Can high-$p_\perp$ theory and data constrain η/s ?

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Based on Phys.Rev.C 108 (2023) 4, 044907

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Outline

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Motivation

- Low-$p_\perp$ observables are used to explore the bulk properties of the QGP created in heavy-ion collisions.
- High-$p_\perp$ probes also become powerful tomography tools; Sensitive to global QGP features, e.g., different temperature profiles or initial conditions.
- QGP tomography: Jointly constraining QGP properties by low and high-$p_\perp$ physics.
- η/s is well constrained by Bayesian analysis in low-$p_\perp$ sector in the temperature range $T_c \lesssim T \lesssim 1.5T_c$ and weakly constrained at larger temperatures.
- High-$p_\perp$ data/theory can serve as complementary tool.

η/s of the medium : Soft-to-hard boundary

- QGP behaves as almost perfect fluid: Remarkably small η/s.
- QGP is expected to behave as weakly interacting gas: Weakly coupled
- Fluid dynamics predicts the η/s to be very low: Strongly coupled
- QGP may behave as perfect fluid near T_c (soft regime) and η/s may increase at high temperature (hard regime).
- Testing the soft-to-hard hypothesis is difficult: Anisotropy is weakly affected by the η/s at high temperature.

High-$p_\perp$ energy loss : Generalized DREENA-A

- **D**ynamical **R**adiative and **E**lastic **EN**ergy loss **A**pproach
  - Based on finite temperature field theory (pQCD) and generalized HTL approach

    M. Djordjevic, PRC 74, 064907, (2006) ; PRC 80, 064909 (2009), M. Djordjevic and U. Heinz, PRL 101, 022302

  - Finite size dynamical QCD medium is considered
  - Takes into account both radiative and collisional energy losses
  - No fitting parameter in the theory

High-$p_\perp$ energy loss : Generalized DREENA-A

- Optimized to incorporate any arbitrary event-by-event fluctuating temperature profile.

  D. Zigic, J. Auvinen, I. Salom, M. Djordjevic, P. Huovinen Phys.Rev.C 106 (2022) 4, 044909

- Constraints on early evolution.

  S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen, M. Djordjevic Phys.Rev.C 105 L021901 (2022)

- Map how the shape of the collision system is manifested in the high-$p_\perp$ data.

  S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen, M. Djordjevic Phys.Lett.B 835, 137501 (2022)

- Shape of the QGP droplet.

  BK, D. Zigic, P. Huovinen, M. Djordjevic, M. Djordjevic and J. Auvinen, Phys. Rev. C **110** (2024) 4, 044906

- DREENA-A is available on http://github.com/DusanZigic/DREENA-A

Phenomenological approach

- Three different $(\eta/s)(T)$ parametrizations have been considered.
- Parameters are adjusted to reproduce low-$p_\perp$ data.
- Temperature profile is generated for each case.
- High-$p_\perp$ predictions found using generalized DREENA-A.
- Compared with high-$p_\perp$ data.

Modeling the bulk evolution

- Initial entropy profiles are generated using TRENTo model.
- 10^4 events for Pb+Pb ($\sqrt{s} = 5.02$ TeV) and Au+Au ($\sqrt{s} = 200$ GeV) collisions.
- Initial free streaming is not preferred by high-$p_\perp$ data.

  S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Phys. Rev. C 105 (2022) 2, L021901

- Onset time for hydrodynamics: $\tau_0 = 1fm$.

  S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and M. Djordjevic, Phys. Rev. C 105 (2022) 2, L021901

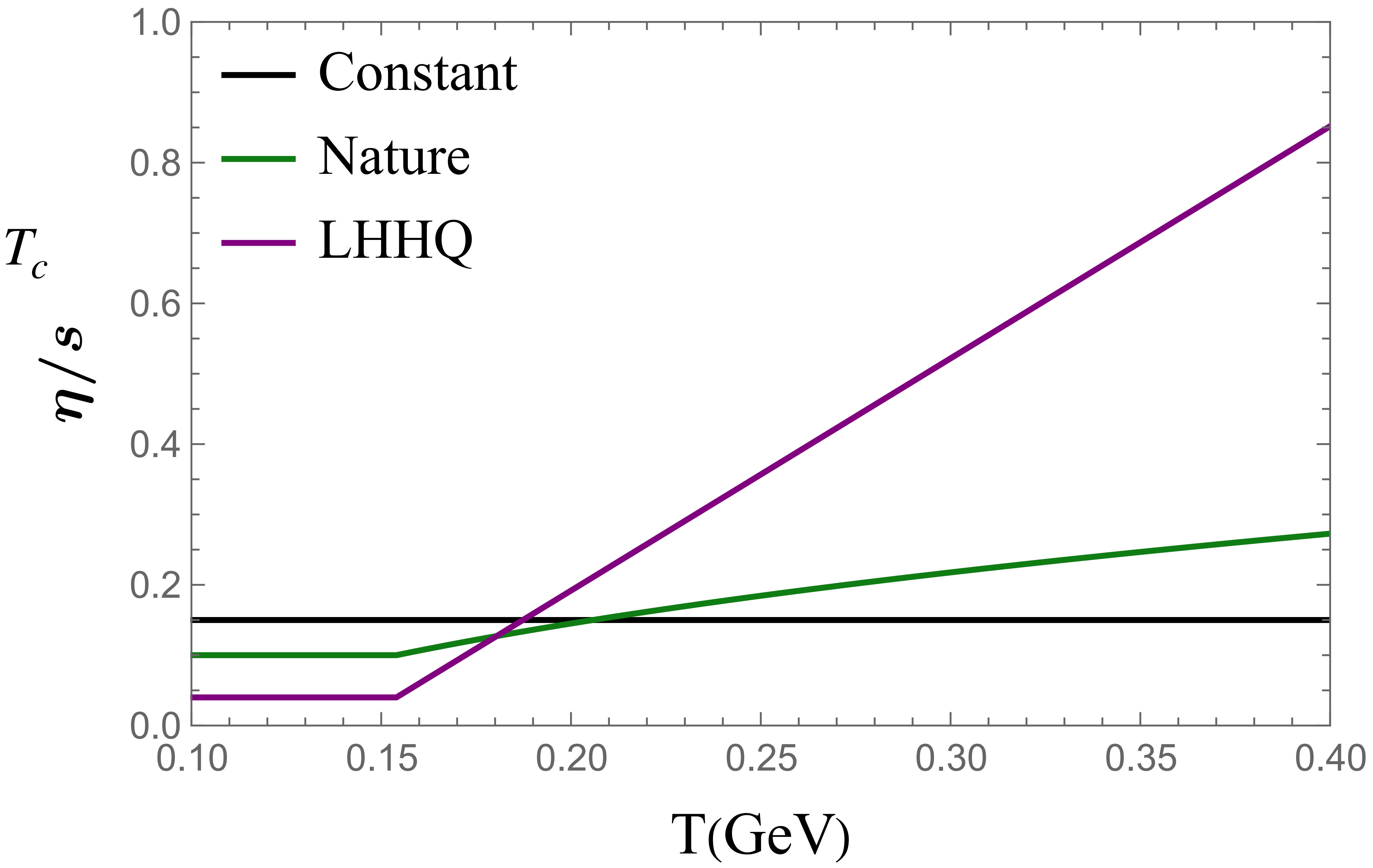
- (2+1)-dimensional fluid dynamical model (VISHNew) + UrQMD

Temperature dependence of η/s

$$(\eta/s)(T) = \begin{cases} (\eta/s)_{\text{min}}, & T < T_c, \\ (\eta/s)_{\text{min}} + (\eta/s)_{\text{slope}}(T - T_c)\left(\dfrac{T}{T_c}\right)^{(\eta/s)_{\text{crv}}}, & T > T_c \end{cases}$$

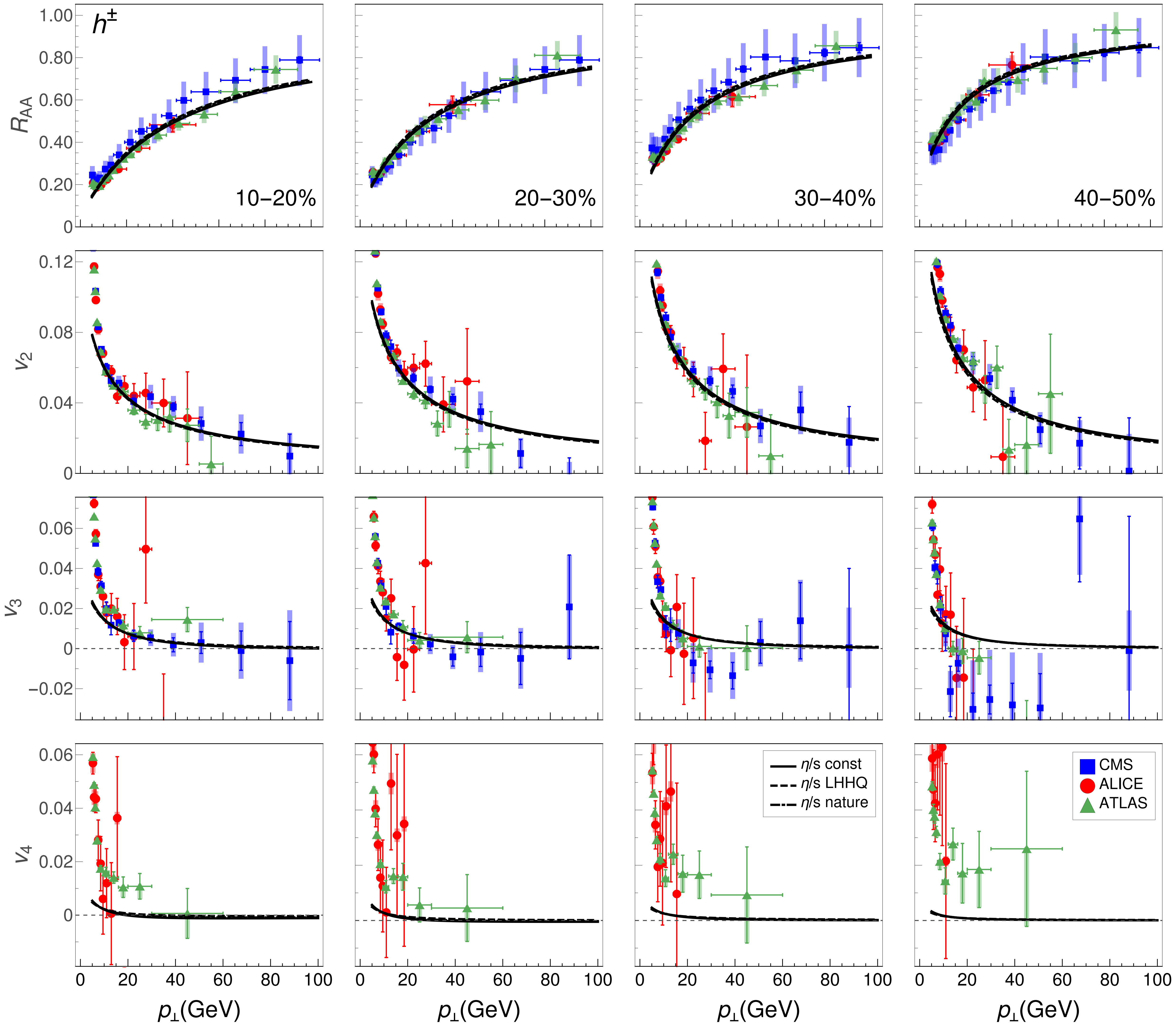
Nature: Nature Phys. 15, no. 11, 1113-1117 (2019)

LHHQ: Phys. Rev. Lett. 106, 212302 (2011)



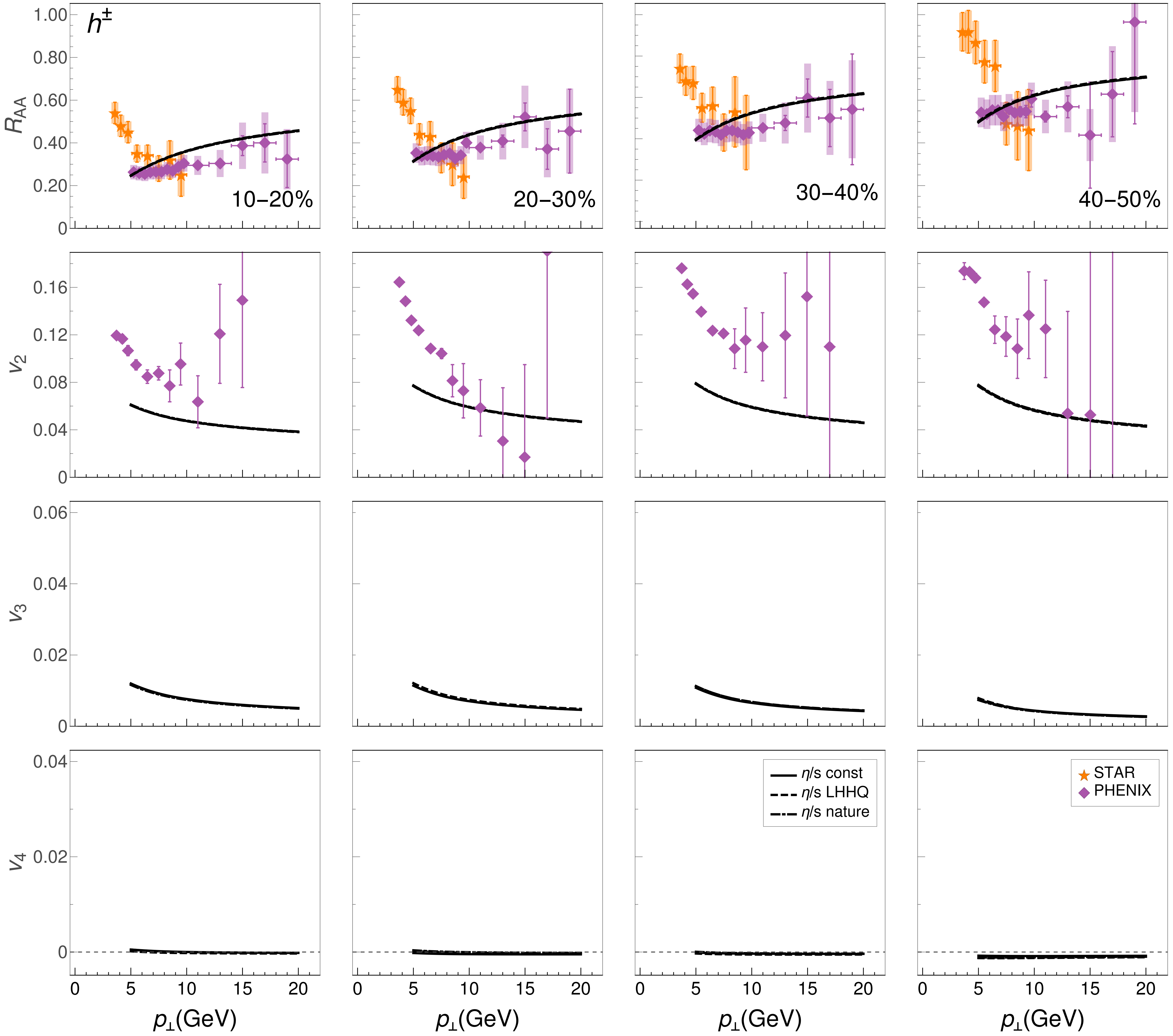
- Pion, kaon, proton multiplicities and $v_2\{4\}$ are reproduced by varying the TRENTo normalization factor for three η/s parametrizations.

Results



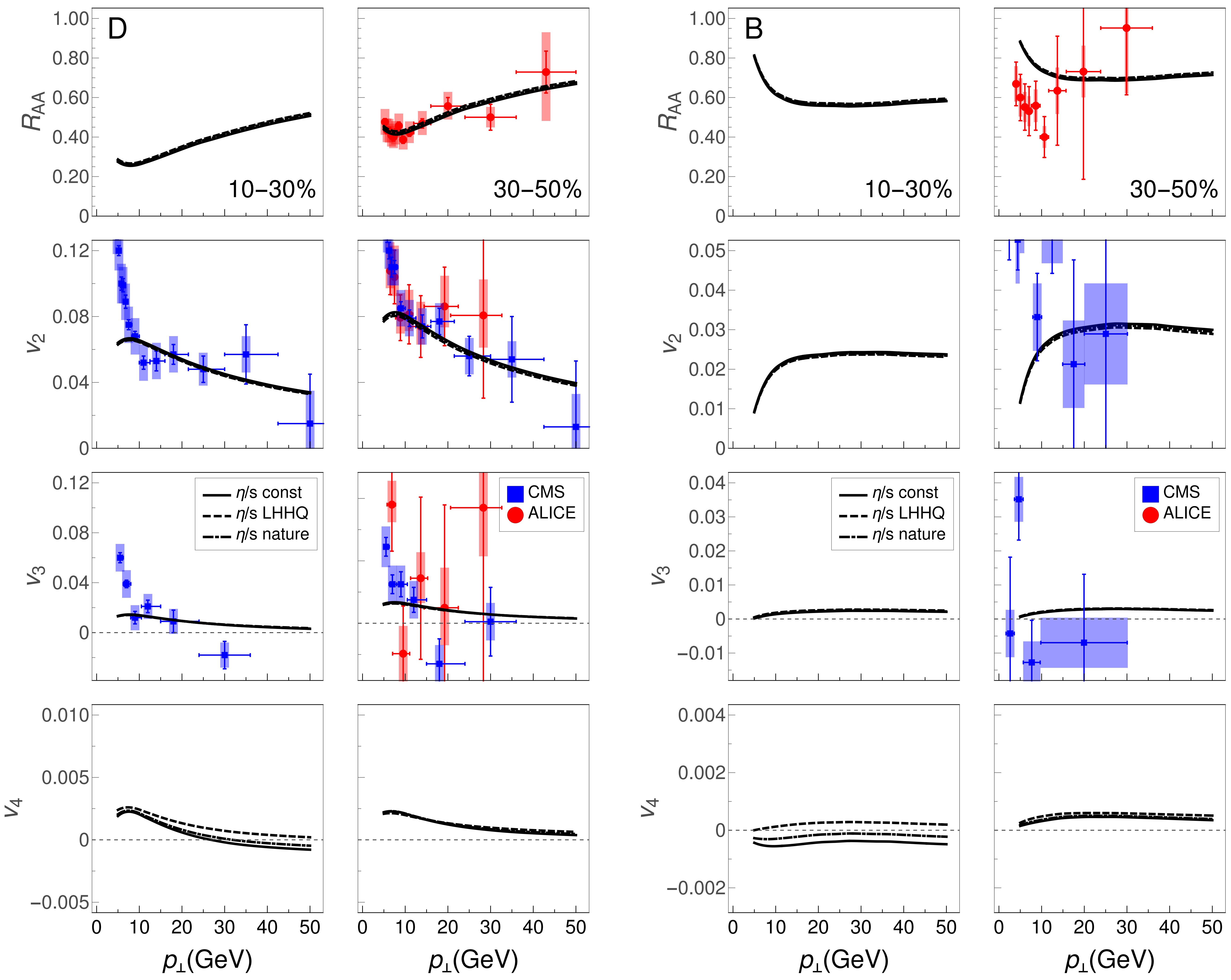
$$\mathrm{Pb} + \mathrm{Pb}\ (\sqrt{s} = 5.02 TeV)$$

Results

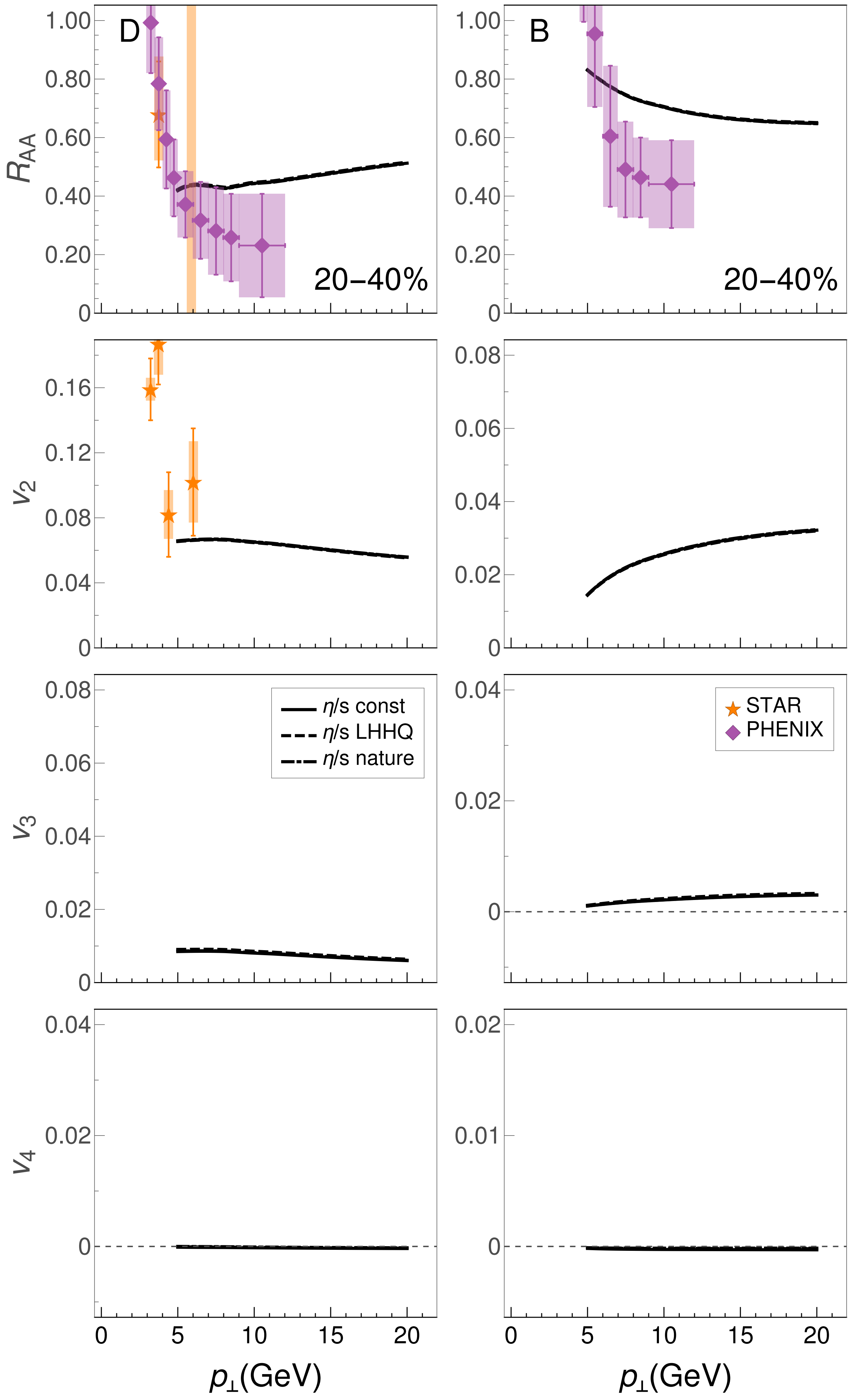


$$\mathrm{Au + Au}\ (\sqrt{s} = 200 GeV)$$

Results



Pb + Pb ($\sqrt{s} = 5.02TeV$)



Au + Au ($\sqrt{s} = 200GeV$)

Theoretical approach :

Jet transport coefficient from dynamical energy loss formalism

- Jet transport coefficient ($\hat{q}$) ≡ Squared average transverse momentum exchange between the medium and the fast parton per unit length
- Interaction between the parton and medium is characterized by the HTL resummed elastic collision rate:

$$\frac{d\Gamma_{el}}{d^2q} = \frac{C_A}{\pi} T\alpha(ET) \frac{\mu_E^2 - \mu_M^2}{(q^2 + \mu_E^2)(q^2 + \mu_M^2)}$$

- In fluid rest frame:

$$\hat{q} = \int_0^{\sqrt{6ET}} d^2q\, q^2 \cdot \frac{d\Gamma_{el}}{d^2q} = C_A T \frac{4\pi}{(11 - \frac{2}{3}n_f)} \frac{\left(\mu_E^2 \ln\left[\frac{6ET + \mu_E^2}{\mu E^2}\right] - \mu_M^2 \ln\left[\frac{6ET + \mu_M^2}{\mu_M^2}\right]\right)}{\ln(\frac{ET}{\Lambda^2})}$$

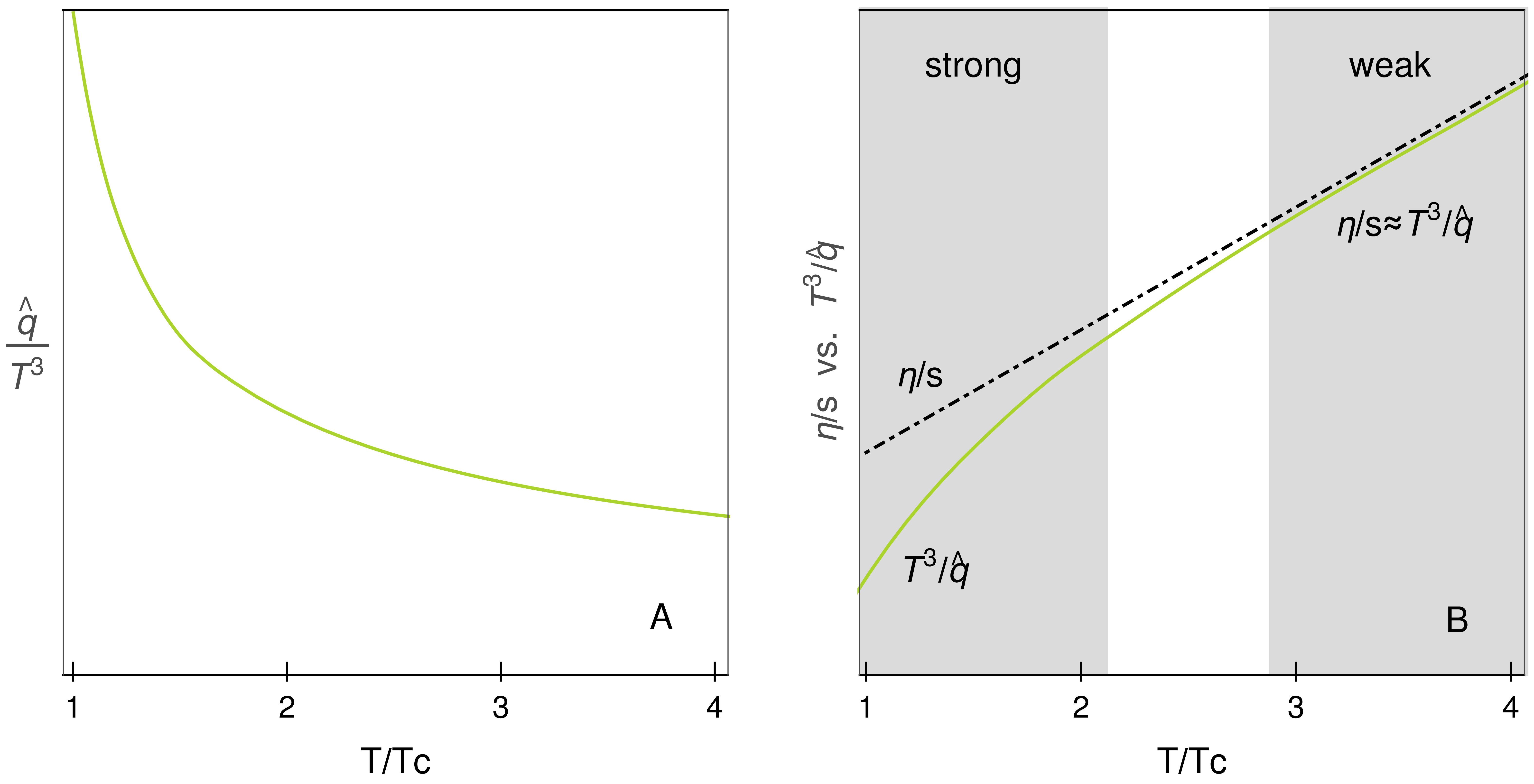
- In weakly coupled limit:

$$\eta/s \approx 1.25T^3/\hat{q}$$

Phys. Rev. Lett. 99 192301 (2007), Phys. Rev. D 104, L071501 (2021)

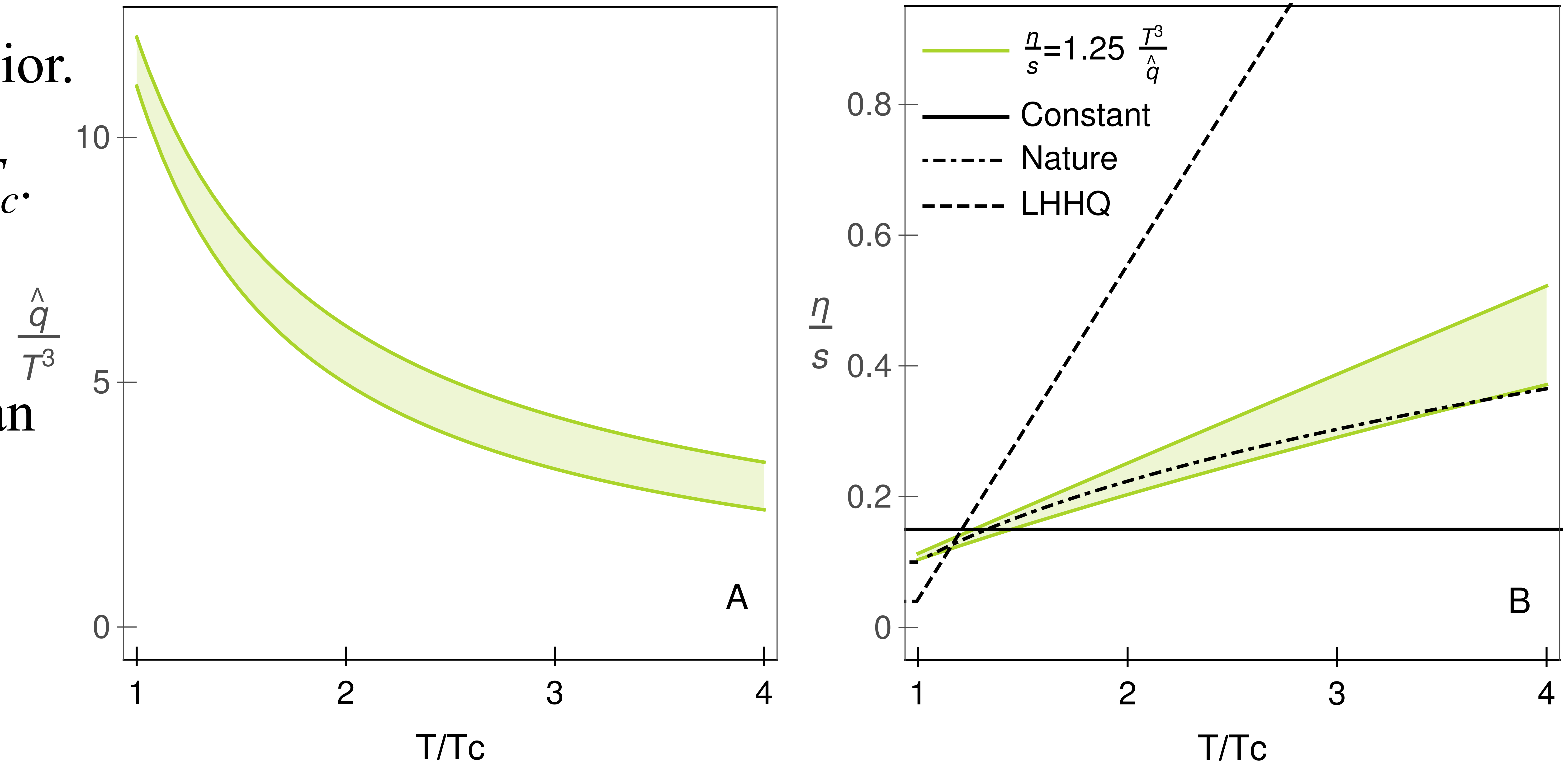
η/s from jet transport coefficient

- $\hat{q}$ quantifies the parton coupling strength in the medium
- $\hat{q}/T^3$ must rise rapidly near T_c from above.
- Our formalism valid in weakly coupled regime.
- $T^3/\hat{q}$ and η/s should agree in the weak coupling regime.
- Soft-to-hard boundary



η/s from jet transport coefficient

- $\hat{q}/T^3$ shows expected behavior.
- Enhanced quenching near T_c.
- η/s is surprisingly close to the constraints from Bayesian analysis.

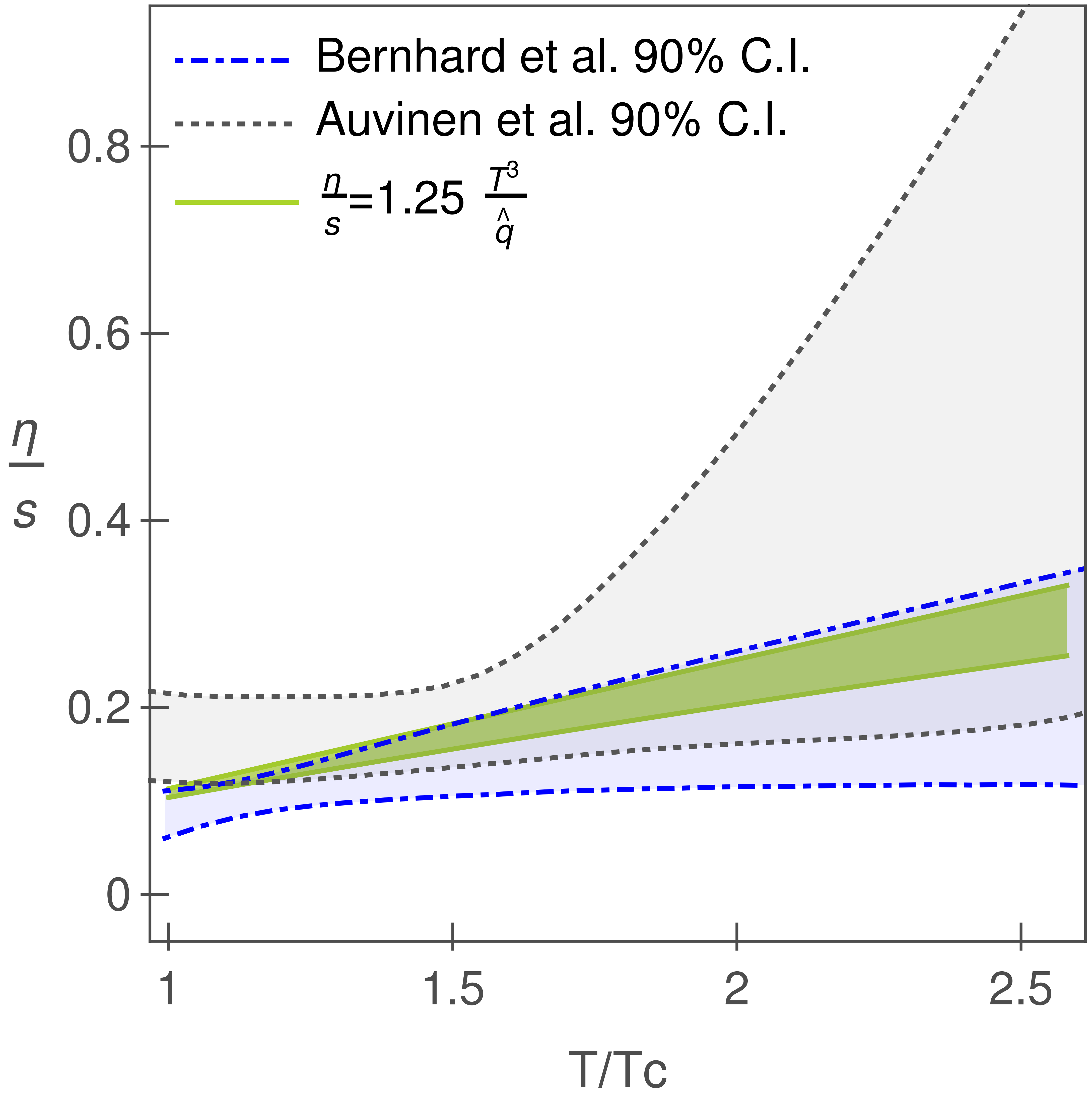


η/s from jet transport coefficient

- Uncertainty due to initial jet energy is very small
- Surprisingly close to the parametrization inspired by the Bayesian analysis.
- Does not drop significantly below the inferred η/s values near T_c .
- No soft-to-hard boundary.

Blue → Nature Phys. 15, no. 11, 1113-1117 (2019)

Black → Phys. Rev. C 102, 044911 (2020)



Summary

- We use generalized DREENA-A to compute high-$p_\perp$ energy loss.
- In the phenomenological approach:
    - Three different $(\eta/s)(T)$ parametrizations have been considered.
    - The predictions from the generalized DREENA-A for three η/s scenarios lead to plots that are almost indistinguishable.
- In the theoretical approach:
    - Jet transport coefficient and jet quenching strength are calculated from the dynamical energy loss formalism.
    - η/s shows surprisingly good agreement all the way to T_c with constraints extracted from existing Bayesian analyses. Provides much smaller uncertainties at high temperatures.
    - No guidance on locating soft-to-hard boundary.

Extreme QCD 2025

- **Dates:** July 2 – 4, 2025
- **Venue**: University of Wroclaw,
  Wroclaw, Poland
- **Student support:** fee, travel,
  accommodation
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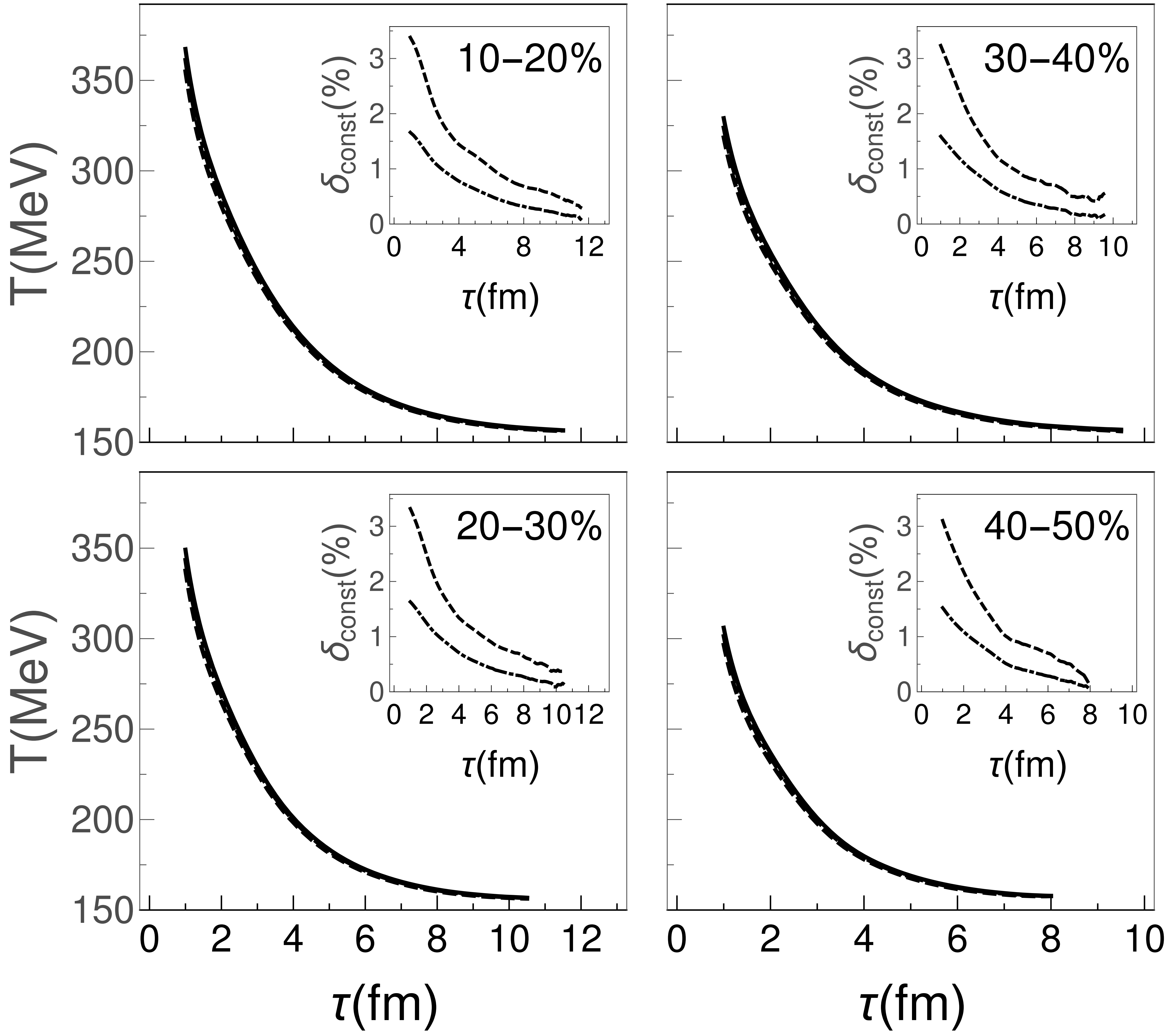
Average jet perceived temperature

BK, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and M. Djordjevic arXiv:2305.11318

- Pb + Pb $\sqrt{s} = 5.02$ TeV
- Full = LHHQ; DotDashed = Nature,
  Dashed = Constant
- Inset: Dotdashed = Nature,
  Dashed = LHHQ
- Temperature difference during evolution
  is very small.
- Insufficient to lead to observable difference
  in the results.



- Mass of light quark $M = \mu_E/6$
- Mass of charm and bottom quark 1.2 GeV and 4.75 GeV
- Gluon mass $m_g = \mu_E/\sqrt{2}$
- $\mu_M/\mu_E = 0.6$
- $\Lambda_{QCD} = 0.2 GeV$
  - Constant η/s (0.15 for Pb+Pb and 0.12 for Au+Au collision)
  - Nature: $(\eta/s)_{\text{min}} = 0.1, (\eta/s)_{\text{slope}} = 1.11, (\eta/s)_{\text{crv}} = -0.48$
  - LHHQ: $(\eta/s)_{\text{min}} = 0.04, (\eta/s)_{\text{slope}} = 3.30, (\eta/s)_{\text{crv}} = 0$
- Bulk viscosity parametrized as $(\zeta/s)(T) = \dfrac{(\zeta/s)_{\text{max}}}{1 + \left(\frac{T - T_0}{(\zeta/s)_{\text{width}}}\right)^2}$ with $(\zeta/s)_{max} = 0.03$, $(\zeta/s)_{width} = 0.022$ and $T_0 = 0.183 GeV$.