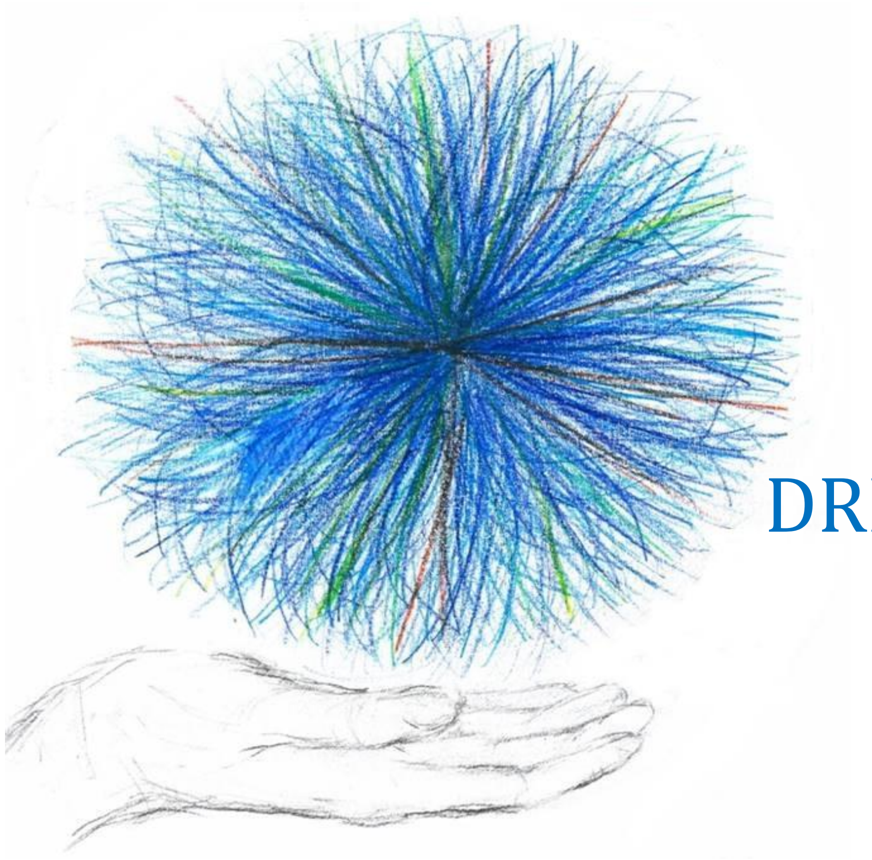


Constraining QGP properties through the DREENA framework with Bayesian inference

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

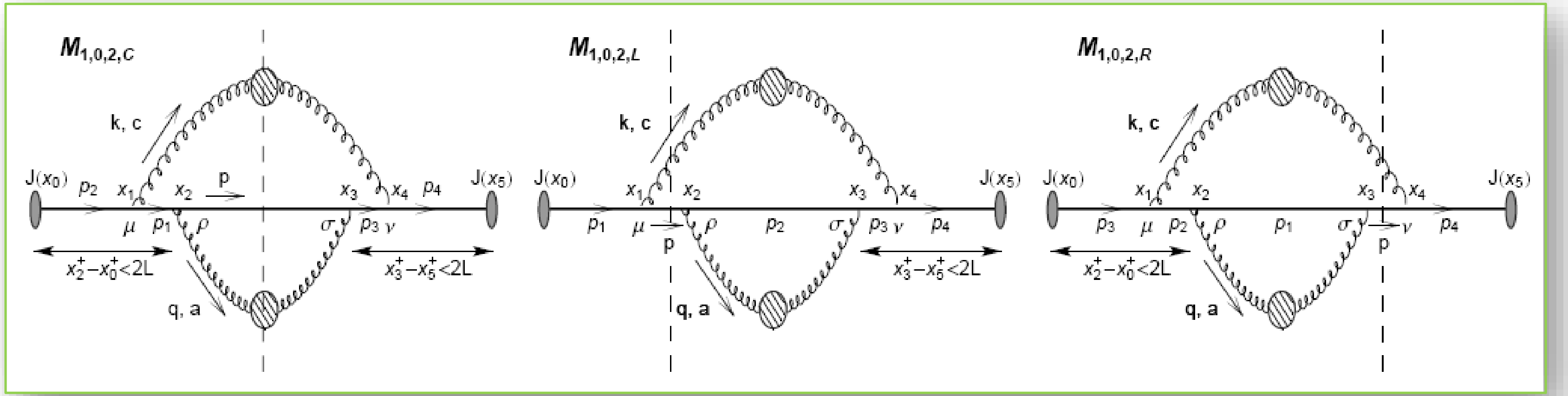
Motivation

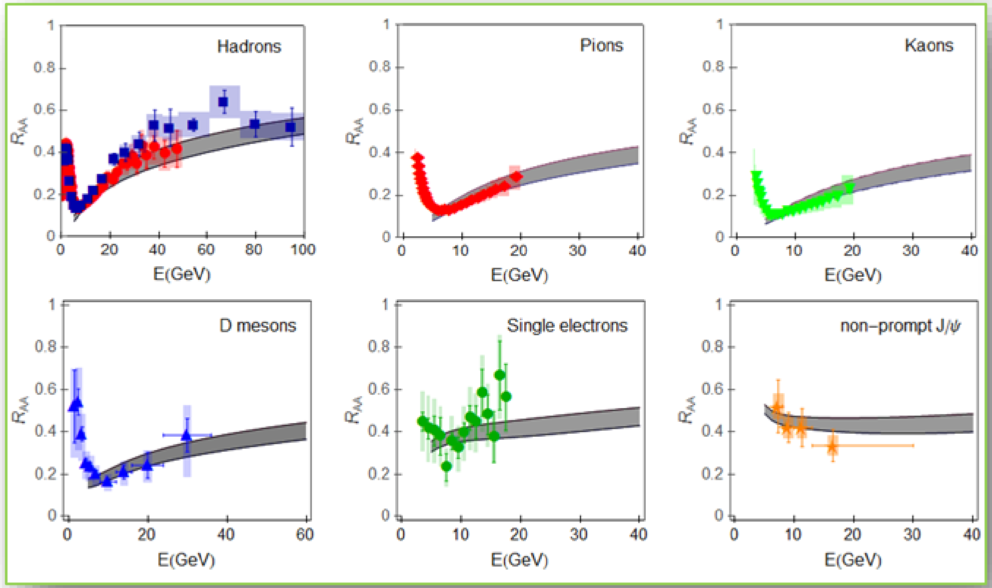
- Energy loss of high-pt light and heavy particles traversing the QCD medium is an excellent probe of QGP properties.
- Theoretical predictions can be compared with a wide range of data from different experiments, collision systems, collision energies, centralities, and observables.
- Can be used with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

The dynamical energy loss formalism

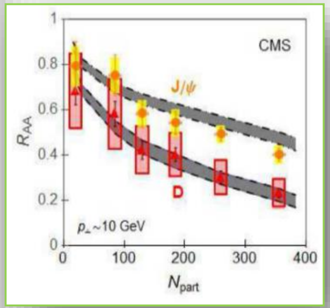
Has the following unique features:

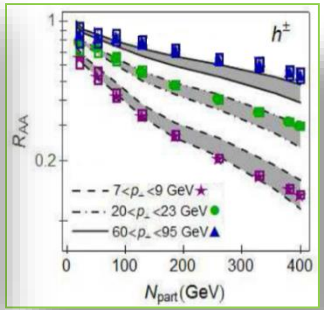
- *Finite size finite temperature* QCD medium of *dynamical* (moving) partons.
- Based on finite *T* field theory and generalized HTL approach.
- Same theoretical framework for both radiative and collisional energy loss.
- Applicable to both light and heavy flavor.
- Finite magnetic mass effects (M. 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.



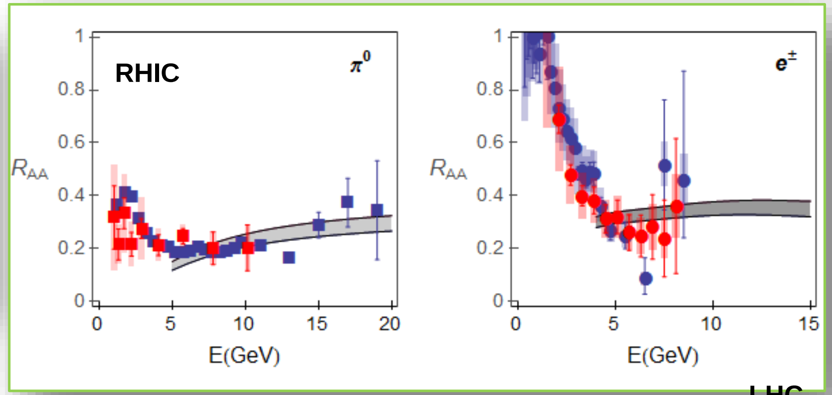


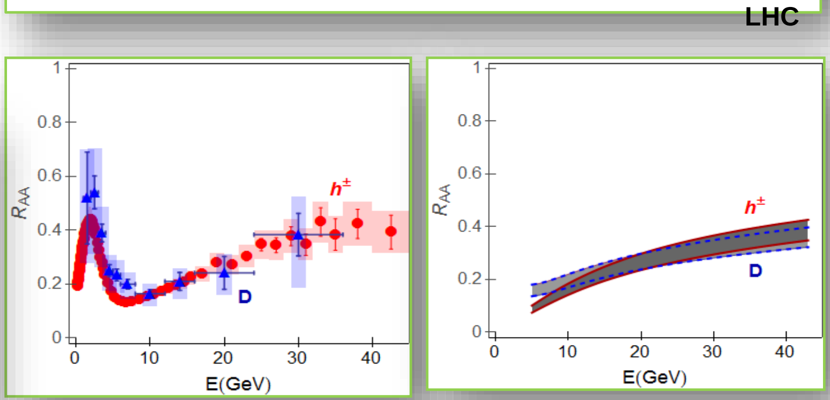
Explains high-pt R_{AA} data for different probes, collision energies, and centralities.





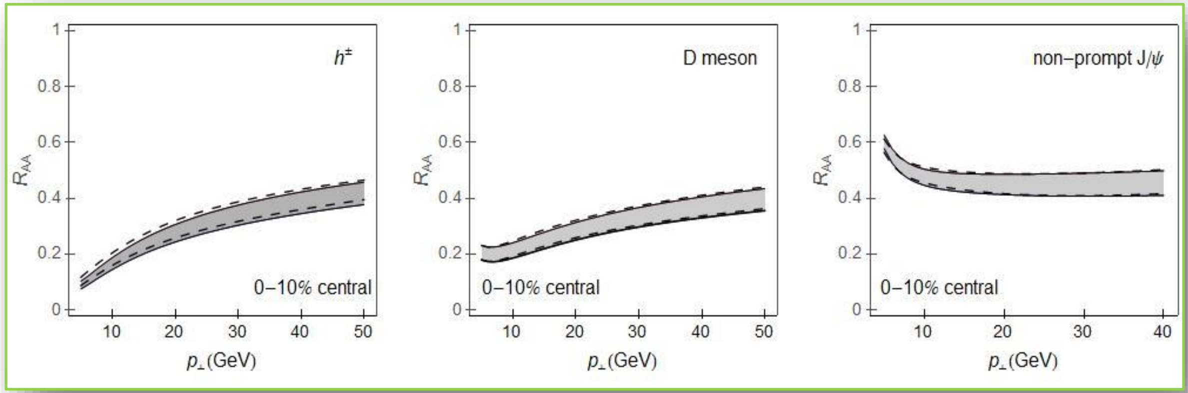
Resolved the longstanding "heavy flavor puzzles at RHIC and LHC".

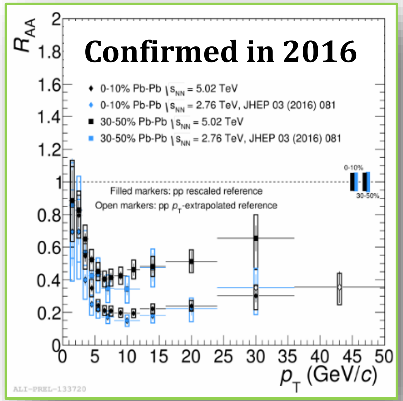




Clear predictive power!

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



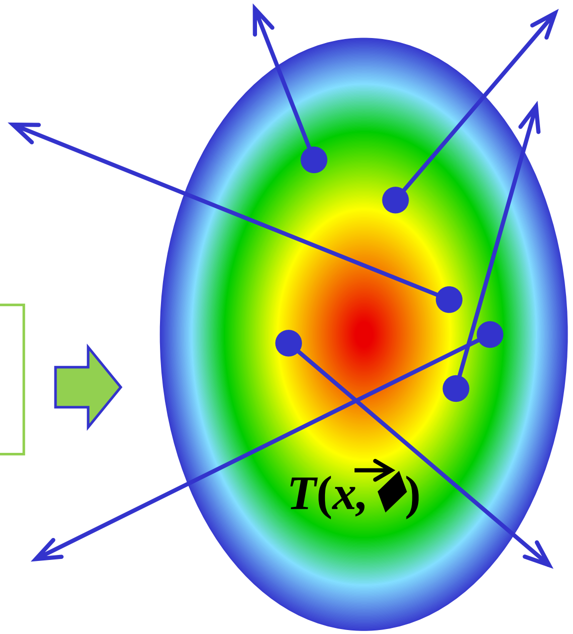


M.D., PRL 112, 042302 (2014)

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

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

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, PRC **108**, 044907 (2023).

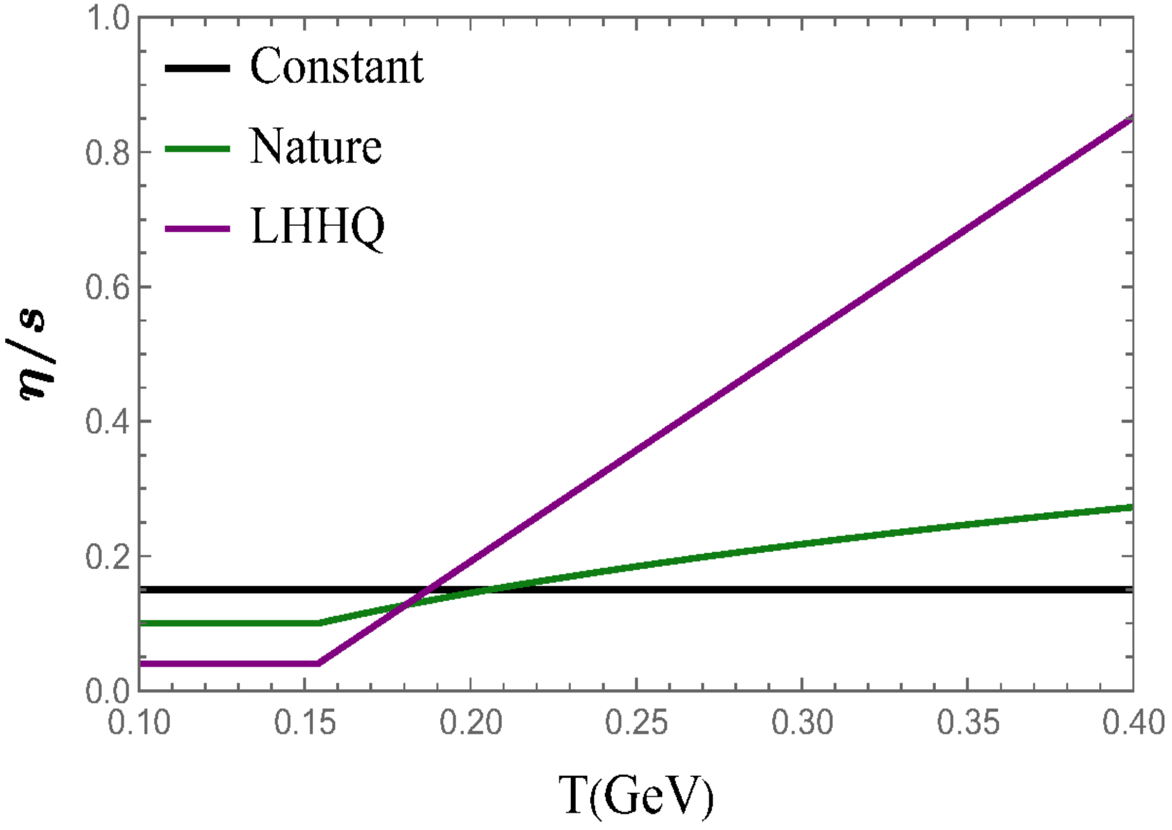
A. Modeling the bulk evolution

- 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, PRC **108**, 044907 (2023).

Temperature dependence of η/s

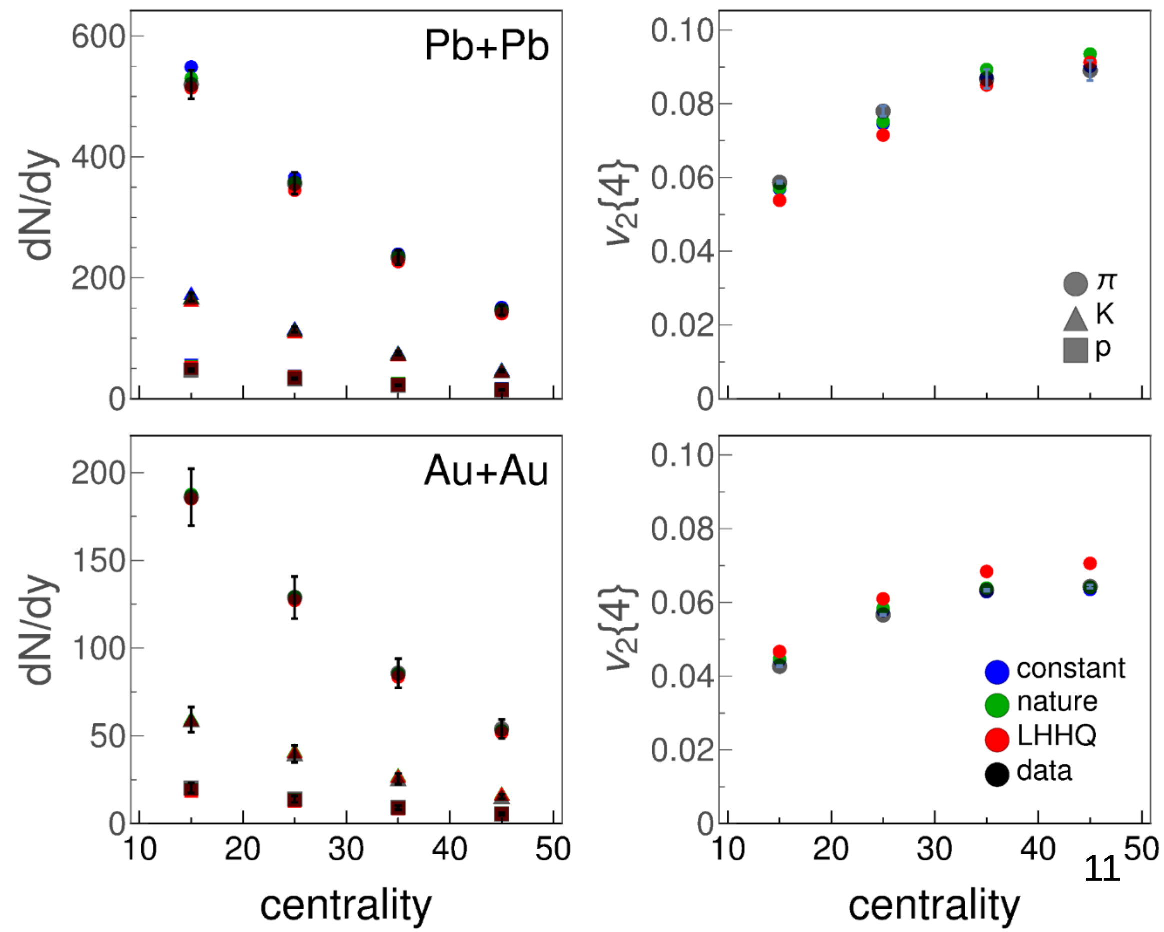
Three different parameterizations:



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

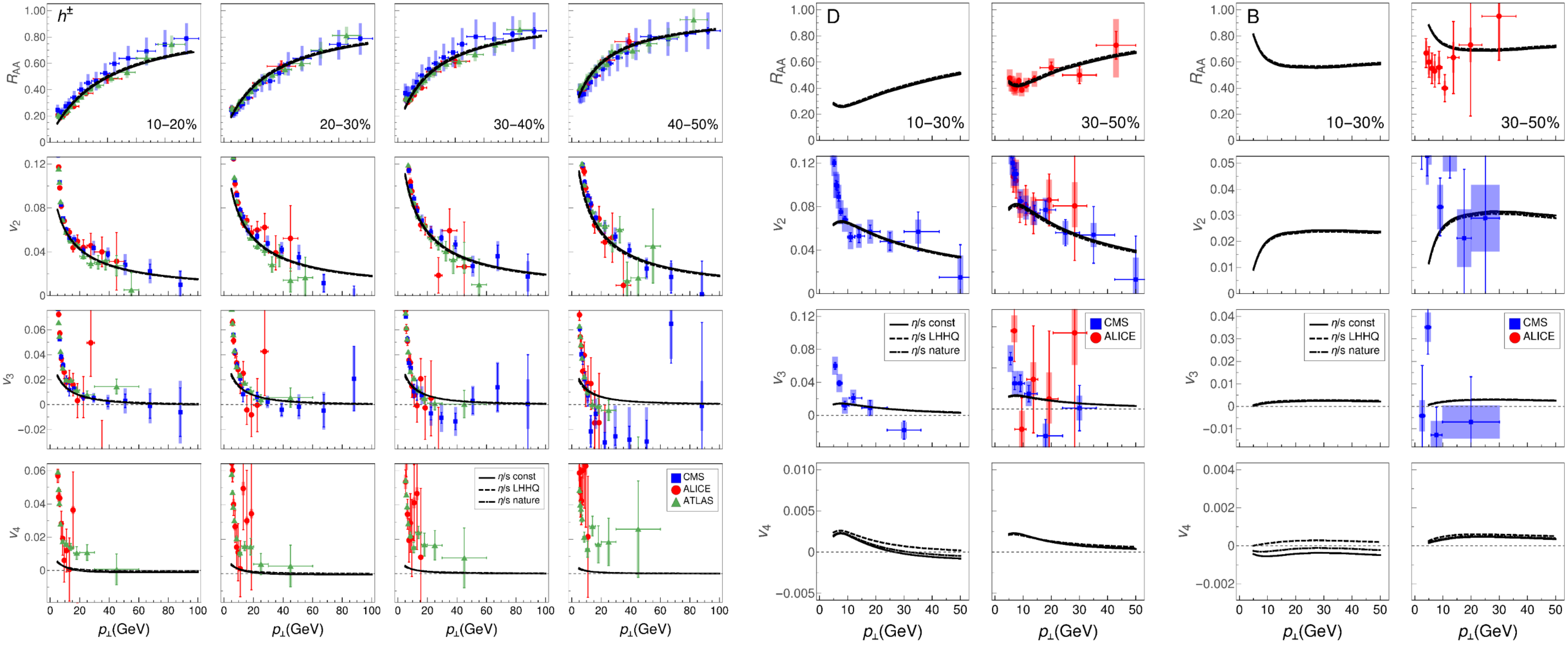
LHHQ: Phys. Rev. Lett. 106, 212302 (2011)

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



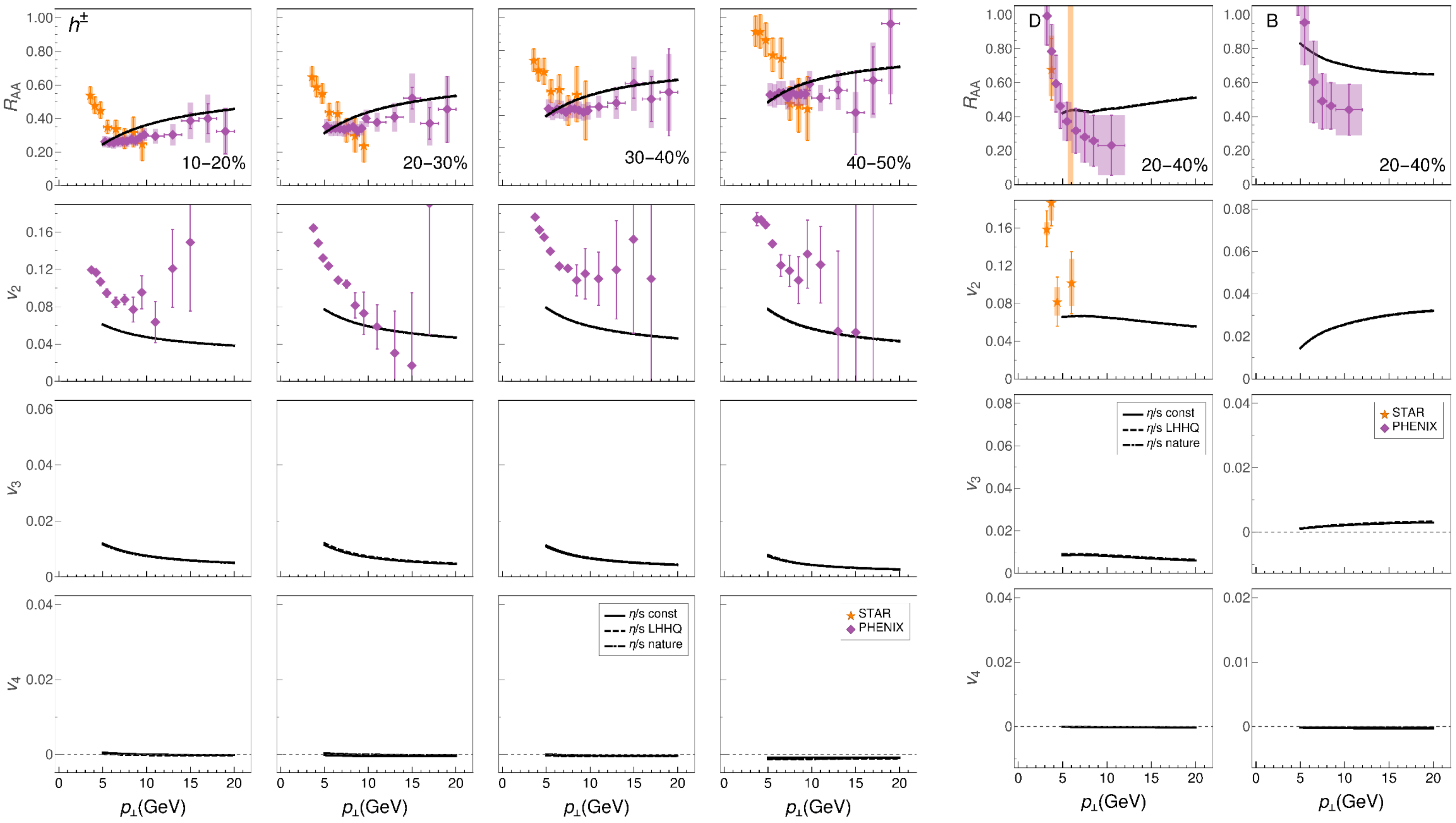
ebeDREENA predictions for light and heavy flavor - LHC

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, PRC **108**, 044907 (2023).



Weak dependence on η/s

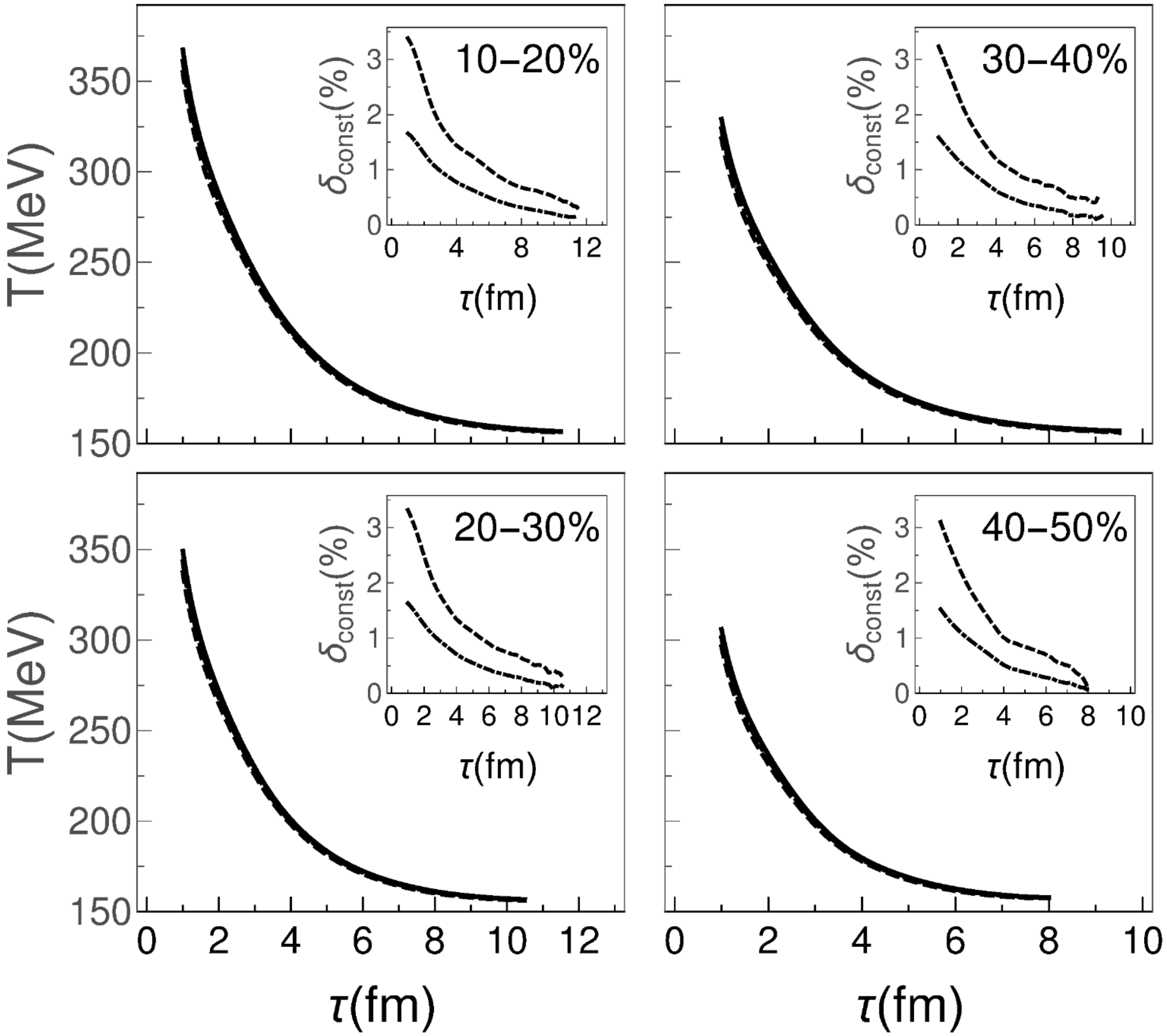
ebeDREENA predictions for light and heavy flavor - RHIC



Weak dependence on η/s

B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, PRC **108**, 044907 (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, PRC **108**, 044907 (2023).

B. 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, PRC **108**, 044907 (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!

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

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

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

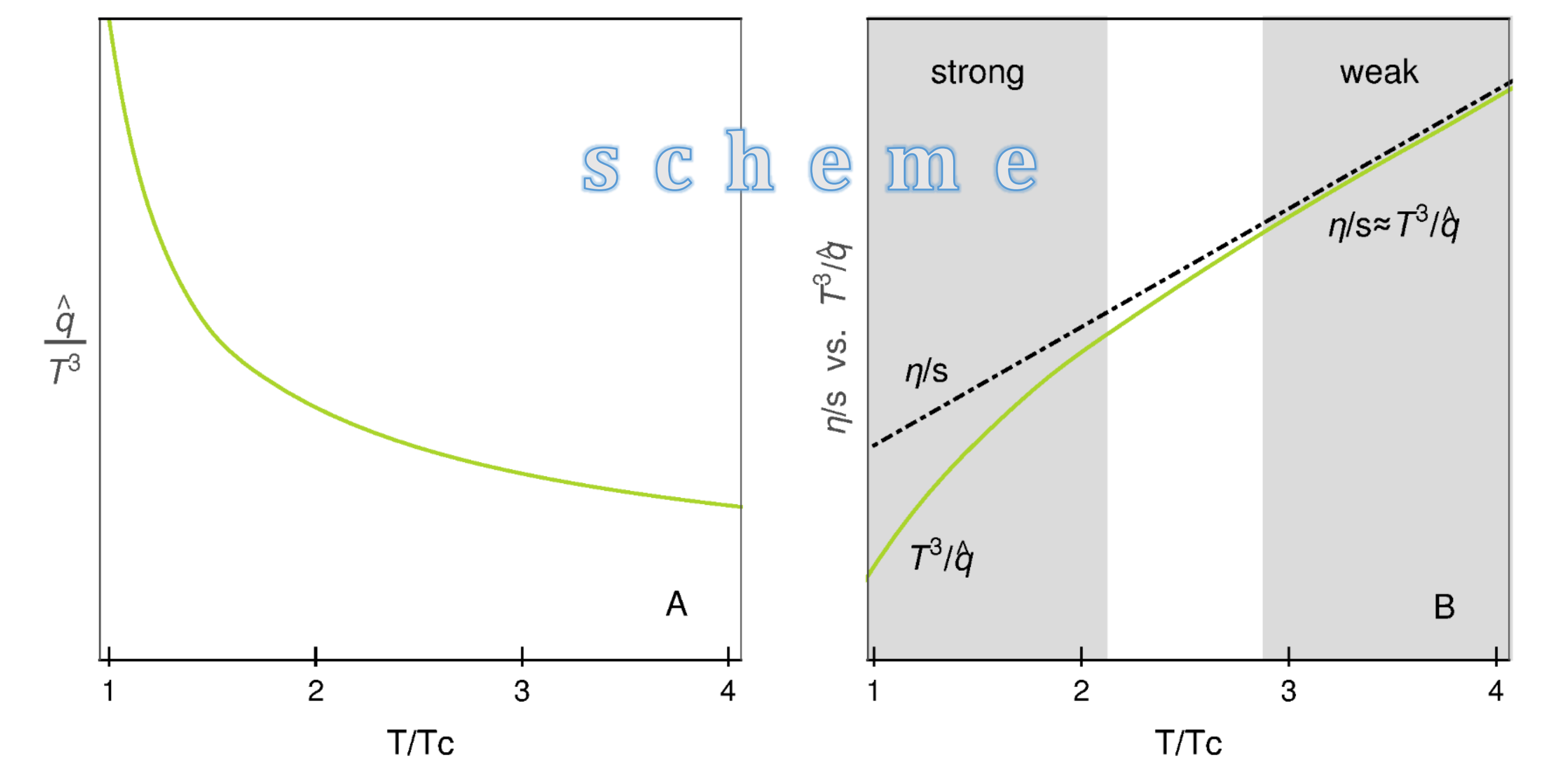
$$x_{ME} = \mu_M / \mu_E$$

- **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.
- At large T, weakly coupled system.
- 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).
- 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, PRC **108**, 044907 (2023).

η/s from the transport coefficient

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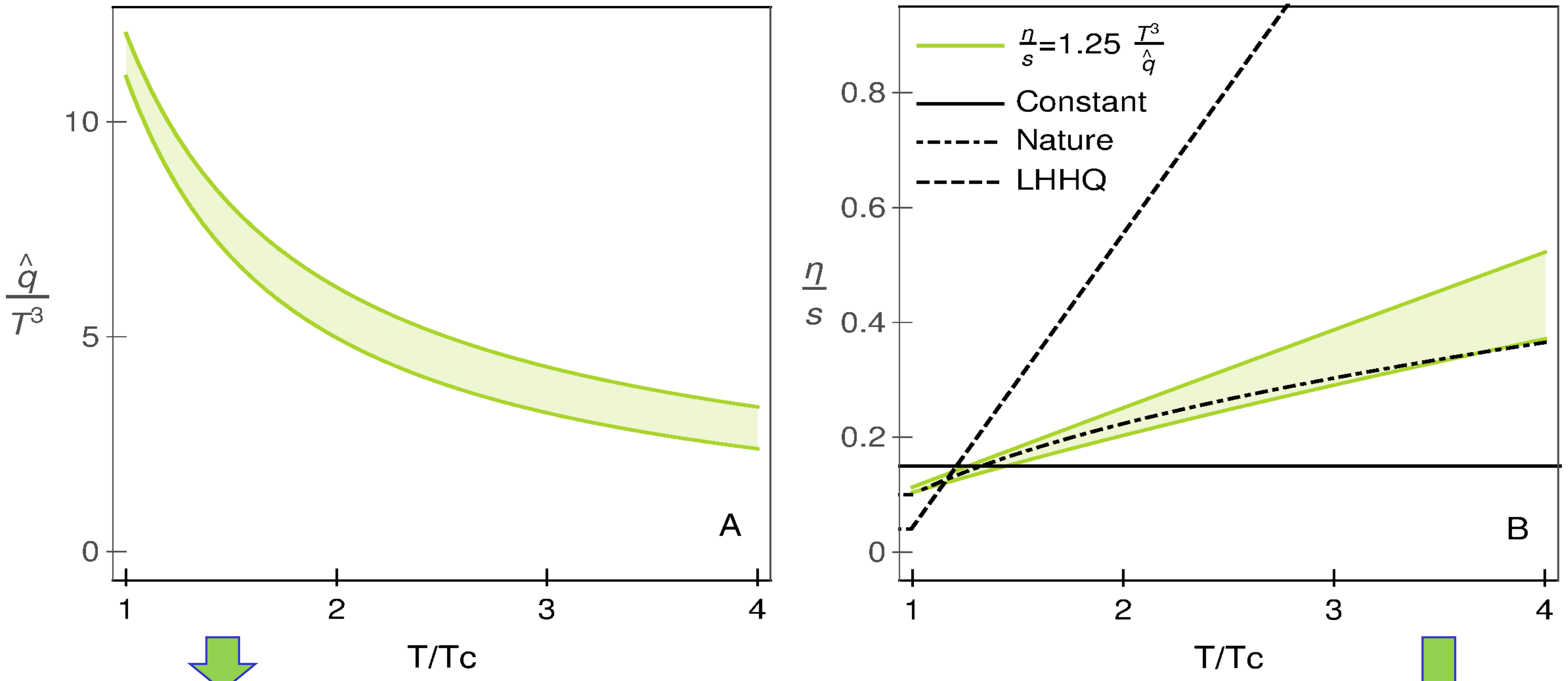


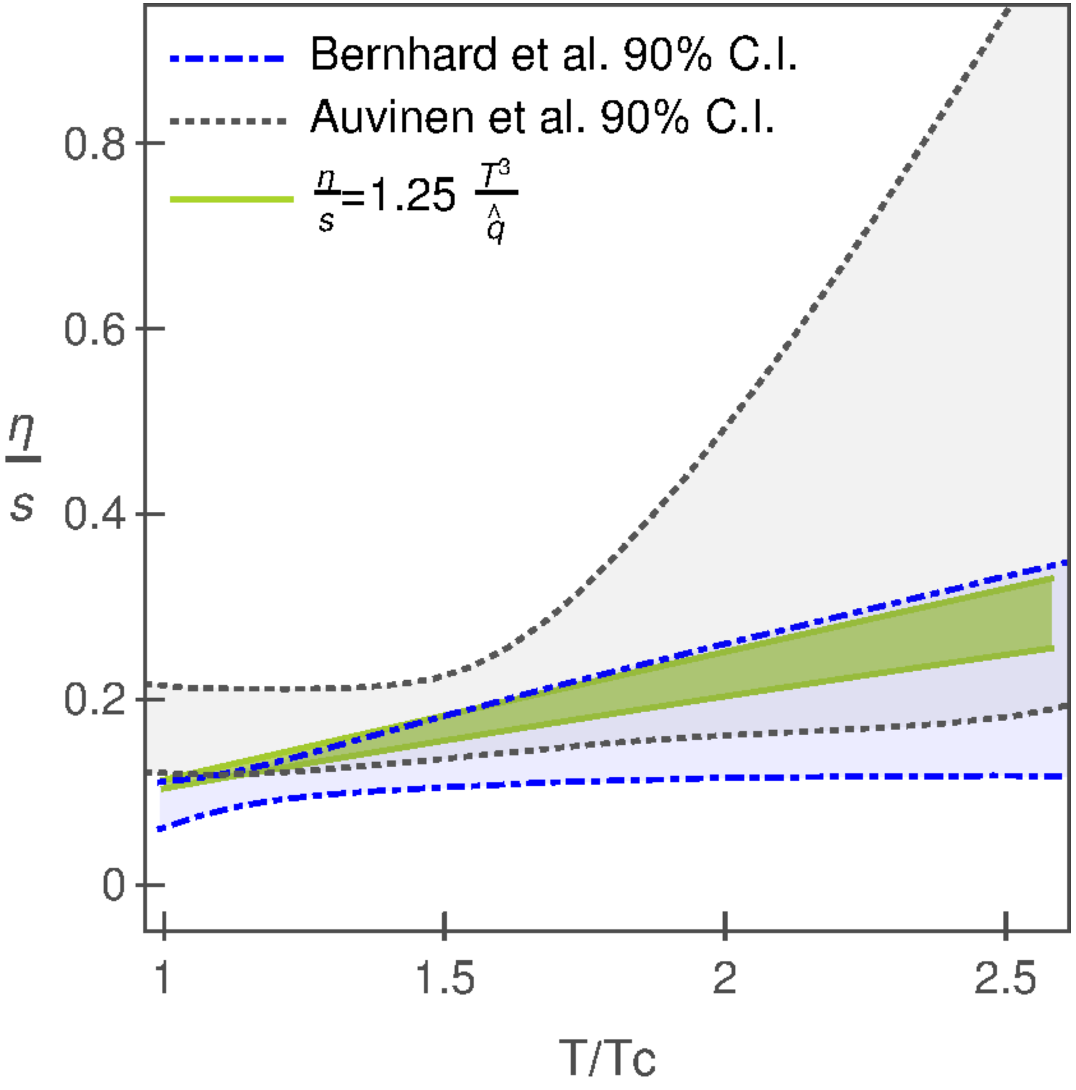
$\frac{\hat{q}}{T^3}$ shows expected behavior, i.e., enhanced quenching near *Tc*.
The enhancement arises from chromo-electric and chromo-magnetic interplay, absent in static models, underscoring dynamic medium importance in energy loss calculations.

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

Comparison with Bayesian analyses and summary

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

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



- η/s shows surprisingly good agreement all the way to T_c with constraints extracted from existing Bayesian analyses. (i.e., it falls precisely in the overlap of the two intervals).
- This agreement is surprising, as near T_c we expect divergence due to strong coupling.
- While the extended agreement supports the model's predictive ability, it raises a question about the absence of expected behavior.
- It is unlikely that the weak coupling regime would extend down to Tc.
- Instead, it was proposed that $\eta/s \approx 1.25\frac{T^3}{\hat{q}}$ holds as long as the quasiparticle picture of QGP is applicable., a condition also necessary for the accuracy of energy loss calculations, such as our dynamical model.
- **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.

Part II: Formal framework for DREENA Bayesian inference

Change selected QGP parameters (discrete values on a grid).

Run hydrodynamics simulations and generate T profiles for each simulation.

Low-pt and DREENA high-pt observable predictions.

Train statistical model (Gaussian process).

Observable predictions for provisional, that is continuous, values of the investigated parameters.

Experimental data:

low-pt, or joint low-pt and high-pt

Bayesian inference (Hamiltonian Monte Carlo sampling)

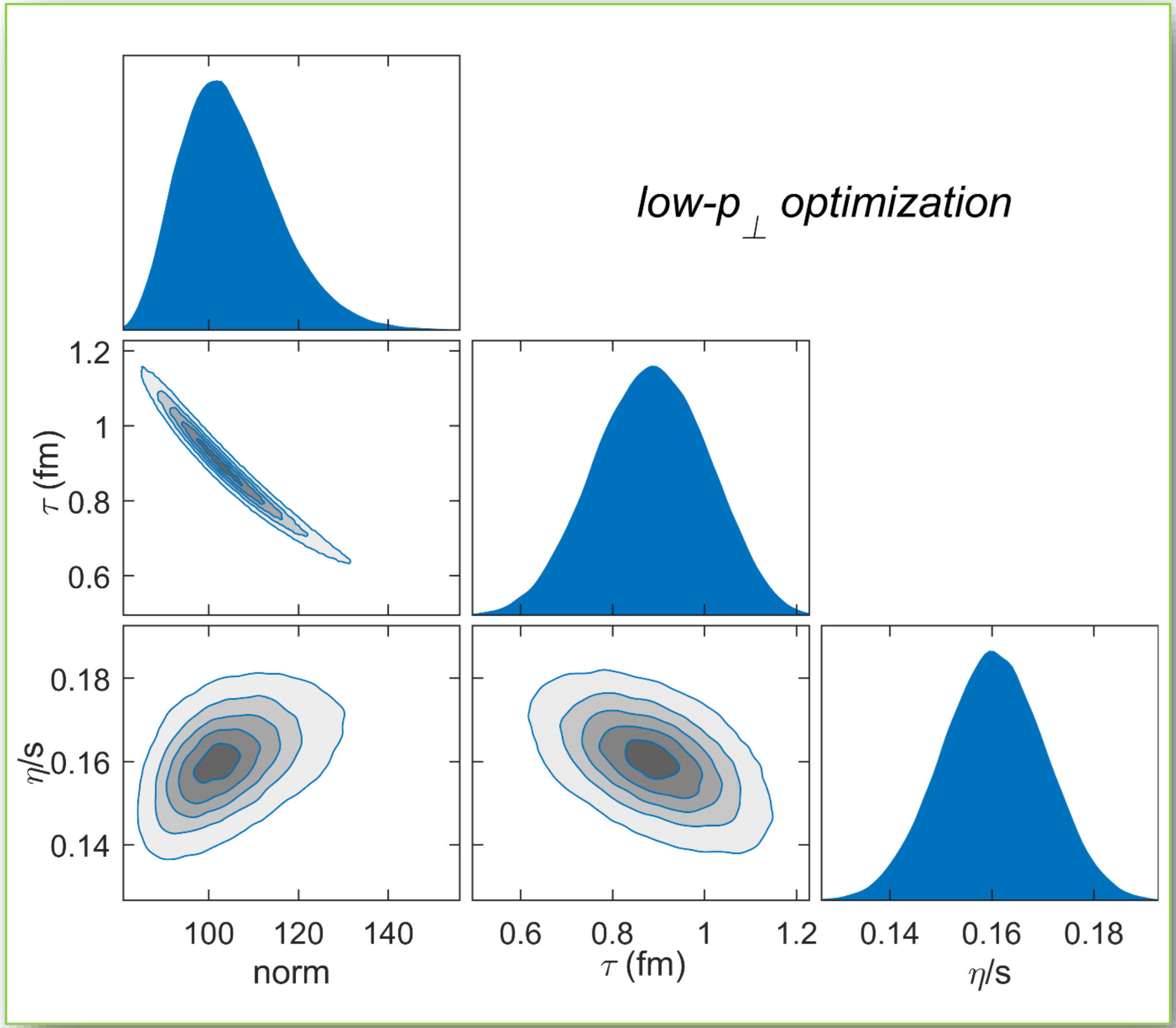
- Parameter posterior distributions.
- Low-pt and high-pt predictions compared with experimental data

- As in the first part of the talk, we assume TRENTo with p=0, and run (2+1)-dimensional fluid dynamical model (VISHNew) with no free streaming.
- Generated latin hypercube with 200 points, with norm, τ and η/s in the following range:
  - τ: 0.2-1.3 fm
  - Constant η/s: 0.02-0.2
  - Norm: 60-360

  All other parameters are as in PRC **108**, 044907 (2023).

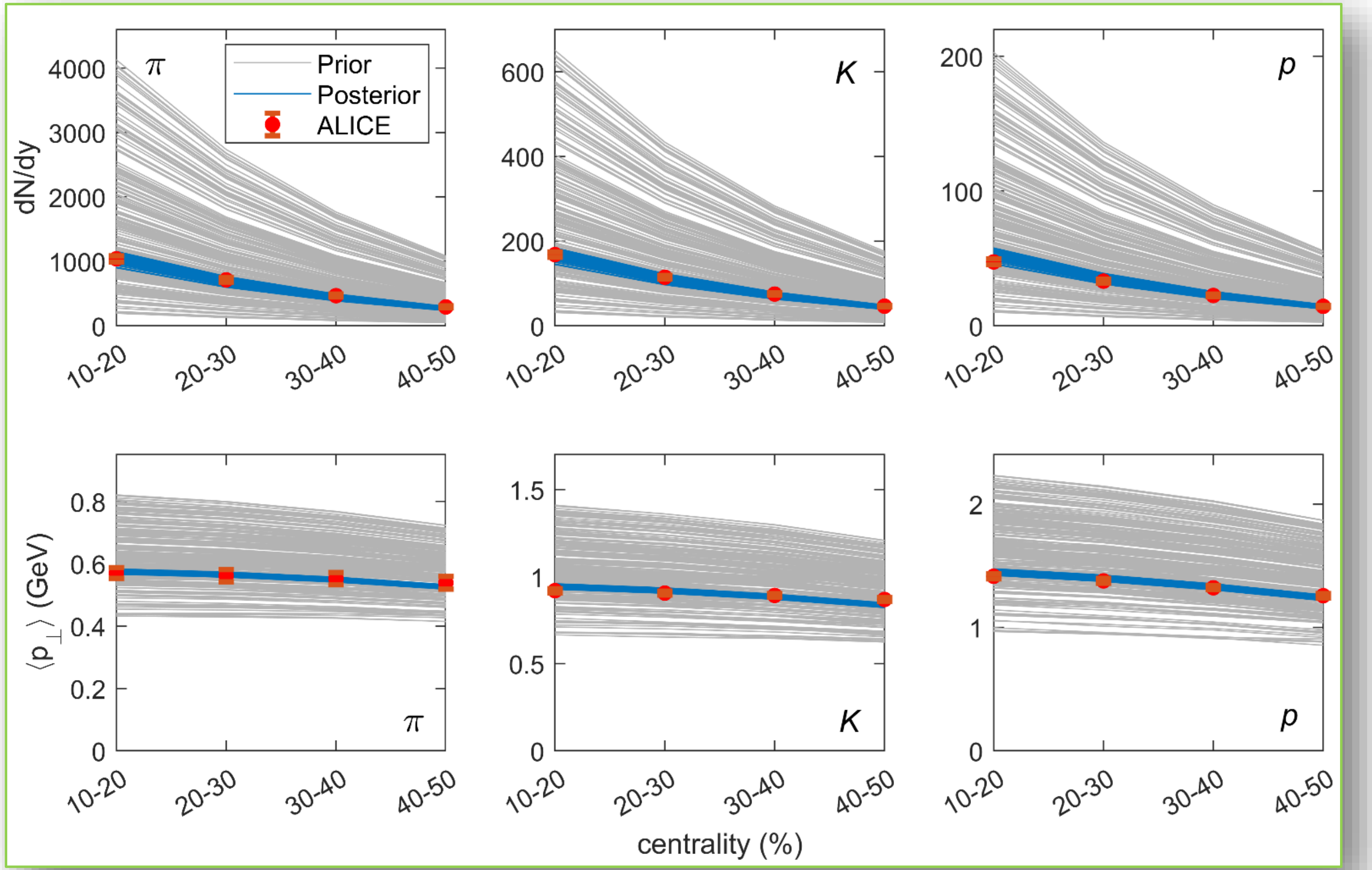
- For each set of parameters, we run average medium evolutions with TRENTo+ VISHNew, to generate low-pt predictions and *T* profiles as an input for DREENA-A.
- Run DREENA-A with these *T* profiles to generate high-pt predictions.
- Statistical inference framework (previous slide) is then employed with these predictions either on only low-pt experimatal data, or jointly on low-pt and high-pt experimental data.

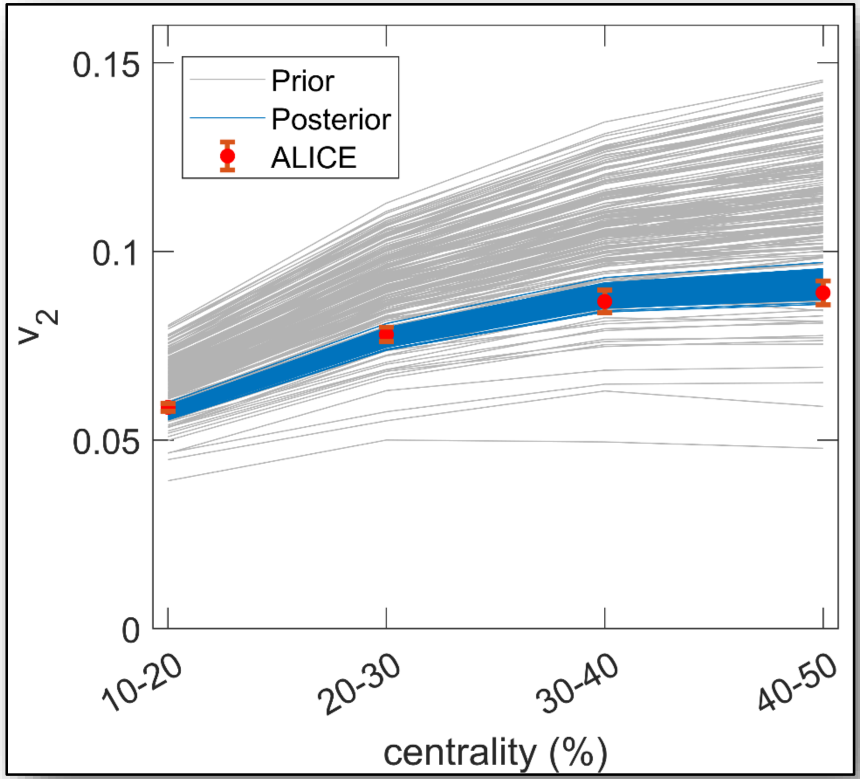
Marginal distribution of parameters obtained with Bayesian inference of low-pt data



M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).

Prior vs. posterior: low-pt data

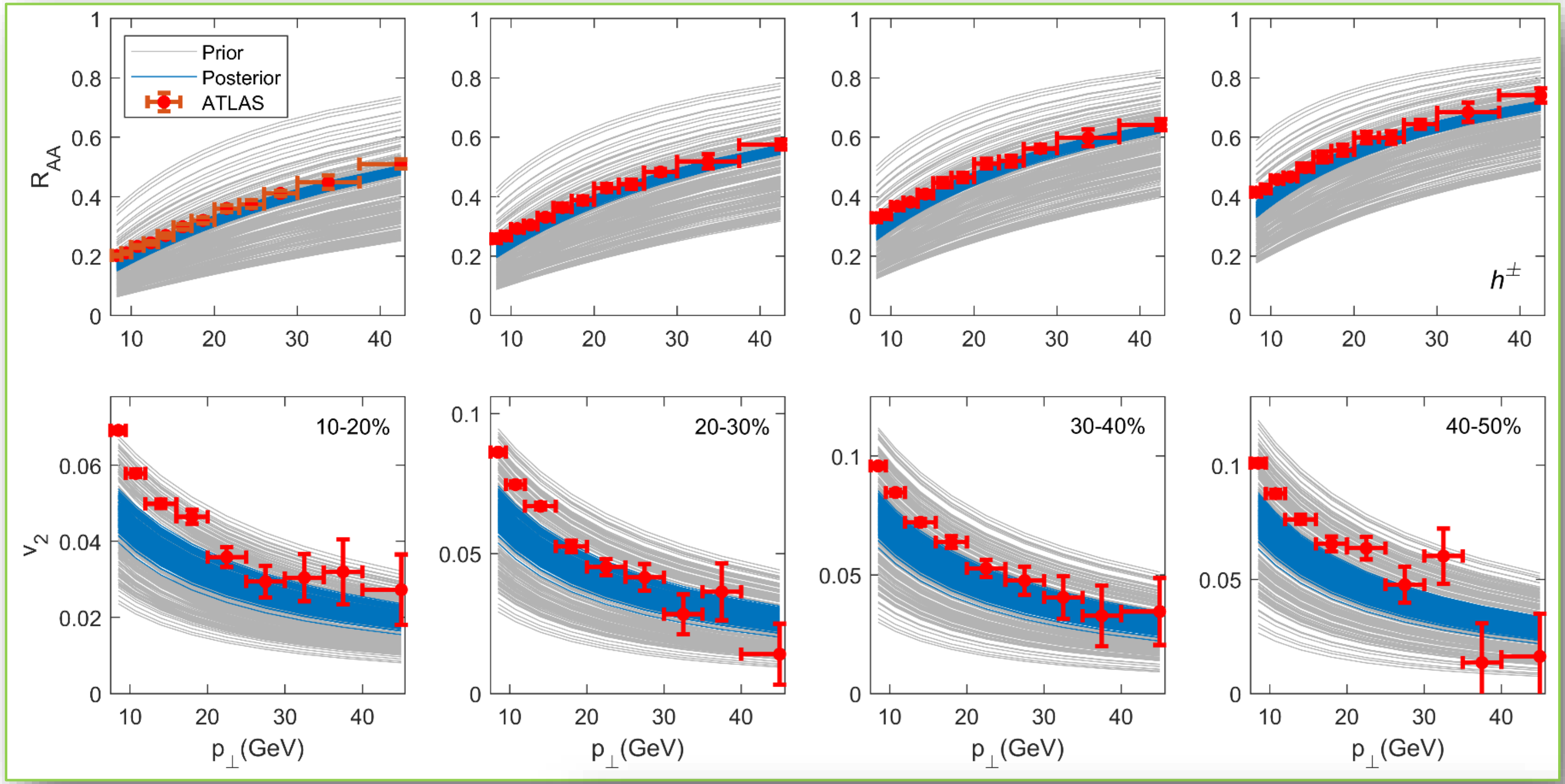


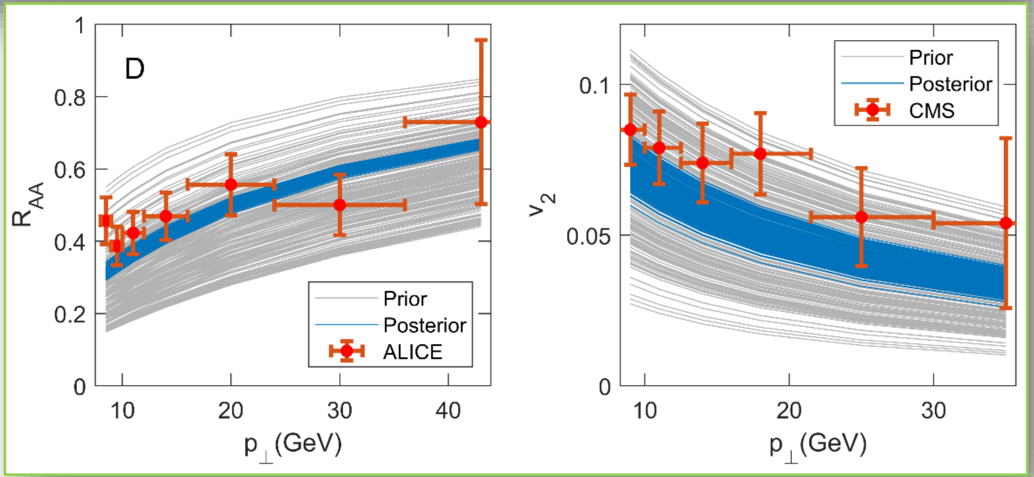


Very good agreement with low-pt data!

M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).

Prior vs. posterior: high-pt data

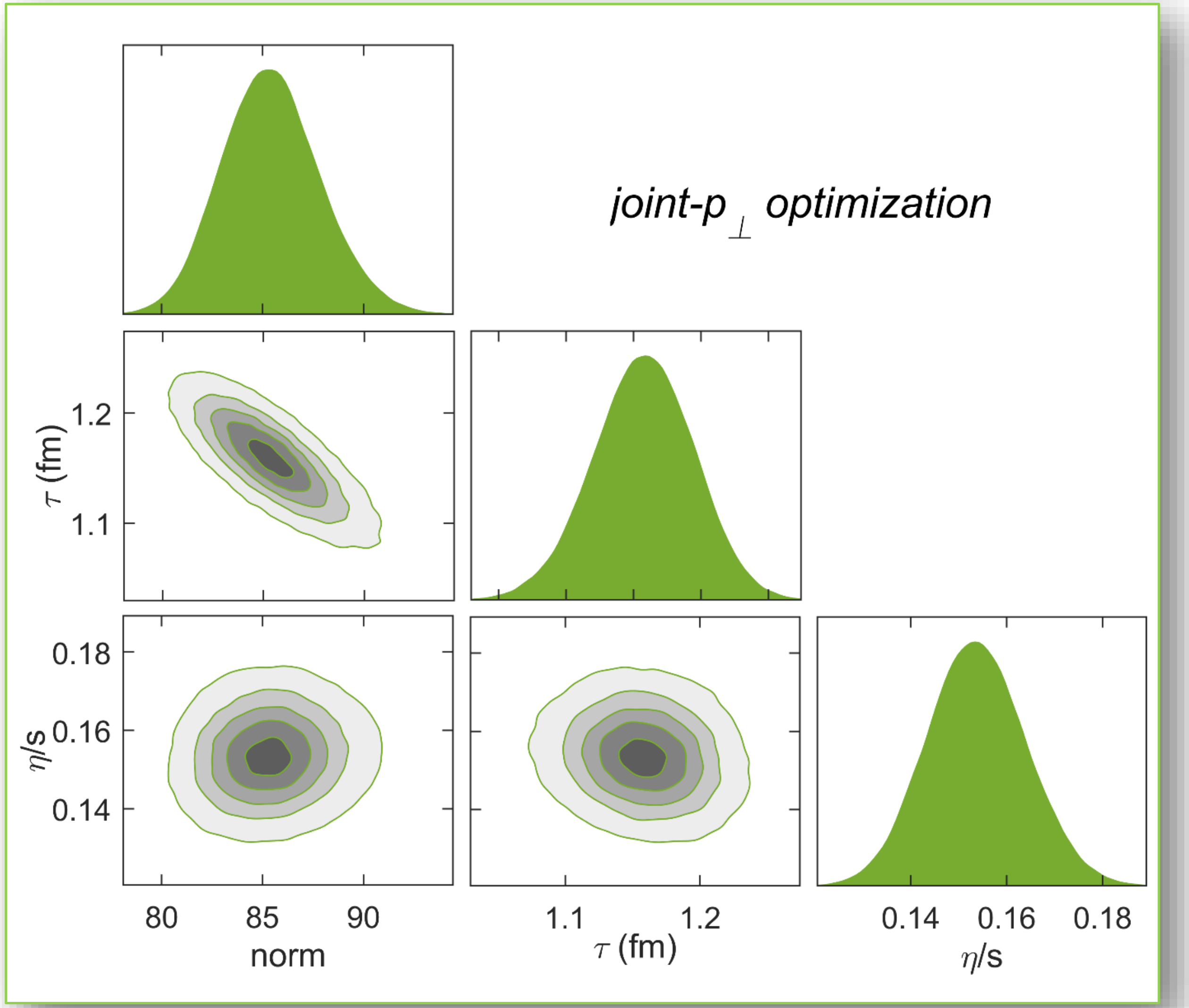




M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).

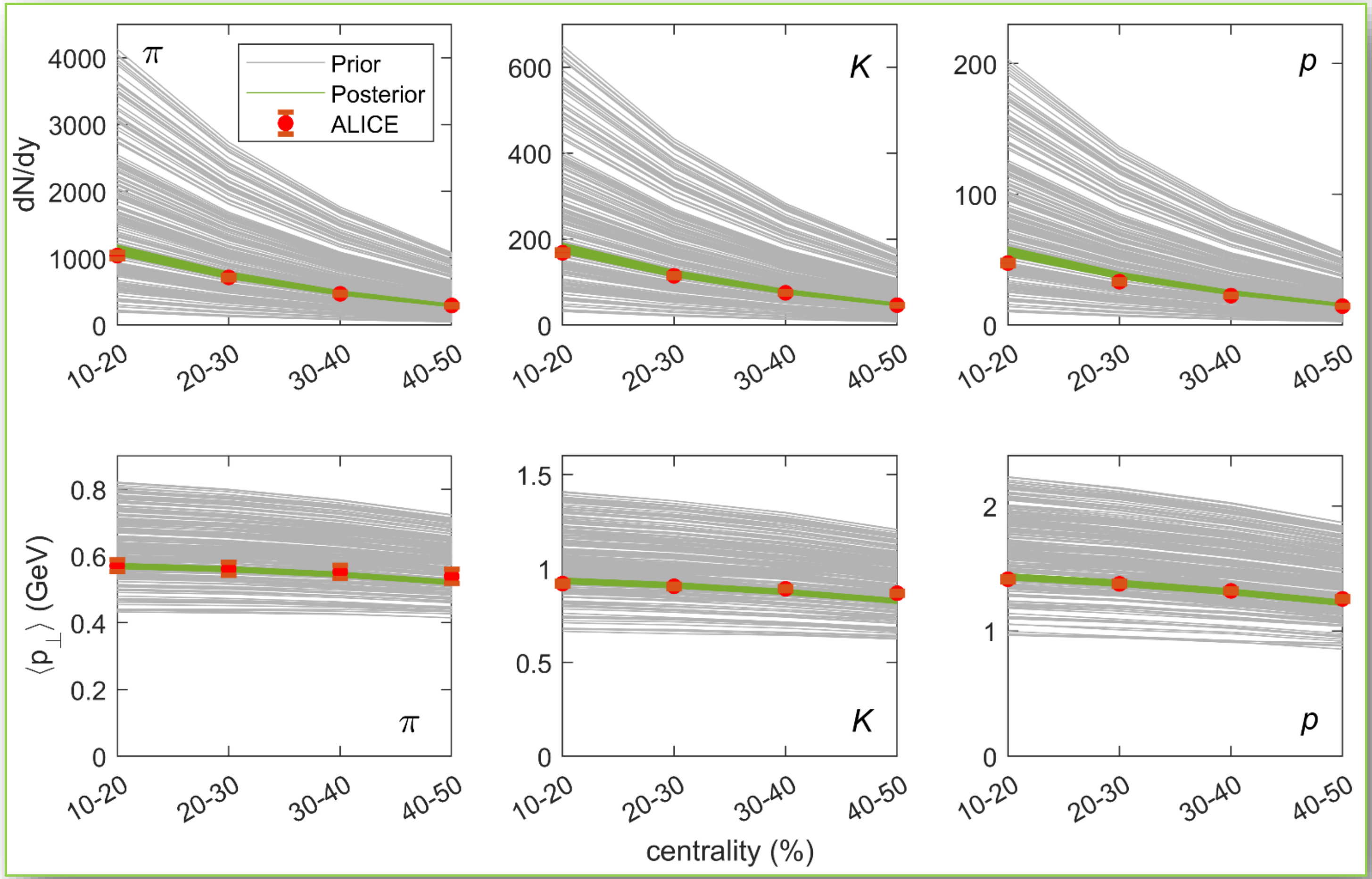
Suboptimal agreement with high-pt data, especially for v_2.

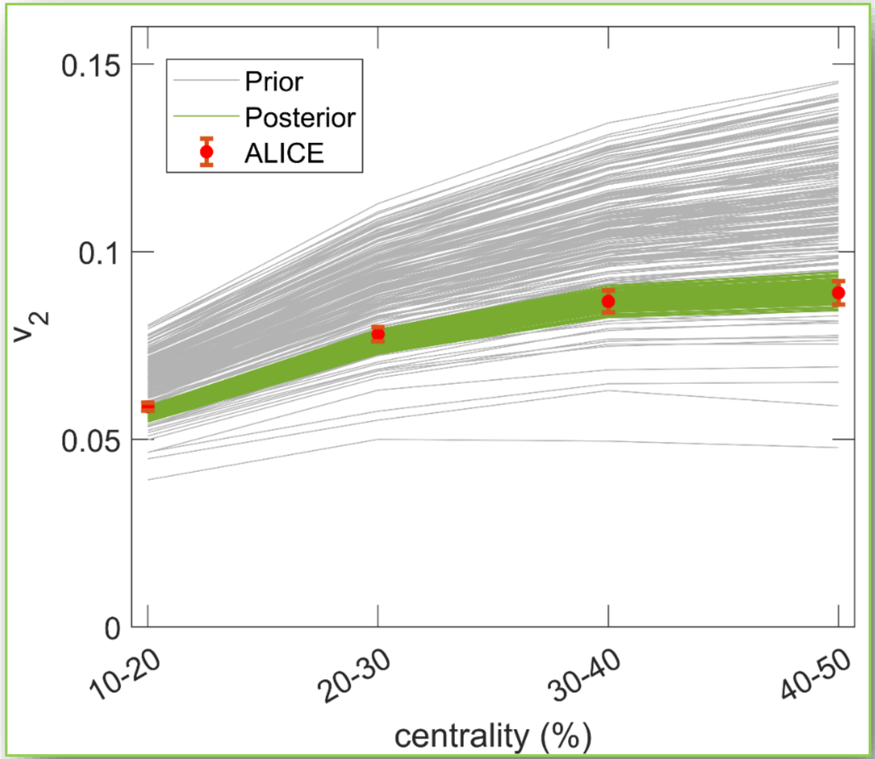
Marginal distribution of parameters obtained with Bayesian inference of both low-pt and high-pt data



M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).

Prior vs. posterior: low-pt data

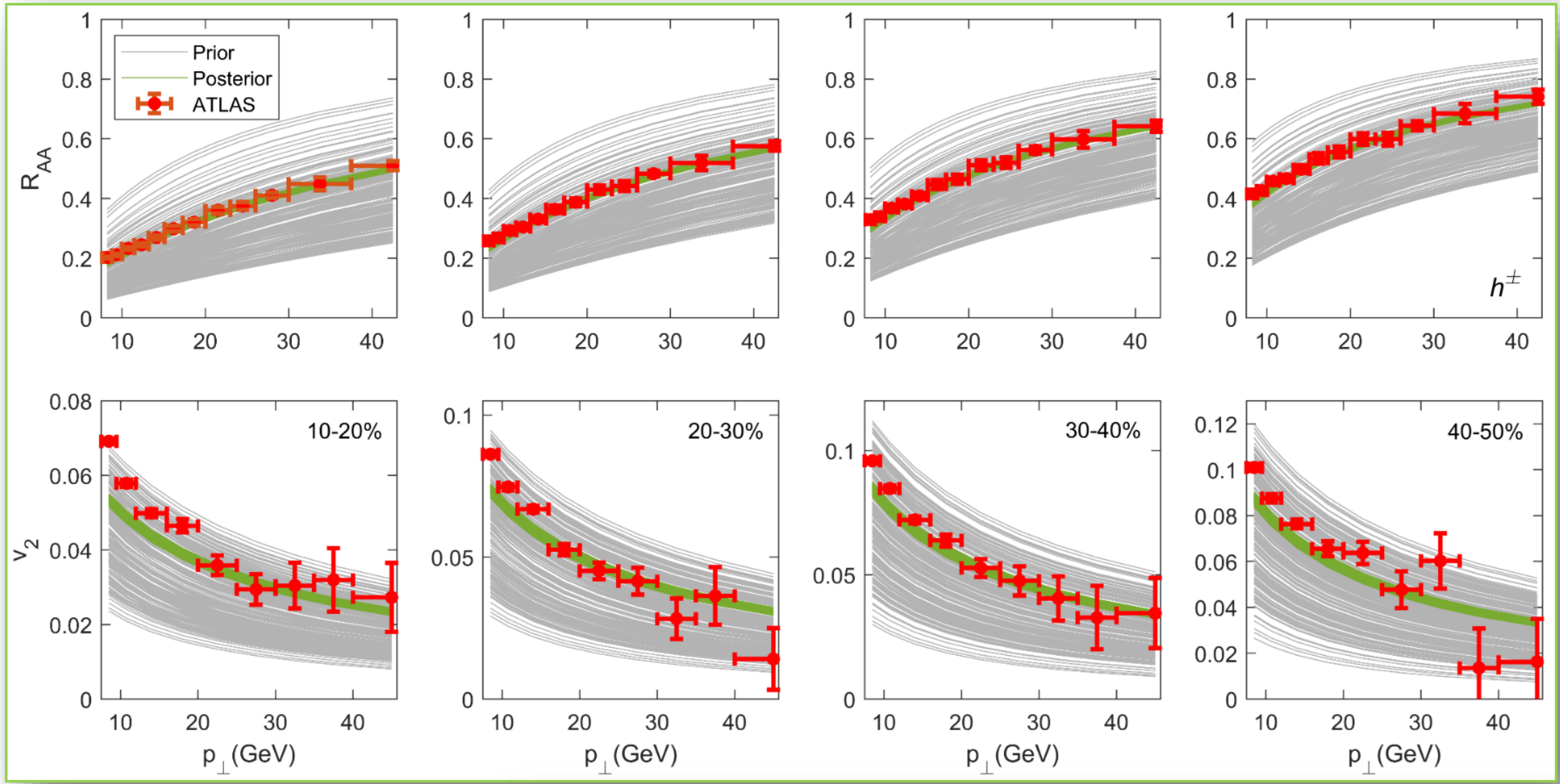


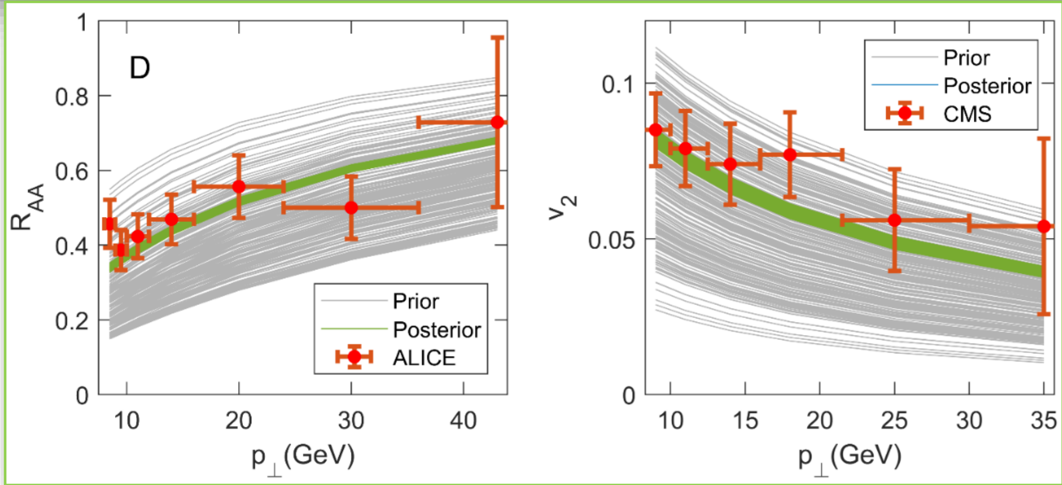


Very good agreement with low-pt data!

M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).

Prior vs. posterior: high-pt data



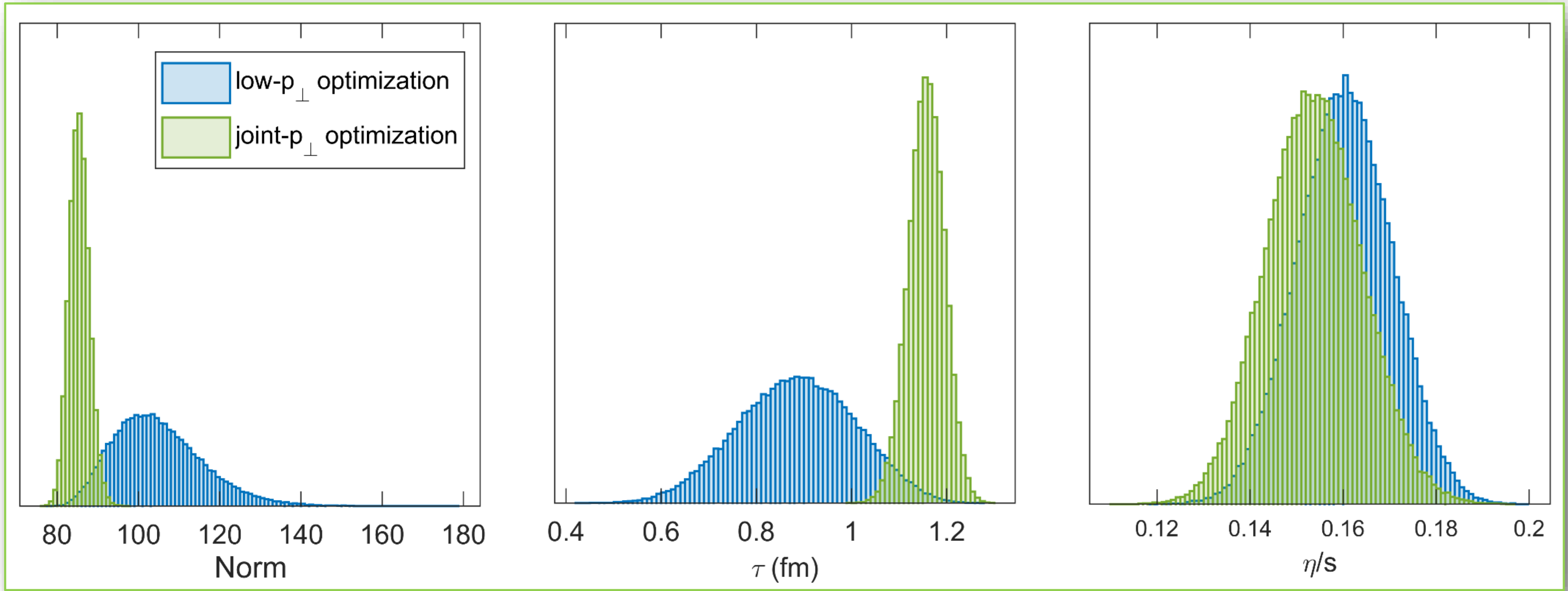


M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).

Very good agreement with high-pt data as well!

Comparison of parameter distributions from low-pt and joint-pt Bayesian inferences

M. Djordjevic, D. Zigic, I. Salom, MD, to be submitted (2024).



Distributions are not inconsistent with each other!

Inclusion of high-pt data significantly narrows the distributions of parameters!

High-pt data are necessary for precision extraction of bulk QGP parameters!

Overall, jet tomography is crucial for constraining QGP properties!

Canyon of river DREENA in Serbia

European Research Council
Established by the European Commission

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА