QGP transport paramaters

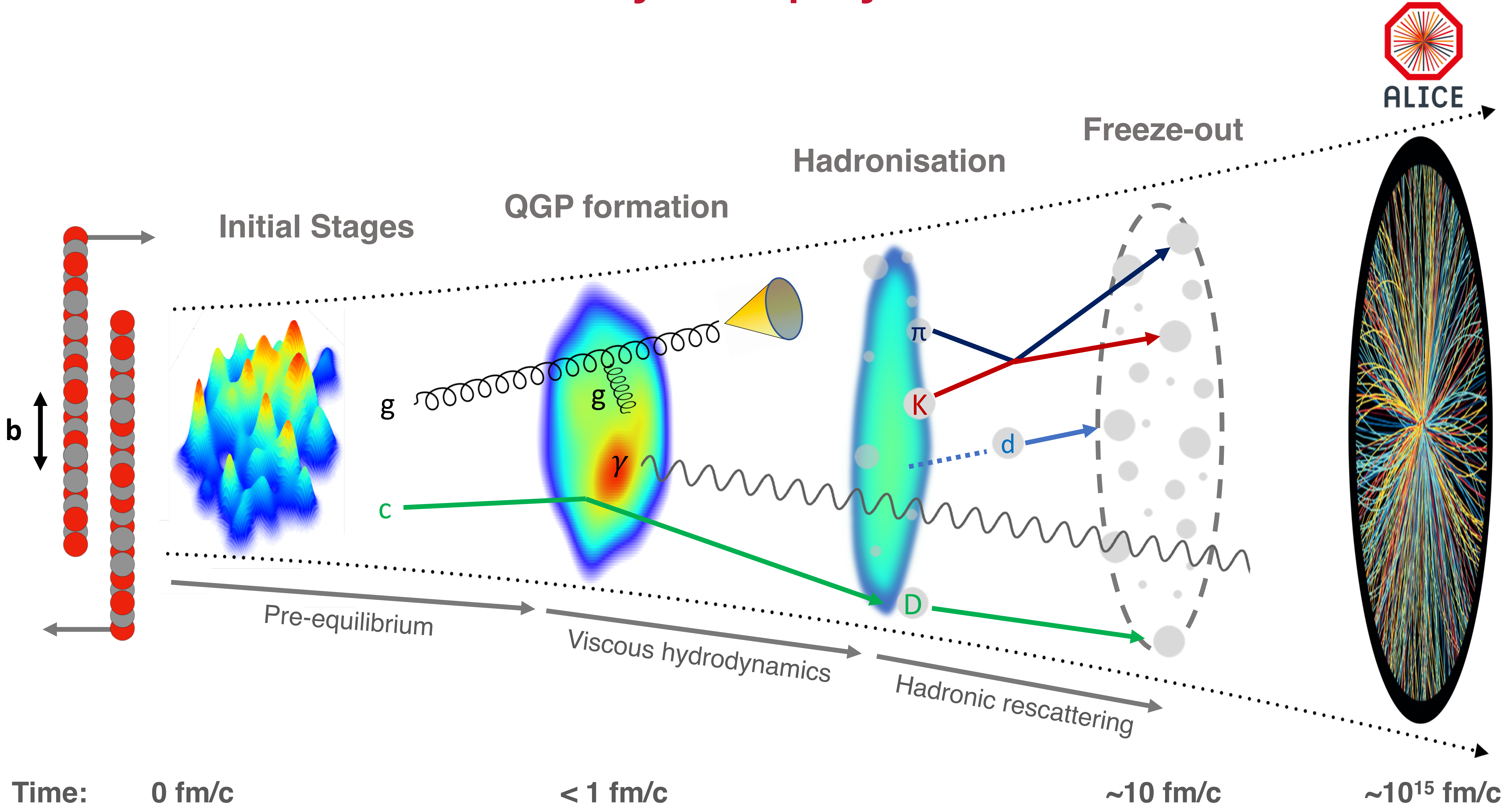
What we have learnt from Bayesian analyses?

Anthony Timmins

- Introduction
- QGP Viscosity
- Charm diffusion
- Jet transport parameter
- Summary

“Standard model” of heavy-ion physics

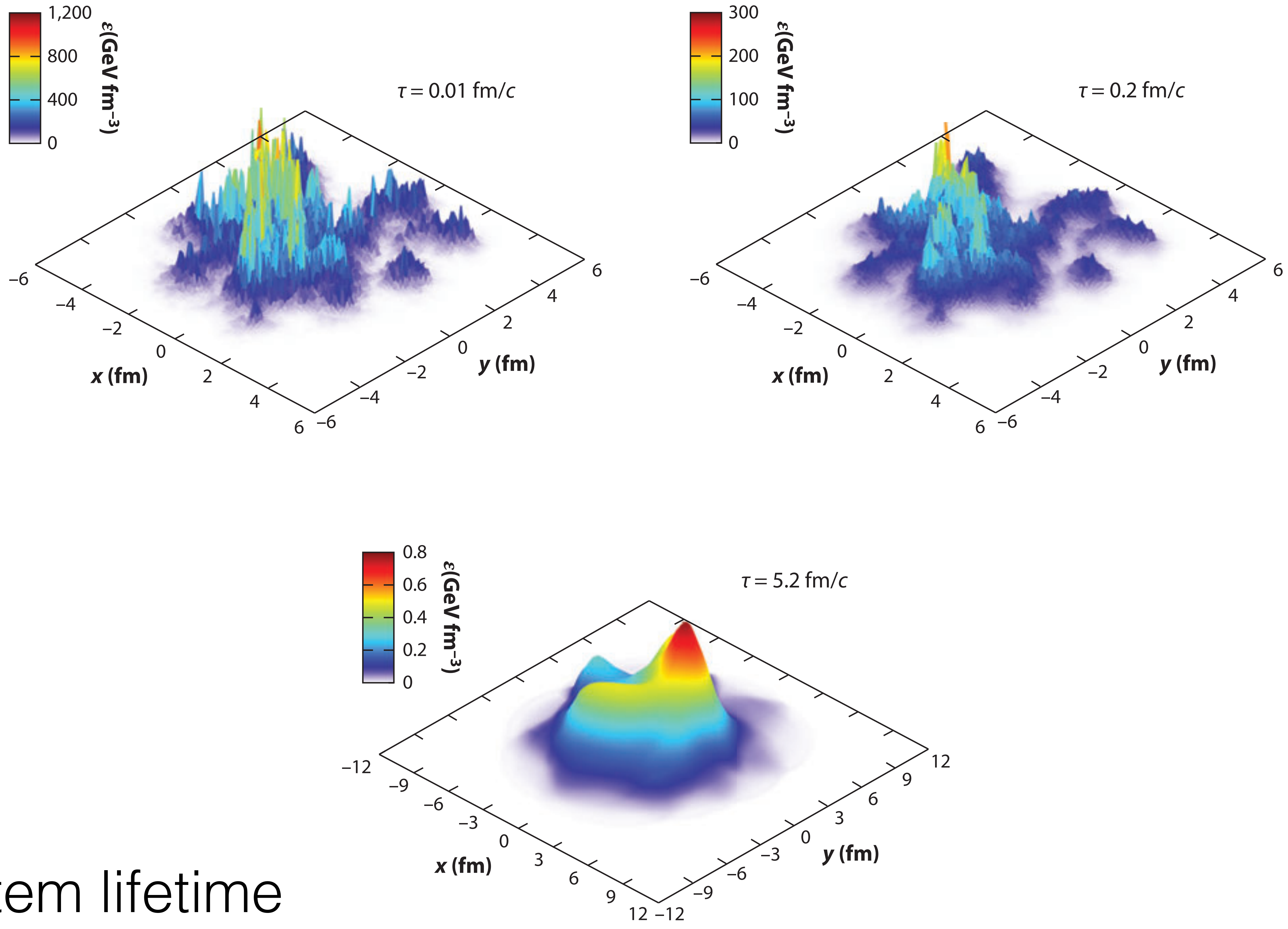
Inspired by Chun Shen’s illustrations



Microscopic properties

Annu. Rev. Nucl. Part. Sci. 63 (2013) 123-151

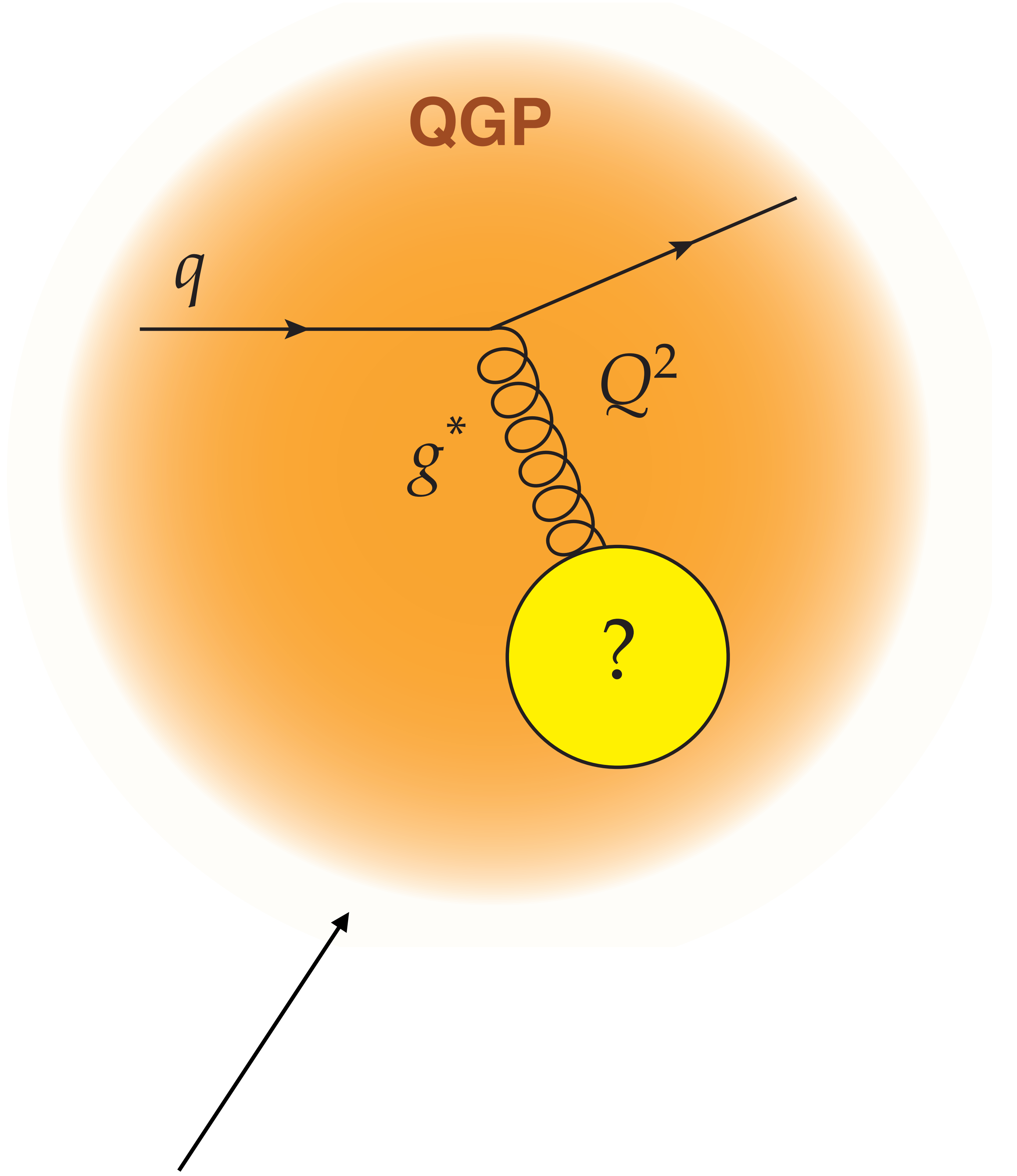
- QGP a system subject to local excitations
  - ✓ Excitations drive system out of equilibrium
  - ✓ Time scale for system to return to equilibrium is relaxation time
- Local excitations possible:
  - ✓ Hot spots from lumpy initial state
  - ✓ Heavy quarks
  - ✓ Jets
- Hydrodynamic flow occurs when relaxation time < system lifetime
  - ✓ Mean free path is smaller than excitation gradients



Microscopic properties

arXiv:1501.06197

- Fluid shear and bulk excitations:
  - ✓ η**/s** and ζ**/s** ∝ shear/bulk relaxation times (hydro)
  - ✓ η/s ∝ mean free path (kinetic theory)
  - ✓ Inhibit anisotropic and radial flow



- Heavy quarks produced very early → out of equilibrium with QGP
  - ✓ Spatial diffusion coefficient $\mathbf{D_s}$ ∝ heavy quark relaxation time
  - ✓ Small D_s → more heavy quark flow

- Jet transport parameter $\hat{q}$
  - ✓ Average transverse momentum exchanged with medium per mean free path

Microscopic properties - strong and weak coupling

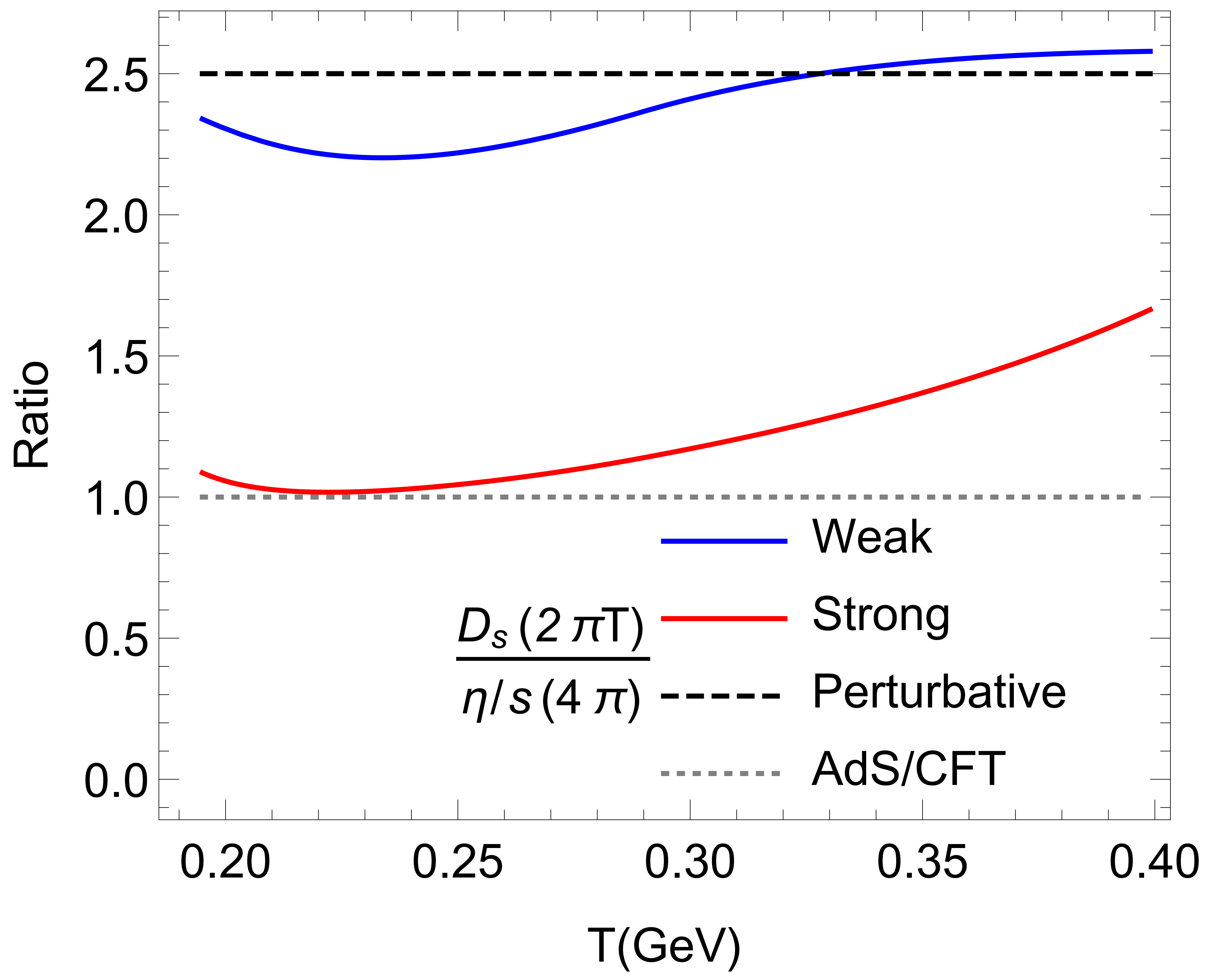
- Weak coupling
  - ✓ Well defined quasi-particles: **QGP a gas**
  - ✓ Interactions: 2→2 or 2→3 processes: pQCD with $\alpha_s < 0.3$

- Strong coupling
  - ✓ Strong correlations between constituents: higher order interactions
  - ✓ Therefore no well defined quasi-particles: **QGP a liquid**

- Momentum scale of excitations scales matters!
  - ✓ Probes with large (enough) energy see a gas
  - ✓ Probes of energy ~ temperature see a liquid

Microscopic properties - how are they related?

Annu. Rev. Nucl. Part. Sci. 69 (2019) 417-445



$$\frac{\eta}{s}\left\{\begin{array}{c}\approx\\ \gg\end{array}\right\}1.25\,\frac{T^3}{\hat{q}}\qquad\left\{\begin{array}{l}\text{for weak coupling,}\\ \text{for strong coupling.}\end{array}\right.$$

Phys. Rev. Lett. 99 (2007) 192301

- Both η/s and (2πT)D_s saturate at $1/4\pi$ & 1 when system becomes infinitely coupled
- $\hat{q}/T^3$ continues to increase i.e. no upper bound
  - ✓ Greater than 1.25/(η/s) in strong coupling regime

Reverend Thomas Bayes

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$$

- English statistician, philosopher and Presbyterian minister, born 1702
- Published only twice: one theological paper & one mathematical paper
- Famous theorem never published

Bayesian analyses in heavy-ion collisions

Posterior probability of Theory parameter(s) given Data

Data/Theory fit quality

Probability of Theory parameter(s) **prior** to Data comparison

$$P(T|D) \propto P(D|T) \times P(T)$$

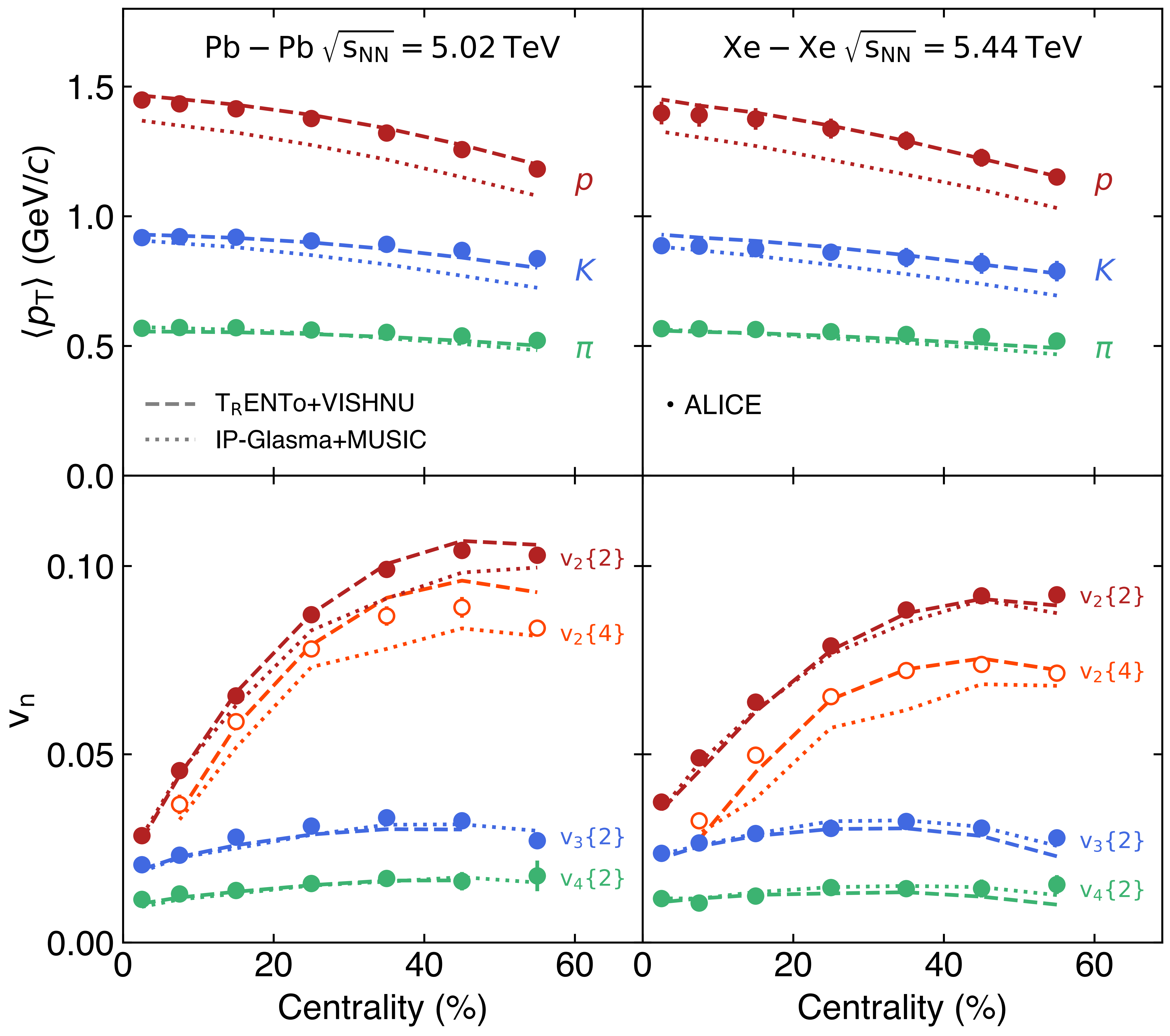
- **Main goal:** obtain full probability distributions of QGP parameters

- Gaussian Process Emulators
  ✓ Used to efficiently explore parameter space

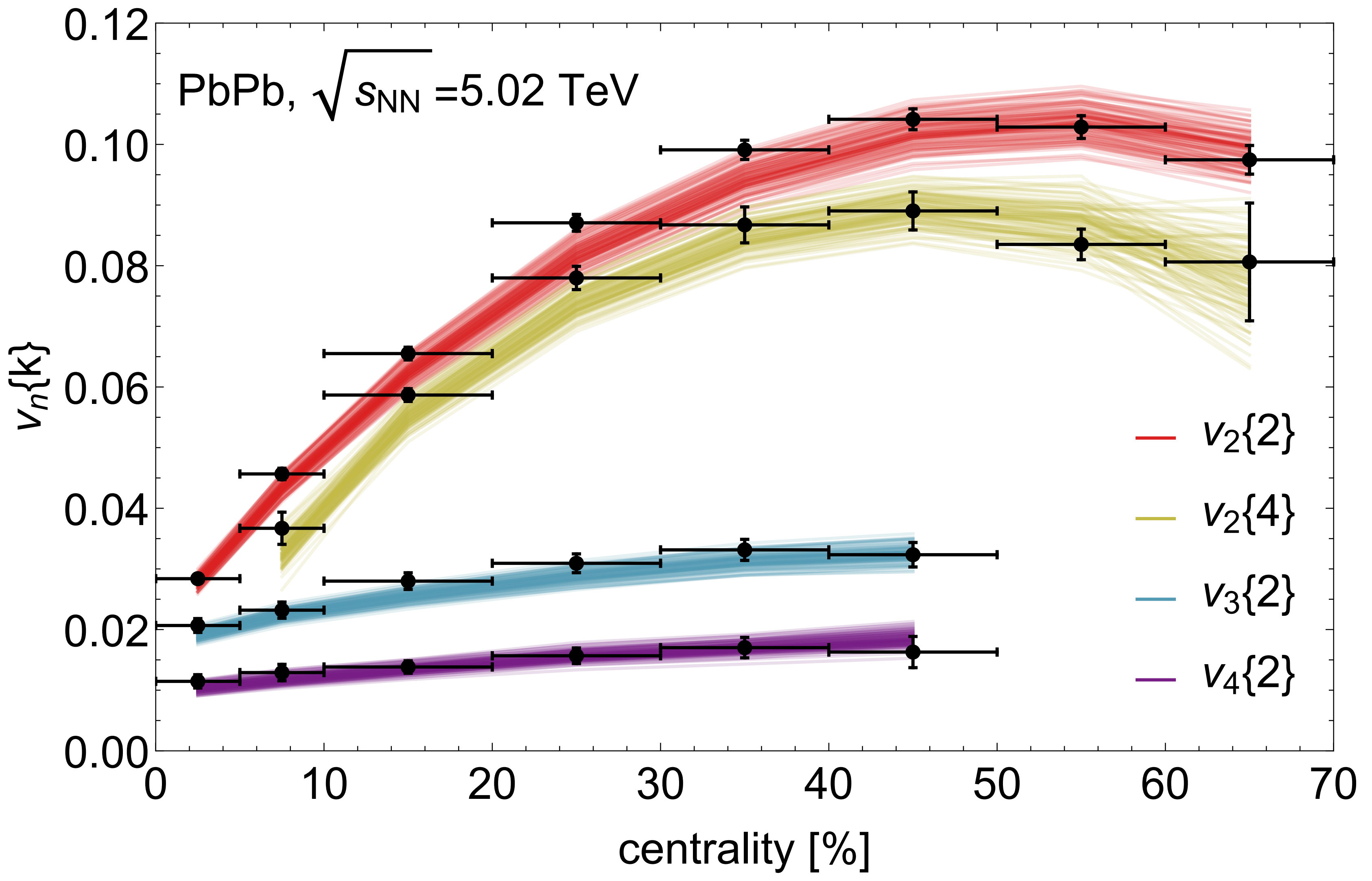
- First application to heavy-ion collisions from Scott et al: PRL 114 (2015) 202301

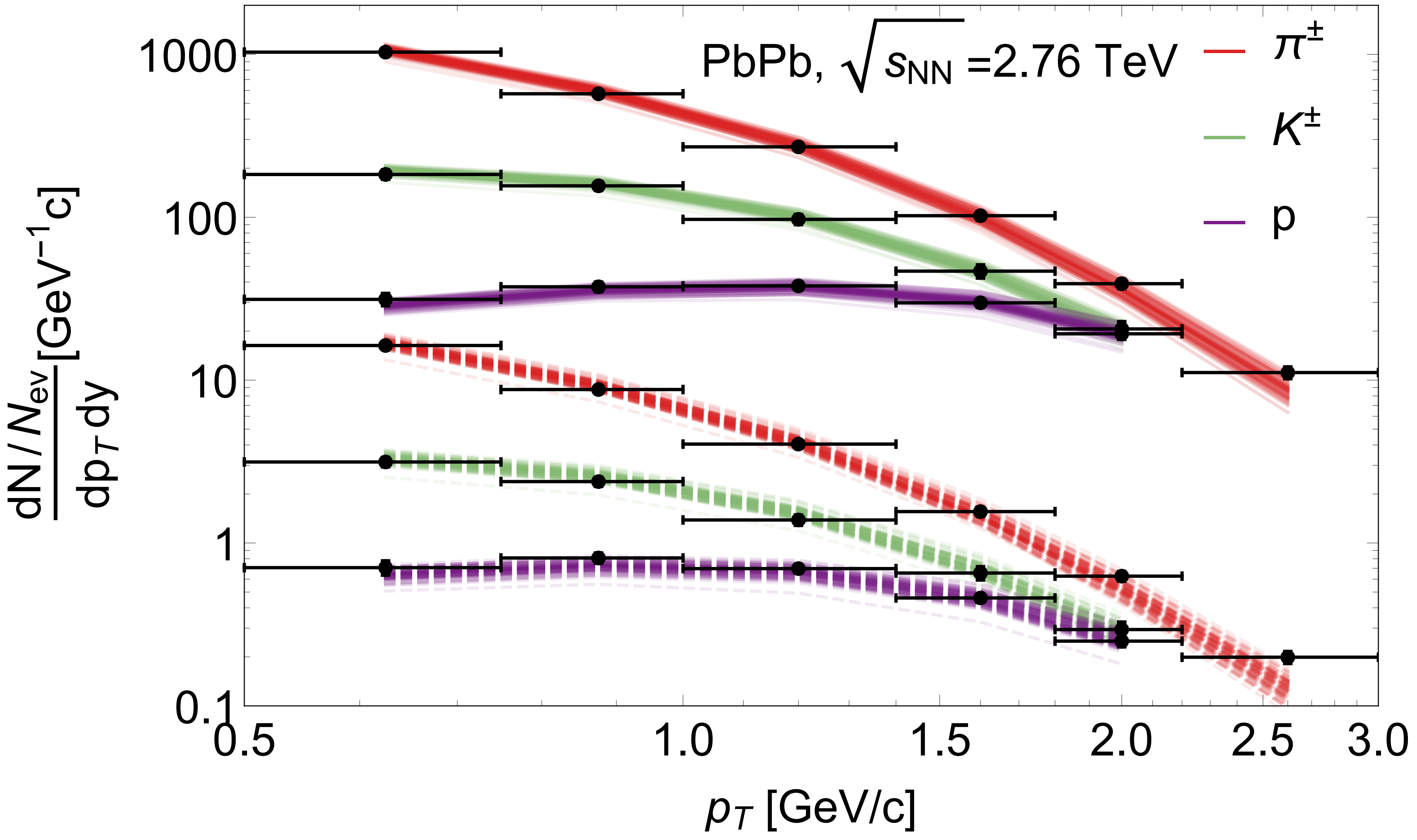
QGP viscosities

- Explored by running full hydrodynamic chain
  - ✓ Initial state + pre-equilibirum + viscous hydro + participation + hadronic afterburner
- Bayesian determination of η**/s(T)** and ζ**/s(T)** gone through several iterations
  - ✓ Duke: 3 publications
  - ✓ JETSCAPE: 2
  - ✓ Trajectum: 2
  - ✓ Jyvaskyla: 1
- Multiply experimental observables used
  - ✓ E.g. Nature Physics 15 (2019) 1113–1117 (Duke) used 13

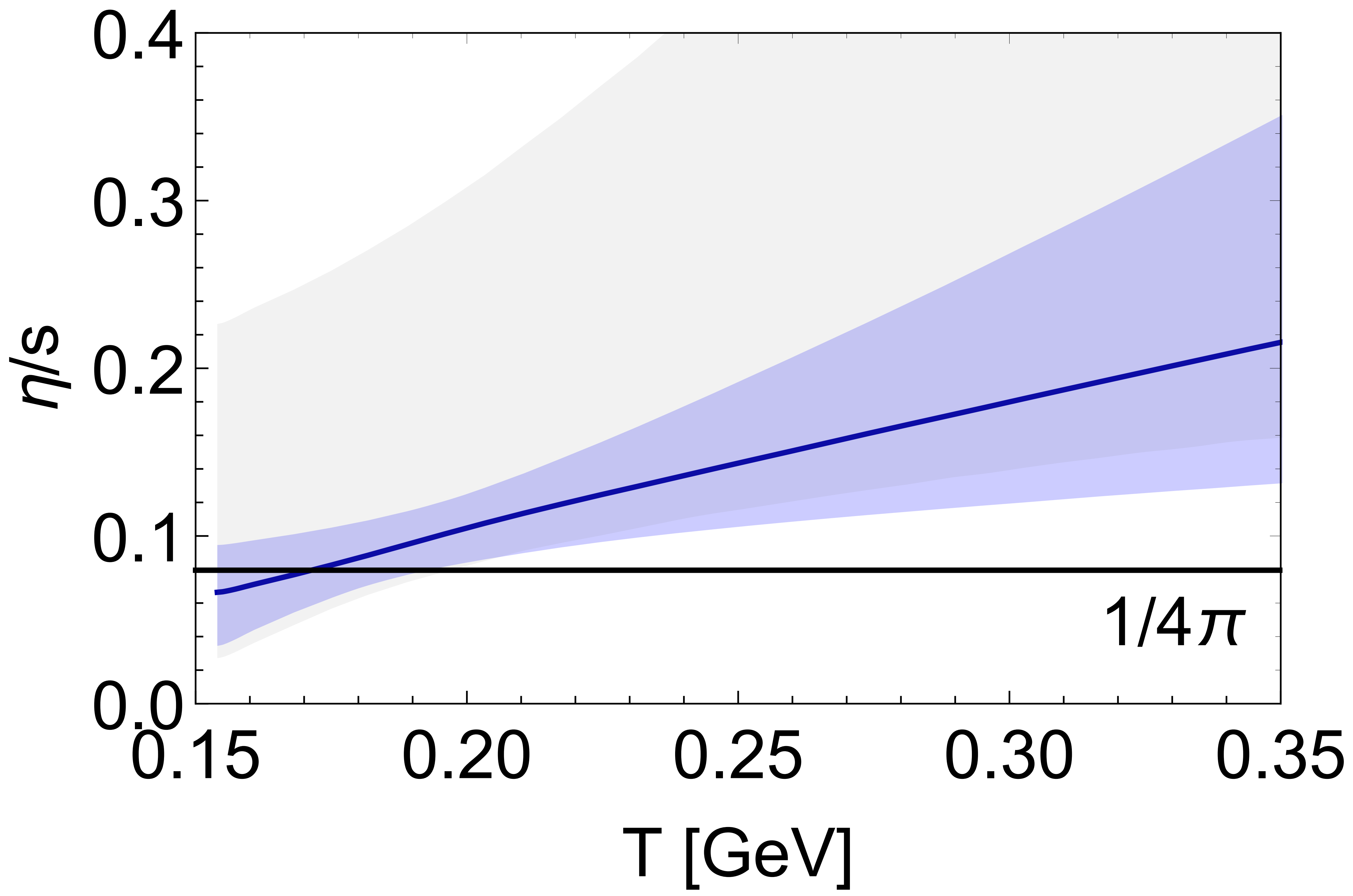


QGP viscosities



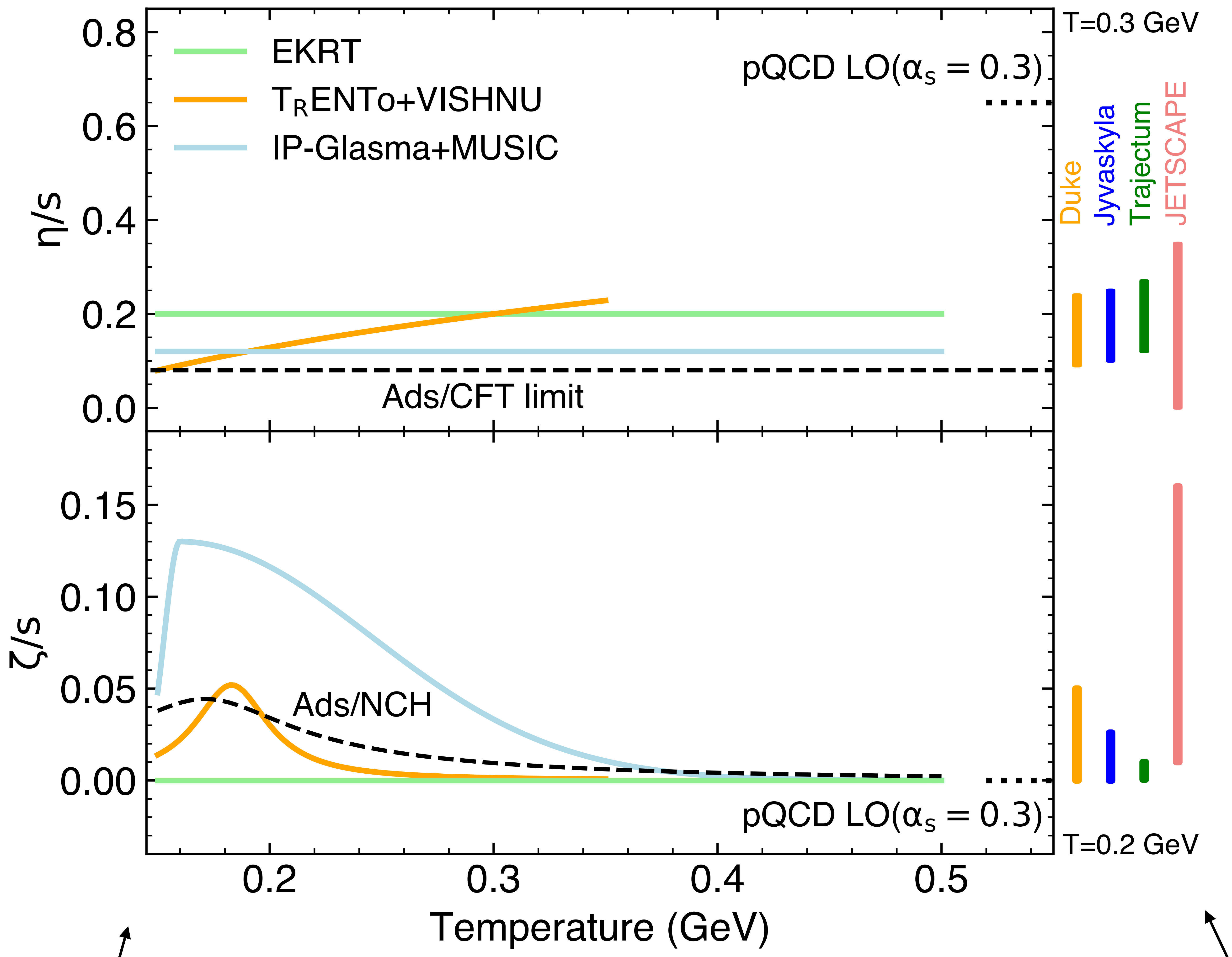


Trajectum: PRL 126 (2021) 202301



- **Posterior distributions (90% C.L)** clearly narrower than **prior distributions**

QGP viscosities - putting it all together



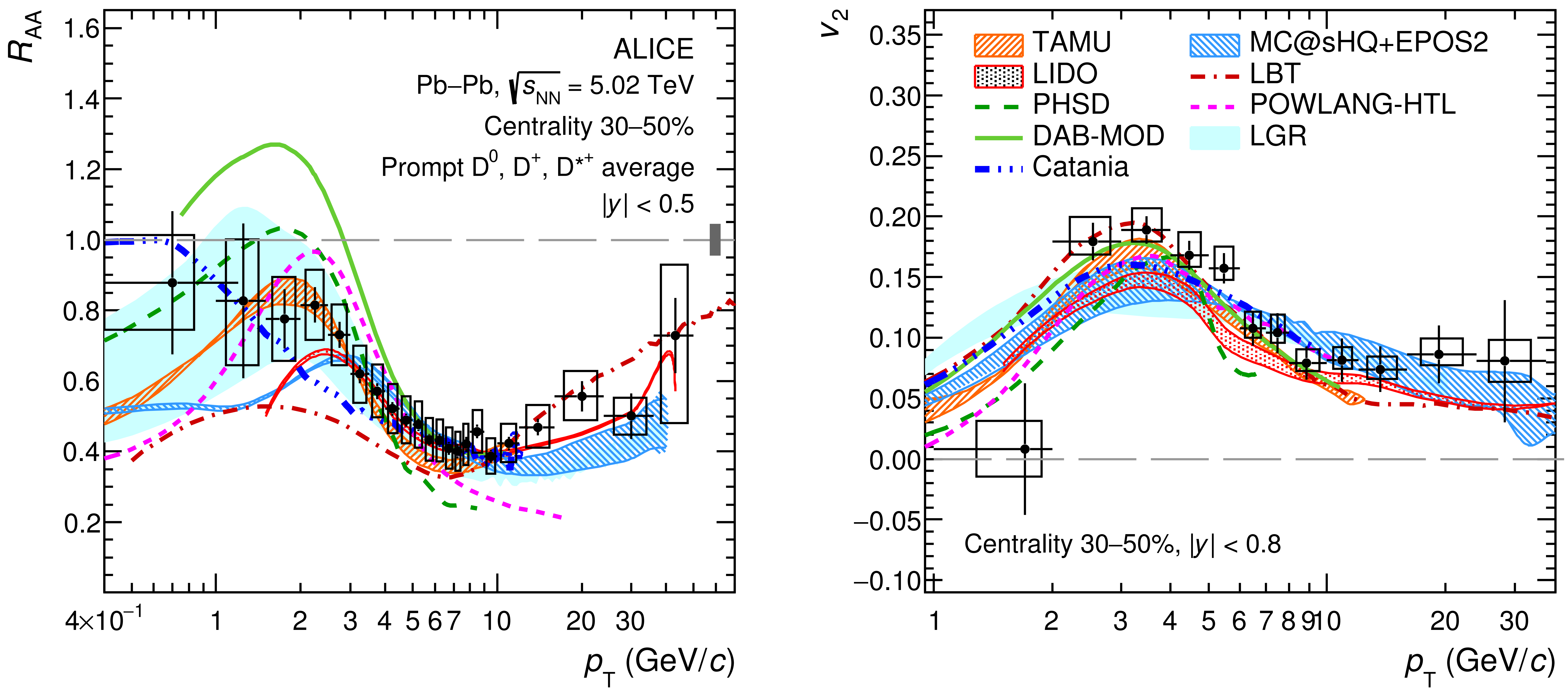
- Differences in posteriors due to?
  - ✓ Different prior ranges/ assumptions
  - ✓ Different datasets
- Common challegene
  - ✓ Lack of knowledge of pre-equil. drives η/s(T) and ζ/s(T) uncertainties

Single η/s(T) and ζ/s(T) that describe data

Posterior bands (90 C.L.) @ single T

Charm diffusion coefficient D_s

ALICE: arXiv:2110.09420



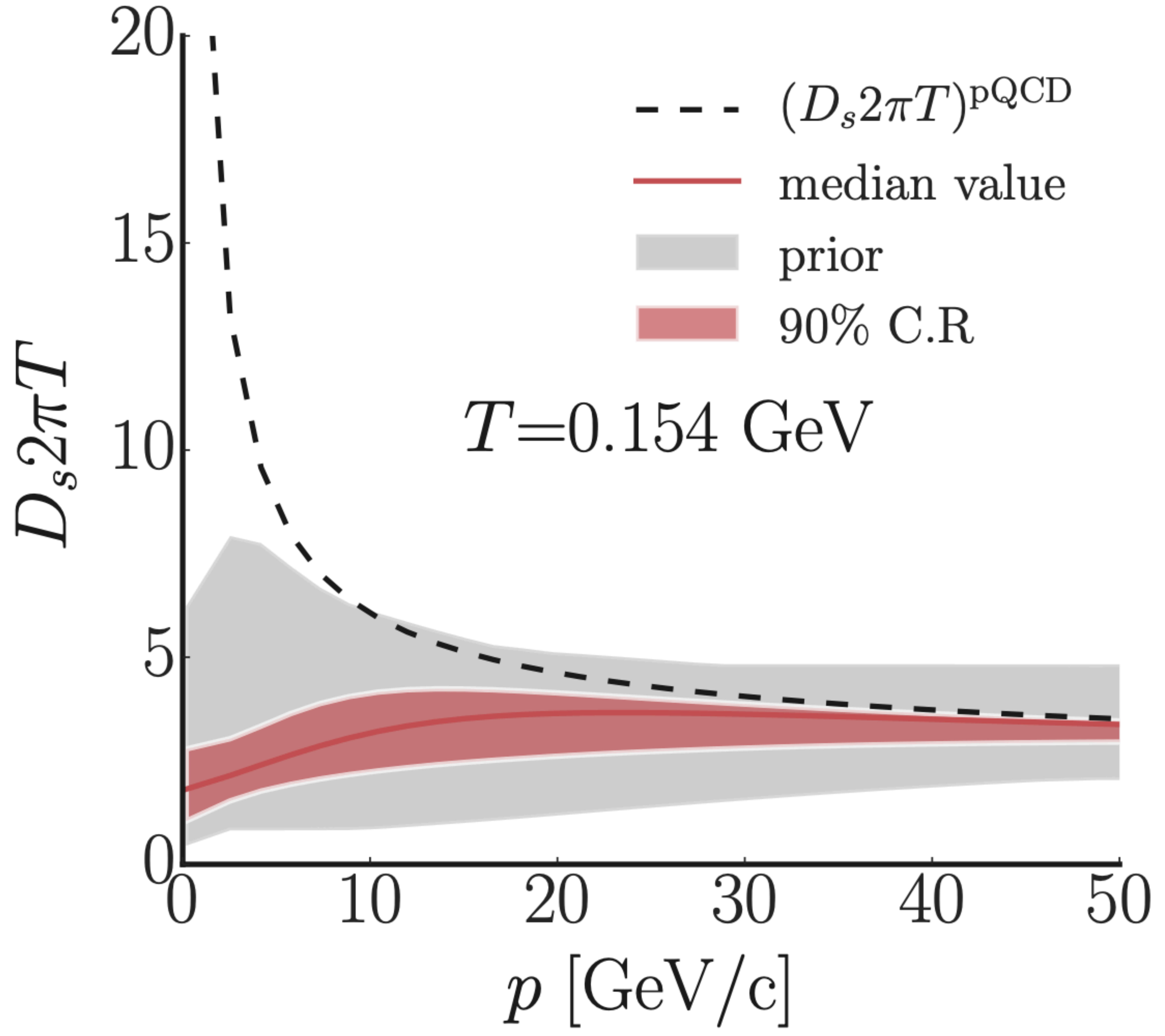
- Typically obtained from D-meson R_{AA} and v_2 measurements at low p_T
- Transport models solve Boltzmann/Langevin equations - ask Jorge/Elena for more details!

Charm diffusion coefficient D_s

- Two Bayesian analyses (RHIC & LHC data)
- Duke+Nantes+WSU: PRC 97 (2018) 014907 →

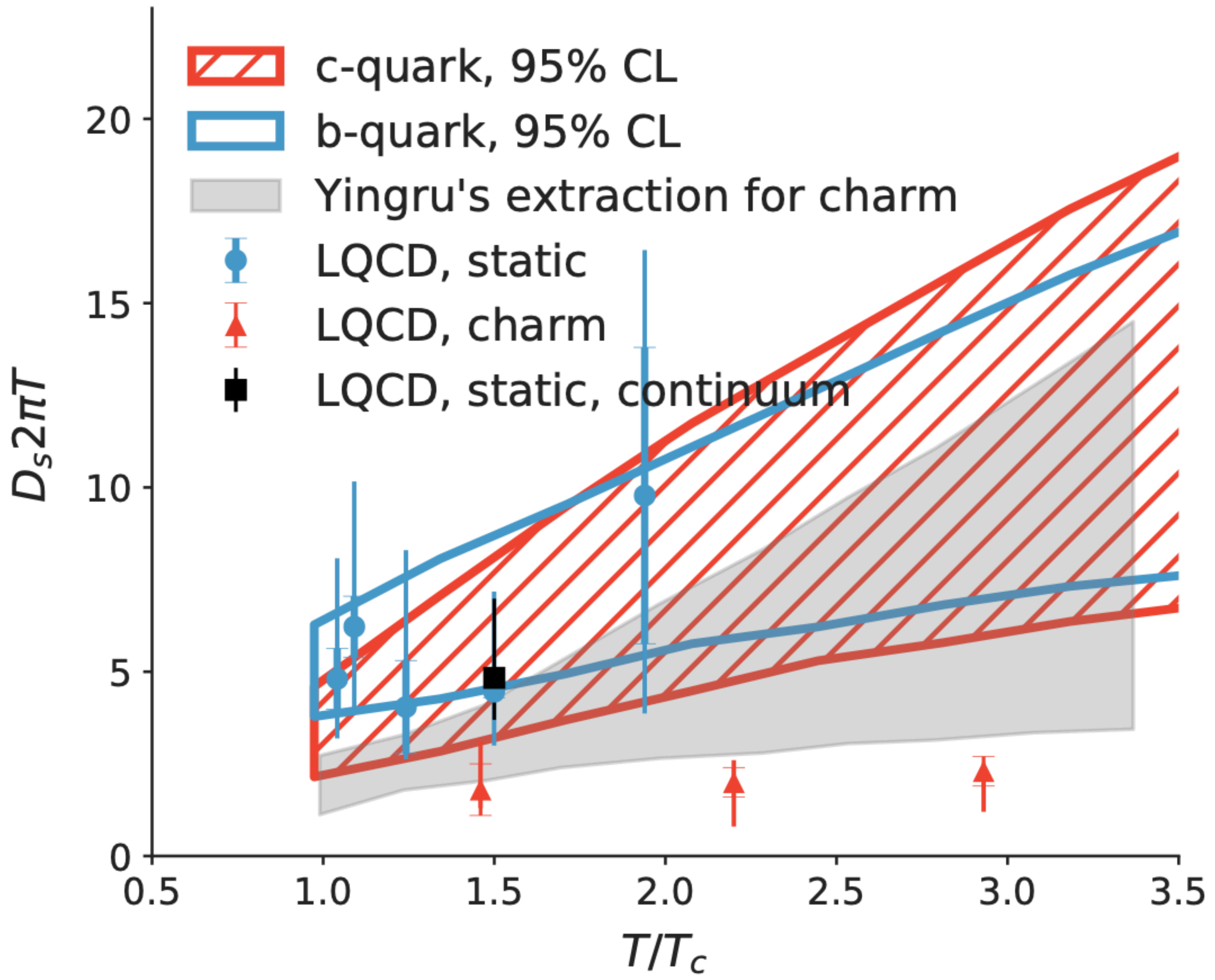
$$D_s 2\pi T(T, \boldsymbol{p}) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\text{linear}} + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\text{pQCD}}.$$

- Duke: PRC 98 (2018) 064901
  - ✓ Included both open charm and bottom mesons



Charm diffusion coefficient D_s

PRC 98 (2018) 064901



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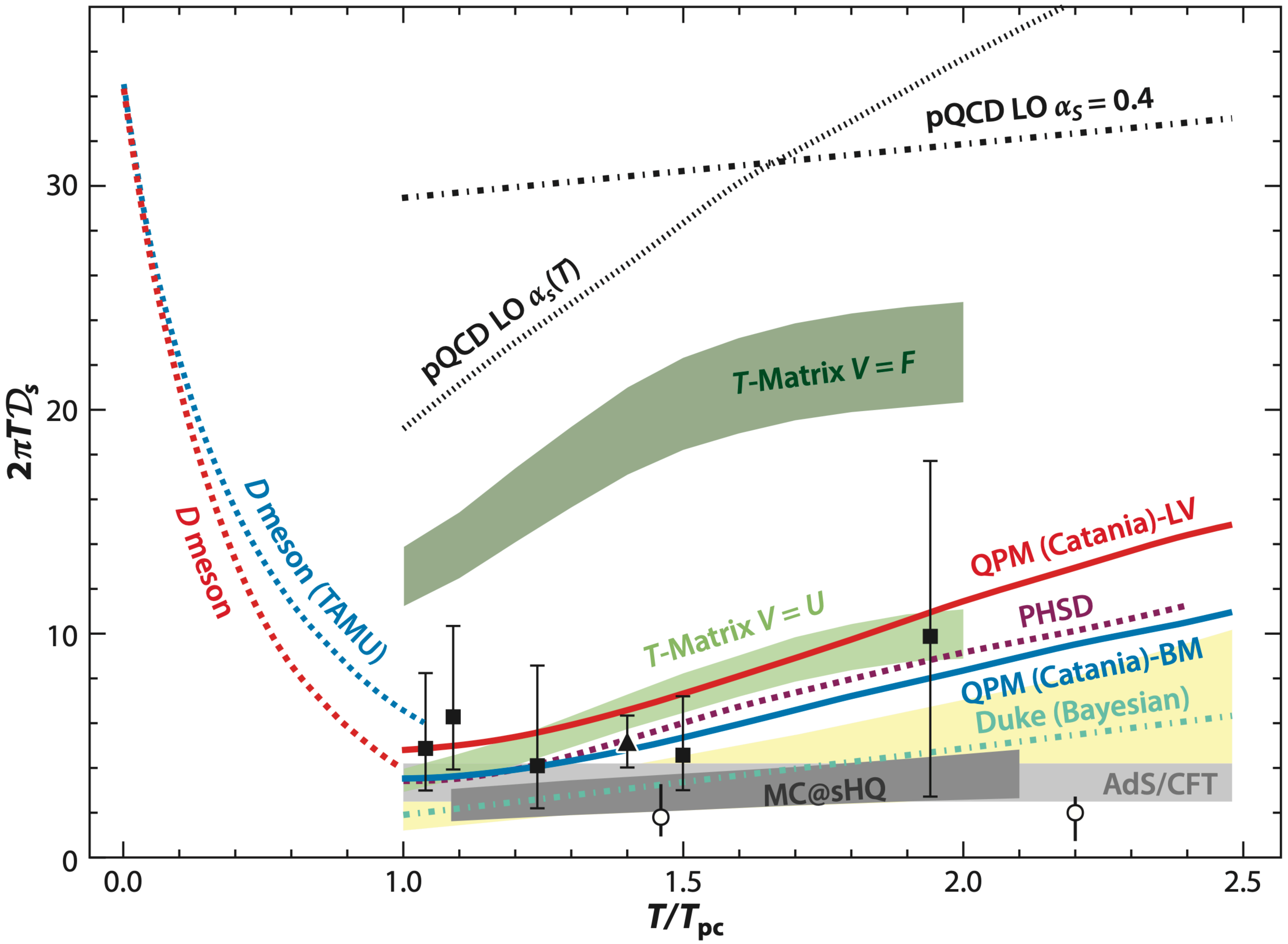
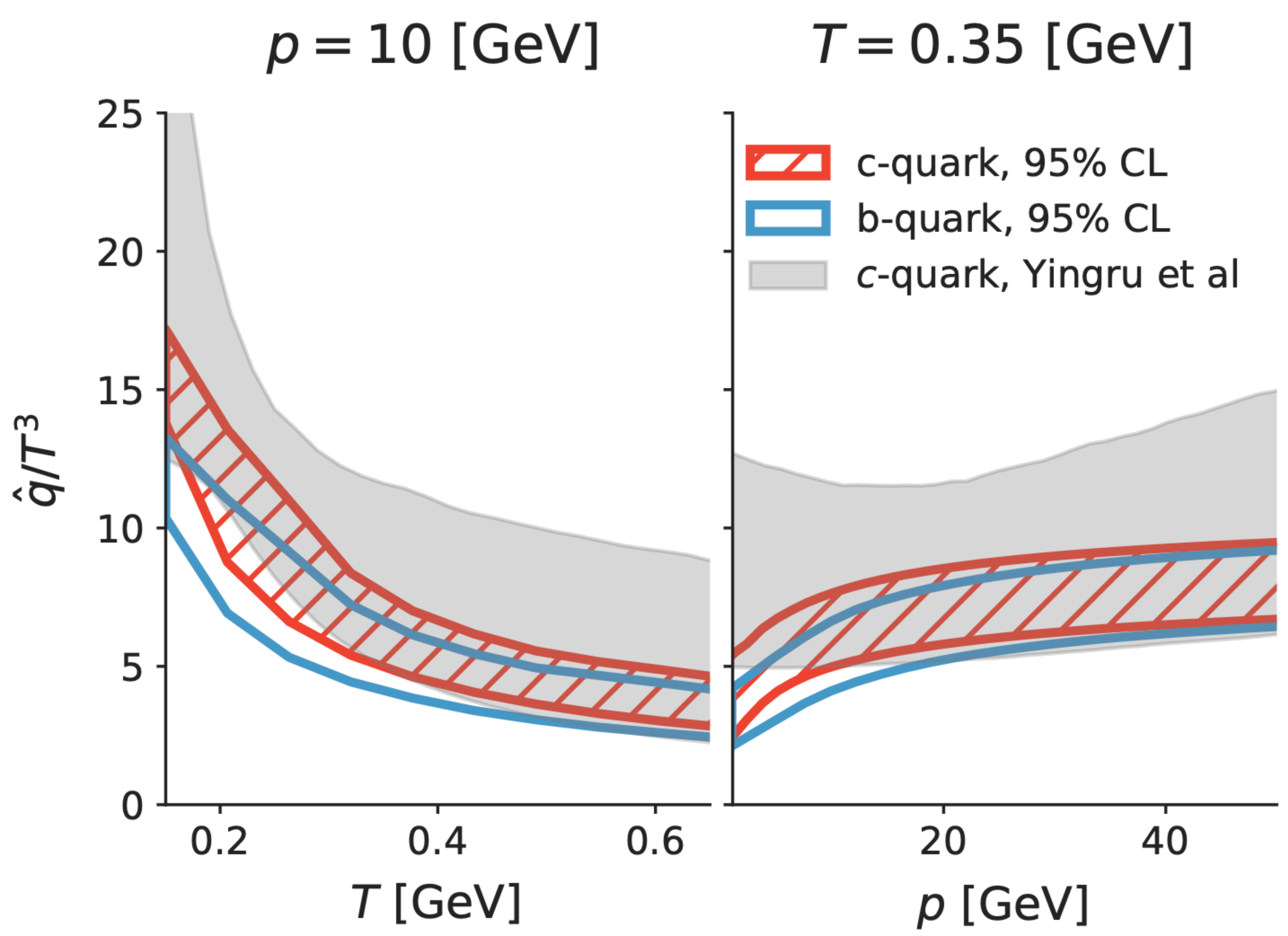
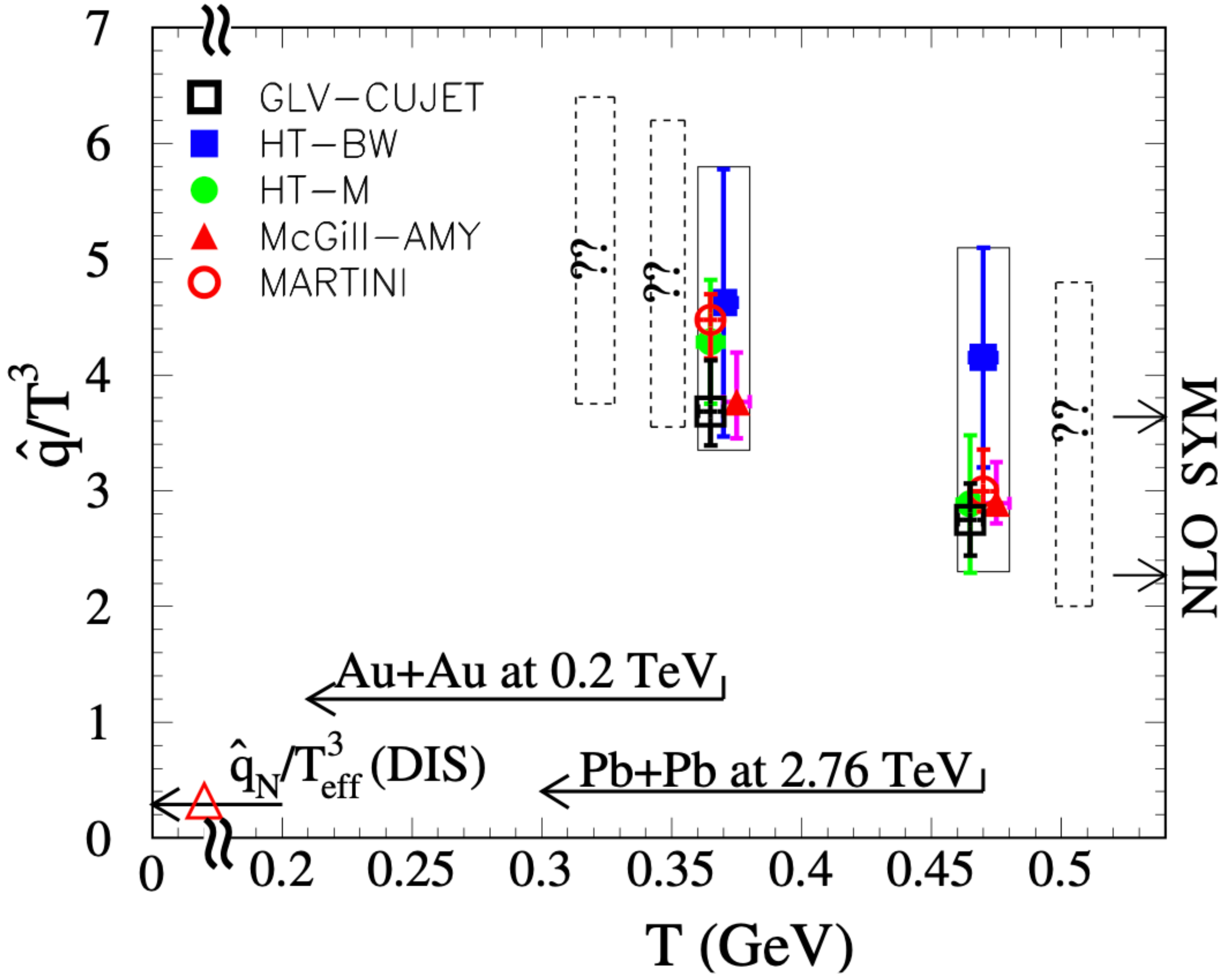


- Posterior ranges overlap with single charm D_s parameterizations used in other models
- Ranges largest at highest temperatures

Jet transport paramater $\hat{q}$



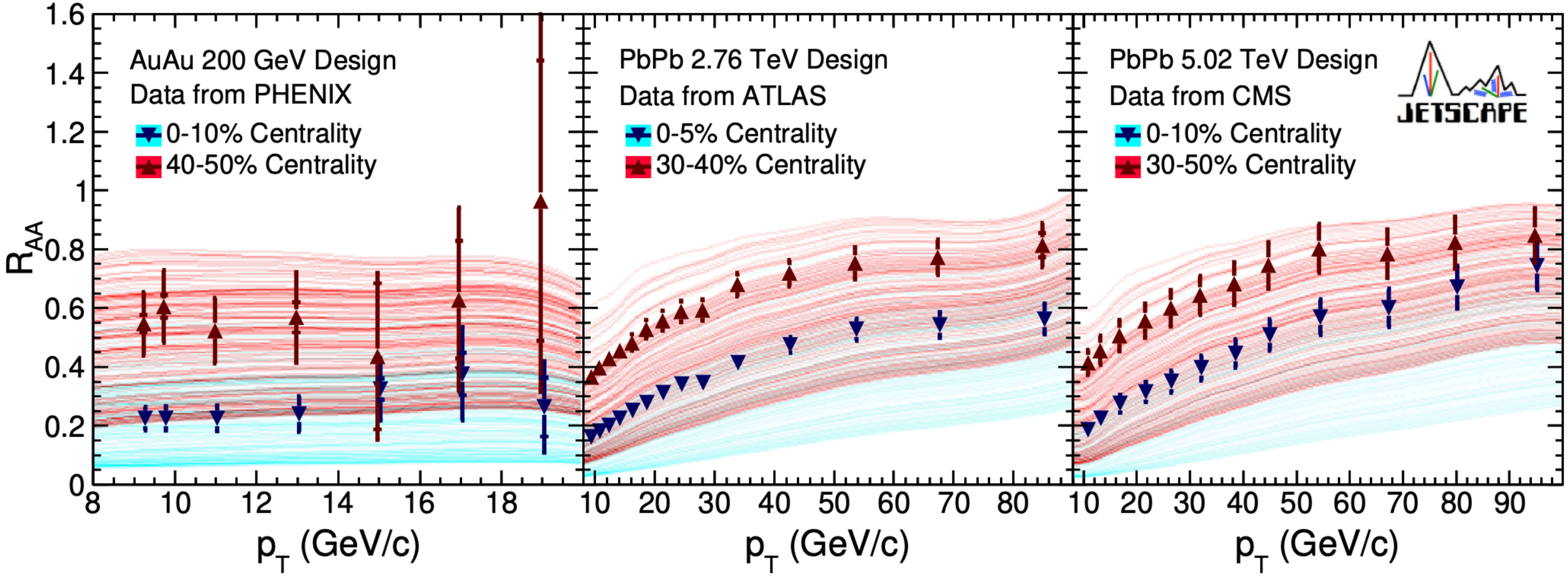
PRC 90 (2014) 014909



- Previous analyses extracted $\hat{q}$ for heavy quarks
- First **light quark/gluon** $\hat{q}$ determined by JET collaboration using charged hadron R_{AA}
    - ✓Least-squares minimization

Jet transport paramater $\hat{q}$

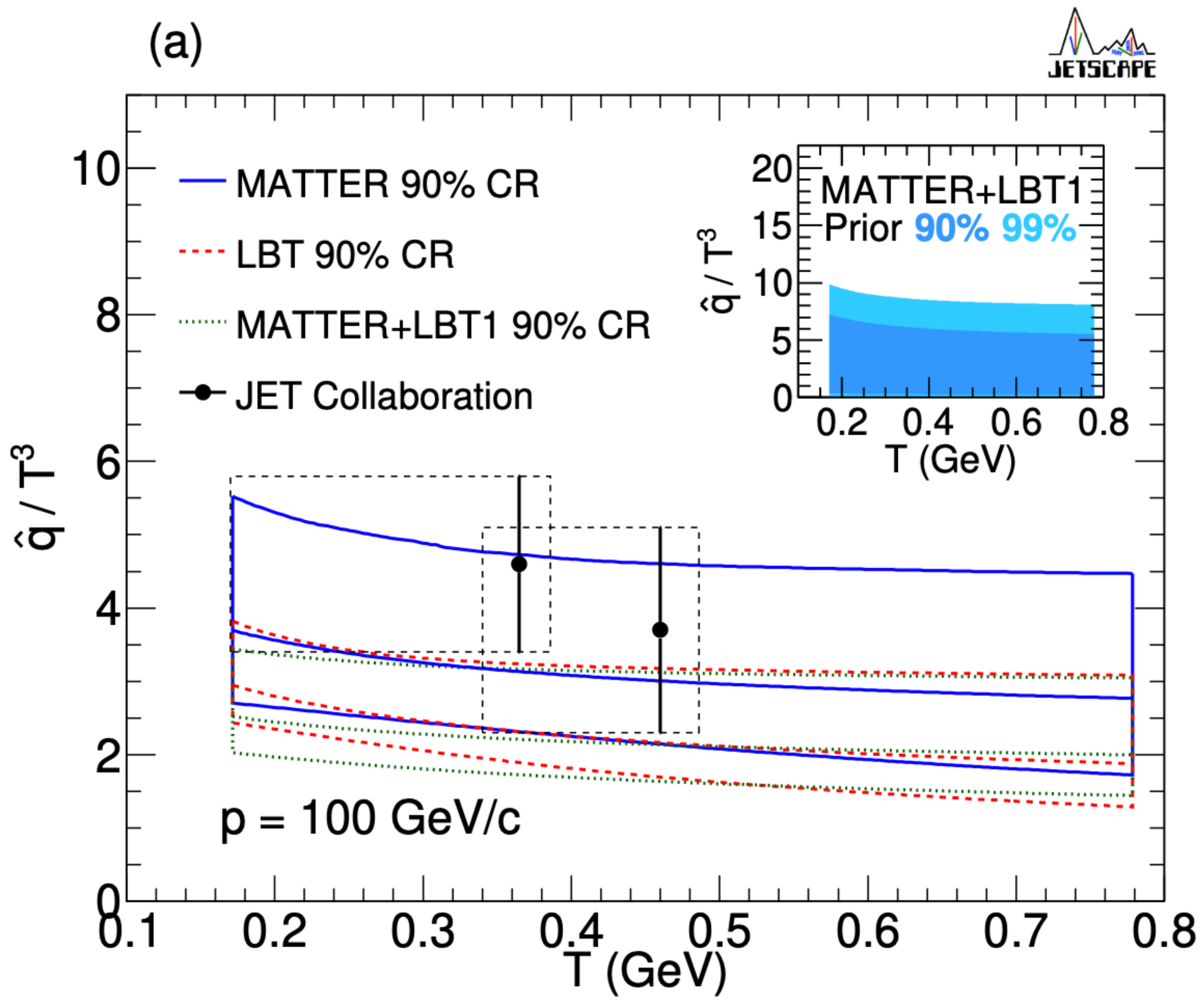
PRC 104 (2021) 024905

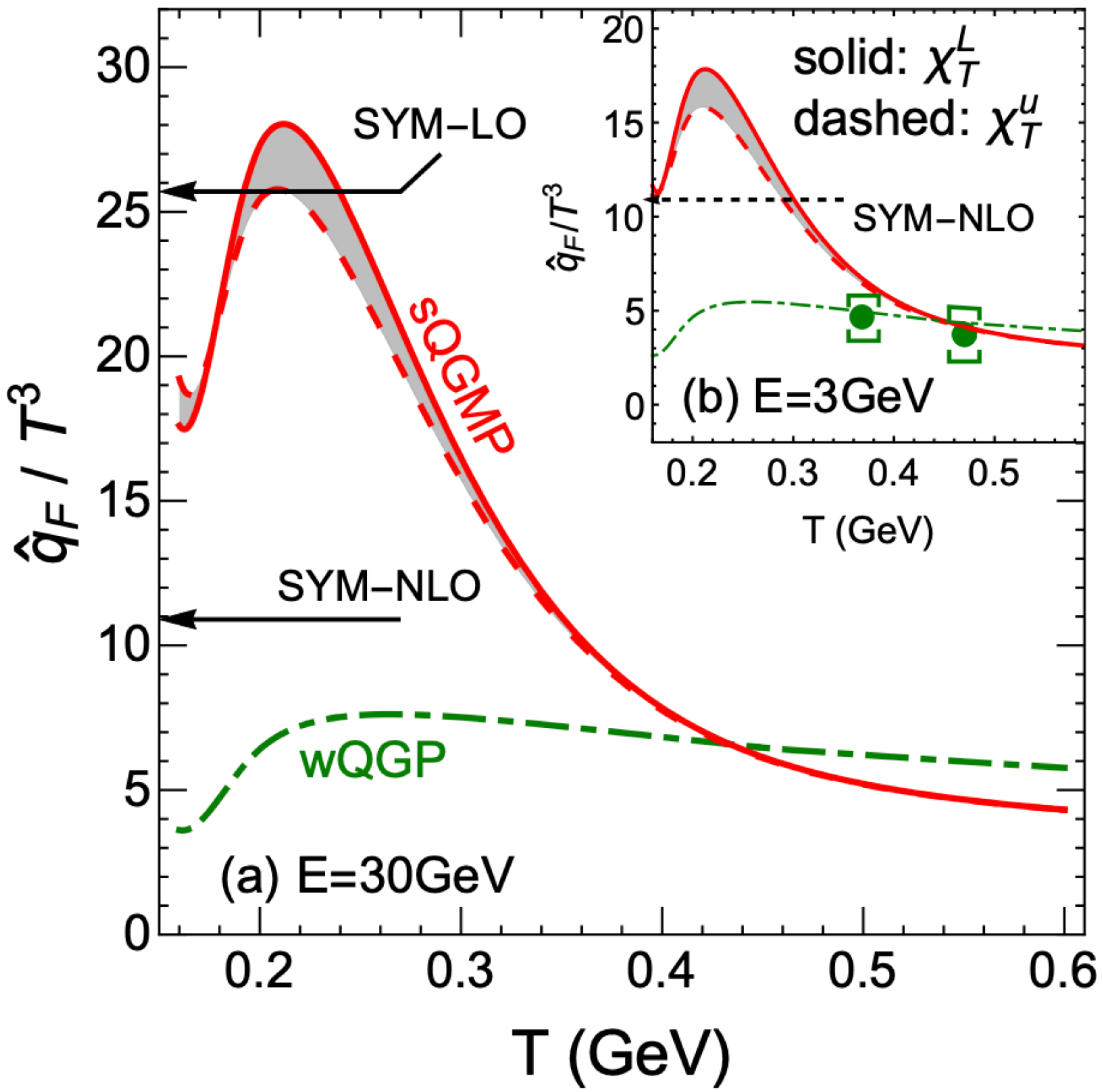


- JETSCAPE attempted first extraction over all temperatures using Bayesian analyses
  - ✓ Charged hadron R_{AA} only 3 energies

- Weak coupling pQCD based MATTER and LBT models explored
  - ✓ Two different $\hat{q}$ paramaterizations

Jet transport paramater $\hat{q}$





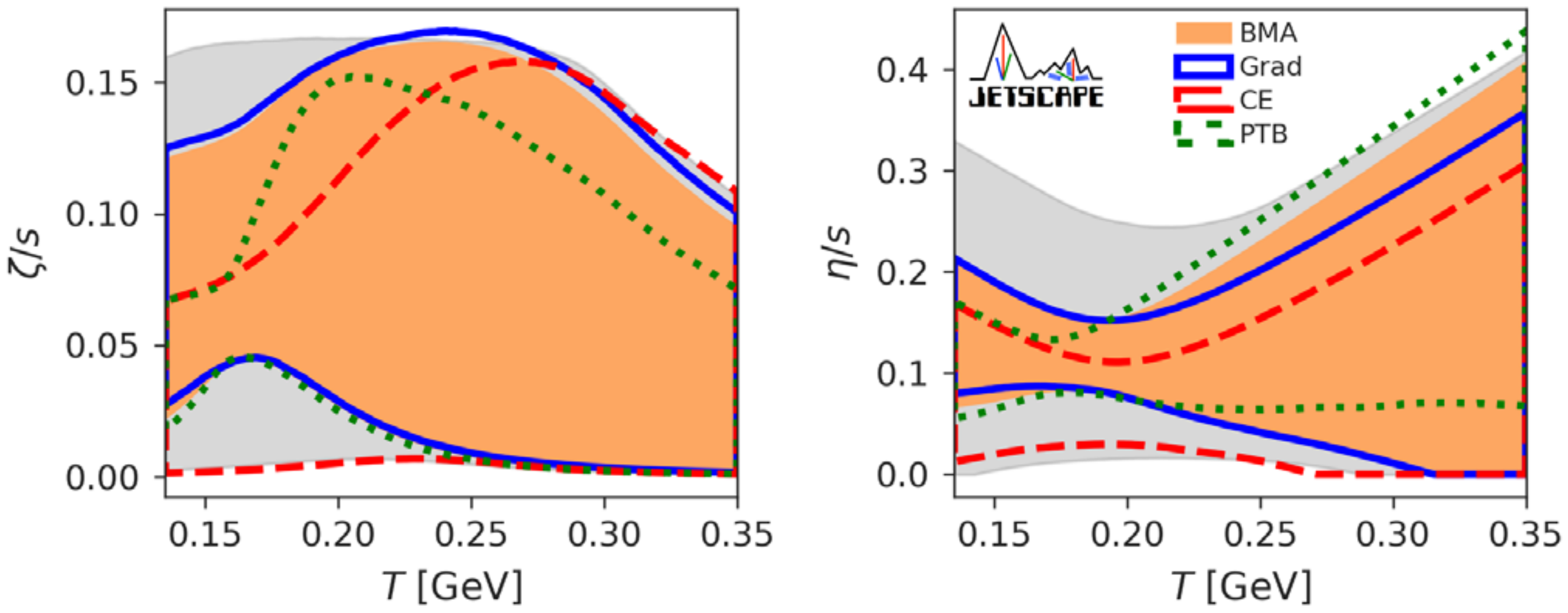
- JETSCAPE $\hat{q}$ posterior ranges provide most extensive mapping for weak coupling models
- Another approaches CUJET 3.1 (weak/strong coupling) that describe high p_{T} h± R_{AA} and v_2 measurements require larger $\hat{q}$ at lower temperatures

Summary and personal thoughts…

- Bayesian analyses have demonstrated:
  - ✓ Possible to construct extensive probability maps for key QGP transport parameters
  - ✓ **Light sector is strongly coupled** on energy scale of QGP temperature via viscosity determinations
  - ✓ Low momentum **charm quarks strongly couple with QGP**

- What needs to be done?
  - ✓ Consensus on how priors determined
  - ✓ **Pre-equilibrium** in hydro chains needs further constraints from data
  - ✓ Better understanding why D_s posterior probabilities diverge a larger temperatures
  - ✓ **Additional observables included for $\hat{q}$** extractions

Backup - JETSCAPE



Phys. Rev. Lett. 126 (2021) 242301

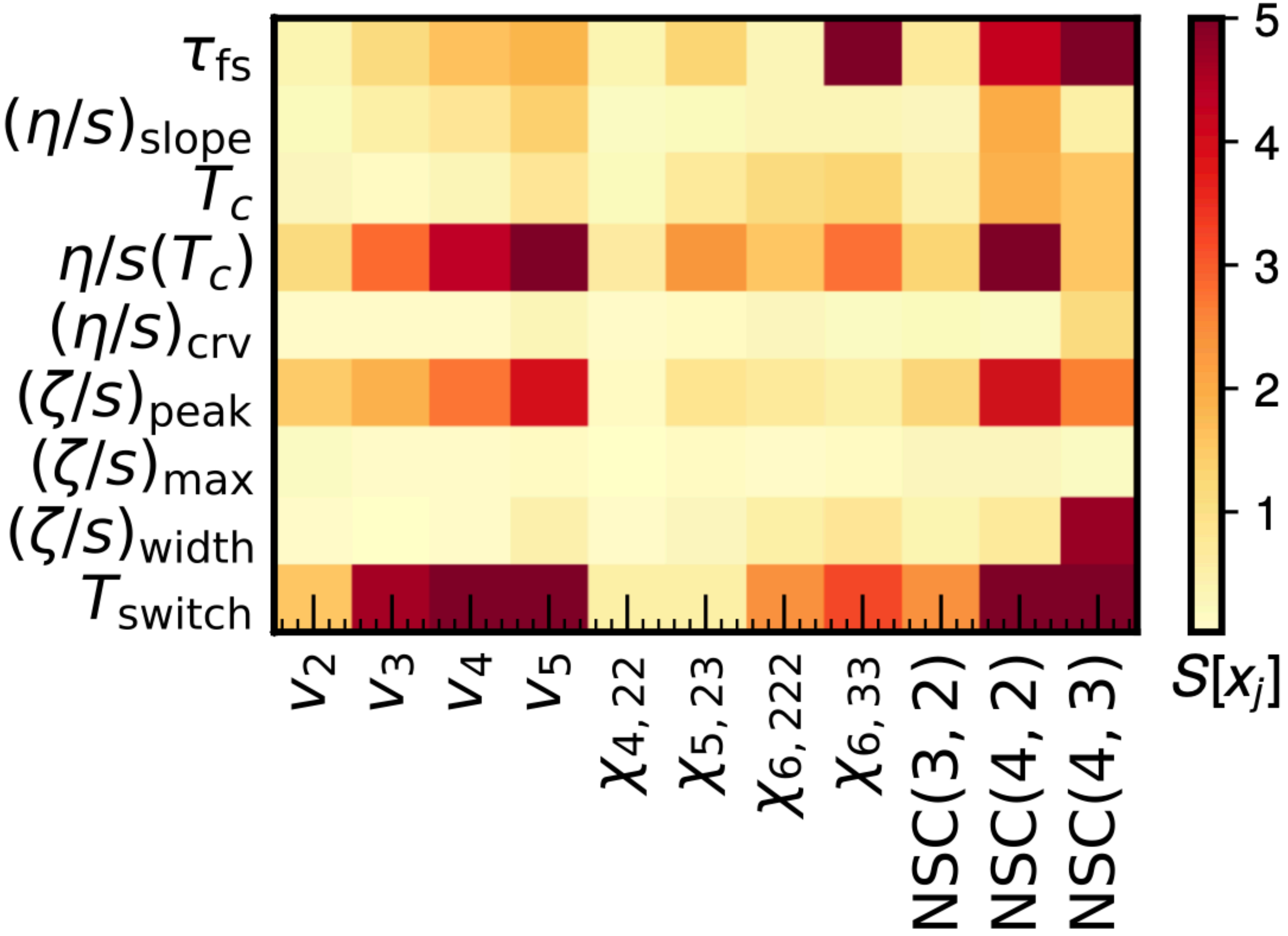
FIG. 1. The 90% credible intervals for the prior (gray), the posteriors of the Grad (blue), Chapman-Enskog (red), and Pratt-Torrieri-Bernhard (green) models, and their Bayesian model average (orange) for the specific bulk (left) and shear (right) viscosities of QGP.

Backup - JETSCAPE

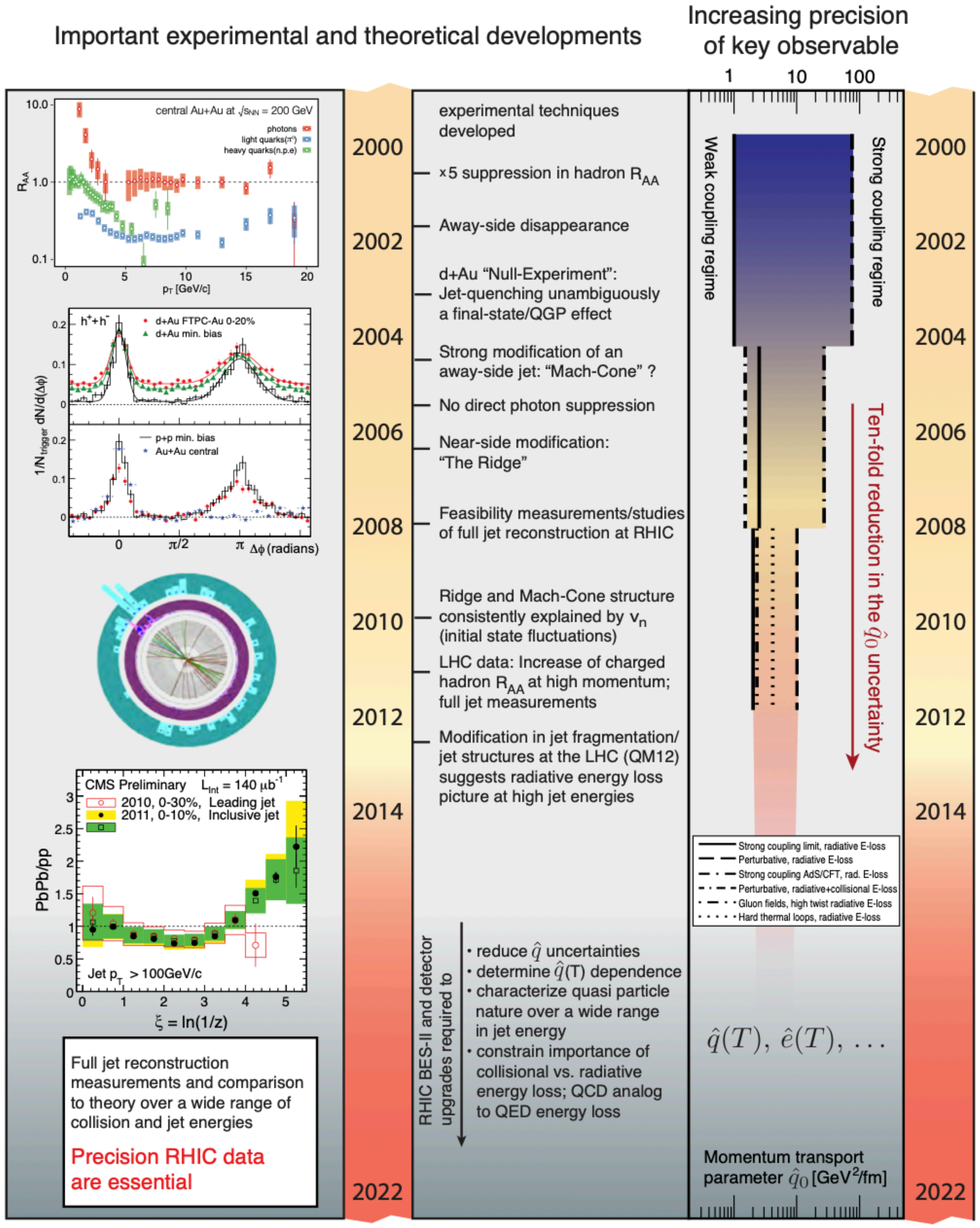
viscosities of QCD. Nevertheless we do believe that the pre-hydrodynamic stage presents one of the major remaining sources of uncertainty in constraining the viscosities of QCD from heavy ion measurements; it will be important to explore different pre-hydrodynamic models in the future.[27]

Phys. Rev. Lett. 126 (2021) 242301

Backup - Jyvaskyla



Backup - A Community White Paper on the Future of Relativistic Heavy-Ion Physics in the US



Backup - CUJET 3 vs. 2