BJÖRN SCHENKE - BROOKHAVEN NATIONAL LABORATORY

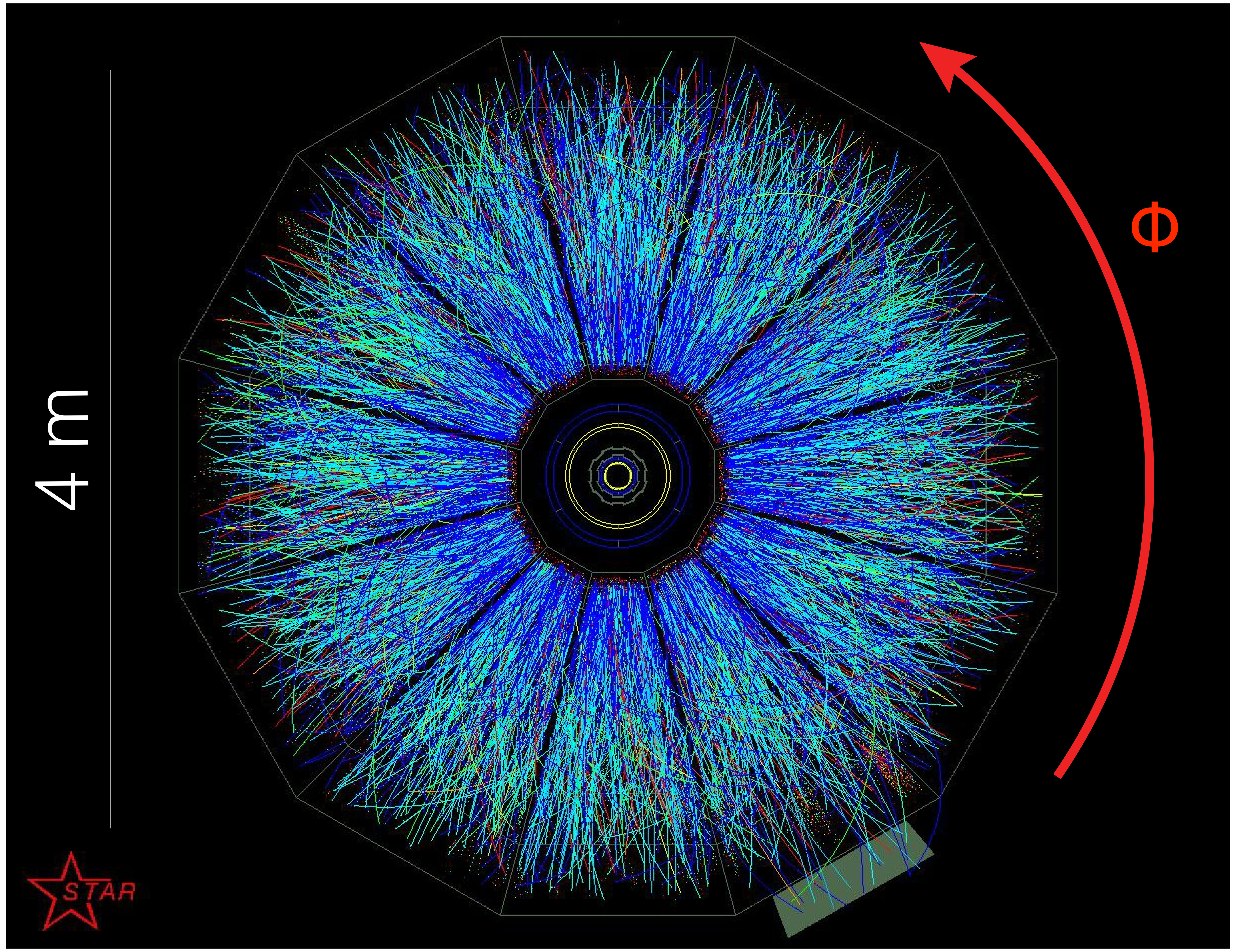
COLLECTIVE PHENOMENA IN SMALL COLLISION SYSTEMS

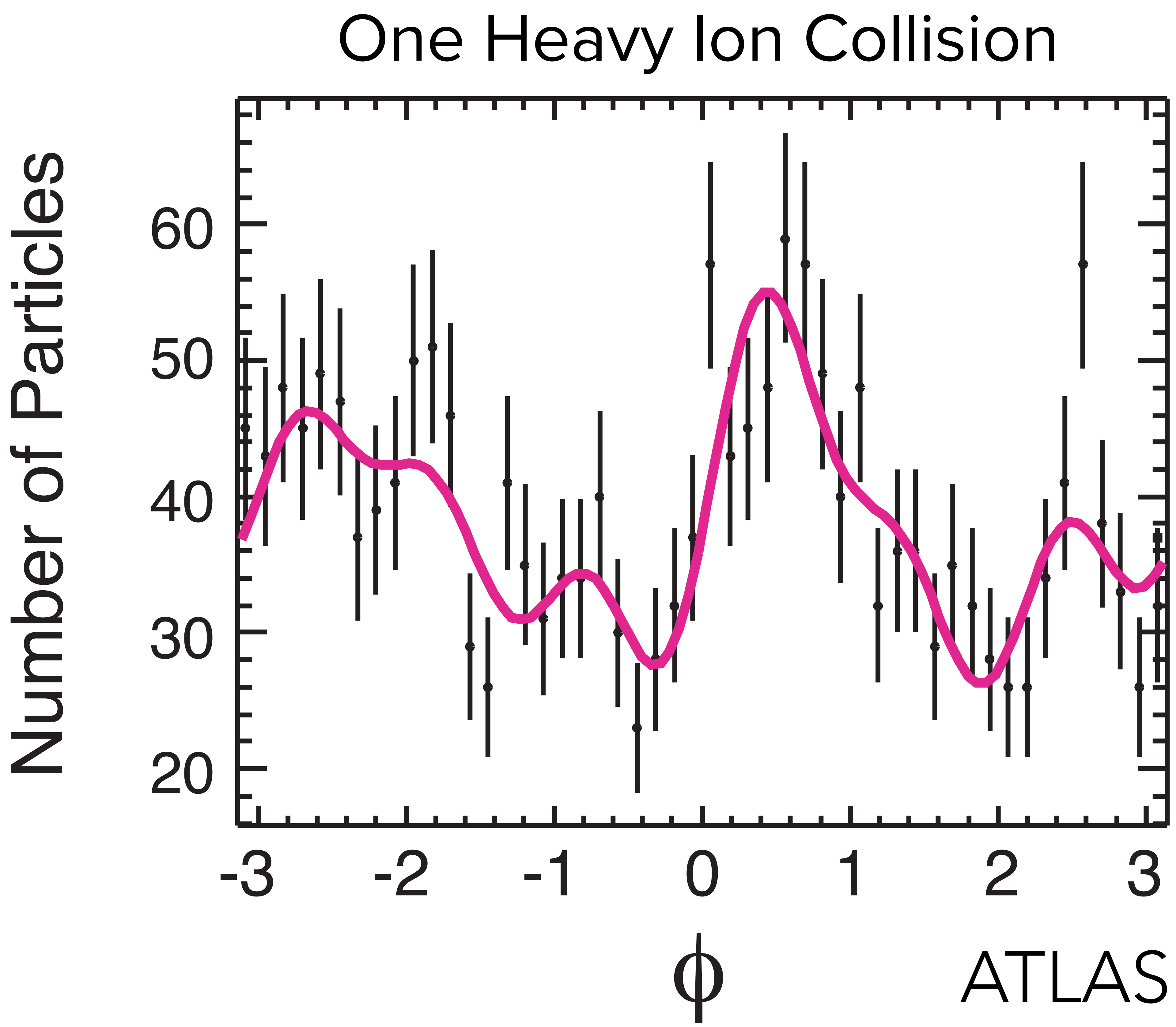
Strong and Electro-Weak Matter 2022
IPhT, Saclay - Université Paris VI, Paris
June 23 2022

Brookhaven™ National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

AZIMUTHAL ANISOTROPIES IN PARTICLE SPECTRA

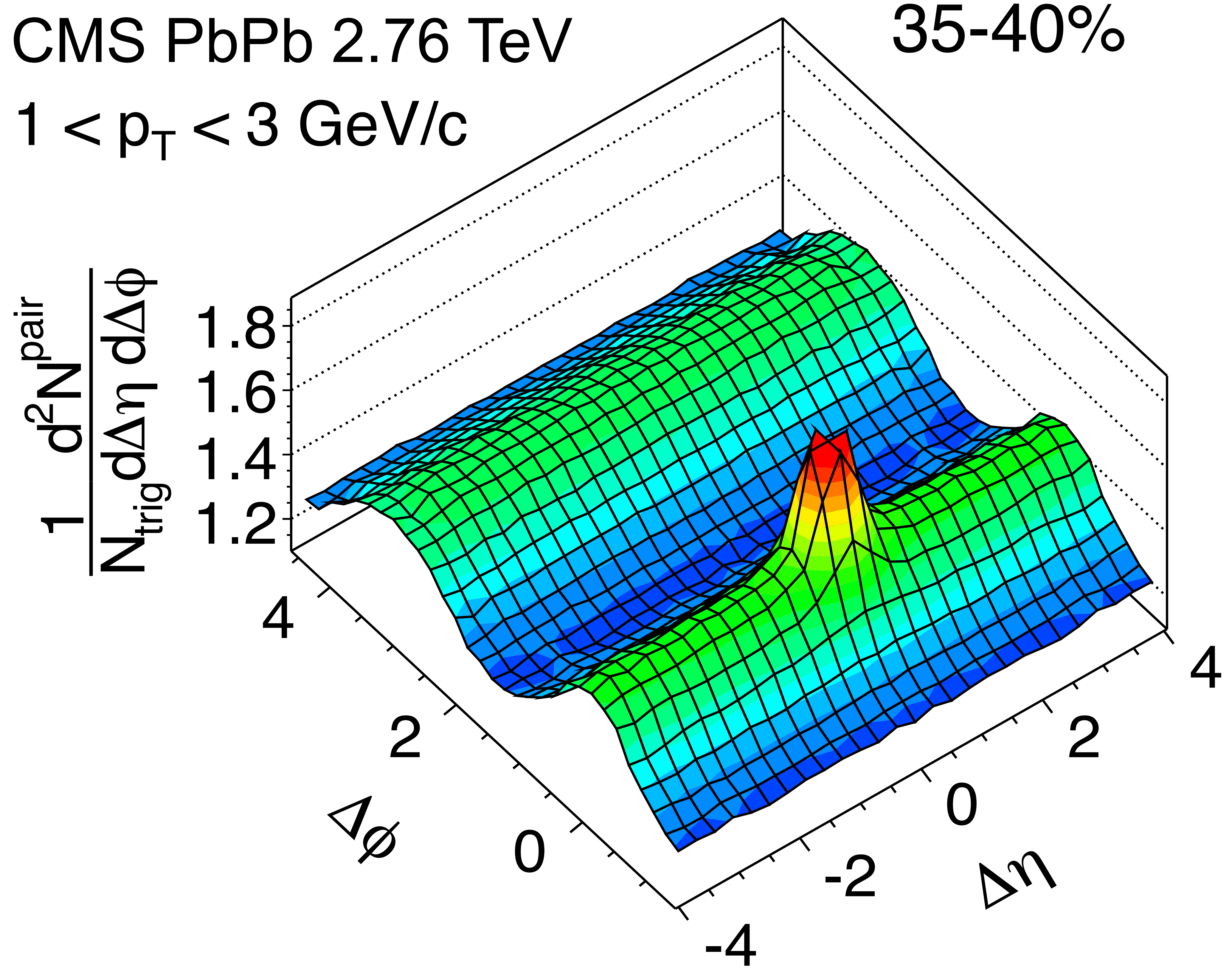




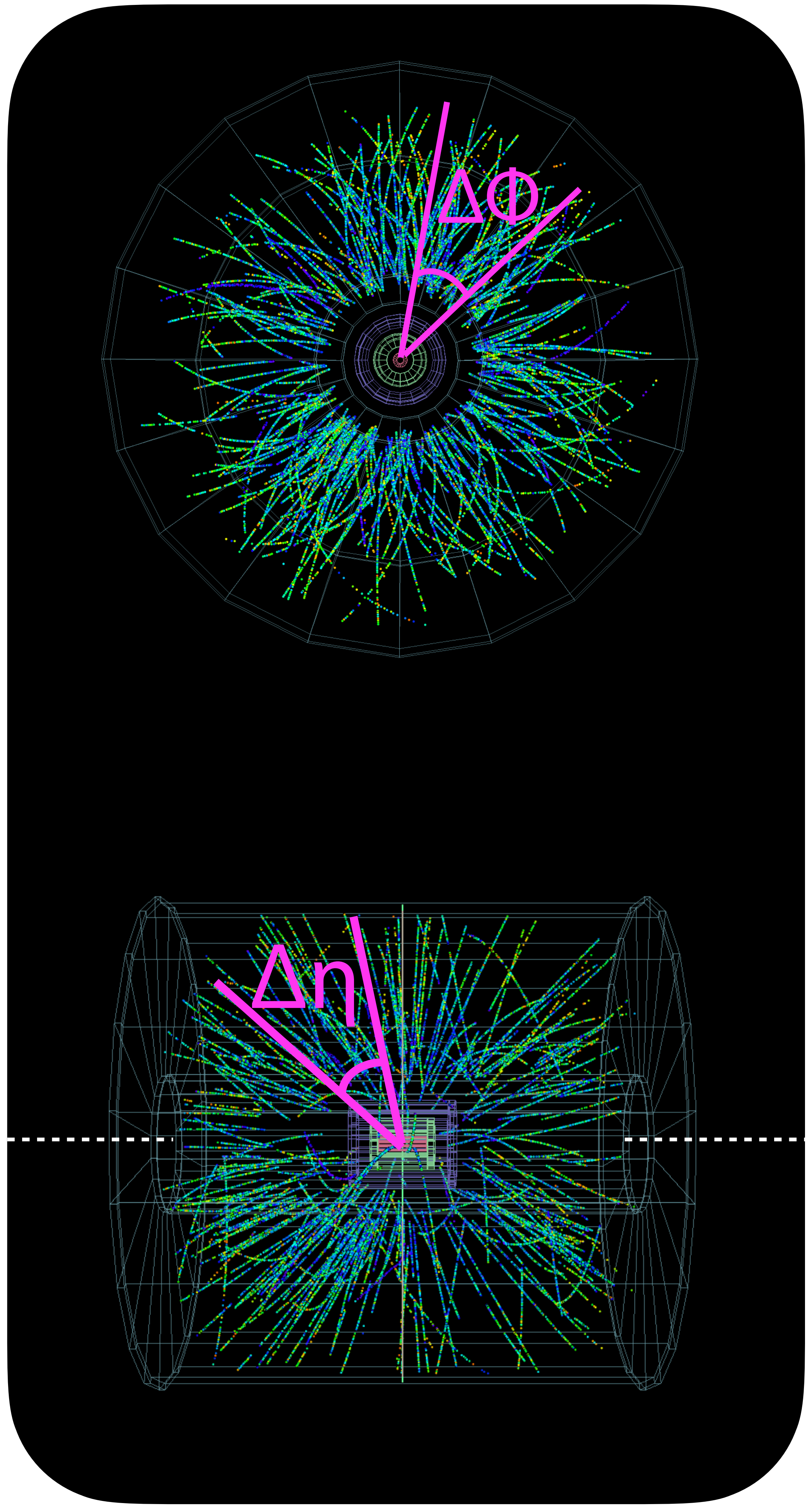
$$\frac{dN}{d\phi} = \frac{N}{\pi}\left(\frac{1}{2} + v_1 \cos[(\phi - \psi_1)] + v_2 \cos[2(\phi - \psi_2)] + v_3 \cos[3(\phi - \psi_3)] + v_4 \cos[4(\phi - \psi_4)] + \ldots\right)$$

MEASURING THE MOMENTUM ANISOTROPY

2-particle correlation vs. Δη and Δϕ:



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



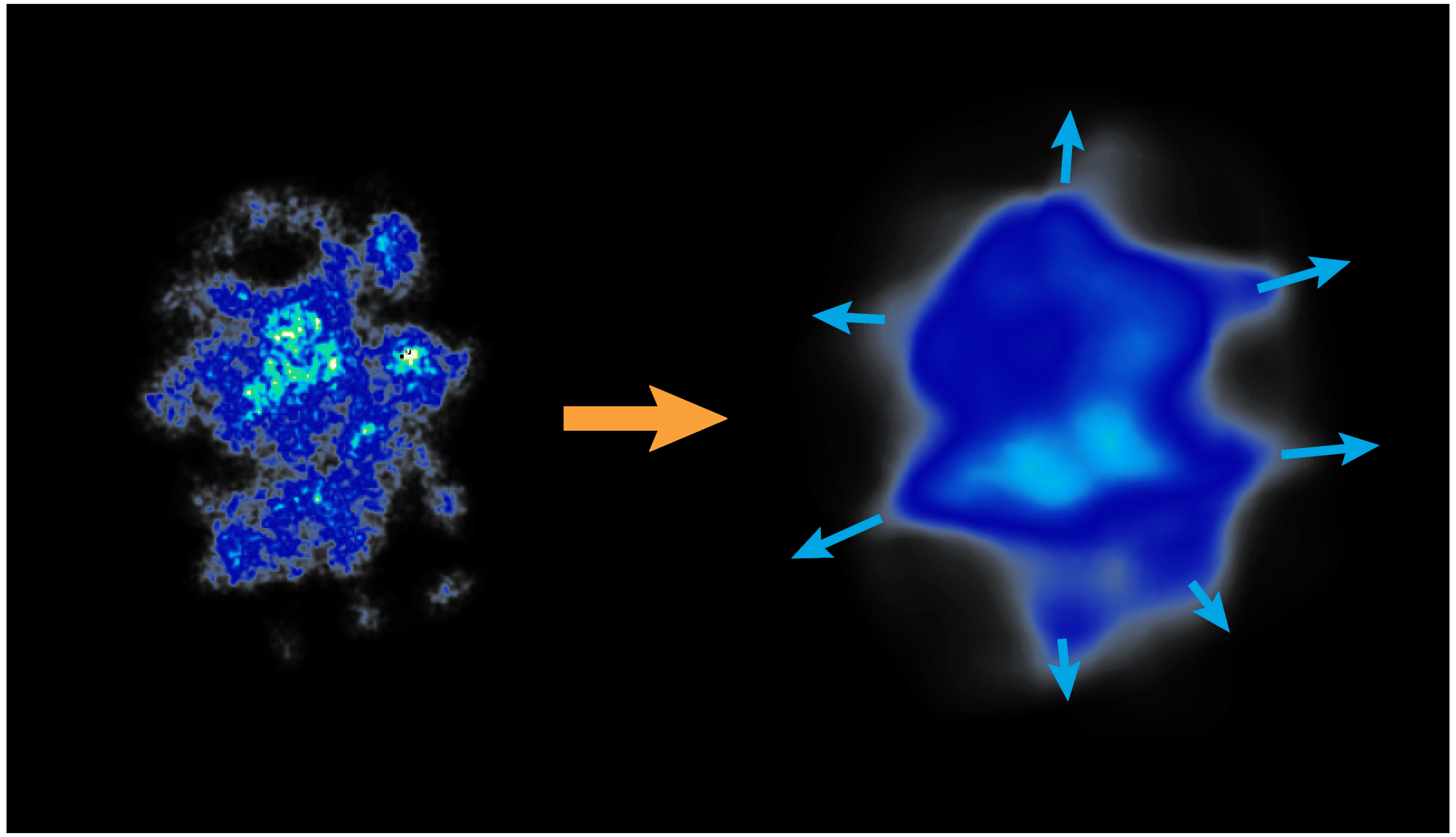
Event Displays: © 2012 CERN, ALICE

ΔΦ: DIFFERENCE IN AZIMUTHAL ANGLE

Δη: DIFFERENCE IN PSEUDO-RAPIDITY

INTERPRETATION: STRONG FINAL STATE EFFECTS

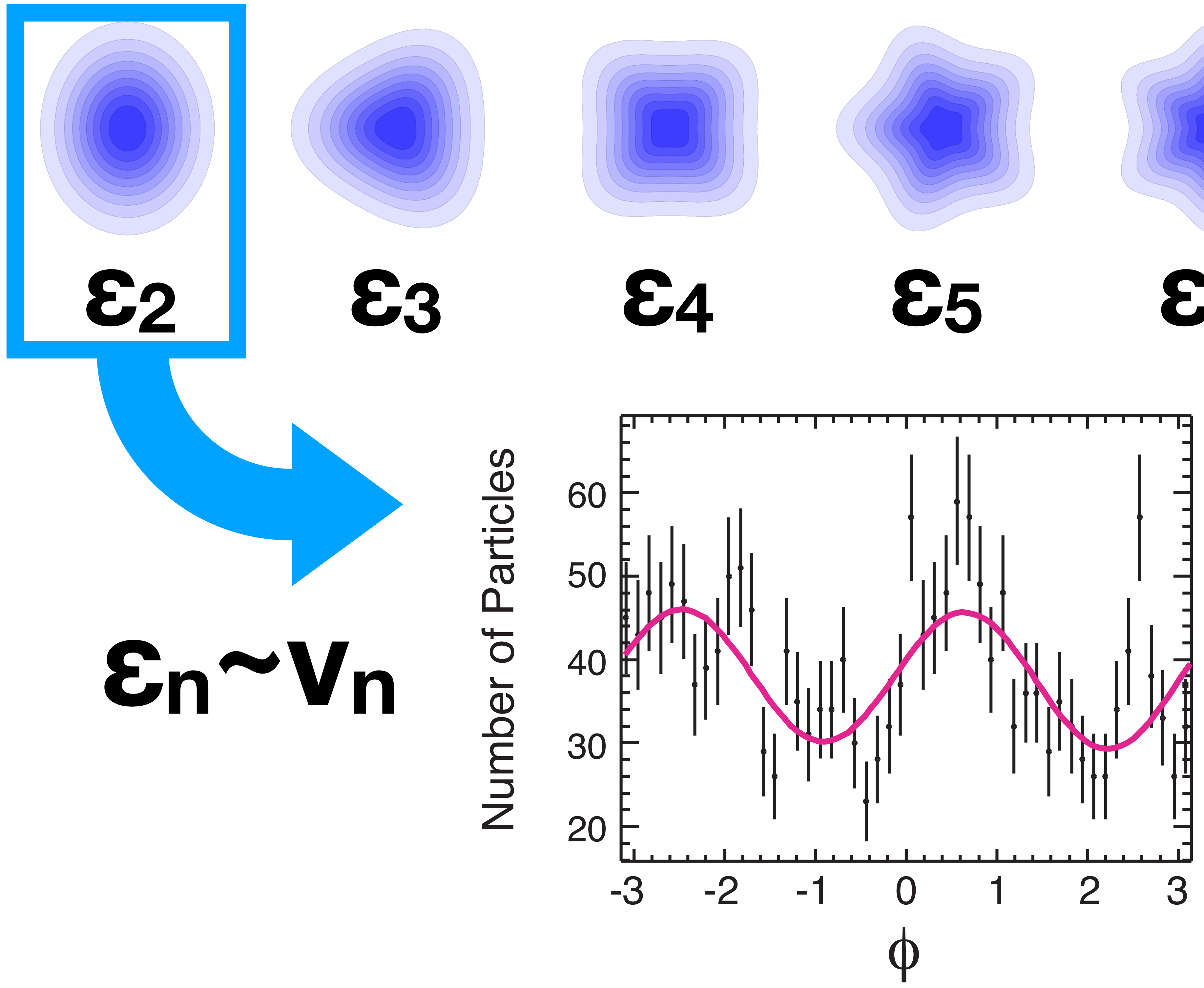
Initial geometry is converted into final state momentum anisotropies
Hydrodynamics describes this well: Pressure gradients at work



Initial energy density distribution

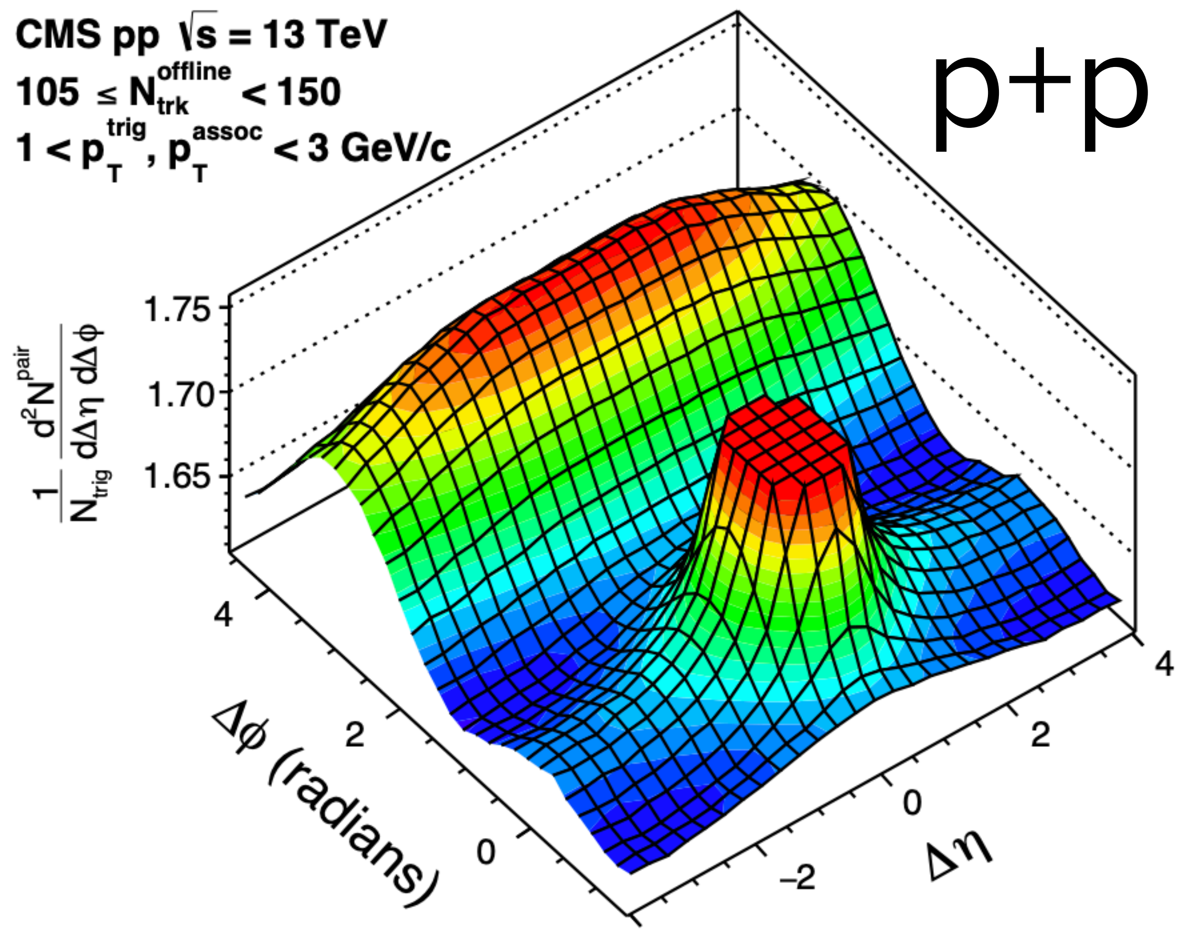
Hydrodynamic expansion

Fourier components of initial geometry

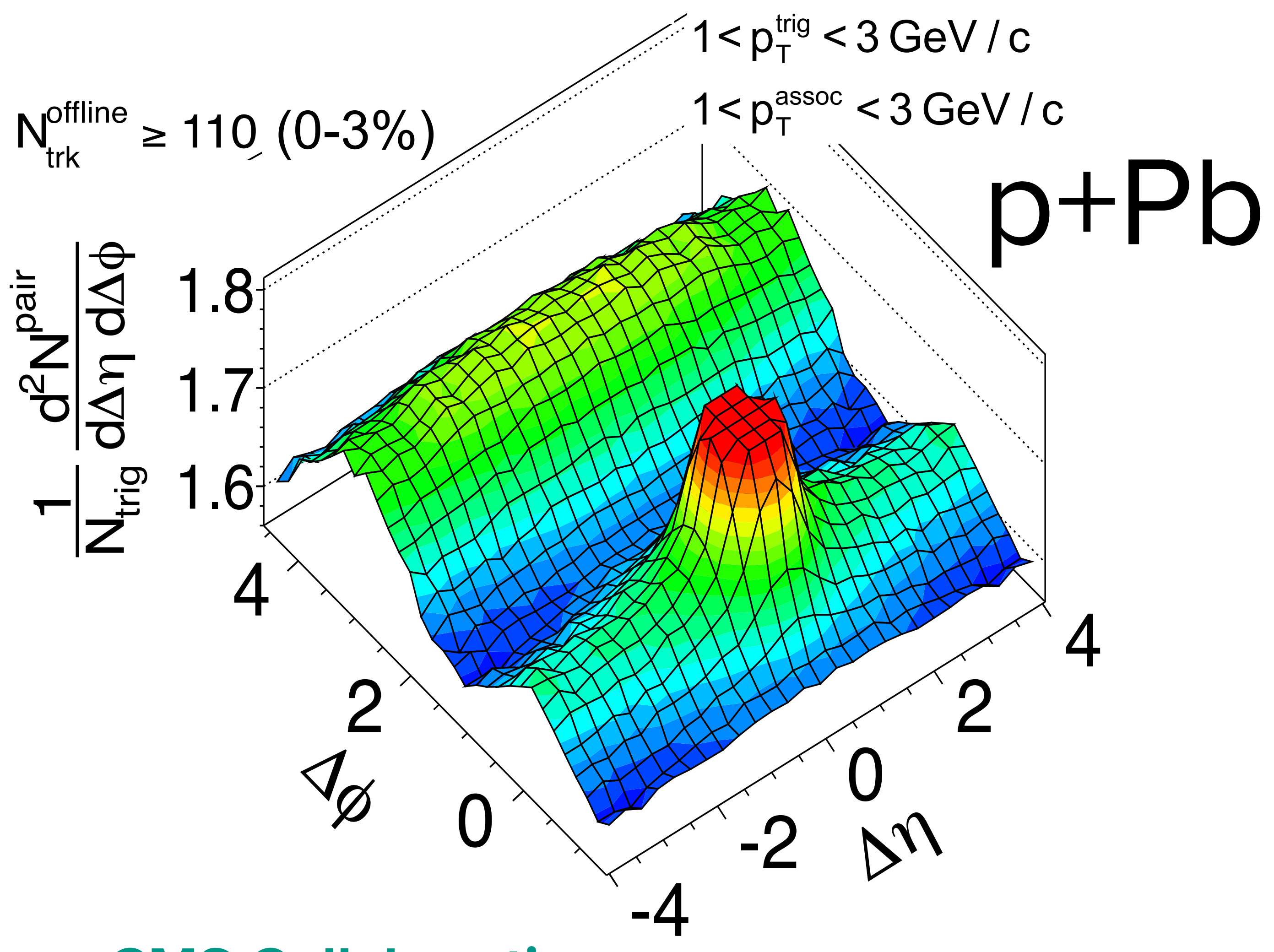


SMALL SYSTEMS: LHC

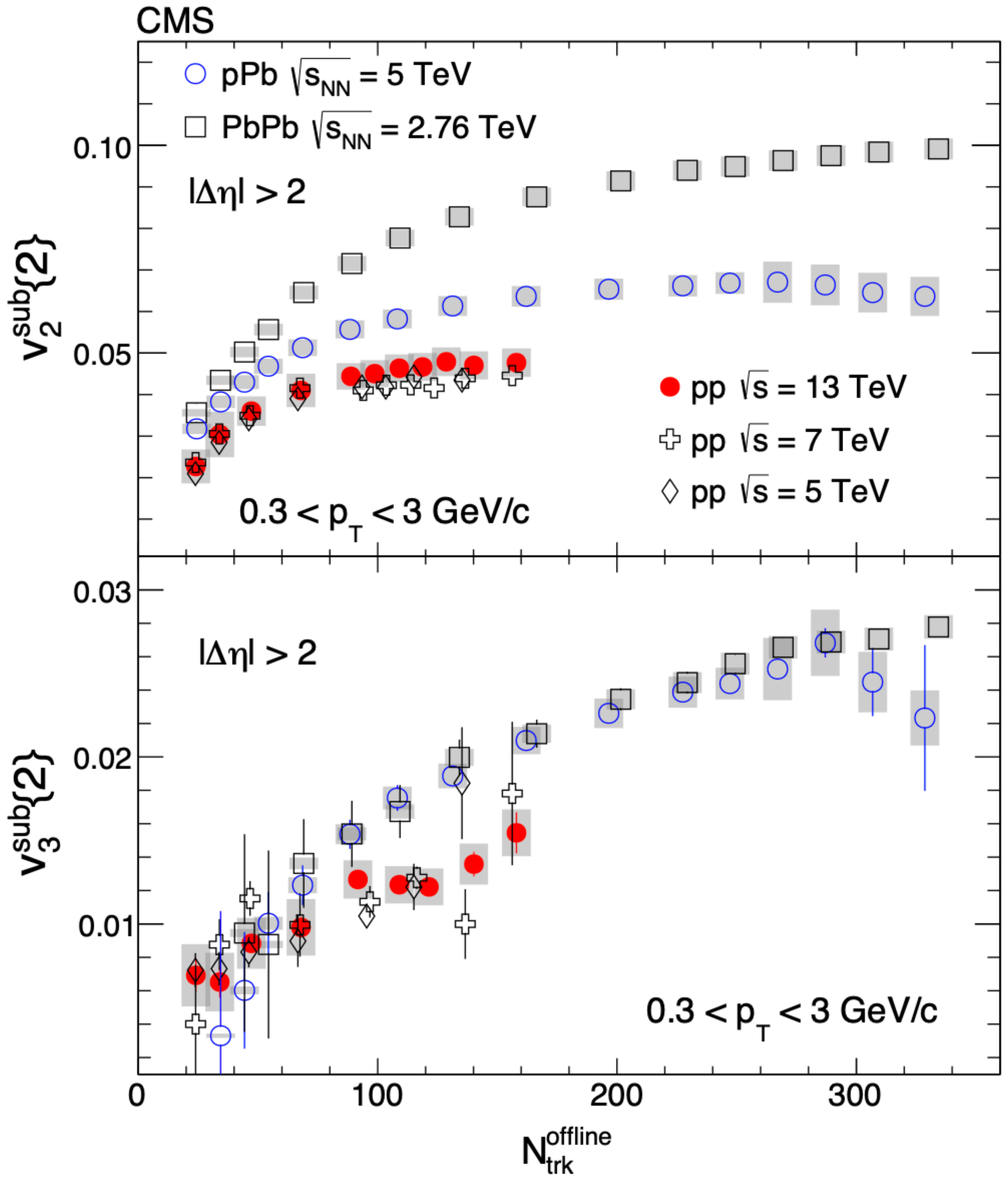
p+p, p+Pb, and low multiplicity Pb+Pb collisions also show clear long range 2-particle correlations



CMS Collaboration, JHEP 09 (2010) 091;
Phys.Lett.B 765 (2017) 193-220



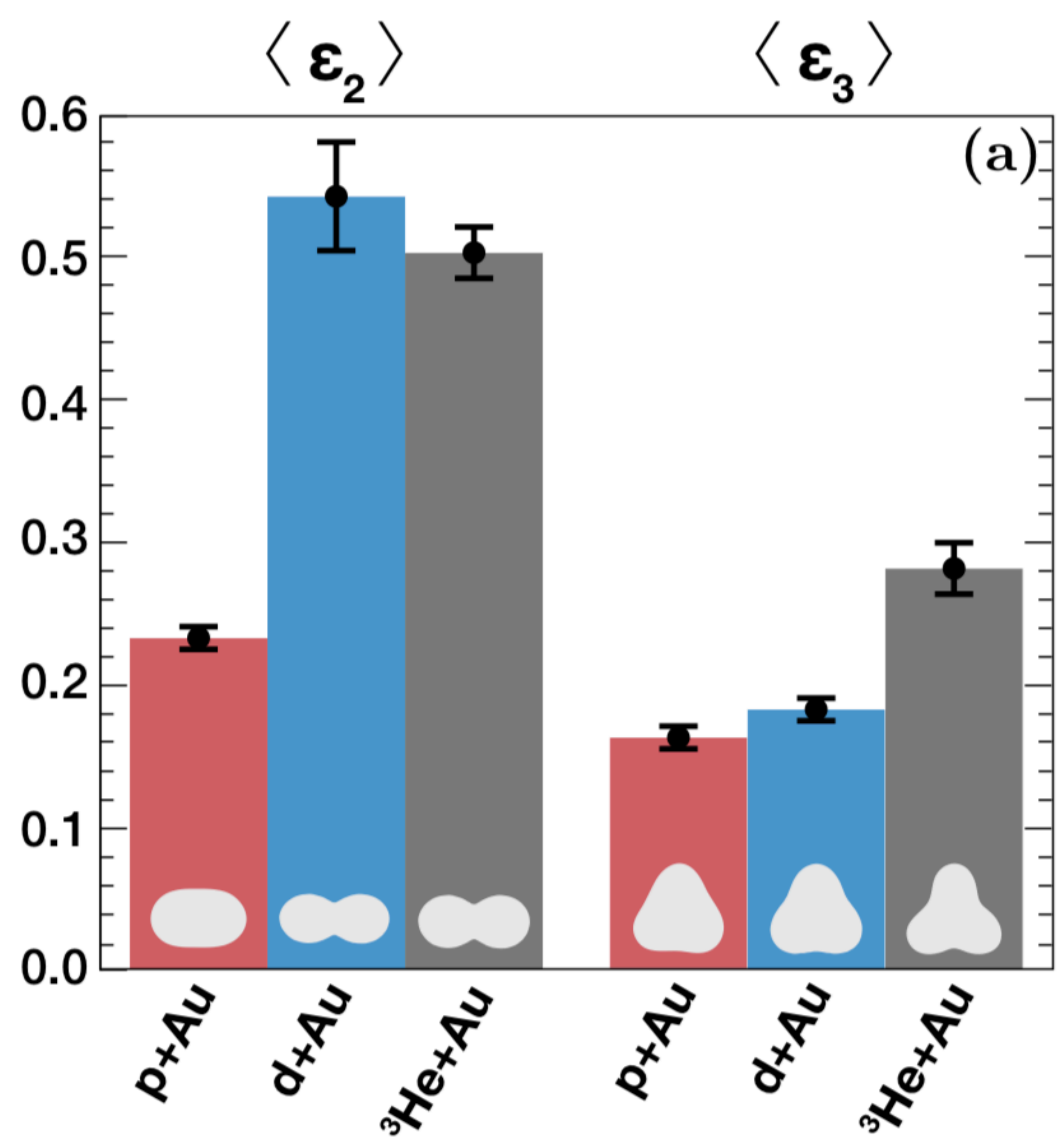
CMS Collaboration
Phys. Lett. B 718 (2013) 795



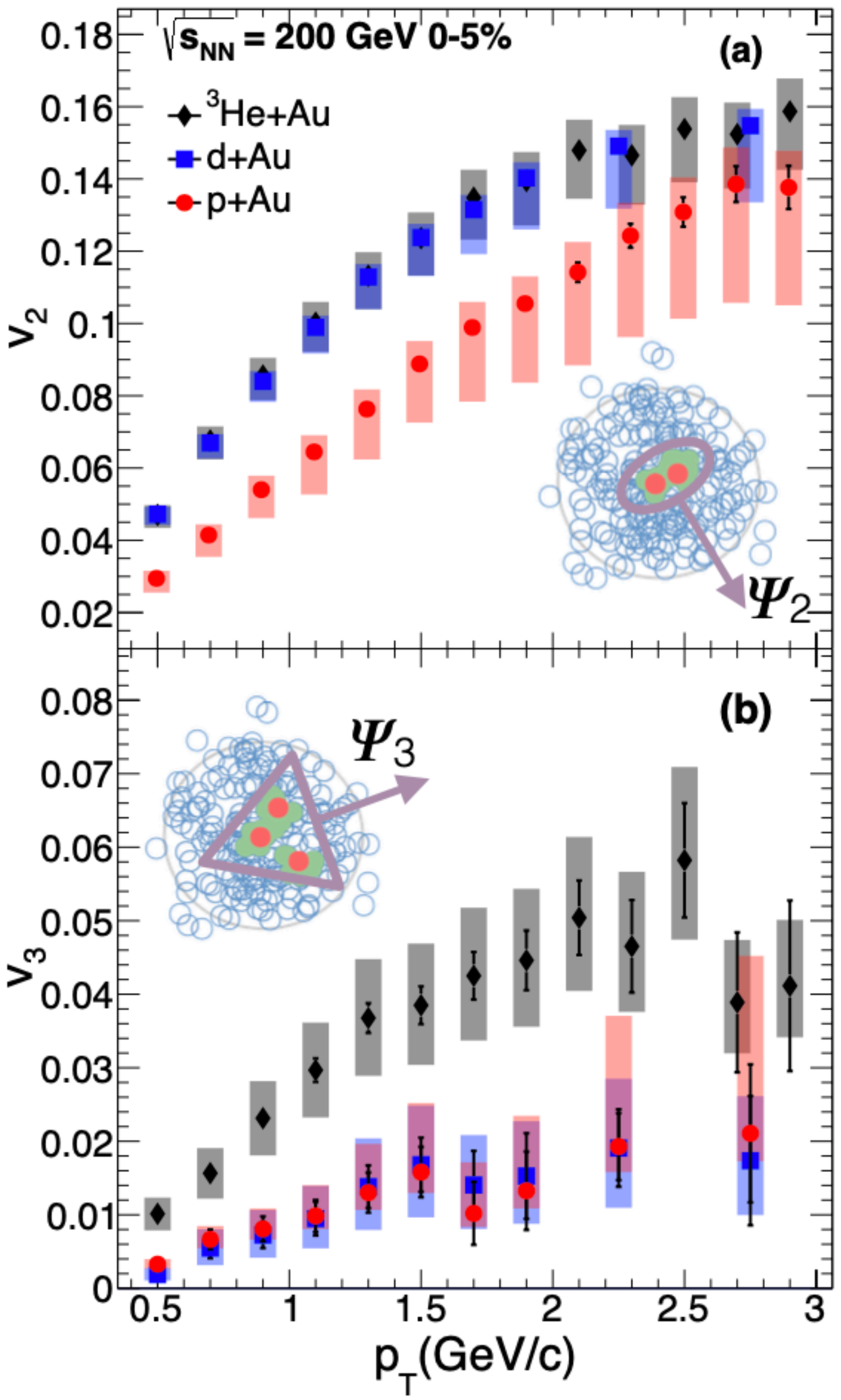
also:
ALICE Collaboration, Phys. Lett. B 719 (2013) 29
ATLAS Collaboration, Phys. Rev. Lett. 110 (2013) 182302

SMALL SYSTEMS: RHIC

p+Au, d+Au, ^{3}He+Au to scan different initial geometries

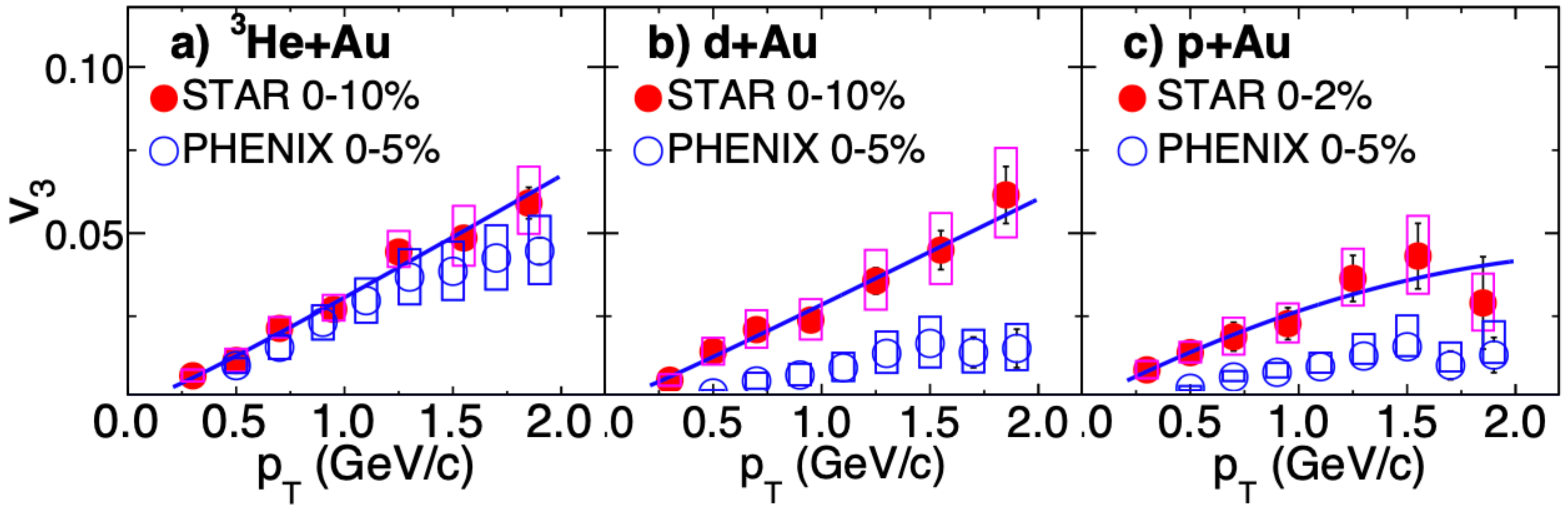


PHENIX



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

STAR



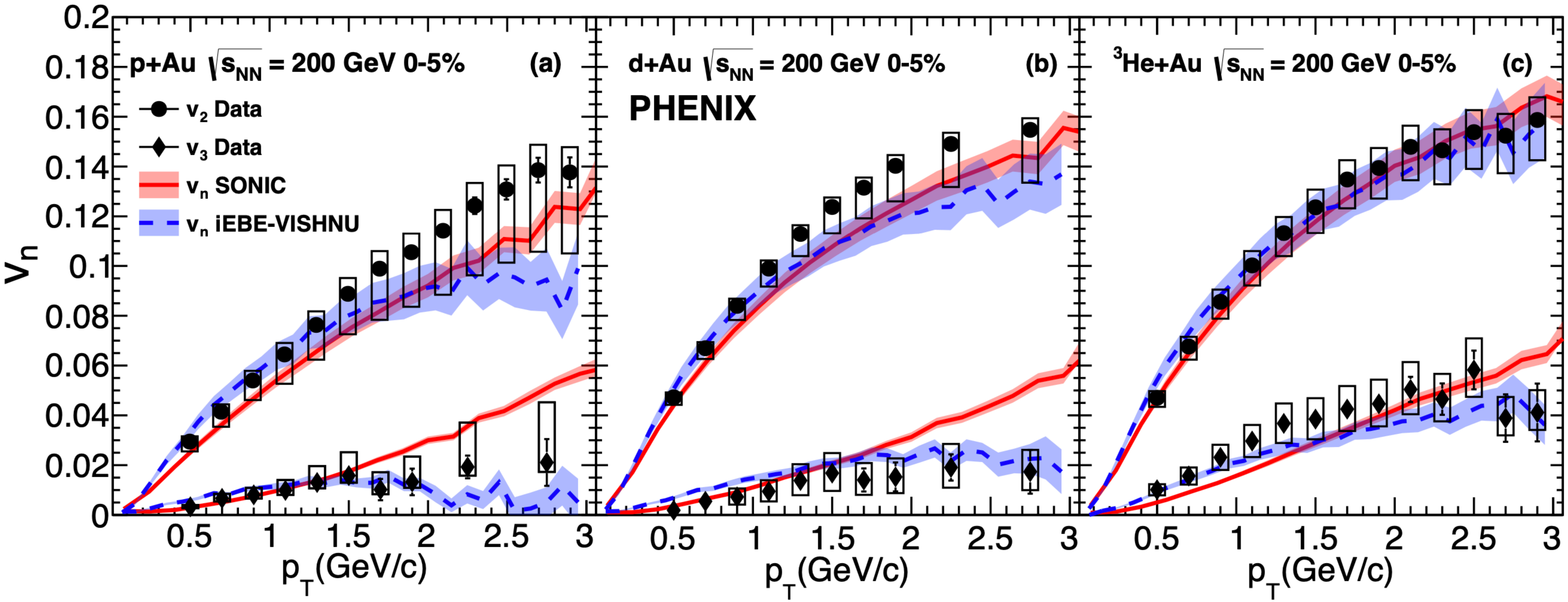
STAR Collaboration, Nucl.Phys.A 1005 (2021) 122041

Hierarchy of v_n consistent with geometry at PHENIX but not STAR

Issue of different rapidity ranges: non-flow and long. decorrelation

HYDRODYNAMIC MODELS DO QUITE WELL

Hydrodynamics based models can describe $v_n\{2\}$ over a wide range of systems and multiplicities

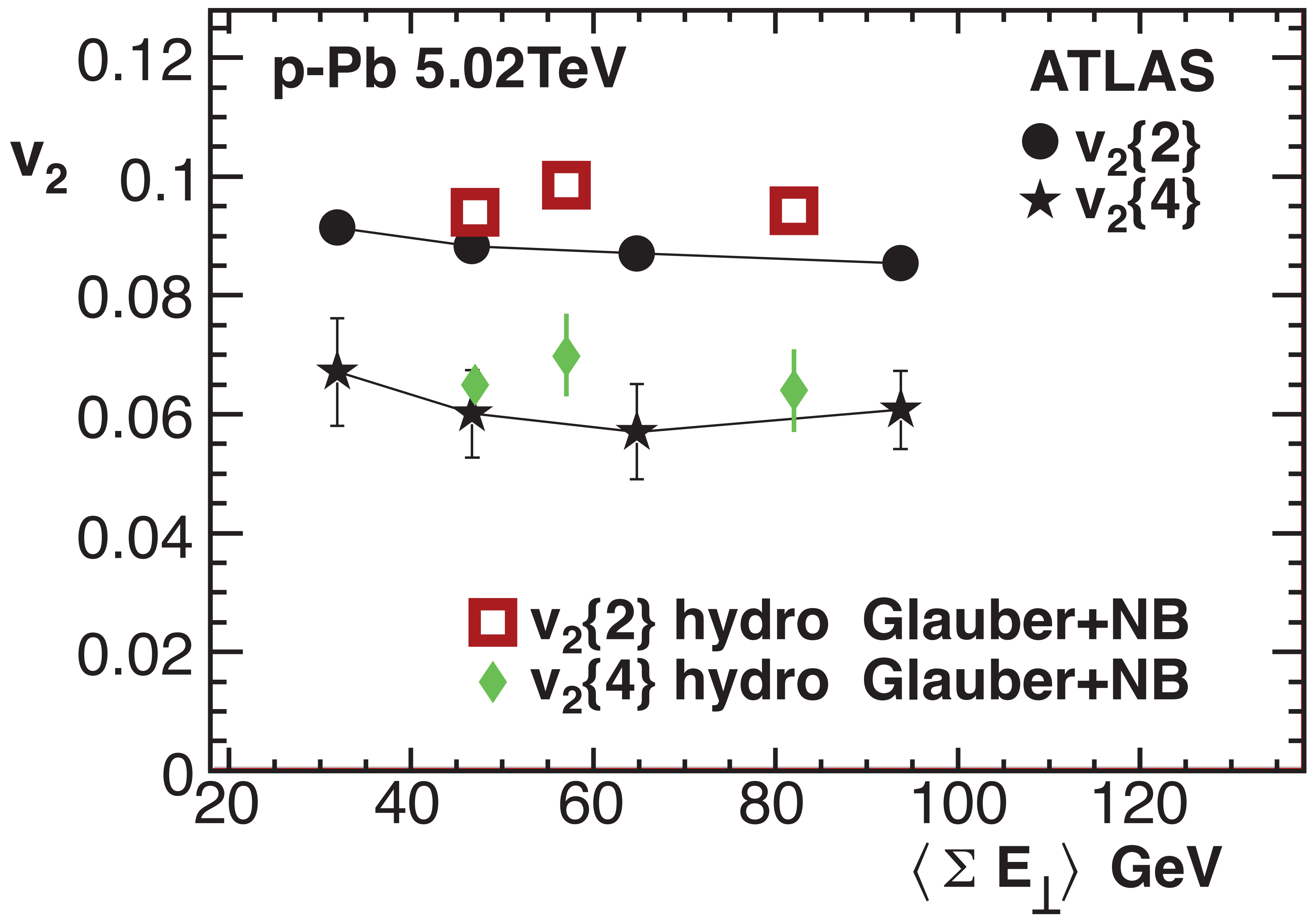


PHENIX Collaboration, Nature Physics 15, 214–220 (2019)

INITIAL GEOMETRY

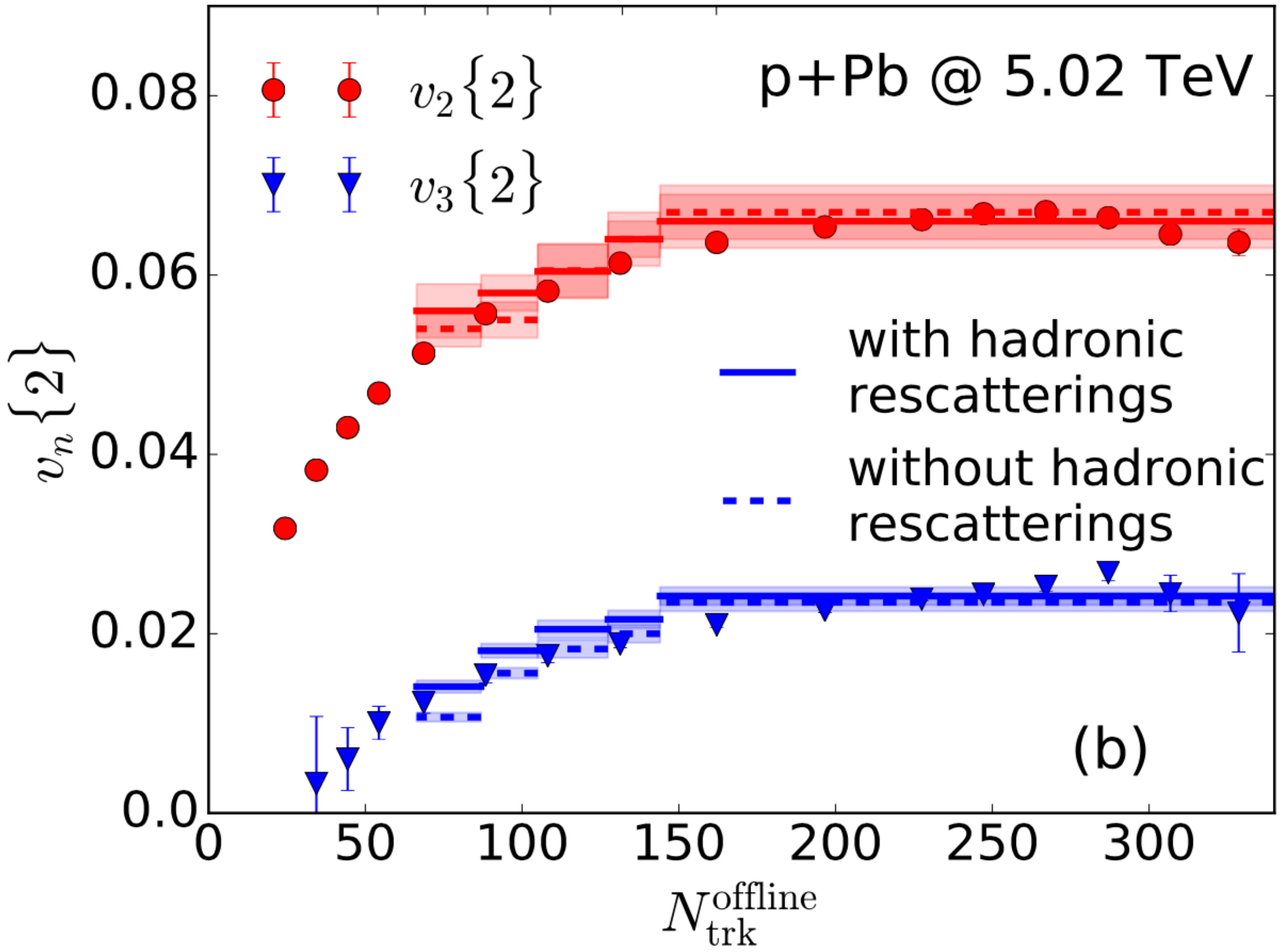
How do we know the initial geometry? Here MC-Glauber model without nucleon substructure

ATLAS Coll. PLB725 (2013) 60-78



Bozek, Broniowski, PRC88 (2013) 014903

CMS Coll. PLB724, 213–240 (2013)



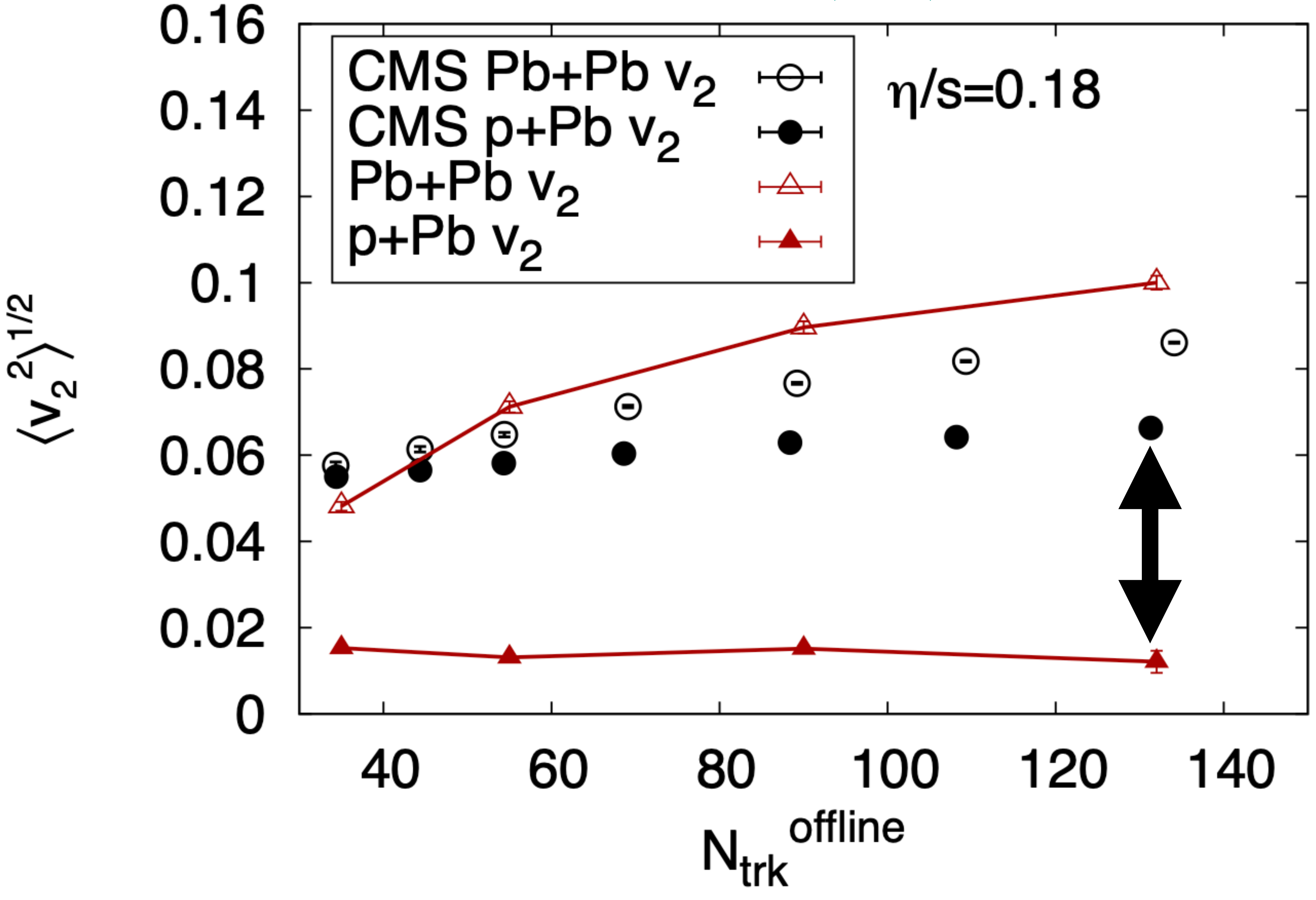
Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; ...

INITIAL GEOMETRY - DIFFERENT MODELS

IP-Glasma + Hydrodynamics underestimates the v_n in p+Pb collisions

CMS Coll. PLB724, 213–240 (2013)

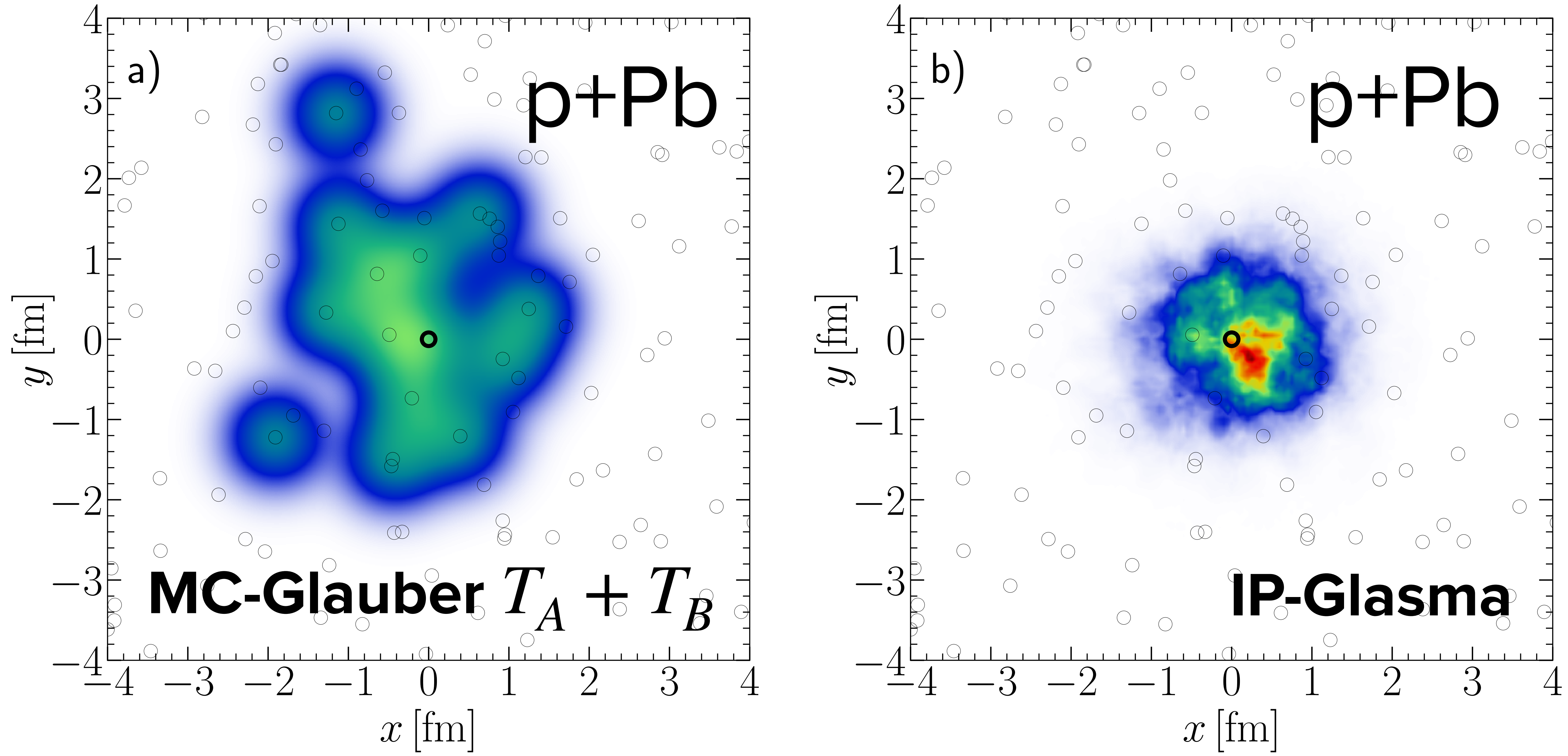


B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301

Reason: Different energy deposition

IP-Glasma follows the shape of the smaller projectile

Round proton → small eccentricities



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

INITIAL GEOMETRY - SUBSTRUCTURE

However, $T_A + T_B$ disfavored because:

1) Centrality dependence of v_2 in A+A collisions G. Giacalone, J. Noronha-Hostler, J.-Y. Ollitrault, Phys. Rev. C 95, 054910 (2017)

2) Bayesian analyses all prefer energy deposition $\sim (T_A T_B)^q$ over $T_A + T_B$ **SEE TALK BY LUZUM**

J.S. Moreland, J.E. Bernhard, and S.A. Bass, Phys. Rev. C 92 (2015) 011901; Nijs, W. van der Schee, U. Gürsoy, R. Snellings, Phys.Rev.Lett. 126 (2021), Phys.Rev.C 103 (2021) 5, 054909; JETSCAPE Collaboration, Phys.Rev.C 103 (2021) 5, 054904

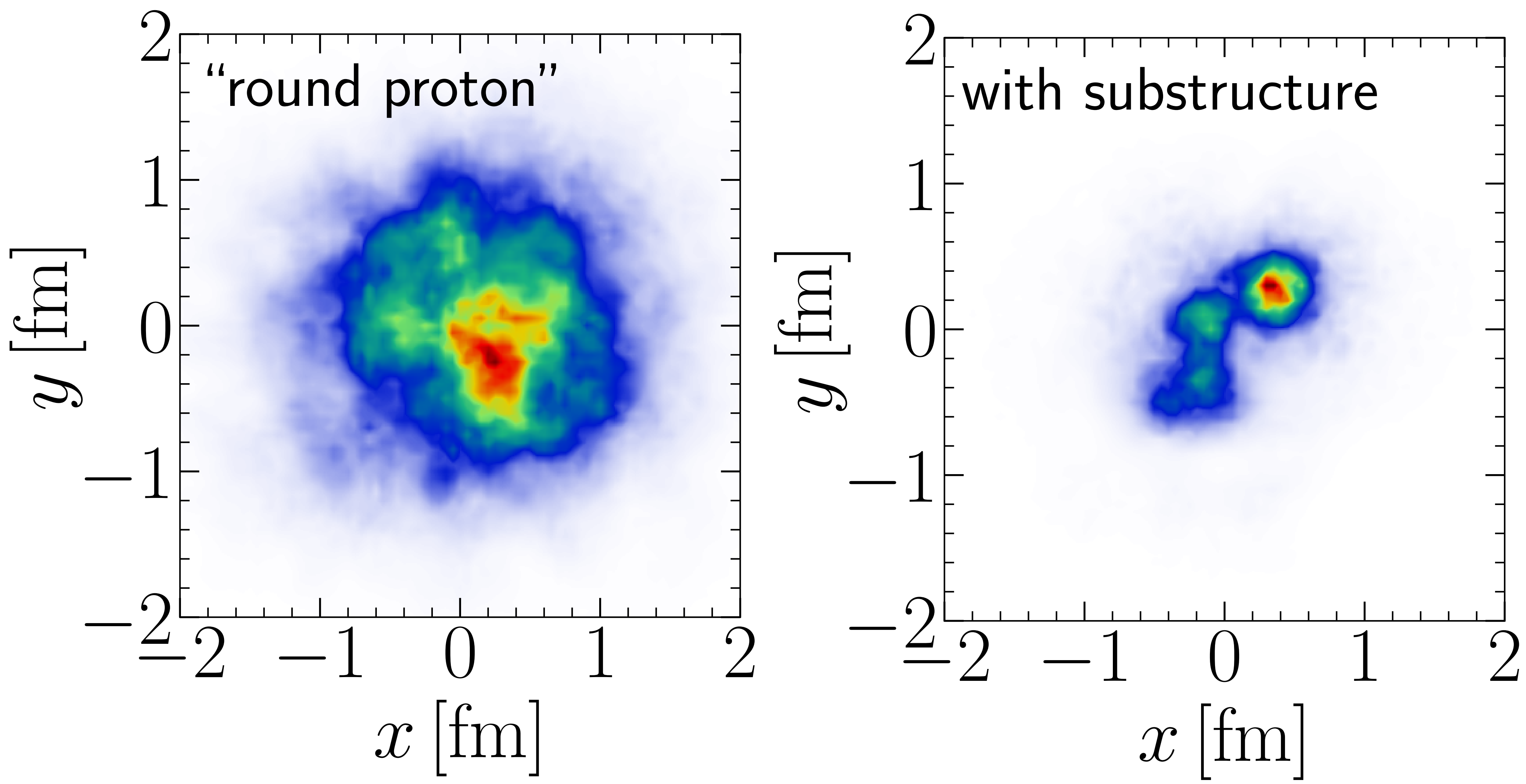
3) Both weak (CGC) and strong (AdS/CFT) calculation produce energy density $\sim (T_A T_B)^q$

T. Lappi, Phys.Lett.B 643 (2006) 11-16; P. Romatschke, J.D. Hogg, JHEP 04 (2013) 048

4) Some observables (e.g. $\langle p_T \rangle - v_2$ correlations) qualitatively different from data for $T_A + T_B$

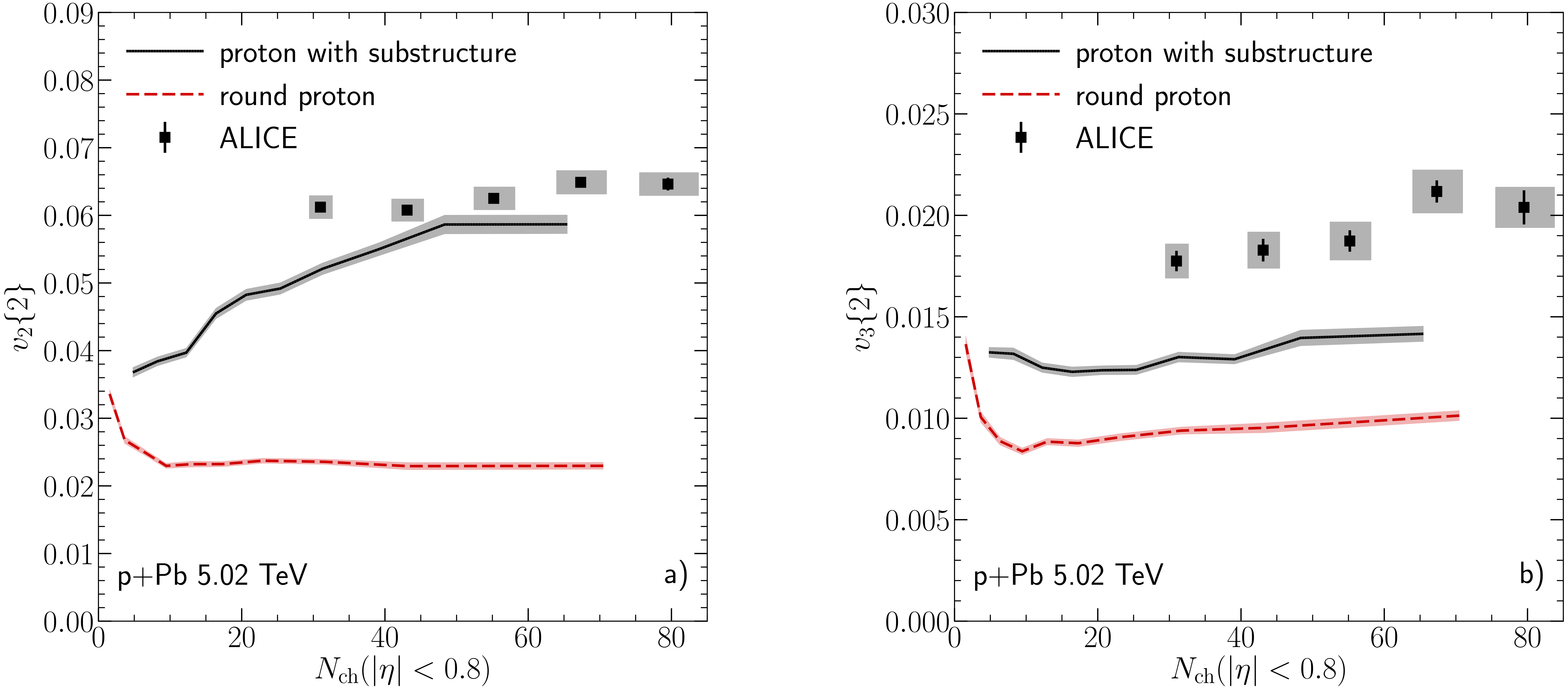
P. Bozek, 1601.04513; ATLAS Collaboration, 1907.05176; Schenke, Shen, Teaney, 2004.00690

If using $(T_A T_B)^q$, substructure is needed.
E.g. N_q hot spots in the nucleon:



EFFECT OF NUCLEON SUBSTRUCTURE

Substructure improves the description of anisotropic flow in p+A collisions with IP-Glasma



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

CONSTRAINTS ON SUBSTRUCTURE

Introduce a model for the nucleon substructure within IP-Glasma

$$T_p(\vec{b}_\perp) = \sum_{i=1}^{N_q} T_q(\vec{b}_\perp - \vec{b}^i_\perp) \qquad T_q(\vec{b}_\perp) = \frac{1}{2\pi B_q} e^{-\vec{b}^2_\perp/(2B_q)}$$

with $\vec{b}^i_\perp$ sampled from a Gaussian with parameter B_{qc}

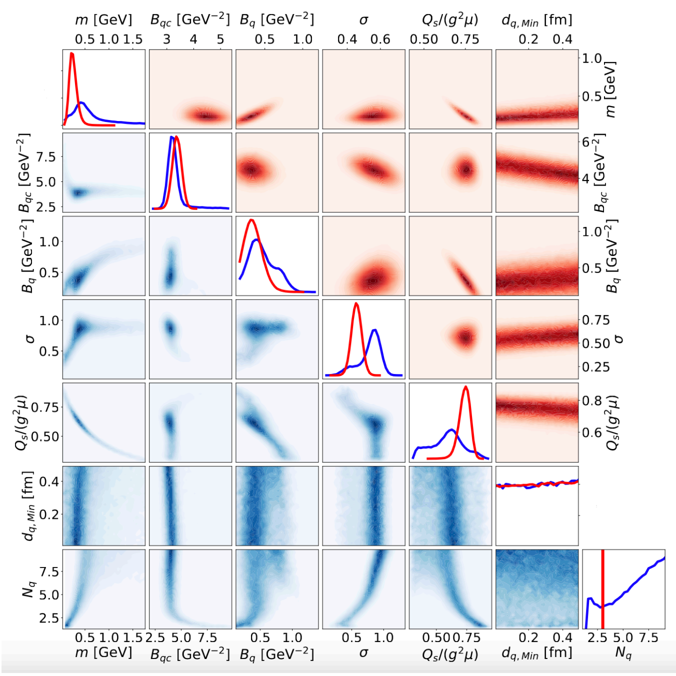
Constrain parameters B_{qc} and B_q with HERA data

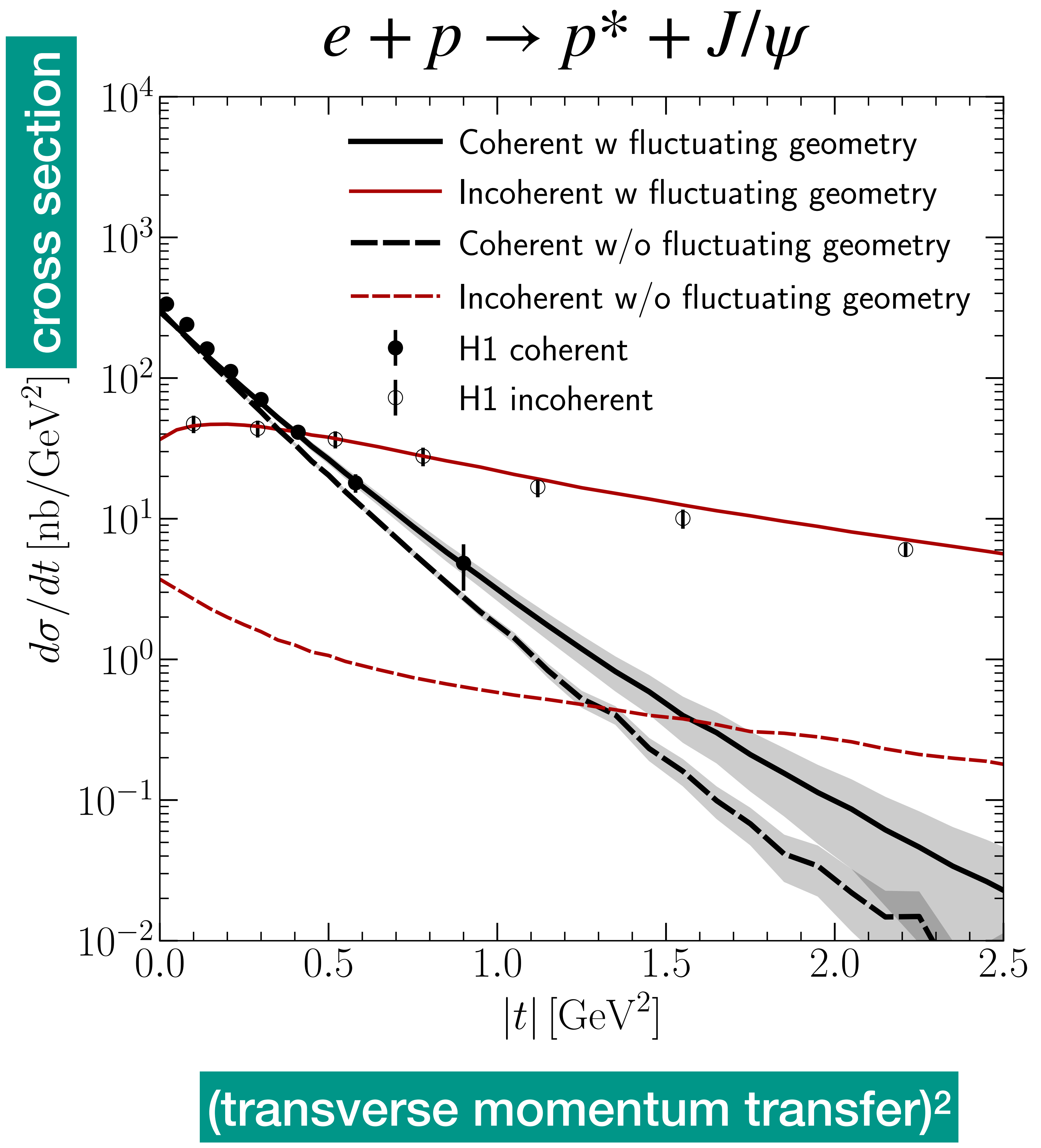
Exclusive diffractive J/Ψ production in e+p:
Incoherent cross section sensitive to fluctuations

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
H. Mäntysaari, B. Schenke, Phys.Rev. D94 (2016) 034042
also see:
S. Schlichting, B. Schenke, Phys.Lett. B739 (2014) 313-319
H. Mäntysaari, Rep. Prog. Phys. 83 082201 (2020)
B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

New Bayesian inference of parameters:

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, 2202.01998

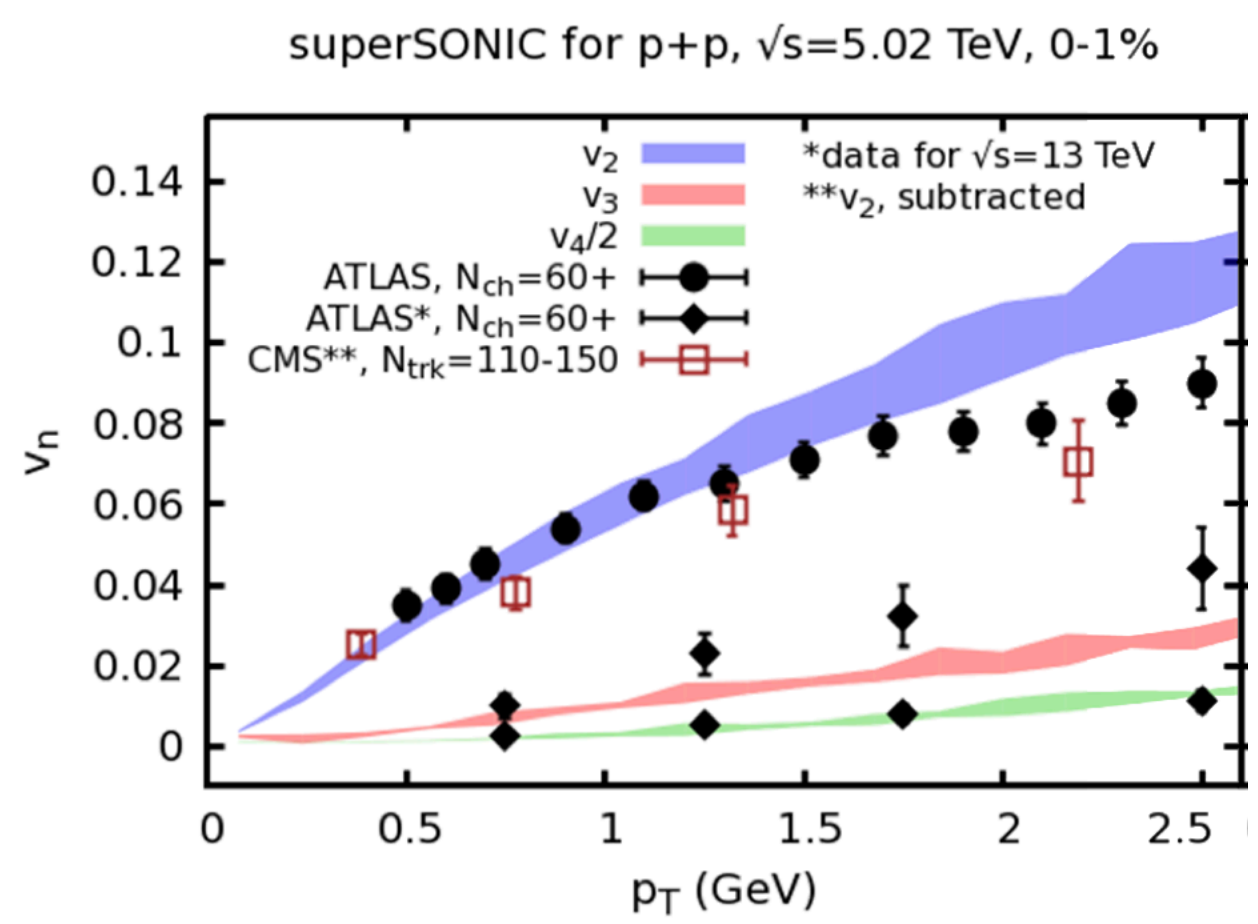




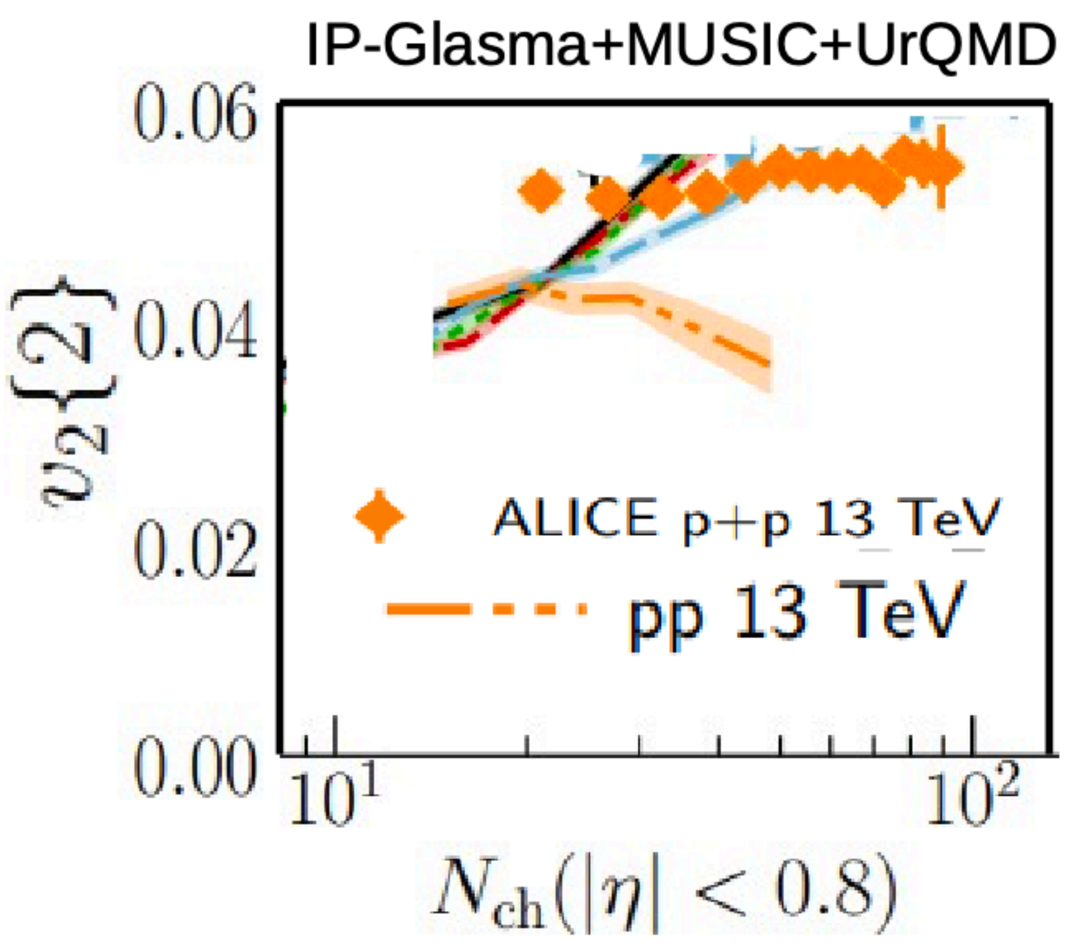
H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

https://share.streamlit.io/chunshen1987/ipglasmadiffractionstreamlit/main/IPGlasmaDiffraction_app.py

p+p COLLISIONS



Weller, Romatschke, 1701.07145



Schenke, Shen, Tribedy 2004.14682

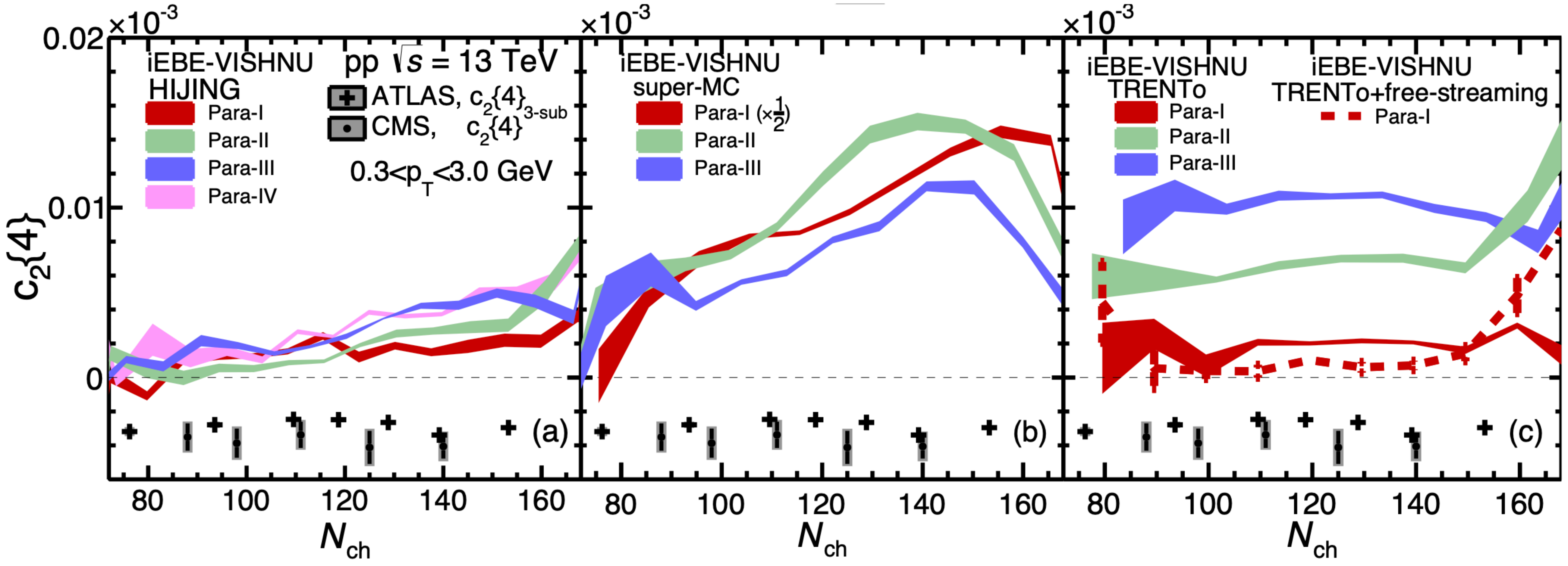
$v_2\{2\}(p_T)$ works ok,
multiplicity dependence harder to get

But 4-particle correlation has wrong sign

If kurtosis of ε_2 modeled with right sign and only linear relation $v_2 \propto \varepsilon_2$ considered, sign can be reproduced

S.F. Taghavi, Phys.Rev.C 104 (2021) 5, 054906

But **non-linearities** in full hydrodynamics destroy this and lead to positive $c_2\{4\}$ while experimentally $c_2\{4\}$<0.

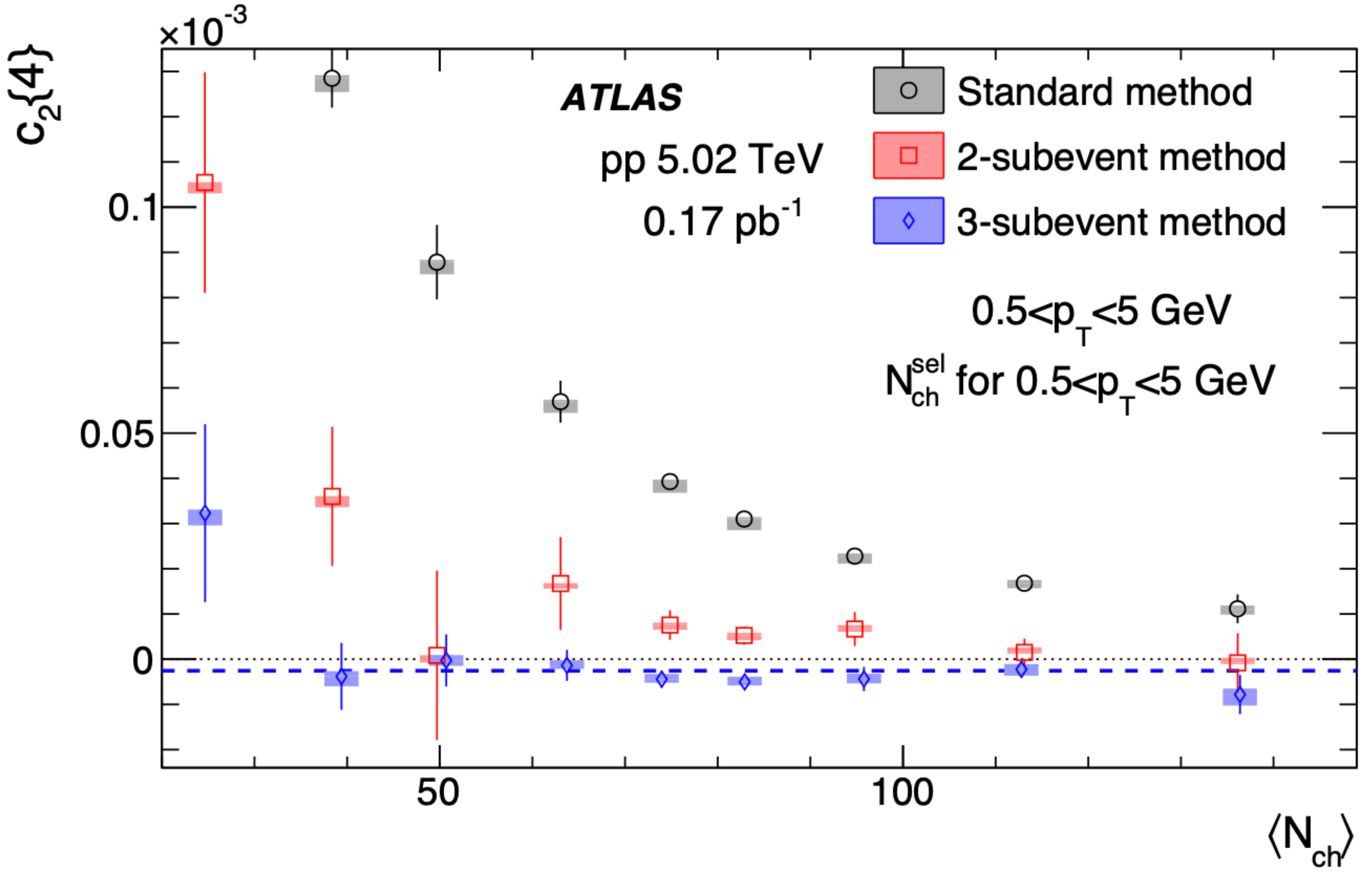


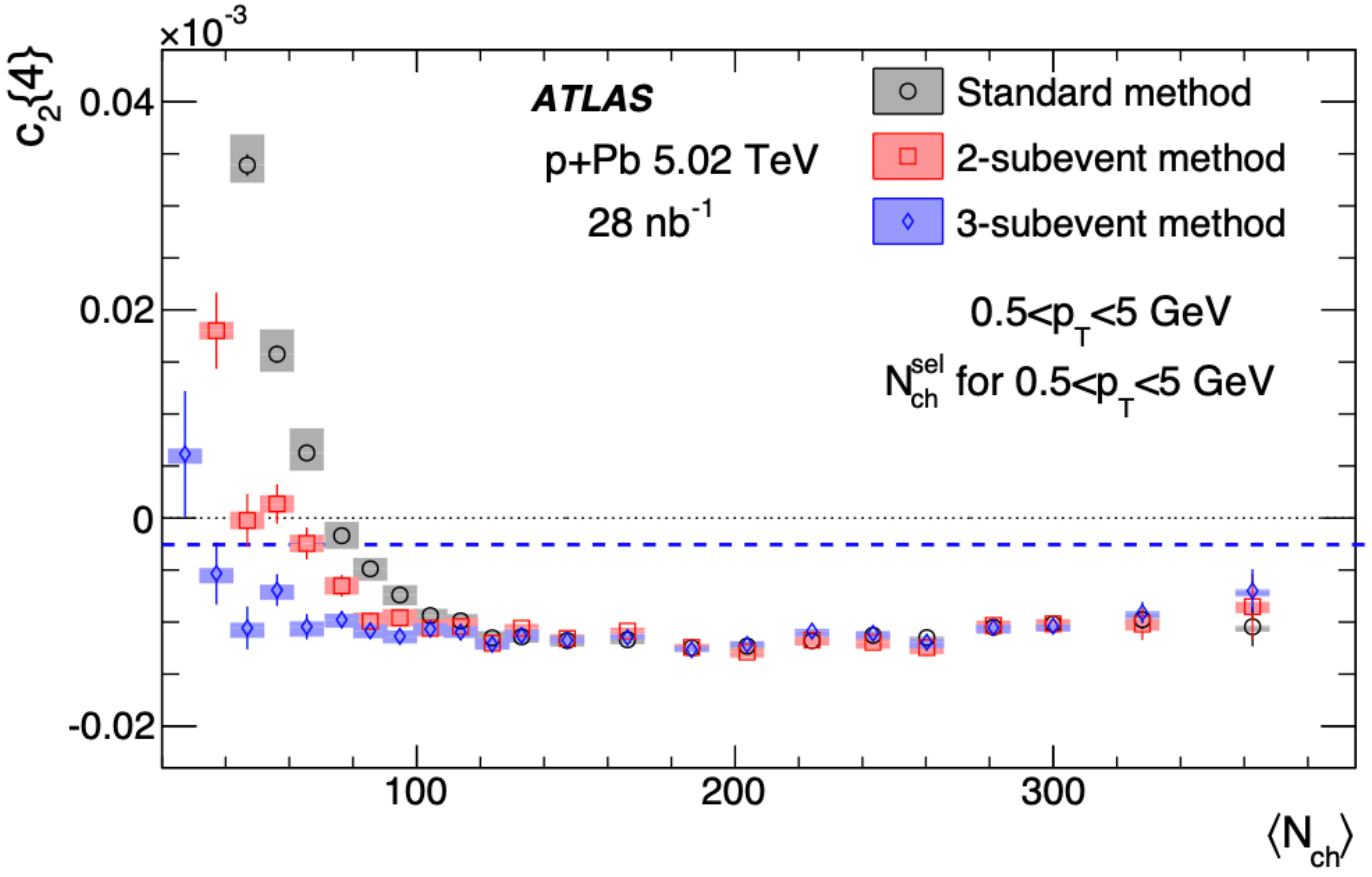
Zhao, Zhou, Xu, Deng, Song, Phys.Lett.B 780 (2018) 495-500
Zhao, Zhou, Murase, Song, Eur.Phys.J.C 80 (2020) 9, 846

$$v_n\{2\} = \sqrt{c_n\{2\}}\,,\quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

4-PARTICLE CORRELATIONS

$$v_n\{2\} = \sqrt{c_n\{2\}}\,, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$





Lots of “non-flow” in p+p (short-range correlations that affect the measurement)

p+Pb collisions much more solid
most of the result at the larger multiplicities from collective behavior

ATLAS Collaboration, Phys.Rev.C 97 (2018) 2, 024904

IS IT HYDRODYNAMICS? GEOMETRY?

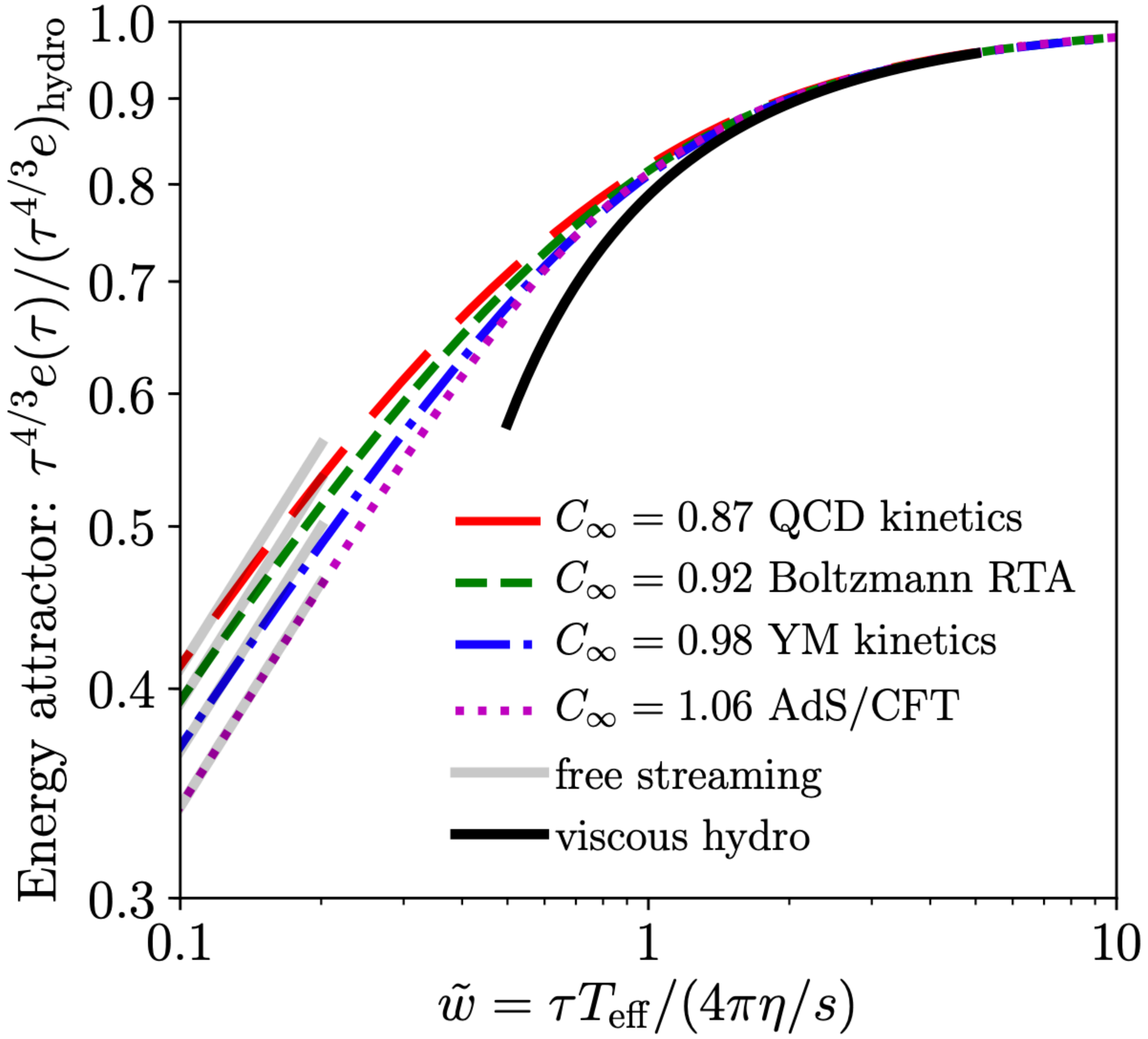
Hydrodynamic attractors are reached times $\mathcal{O}(1\text{fm})$
Largely independent from the underlying microscopic theory

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

See reviews Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299
Romatschke, Romatschke, 1712.05815

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



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)

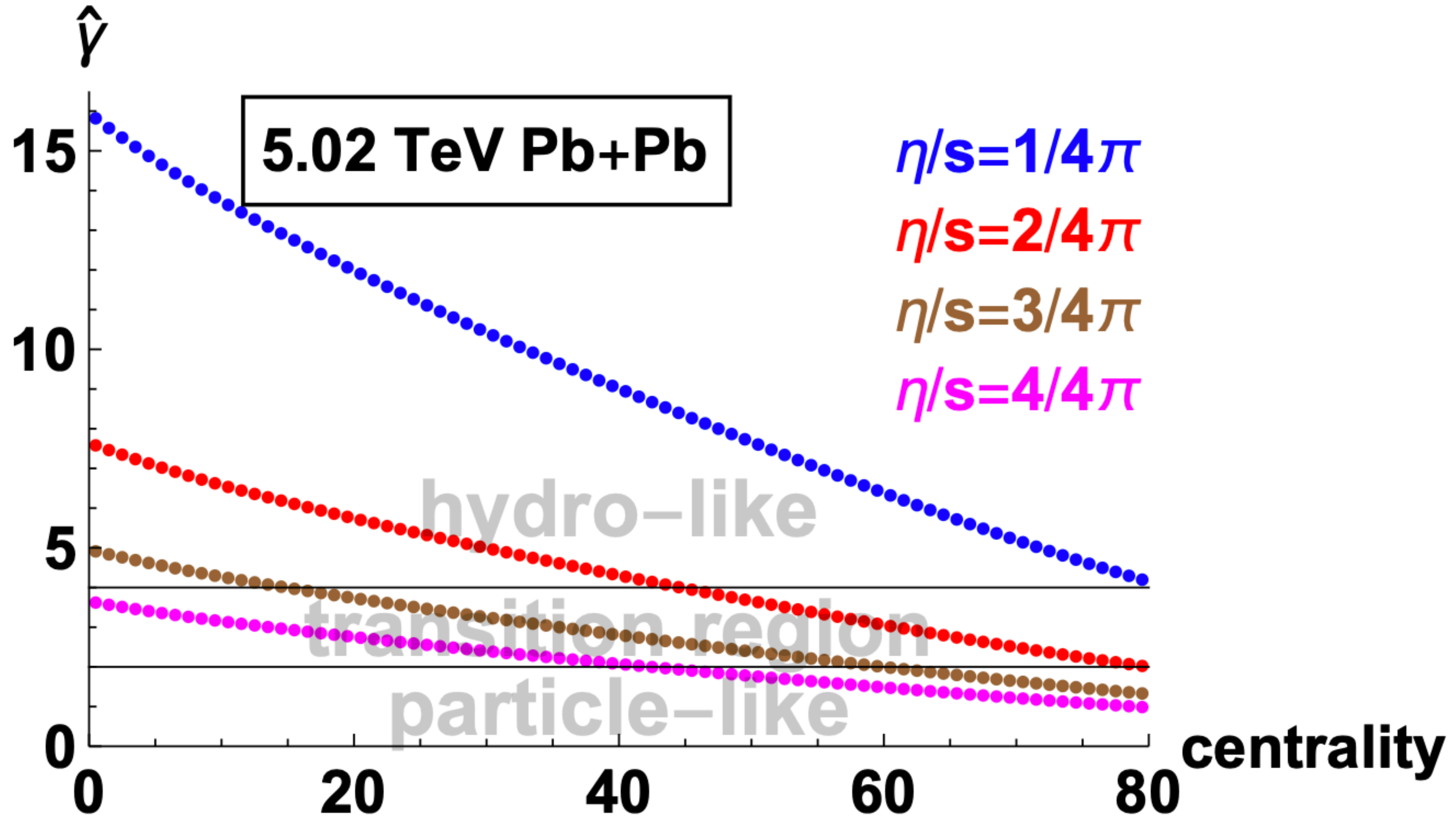
SEE TALKS BY DU, CARRINGTON, MONDKAR, PLASCHKE, OCHSENFELD, SCHEIHING HITSCHFELD, WERTHMANN

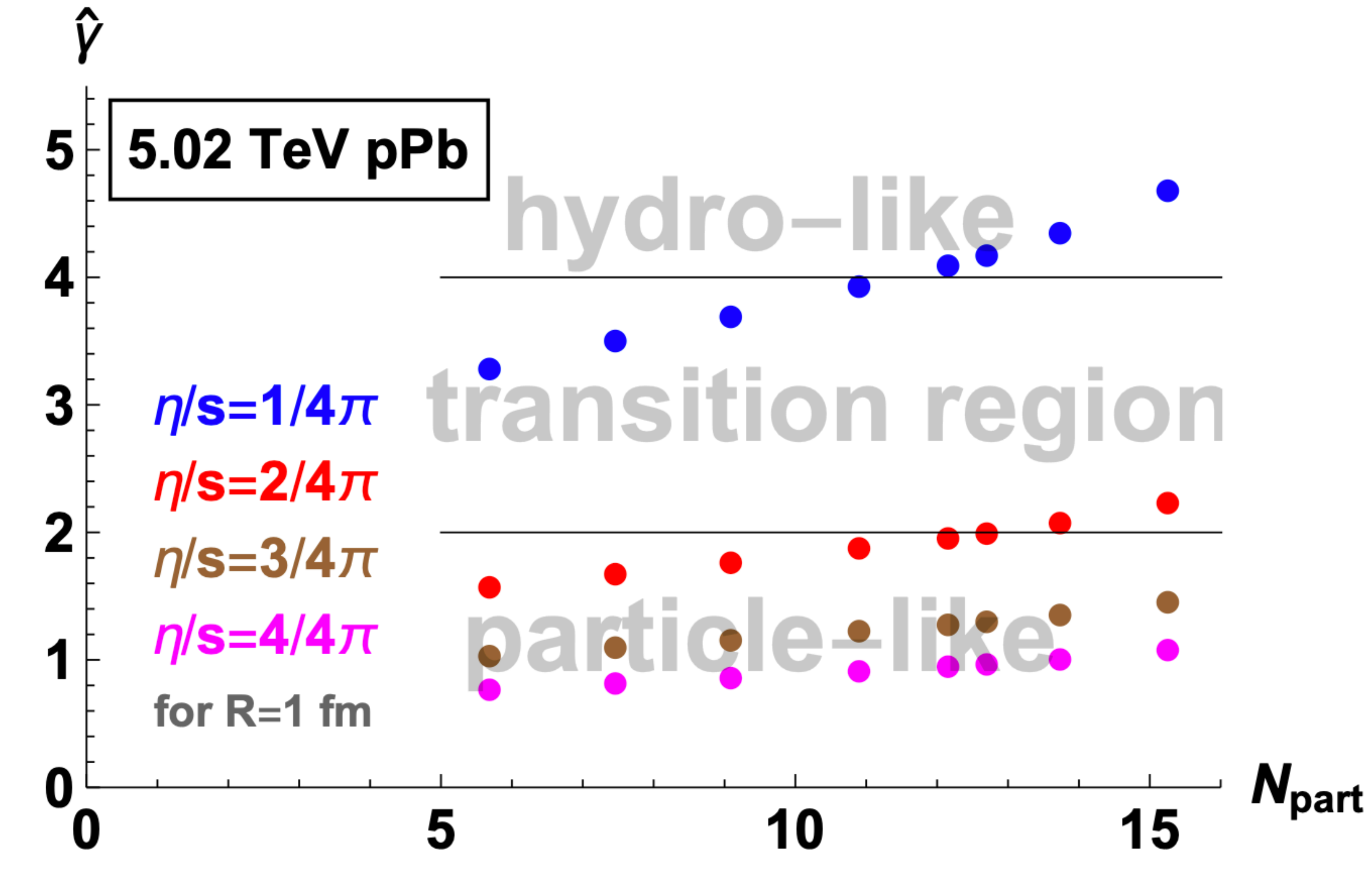
Small systems are more sensitive to violations of causality in the hydrodynamic implementation

F. S. Bemfica, M. M. Disconzi, V. Hoang, J. Noronha, M. Radosz, Phys.Rev.Lett. 126 (2021) 22, 222301

SEE TALK BY BEA

EVEN IF NOT HYDRO - GEOMETRY PLAYS A ROLE



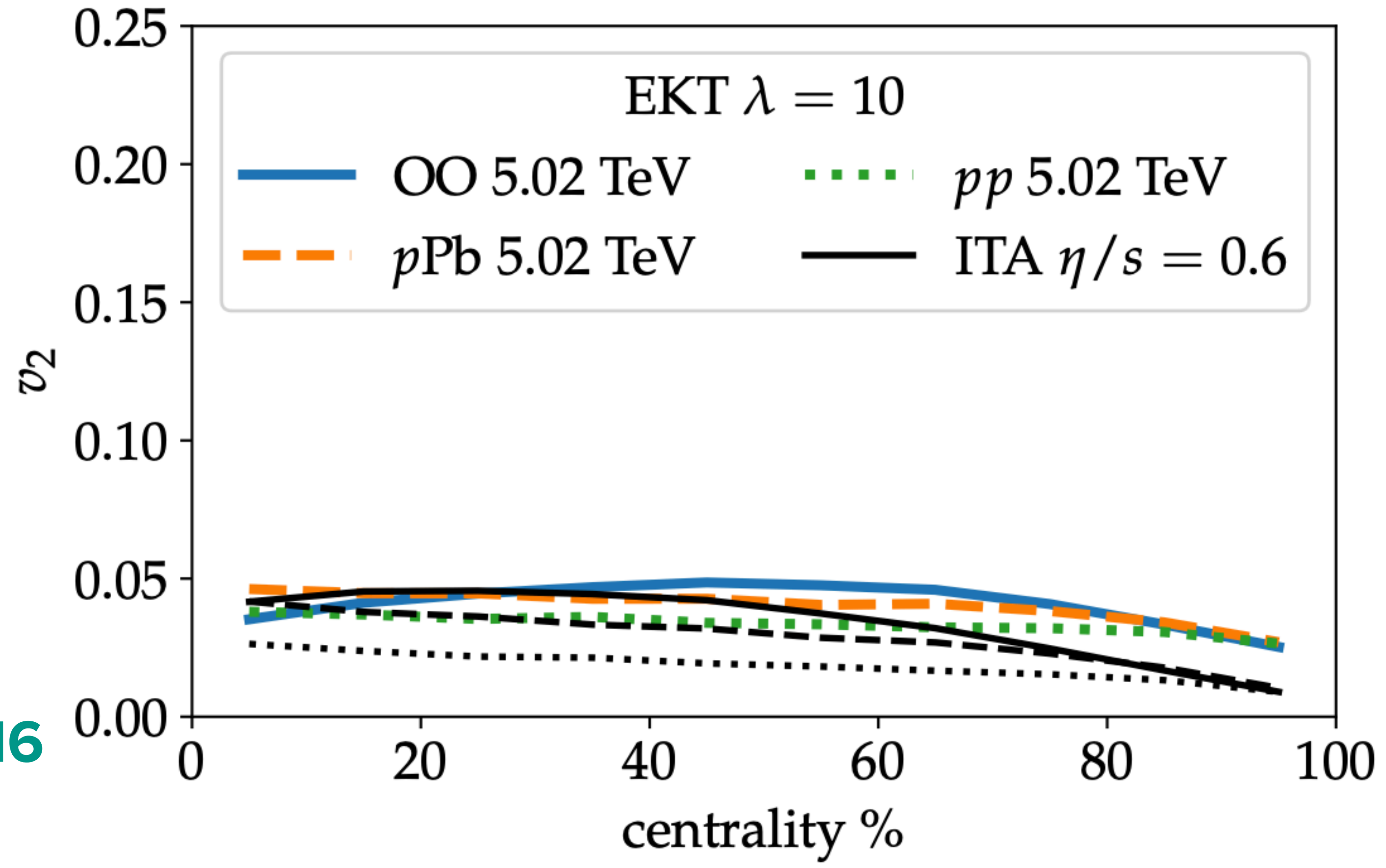


Kinetic theory study: Kurkela, Wiedemann, Wu, Eur.Phys.J.C 79 (2019) 11, 965

Fluid-like excitations dominate collectivity in central nucleus-nucleus collisions

Non-hydrodynamic modes dominate in p+Pb collisions at the LHC and contribute to flow in peripheral A+A

QCD effective kinetic theory (EKT) with single-hit approximation (linearization in number of scatterings) gets significant v_2



Kurkela, Mazeliauskas, Törnkvist, JHEP 11 (2021) 216

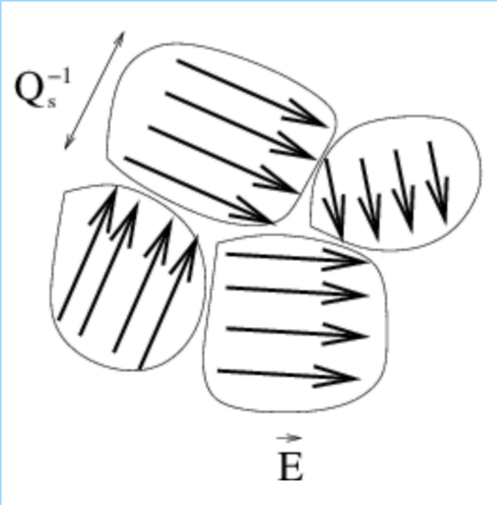
Scaling of v_n with geometry observed in the limit of very few scatterings

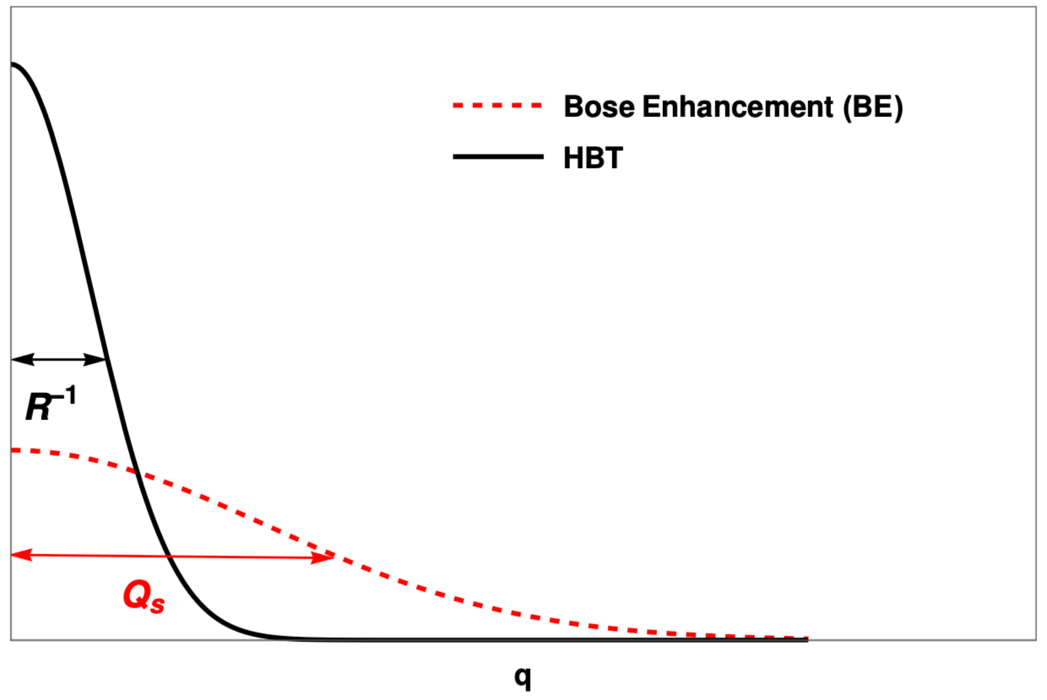
Borghini, Feld, Kersting Eur.Phys.J.C 78 (2018) 10, 832

ALTERNATIVES? INITIAL MOMENTUM ANISOTROPIES

Sources of correlations in the Color Glass Condensate (CGC):

see reviews: S. Schlichting, P. Tribedy, Adv. High Energy Phys. 2016 (2016) 8460349; T. Altinoluk, N. Armesto, Eur.Phys.J.A 56 (2020) 8, 215

	Classical		Quantum
Local anisotropy	 $1/Q_s$	Bose enhancement in incoming wave function	
Density gradients	$\frac{dQ_s}{db}/Q_s$	Gluonic HBT	



Incoming gluons need to be close in the transverse plane to feel the same local structure of the target

Both come with similar contribution for enhancement of anti-aligned momenta

also much work on odd harmonics from the CGC (e.g. subeikonal corrections)

see T. Altinoluk, N. Armesto, Eur.Phys.J.A 56 (2020) 8, 215

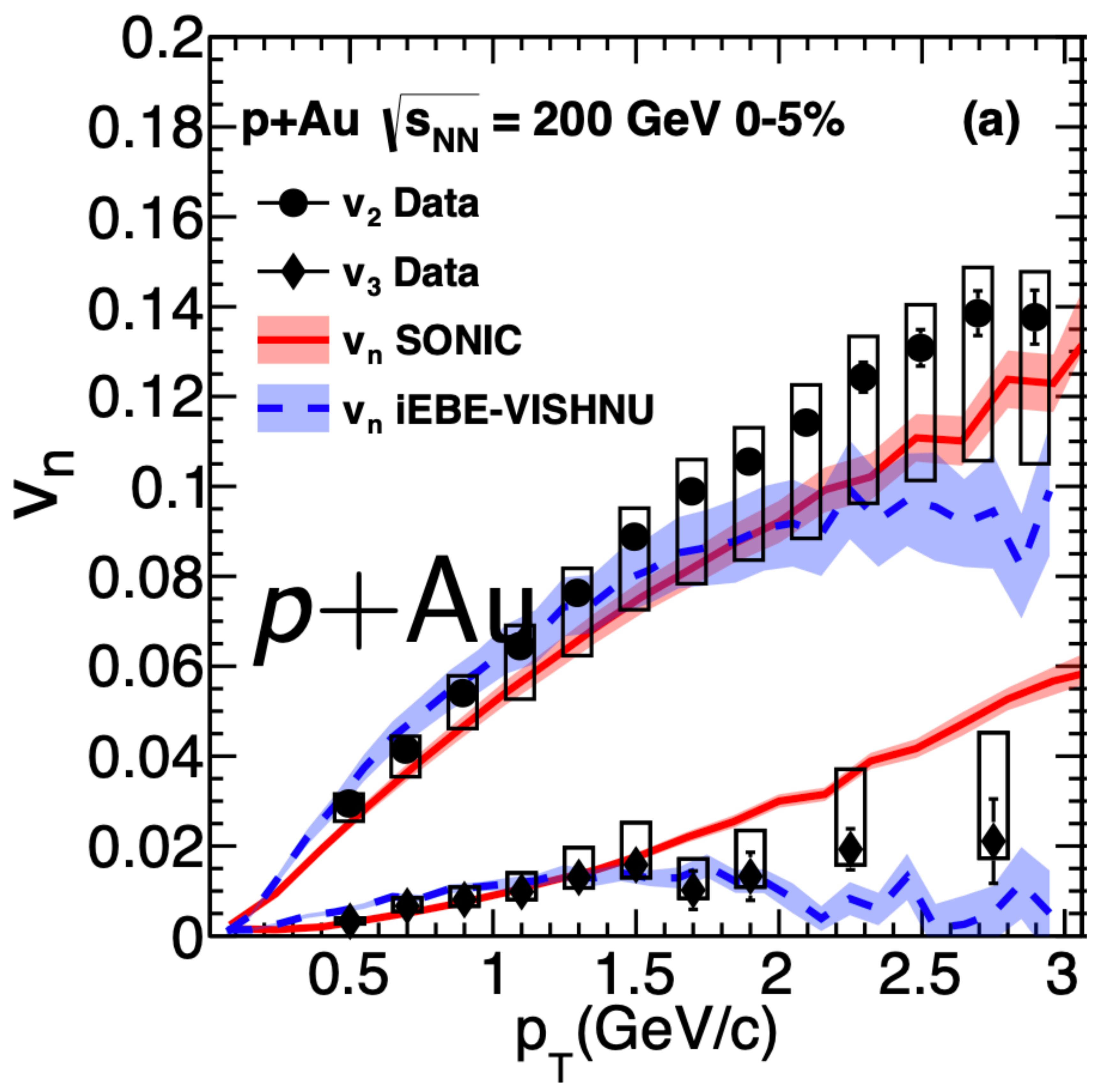
Further alternatives are string percolation and string shoving models

Andres et al., Phys.Rev.C 90 (2014) 5, 054902 ; C. Bierlich et al., 1612.05132

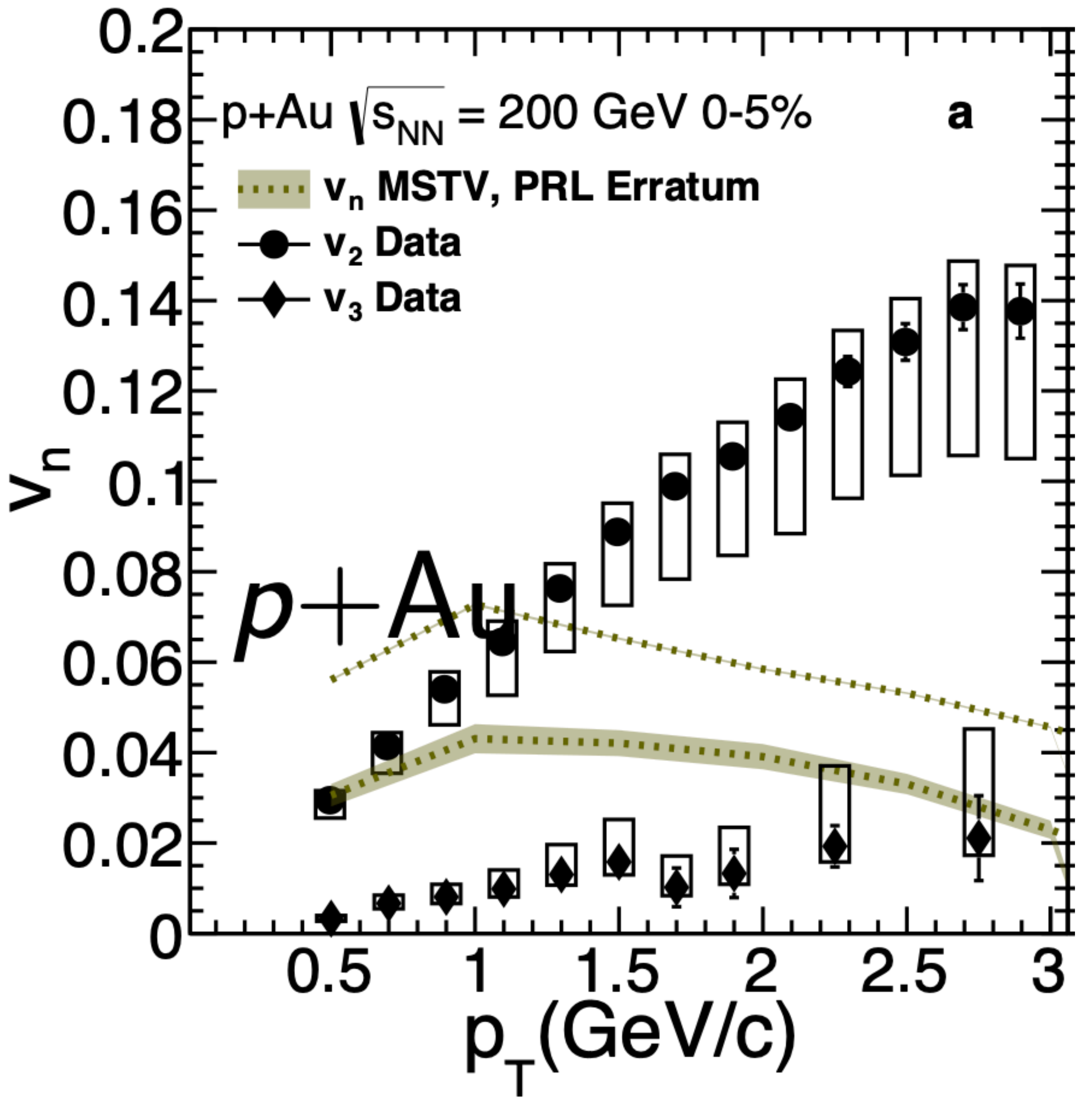
FACING THE EXPERIMENTAL DATA

Qualitative features of the data are not well described by initial state anisotropy *alone*

GEOMETRY RESPONSE ONLY



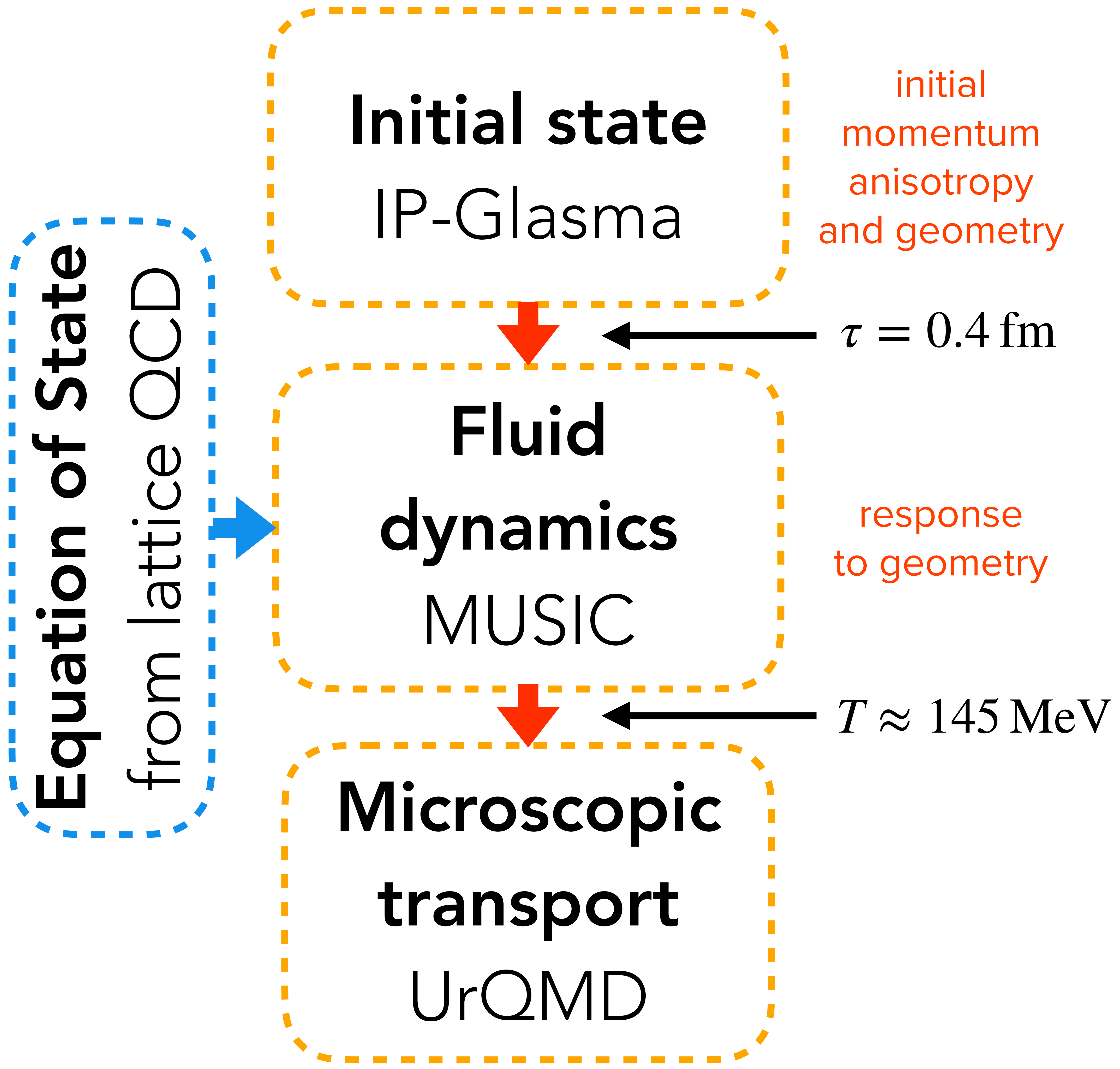
INITIAL MOMENTUM ANISOTROPY ONLY

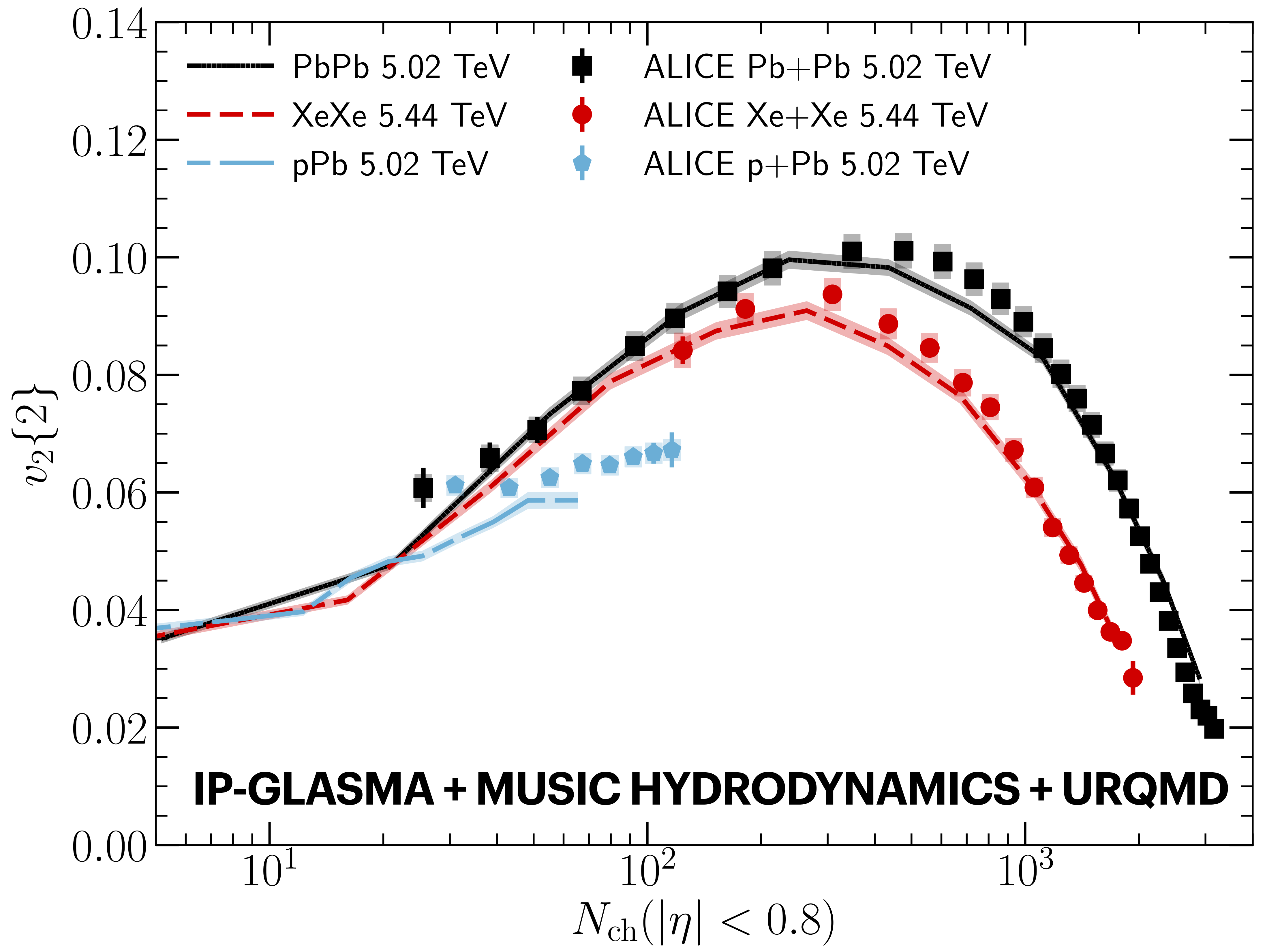


R. Belmont at the 2020 RHIC & AGS Users' Meeting

PHENIX Collaboration, Nature Physics 15, 214–220 (2019)
M. Mace, V. V. Skokov, P. Tribedy, R. Venugopalan , Phys. Rev. Lett. 123, 039901 (2019)

ONE MODEL WITH BOTH INITIAL AND FINAL STATE CONTRIBUTIONS





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

INITIAL VS. FINAL STATE EFFECTS

B. Schenke, C. Shen, P. Tribedy,Phys.Lett.B 803 (2020) 135322

Initial state anisotropies are significant and can affect the final result at low multiplicity

$$Q_\varepsilon = \frac{\mathrm{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle |\mathcal{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

CORRELATION OF THE FINAL ELLIPTIC FLOW V_2

WITH

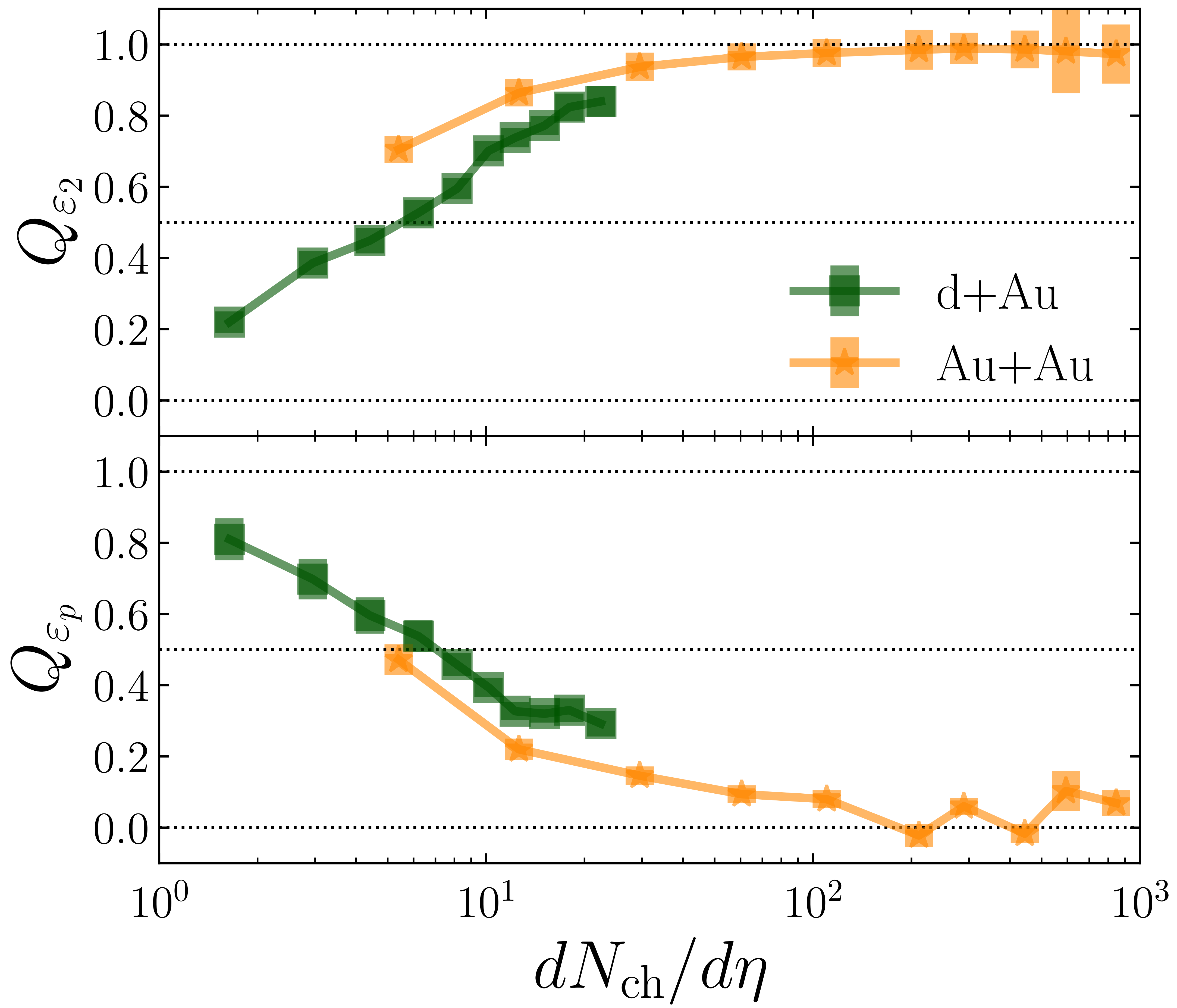
THE GEOMETRIC ELLIPTICITY

$$\mathcal{E}_2 = \varepsilon_2 e^{i2\psi_2} = \frac{\langle x^2 - y^2 \rangle + i \langle 2xy \rangle}{\langle x^2 + y^2 \rangle}$$

AND

THE INITIAL MOMENTUM ANISOTROPY

$$\mathcal{E}_p = \varepsilon_p e^{i2\psi_2^p} = \frac{\langle T^{xx} - T^{yy} \rangle + i \langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$



HOW TO DISTINGUISH THE SOURCES EXPERIMENTALLY

P. Bozek, Phys. Rev. C 93, 044908 (2016); B. Schenke, C. Shen, D. Teaney, Phys. Rev. C 102, 034905 (2020)

The correlation of $[p_T]$ and v_n fluctuations could do that!

Define $\hat{\rho}(v_n^2, [p_T]) = \dfrac{\langle \hat{\delta} v_n^2 \, \hat{\delta}[p_T] \rangle}{\langle (\hat{\delta} v_n^2)^2 \rangle \langle (\hat{\delta}[p_T])^2 \rangle}$

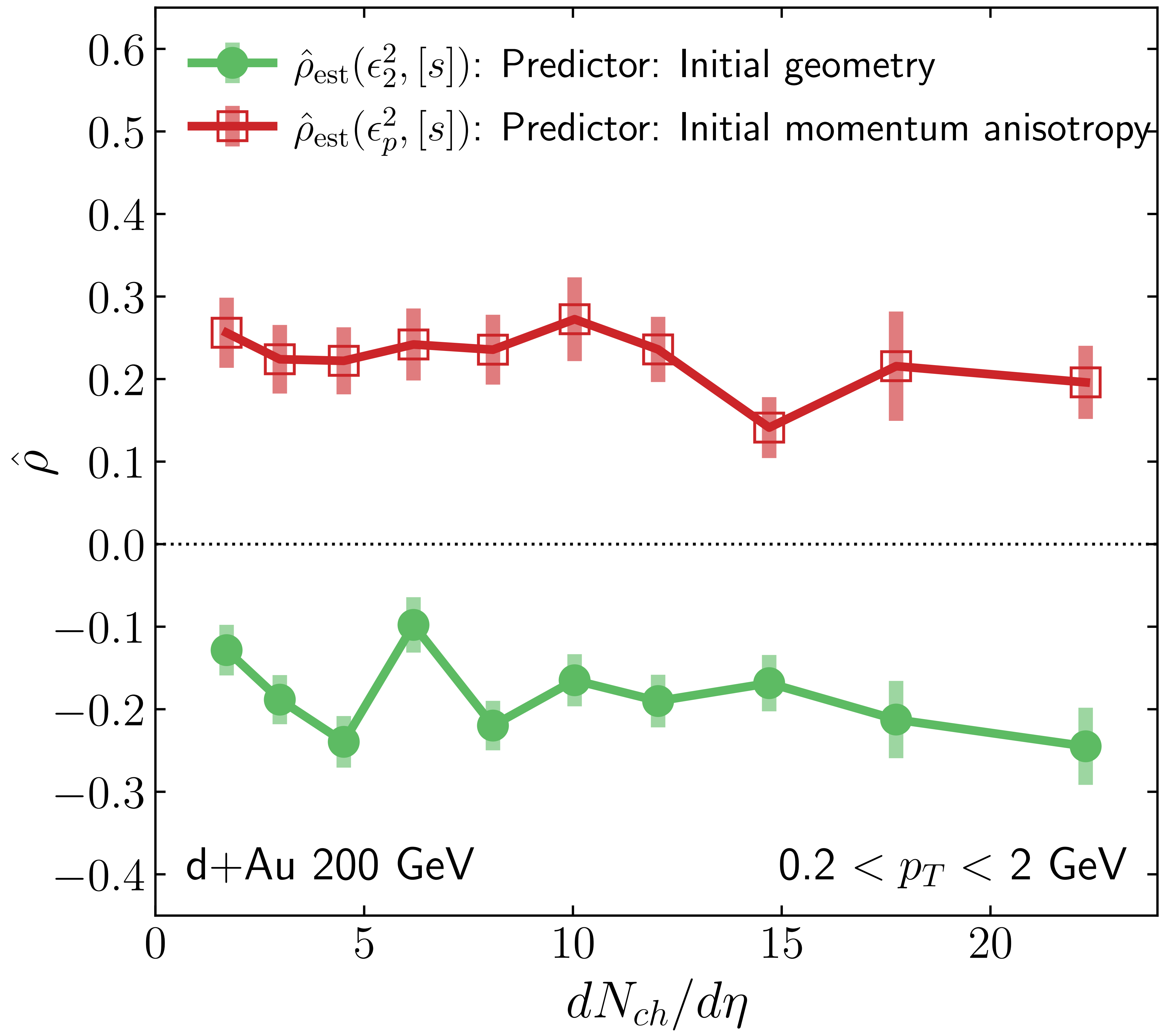
$$\delta O \equiv O - \langle O \rangle$$

$\hat{\delta} O \equiv \delta O - \dfrac{\langle \delta O \delta N \rangle}{\sigma_N^2} \delta N$ is the variation of O at fixed multiplicity

A. Olszewski, W. Broniowski, Phys. Rev. C96, 054903 (2017)

DIFFERENT SOURCES PREDICT DIFFERENT SIGNS

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

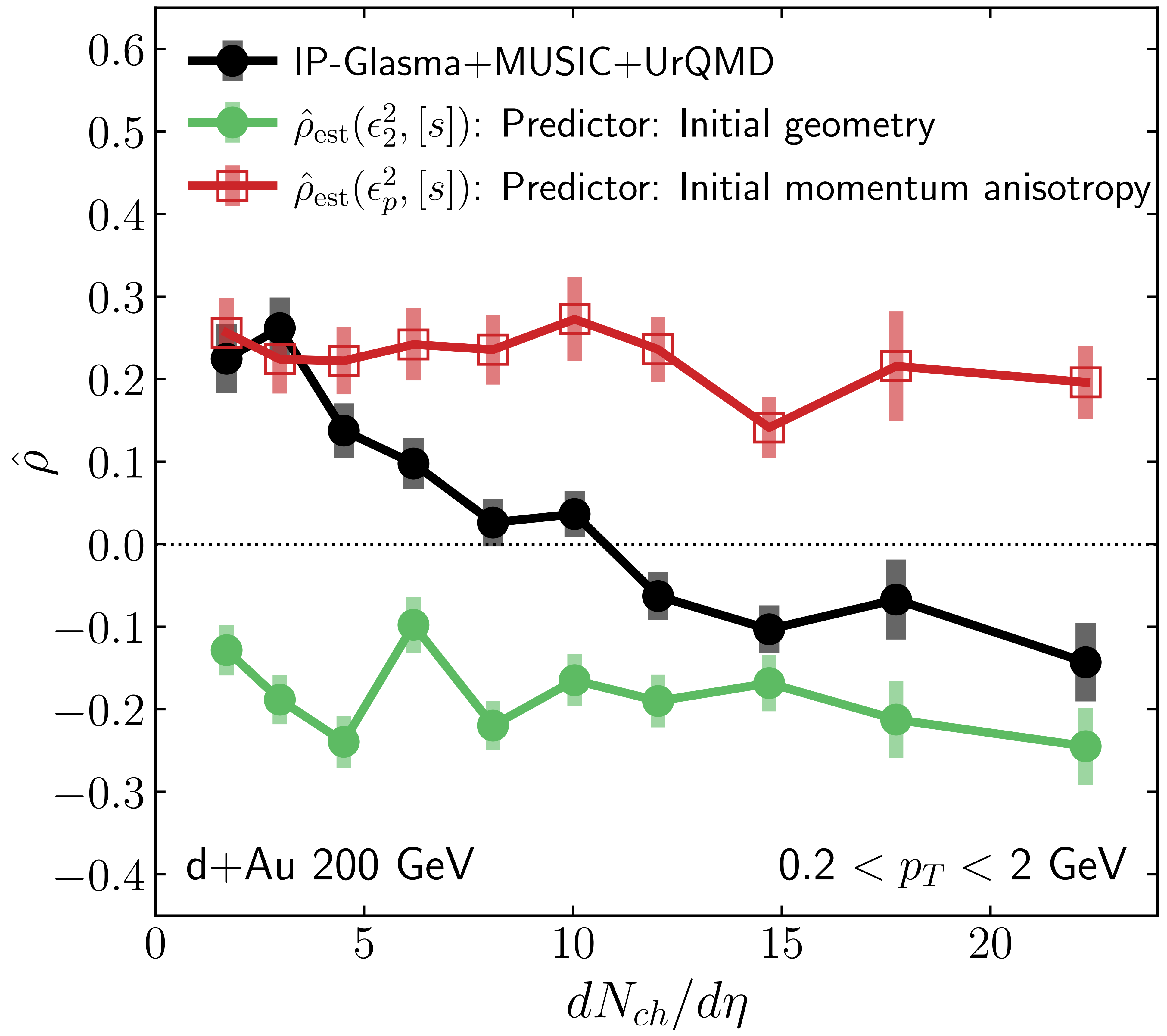


Initial momentum anisotropy : positive sign

final state response to the initial geometry : negative sign

DIFFERENT SOURCES PREDICT DIFFERENT SIGNS

G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301



Below $dN_{\rm ch}/d\eta \approx 10$
initial momentum anisotropy dominates

Above $dN_{\rm ch}/d\eta \approx 10$
final state response to the initial geometry dominates

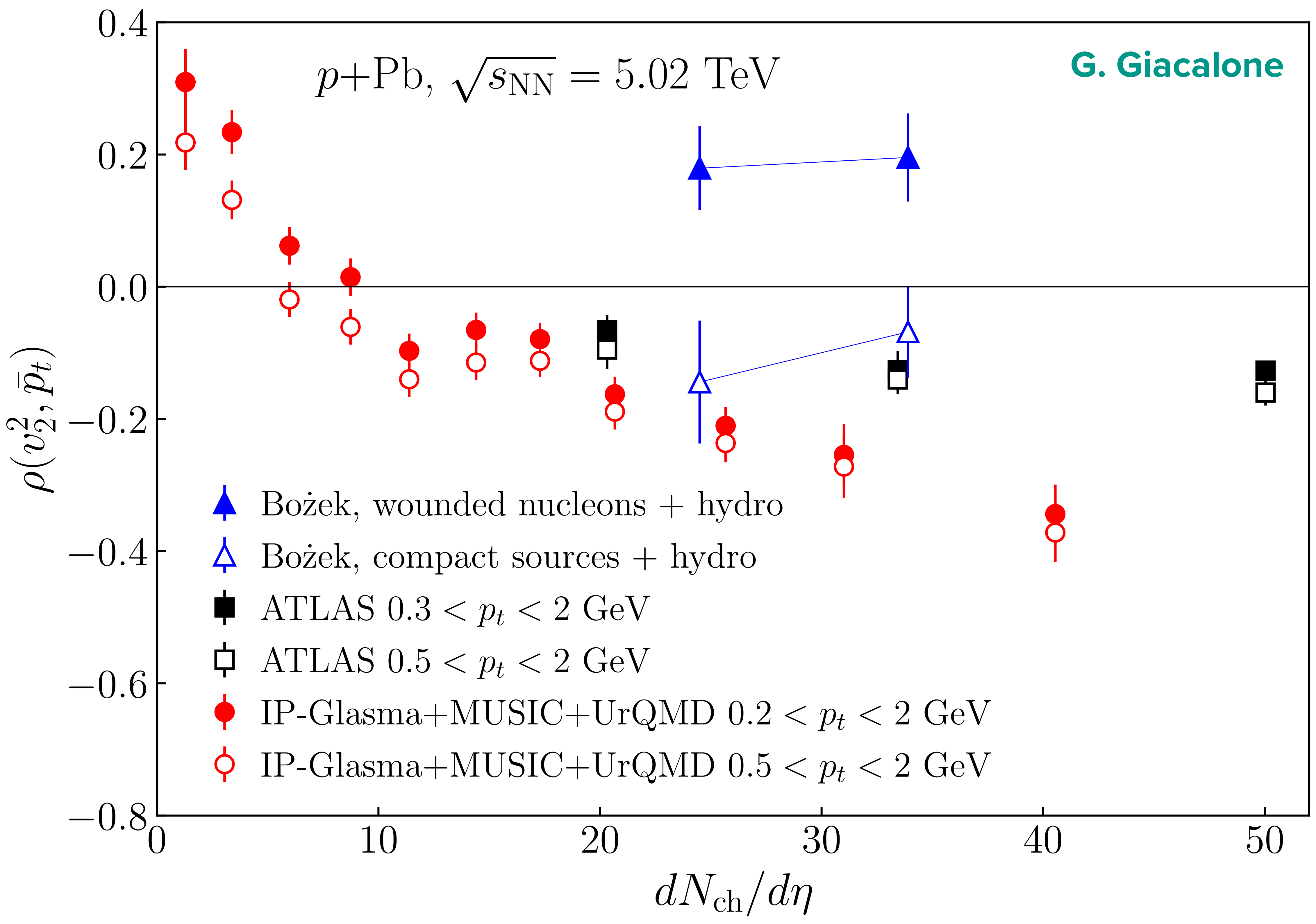
The observable moves from one predictor to the other

Is it detectable?
Very low multiplicity
Non-flow can mimic the signal

C. Zhang, A. Behera, S. Bhatta, J. Jia, Phys.Lett.B 822 (2021) 136702
S. H. Lim, J. L. Nagle, Phys.Rev.C 103 (2021) 6, 064906

Not the usual “saturation physics” effect. Visible at **low** $N_{\rm ch}$ because little final state effects.
Caveat: Is Q_s large enough at low $N_{\rm ch}$ to warrant use of the framework?

MORE INFORMATION ON THE GEOMETRY



Experimental data (black points) in p+Pb collisions is negative as predicted by geometry

Actually depends on the geometry model: The $T_A + T_B$ type models predict positive ρ

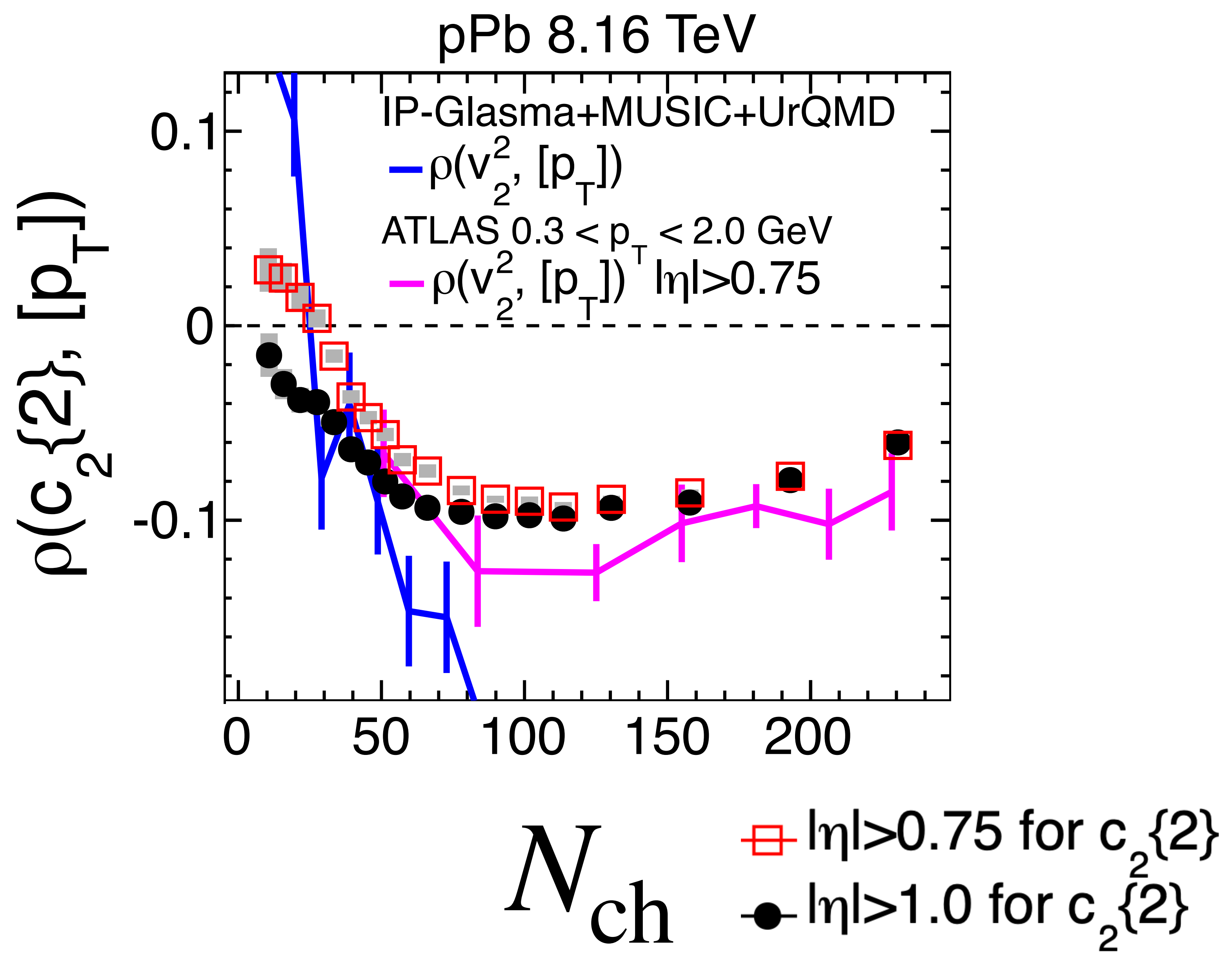
So, another hint that $(T_A T_B)^q$ is preferred

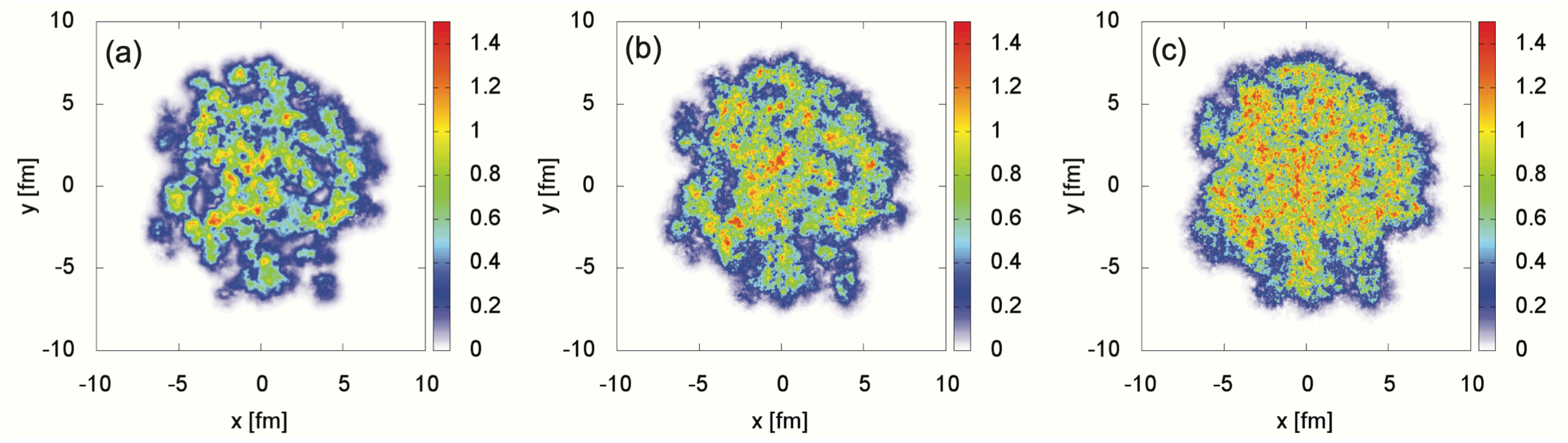
Bozek, Phys.Rev.C 93 (2016) 4, 044908
ATLAS Collaboration, Eur.Phys.J.C 79 (2019) 12, 985
Bożek, Mehrabpour, Phys.Rev.C 101 (2020) 6, 064902
G. Giacalone, B. Schenke, C. Shen, Phys. Rev. Lett. 125 (2020) 19, 192301

IS CGC SIGNAL LONG RANGE IN RAPIDITY?

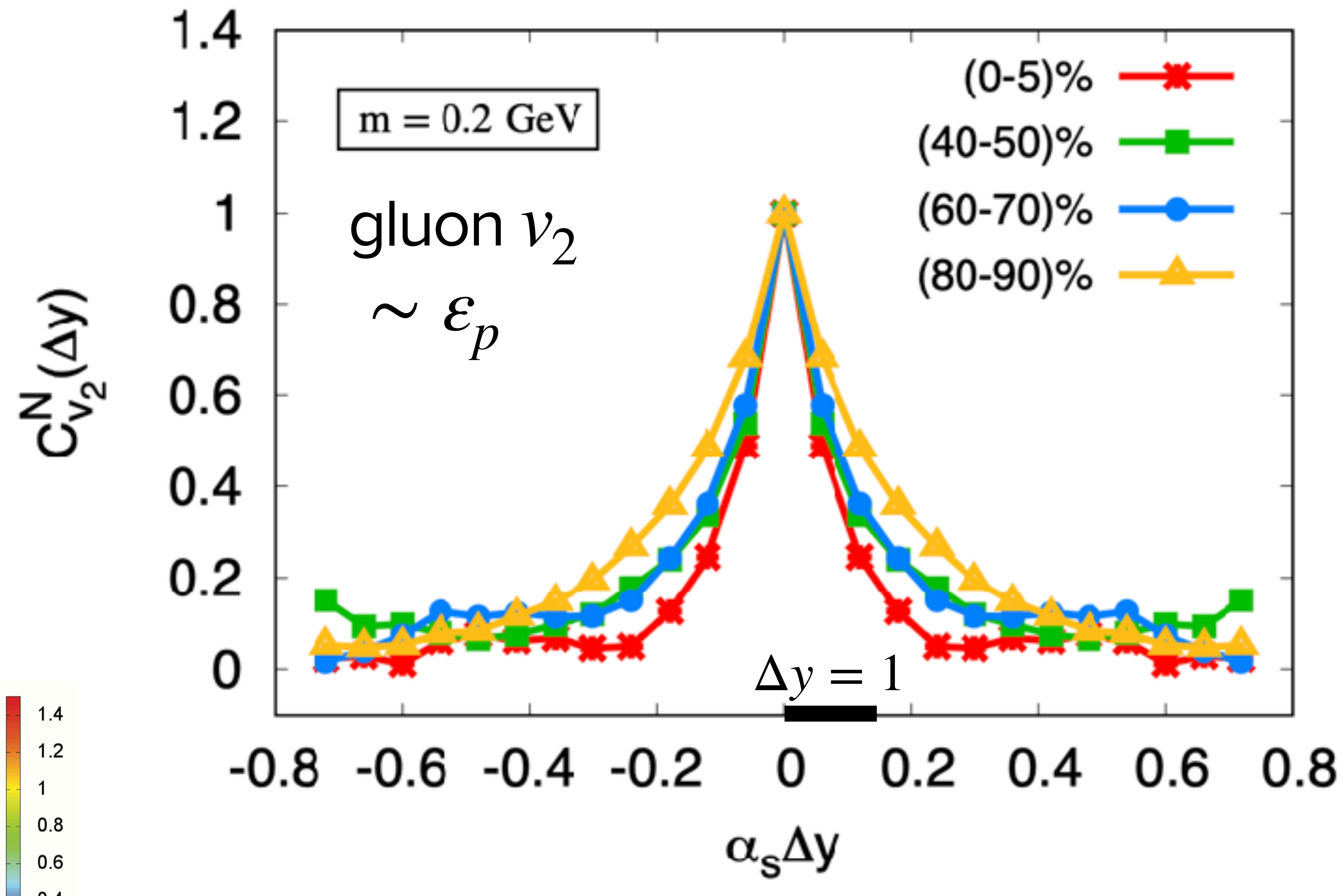
CMS sees a sign change but it disappears with increasing pseudo-rapidity η gap

CMS Collaboration, CMS-PAS-HIN-21-012





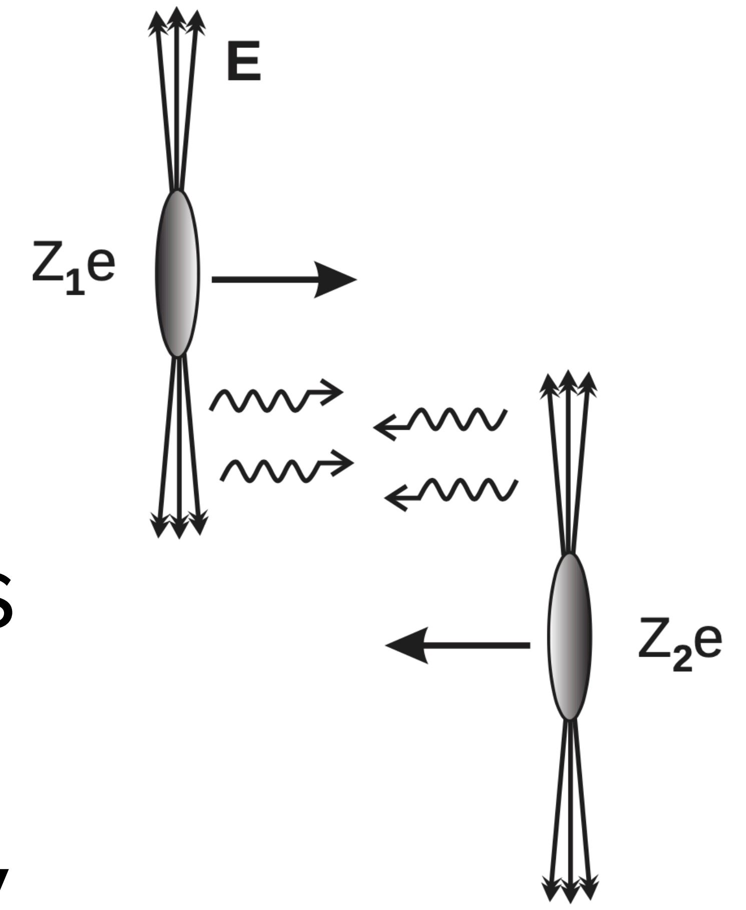
Employ JIMWLK small-x evolution to the proton and nucleus



Expect signal to vanish with η-gap like (other) non-flow

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

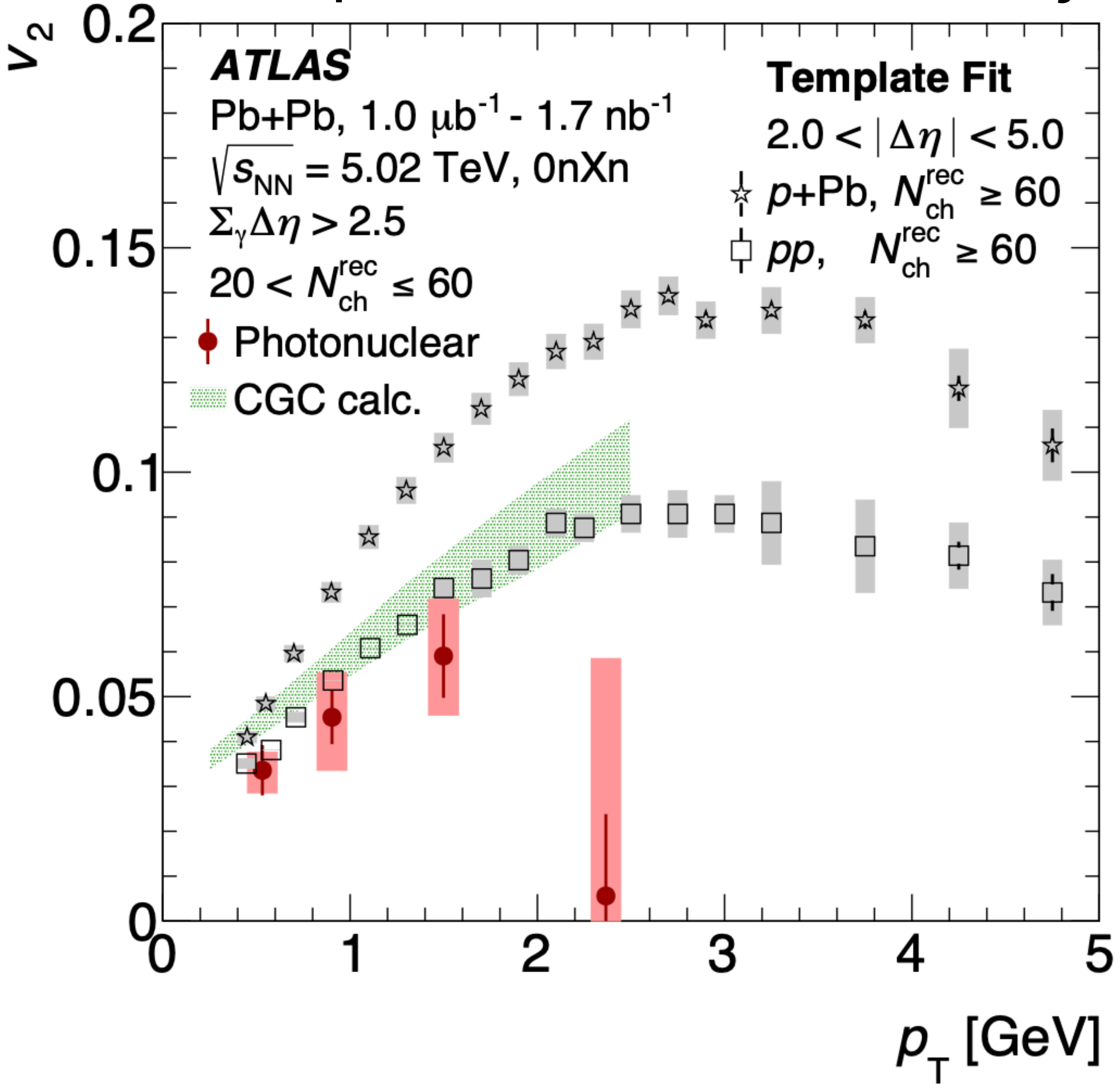
TO THE EXTREME: γ^*-NUCLEUS COLLISIONS



ATLAS has measured v_2 in ultra-peripheral collisions (UPC) → photon-nucleus collisions

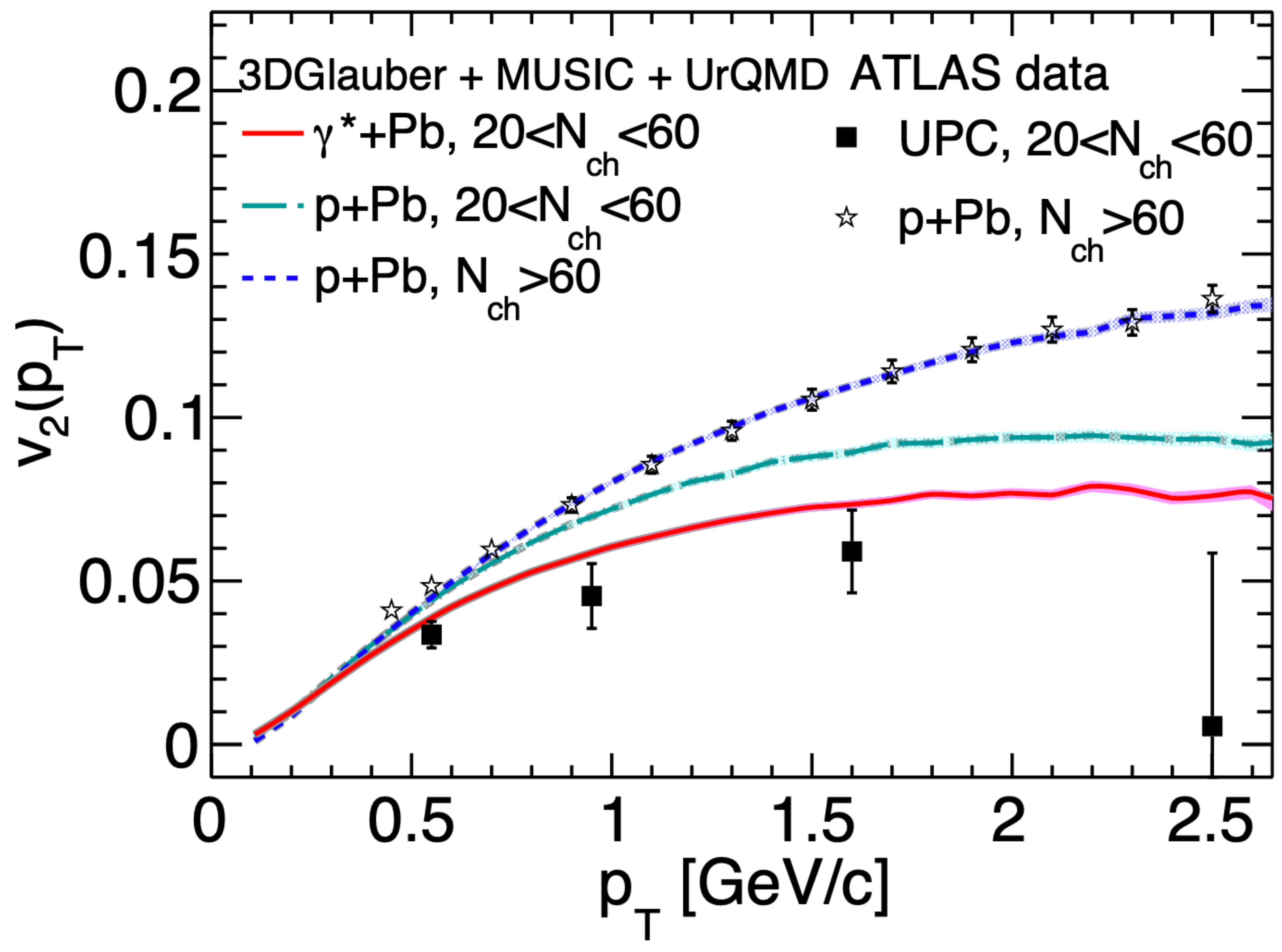
ATLAS Collaboration, Phys. Rev. C. 104 (2021) 014903

compared to initial state only



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

compared to final state only



W. Zhao, C. Shen, B. Schenke, 2203.06094

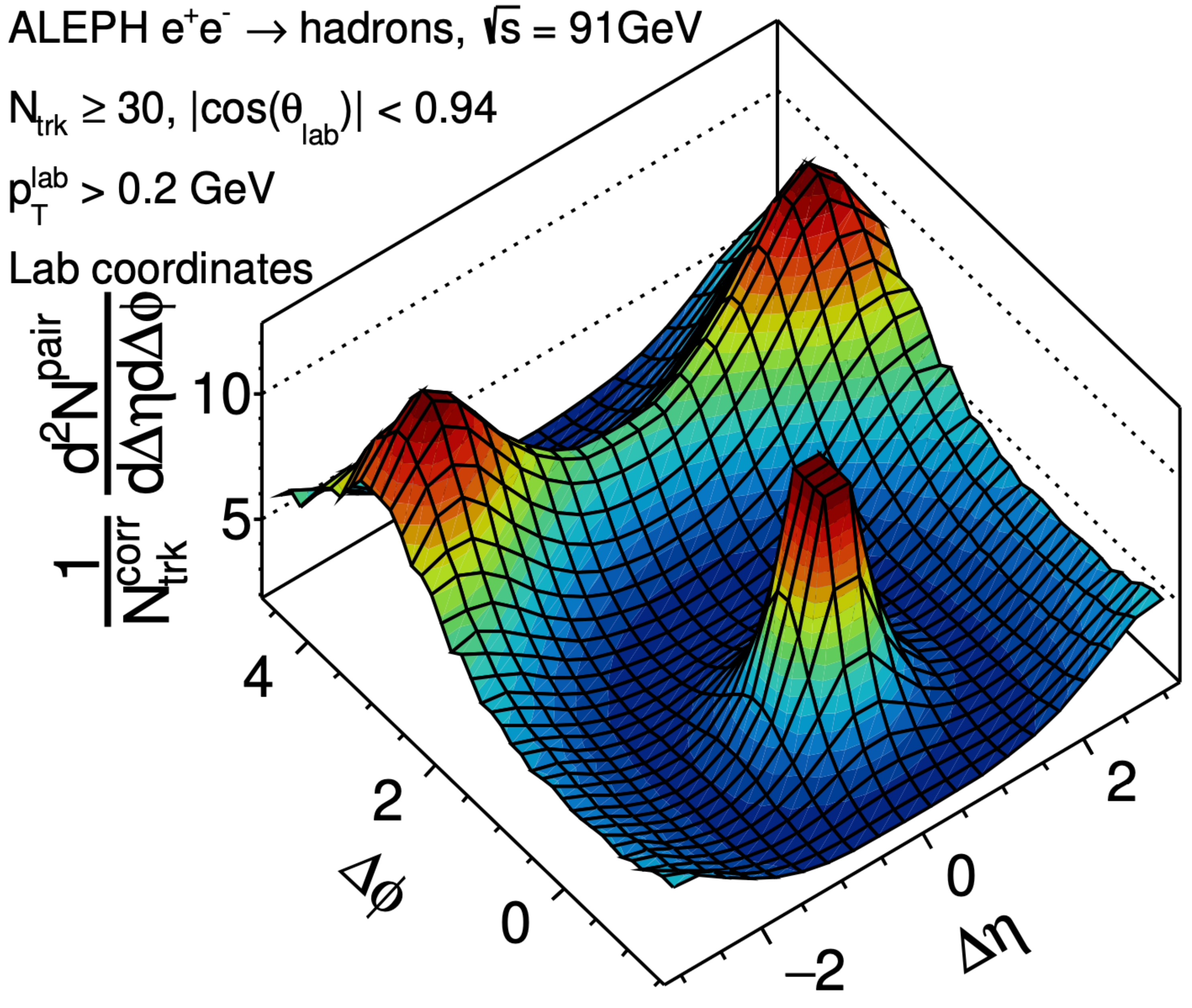
longitudinal decorrelation important!

Models predict opposite Q^2-dependence. Test at the EIC?

OTHER EXTREMELY SMALL SYSTEMS

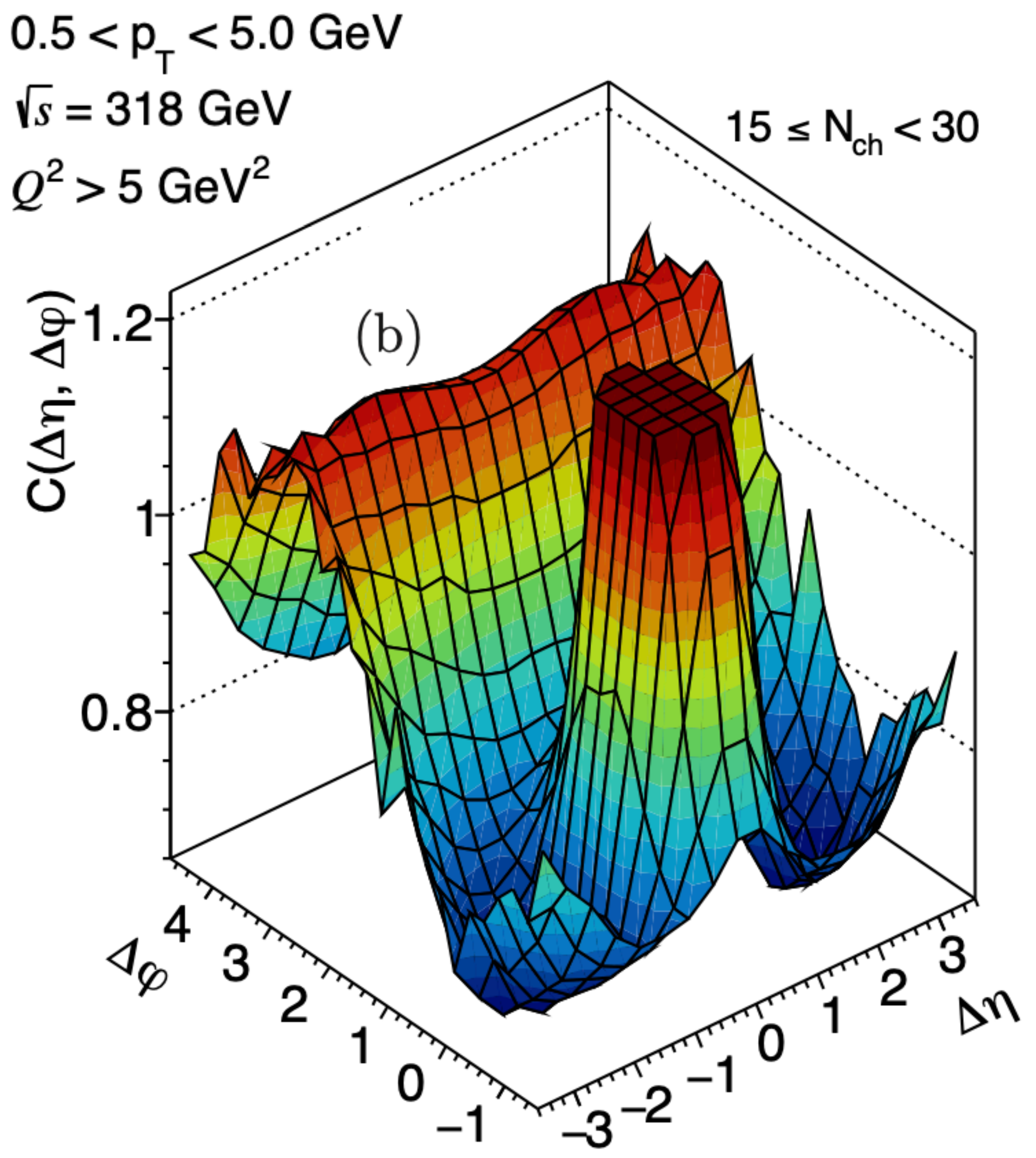
No long-range correlations observed:

$e^+ + e^- \rightarrow$ hadrons



A. Badea et al., Phys.Rev.Lett. 123 (2019) 21, 212002

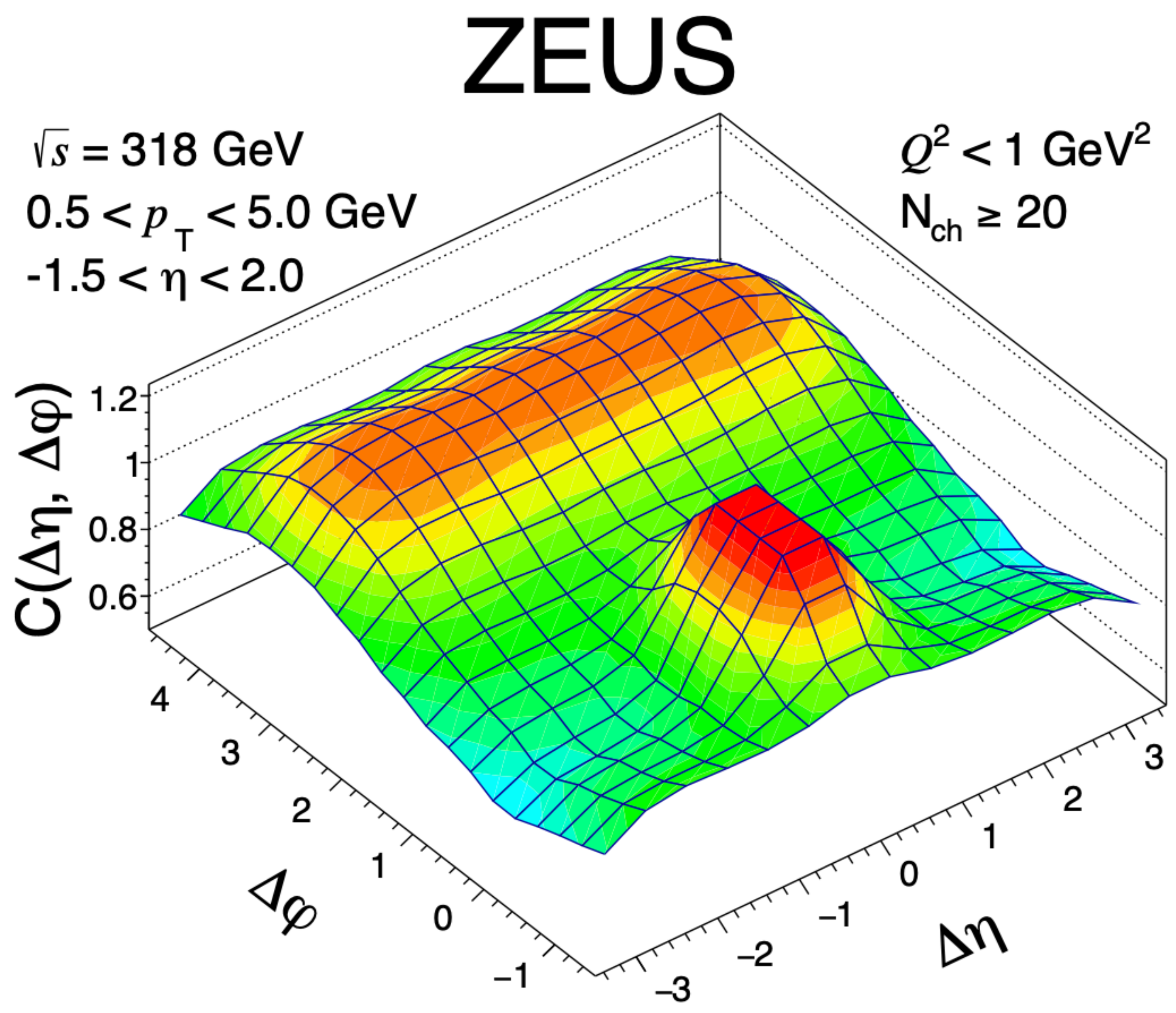
DIS $e + p \rightarrow$ hadrons



ZEUS Collaboration, JHEP 04 (2020) 070

Photoproduction

$e + p \rightarrow$ hadrons



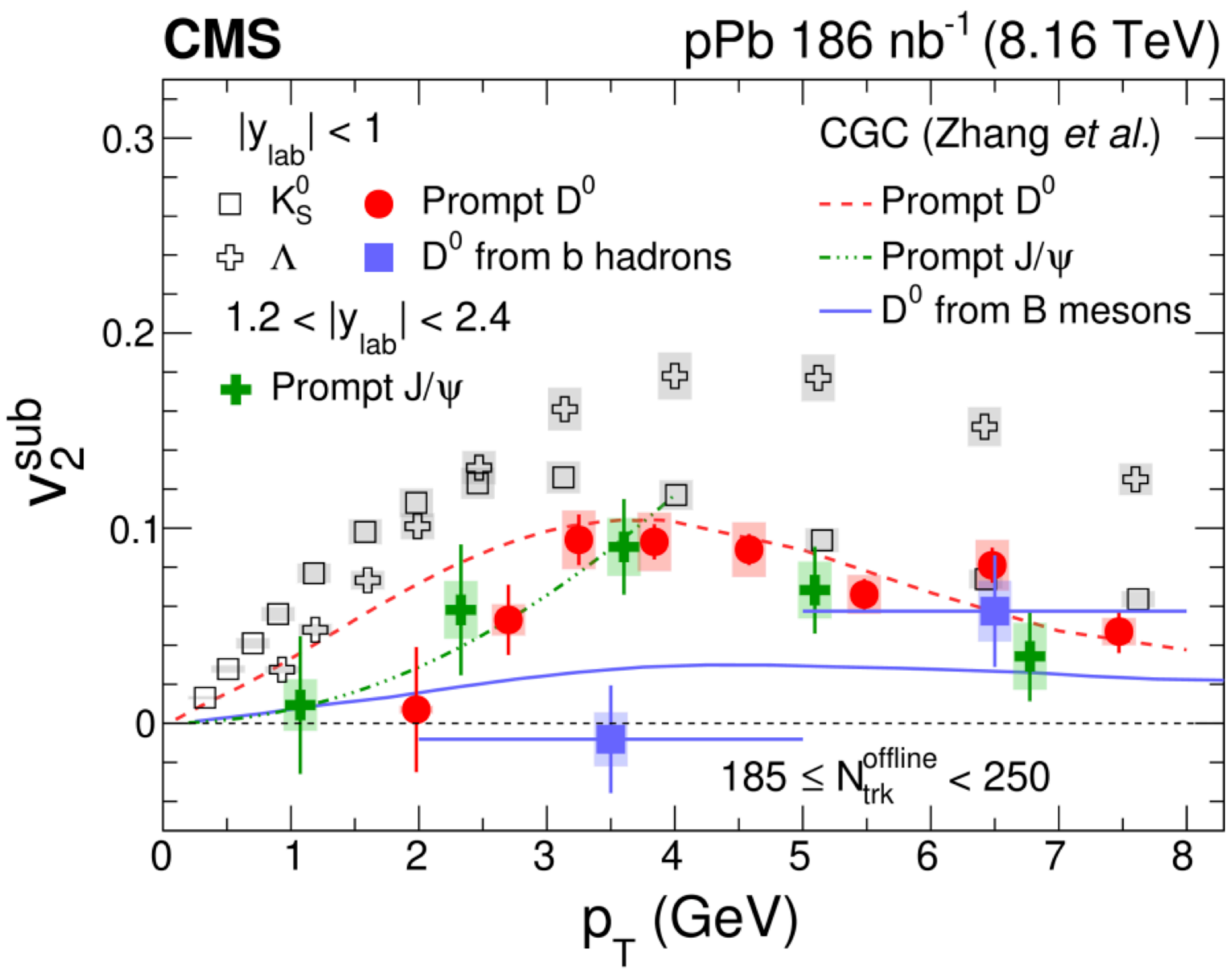
ZEUS Collaboration, JHEP 12 (2021) 102

$\gamma^* + p$ at LHC shows no sign of collectivity CMS Collaboration, 2204.13486

γ^*+Pb at RHIC shows no clear sign of collectivity STAR Collaboration, Tong Liu (for the STAR Collaboration), Quark Matter 2022

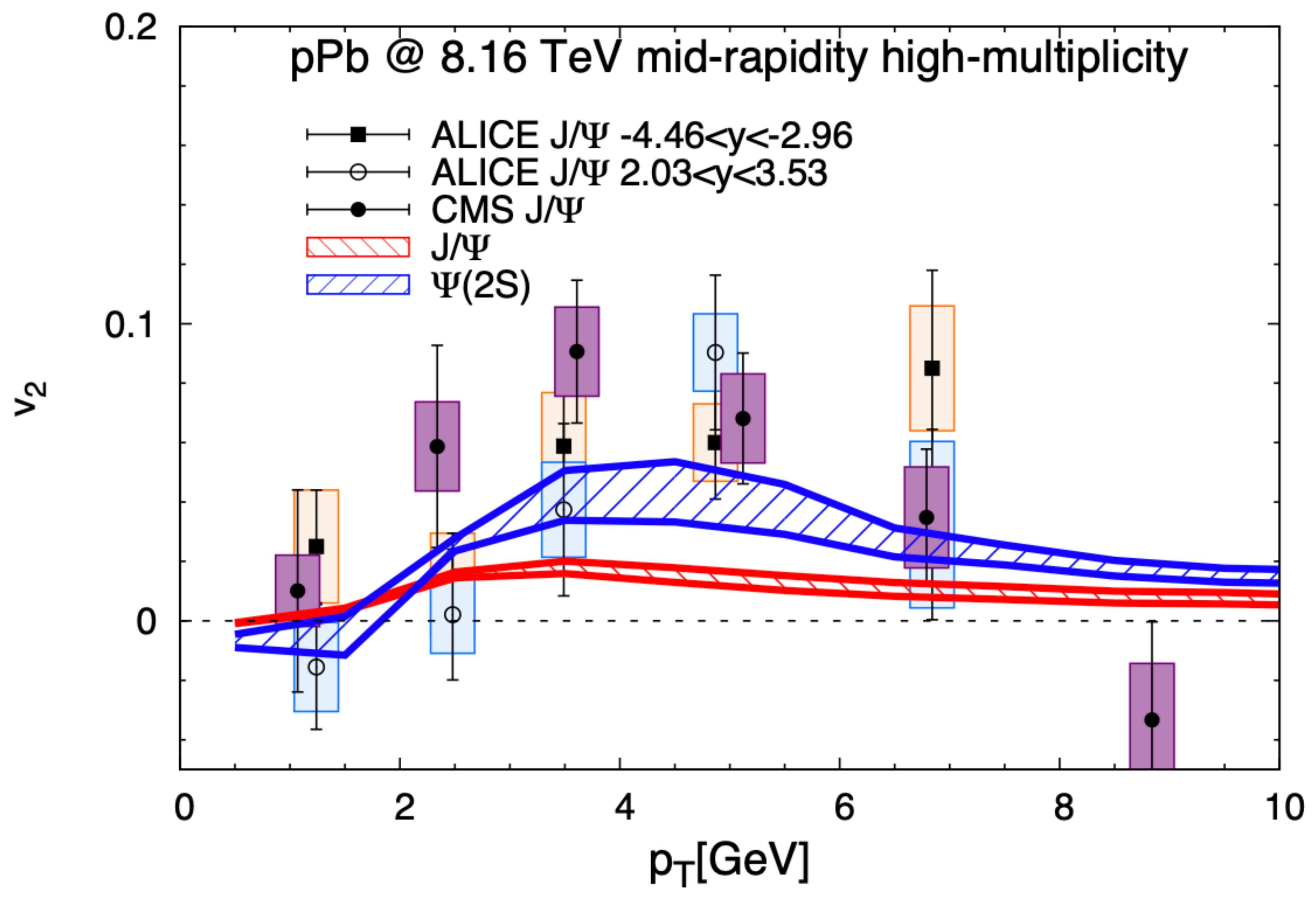
HEAVY QUARK ANISOTROPY IN SMALL SYSTEMS

initial state only



Zhang, Marquet, Qin, Wei, Xiao, Phys.Rev.Lett. 122 (2019) 17, 172302

final state only

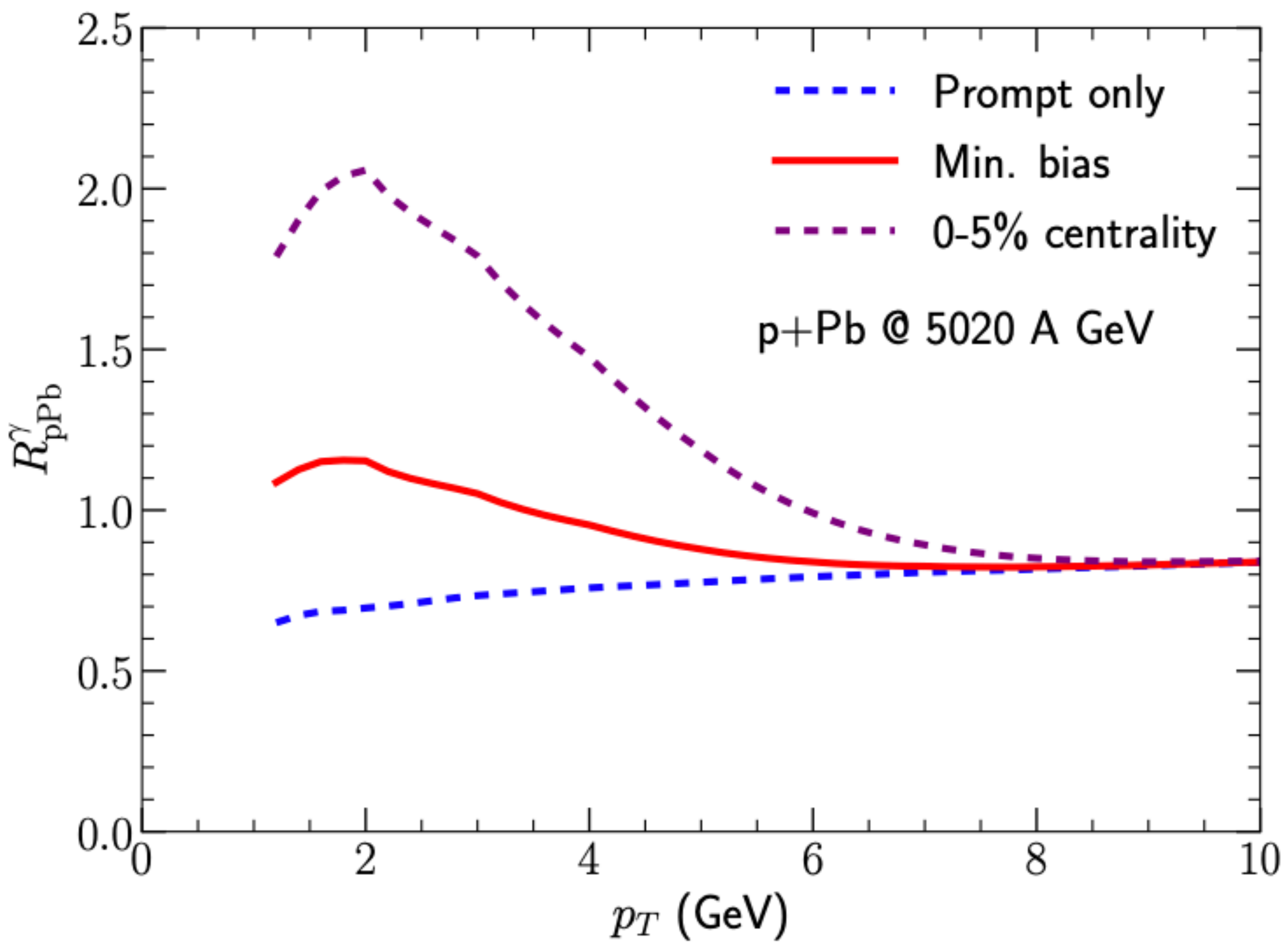


X. Du, R. Rapp, JHEP 03 (2019) 015
CMS Collaboration, Phys.Lett. B 791 (2019) 172-194
ALICE Collaboration, Phys. Lett. B 780 (2018) 7

ELECTROMAGNETIC PROBES

If a QGP is formed in small systems, thermal photons (and dileptons) should be enhanced

C. Shen, J.-F. Paquet, G.S. Denicol, S. Jeon, C. Gale, Phys.Rev.C 95 (2017) 1, 014906
C. Gale, J.-F. Paquet, B. Schenke, C. Shen, Phys.Rev.C 105 (2022) 1, 014909

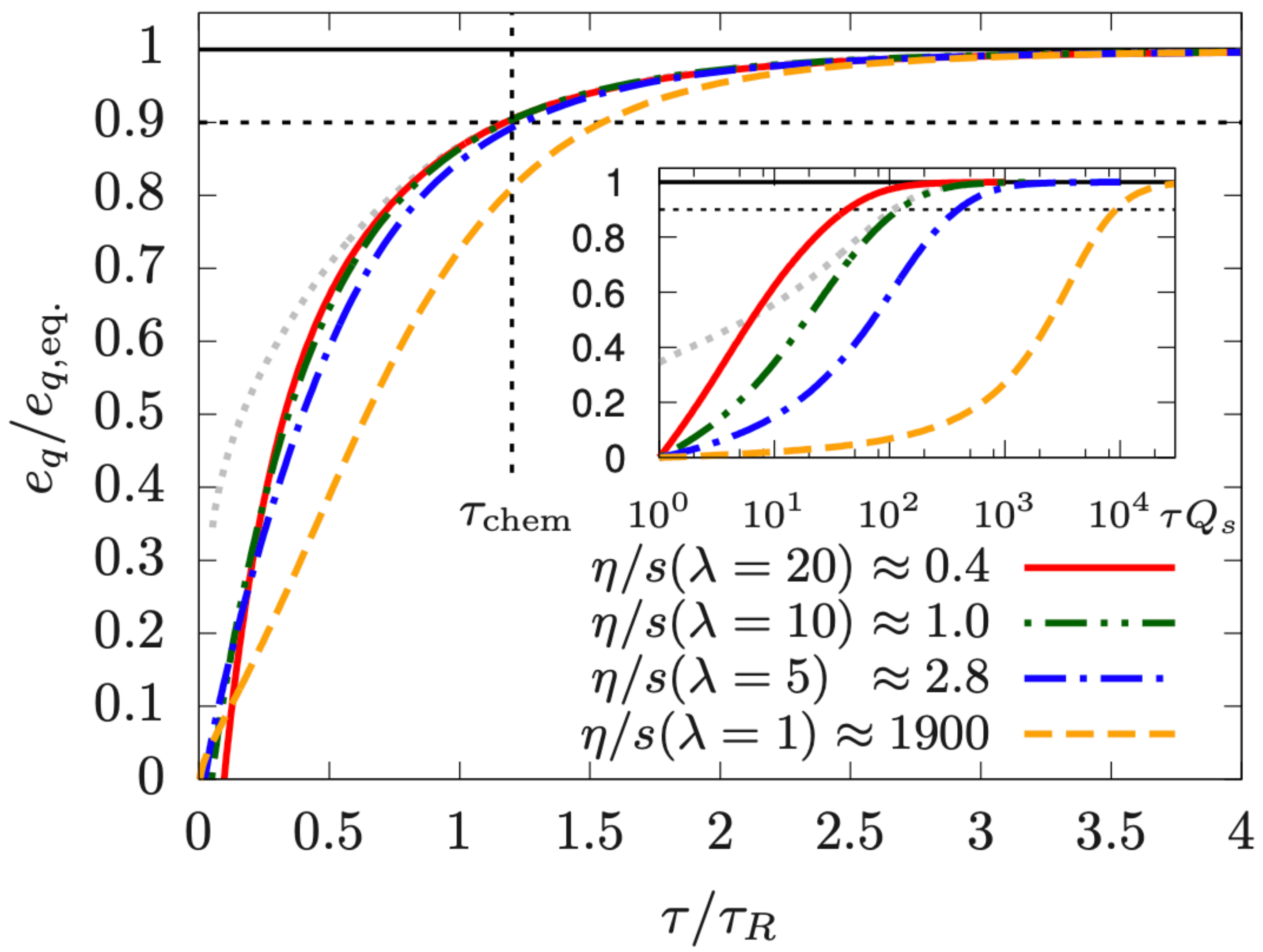


Use EM-probes to study early-time dynamics

B.S. Kasmaei, M. Strickland Phys. Rev. D 102 (2020) 014037
J. Churchill, L. Yan, S. Jeon, C. Gale, Phys. Rev. C 103 (2021) 024904
C. Gale, J.-F. Paquet, B. Schenke, C. Shen, Phys.Rev.C 105 (2022) 1, 014909

EM-probes also sensitive to chemical equilibration

A. Kurkela, A. Mazeliauskas, Phys. Rev. Lett. 122 (2019) 142301
A. Kurkela, A. Mazeliauskas, Phys. Rev. D 99 (2019) 054018
X. Du, S. Schlichting, Phys.Rev.D 104 (2021) 5, 054011
X. Du, S. Schlichting, Phys.Rev.Lett. 127 (2021) 12, 122301



Collisions with $dN_{\mathrm{ch}}/d\eta \gtrsim 100$ can chemically equilibrate

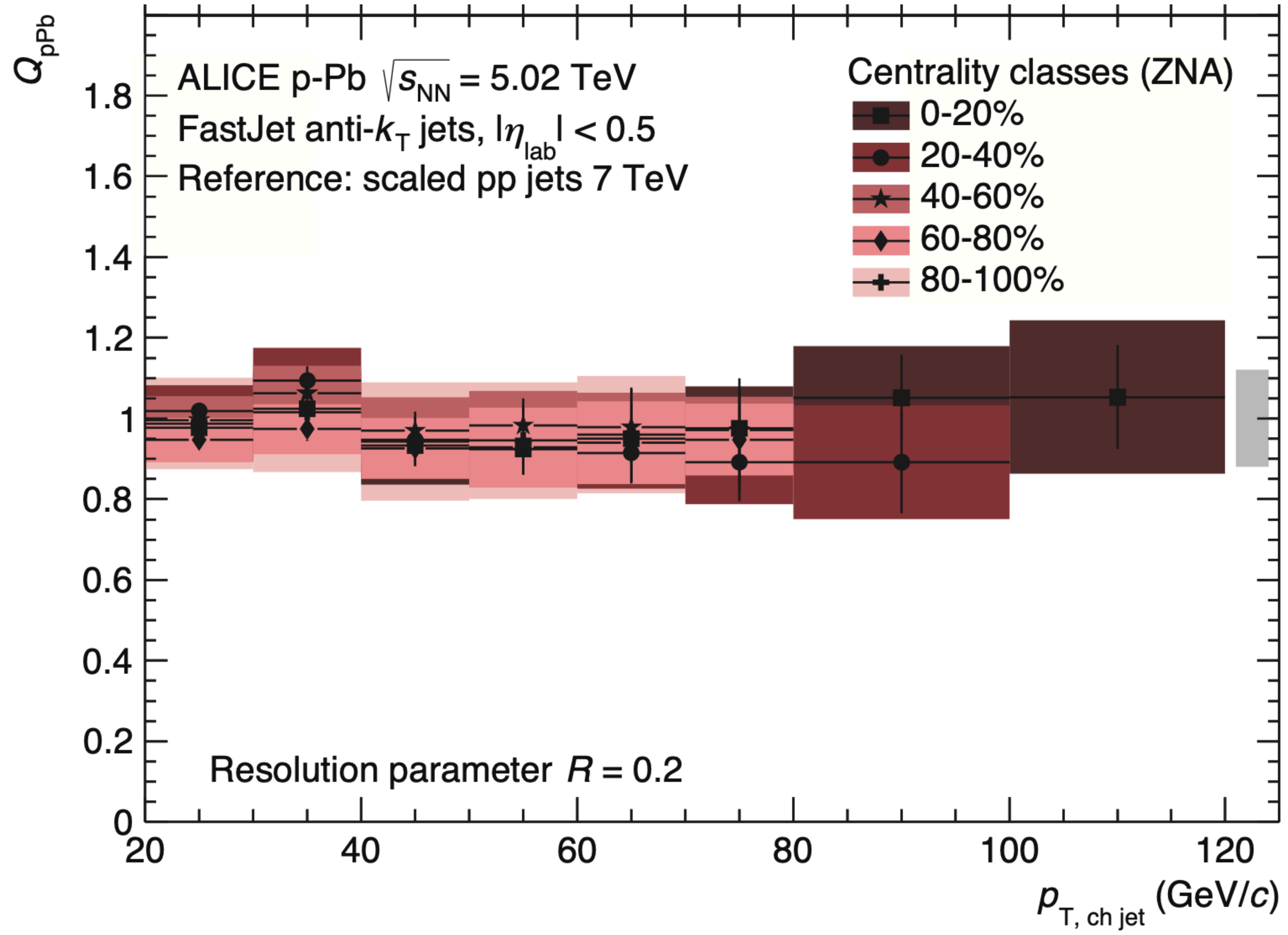
SEE TALK BY DU

HIGH TRANSVERSE MOMENTUM

No apparent jet quenching is observed in e.g. p+Pb collisions

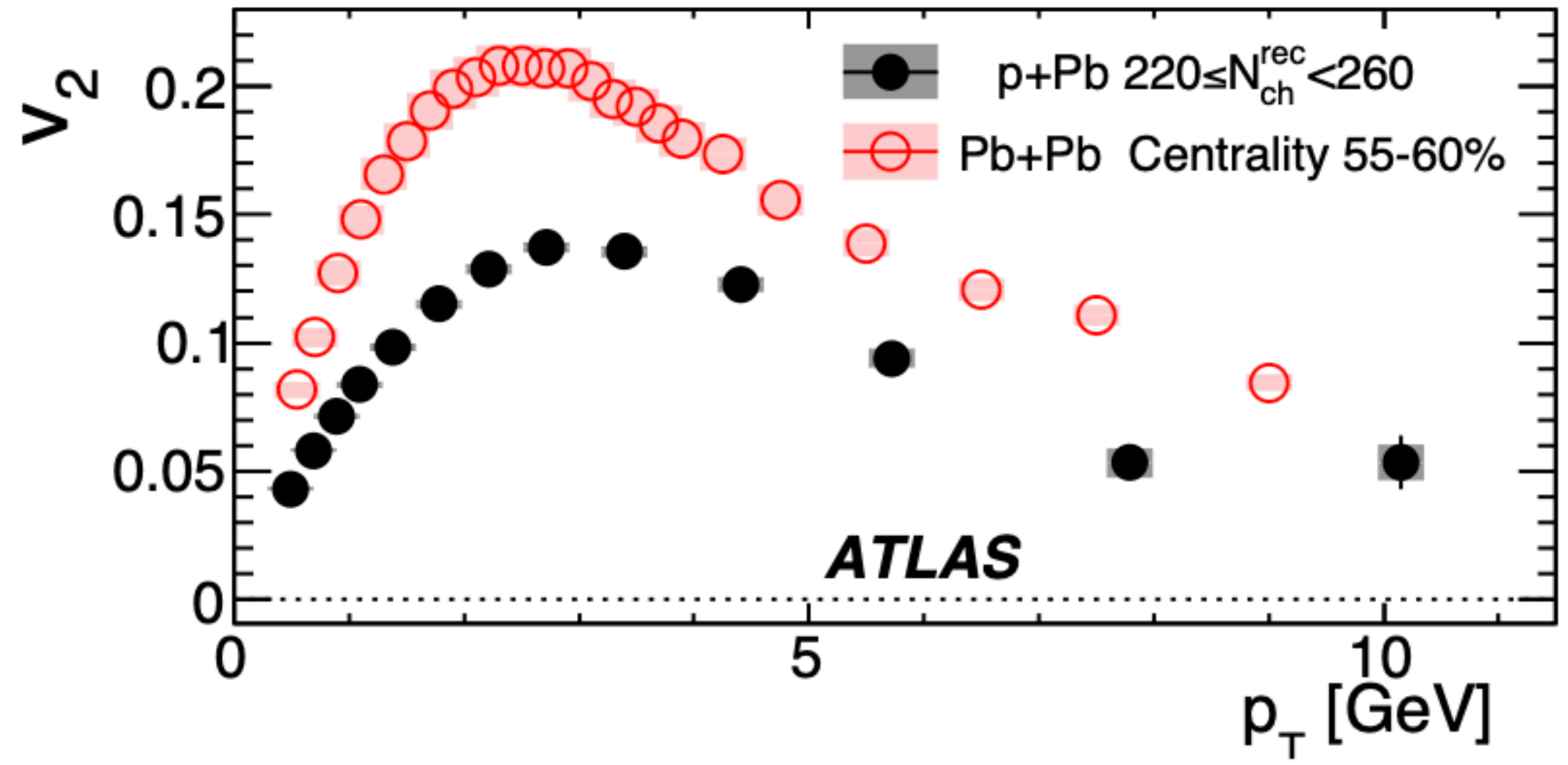
Calculations predict quenching in high multiplicity p+Pb collisions, but experimental centrality selection is hard/biased in small systems. Using spectator neutrons to select event class: no suppression found →

ALICE Collaboration, Eur. Phys. J. C76 (2016) no. 5, 271



Yet, there is a momentum anisotropy at high p_T

What is its source? ATLAS Collaboration, Phys.Rev.C 90 044906 (2014)



Further insight needed:

Different system sizes

Compare p+Pb to O+O collisions at RHIC and LHC

Detailed analyses with sPHENIX at RHIC

SUMMARY

Small system studies have pushed boundaries:

Lead to improved experimental methods, e.g. to better distinguish collectivity from other correlations

Triggered tremendous theoretical efforts that are useful beyond the immediate application to small systems (better understanding of hydrodynamic theories, “thermalization”, kinetic theory, nucleon structure, many-body gluon correlations, …)

Dominant role of initial geometry in p+A and larger systems is established
But many aspects need better understanding,
especially when going towards lower multiplicities and p+p, γ^*+A

BACKUP

SUMMARY - EXTENDED

- Collectivity (long-range rapidity correlations) observed in systems as $\gamma^* + \text{Pb}$, p+p, and p+A
- At least in p+A and larger systems geometry drives collectivity
- Nucleon substructure required by preferred models
- Small systems push the limits of hydrodynamics, triggered a lot of research in understanding theory of hydrodynamics, and kinetic theory better
- Initial momentum anisotropy found to dominate for $dN_{\text{ch}}/d\eta \lesssim 10$ - correlation between mean transverse momentum and v_2 is sensitive observable
- No collectivity observed in $e^+ + e^-$, $e + p$ (DIS and photo production), but in ultra-peripheral Pb+Pb
- Both initial and final state descriptions can describe UPC data - Q^2-dependence (EIC) can distinguish
- Heavy flavor flow, electromagnetic and high momentum probes provide further insight