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Brookhaven National Laboratory™

STAR'S CONTRIBUTION TO UNDERSTANDING THE BULK PROPERTIES OF THE QGP

Björn Schenke, Brookhaven National Laboratory

STAR 25-year Celebration
BNL
December 18, 2025

SOME HISTORY

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

2002: First full-energy Au+Au run

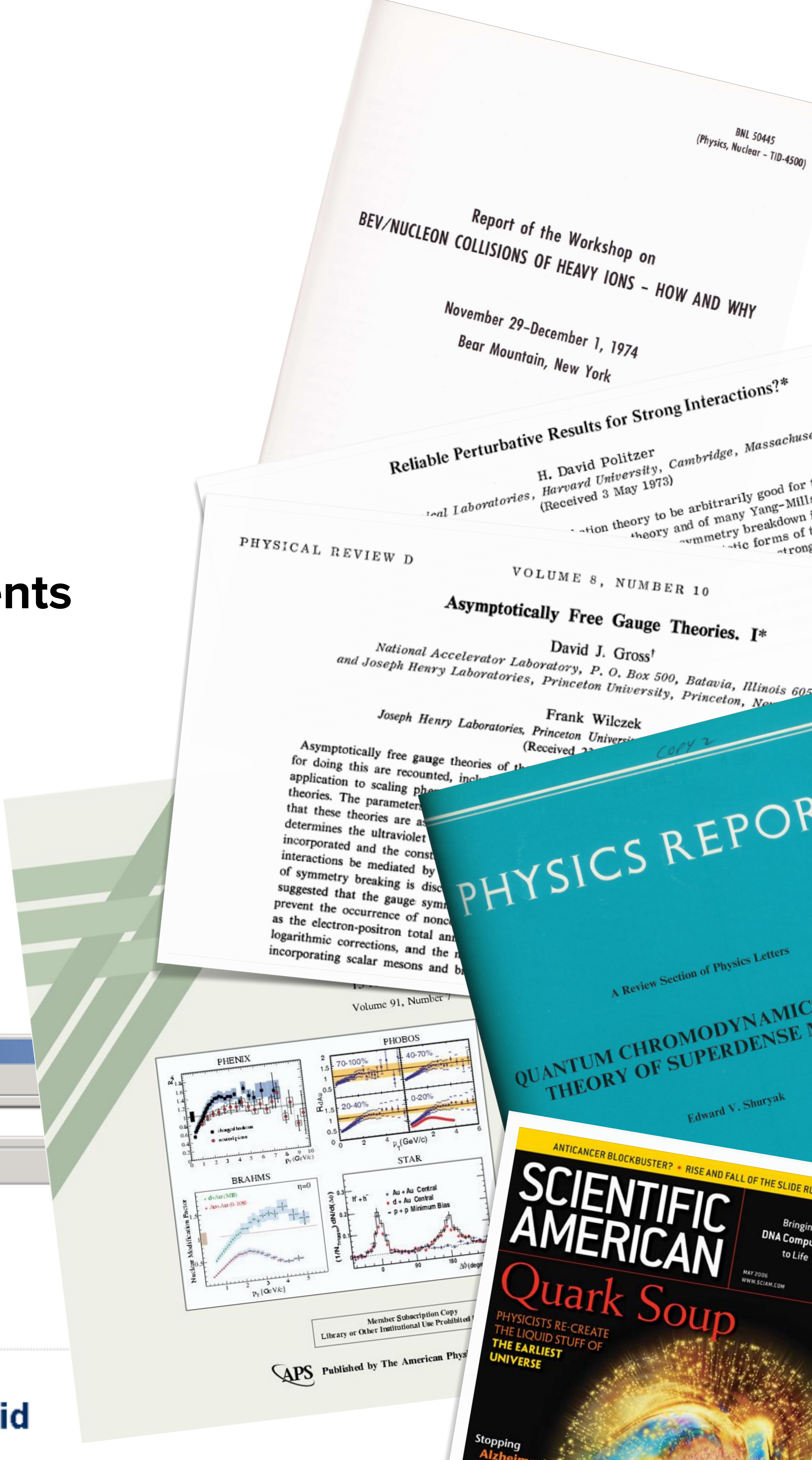
2005: BNL press release: RHIC Scientists Serve Up "Perfect" Liquid

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

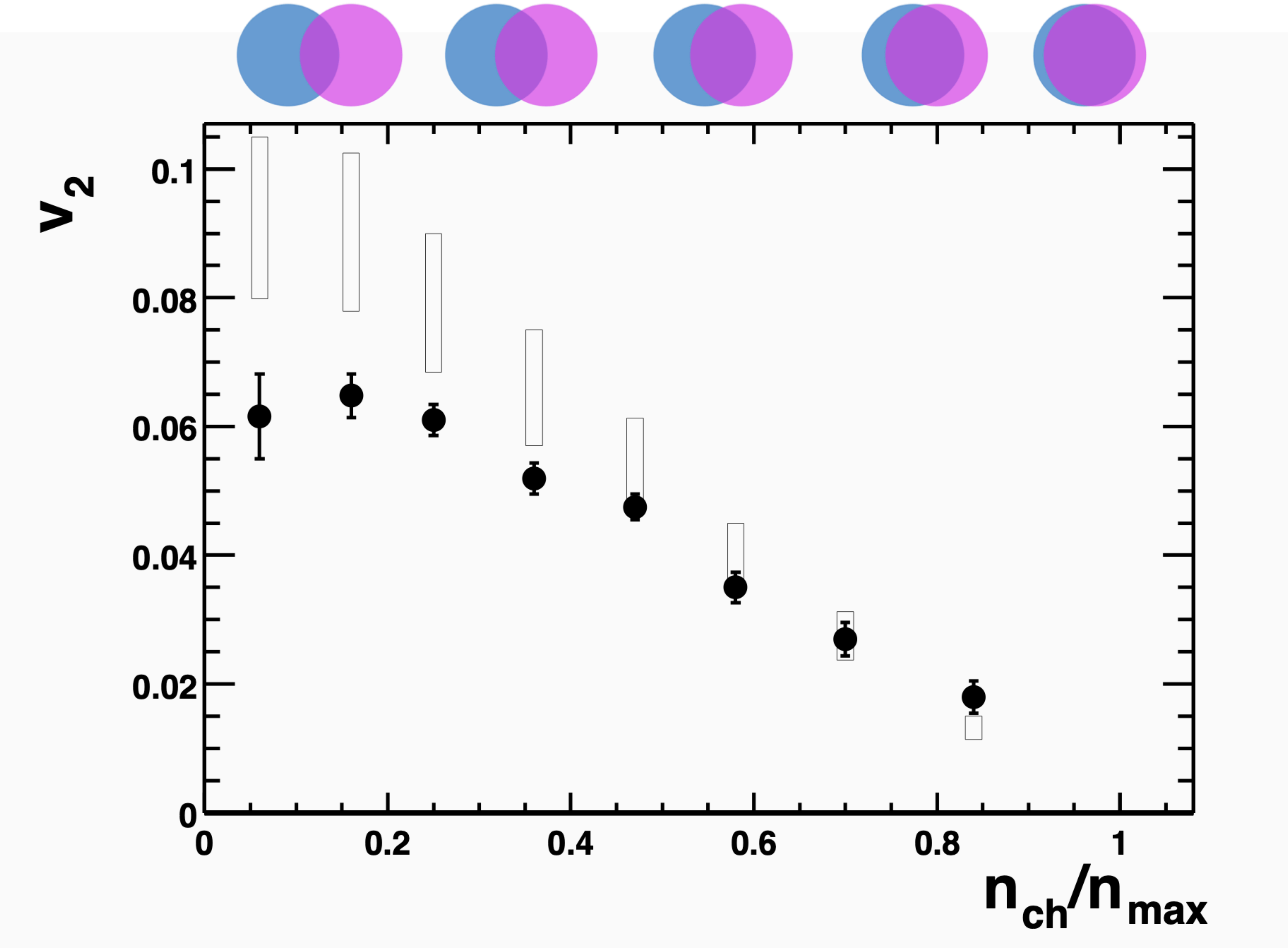
2015: RHIC small system scan

2021: RHIC Beam Energy II



ELLIPTIC FLOW DISCOVERY

Elliptic flow in Au + Au collisions at s_NN^(1/2) = 130 GeV, STAR Collaboration K.H. Ackermann et al.
***Phys.Rev.Lett.* 86 (2001) 402-407 • e-Print: nucl-ex/0009011** **see Raimond Snellings' talk**



Solid points: STAR data

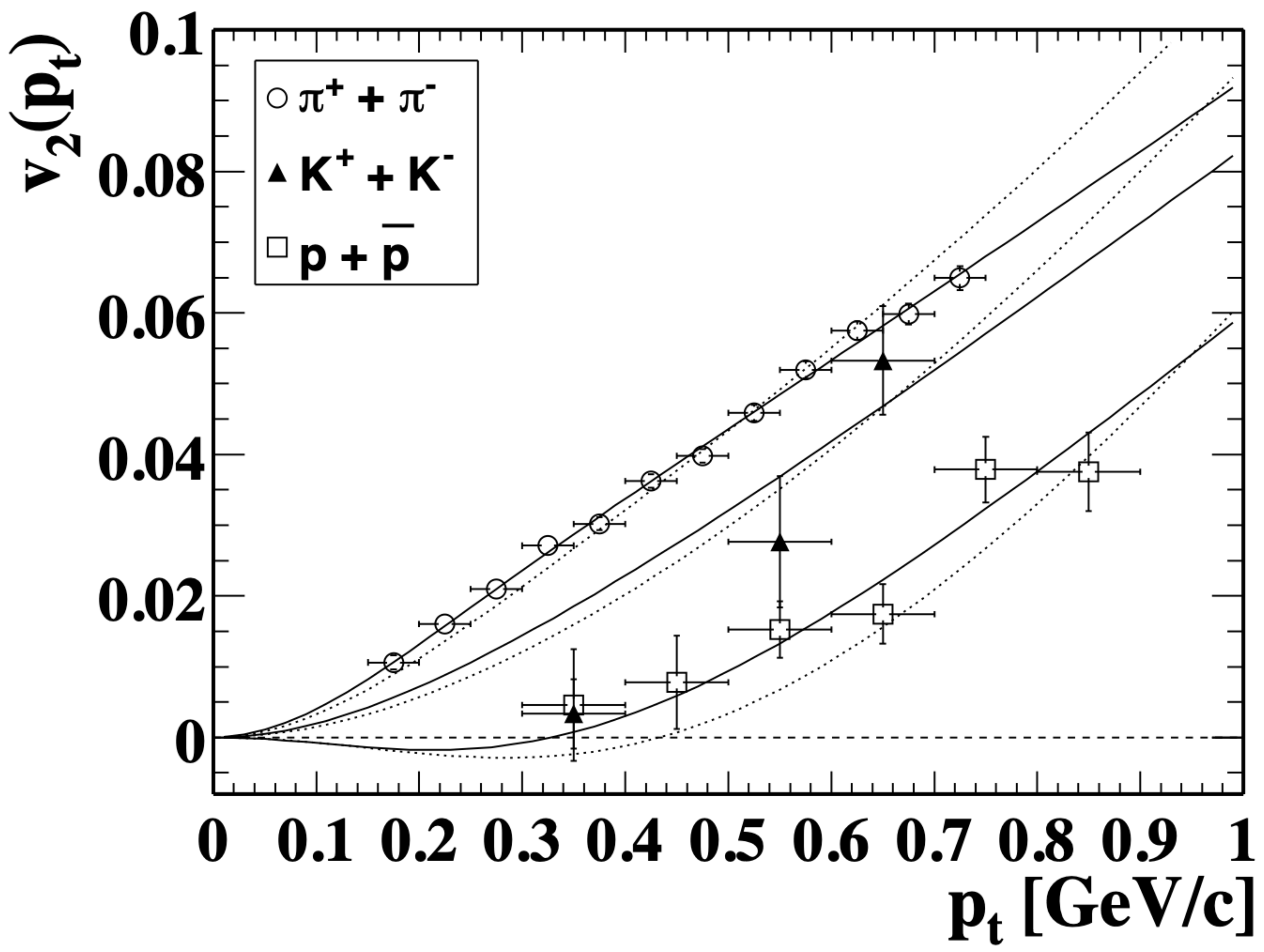
Boxes: Expectation from ideal hydrodynamics (scaled eccentricities)

"Comparing to estimates [18] based on transport cascade models, we find that elliptic flow is underpredicted by RQMD by a factor of more than 2. Hydrodynamic calculations [6,8] for RHIC energies overpredict elliptic flow by about 20-50%.

This is just the reverse of the situation at the SPS where RQMD gave a reasonable description of the data and hydrodynamic calculations were more than a factor of two too high [13]. "

PARTICLE ID FLOW

Identified particle elliptic flow in Au + Au collisions at s(NN)(1/2) = 130-GeV**
STAR Collaboration, C. Adler et al., Phys.Rev.Lett. 87 (2001) 182301, e-Print: nucl-ex/0107003 [nucl-ex]



Solid lines: modified blast wave model fit (including spatially anisotropic freeze-out hyper-surface)

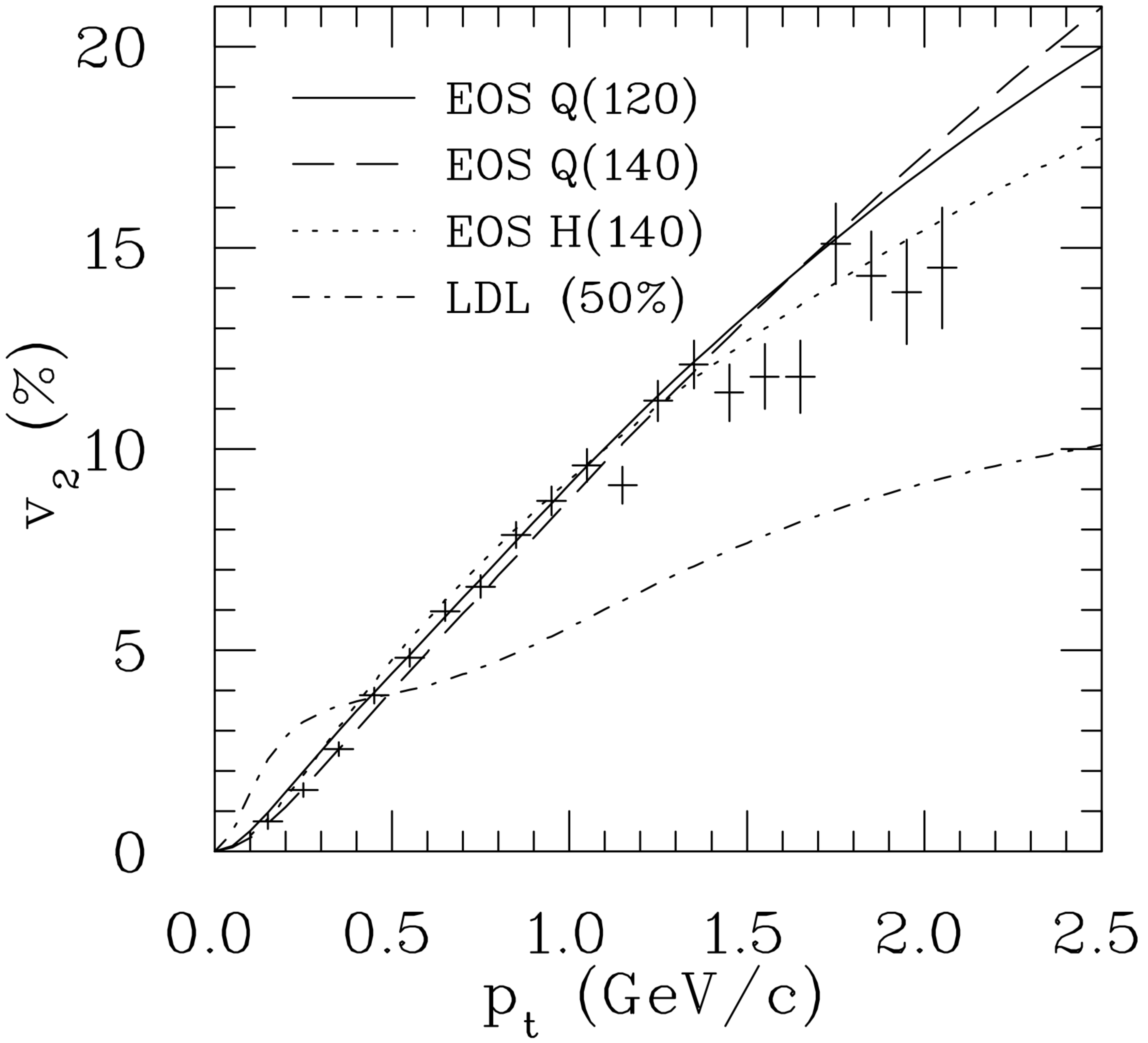
Dotted lines: unmodified blast wave model fit

“We have made the ***first measurement of identified particle elliptic flow at RHIC****. The measured elliptic flow as a function of* p_T *and centrality differs significantly for particles of different masses. This* ***mass dependence*** *can be described with a simple hydrodynamic-motivated Blast Wave model.”*

Compatible with all particles emerging from a common velocity field, modifying their momentum depending on particle mass.

FLUID DYNAMICS

P.F. Kolb, J. Sollfrank, and U. Heinz, Phys. Rev. C 62 (2000) 054909. (predictions)
P.F. Kolb, P. Huovinen, U. Heinz, H. Heiselberg, Phys.Lett.B 500 (2001) 232-240



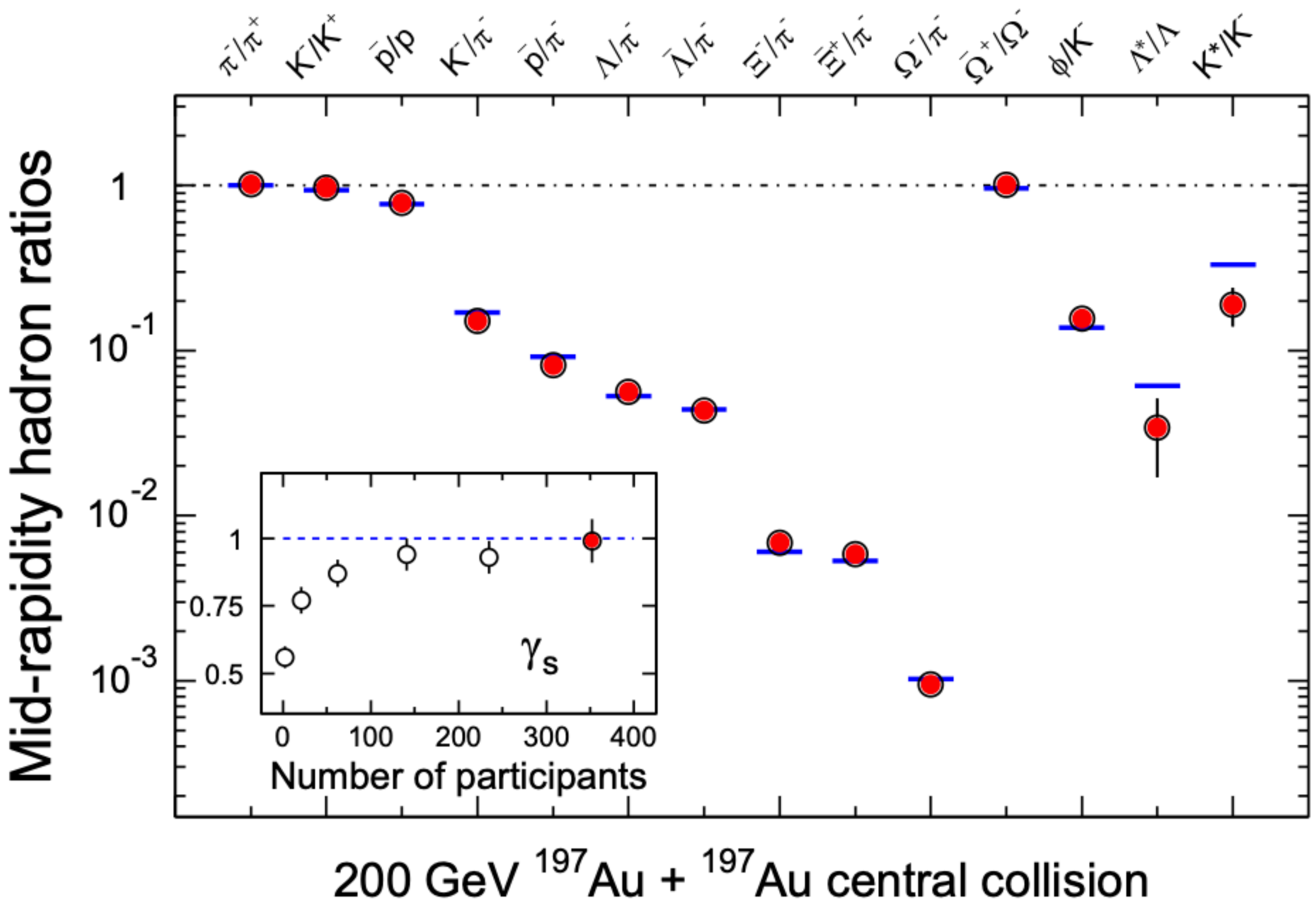
STAR data was used to compare to first ideal hydrodynamic calculations

K.H. Ackermann et al., *Phys.Rev.Lett.* 86 (2001) 402-407

*"The recent elliptic flow data from Au+Au collisions at RHIC show **remarkable quantitative agreement** with the hydrodynamical model, indicating a large degree of thermalization in the earliest collision stages, well before hadronization. "*

CHEMICAL FREEZE-OUT

Probing collision dynamics at RHIC, Olga Barannikova (for the STAR Collaboration), arXiv:nucl-ex/0403014
Experimental and theoretical challenges in the search for the quark gluon plasma:
The STAR Collaboration's critical assessment of the evidence from RHIC collisions, STAR Collaboration,
John Adams et al., Nucl.Phys.A 757 (2005) 102-183 • e-Print: nucl-ex/0501009 [nucl-ex]

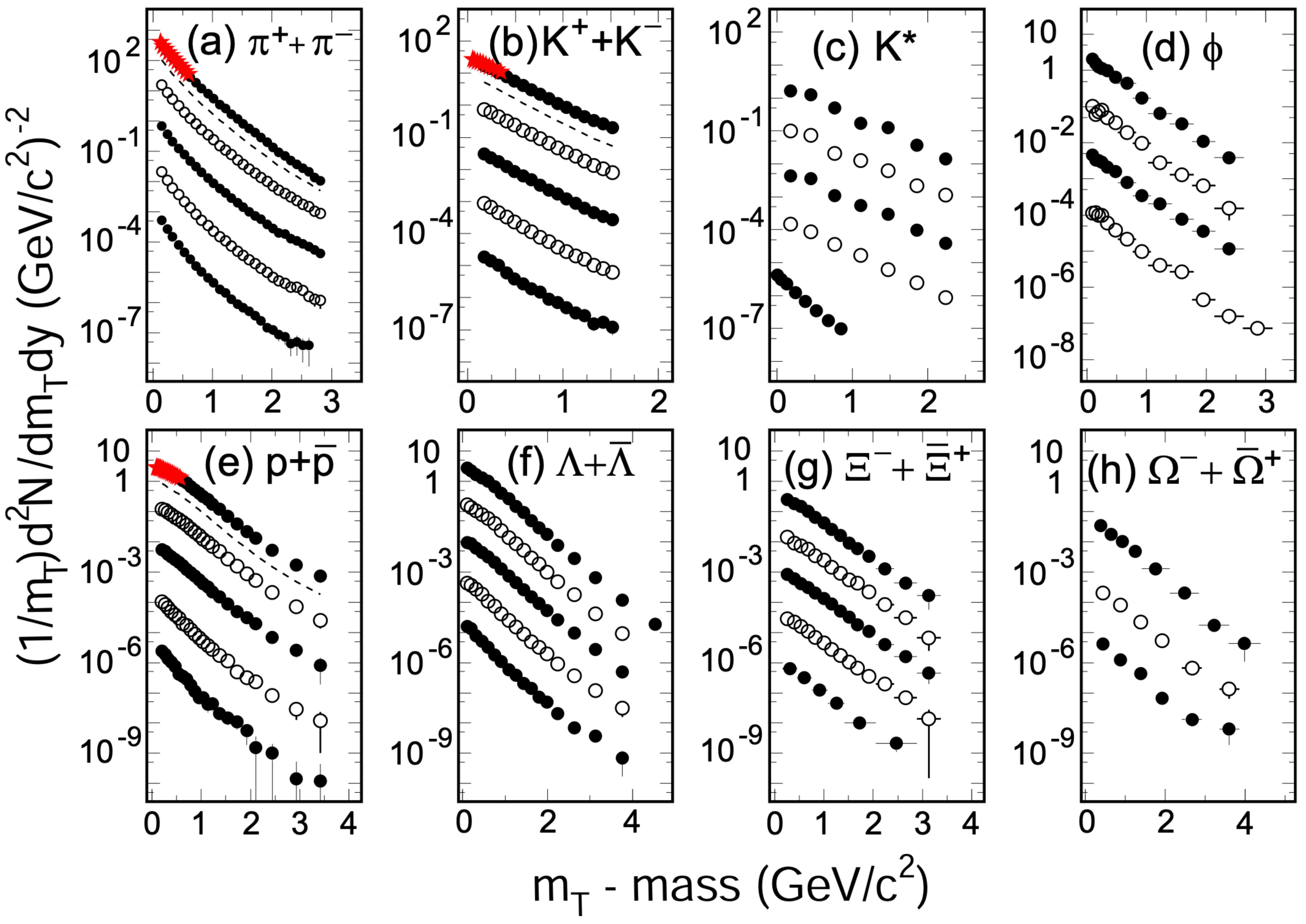


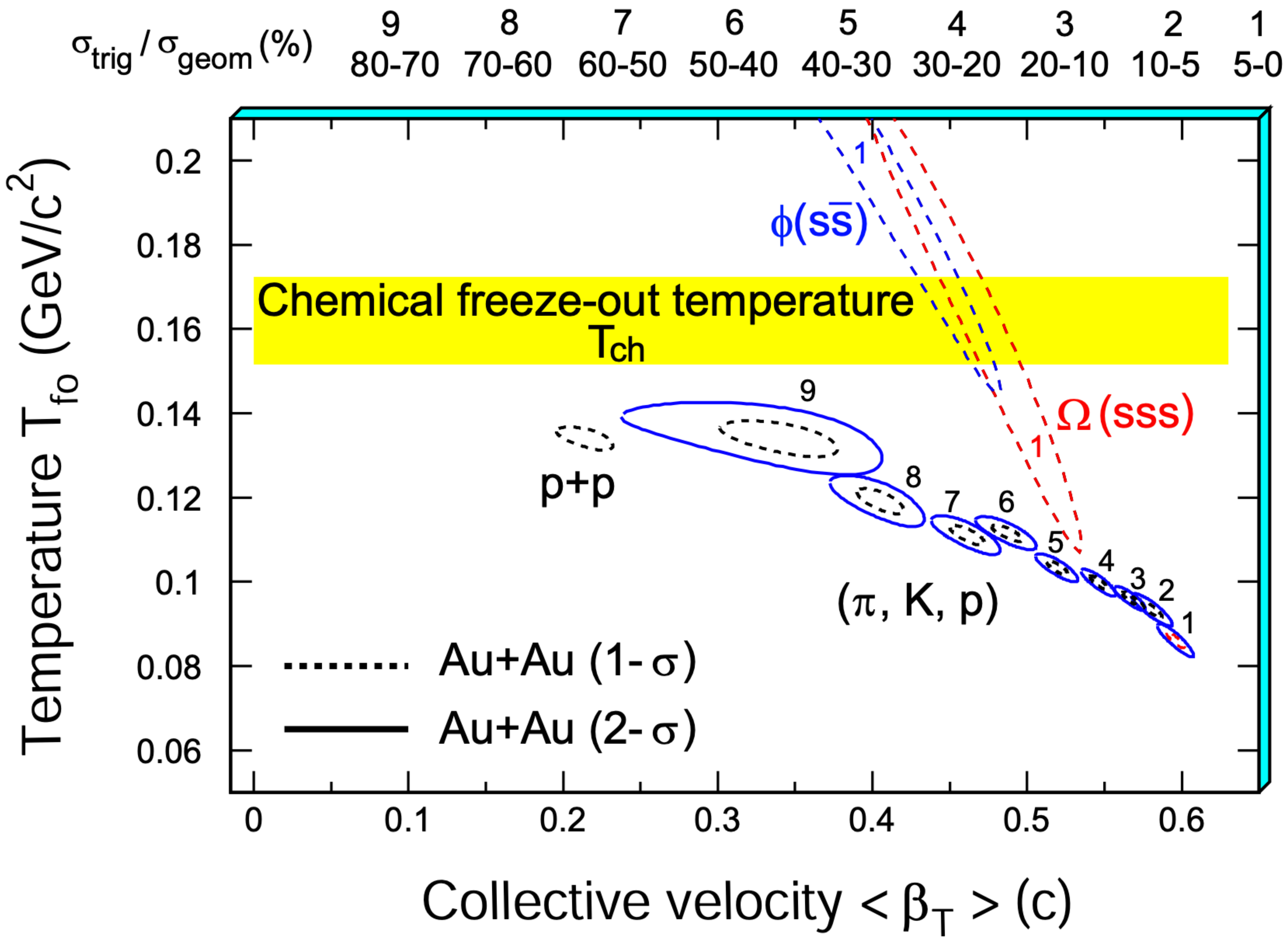
Thermal model fits compared to STAR data

Fit parameters:
$T_{\rm ch} = 163 \pm 4\,{\rm MeV}, \mu_B = 24 \pm 4\,{\rm MeV}, \gamma_s = 0.99 \pm 0.07$

$T_{\rm ch}$: chemical freeze-out temperature

KINETIC FREEZE-OUT





Blast wave fits to these spectra allow extraction of kinetic freeze-out temperature $T_{\rm fo}$ and radial flow velocity $\langle\beta_T\rangle$

C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 89 (2002) 092301; J. Adams et al. [STAR Collaboration], Phys. Lett. B595 (2004) 143; J. Adams et al. [STAR Collaboration], Phys. Rev. C70 (2004) 041901; J. Adams et al. [STAR Collaboration], nucl-ex/0406003 S.S. Adler et al. [PHENIX Collaboration], Phys. Rev. C69 (2004) 034909, E. Yamamoto et al. [STAR Collaboration], Nucl. Phys. A715 (2003) 466c, K. Schweda et al. [STAR Collaboration], J. Phys. G 30 (2004) S693, John Adams et al., Nucl.Phys.A 757 (2005) 102-183

PERFECT FLUID DISCOVERY

By **2005** all RHIC experiments had collected enough evidence of the formation of a QGP phase in Au+Au collisions including the elliptic flow, whose magnitude, centrality, and transverse momentum dependence was well described by hydrodynamic models, that BNL published a press release announcing the discovery of the perfect liquid QGP.

Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions, STAR Collaboration, John Adams et al., Nucl.Phys.A 757 (2005) 102-183 • e-Print: nucl-ex/0501009 [nucl-ex]

An assessment of the insights gained from the heavy-ion program at the CERN SPS during the 1980s and 1990s concluded that compelling evidence for the creation of “a new form of matter” had been found but stopped short of claiming unambiguous discovery of the quark-gluon plasma, nor did it comment on its perfectly liquid collective dynamical properties.

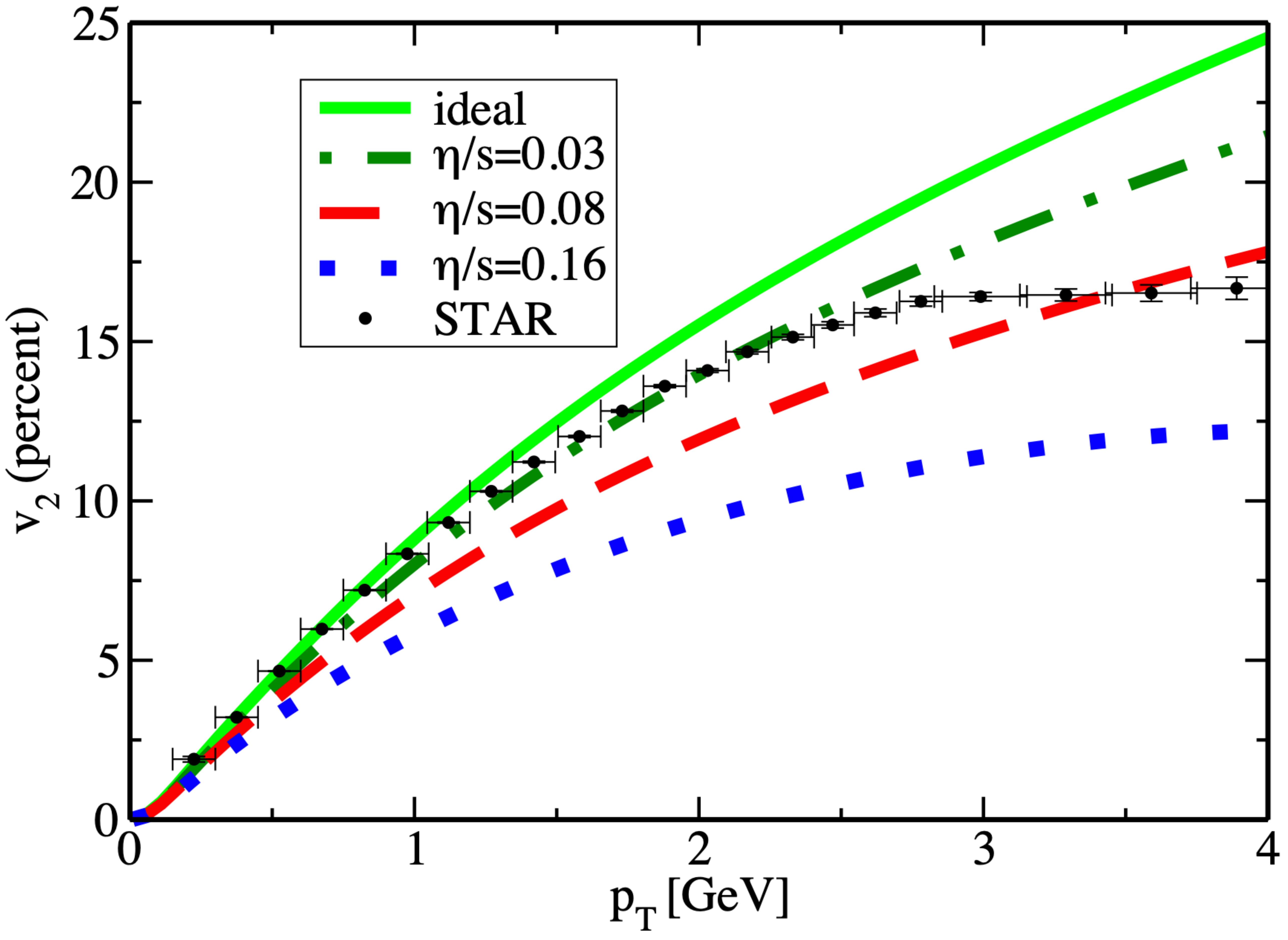
The latter became only obvious after theory had progressed to a quantitative understanding of the bulk of the very comprehensive and precise experimental data collected at RHIC.

U. Heinz, M. Jacob, (2000). arXiv:nucl-th/0002042 (unpublished)

see Ulrich Heinz, Björn Schenke, e-Print: 2412.19393, in “Quark Gluon Plasma at Fifty - A Commemorative Journey”

VISCOUS HYDRODYNAMICS

P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301
STAR Collaboration, J. Adams, Phys.Rev.Lett. 127 (2021) 6, 069901



First viscous fluid dynamic calculations were compared to STAR data

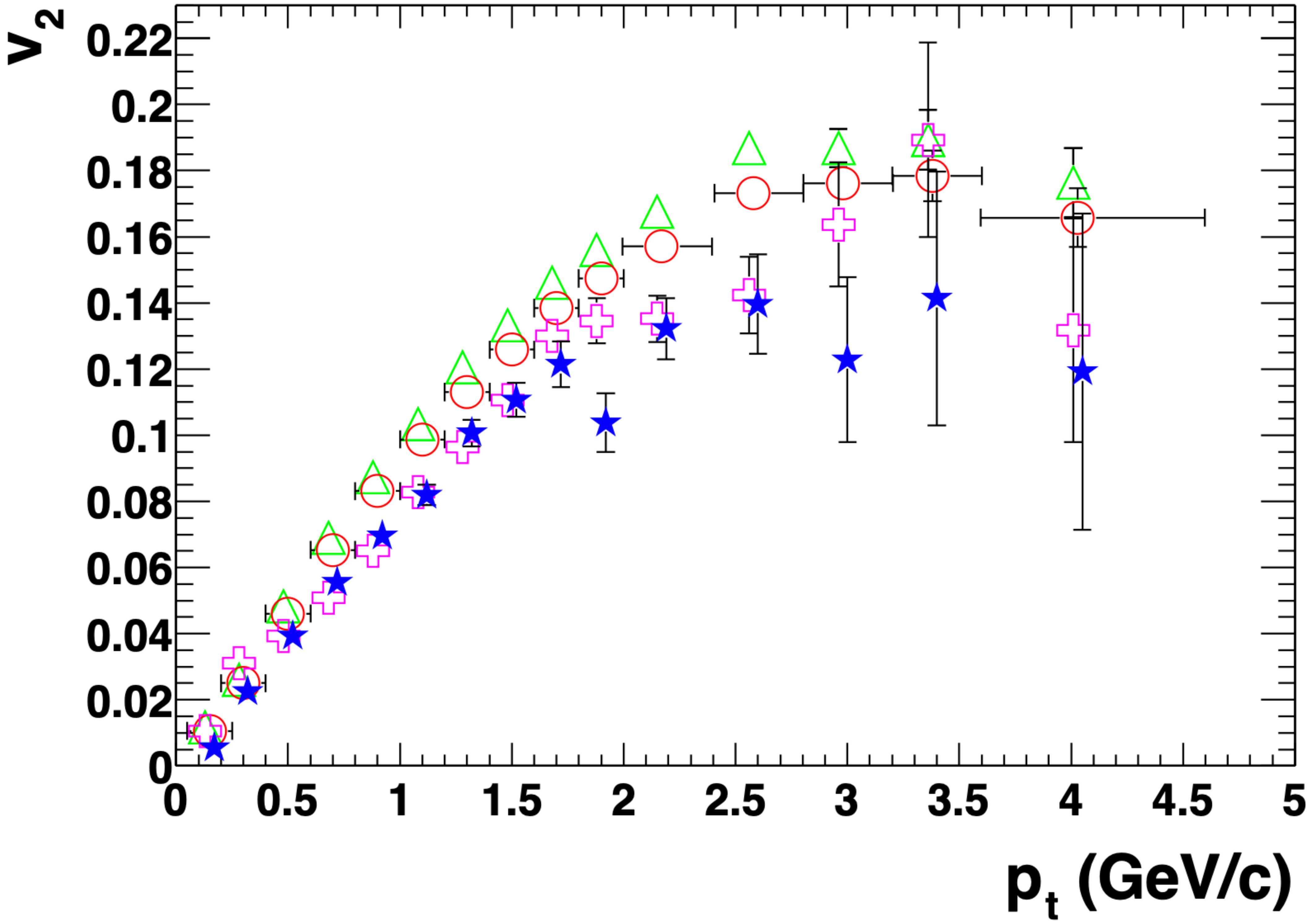
Precision of data was already good enough to constrain the viscosity in principle

However, uncertainties in the initial state, fluctuations, and related definition of v_2 were not fully considered at the time

FLOW FLUCTUATIONS

STAR Collaboration, C. Adler et al., Phys.Rev.C 66 (2002) 034904
N. Borghini, P. M. Dinh and J. Y. Ollitrault, Phys. Rev. C 63 (2001) 054906
H.J. Drescher, S. Ostapchenko, T. Pierog, K. Werner, Phys. Rev. C 65, 054902 (2002)
C.E. Aguiar, Y. Hama, T. Kodama, T. Osada, Nucl.Phys.A 698 (2002) 639-642
A. Bilandzic, R. Snellings, S. Voloshin, Phys.Rev.C 83 (2011) 044913

First signs of flow fluctuations were apparent in two- and four-particle correlation measurements of v_2



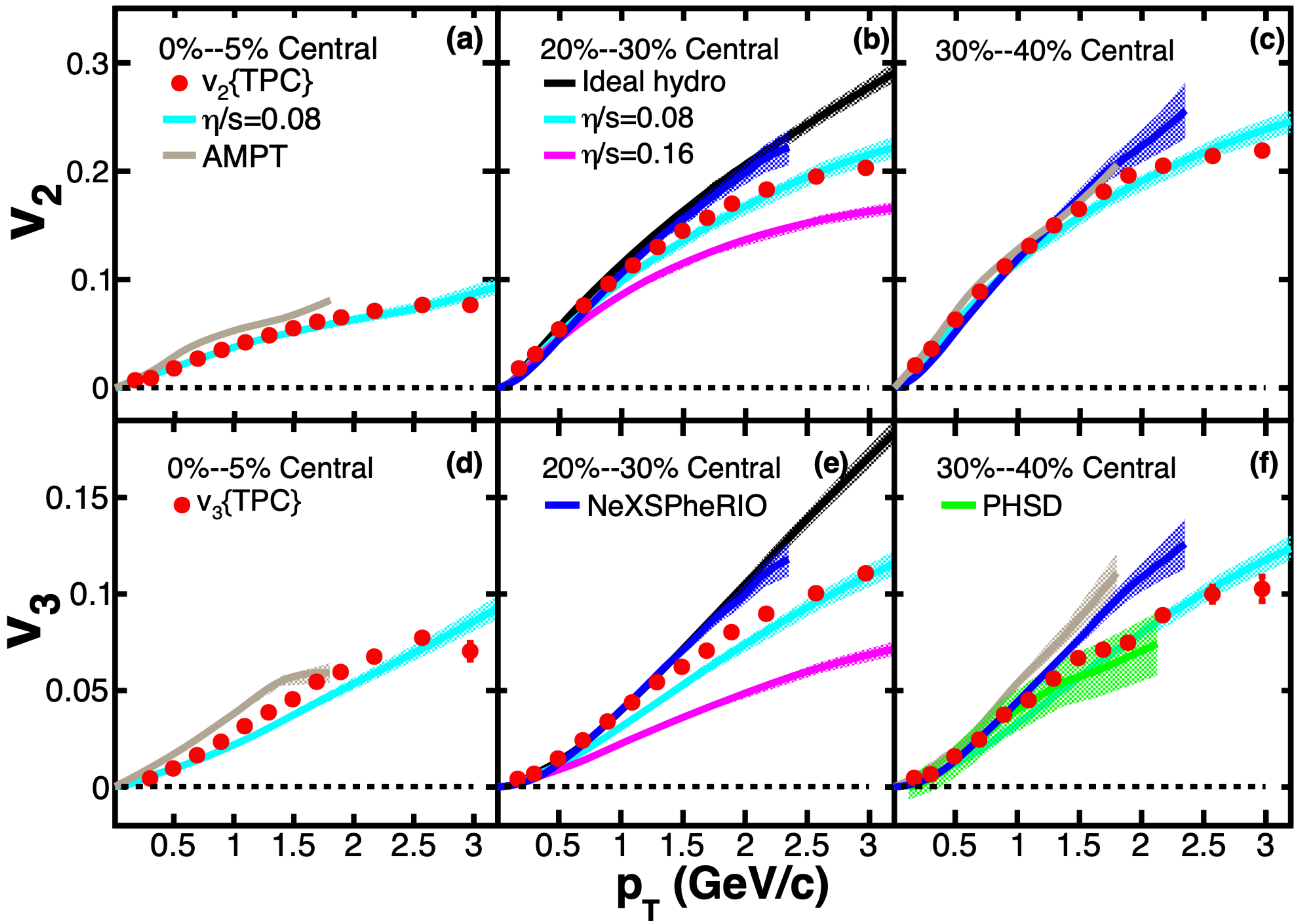
Triangles: $v_2\{2\}$
Stars: $v_2\{4\}$
Circles: event-plane method
Crosses: ‘quarter-events’ to reduce non-flow

Expected behavior:
$v_2\{2\} > v_2\{4\}$

because for a Gaussian:
$$v_2\{2\}^2 = \langle v_2 \rangle^2 + \sigma^2$$
$$v_2\{4\}^2 \approx \langle v_2 \rangle^2 - \sigma^2$$

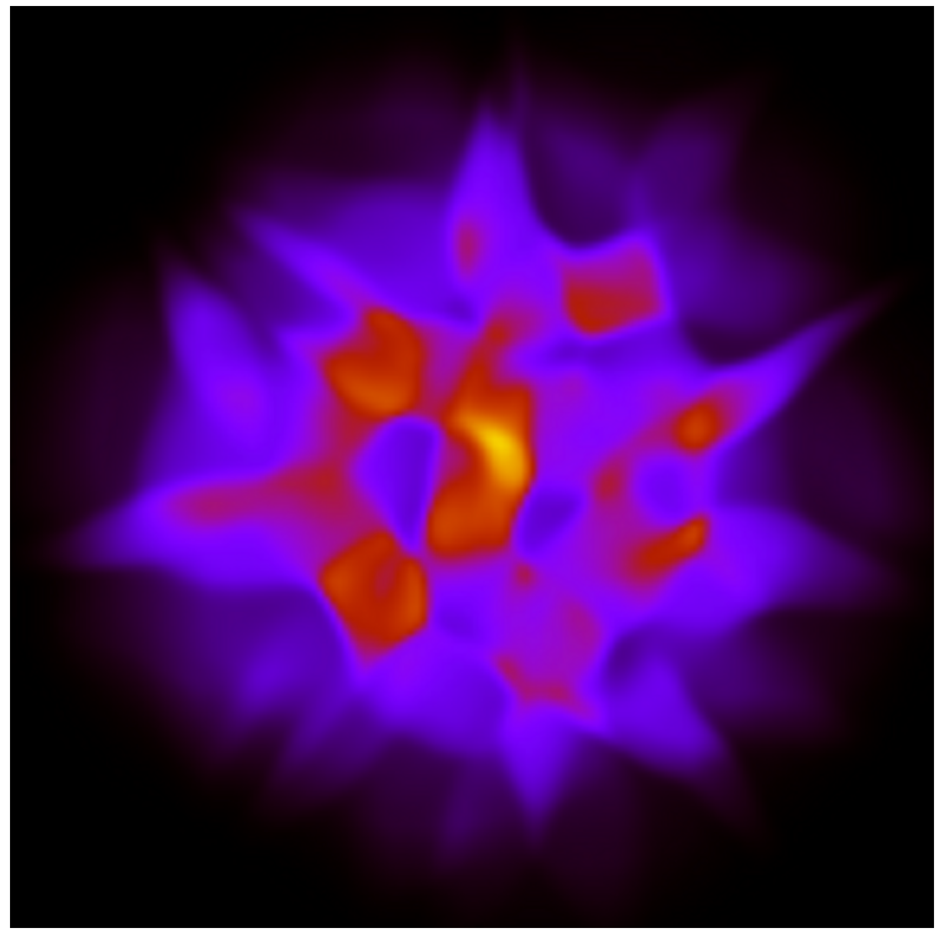
FLUCTUATIONS AND HIGHER HARMONICS

B. Alver, G. Roland, Phys.Rev.C 81 (2010) 054905, Phys.Rev.C 82 (2010) 039903 (erratum); B. H. Alver, C. Gombeaud, M. Luzum, J.-Y. Ollitrault, Phys.Rev.C 82 (2010) 034913; STAR Collaboration, B. I. Abelev et al., arXiv:0806.0513 [nucl-ex]; STAR Collaboration, L. Adamczyk et al., Phys.Rev.C 88 (2013) 1, 014904; NeXSpherio: F. G. Gardim, F. Grassi, M. Luzum and J. -Y. Ollitrault, Phys. Rev. Lett. 109, 202302 (2012); AMPT: J. Xu and C. M. Ko, Phys. Rev. C 84, 014903 (2011); PHSD: V. P. Konchakovski, E. L. Bratkovskaya, W. Cassing, V. D. Toneev, S. A. Voloshin and V. Voronyuk, Phys. Rev. C85, 044922 (2012); Viscous Hydro: B. Schenke, S. Y. Jeon, and C. Gale, Phys. Rev. Lett. 106, 042301 (2011); STAR Collaboration, L. Adamczyk, Phys.Rev.Lett. 116 (2016) 11, 112302



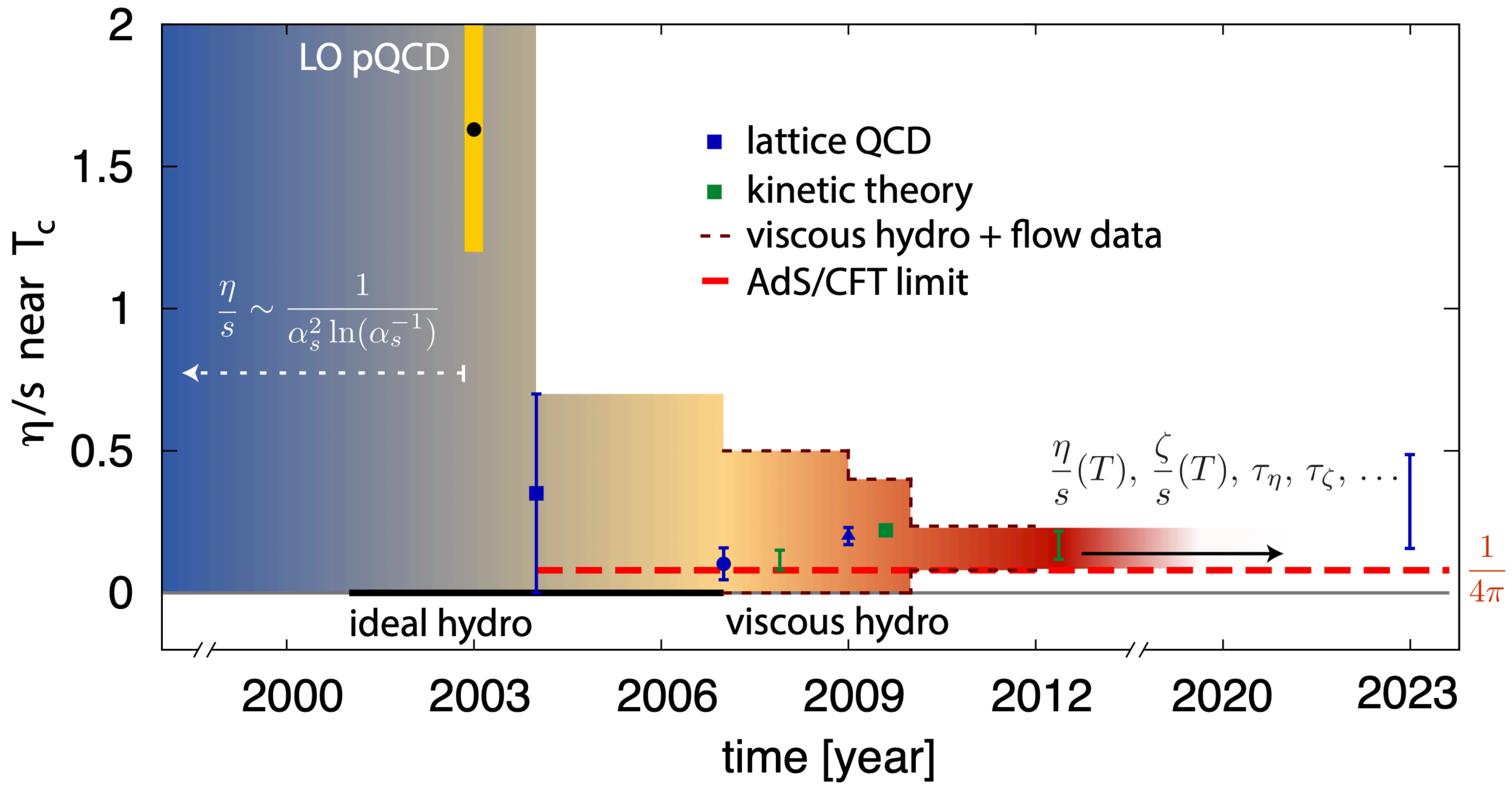
Alver and Roland clarified that there should be odd harmonics when there are fluctuating initial geometries

Predictions of v_3 from hydrodynamic calculations described the STAR data well



TRANSPORT COEFFICIENTS

Ulrich Heinz, Björn Schenke, e-Print: 2412.19393, in “Quark Gluon Plasma at Fifty - A Commemorative Journey”



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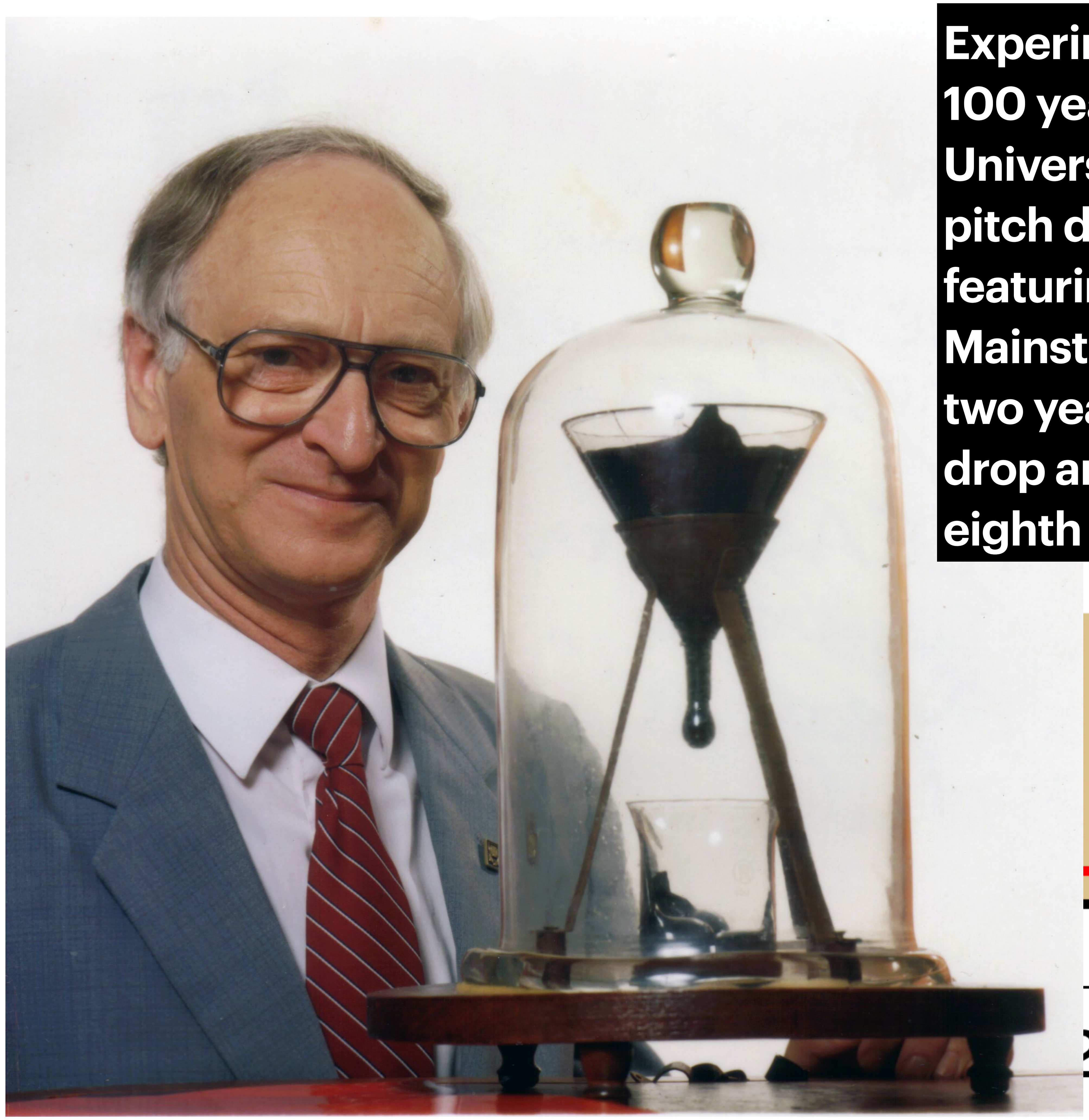
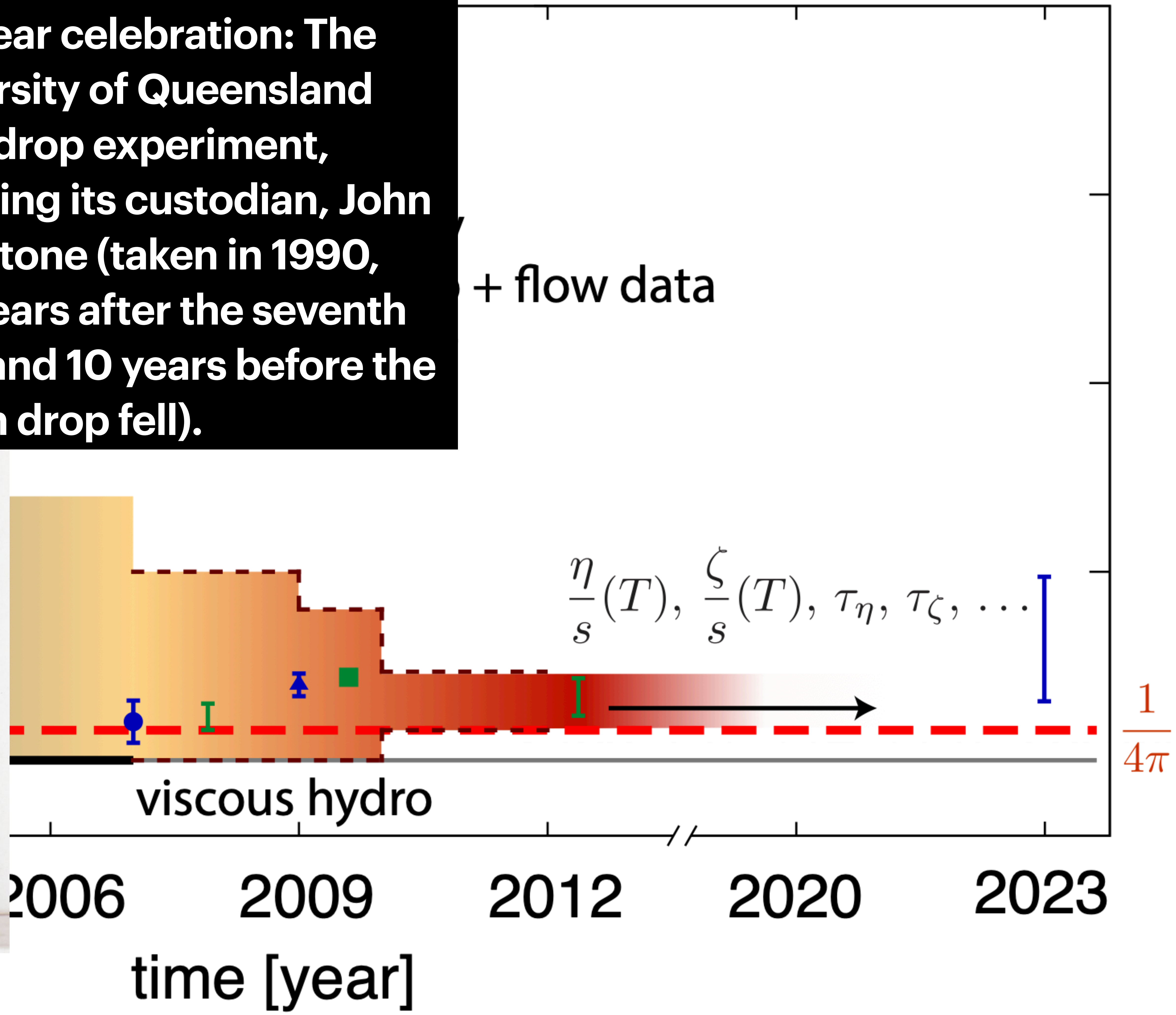


Experiment with an almost 100 year celebration: The University of Queensland pitch drop experiment, featuring its custodian, John Mainstone (taken in 1990, two years after the seventh drop and 10 years before the eighth drop fell).

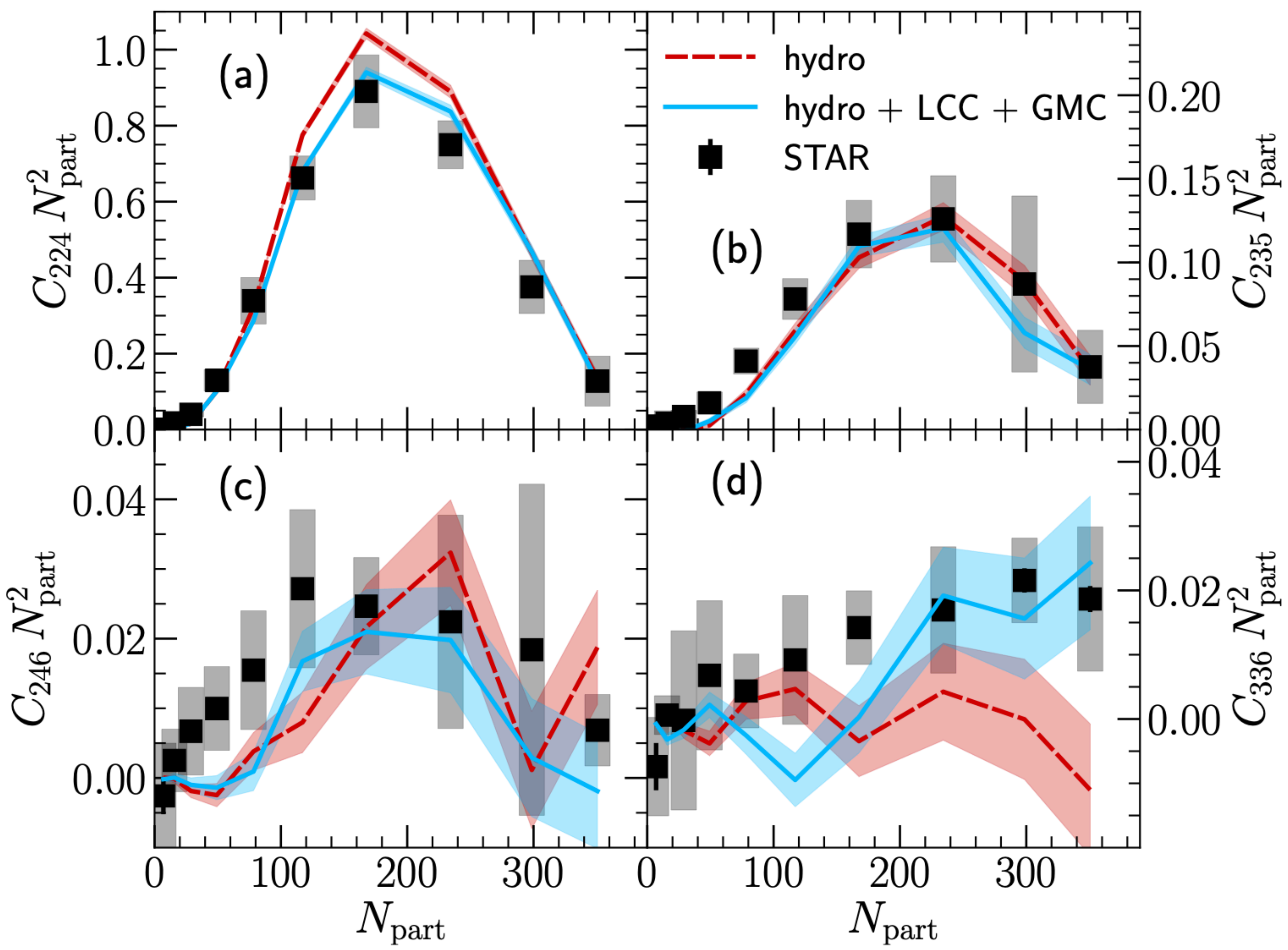


THREE-PARTICLE CORRELATIONS

STAR Collaboration, L. Adamczyk, Phys.Rev.C 98 (2018) 3, 034918
B. Schenke, C. Shen, P. Tribedy, Phys.Rev.C 99 (2019) 4, 044908

$$C_{m,n,m+n} = \langle \cos(m\phi_1 + n\phi_2 - (m+n)\phi_3) \rangle$$

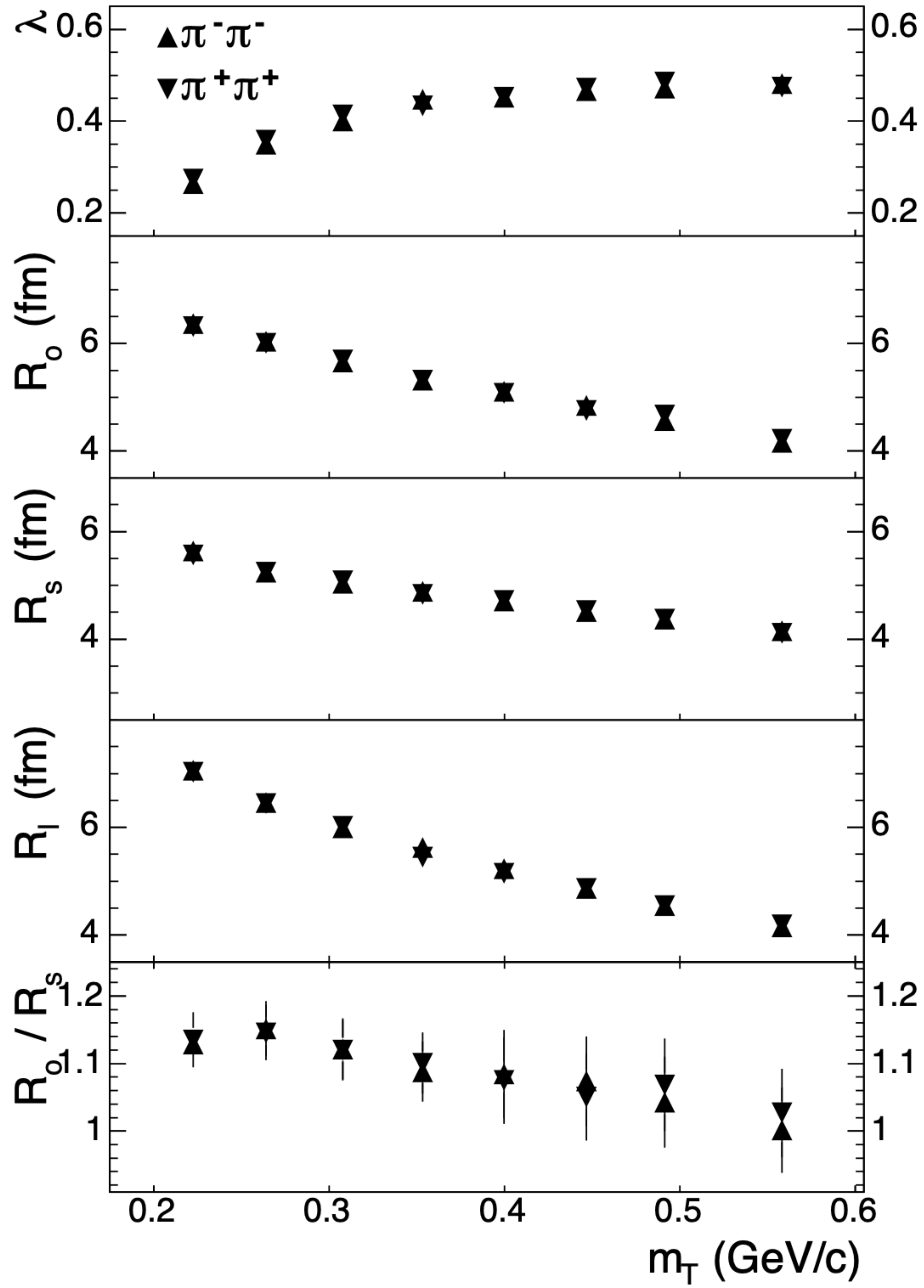
- STAR pioneered measurement of charge inclusive three-particle azimuthal correlations in the RHIC BES
- Allows to measure correlations between harmonic amplitudes and phases
- Strong relative pseudorapidity (Δη) dependence between the particles associated with different harmonics
- Insight into breaking of longitudinal invariance of the initial state geometry at RHIC
- Highlighted the importance of charge and momentum conservation, especially for correlators involving the first harmonic



SPACE–TIME STRUCTURE OF THE BULK

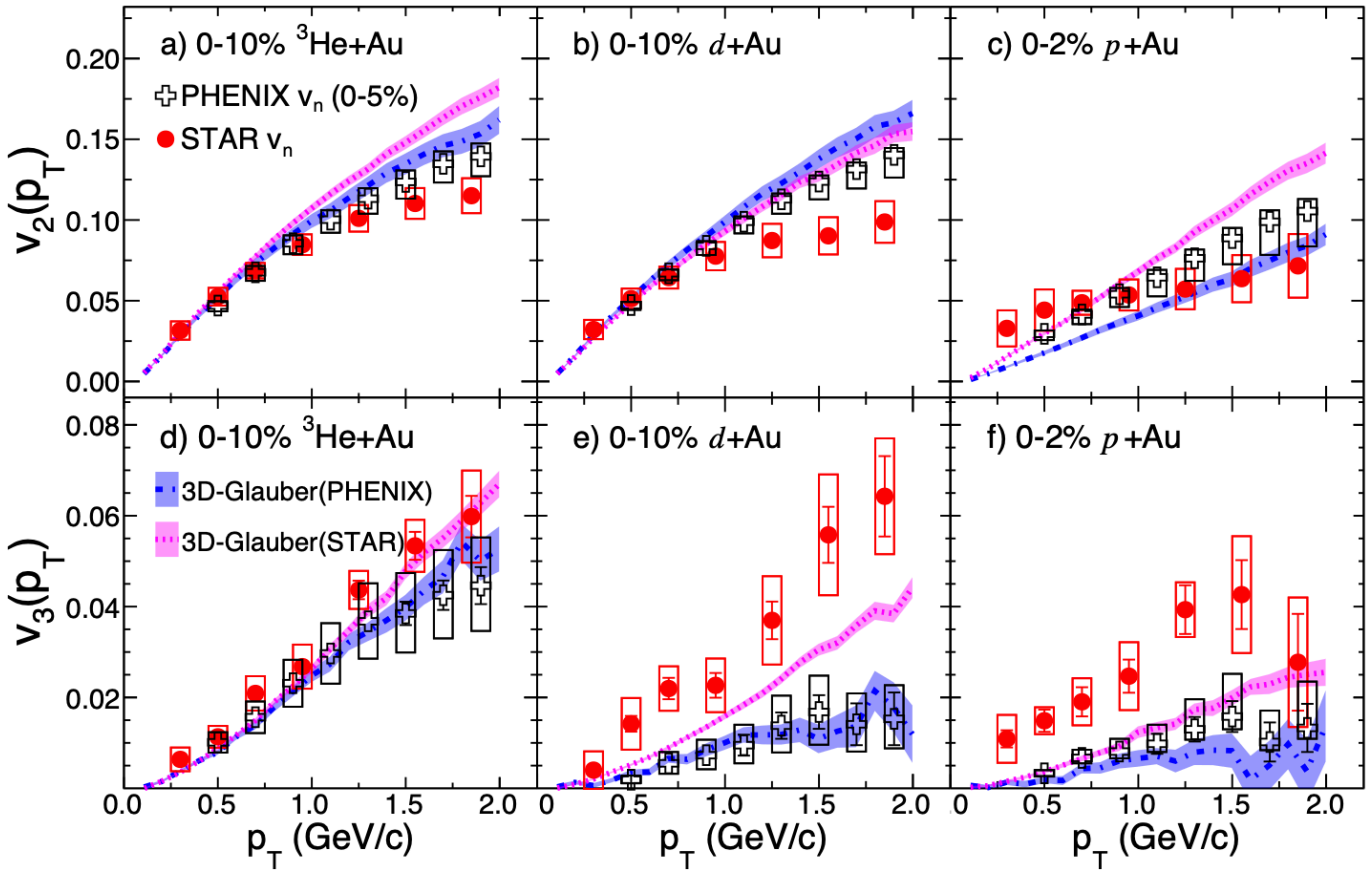
STAR Collaboration, C. Adler et al., Phys.Rev.Lett. 87 (2001) 082301
STAR Collaboration, J. Adams et al., Phys.Rev.C 71 (2005) 044906

- HBT: R's: Gaussian fits to the spatial size and shape of the outgoing phase space cloud of particles of a specific momentum:
  - R_O: outward (parallel to the momentum of the particle)
  - R_S: sideward (perpendicular to the beam and to the particle's momentum)
  - R_L: longitudinal (along the beam axis) - related to emission time
- Early ideal **hydrodynamic models tended to over-predict R_L and the R_O/R_S ratio**, suggesting that the explosion was more rapid, and with a more sudden emission than that portrayed by the models.
- Including pre-equilibrium flow, using a stiffer equation of state, and incorporating viscosity helped solve this puzzle S. Pratt, Acta Phys.Polon.B 40 (2009) 1249-1256



SMALL SYSTEMS

STAR Collaboration, M.I. Abdulhamid, Phys.Rev.Lett. 130 (2023) 24, 242301
W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys.Rev.C 107 (2023) 1, 014904
PHENIX Collaboration, Nature Phys. 15, 214–220 (2019), 107 (2023) 1, 014904
STAR Collaboration, Phys.Rev.C 110 (2024) 6, 064902



- Small system flow differs between STAR and PHENIX
- Longitudinal flow decorrelations lead to smaller v_3 for PHENIX, explaining ~50% of the difference

PHENIX:
(p, d)+Au: $\eta_1 \in [-3.9, -3.1]$,
$\eta_2 \in [-0.35, 0.35]$
^{3}He+Au: $\eta_1 \in [-3, -1]$,
$\eta_2 \in [-0.35, 0.35]$

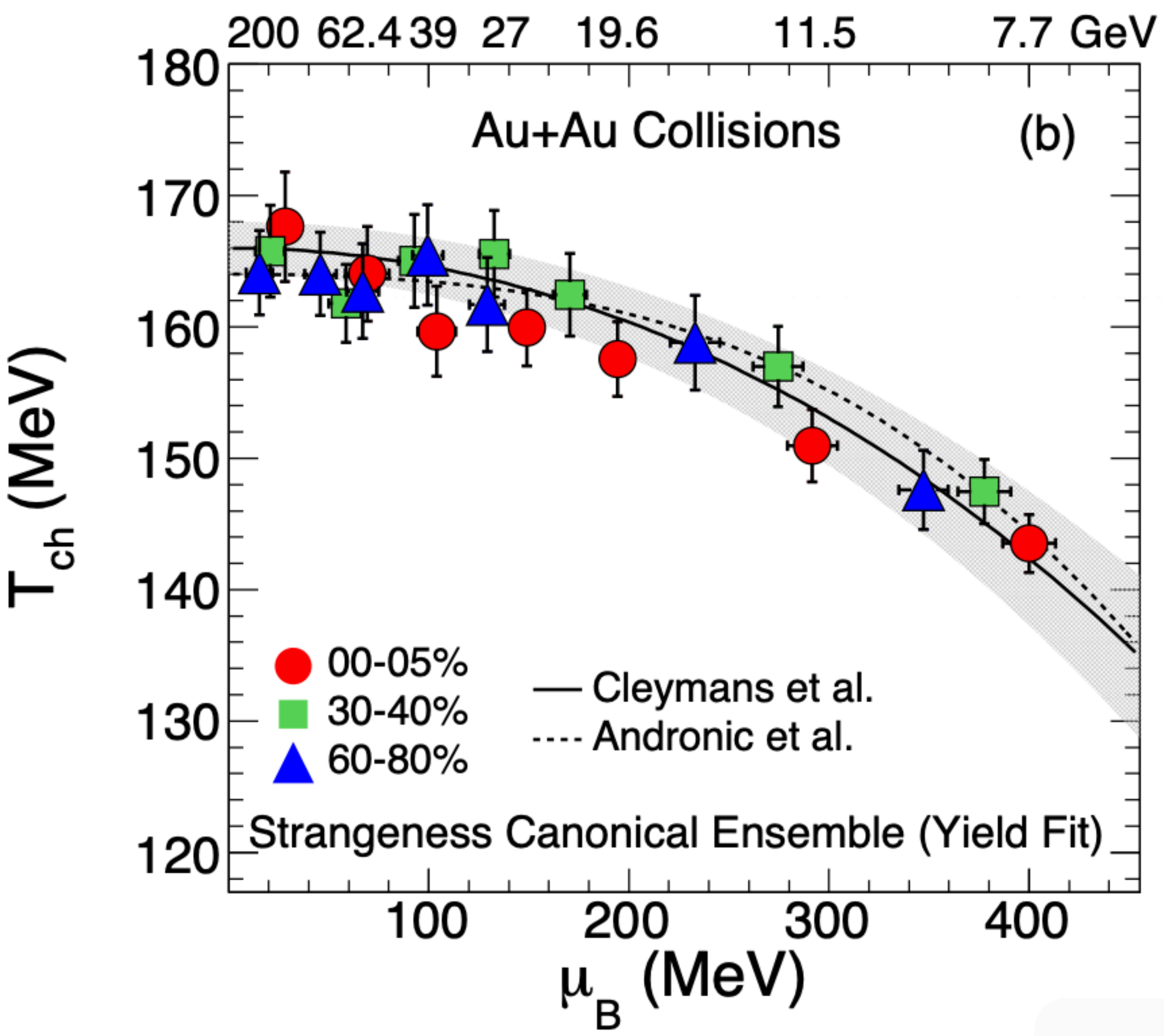
STAR:
$\eta \in [-0.9, 0.9]$ with $|\Delta\eta| > 1$

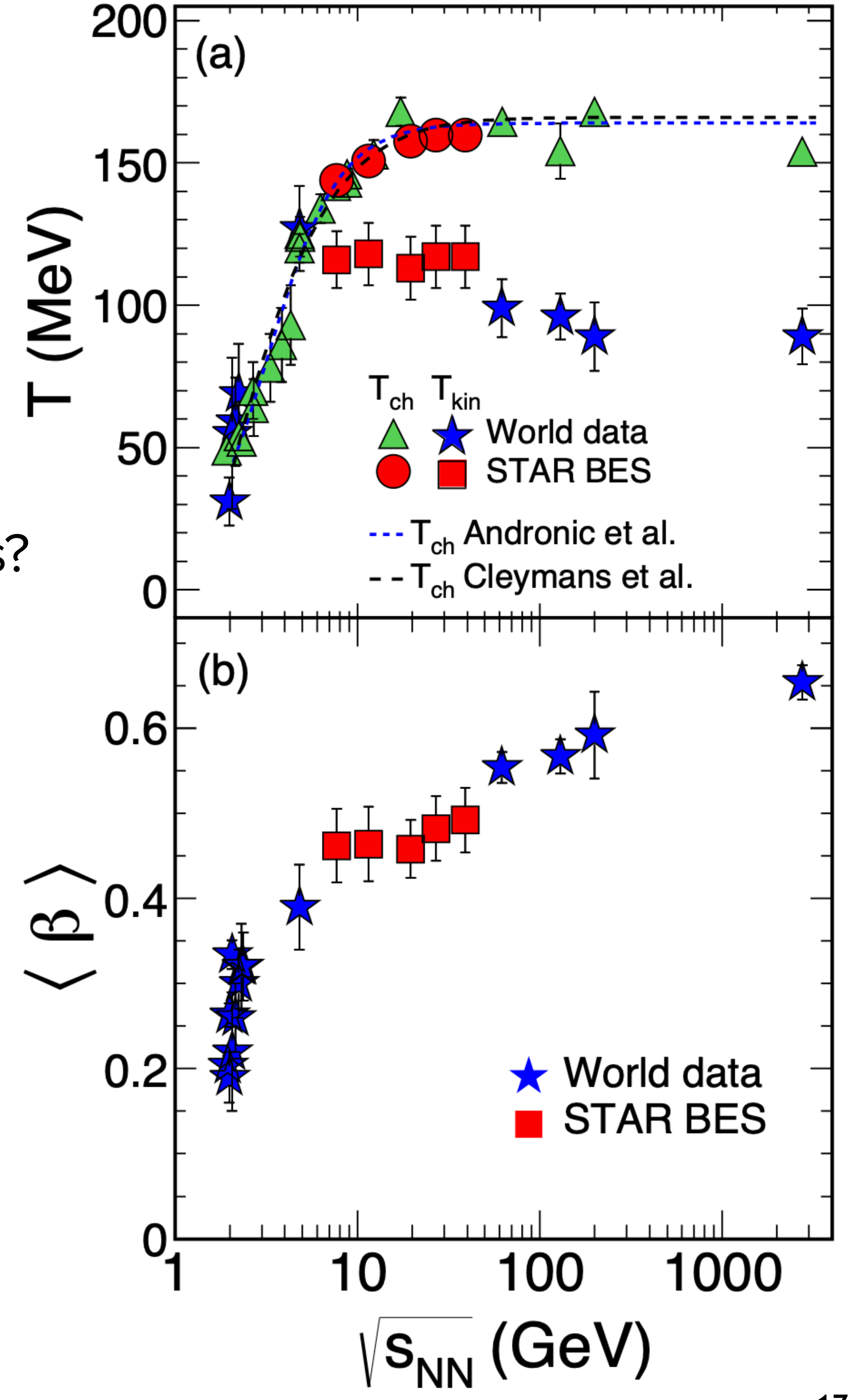
- STAR measurement shed light on these complications of interpreting small system flow

BEAM ENERGY SCAN

STAR Collaboration, Bulk properties of the medium produced in relativistic heavy-ion collisions from the Beam Energy Scan Program", Phys. Rev. C 96, 044904 (2017) see Mathias Labonte's talk

- Bulk properties across the phase diagram with BES
- Thermal model fits →chemical freeze-out
- Blast-wave model fits → kinetic freeze-out
- Separation between $T_{\rm ch}$ and $T_{\rm kin}$ increases with energy. More hadronic interactions between chemical and kinetic freeze-out at higher energies?

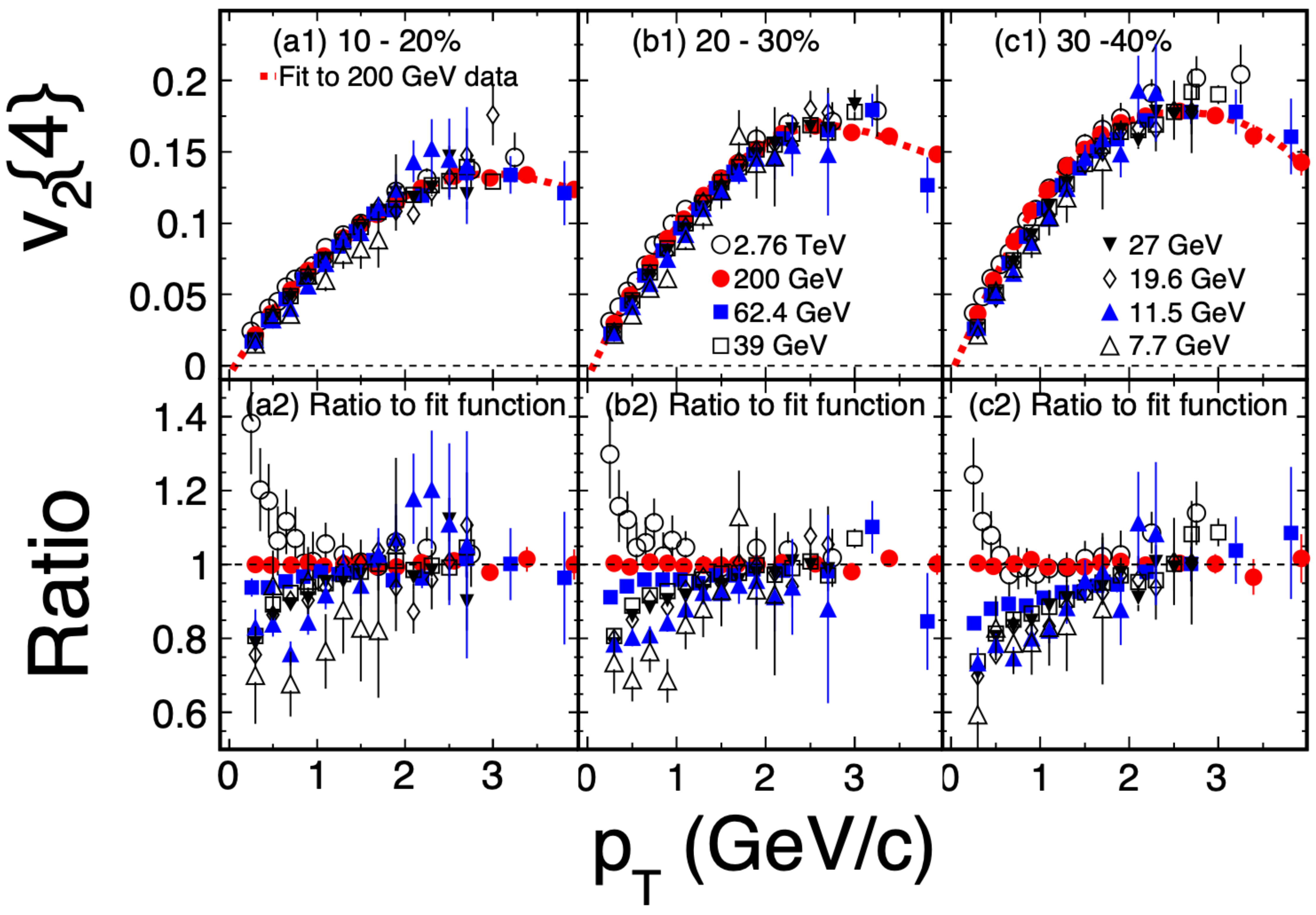


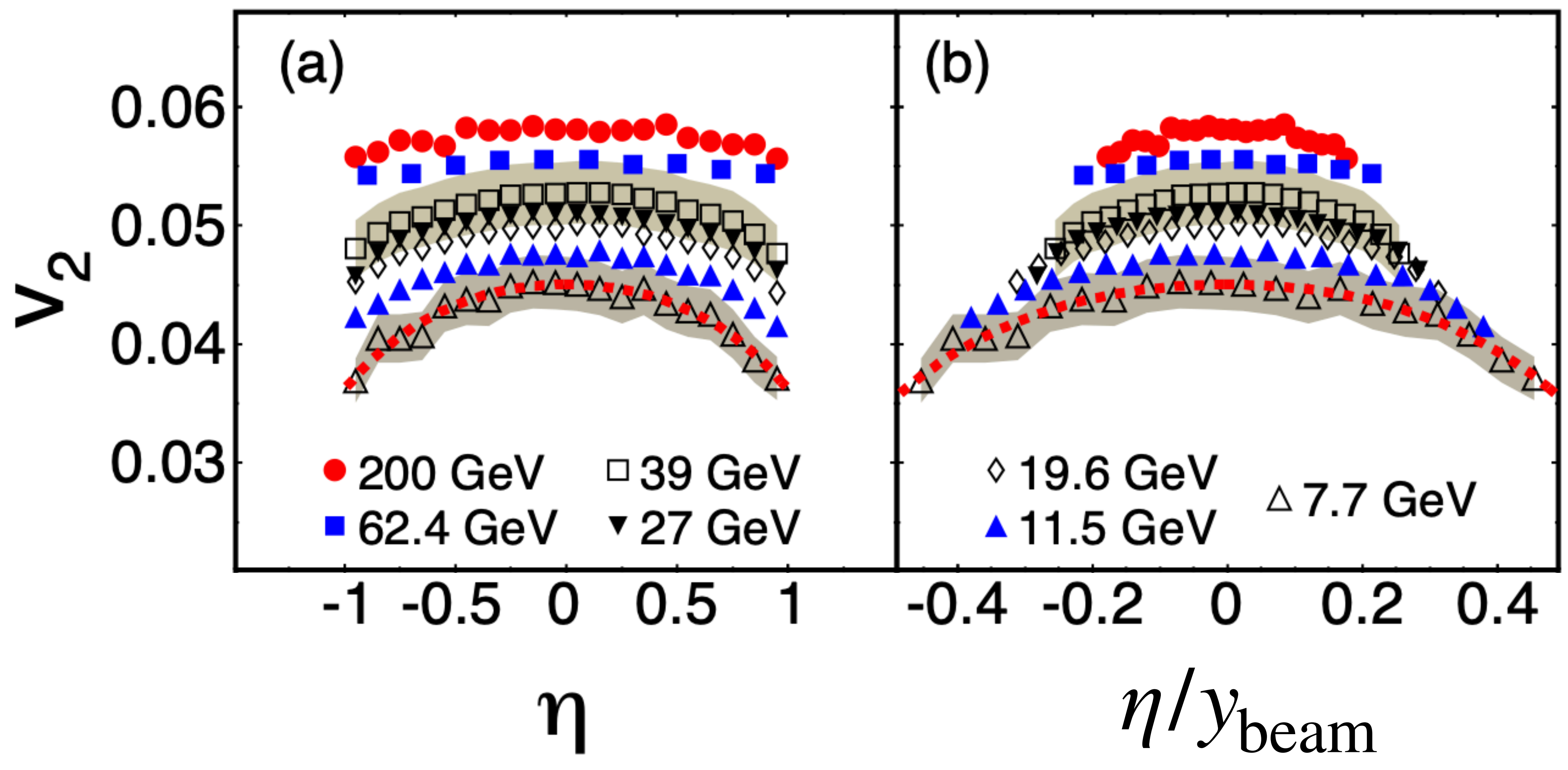


BEAM ENERGY SCAN FLOW

STAR Collaboration, L. Adamczyk et al., Phys.Rev.C 86 (2012) 054908

- Some energy dependence of $v_2\{4\}(p_T)$ at low p_T
- Increase of integrated v_2 with energy dominated by increase in $\langle p_T \rangle$



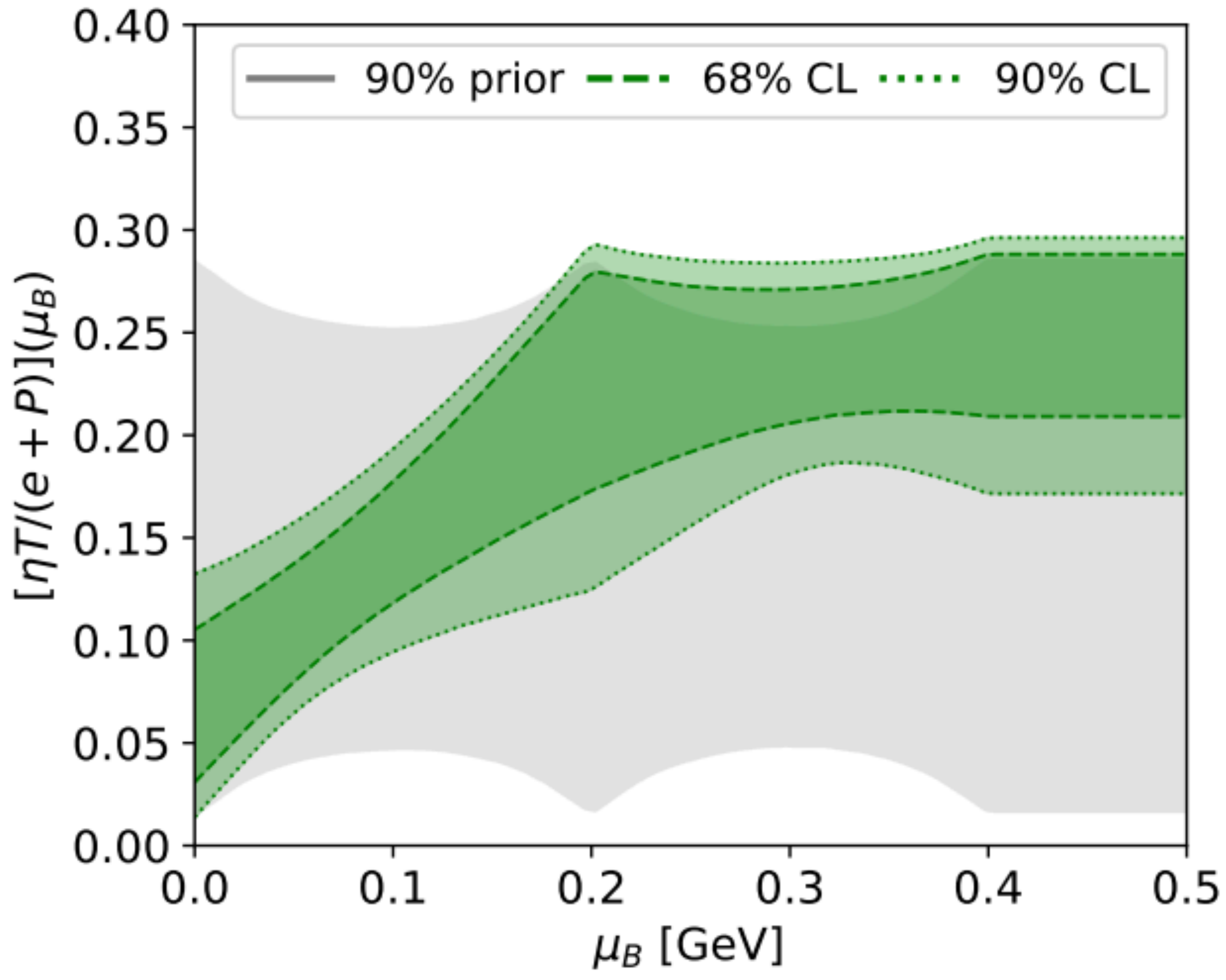


EXTRACTING MEDIUM PROPERTIES

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

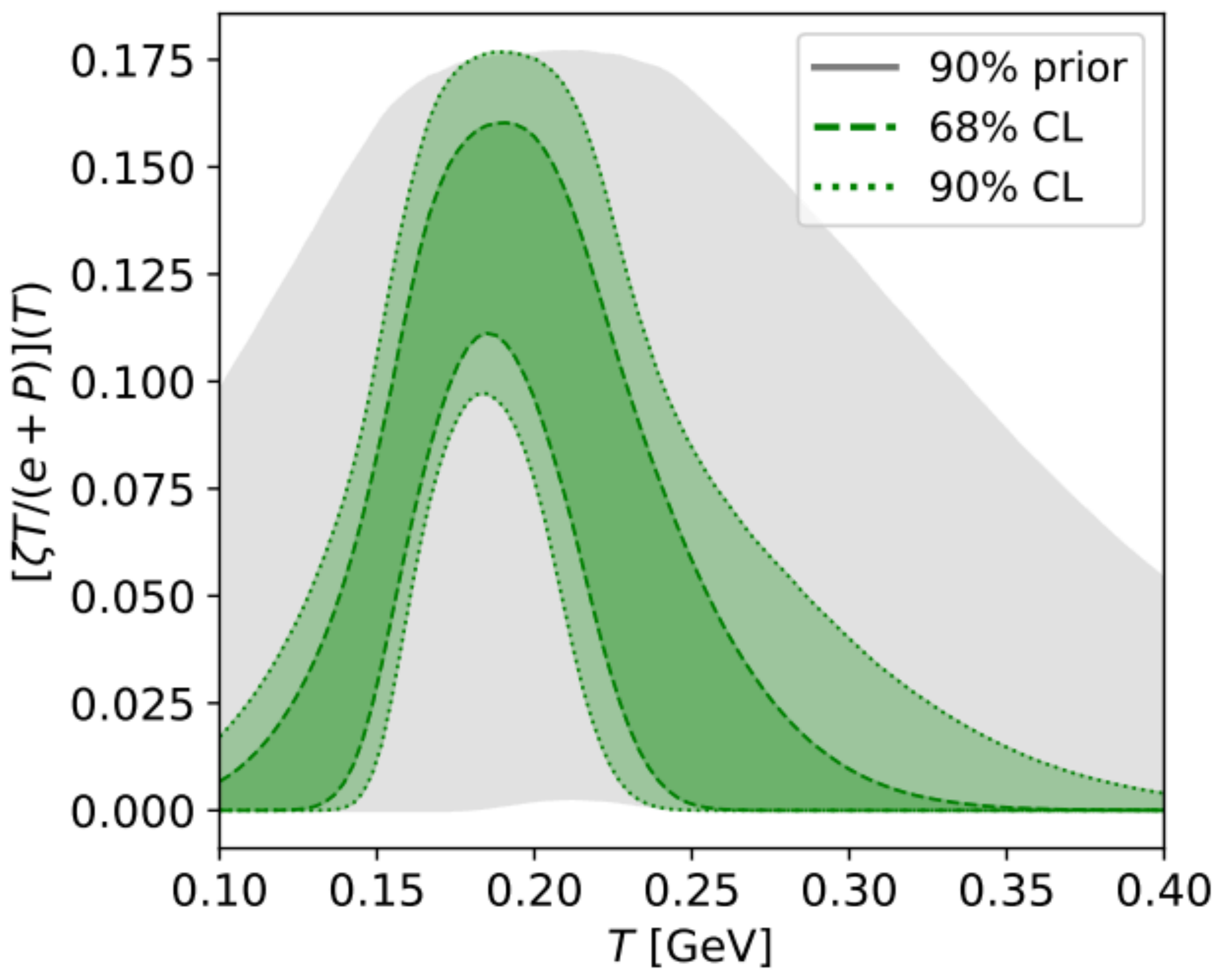
- Properties of the medium across the phase diagram
- Bayesian analysis using STAR beam energy scan data on particle spectra and correlations

Shear viscosity



Baryon chemical potential

Bulk viscosity



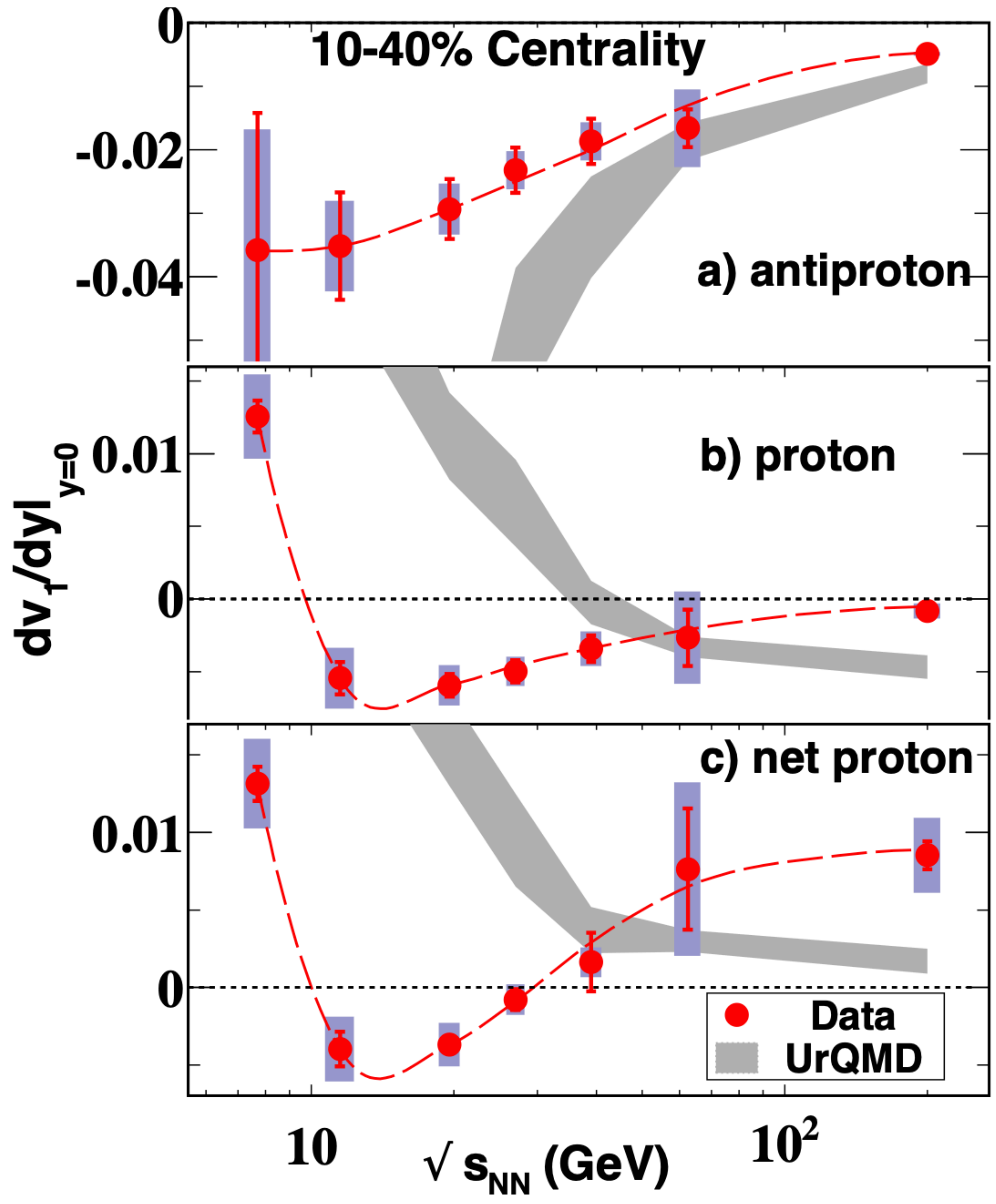
temperature

BEAM ENERGY SCAN DIRECTED FLOW

STAR Collaboration, L. Adamczyk et al., Phys.Rev.Lett. 112 (2014) 16, 16230

- Net-proton directed flow was predicted to have a minimum with collision energy in a hydro calculation with a first-order phase transition, termed the "softest point collapse" H. Stöcker, Nucl. Phys. A 750, 121 (2005)
- Describing v_1 using hydrodynamic models is notoriously difficult - my opinion
- The calculated directed flow is very sensitive to details in the description of the initial state, the freeze out prescription as well as the method of determining the event plane

J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, Phys.Rev.C 89 (2014) 5, 054913

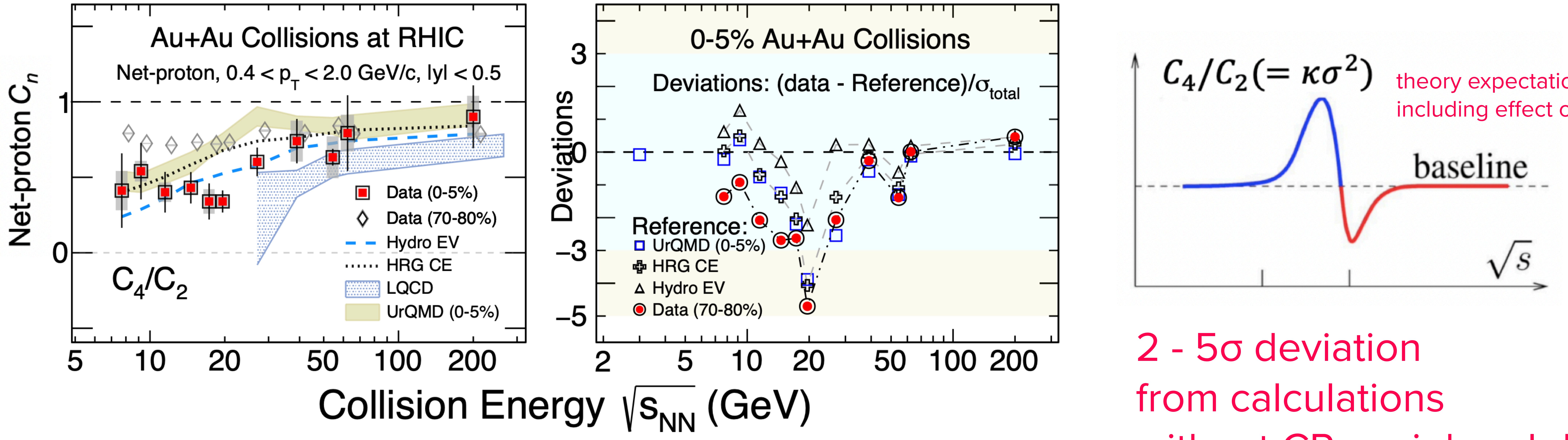


QCD CRITICAL POINT SEARCH

see Ashish Pandav's talk

STAR Collaboration, Phys.Rev.Lett. 112 (2014) 03230; STAR Collaboration, Phys.Rev.Lett. 126 (2021) 9, 092301
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. Studies will continue in STAR, plus programs at LHC/SPS, RHIC/AGS, FAIR/SIS, HIAF, J-PARC, and going to fully net-baryon (neutrons etc.) measurements



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

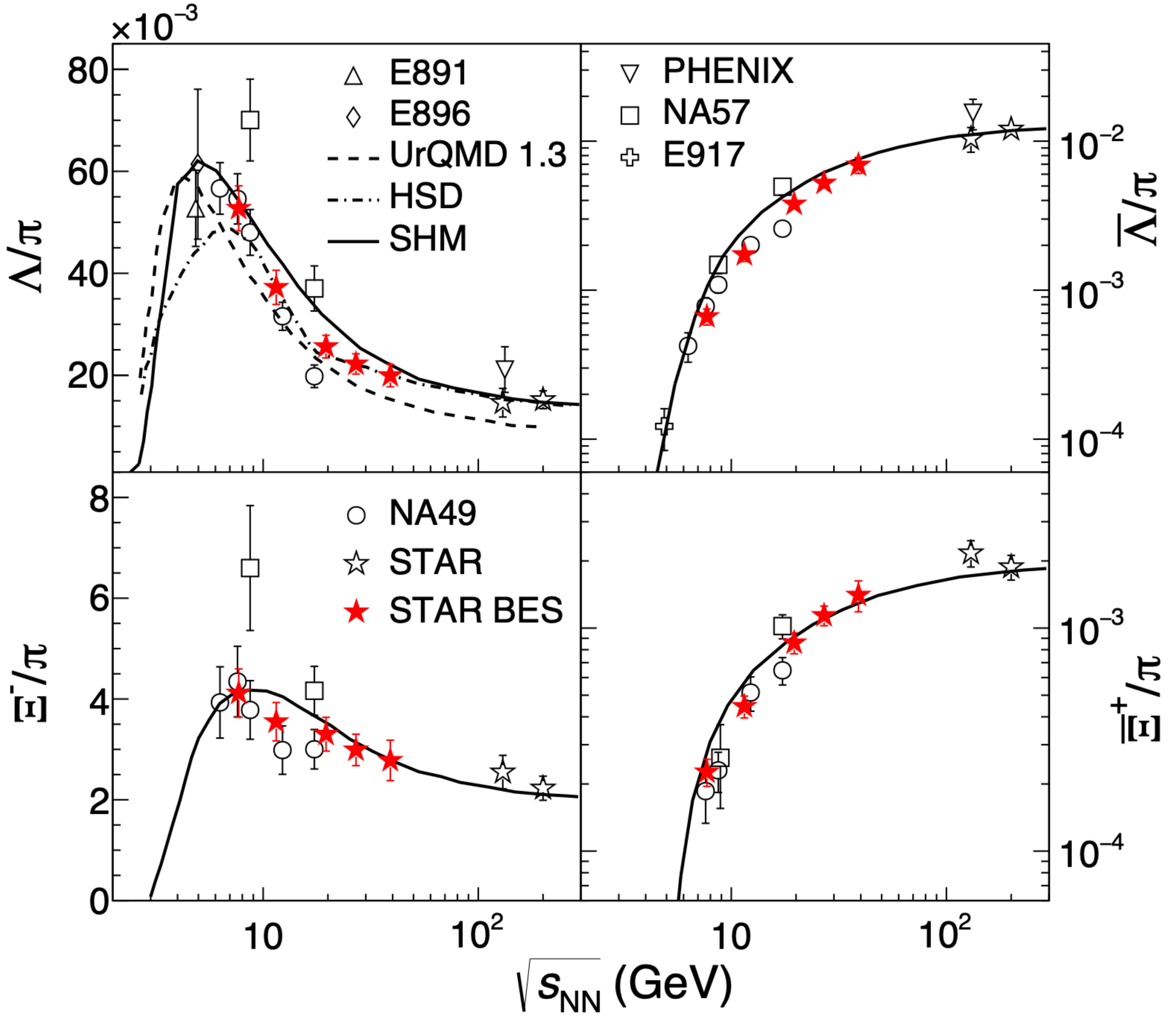
STRANGENESS PRODUCTION

STAR Collaboration, J. Adam et al., Phys.Rev.C 102 (2020) 3, 034909
STAR Collaboration, M.I. Abdulhamid et al., JHEP 10 (2024) 139

- Strangeness production is consistent with a chemically equilibrated hadron gas along a universal freeze-out curve from AGS to RHIC, with strange baryon/π ratios peaking near $\sqrt{s} \approx 8\,\mathrm{GeV}$ where net-baryon density is maximal

  J. Randrup, J. Cleymans, Phys.Rev.C 74 (2006) 047901

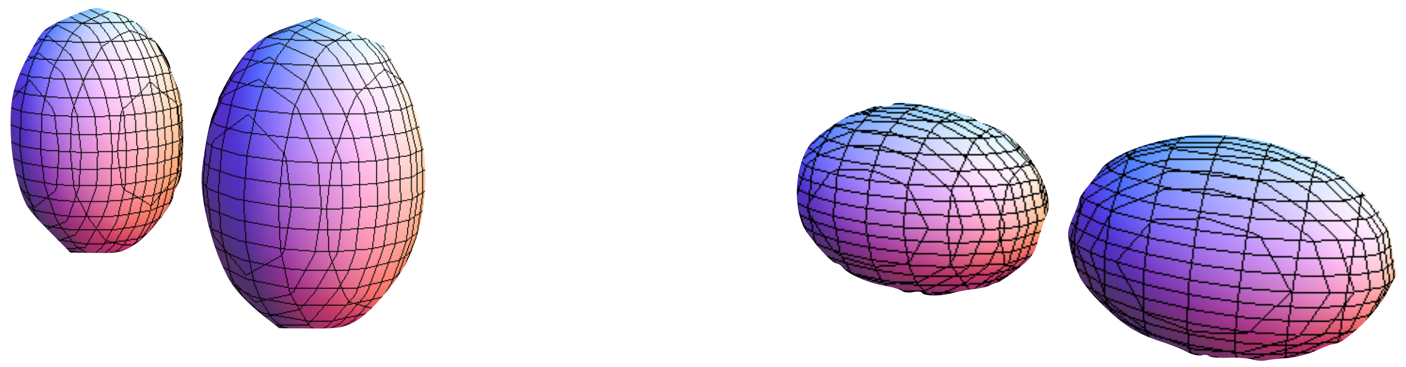
- Latest results from STAR include measurements at $\sqrt{s} = 3\,\mathrm{GeV}$ of strange-hadron yields and ratios. Those are described only by a canonical thermal model with a finite strangeness correlation radius together with hadronic transport. At $\sqrt{s} = 3\,\mathrm{GeV}$ we have a hadron-dominated medium with local conservation.



NUCLEAR STRUCTURE

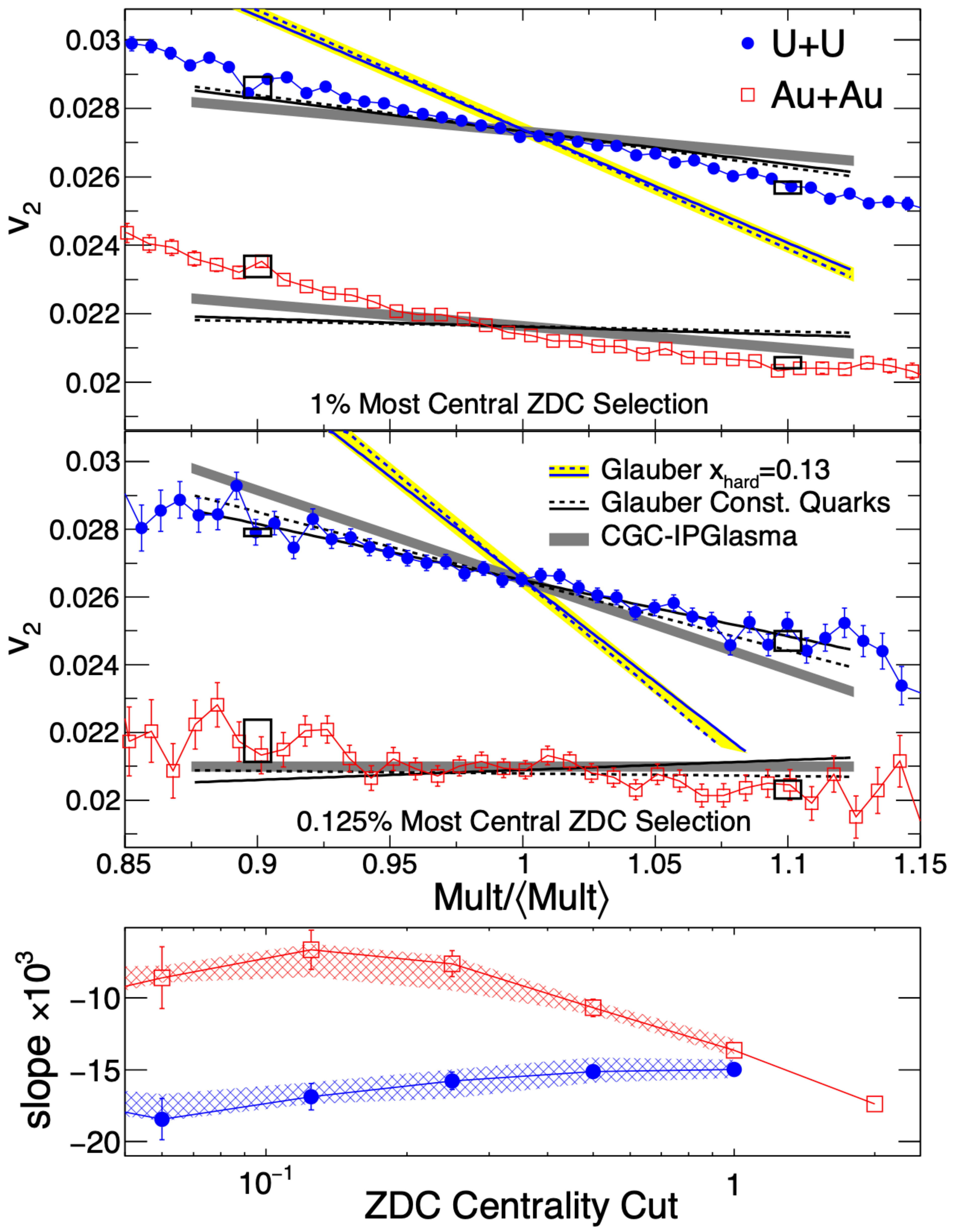
STAR Collaboration, L. Adamczyk et al., Phys.Rev.Lett. 115 (2015) 22, 222301

- STAR has shown that the measured flow anisotropies are sensitive to nuclear deformation
- 0.125% most central events: Au+Au slope nearly flat but U+U slope negative: In U+U the multiplicity variation at fixed small impact parameter is dominated by the orientation of the deformed uranium nuclei (tip–tip vs body–body)



U+U, side-side U+U, tip-tip

- Glauber model with dependence of the multiplicity on the number of binary nucleon-nucleon collisions does not work
- v_2 vs. multiplicity can be better described by other models, such as gluon saturation or quark participant models



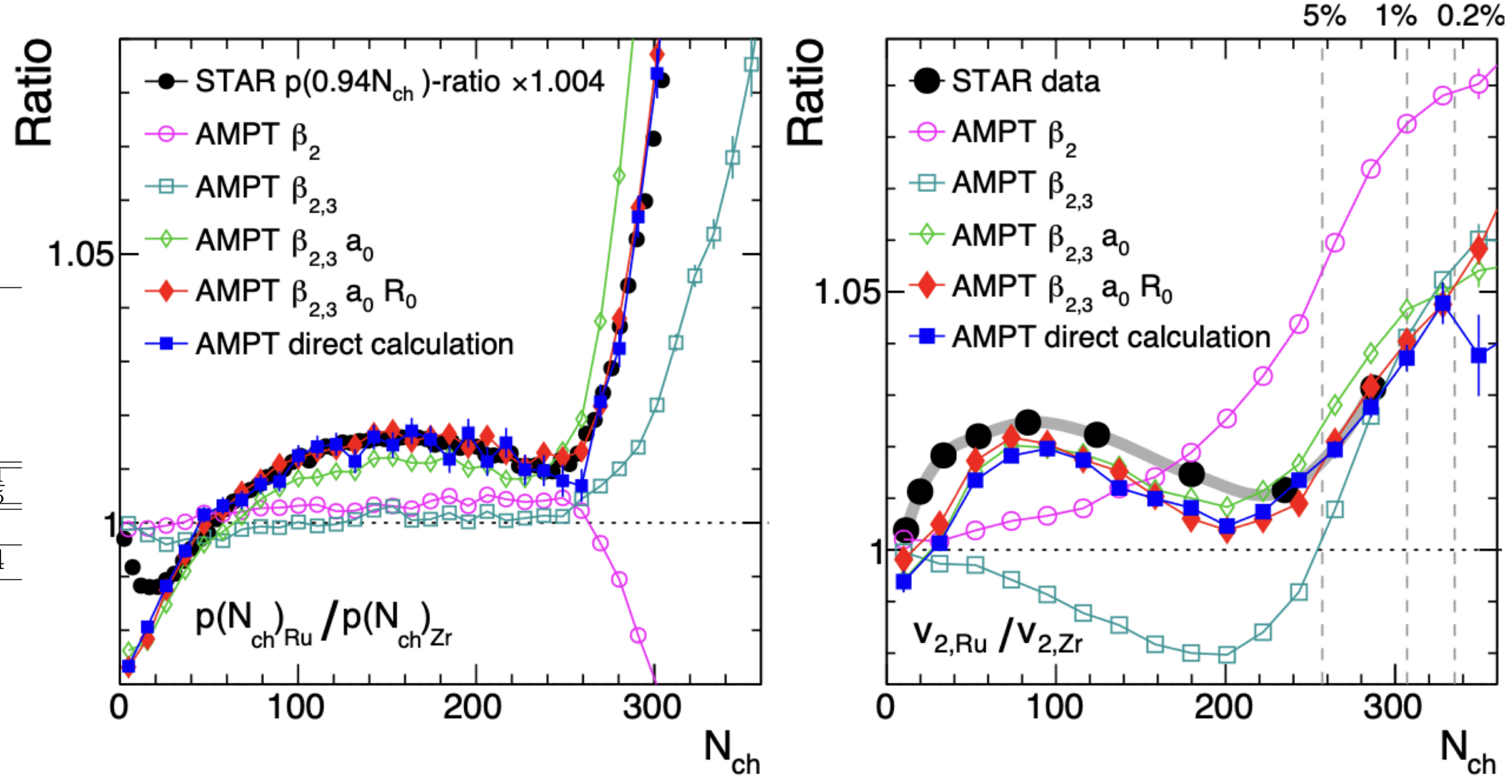
IMAGING NUCLEAR SHAPES

J. Jia, C. Zhang, Phys.Rev.C 107 (2023) 2, L021901
STAR Collaboration, M. Abdallah et al., Phys. Rev. C 105, 014901 (2022) → see the next talk by Zhiwan Xu on CME searches
STAR Collaboration, M.I. Abdulhamid et al., Nature 635 (2024) 8037, 67-72

- Isobar ratios for $p(N_{\mathrm{ch}})$ and v_2
- STAR data vs. AMPT with different nuclear structure parameter

	R_0 (fm)	a_0 (fm)	β_2	β_3
Case 1: ^{96}Ru	5.09	0.46	0.162	0
Case 2	5.09	0.46	0.06	0
Case 3	5.09	0.46	0.06	0.20
Case 4	5.09	0.52	0.06	0.20
Case 5: ^{96}Zr	5.02	0.52	0.06	0.20
Ratios	$\frac{\text{Case 1}}{\text{Case 2}}$	$\frac{\text{Case 1}}{\text{Case 3}}$	$\frac{\text{Case 1}}{\text{Case 4}}$	$\frac{\text{Case 1}}{\text{Case 5}}$
Case 1 and 5 difference	ΔR_0	Δa	$\Delta\beta_2^2$	$\Delta\beta_3^2$
	0.07 fm	-0.06 fm	0.0226	-0.04

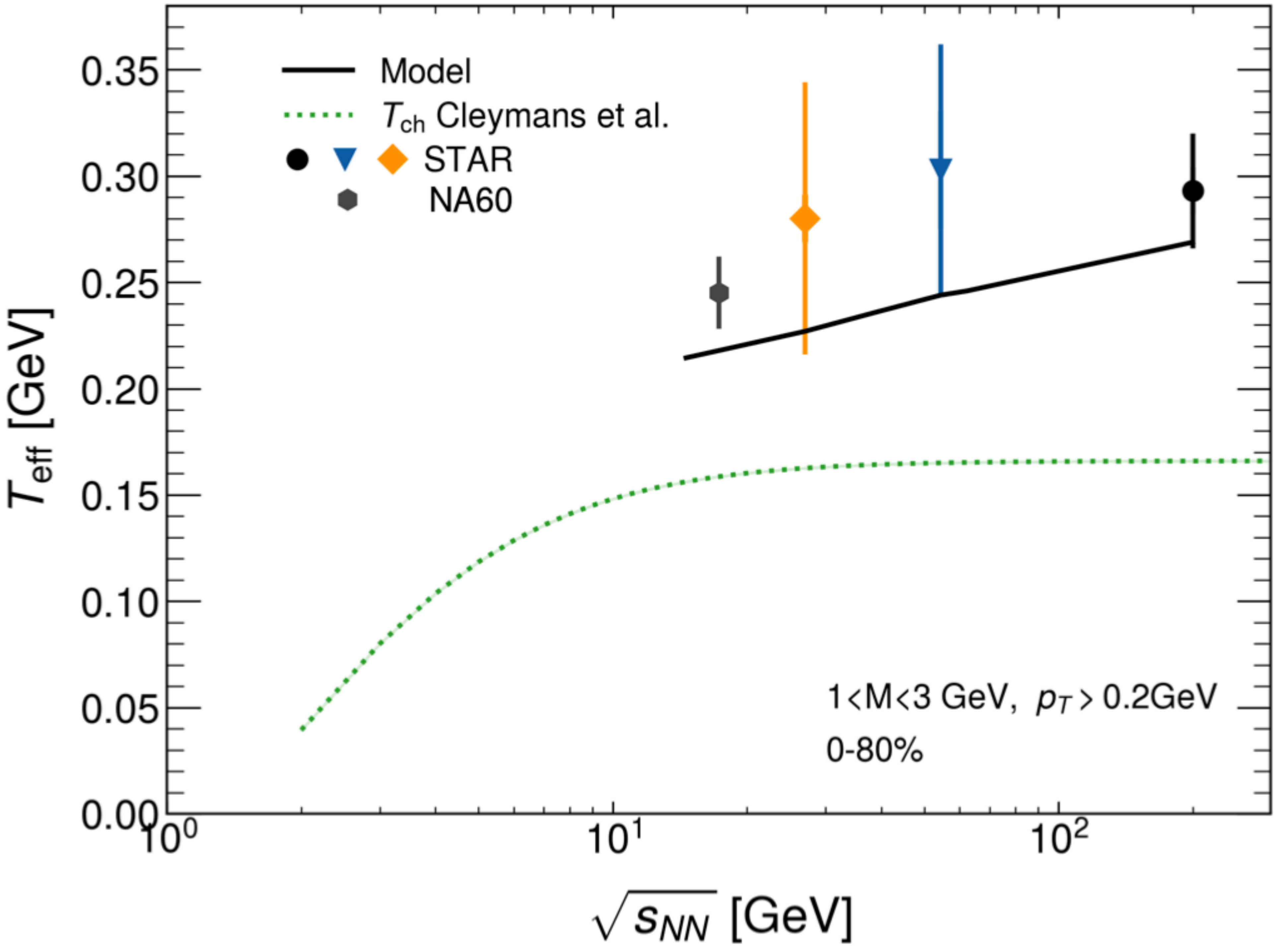
- Strong sensitivity to nuclear structure details
- Detailed study presented for Uranium-238 nuclei in Nature

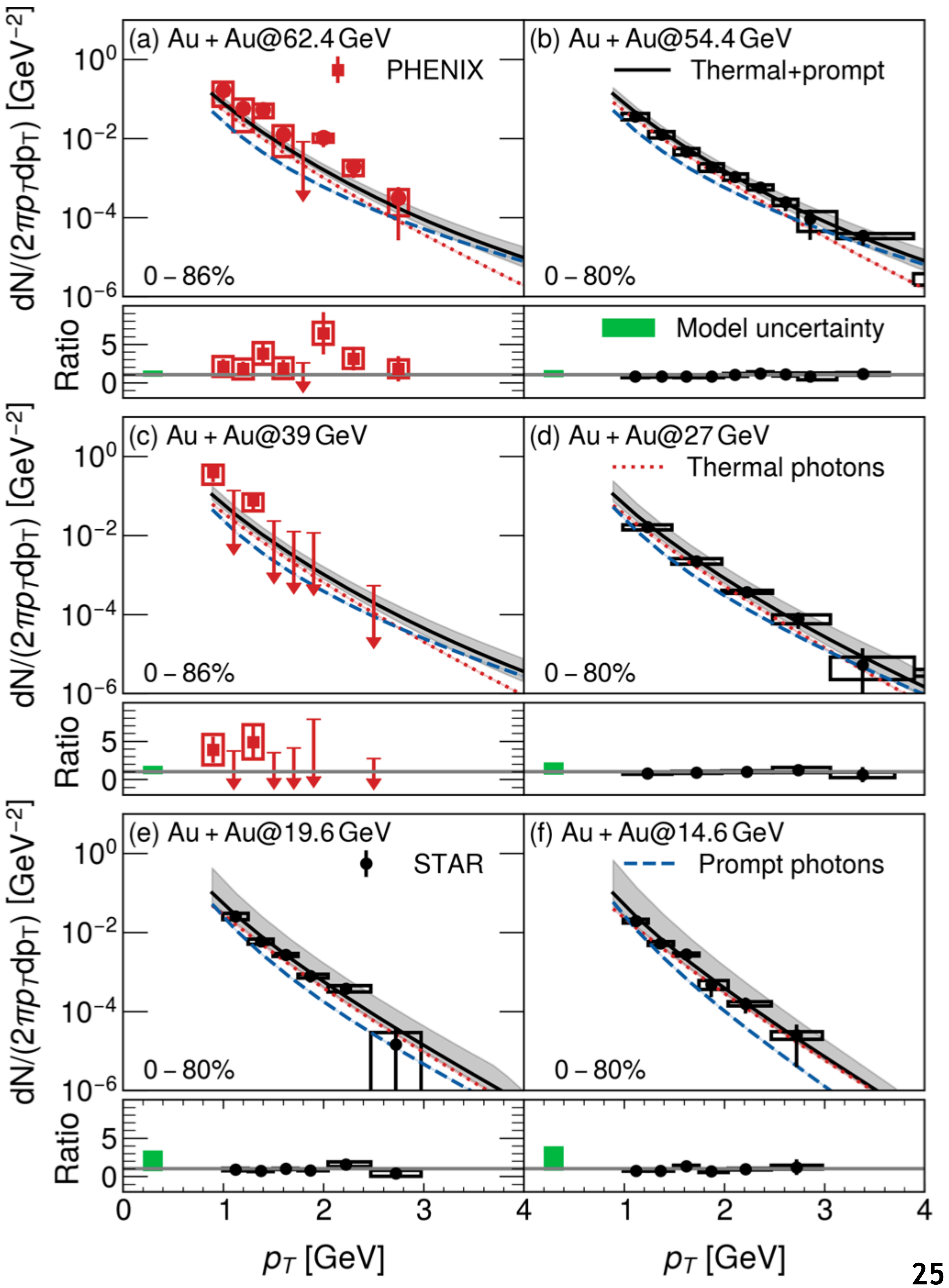


ELECTROMAGNETIC PROBES

STAR Collaboration, Nature Commun. 16, 9098 (2025)
NA60 Collaboration, Eur. Phys. J. C59, 607–623 (2009)
STAR BES-II data, QM2025, Frankfurt, Germany; PHENIX Collaboration, Phys. Rev. C 107, 024914 (2023)
X.-Y. Wu, C. Gale, S. Jeon, J.-F. Paquet, B. Schenke, C. Shen, arXiv:2511.08773

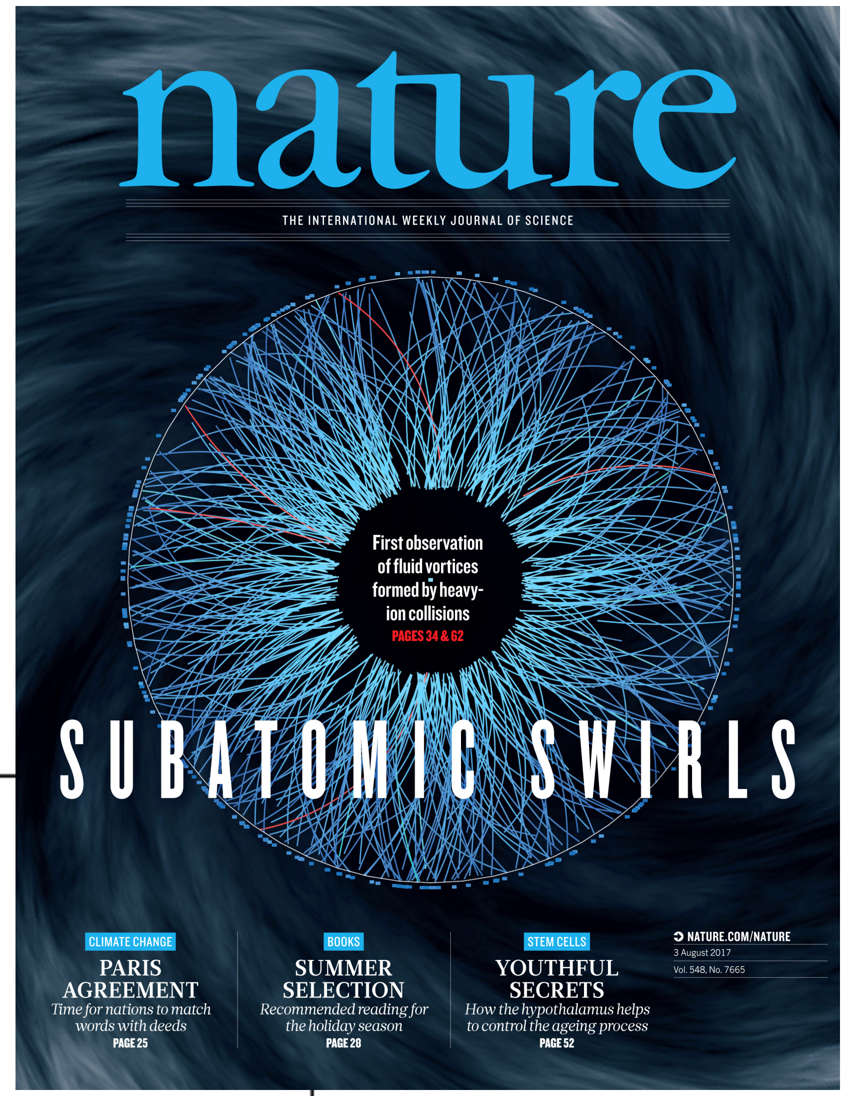
- STAR has measured photons and dileptons
- Extracted effective QGP temperature using dileptons
- Model describes STAR data on direct photons well



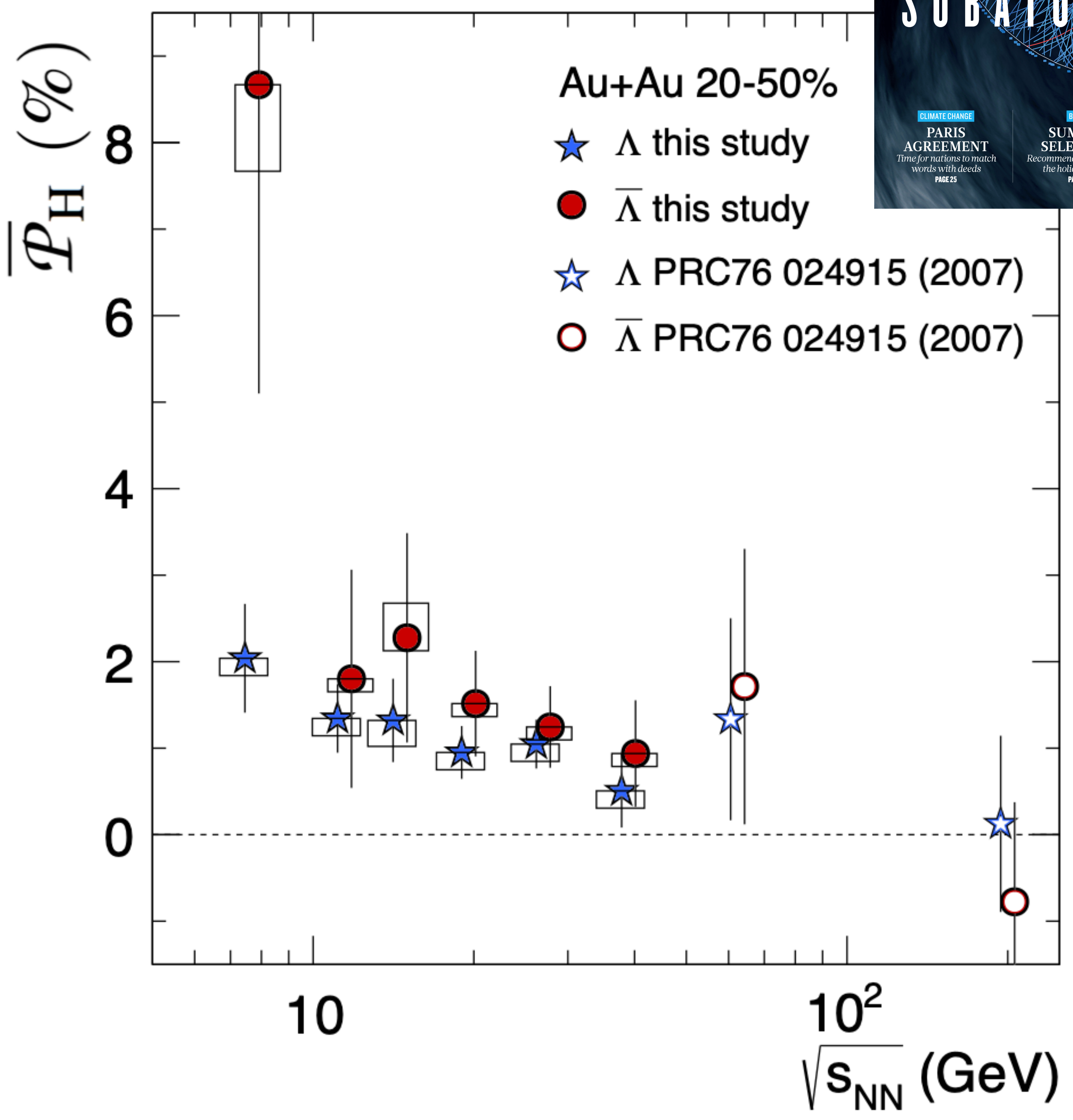


FLUID VORTICITY

STAR Collaboration, L. Adamczyk et al., Nature 548 (2017) 62-65
STAR Collaboration, J. Adam et al., Phys. Rev. Lett. 123, 132301 (2019),



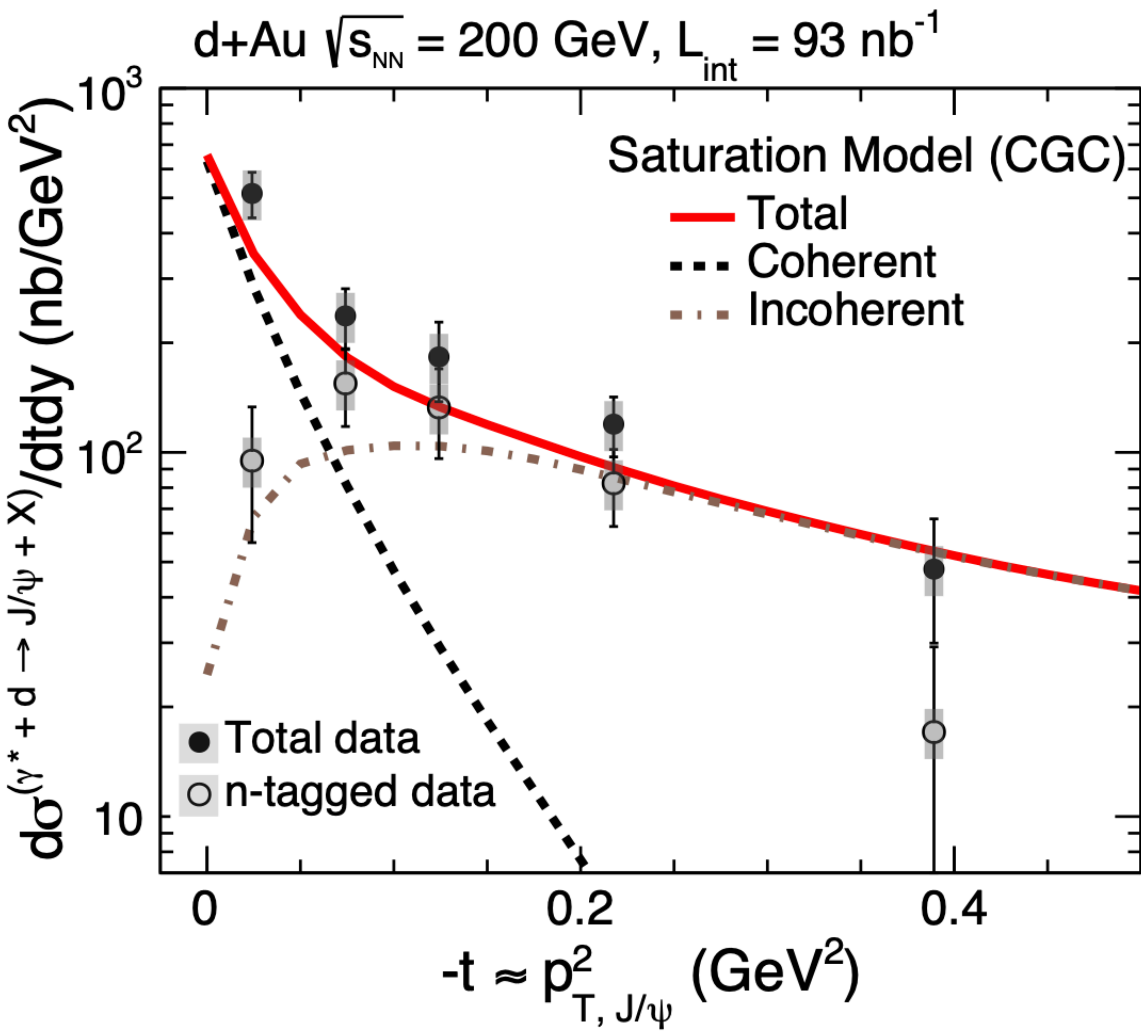
- STAR has shown that the QGP is not just the most perfect but also the most vortical fluid
- Spin-orbit coupling can generate a spin alignment, or polarization, along the direction of the vorticity which is on average parallel to the angular momentum of the collision
- Measured global Λ hyperon polarization
- Fluid vorticity then can be estimated as $\omega = k_B T(\bar{\mathscr{P}}_{\Lambda'} + \bar{\mathscr{P}}_{\bar{\Lambda}'})/\hbar$
- STAR found $\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$
- The next largest vorticity generated is in superfluid nanodroplets with $\omega = 10^7 s^{-1}$
- STAR's measurement of *local* Λ polarization triggered significant developments in spin-hydrodynamics



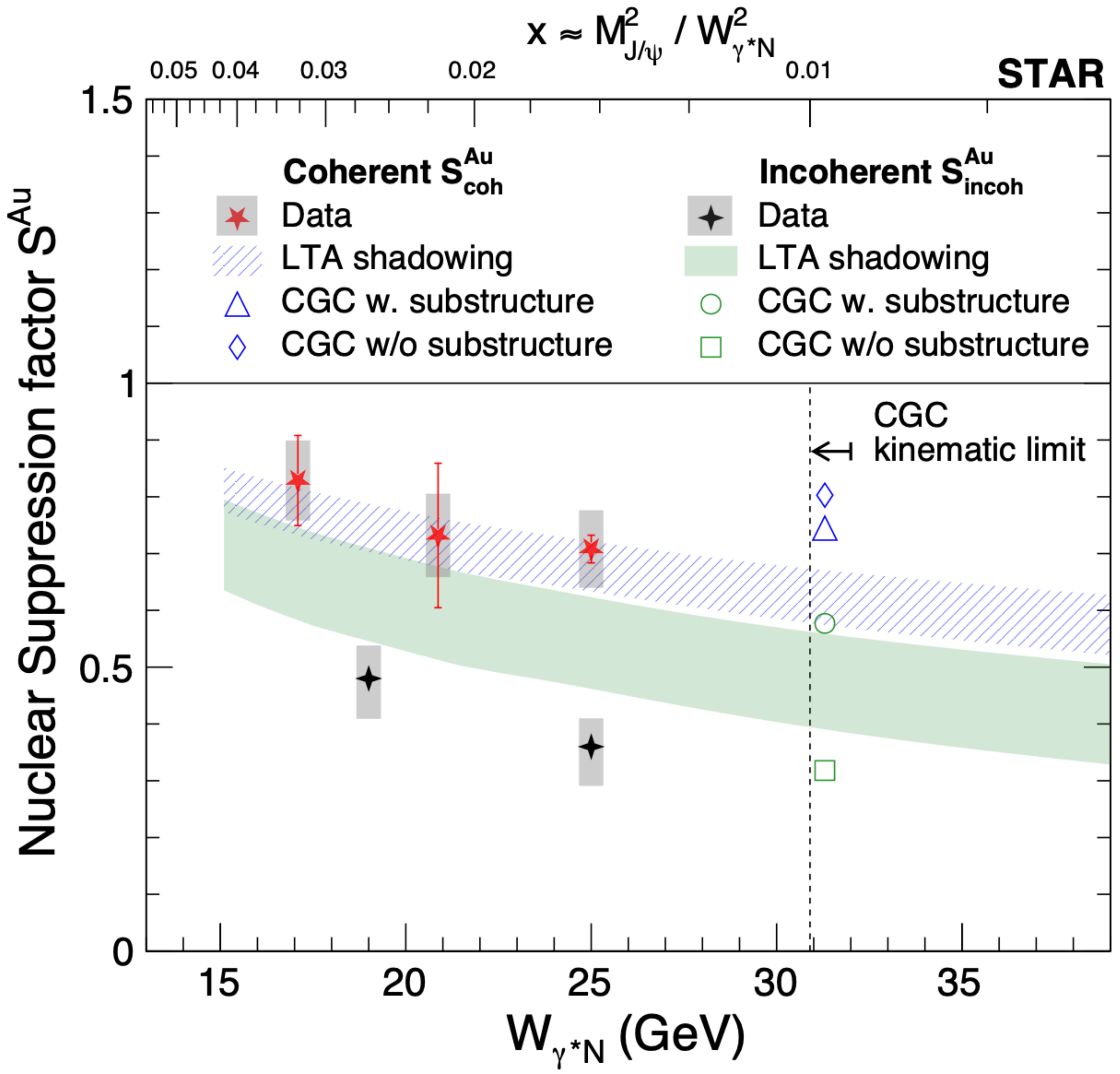
ULTRA-PERIPHERAL COLLISIONS

STAR Collaboration, M. Abdallah, Phys.Rev.Lett. 128 (2022) 12, 122303
STAR Collaboration, M.I. Abdulhamid, Phys.Rev.Lett. 133 (2024) 5, 052301

- STAR pioneered ultra-peripheral collisions which can be used to constrain the initial state of heavy ion collisions → help constrain QGP properties



d+Au UPC: Constrain the lumpiness of the gluon distribution



Coherent and incoherent J/ψ nuclear suppression

SUMMARY

- STAR made substantial contributions to understanding QGP bulk properties
- We have learned a lot about the temperature, transport properties, chemistry, and spatial structure of heavy ion collisions from STAR data
- Questions remain: Detailed phase structure (critical point?), details of baryon stopping and charge stopping, limits of collectivity, etc.
- So, I hope data analysis will continue with full force and STAR will keep producing high impact results as it has been for 25 years!

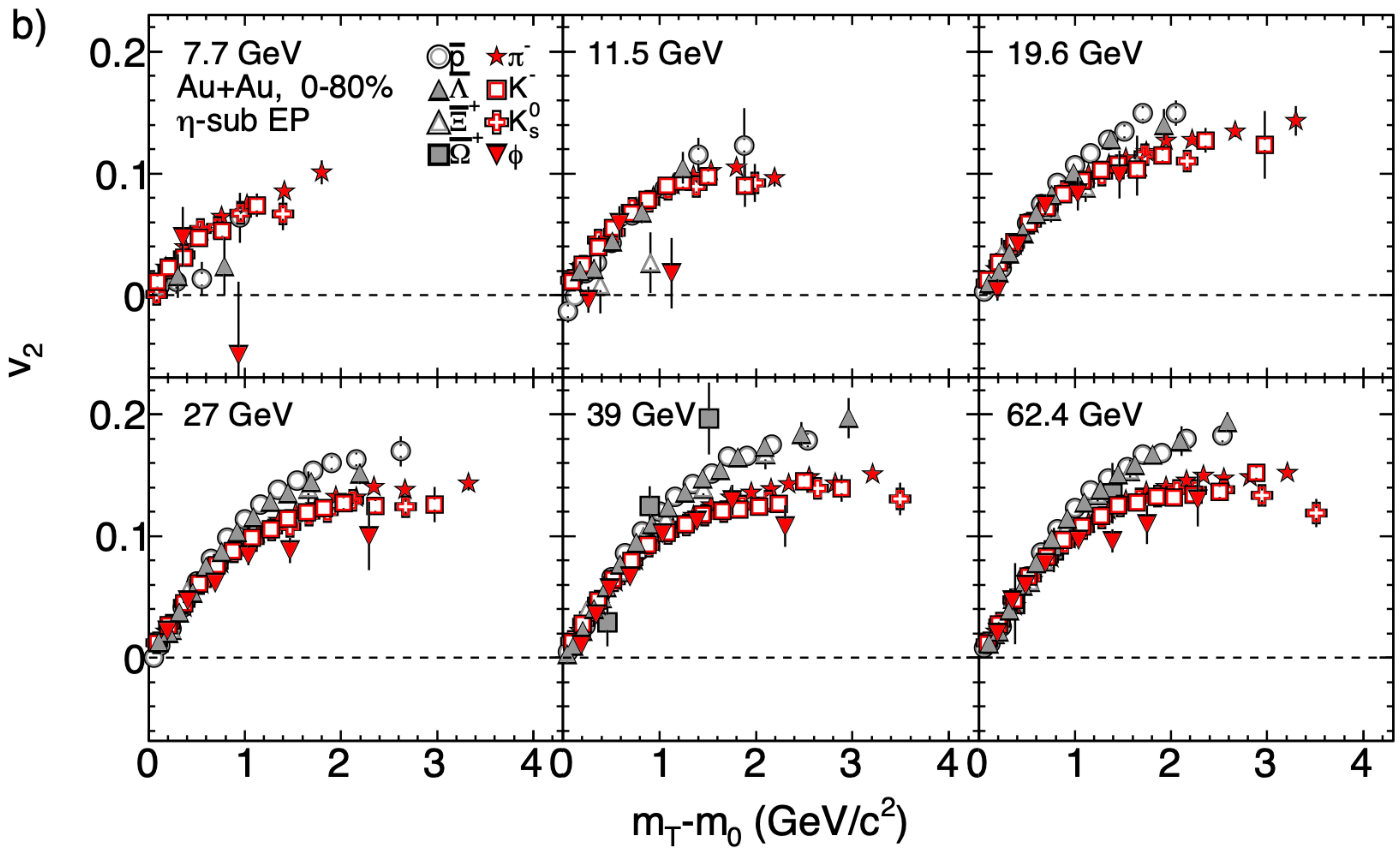
Congratulations!

BACKUP

BEAM ENERGY SCAN FLOW

STAR Collaboration, L. Adamczyk et al., Phys.Rev.C 88 (2013) 014902

- Baryon-meson splitting disappears for anti-particles at lower collision energies
- So, no NCQ scaling at the lowest energies



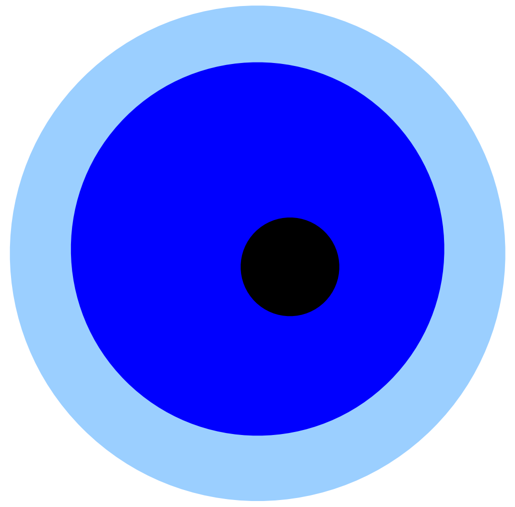
NEUTRON SKIN

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

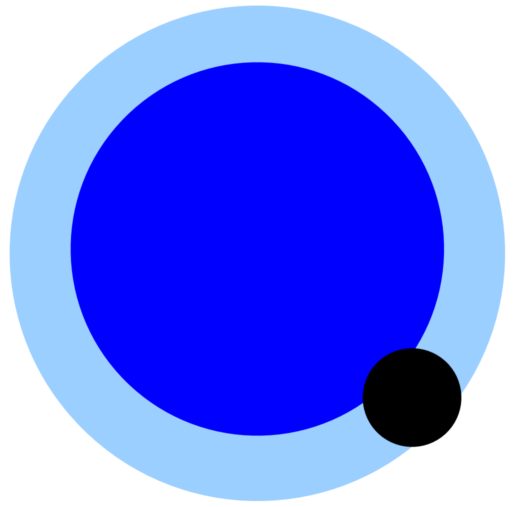
- Measurements of electric vs. baryon charge as function of centrality is also sensitive to neutron skin
- LHCb could measure the double ratio in p+Pb collisions:

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

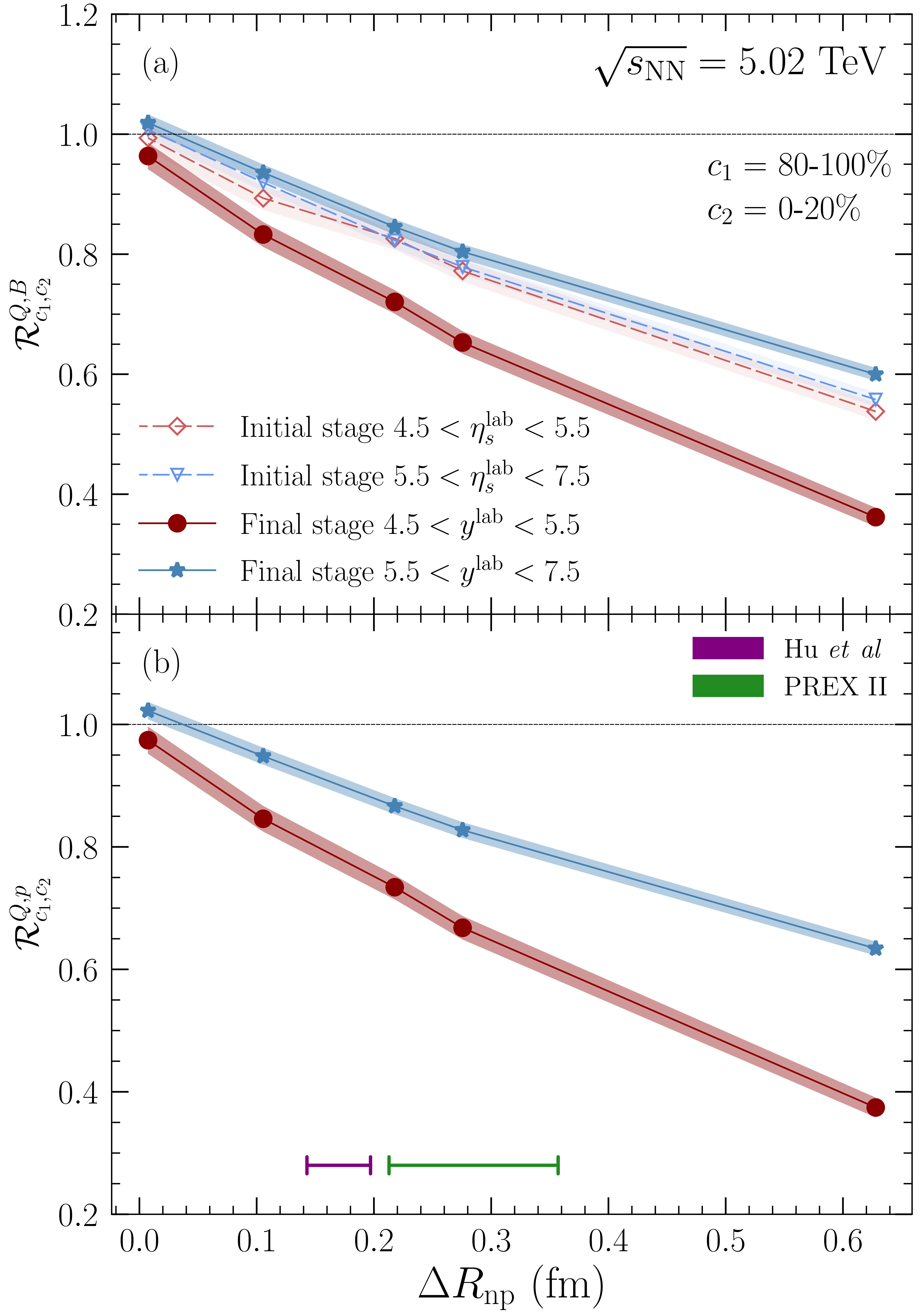
c_1 and c_2: peripheral and central centrality class, resp.
Q and B: electric and baryon charge, respectively



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

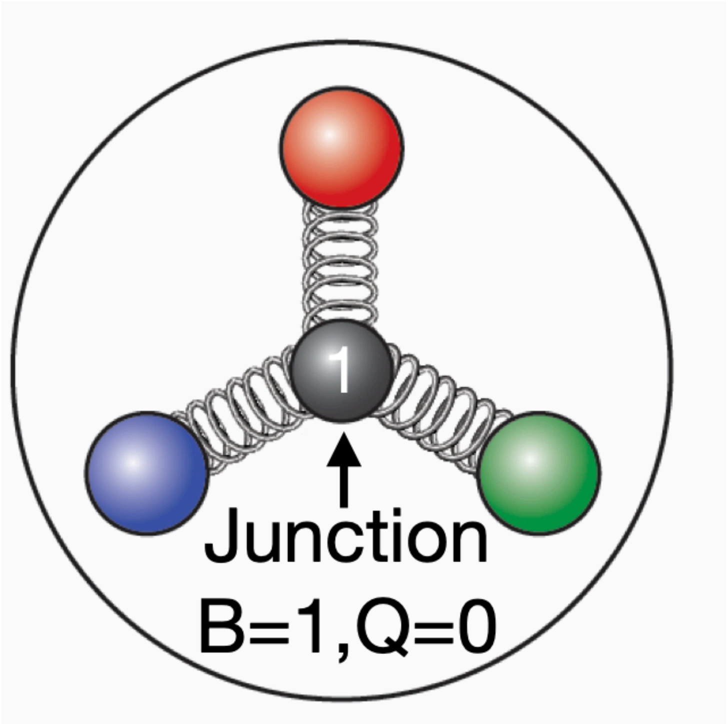


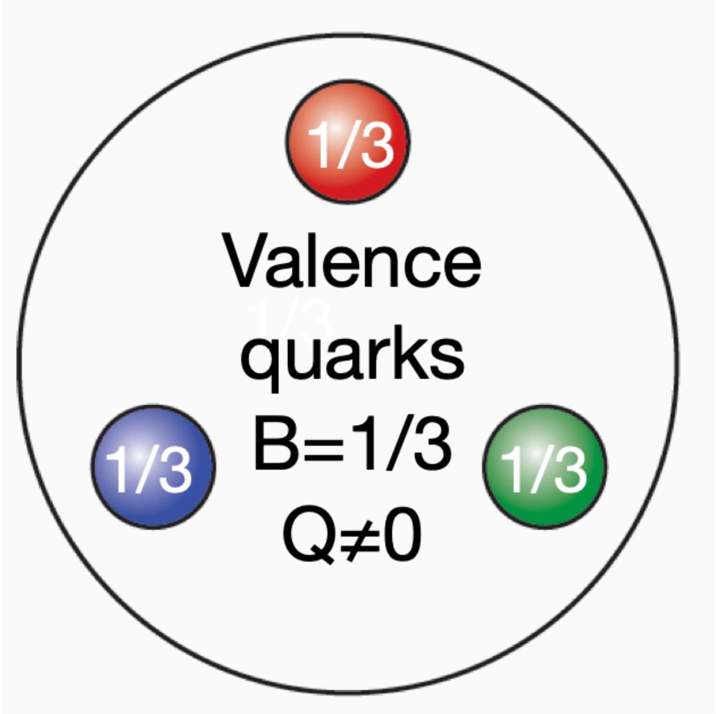
peripheral collision:
proton hits $n > p$
depending on neutron skin
transport $Q < B$
towards mid rapidity

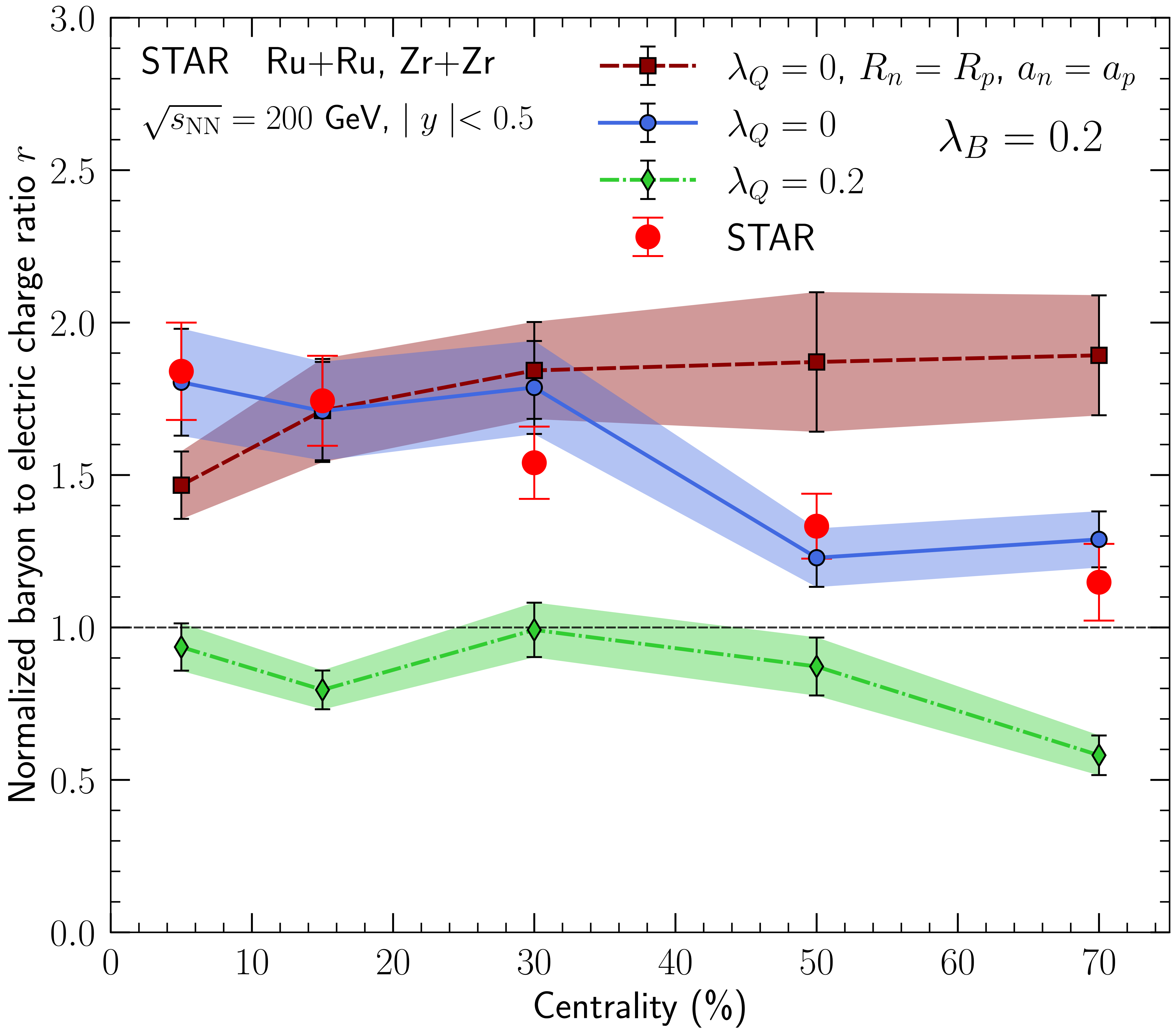


WHAT CARRIES BARYON NUMBER?

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







baryon junction, no neutron skin

baryon junction, neutron skin for Zr

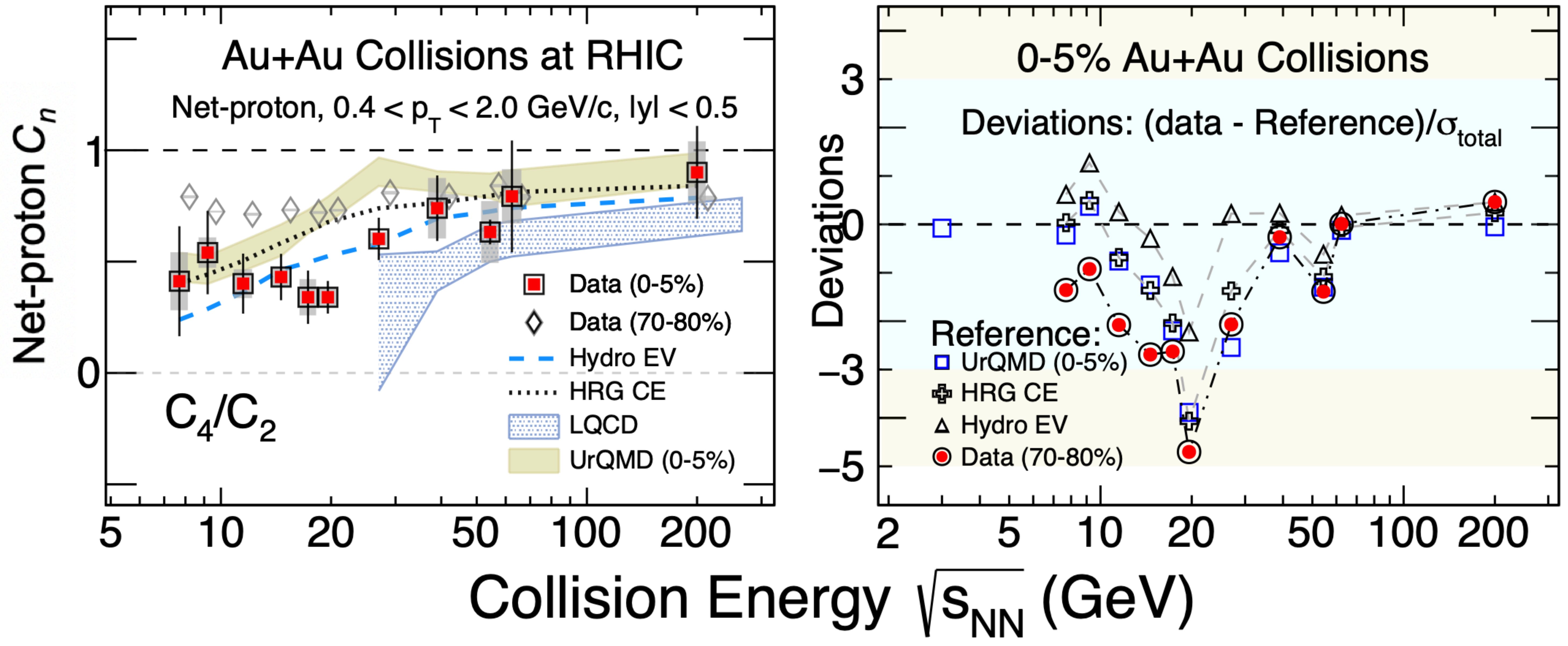
baryon number carried by valence quarks (with neutron skin)

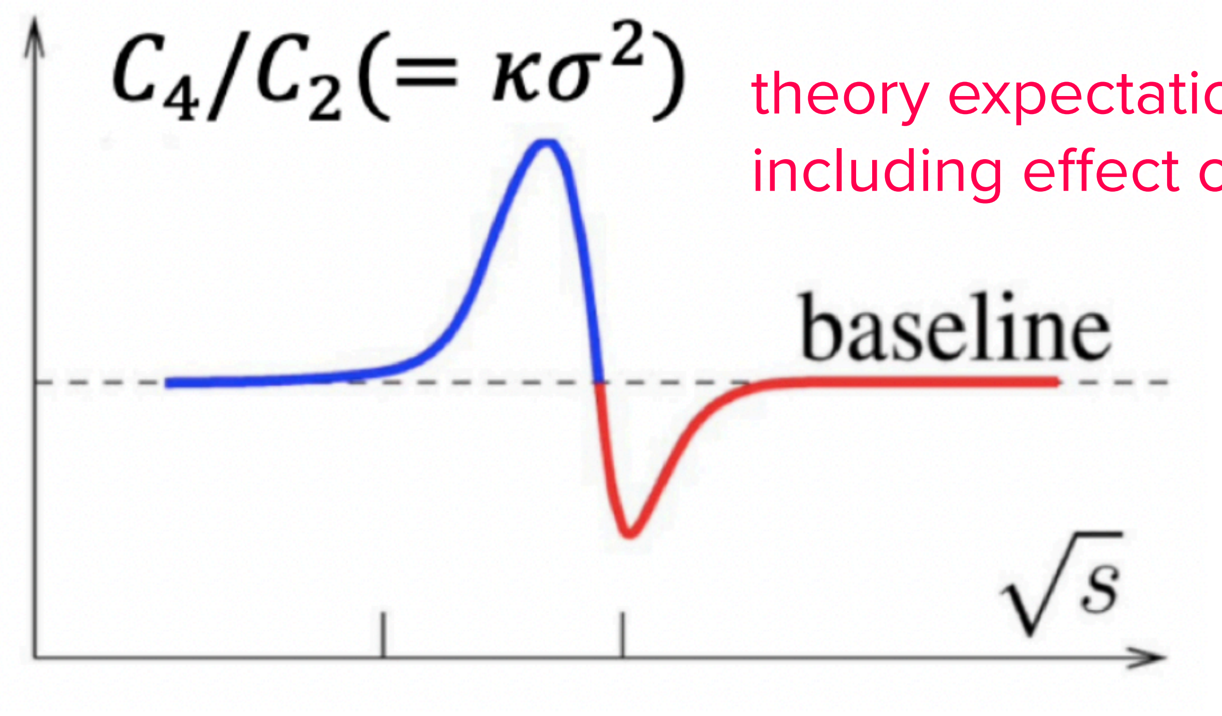
The ratio of the mean net-baryon number (⟨B⟩) to the net-charge difference between Ru+Ru and Zr+Zr collisions (ΔQ), scaled by ΔZ/A= 4/96, as a function of centrality

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

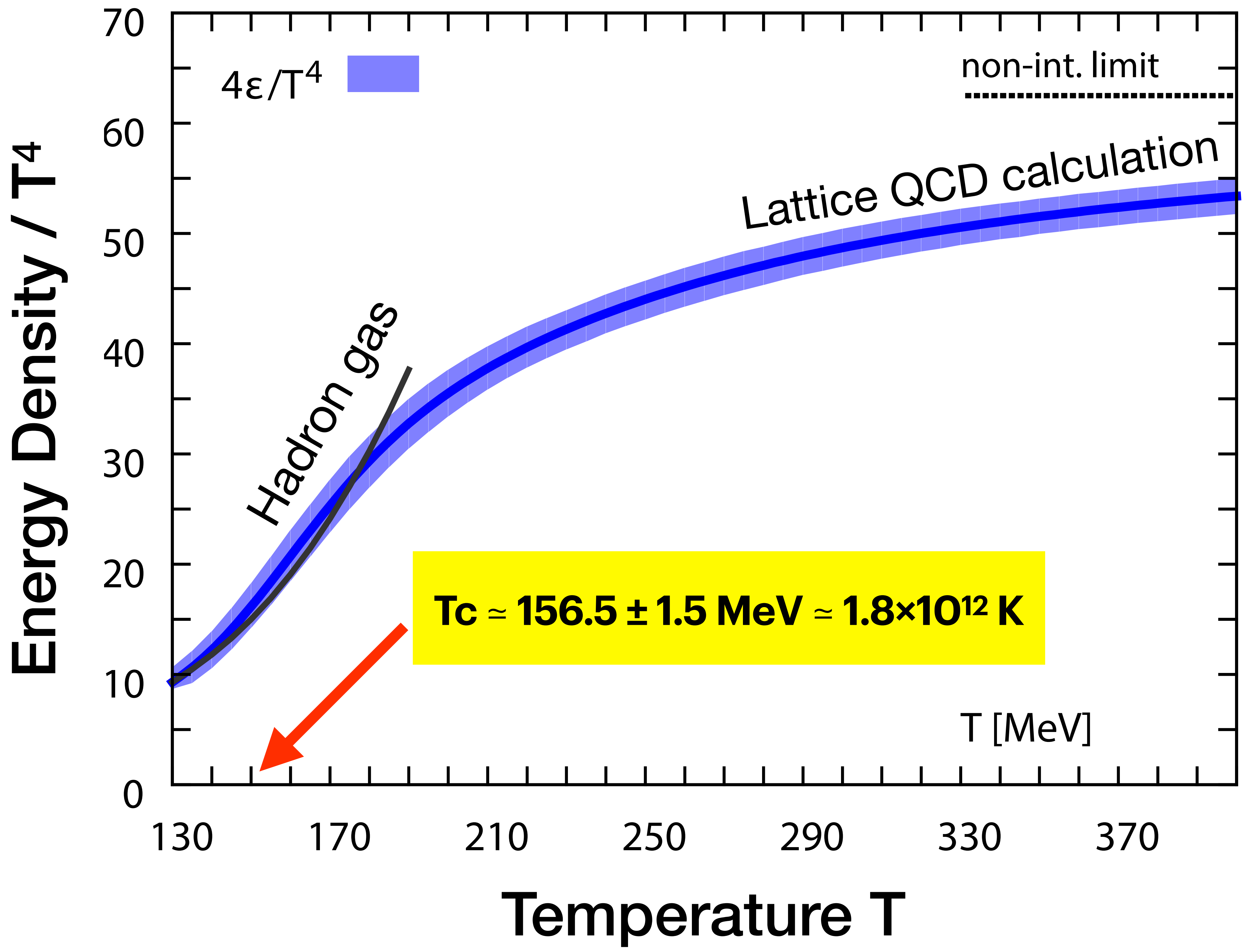




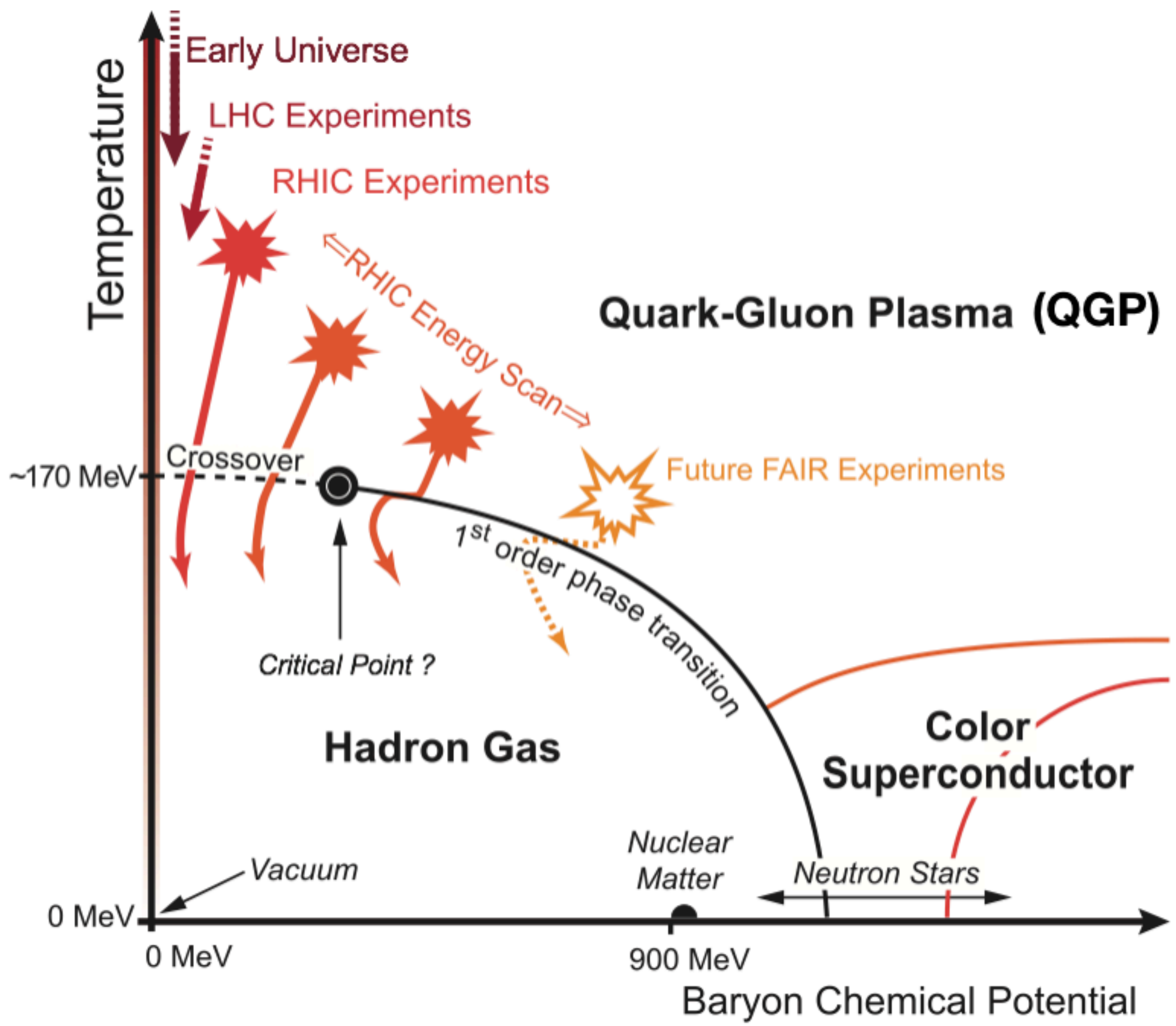
theory expectation including effect of critical point

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

QUARK-GLUON PLASMA



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

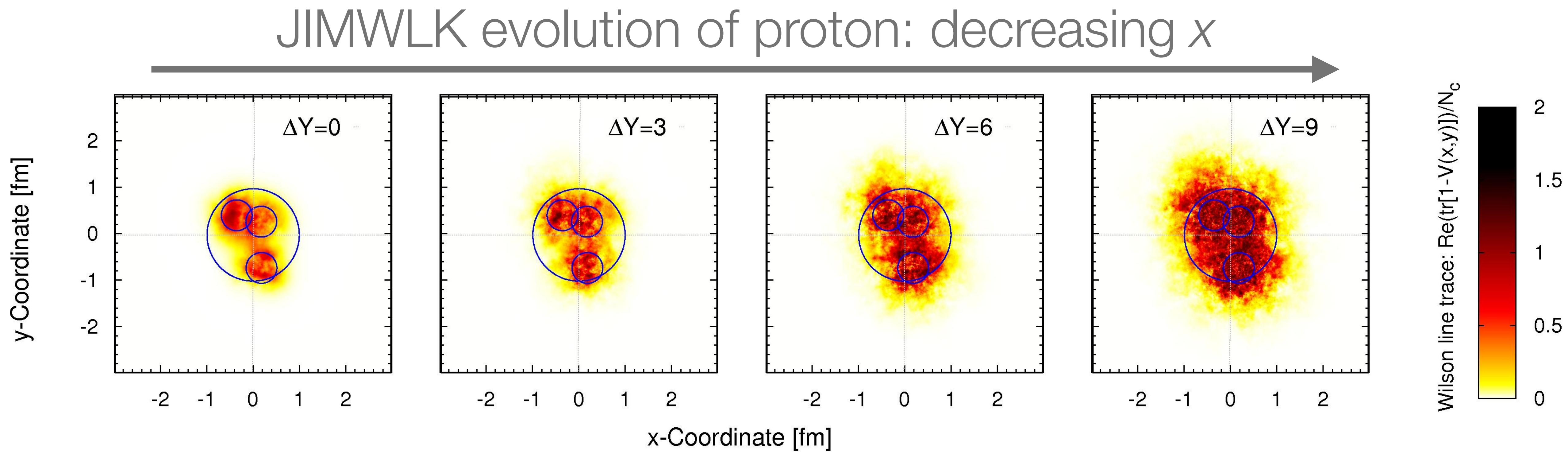


INITIAL STATE - LATEST DEVELOPMENTS

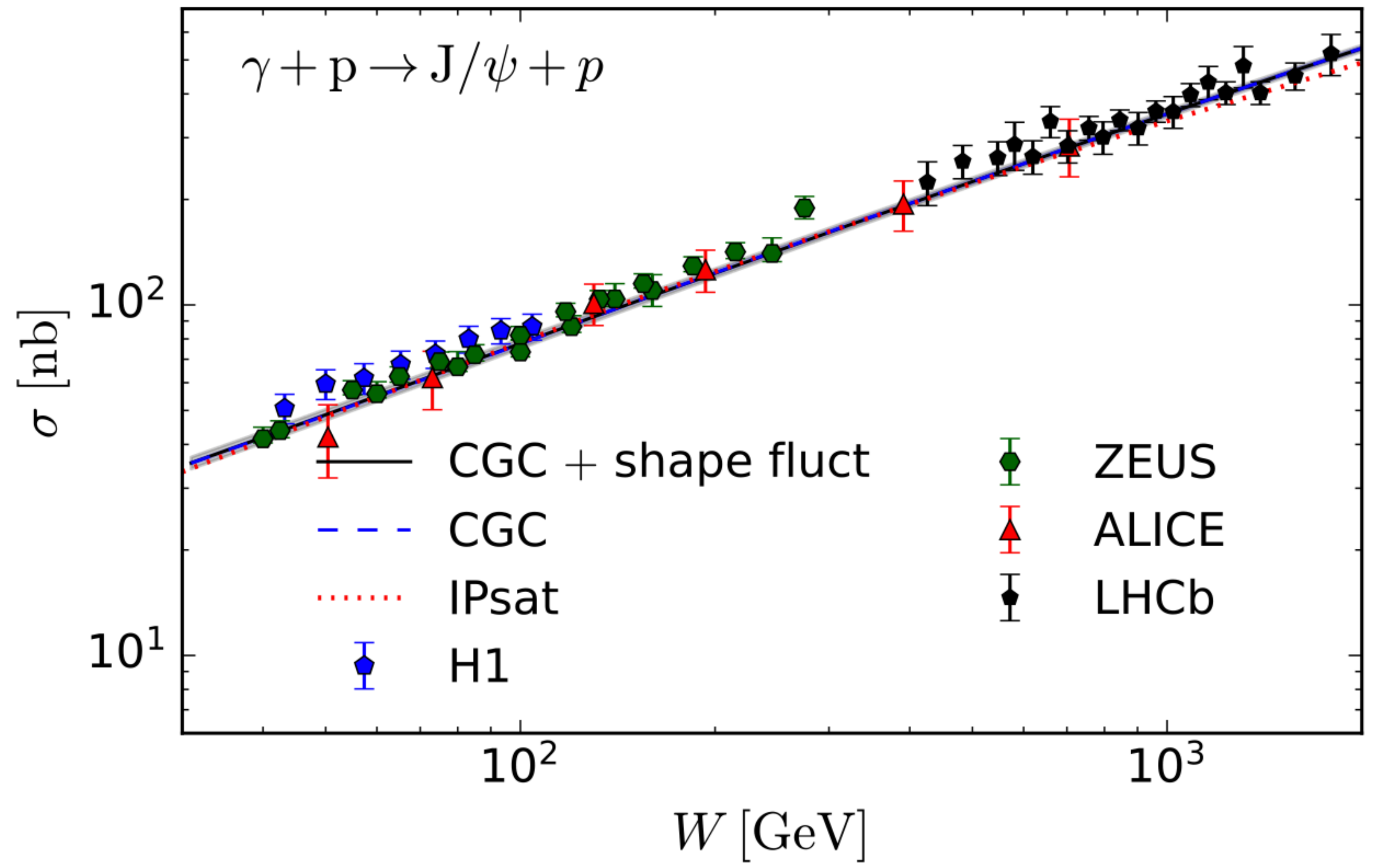
High energy collisions: **Color Glass Condensate** framework

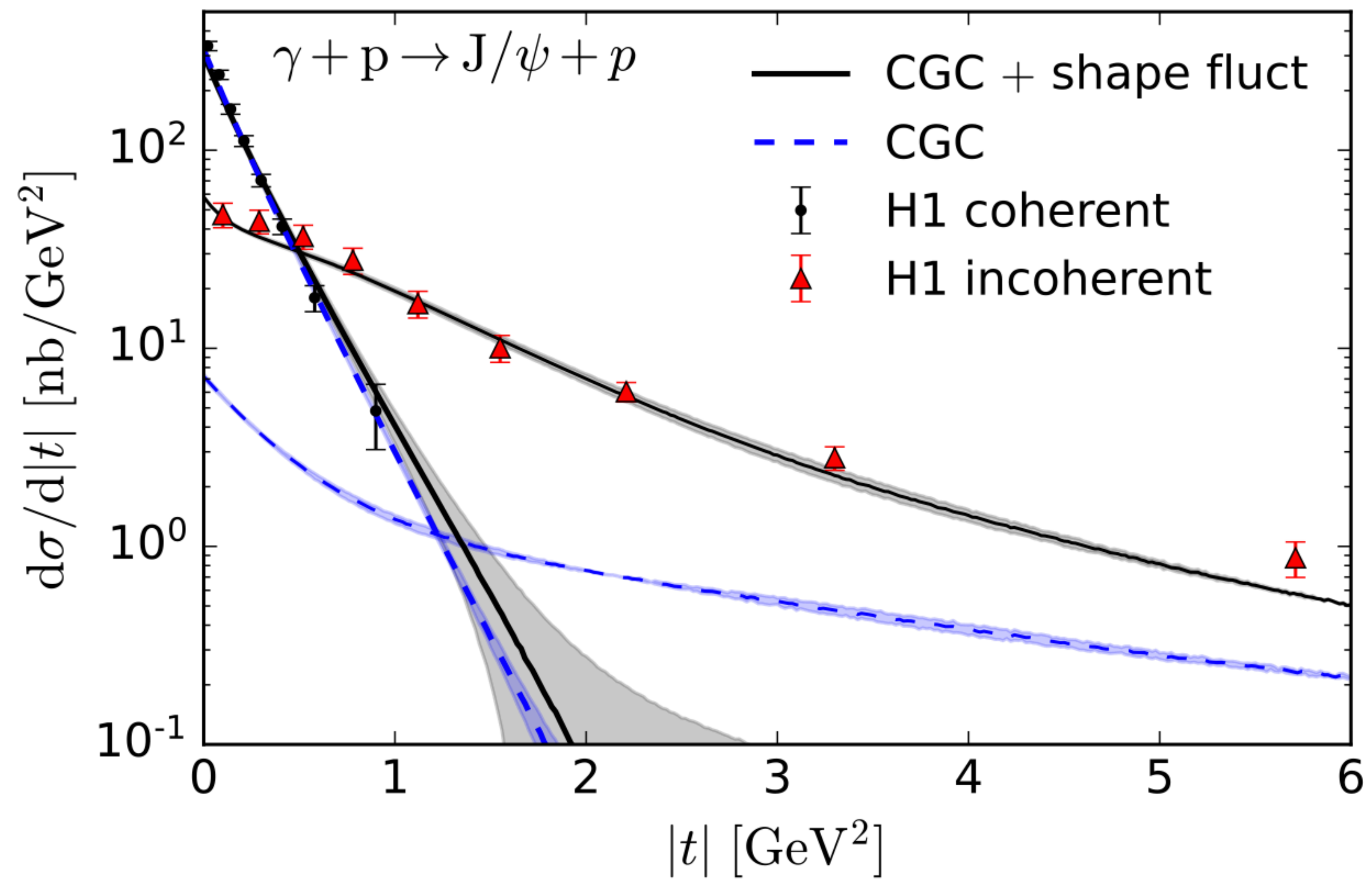
Apply to both **diffractive DIS and heavy ion collisions**

- 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. B739, 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. D94 (2016) 034042; H. Mäntysaari, Rep. Prog. Phys. 83 082201 (2020)
B. Schenke, Rep. Prog. Phys. 84 082301 (2021)

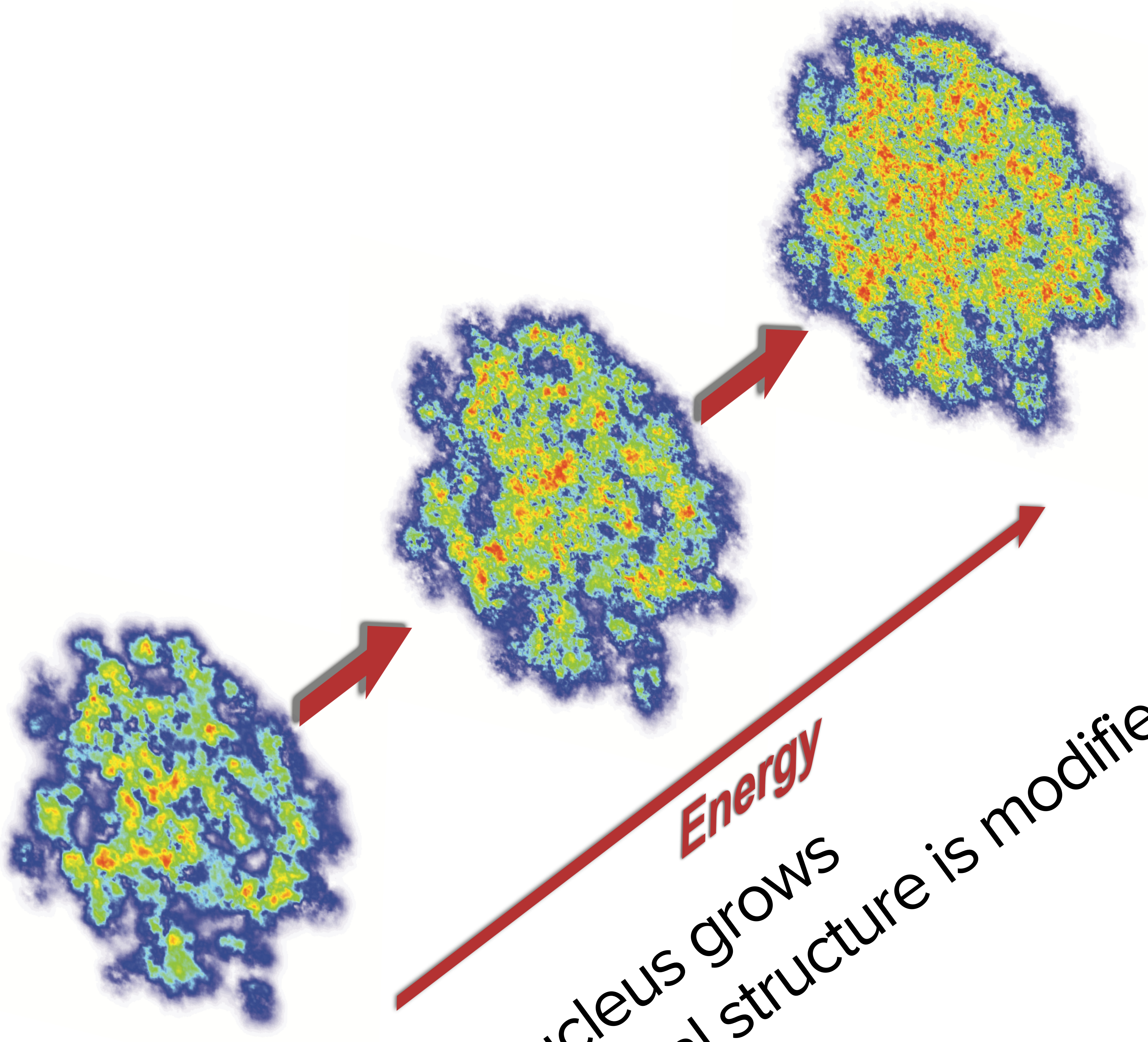
H. Mäntysaari, F. Salazar, B. Schenke, Phys.Rev.D 106 (2022) 7, 074019

For Bayesian analysis see: H. Mäntysaari, H. Roch, F. Salazar, B. Schenke, C. Shen, W. Zhao, arXiv:2507.14087

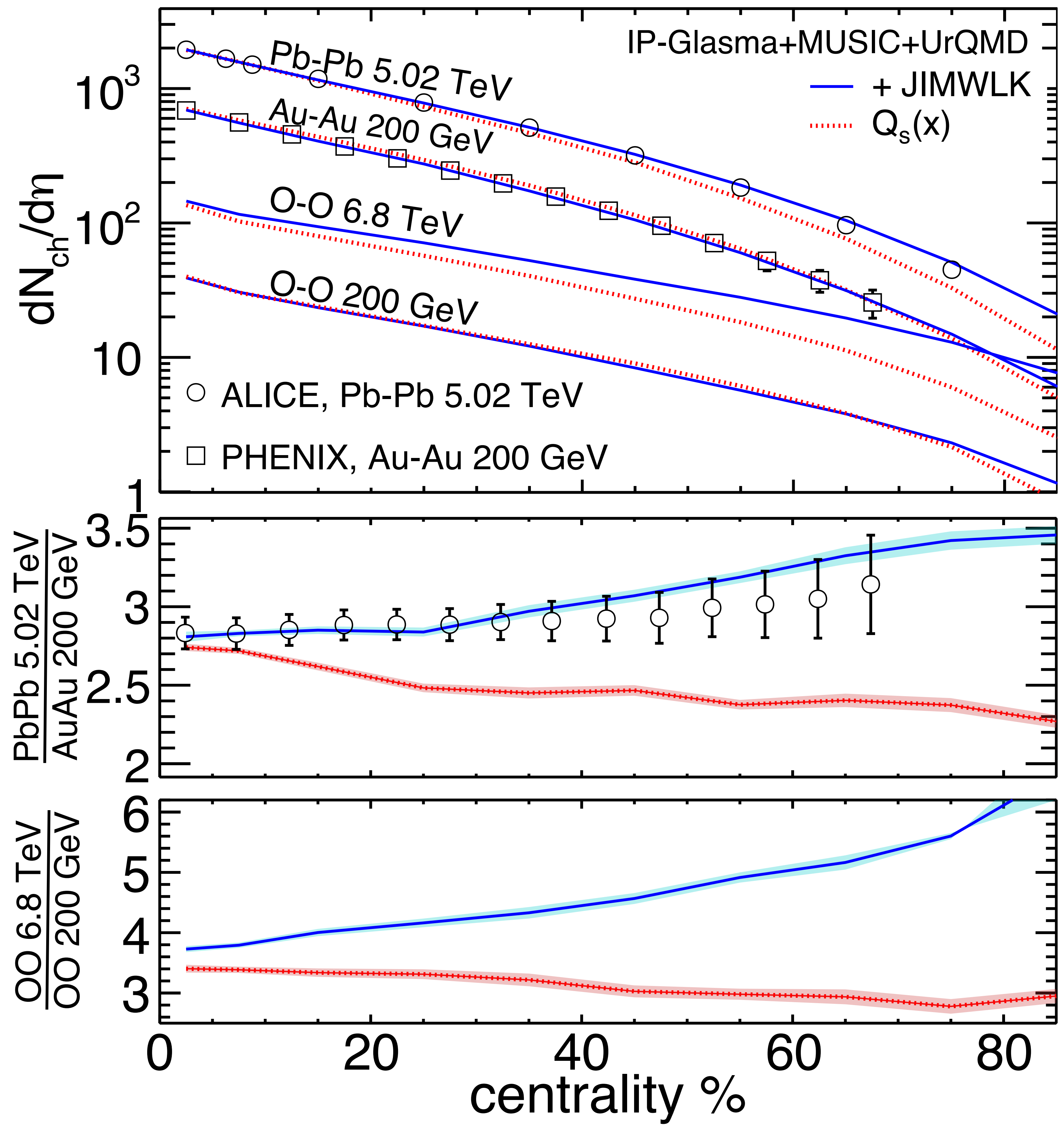
INCLUDING NON-LINEAR QCD EVOLUTION

- 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



- Nucleus grows
- Internal structure is modified



Blue: incl. energy evolution

Red: w/o energy evolution

Stronger effect in smaller systems

APPLICABILITY OF HYDRODYNAMICS

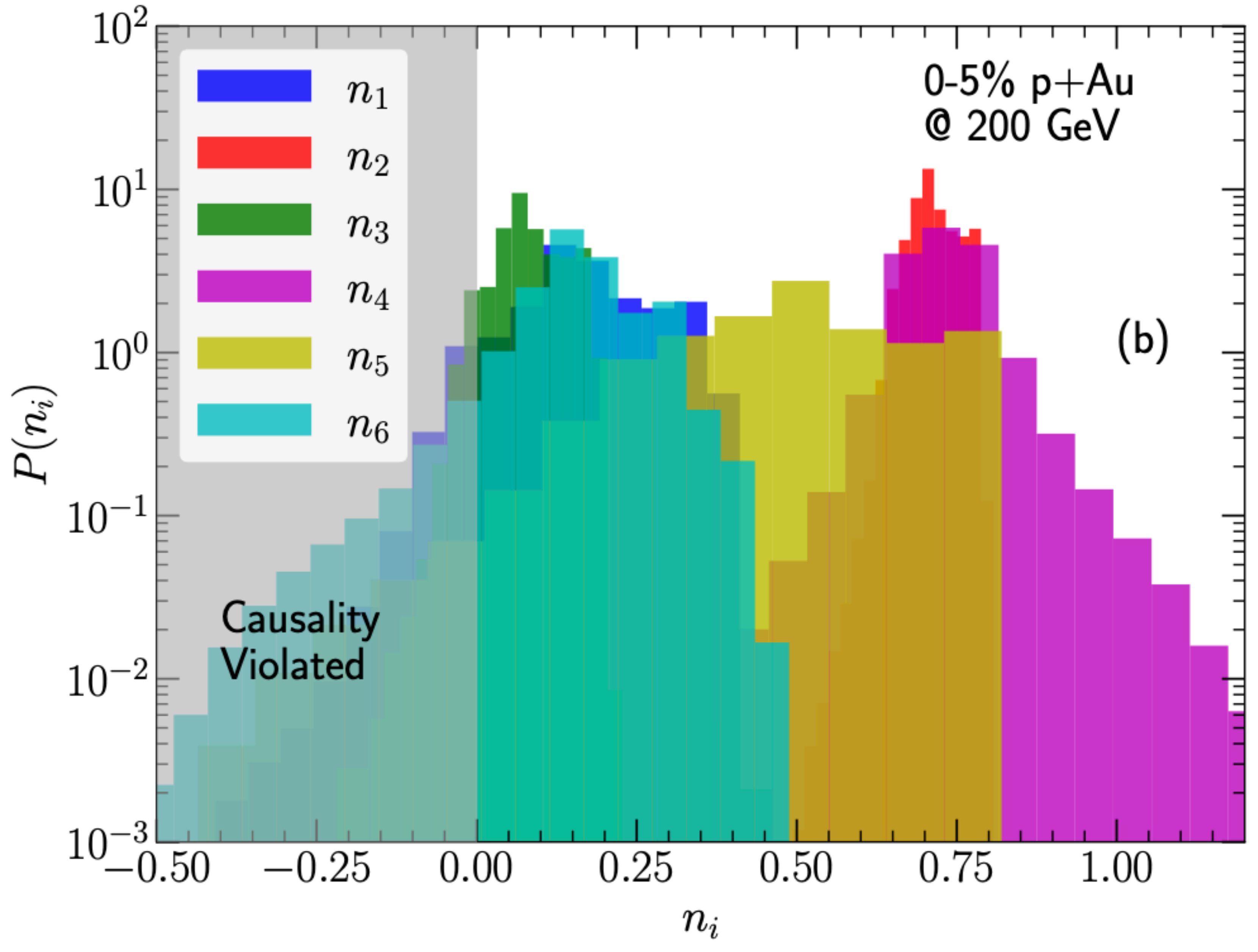
- Initial transverse volume in small systems 50 × smaller than in central Pb+Pb
- Locally large Knudsen (macroscopic scale / microscopic scale) and inverse Reynolds numbers (ratio of viscous forces to inertial forces)
- Could lead to inaccurate results
- Far from equilibrium, causality could be violated
- 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



values of 6 causality conditions

APPLICABILITY OF HYDRODYNAMICS

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

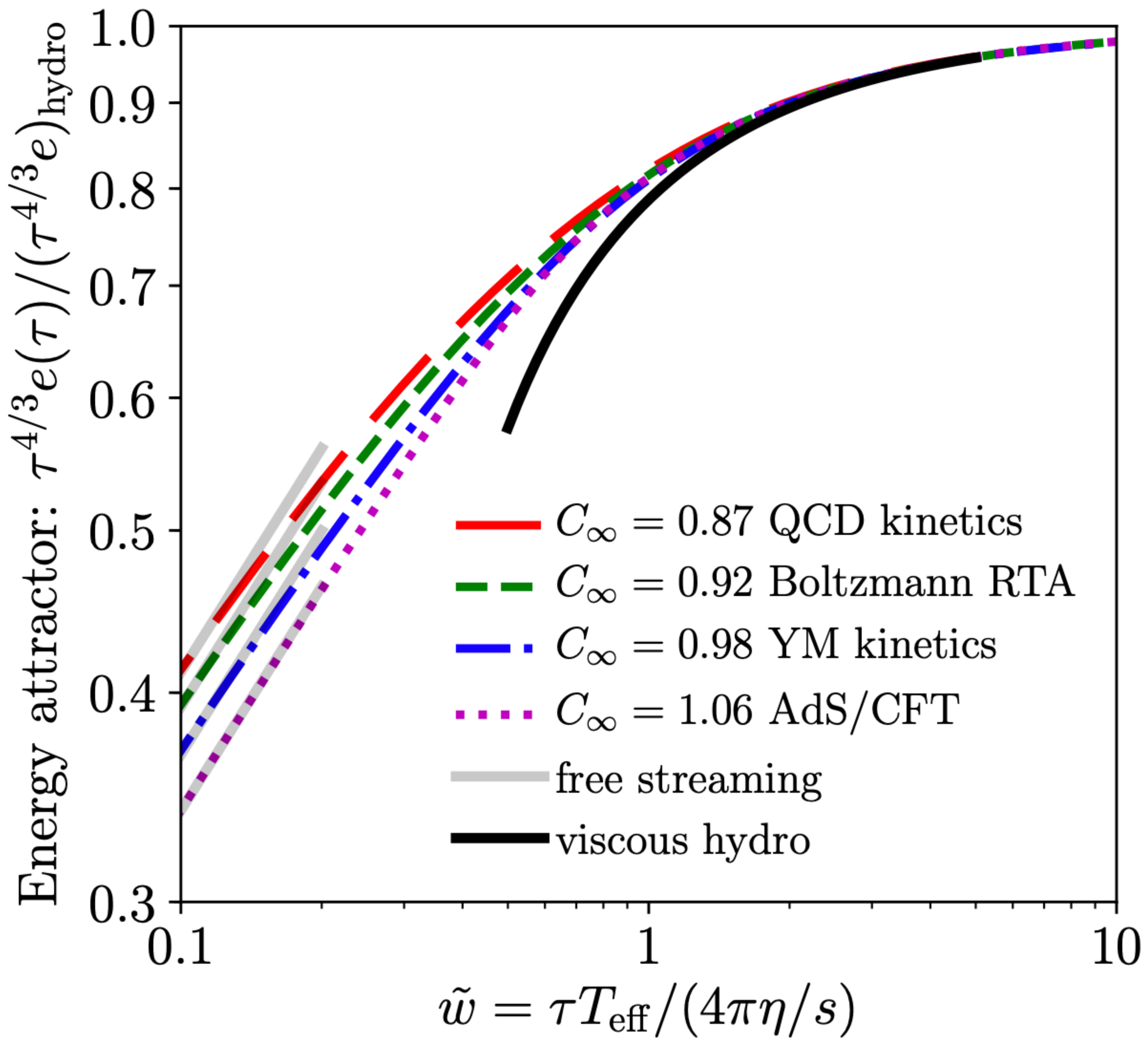
Hydrodynamic attractors are reached at times $\mathcal{O}(1\mathrm{fm})$
Largely independent of the underlying microscopic theory

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

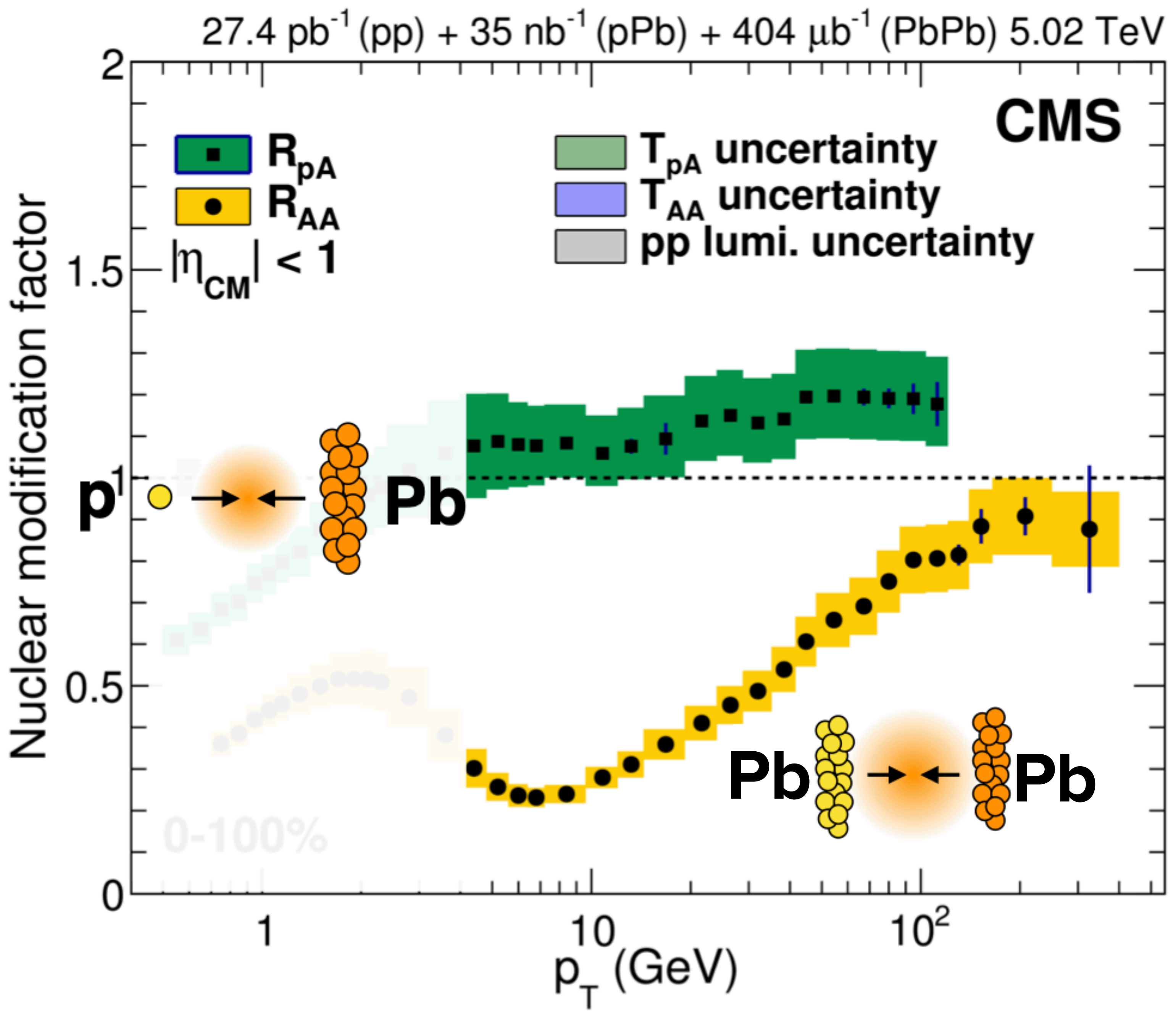


Giacalone, Mazeliauskas, Schlichting, Phys.Rev.Lett. 123 (2019) 26, 262301
S. Kamata, M. Martinez, P. Plaschke, S. Ochsenfeld, S. Schlichting Phys.Rev.D 102 (2020) 5, 056003 (2004.06751)

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

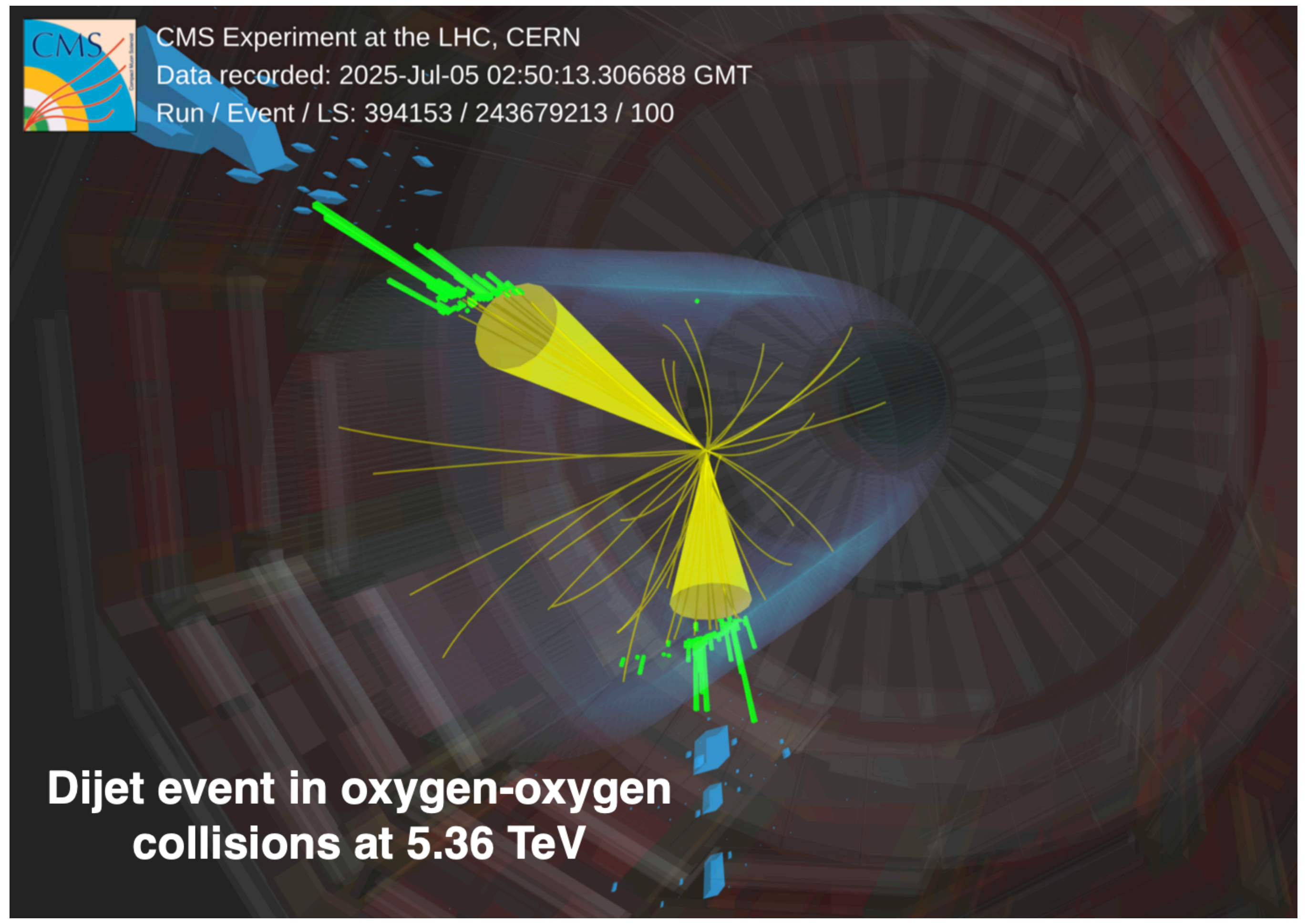
JET QUENCHING IN SMALL SYSTEMS?

- 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

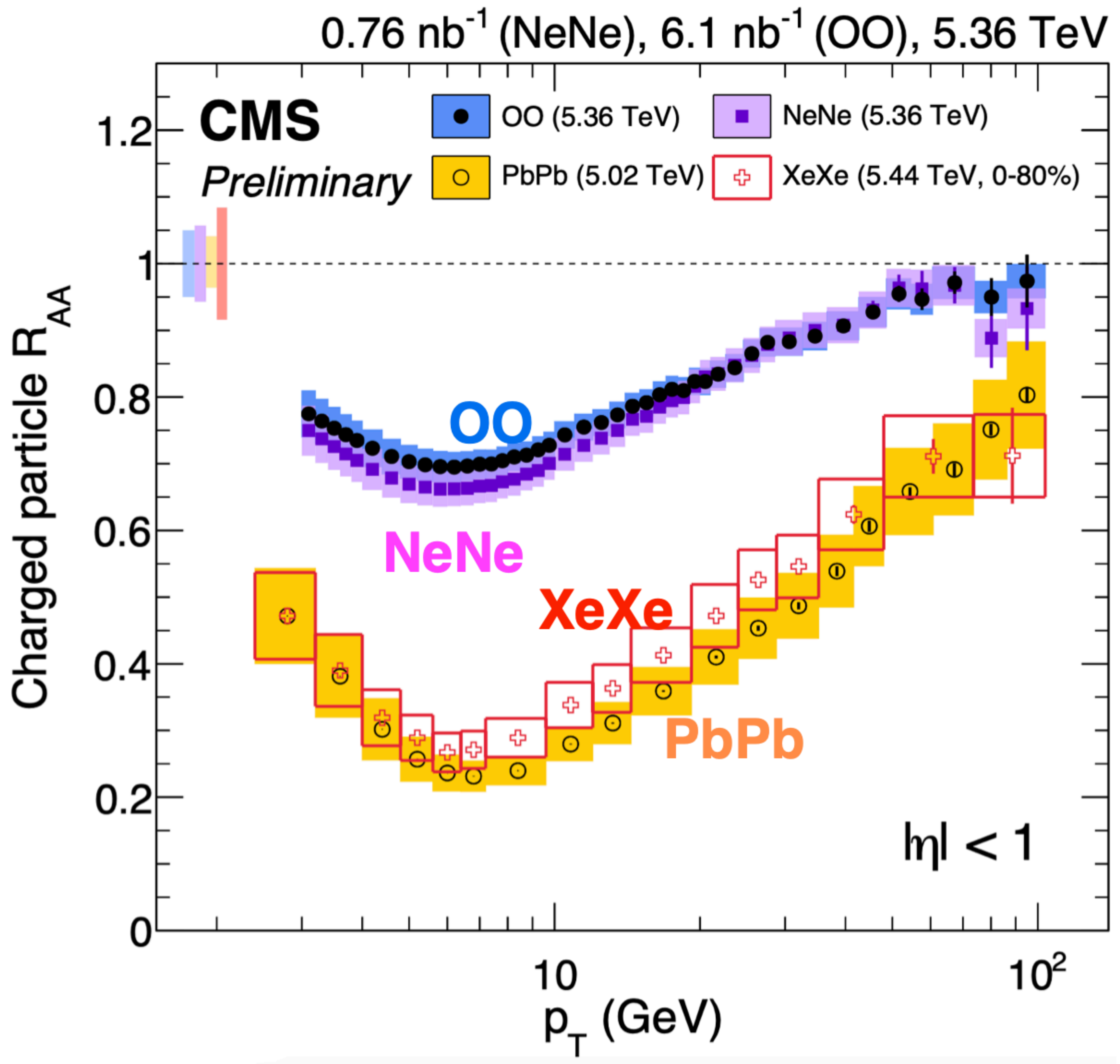
- Motivates study of small symmetric collision systems with better controlled geometry: **New O+O and Ne+Ne runs**



- 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

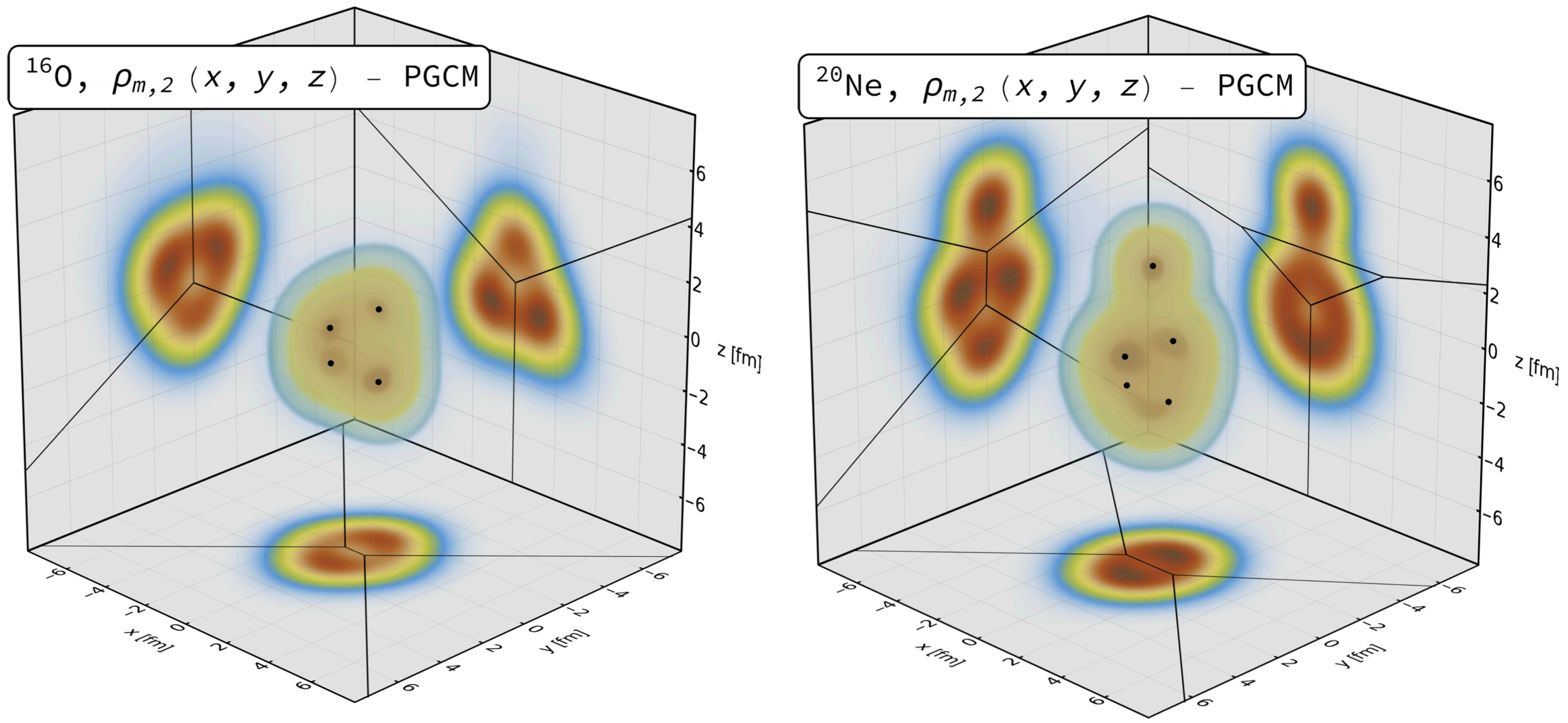
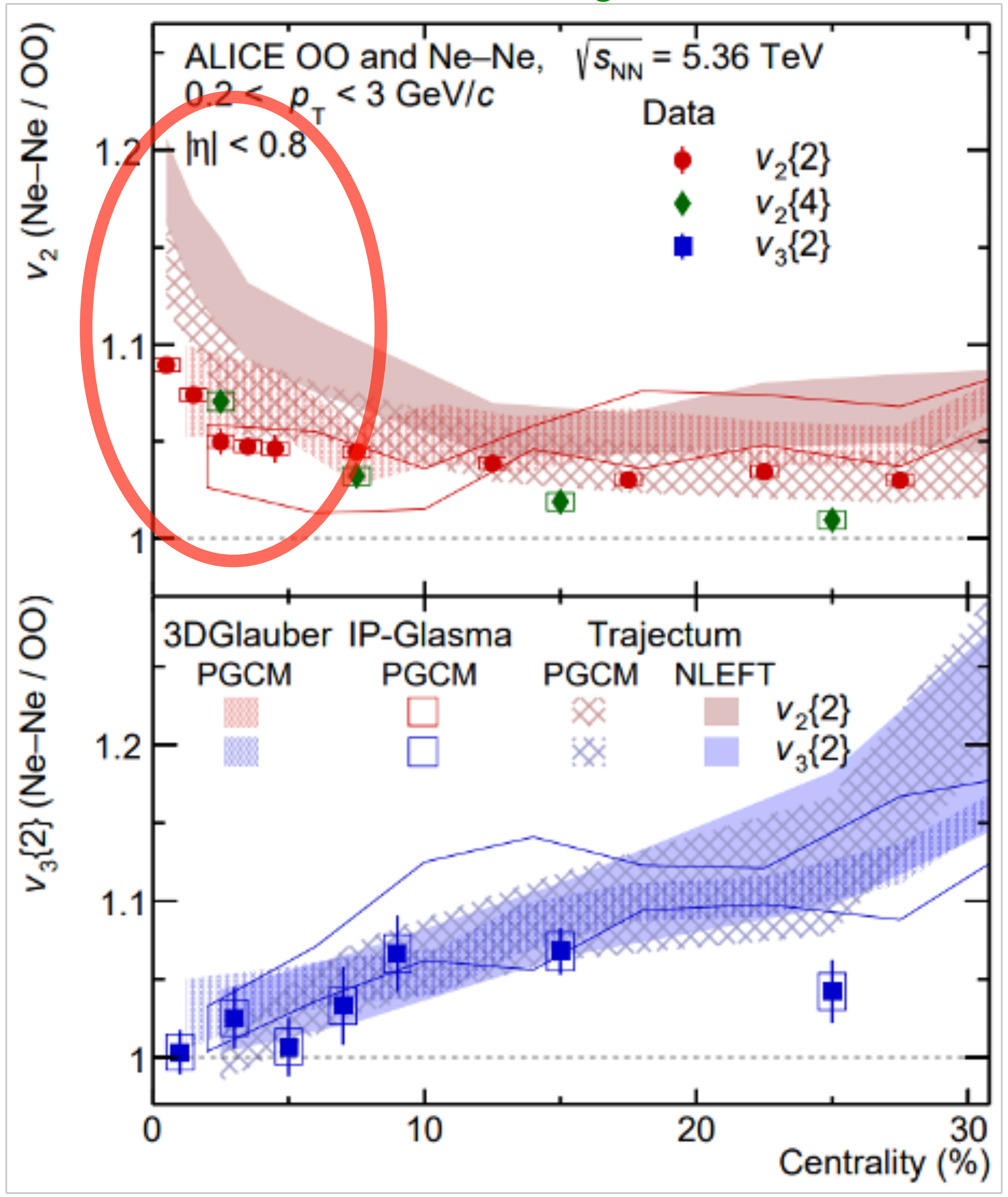


Figure. form G. Giacalone et al, Phys.Rev.Lett. 135 (2025) 1, 012302
using ab-initio Projected Generator Coordinate Method

New data from Initial Stages 2025 Conference



ALICE, CERN-EP-2025-203

- Predictions of the ratio of anisotropic flow in Ne+Ne/O+O agree rather well with the data

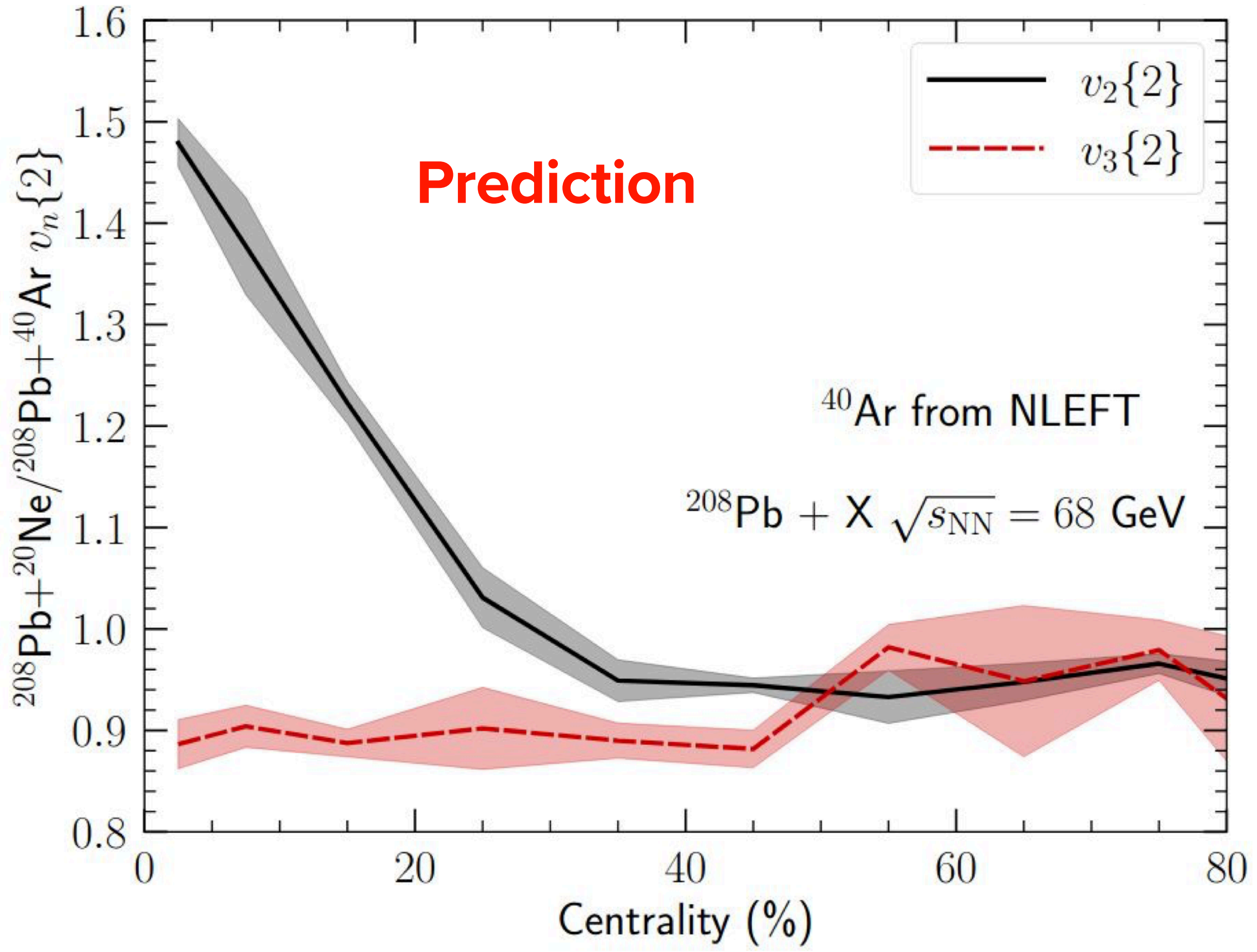
- More deformed shape of neon-20 nucleus shows effect in central collisions:
  More shape fluctuations lead to larger v_2

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)

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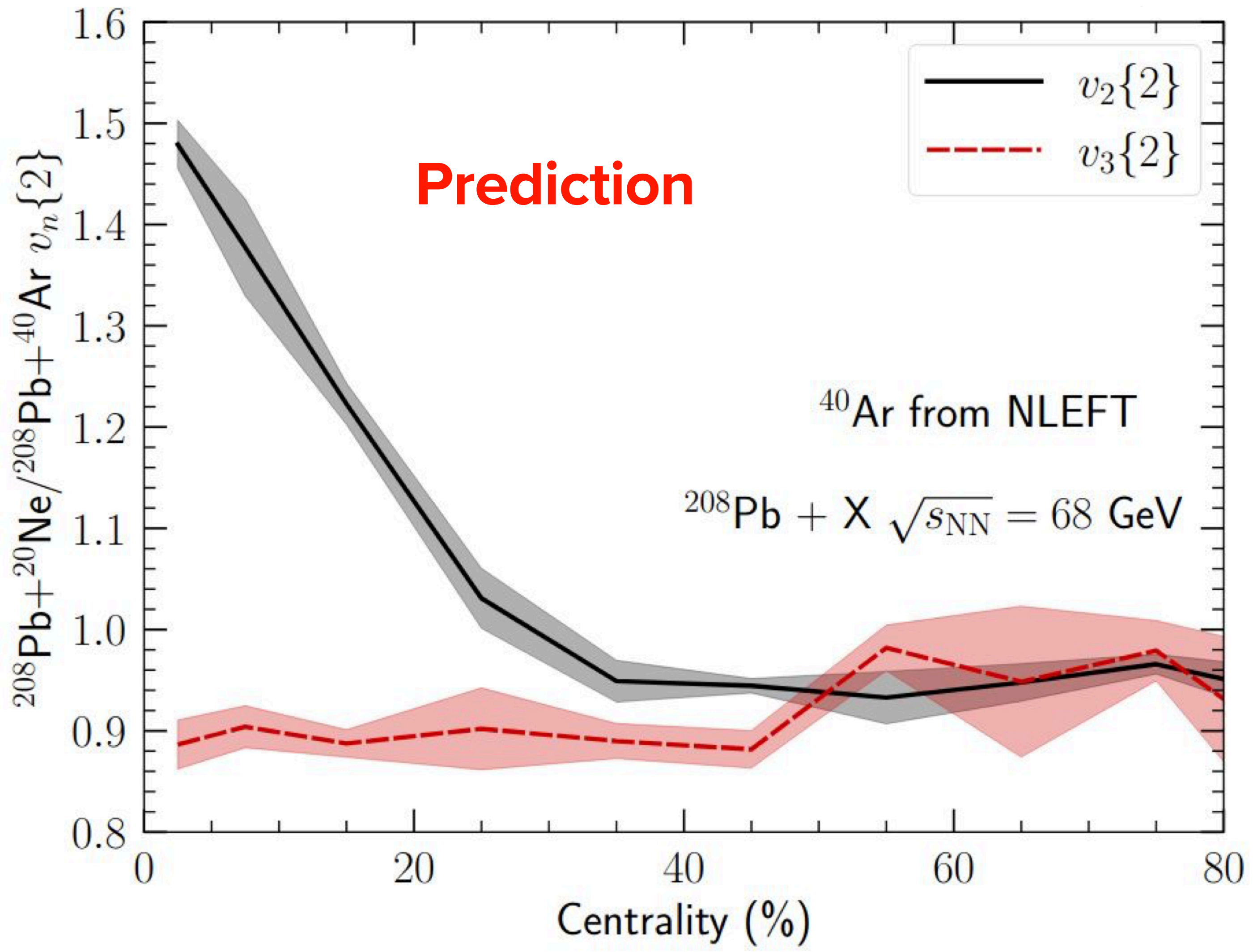

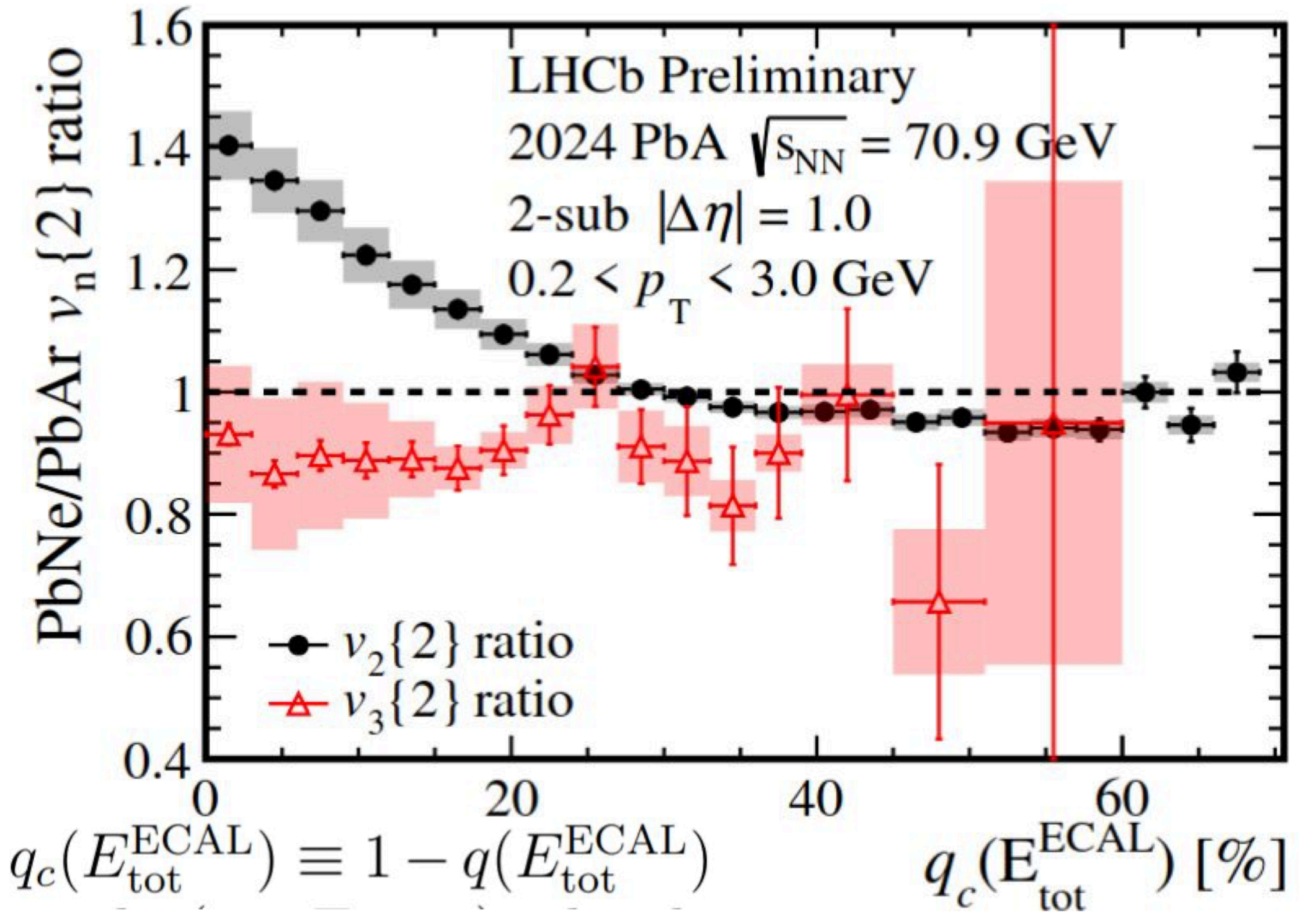

https://indico.cern.ch/event/1479384/contributions/6663093/attachments/3132588/5557527/IS25.pdf (SMOG2) LHCb-CONF-2025-001, in preparation

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

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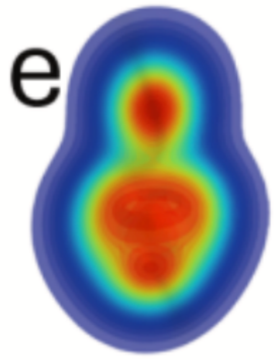
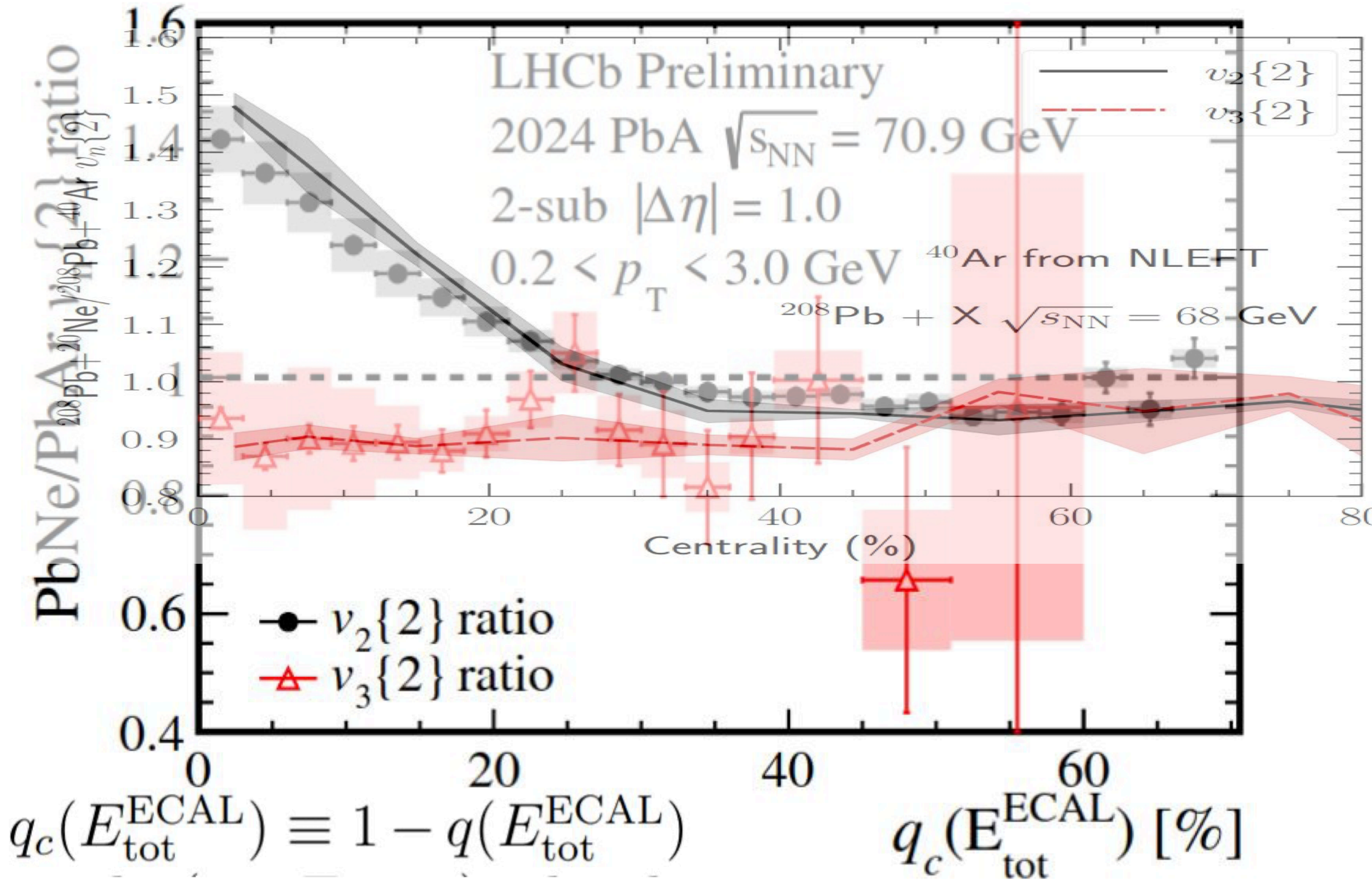
Initial overlap region of Pb nucleus
with Wile E. Coyote shaped nucleus

- 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





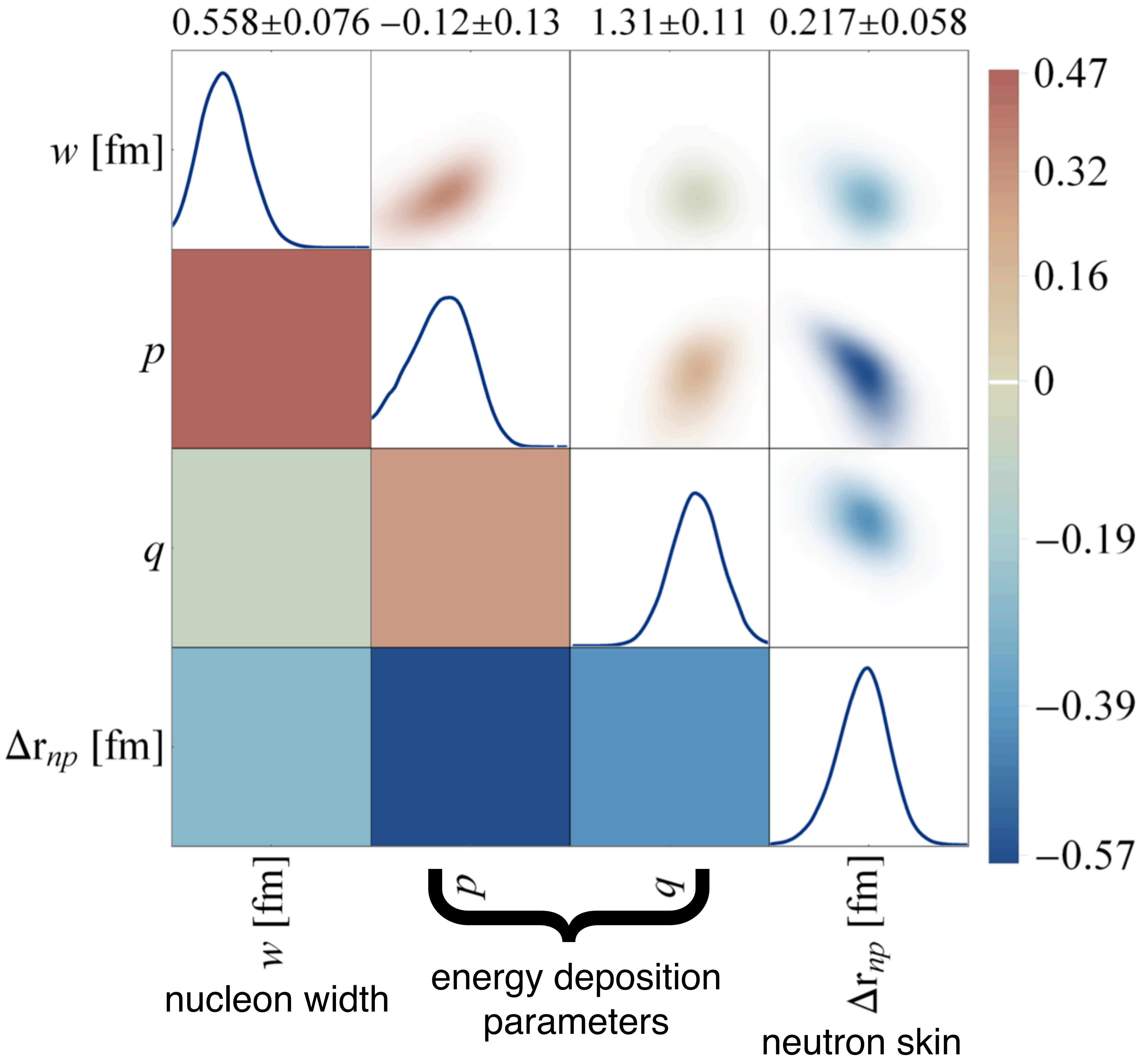
https://indico.cern.ch/event/1479384/contributions/6663093/attachments/3132588/5557527/IS25.pdf (SMOG2)
LHCb-CONF-2025-001, in preparation

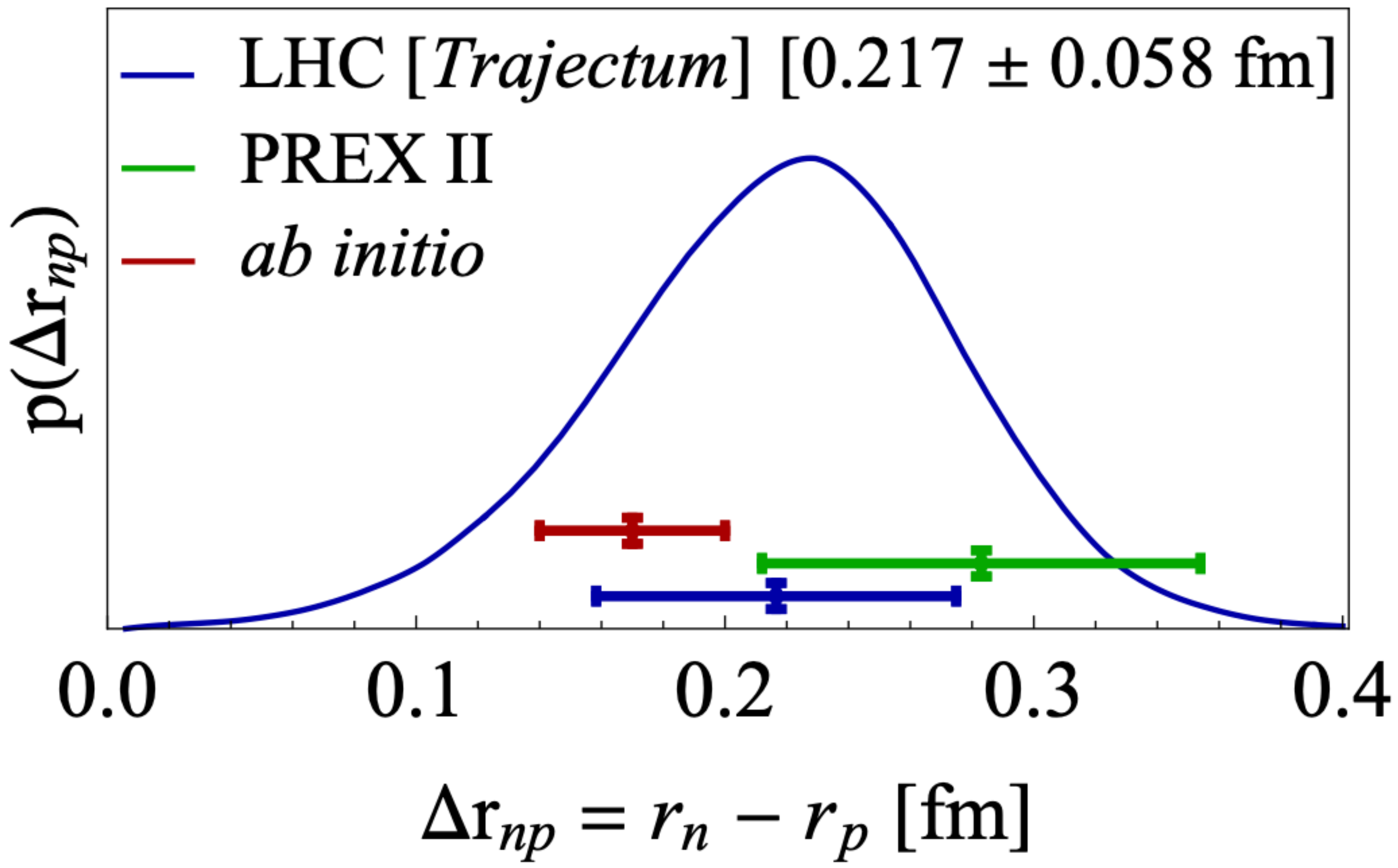
Prediction: Quark Matter 2025: https://indico.cern.ch/event/1334113/contributions/6289808/ (B. Schenke, C. Shen, H. Mäntysaari and W. Zhao)

NEUTRON SKIN

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

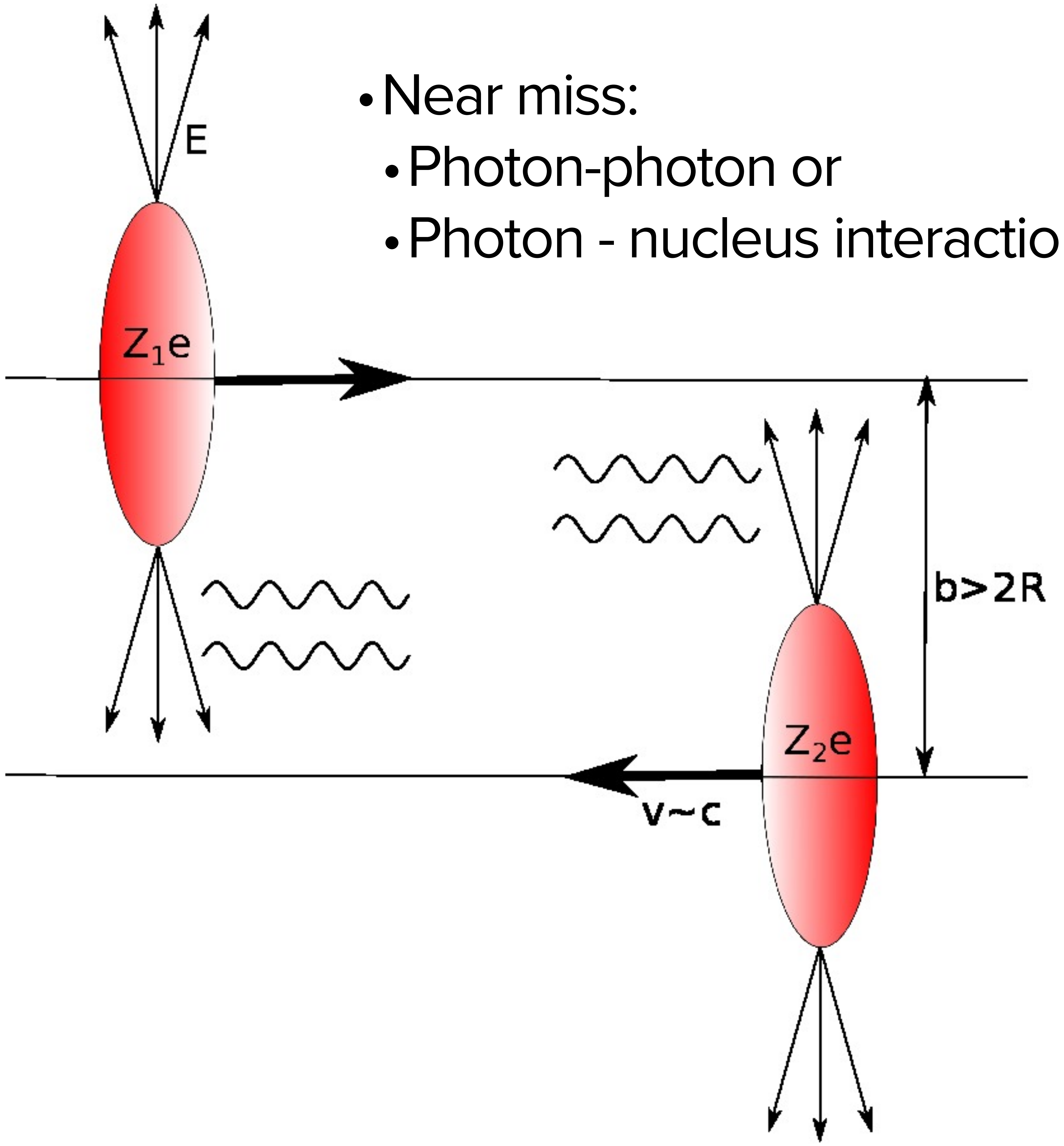
- Bayesian analysis of Pb+Pb data from LHC allows to extract the neutron skin
- Neutron skin affects diffuseness of the Pb nuclei, which affects centrality dependence of particle production and flow observables





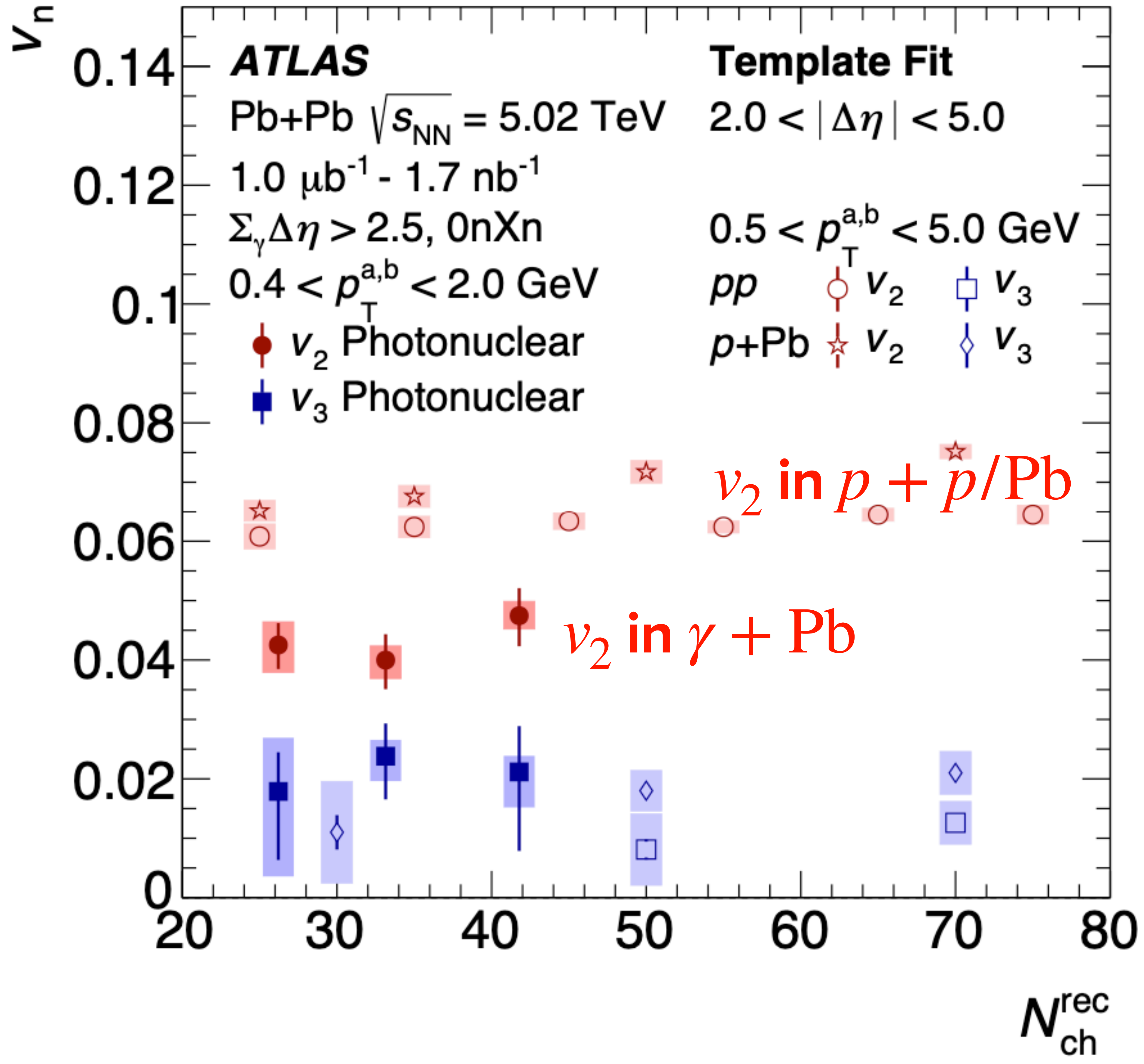
D. Adhikari et al. (PREX), Phys. Rev. Lett. 126, 172502 (2021)
B. Hu et al., Nature Phys. 18, 1196 (2022)

ULTRA-PERIPHERAL COLLISIONS



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

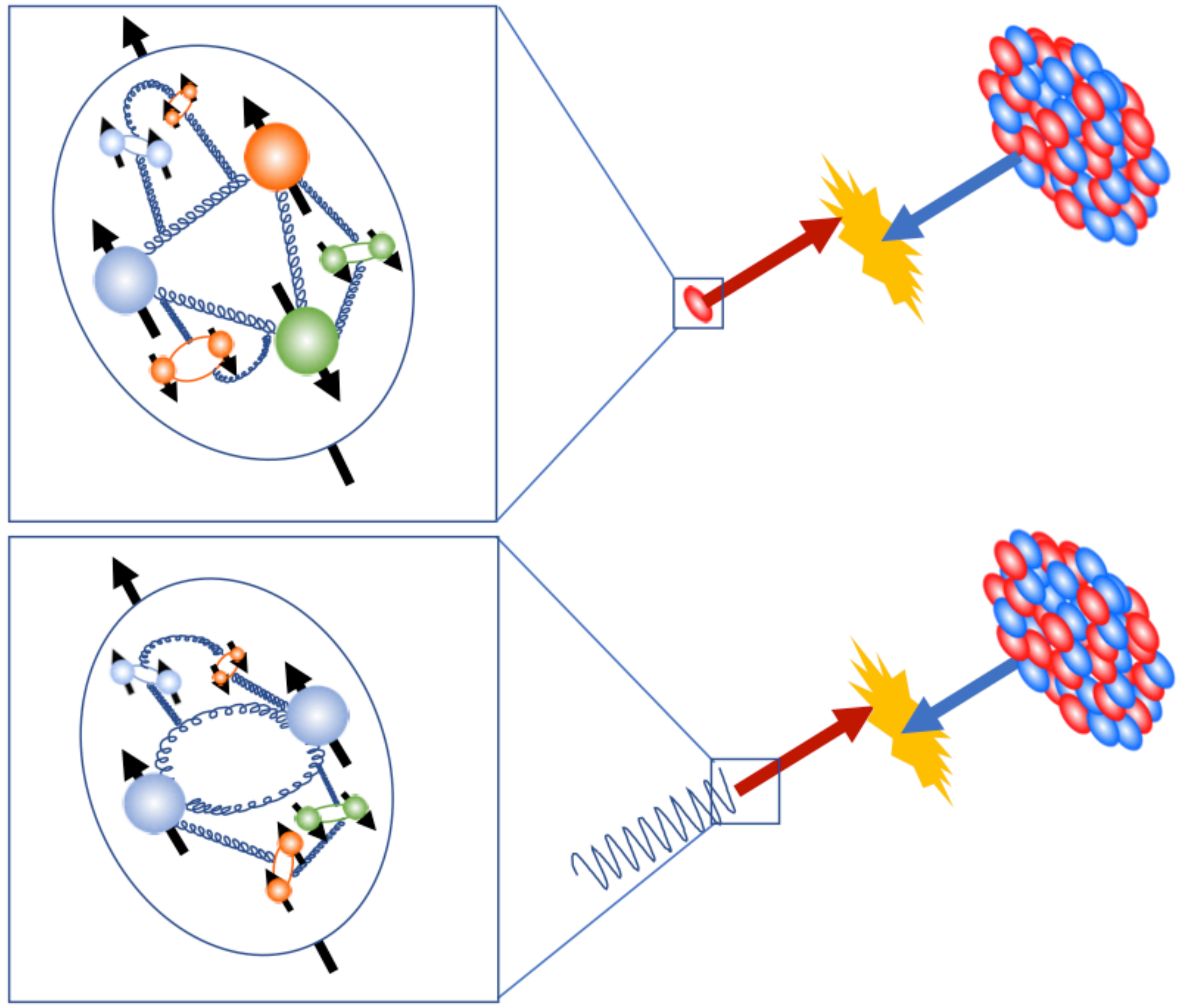
- Again: Collectivity when many particles are produced?



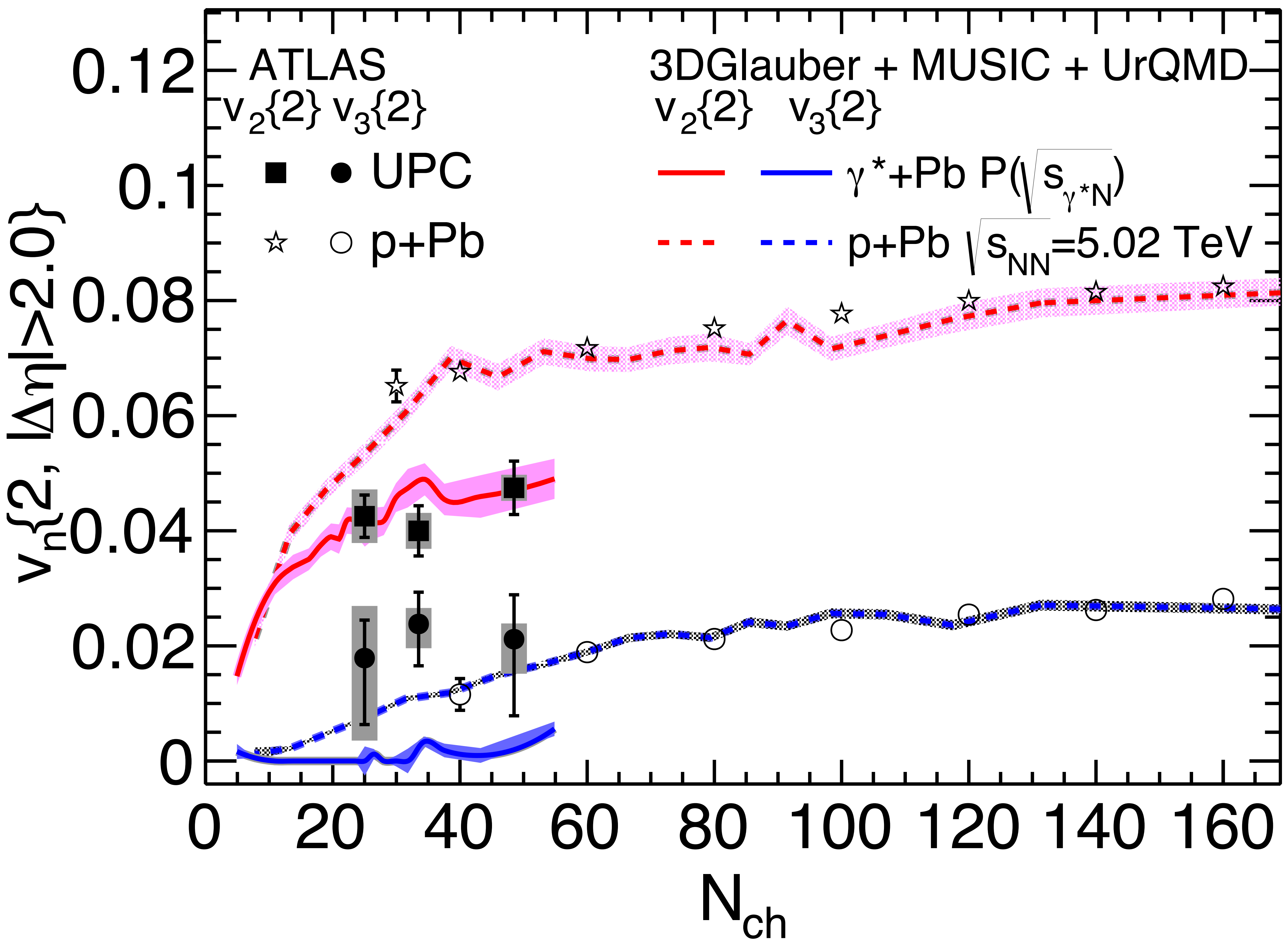
ATLAS Collaboration, Phys. Rev. C 104, 014903 (2021)

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

Experimental data: ATLAS Collaboration, Phys. Rev. C 104, 014903 (2021)
Alternative description without flow: Y. Shi, L. Wang, S. Y. Wei, B. W. Xiao and L. Zheng, Phys. Rev. D 103, 054017 (2021)

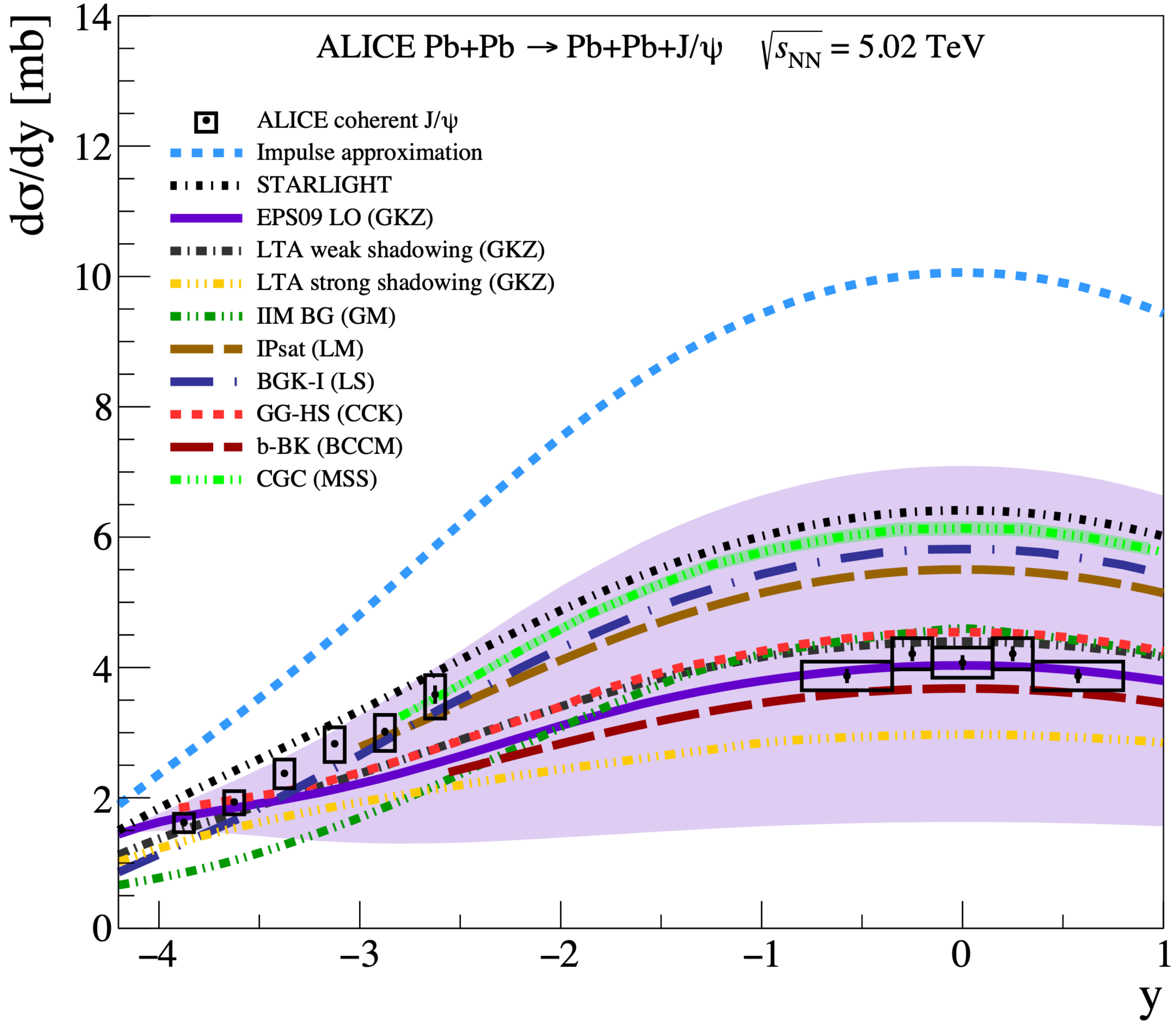
EXCLUSIVE PROCESSES: PREVIEW TO EIC

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 γ+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, ...



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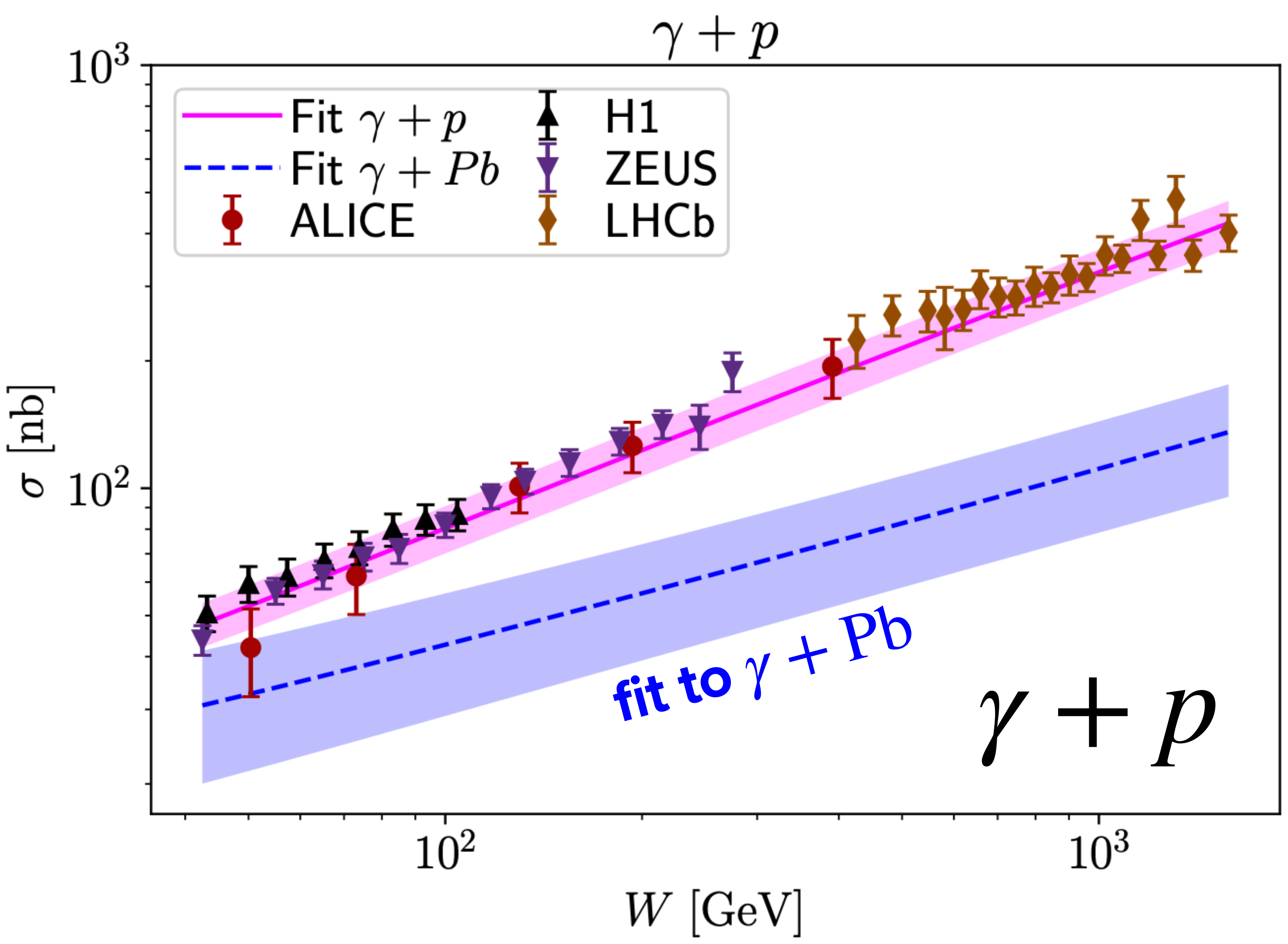
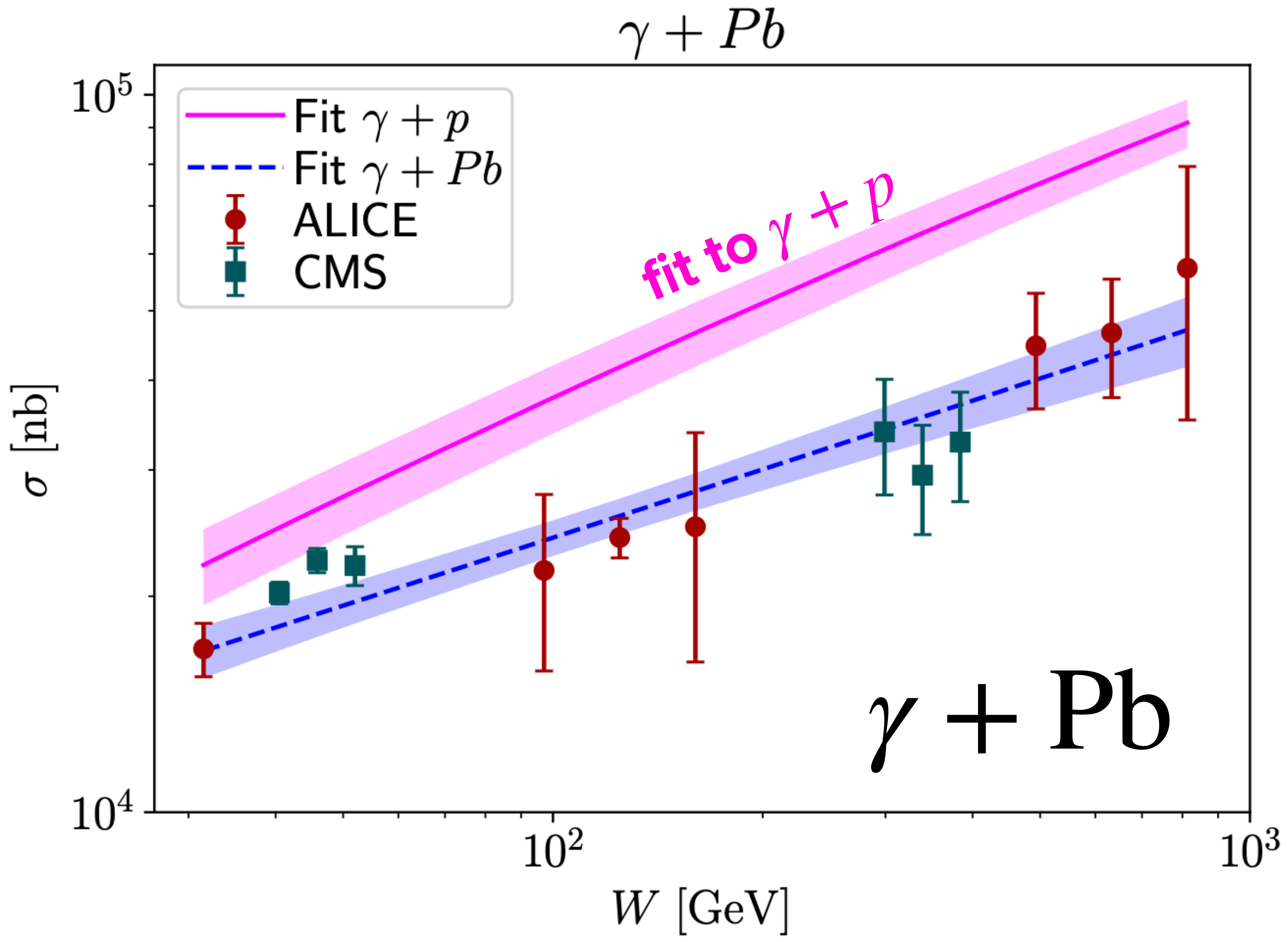
H. Mäntysaari, H. Roch, F. Salazar, B. Schenke, C. Shen, W. Zhao, e-Print: 2507.14087
Global Bayesian Analysis of J/ψ Photoproduction on Proton and Lead Targets

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





Bayesian analysis using Gaussian Process Emulator.

Simultaneous description of $\gamma + p$ and $\gamma + \mathrm{Pb}$ 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

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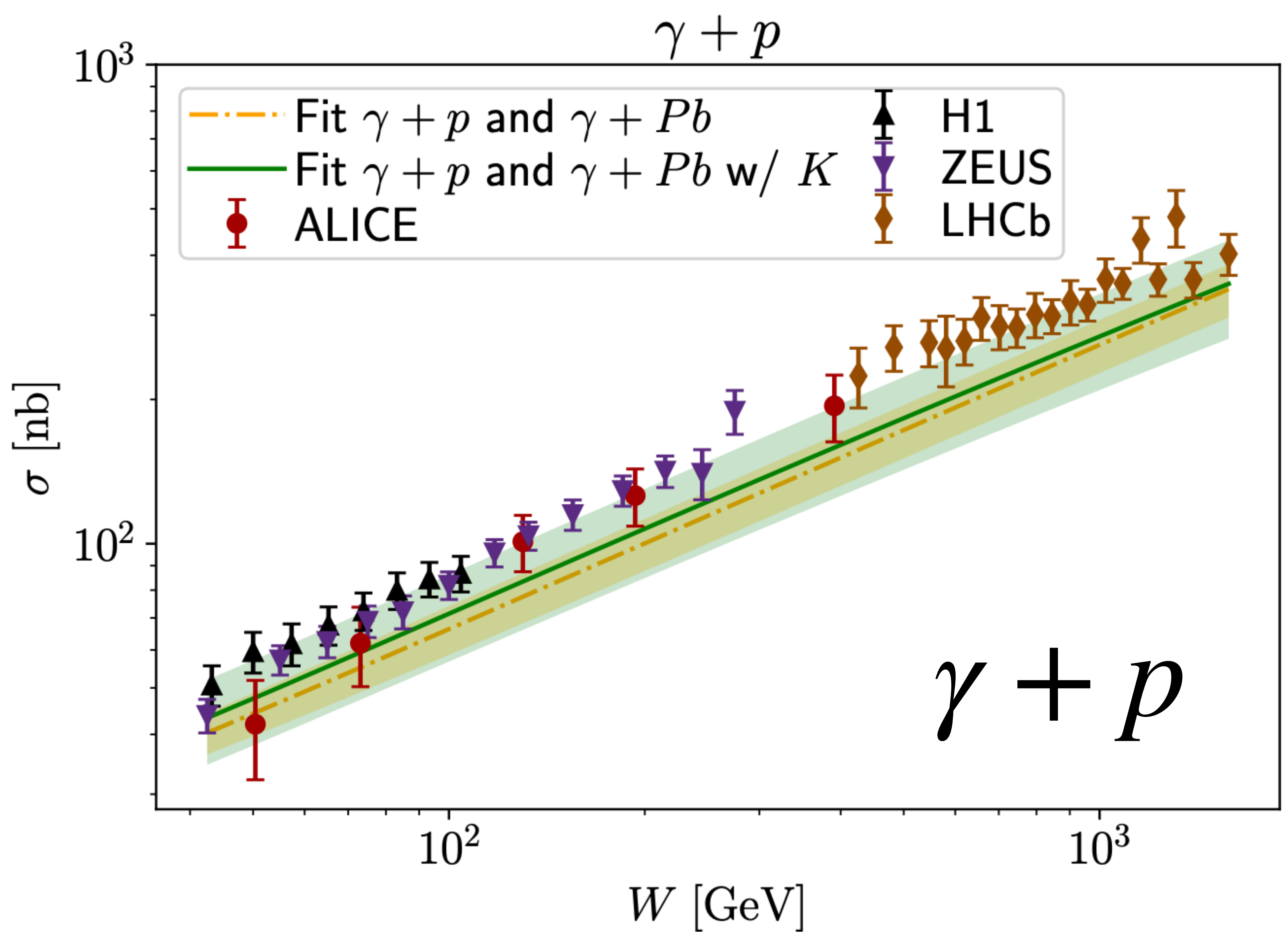

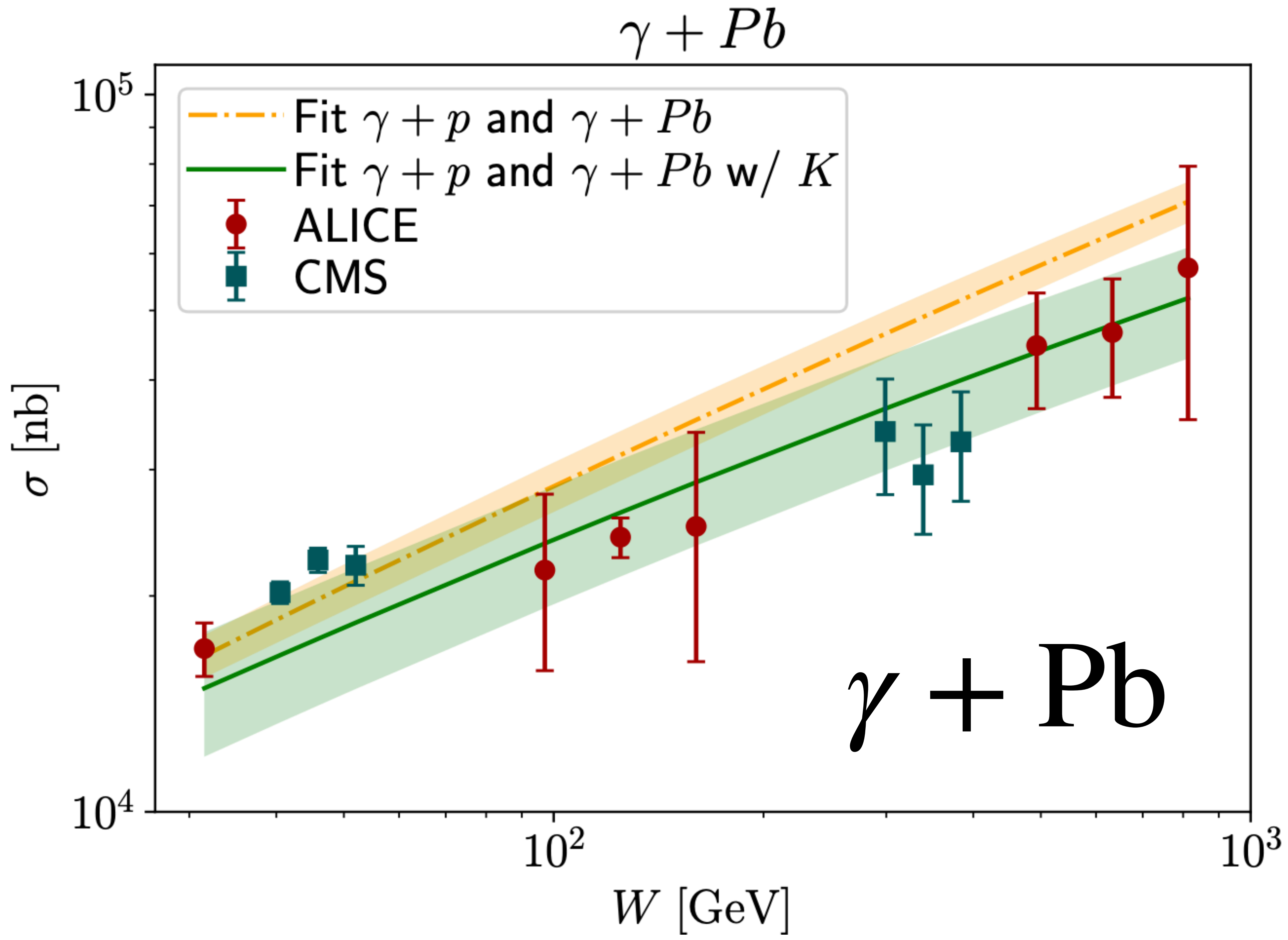

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