U.S. DEPARTMENT OF ENERGY | Office of Science

Brookhaven™ National Laboratory

# COLLECTIVITY IN p+A COLLISIONS

**BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY**

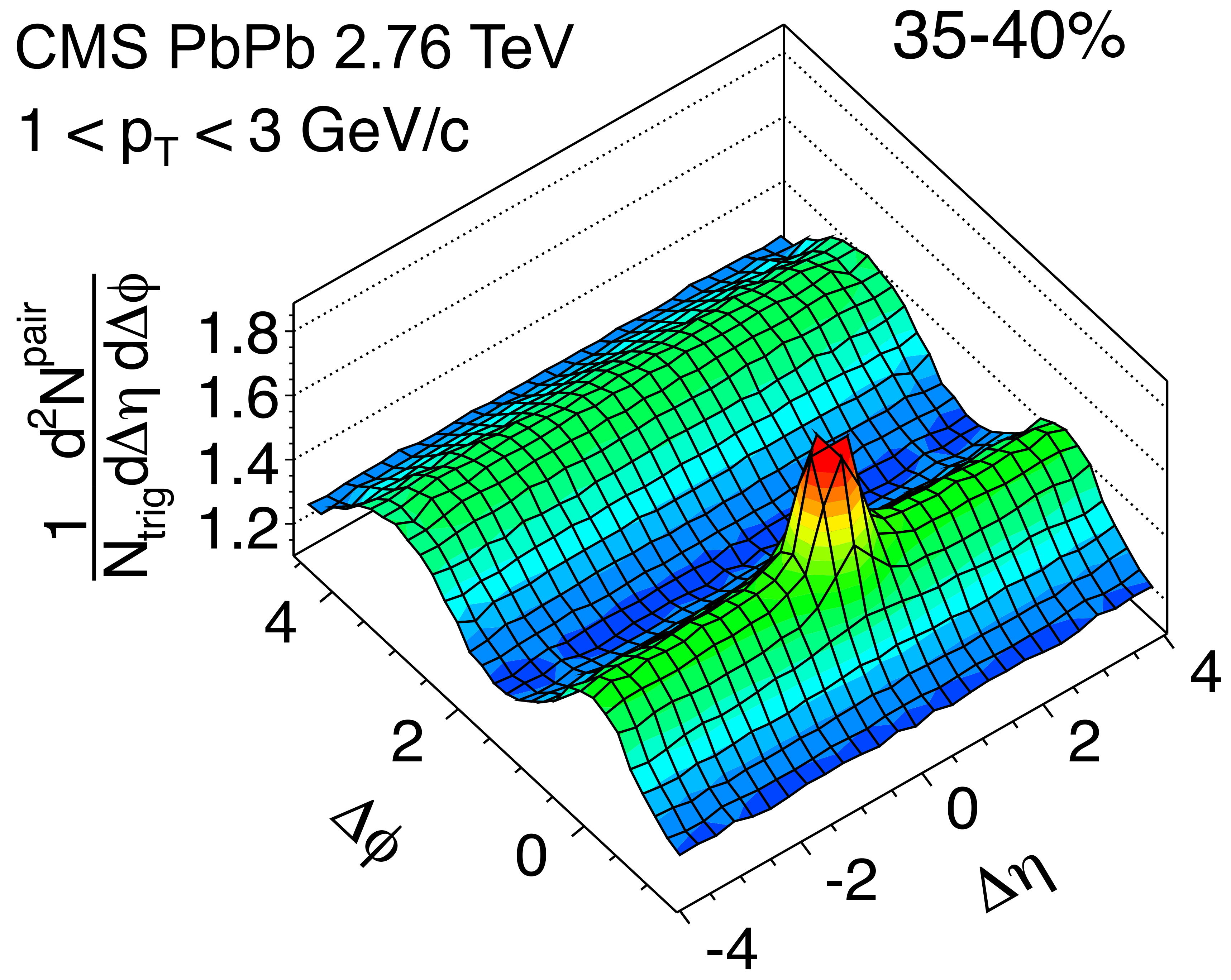
**JULY 5 2024**

**PHYSICS WITH HIGH-LUMINOSITY PROTON-NUCLEUS COLLISIONS AT THE LHC**
**CERN**

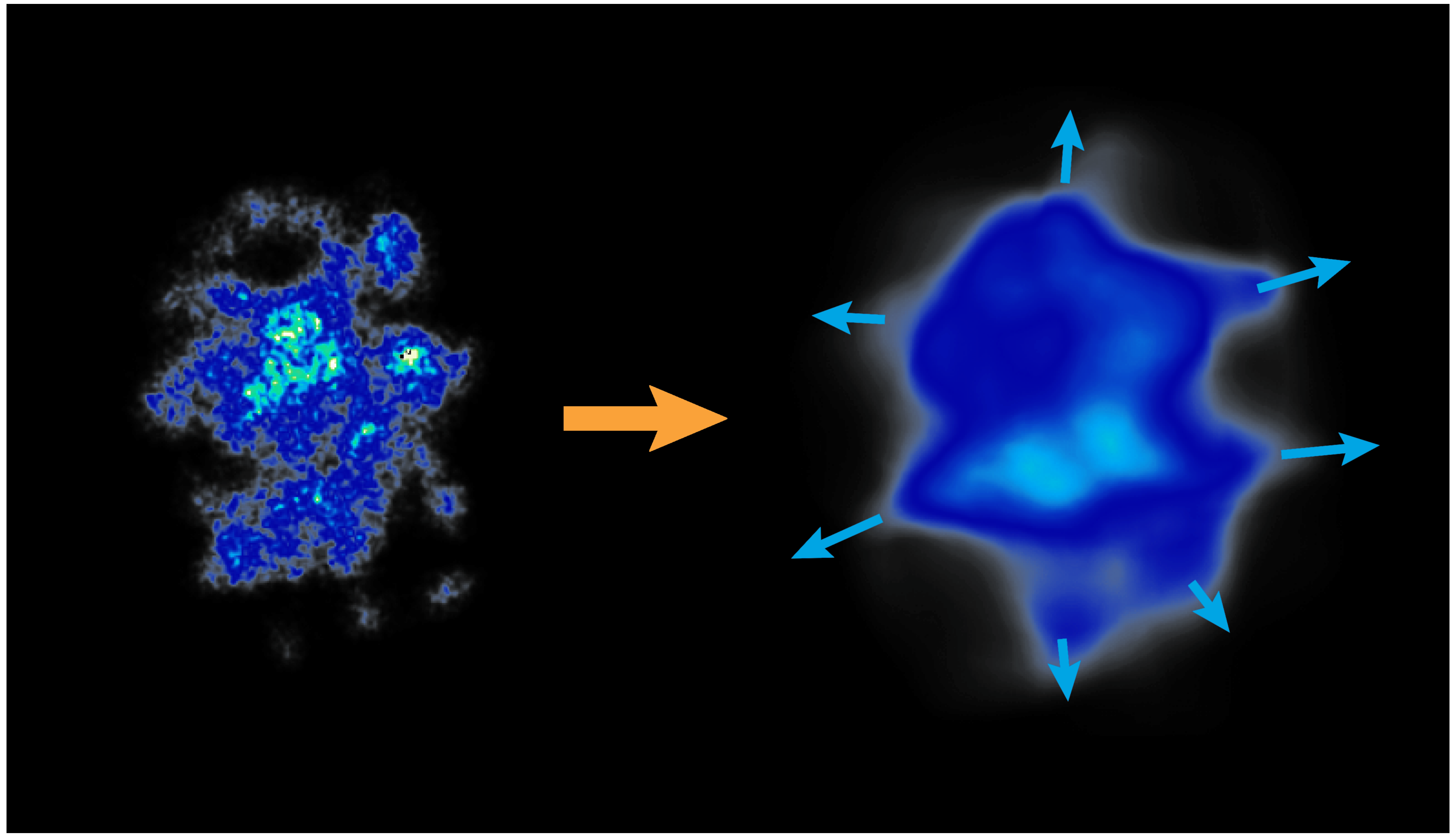
# COLLECTIVITY IN NUCLEAR COLLISIONS

- **Azimuthal anisotropies in particle spectra, long-range correlated in rapidity, indicate strong final state effects that convert initial geometry**

2-particle correlation vs. Δη and Δϕ:



CMS COLL., EUR. PHYS. J. C72 (2012)



Initial energy density distribution

Hydrodynamic expansion

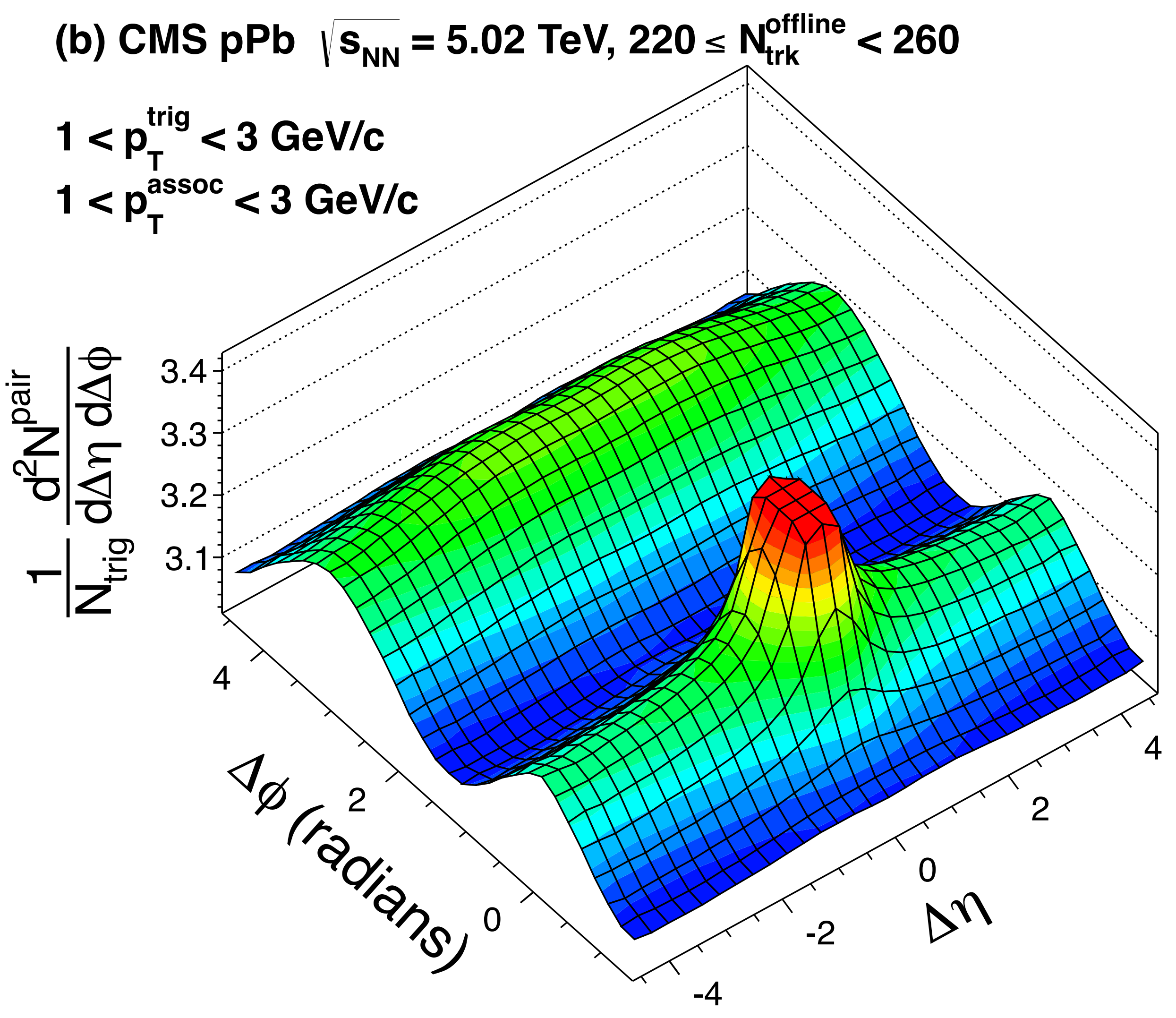
# HISTORY OF p+A AT LHC

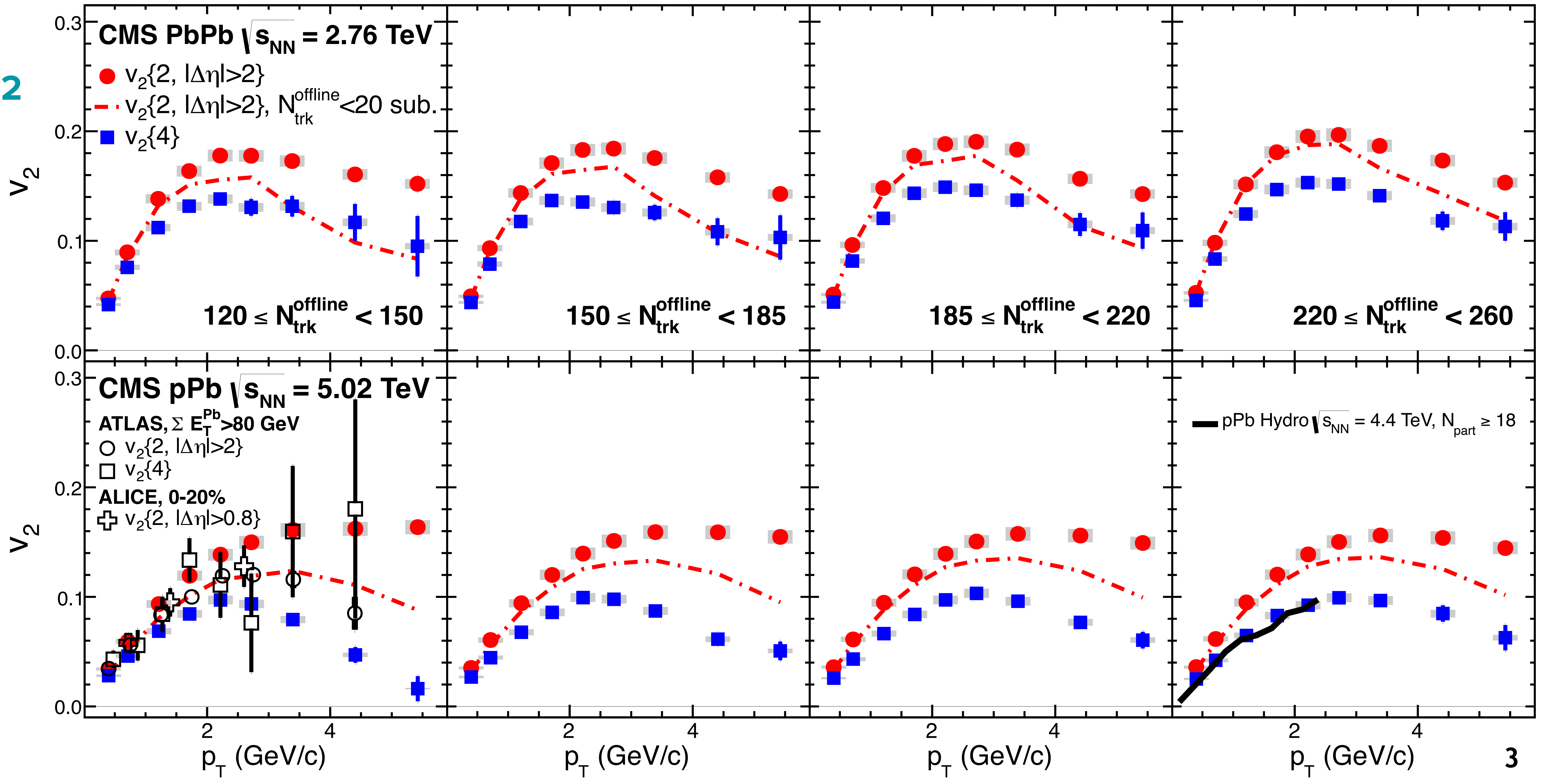
- First p+Pb collisions at LHC: 2012, higher luminosity in 2013
- First collectivity measurement in p+Pb (after p+p in 2010):

Long-range angular correlations on the near and away side in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
ALICE Collaboration, Phys.Lett.B 719 (2013) 29-41 (926 citations)
Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC
CMS Collaboration, JHEP 09 (2010) 091 (1212 citations)

- Followed by:

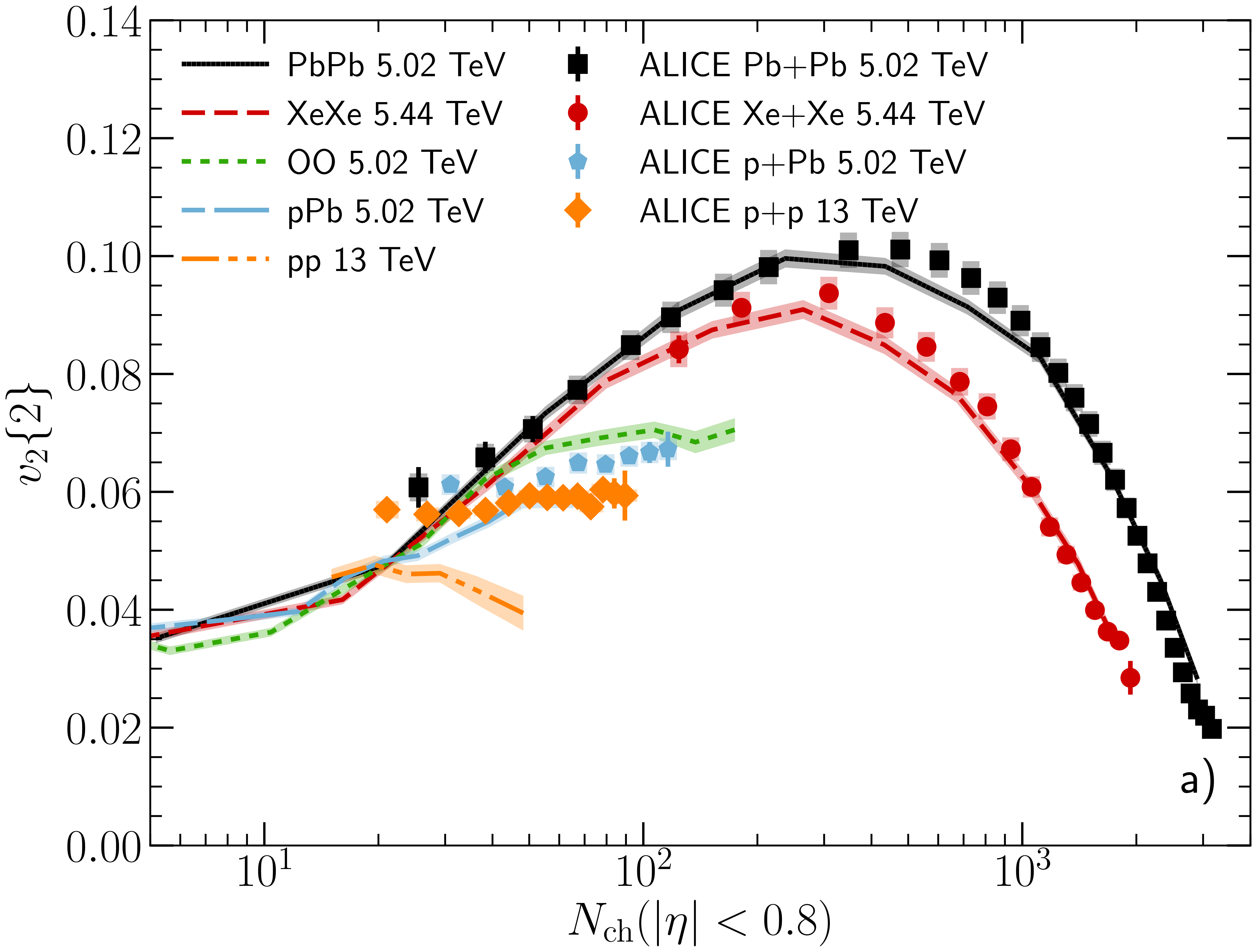
ATLAS Collaboration, Phys.Rev.Lett. 110 (2013) 18, 182302
ATLAS Collaboration, Phys.Lett.B 725 (2013) 60-78
CMS Collaboration, Phys.Lett.B 724 (2013) 213-240





# SUCCESS OF HYDRODYNAMICS

B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 4, 044905

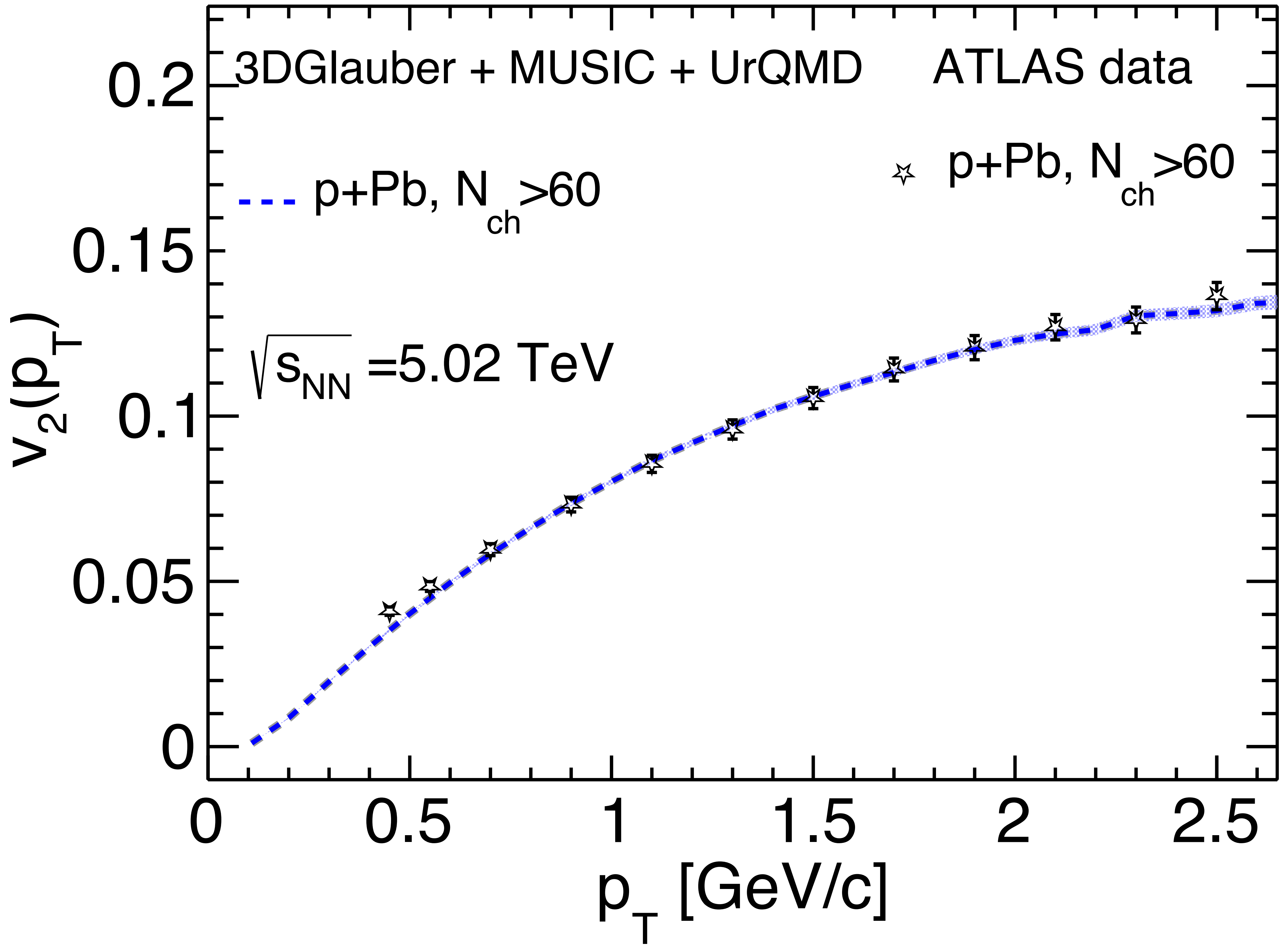


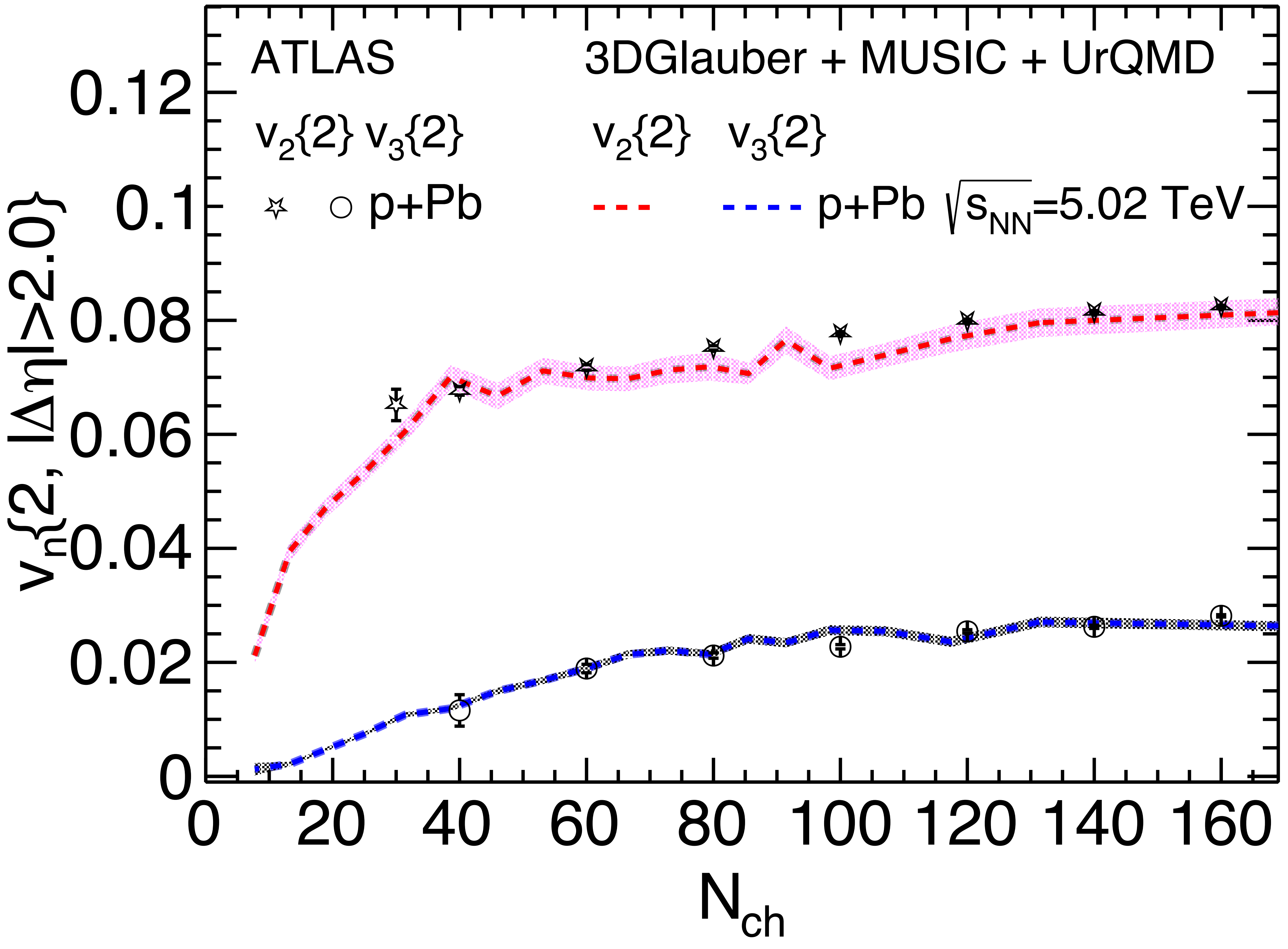
ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301

- Hydrodynamic models can describe wide range of data
- No good agreement in p+p
- But success in p+Pb had big impact

# HYDRODYNAMICS DESCRIBES p+A

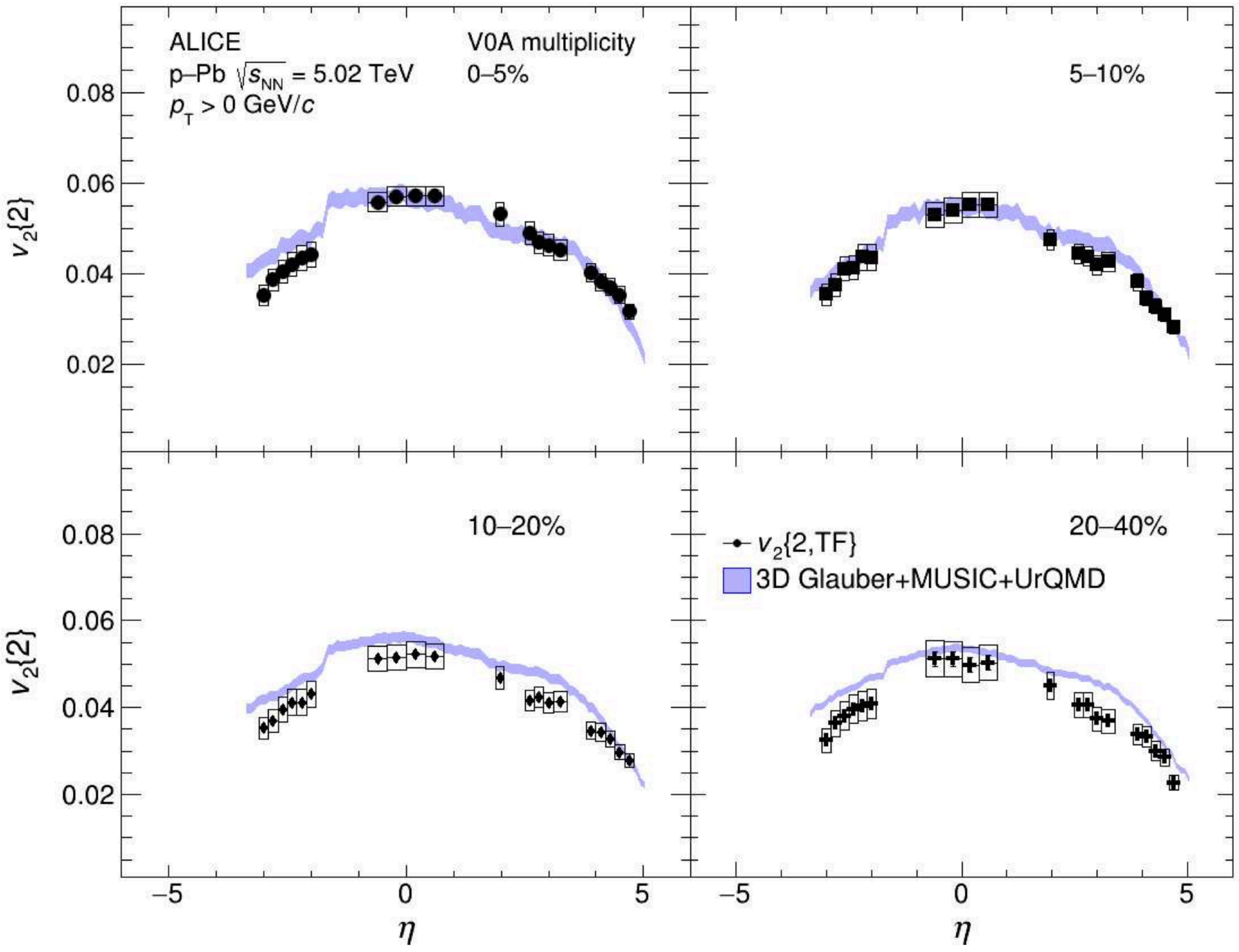
- 3+1D hydrodynamic models can describe p+Pb data very well





W. Zhao, C. Shen, and B. Schenke, Phys. Rev. Lett. 129 (2022) 252302
ATLAS Collaboration, Phys. Rev. C 96 (2017) 024908

# ELLIPTIC FLOW VS. RAPIDITY



- Elliptic flow vs. pseudo-rapidity in p+Pb within 3+1D viscous fluid dynamics
- Using 3D-MC-Glauber initial state model

ALICE Collaboration, JHEP 01 (2024) 199
W. Zhao, C. Shen, and B. Schenke
Phys. Rev. Lett. 129 (2022) 252302

# BIG IMPACT OF p+A PROGRAM (COLLECTIVITY)

- Triggered an intense program, both theoretical and experimental, to understand the origins of the long-range correlations
- Interpretation: Strong final state effects as in A+A collisions, or initial state correlations emerging from color correlations in the gluon fields of incoming nuclei
- Success of hydrodynamic models in describing p+A data triggered fundamental research into applicability of hydrodynamics

  **New theories of relativistic hydrodynamics in the LHC era**
  **Wojciech Florkowski, Michal P. Heller, Michal Spalinski, Rept.Prog.Phys. 81 (2018) 4, 046001**

- Motivated “small system scan” at RHIC: p+Au, d+Au, $^3$He+Au

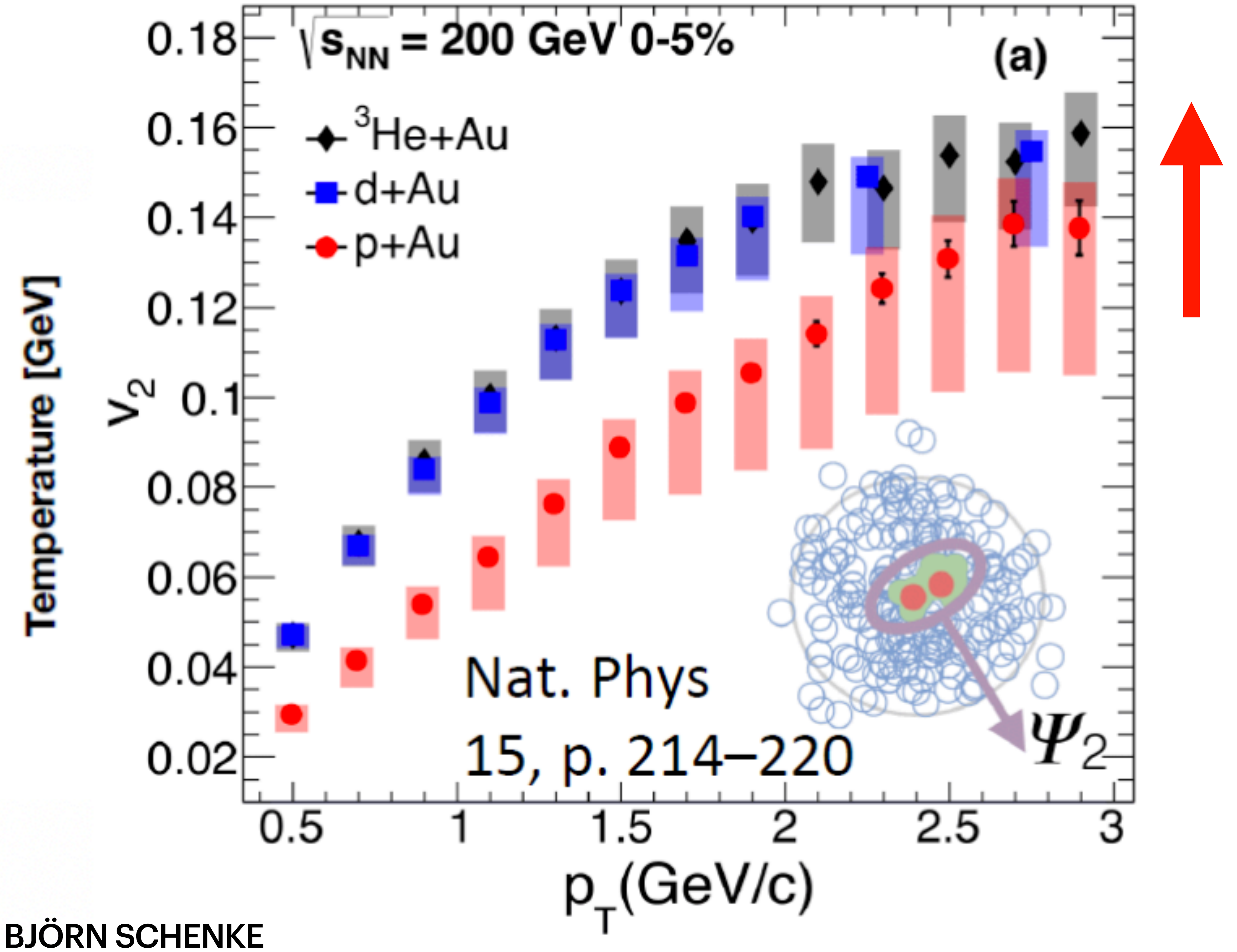
  **PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)**

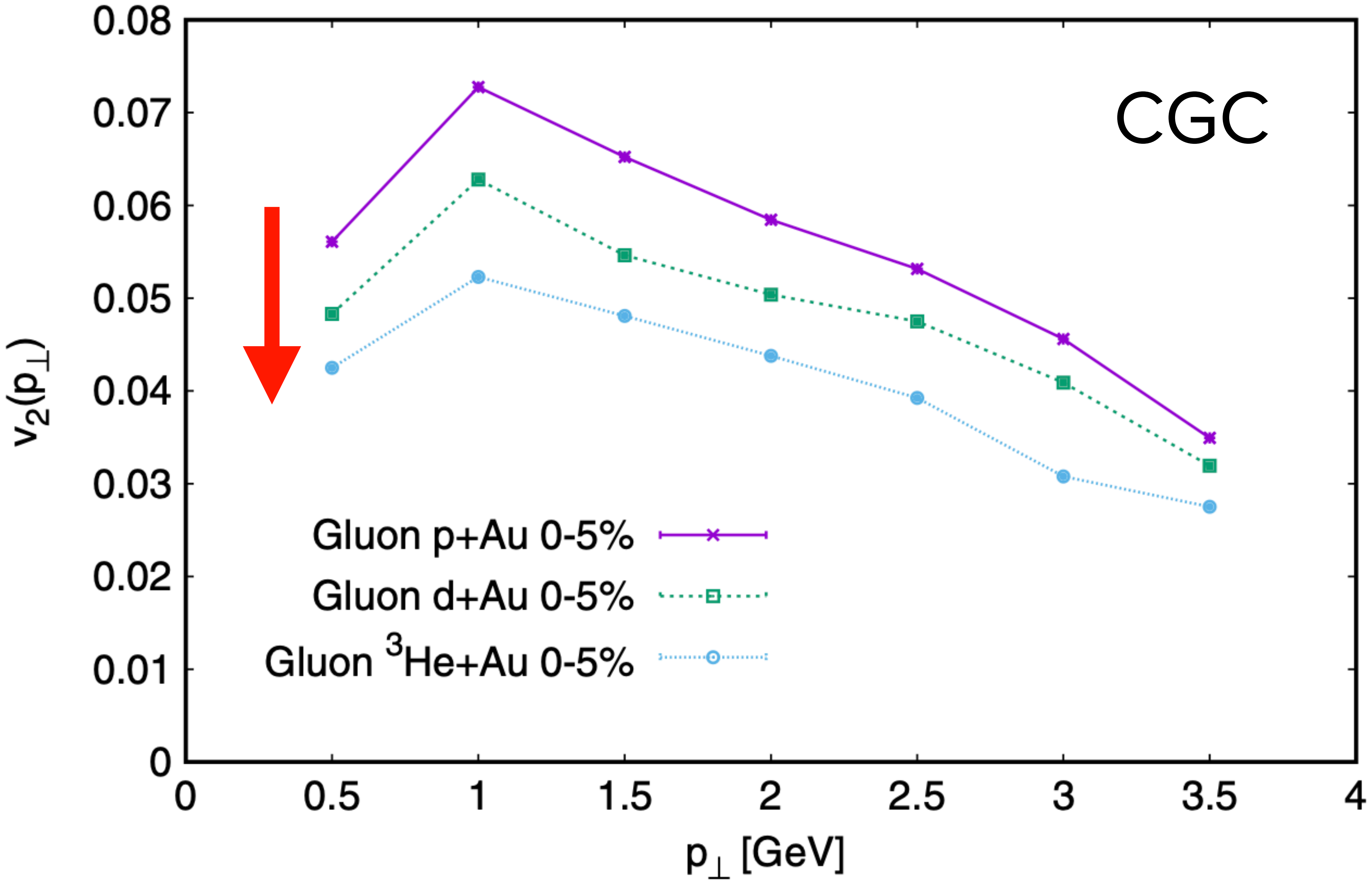
- Triggered developments of non-equilibrium transport, hybrid models, …

# 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 color charge correlations in the Color Glass Condensate: Cannot get all systematics right:





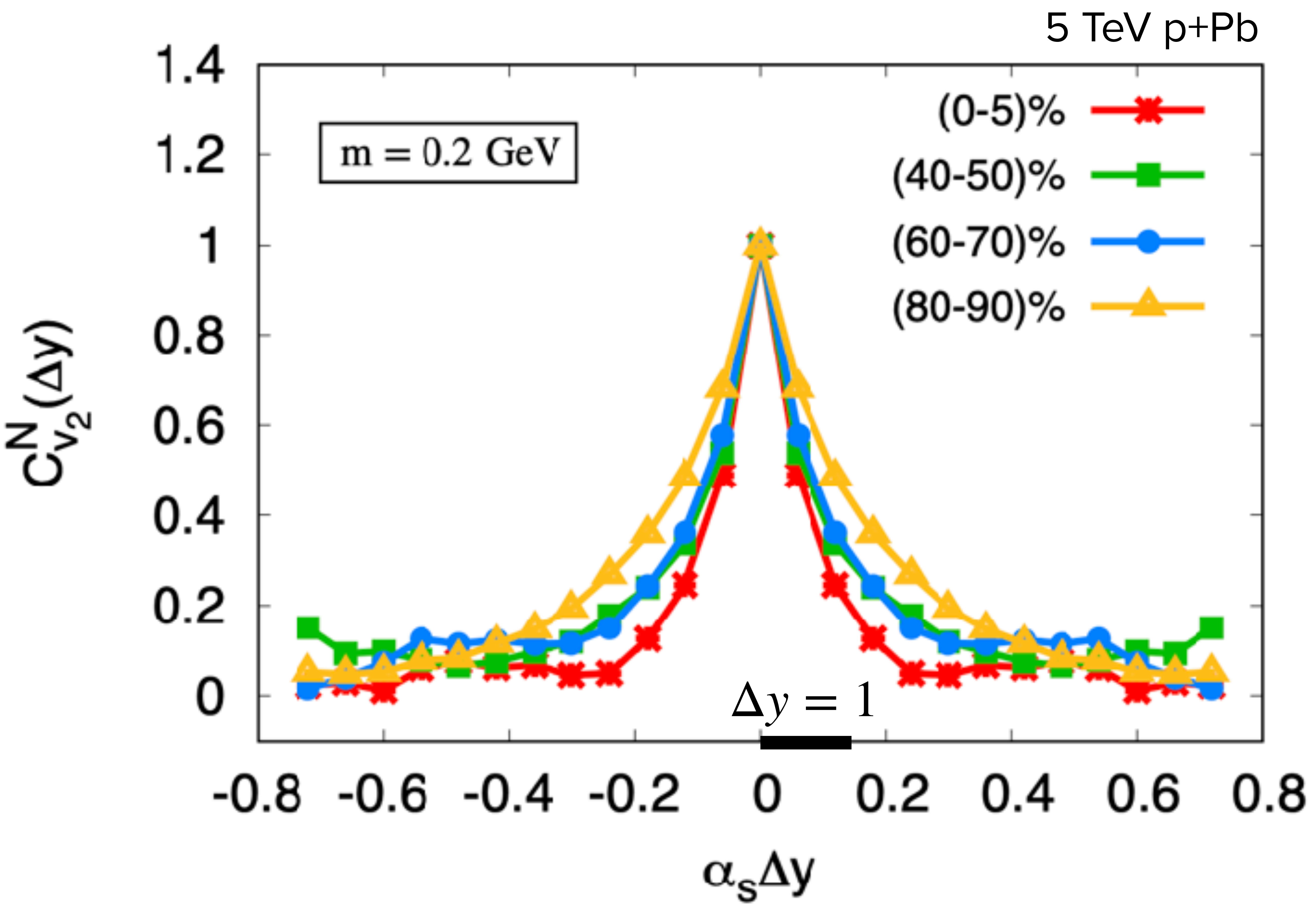
# RAPIDITY DEPENDENCE OF INITIAL ANISOTROPY

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

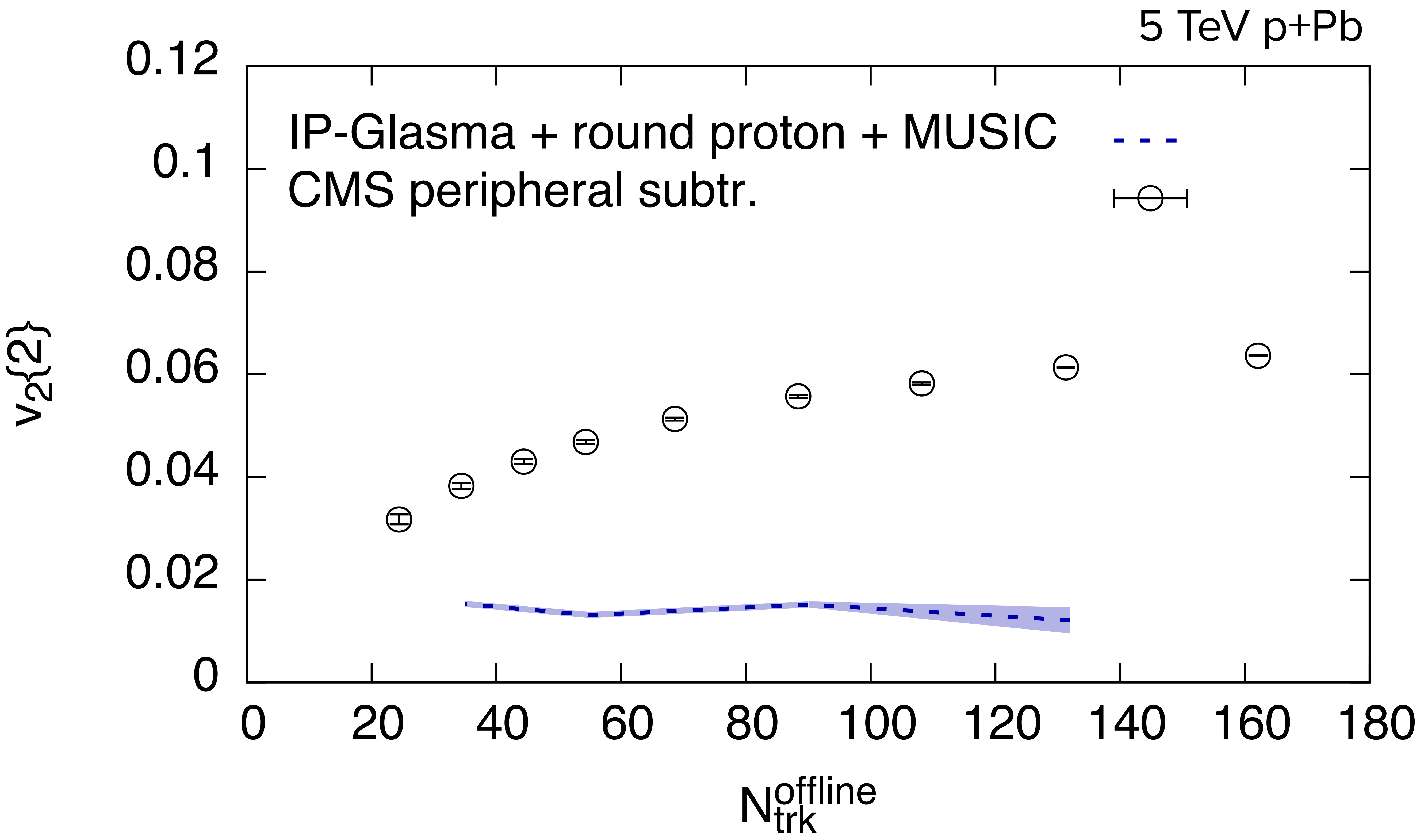


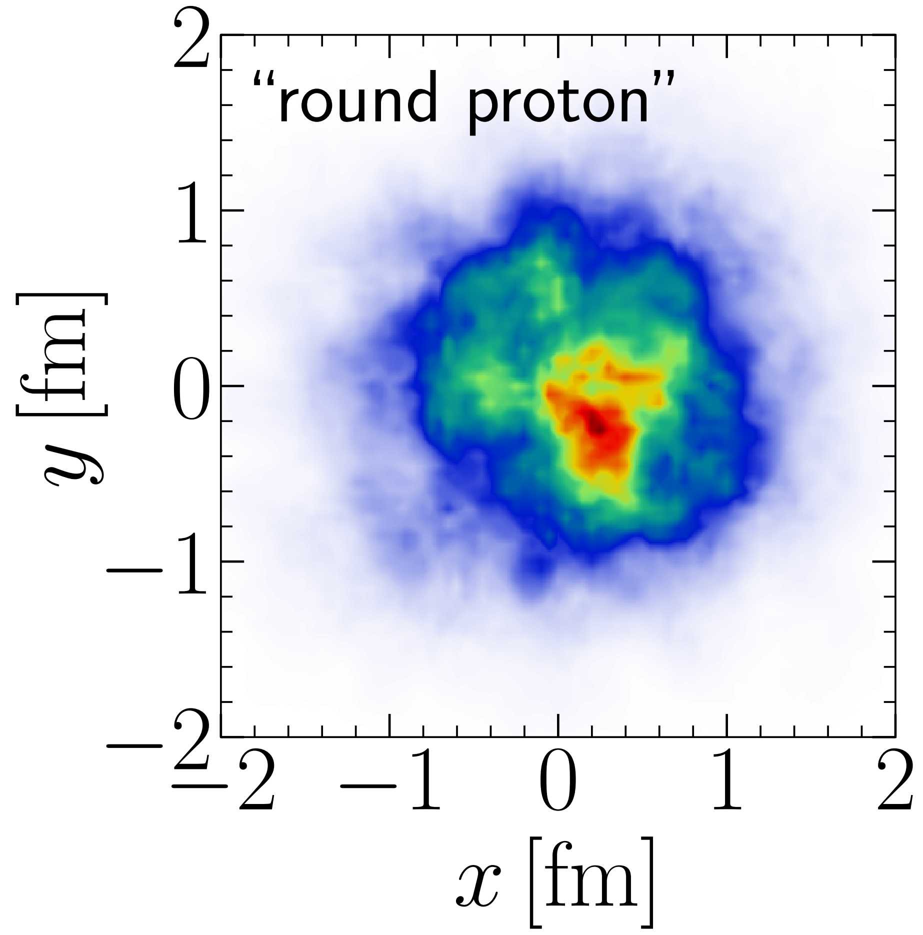
→ Strong final state interactions needed to describe data

# PROTON SUBSTRUCTURE

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)

Describing the data using hydrodynamic models prefers a proton with substructure:





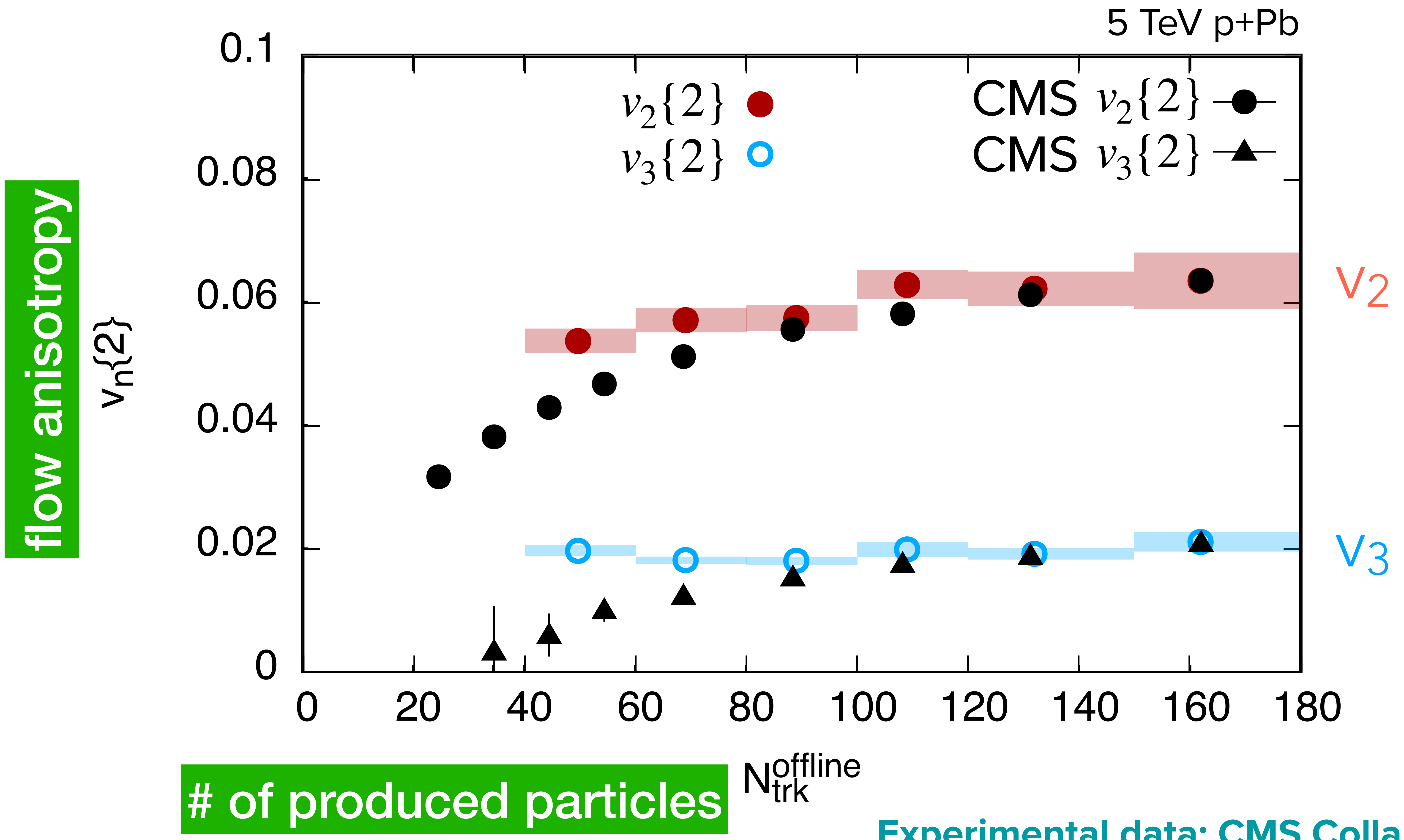
Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

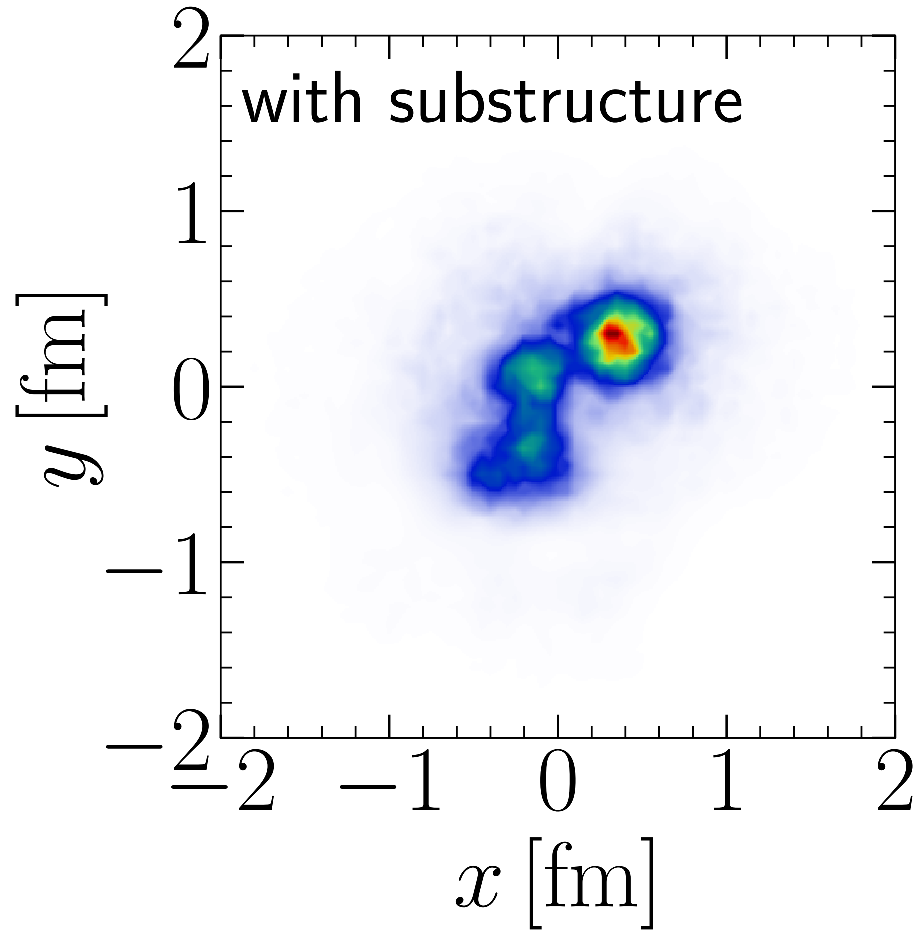
Proton without substructure + IP-Glasma initial state: Fails to describe the data

# PROTON SUBSTRUCTURE

**H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)**

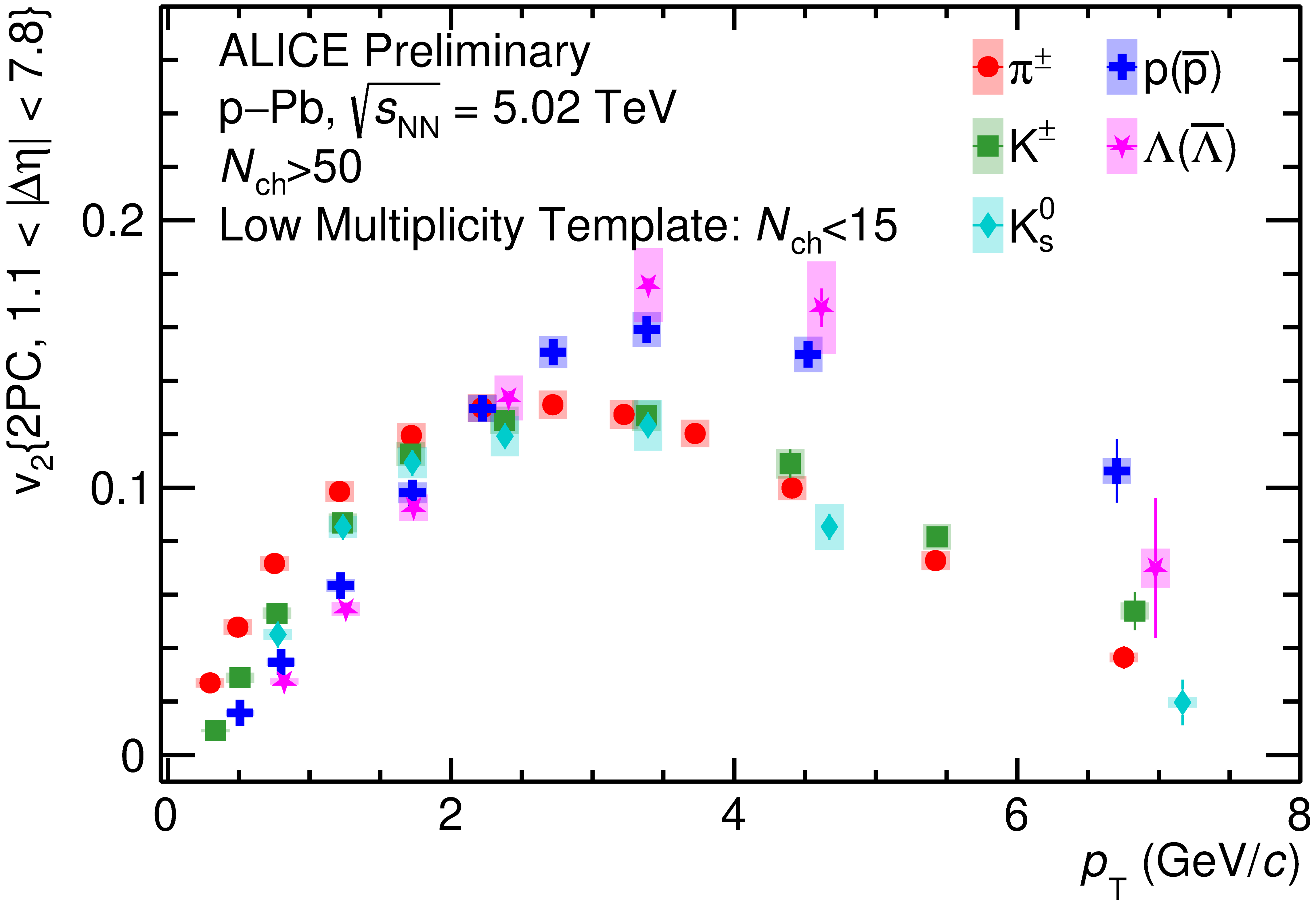
Use a fluctuating proton shape constrained by HERA incoherent diffraction data:





**Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)**

# PARTONIC ORIGIN OF FLOW



ALI-PREL-573065

ALICE Collaboration, Y. Zhou at SQM24

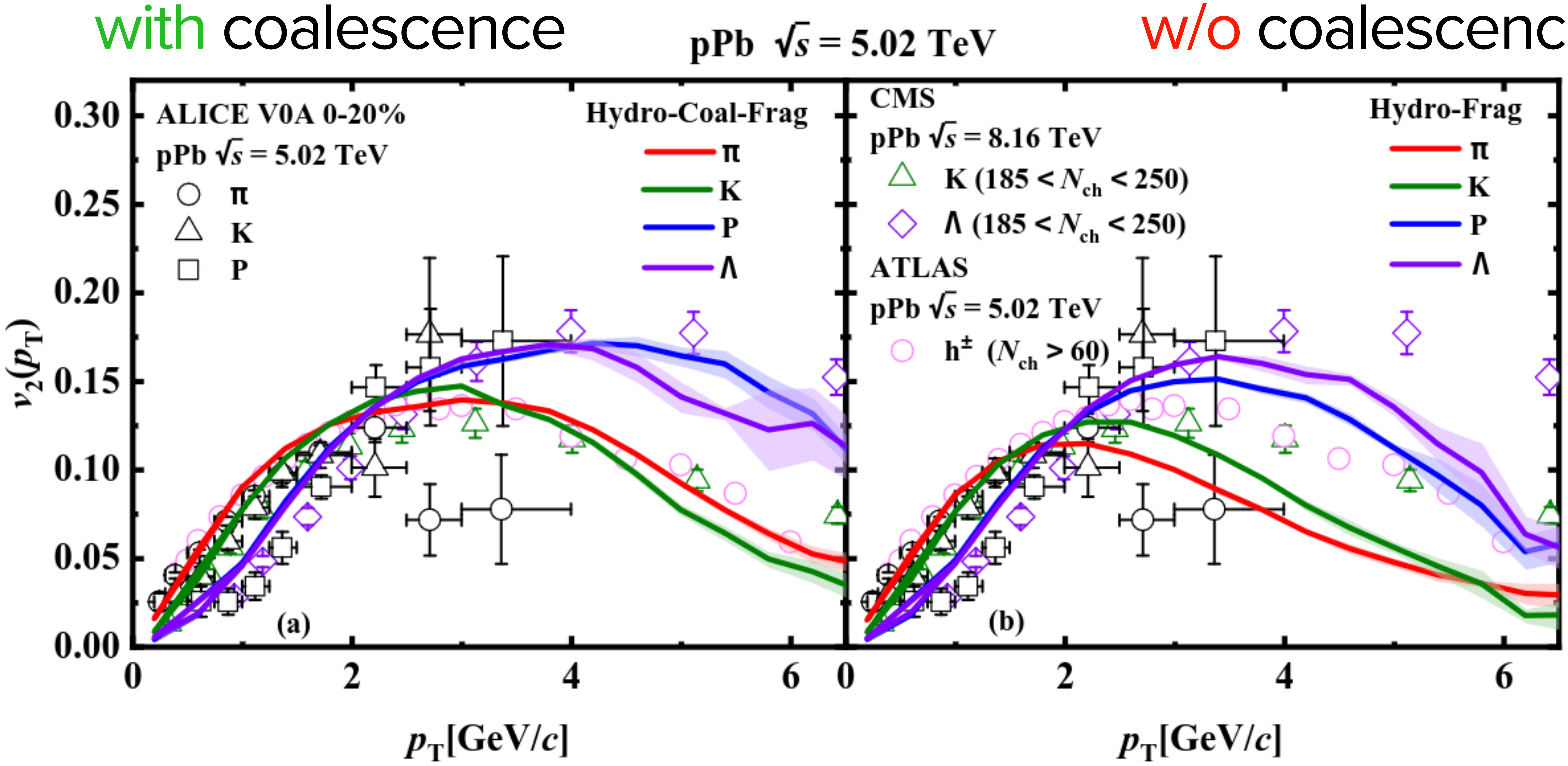
- $p_T < 3$ GeV/c - Mass ordering
- $3 < p_T < 6$ GeV/c:
  - Baryon-meson grouping ( $\sim 1\sigma$ confidence)
  - Splitting between baryons and mesons $v_2$ ( $\sim 5\sigma$ confidence)

# PARTONIC ORIGIN OF FLOW

Y. Wang , W. Zhao, H. Song, arXiv:2401.00913

with coalescence

w/o coalescence

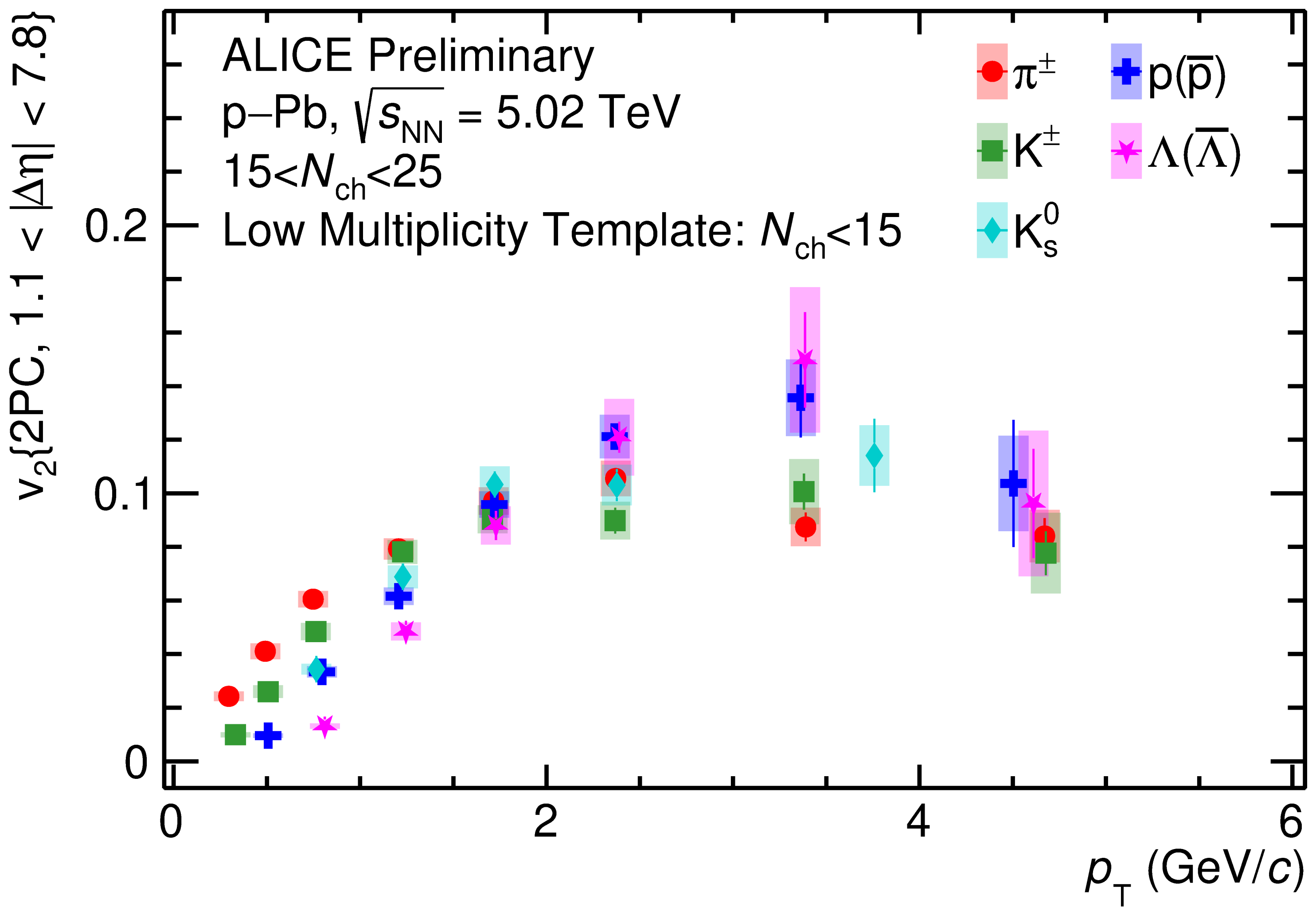


$3 < p_T < 6$ GeV:

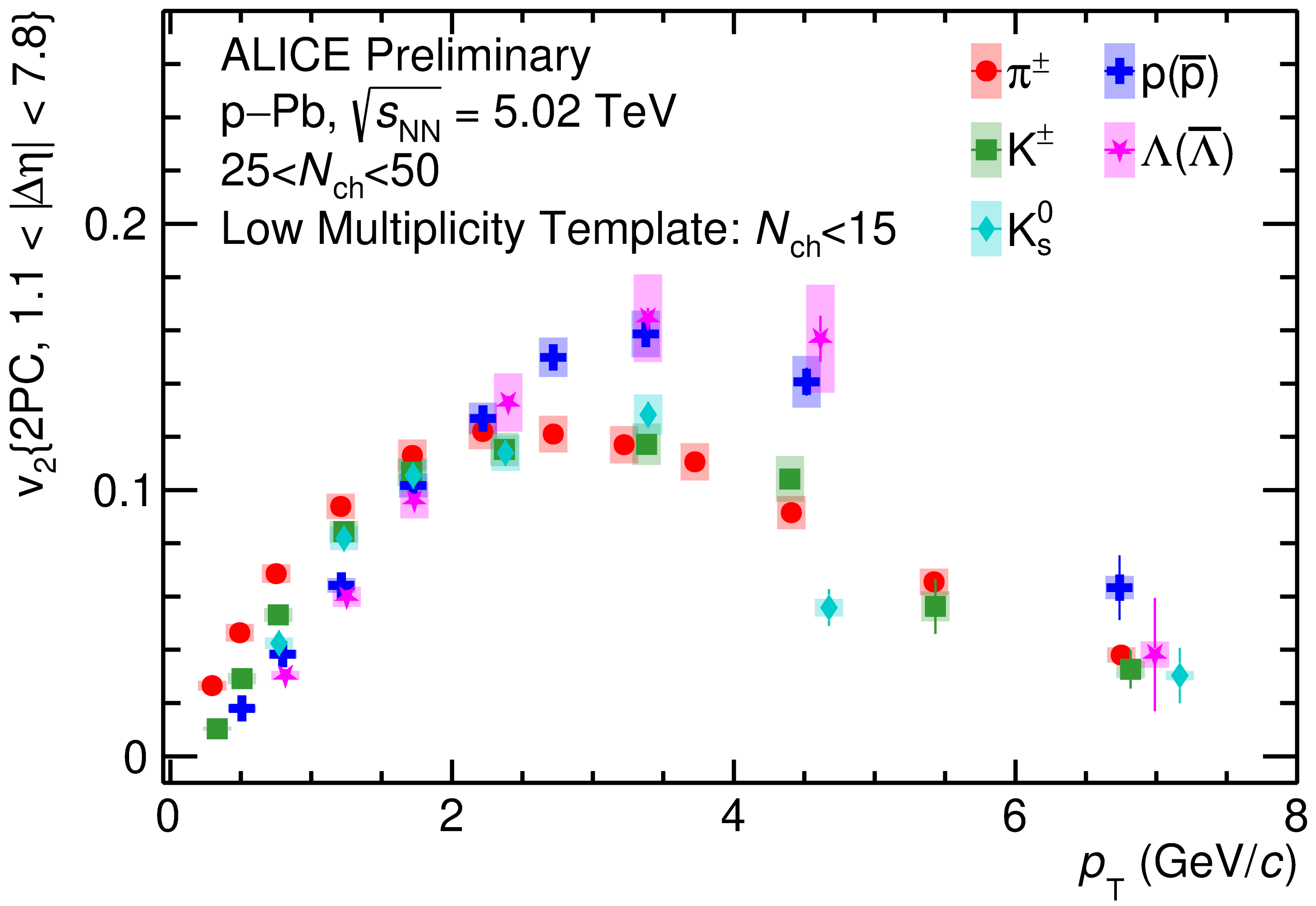
Model with quark-coalescence better reproduces $v_2$ at larger $p_T$ and baryon/meson grouping and splitting

# PARTONIC FLOW AT LOWER $N_{\mathrm{ch}}$

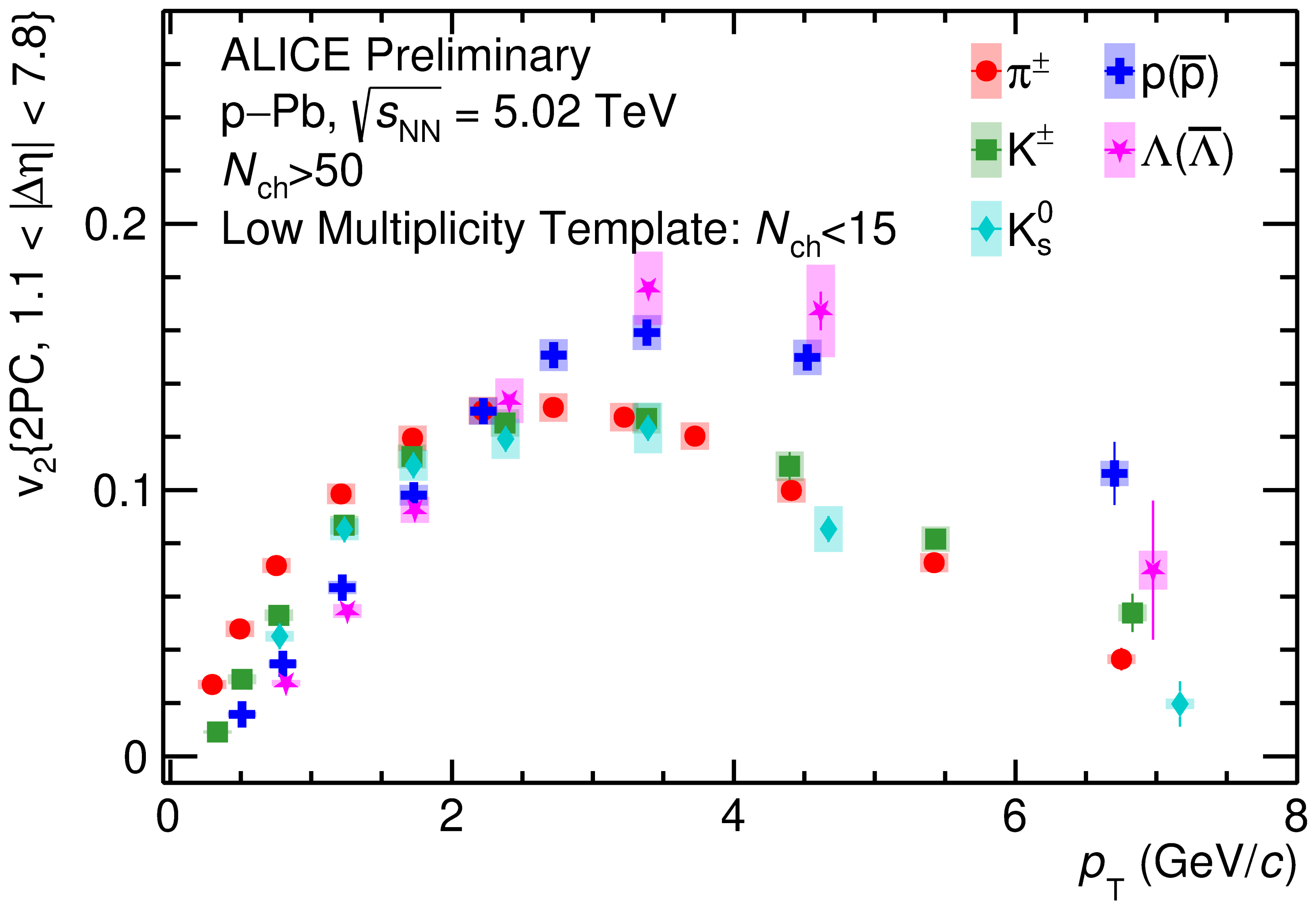
increasing $N_{\mathrm{ch}}$



ALI-PREL-573055



ALI-PREL-573060



ALI-PREL-573065

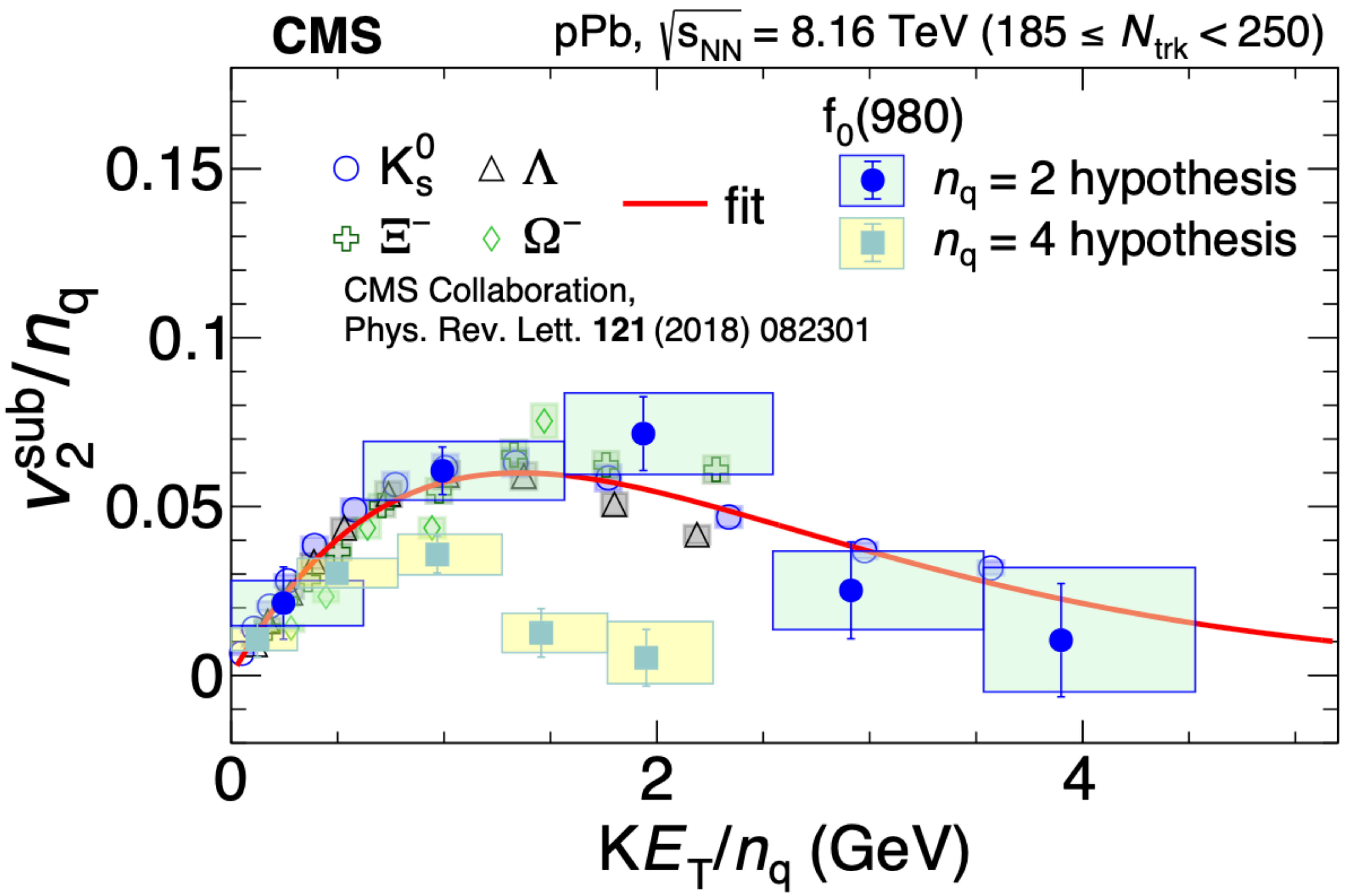
**ALICE Collaboration**

$N_{\mathrm{ch}} > 25$: Baryon-meson grouping and splitting of $v_2$ at intermediate $p_T$

$15 < N_{\mathrm{ch}} < 25$: grouping and splitting (within 2σ confidence), partonic flow picture not clear

Future: PID flow differential in $\eta$? Learn more about conserved charge transport

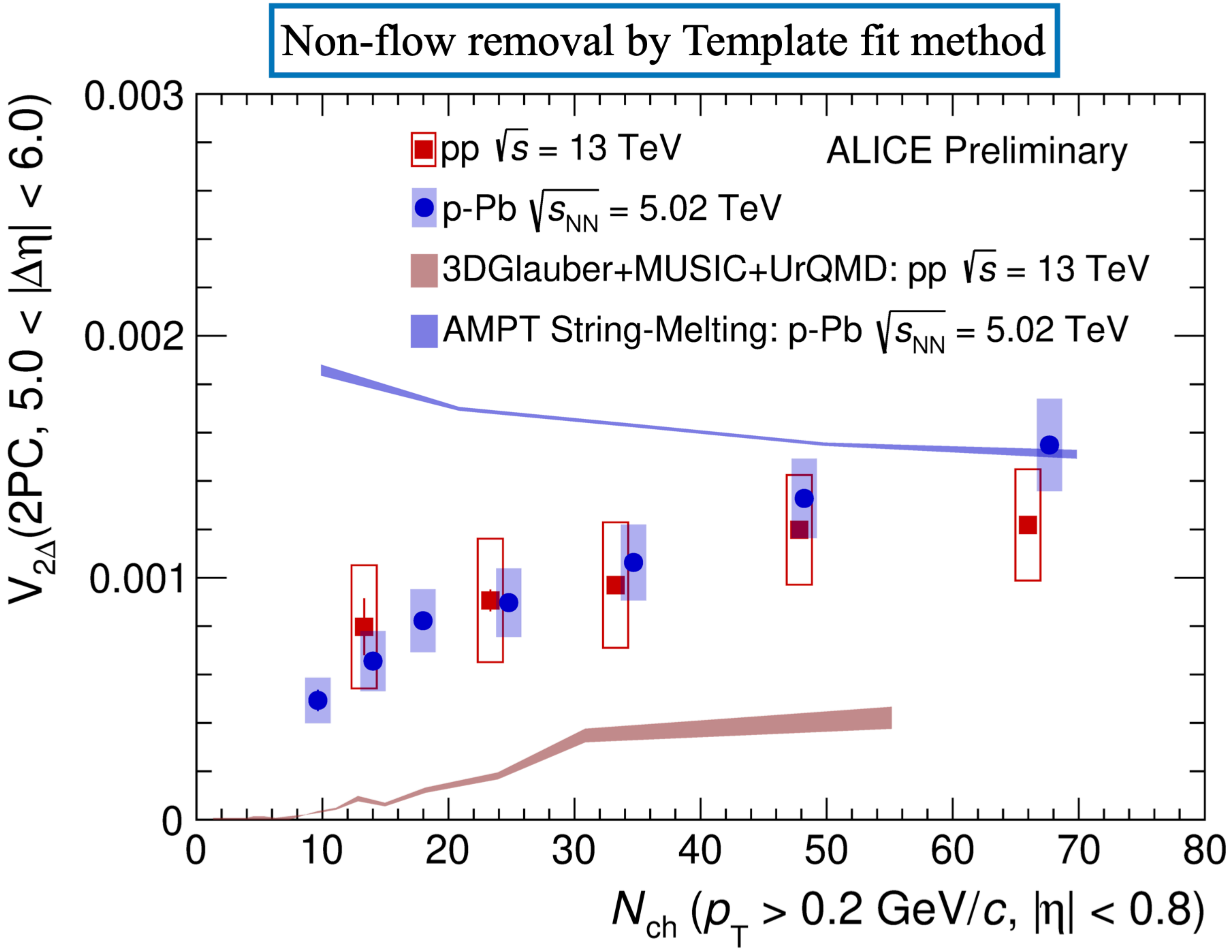
# QUARK CONTENT OF HADRONS



- **Inferring the quark content of $f_0(980)$ from its elliptic flow in p+Pb collisions**

**CMS Collaboration, arXiv:2312.17092**

# ULTRA-LONG RANGE CORRELATION

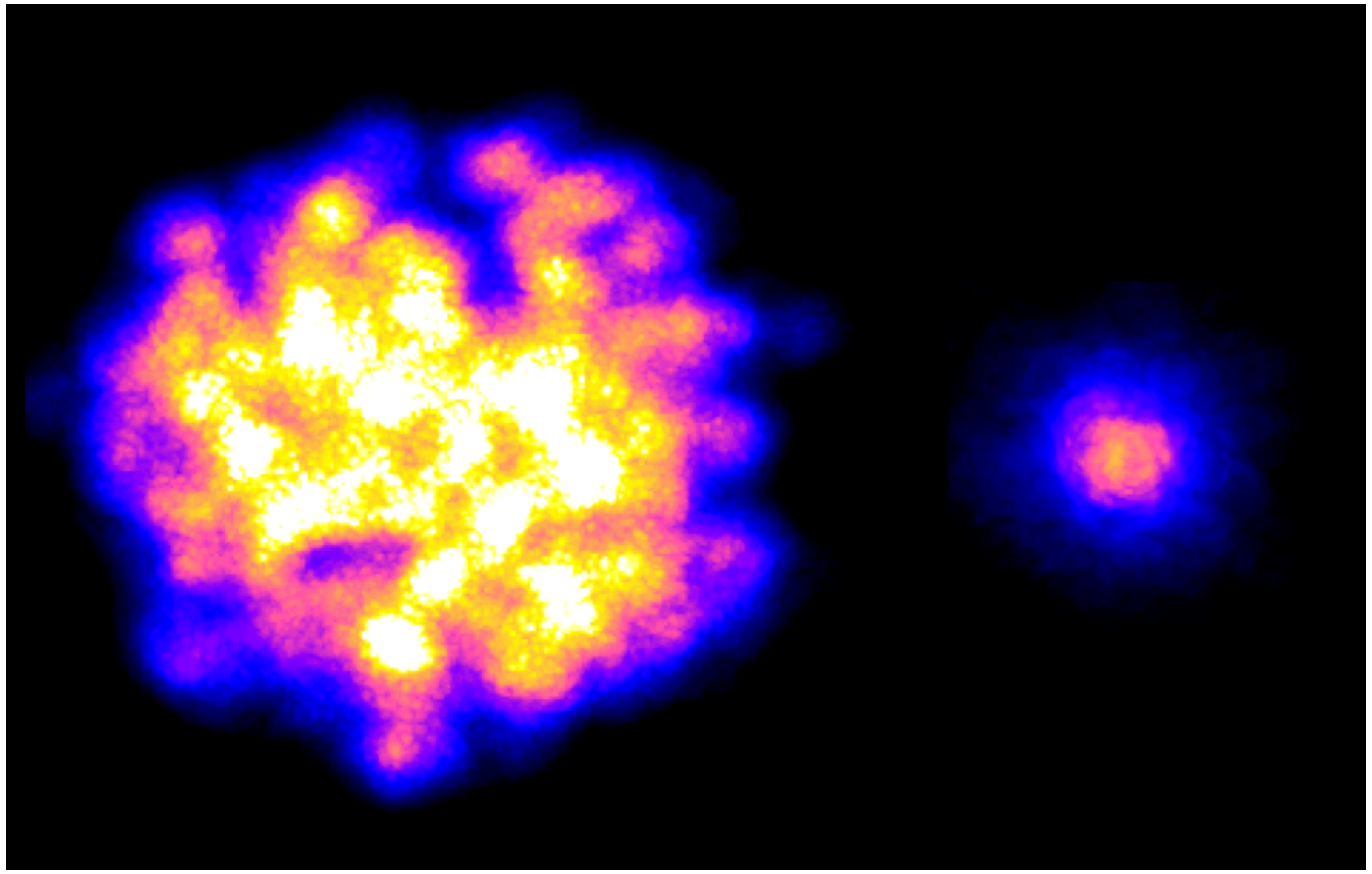


- p+p collisions at 13 TeV
- p+Pb collisions at 5.02 TeV
- $5 < |\Delta\eta| < 6$
- Models do not describe the data
- p+A can help constrain models of 3D geometry
- Applicability of hydrodynamics?

**ALICE Collaboration, ALI-PREL-573662**

# QUESTIONS ABOUT HYDRODYNAMICS

- Initial transverse volume in small systems $\sim 40 \times$ smaller than in central Pb+Pb
- Locally large Knudsen (macroscopic scale / microscopic scale) and inverse Reynolds numbers (ratio of viscous forces to inertial forces)
- How can hydrodynamics work so well to describe p+A collisions?



**central Pb+Pb** **p+Pb**

# HYDRODYNAMIC THEORY

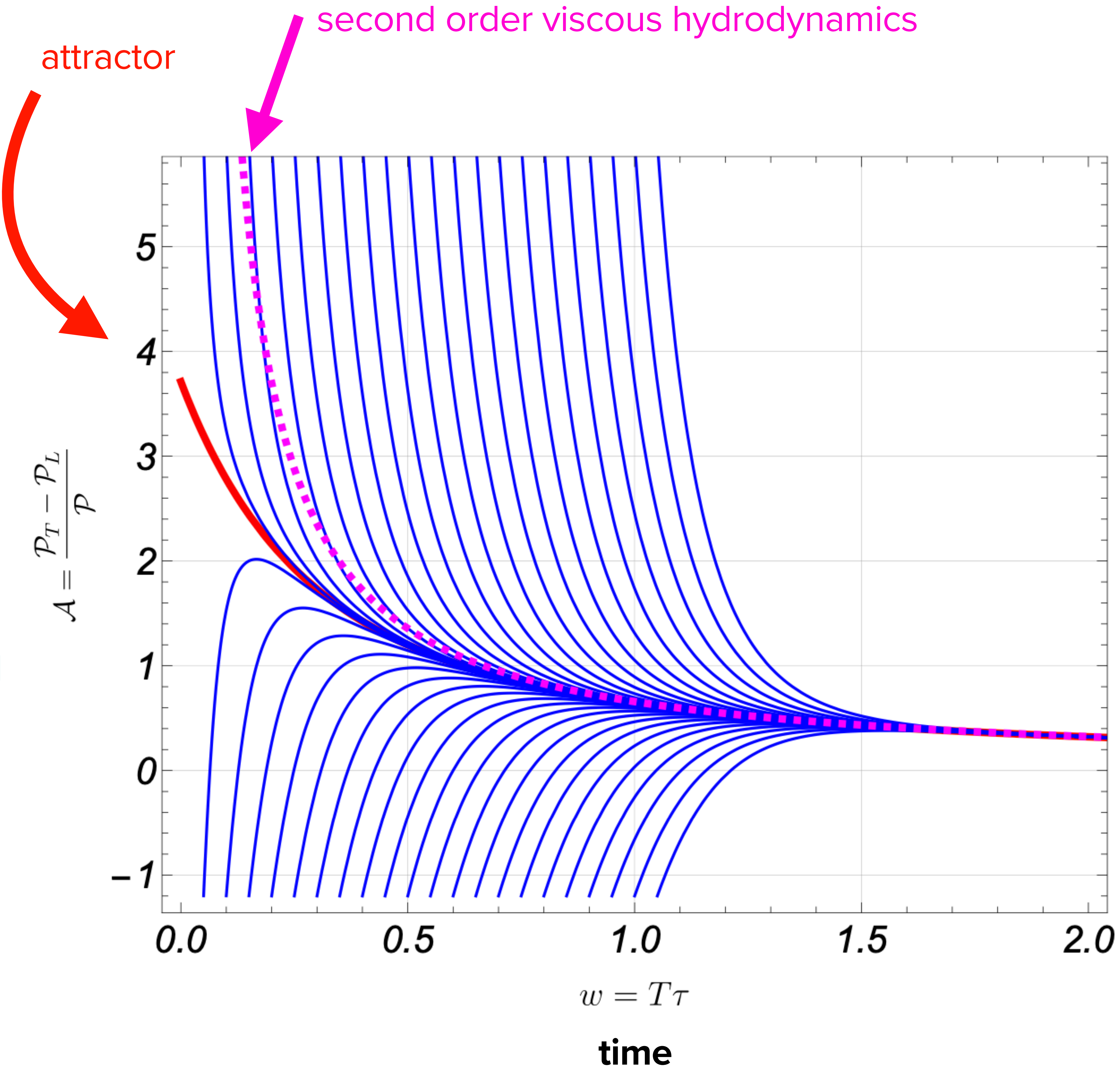
- Results from p+A collisions triggered fundamental research into foundations of hydrodynamics and its applicability beyond the regime of small Knudsen number

**M. P. Heller and M. Spalinski, Phys. Rev. Lett. 115(7), 072501 (2015).**
**M. Strickland, J. Noronha, and G. Denicol, Phys. Rev. D. 97(3), 036020 (2018)**
**J. Jankowski, M. Spalinski, Prog. Part. Nucl. Phys. 132, 104048 (2023)**

- The solution of the dynamical equations converges quickly to an attractor through non-hydrodynamic mode decay

**M. P. Heller, R. A. Janik, and P. Witaszczyk, Phys. Rev. Lett. 110(21), 211602 (201**
**A.Buchel, M.P.Heller, J.Noronha, Phys. Rev. D94(10), 106011 (2016)**

- The nonlinear hydrodynamic gradient series can diverge, but the series may be (Borel-)resummed to give rise to the hydrodynamic attractor



**W. Florkowski, M. P. Heller, M. Spalinski, New theories of relativistic hydrodynamics in the LHC era, Rept.Prog.Phys. 81 (2018) 4, 046001**

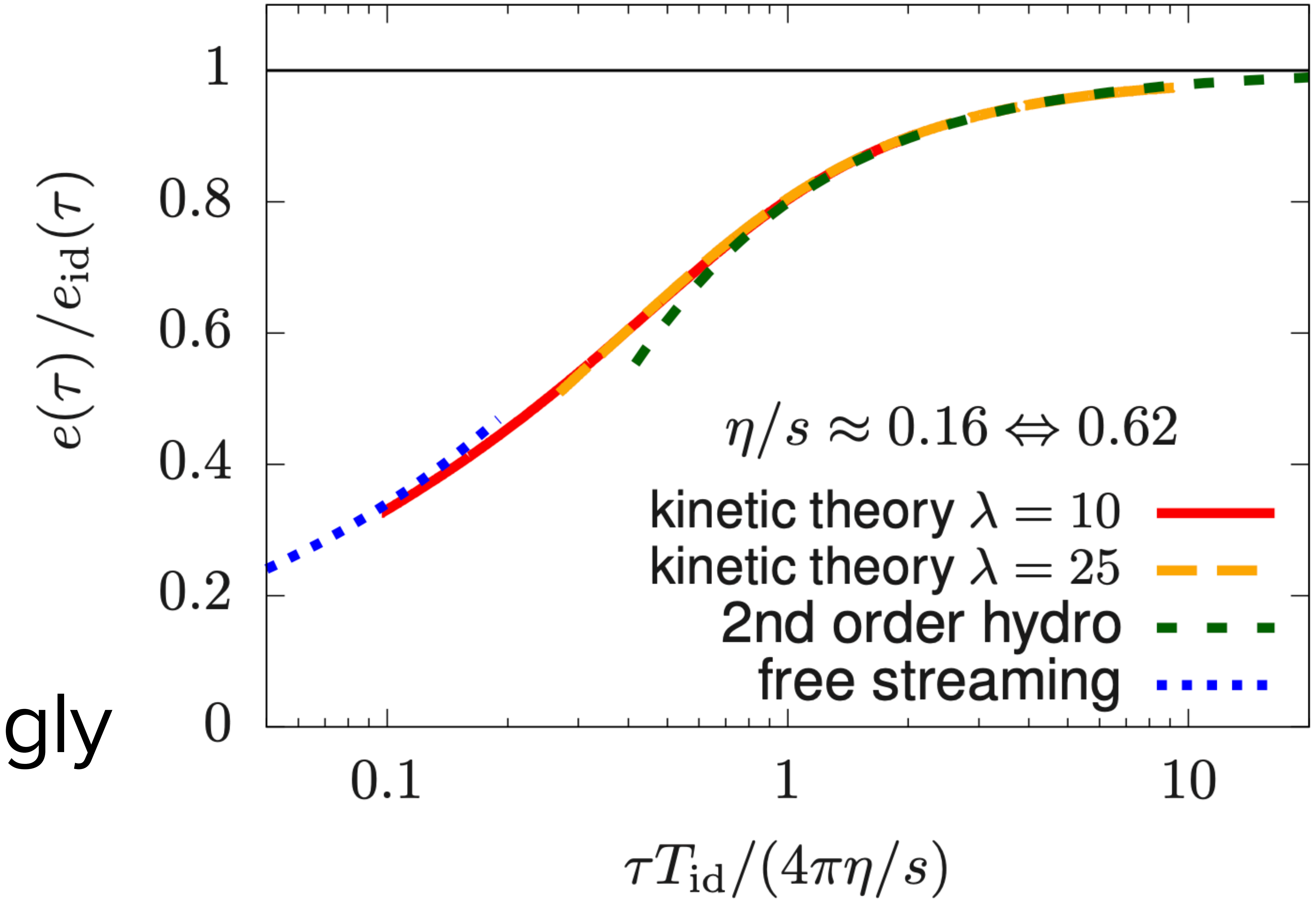
# SMOOTHLY CONNECTING TO HYDRODYNAMICS

- p+A collisions motivated developments of non-equilibrium early time descriptions, for example using effective kinetic theory

A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, and D. Teaney
Phys. Rev. Lett. 122(12), 122302 (2019)

- The non-equilibrium evolution follows a universal attractor curve which smoothly interpolates between free streaming at early times and viscous hydrodynamics at late times

- See also Soeren Schlichting's talk for proposal to measure how strongly interacting system is

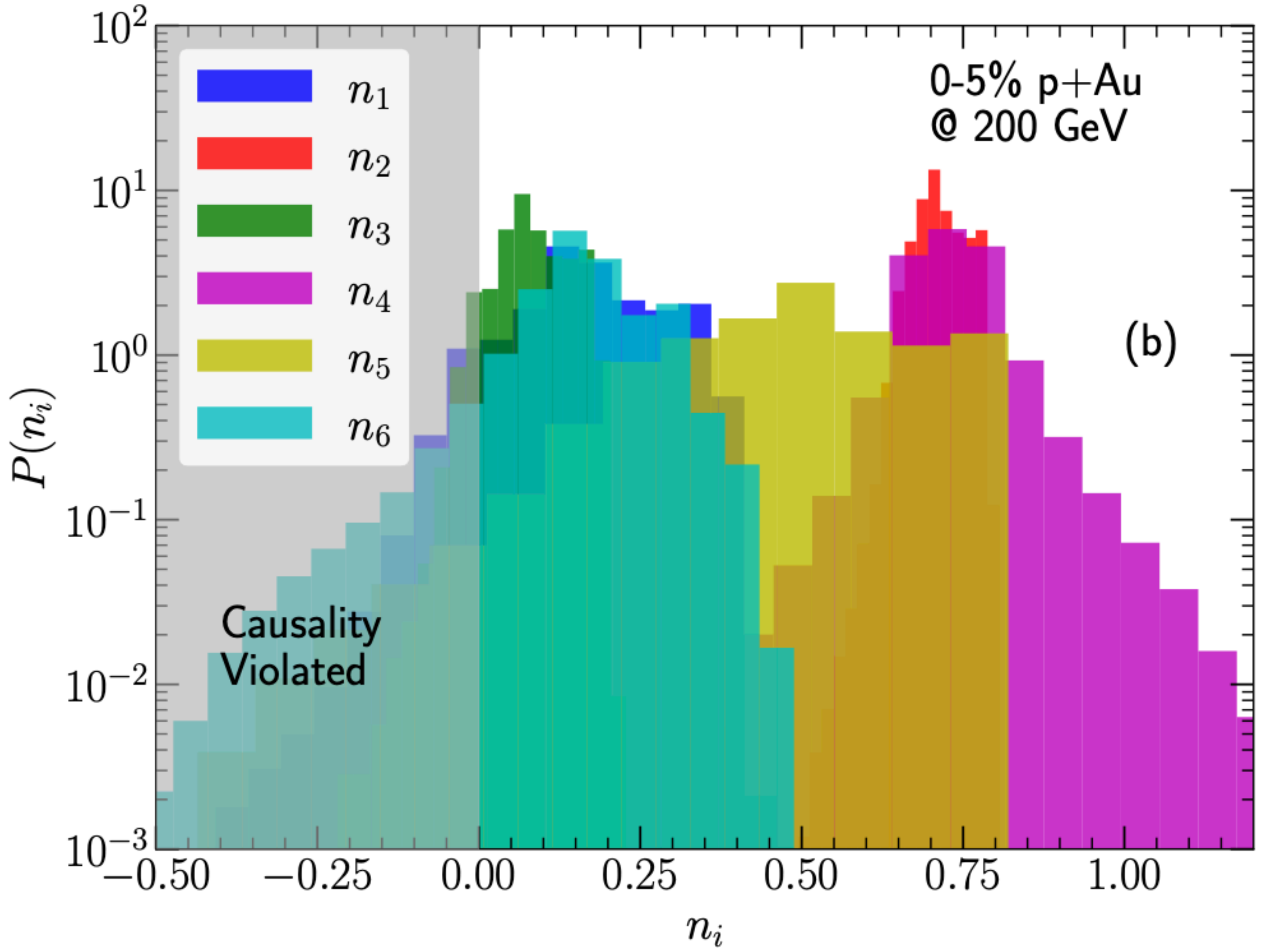


# APPLICABILITY OF HYDRODYNAMICS

- Attractor explains why hydro works eventually
- But far from equilibrium situation could still lead to inaccurate results
- Far from equilibrium, causality can be violated
- Alternative to Israel-Stewart like theories, BDNK, can be shown to be causal

**BDNK:**
F. S. Bemfica, M. M. Disconzi, and J. Noronha, Phys. Rev. X. 12(2), 021044 (2022)
P. Kovtun, JHEP 10 (2019) 034

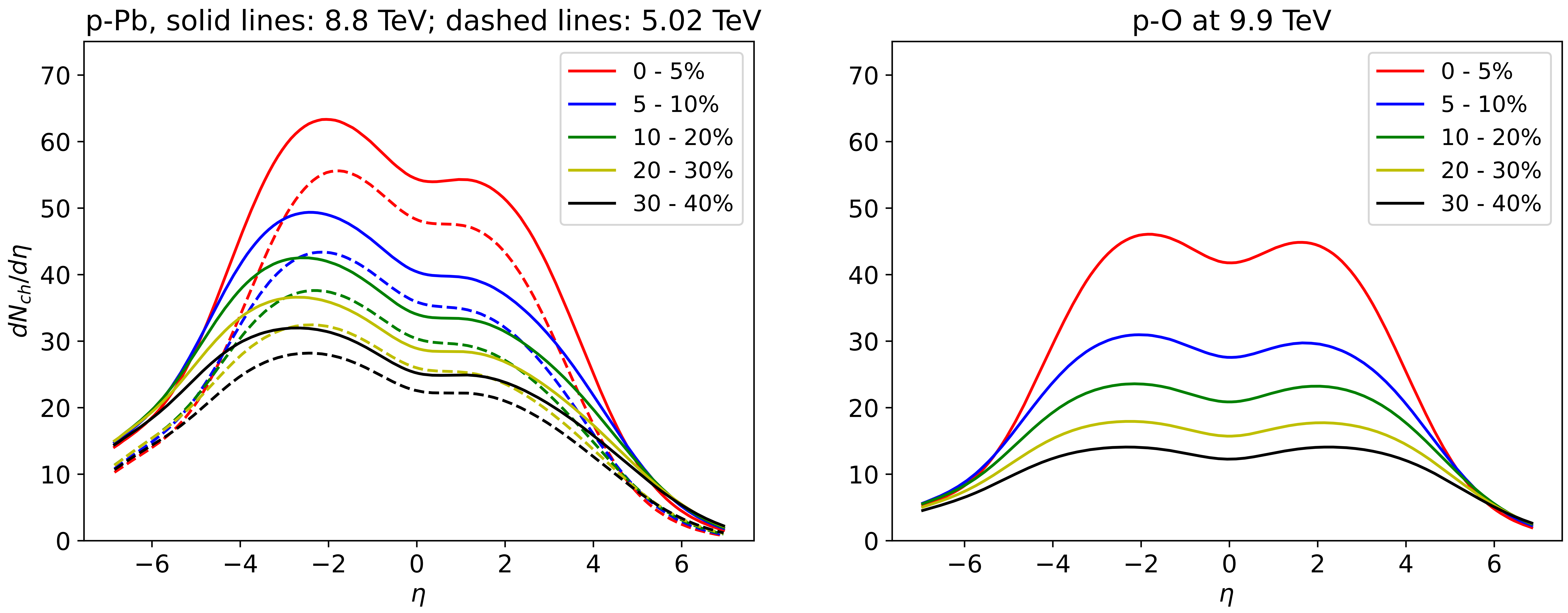
**Causality:**
C. Plumberg, D. Almaalol, T. Dore, J. Noronha, J. Noronha-Hostler, Phys. Rev. C. 105(6), L061901 (2022)
C. Chiu and C. Shen, Phys. Rev. C. 103(6), 064901 (2021)
ExTrEMe Collaboration, R. Krupczak et al., Phys.Rev.C 109 (2024) 3, 034908



values of 6 causality conditions

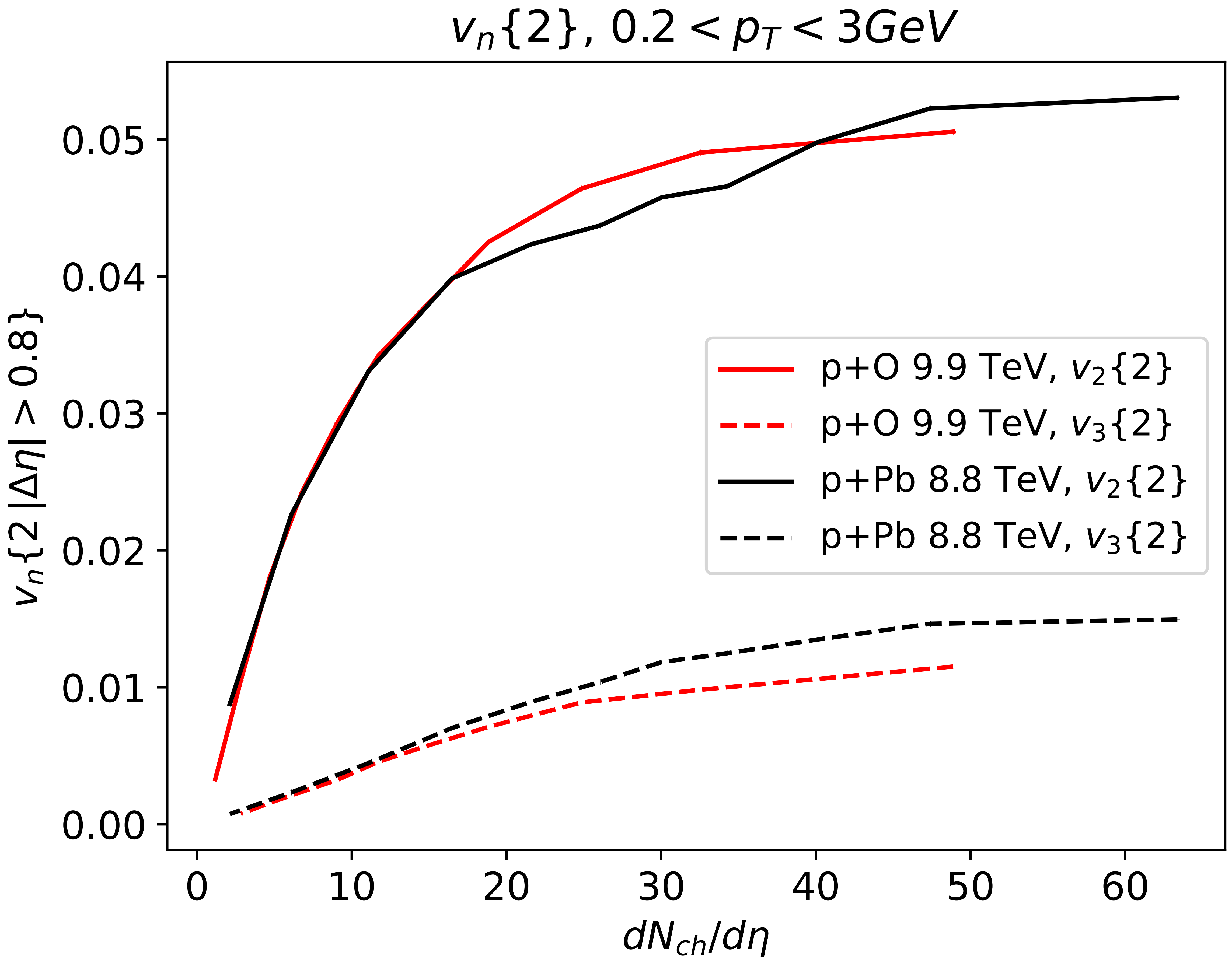
# HIGHER ENERGY p+Pb AND p+O

**3+1D Hydrodynamics, W. Zhao, C. Shen, B. Schenke**



# ANISOTROPIC FLOW

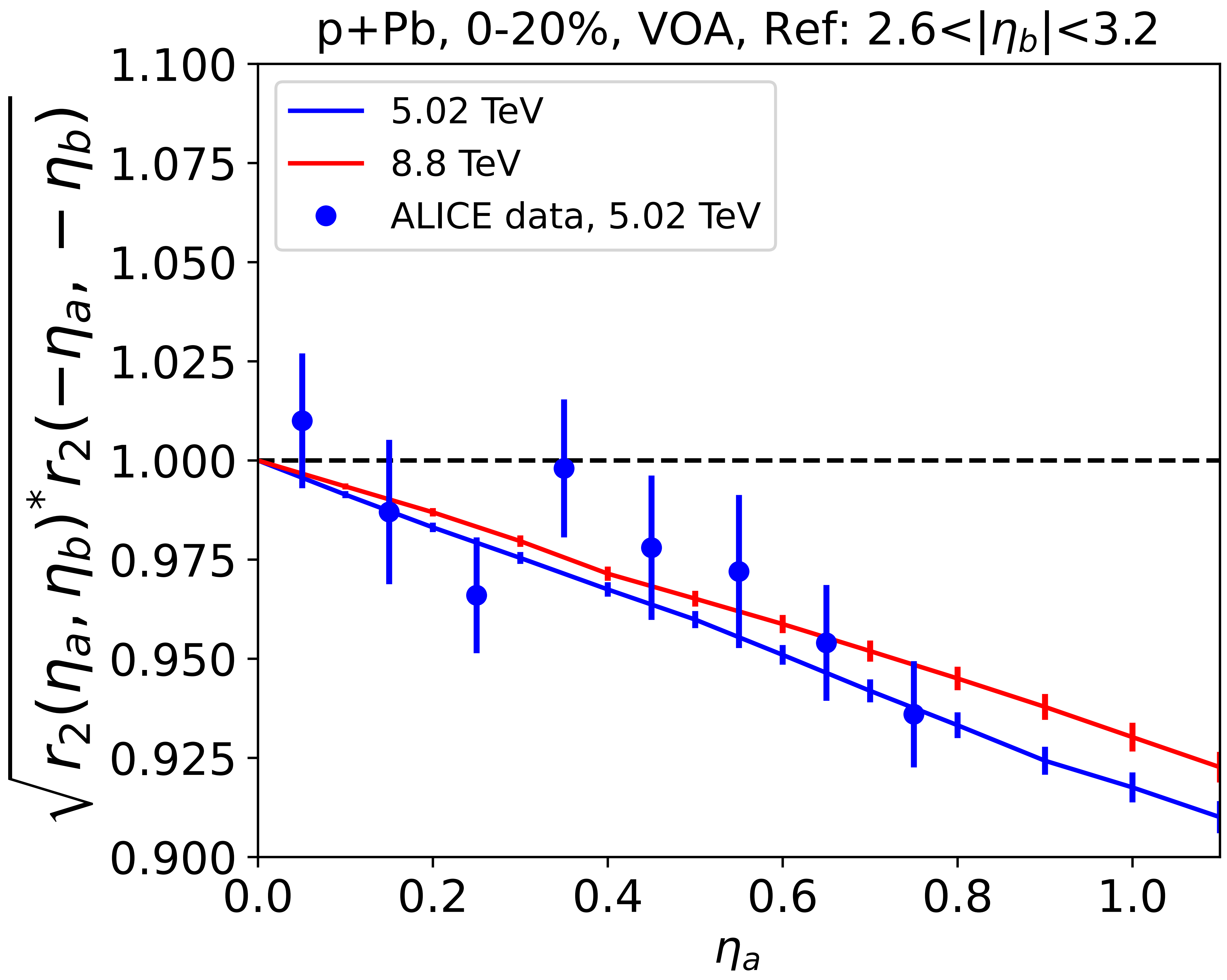
**3+1D Hydrodynamics, W. Zhao, C. Shen, B. Schenke**



- 3+1D hydrodynamics predicts similar $v_2$ and $v_3$ in p+Pb and p+O at the same multiplicity

# LONGITUDINAL STRUCTURE

**3+1D Hydrodynamics, W. Zhao, C. Shen, B. Schenke**



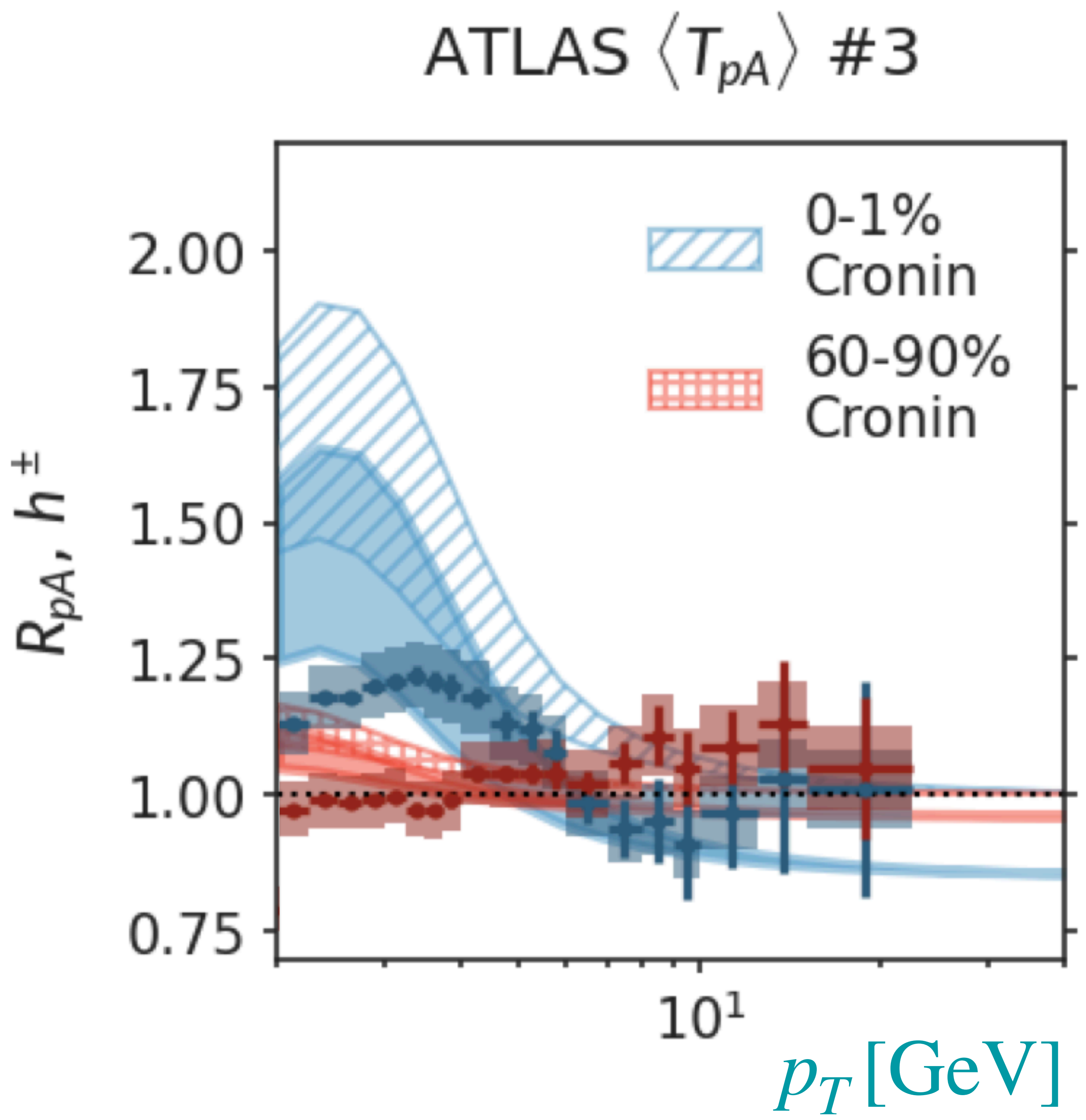
**Data from ALICE Collaboration, ALI-PREL-548886**

$$r_n(\eta_a,\eta_b) = \frac{V_{n\Delta}(-\eta_a,\eta_b)}{V_{n\Delta}(\eta_a,\eta_b)}$$

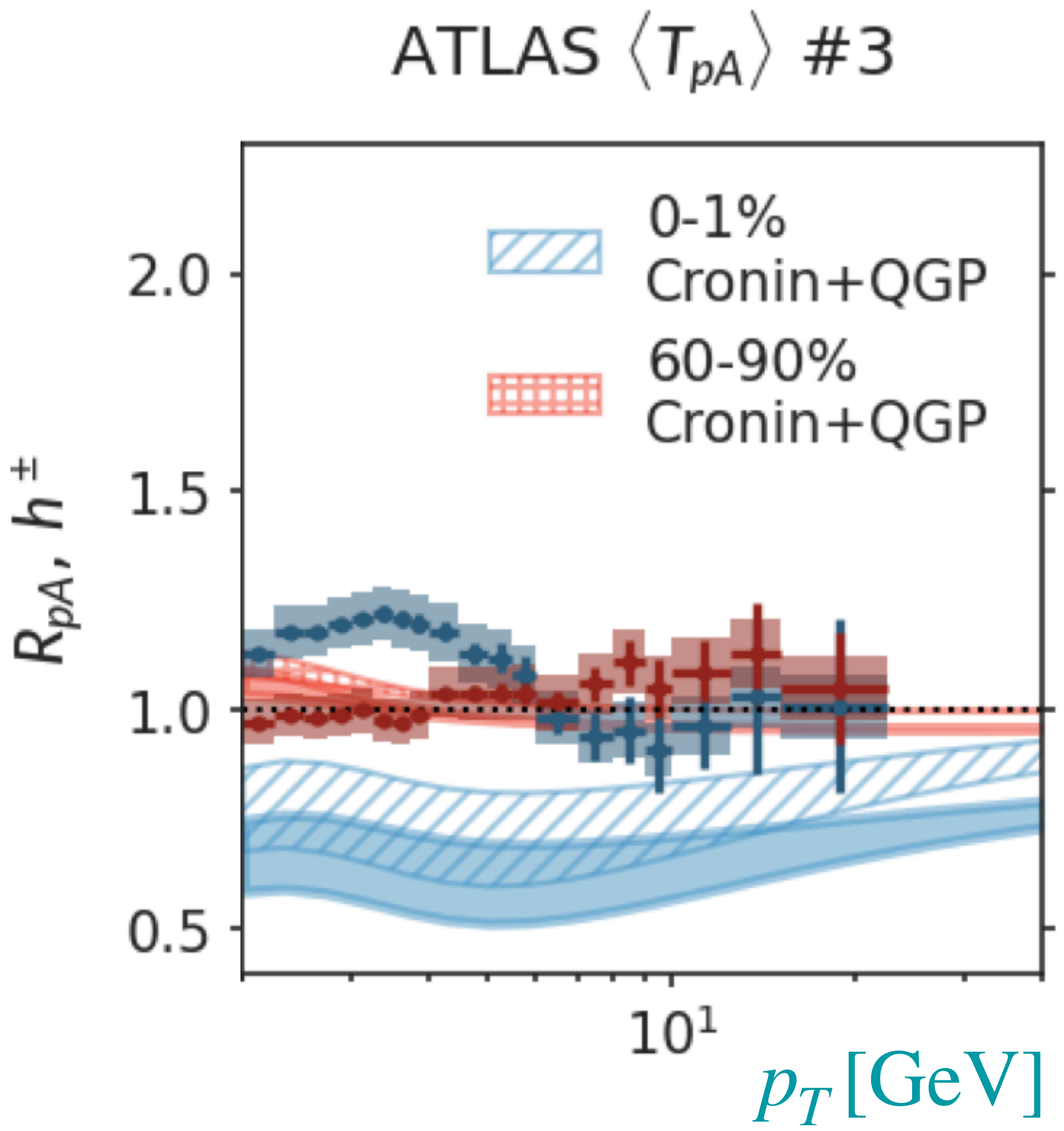
- then symmetrized, because we have an asymmetric system
- less decorrelation at higher energy: system stretched in rapidity (slightly more boost-invariant)
- p+A crucial to constrain 3D initial state models/understand energy deposition and baryon stopping

# 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**

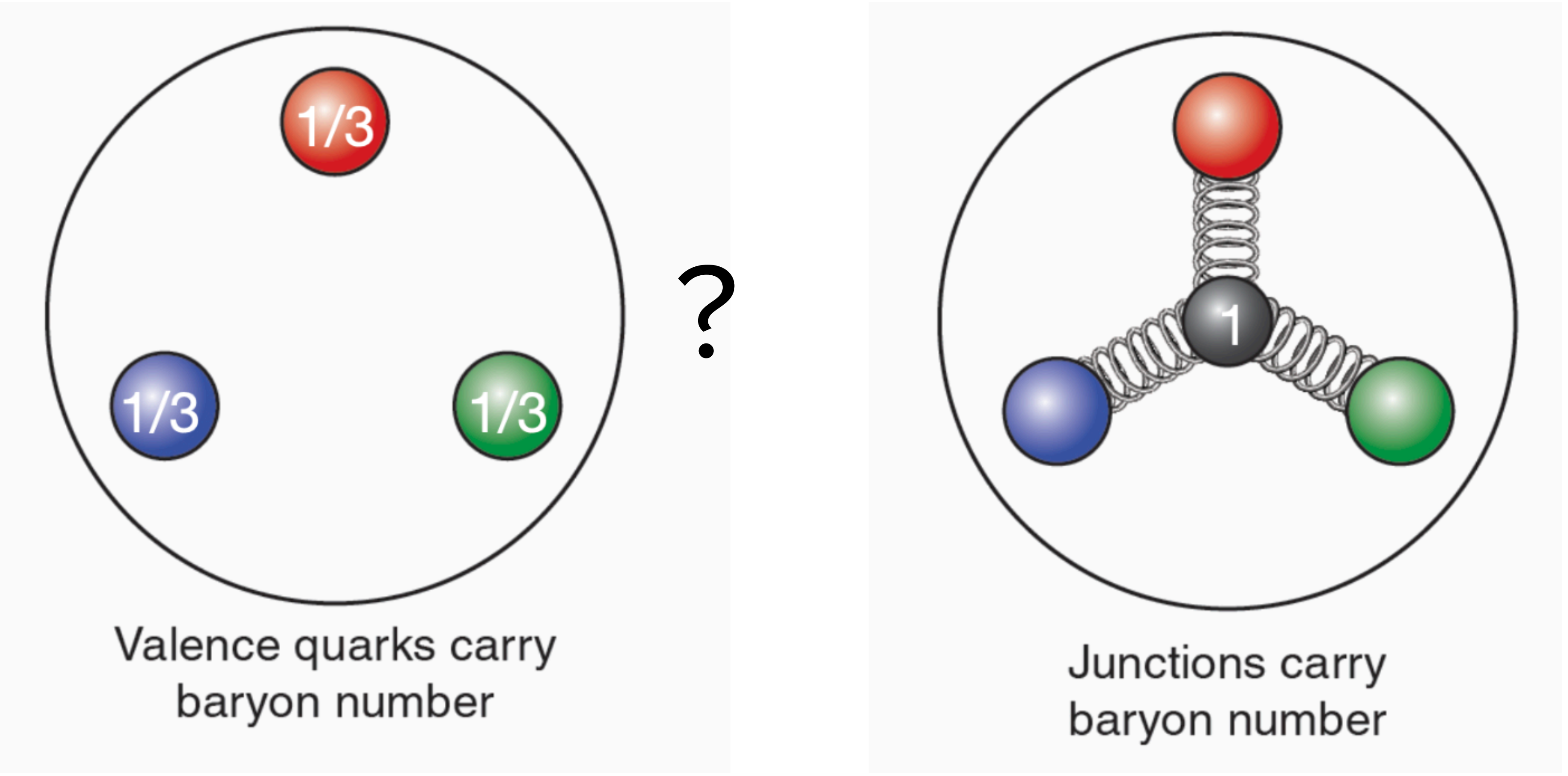
Correlation between hard and soft degrees of freedom important

**A. Majumder for JETSCAPE, arXiv:2308.02650**

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

# BARYON JUNCTIONS

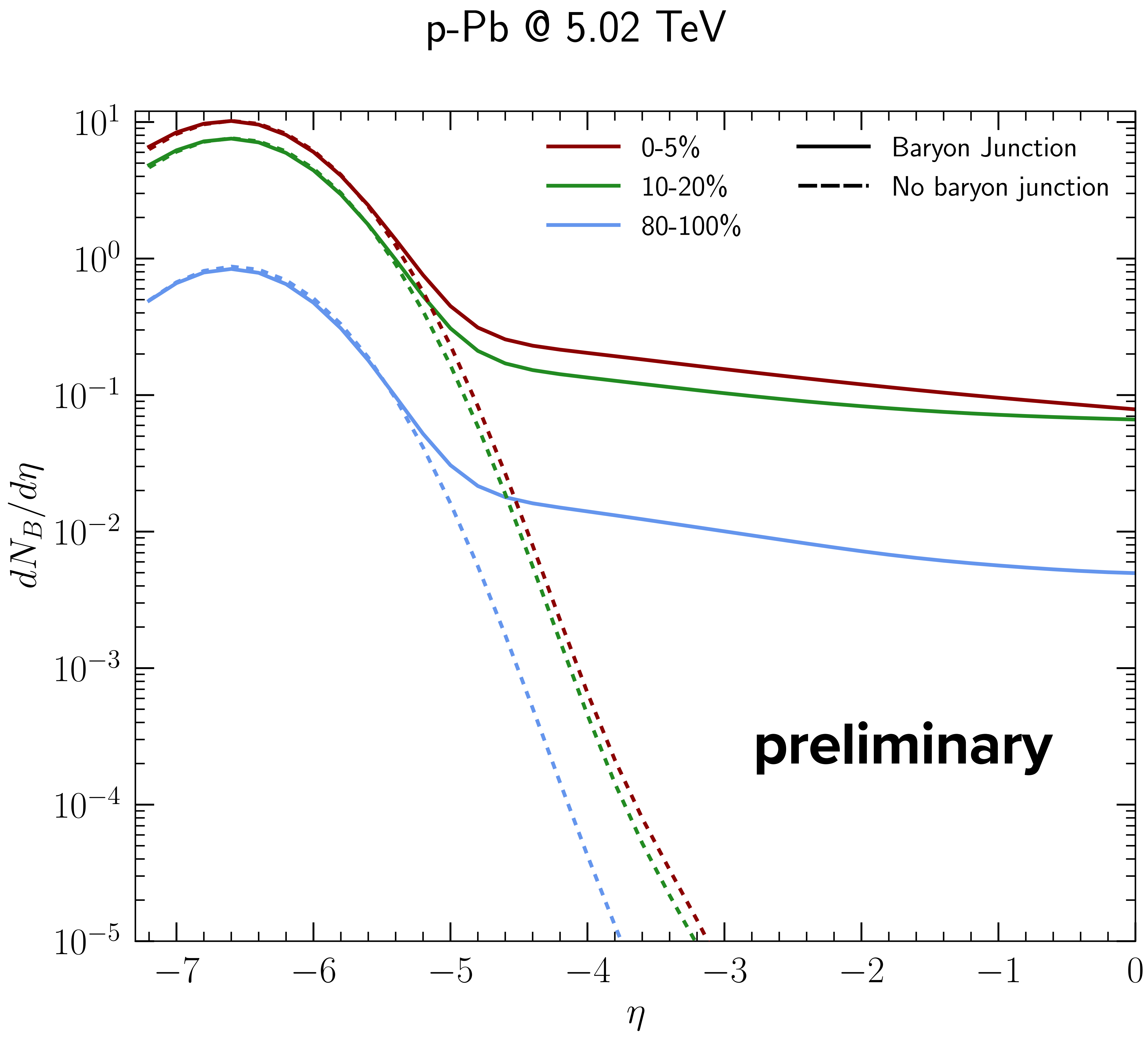
**G. Pihan, A. Monnai, B. Schenke, C. Shen, in preparation**



- p+A collisions could help understand what carries baryon number and how it is transported in a collision
- Junction picture predicts certain rapidity dependence for baryon stopping

**D. Kharzeev, Phys. Lett. B 378, 238 (1996)**

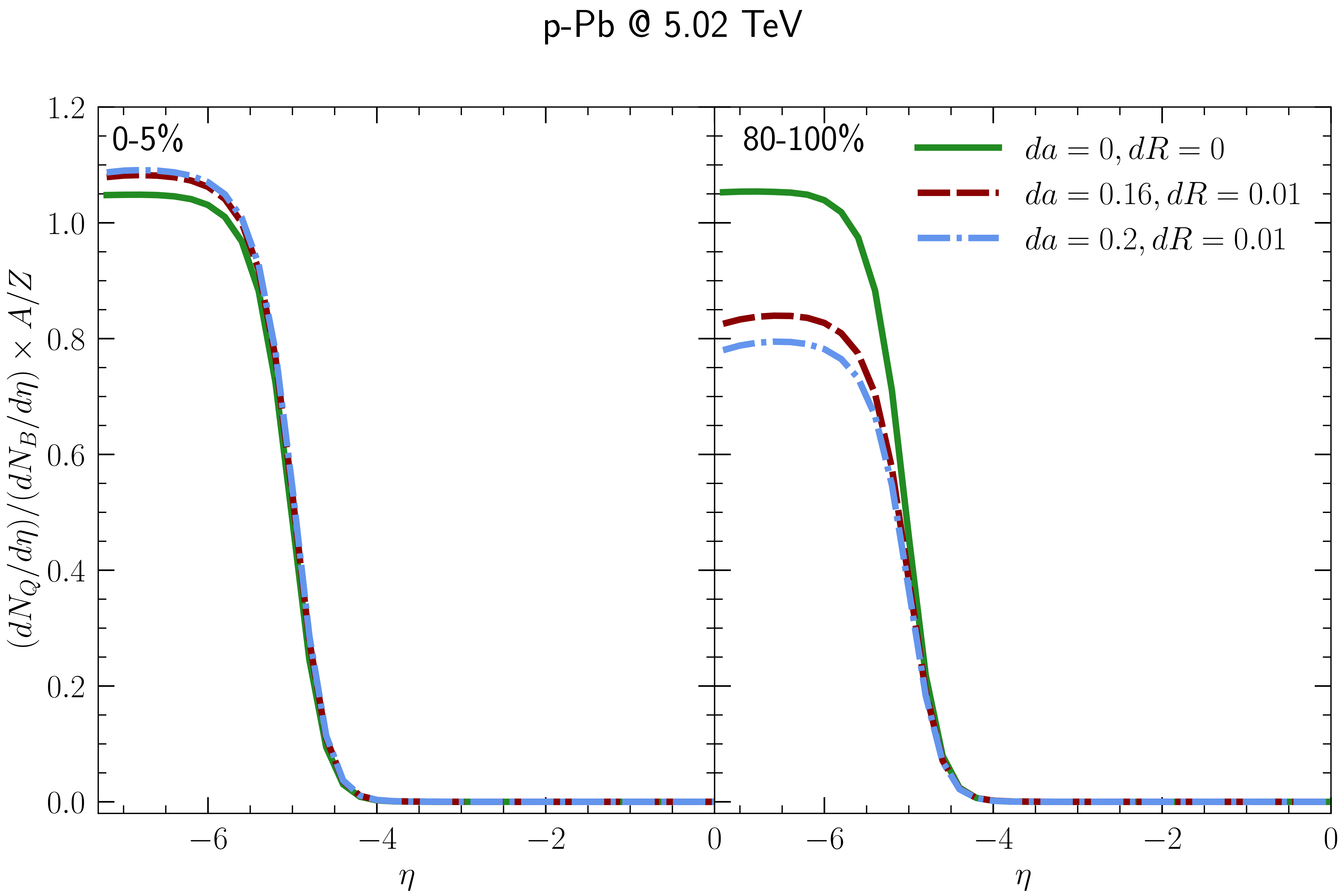
**G.Pihan, A. Monnai, B. Schenke, C. Shen, arXiv:2405.19439**



# NEUTRON SKIN

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

- Studying both baryon and electric charge stopping one could extract information on the neutron skin of the target



**no neutron skin**

**neutron skin from older results**

**PREX-2 size neutron skin**

- Ratios between p+Pb and p+p at similar multiplicity could help reduce systematic errors on net-charge measurements

# SUMMARY

- The p+A program had a significant impact on our understanding of collectivity in heavy ion collisions
- Triggered fundamental theoretical research into relativistic fluid dynamics, kinetic theory, thermalization, and correlations in the initial state
- Are we creating the smallest, most perfect fluid in these collisions?
- We can learn about QCD many-body physics
- Measurements can provide insight into proton structure
- Potential to also measure nuclear structure effects, like neutron skin in Pb
- 3D collision geometry in asymmetric systems provides important information on energy deposition, conserved charge stopping

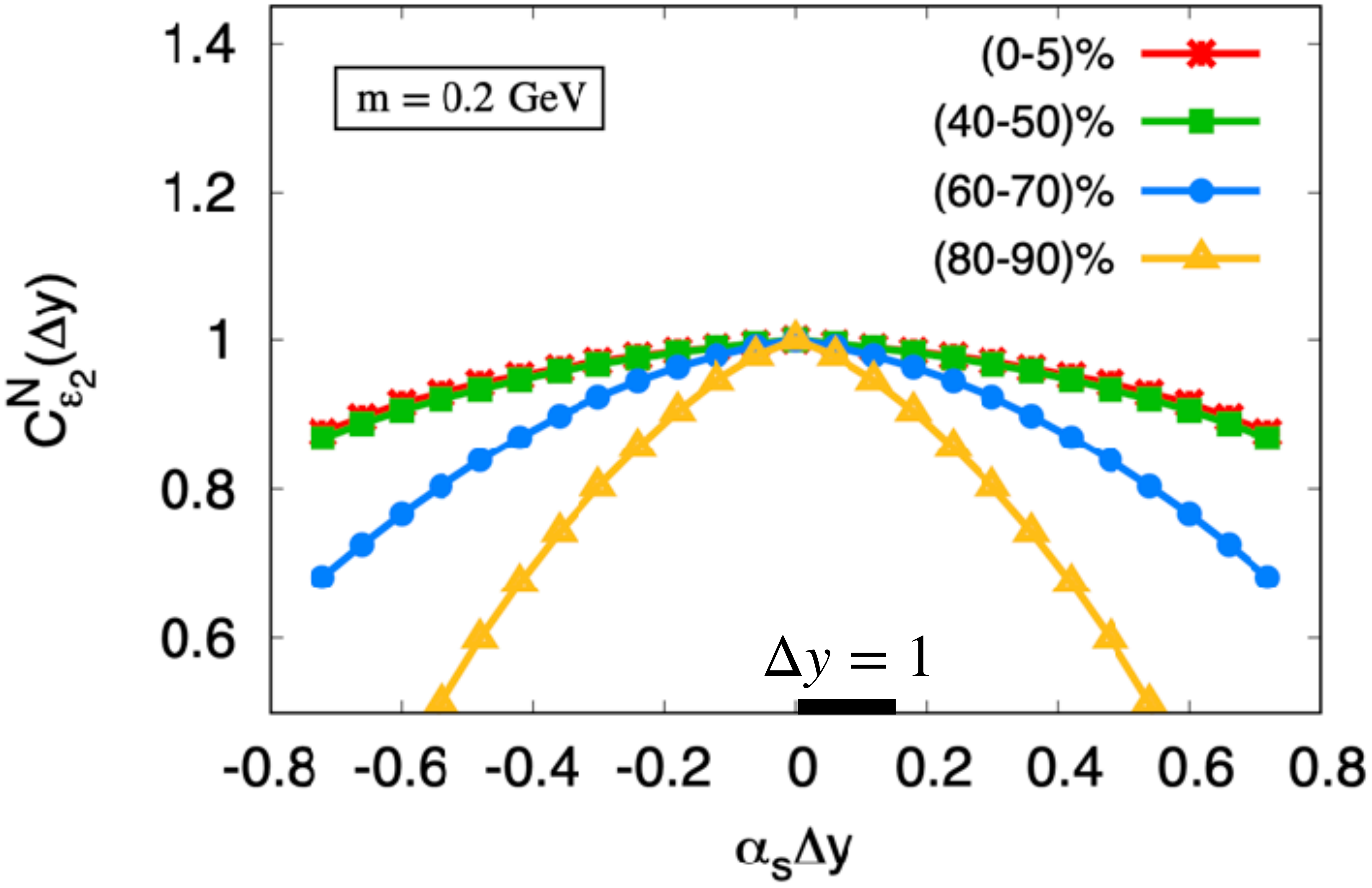
# BACKUP

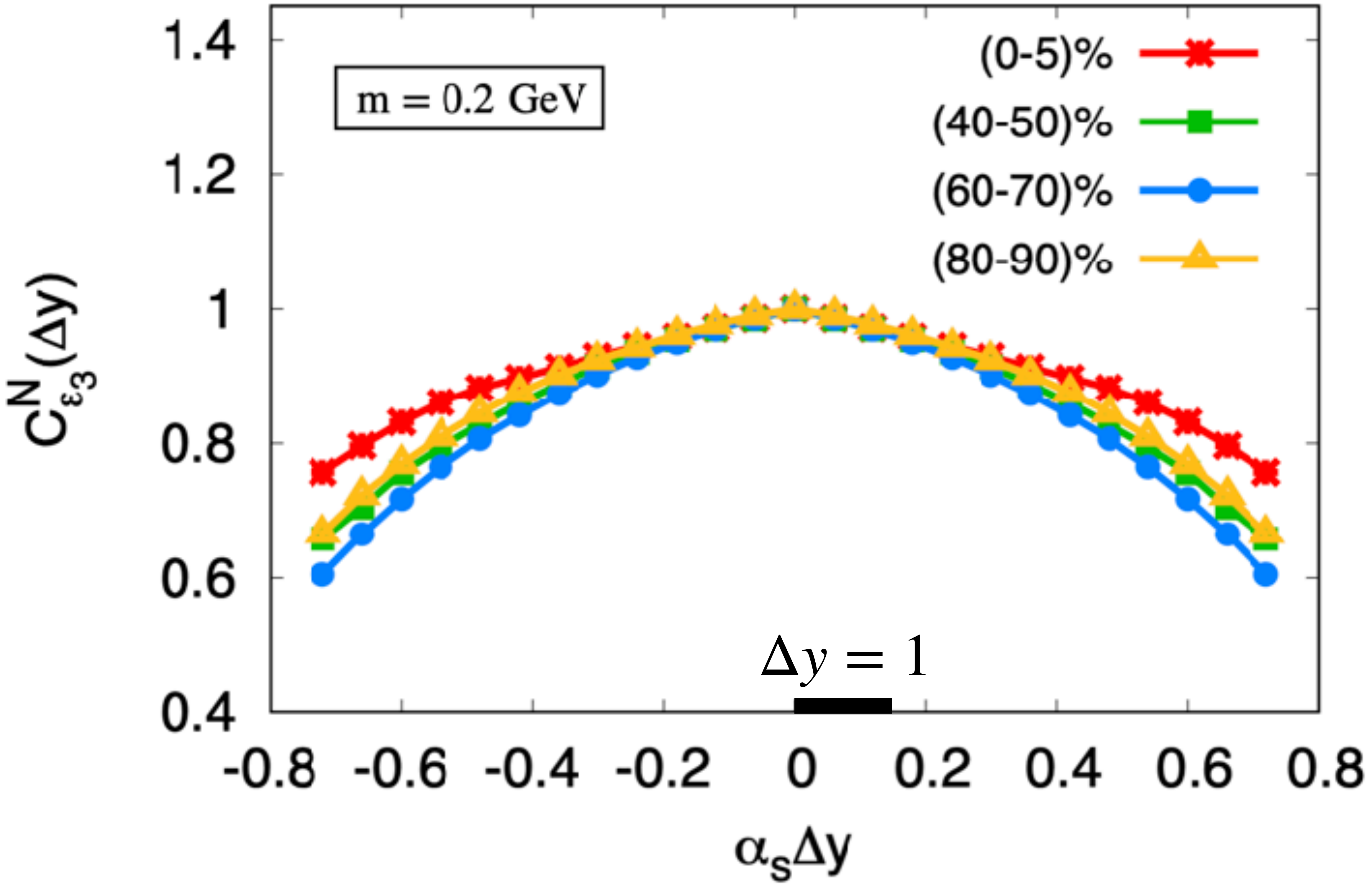
# RAPIDITY DEPENDENCE OF GEOMETRY

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

The geometry, quantified here with $\varepsilon_2$ and $\varepsilon_3$, decorrelates slowly

5 TeV p+Pb



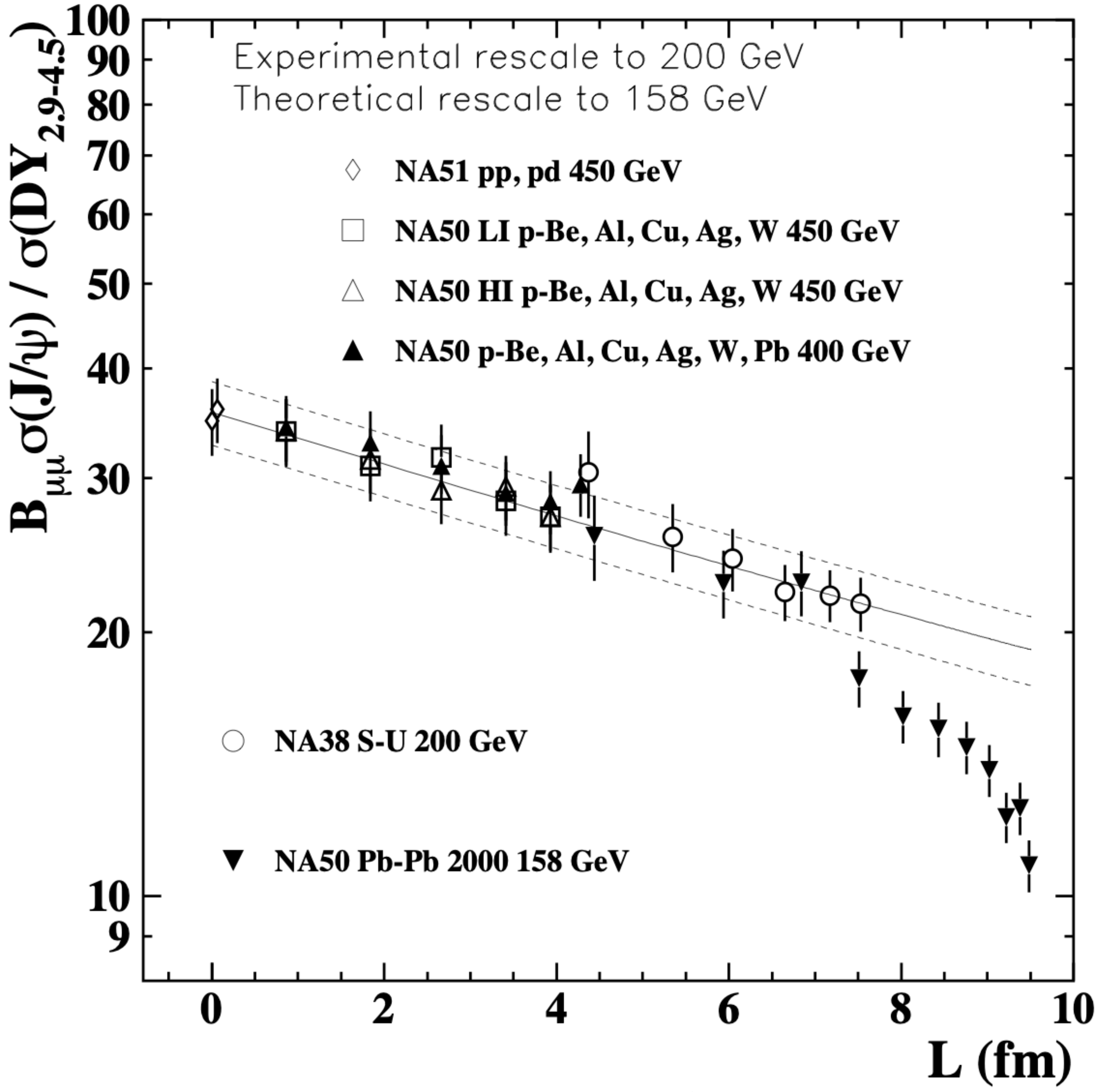


but rapidity dependence is not insignificant

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

# J/PSI SUPPRESSION IN SMALL SYSTEMS

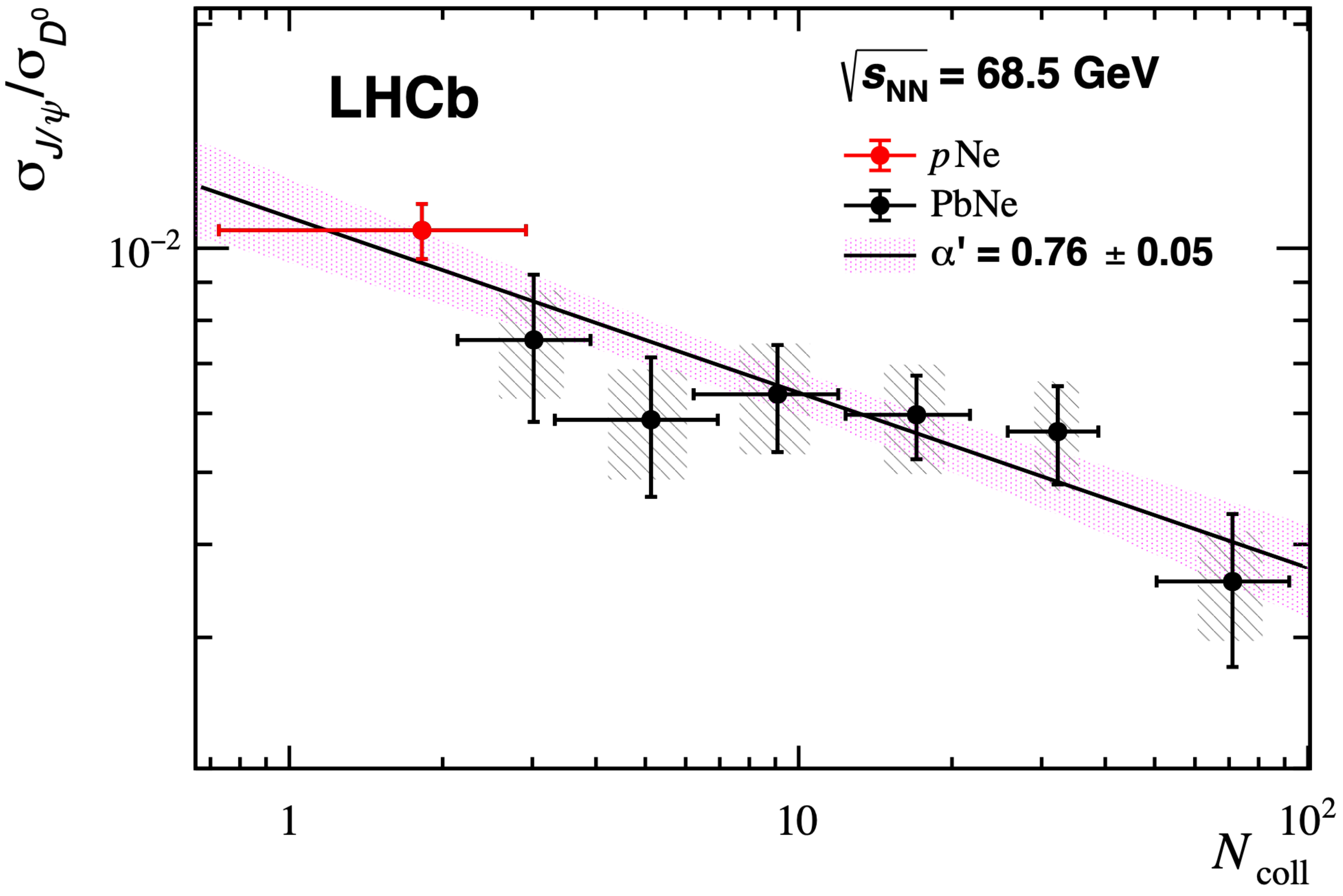
NA50 Collaboration
Eur.Phys.J.C 39 (2005) 335-345



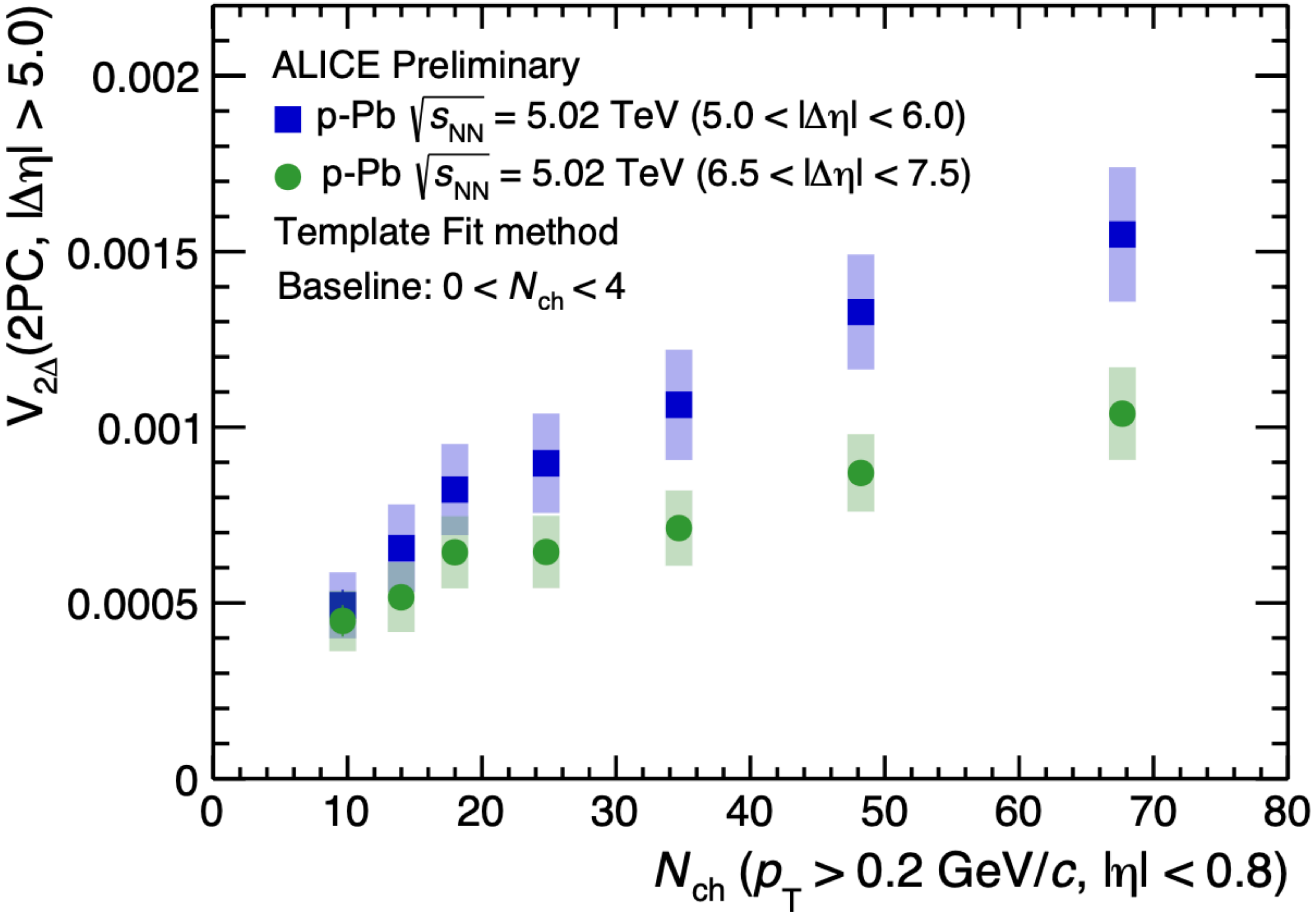
system size →

No QGP-like $J/\psi$ suppression in Pb+Ne

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



# ULTRA-LONG RANGE CORRELATION



p+Pb collisions at 5.02 TeV

$5 < |\Delta\eta| < 6$

$6.5 < |\Delta\eta| < 7.5$

ALICE Collaboration, preliminary

# FAR FROM EQUILIBRIUM HYDRODYNAMICS

- Resummation of the gradient series may also provide a way to define transport coefficients far from equilibrium

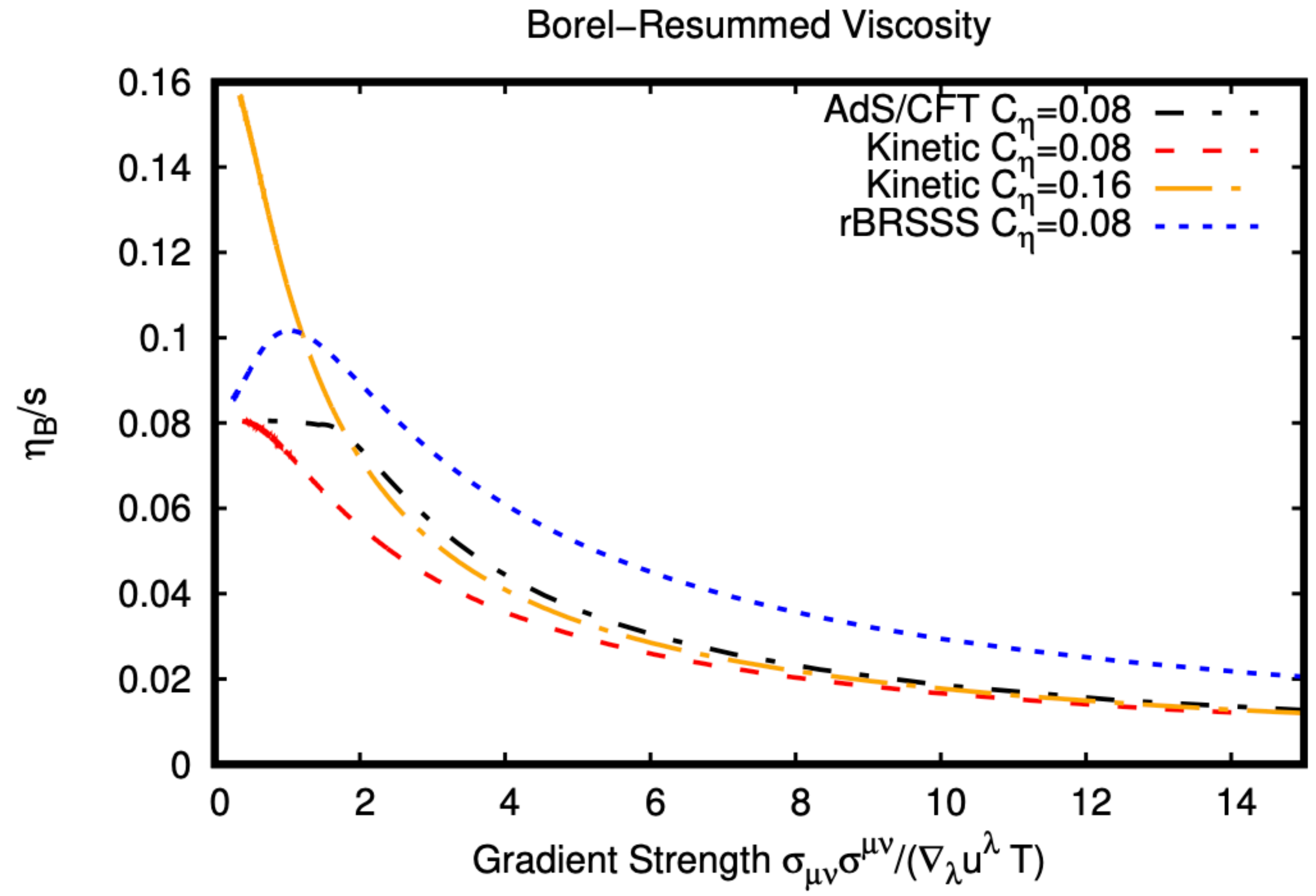
- For large gradient strength (far from equilibrium), the effective viscosity $\eta_B/s \to 0$

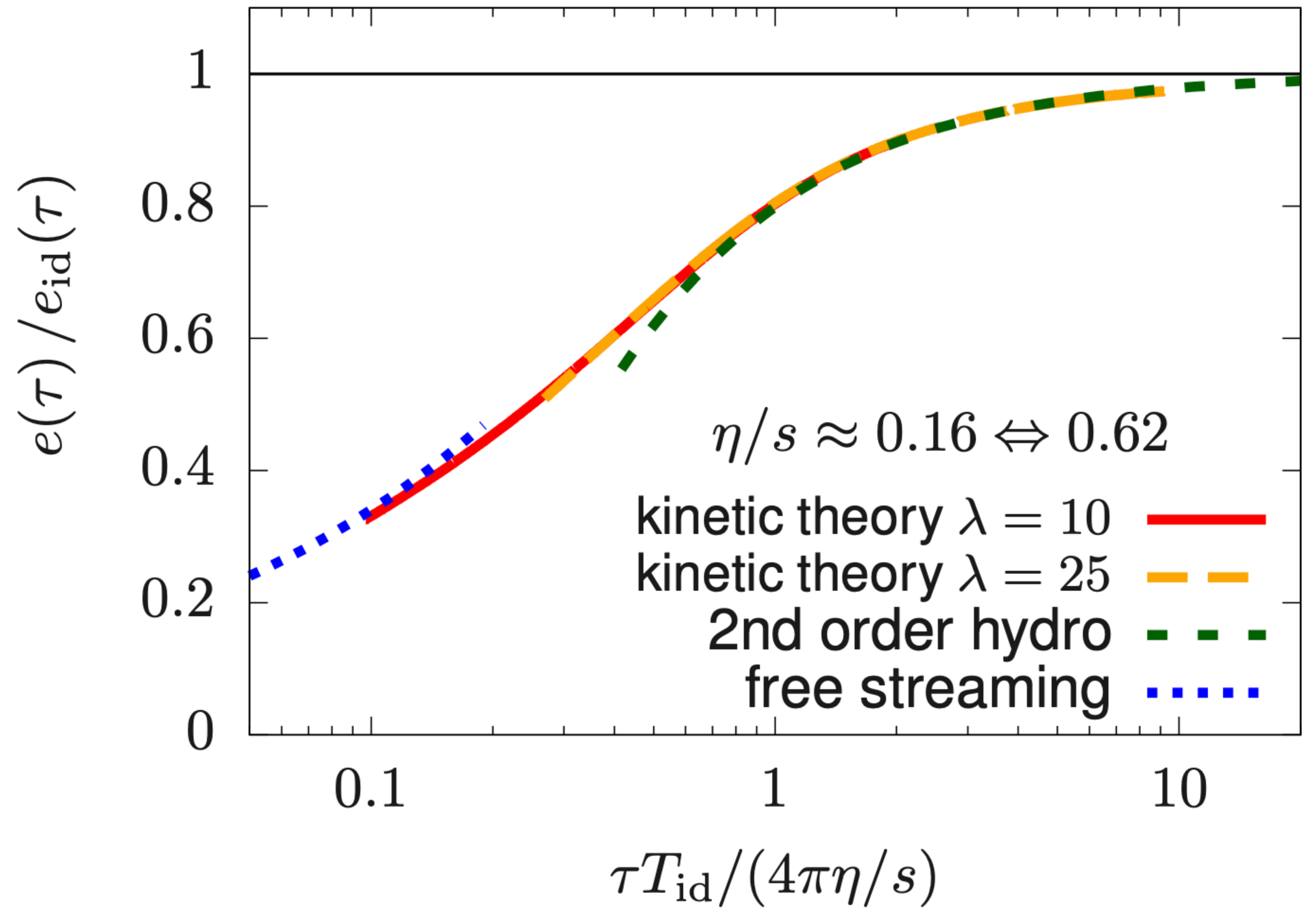
  P. Romatschke, Phys. Rev. Lett. 120(1), 012301 (2018)

- p+A collisions motivated developments of non-equilibrium early time descriptions, for example using effective kinetic theory

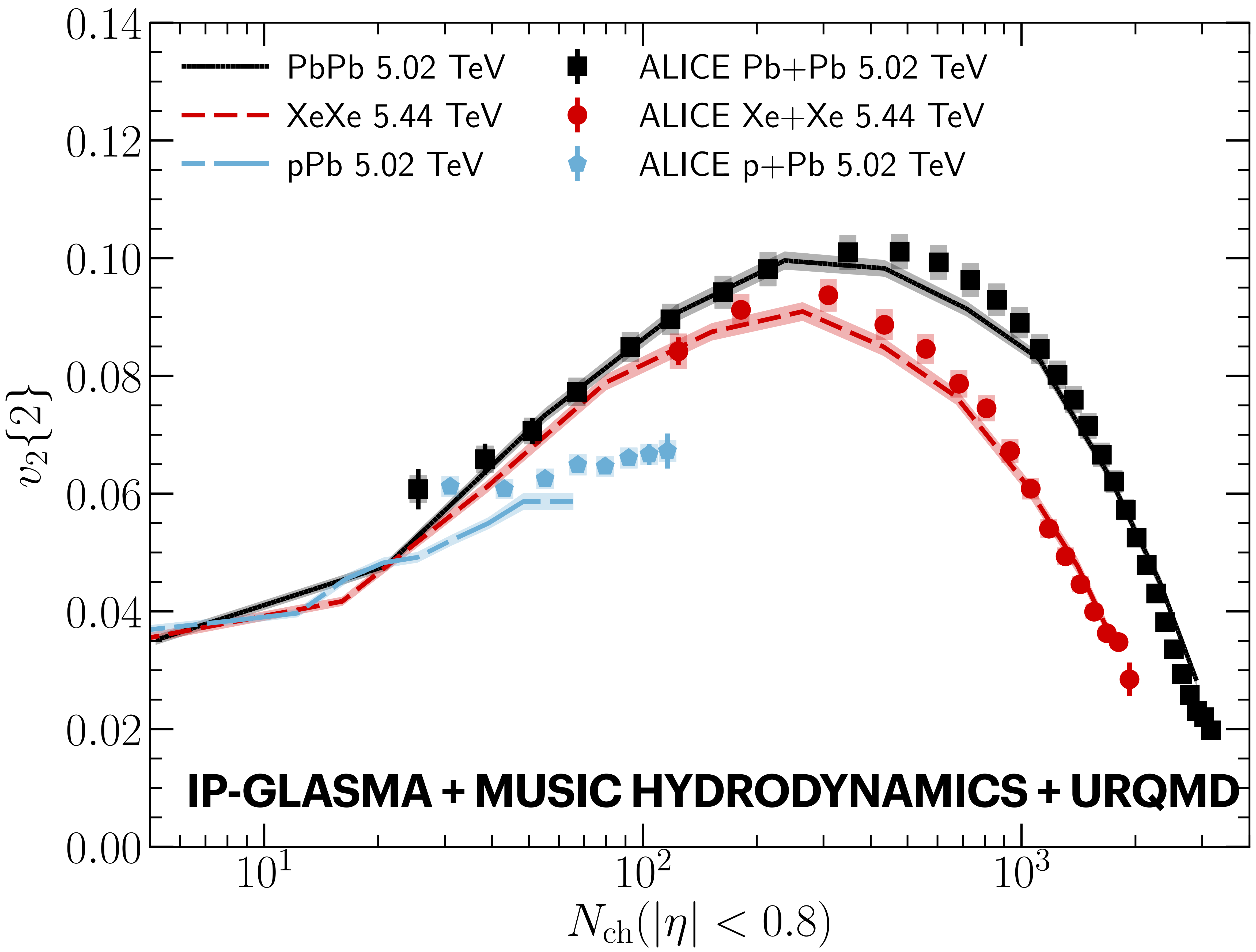
  A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, and D. Teaney
  Phys. Rev. Lett. 122(12), 122302 (2019)

- The non-equilibrium evolution follows a universal attractor curve which smoothly interpolates between free streaming at early times and viscous hydrodynamics at late times





# FLOW IN SMALL SYSTEMS



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

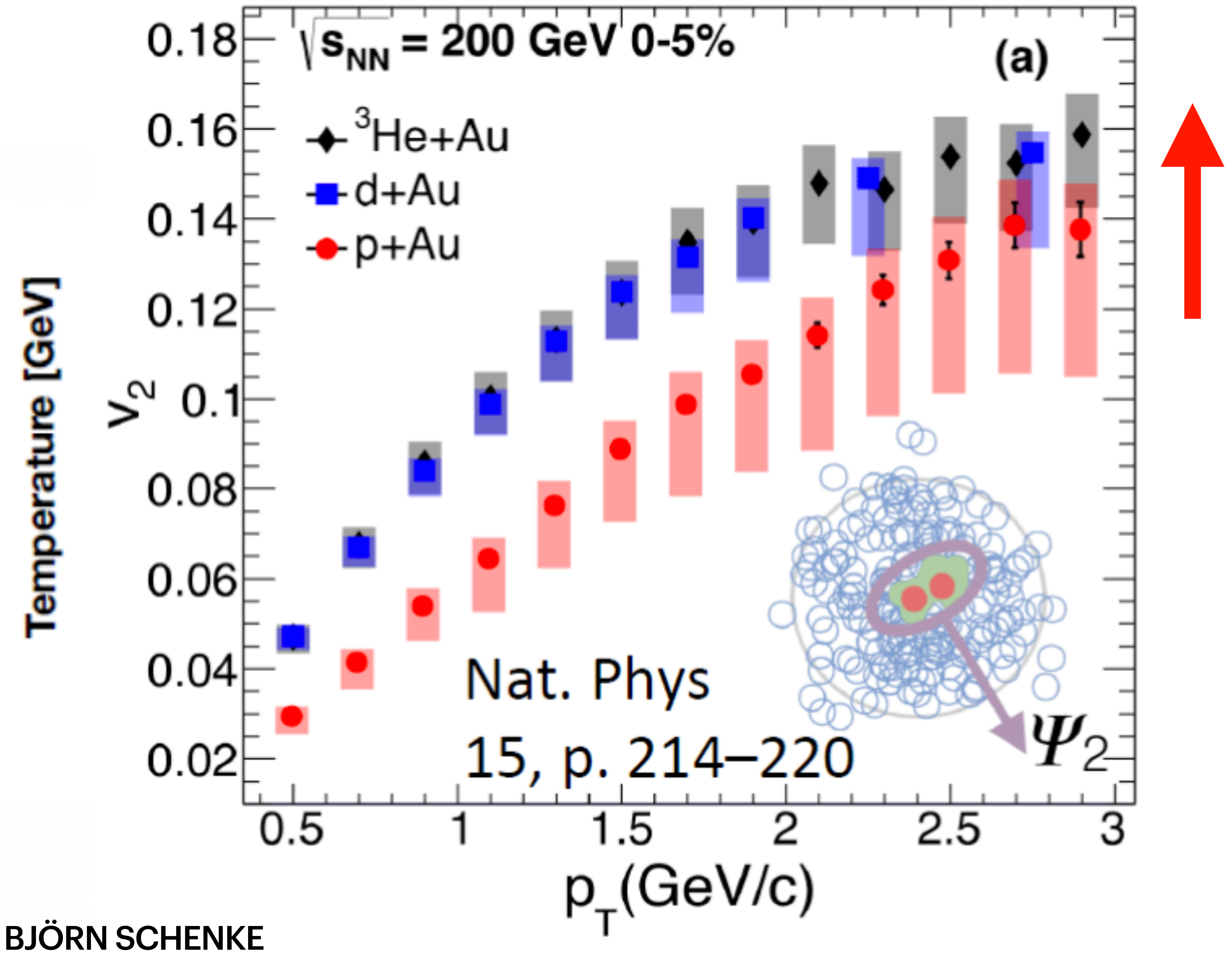
**There is evidence that the same is true in high multiplicity small systems**

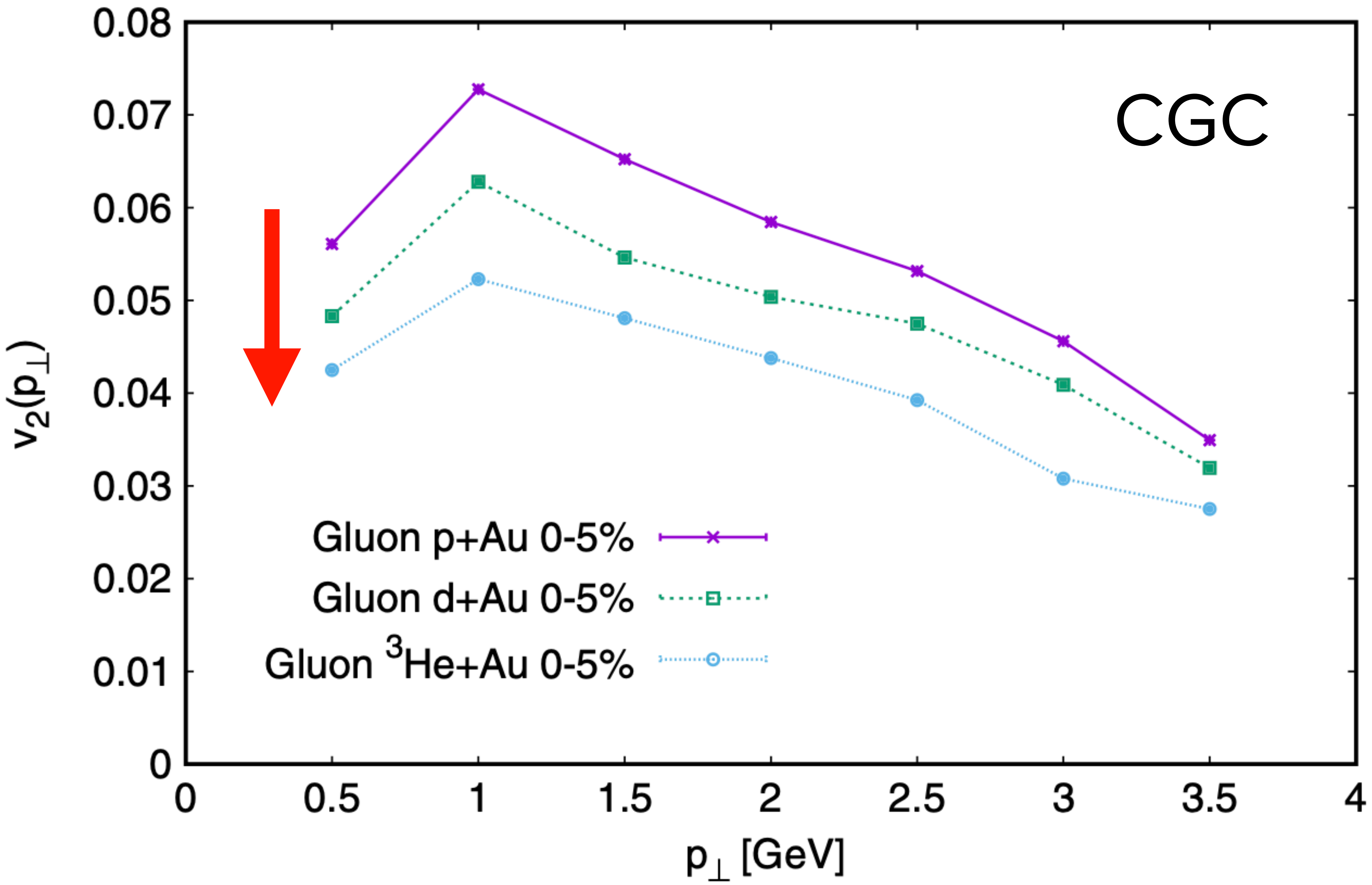
**B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 102 (2020) 044905**
**ALICE Collaboration, Phys.Rev.Lett. 123 (2019) 142301**

# 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:

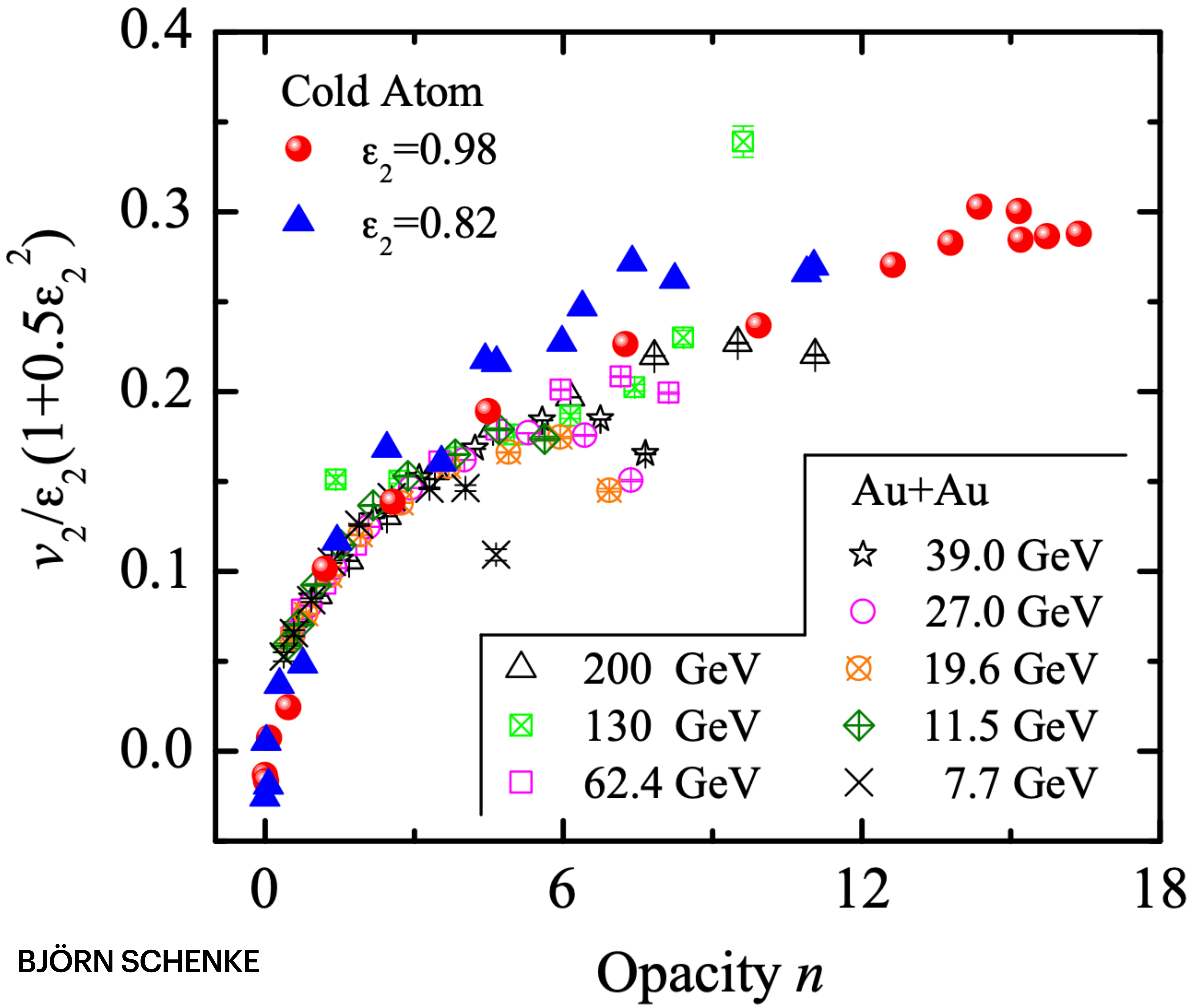




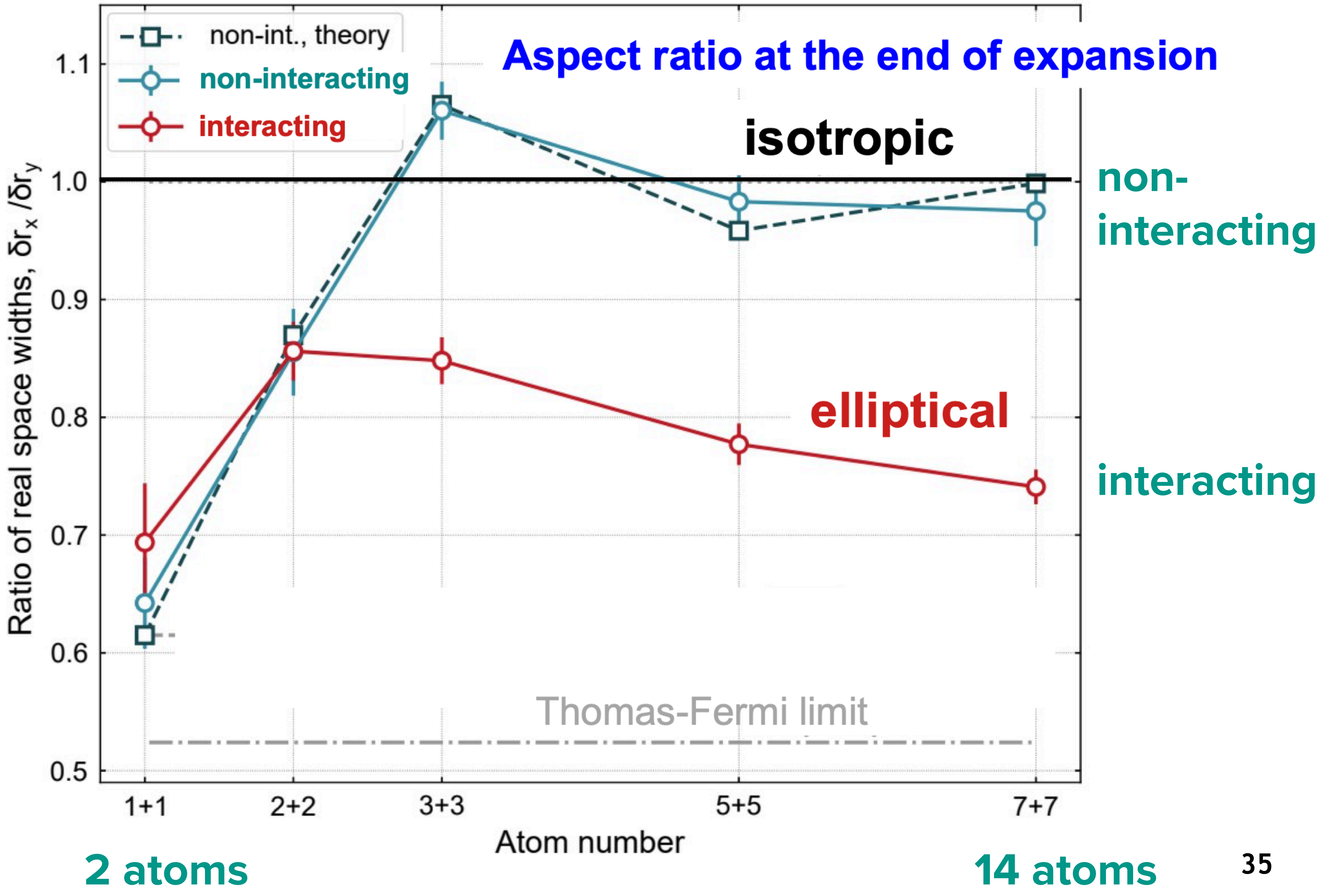
# INSIGHTS FROM COLD ATOMS

**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: $v_2/\varepsilon_2$ agree



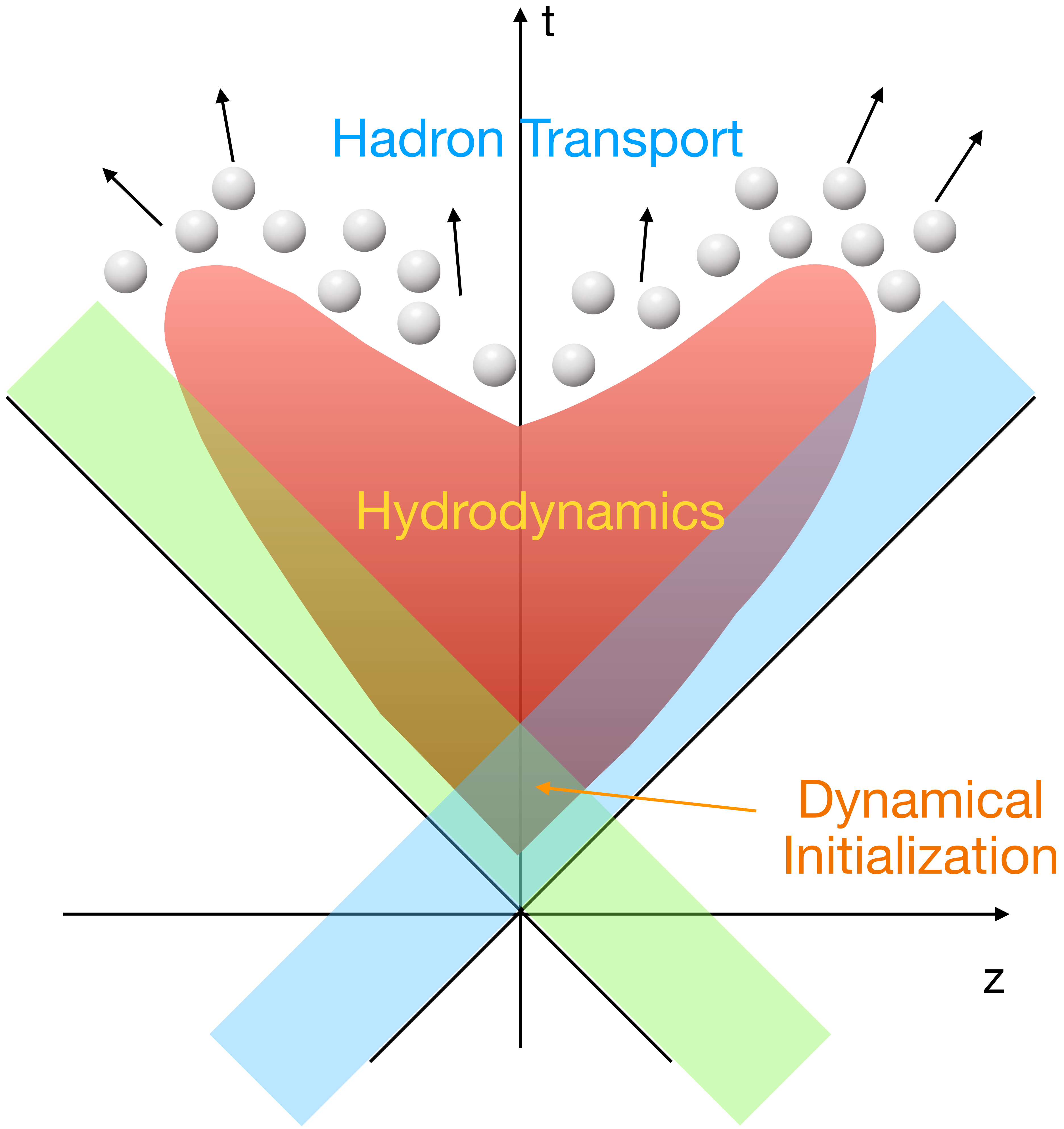
Very few particles: interaction drives elliptic flow for $N_{\text{atoms}} \geq 6$ **see talk by Lars Heyen**



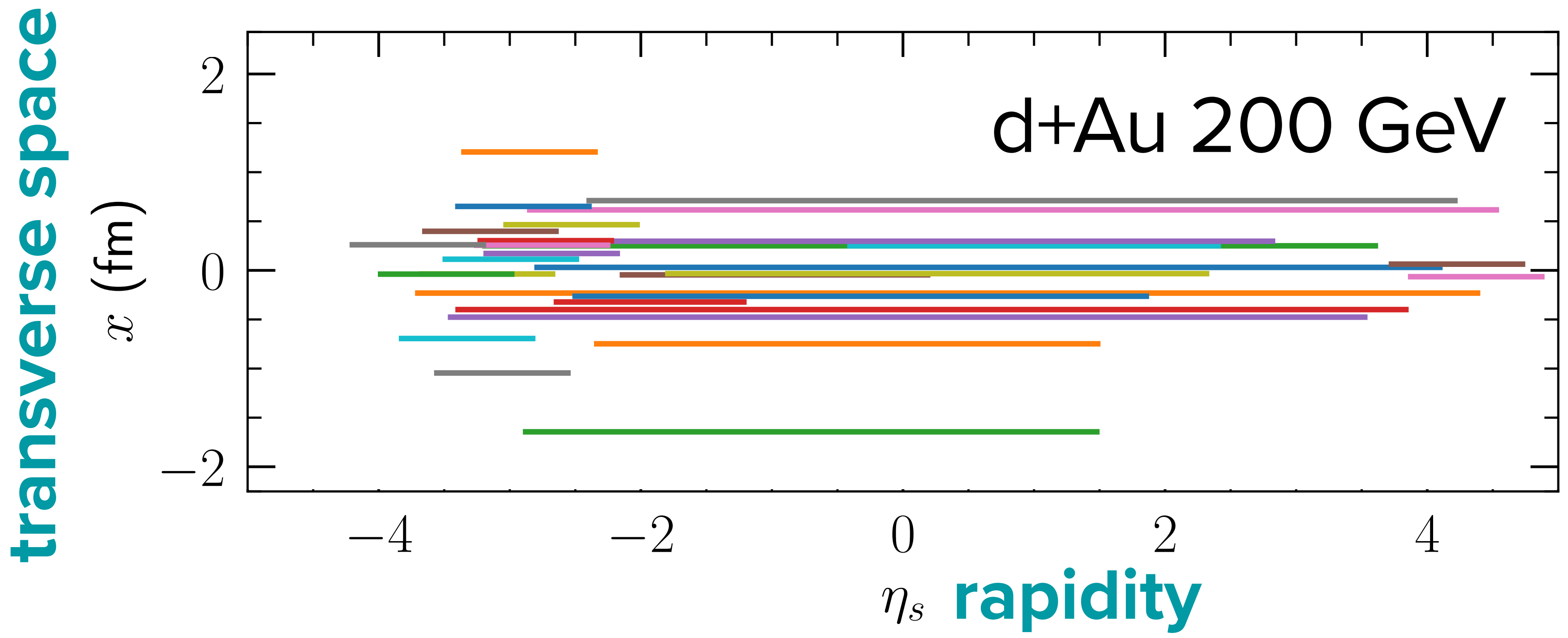
BJÖRN SCHENKE

# DYNAMIC 3+1D SIMULATION

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

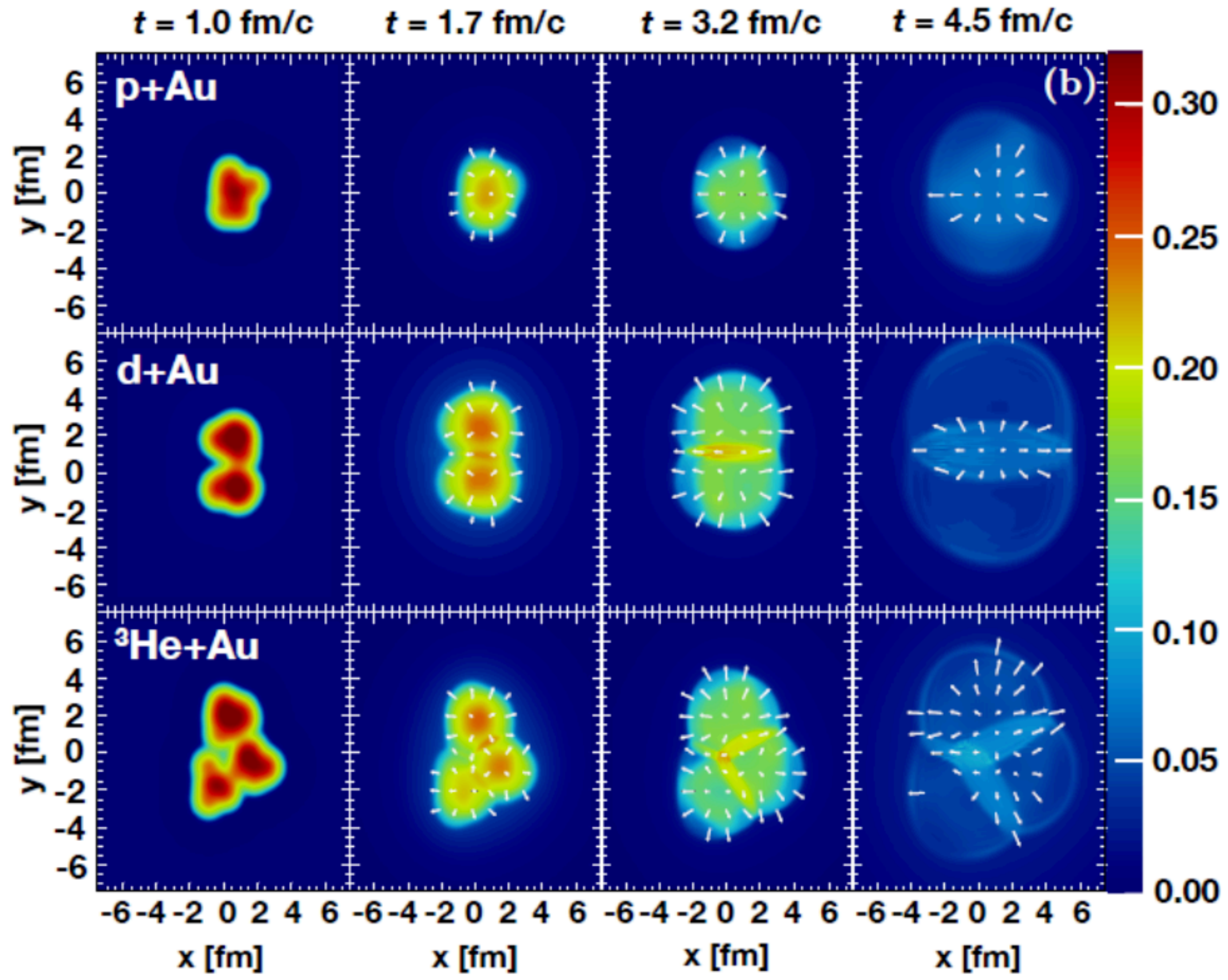


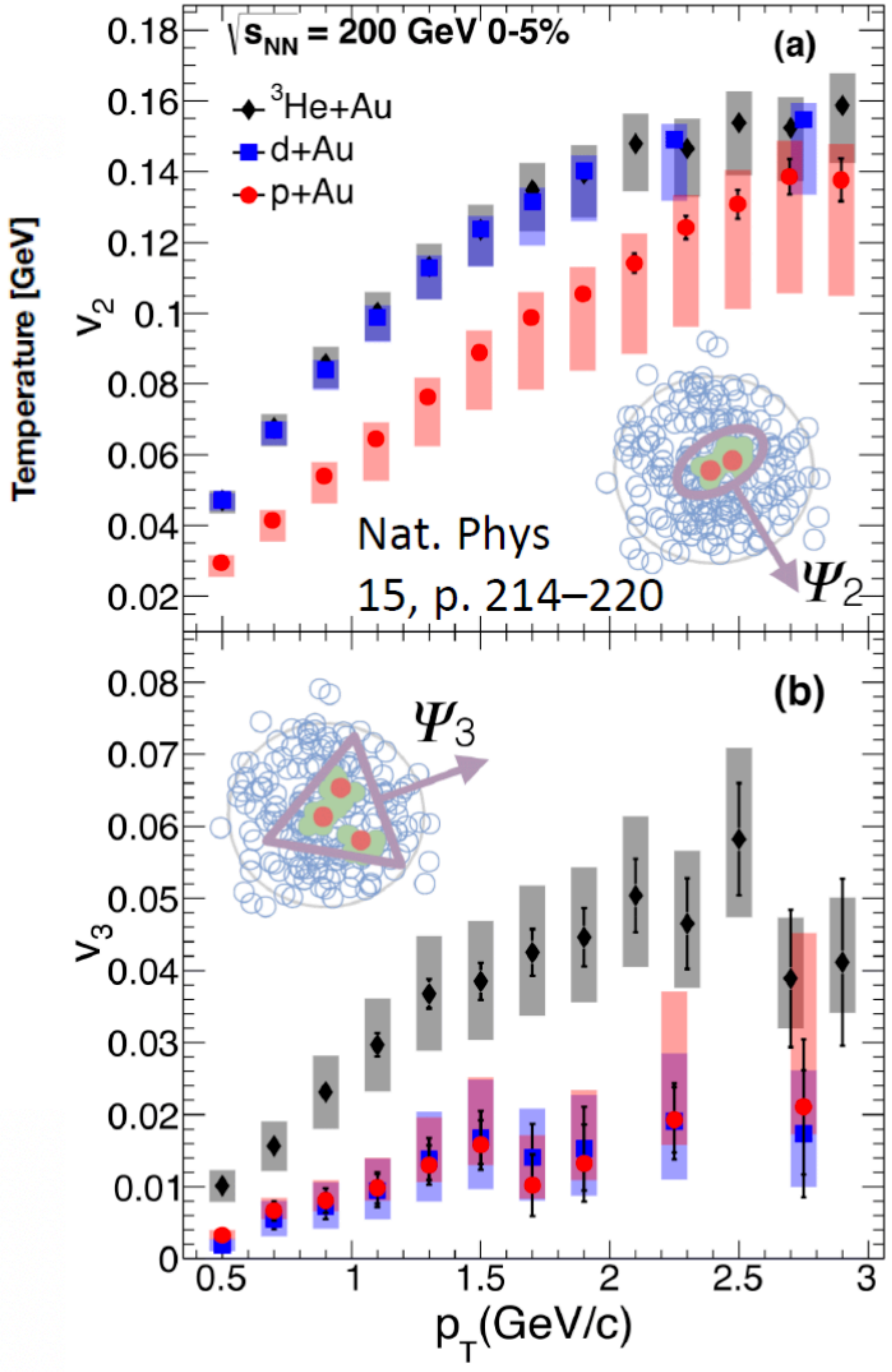
- Simulate small systems dynamically in 3+1D
- Initialize using MC-Glauber + string deceleration model with source terms in hydro
- Provides fluctuating transverse+longitudinal geometry



# SMALL SYSTEM SCAN AT RHIC

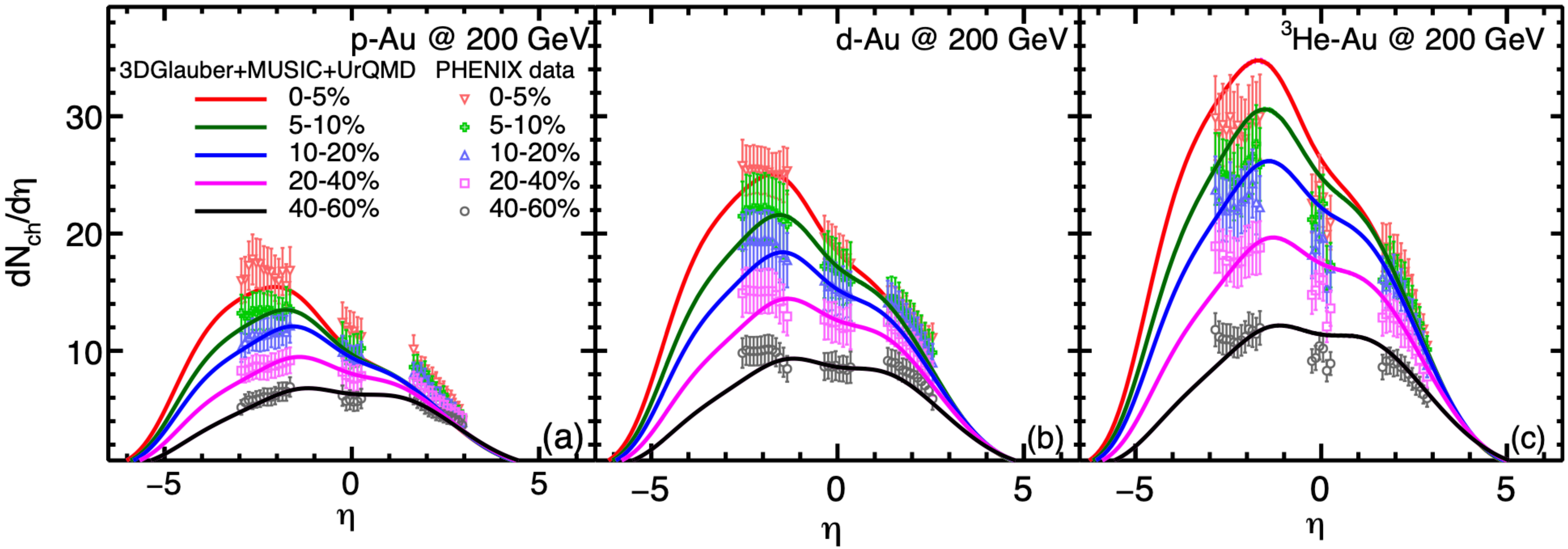
PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)





# MULTIPLICITY VS. RAPIDITY

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

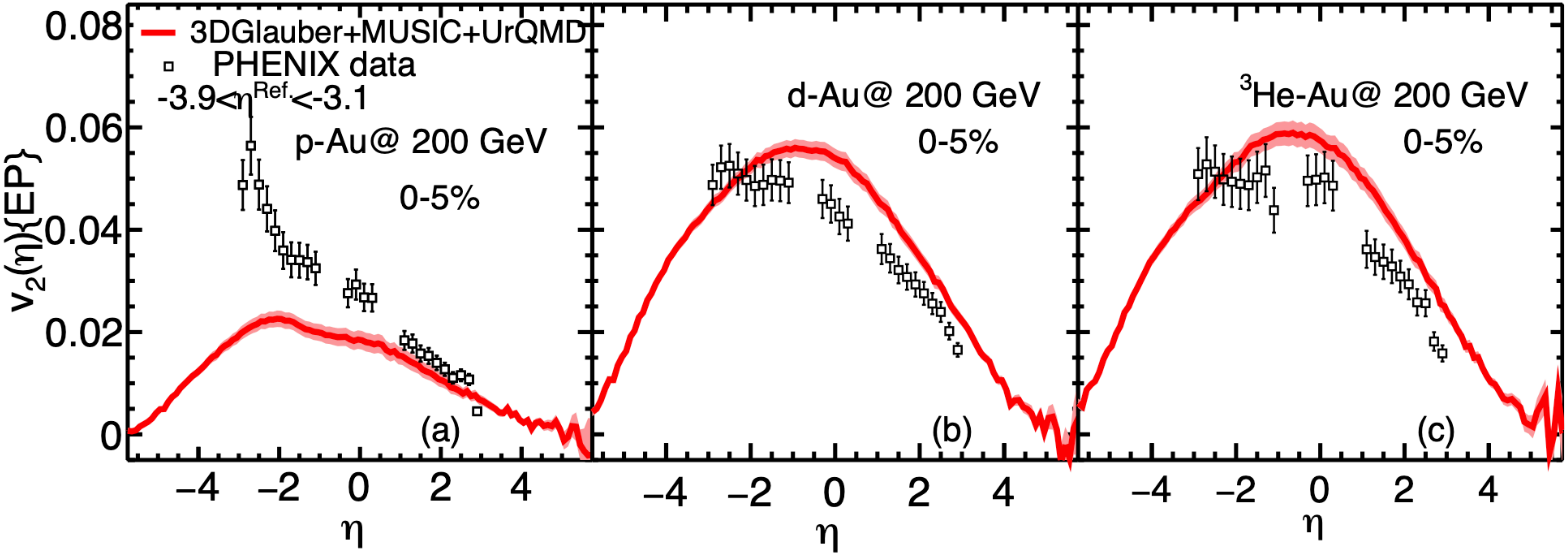


The (3+1)D hybrid model captures the rapidity and centrality dependence of $dN^{\mathrm{ch}}/d\eta$ for all asymmetric systems

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

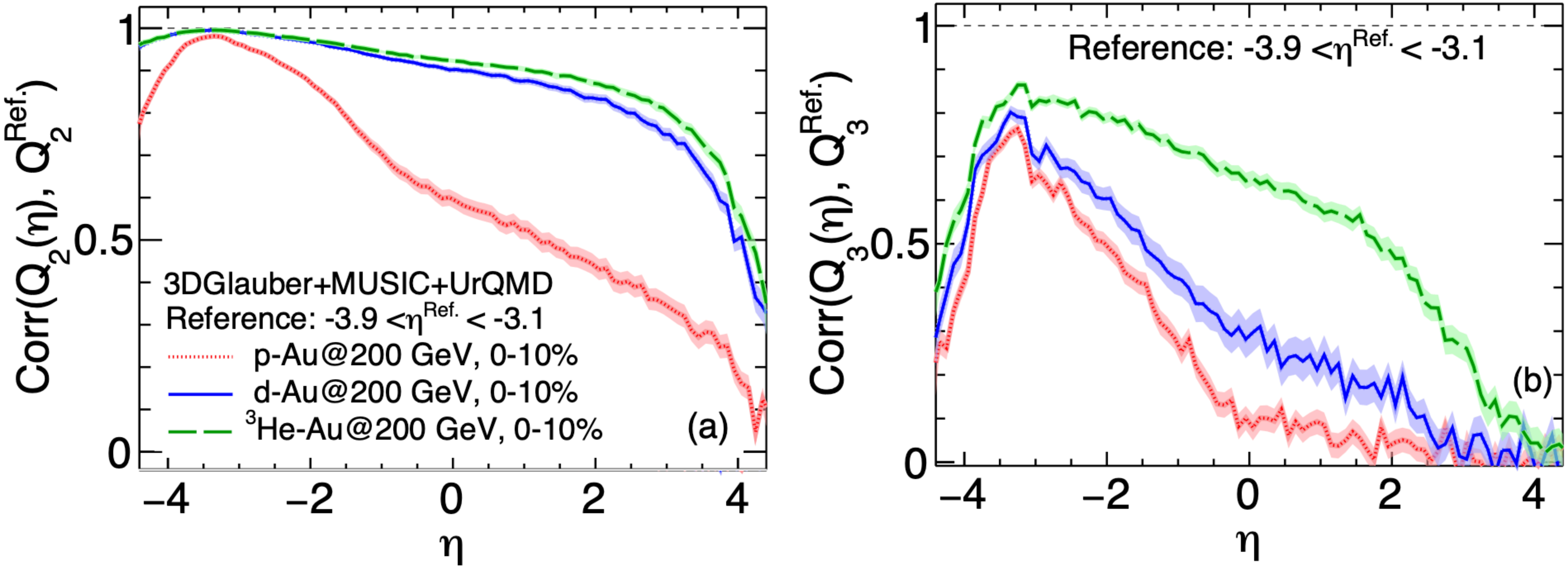


- Pseudo-rapidity dependence of $v_2\{EP\}$ reproduced for d+Au and $^3$He+Au
- The elliptic flow in $\eta < 1$ in p+Au collisions is underestimated because of the strong longitudinal flow decorrelation in our model + potential non-flow

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

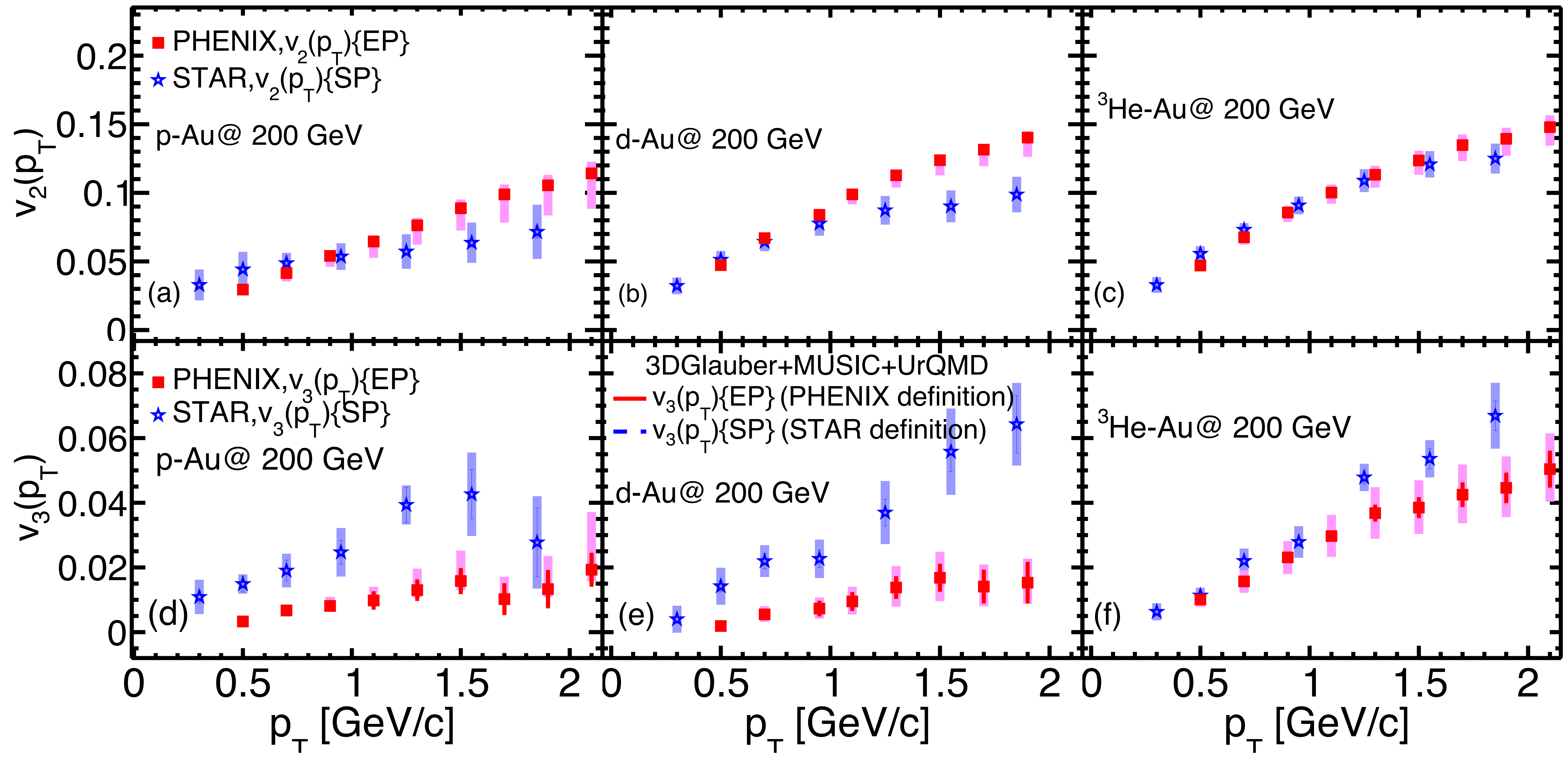


- Decorrelation is much stronger in the smaller p+Au system
- Decorrelations of $v_3$ flow vectors are much stronger than $v_2$
- **Hierarchy between $v_n$ and systems driven by decorrelation in this model**

**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



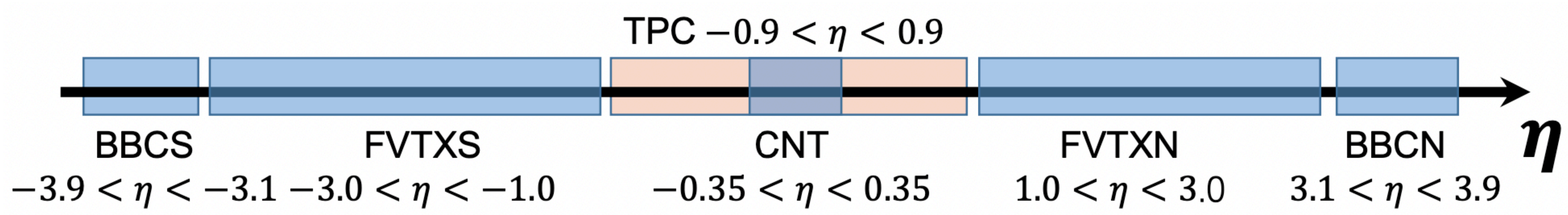
**PHENIX**:

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

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

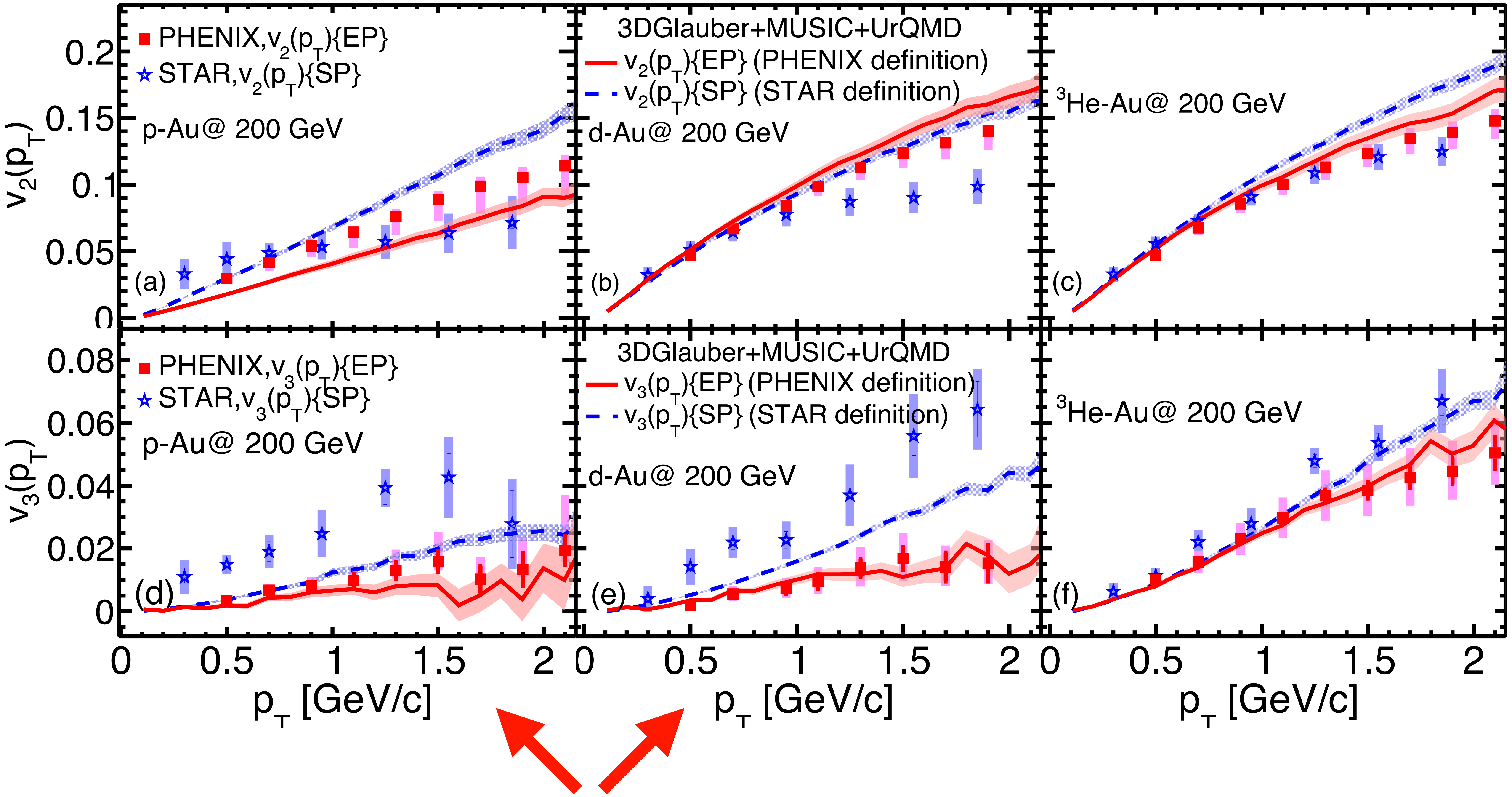
**STAR**:

$\eta \in [-0.9, 0.9]$ 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**:

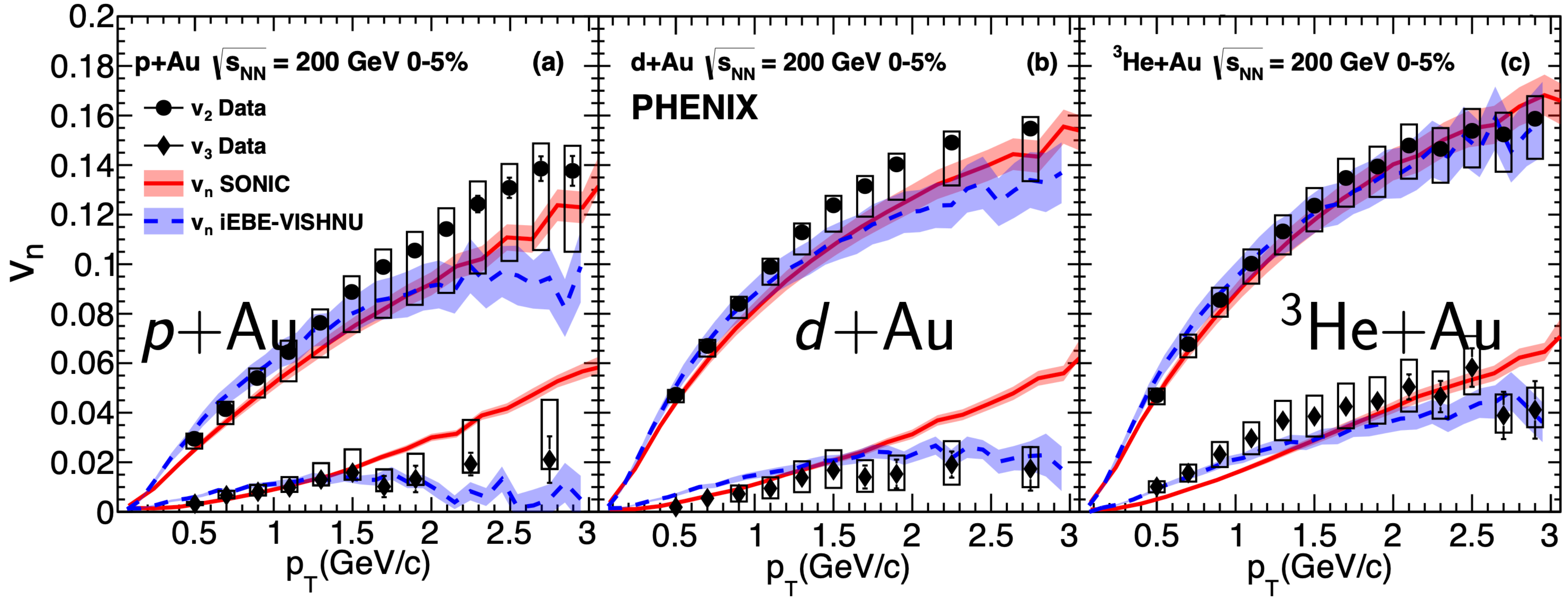
$\eta \in [-0.9, 0.9]$ with $|\Delta\eta| > 1$

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

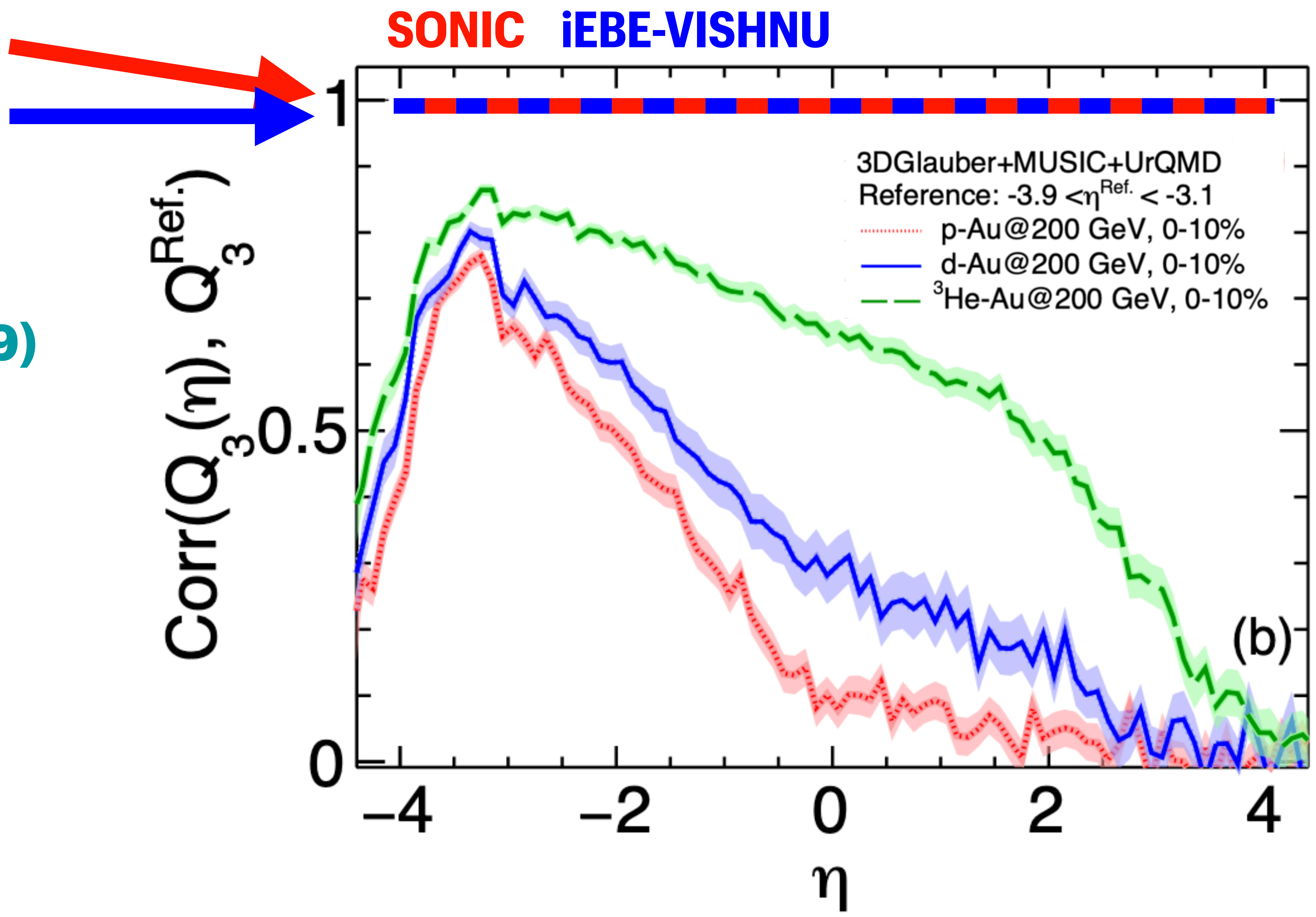
**Longitudinal flow decorrelations lead to smaller $v_3(p_T)$ for PHENIX, explaining ~50% of the difference between the two measurements**

# COMPARISON WITH BOOST INVARIANT MODELS

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



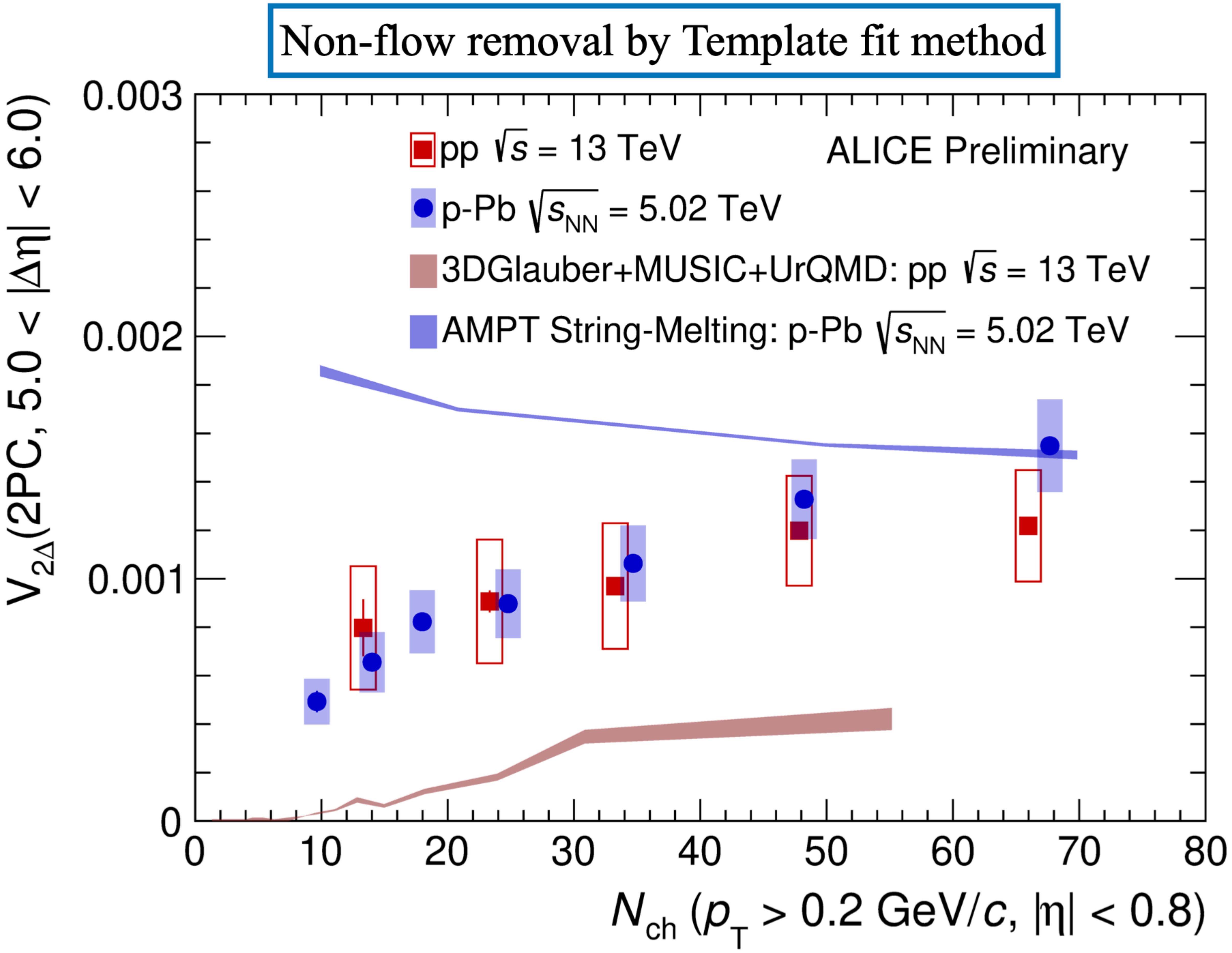
**PHENIX Collaboration, Nature Phys. 15, no.3, 214-220 (2019)**



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

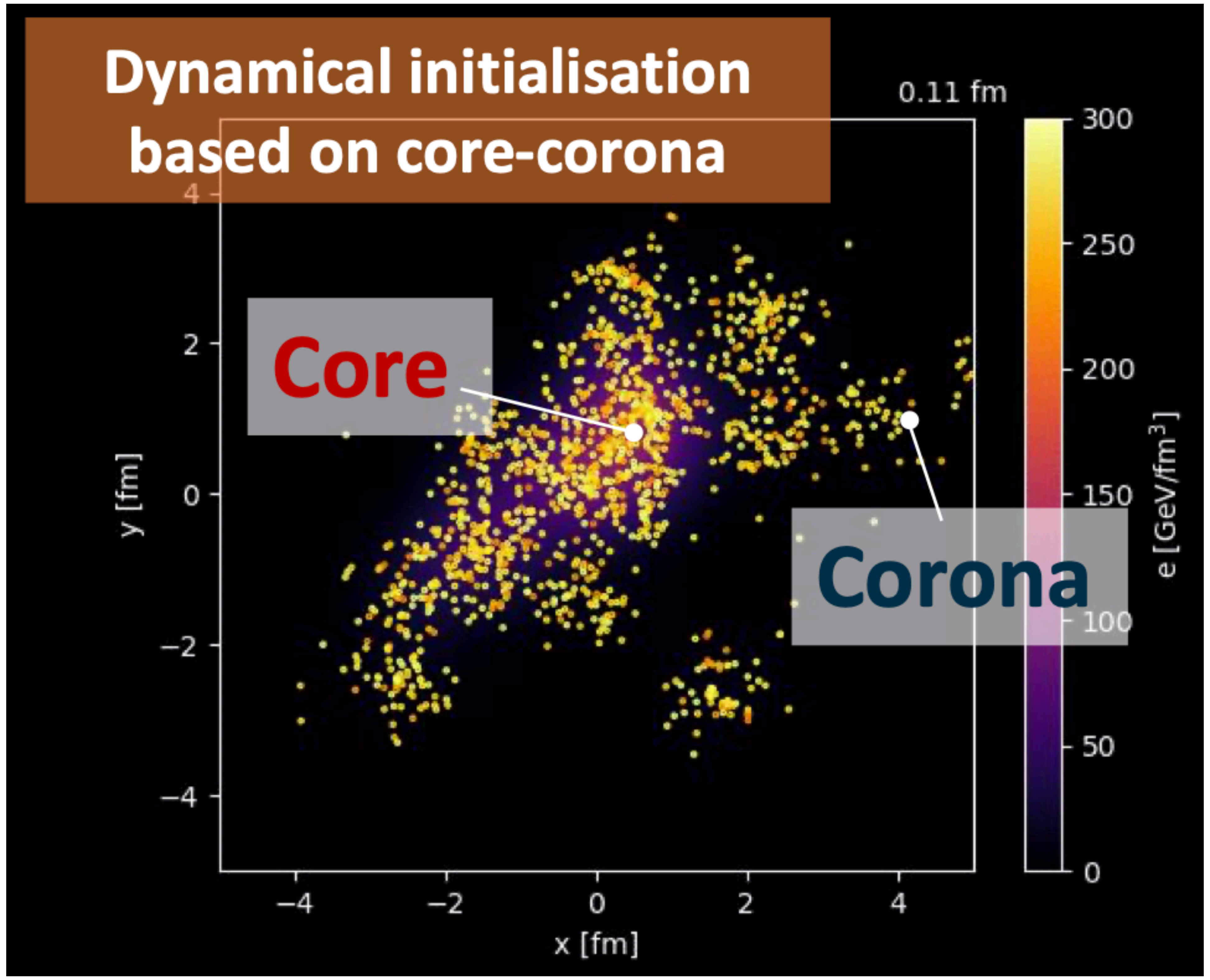
# VERY LONG RANGE CORRELATIONS

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



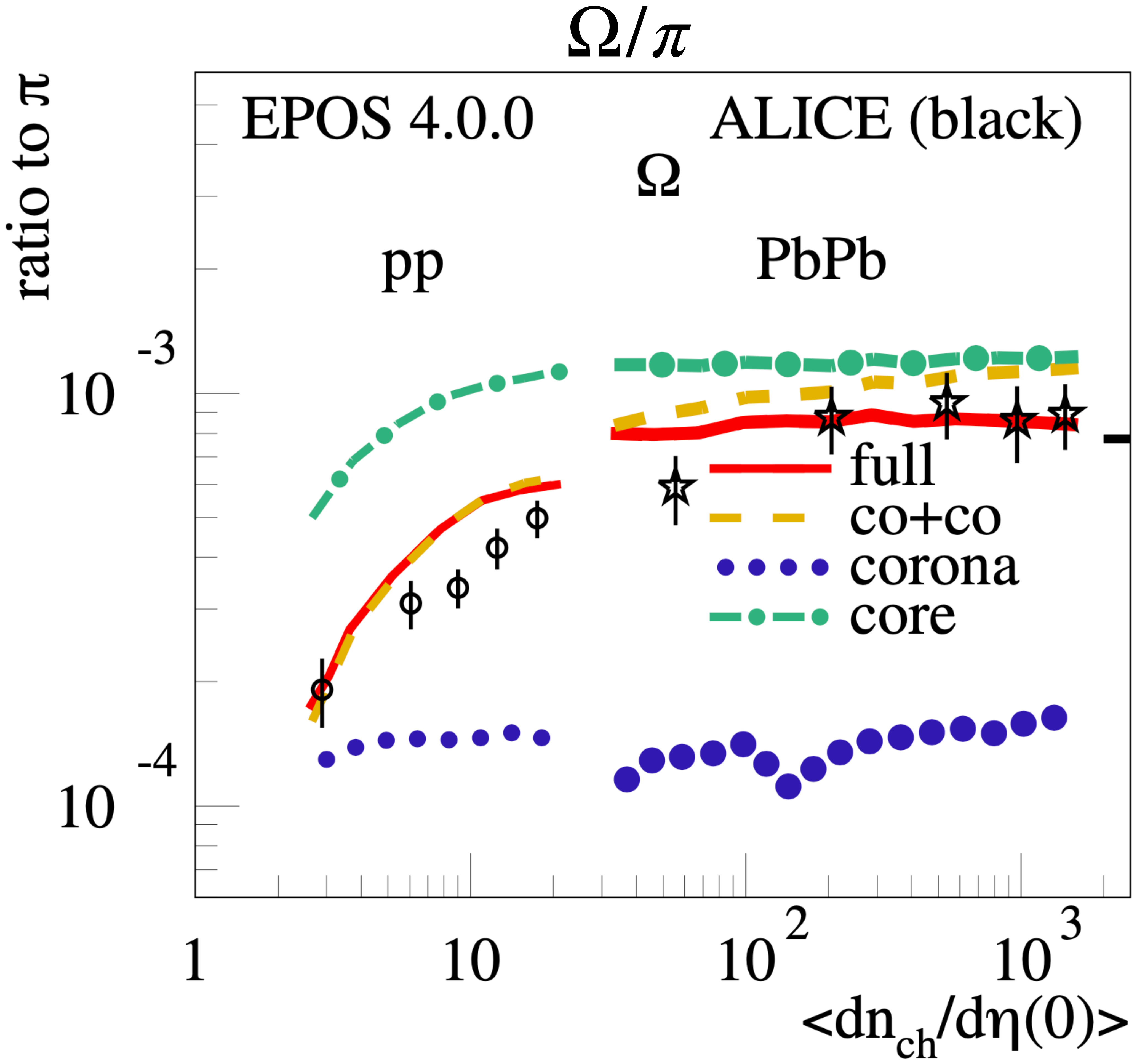
- p+p collisions at 13 TeV
- $5 < |\Delta\eta| < 6$
- Models do not describe the data
- Need better description of 3D geometry
- Applicability of hydrodynamics?

# CORE+CORONA PICTURE



Y. Kanakubo, Quark Matter 2023

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

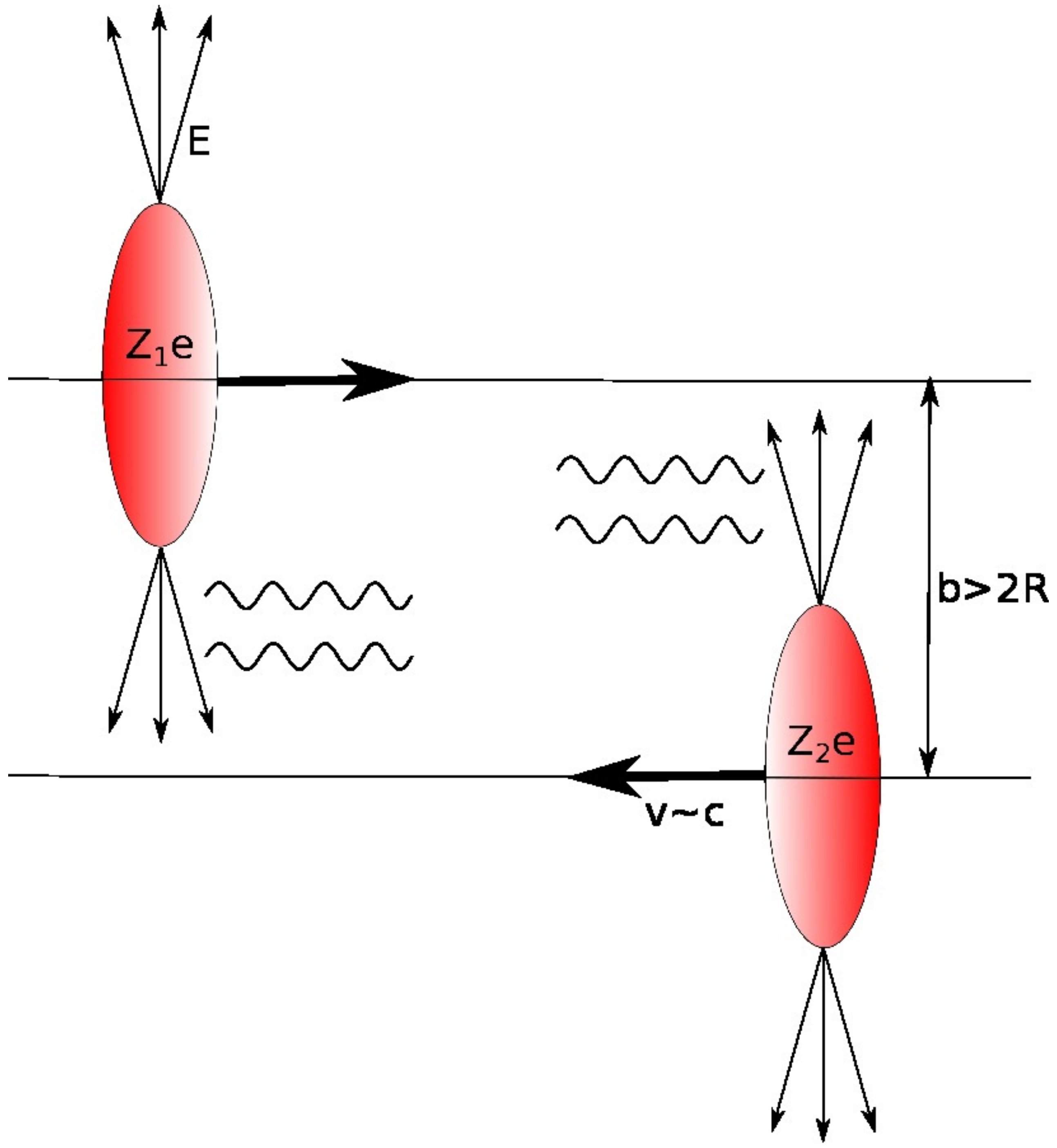


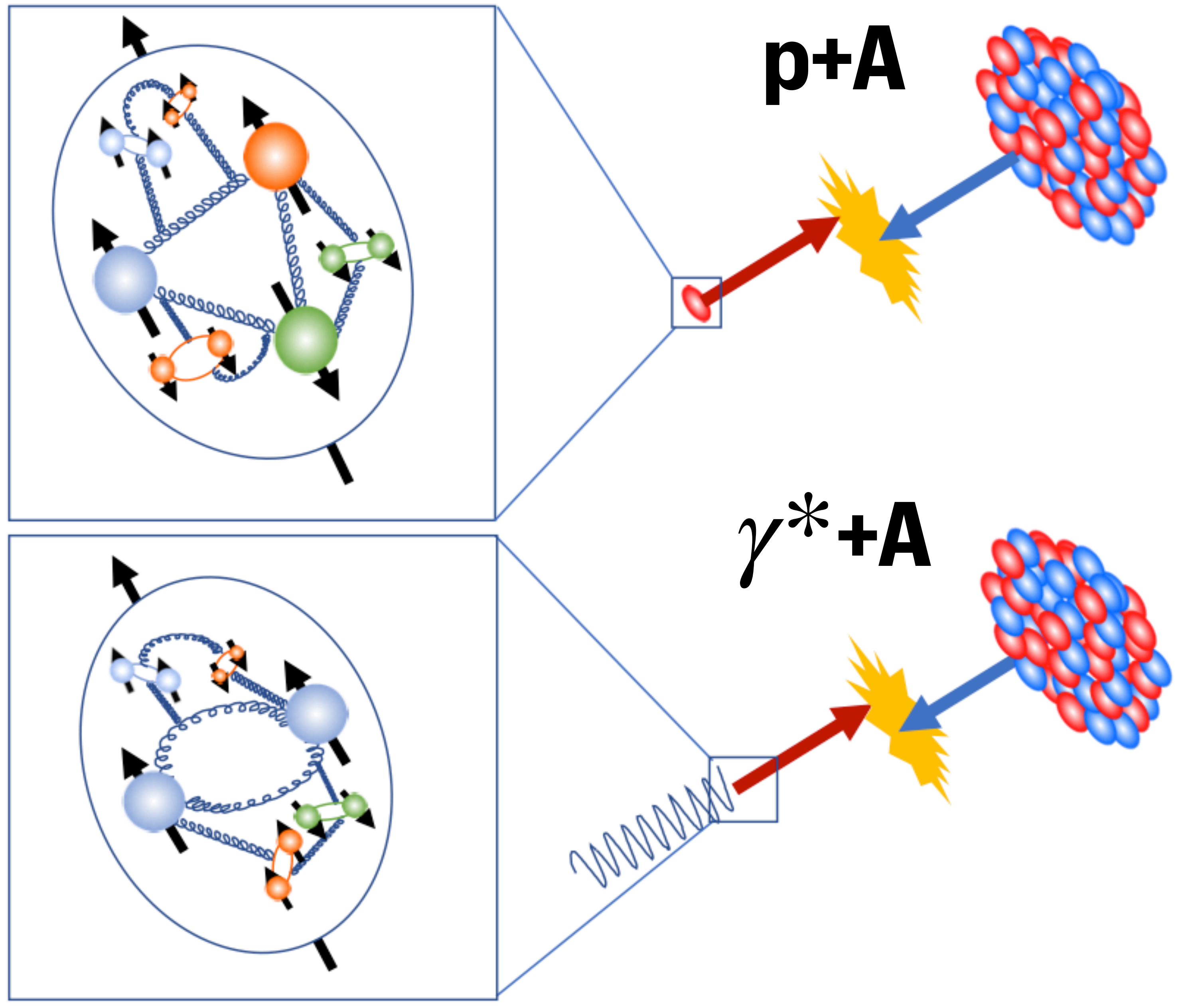
K. Werner, Phys.Rev.C 108 (2023) 6, 064903
see talk by P.B. Gossiaux

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

# SMALLER: ULTRAPERIPHERAL COLLISIONS

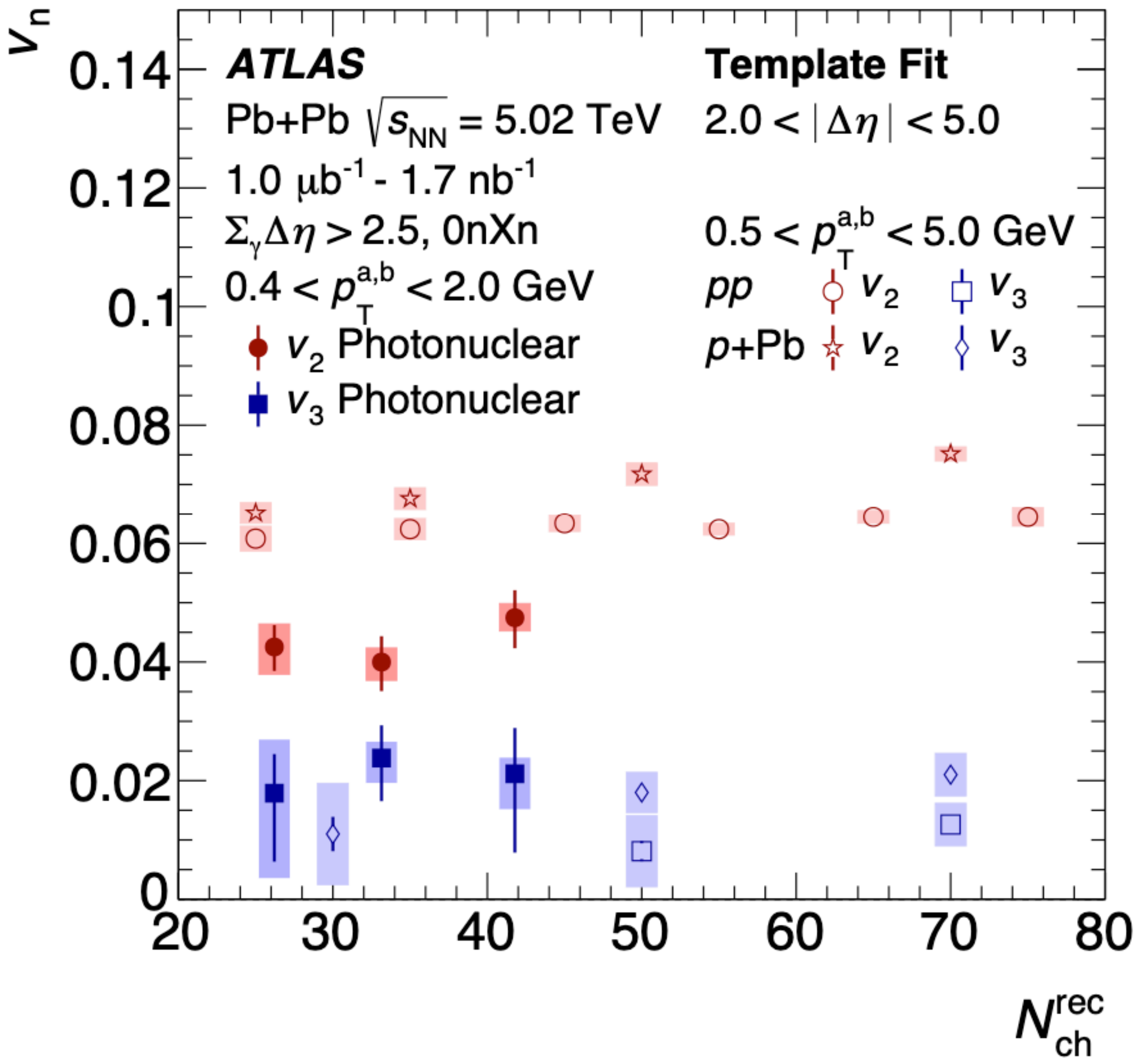
W. Zhao, C. Shen and B. Schenke, Phys.Rev.Lett. 129 (2022) 25, 252302





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

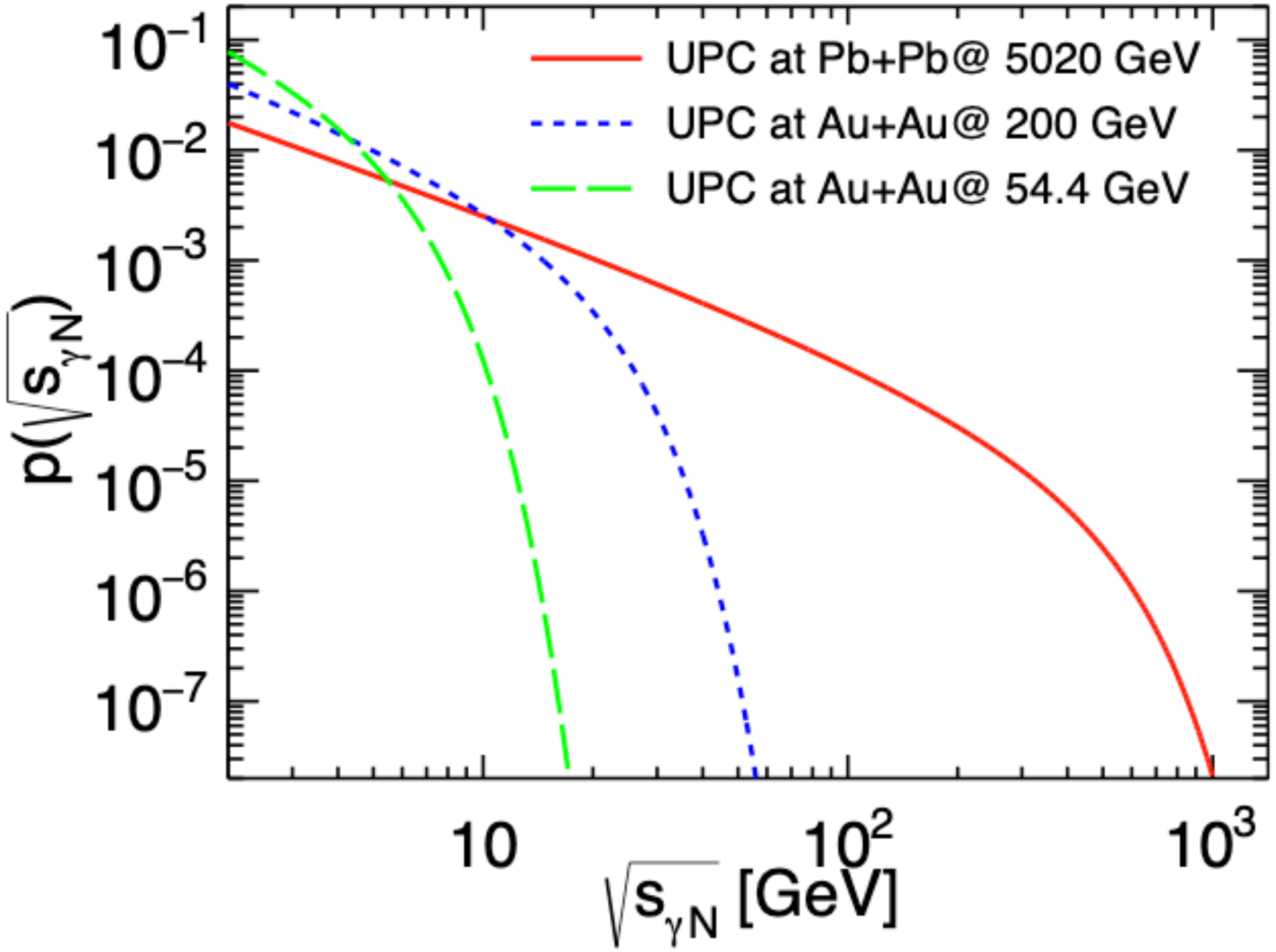
# MODELING $\gamma^* + \text{Pb}$

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

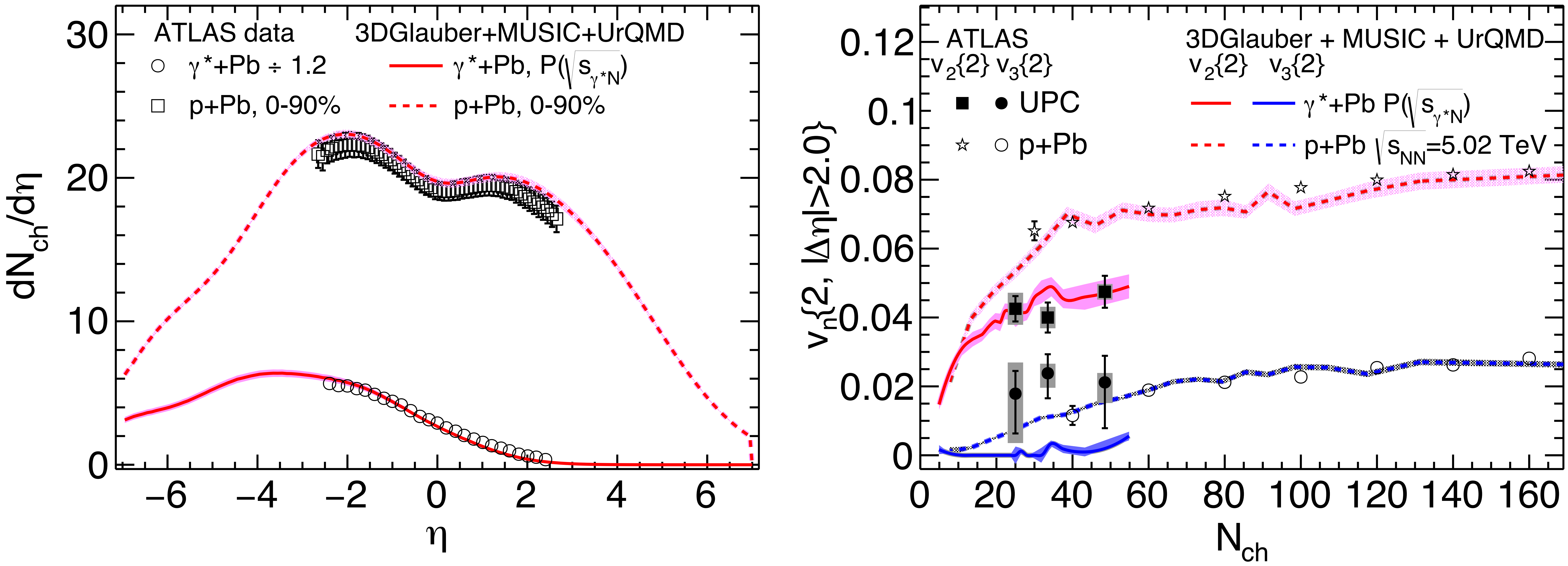
↓

- 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 $\gamma^*$+A

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

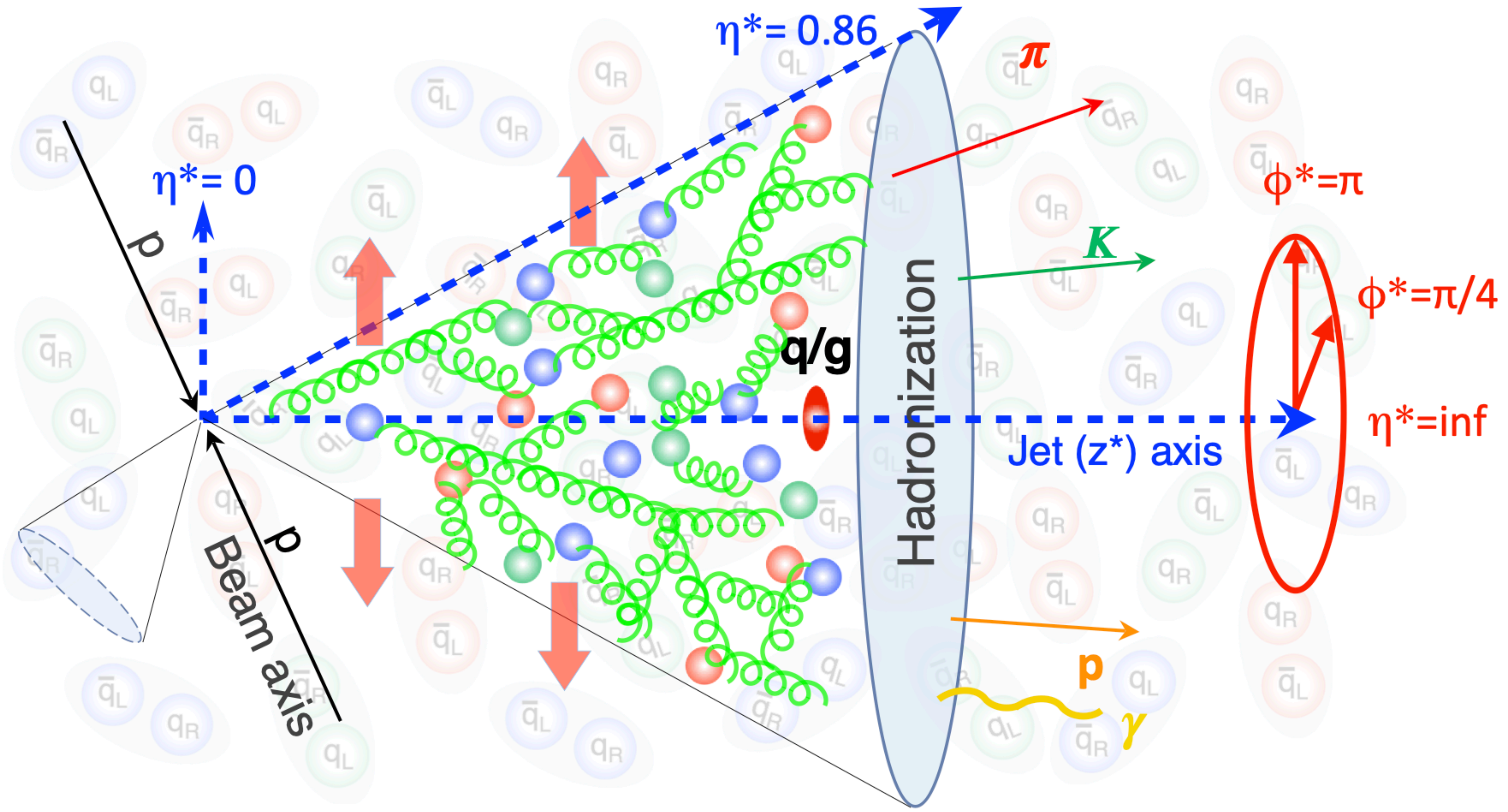


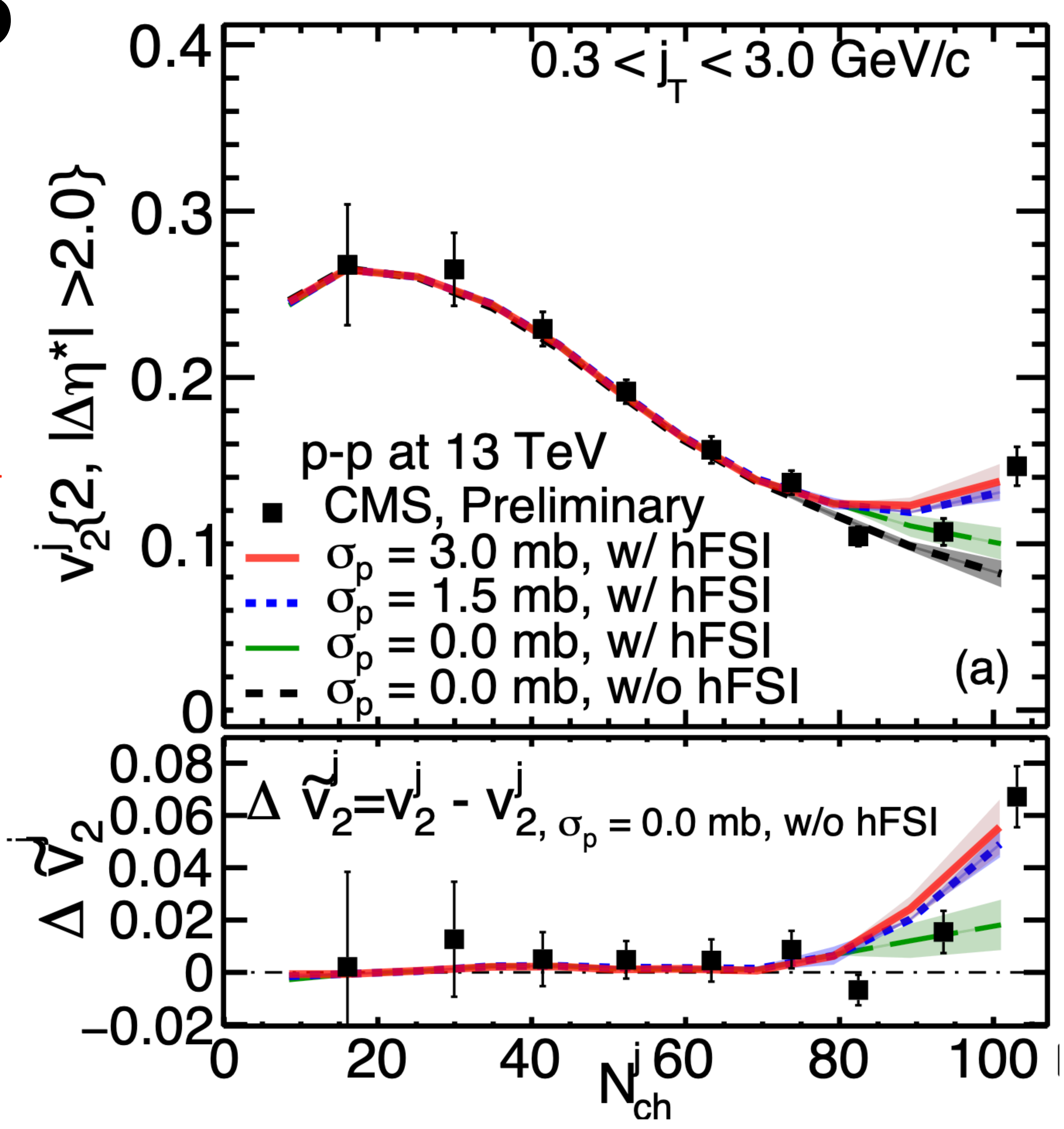
- Shapes of $dN_{ch}/d\eta$ reproduced for p+Pb and $\gamma^*$+Pb collisions
- Elliptic flow difference between p+Pb and $\gamma^*$+Pb collisions reproduced
  Driven by different amount of longitudinal flow decorrelation

# FLOW INSIDE JETS

**CMS Collaboration, arXiv:2312.17103**

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

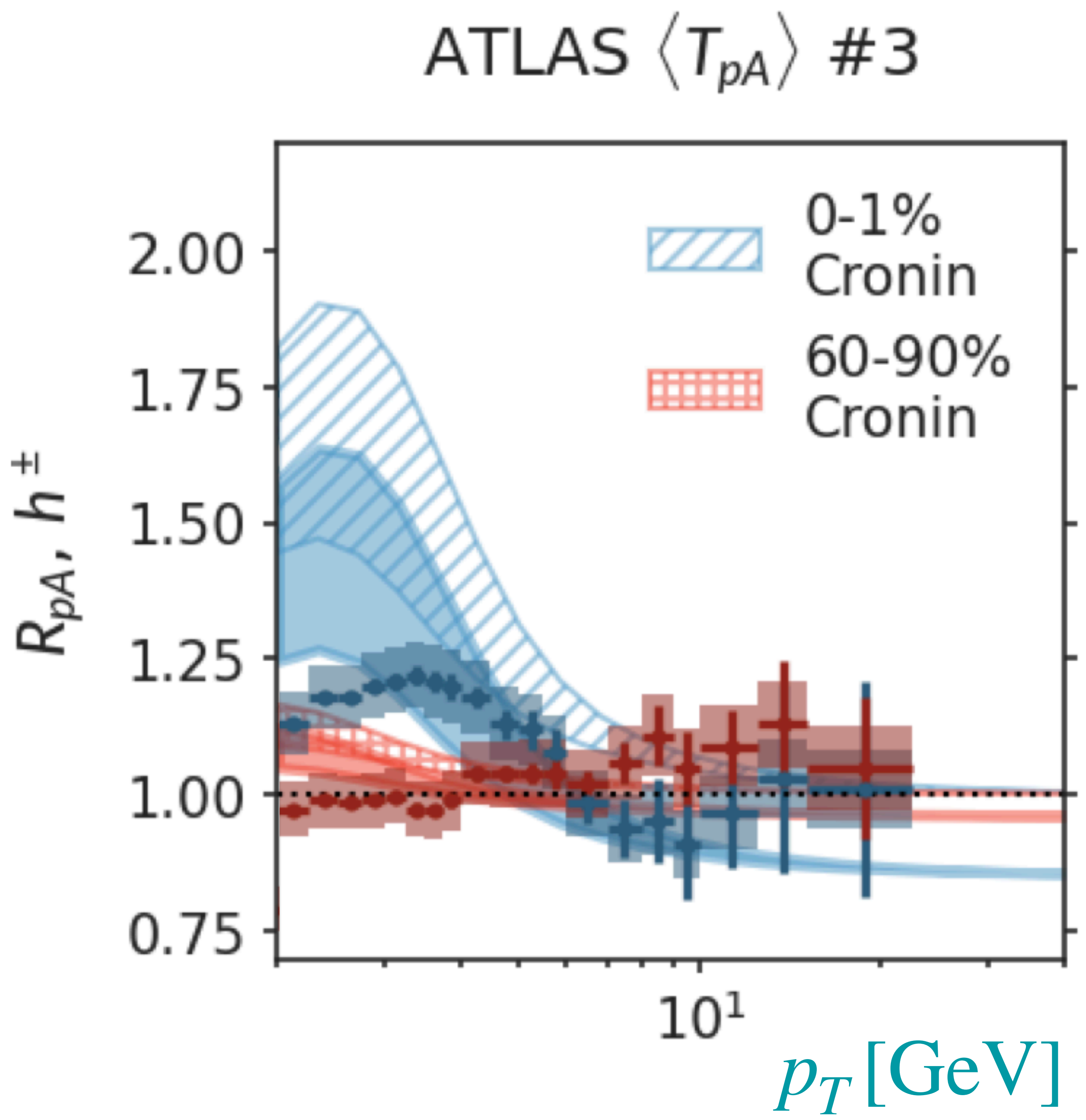




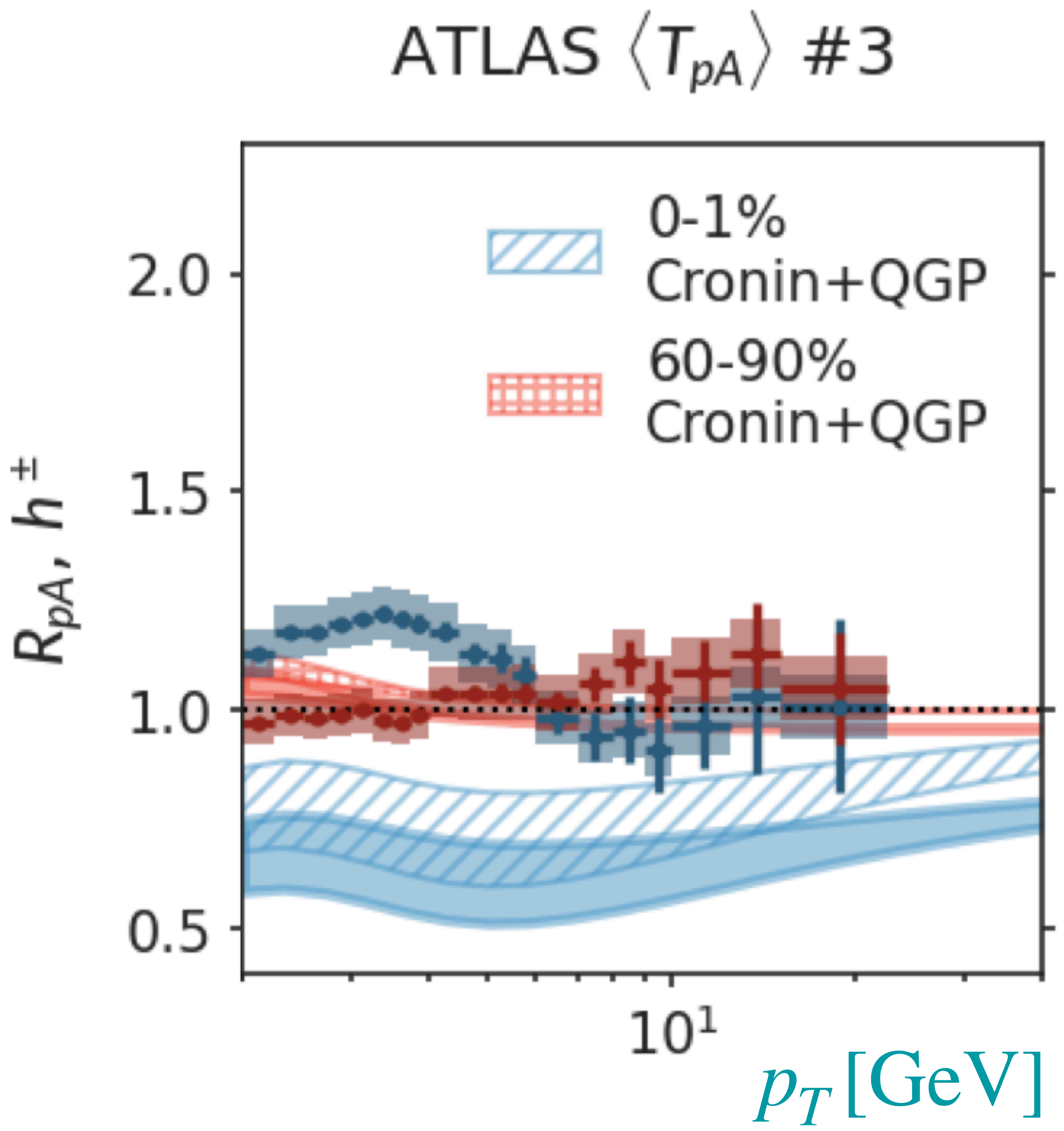
Final state effects can explain increase of $v_2$ at high multiplicity

# 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

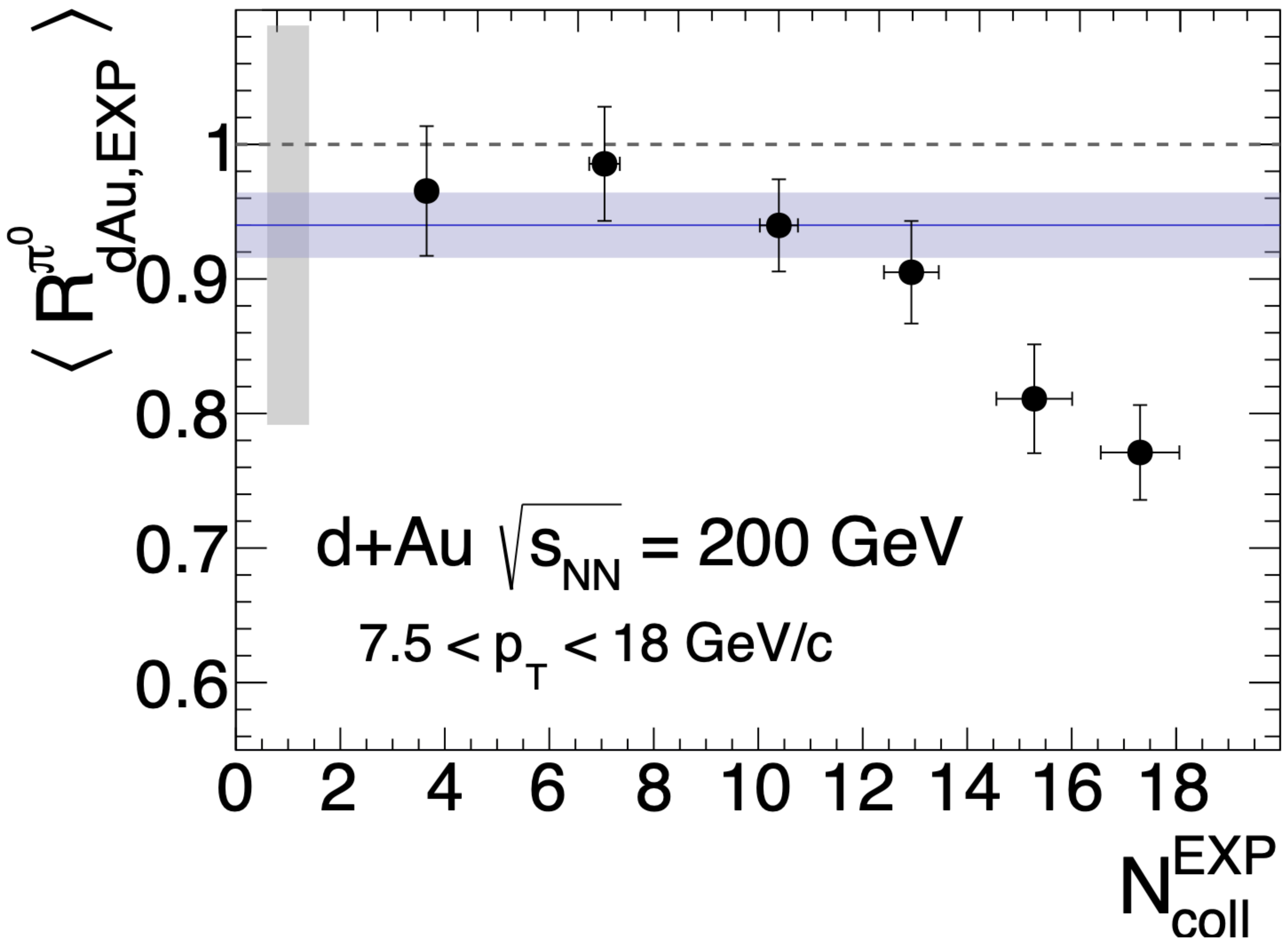
A. Majumder for JETSCAPE, arXiv:2308.02650

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

# HARD PROBES - EXPERIMENTAL $N_{\mathrm{coll}}$

Removing centrality selection bias in $\pi^0$ suppression in d+Au collisions:

PHENIX Collaboration, arXiv:2303.12899



event activity from direct photons

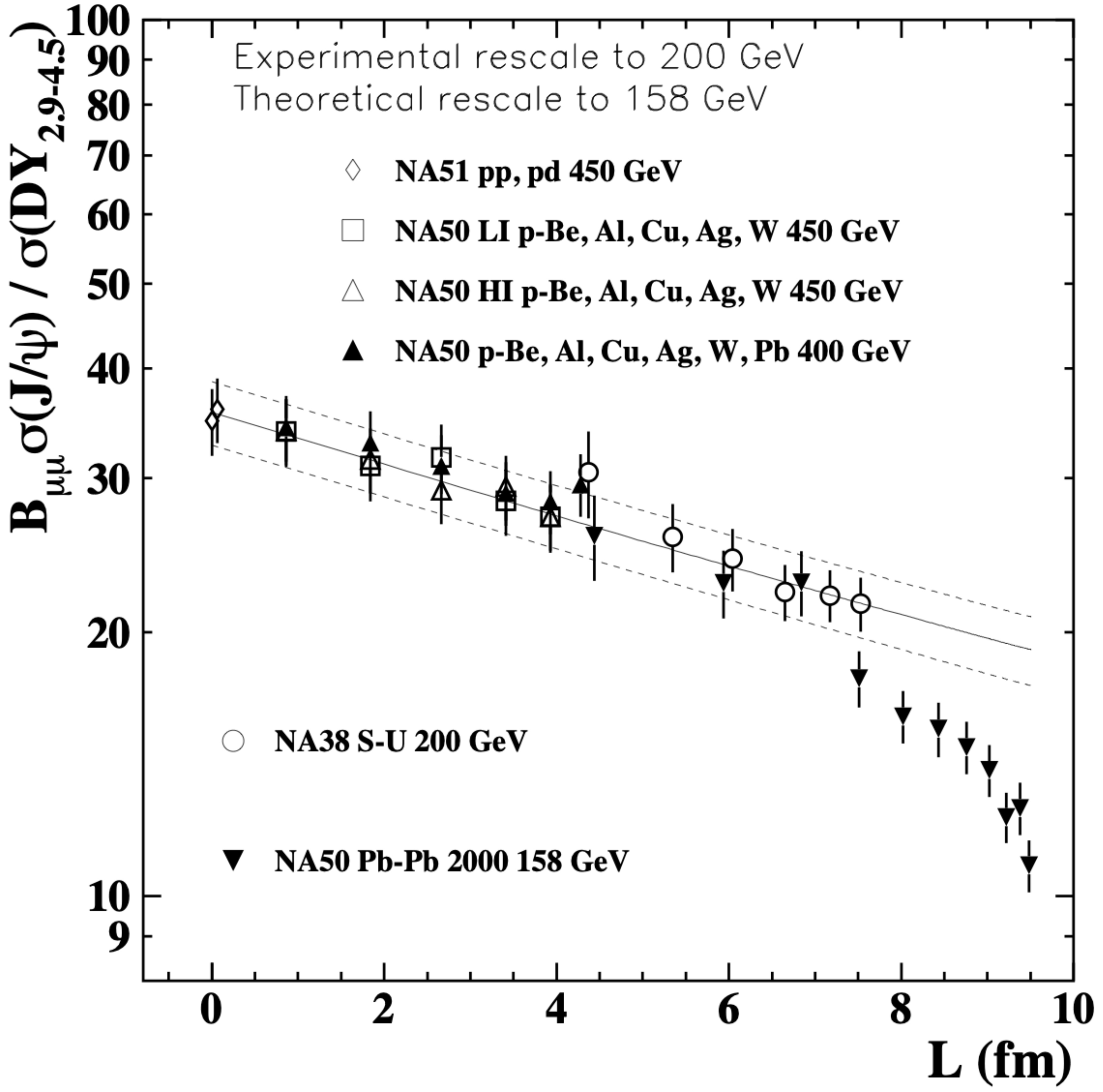
- Direct photons as benchmark for particle production from hard-scattering processes

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

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

# J/PSI SUPPRESSION IN SMALL SYSTEMS

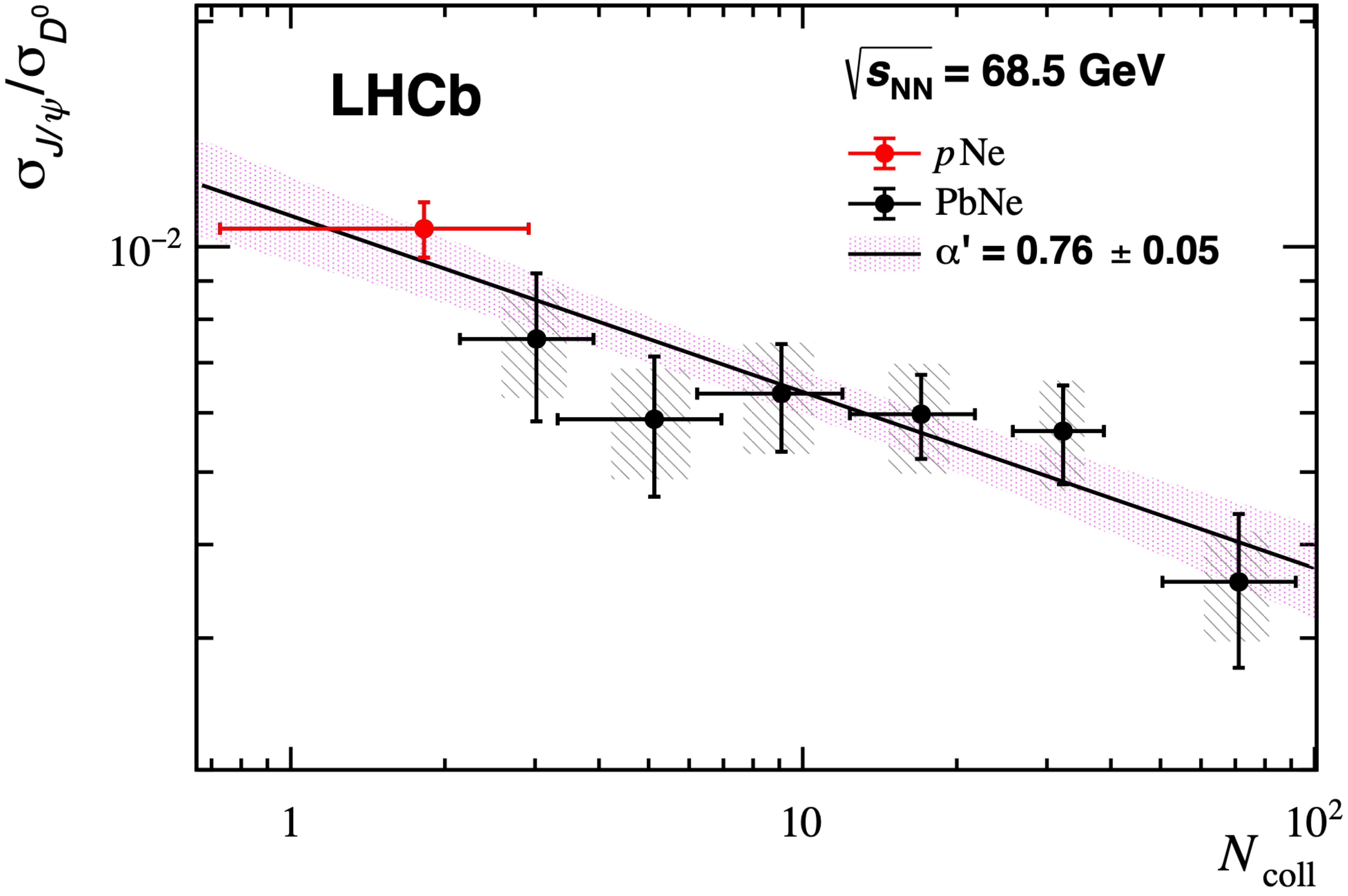
NA50 Collaboration
Eur.Phys.J.C 39 (2005) 335-345



system size →

No QGP-like $J/\psi$ suppression in Pb+Ne

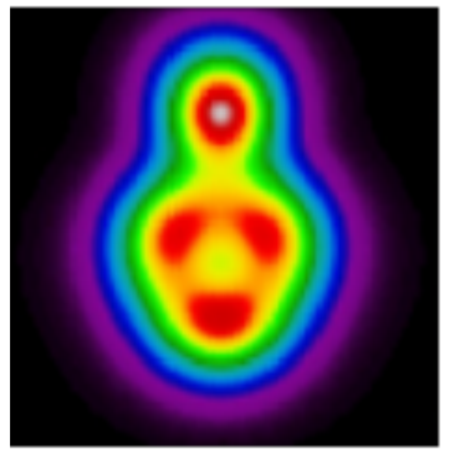
LHCb Collaboration, Eur.Phys.J.C 83 (2023) 7, 658



# Pb+Ne and Pb+O

G. Giacalone et al, arXiv:2405.20210

- Flow sensitive to shapes of Ne and O



- 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