



The QGP as We Understand It

20 Years Later

Berndt Mueller (Duke Univ.)

RHIC Science Symposium

May 14, 2026

Brookhaven National Laboratory

“What is the QGP made of ?”

2506.07181 [nucl-th]

QGP - April 18, 2005: Day 1

RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted – raising many new questions

April 18, 2005

TAMPA, FL – The four detector groups conducting research at the [Relativistic Heavy Ion Collider](#) (RHIC) – a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory – say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"This is fluid motion that is nearly 'perfect,'" Aronson said, meaning it can be explained by equations of hydrodynamics.

"The finding of a nearly perfect liquid in a laboratory experiment recreating the conditions believed to have existed a few microseconds after the birth of the universe is truly astonishing," said Praveen Chaudhari, Director of Brookhaven Lab.

What do we know
And how do we know it?

QGP: What we “knew” all along

Understood before RHIC:

- ★ Color degrees of freedom of quarks and gluons contribute to thermodynamics:
Degeneracies: $d(\text{quarks}) = 3$, $d(\text{gluons}) = 8 \longrightarrow P$ and ε rise rapidly with T
- ★ Thermal gluons enhance scattering and reaction rates (strange quarks, jets)
- ★ Color force between quarks is screened by thermal gluons: no quark bound states
- ★ Dynamical quark mass ($300 \text{ MeV} \approx \frac{1}{3} M_{\text{nucleon}}$) disappears, only Higgs mass remains

Initially overlooked (but could have been “known”):

- ★ QGP is strongly coupled \longrightarrow superb fluid properties (low kinematic shear viscosity)

Probes of the QGP

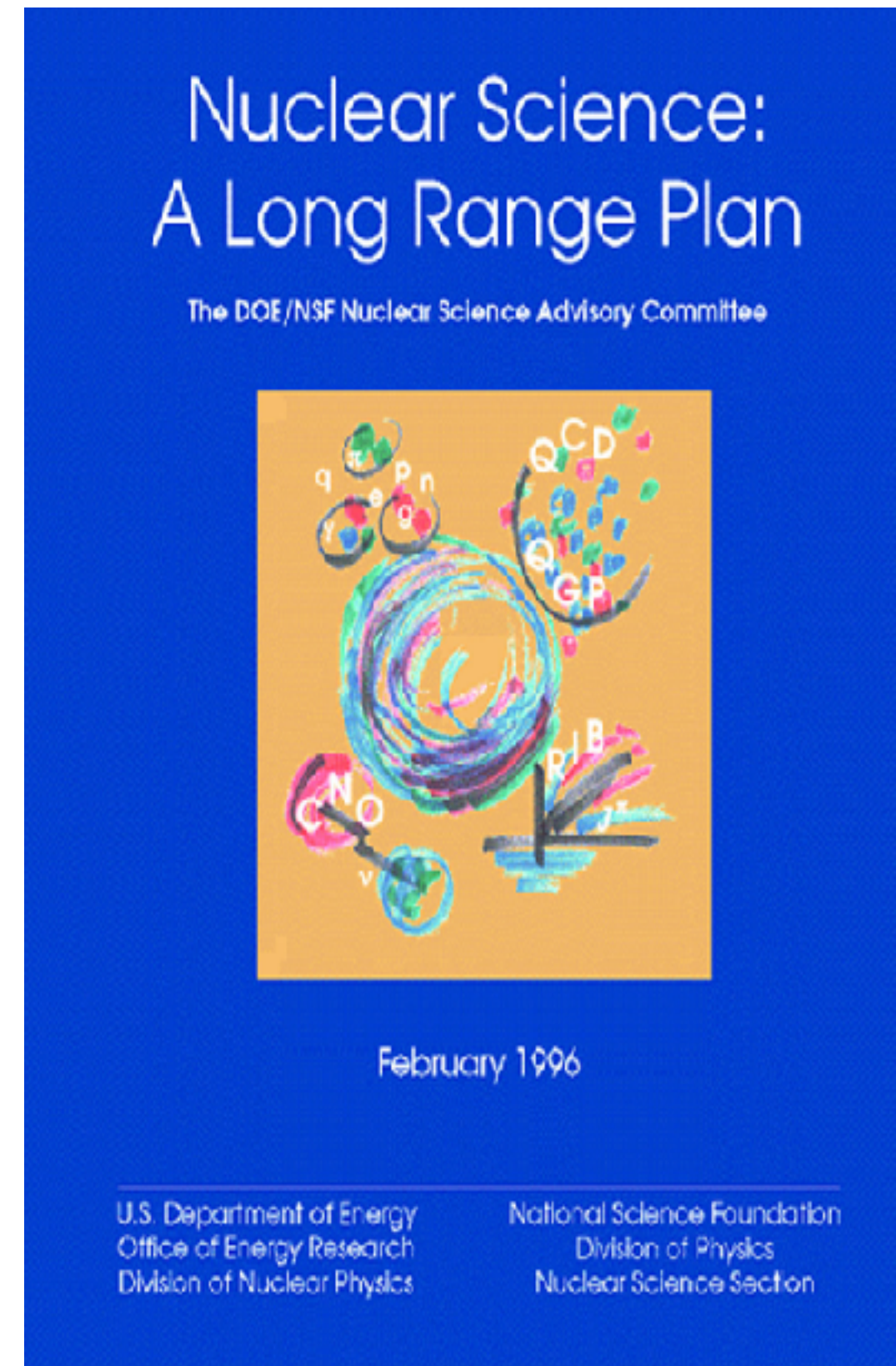
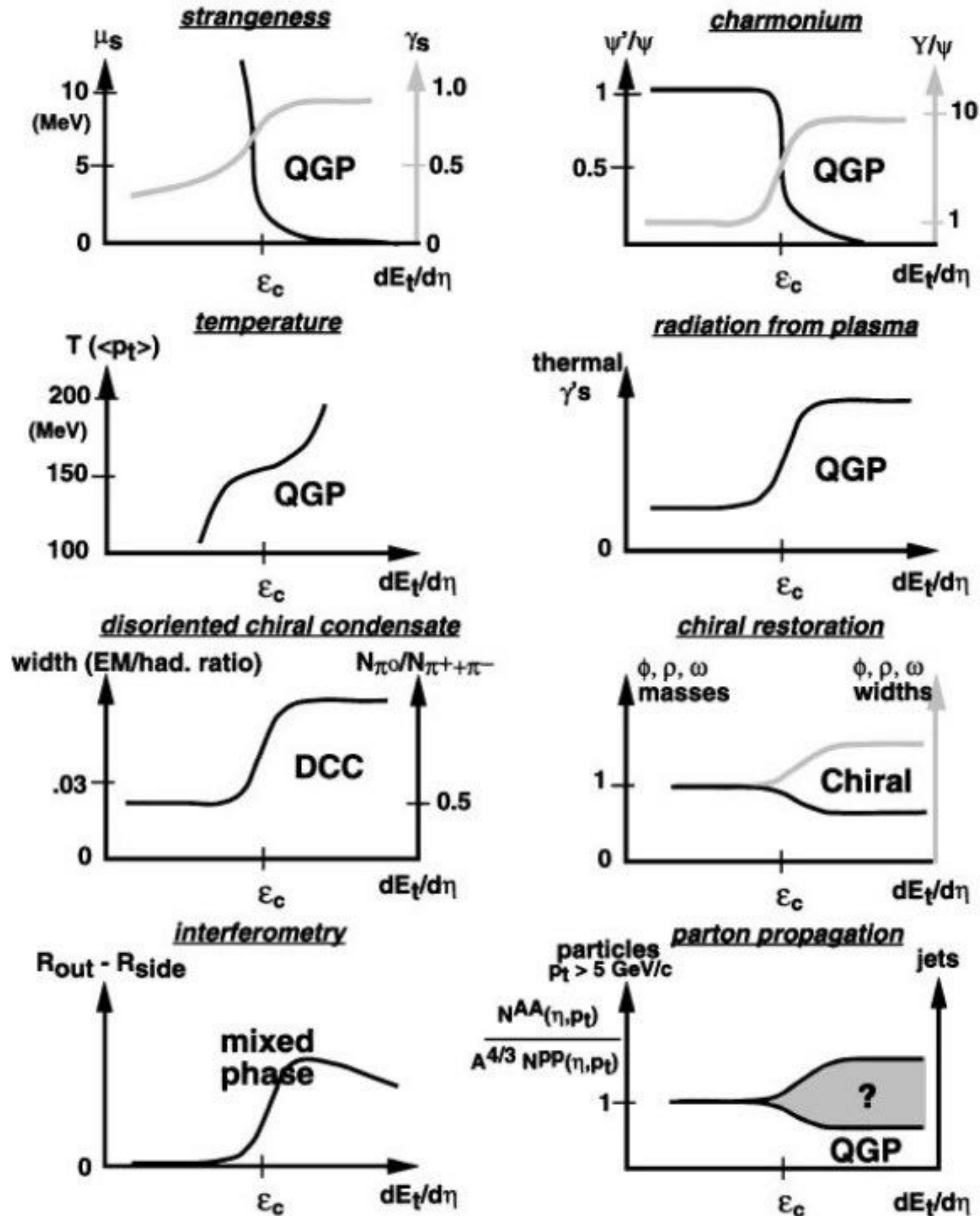
Scientific studies require probes!

- ★ Strange quarks: Mass drops from ~ 500 MeV to ~ 100 MeV — more easily produced
- ★ Quarks coalesce into hadrons at universal temperature T_c
- ★ Heavy quarks (c and b) cannot form bound states inside the QGP
- ★ Entropy density (also energy density and pressure) reflect liberated quarks/gluons
- ★ Enhanced scattering rates for energetic quarks (energy loss / jet quenching)

Unexpected but very important:

- ★ Low viscosity: Large, undamped collective flow and sound propagation

SIGNATURES



THE SEARCH FOR THE QUARK- GLUON PLASMA

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KEY WORDS: QCD, deconfinement, chiral symmetry restoration, high density nuclear matter, relativistic heavy ion collisions, AGS, SPS, RHIC, LHC, quark matter, phase transitions

Abstract

We provide an overview of the present understanding of the transition from hadrons to a quark-gluon plasma, its signatures, and the experimental results so far. We discuss results of numerical simulations of the lattice gauge theory and critically evaluate the various observables that have been proposed as signatures of the QCD phase transition. We place the existing data from relativistic heavy ion experiments at the Brookhaven AGS and CERN SPS into perspective and provide an overview of the techniques and strategies that will be employed in the search for the quark-gluon plasma at heavy ion colliders, such as RHIC and the LHC.

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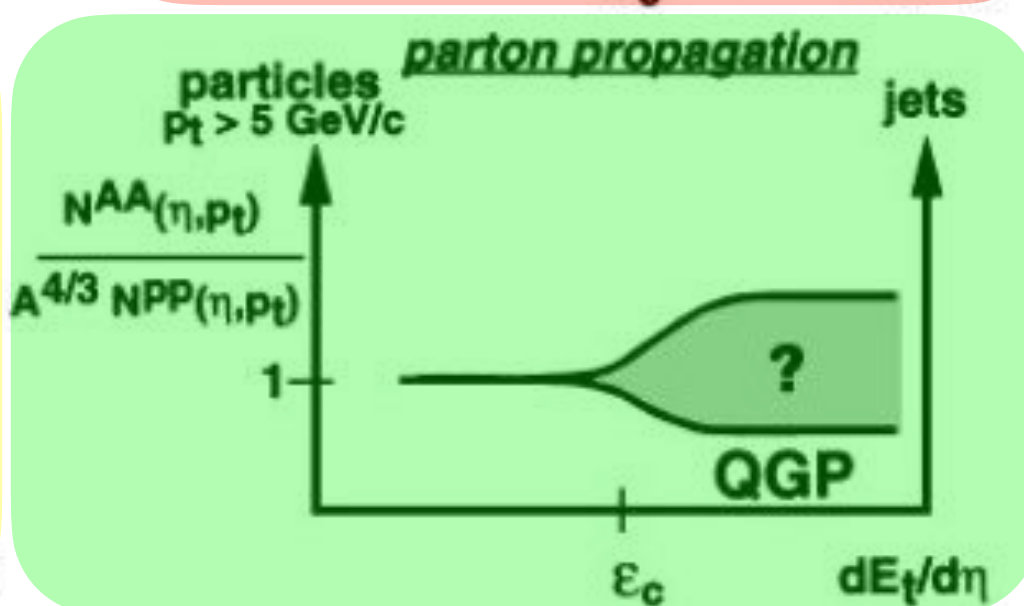
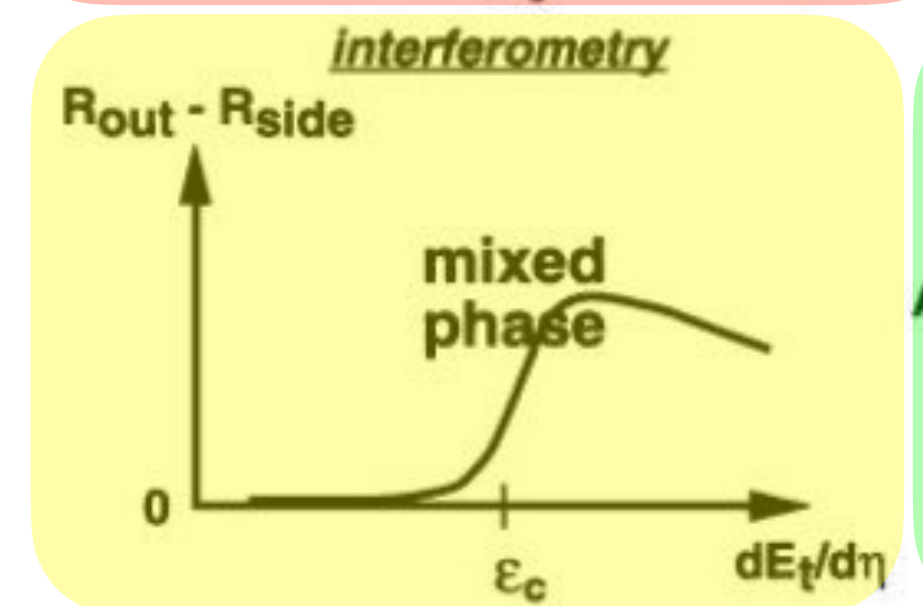
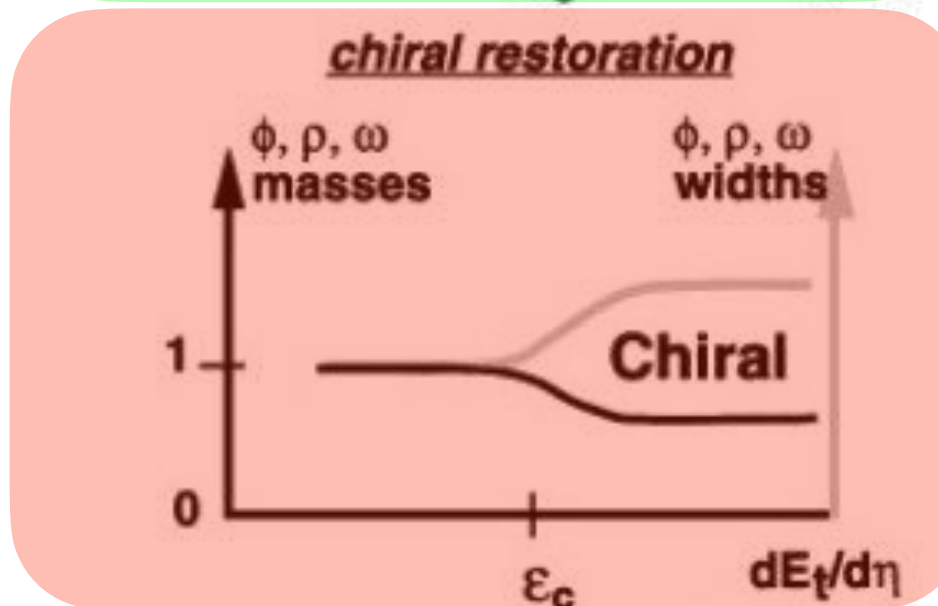
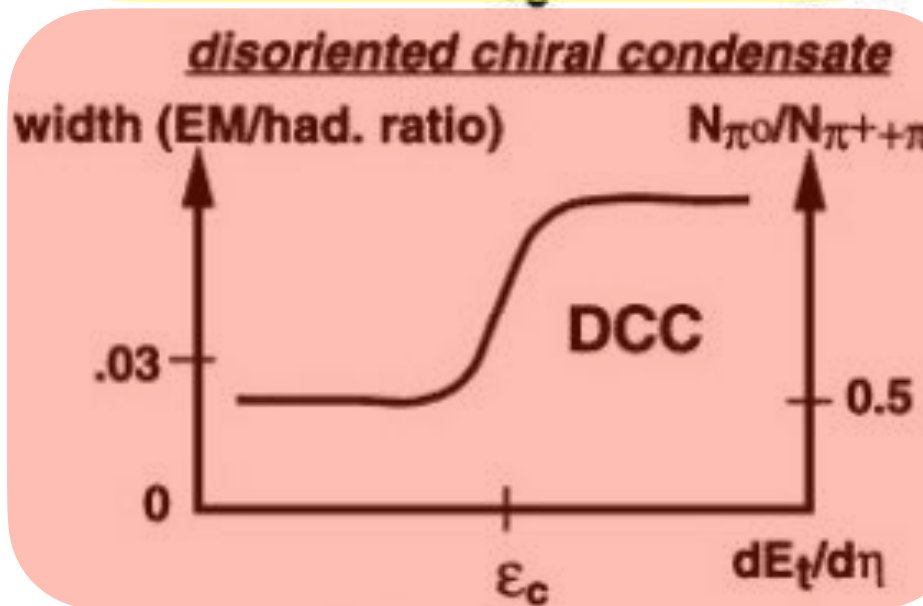
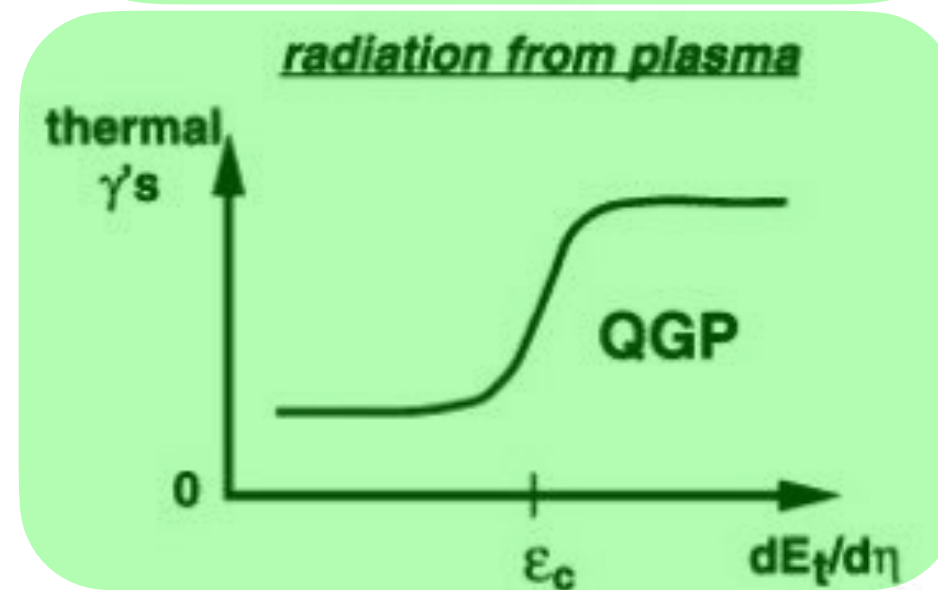
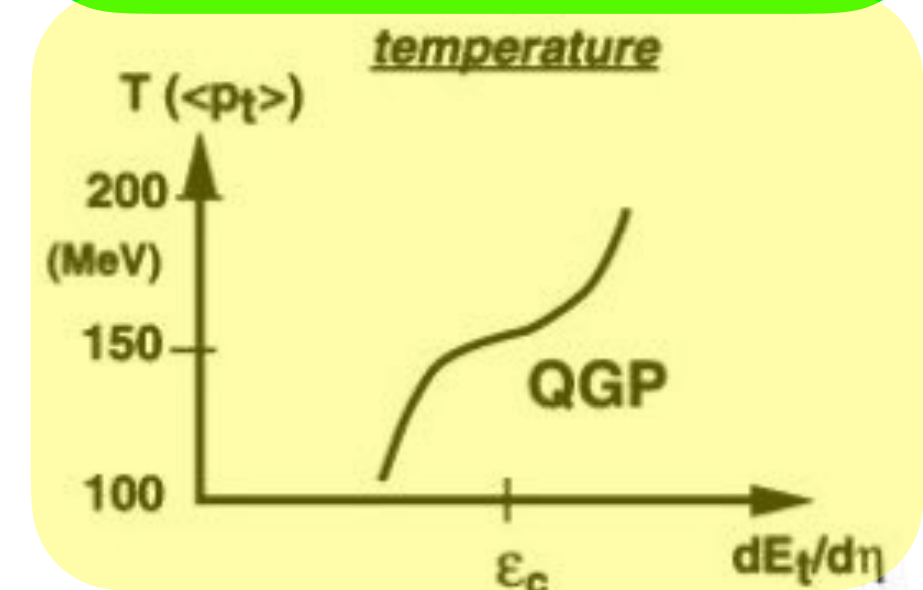
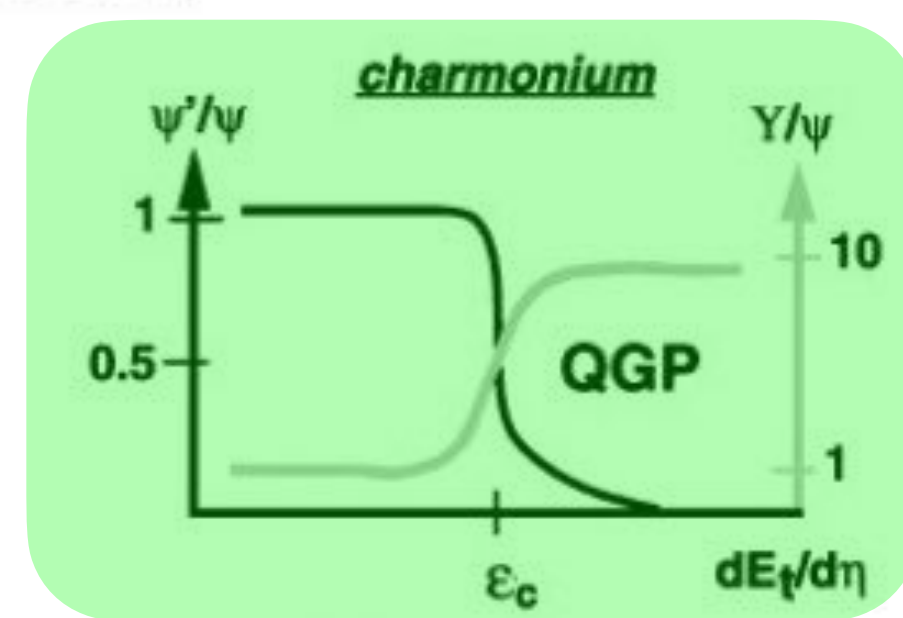
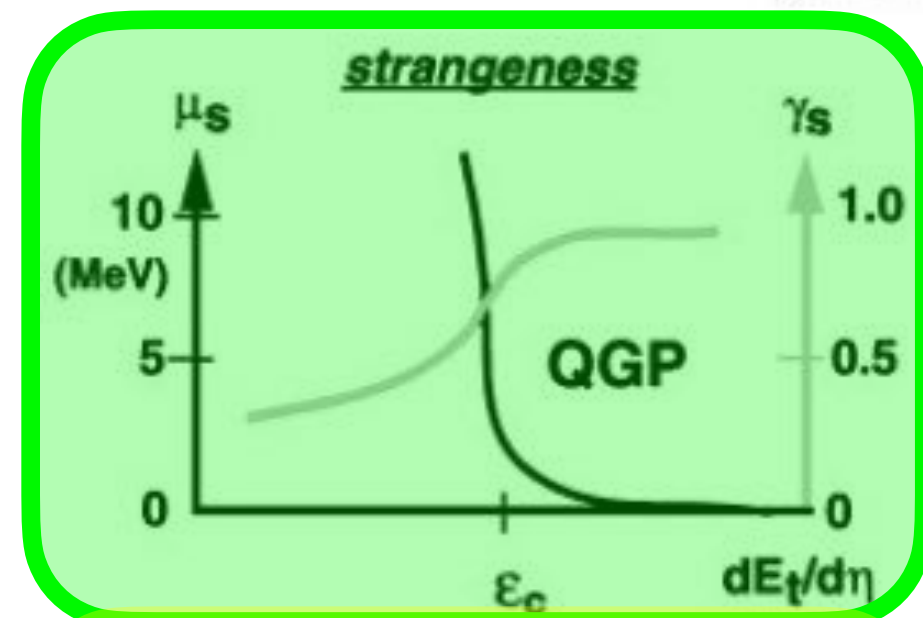
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J.W. Harris and B. Müller,
 Annu. Rev. Nucl. Part. Sci. 46 (1996) 71
 arXiv:hep-ph/9602235

Recent Update:

“QGP Signatures Revisited”
 Eur. Phys. J. C 84 (2024) 247
 arXiv:2308.05743 [hep-ph]

SIGNATURES



- Delivered on expectations
- Brought useful insights
- Failed to deliver

Collective flow

Quark coalescence

Jet quenching

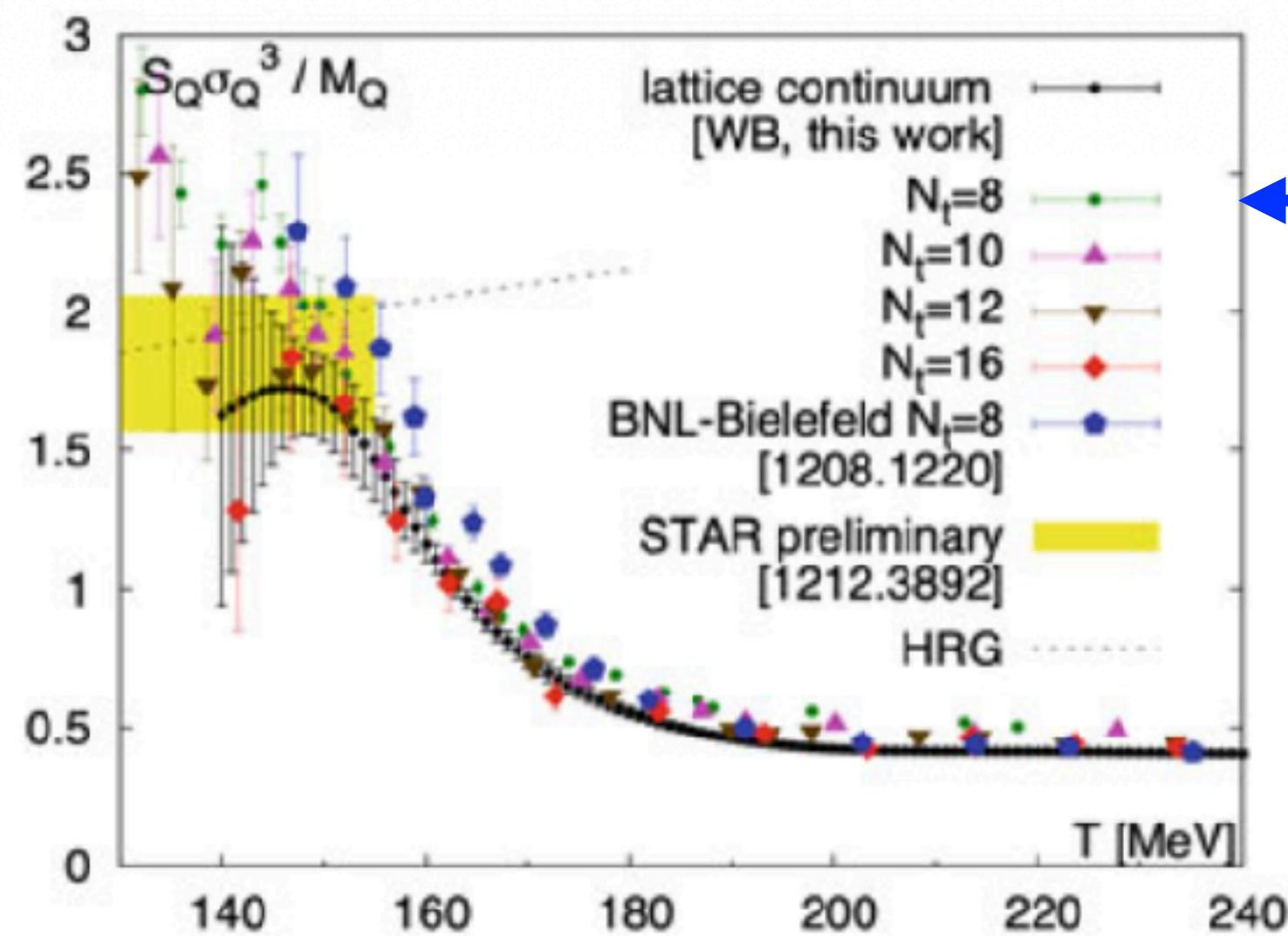
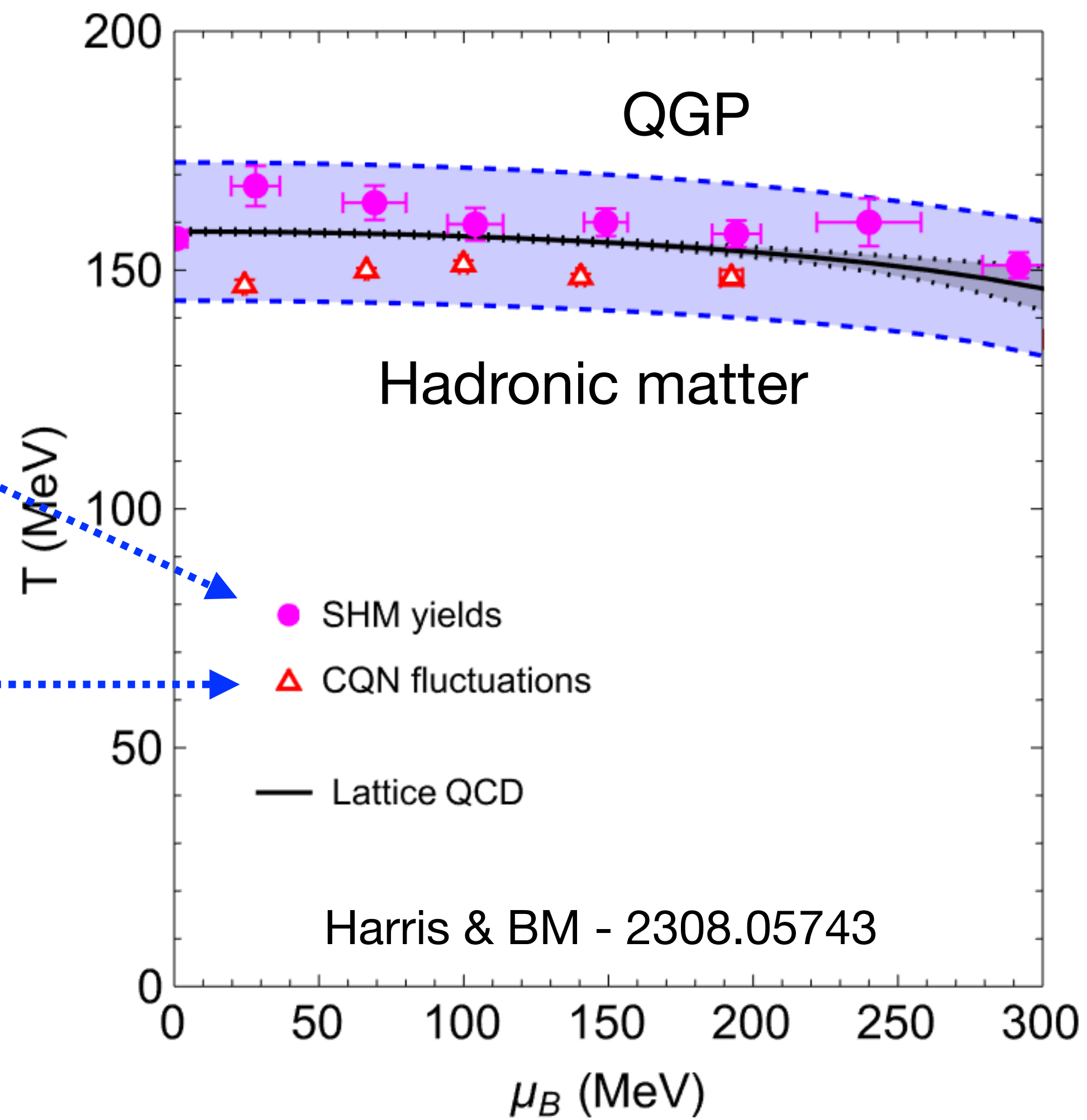
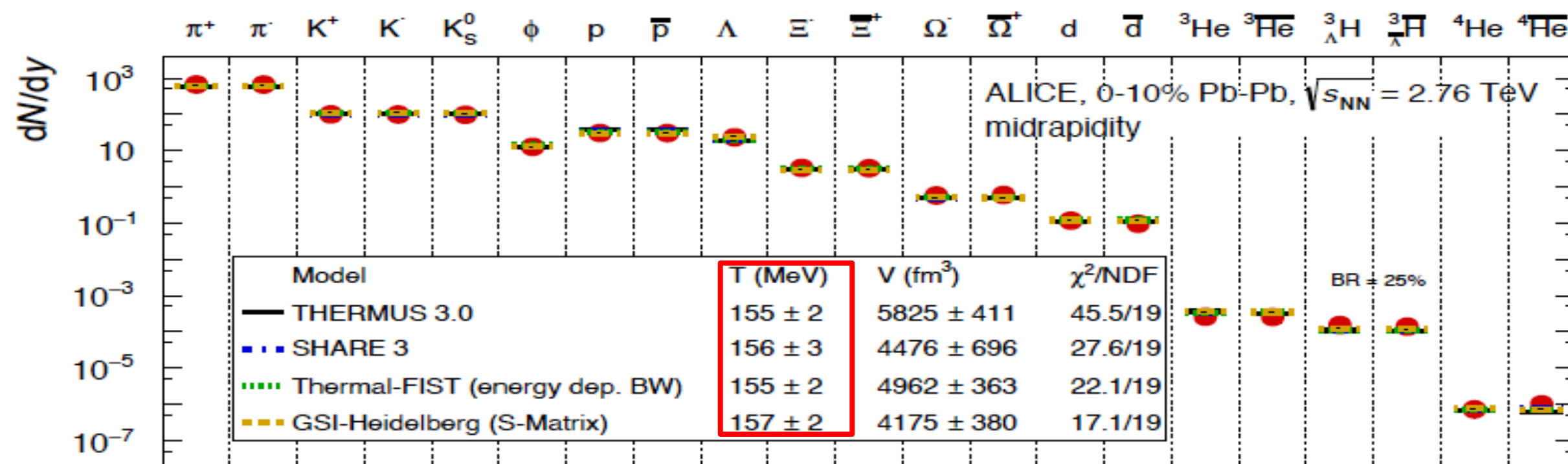
QGP vorticity

What we know today

- QGP equation of state consistent with lattice QCD calculations ($T_c = 155 - 160$ MeV)
- Collective flow of expanding QGP is carried by individual quarks (N_Q scaling)
- QGP contains thermally excited gluons (flavor equilibration)
 - **The QGP is really a quark-gluon plasma!**
- QGP has exceptionally low kinematic shear viscosity (“perfect fluid”)
- QGP sustains long-lived vorticity
- QGP has large stopping power for partons
 - **The QGP is a strongly coupled relativistic plasma**
- *Open question: Which mechanism creates a liquid without short-range repulsion?*
- *Open question: How small can a QGP be? How does it thermalize?*
- *Open question: Is there a critical point in the QCD phase diagram?*

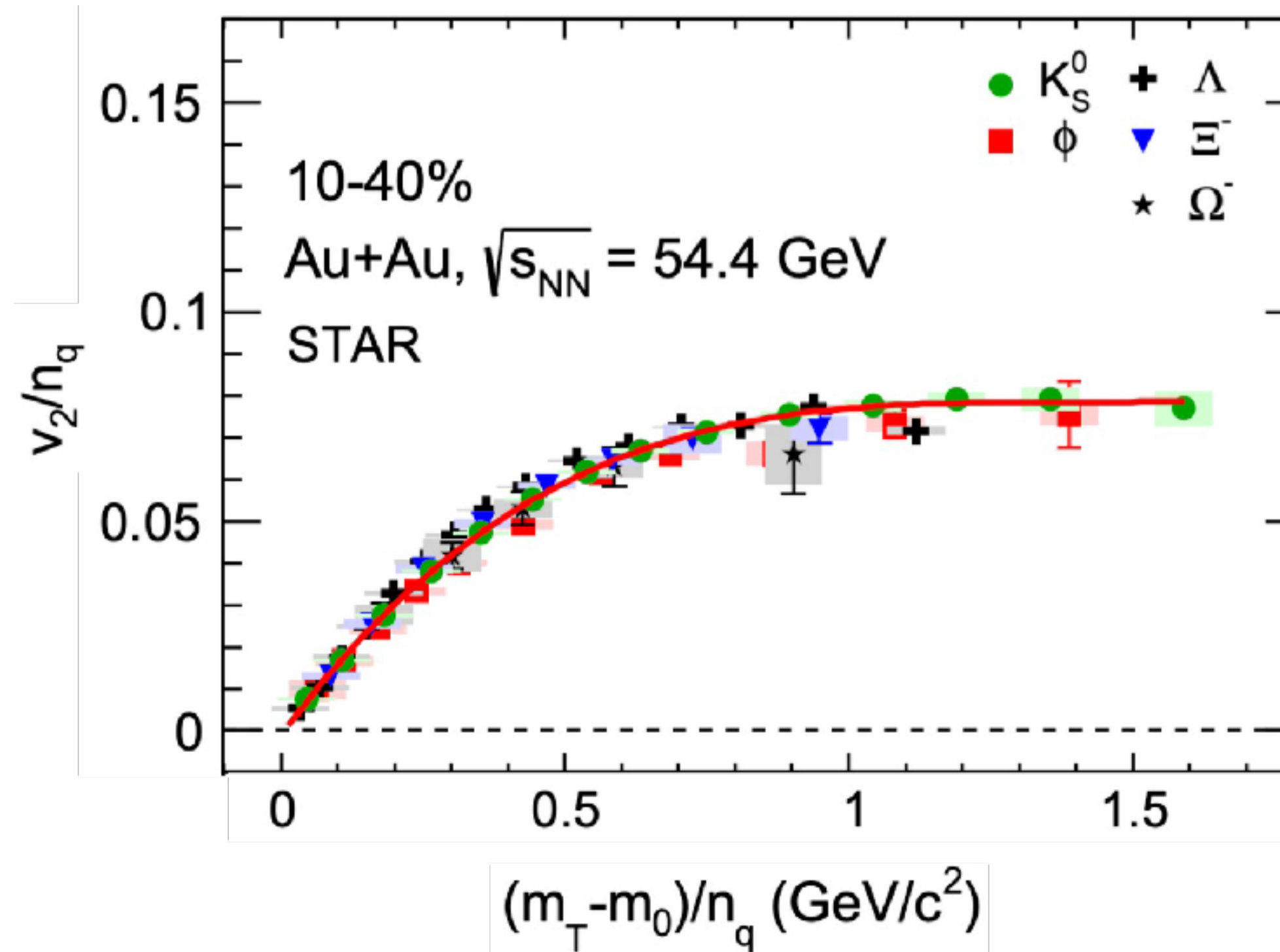
QGP Phase boundary: $T_c(\mu_B)$

Discovered at RHIC



Valence quark coalescence

Discovered at RHIC



Collective flow components v_n of different hadrons scale with valence quark number:

$$n_q = 2 \text{ (mesons)} \quad n_q = 3 \text{ (baryons)}$$

$$v_n^{\text{quark}}(m_T) = \frac{1}{n_q} v_n^{\text{hadron}}(m_T/n_q)$$

→ All hadrons emerge from a common fluid made of collectively flowing quarks (and gluons)

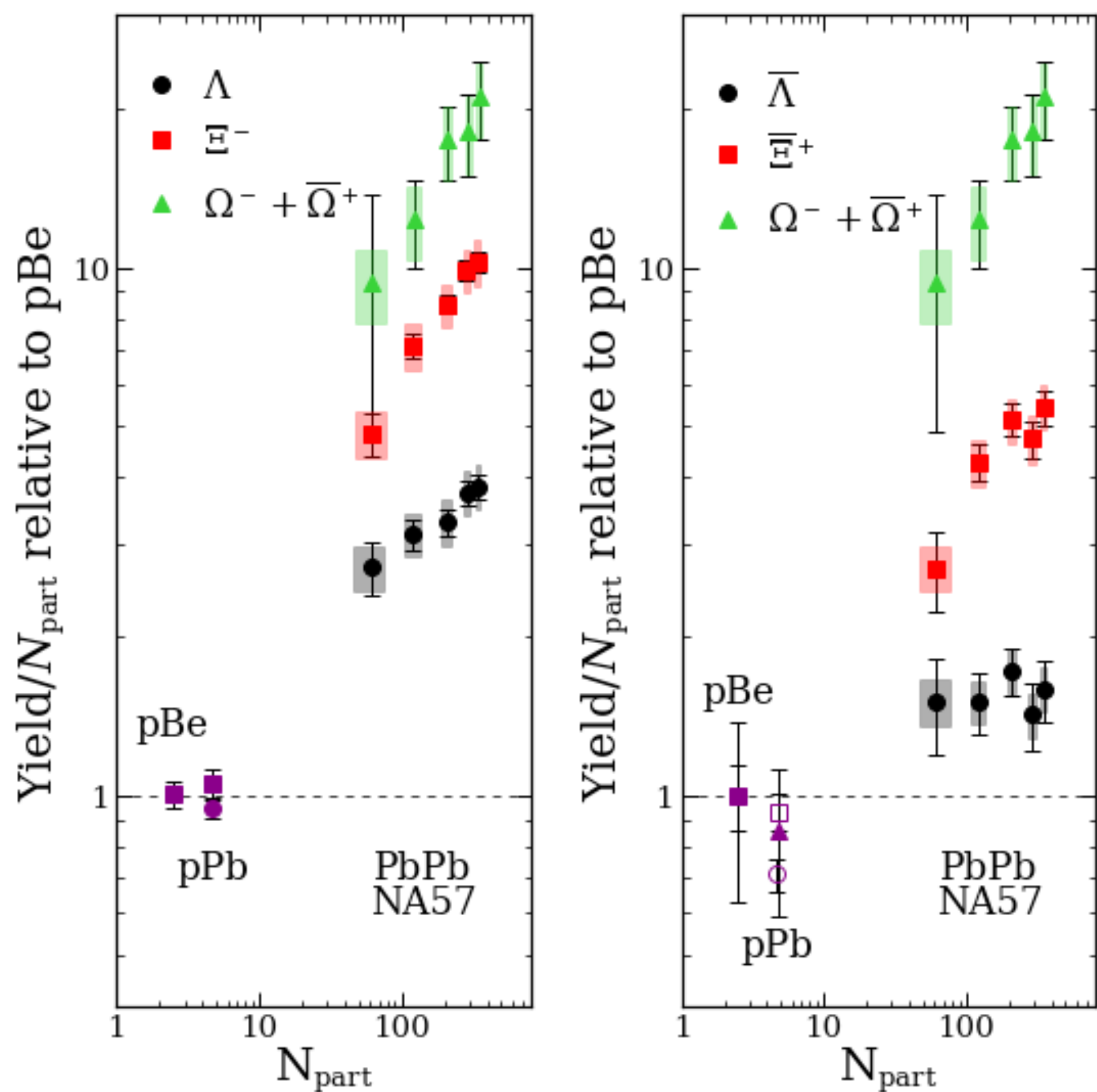
Scaling law has been used to determine whether certain excited hadron states are standard $(q\bar{q})$ states or exotic tetra quark-states $(qq\bar{q}\bar{q})$.

Multi-strange Baryon Enhancement

Confirmed at RHIC

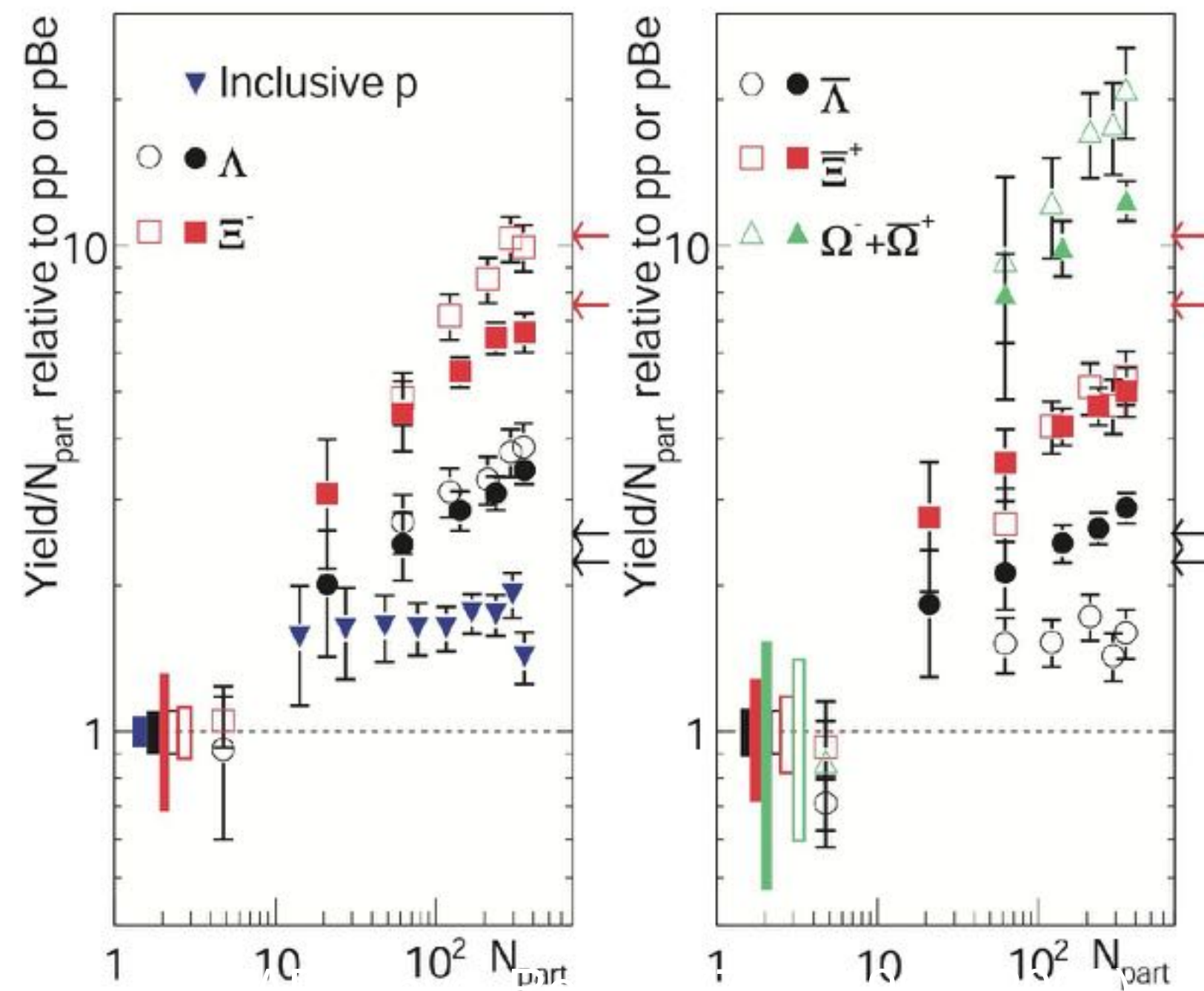
Na57 (SPS)

$\sqrt{s_{NN}} = 17.3$ GeV Pb+Pb



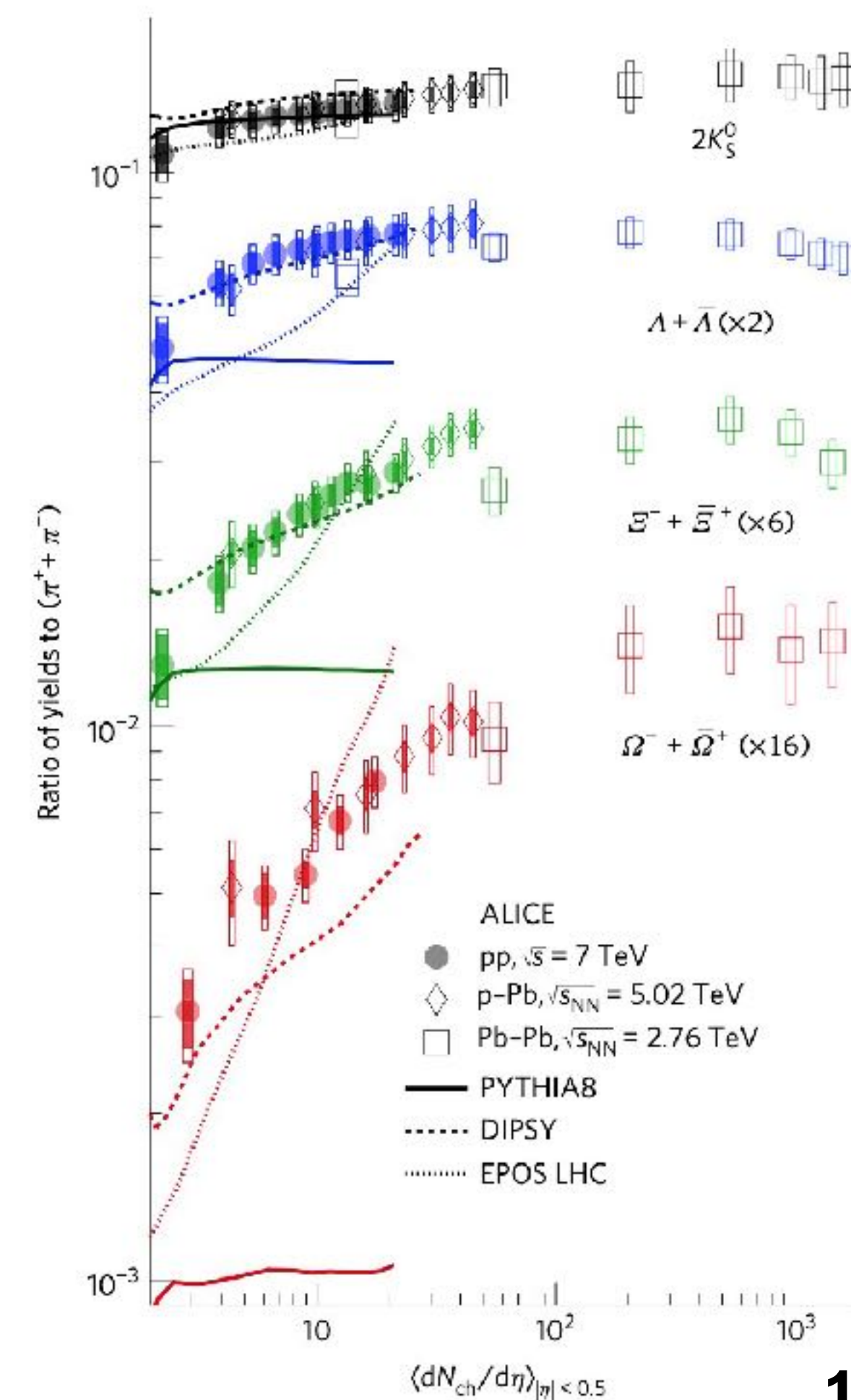
STAR (RHIC)

$\sqrt{s_{NN}} = 200$ GeV Au+Au



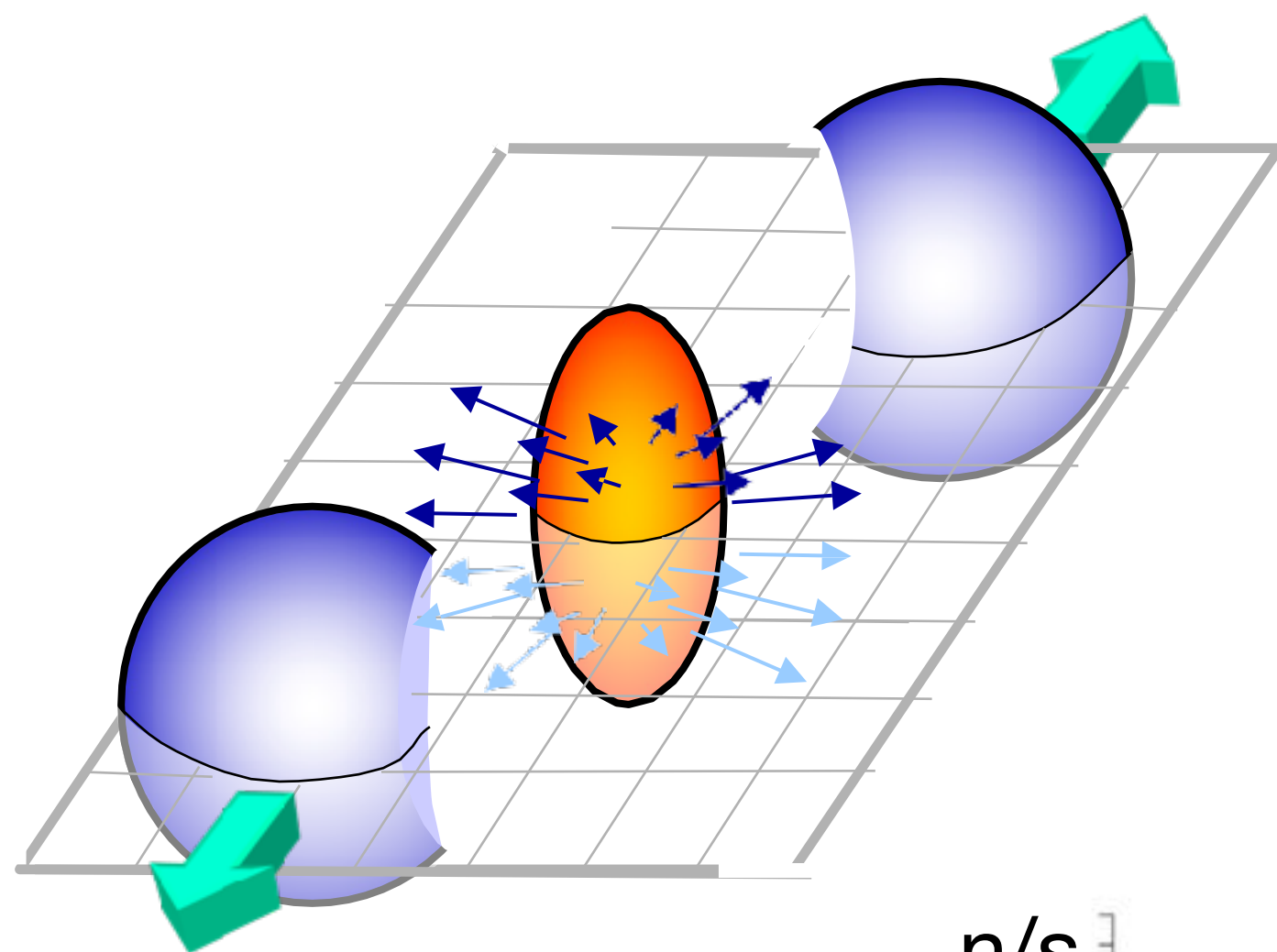
ALICE (LHC)

$\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb



QGP collective flow

Discovered at RHIC



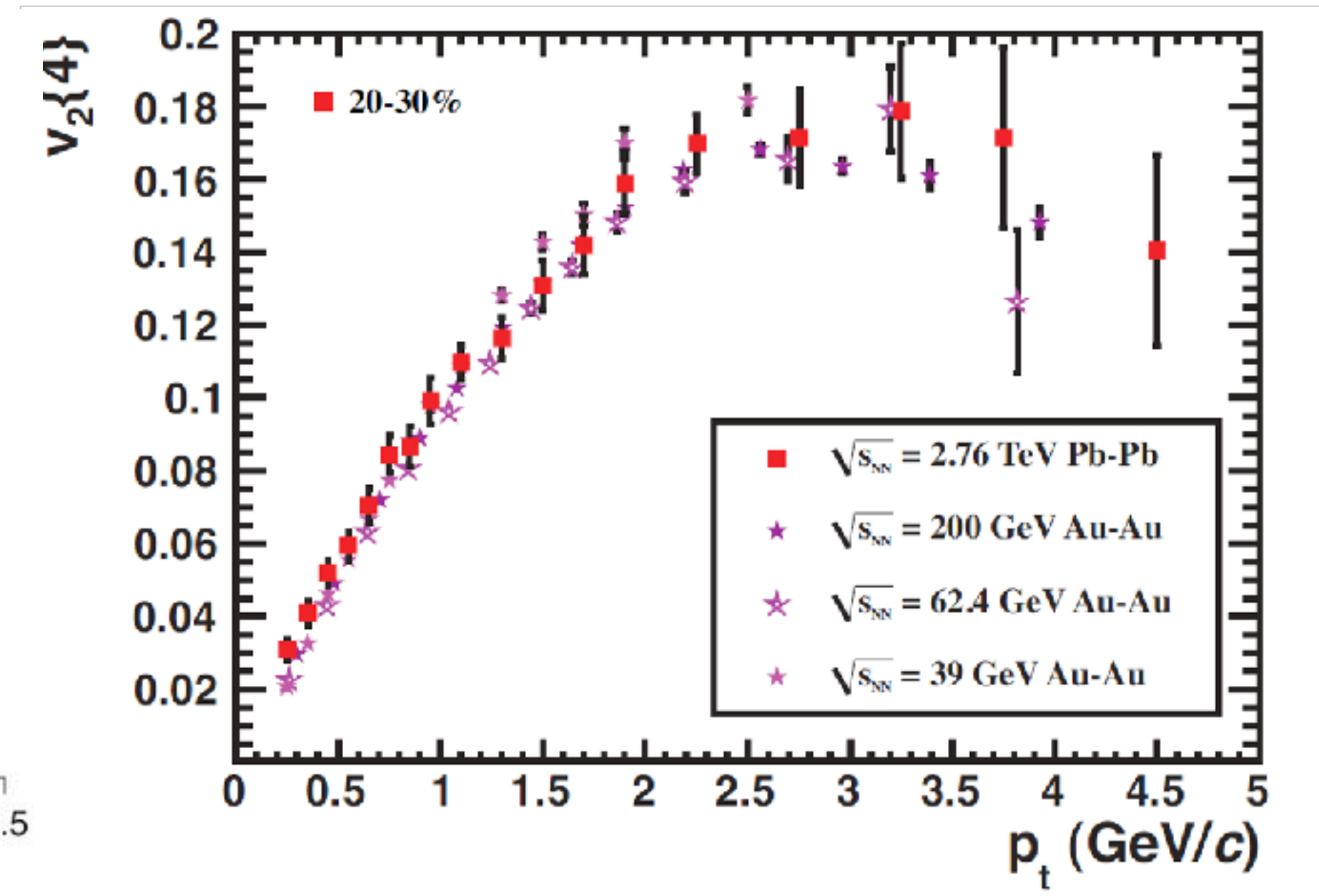
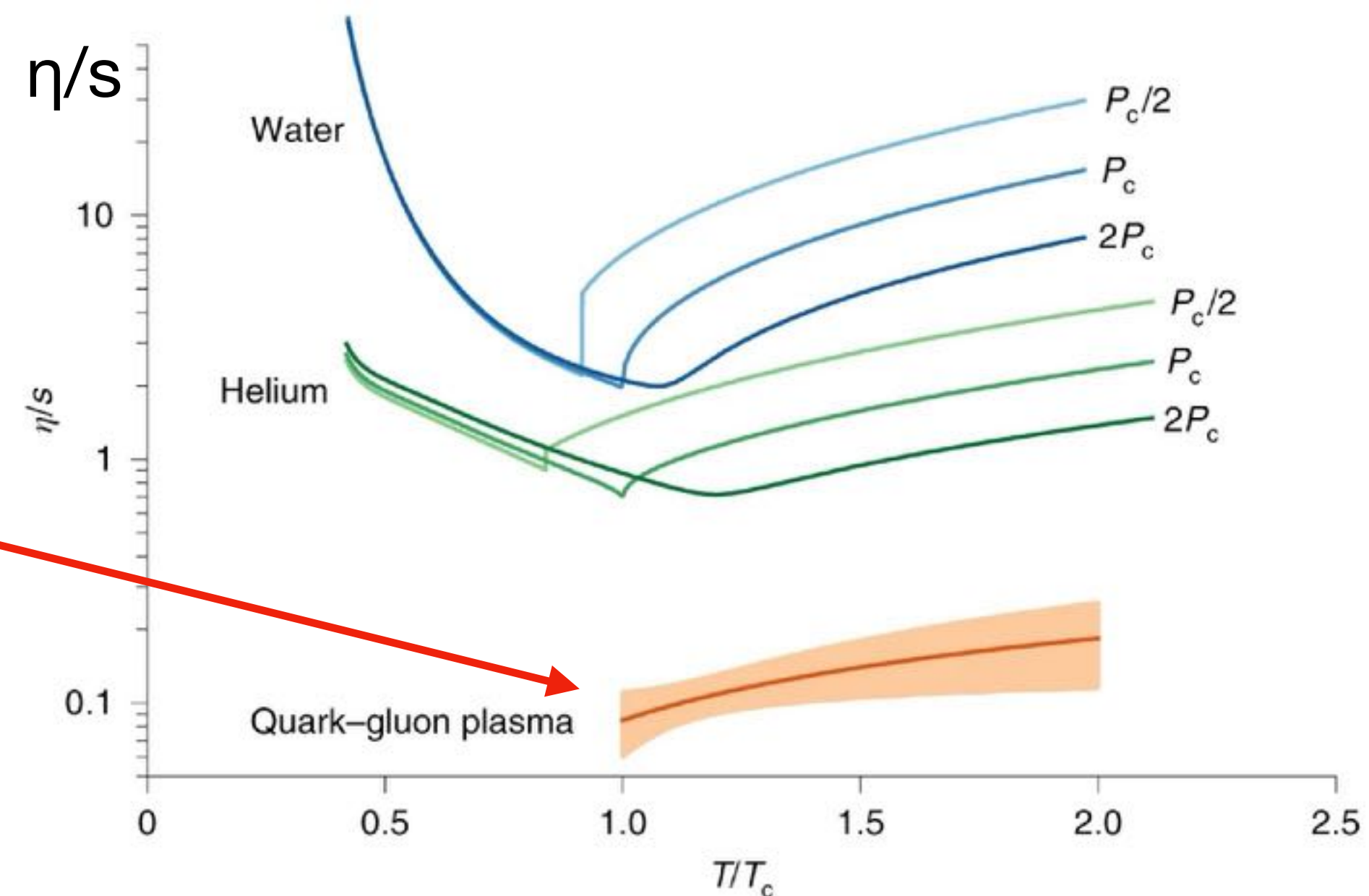
QGP collective flow is well established.

Fireball shape is characterized by eccentricity: ϵ_2

Hydrodynamical expansion: $\epsilon_2 \rightarrow$ collective flow $v_2(p_T)$

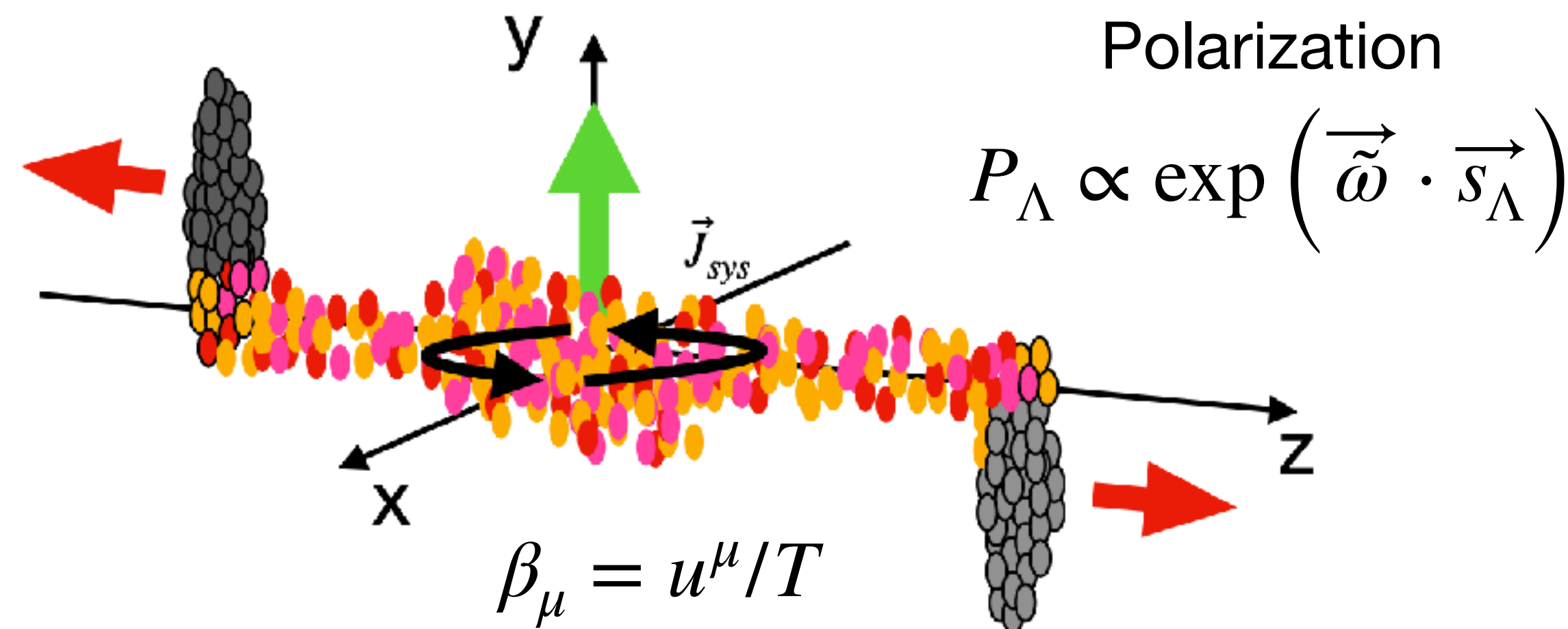
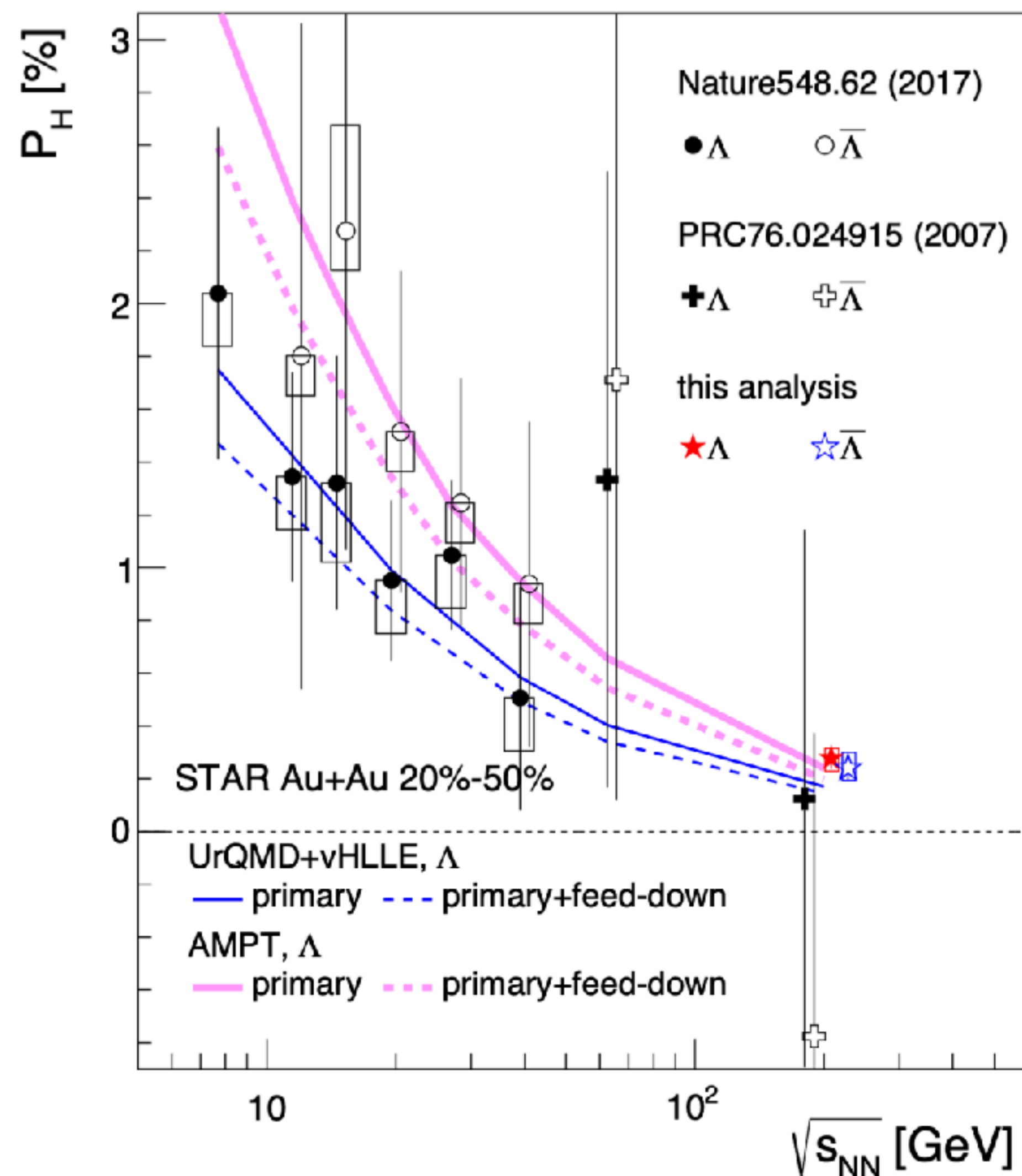
Ratio v_2/ϵ_2 is **very** sensitive to the viscosity of the QGP.

Main result:
 $\frac{\eta}{s} \approx 0.1 - 0.15$
 Most "perfect" fluid!



Global polarization

Discovered at RHIC



Thermal vorticity: $\tilde{\omega}_{\mu\nu} = \frac{1}{2} (\partial_\nu \beta_\mu - \partial_\mu \beta_\nu)$

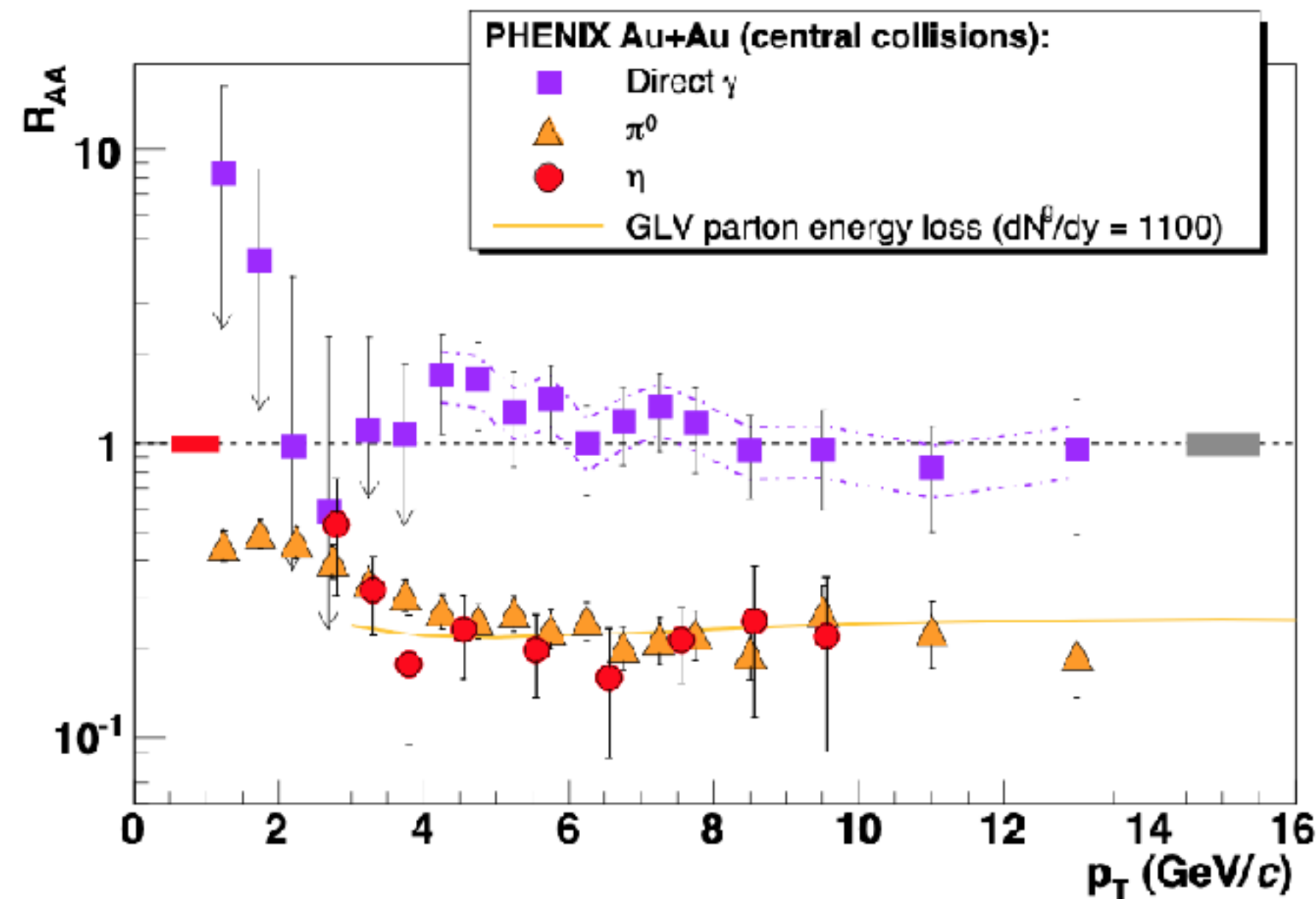
Long-lived vorticity requires low kinematic shear viscosity:

$$\frac{\partial \omega}{\partial t} \propto \frac{\eta}{sT} \nabla^2 \omega$$

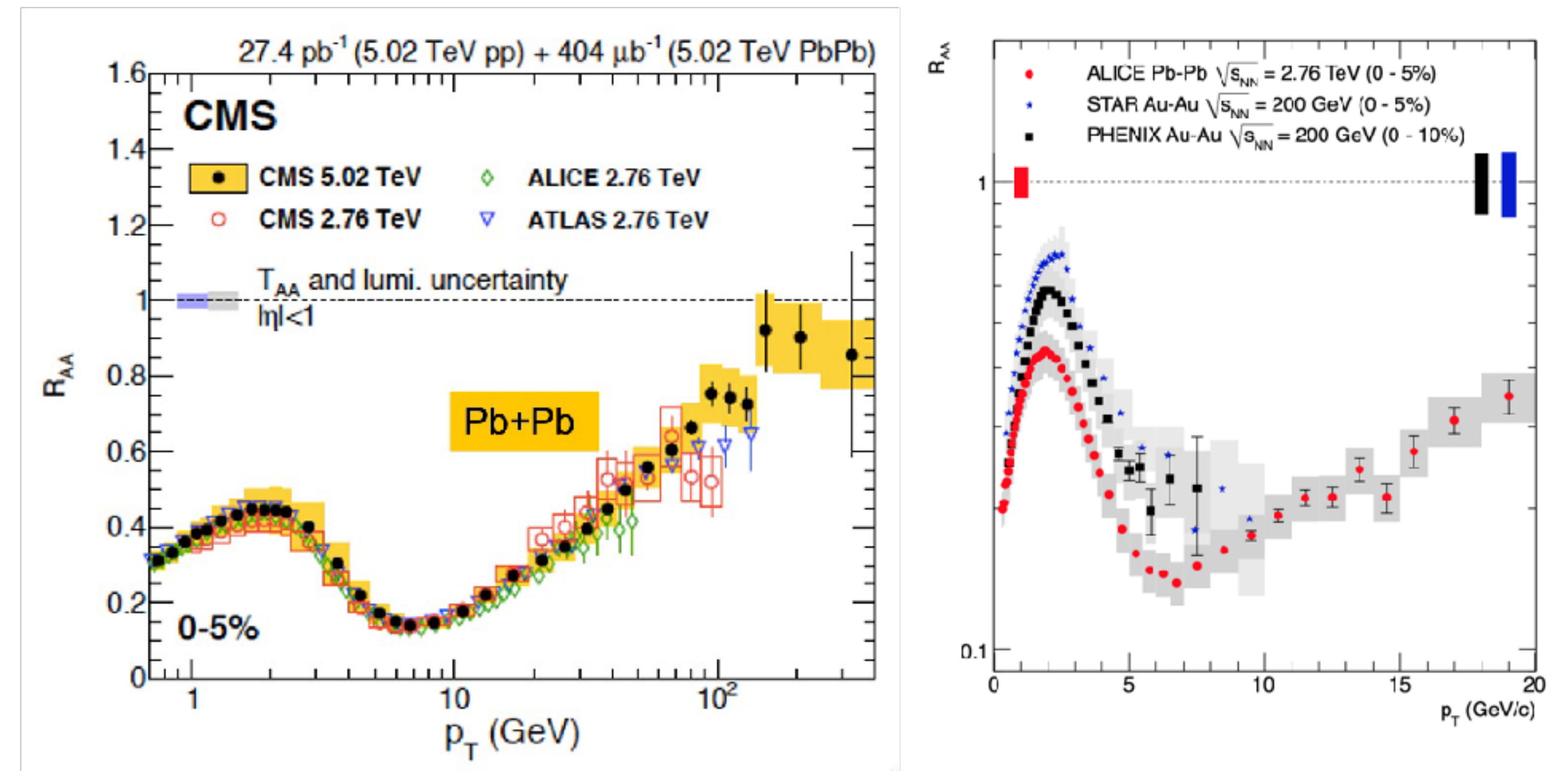
Jet quenching

Discovered at RHIC

RHIC (Au+Au)



LHC (Pb+Pb)



Photons are **not** suppressed
 All hadrons are equally suppressed
 → Energy loss of quarks/gluons

Suppression increases with growing beam energy
 but decreases with growing jet p_T

Very active area with many new results and ideas

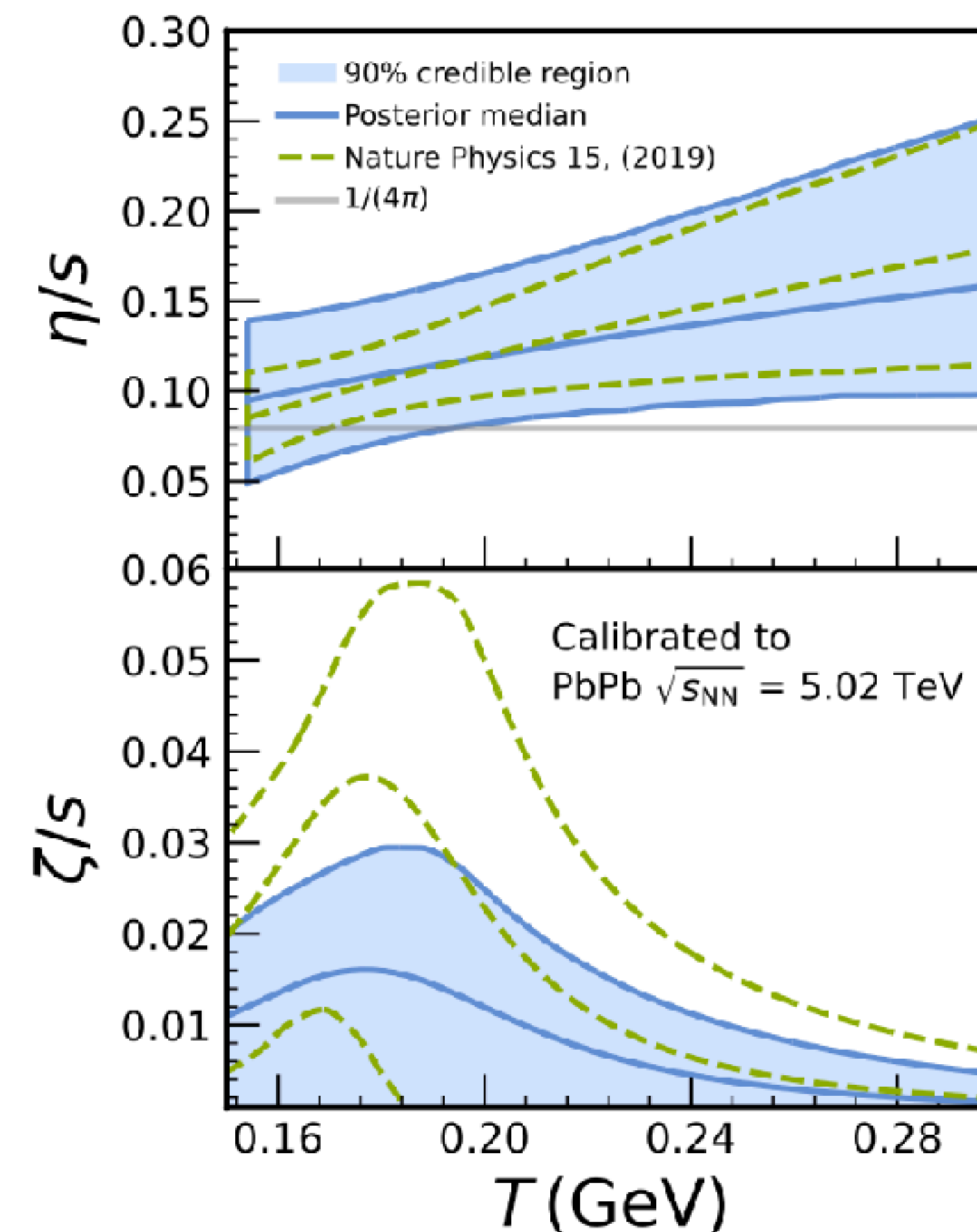
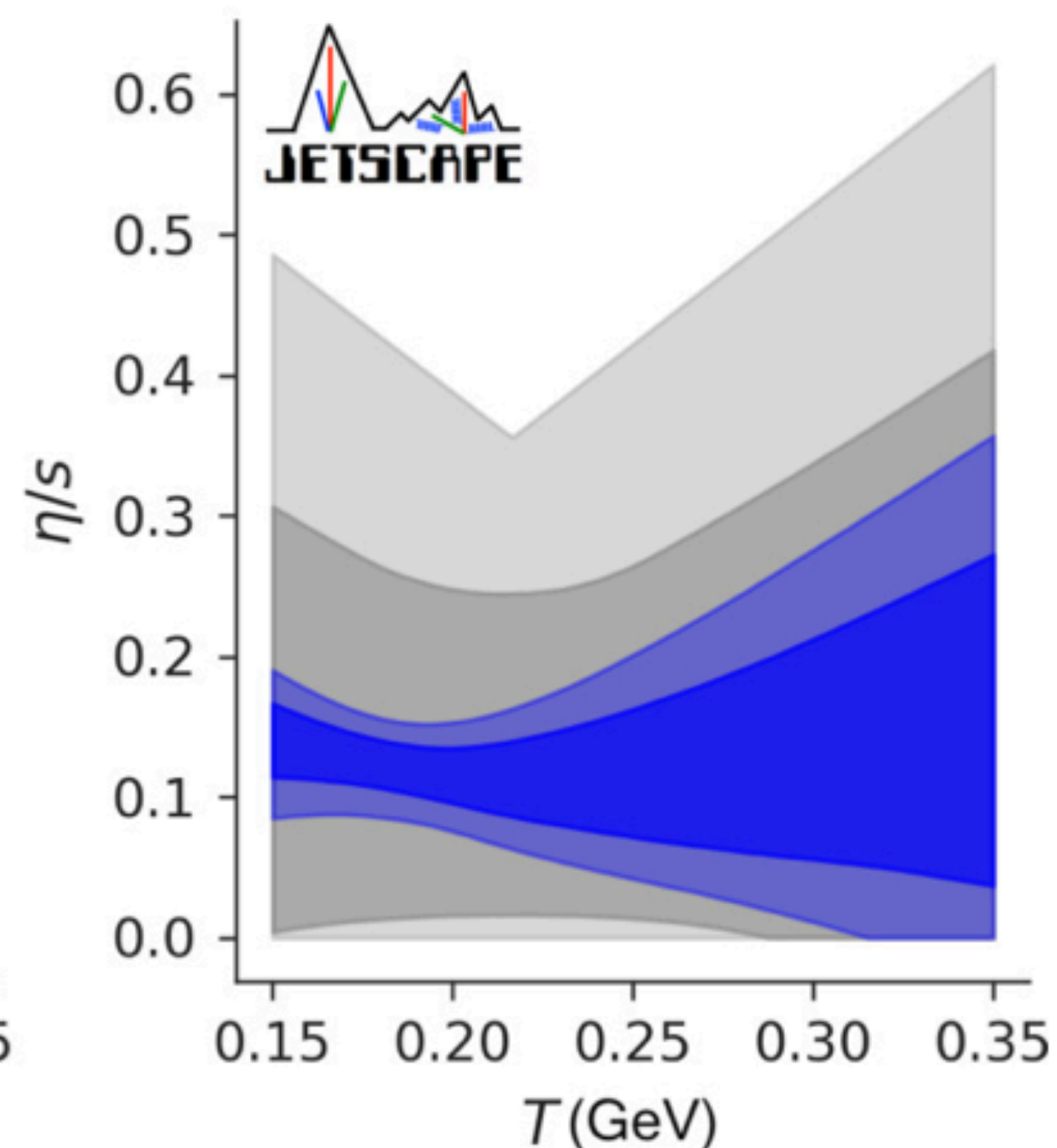
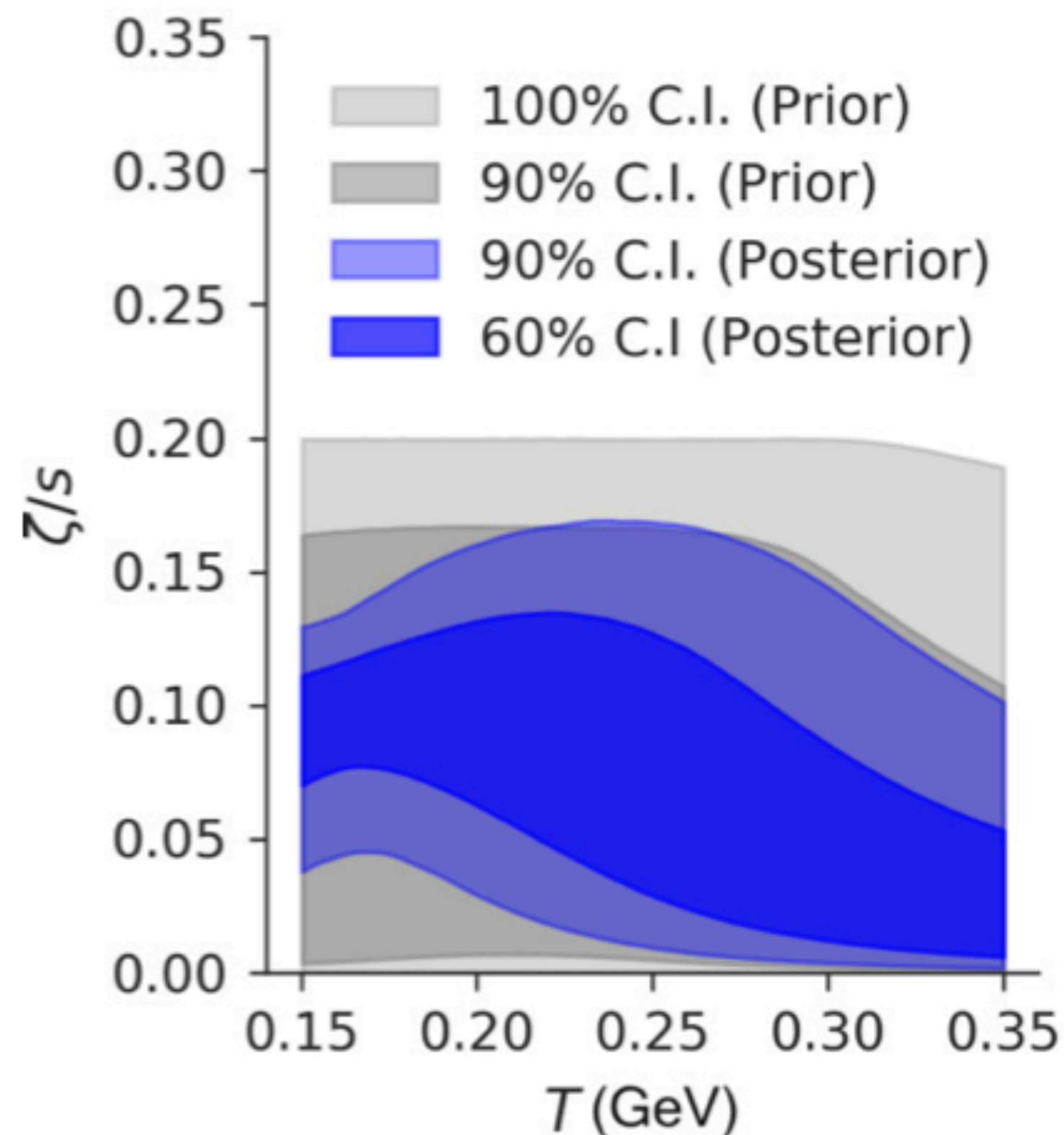
QGP viscosity

Pioneered by US theorists

Combined Bayesian analysis of Au+Au (RHIC) and Pb+Pb (LHC)

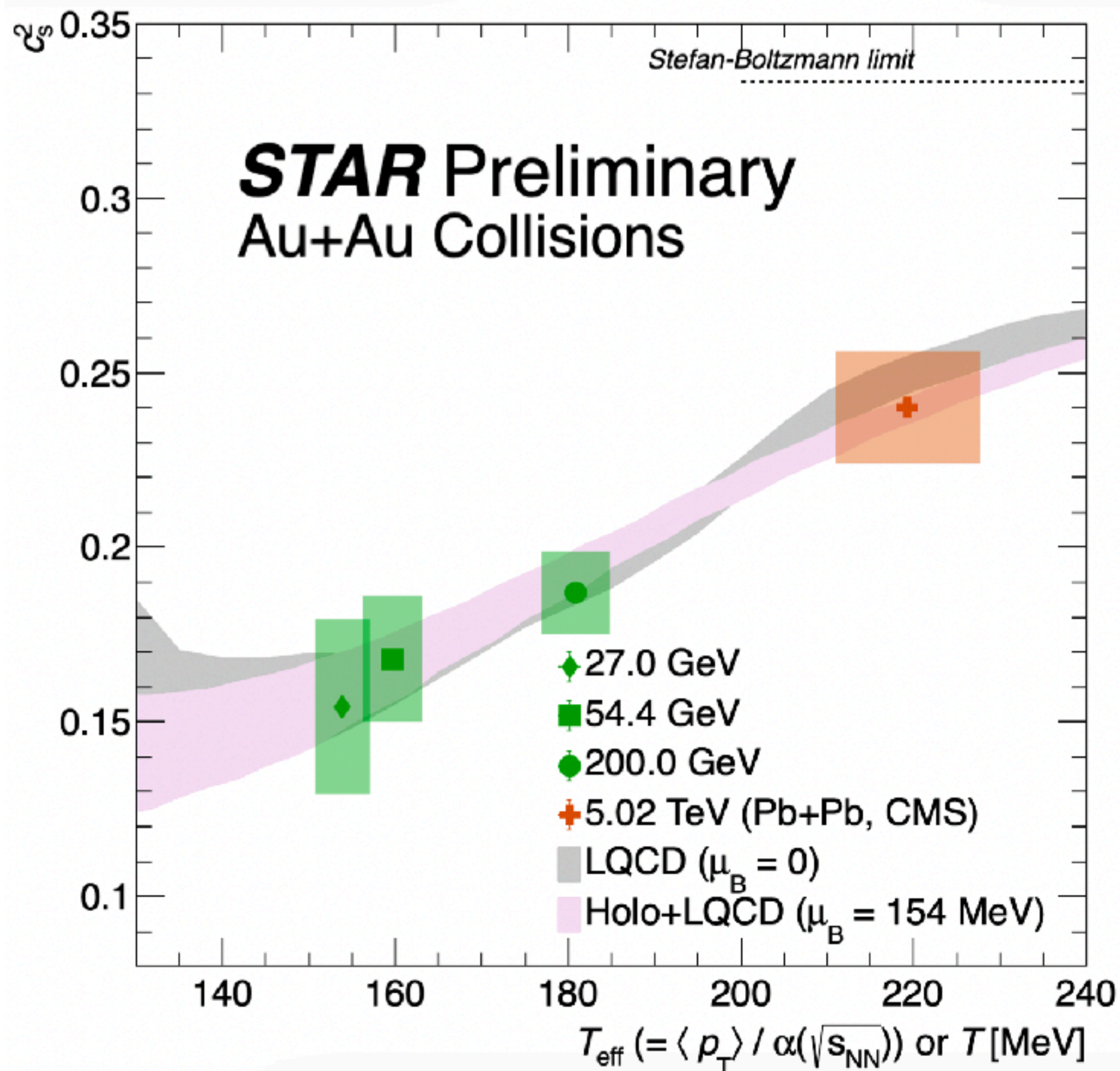
JETSCAPE, Phys. Rev. C **103** (2021) 054904

Parkkila, Onnerstad & Kim,
Phys. Rev. C **104** (2021) 054904



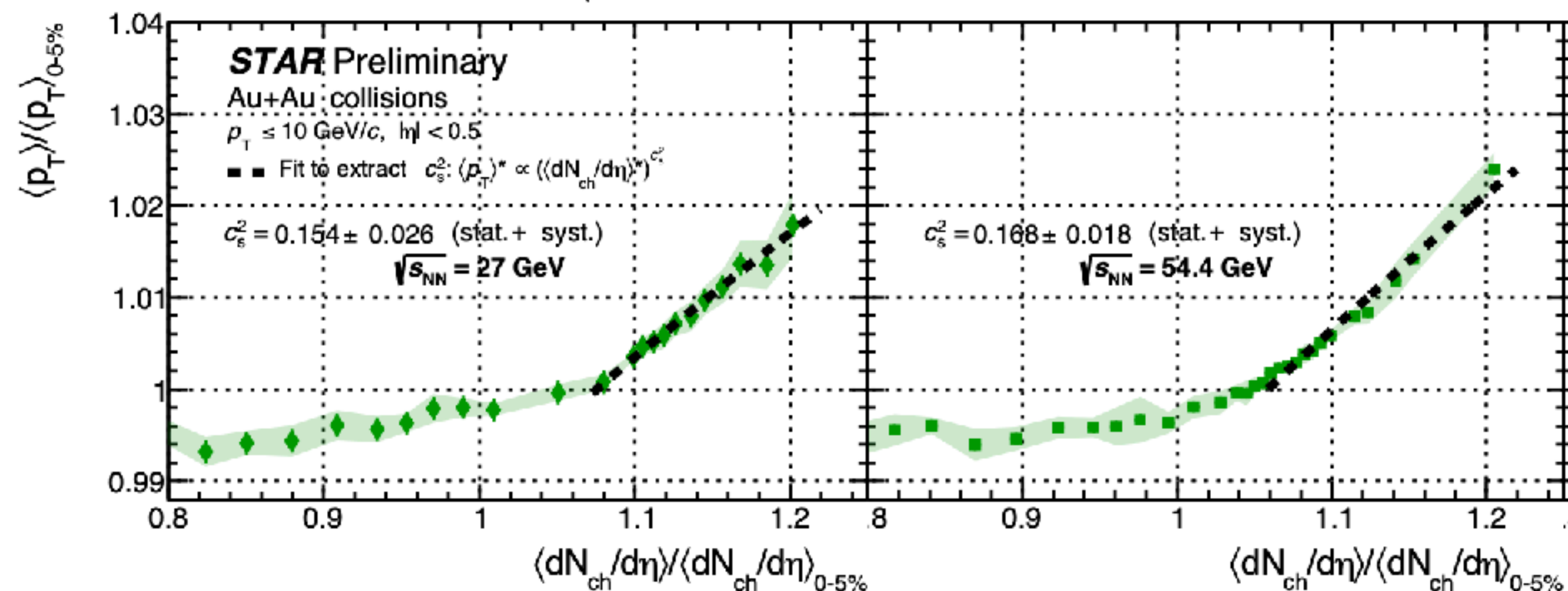
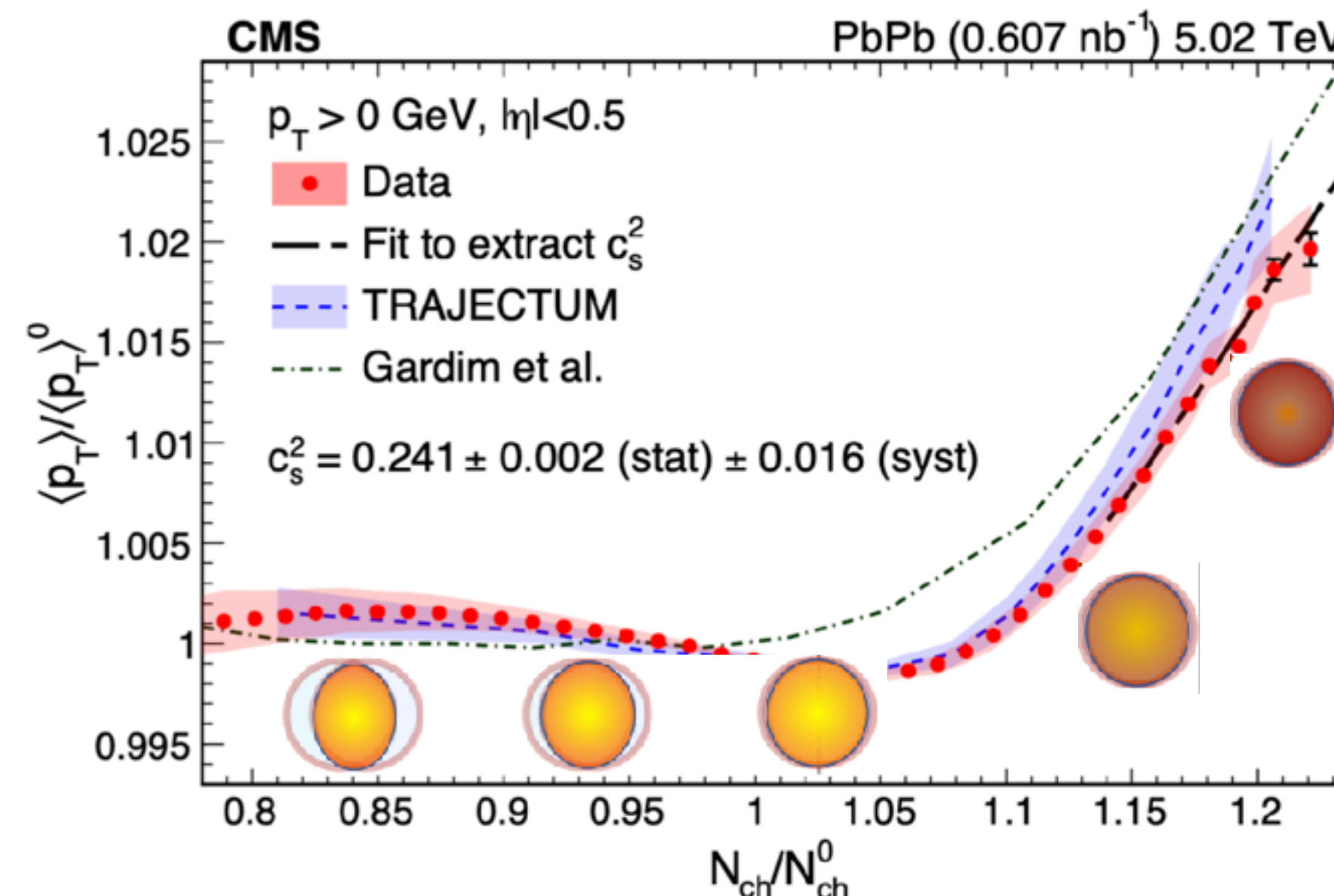
Bulk EoS: Equilibrium

C. Broodo (presented at SQM2026)



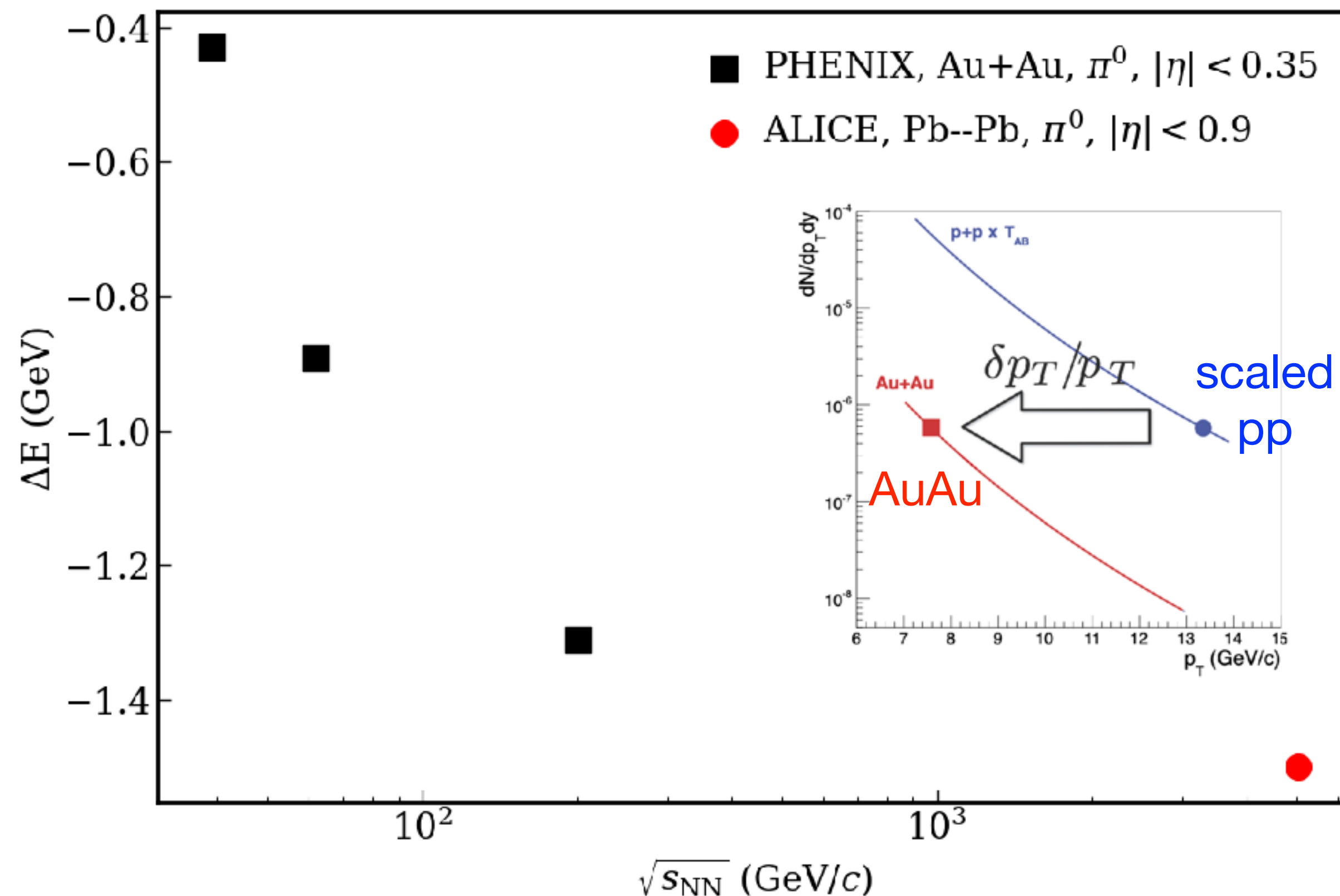
Speed of sound

$$c_s^2 \approx \frac{\ln \langle p_T \rangle}{d \ln N_{\text{ch}}}$$

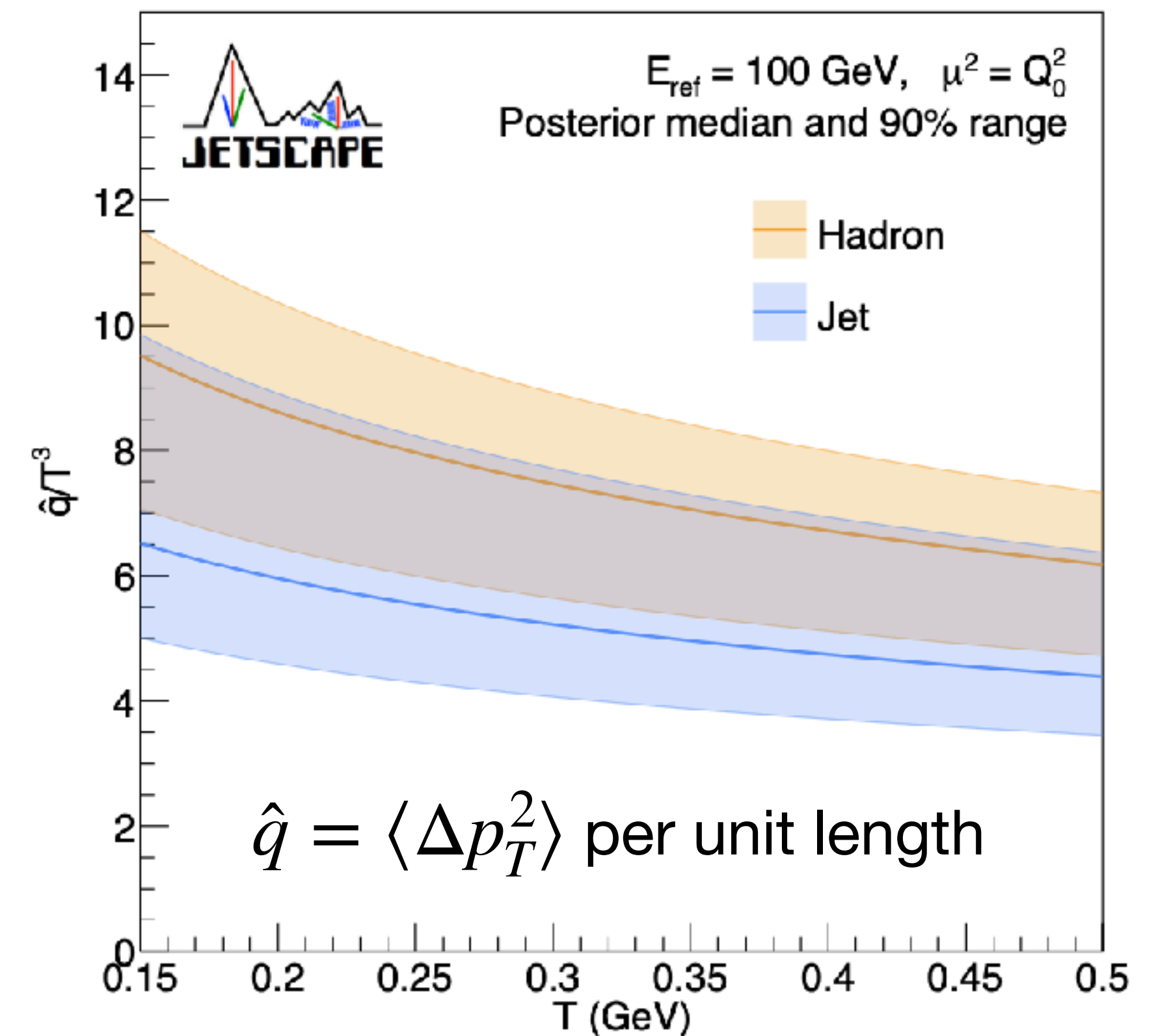


QGP stopping power (\hat{q})

Parton energy loss ΔE determined from energy shift of inclusive hadron spectrum



Radiative energy loss: $\frac{dE}{dz} \approx -\frac{\alpha_s N_c}{4} \hat{q} L$

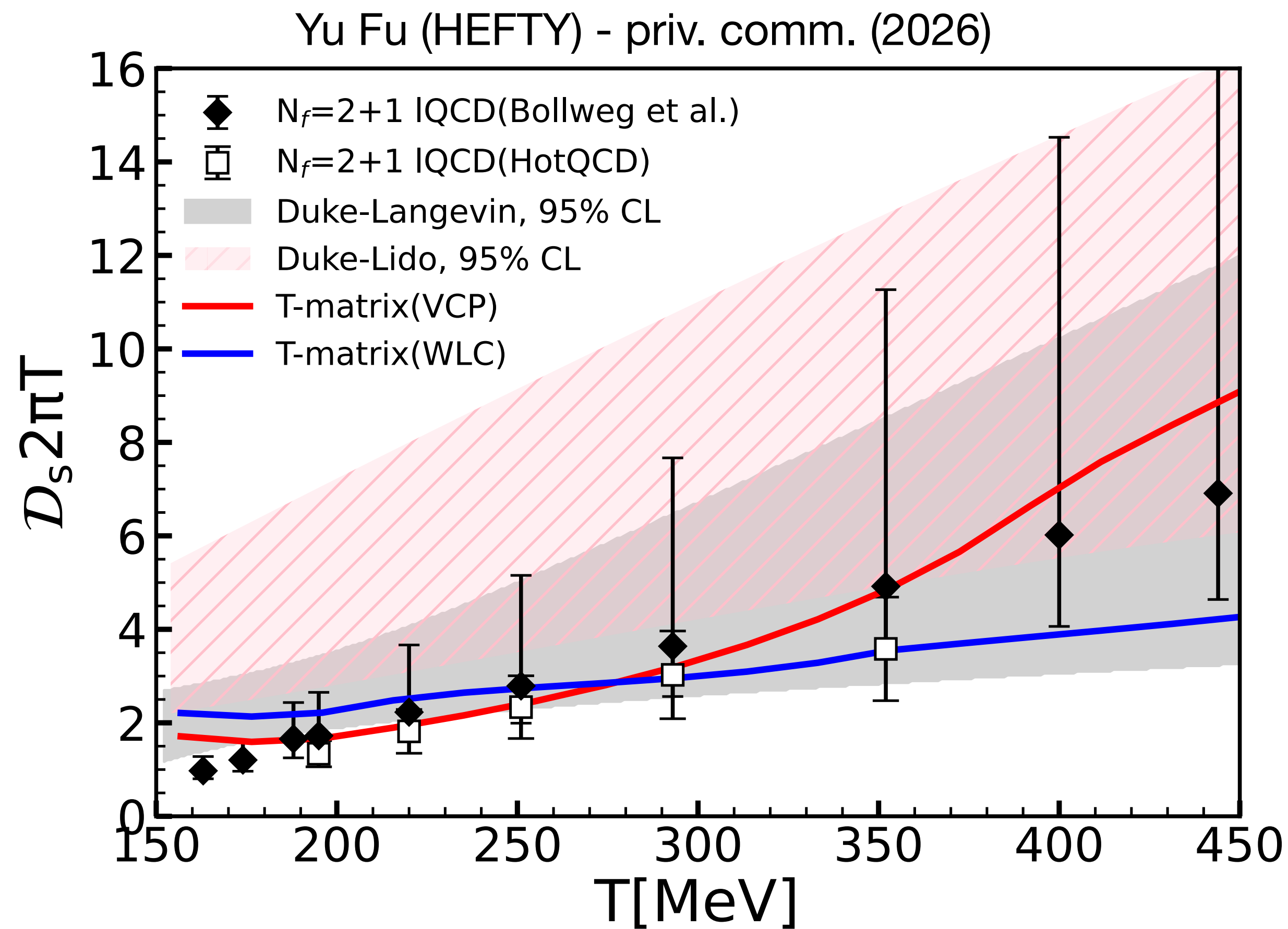


Heavy quark diffusion

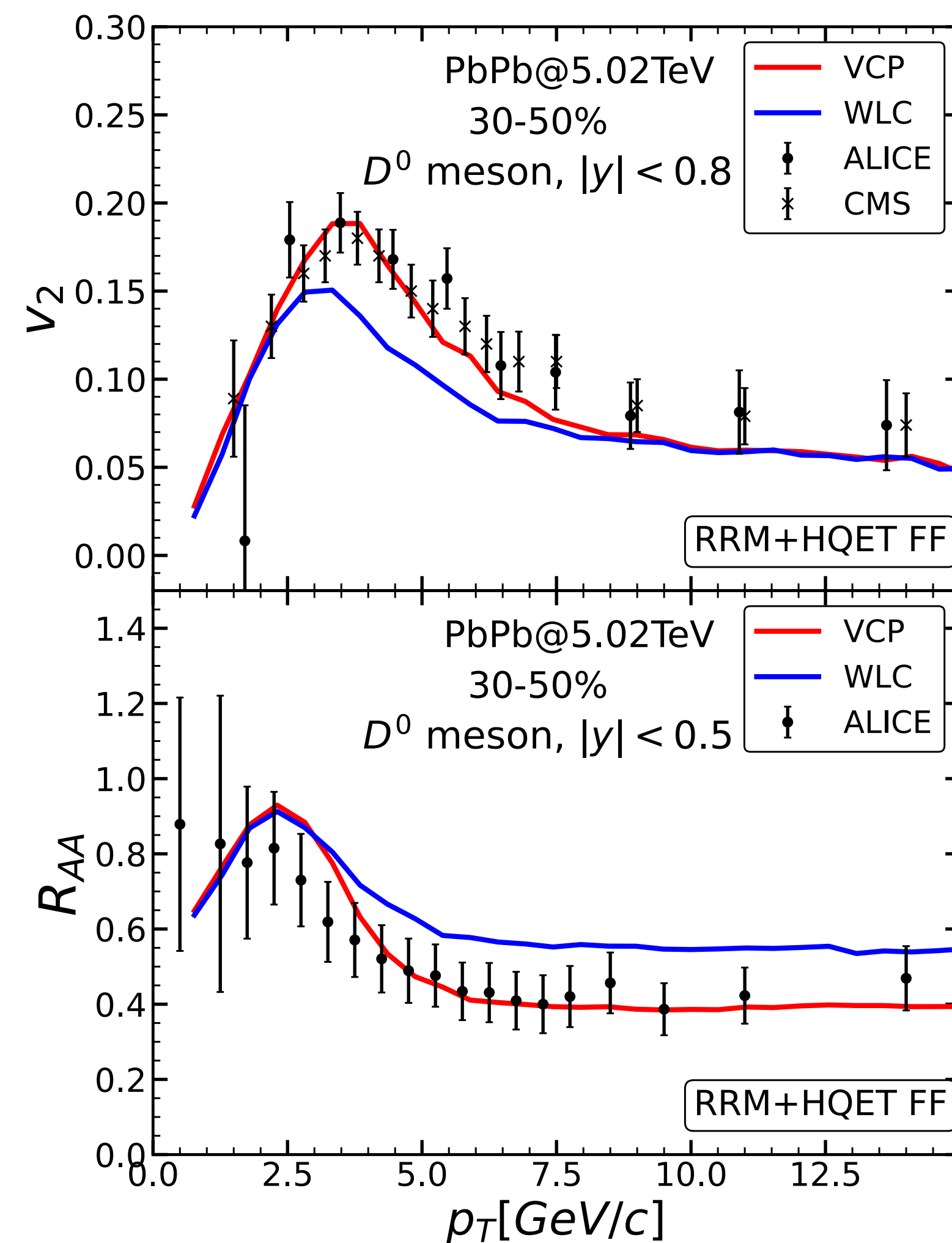
D_s = spatial diffusion coefficient

κ = momentum diffusion coefficient

$$D_s = \frac{2T^2}{\kappa}$$



HEFTY Collab. - 2509.13881

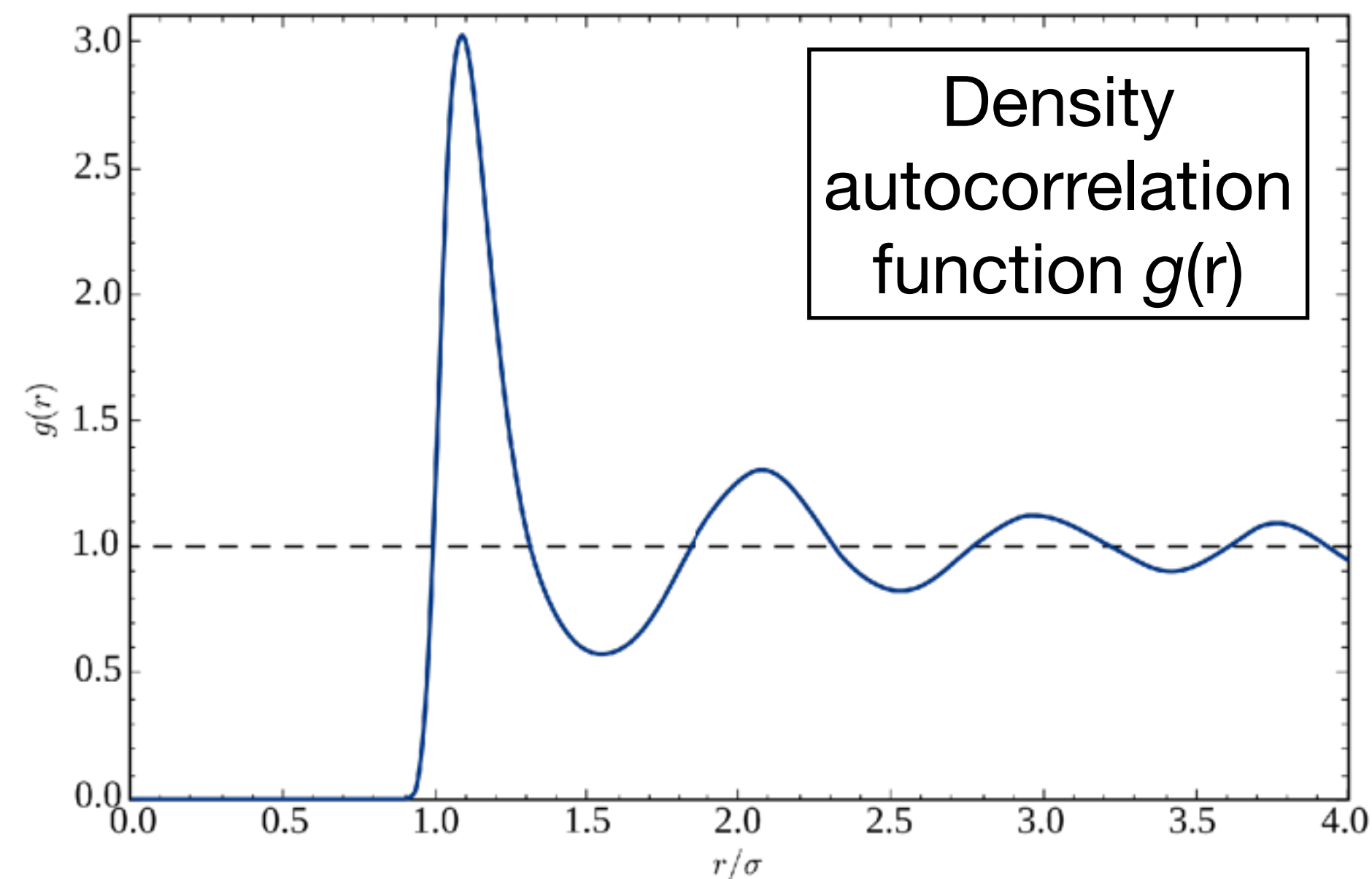


What we know
that we don't know

Is it a Liquid?

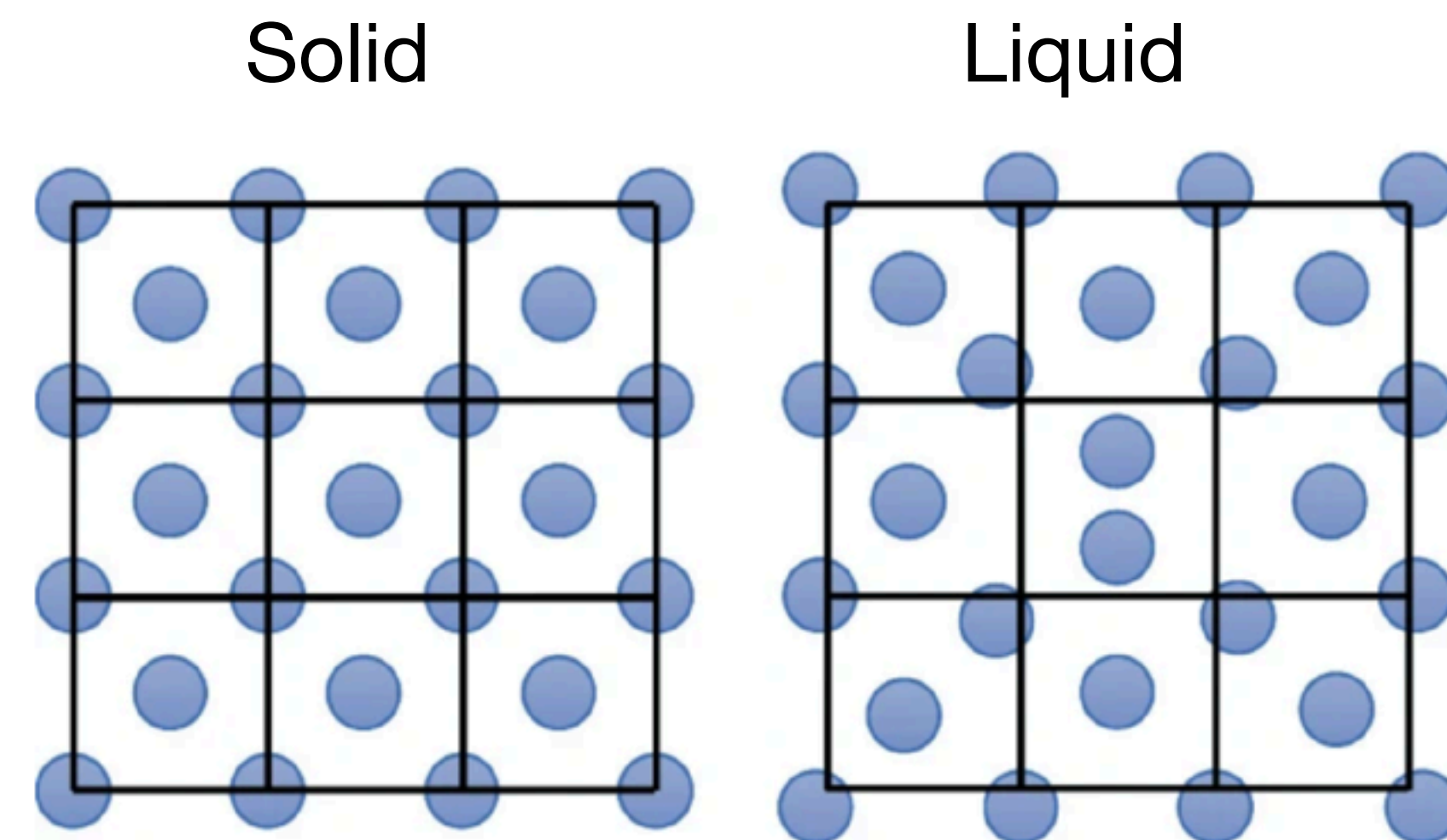
What makes a strongly coupled fluid a **Liquid** ?

Liquids have no long-range structure



Requires strong short-range repulsion

Liquids have elasticity at high frequency



Liquids behave like amorphous solids on short time scales

It is a liquid - but...

None of these concepts applies to a relativistic gauge plasma where particle number is not conserved

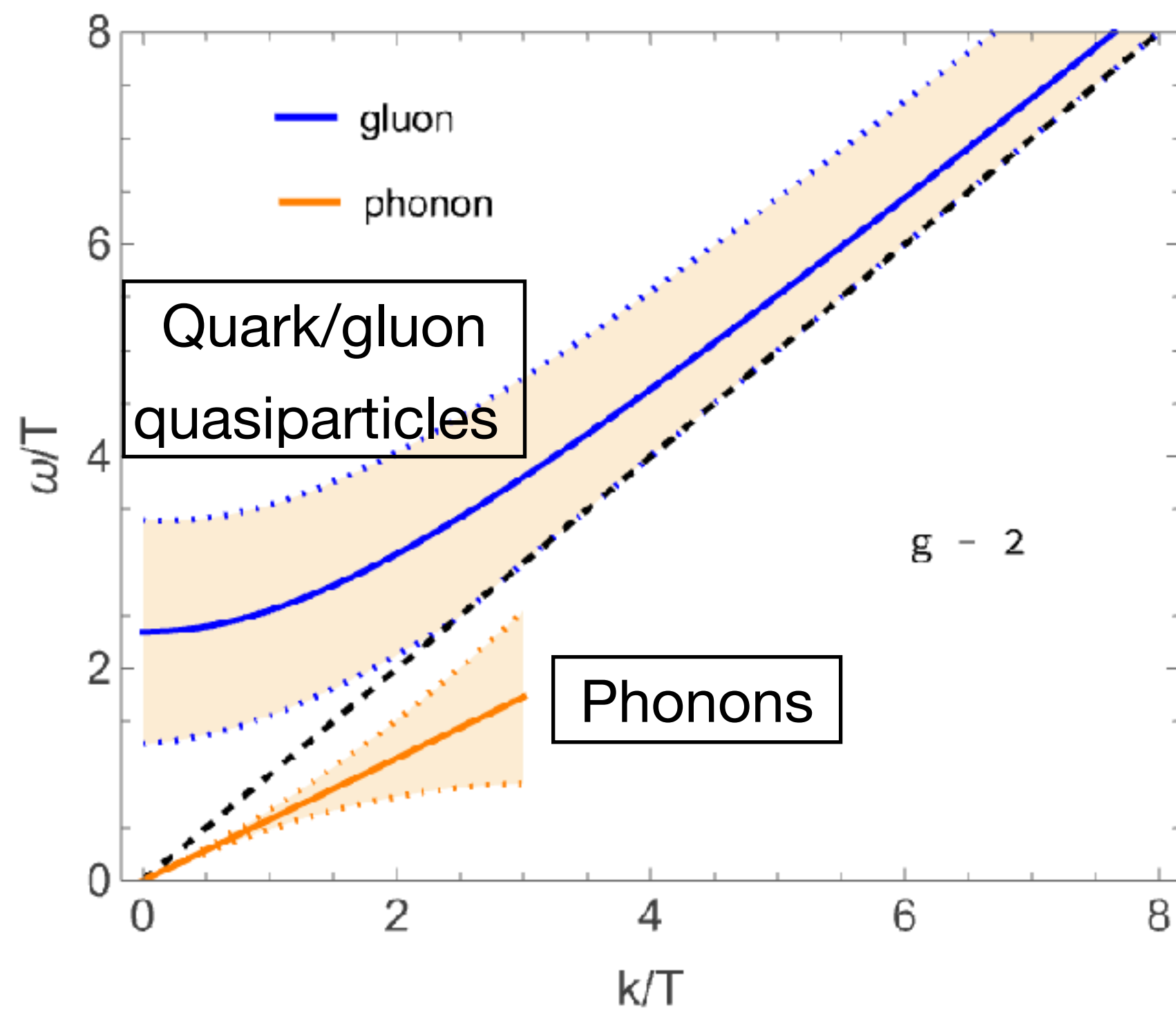
A new paradigm is needed!

	Intermolecular forces	Ratio of amplitude of random thermal movement of molecules to d_0	Molecular arrangement	Type of statistics needed
solid	strong	$\ll 1$	ordered	quantum
liquid	medium	of order unity	partially ordered	quantum + classical
gas	weak	$\gg 1$	disordered	classical

From: G. K. Batchelor - An Introduction to Fluid Dynamics

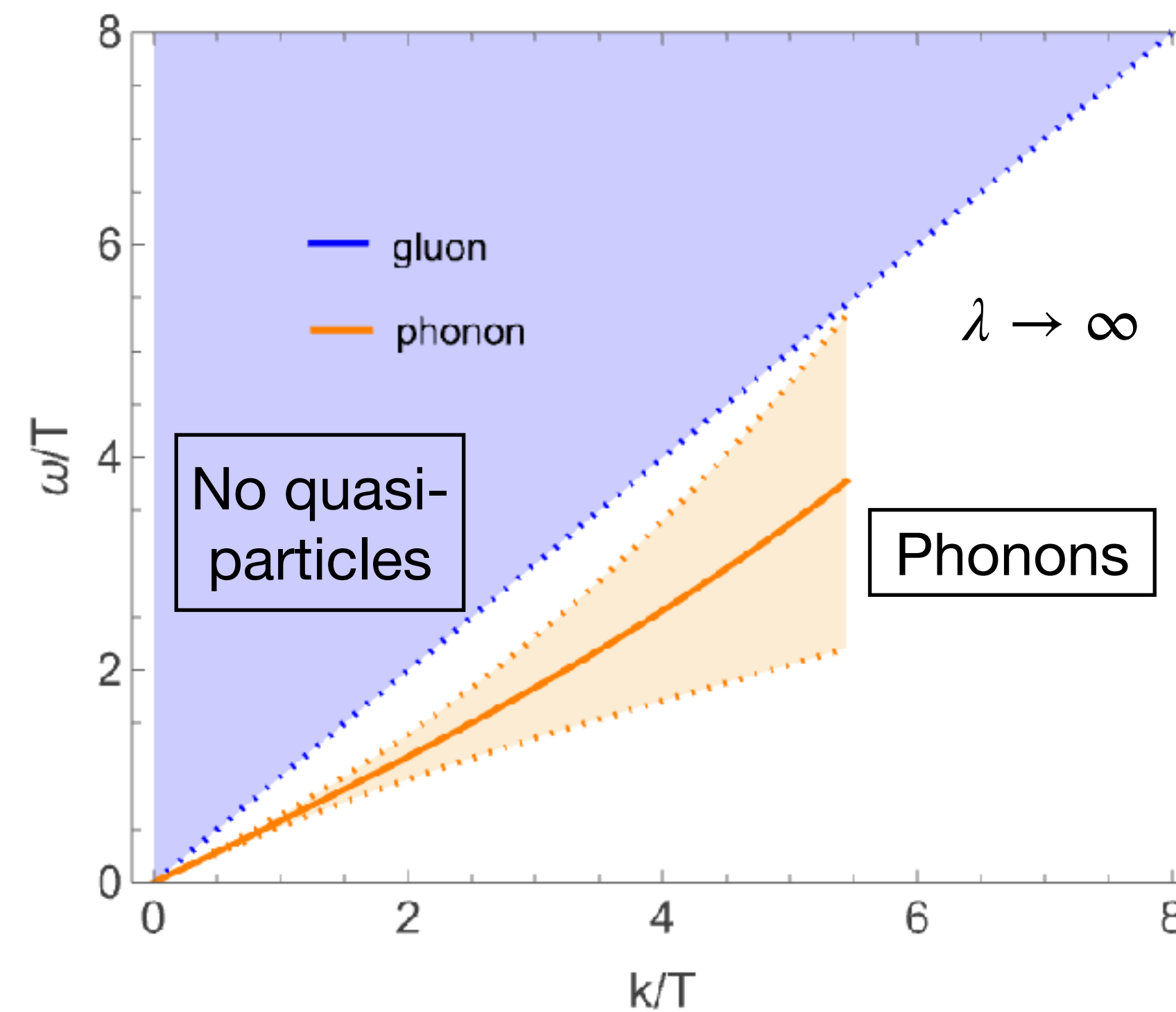
Where is the fluid - quasiparticle boundary?

Strong coupling: QCD at $\alpha_s = \frac{g^2}{4\pi} = 0.32$



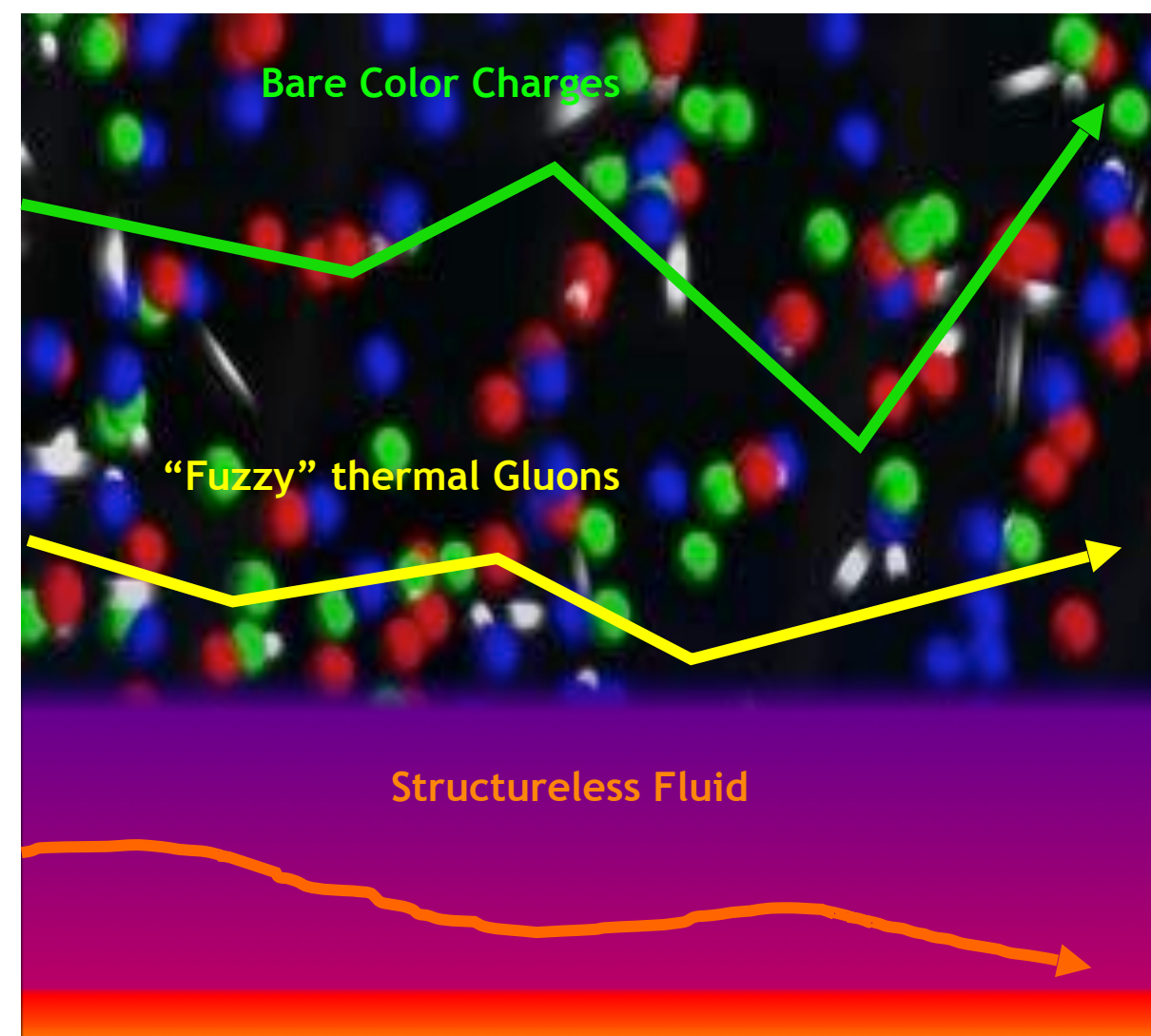
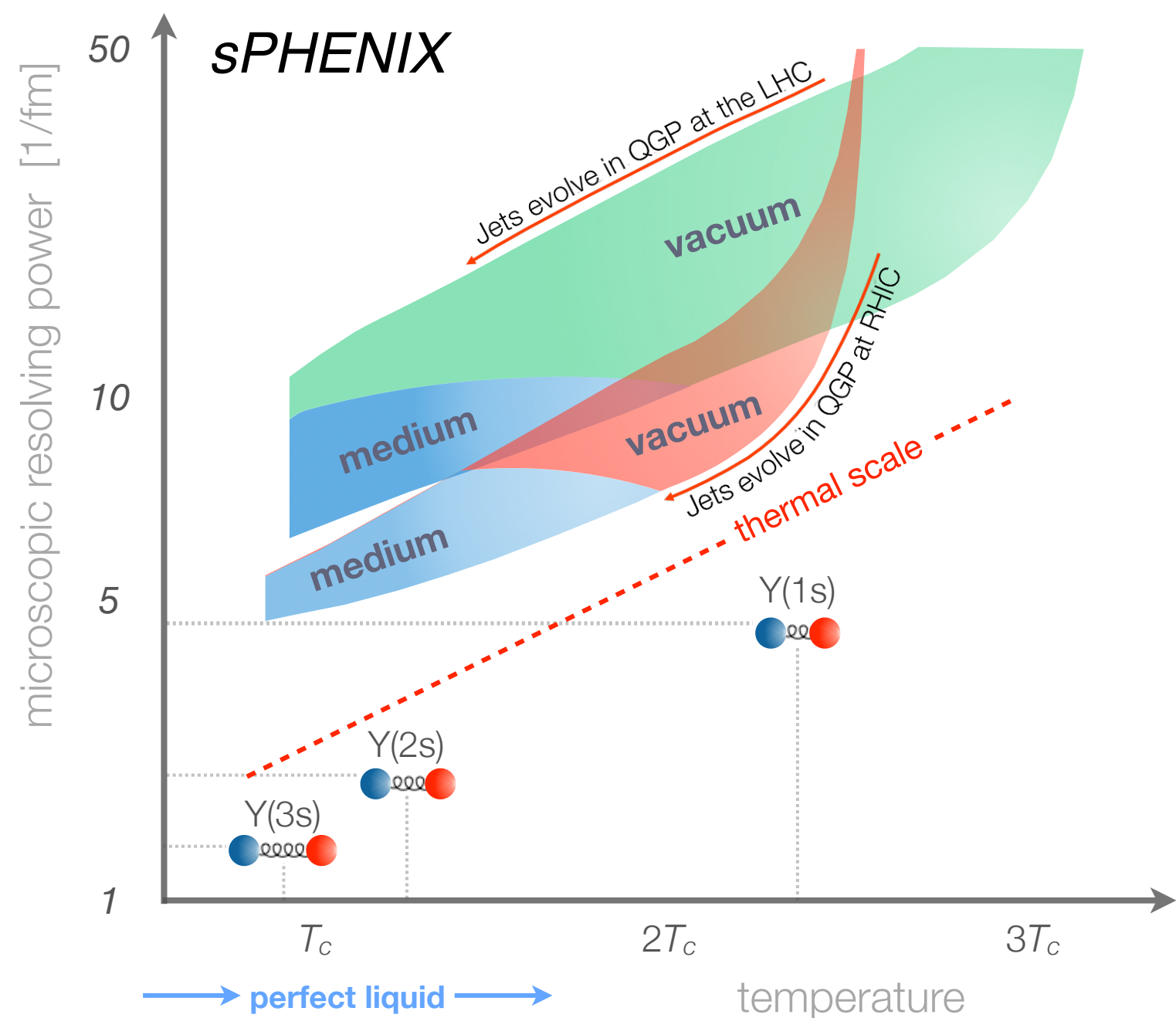
Dense quasiparticle plasma

Strong coupling: $N = 4$ SYM at $\lambda \rightarrow \infty$



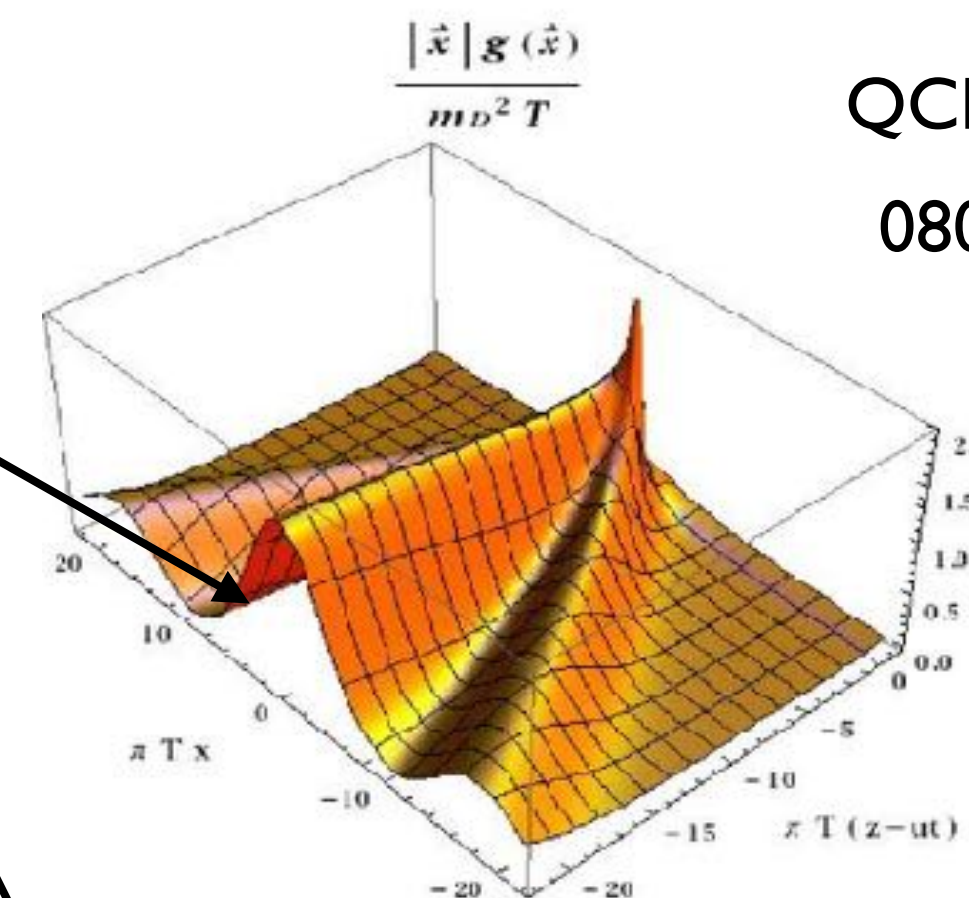
Structureless liquid plasma

Jet-medium response



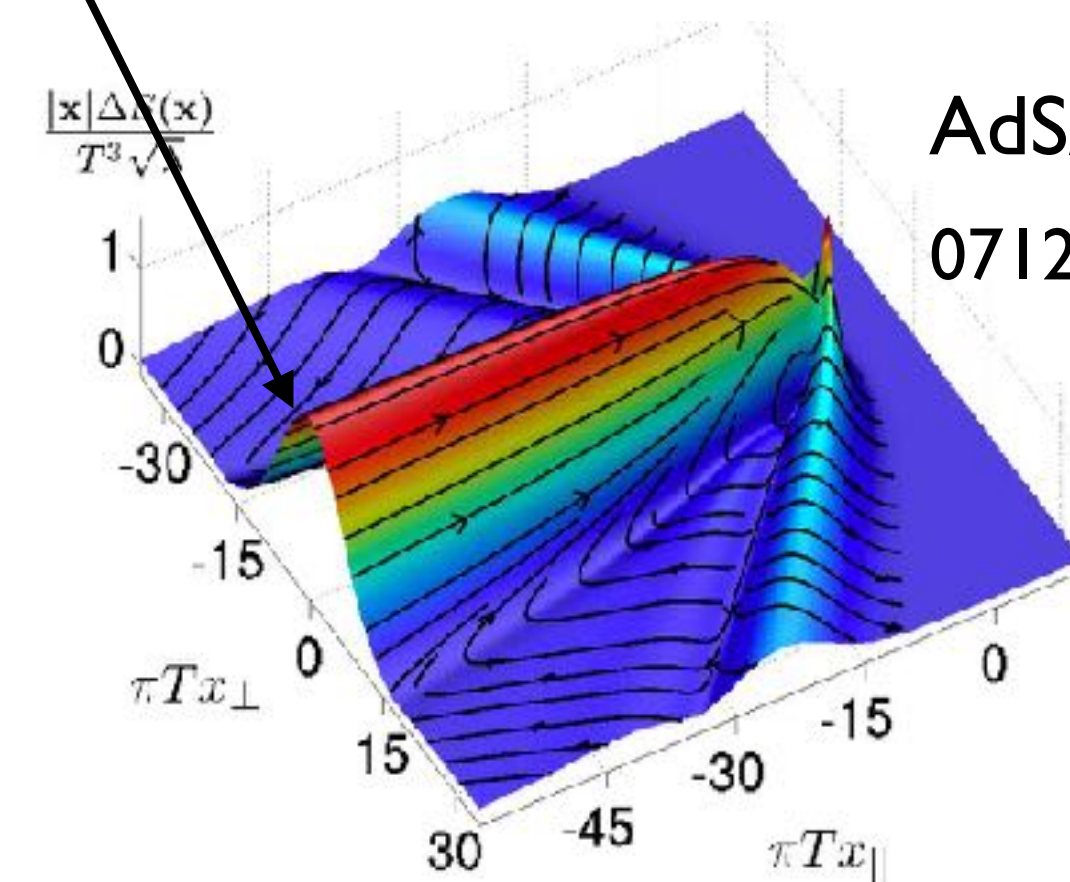
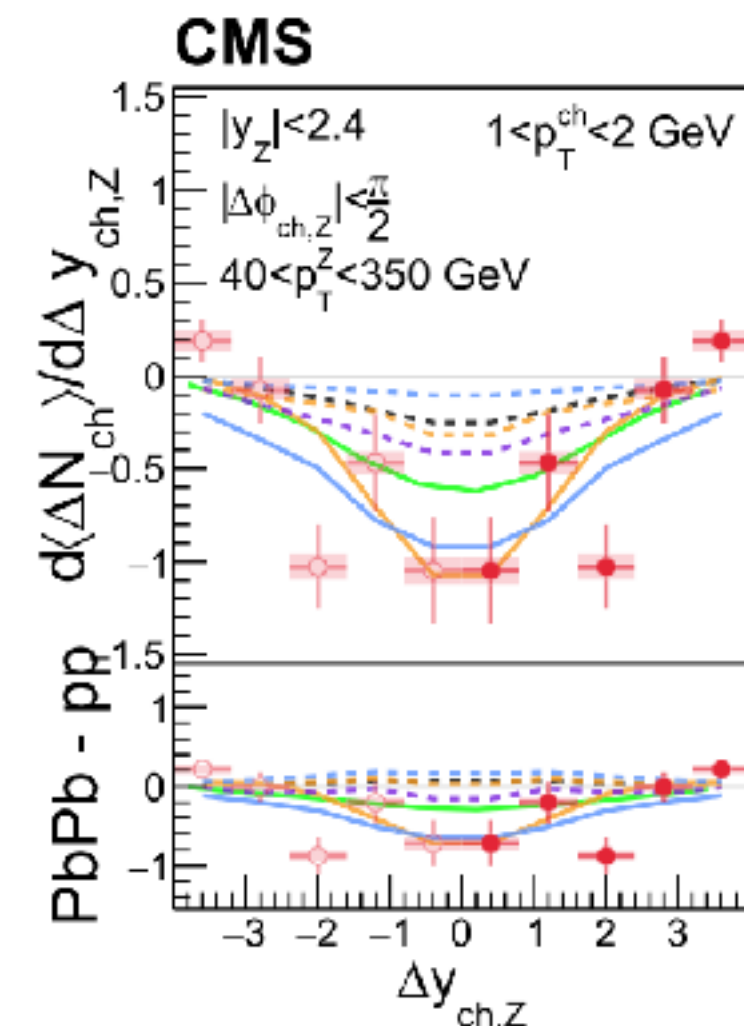
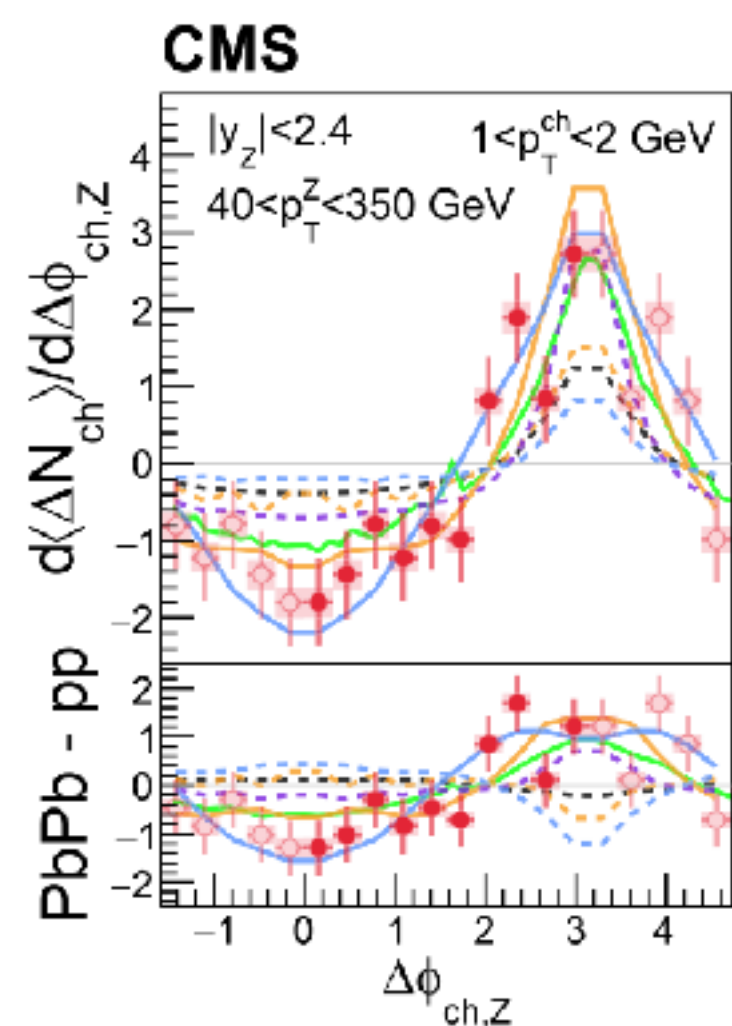
Diffusion wake

Momentum response



QCD—HTL
0802.2254

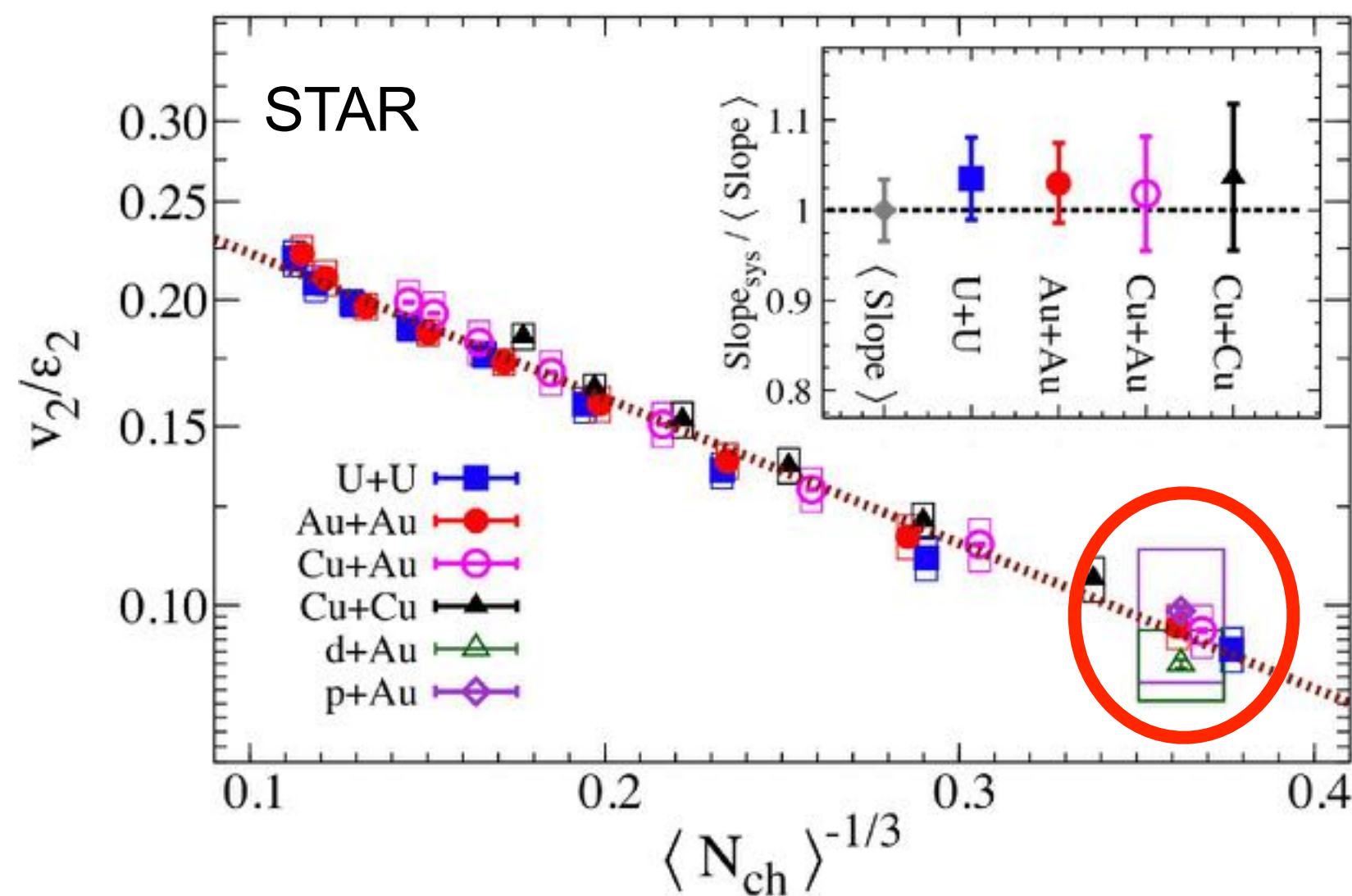
Jet wake finally detected
Unique probe of fluid response
Can we detect scattering of jet fragments on quasiparticles?



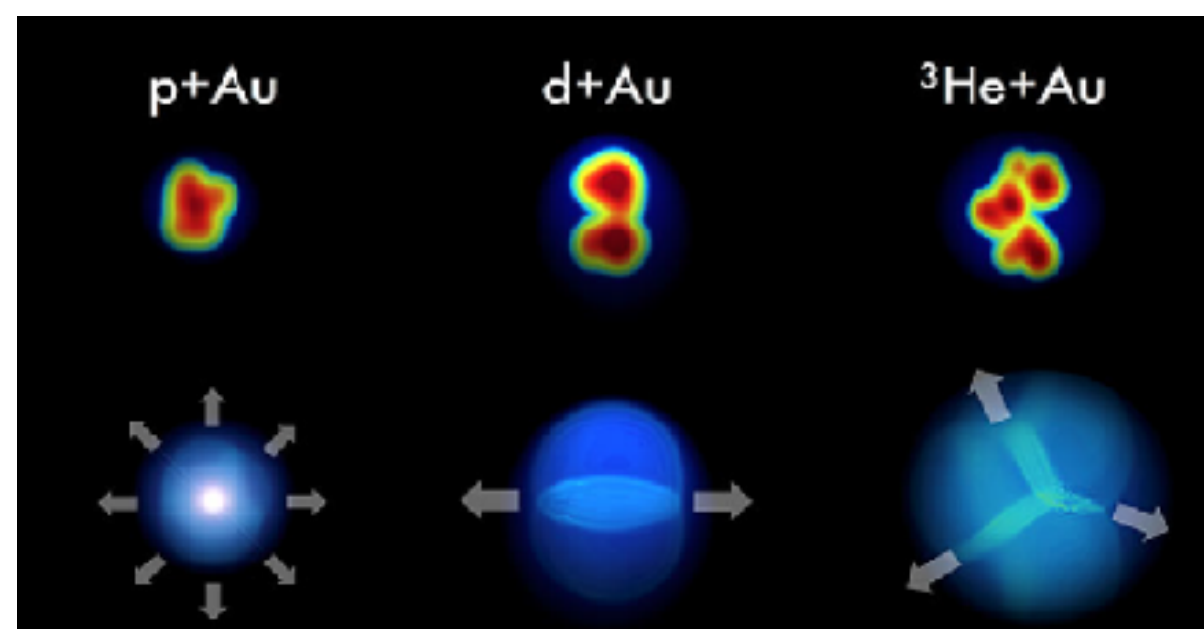
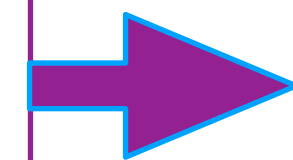
AdS/CFT
0712.0050

How small can a QGP be?

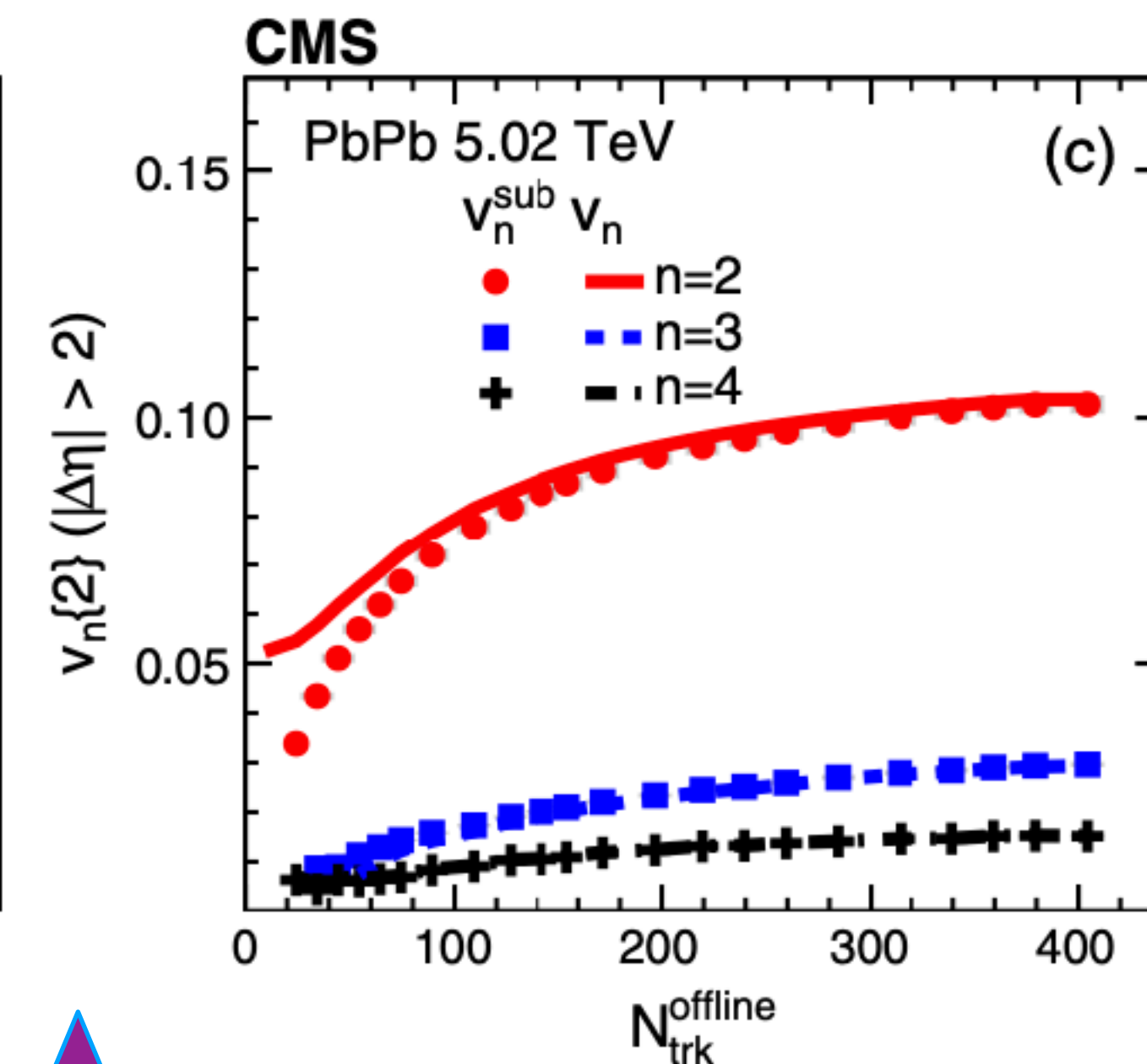
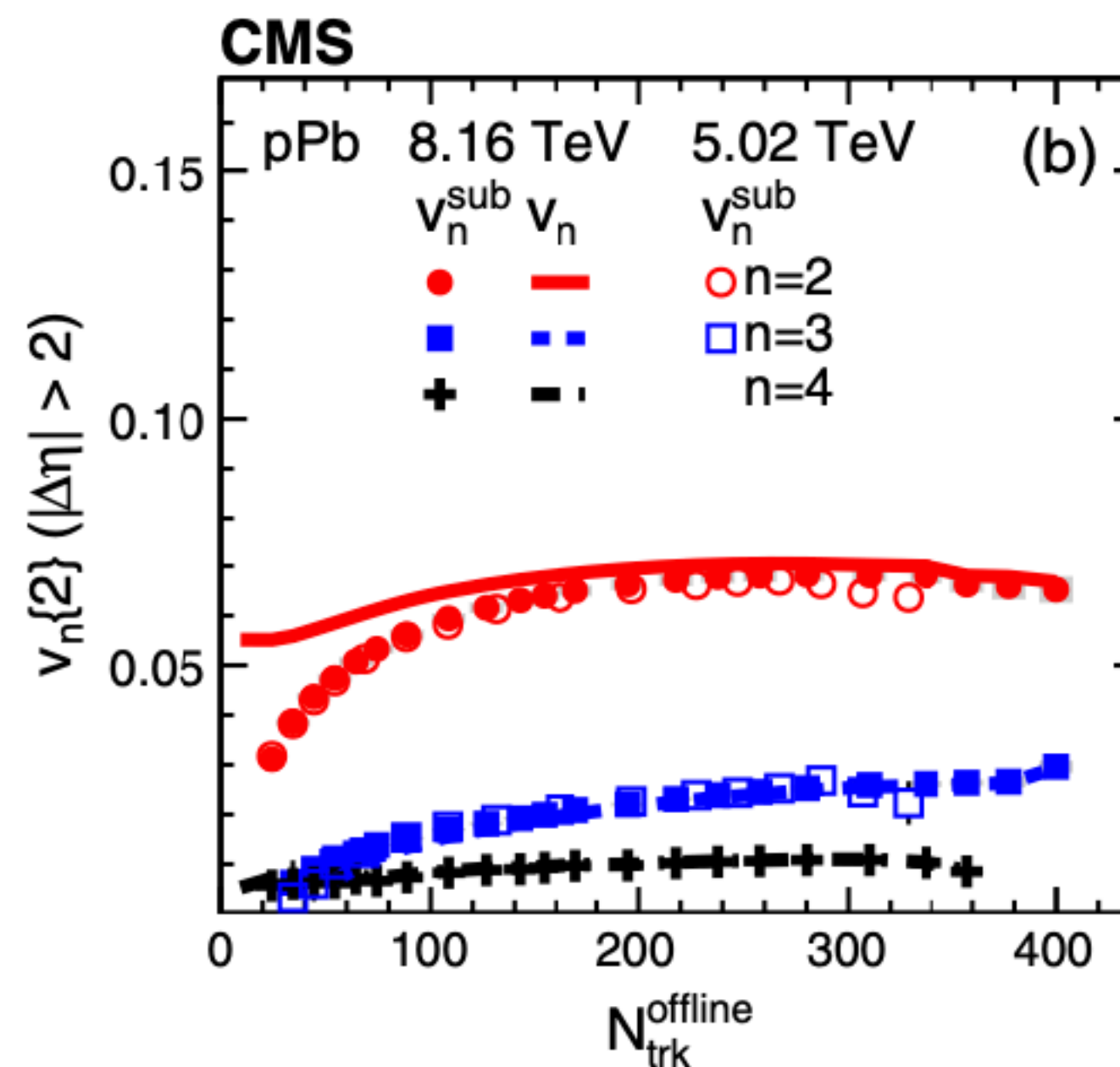
$$\text{Volume} \sim N_{\text{ch}} \rightarrow \langle N_{\text{ch}} \rangle^{-1/3} \sim \frac{1}{R}$$



Ordering of flows (v_2, v_3) follows the ordering of shapes (ϵ_2, ϵ_3) [@RHIC]



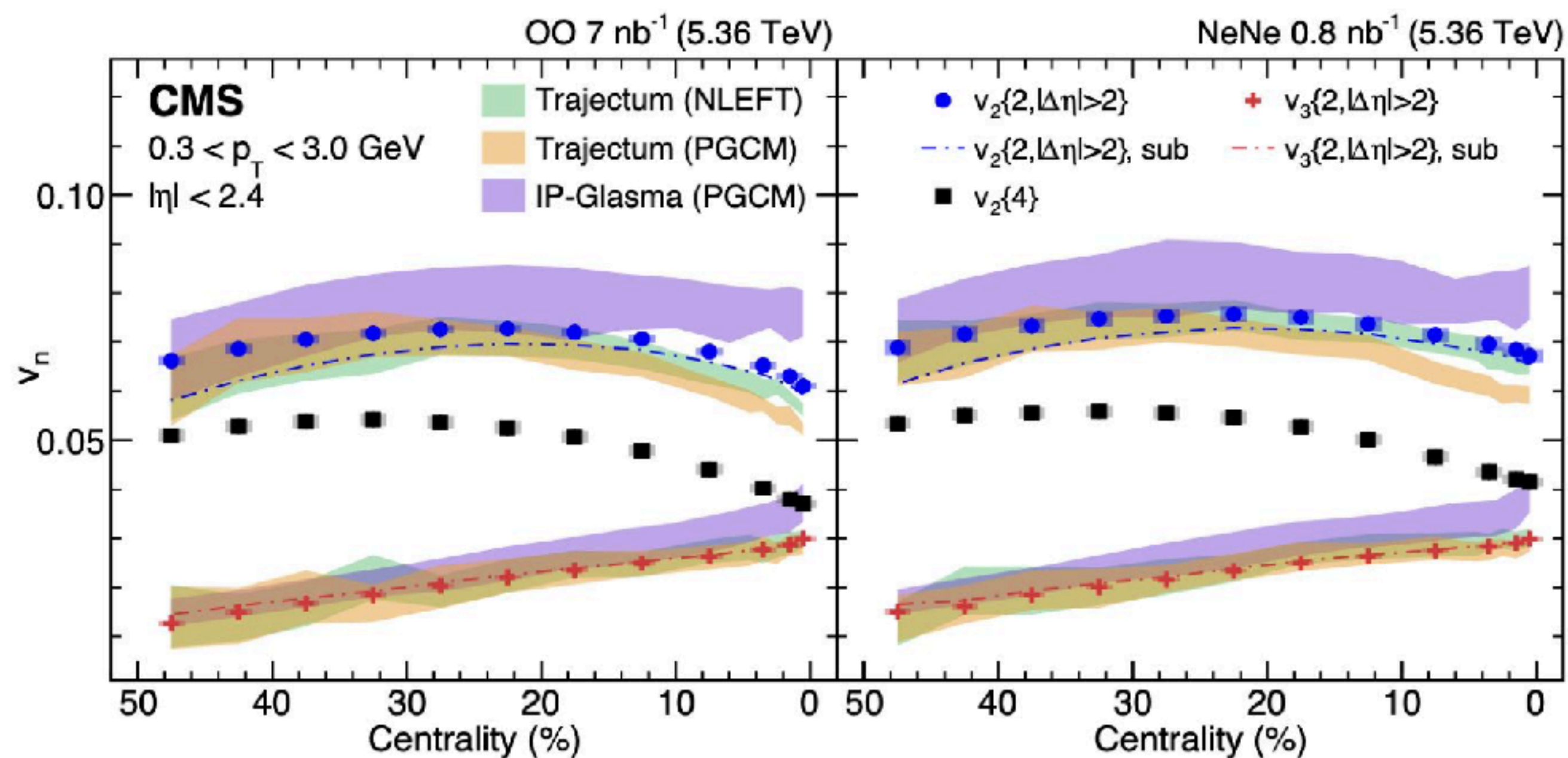
The QGP droplets created in collisions of p+Au, d+Au, ^3He +Au have characteristically different shapes resulting in different emission patterns.



Magnitude and ordering of flows (v_2, v_3, v_4) in pPb similar to PbPb [@LHC]

Yes, O-O collisions make QGP

Observed at RHIC

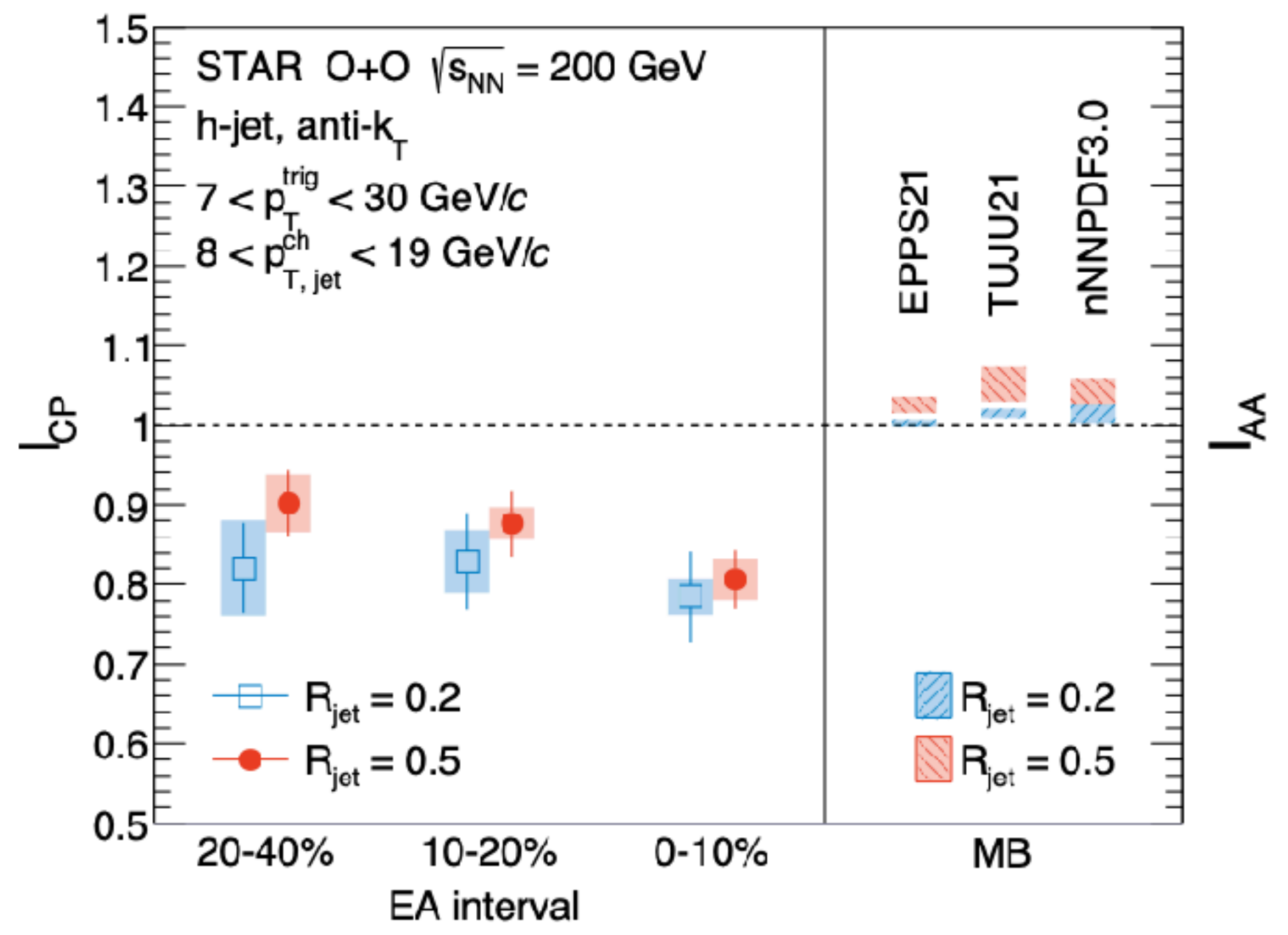


← Decreasing overlap region

[arXiv.2510.02580](https://arxiv.org/abs/2510.02580)

LHC data confirm predictions of hydrodynamic flow from QGP formation and close the gap between Pb-Pb and p-Pb.

STAR - 2604.13935



First measurement of parton energy loss in small systems (O+O) by STAR

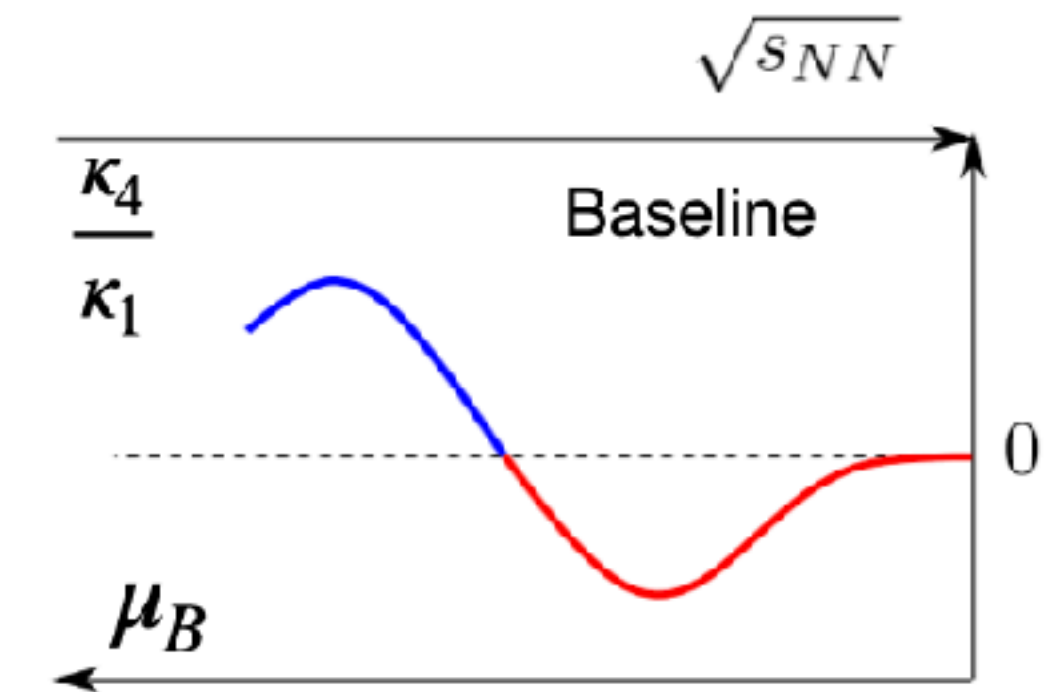
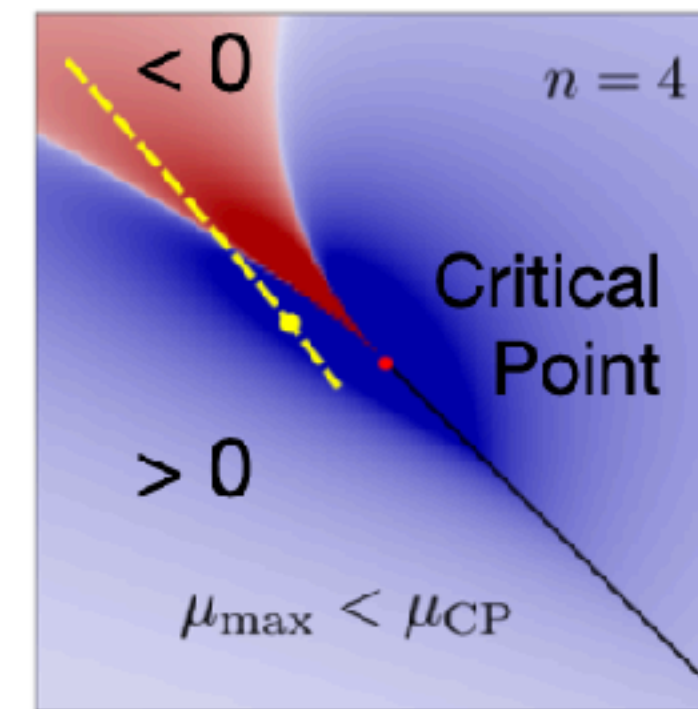
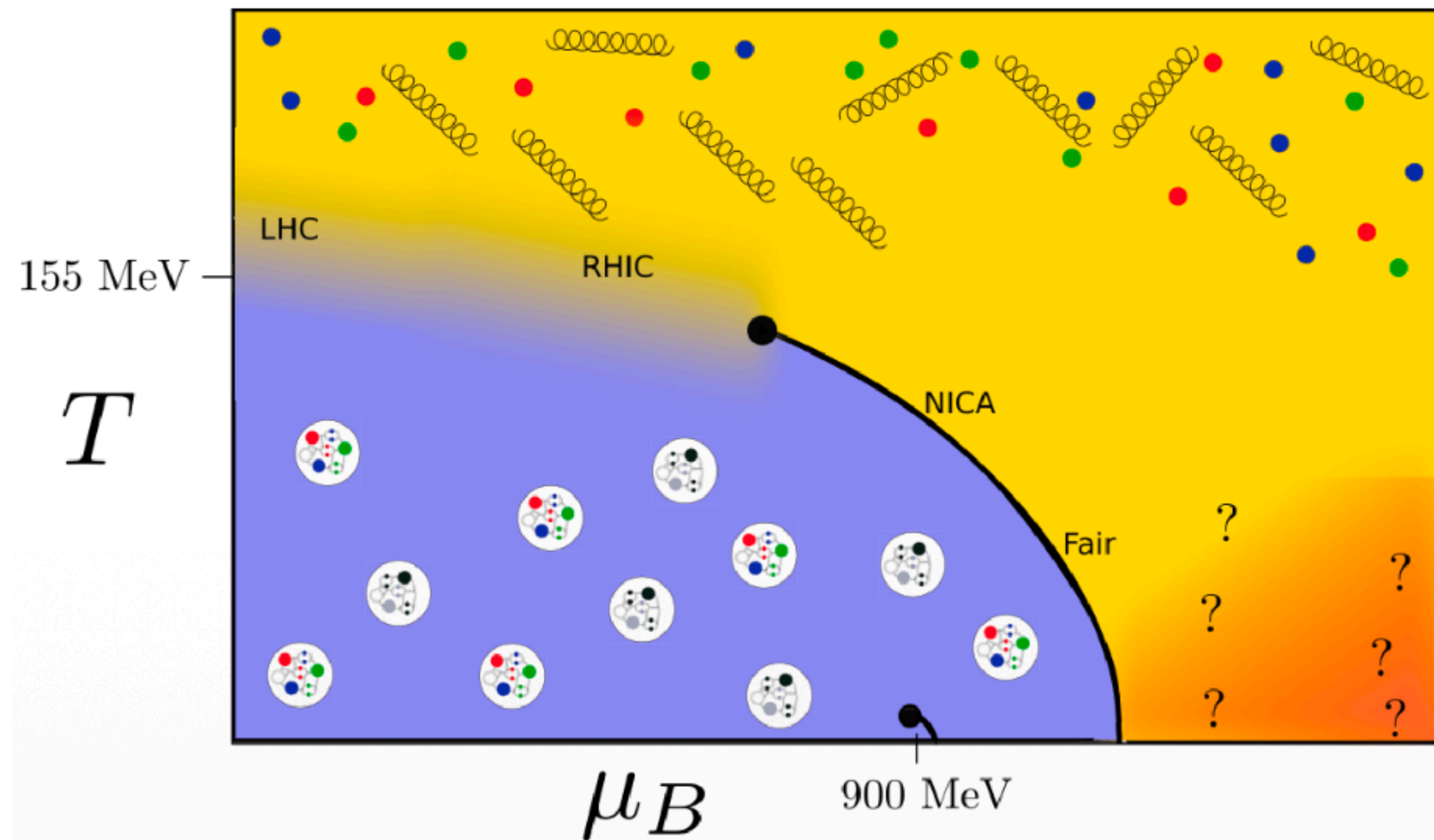
Momentum loss out of cone: 0.77 GeV/c

Is there a QCD critical point?

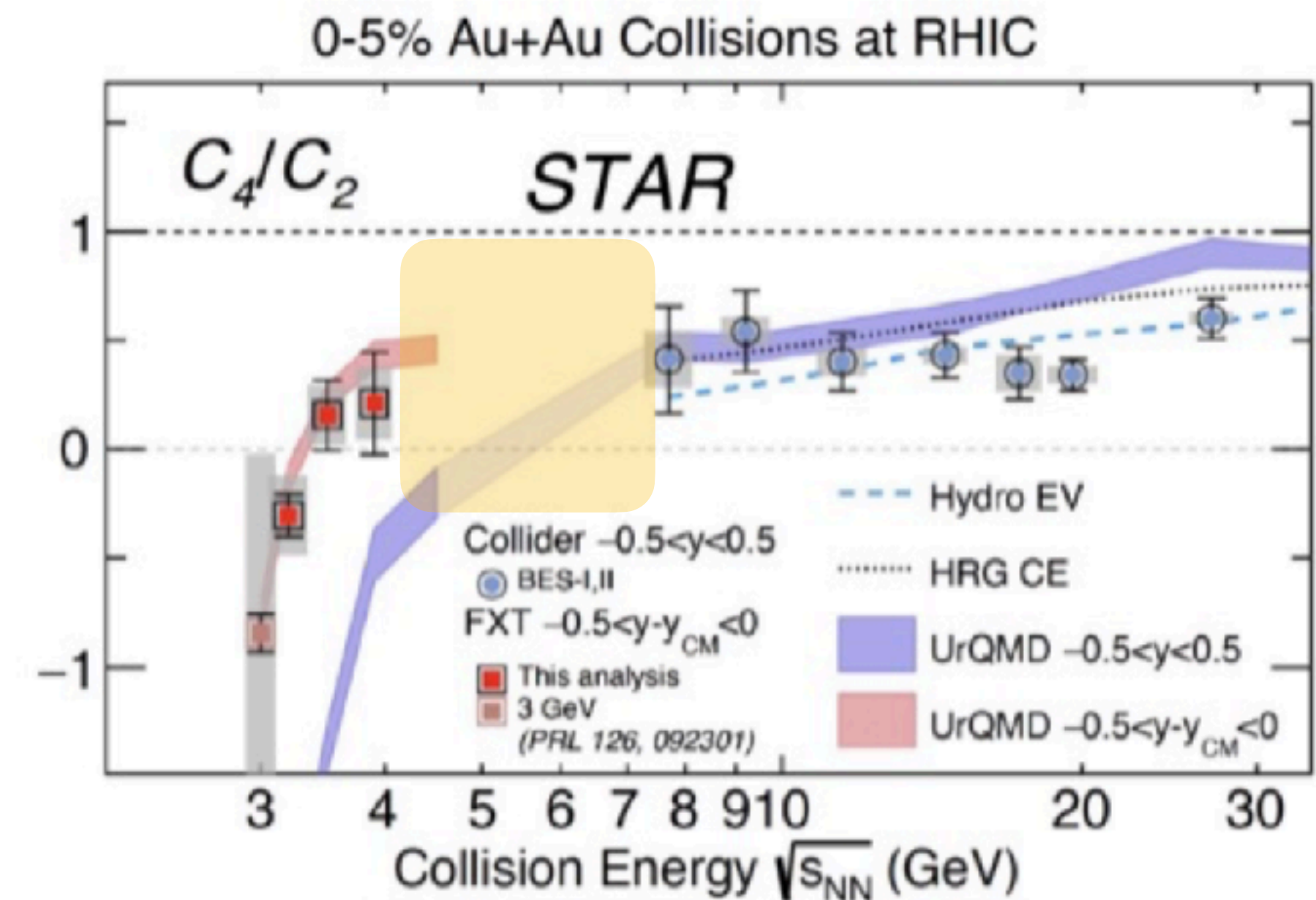
To Be Decided by RHIC

Schematic QCD phase diagram / critical point and experimental facilities

J. Guenther - CPOD 20267

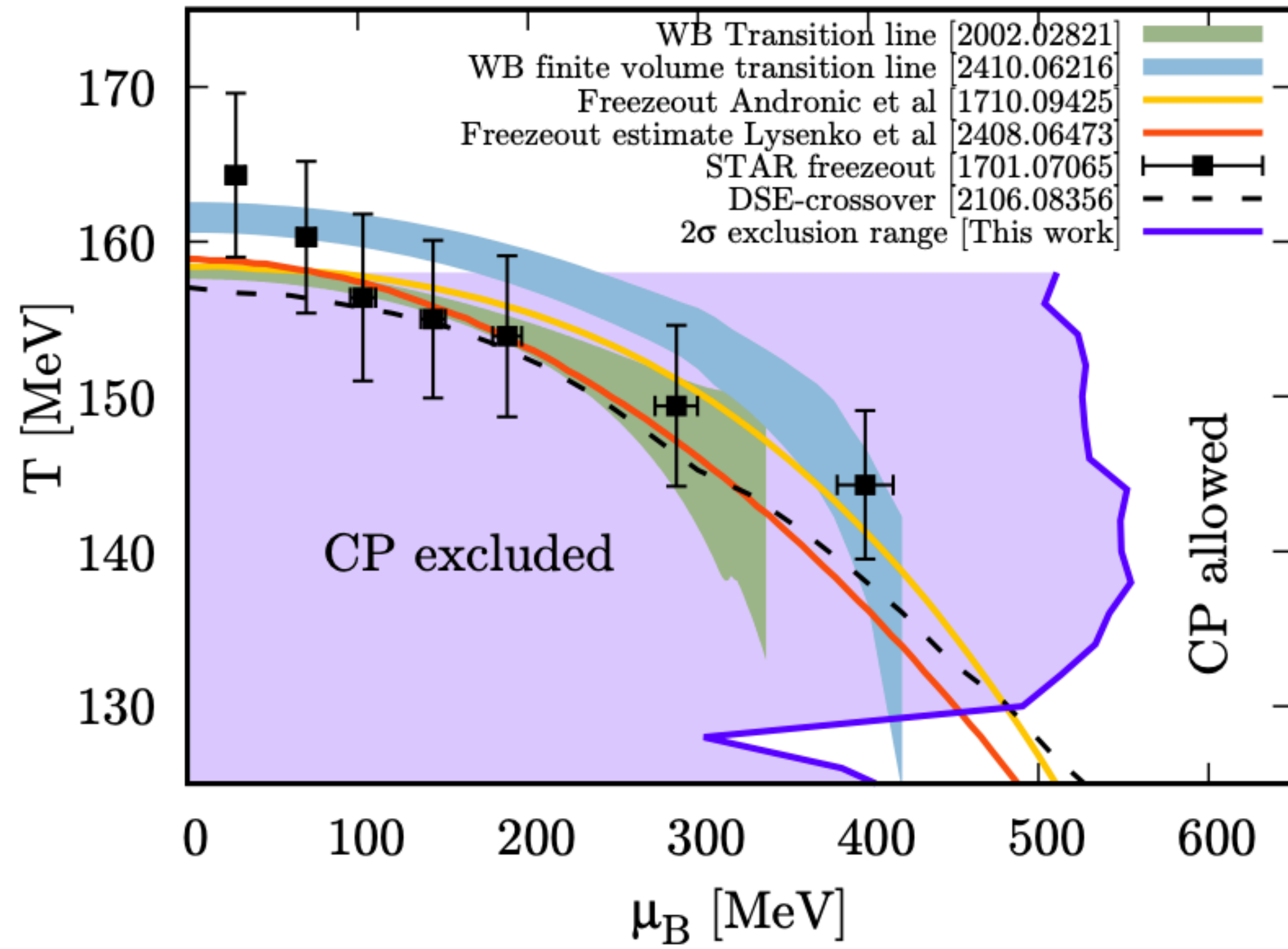


Best signal: Kurtosis of net baryon fluctuations

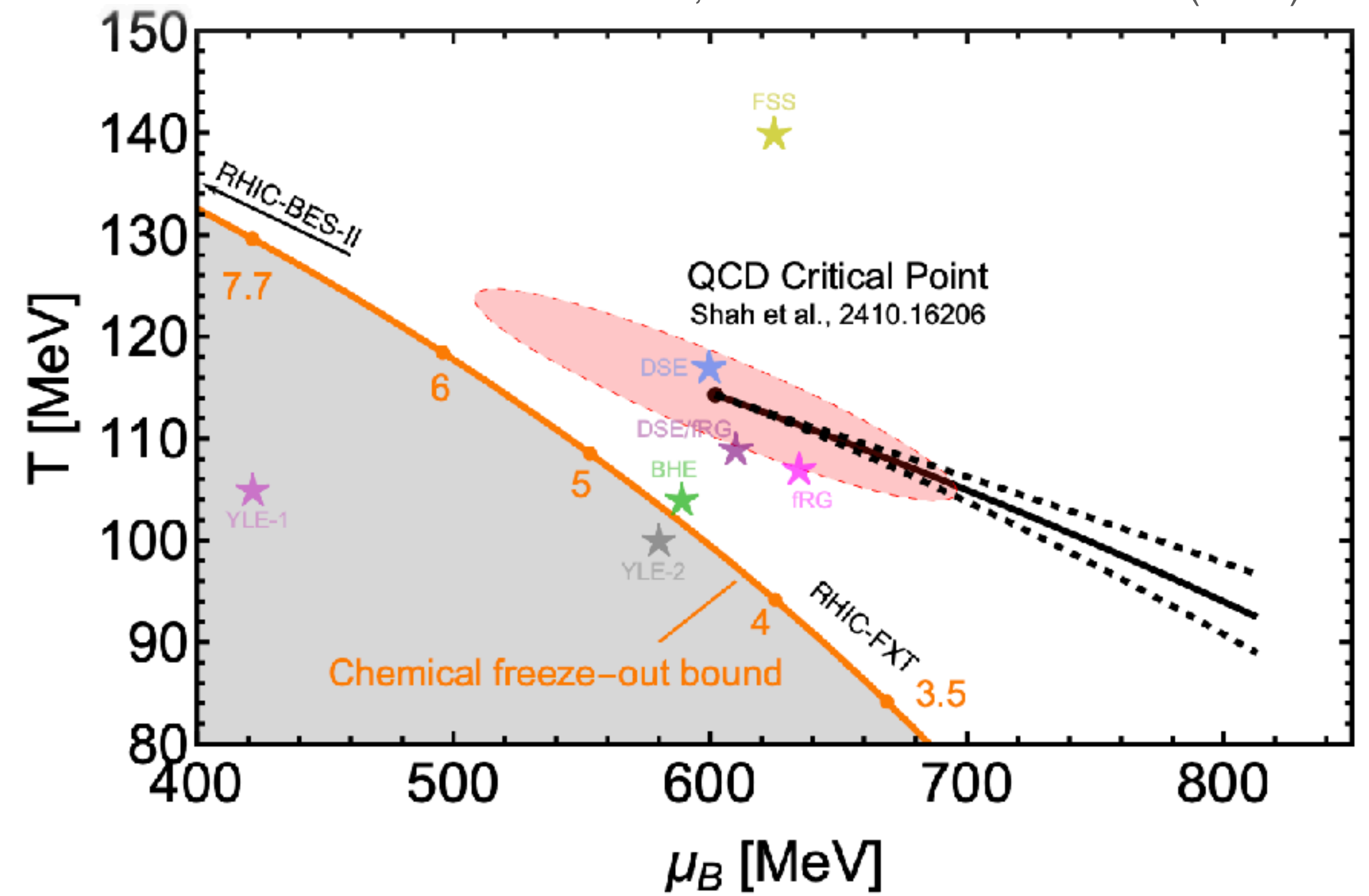


QCD critical point location?

S. Borsanyi et al. - 2502.10267



V. Vovchenko and V. Koch, J.Subatomic Part.Cosmol. (2025)



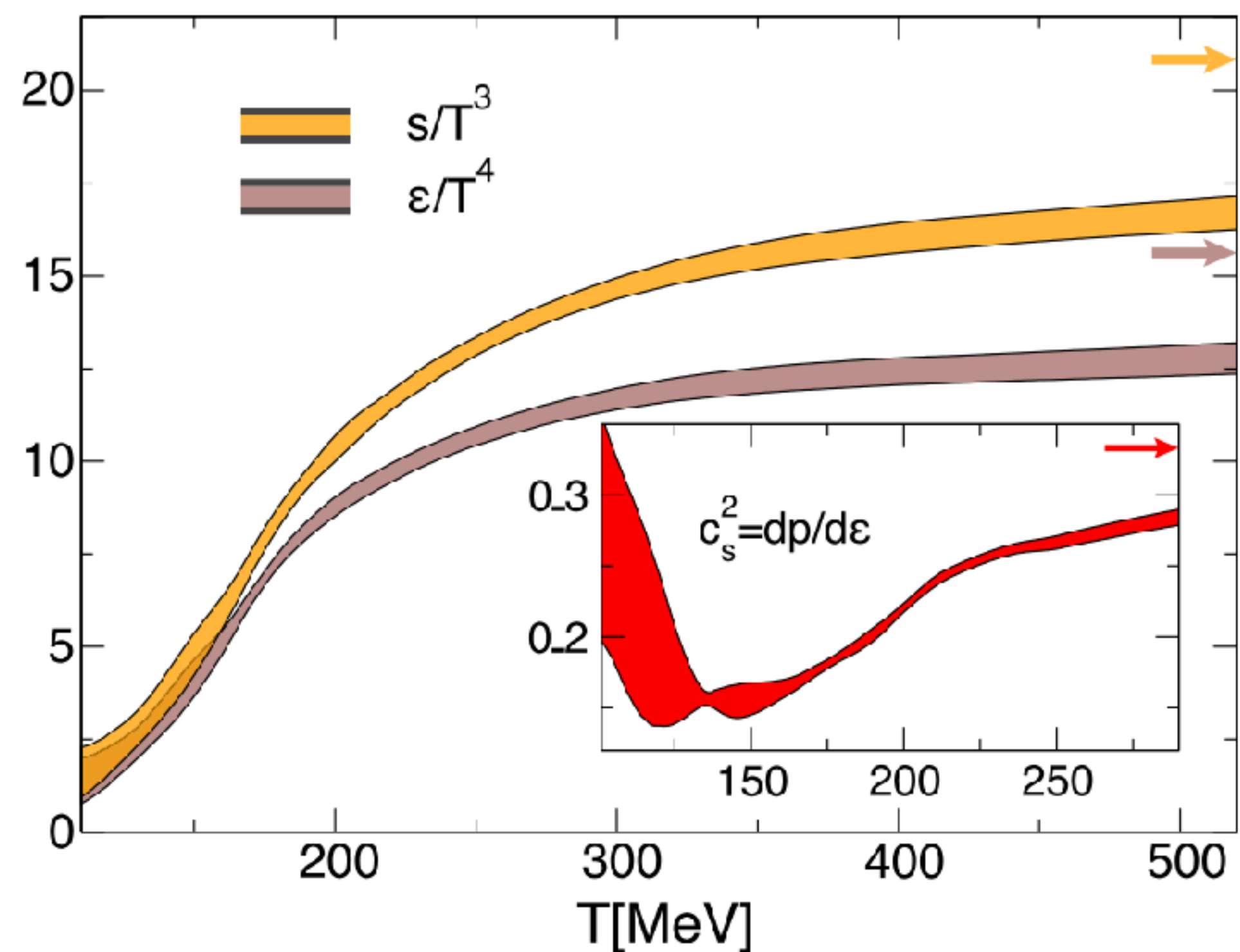
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- **Open question:** Which mechanism creates a liquid without short-range repulsion?
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- **Open question:** Is there a critical point in the QCD phase diagram?

Backup slides

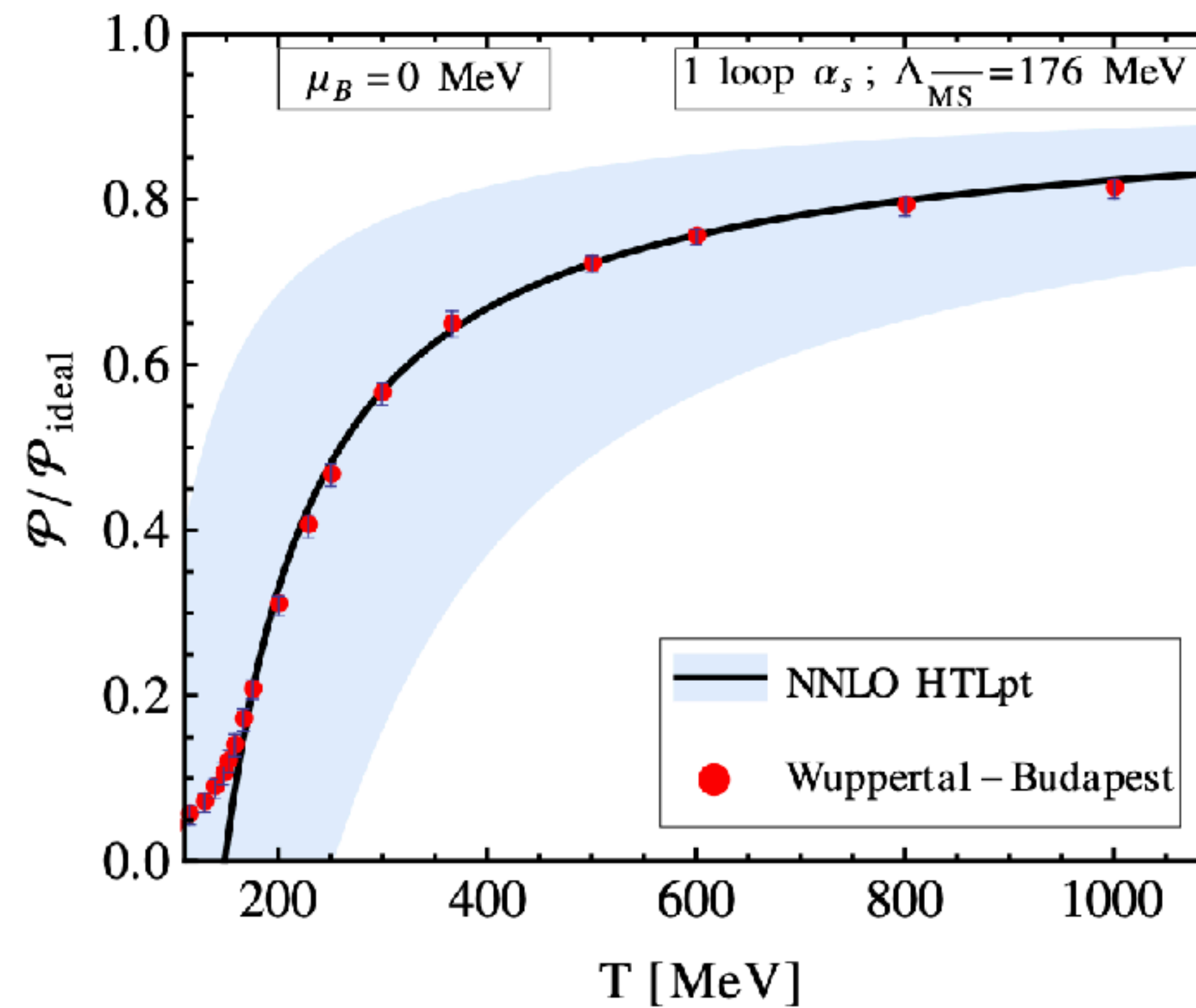
QGP equation of state

$N_f = 3$ equation of state



Borsanyi et al., PLB 730 (2014) 99

HTL resummed perturbation theory at NNLO



J.O.Andersen et al., 1411.1253 [hep-ph]

EOS at high μ

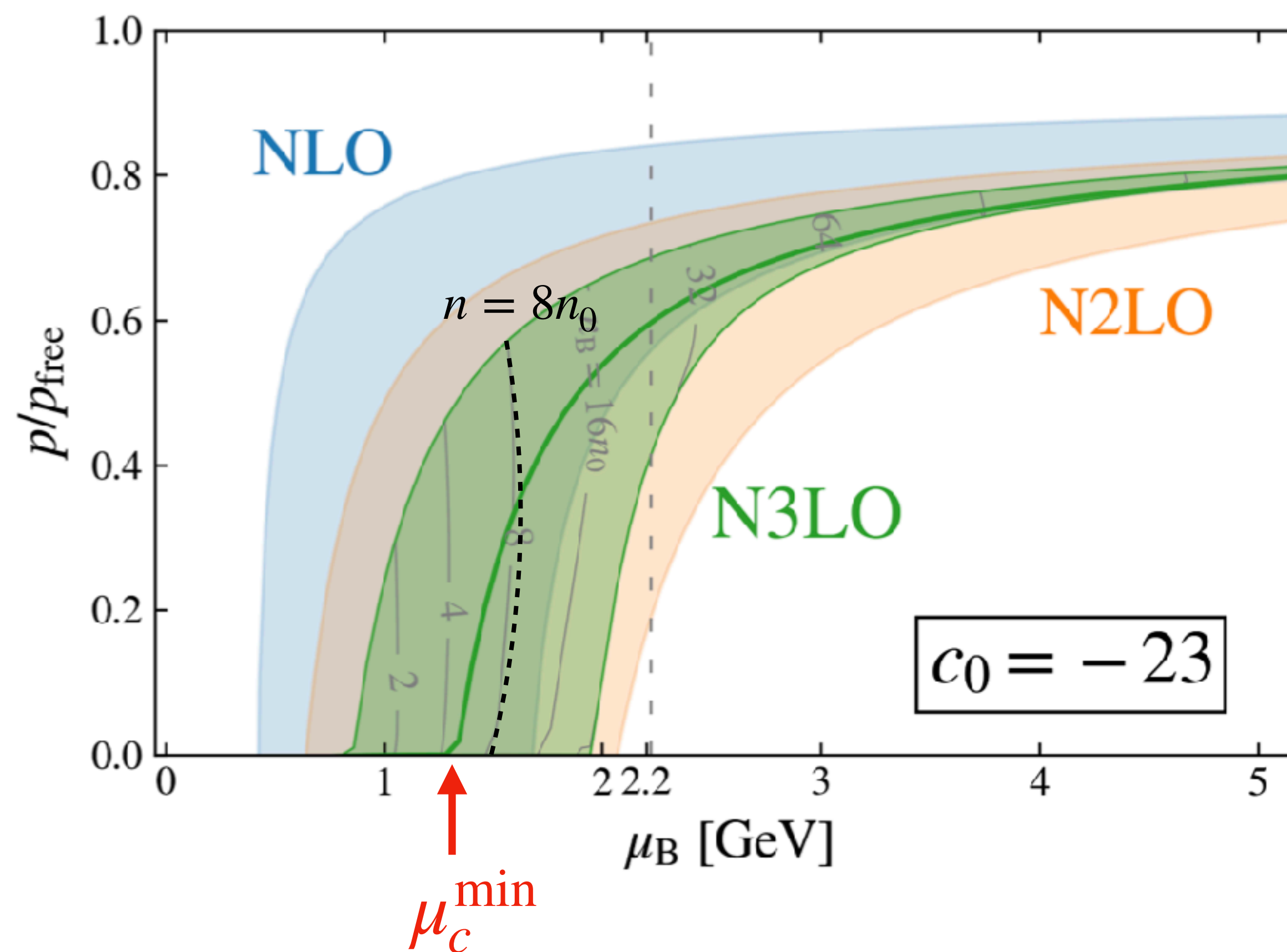
T. Gorda, et al., PRL 131 (2023) 181902

EOS at N3LO = $O(\alpha_s^3 \ln \alpha_s)$

$$p^m = \left(\text{diagram 1} + \text{diagram 2} + \text{diagram 3} + \text{diagram 4} + \text{diagram 5} \right) + \left(\text{diagram 6} + \text{diagram 7} + \text{diagram 8} + \text{diagram 9} \right)$$

$$\frac{p}{p_{\text{free}}} \simeq 1 - 2 \left(\frac{\alpha_s}{\pi} \right) - 3 \left(\frac{\alpha_s}{\pi} \right)^2 \left[\ln \left(3 \frac{\alpha_s}{\pi} \right) + 3 \ln X + 5.0021 \right] + 9 \left(\frac{\alpha_s}{\pi} \right)^3 \left[c_{3,2} \ln^2 \left(3 \frac{\alpha_s}{\pi} \right) + c_{3,1}(X) \ln \left(3 \frac{\alpha_s}{\pi} \right) + c_{3,0}(X) \right]$$

Bayesian analysis of “most likely” value of $c_{3,0}$

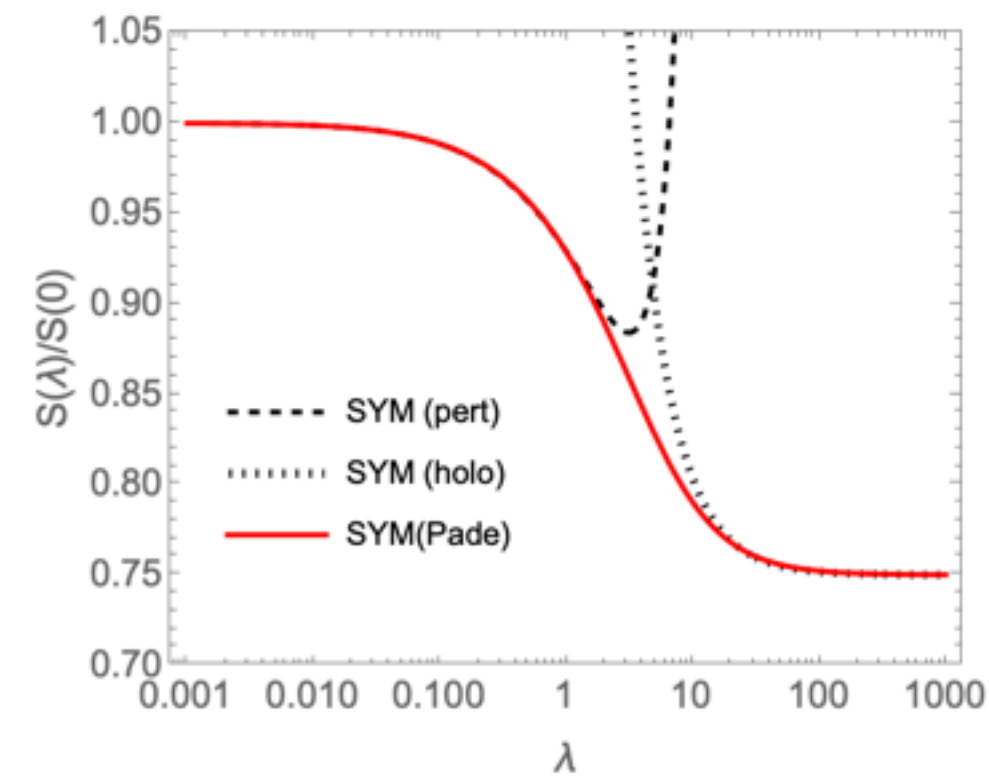


Weak vs. Strong Coupling in $N = 4$ SYM

BM - 2507.06845

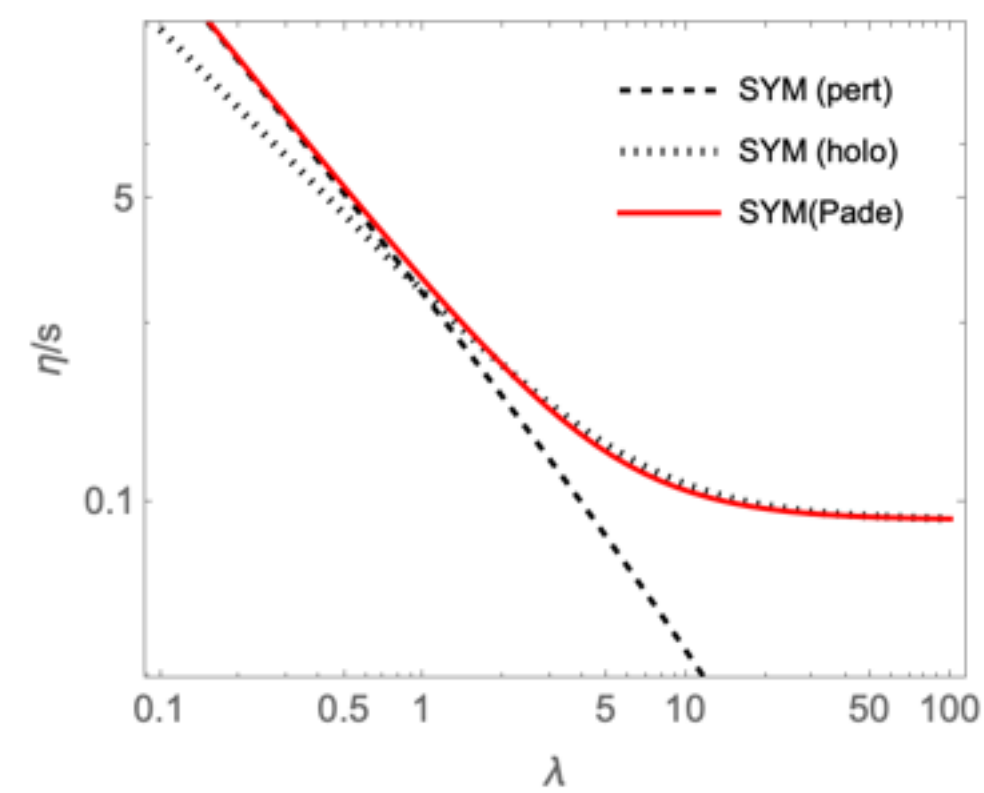
Entropy (normalized)

$$s(\lambda)/s_0$$



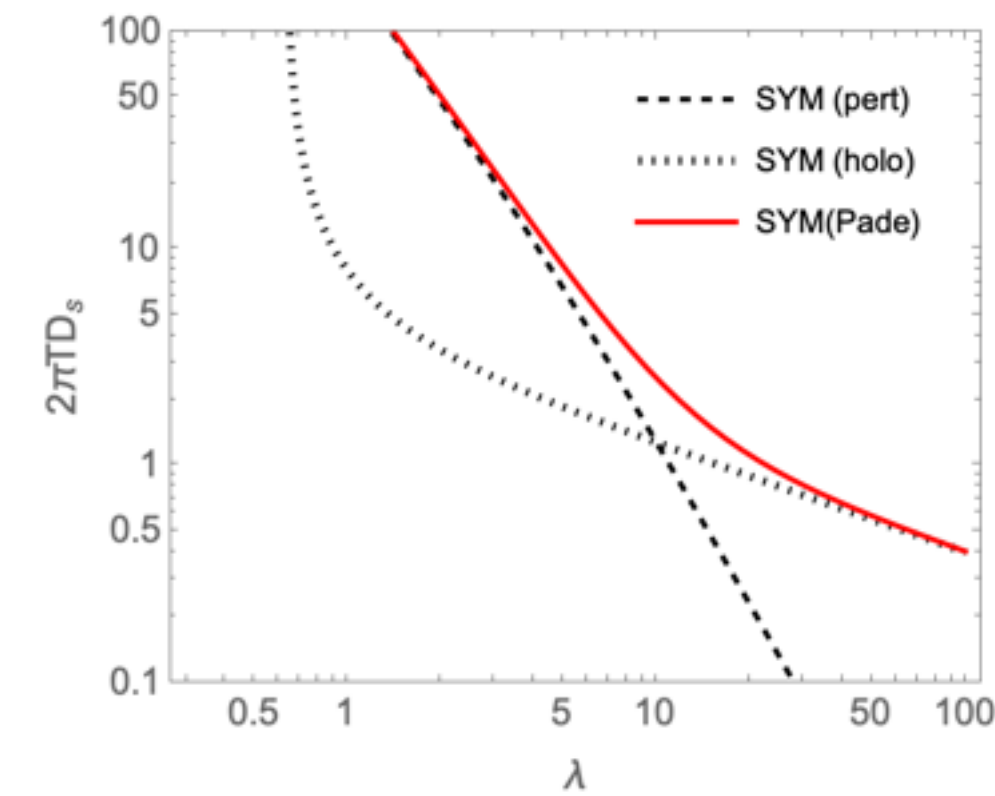
Kin. shear viscosity

$$\eta/s$$



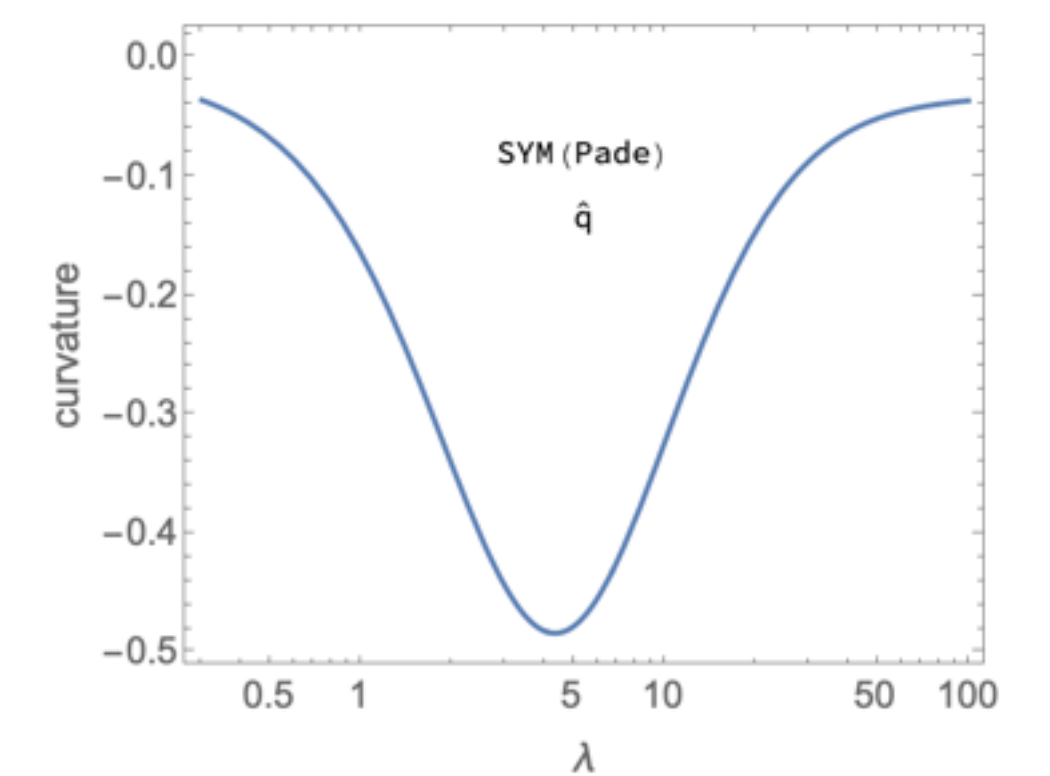
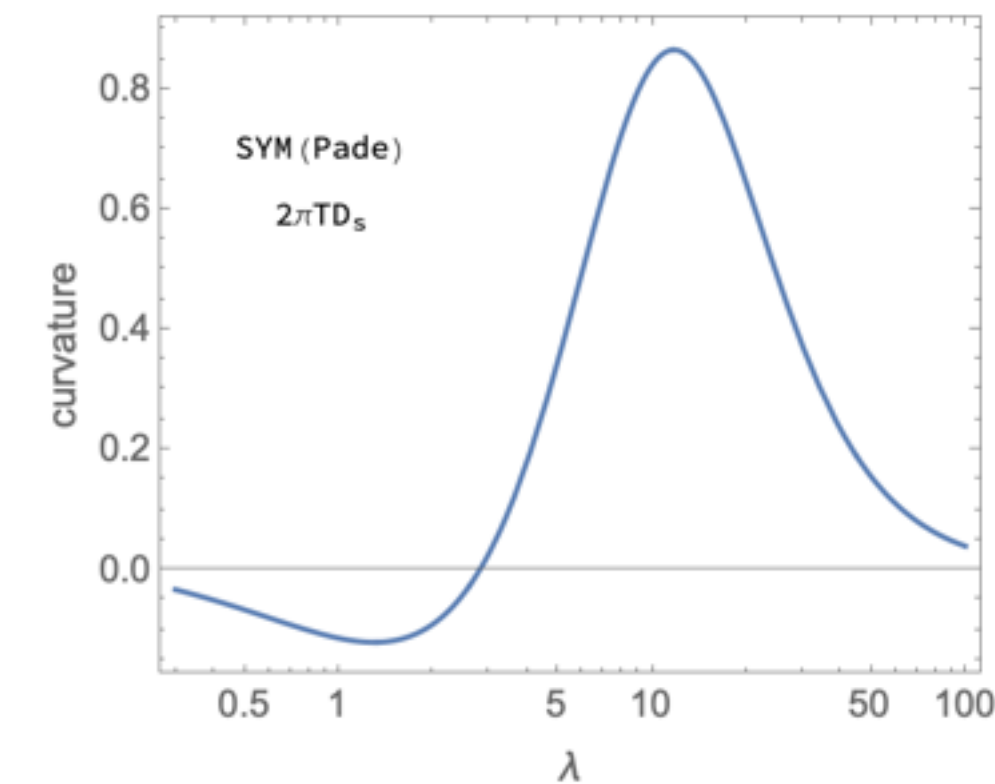
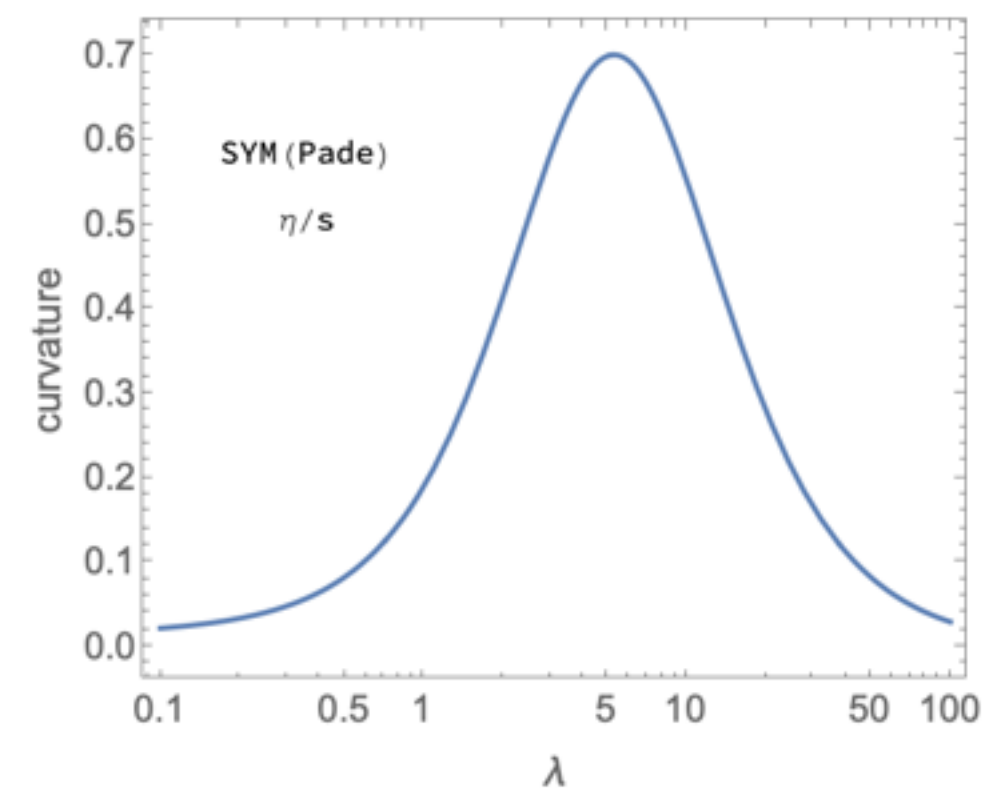
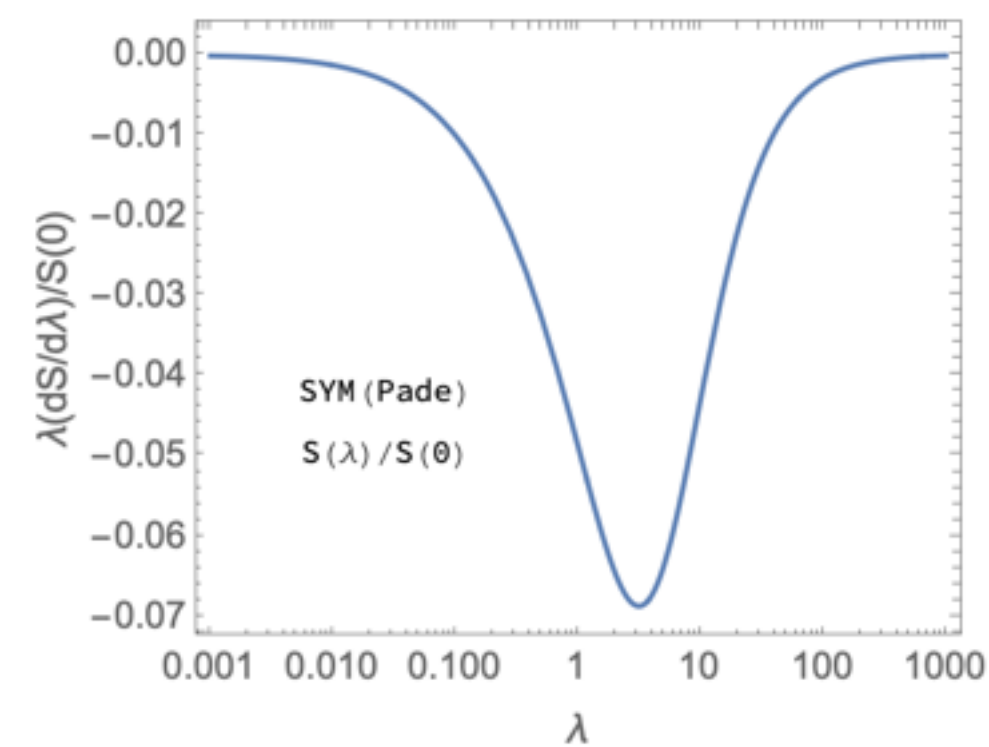
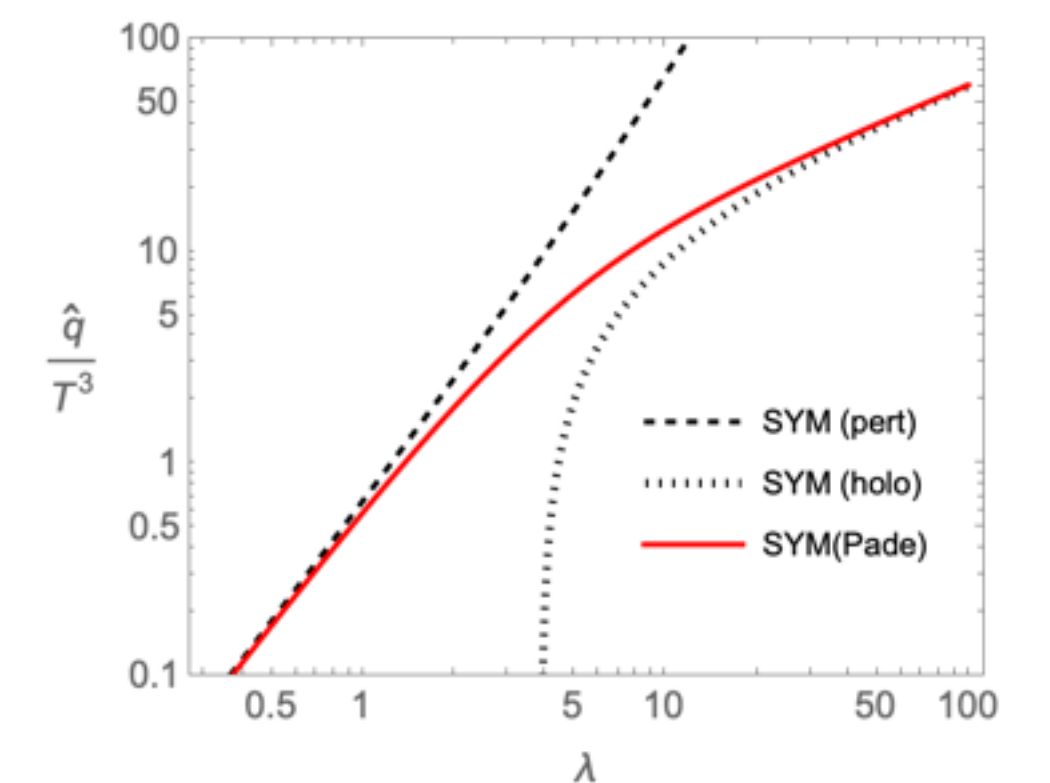
Diffusion constant

$$2\pi TD_s$$



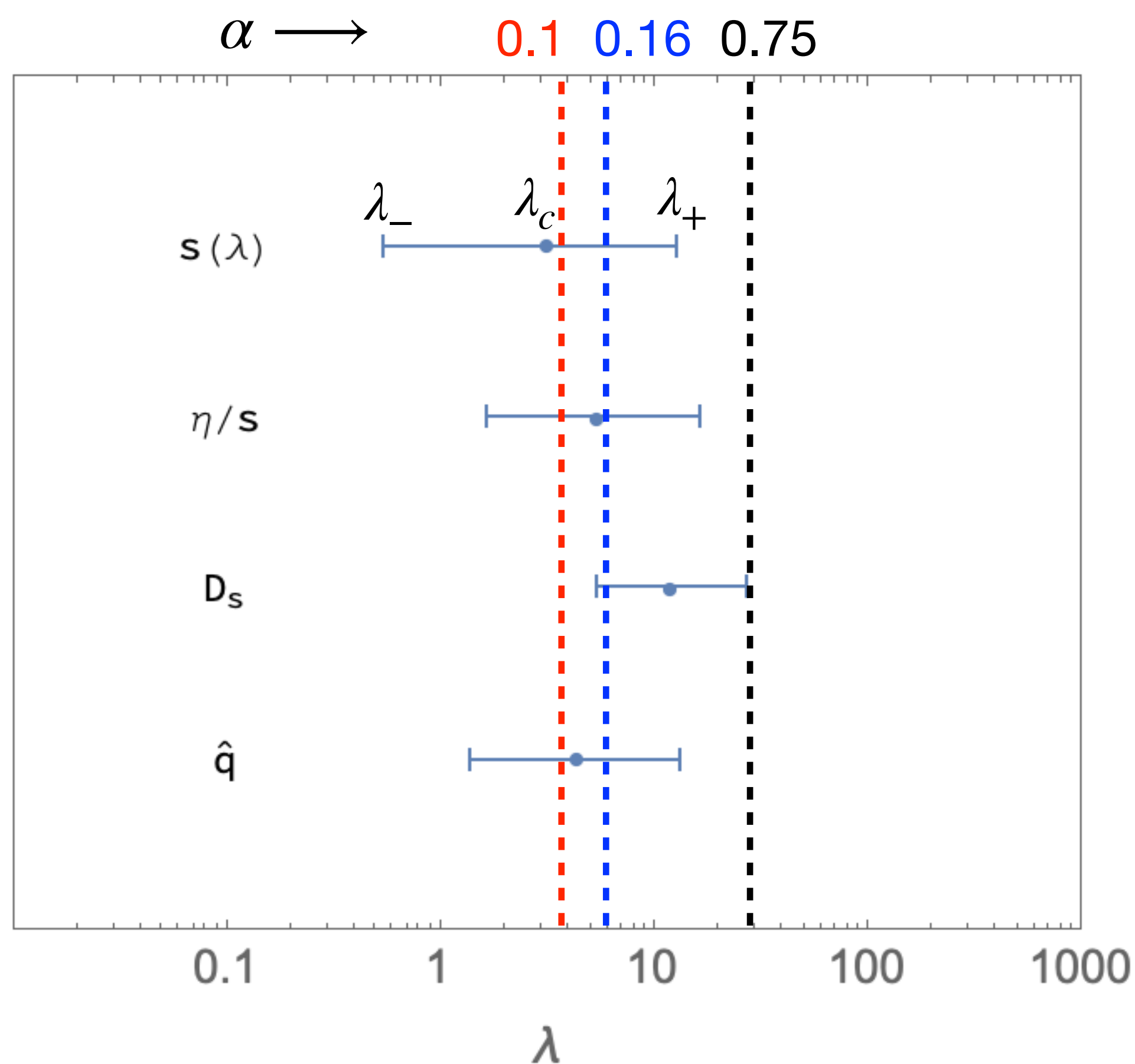
Momentum broadening

$$\hat{q}/T^3$$

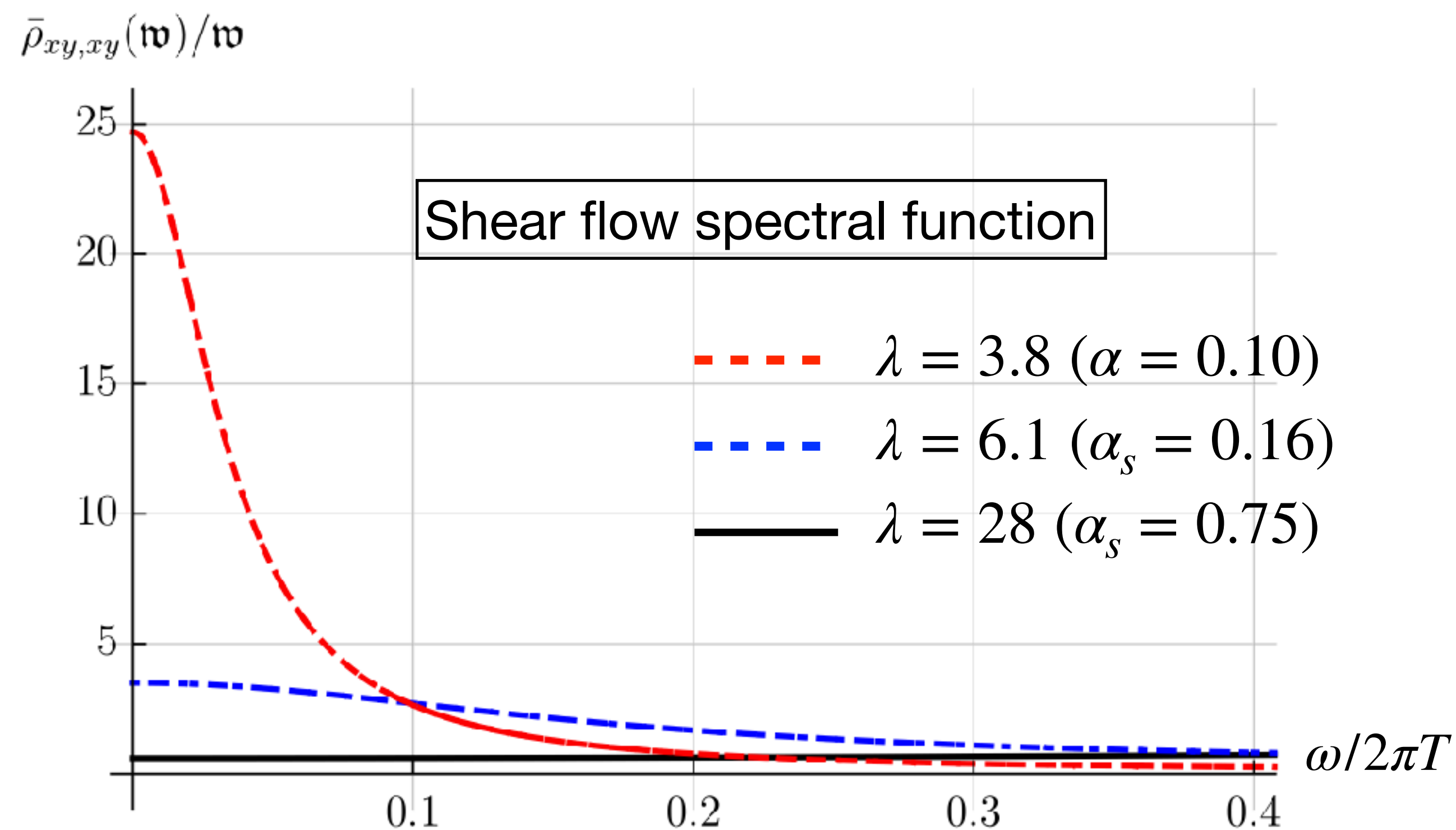


Emergence of quasiparticles in AdS/CFT

Low-energy peak emerging in strong coupling expansion for $\lambda < 4$ reflects quasiparticle transport.



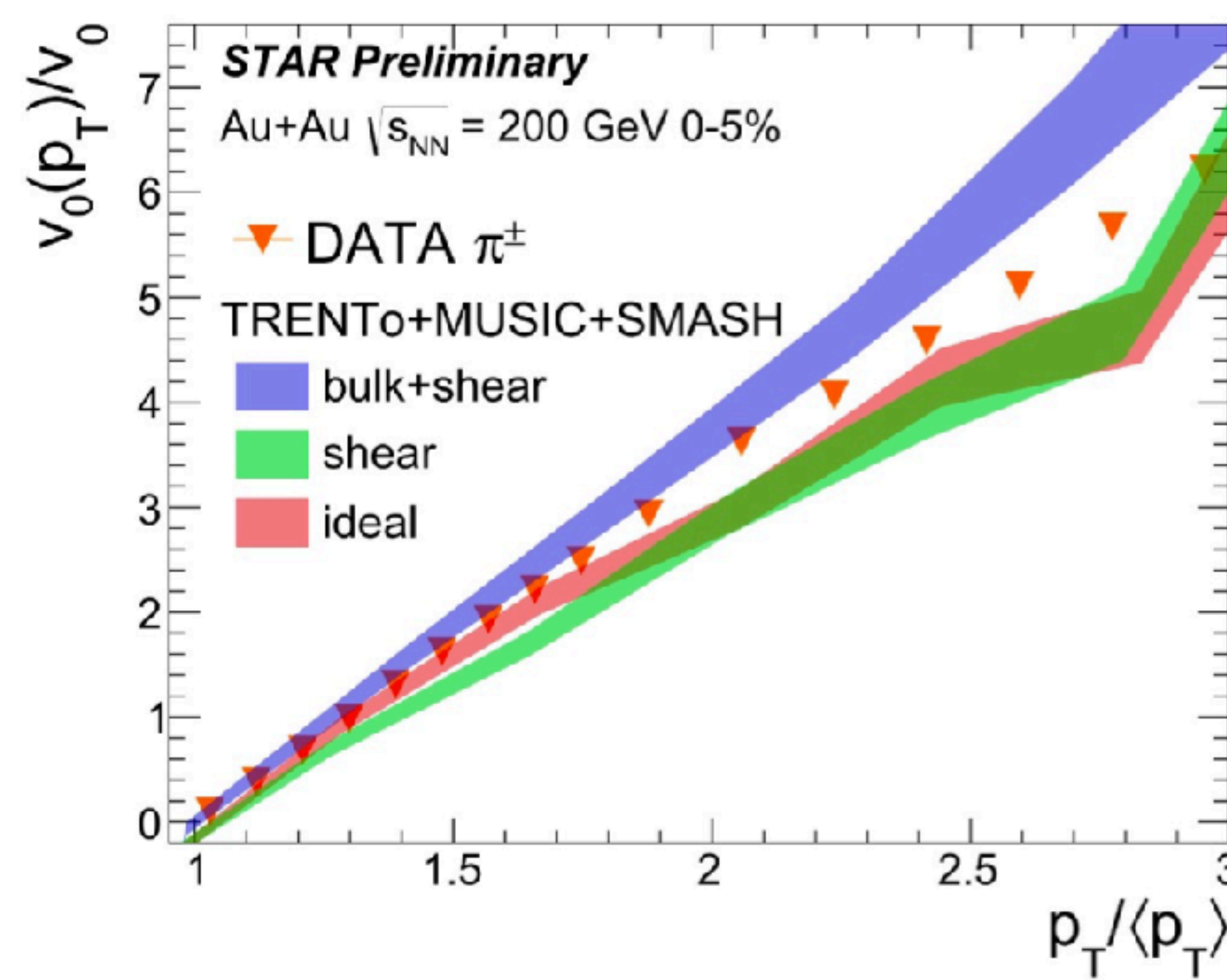
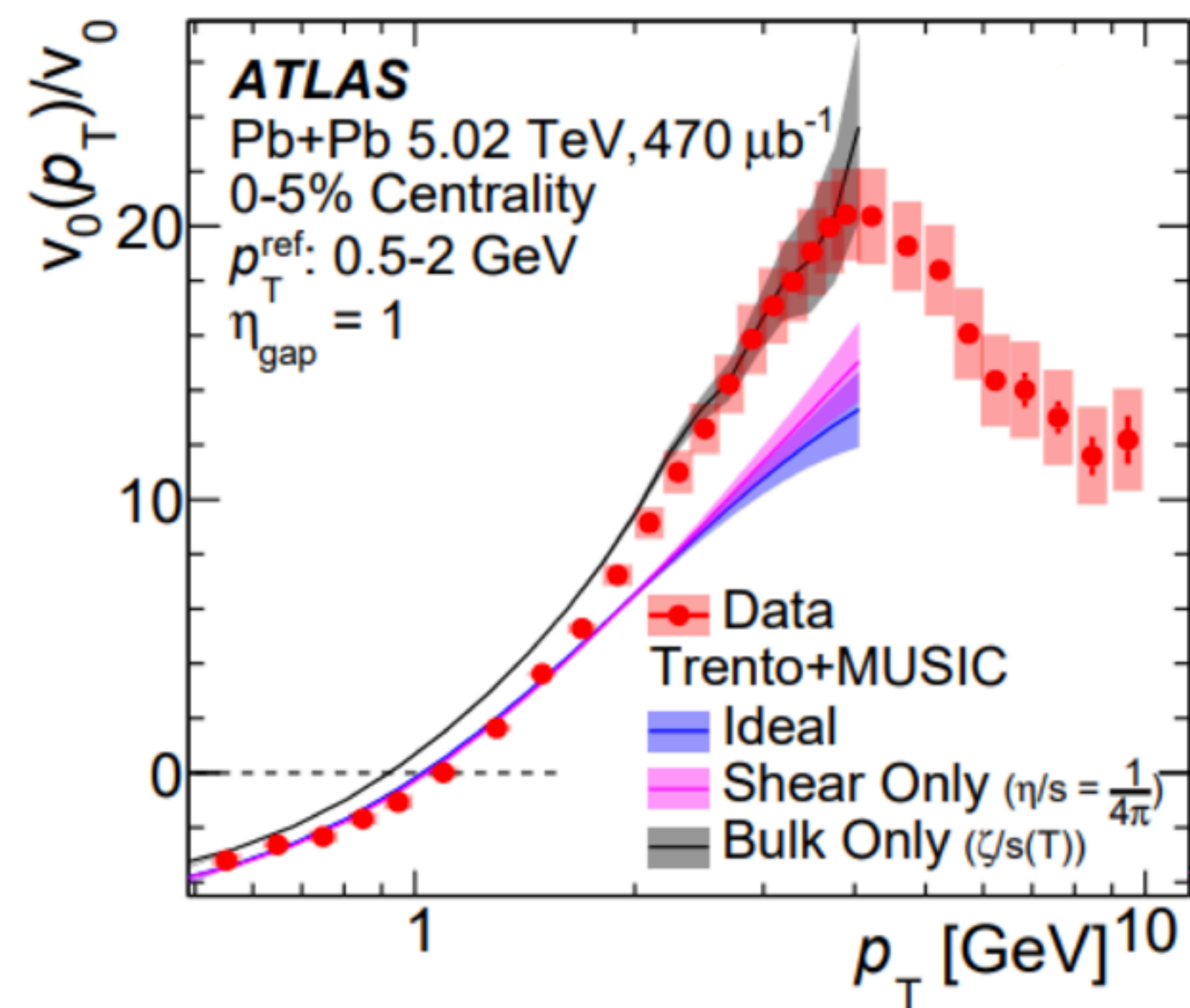
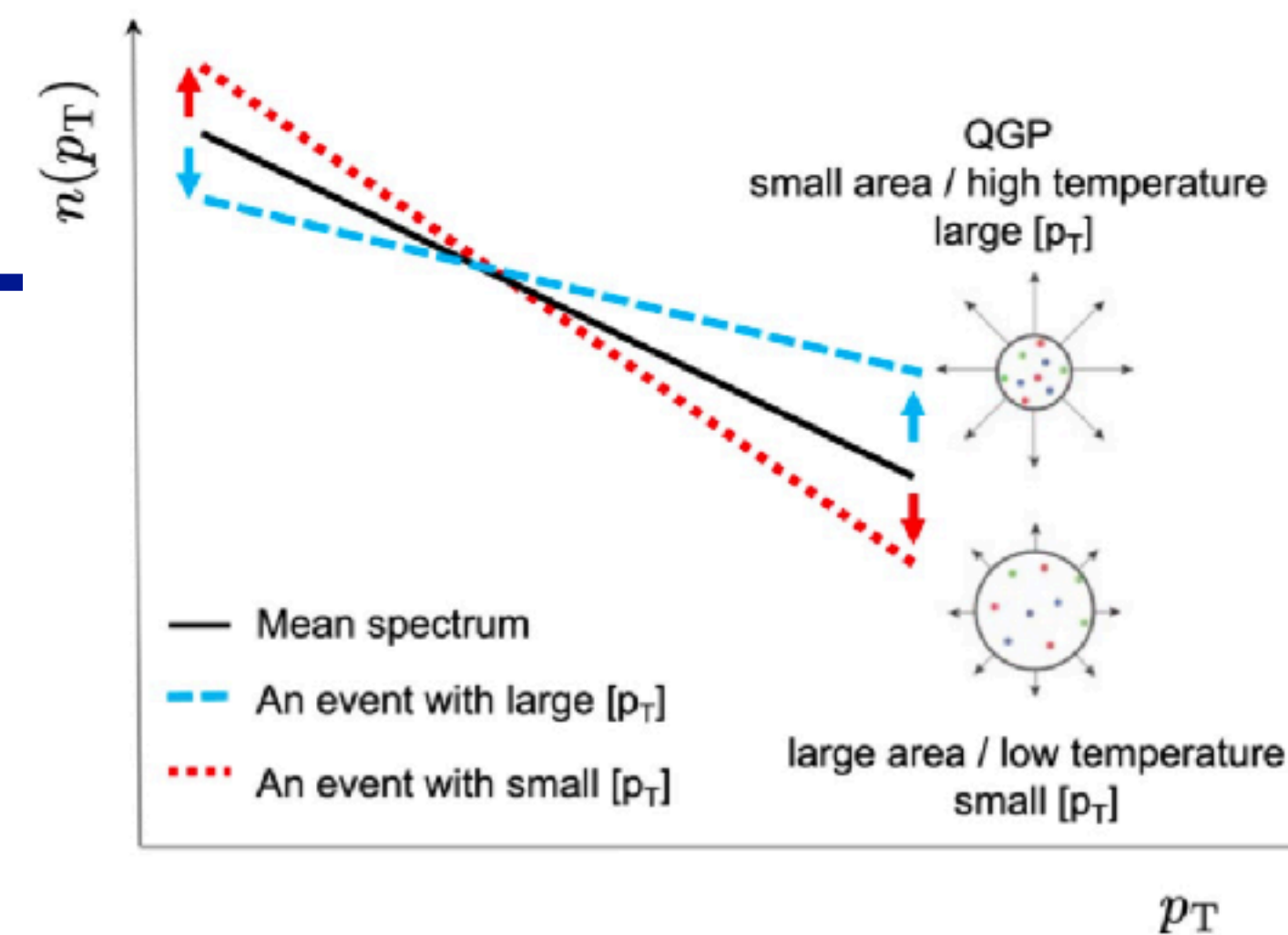
Casalderrey-Solana et al. - 1806.10997



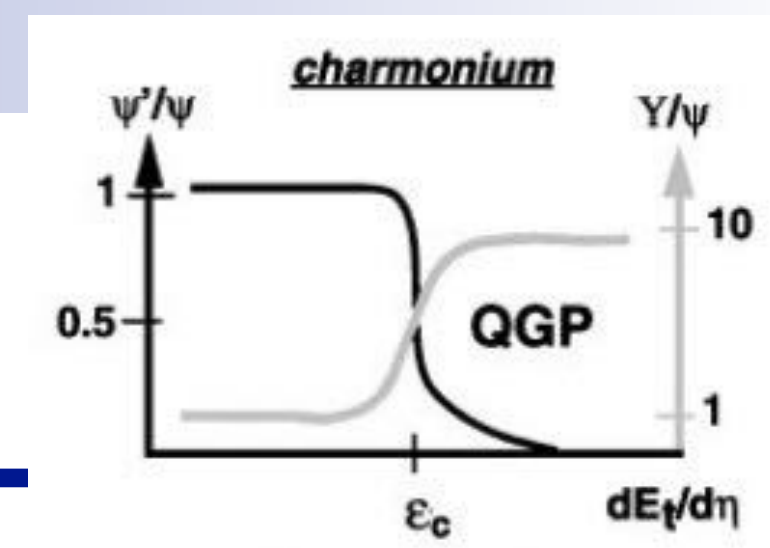
New observable: $v_0(p_T)$

Radial flow - p_T fluctuations

$$\frac{\langle \delta n(p_T) \delta [p_T] \rangle}{\langle n(p_T) \rangle \langle [p_T] \rangle} = v_0(p_T) v_0$$

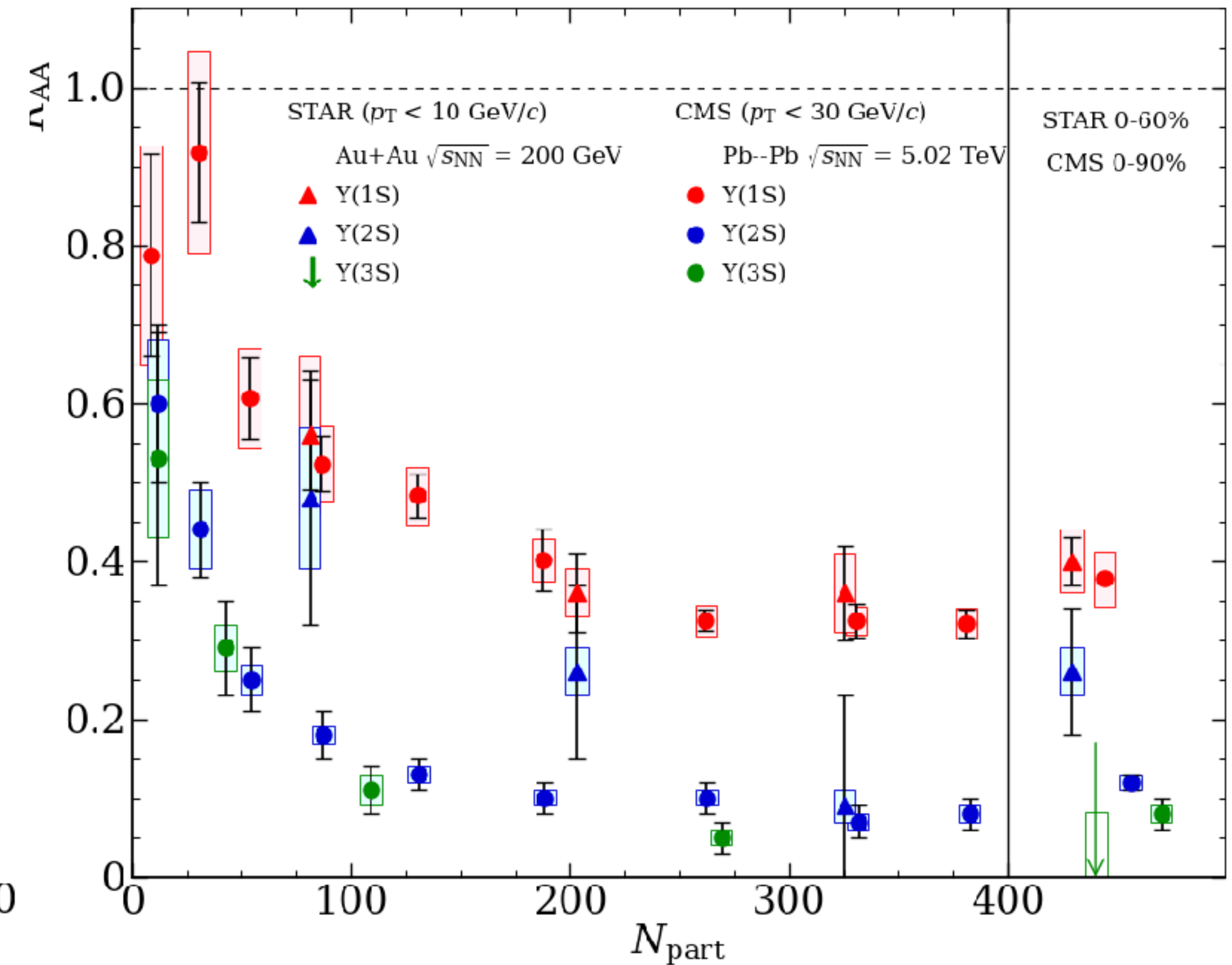
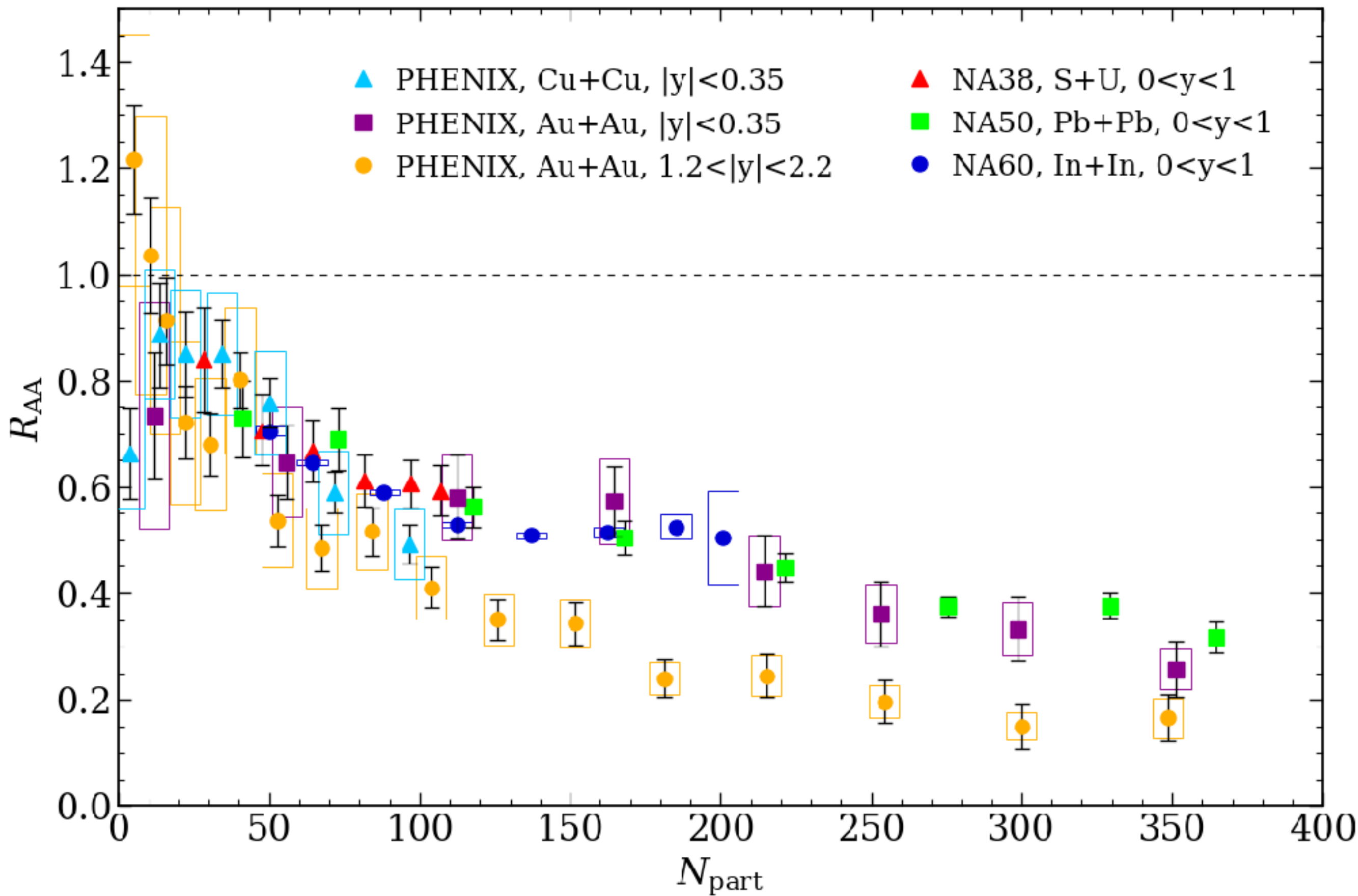


Quarkonia – Sequential Suppression



RHIC: J/ψ (ψ' is even more suppressed)

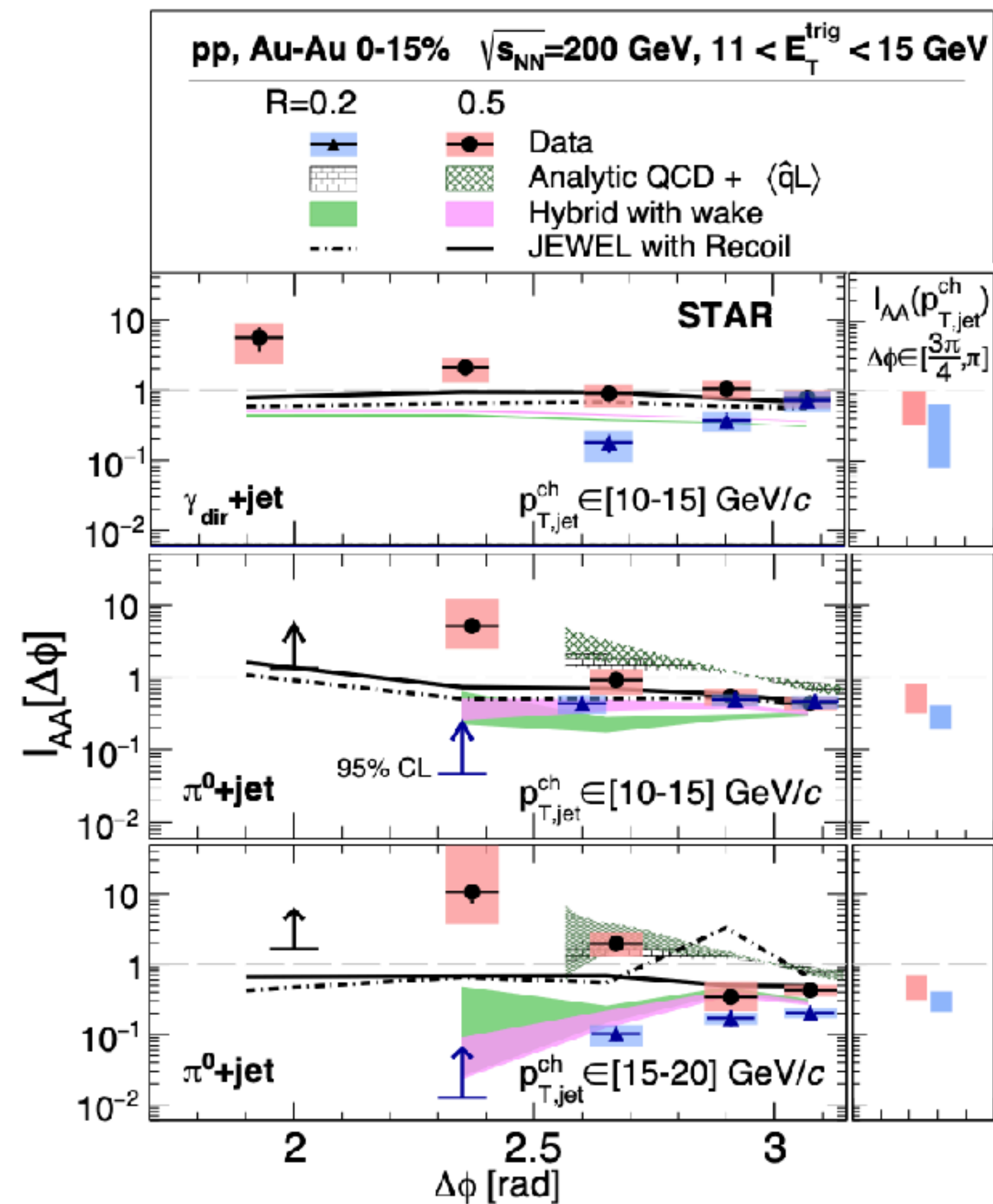
RHIC/LHC: Y(1s), Y(2s), Y(3s)



Jet-medium response

Observed at RHIC

STAR - 2505.05789



Acoplanarity strongly enhanced in π^0 and γ -triggered jets for $R = 0.5$ and not for $R = 0.2$.

Strong evidence for diffuse jet-QGP medium response but no evidence yet for quasiparticle scattering.