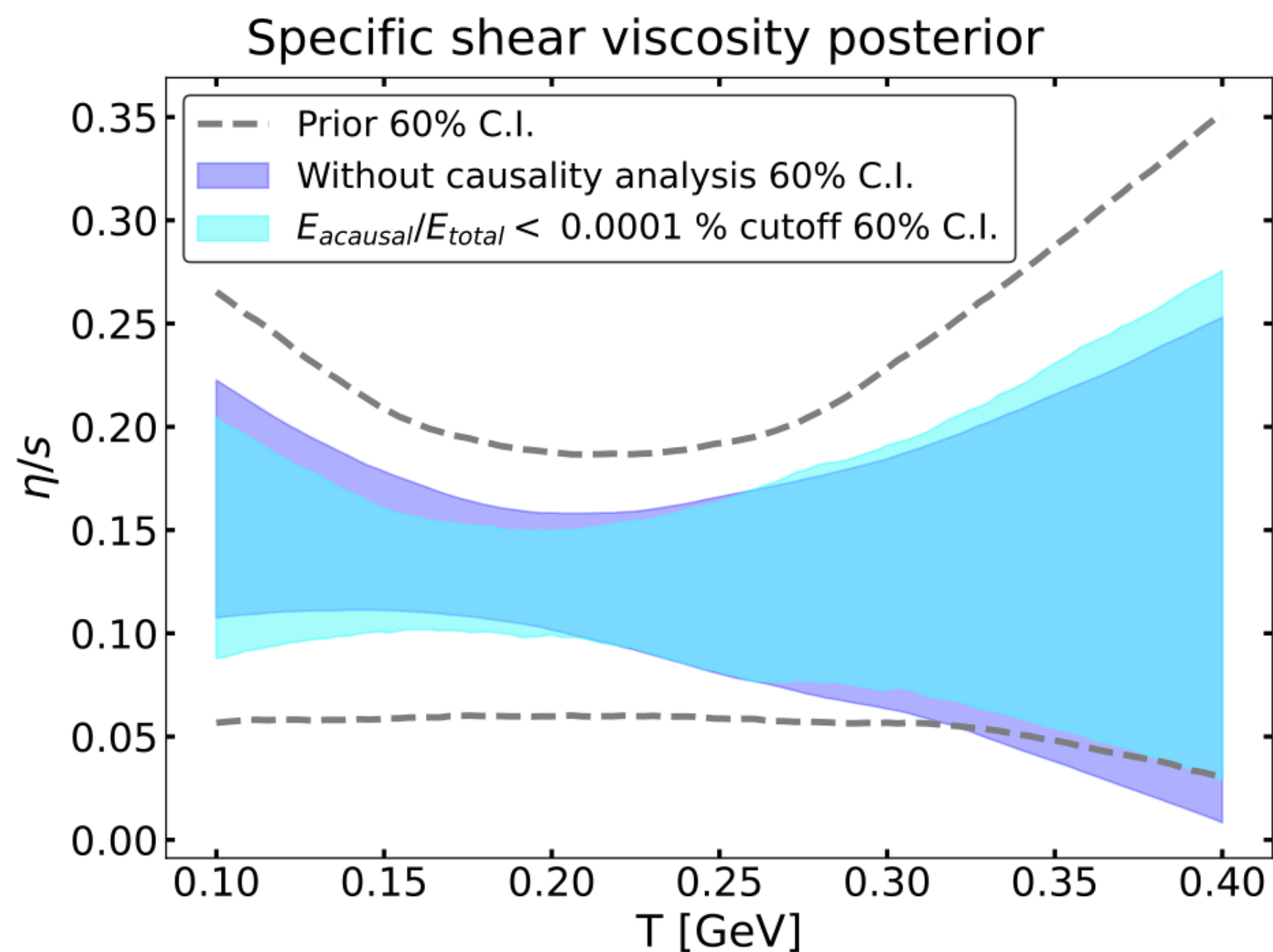
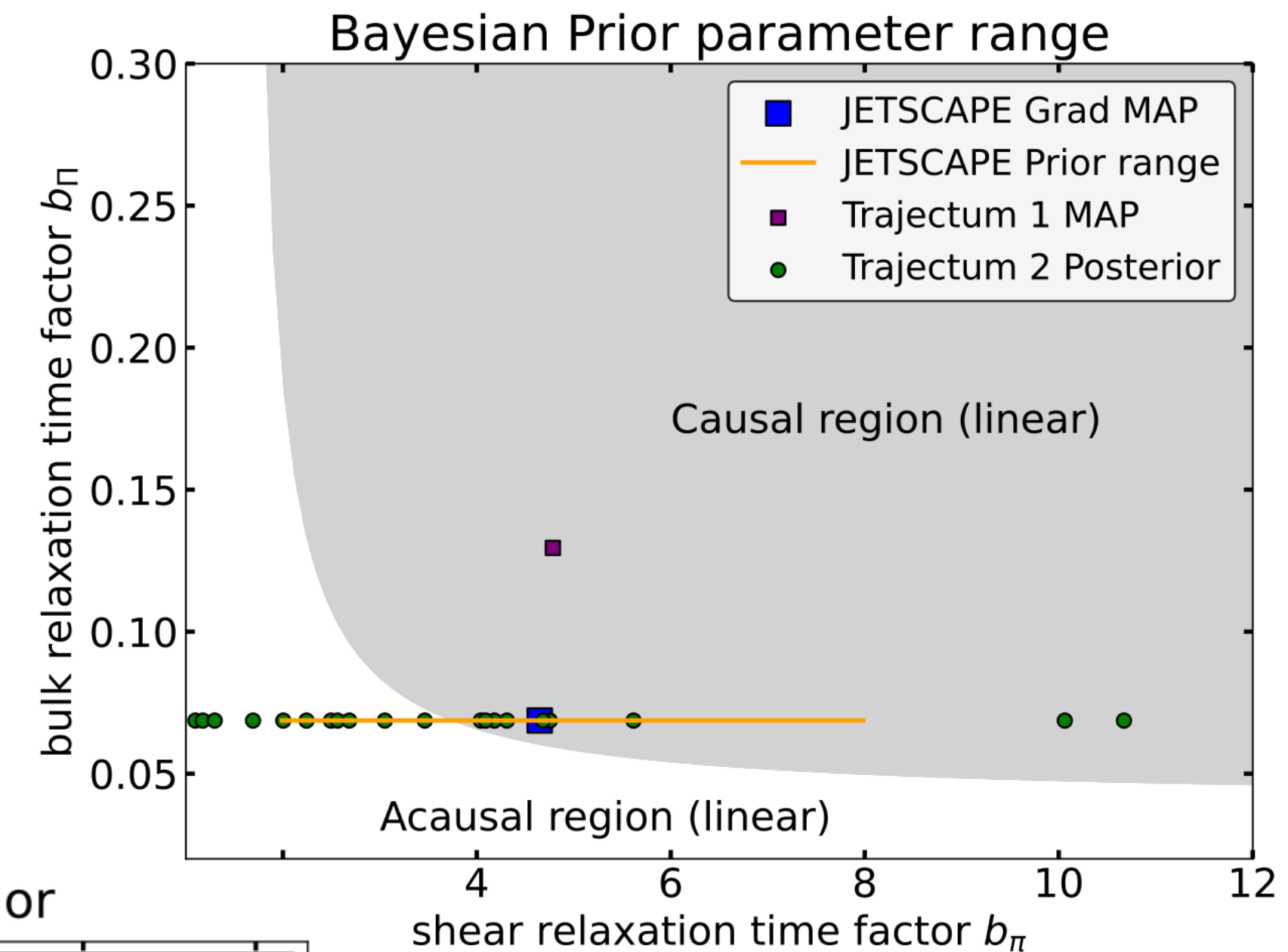
There are necessary and sufficient causality conditions

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

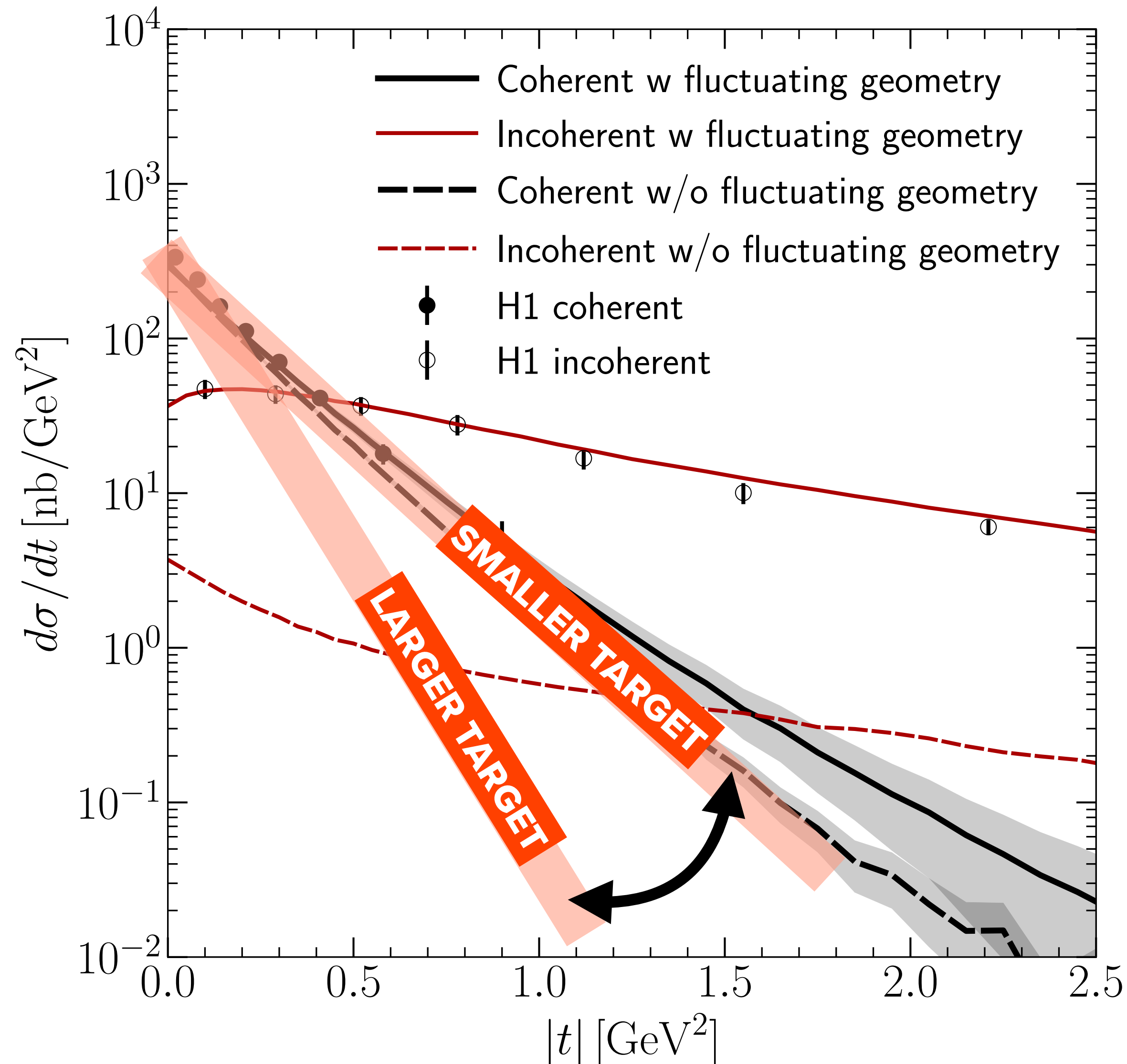
For certain parameter values, the conditions can be violated

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, arXiv:2409.17127](#)



PROTON RADIUS MEASUREMENT



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

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

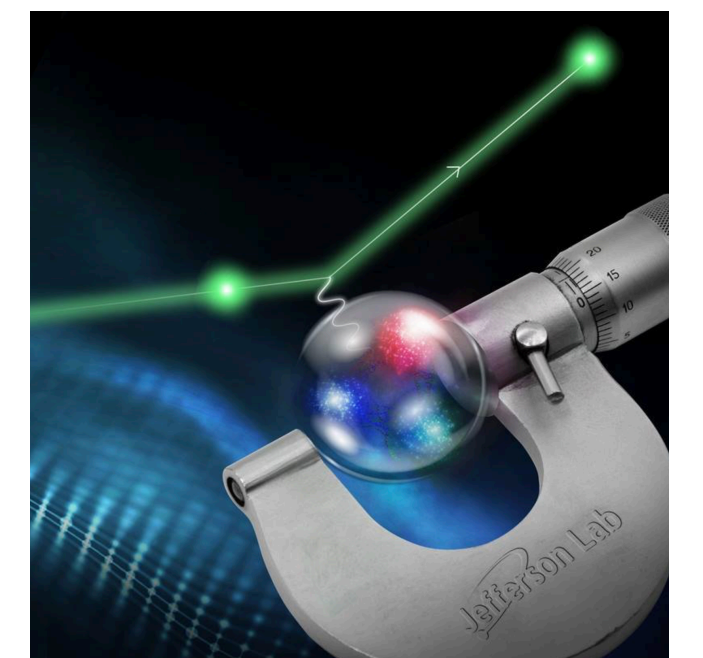
Extracted value for $r_p^g \approx 0.6$ fm

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



COLLISION KINEMATICS FOR $\gamma^* + \text{Pb}$

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

- Energy of the incoming quasi-real photon fluctuates event by event:

$$\frac{dN^\gamma}{dk_\gamma} = \frac{2Z^2\alpha}{\pi k_\gamma} \left[w_R^{AA} K_0(w_R^{AA}) K_1(w_R^{AA}) - \frac{(w_R^{AA})^2}{2} (K_1^2(w_R^{AA}) - K_0^2(w_R^{AA})) \right]$$

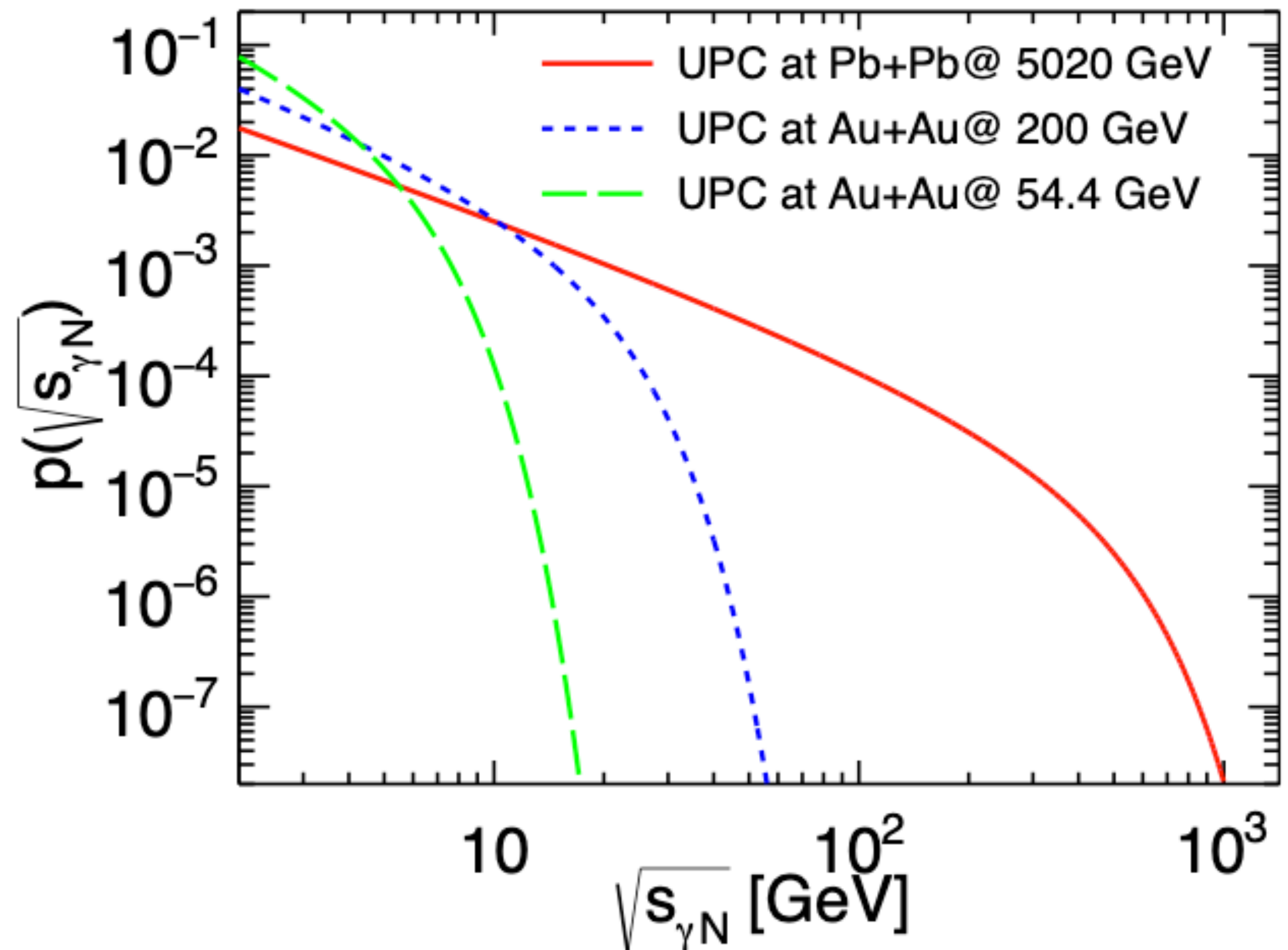
$$w_R^{AA} = 2k_\gamma R_A / \gamma_L \quad \text{with} \quad \gamma_L = \sqrt{s_{NN}} / (2m_N)$$

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

$$\sqrt{s_{\gamma N}} = (2k_\gamma \sqrt{s_{NN}})^{1/2}$$

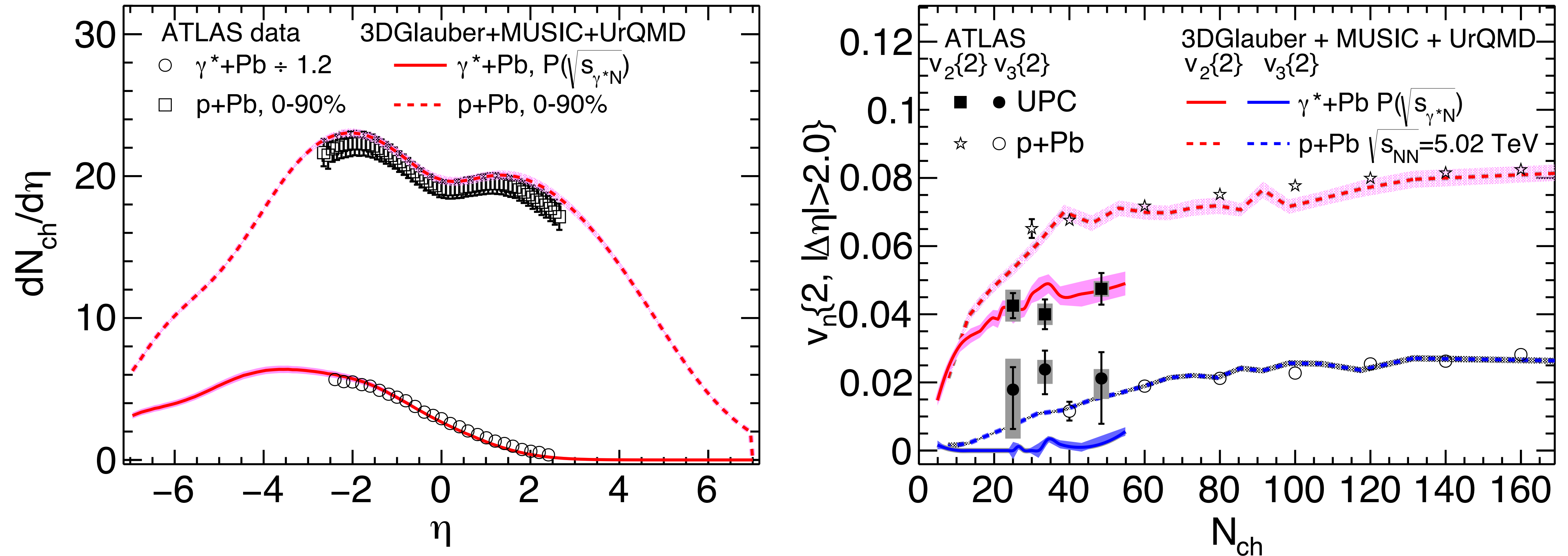
- Center of mass rapidity of $\gamma^* + A$ collision fluctuates in the lab frame

$$\Delta y = y_{\text{beam}}(\sqrt{s_{\gamma N}}) - y_{\text{beam}}(\sqrt{s_{NN}})$$



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

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

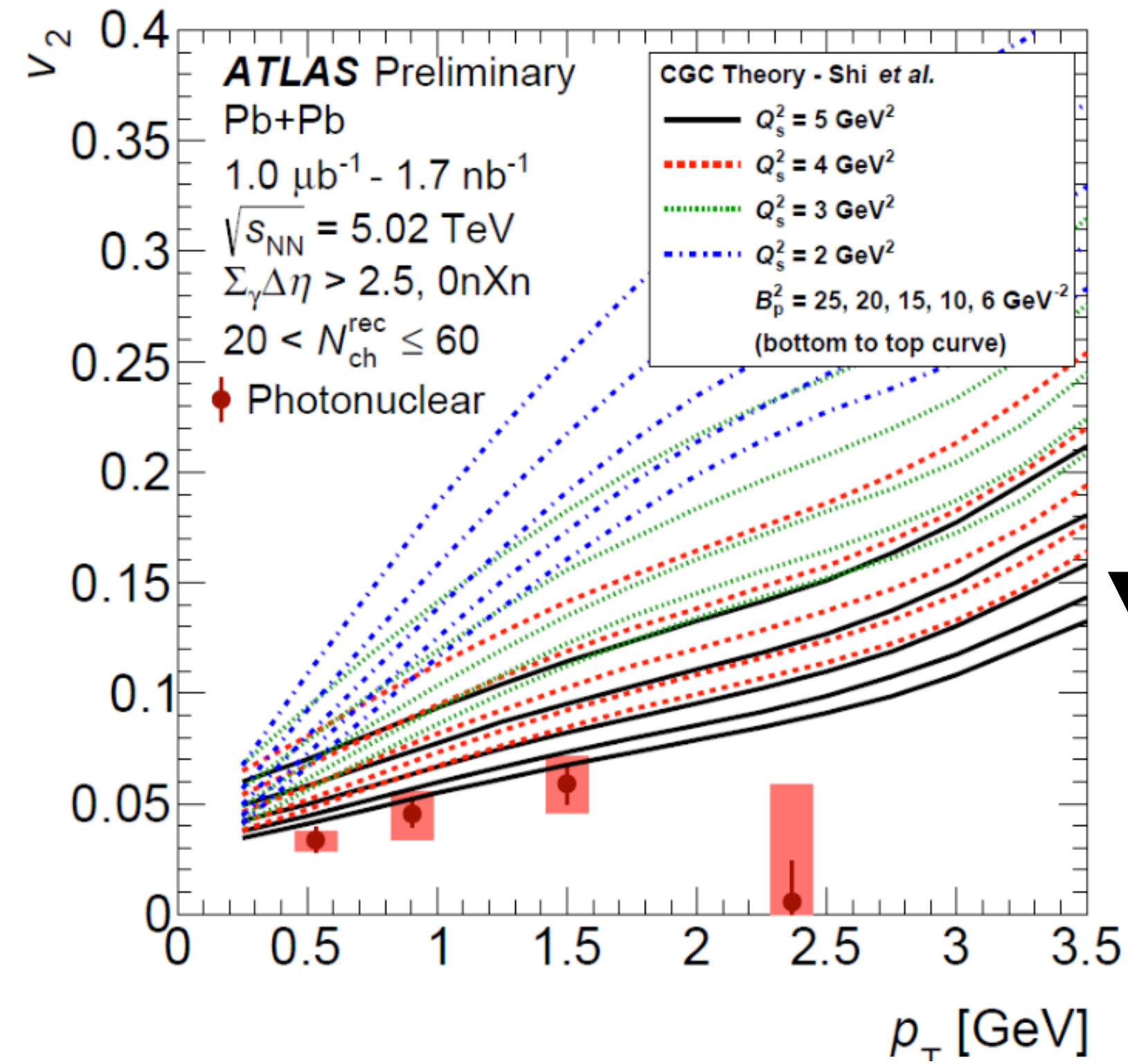
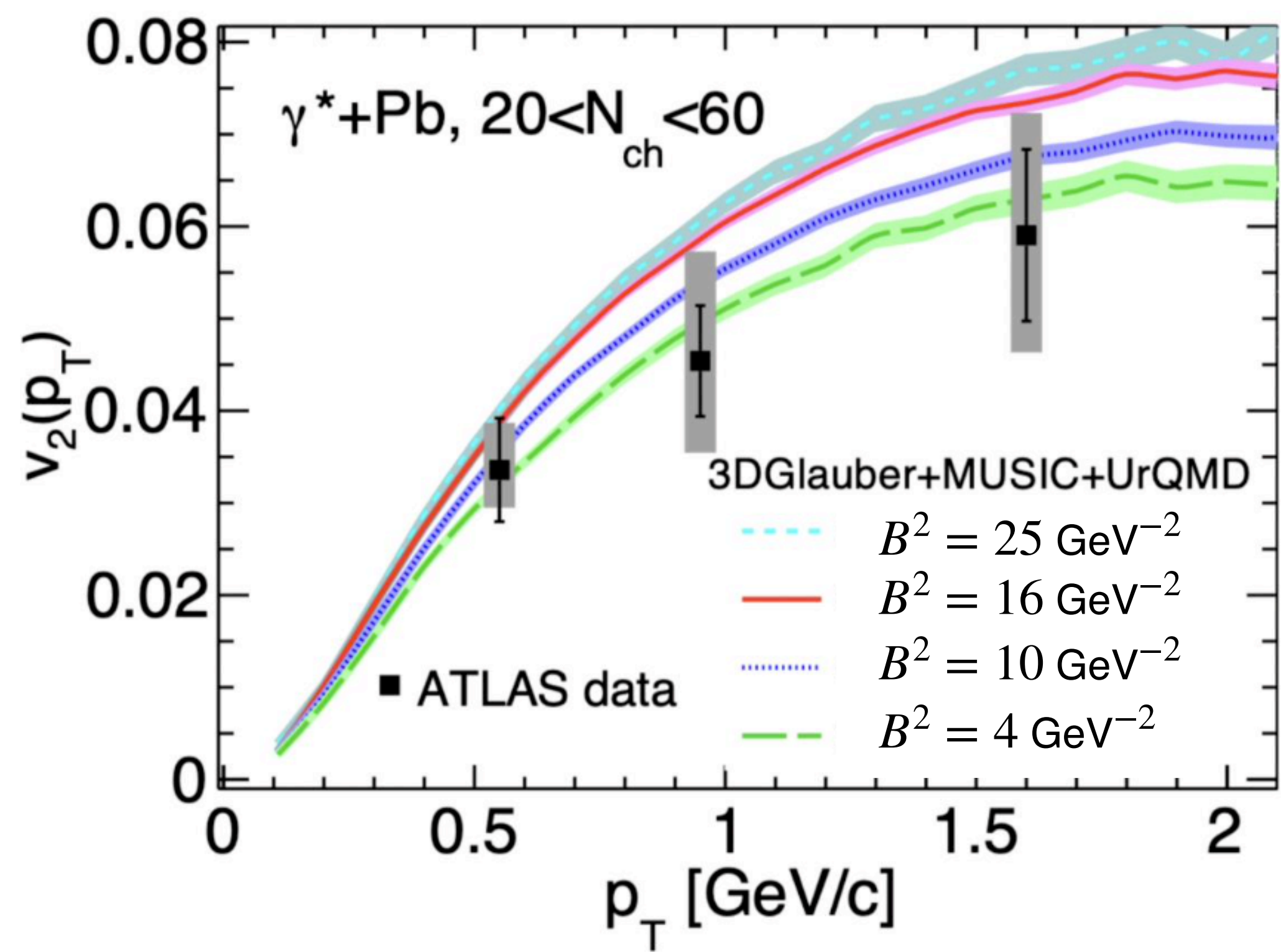


- Shapes of $dN_{ch}/d\eta$ reproduced for p+Pb and γ^*+Pb collisions
- Elliptic flow difference between p+Pb and γ^*+Pb collisions reproduced - driven by different amount of longitudinal flow decorrelation

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 $v_2 \propto 1/B^2$