



Quark-Gluon Plasma @ 50

Status and open questions

Berndt Mueller

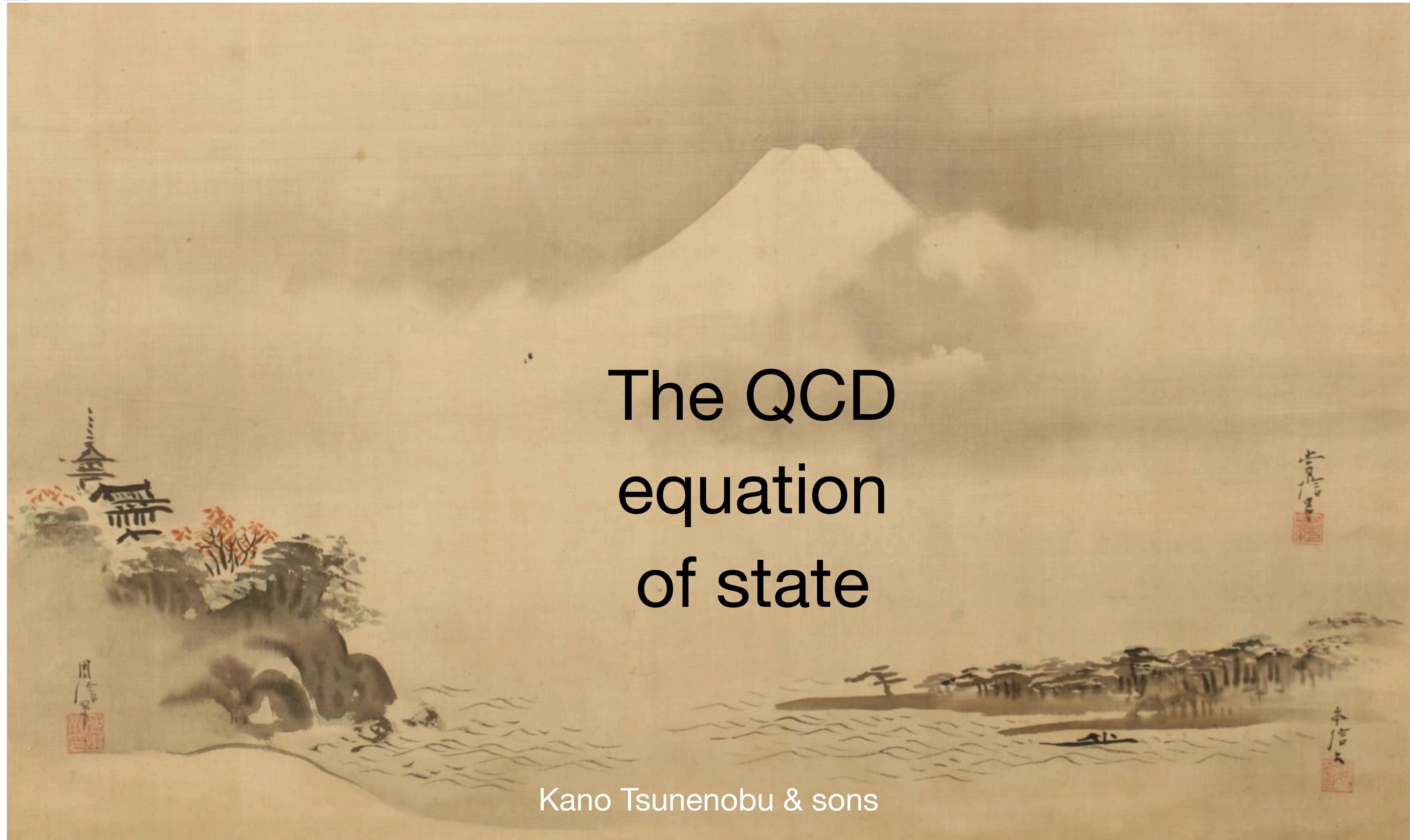
TNP 2026

April 20, 2026

Jiaoxi, Yilan, Taiwan

Outline

- QCD equation of state
- QGP structure
- The liquid QGP
- QCD critical point?
- Polarization & vorticity
- Thermalization
- Transport properties
- Jet showers
- Medium response

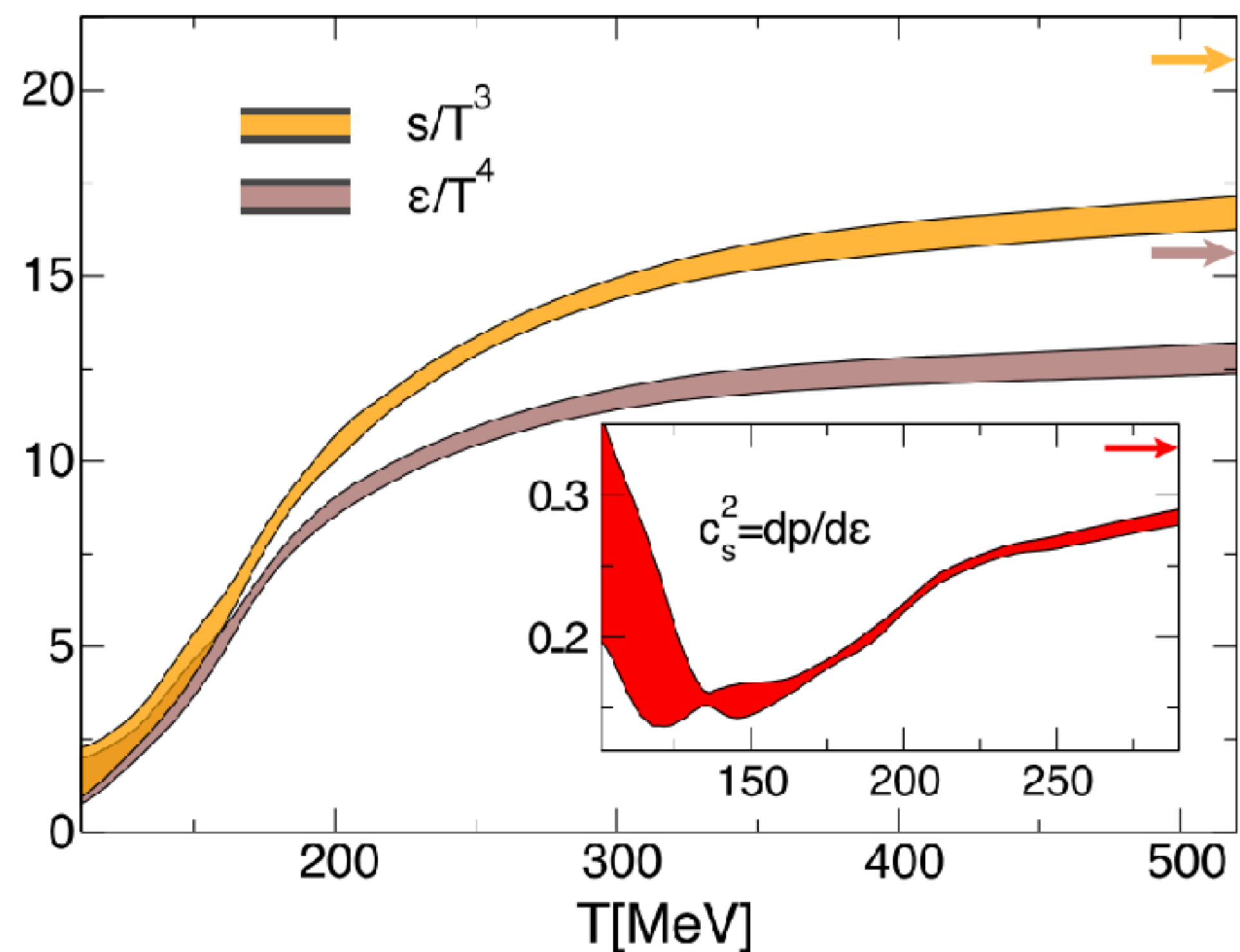


The QCD equation of state

Kano Tsunenobu & sons

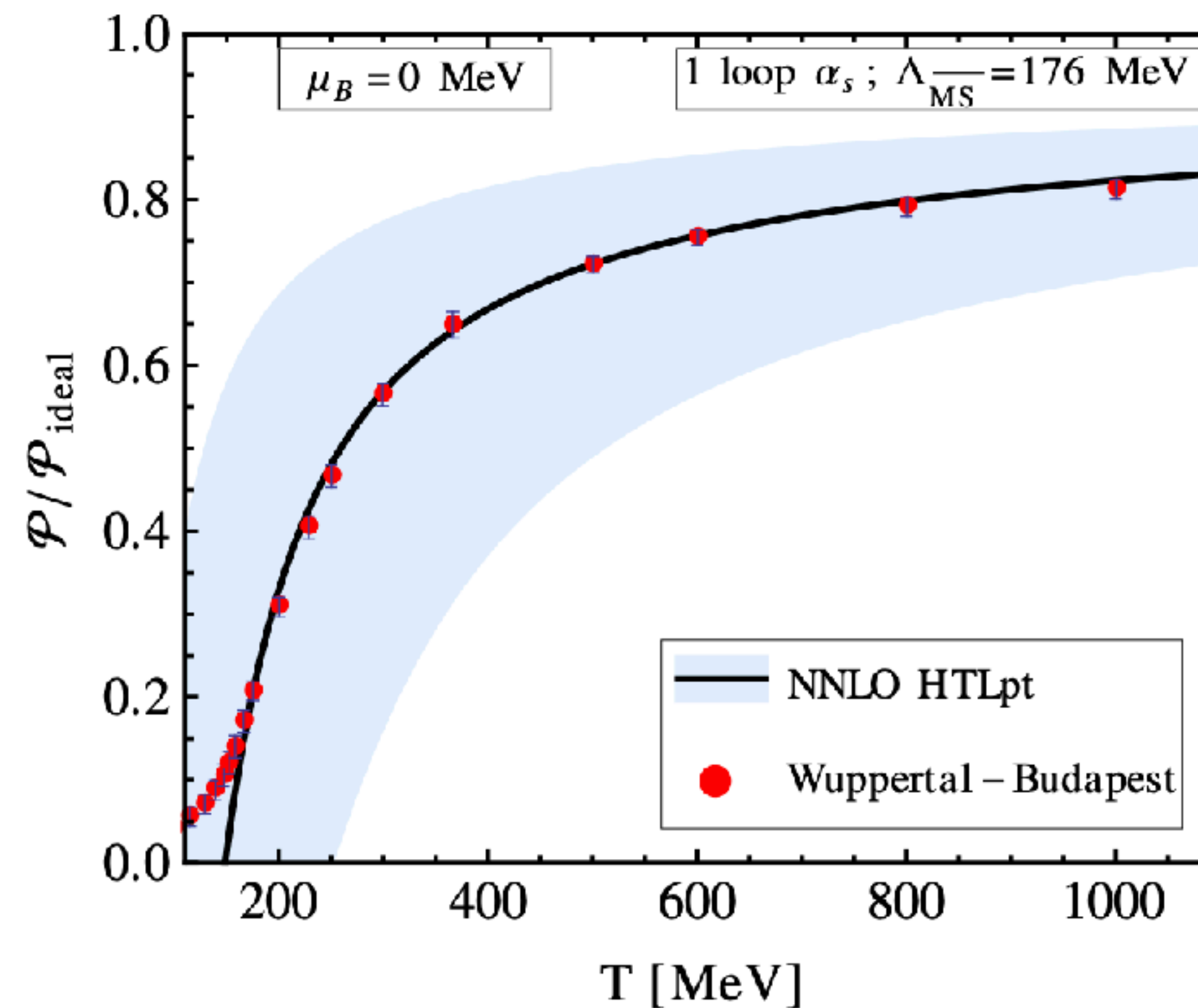
QGP equation of state

$N_f = 3$ 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 = $O(\alpha_s^3 \ln \alpha_s)$

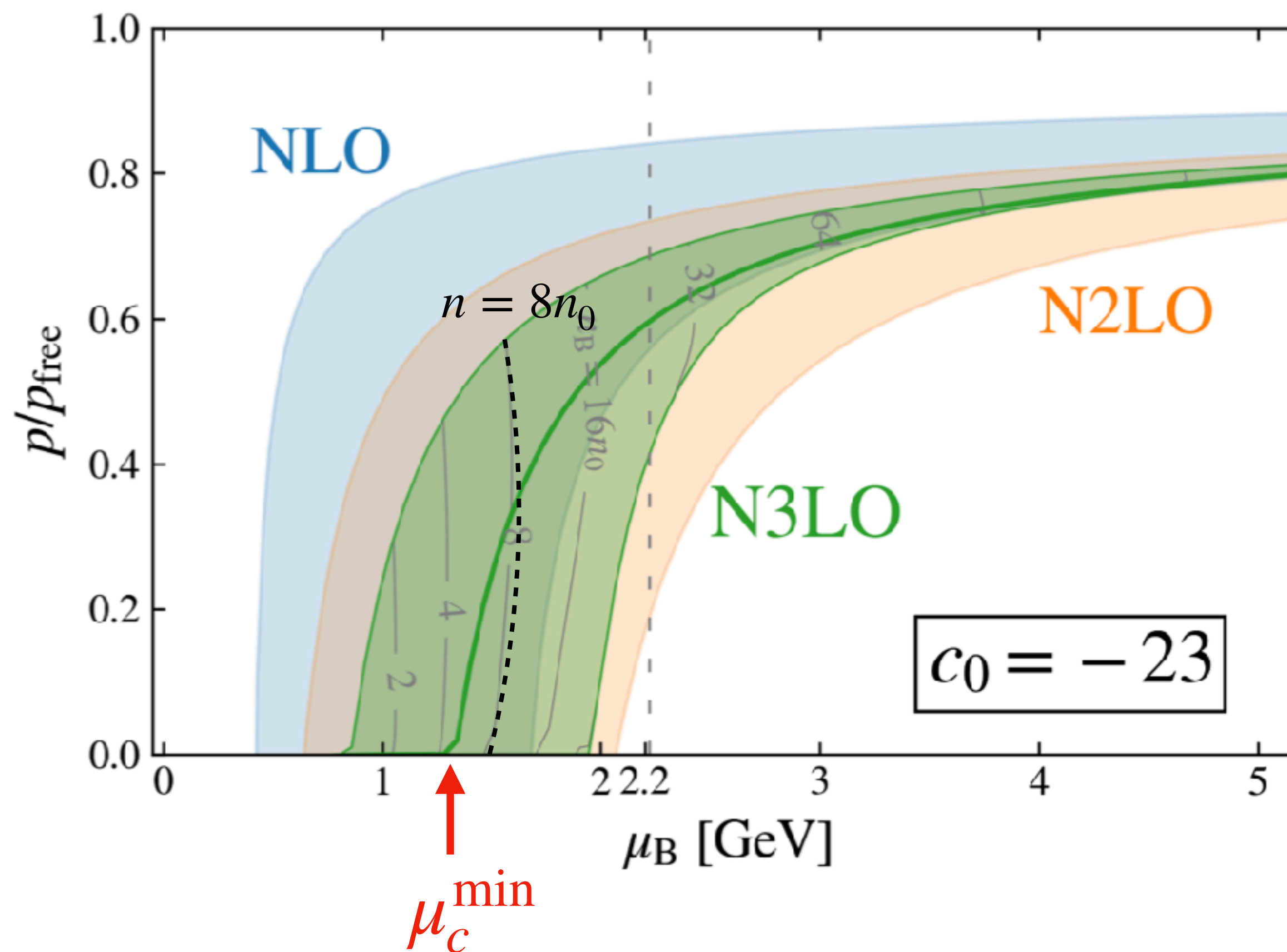
$$p^m = \left(\text{diagram 1} + \text{diagram 2} + \text{diagram 3} + \text{diagram 4} + \text{diagram 5} \right)$$

$$+ \left(\text{diagram 6} + \text{diagram 7} + \text{diagram 8} + \text{diagram 9} \right)$$

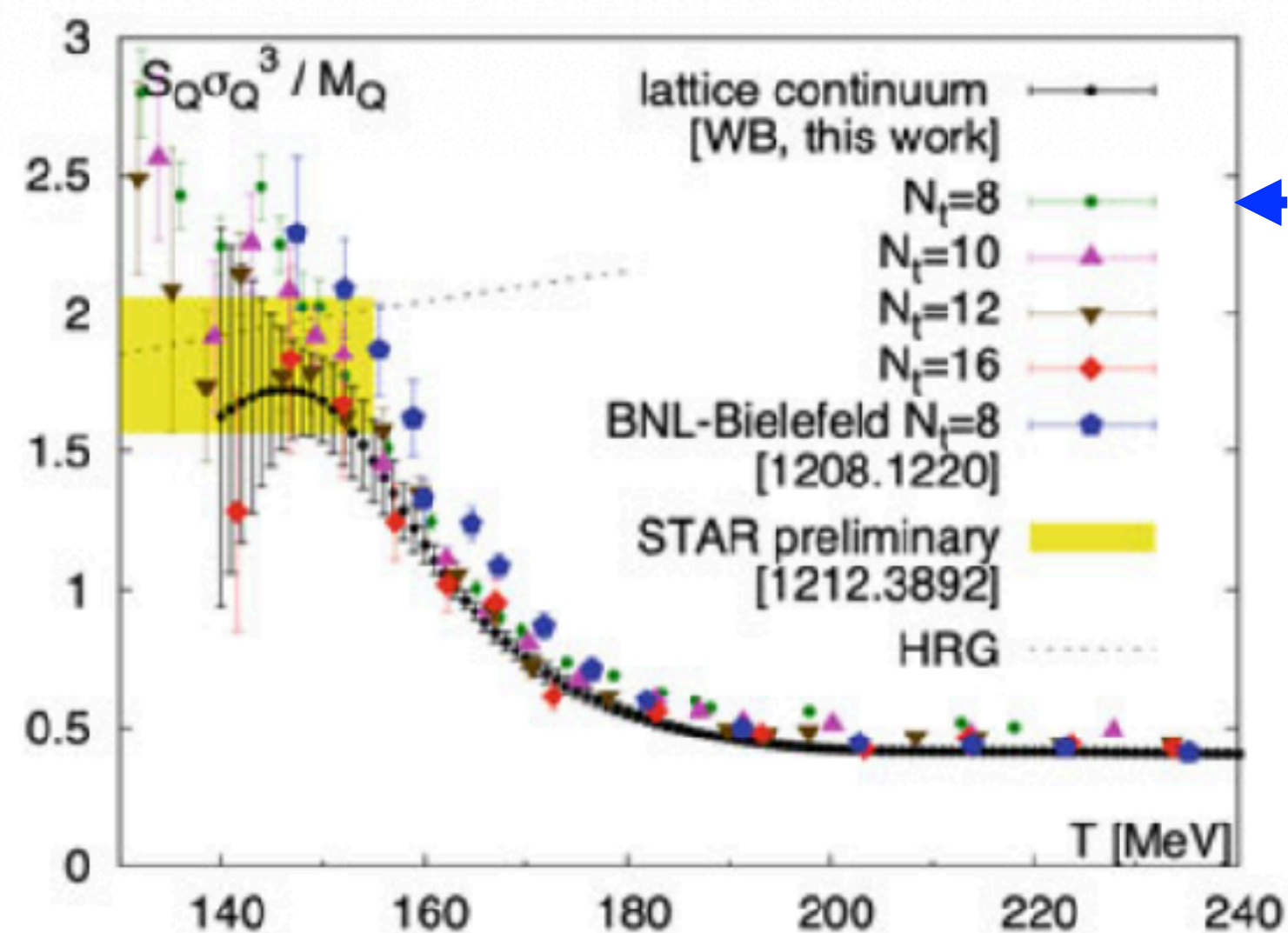
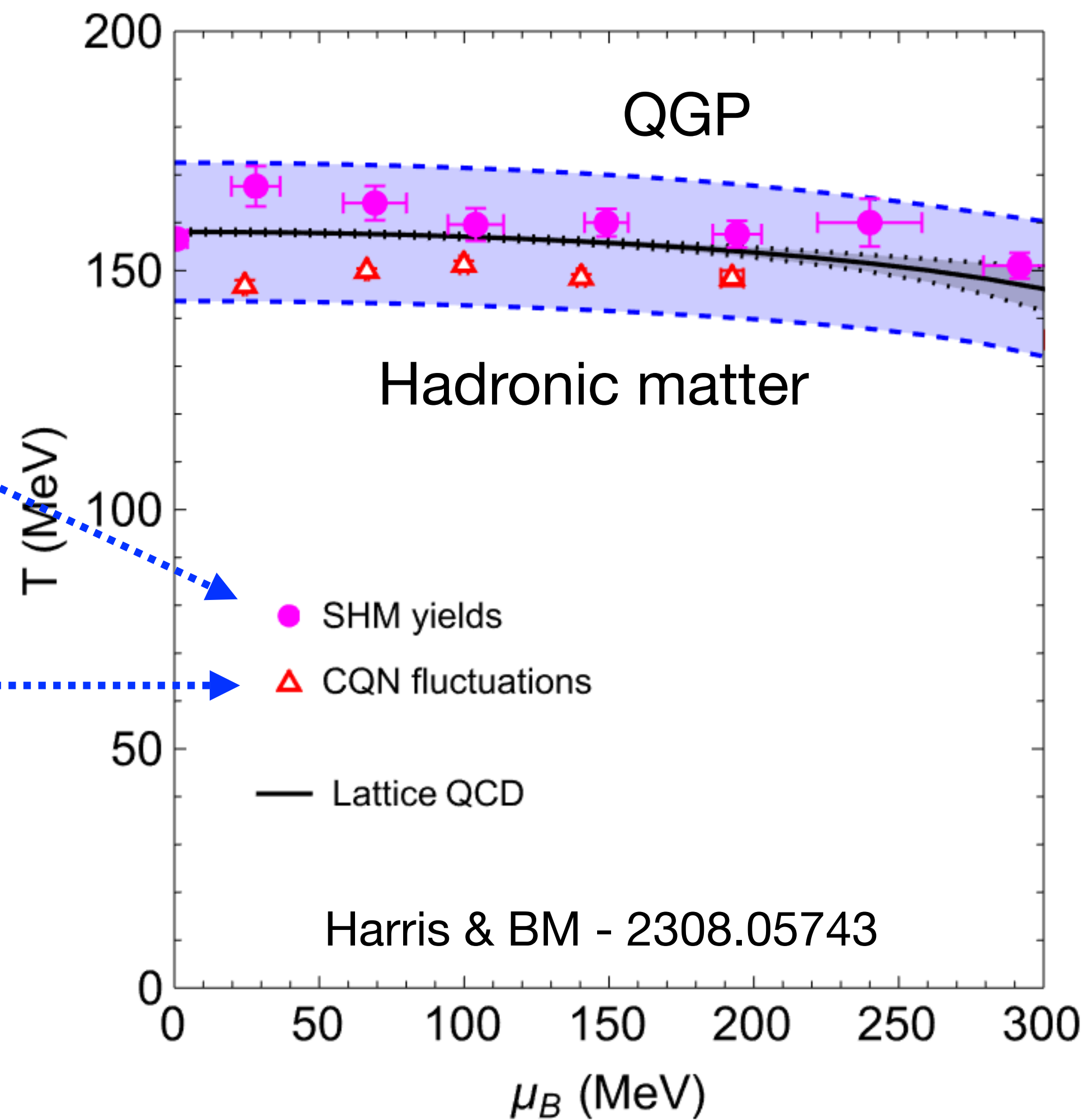
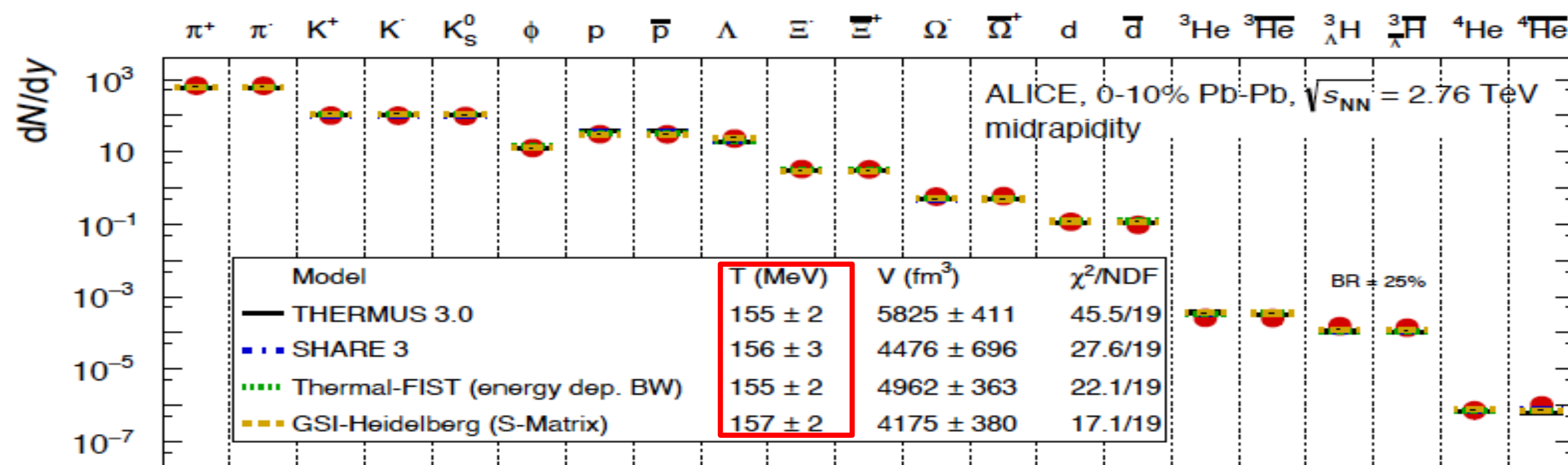
$$\frac{p}{p_{\text{free}}} \simeq 1 - 2 \left(\frac{\alpha_s}{\pi} \right) - 3 \left(\frac{\alpha_s}{\pi} \right)^2 \left[\ln \left(3 \frac{\alpha_s}{\pi} \right) + 3 \ln X + 5.0021 \right]$$

$$+ 9 \left(\frac{\alpha_s}{\pi} \right)^3 \left[c_{3,2} \ln^2 \left(3 \frac{\alpha_s}{\pi} \right) + c_{3,1}(X) \ln \left(3 \frac{\alpha_s}{\pi} \right) + c_{3,0}(X) \right]$$

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



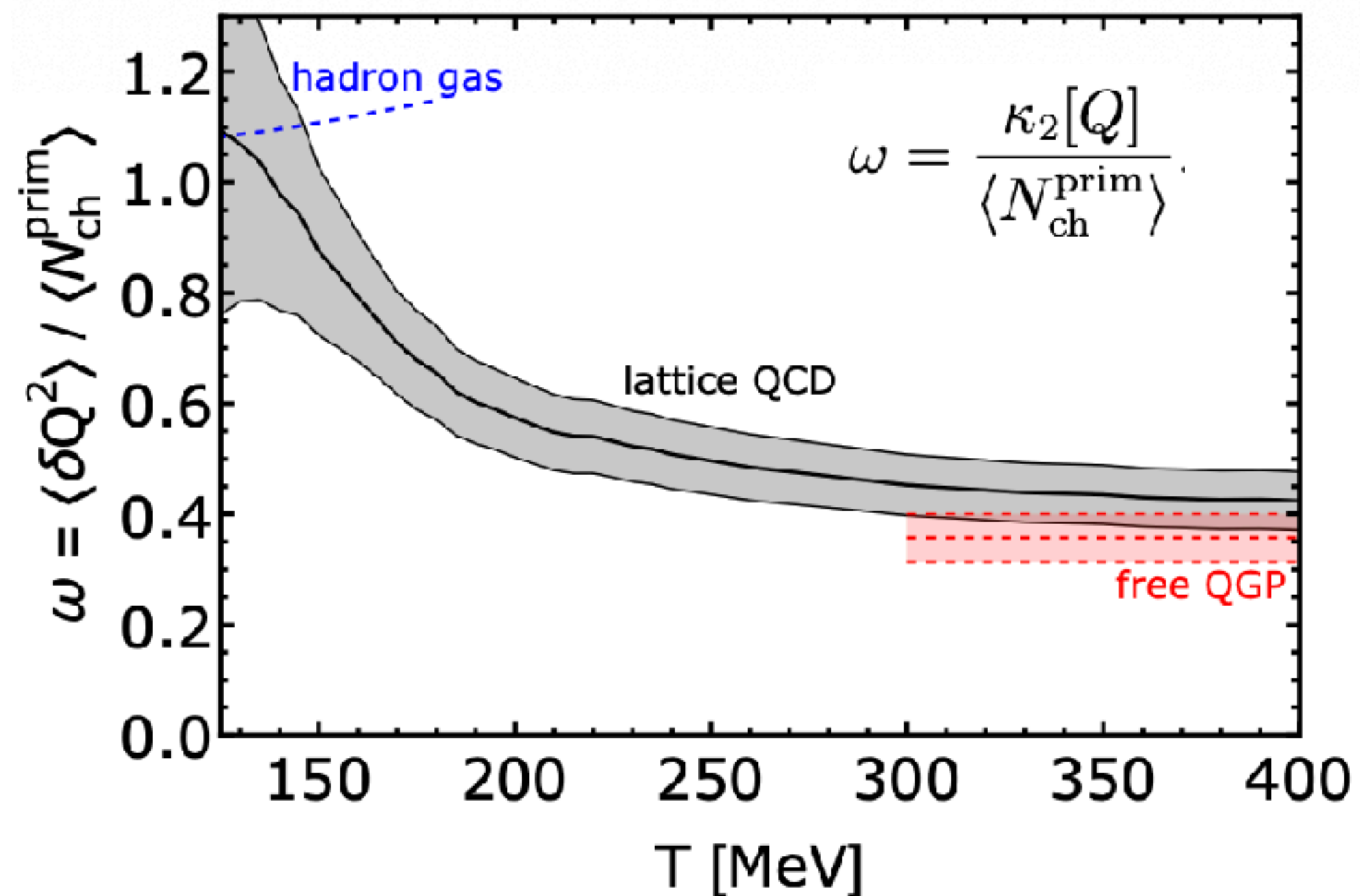
QGP Phase boundary: $T_c(\mu_B)$



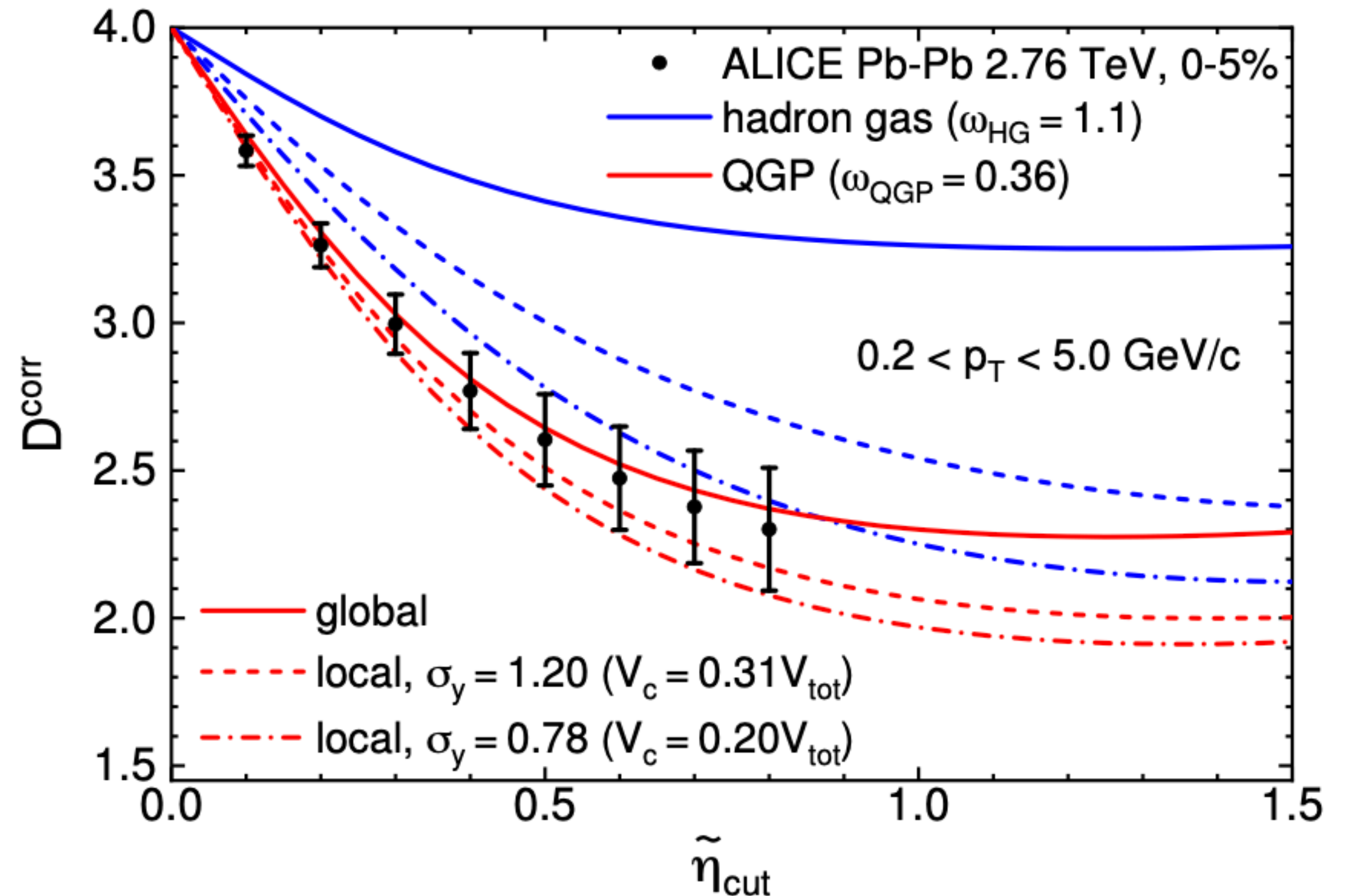
Net charge fluctuations

Proposed as deconfinement probe in 2000
(Jeon-Koch; Asakawa-Heinz-BM)

New analysis by Parra et al., 2504.01085



$$D \approx 4\omega_{\text{corr}}$$



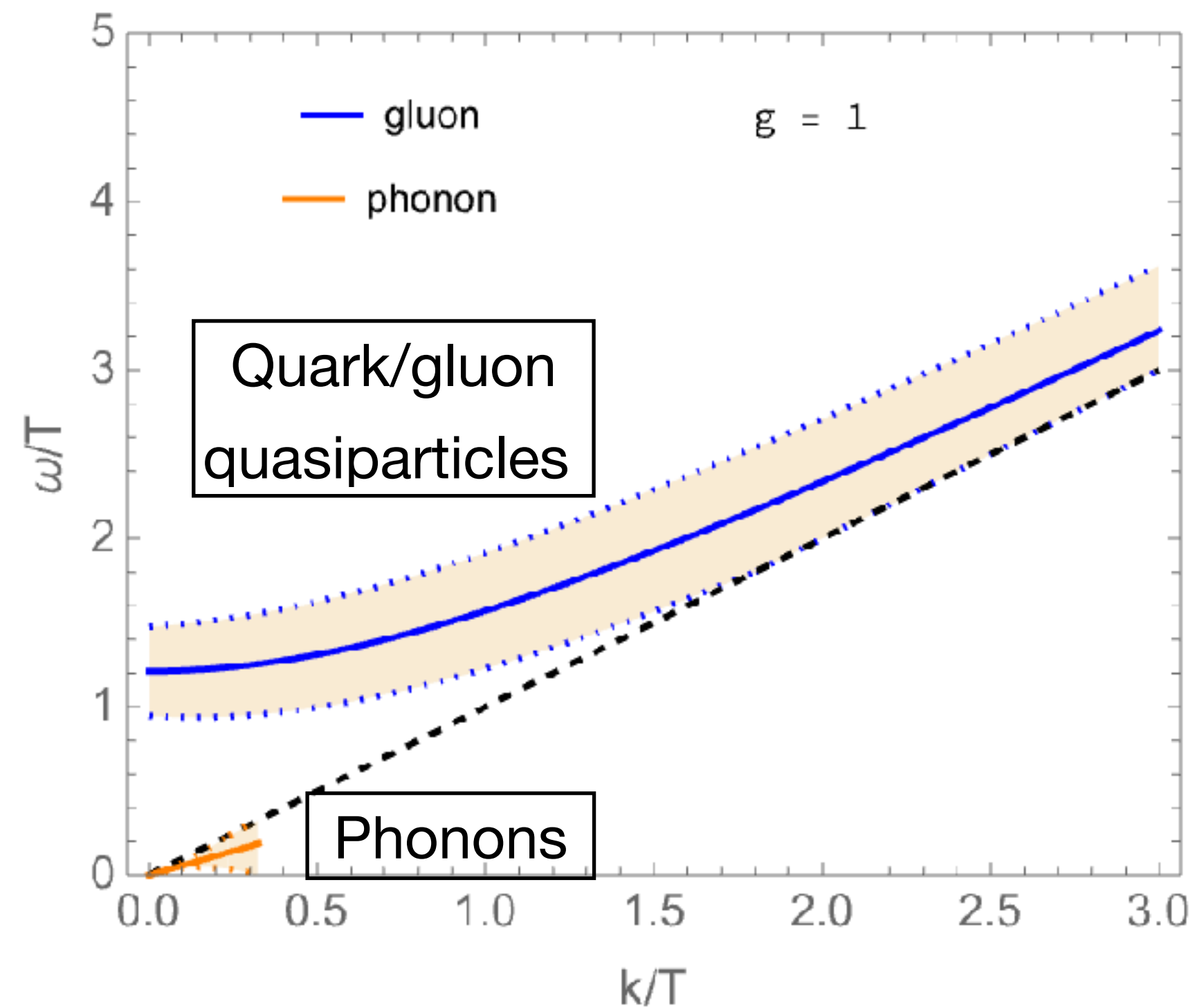


Standing Buddha (Gupta Dynasty)

QGP Structure

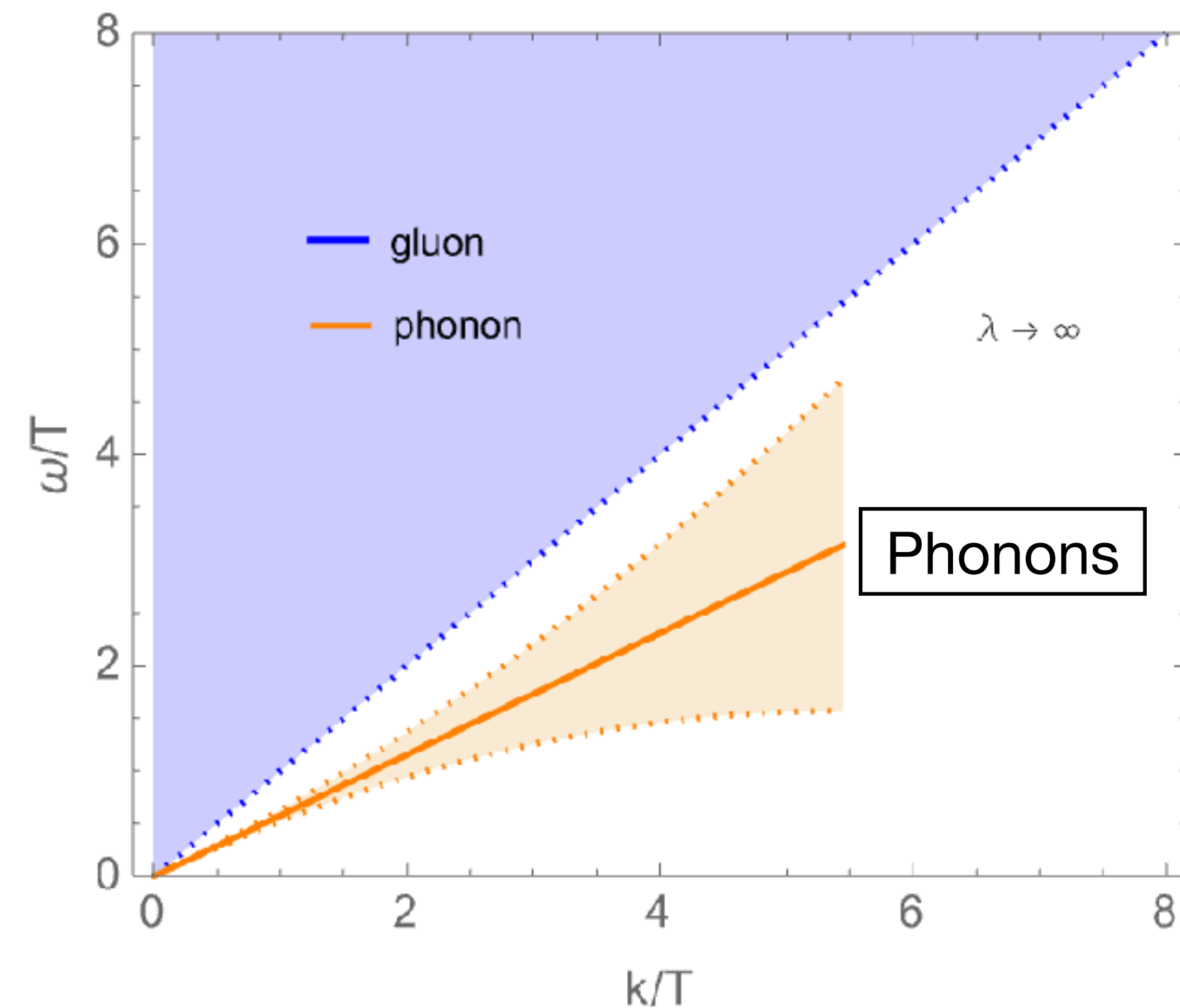
The extremes

Weak coupling: QCD at $\alpha_s = \frac{1}{4\pi} = 0.08$



Dilute quasiparticle plasma

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



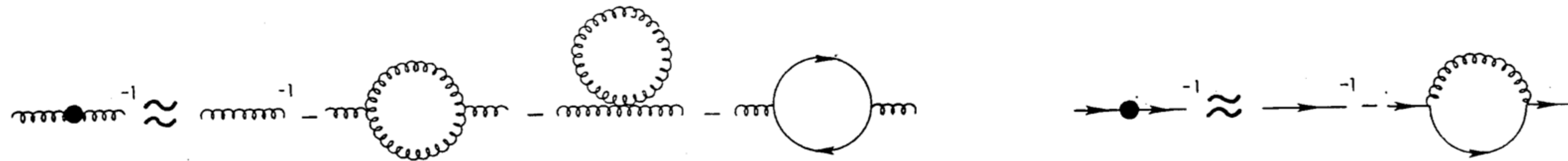
Structureless liquid plasma

Hard-thermal loops

QCD at finite temperature is highly infrared divergent with two relevant scales:

Chromoelectric regime: $k \sim gT$, characterized by Debye mass $m_D^2 = \frac{N_c + \frac{1}{2}N_f}{3} g^2 T^2 = \frac{3}{2}(gT)^2$

$$\mathcal{L}_{\text{HTL}} = -\frac{1}{2} \text{tr} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_D^2 \int d^2 \hat{u} \text{tr} F^{\mu\alpha} u_\alpha \frac{1}{(u \cdot D(A) + i\epsilon)^2} u^\beta F_{\beta\mu} + \mathcal{L}_{\text{quarks}}$$



Static chromomagnetic sector: $k \sim g^2 T$, representing a three-dimensional confining euclidean gauge theory: Truly nonperturbative; requires lattice simulation.

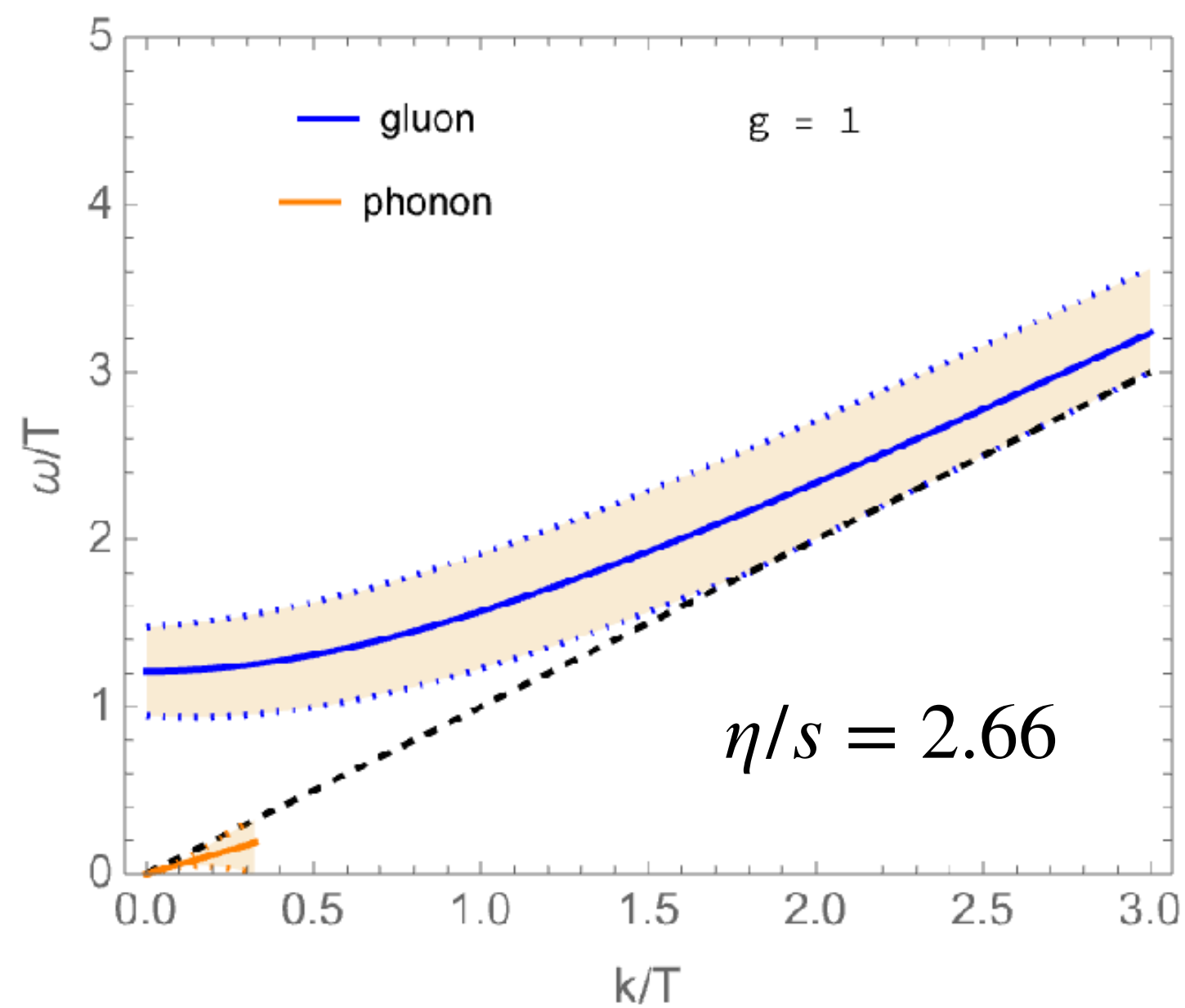
Dynamical magnetic mass scale (confinement scale): $m_M \approx \frac{g^2 N_c T}{2\pi}$

HTL Dispersion Relations

$$g = 1 \quad \alpha_s = 0.08$$

Weak coupling

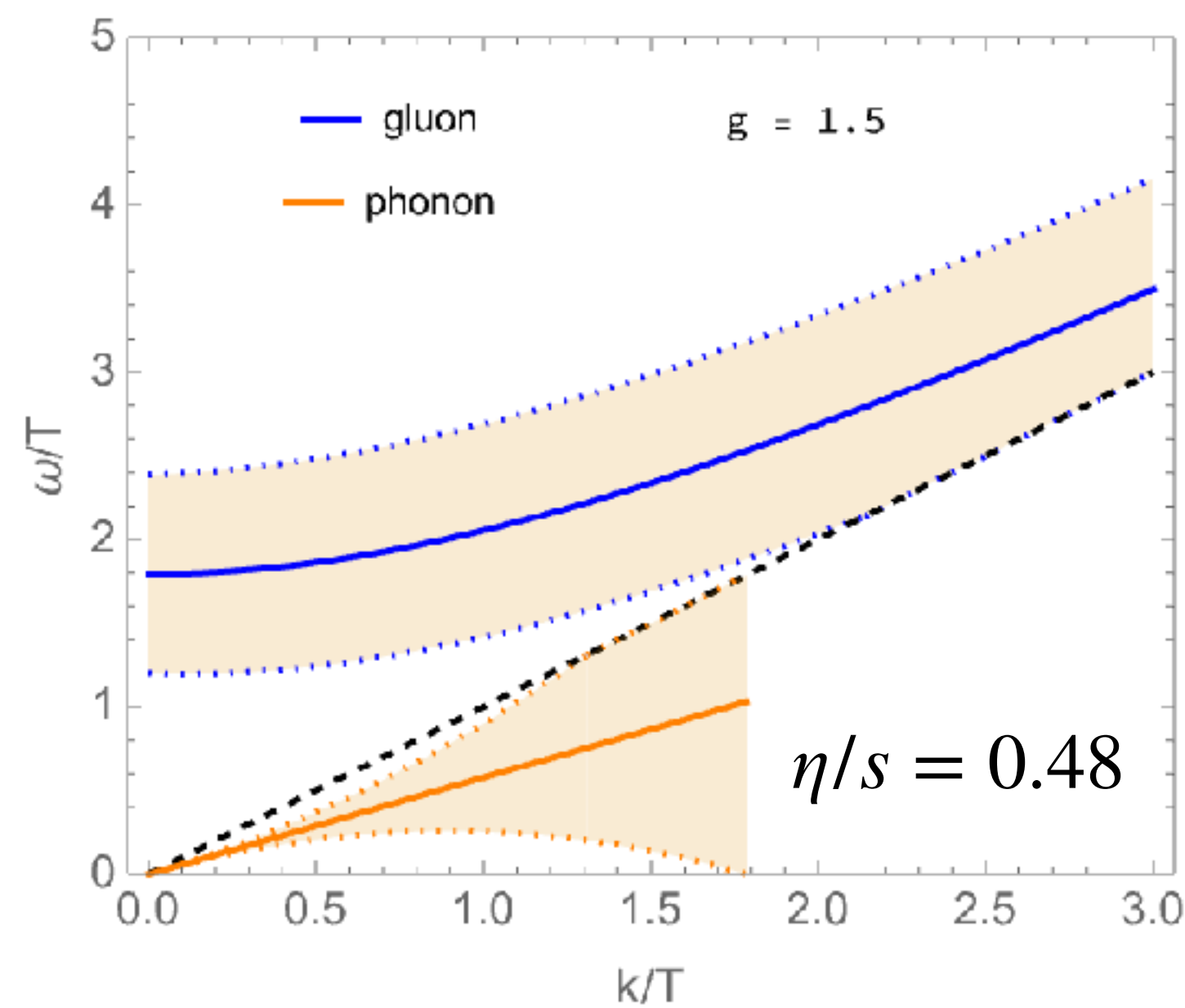
Gluons are good quasiparticles
at all momenta



$$g = 1.5 \quad \alpha_s = 0.18$$

Intermediate coupling

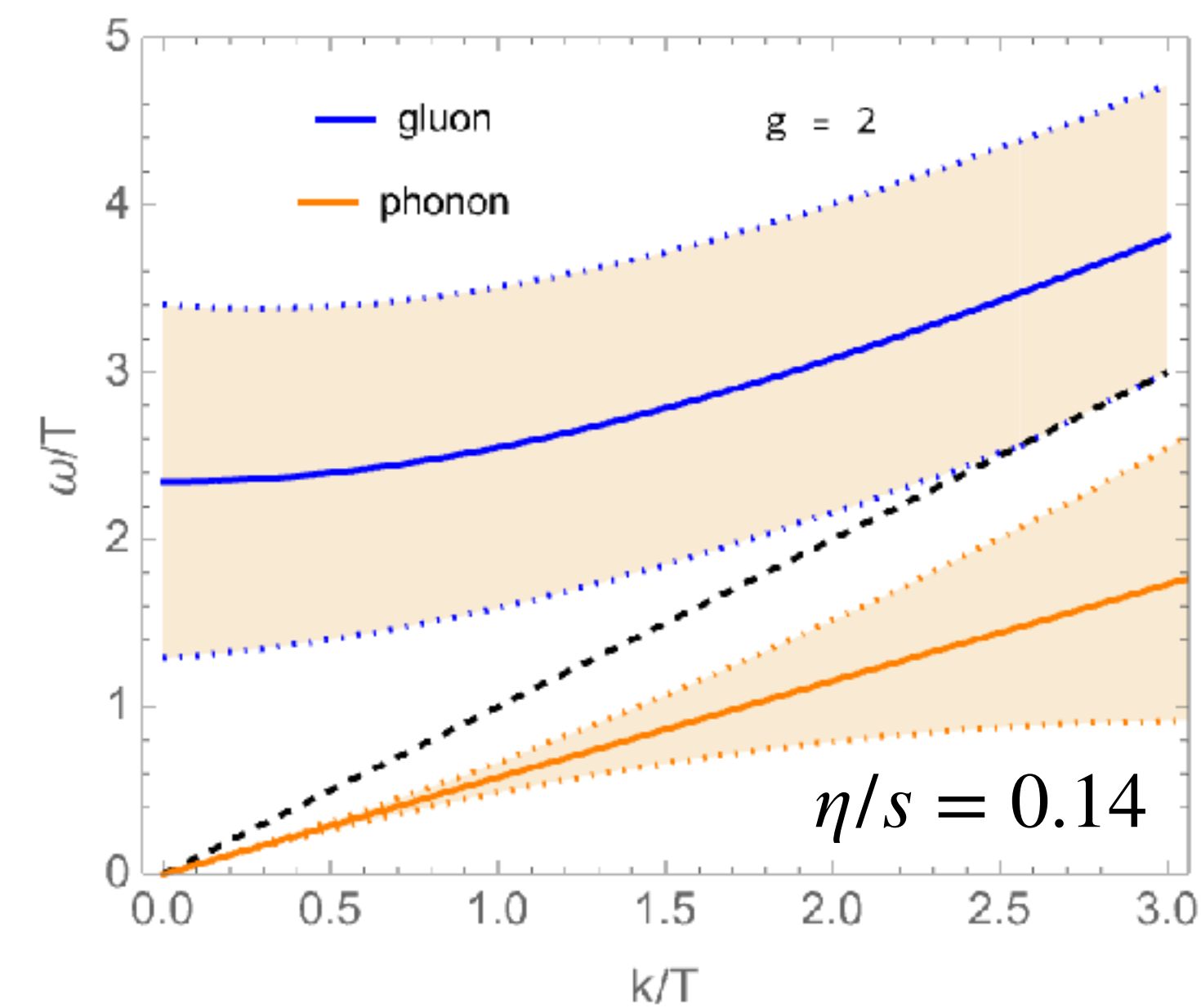
Phonons are good quasiparticles
at thermal momenta



$$g = 2 \quad \alpha_s = 0.32$$

Strong coupling

Phonons are good quasiparticles
at thermal momenta

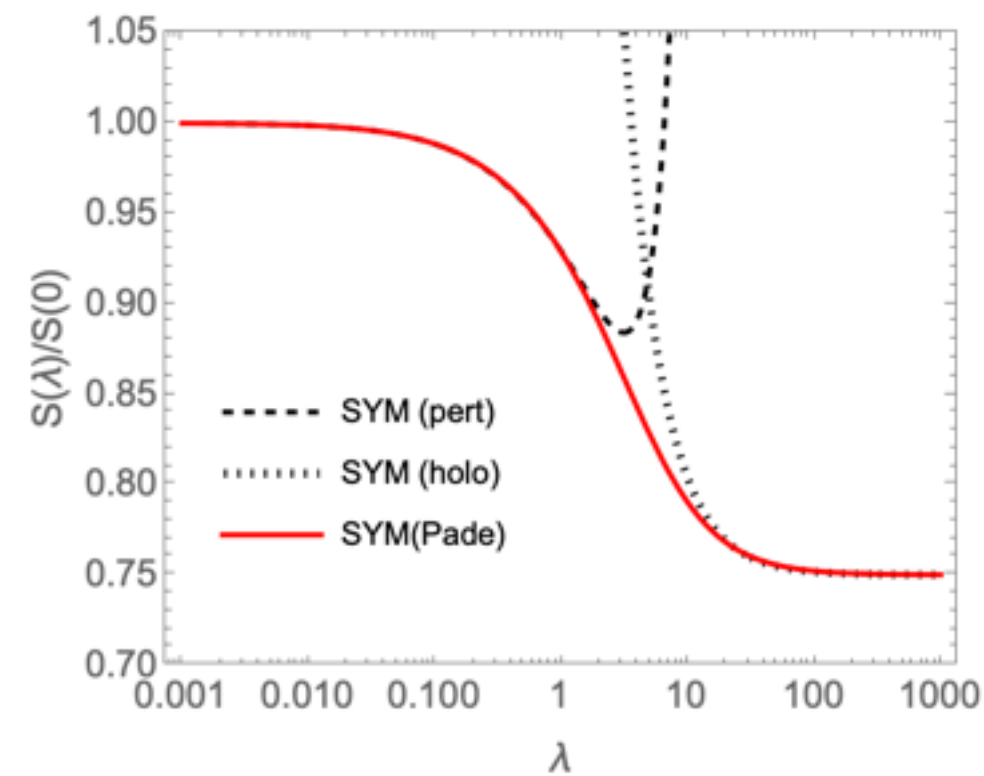


Weak vs. Strong Coupling in $N = 4$ SYM

BM - 2507.06845

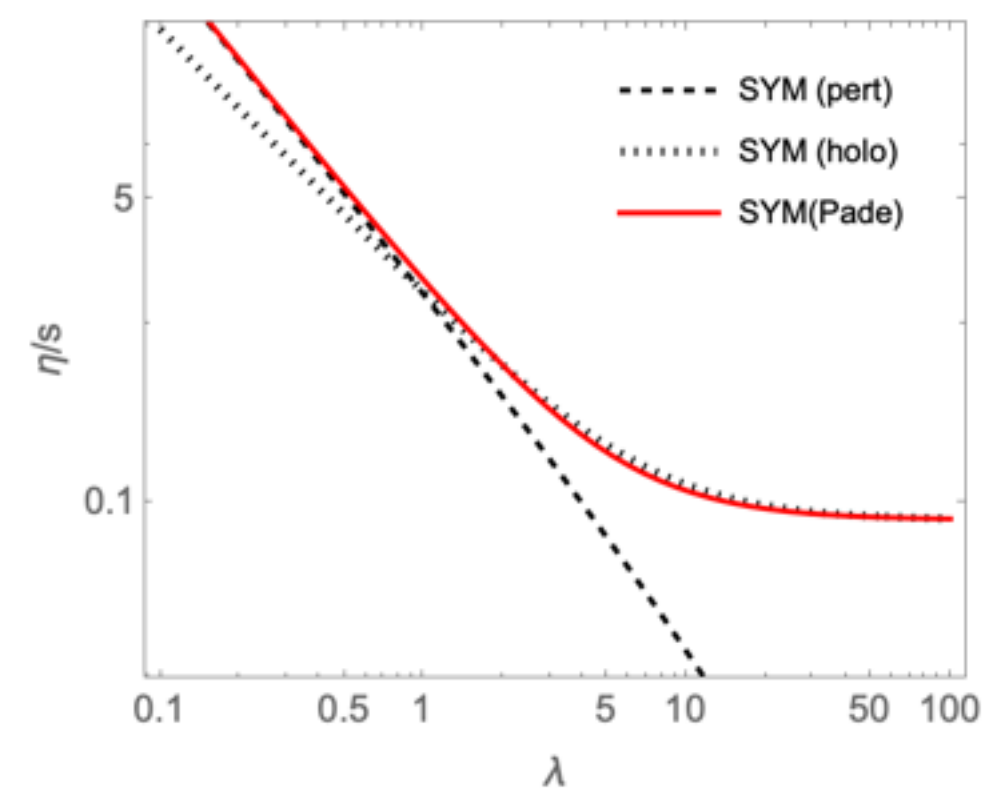
Entropy (normalized)

$$s(\lambda)/s_0$$



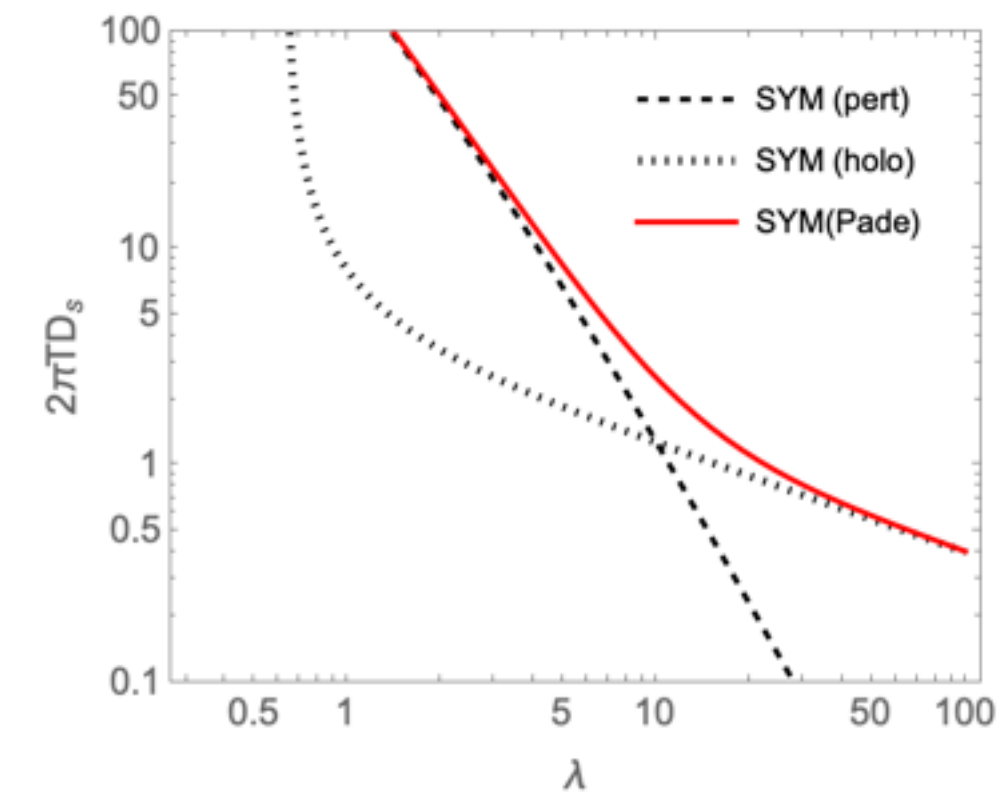
Kin. shear viscosity

$$\eta/s$$



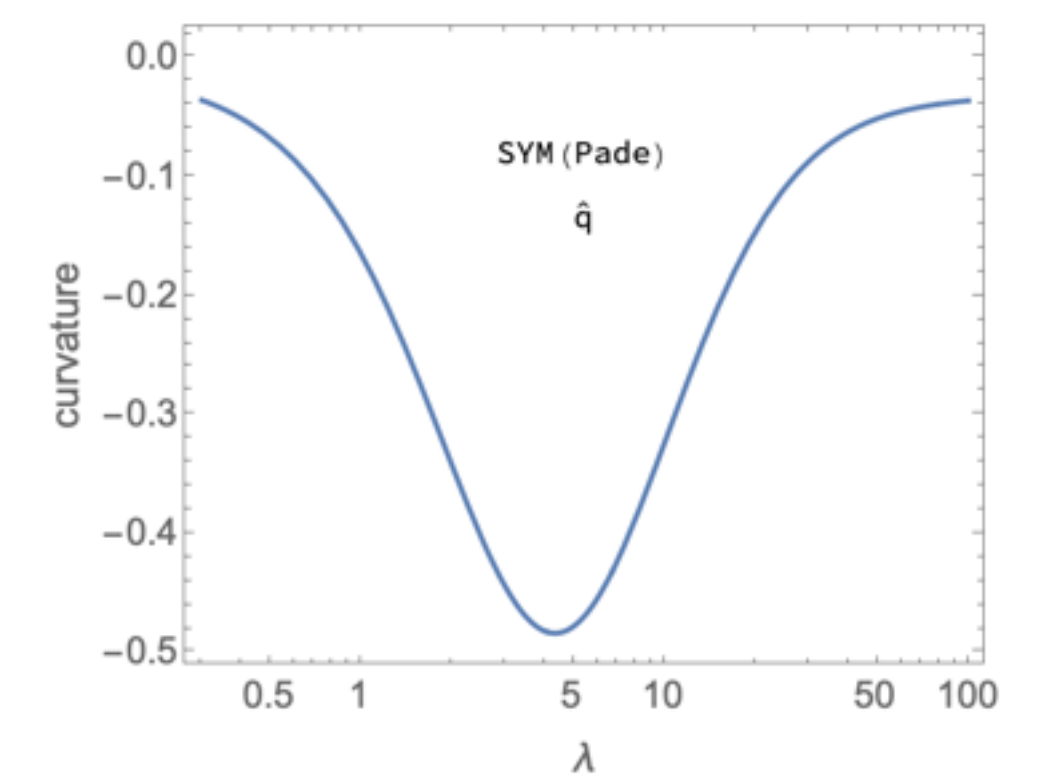
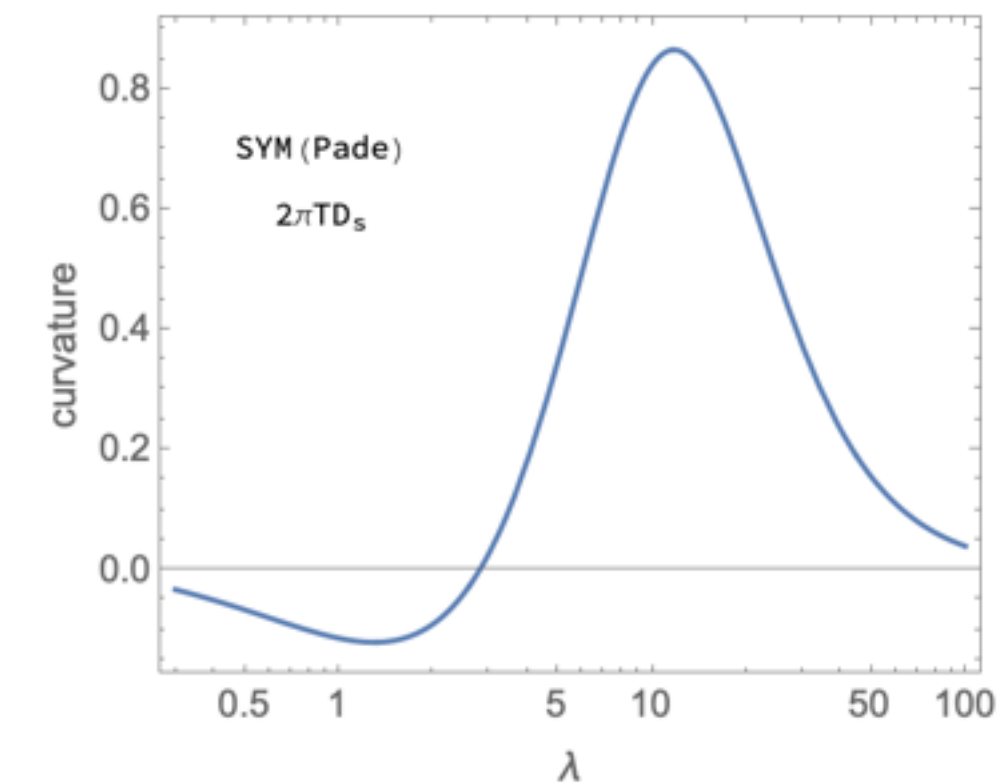
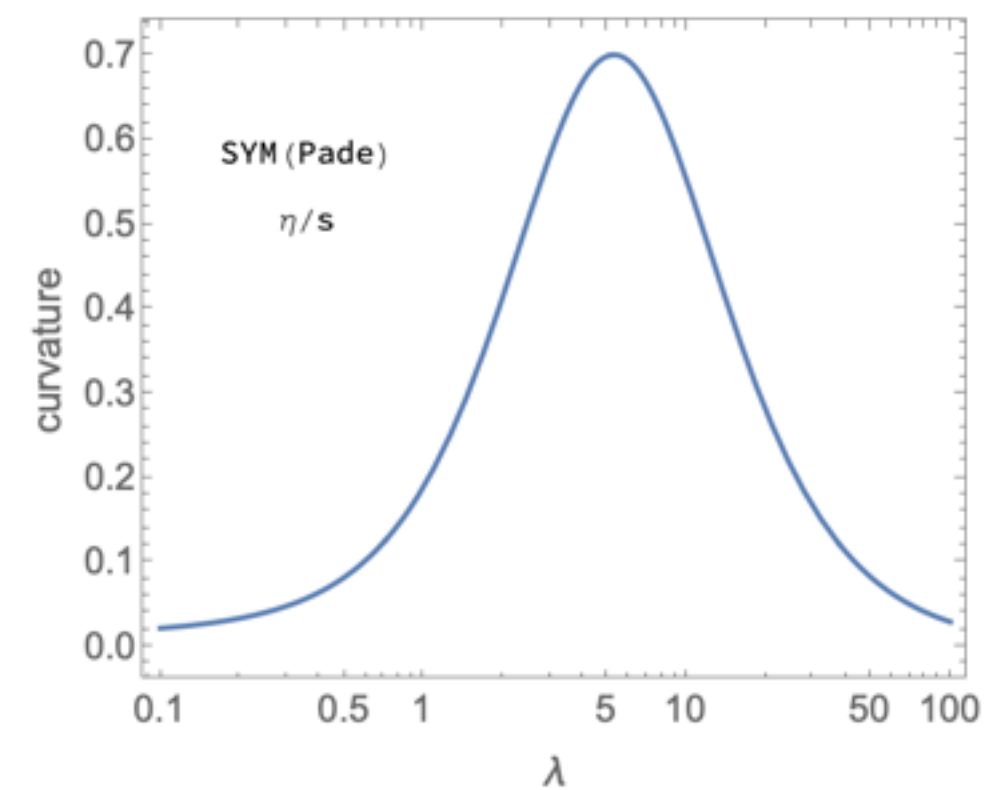
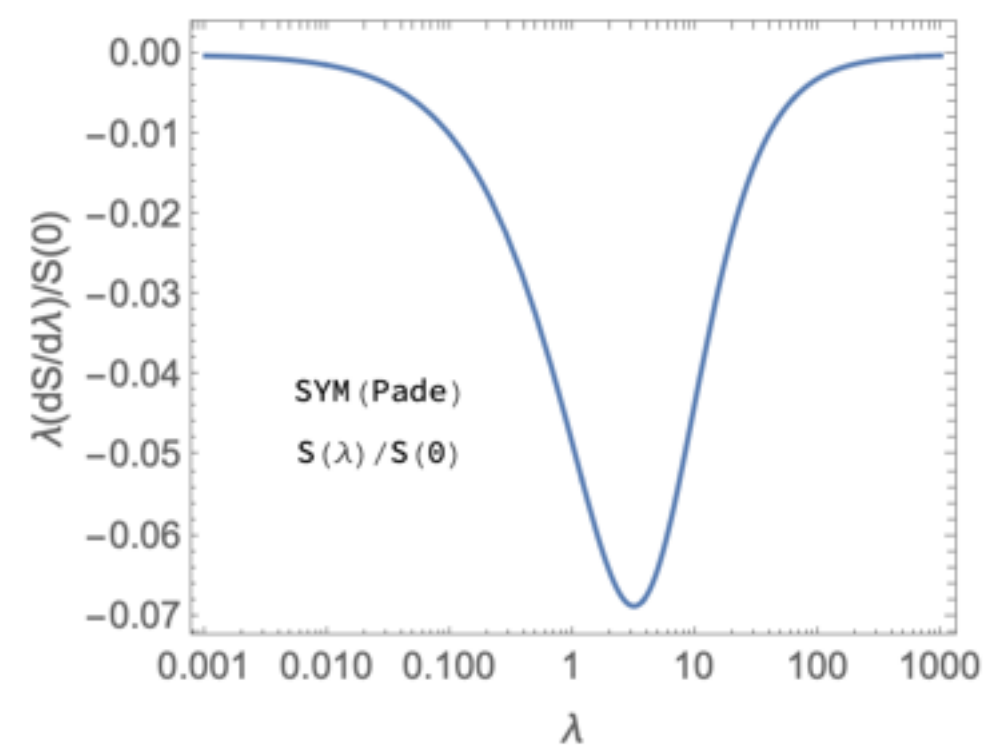
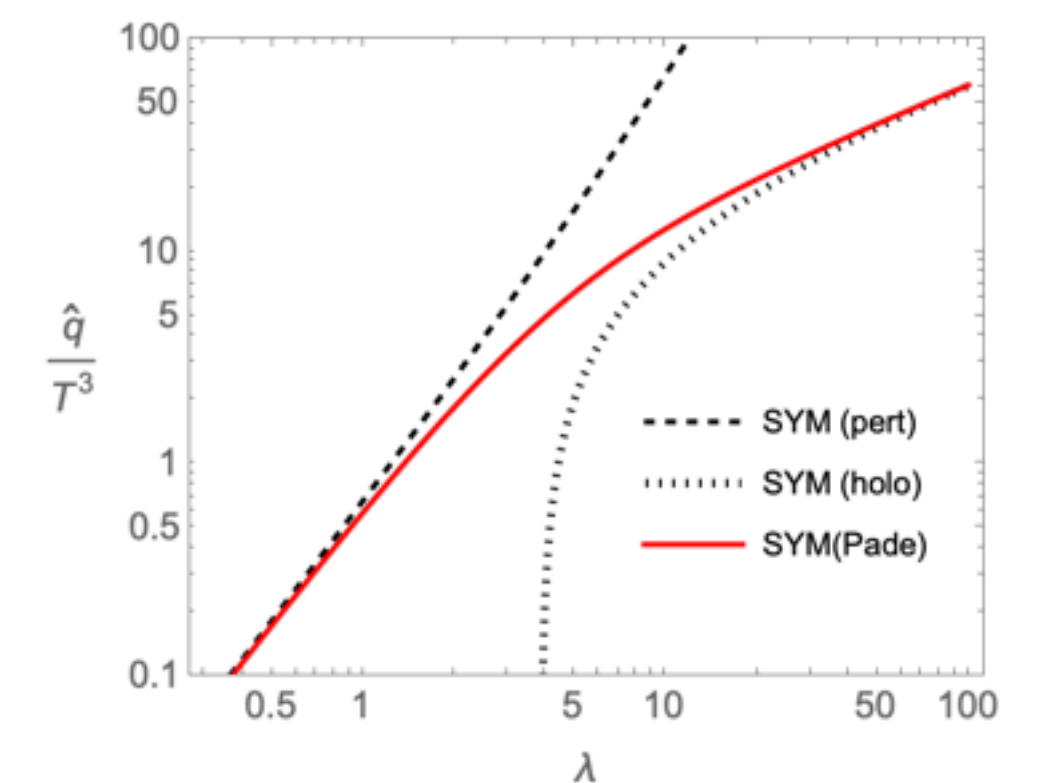
Diffusion constant

$$2\pi TD_s$$

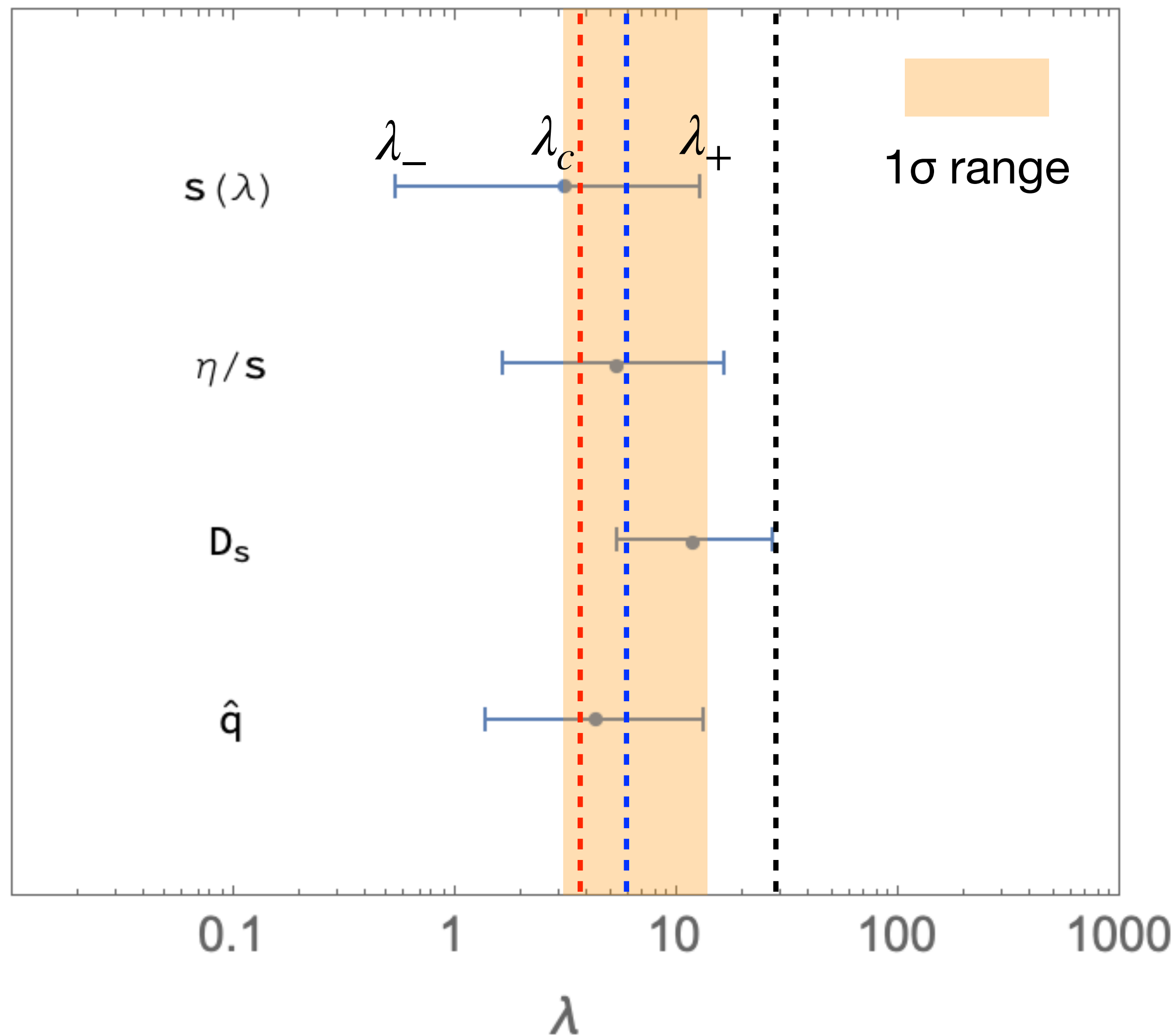


Momentum broadening

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



Transition Region



't Hooft coupling:

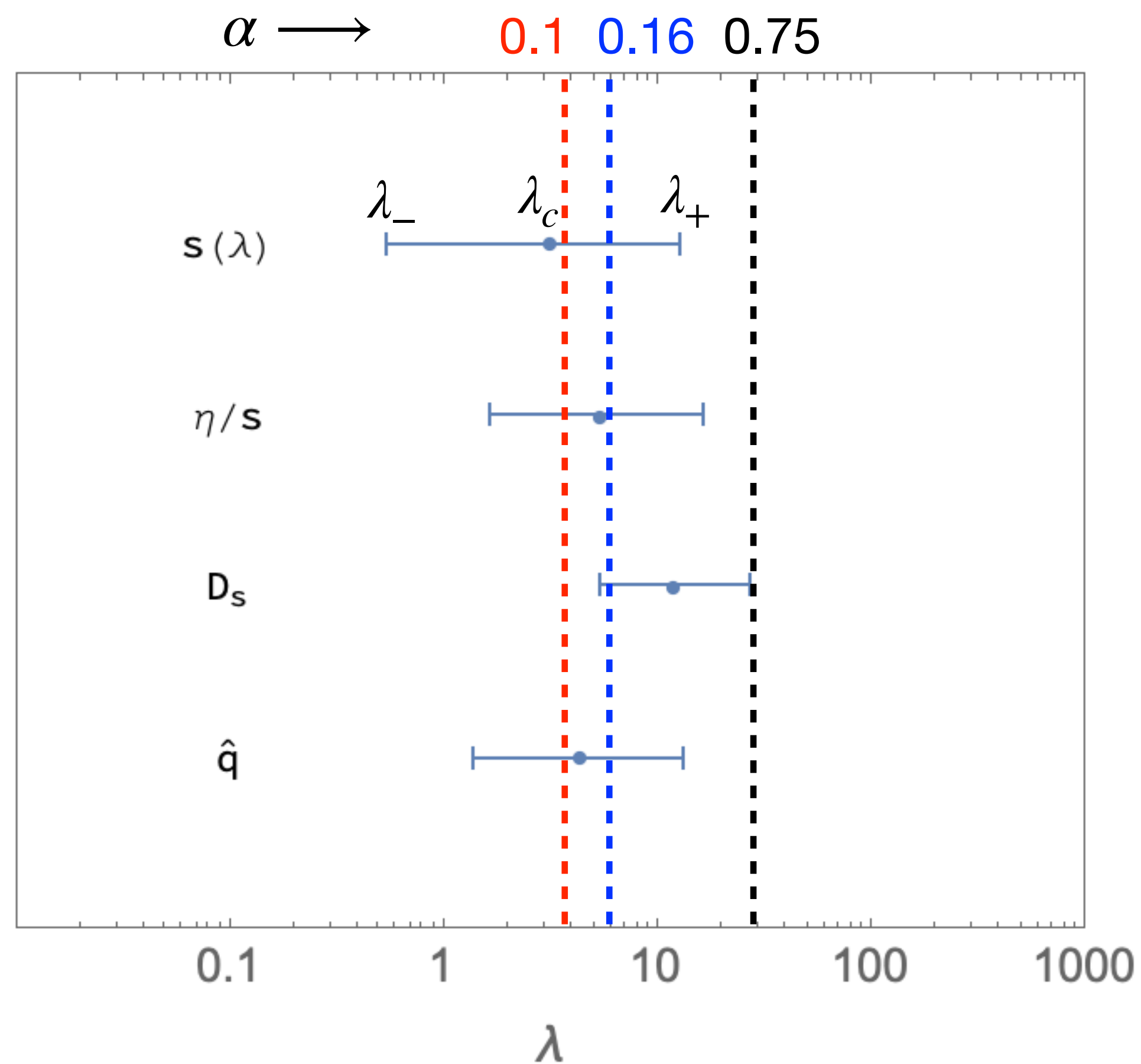
$$\lambda = g^2 N_c \rightarrow 12\pi\alpha_{\text{YM}}$$

Quantity	λ_c	λ_-	λ_+	$f(\lambda_c)$
$s(\lambda)/s_0$	3.14	0.54	12.95	0.859
η/s	5.28	1.69	16.38	0.180
$2\pi T D_s$	11.74	5.54	27.36	2.04
\hat{q}/T^3	4.36	1.39	13.25	5.47

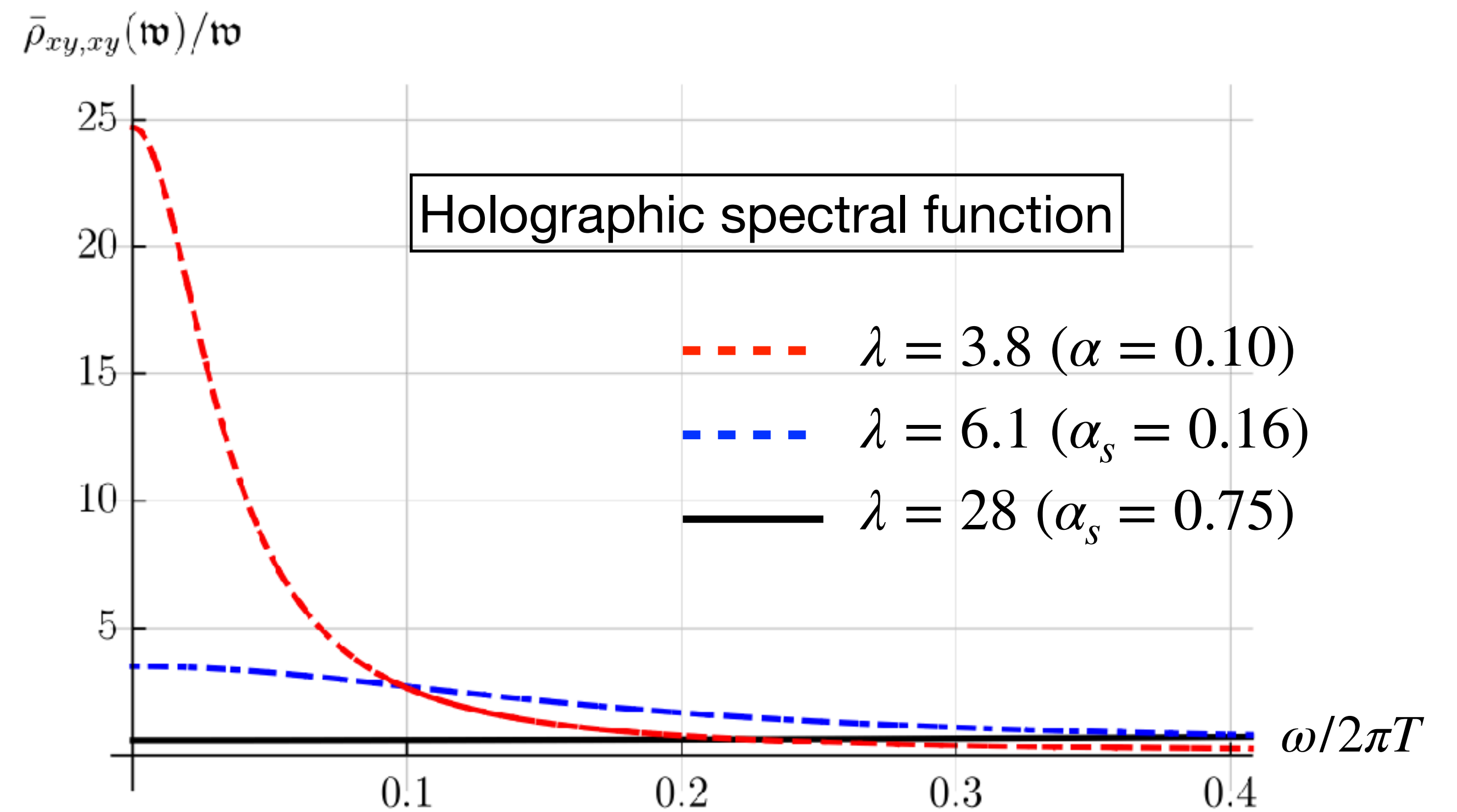
Transition region: $3 < \lambda < 14$

Emergence of quasiparticles

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



Casalderrey-Solana et al. - 1806.10997

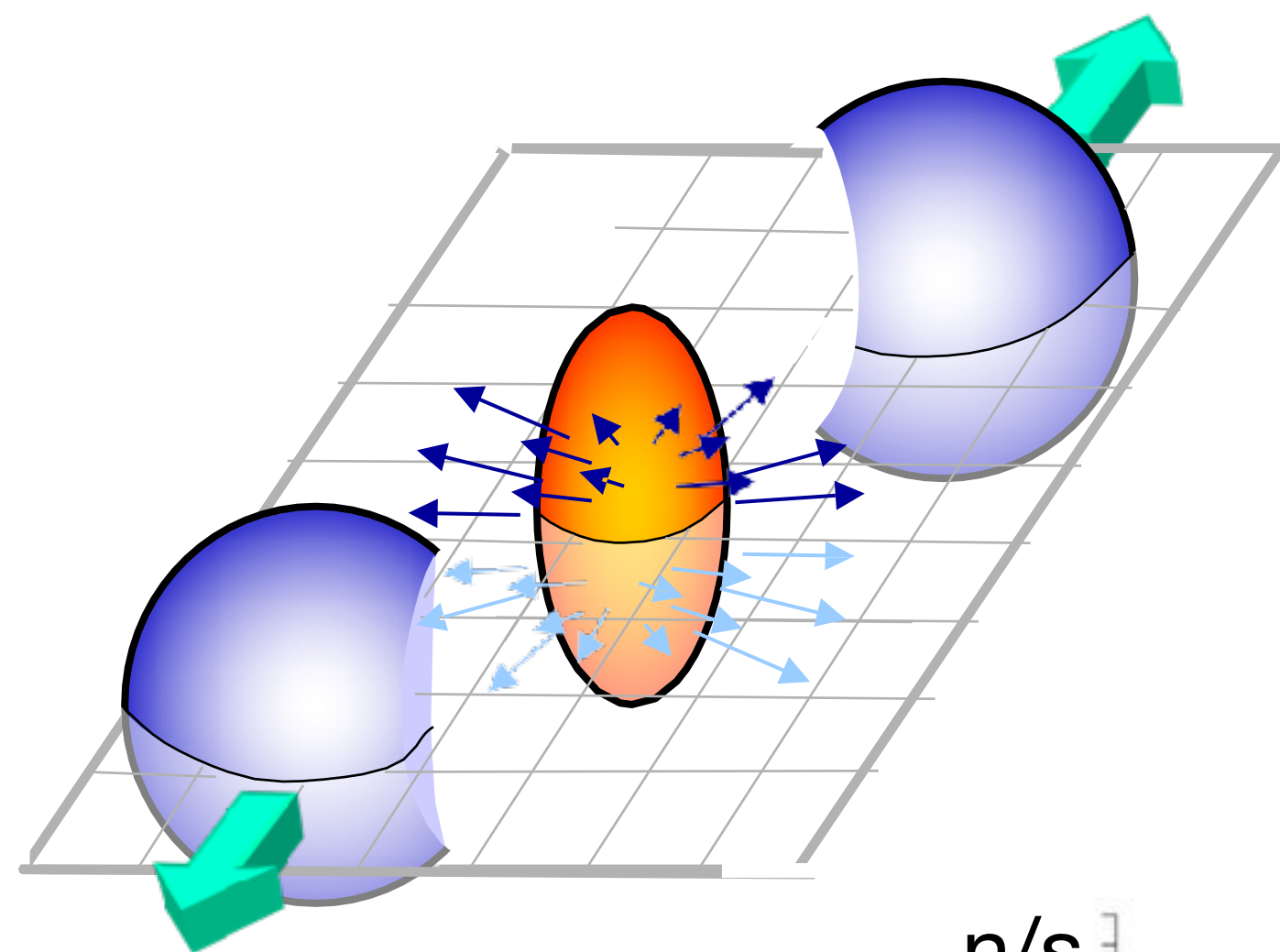




Buddha Shakyamuni (Tang Dynasty)

The Liquid QGP

QGP collective flow



QGP collective flow is well established.

Fireball shape is characterized by eccentricity: ϵ_2

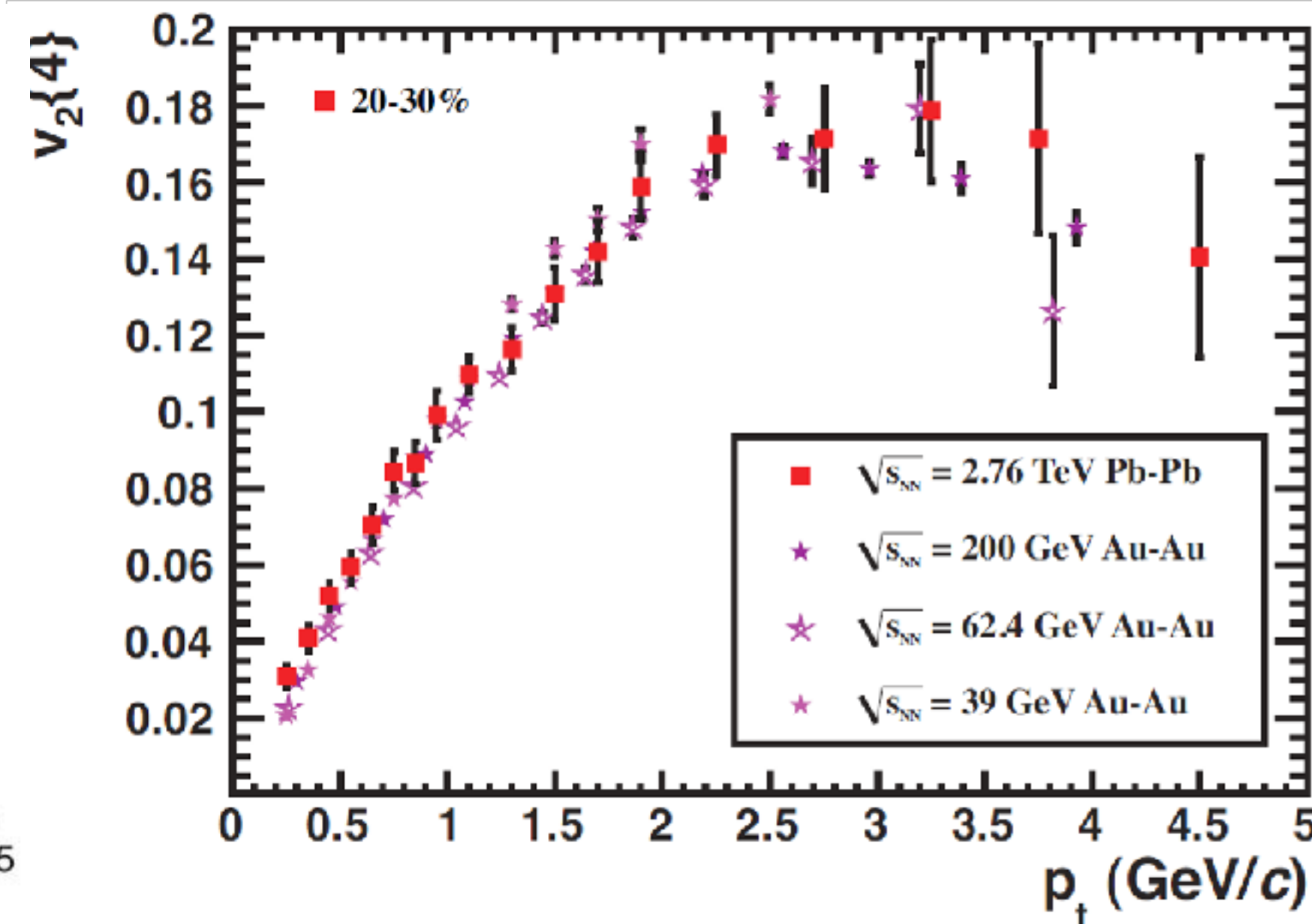
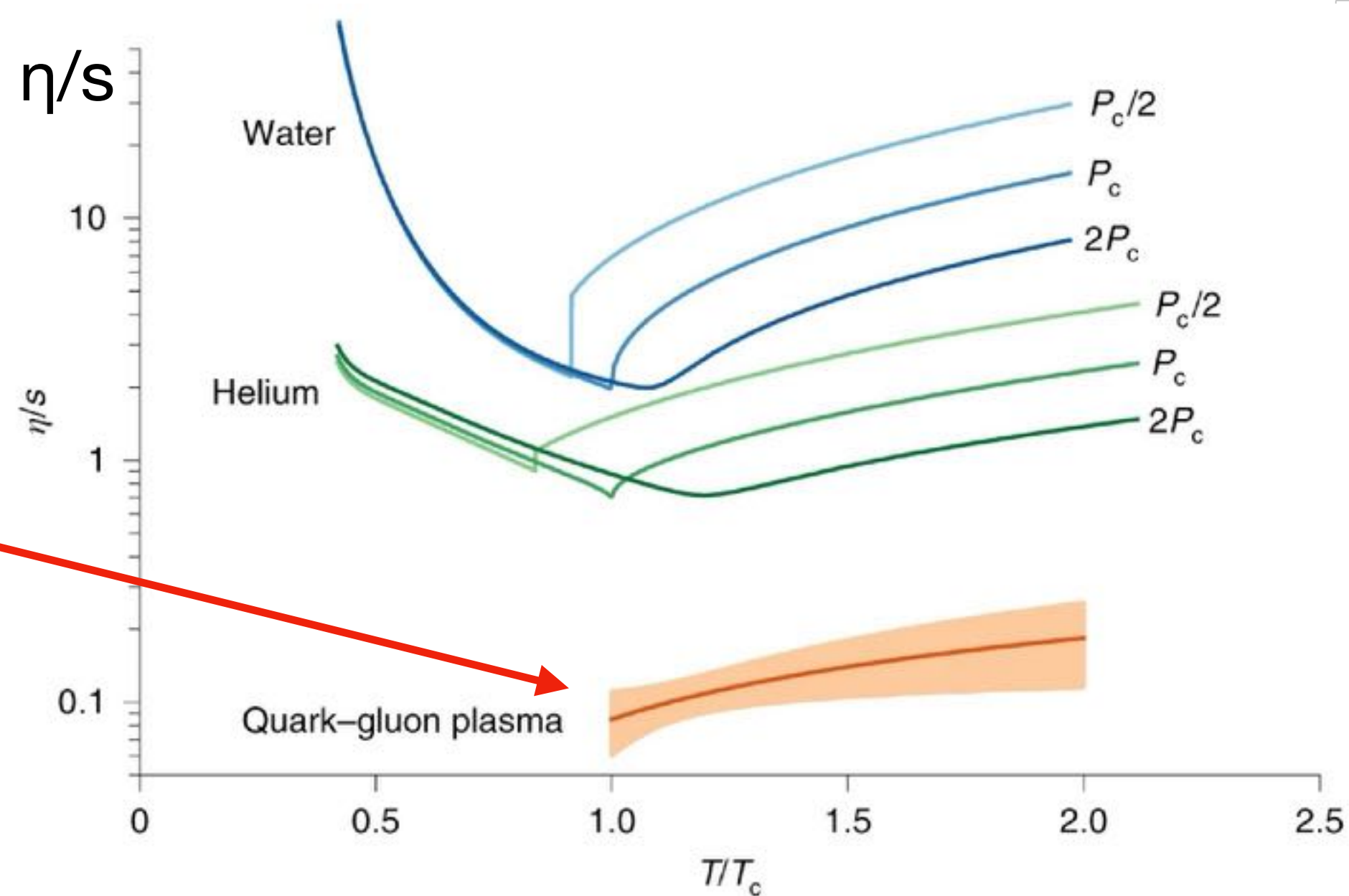
Hydrodynamical expansion: $\epsilon_2 \rightarrow$ collective flow $v_2(p_T)$

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!



2 central open questions

Question 1: **What are the limits to QGP liquid behavior?**

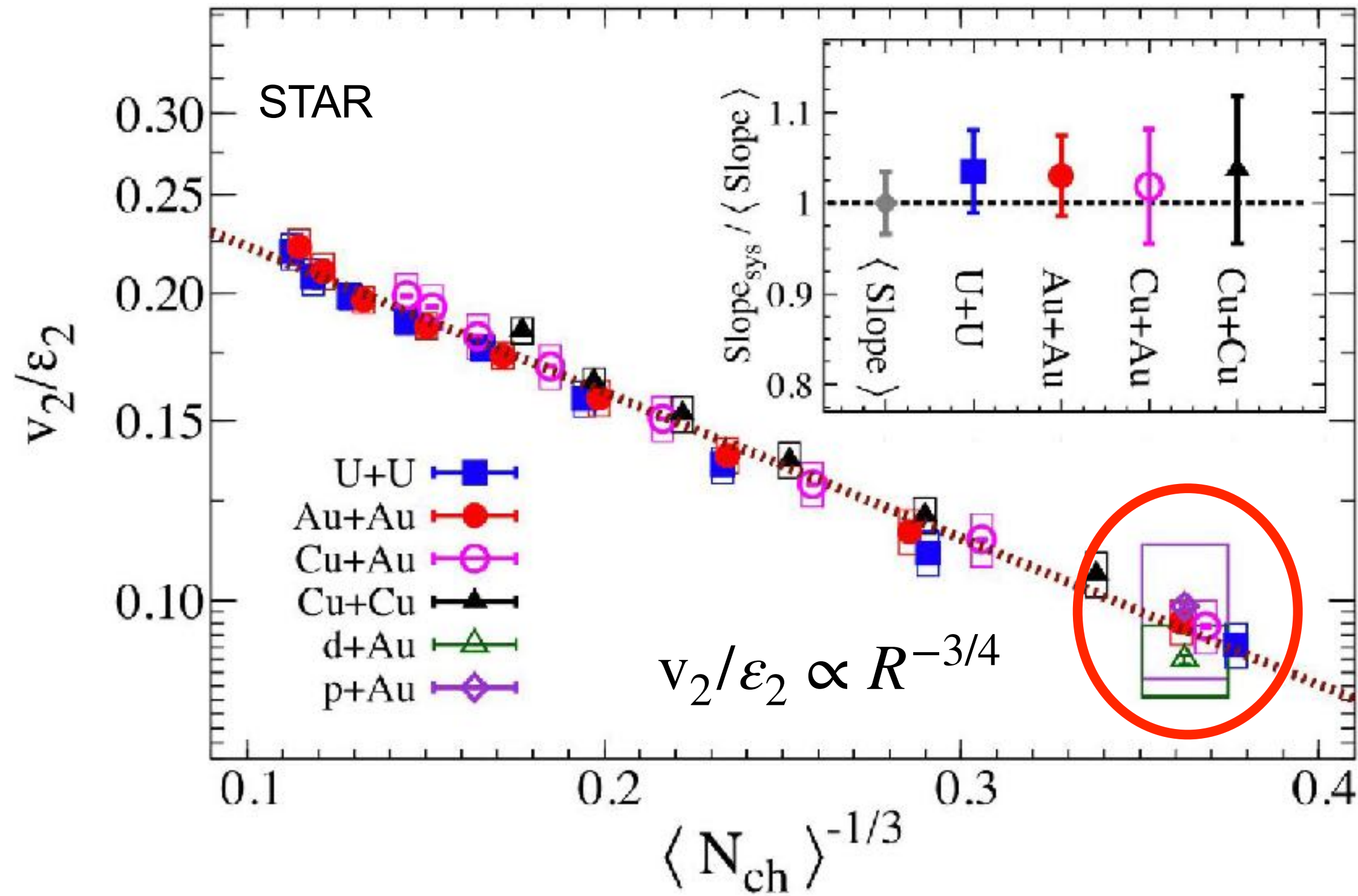
- At which momentum k does the particulate substructure manifest itself?
- How small can a QGP droplet be and still behave as a liquid droplet?
- How do we experimentally best probe this limit?

Question 2: **What makes the QGP such a “perfect” liquid?**

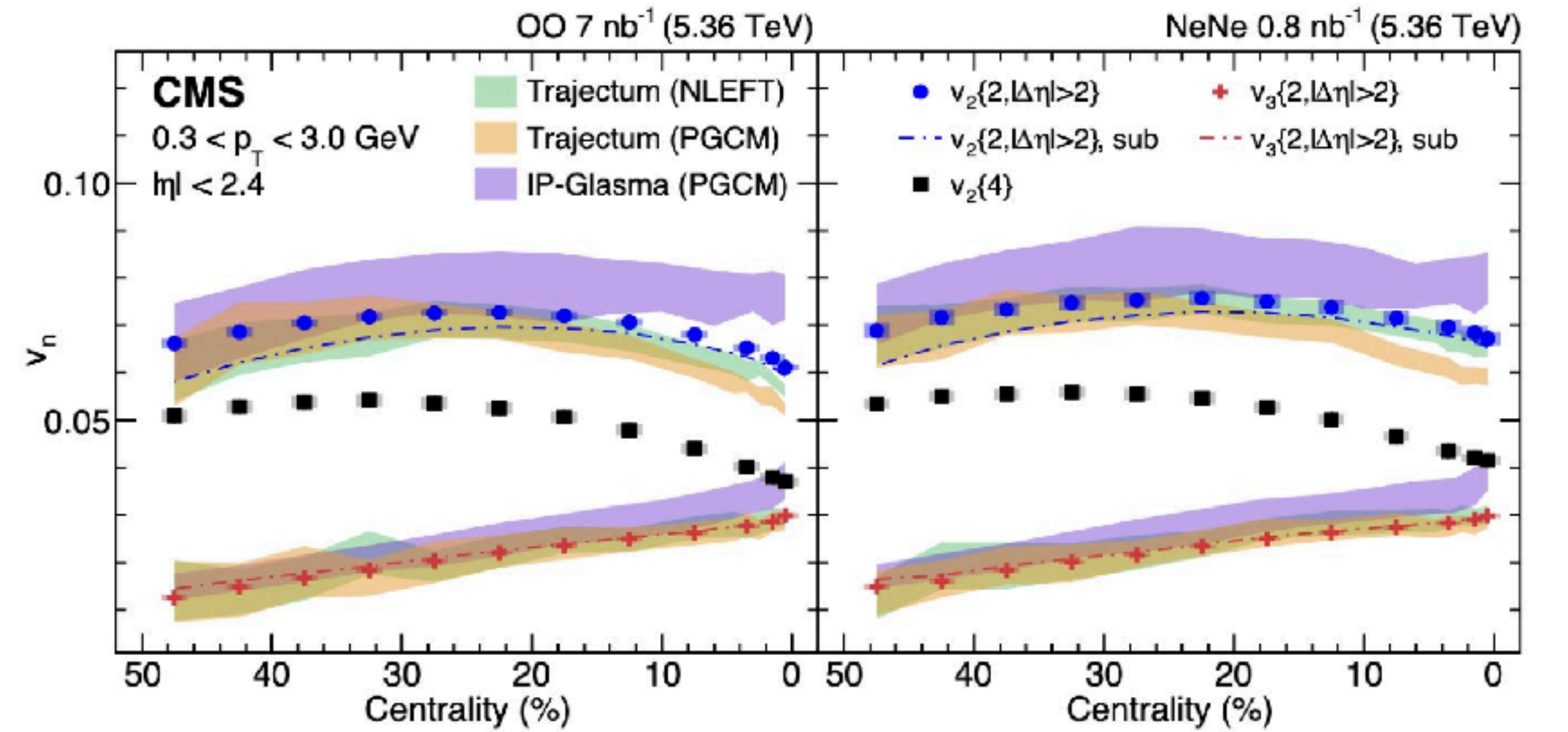
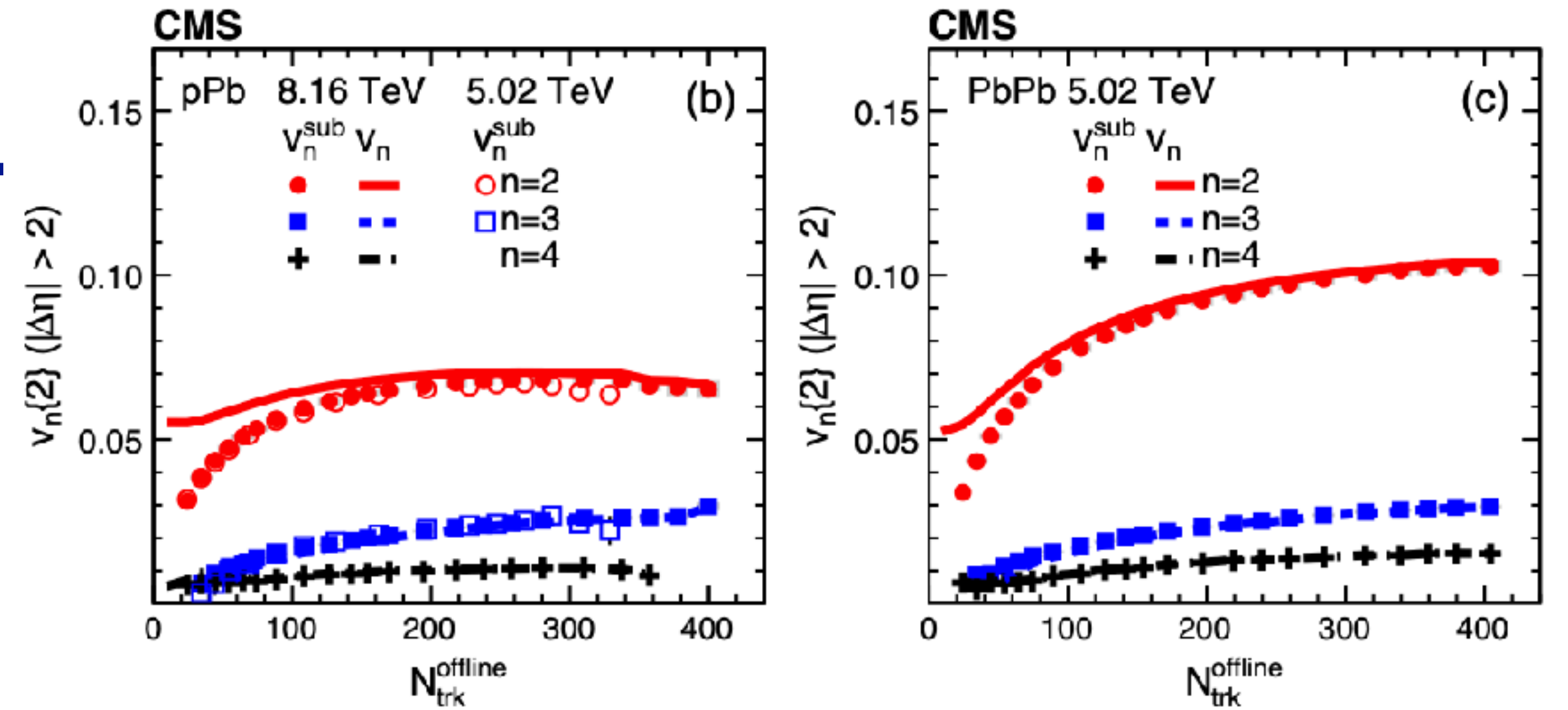
- Strongly coupled states of matter can take many forms (solid, glass, liquid,....)
- Does the QGP fit into the established theories of liquid behavior?
- If not, what is the correct model / theory of QGP liquidity?

The limits of liquidity

EPJ Web Conf. 222 (2019) 01004



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



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

Decreasing overlap region

The liquid state - a hard problem

ABOUT LIQUIDS

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Switzerland*

Transactions NY Acad. Sciences **38** (1977) 202

Introduction

Under ordinary terrestrial conditions matter appears in three states of aggregation: solids, liquids, and gases. The existence and the general properties of solids and gases are relatively easy to understand once it is realized that atoms or molecules have certain typical properties and interactions that follow from quantum mechanics. **Liquids are harder to understand.** Assume that a group of intelligent theoretical physicists had lived in closed buildings from birth such that they never had occasion to see any natural structures. Let us forget that it may be impossible to prevent them to see their own bodies and their inputs and outputs. What would they be able to predict from a fundamental knowledge of quantum mechanics?

They probably would predict the existence of atoms, of molecules, of solid crystals, both metals and insulators, of gases, but most likely not the existence of liquids.

Two approaches:

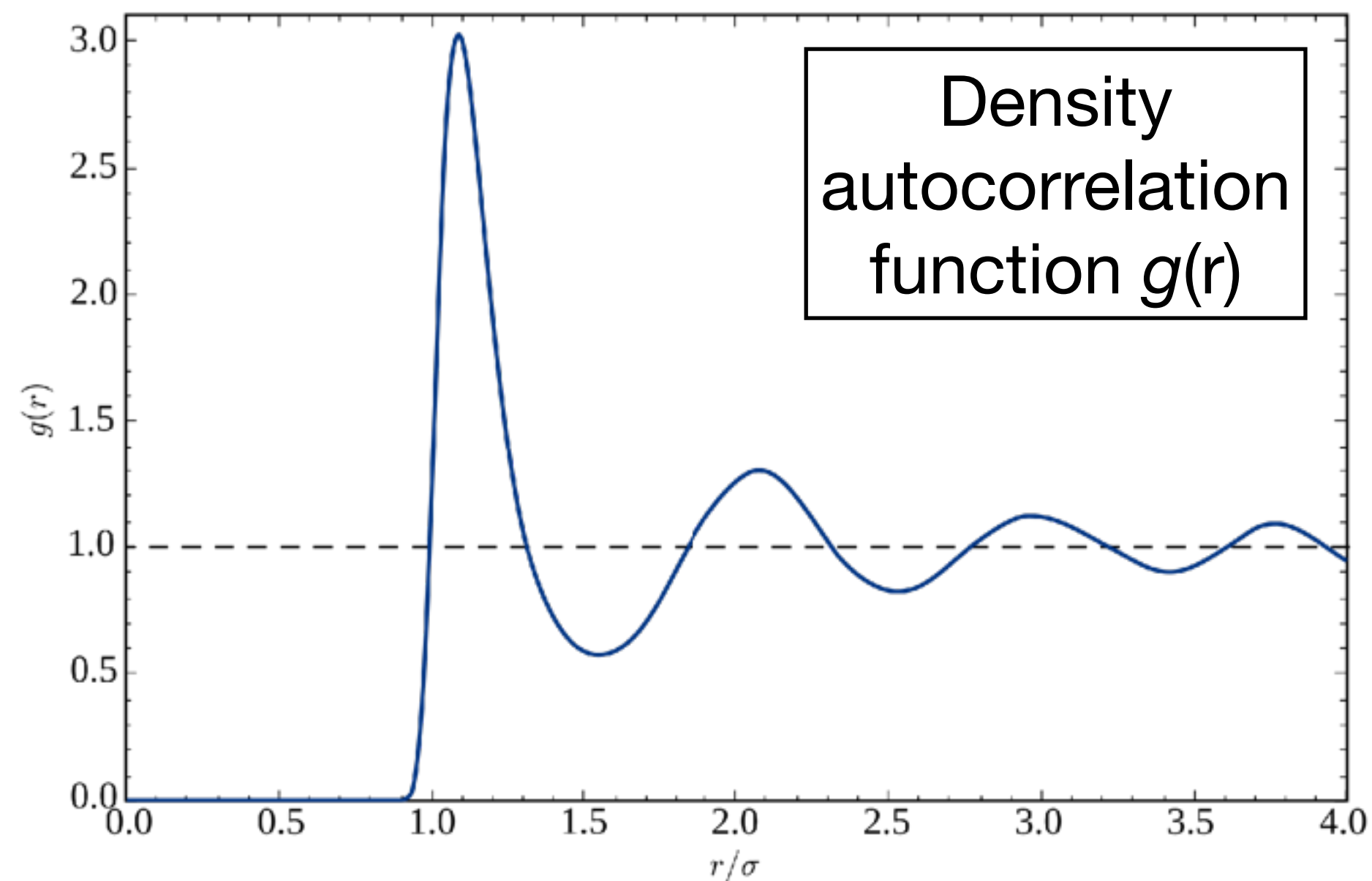
1. Structural theory (Born & Green - 1946)
2. Kinetic theory (Frenkel - 1926/1947)



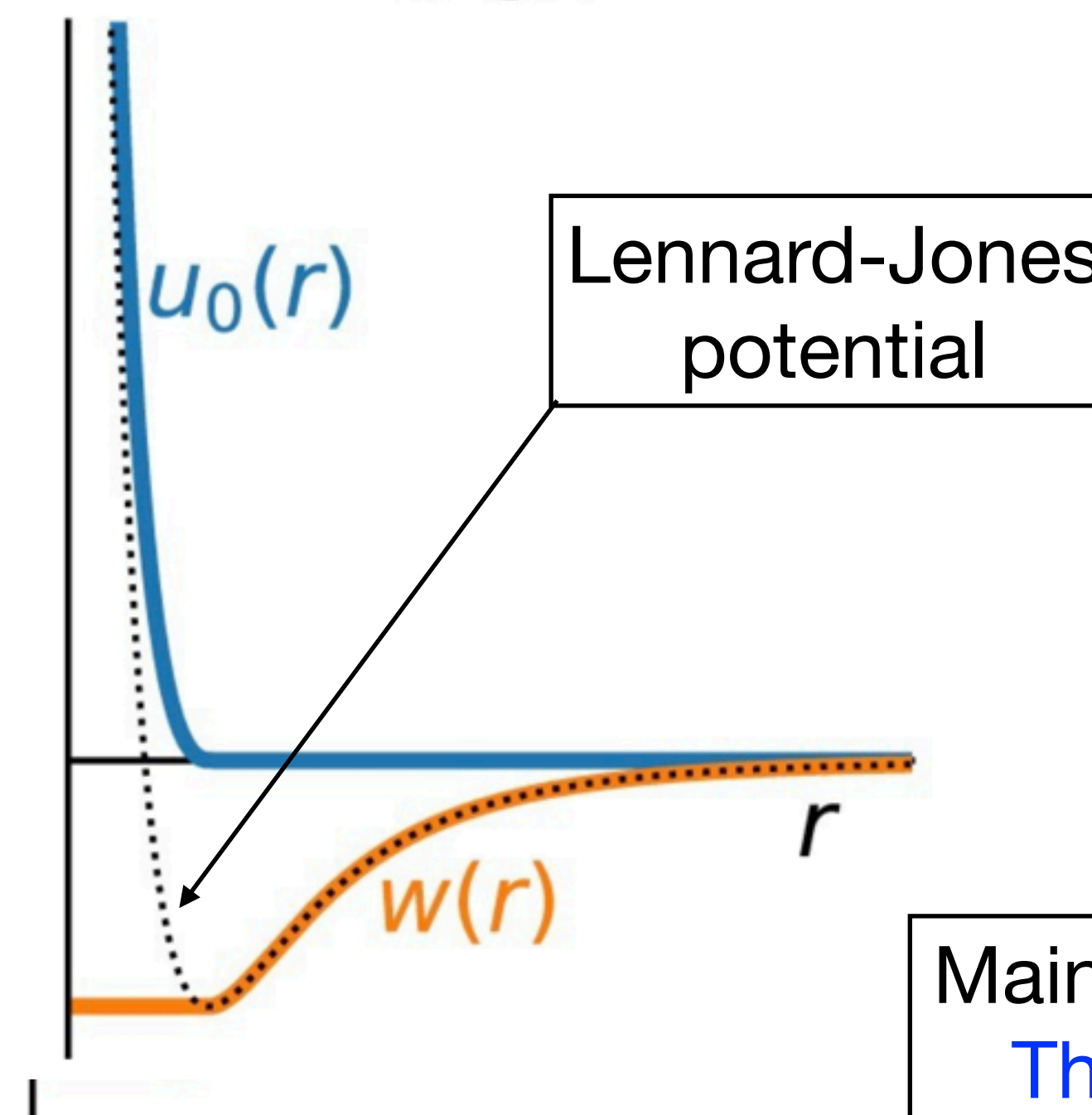
Bodhidharma (Kawanabe Kyosai)

Structure of liquids

Liquids have no long-range structure



WCA



Weeks, Chandler & Andersen,
J. Chem. Phys. **54** (1971) 5237

$$w(r) = U(r) - u_0(r)$$

acts as perturbation

Main challenge of this approach:
There is no small parameter.

Strong **short-range repulsion** is balanced by **long-range attraction** (shared by solids and glasses).

Problem: There is no repulsive core in the QGP

Kinetics of liquids

Trachenko - 2309.15205

Proctor & Trachenko, Rep. Prog. Phys. **87** (2024) 098001

Kinetic properties of liquids are carried by collective excitations (phonons), similar to solids.

Difference: **Liquids cannot sustain static/slow shear** → **no transverse phonons for $\omega < \omega_F$**

However, on short times $t < \tau = \tau_{\text{jump}}$, a liquid behaves like an amorphous solid.

Dynamical shear velocity field (Maxwell-Frenkel)

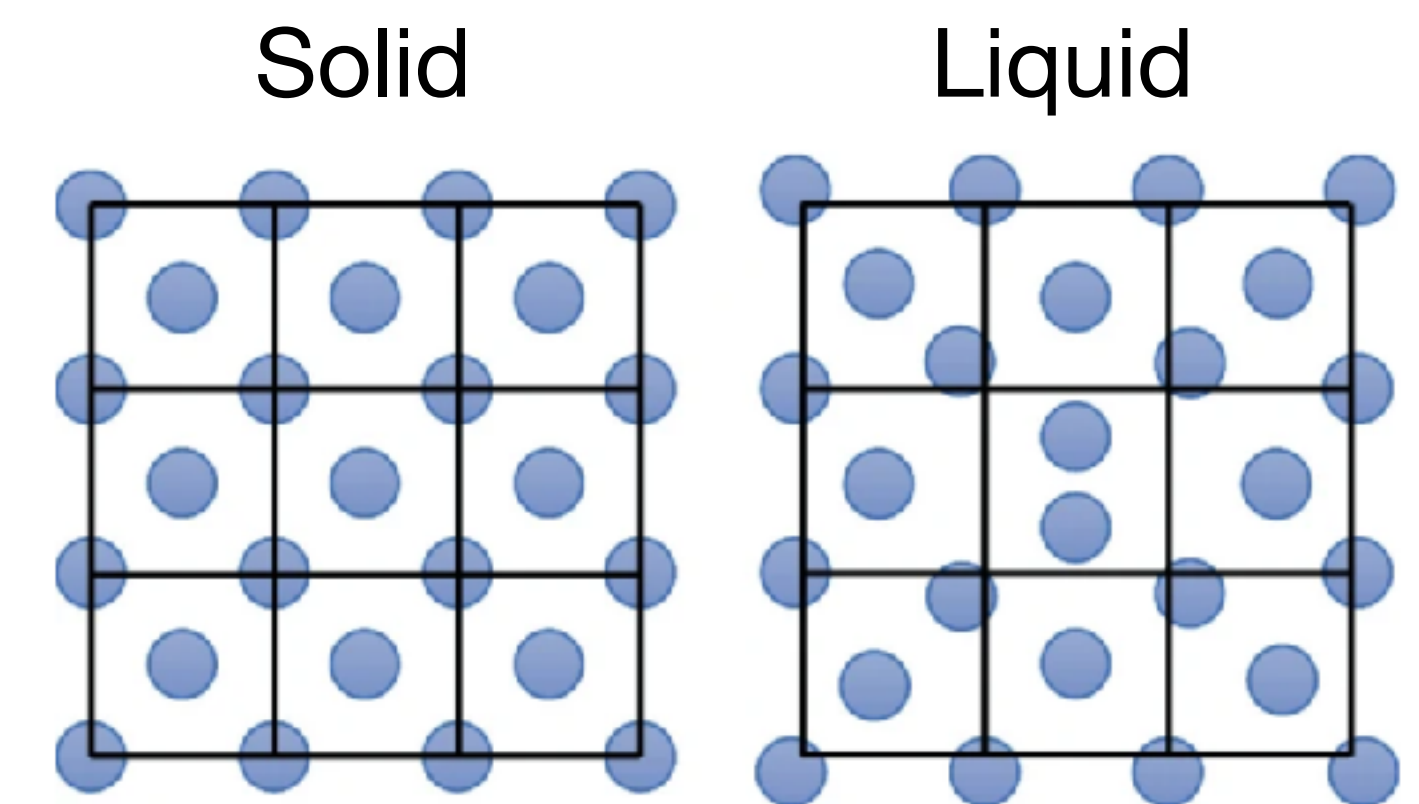
$$v(r, t) \propto \exp\left(ikr - i\omega_k t - \frac{t}{2\tau}\right) \quad \text{with} \quad \omega_k^2 = c_s^2 k^2 - \frac{1}{4\tau^2} \equiv c_s^2 k^2 - \omega_F^2$$

$\omega < \omega_F$: Transverse phonons do **not** propagate

$\omega > \omega_F$: Transverse phonons propagate ballistically

Small parameter: Displacement of individual constituents

Applicable to the QGP ???



A liquid *sui generis*?

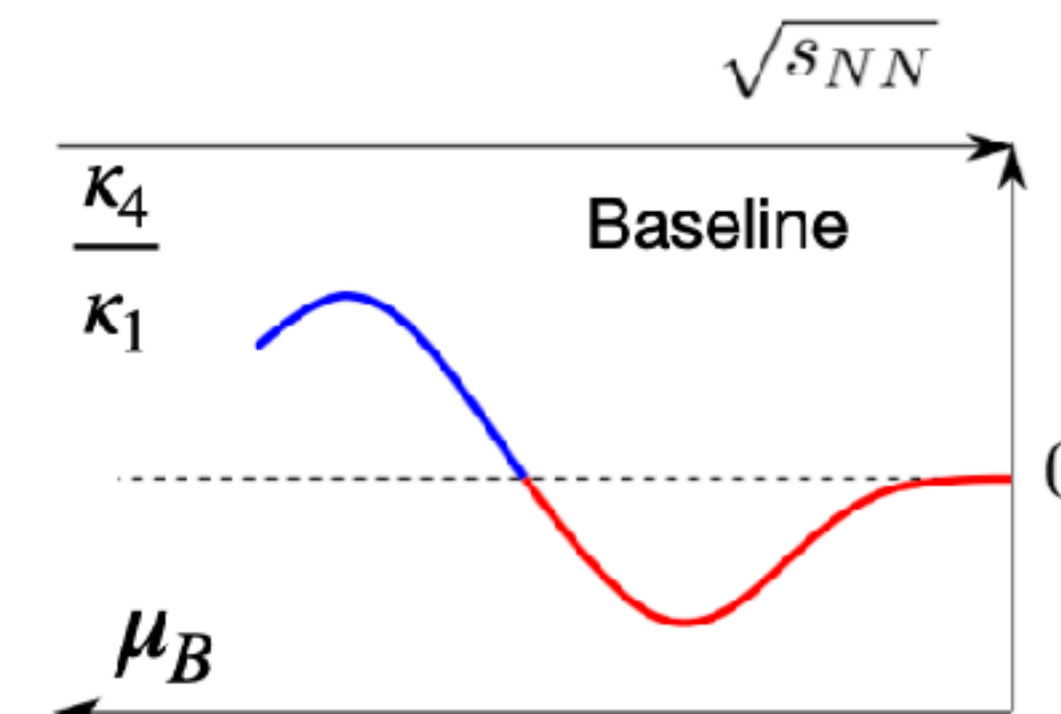
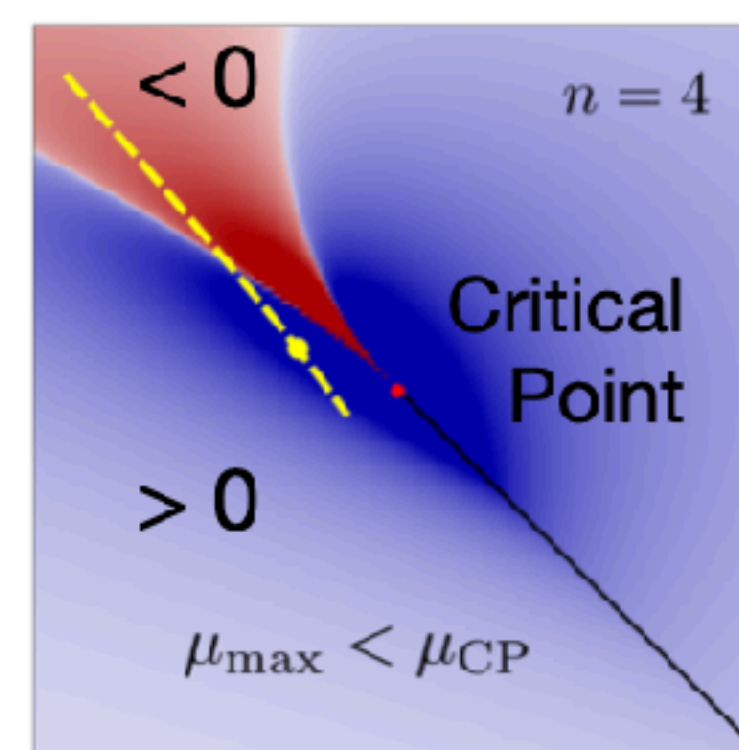
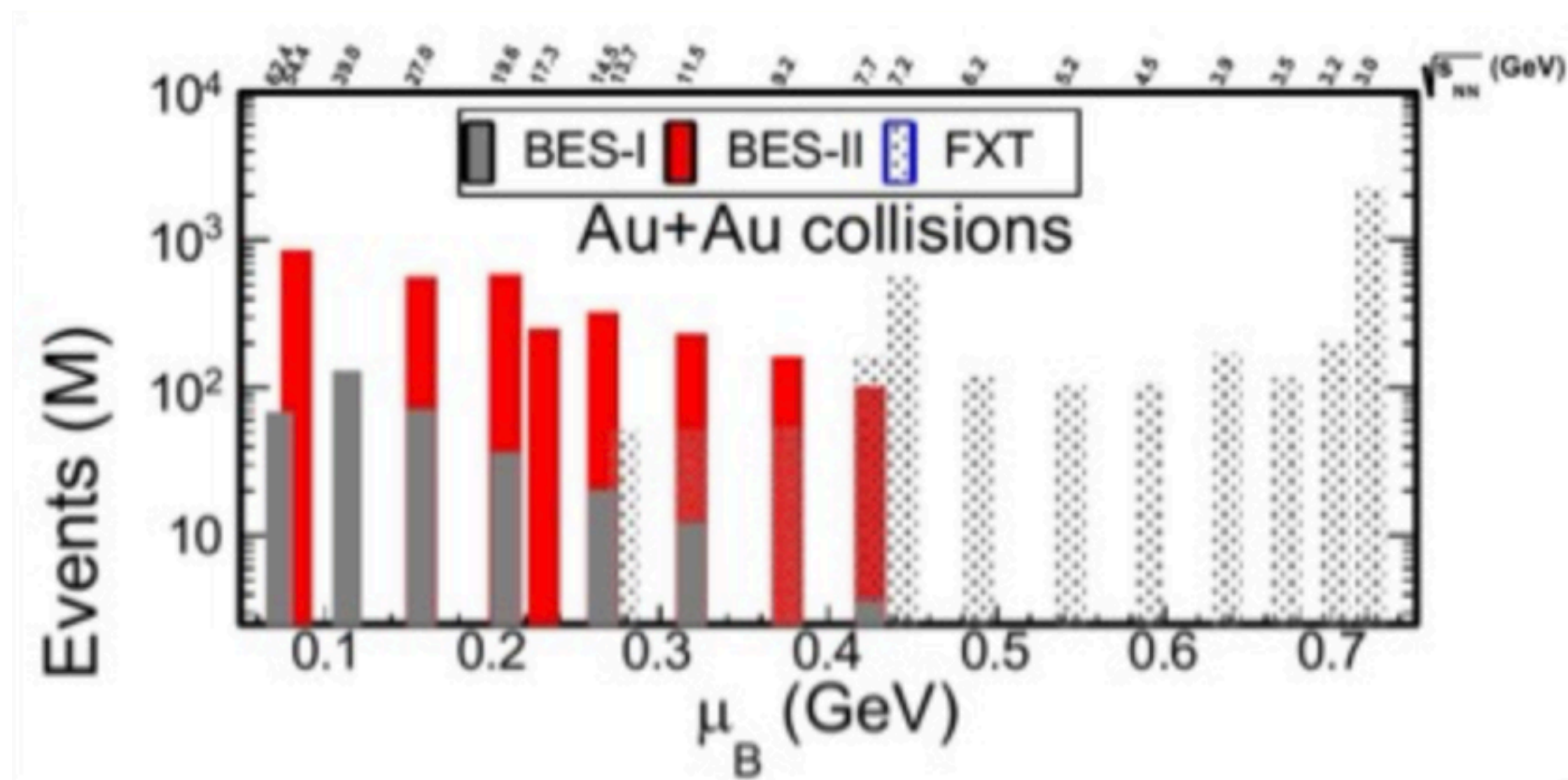
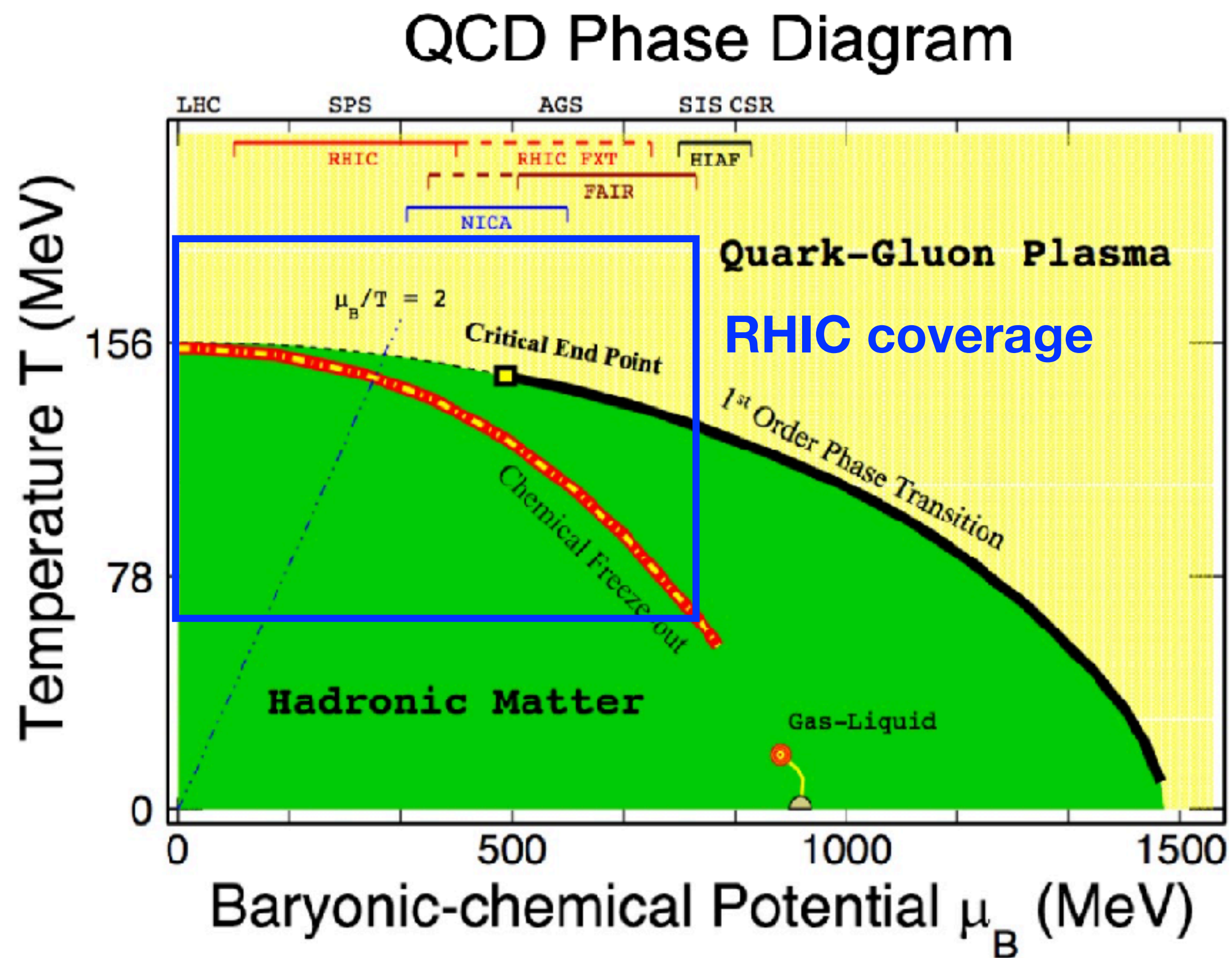
- The Born-Green theory of liquids does not apply to the QGP, because there is no hard repulsive core.
 - Could the hard core be replaced by an absorptive core - gluons and quarks are strongly absorbed at short distance?
- The Frenkel theory of liquids does not apply to the QGP, because at short distances the QGP behaves like a gas, not a solid (asymptotic freedom).
 - What serves as a small parameter in this case?
- Do we need a completely new paradigm for strongly coupled relativistic liquids, in which particle number is not conserved?
 - Does holography provide path to such a novel theoretical paradigm?



Buddha Maitreya (Wei Dynasty)

Critical Point

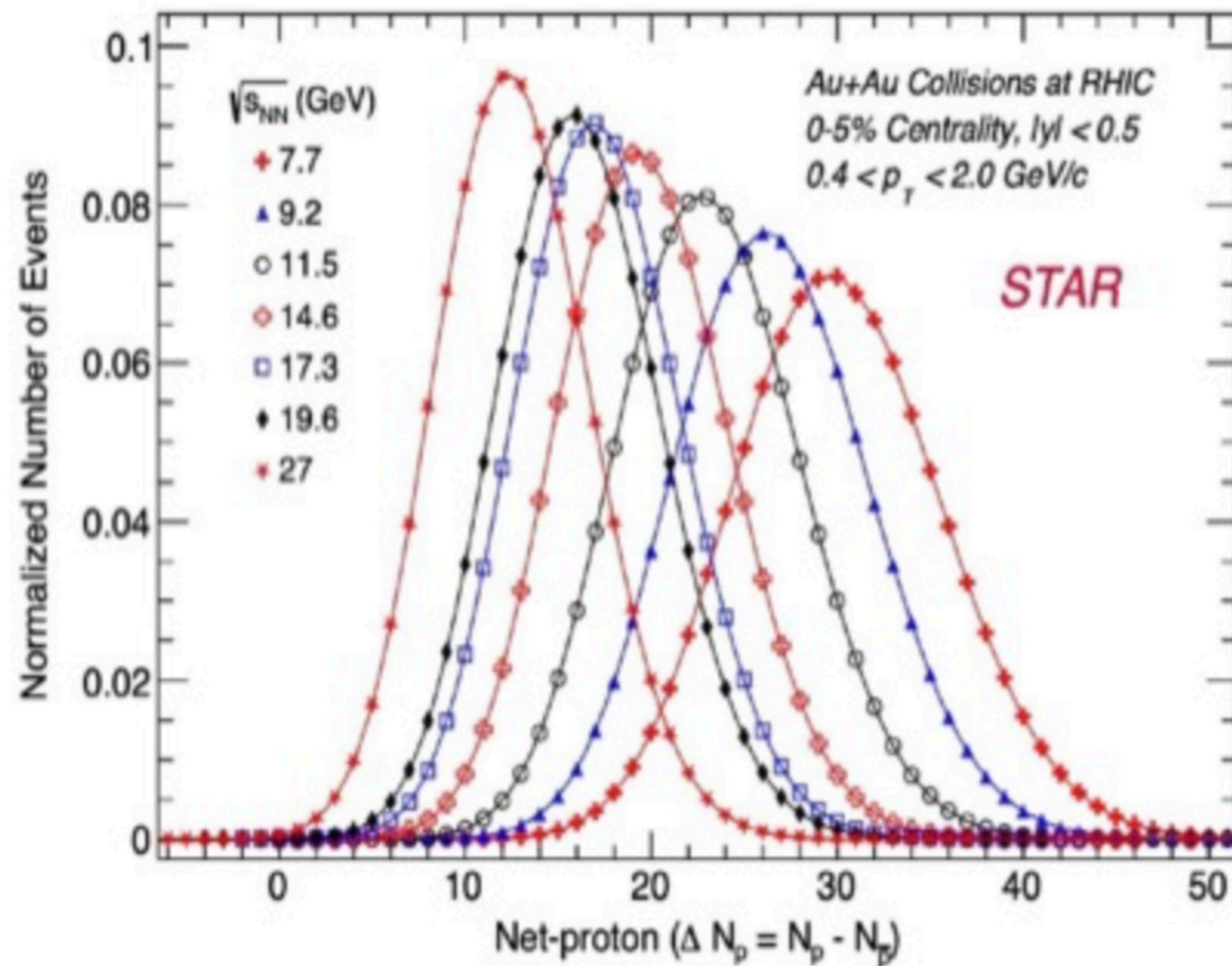
Is there a QCD critical point?



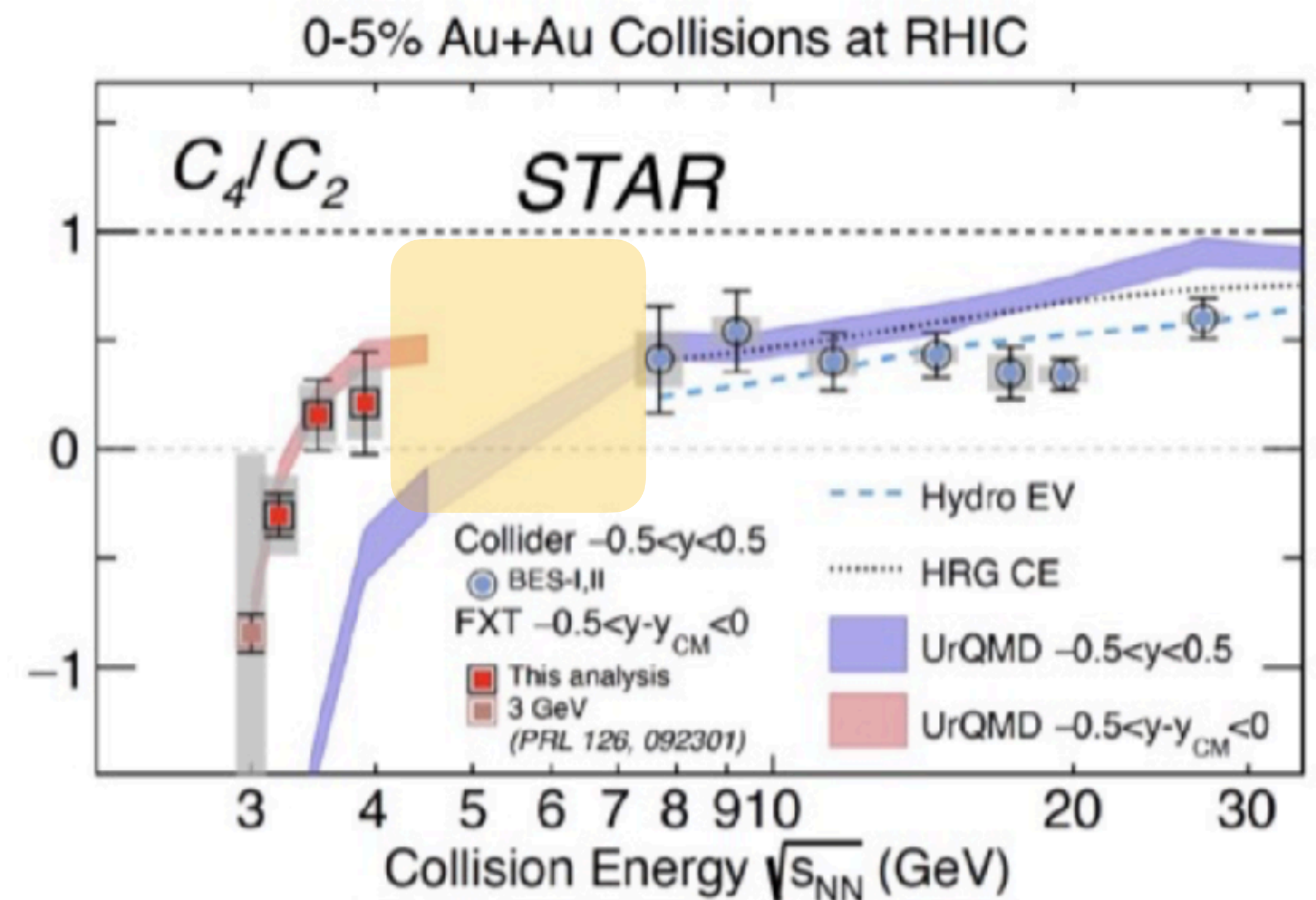
Kurtosis of net baryon fluctuations

Net proton fluctuations

Full distributions are measured, look at various ratios of moments (factorial, cumulants, etc.)



No obvious signs of critical phenomena yet, but there is a big gap between 4 – 7 GeV. Data have been taken, but not yet analyzed.

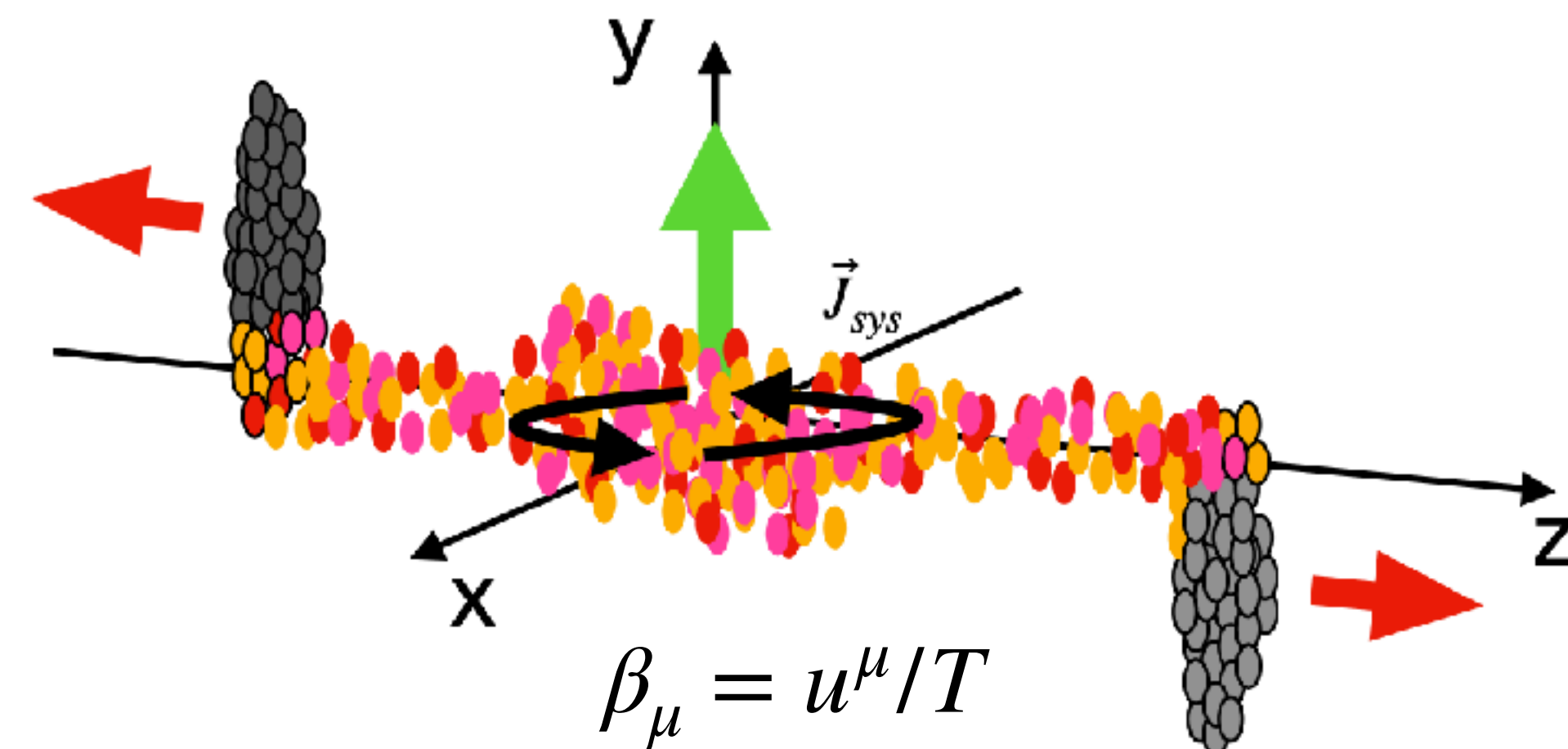
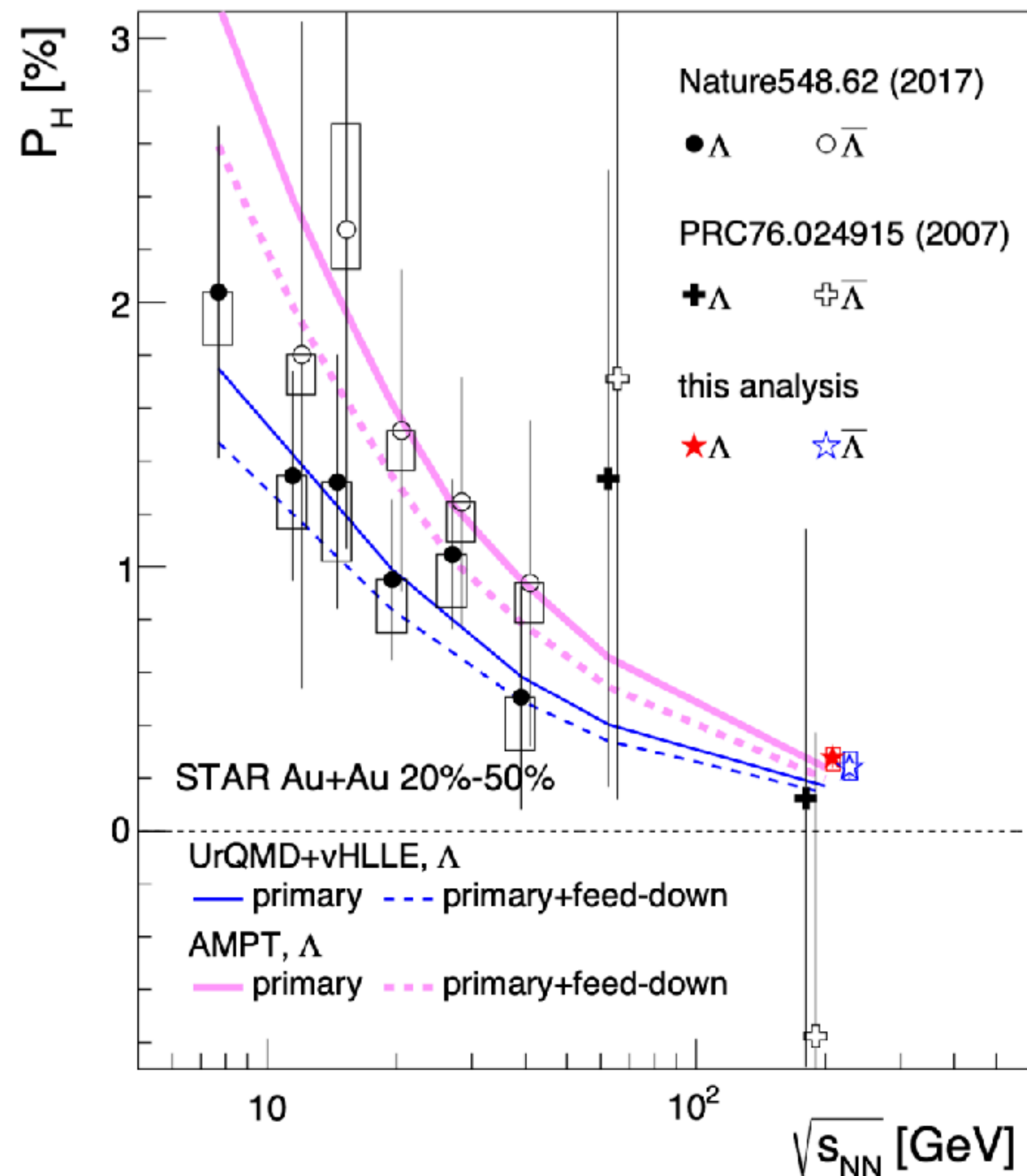




Crowned Buddha (Burma)

Vorticity and Polarization

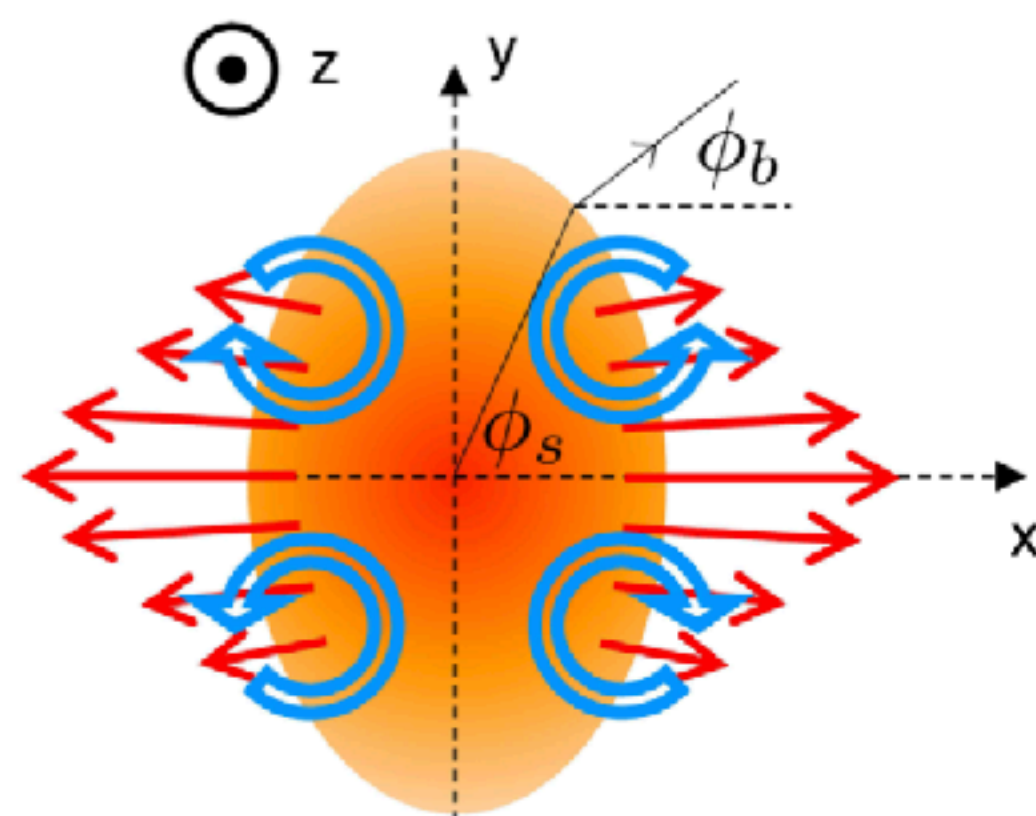
Global polarization



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

Polarization: $P_\Lambda \propto \exp(\vec{\tilde{\omega}} \cdot \vec{s}_\Lambda)$

Local polarization



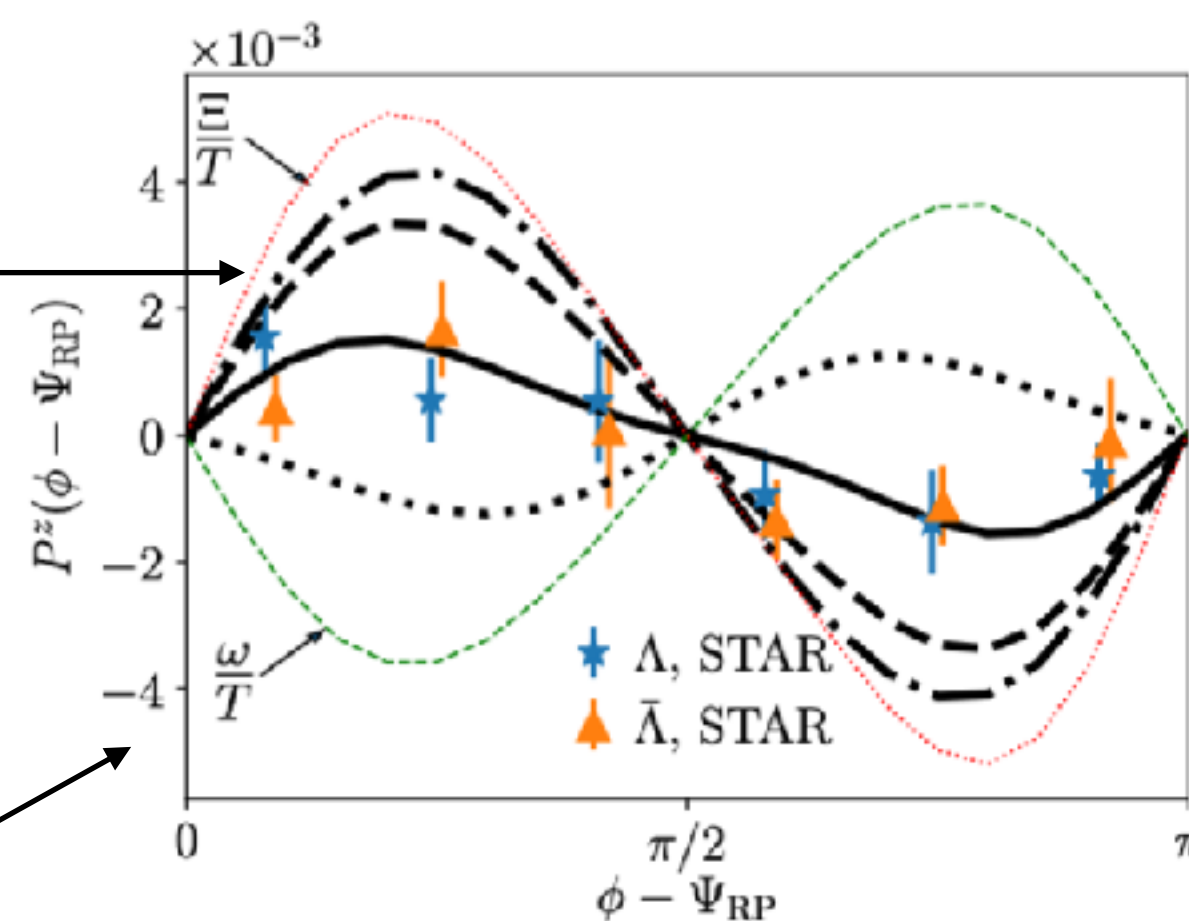
$$P_z = \frac{\langle \cos \theta_p^* \rangle}{\alpha_H \langle \cos^2 \theta_p^* \rangle}$$

Thermal shear

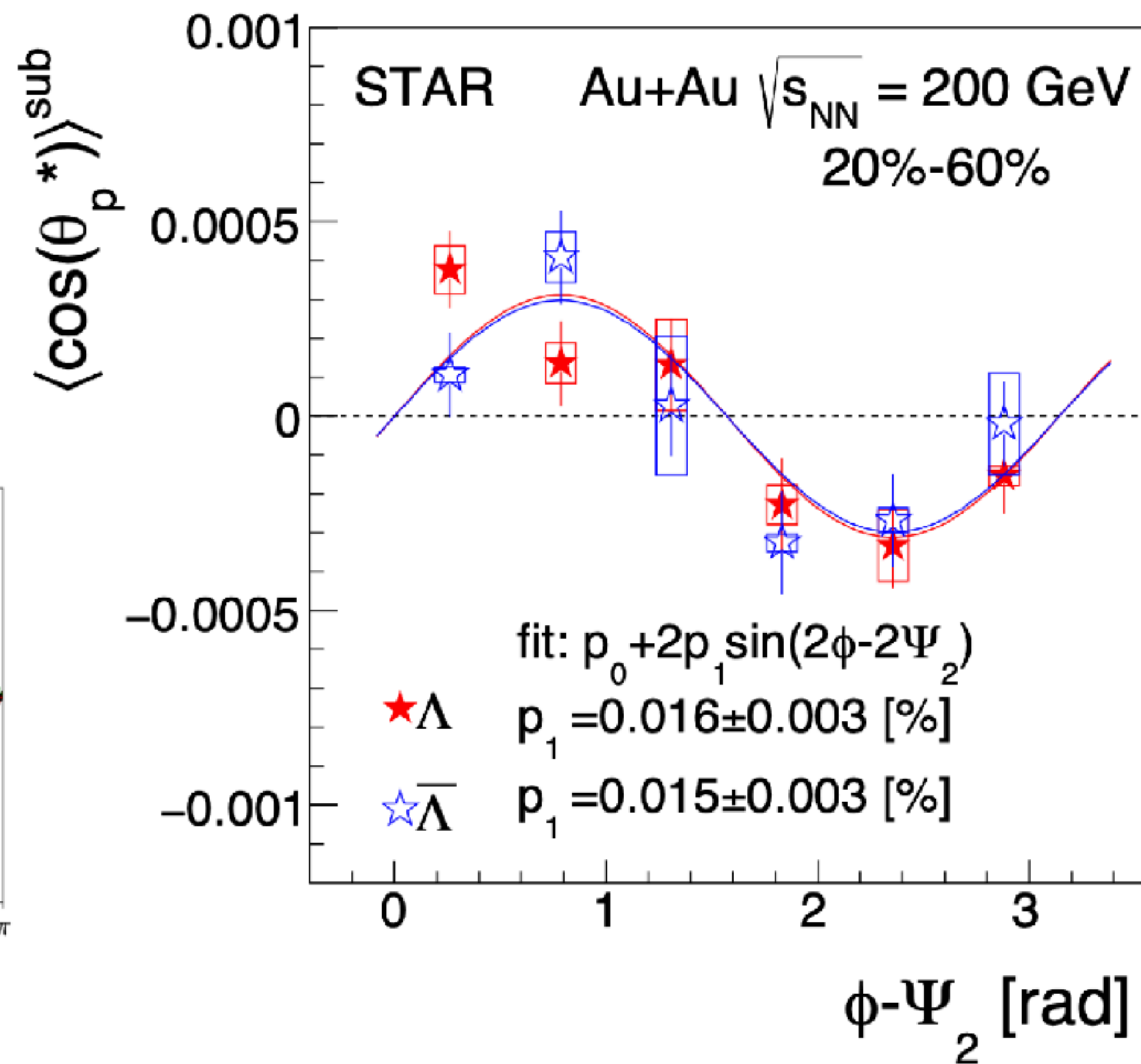
$$\xi_{\mu\nu} = \frac{1}{2} (\partial_\nu \beta_\mu + \partial_\mu \beta_\nu)$$

Thermal vorticity:

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

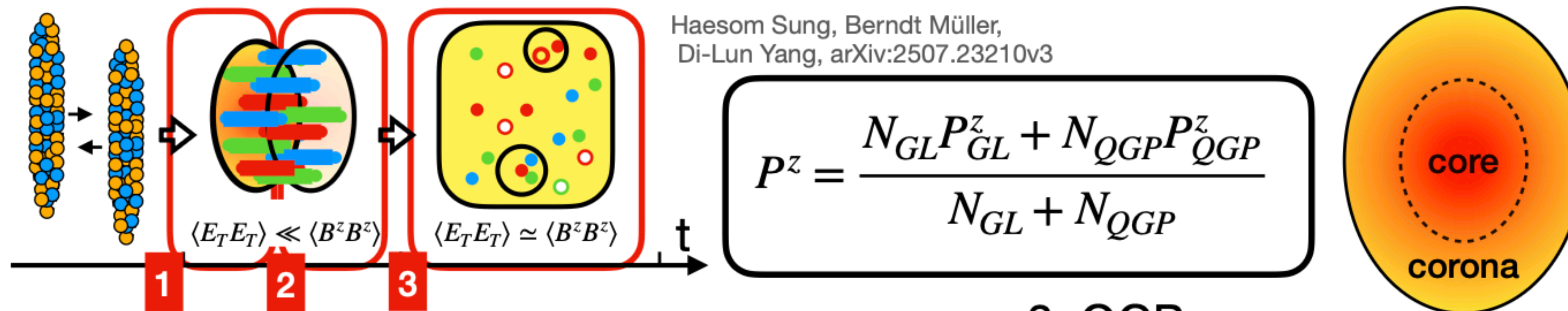


J. Adam et al. (STAR), PRL 123 (2019) 13, 132301

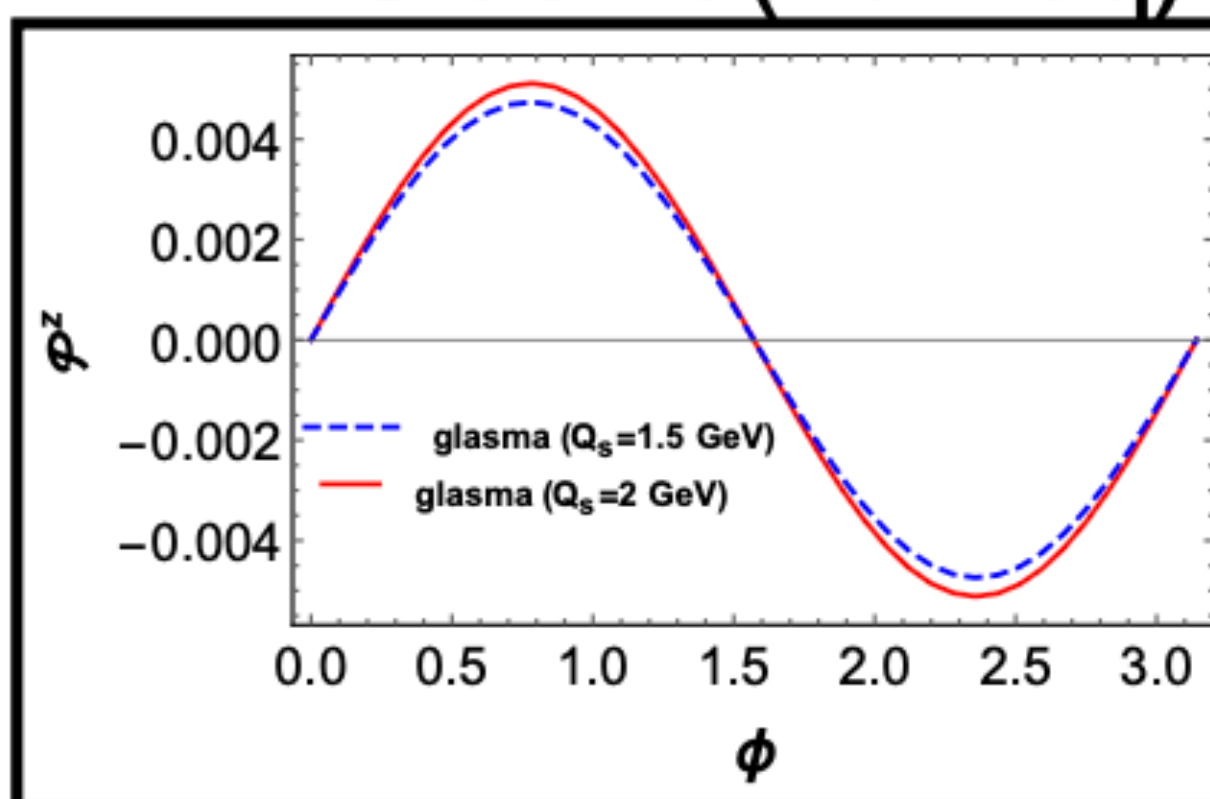


Glasma - QGP competition?

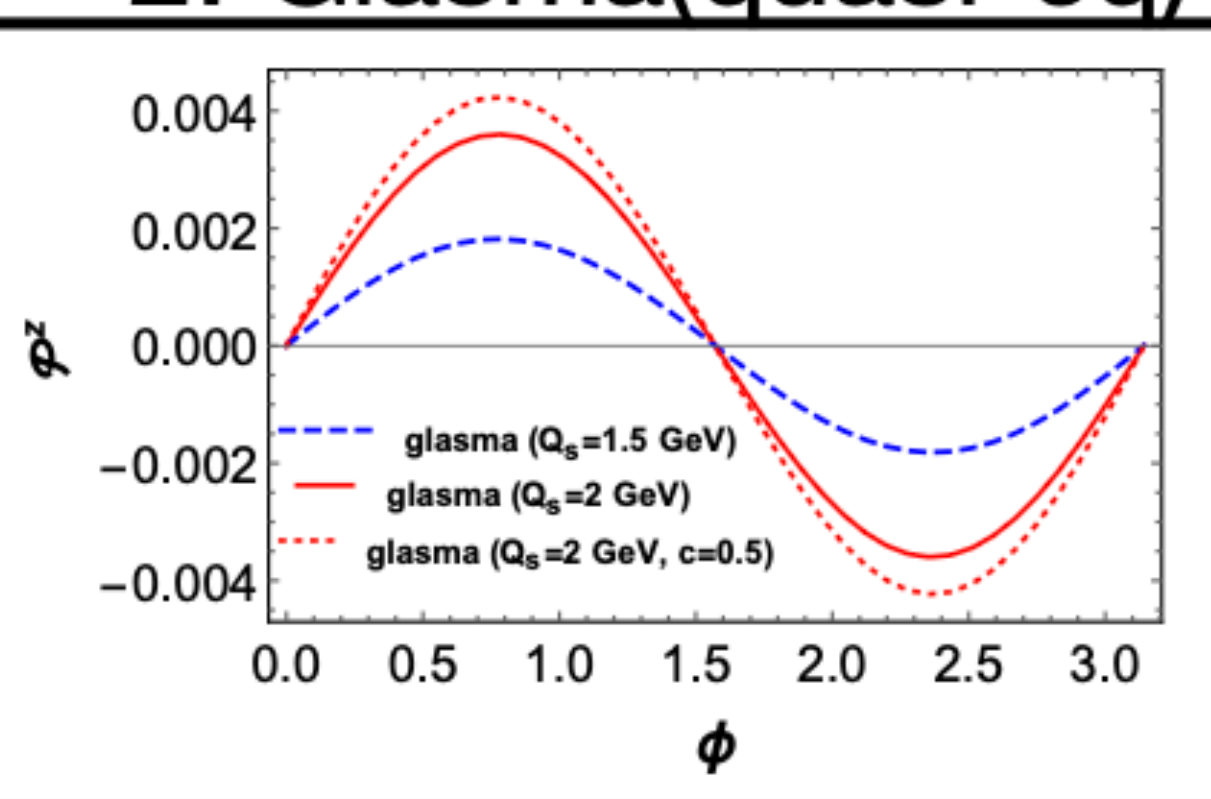
Haesom Sung - Talk at SQM 2026



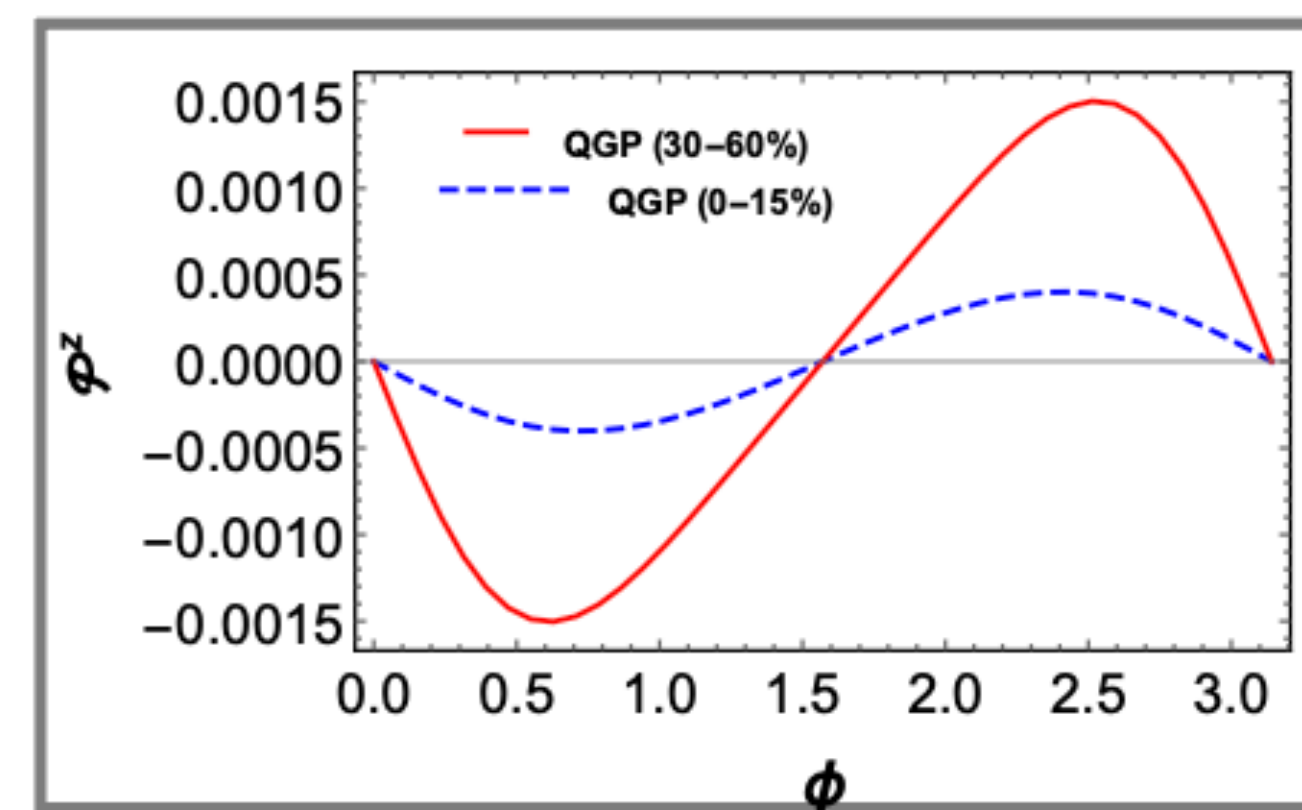
1. Glasma(non-eq)



2. Glasma(quasi-eq)



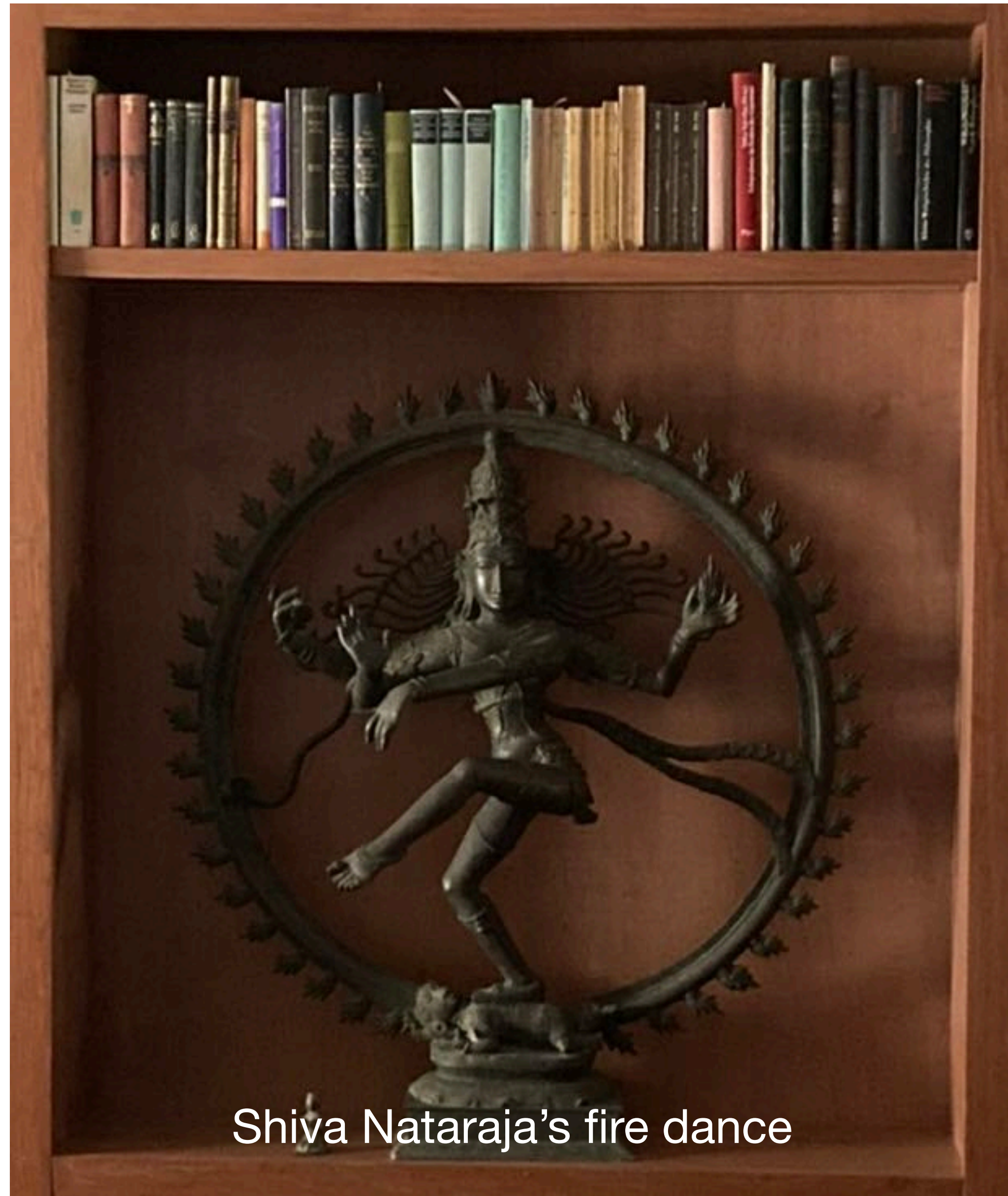
3. QGP



In **small system**, $N_{GL} \gg N_{QGP}$, so we can expect the **Sinusoidal** structure in azimuthal angle

+Hydrodynamic contribution
(vorticity+shear)

F. Becattini et al., PRL 127,272302 (2021)
Baochi Fu et al., PRL 127 (2021) 14,
142301



Shiva Nataraja's fire dance

Thermalization

Eigenstate thermalization hypothesis (ETH)

A pure quantum system in an energy eigenstate can look “thermal” to local probes:

J.M. Deutsch, Phys. Rev. A 43 (1991) 2046; M. Srednicki, Phys. Rev. E 50 (1994) 888

Matrix elements of local operators for energy eigenstates can be represented as

$$\langle n|O|m\rangle = \langle O\rangle_{\text{mc}}(E)\delta_{nm} + e^{-S(E)/2} f(E, \omega) R_{nm}$$

$$E = (E_n + E_m)/2$$

$$\omega = E_n - E_m$$

Diagonal part close to microcanonical ensemble average

Correction suppressed exponentially by system size

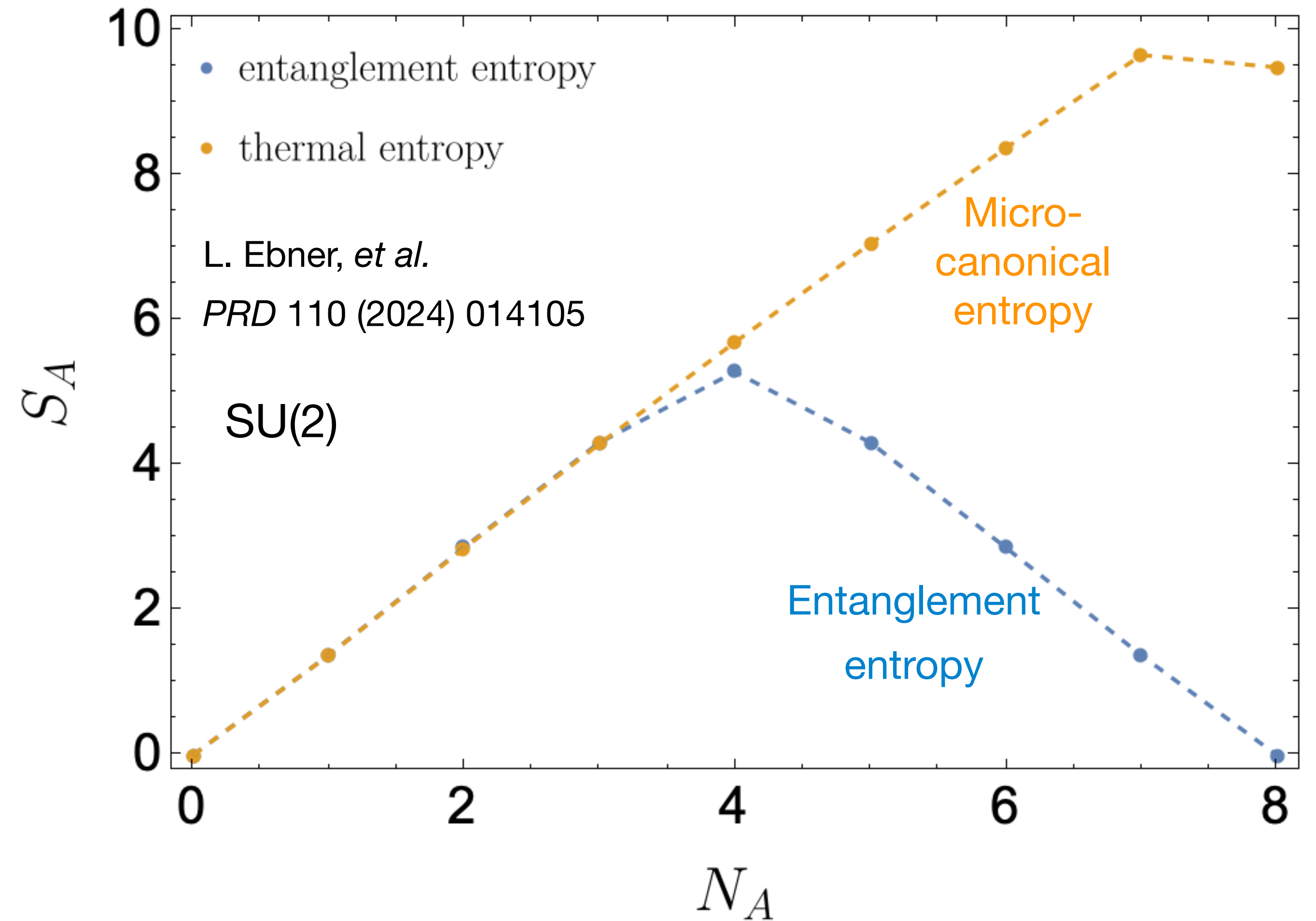
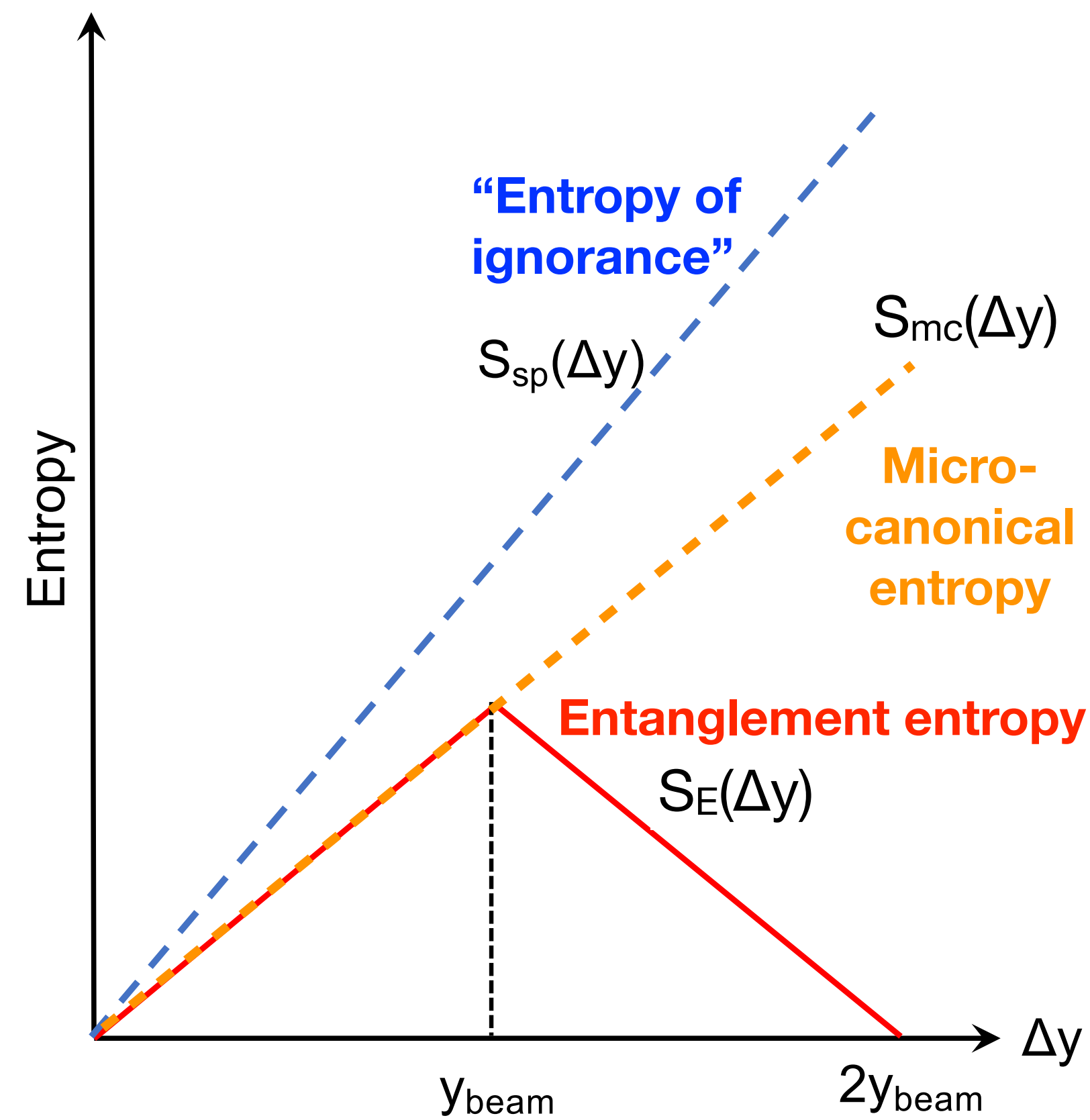
Gaussian random matrix

Eigenstate thermalization

When observed through a local measurement, energy eigenstates of a complex quantum system appear “thermal”

Spectral function decays with ω

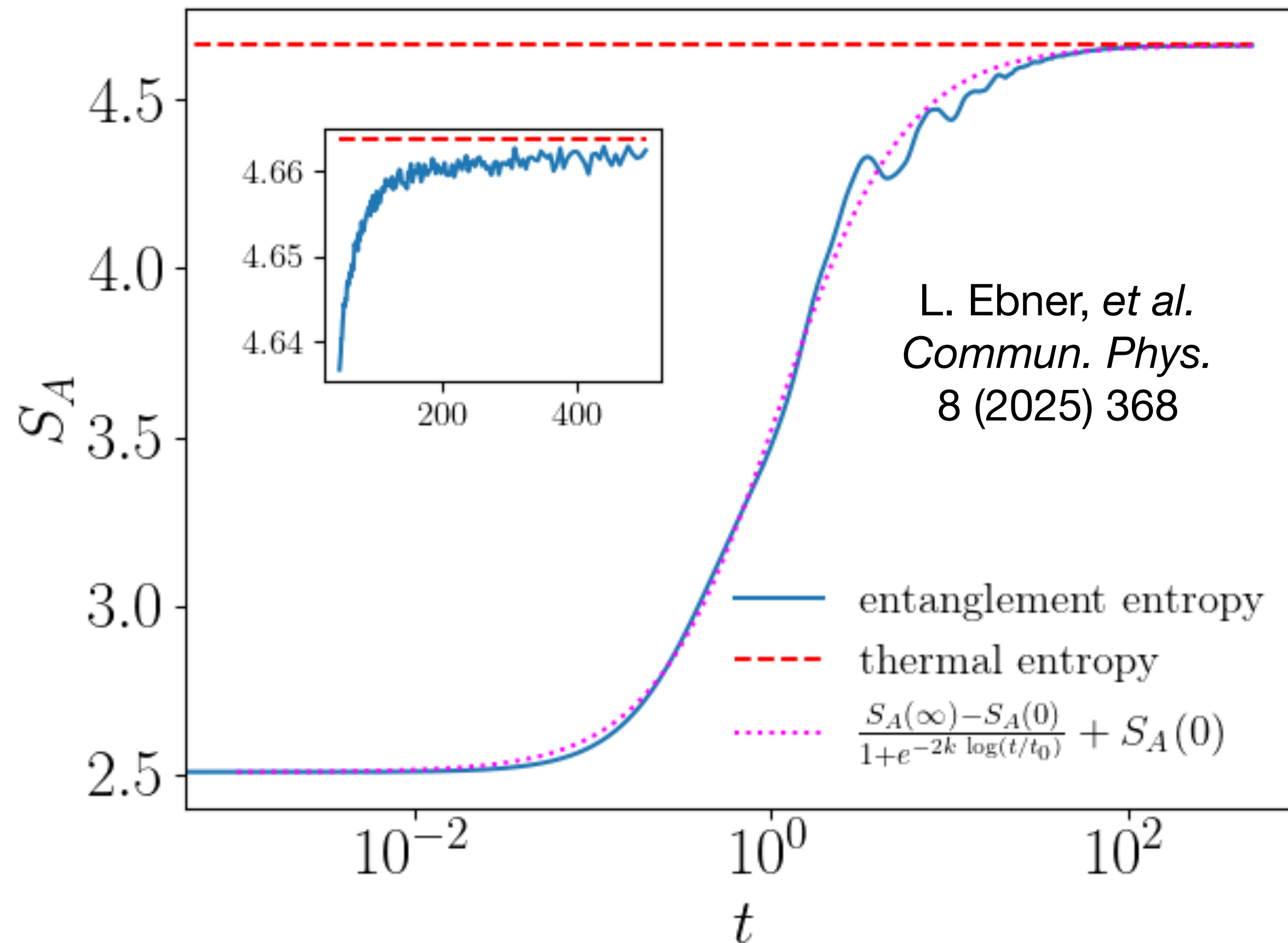
Page curve for gauge theories



Two-step thermalization

Step 1: Entanglement entropy introduced by observation on a subsystem

Step 2: Approach to micro-canonical (thermal) entropy on a universal time scale



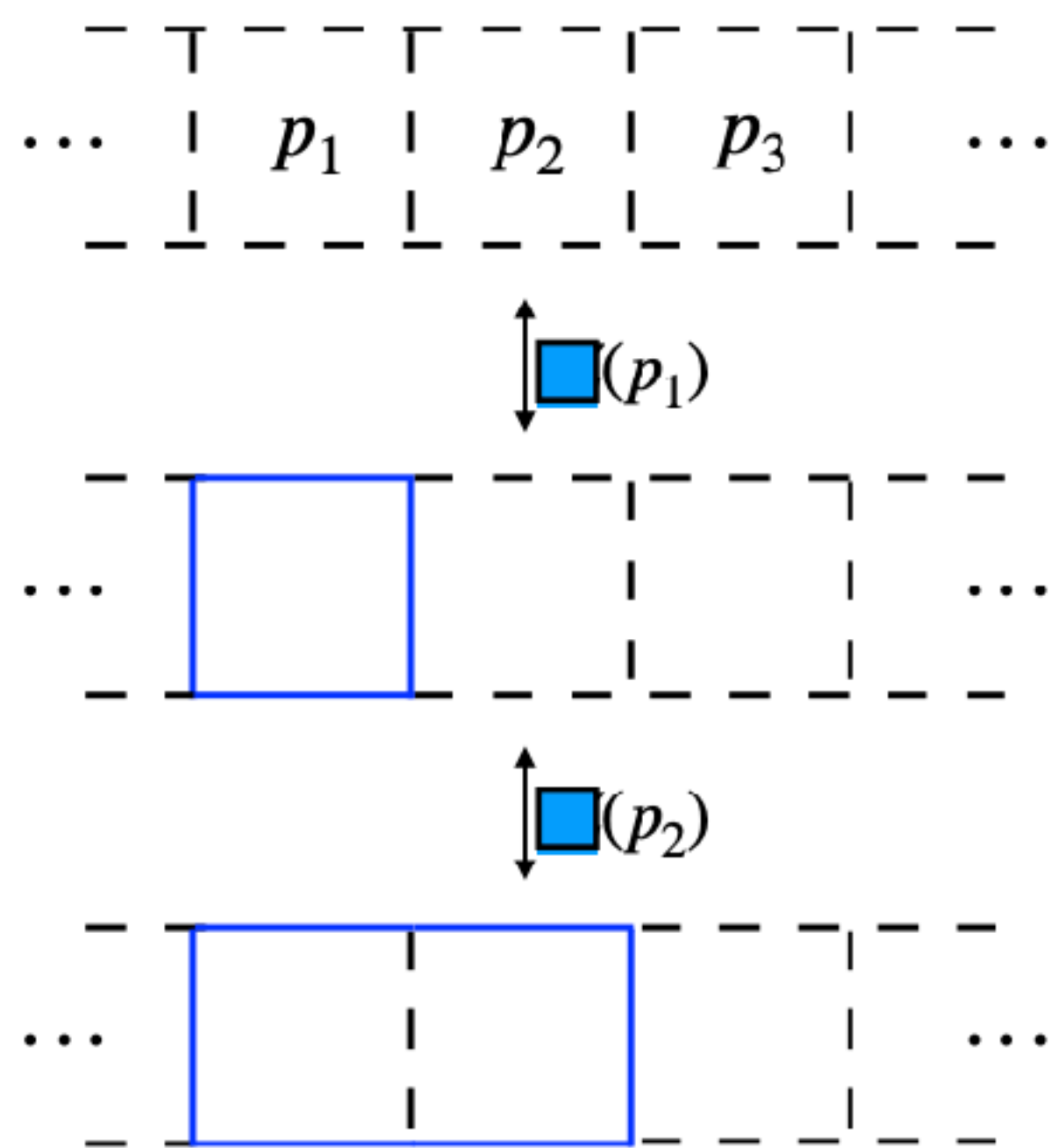
Future progress will rely on quantum computers.

Exact simulation (left) is equivalent to $O(20)$ qubits.

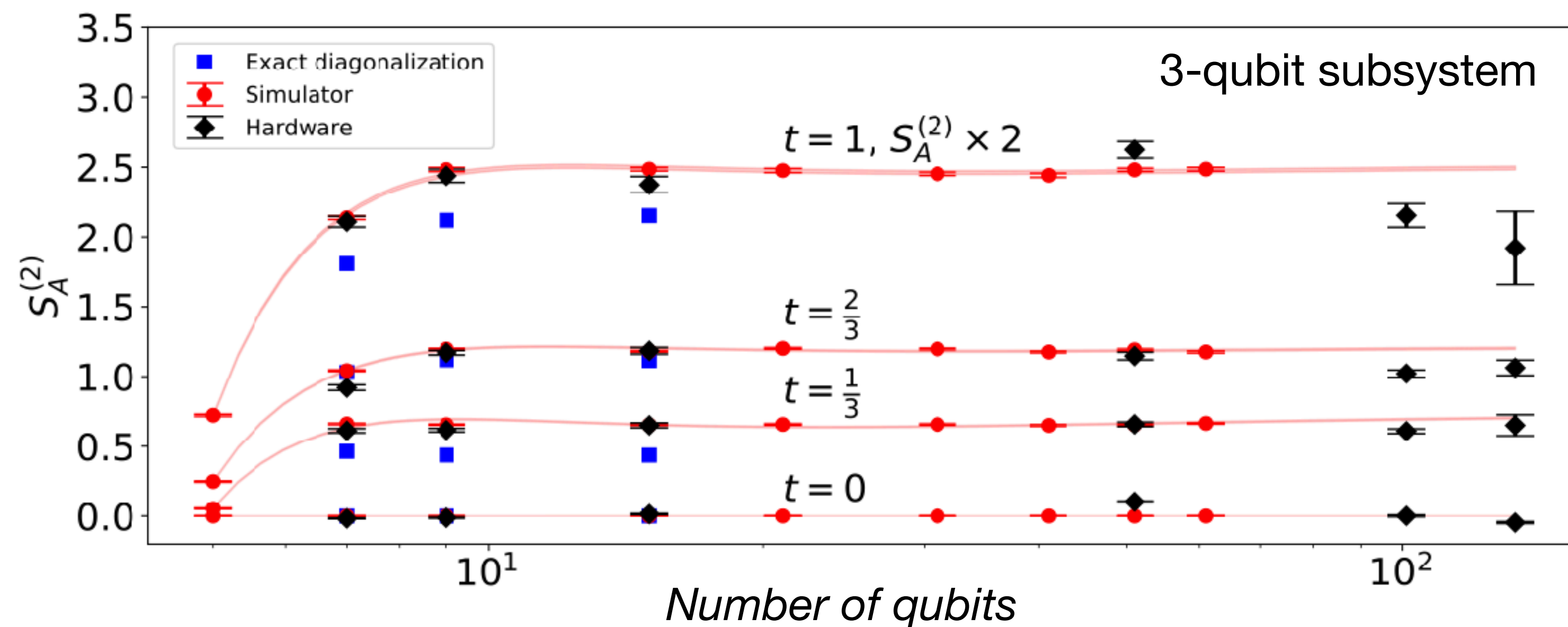
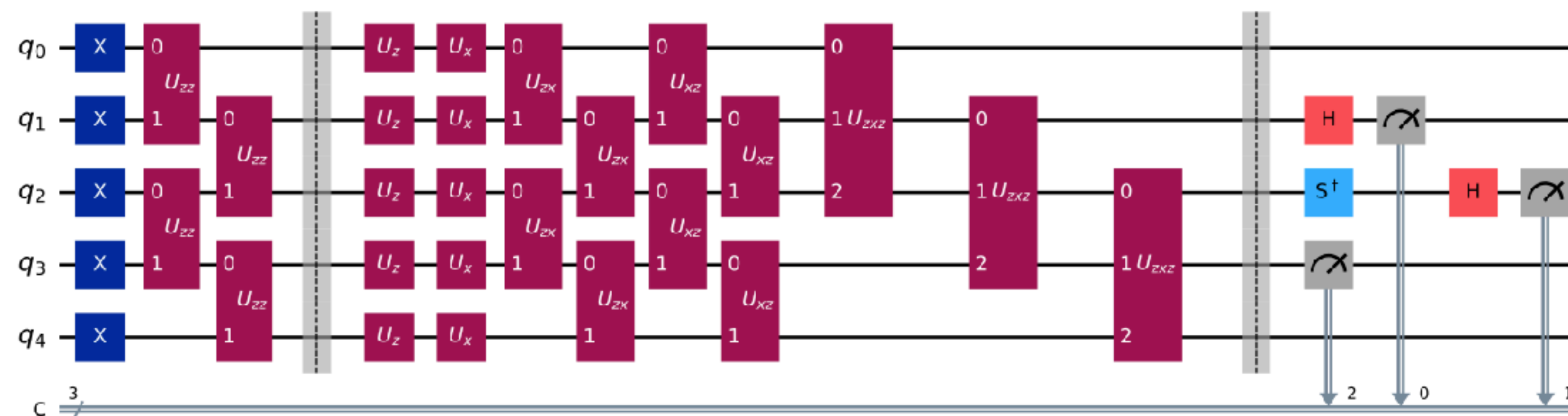
We recently completed a quantum computation on $O(100)$ qubits.

QC implementation up to $N_{\text{qubits}} > 151$

JW Chen et al. - 2603.23948



Spin-1/2 representation of a SU(2) plaquette chain



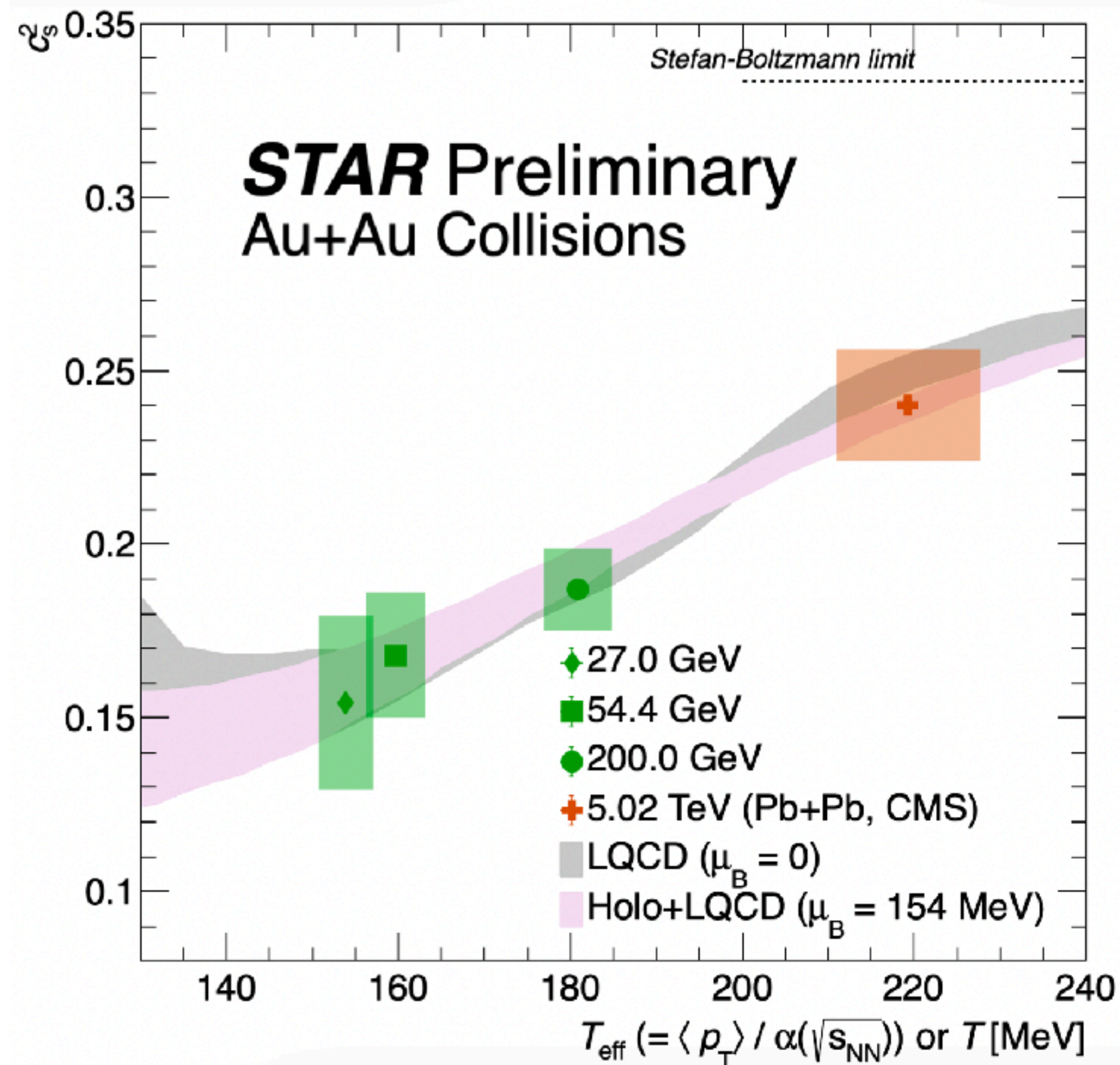


Qilin carrying a small qilin

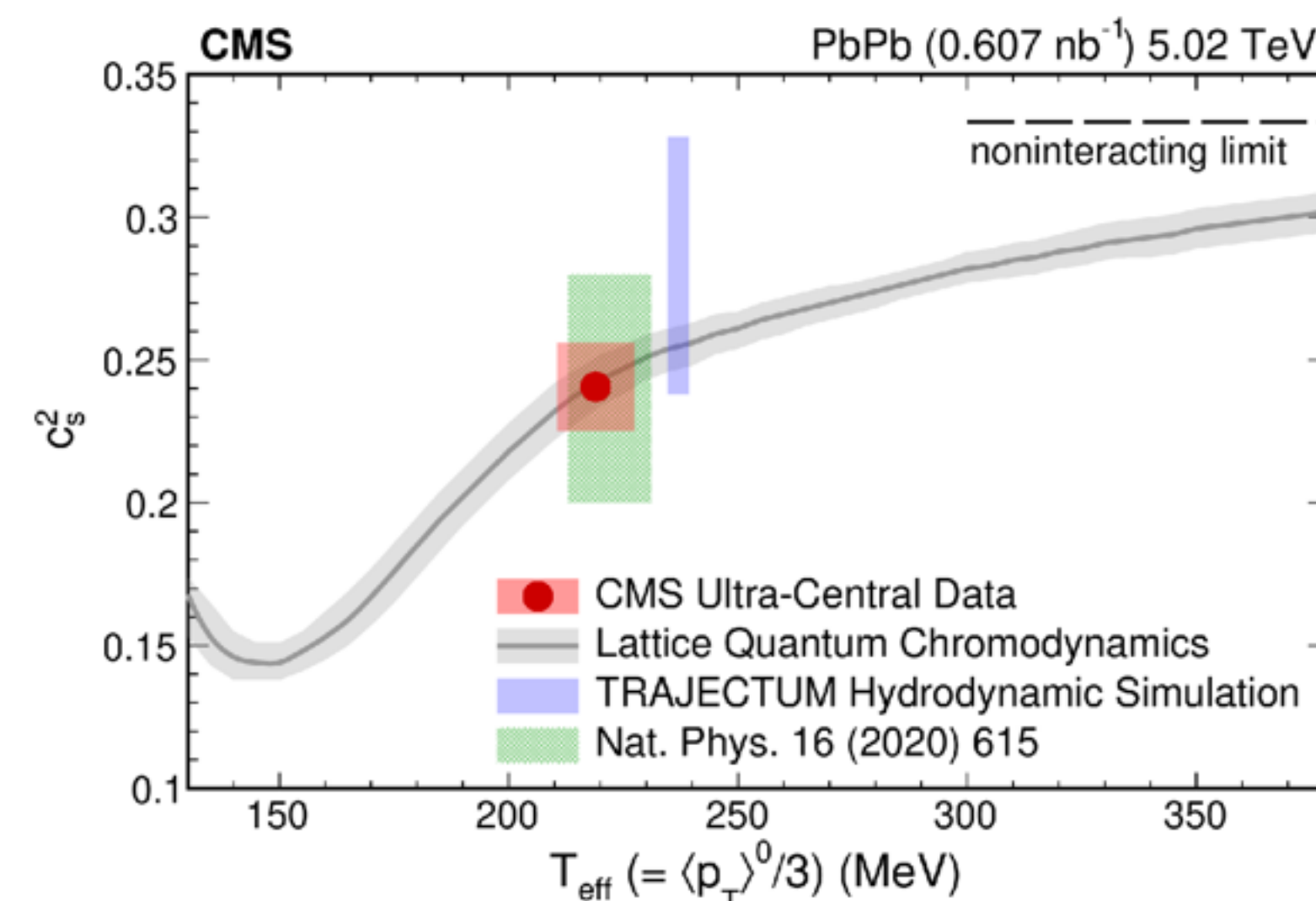
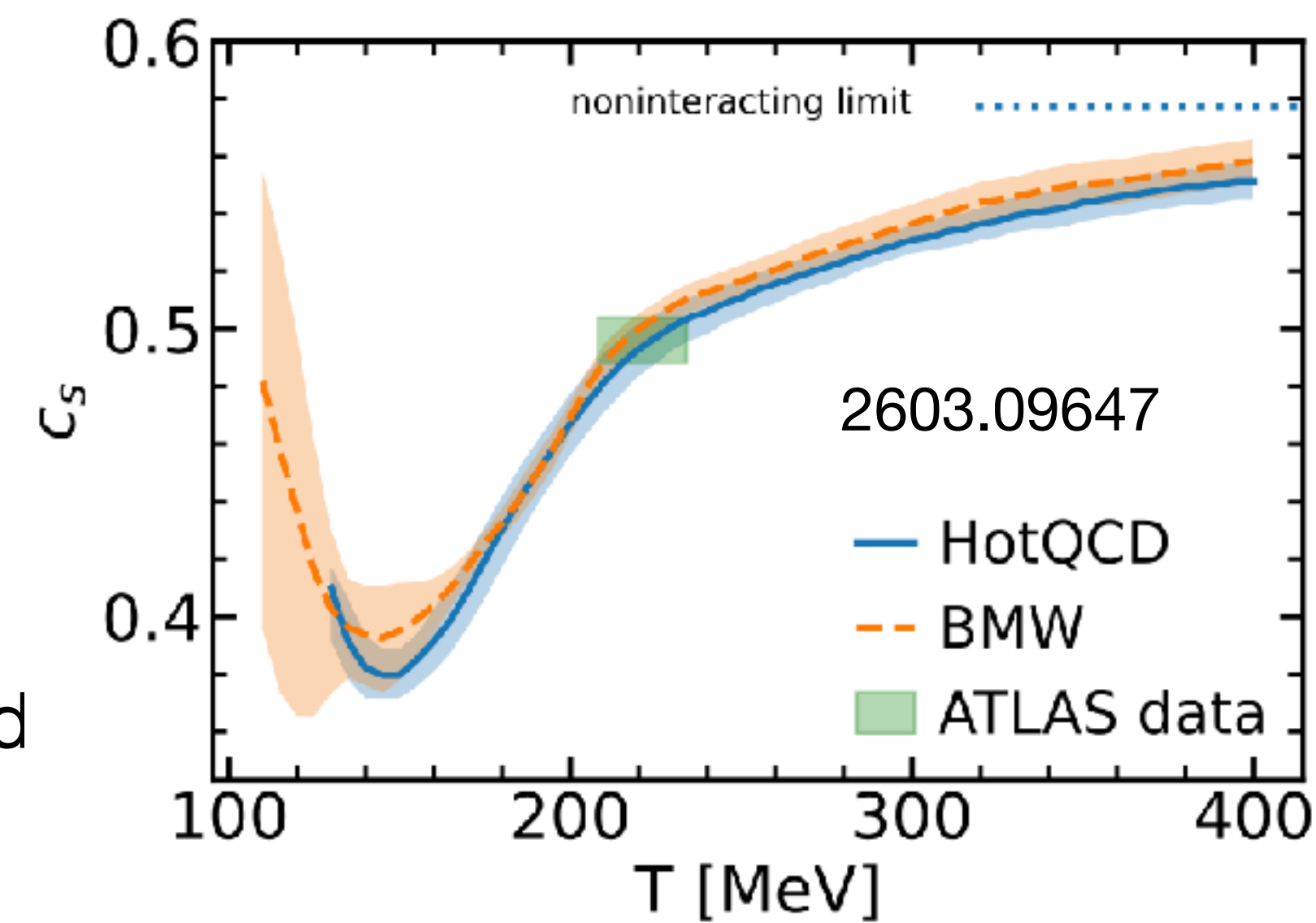
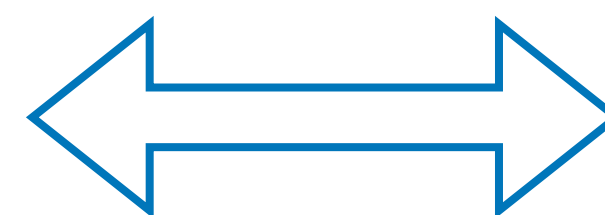
Transport properties

Bulk EoS: Equilibrium

C. Broodo (presented at SQM2026)



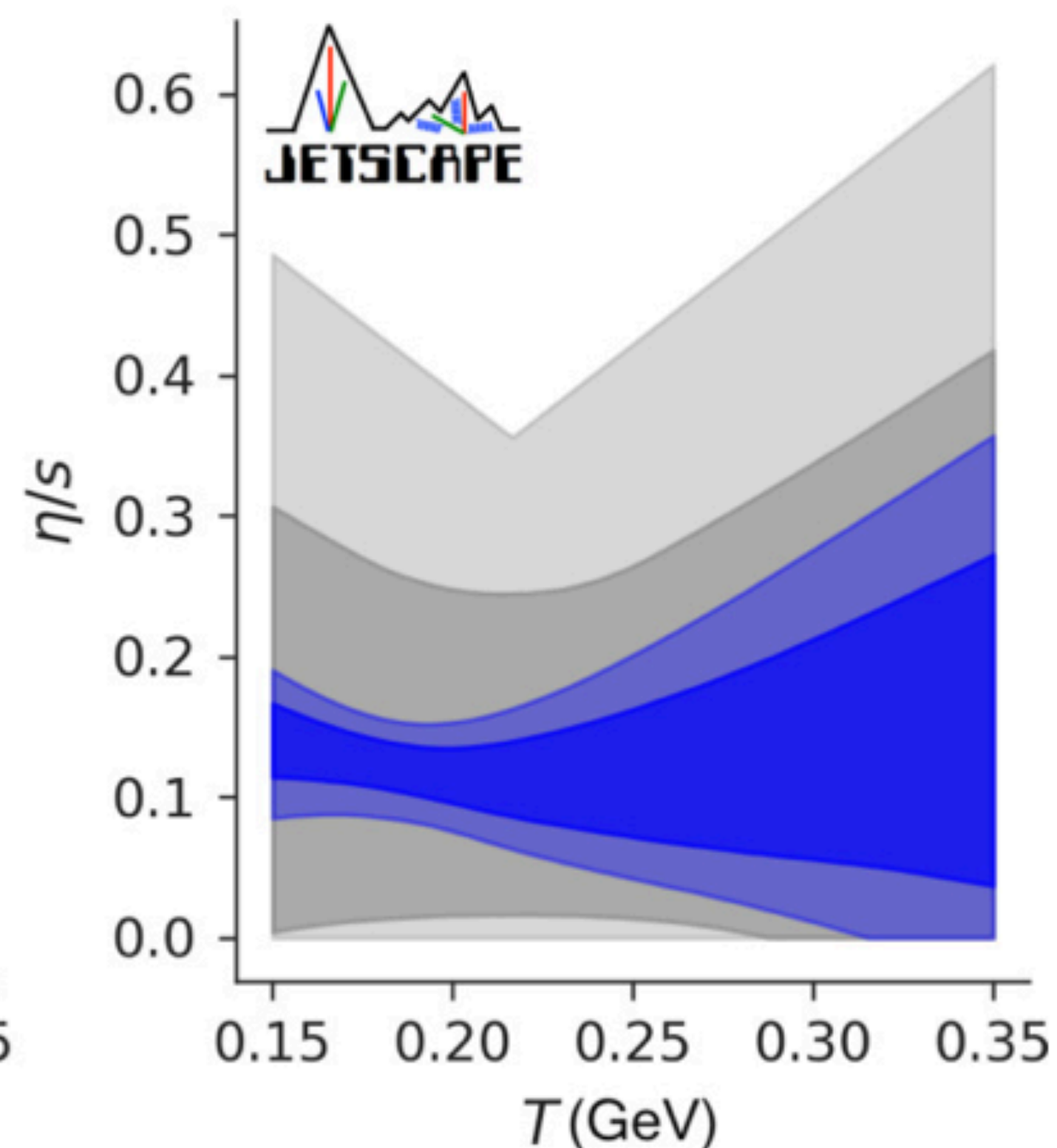
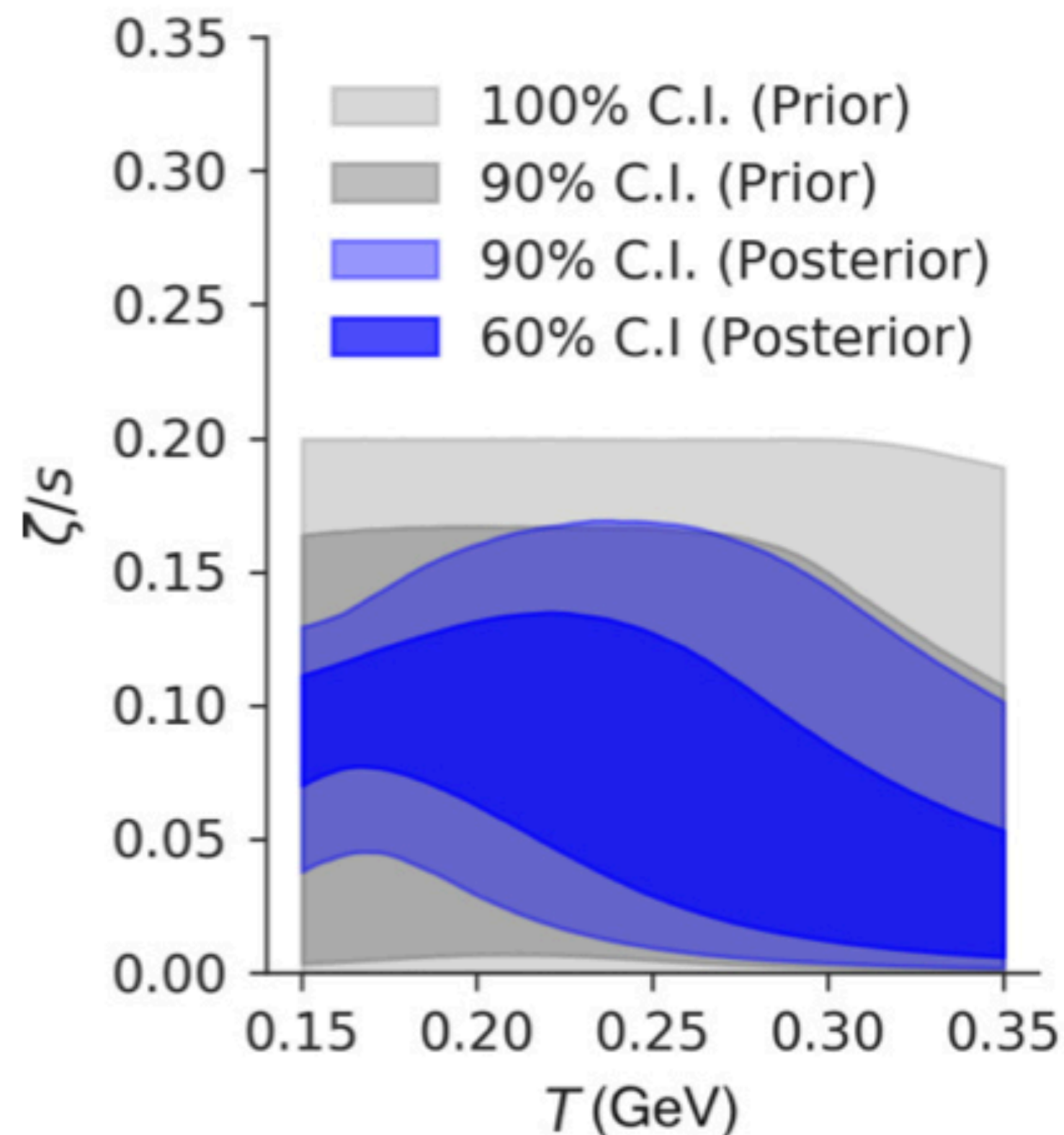
Speed of sound



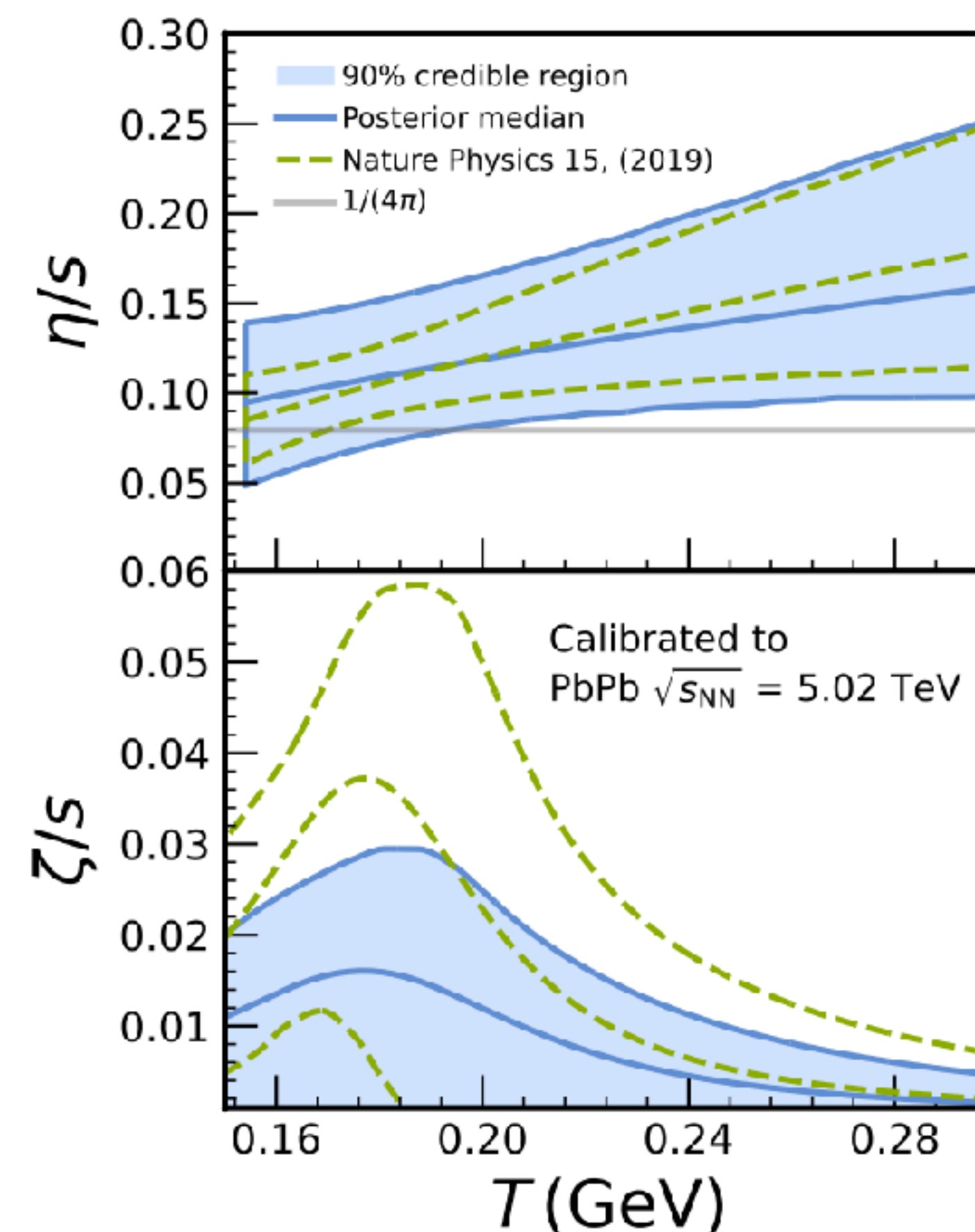
Bulk EoS: Non-equilibrium

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

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



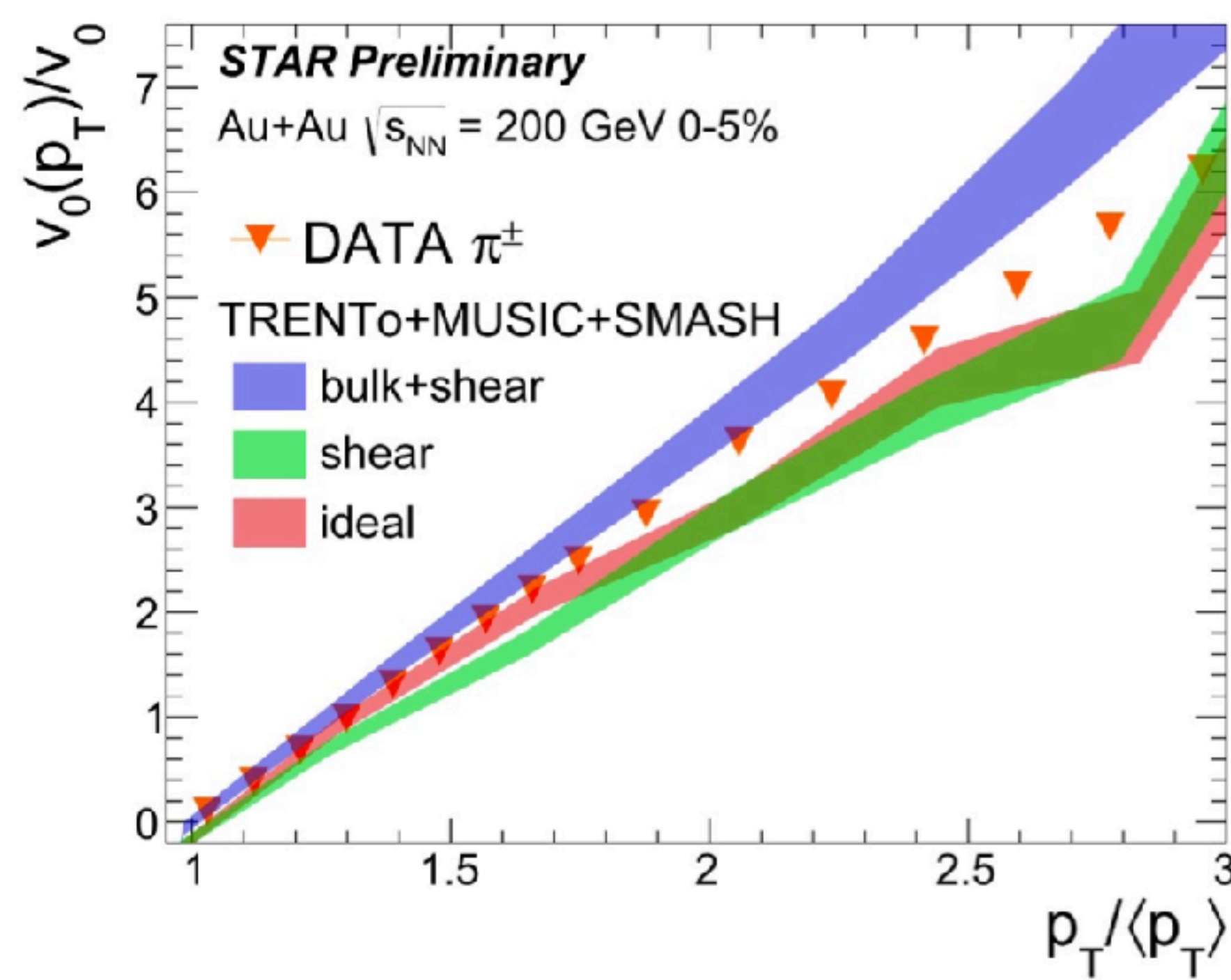
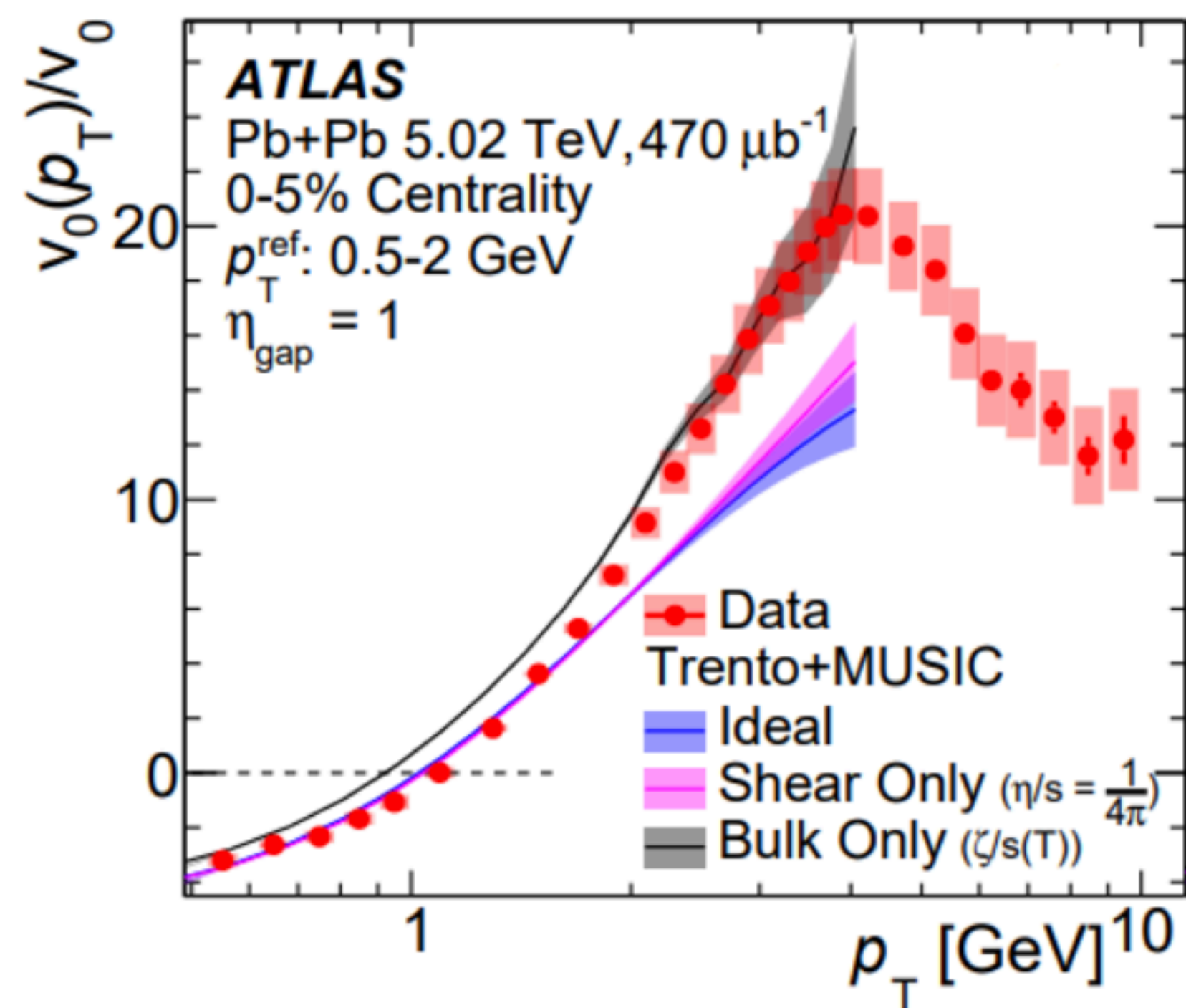
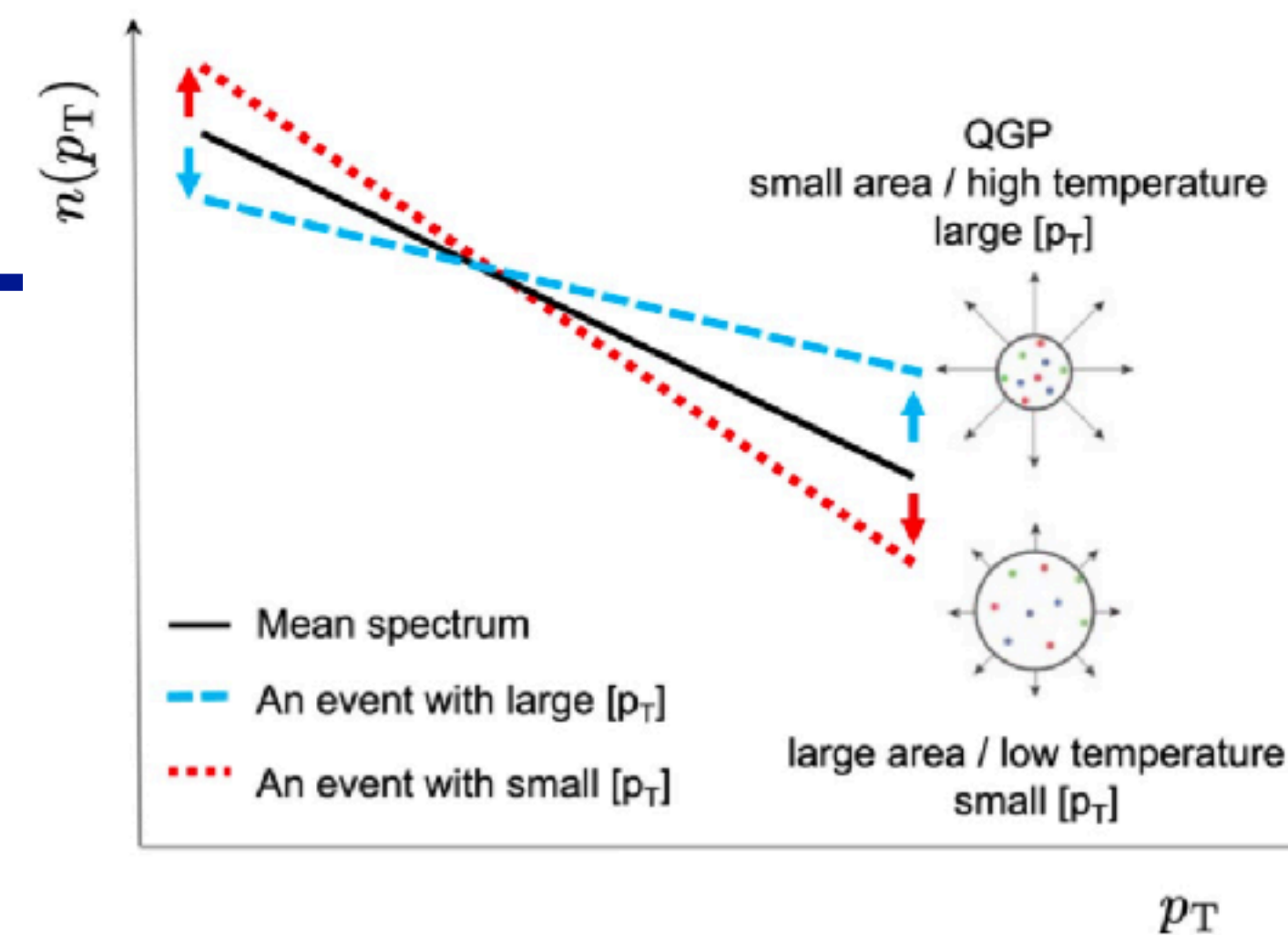
Parkkila, Onnerstad & Kim,
Phys. Rev. C **104** (2021) 054904



New observable

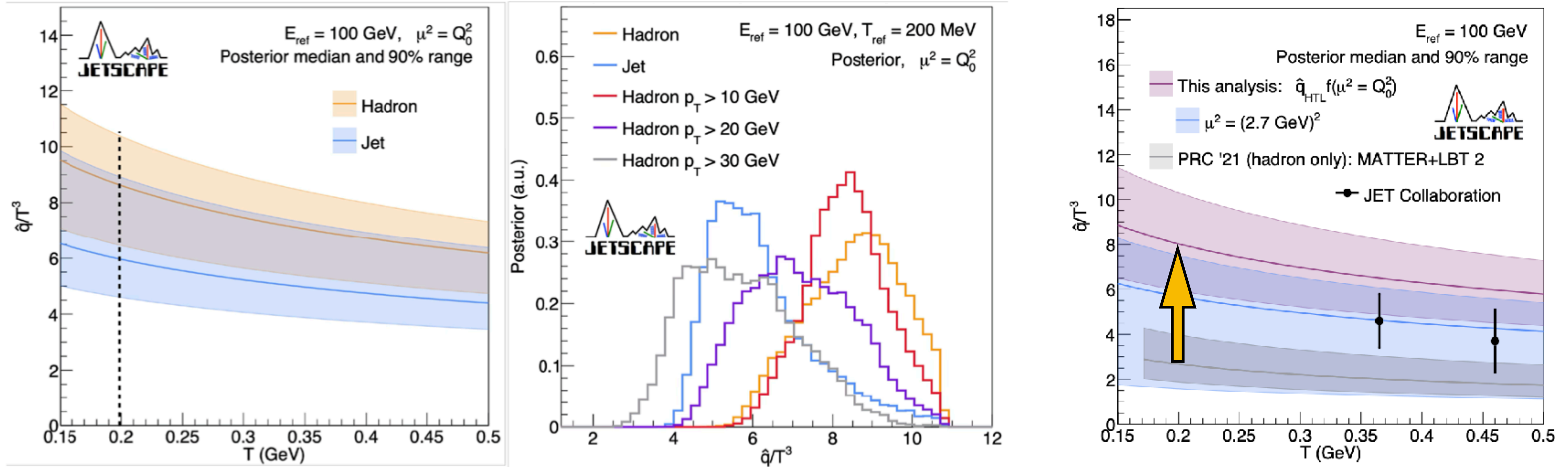
Radial flow - p_T fluctuations

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



Jet quenching parameter \hat{q}

JETSCAPE Coll. - 2408.08247



Recent analysis by R. Ehlers [EPJ Web of Conferences **339**, 01010 (2025)] suggests that systematic errors from data selection and model construction are still quite large.

See also: T. Renk - 1408.6684 on the constraining power of high- p_T observables

Heavy quark diffusion

Yu Fu - Tu (I) 16:45

D_s = spatial diffusion coefficient

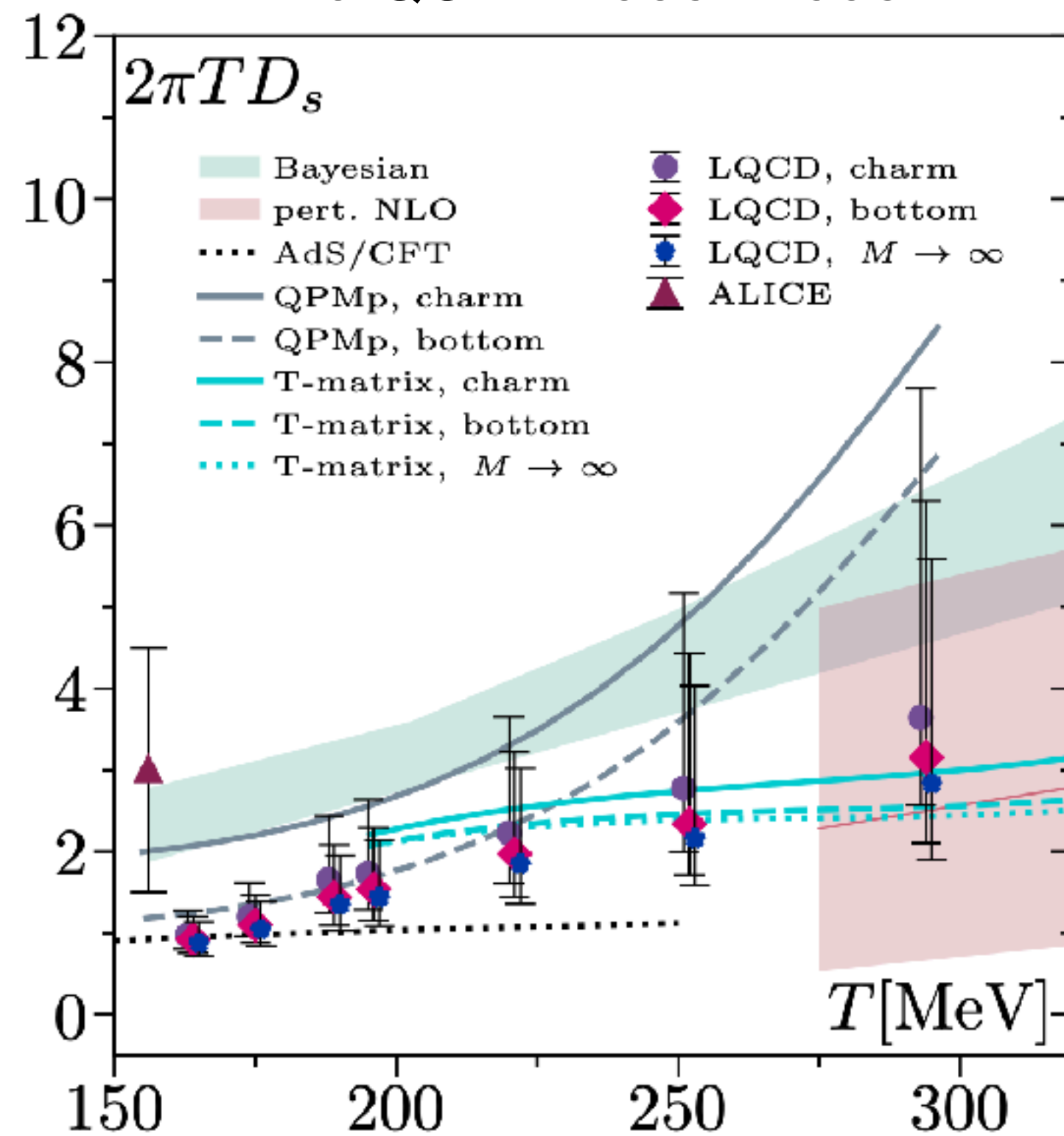
κ = momentum diffusion coefficient

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

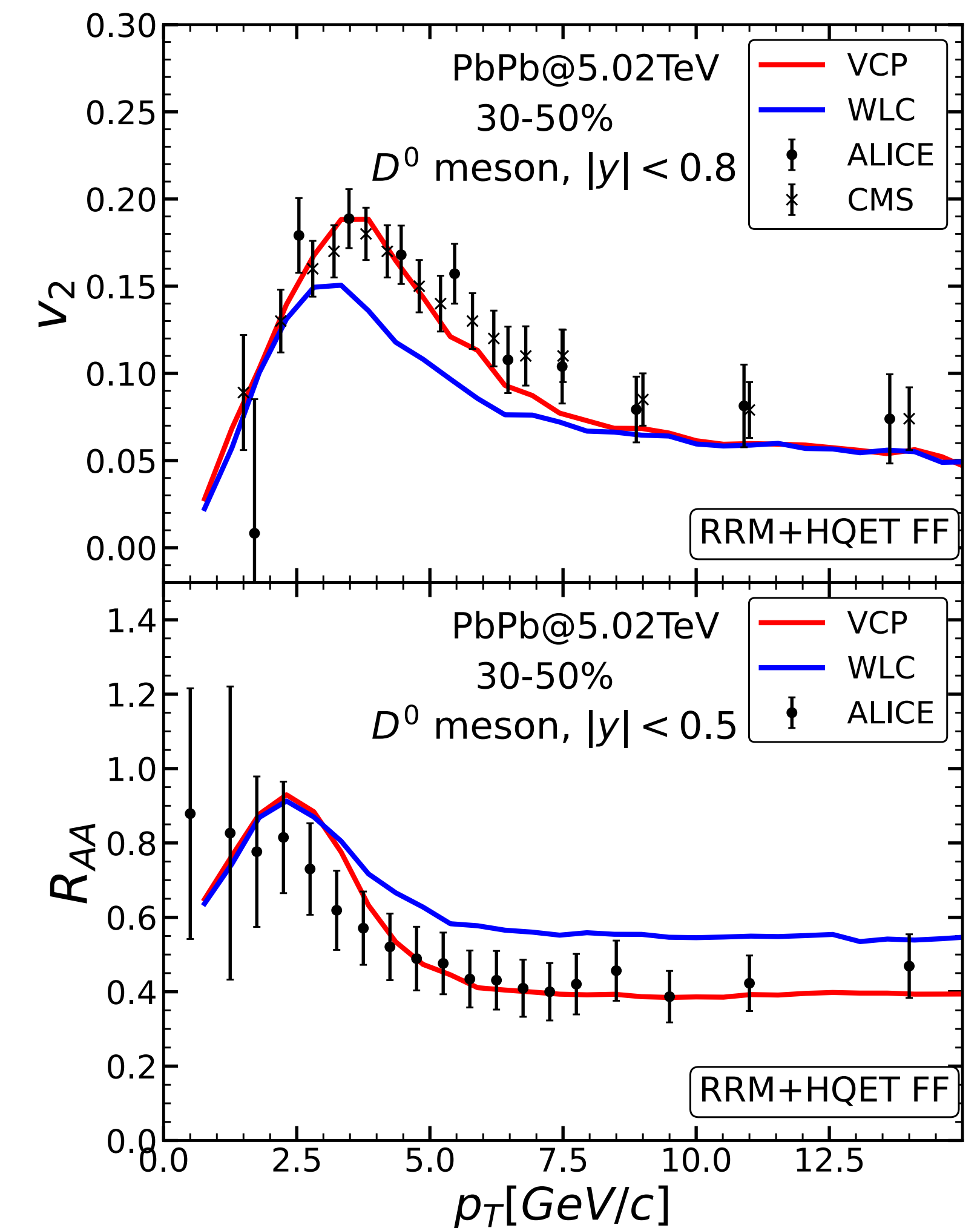
$$\frac{df_Q}{dt} = \mathcal{D}[f_Q] + C_{1\leftrightarrow 2}[f_Q]$$

\mathcal{D} = Fokker-Plack op.
 Linear Boltzmann
 Recombination

HotQCD - 2506.11958



HEFTY Collab. - 2509.13881



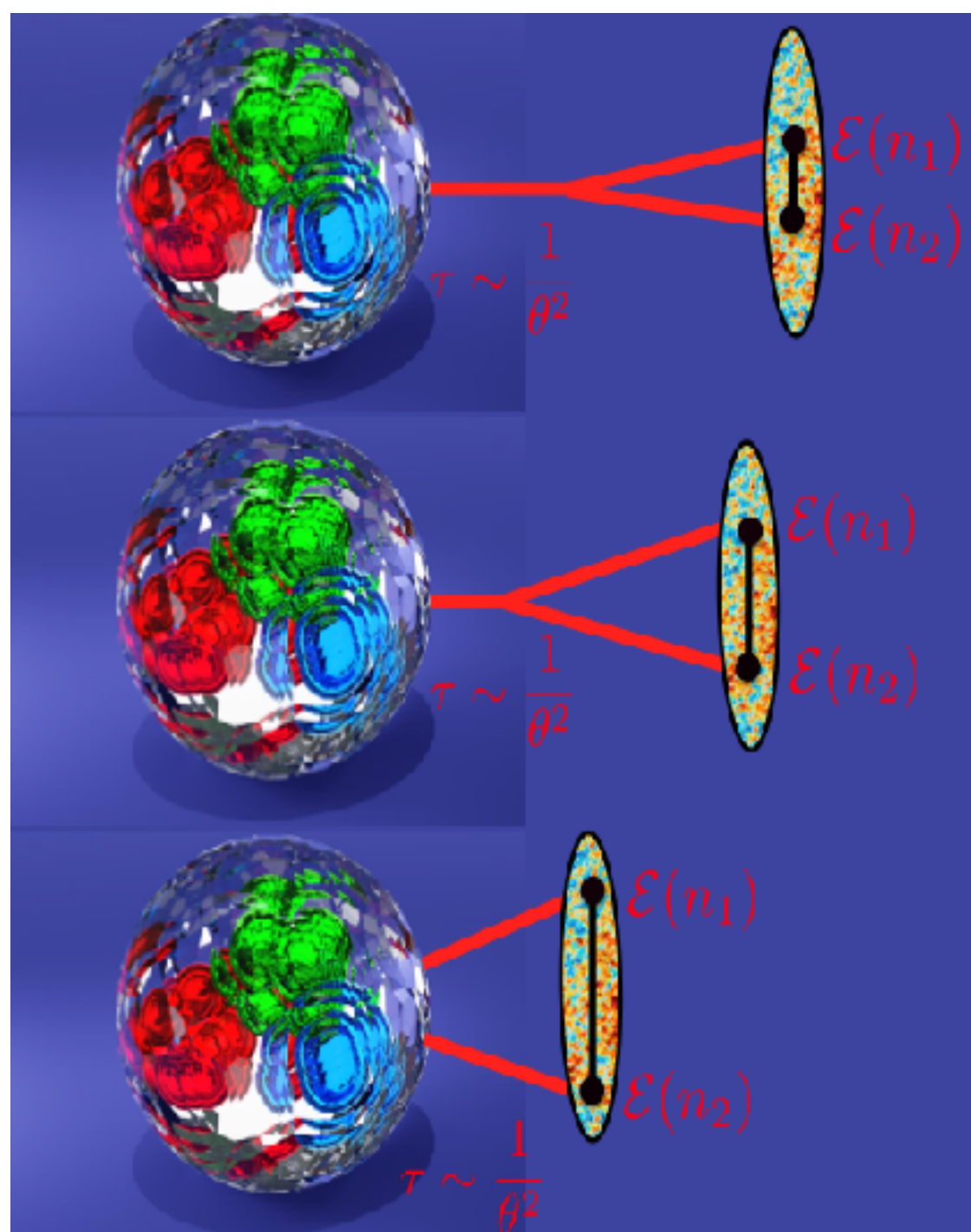


The 16 Arhats

Jet showers

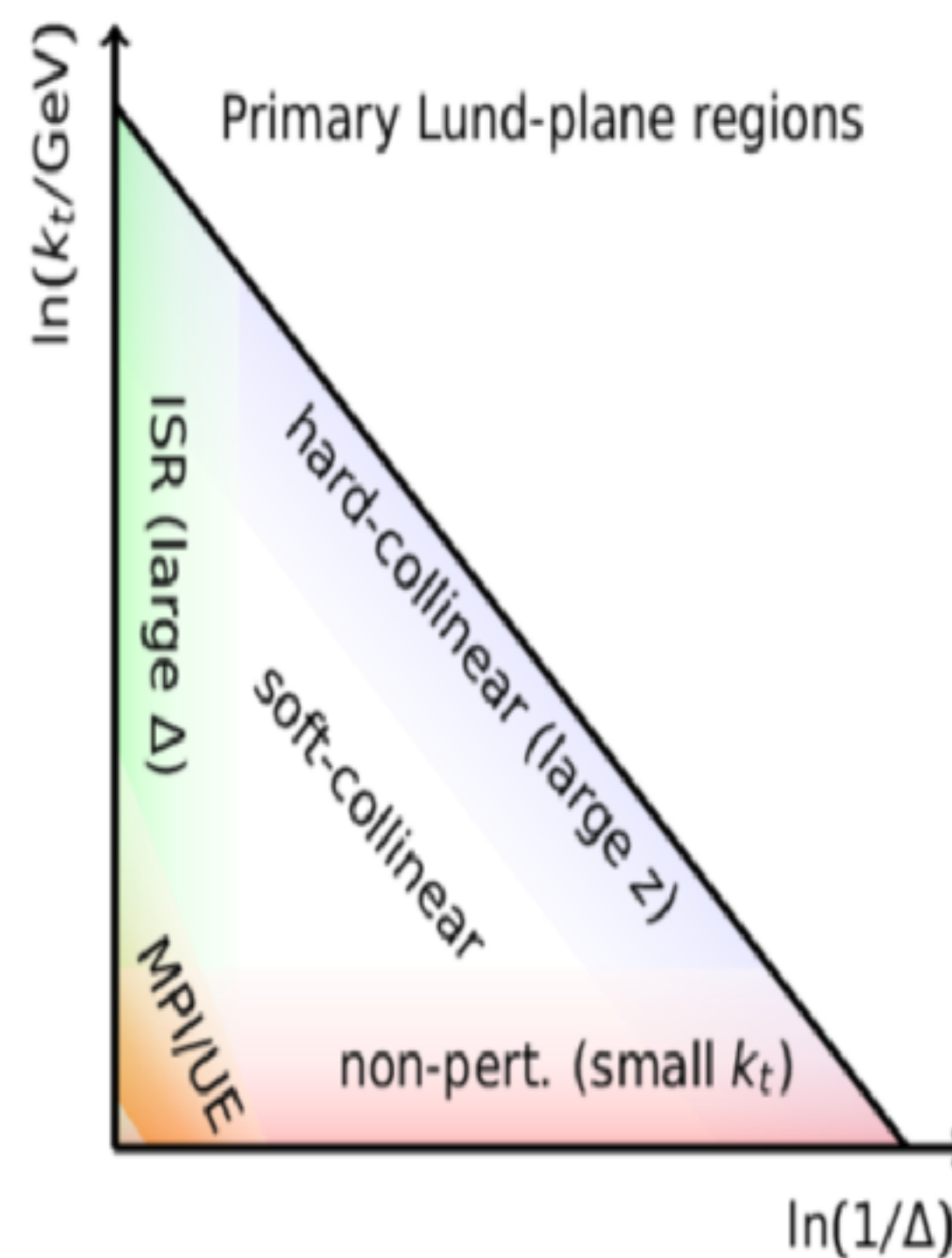
3 different approaches

Energy flow correlators



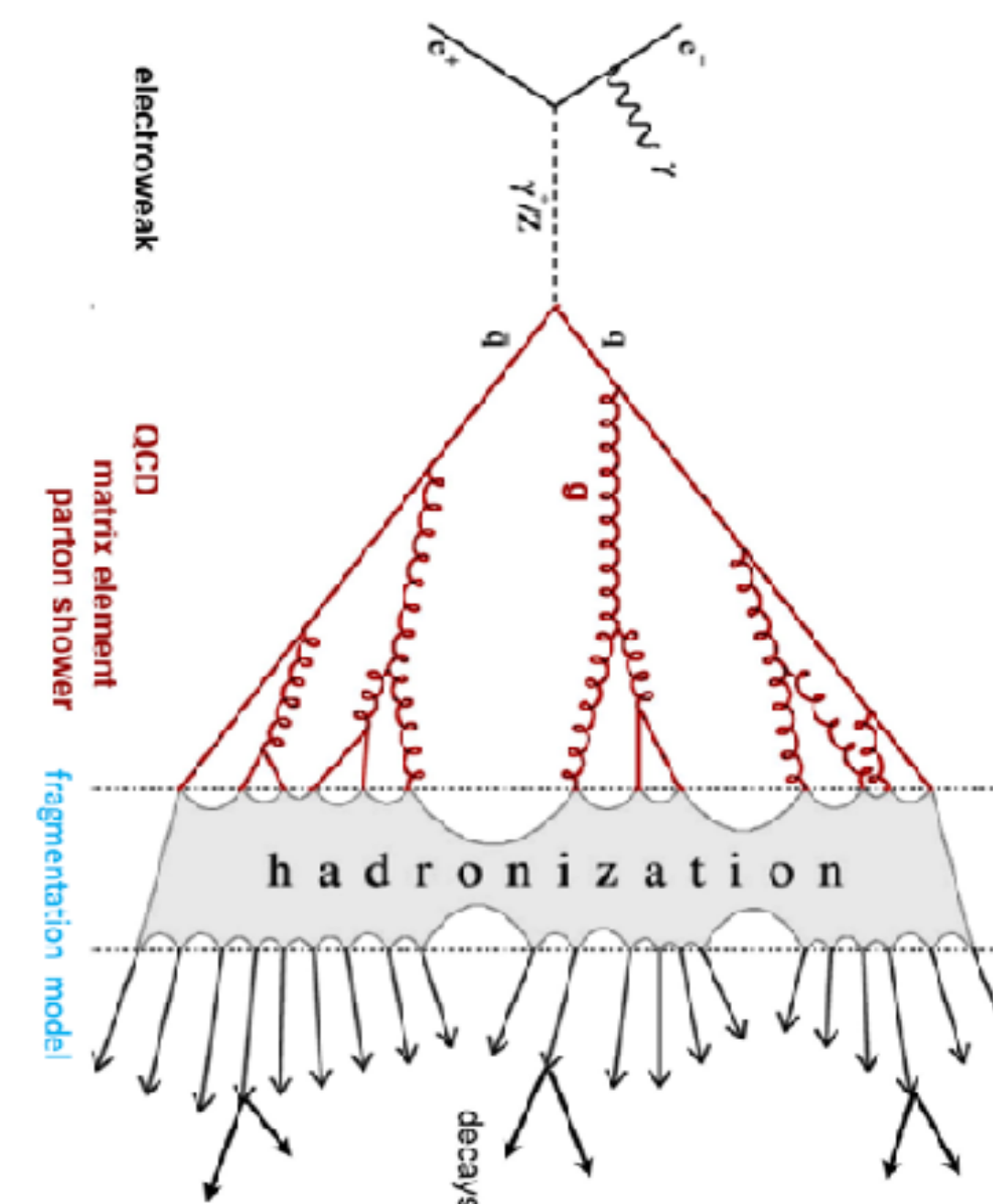
Angle θ probes QCD scales
Can access nonpert. physics

The Lund plane



Splitting pattern domains
Focus on pQCD

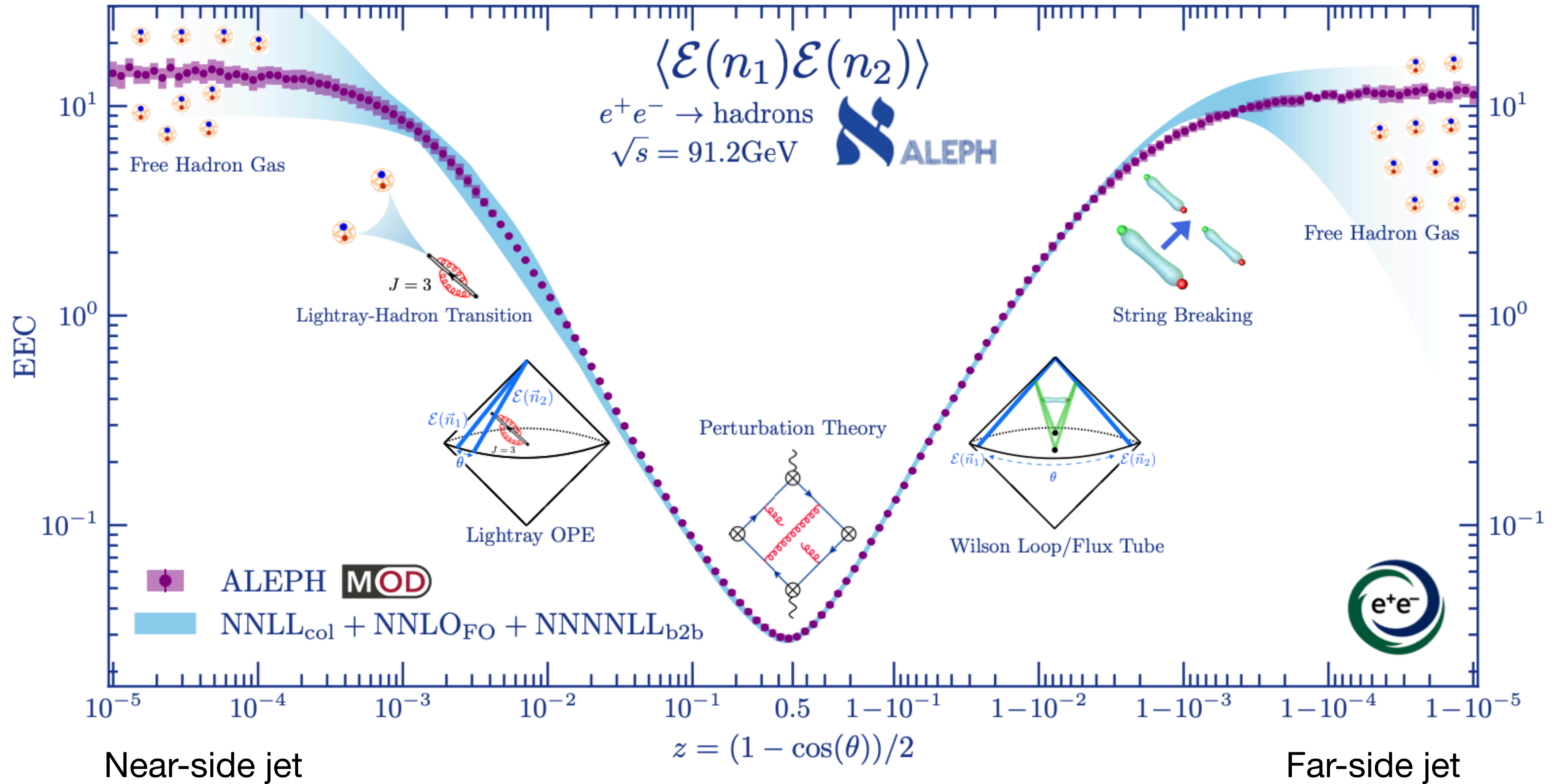
Jet shower MC generators



Full jet event structure
Requires modeling

EEC in vacuum

H. Bossi et al. - 2511.00149

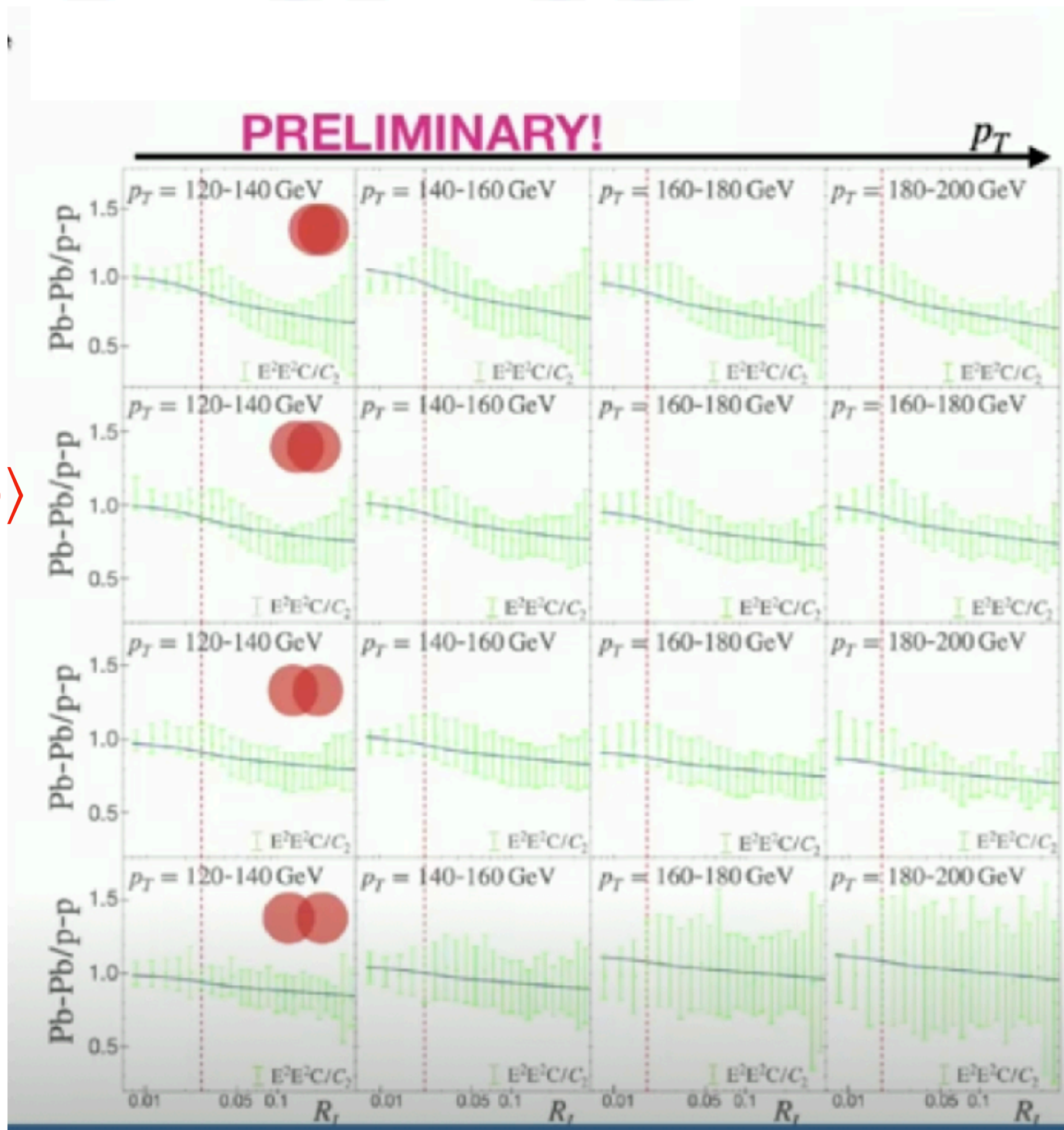


Medium effects on EECs

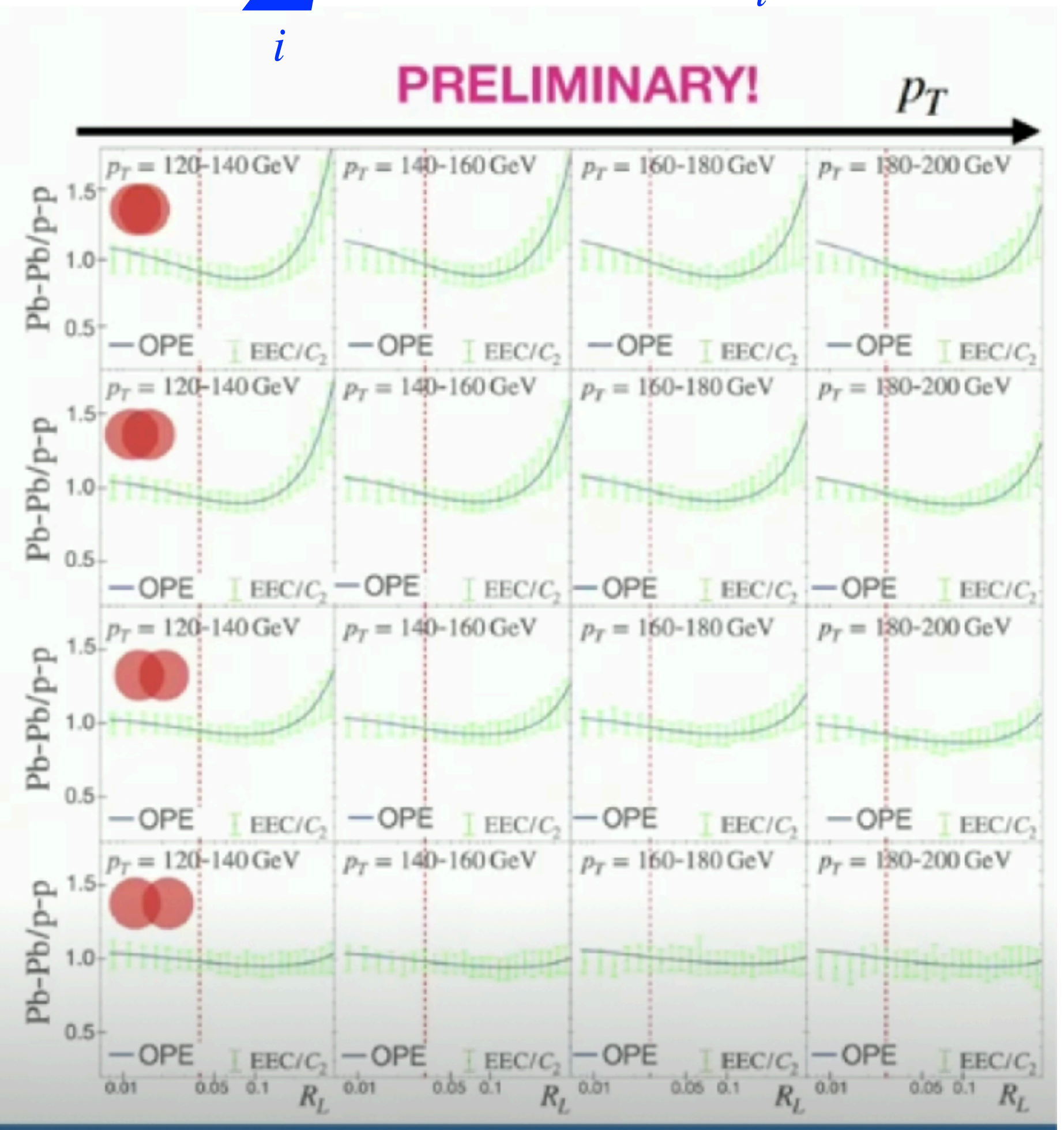
Andres, Aretz, Holguin, Lee

Light-ray OPE analysis: $\langle AA | E^n(n_1) E^m(n_2) | AA \rangle = \sum_i C_i \theta_i^{\delta_i^{(n,m)}} \langle AA | \mathbf{O}_i^{[n+m+1]} | AA \rangle$

$\langle E^2(n_1) E^2(n_2) \rangle$

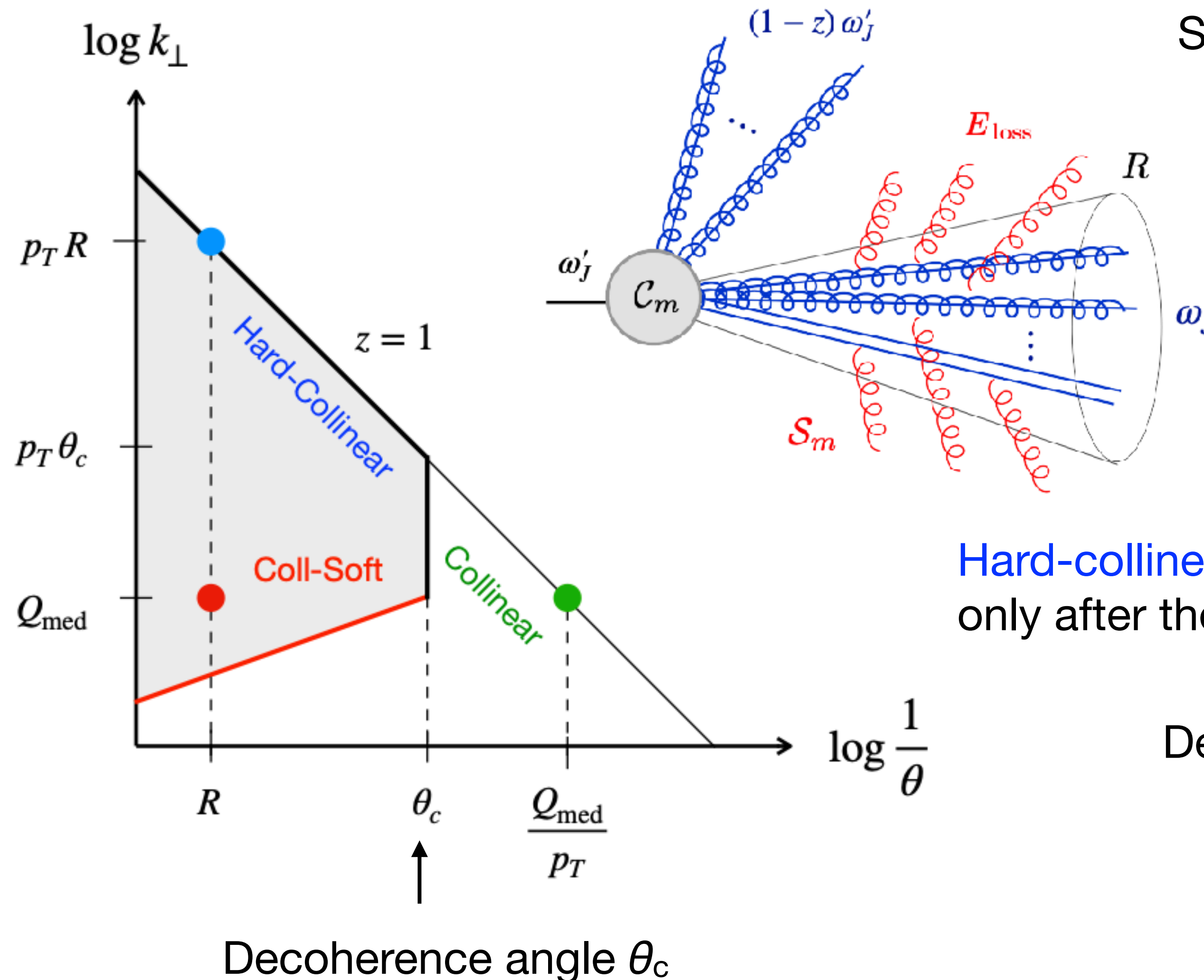


$\langle E(n_1) E(n_2) \rangle$



Jet quenching in the Lund plane

Mehtar-Tani et al. - 2409.05957



Scale separation:

$$p_T \gg p_T R \gtrsim E_{\text{loss}} \gg Q_{\text{med}} \gtrsim T$$

Use EFT techniques to factorize collinear jet showering from medium induced radiation and jet energy loss

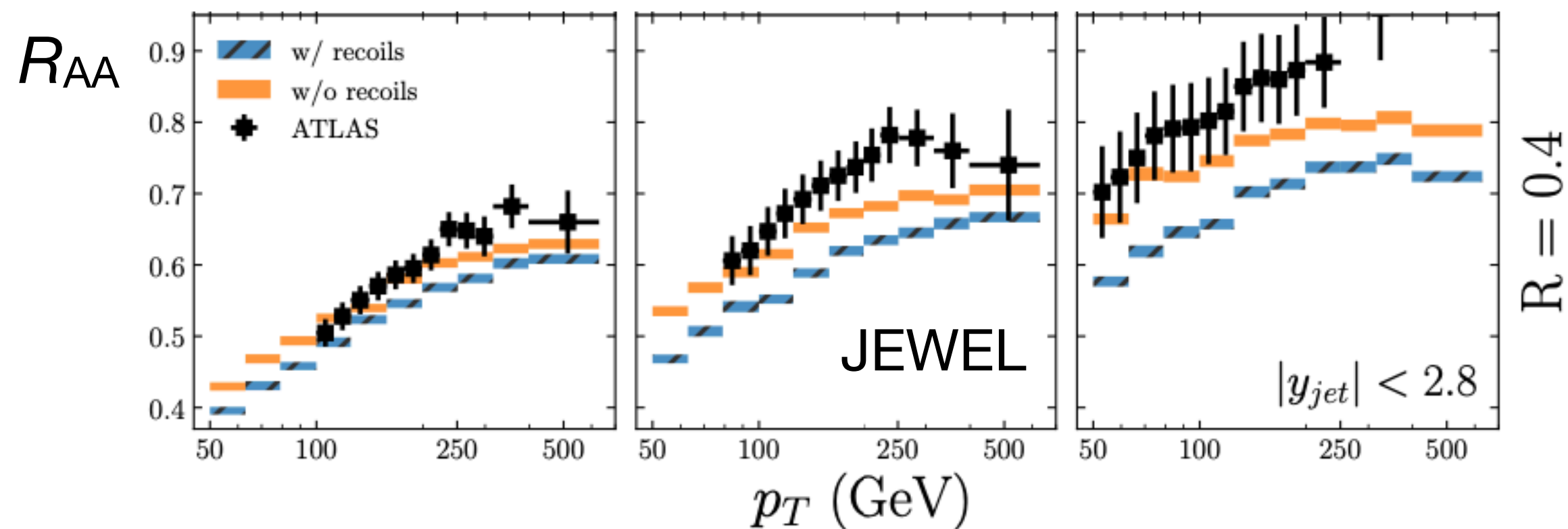
Hard-collinear partons act as sources of collinear-soft radiation only after they have decohered from their parents:

Decoherence parameter:

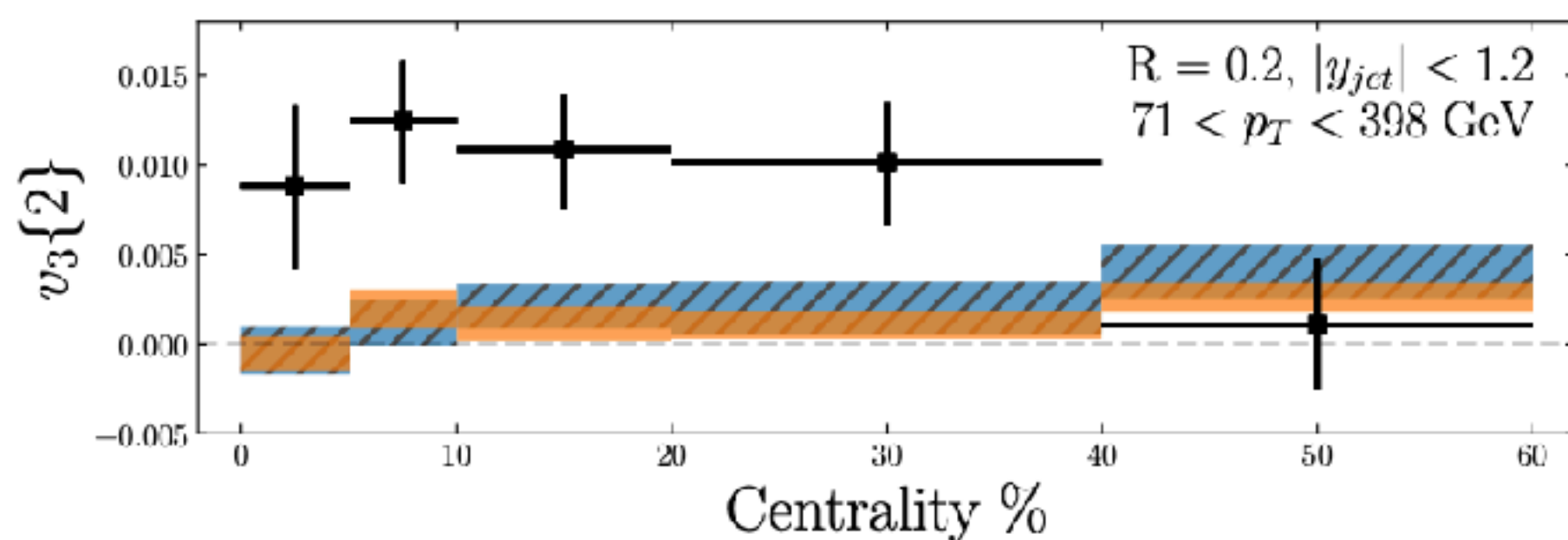
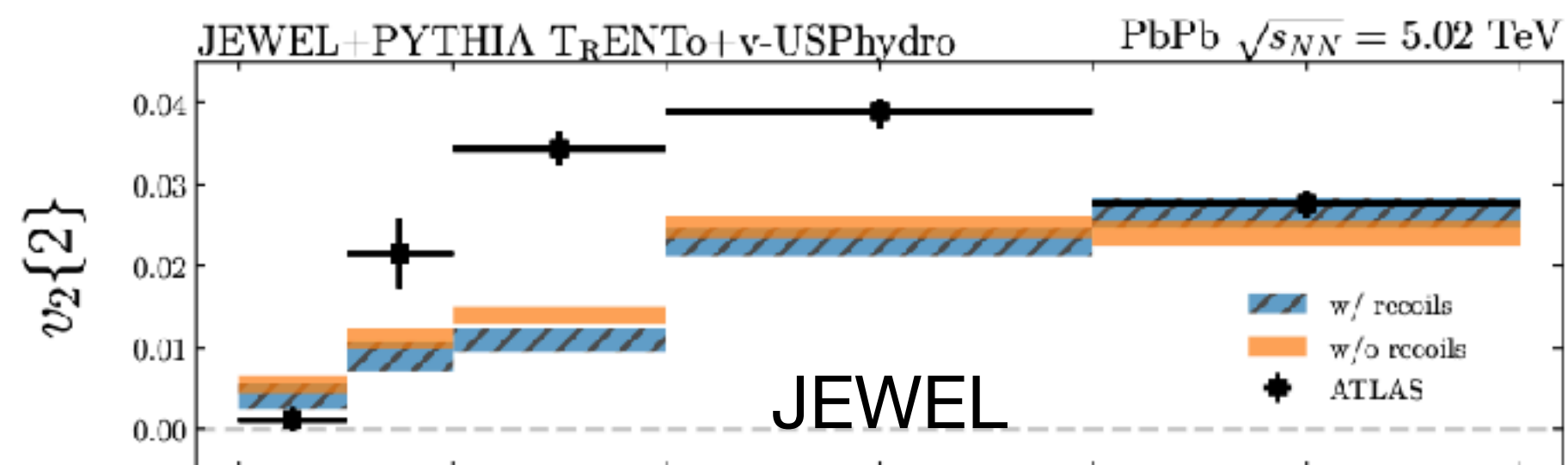
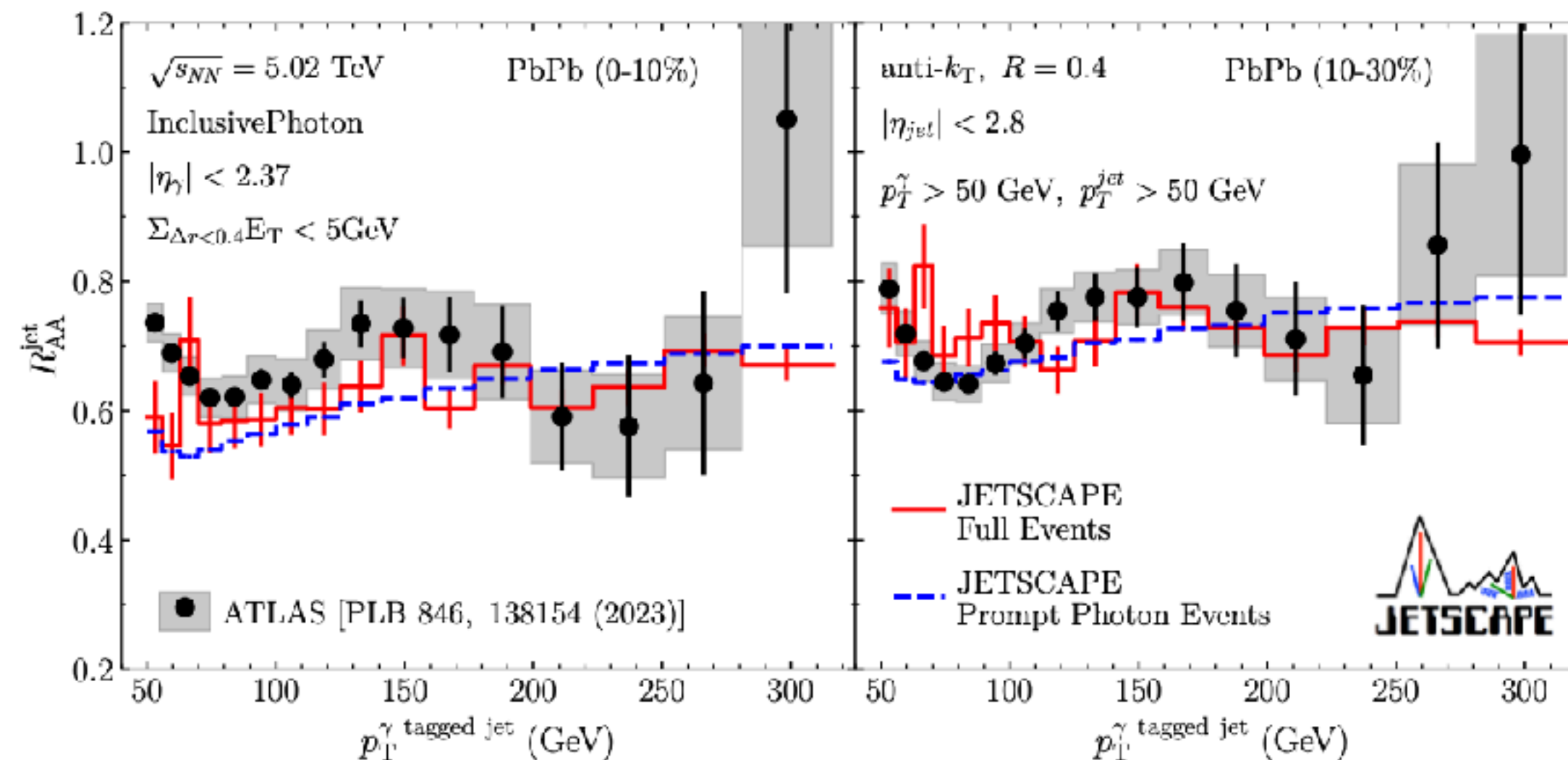
$$\Delta_{\text{med}}(\theta) \approx 1 - \exp\left(-\frac{1}{12} \hat{q} L^3 \theta^2\right)$$

Jet shower MC models

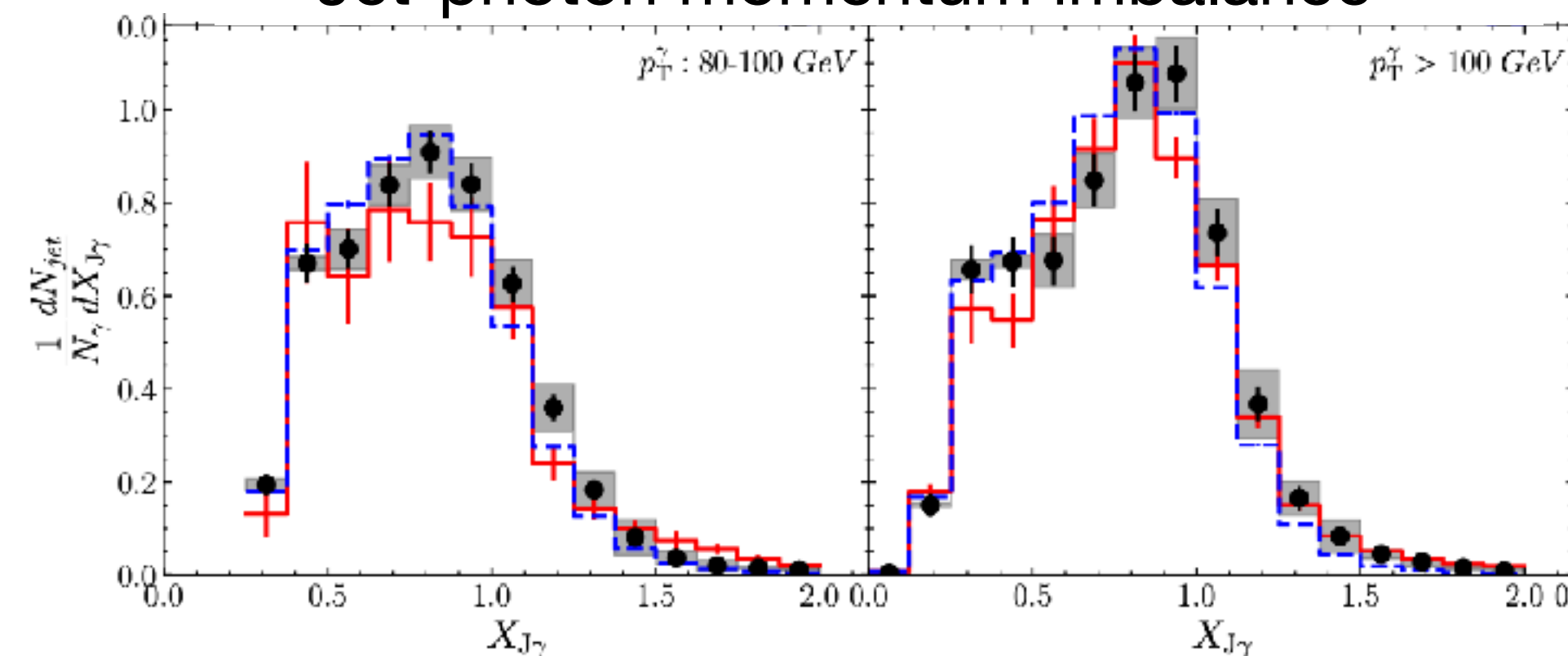
Barreto et al. - 2206.02061. Pb+Pb 5.02 TeV

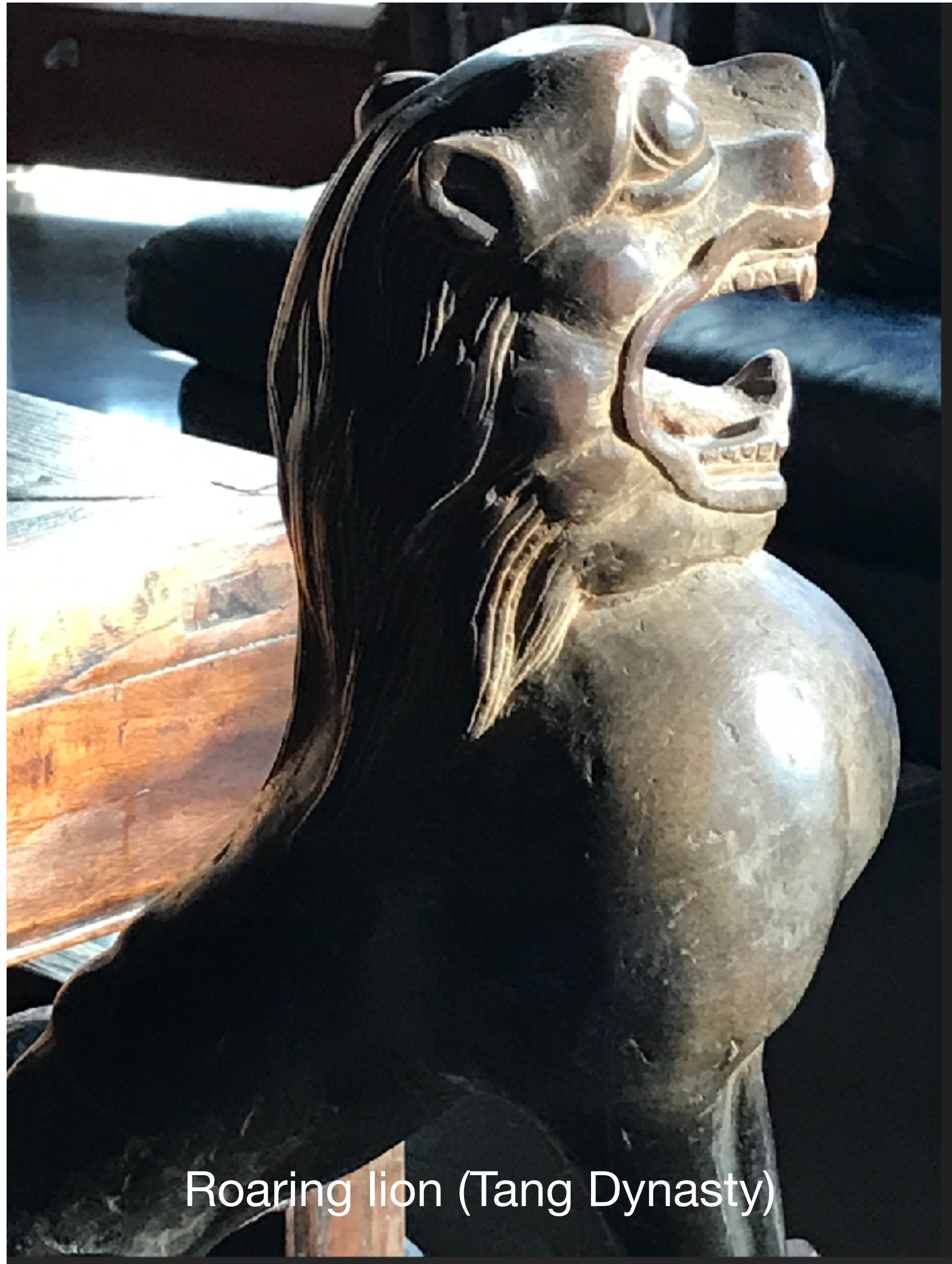


JETSCAPE Coll. - 2412.19738. γ -triggered jets



Jet-photon momentum imbalance





Roaring lion (Tang Dynasty)

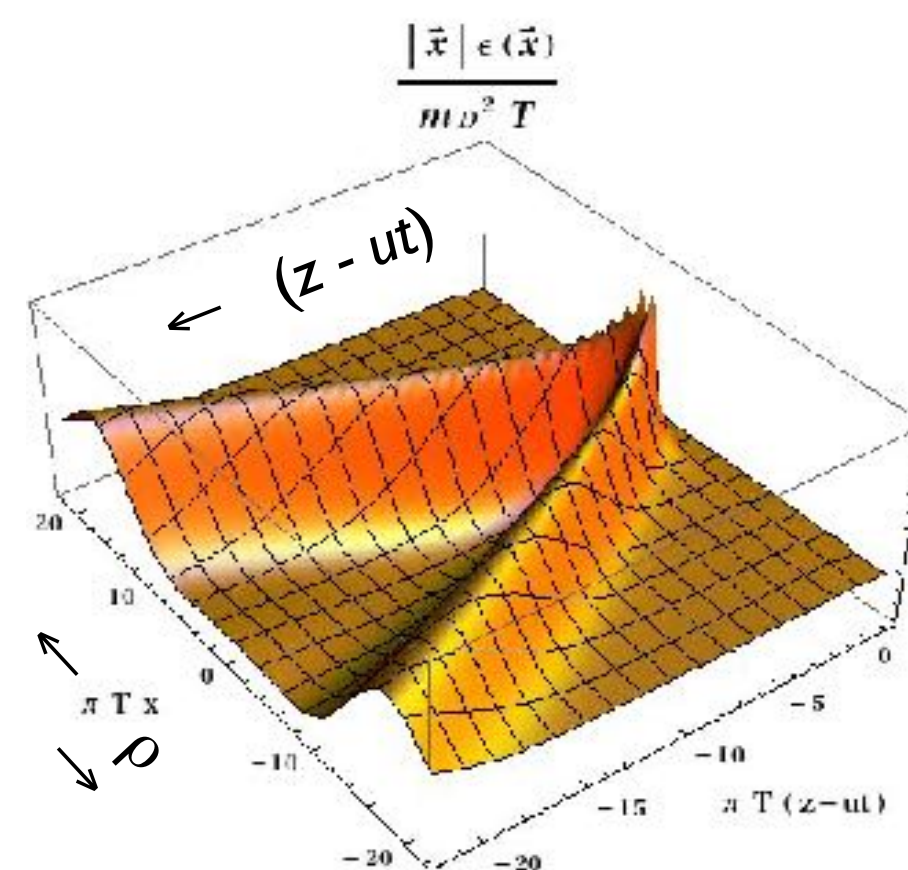
Medium Response

Diffusion wake

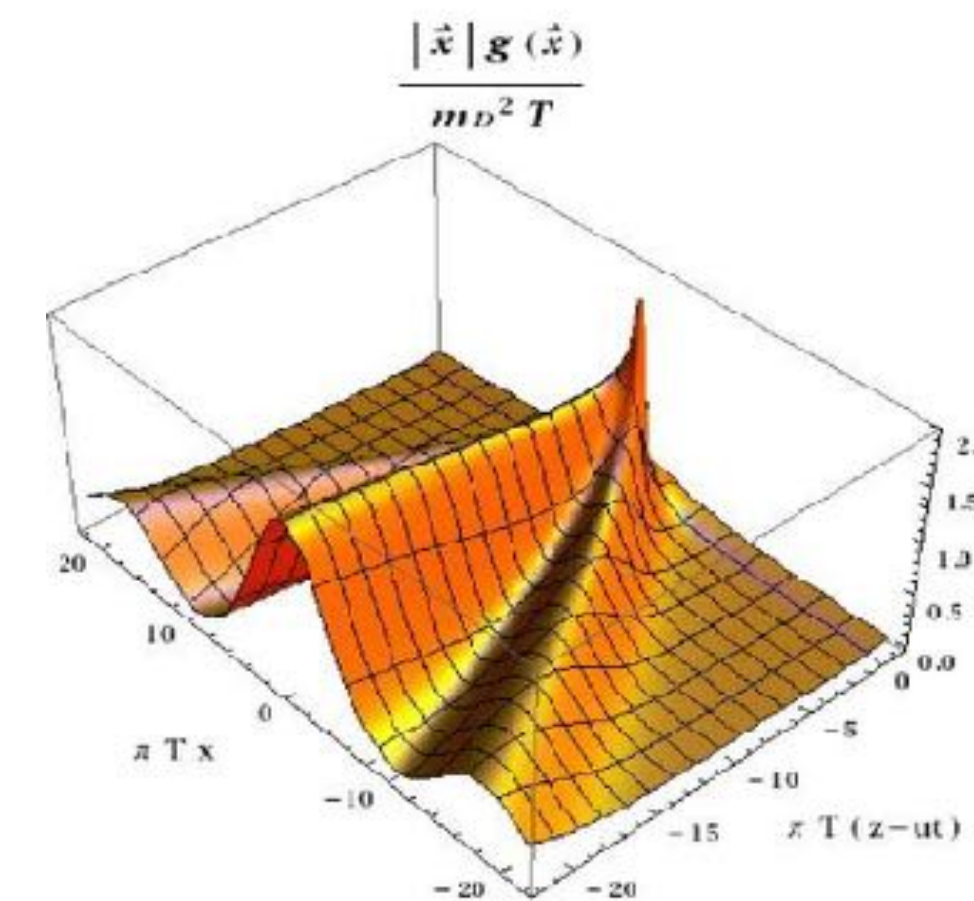
An energetic (“heavy”) colored object moving through the QGP deposits energy-momentum, which results in a coming perturbation, the *wake*.

The leading part is mostly phonons (sonic boom); the trailing part is fully diffusive, as low-frequency shear does not propagate ballistically.

Energy response



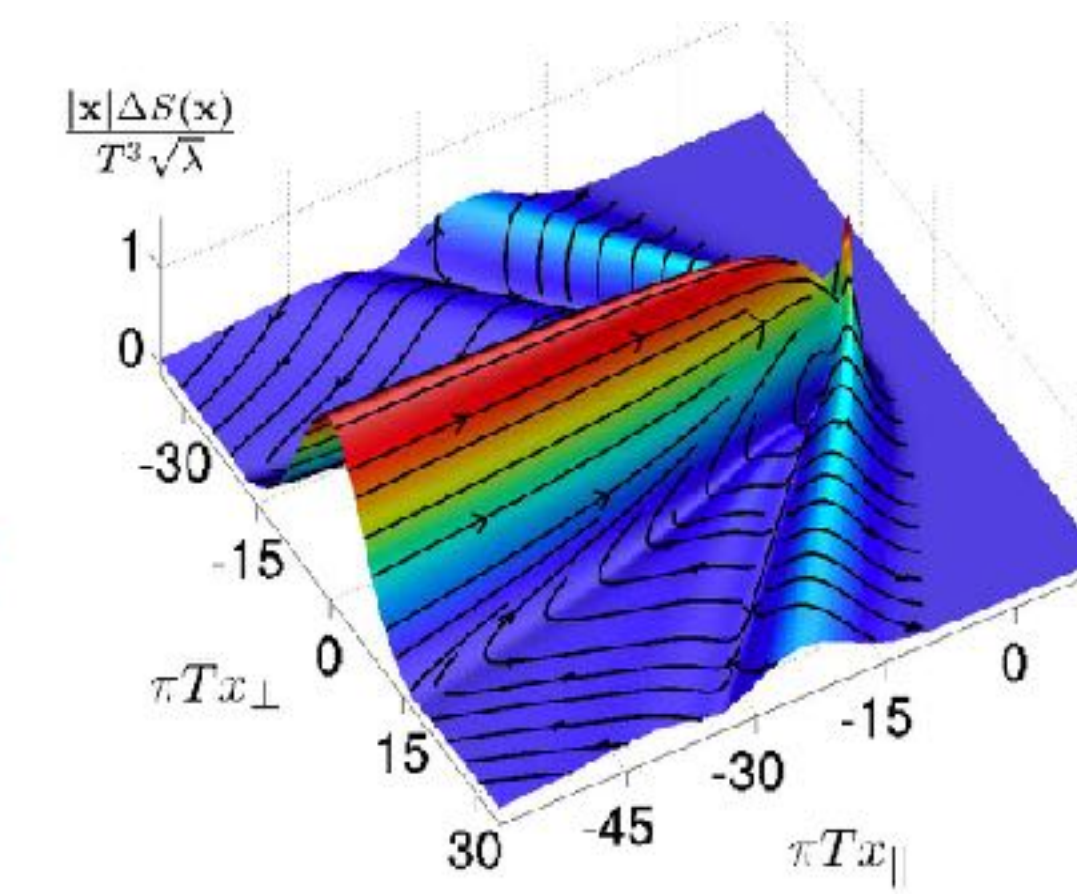
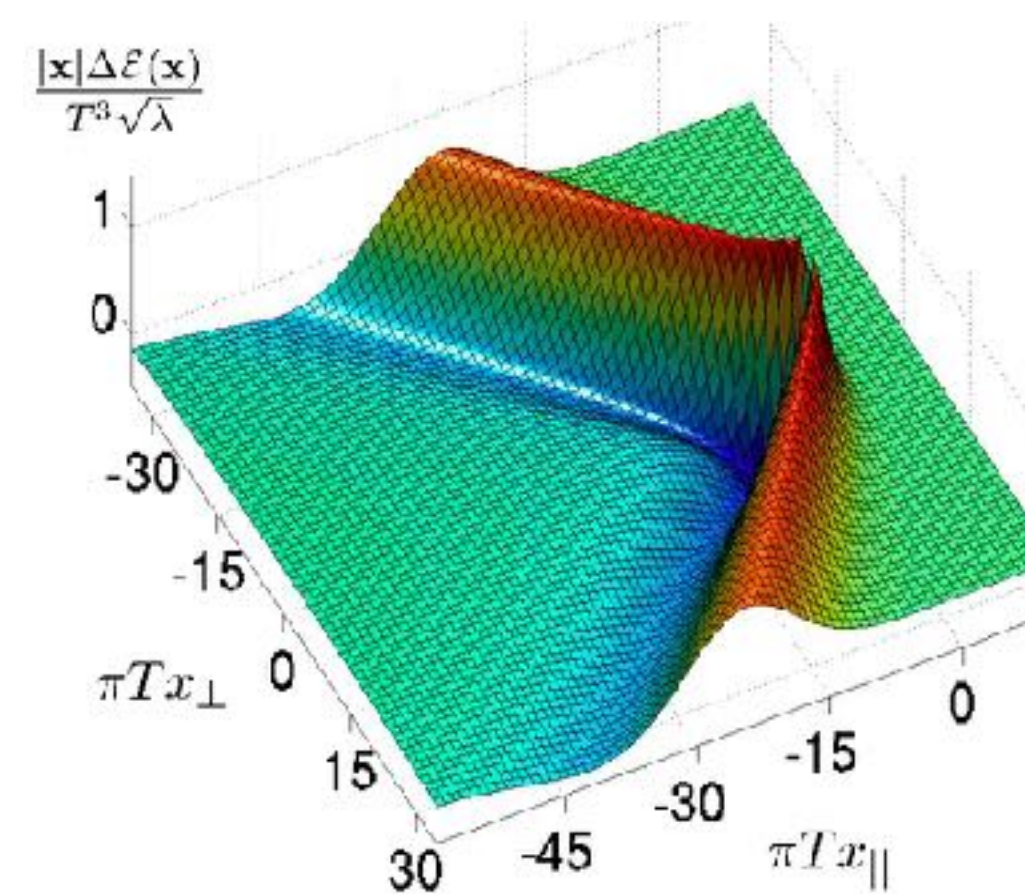
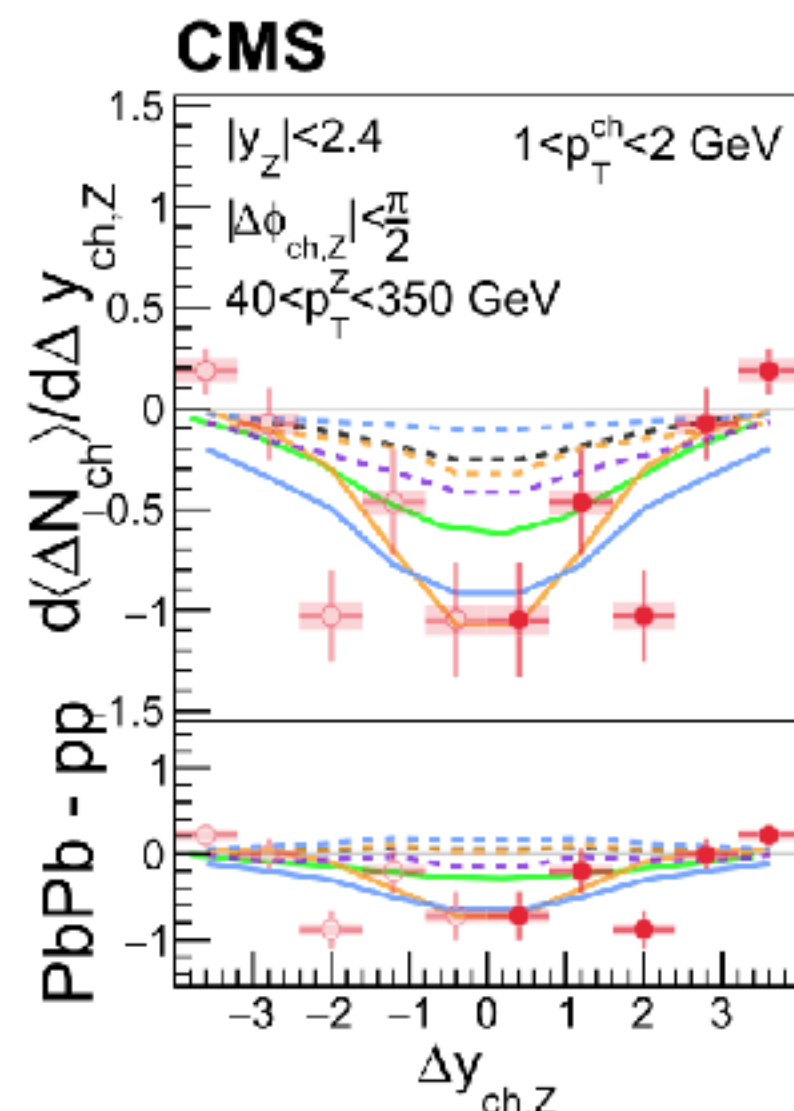
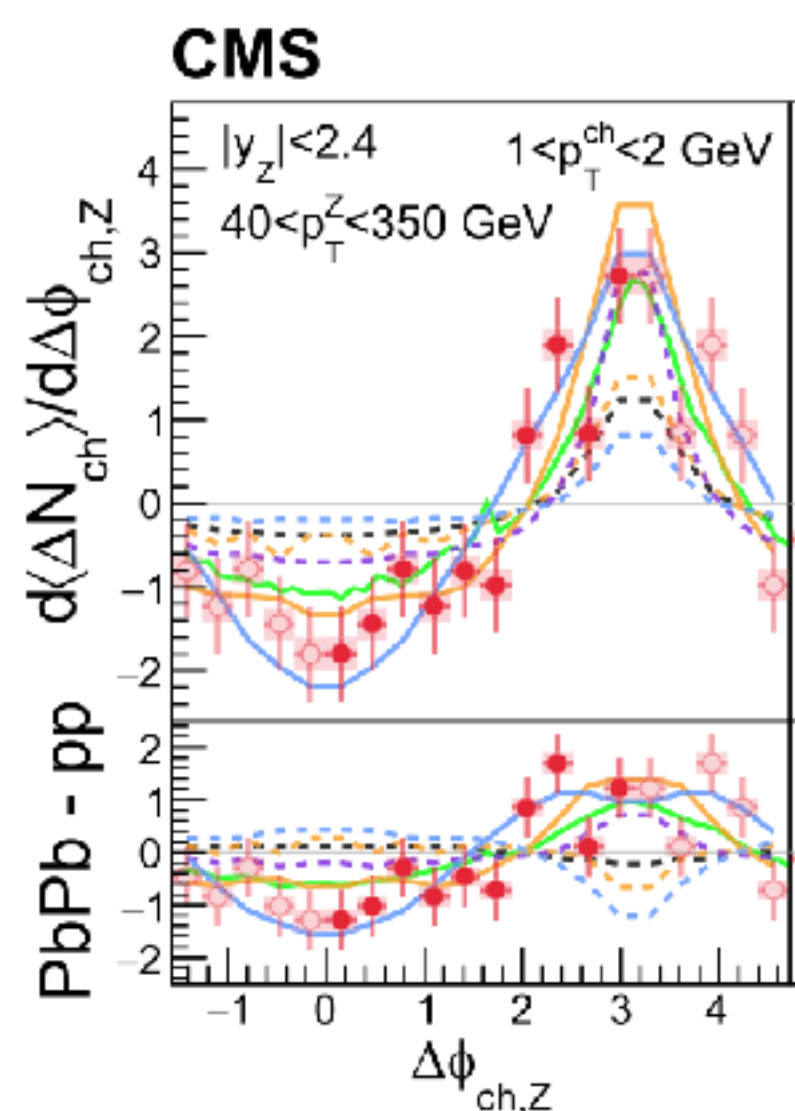
Momentum response



$u = 0.99955 c$

Neufeld et al.
arXiv:0802.2254

QCD—HTL

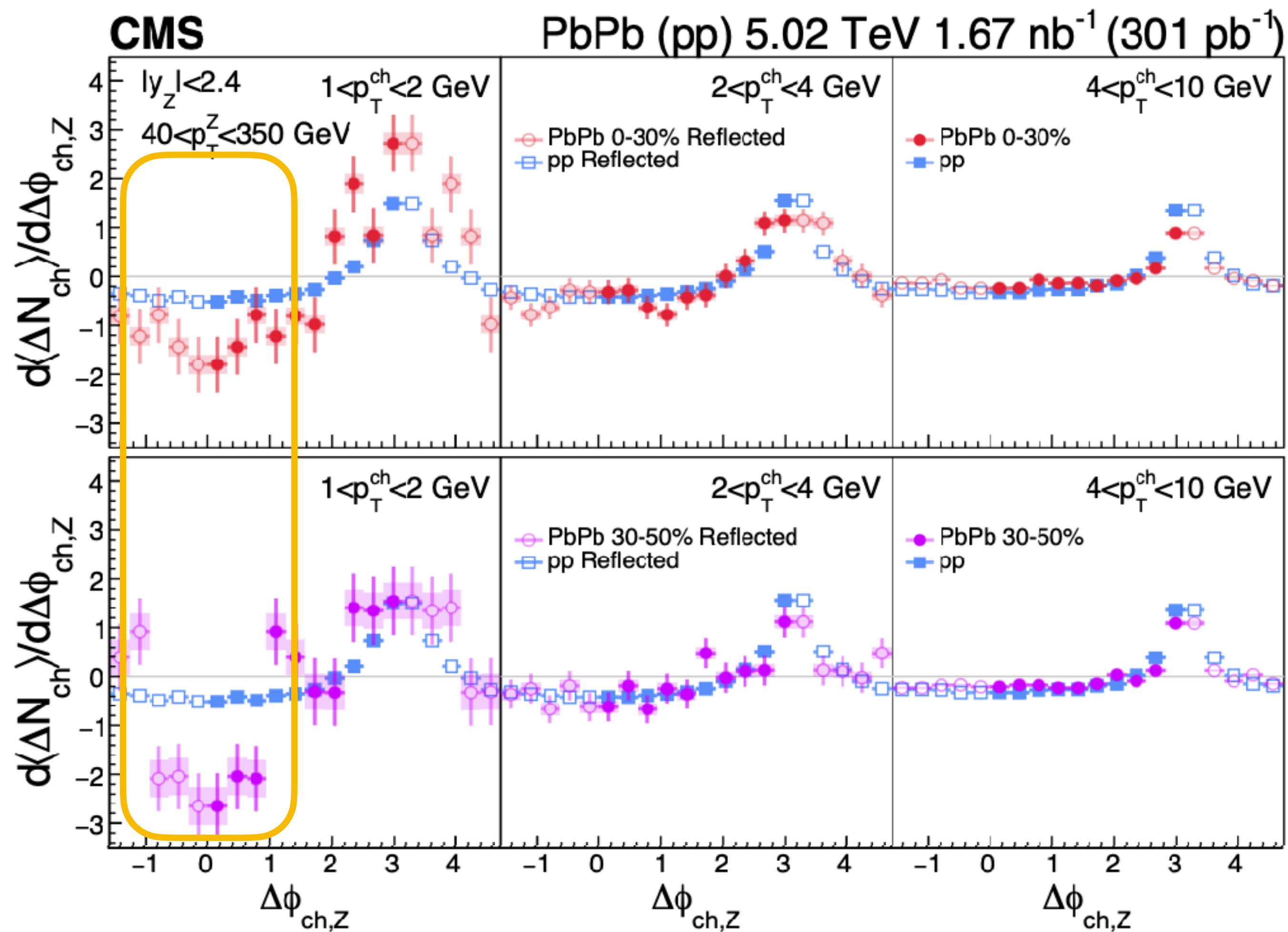


Chesler & Yaffe
arXiv:0712.0050

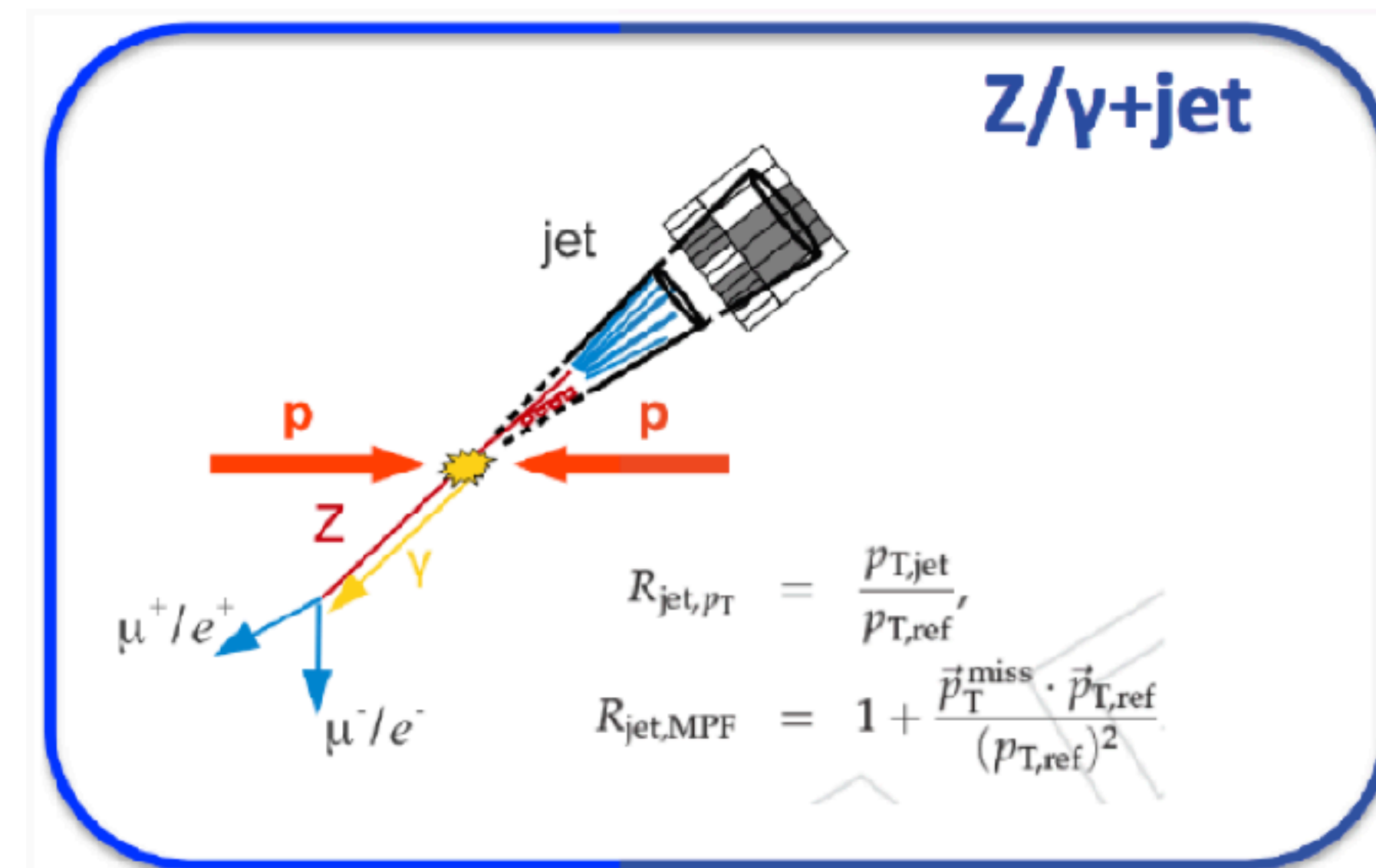
N=4 SYM

$u = 0.75 c$

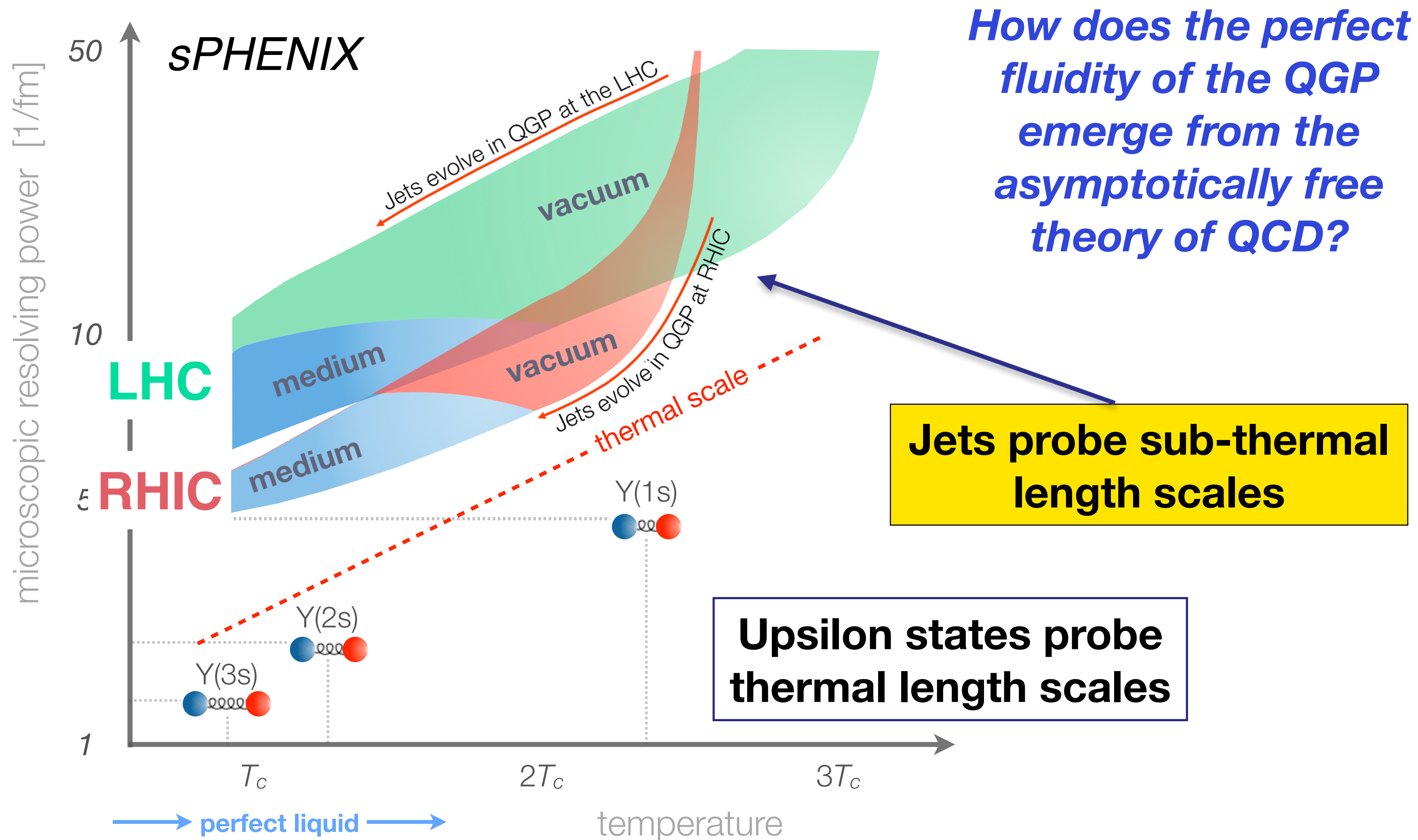
Z-boson — jet correlations



Diffusion wake: Enhancement in jet direction; depletion in Z-direction



Probing scales within the medium



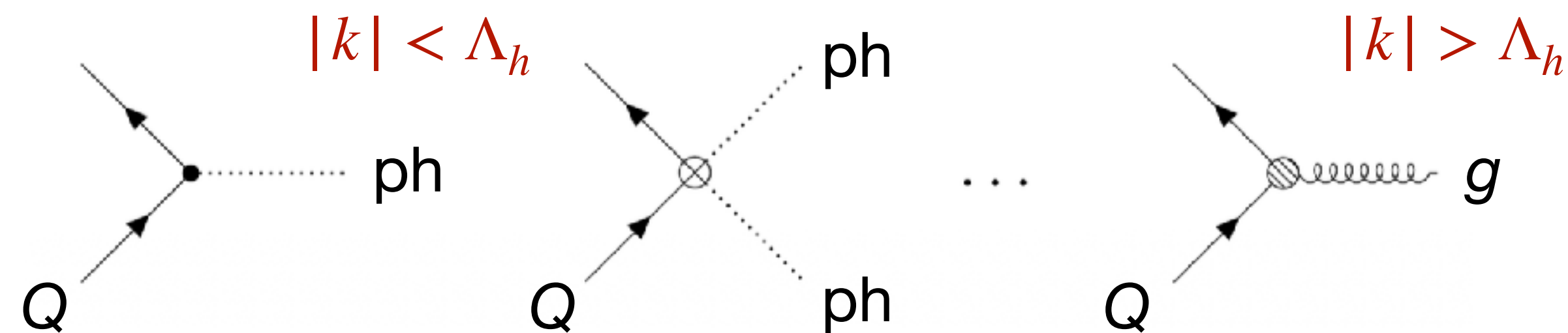
Heavy quark + fluid EFT

Kirchner et al. - 2510.13942

Treat fluid as effective scalar field with phonon excitations

$$\mathcal{L} = F(J^\mu J_\mu) \quad J^\mu = \frac{1}{3!} \varepsilon^{\mu\nu\rho\sigma} \varepsilon_{IJK} \partial_\rho \phi^J \partial_\nu \phi^K \partial_\sigma \phi^I$$

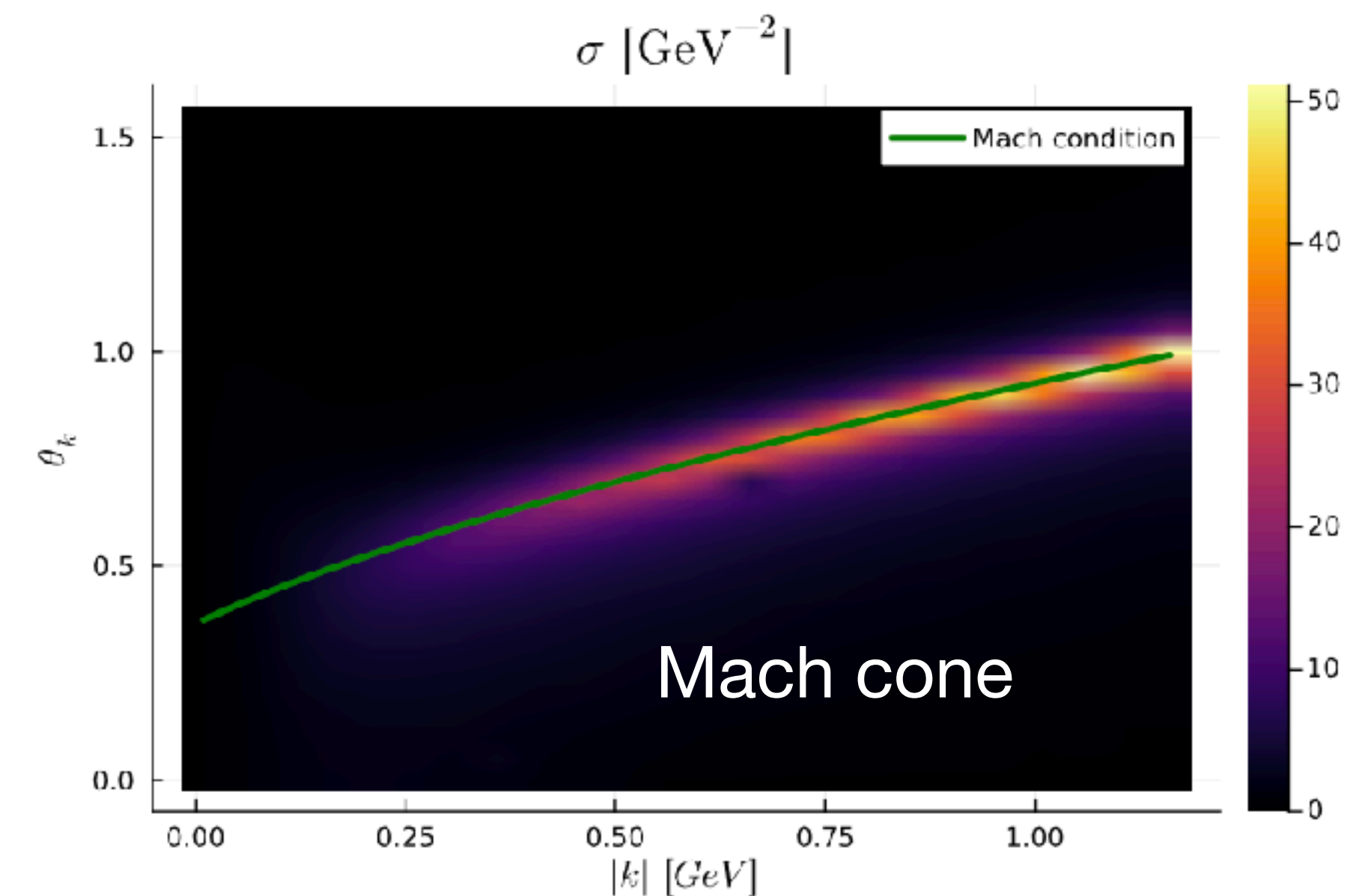
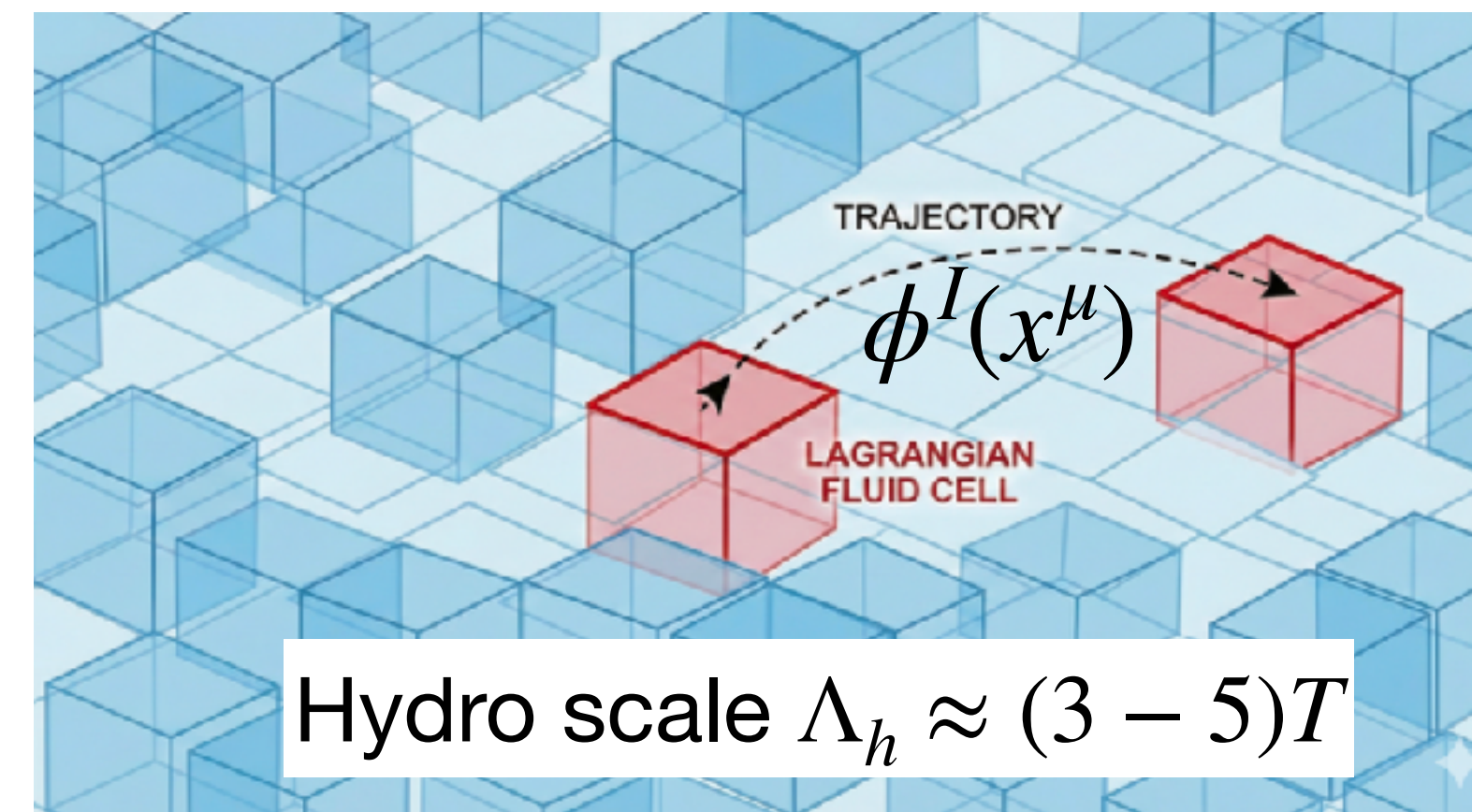
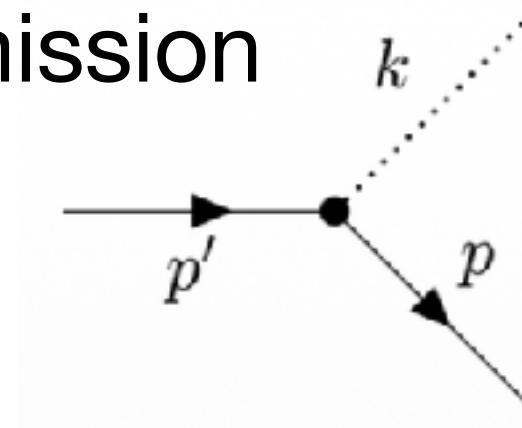
Couple heavy quark to fluid field (phonons) and gluons



Heavy quark-thermal phonon scattering



Phonon emission





Buddha Vairocana (Kashmir)

Questions?