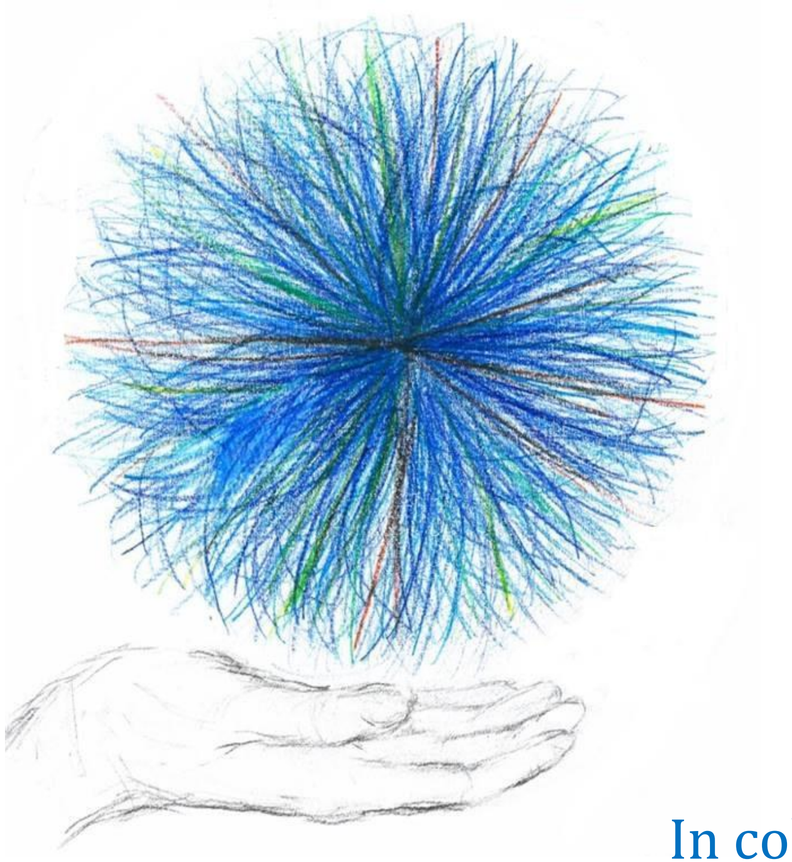


Constraining η/s through high-$p_\perp$ QGP tomography

Magdalena Djordjevic, IPB

In collaboration with: Bithika Karmakar, Dusan Zigic, Jussi Auvinen, Igor Salom, Marko Djordjevic, and Pasi Huovinen

erc European Research Council

МИНИСТАРСТВО ПРОСВЕТЕ, НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

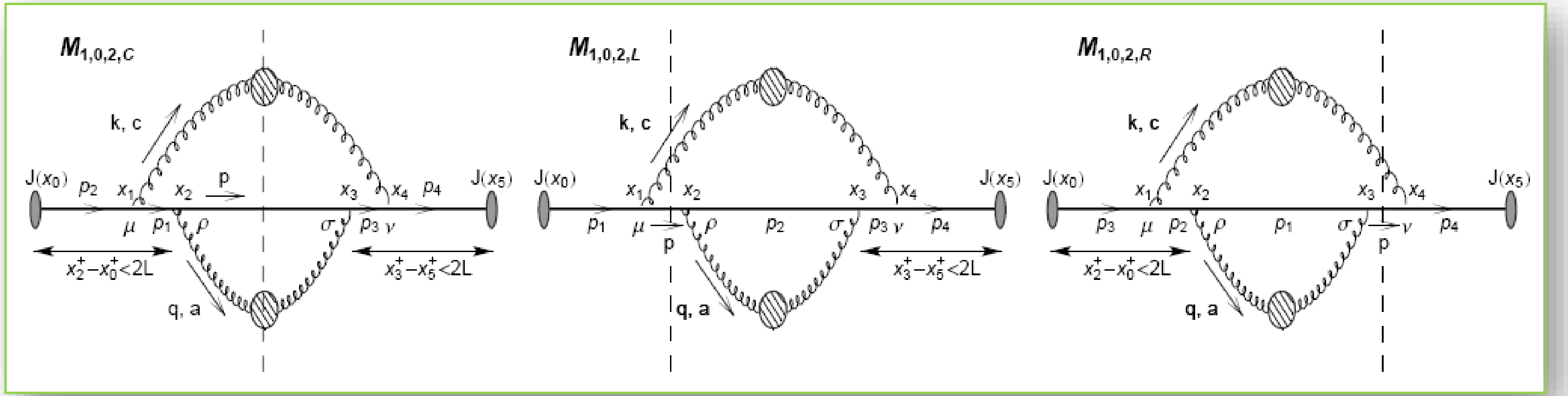
Motivation

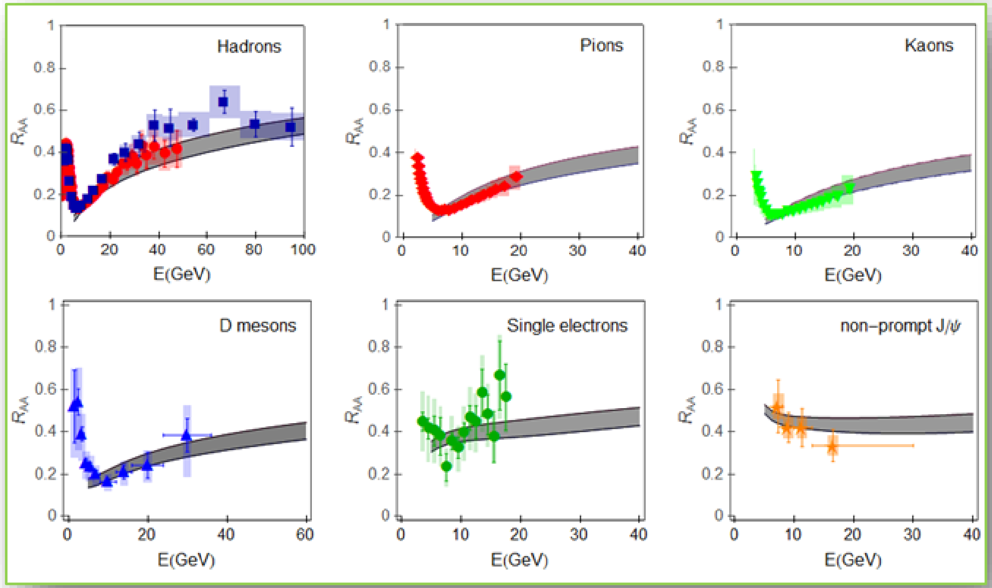
- Energy loss of high-pt light and heavy particles traversing the QCD medium is an excellent probe of QGP properties.
- Theoretical predictions can be compared with a wide range of data from different experiments, collision systems, collision energies, centralities, and observables.
- Can be used with low-pt theory and experiments to study the properties of created QCD medium, i.e., for precision QGP tomography.

The dynamical energy loss formalism

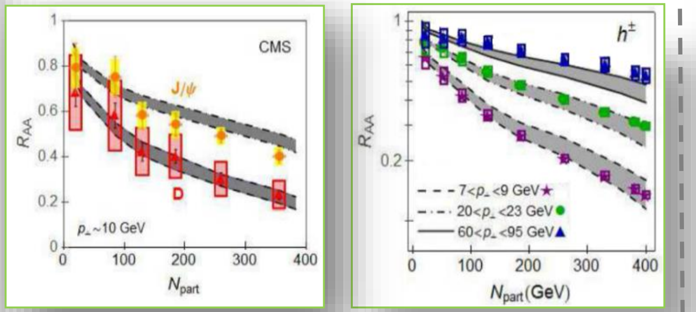
Has the following unique features:

- *Finite size finite temperature* QCD medium of *dynamical* (moving) partons.
- Based on finite T field theory and generalized HTL approach.
- Same theoretical framework for both radiative and collisional energy loss.
- Applicable to both light and heavy flavor.
- Finite magnetic mass effects (M. D. and M. Djordjevic, PLB 709:229 (2012))
- Running coupling (M. D. and M. Djordjevic, PLB 734, 286 (2014)).
- Relaxed soft-gluon approximation (B. Blagojevic, M. D. and M. Djordjevic, PRC 99, 024901, (2019)).
- Included higher-order in opacity effects (S. Stojku, B. Ilic, I. Salom, MD, PRC in press, (2023)).
- No fitting parameters in the model.
- Temperature as a natural variable in the model.

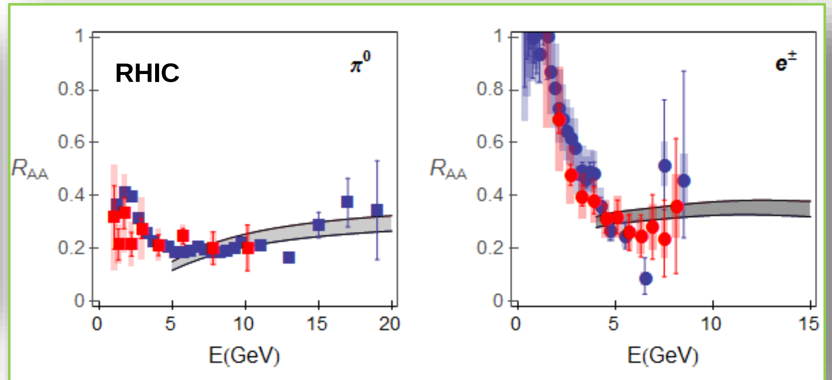


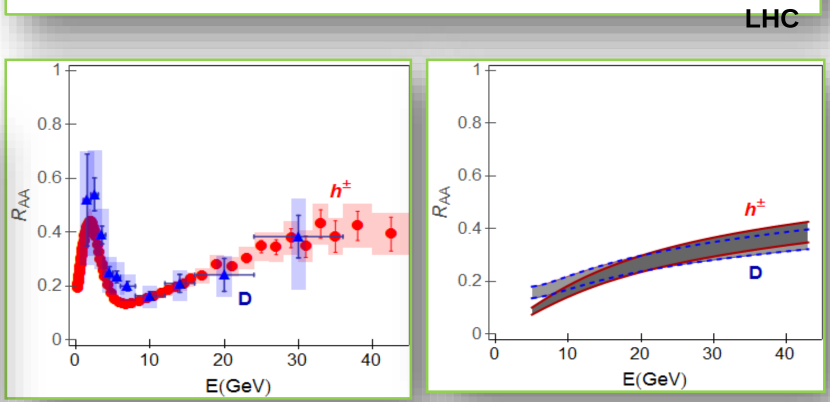


Explains high-pt R_{AA} data for different probes, collision energies, and centralities.



Resolved the longstanding “heavy flavor puzzles at RHIC and LHC”.

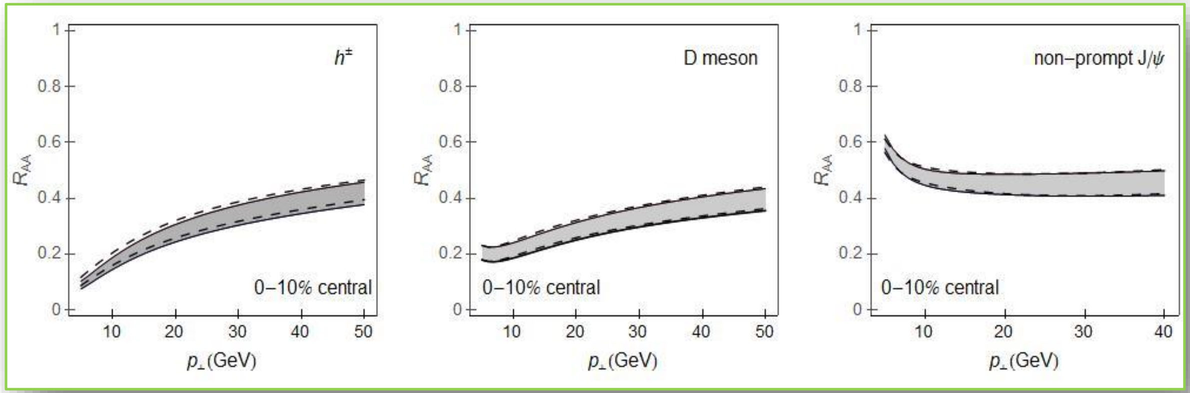


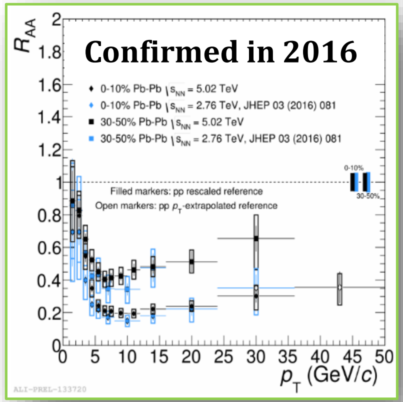


M.D., PRL 112, 042302 (2014)

Clear predictive power!

M.D. et al., PRC 92 (2015)

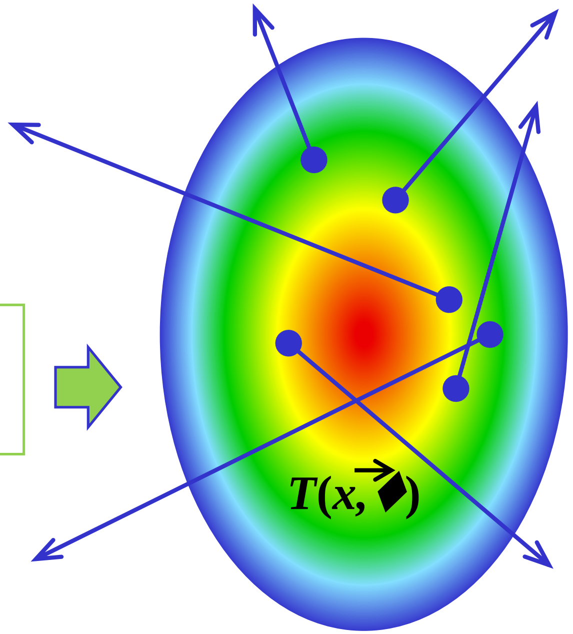




A realistic description for parton-medium interactions! → Suitable for QGP tomography!

The main idea behind high-pt QGP tomography

When high-pt particles go through QGP, they lose energy.



This energy loss is sensitive to QGP properties.

We can realistically predict this energy loss.

High-pt probes are powerful tomographic tools.

Use them to infer some bulk QGP properties.

DREENA-A framework as a QGP tomography tool

To use high pt data/theory to explore the bulk QGP:

- Include any, arbitrary, medium evolution as an input.
- Preserve all dynamical energy loss model properties.
- Develop an efficient (timewise) numerical procedure.
- Generate a comprehensive set of light and heavy flavor predictions.
- Compare predictions with the available experimental data.
- If needed, iterate a comparison for different combinations of QGP medium parameters.
- Extract medium properties consistent with both low and high-pt theory and data.

Develop fully optimized DREENA-A framework.

DREENA: Dynamical Radiative and Elastic ENergy loss Approach; A: Adaptive temperature profile.

D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic Front.in Phys. 10 (2022) 957019

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

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

(Details in talk by Dusan Zigic, Wednesday).

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

- Low-$p_\perp$ observables are widely used to explore the bulk QGP properties.
- The QGP η/s has been extensively investigated in heavy-ion collision experiments.
- η/s is well constrained by Bayesian analysis in the low-$p_\perp$ sector in the temperature range $T_c \lesssim T \lesssim 1.5T_c$, but weakly constrained at larger temperatures.
- High-$p_\perp$ probes also powerful tomography tools, sensitive to global QGP features, e.g., different temperature profiles or initial conditions.
- **Our aim:** put constraints on η/s by analyzing high-$p_\perp$ observables using the DREENA-A and dynamical energy loss.

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

- QGP is expected to behave as a 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 temperatures (hard regime).
- Testing the soft-to-hard hypothesis is difficult: Anisotropy is weakly affected by the η/s at high temperatures.
- High-$p_\perp$ data/theory can serve as a complementary tool.

Constraining η/s through high-pt data

- Three different (η/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.

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).

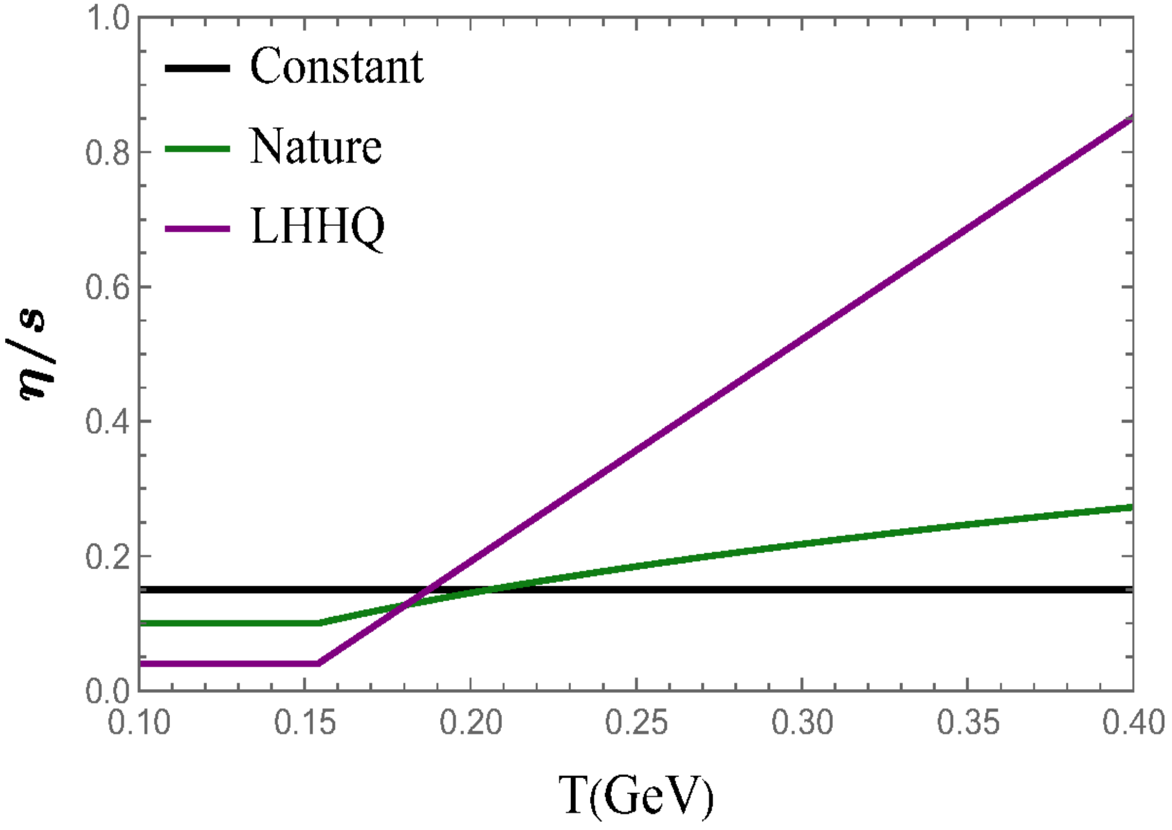
Modeling the bulk evolution

- Initial entropy profiles are generated using TRENTo model.
- 10^4 events for Pb+Pb (5.02 TeV) and Au+Au (200 GeV).
- Events sorted in centrality classes.
- Initial free streaming is not preferred by high-$p_\perp$ data.
  S. Stojku, J.Auvinen, M. Djordjevic, P.Huovinen and MD, Phys. Rev. C 105 (2022) 2, L021901
- Onset time for hydrodynamics: $\tau_0 = 1 fm$.
  S. Stojku, J.Auvinen, M. Djordjevic, P.Huovinen and MD, Phys. Rev. C 105 (2022) 2, L021901
- (2+1)-dimensional fluid dynamical model (VISHNew) used to simulate the medium evolution.

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).

Temperature dependence of η/s

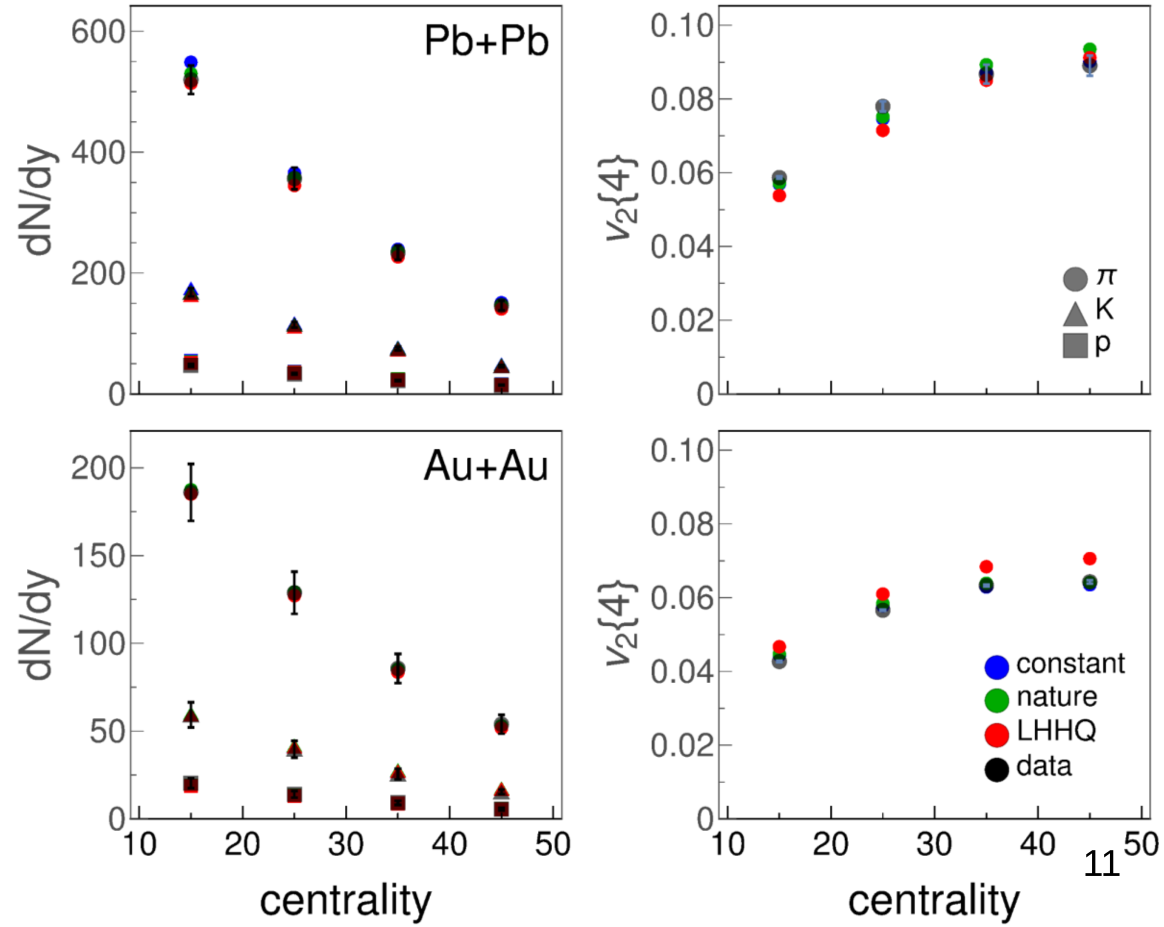
Three different parameterizations:



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

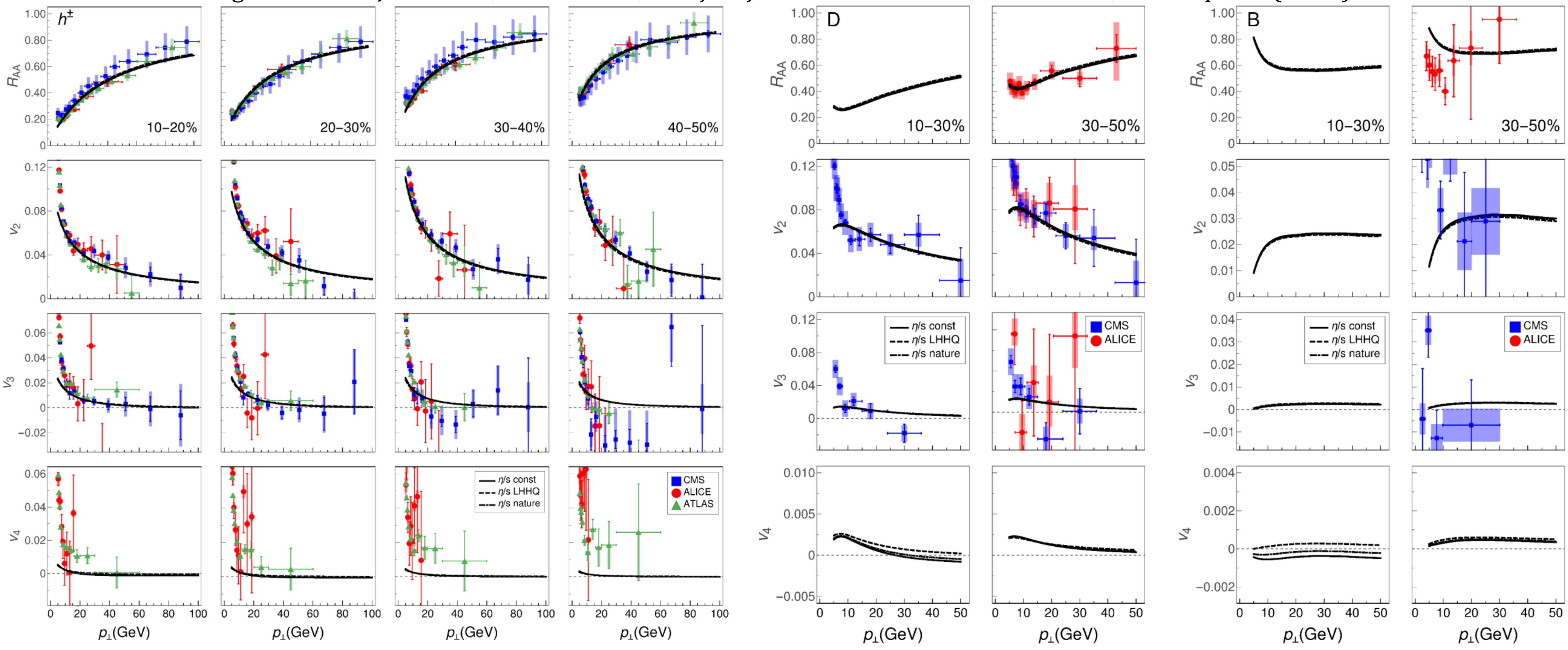
LHHQ: Phys. Rev. Lett. 106, 212302 (2011)

Pion, kaon, proton multiplicities, and $v2\{4\}$ are reproduced by varying the TRENTo normalization factor for three η/*s* parametrizations.



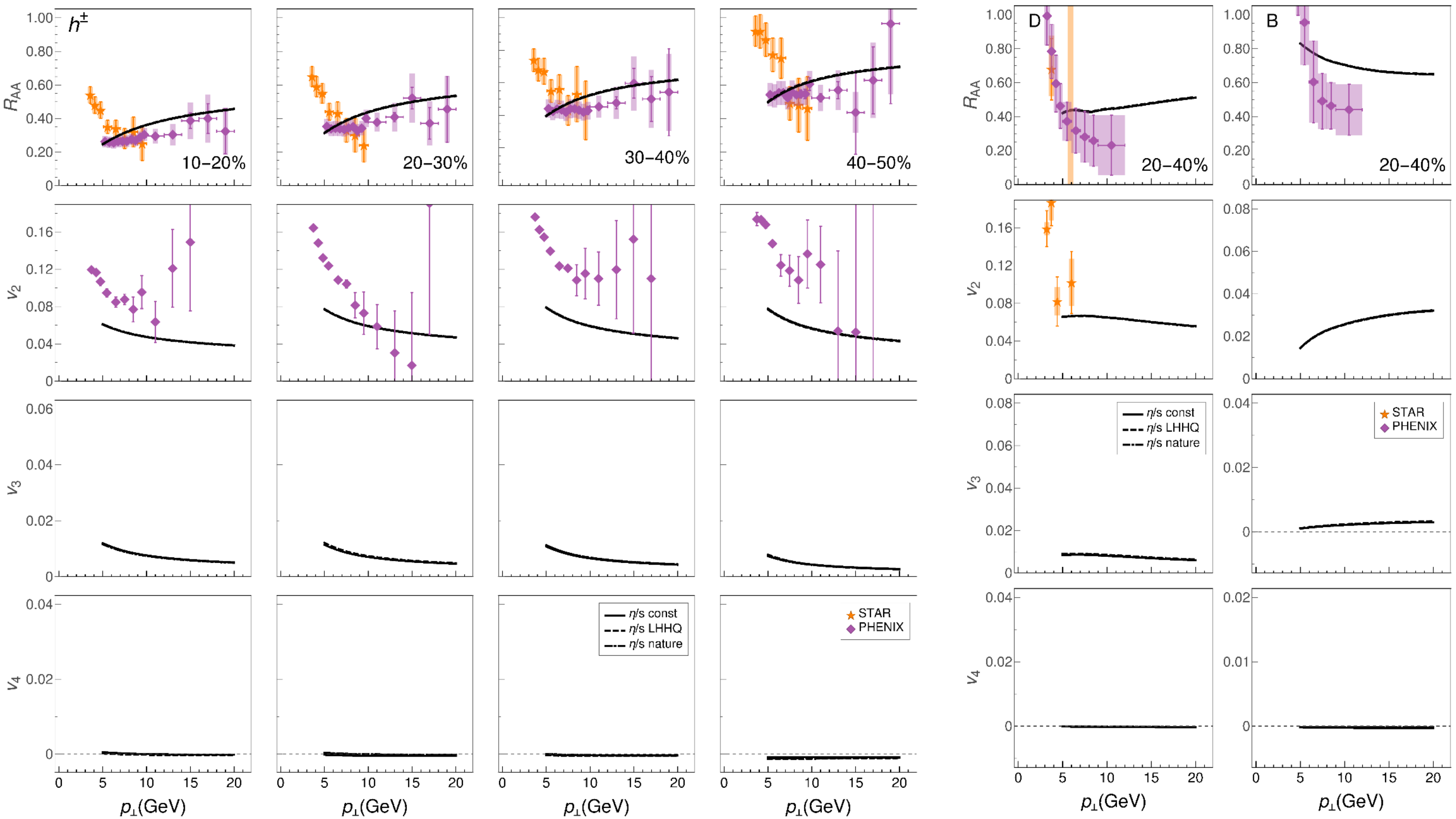
ebeDREENA predictions for light and heavy flavor - LHC

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).



Weak dependence on η/s

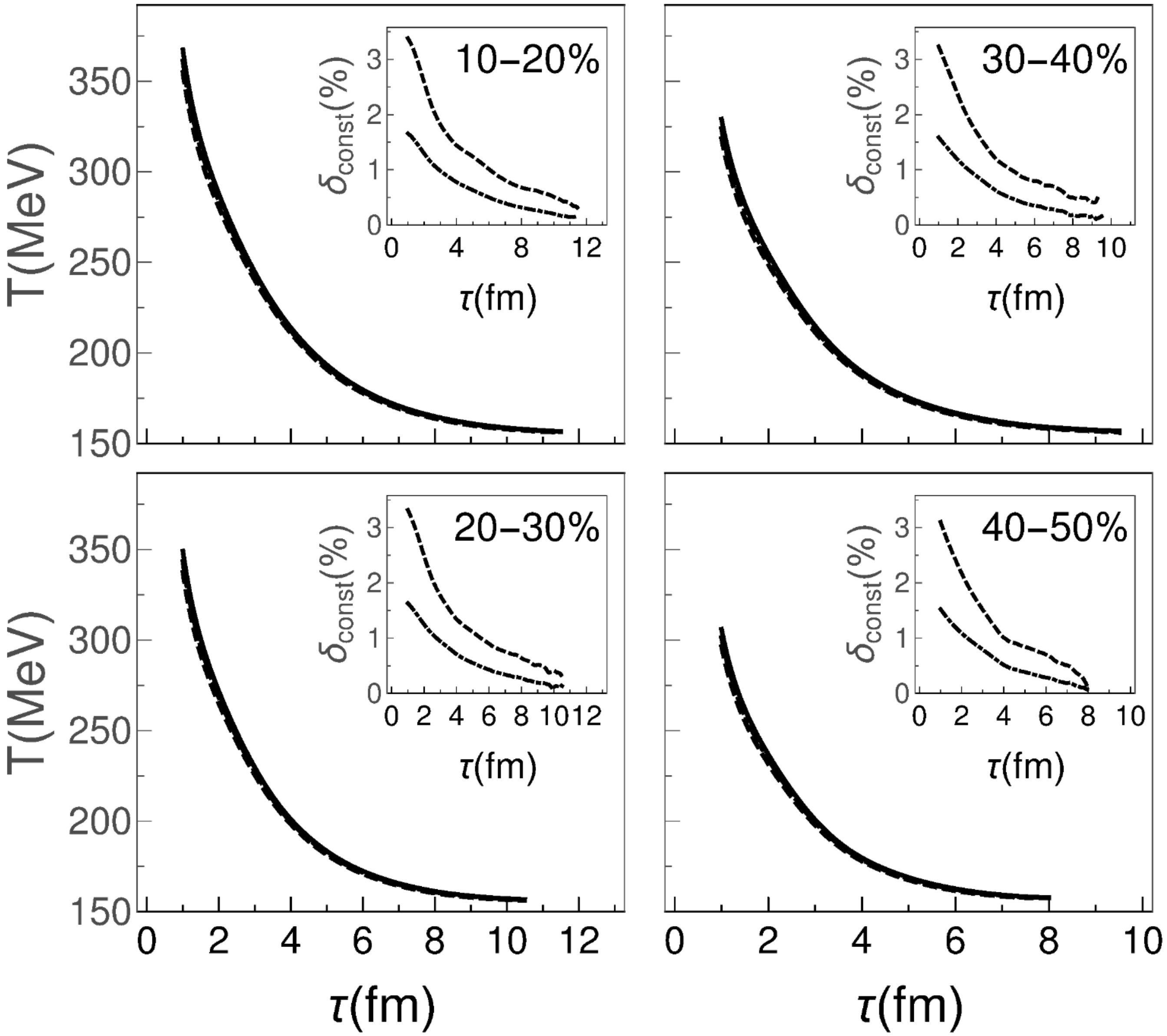
ebeDREENA predictions for light and heavy flavor - RHIC



Weak dependence on η/s

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).

Average jet perceived temperature



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.

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).

Constraining η/s from the dynamical energy loss $\hat{q}$

Dynamical energy loss:

Capable of accurately reproducing observed R_{AA} without fitting parameters.

Can adequately describe interactions between high-pt particles and the QCD medium.

Reasonable to estimate (η/s)(T) theoretically using the dynamical energy loss model.

Need to estimate the jet quenching parameter $\hat{q}$.

Crucial for assessing interaction strength between jet partons and nuclear matter.

Quantifies the transverse momentum broadening of fast parton due to its elastic scatterings with the medium.

Valuable tool for various purposes:

- Insight into jet quenching phenomena.
- Estimation of bulk medium property (η/s).
- In a weakly coupled limit: $\eta/s \approx 1.25 \frac{T^3}{\hat{q}}$.

Derivation of $\hat{q}$

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).

- In dynamical perturbative QCD medium, the interaction between high-pt partons and QGP constituents can be characterized by:

$$\frac{d\Gamma_{el}}{d^2q} = 4C_A\left(1+\frac{nf}{6}\right)T^3\frac{\alpha_s^2}{q^2\left(q^2+\mu_E^2\right)}$$

- After including running coupling and finite magnetic mass, the elastic collision rate becomes:

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

- Debye mass is obtained by self consistently solving the following equation (W-Lambert function (Peshier, hep-ph/0601119):

$$\mu_E^2 = \left(1+\frac{n_f}{6}\right)4\pi\alpha\left(\mu_E^2\right)T^2$$

$$\mu_E = \sqrt{\Lambda^2\frac{\xi(T)}{W(\xi(T))}}$$

$$\alpha(t) = \frac{4\pi}{(11-\frac{2}{3}n_f)}\frac{1}{\ln\left(\frac{t}{\Lambda^2}\right)} \qquad \xi(T) = \frac{1+\frac{n_f}{6}}{11-\frac{2}{3}n_f}\left(\frac{4\pi T}{\Lambda}\right)^2$$

Derivation of $\hat{q}$

- In the fluid rest frame:

  Weakly dependent on E!

$$\hat{q} = \int_0^{\sqrt{6ET}} d^2q\, q^2 \cdot \frac{d\Gamma_{el}}{d^2q}$$
$$= C_A T \alpha(ET) \int_0^{6ET} dq^2\, q^2 \left(\frac{1}{q^2+\mu_M^2} - \frac{1}{q^2+\mu_E^2} \right)$$
$$= C_A T \alpha(ET) \left(\mu_E^2 \ln\left[\frac{6ET+\mu_E^2}{\mu E^2}\right] - \mu_M^2 \ln\left[\frac{6ET+\mu_M^2}{\mu_M^2}\right] \right)$$

- In the limit of $ET \to \infty$, reduces to the expression independent of jet energy:

$$\hat{q} = C_A \left(\frac{4\pi}{11 - \frac{2}{3}n_F} \right)^2 \frac{4\pi \left(1+\frac{n_F}{6}\right)}{W(\xi(T))} \left(1 - x_{ME}^2\right) T^3$$

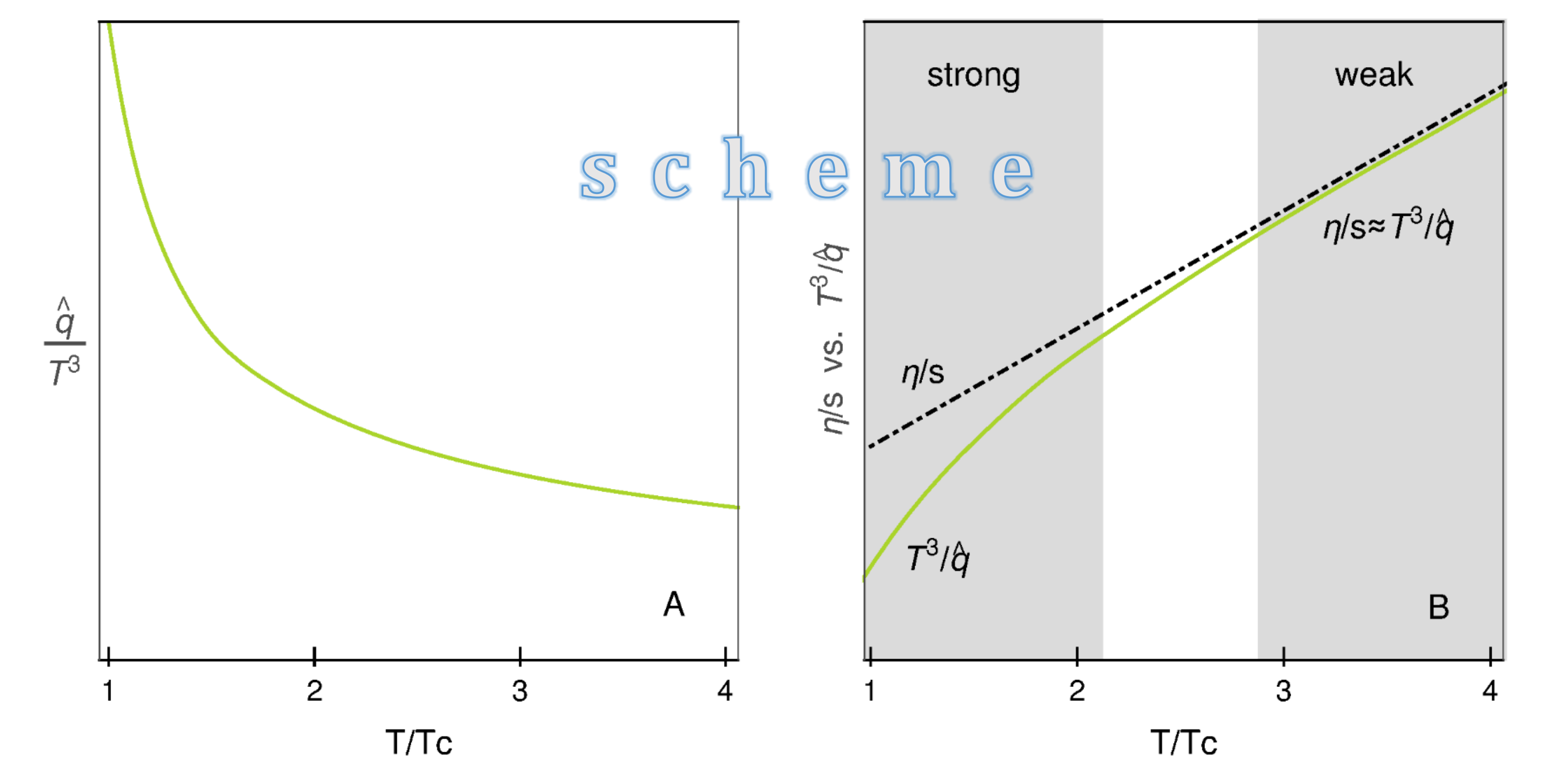
$$x_{ME} = \mu_M / \mu_E$$

- **Expected behavior:** as a property of the medium $\hat{q}$ should be independent (or weakly dependent) on jet energy.

What we expect from previous knowledge?

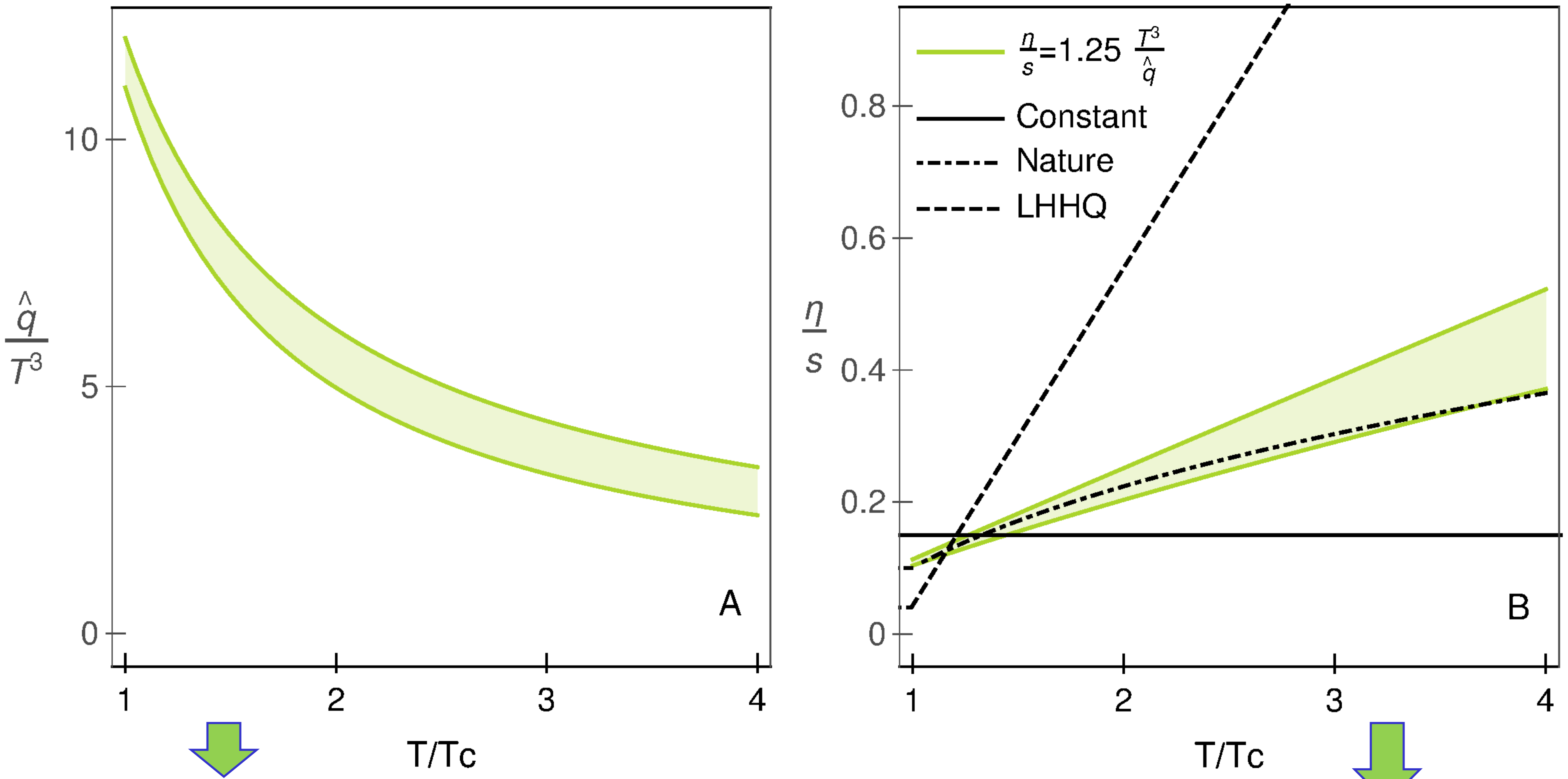
- Sensitive to the coupling strength in QGP: weak coupling enlarges η/s and reduces $\frac{\hat{q}}{T^3}$, and vice versa for strong coupling.
- In the weakly coupled regime (Majumder, Muller, Wang, PRL 99, 2007) $\eta/s \approx 1.25\frac{T^3}{\hat{q}}$.
- A rise in $\frac{\hat{q}}{T^3}$ near T_c is predicted to be essential for explaining high-$p_\perp$ v_2. (Liao&Shuryak, PRL 102, 2009).
- At large T, weakly coupled system.
- Near T_c, strongly coupled limit, and $\frac{T^3}{\hat{q}}$ should significantly deviate from η/s.
- **Soft-to-hard boundary:** the transition region from strong to weak coupling.

η/s and $\frac{\hat{q}}{T^3}$ are key transport coefficients in QGP.



B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).

η/s from the transport coefficient



$\frac{\hat{q}}{T^3}$ shows expected behavior, i.e., enhanced quenching near Tc.

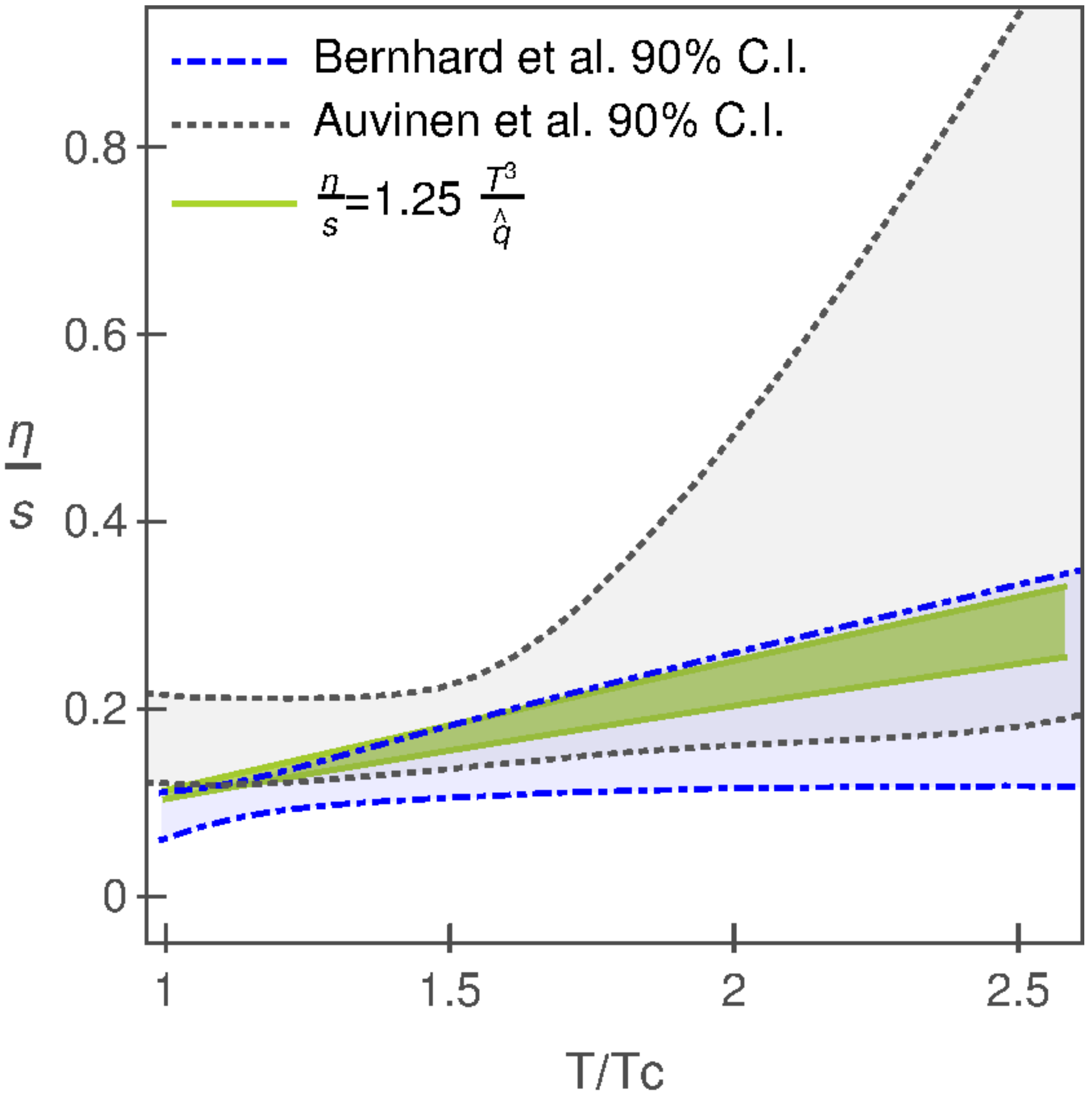
η/s is surprisingly close to the constraints from Bayesian analysis.

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, arXiv:2305.11318, PRC in press (2023).

Comparison with Bayesian analyses

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

Gray: Phys. Rev.C 102,044911 (2020)



- Uncertainty due to initial jet energy is small.
- η/s from $\frac{\hat{q}}{T^3}$ aligns well across the entire temperature range with two state-of-the-art Bayesian analyses, i.e., it falls precisely in the overlap of the two intervals.
- This agreement is surprising, extending even to Tc, where we expect divergence due to strong coupling.
- It is unlikely that the weak coupling regime would extend down to Tc. Instead, it suggests that the quasiparticle picture of QGP is applicable in the entire region.
- No soft-to-hard boundary.

Summary

- Use DREENA-A to generate high-$p_\perp$ predictions based on dynamical energy loss:
  - Different temperature profiles corresponding to various $(\eta/s)(T)$ parametrizations were generated.
  - These profiles were used in the DREENA-A framework to predict R_{AA}, v_2, v_3, and v_4.
  - The difference in high-pt predictions are small, making it challenging to differentiate between various $(\eta/s)(T)$ parametrizations based on experimental data from RHIC and LHC.
- In the theoretical approach:
  - Transport coefficient is 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.
  - Surprising as it extends to the strongly coupled regime near T_c, challenging expectations based on weak coupling approximations.
  - **Intriguing hypothesis:** The quasiparticle picture remains valid at the entire temperature range.
  - This obscures estimation of the soft-to-hard boundary, a major unresolved issue.
- Overall, jet tomography continues to be useful tool for constraining QGP properties.

Canyon of river DREENA in Serbia

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