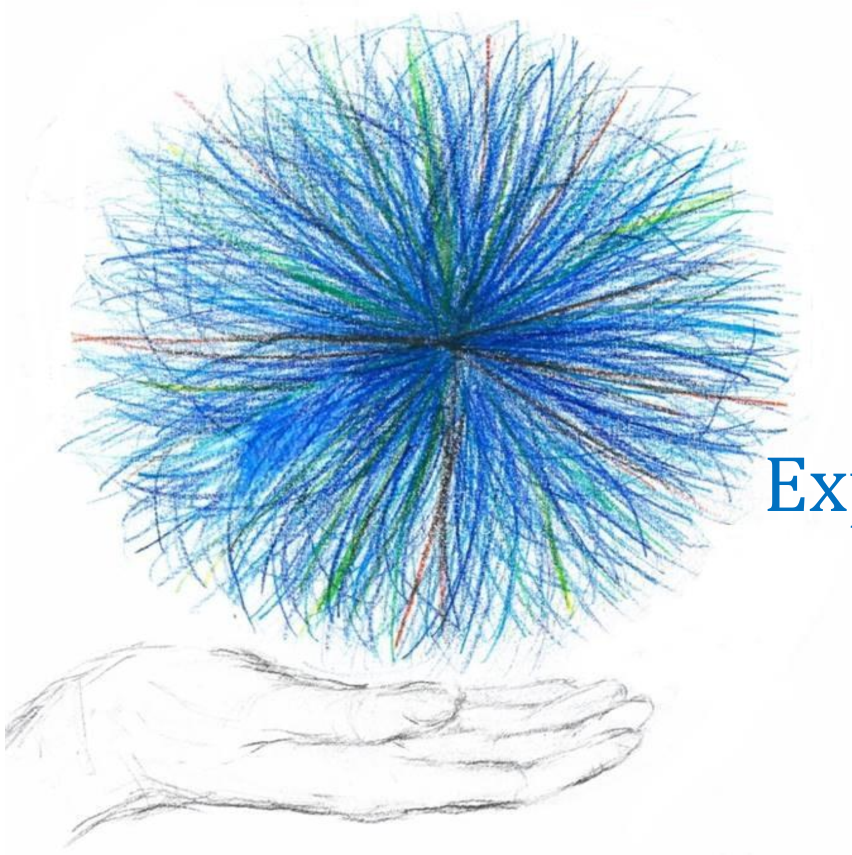


Exploring QGP properties through unified high-pt and low-pt approach with Bayesian Inference

Magdalena Djordjevic, IPB

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

European Research Council

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

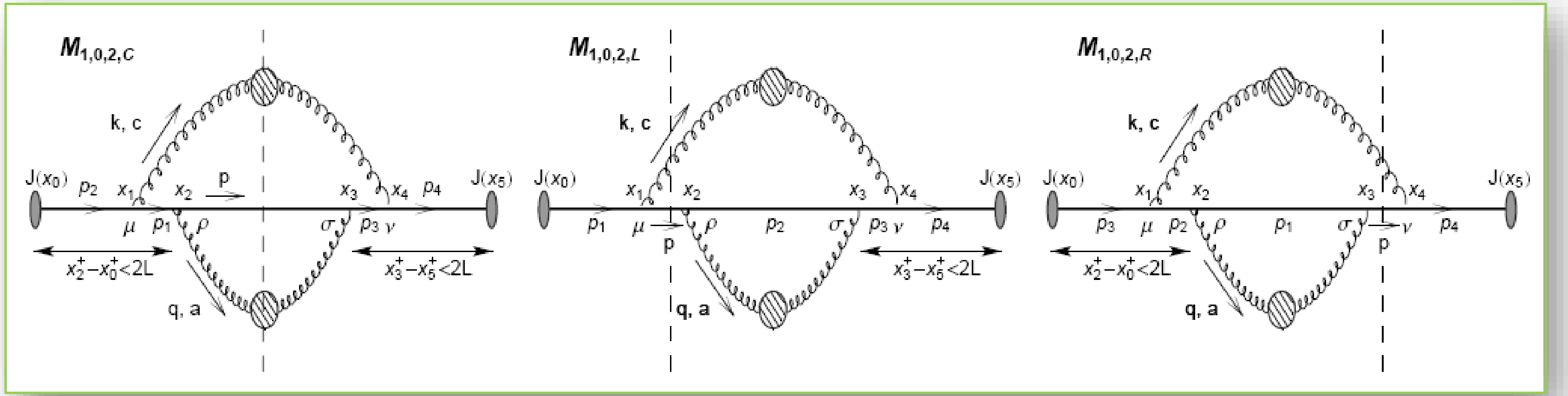
Motivation

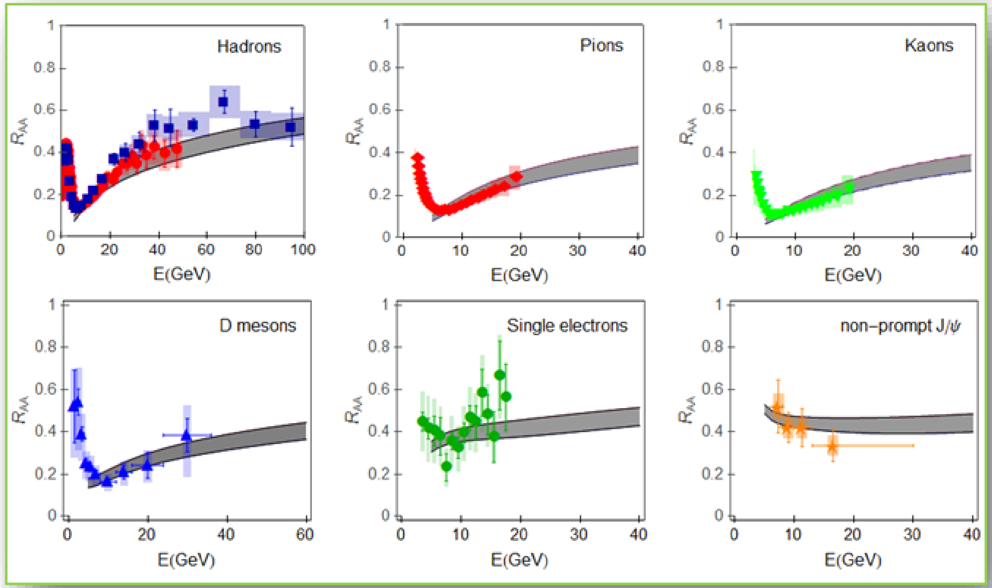
- Energy loss of high-pt light and heavy particles traversing the QCD medium is an excellent probe of QGP properties.
- Theoretical predictions can be compared with a wide range of data from different experiments, collision systems, collision energies, centralities, and observables.
- Can be used jointly 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

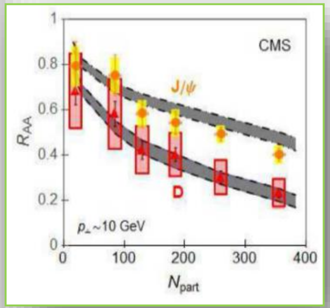
Has the following unique features:

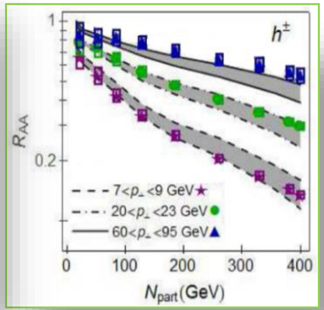
- *Finite size finite temperature* QCD medium of *dynamical* (moving) partons.
- Based on finite *T* field theory and generalized HTL approach.
- Same theoretical framework for both radiative and collisional energy loss.
- Applicable to both light and heavy flavor.
- Finite magnetic mass effects (M.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



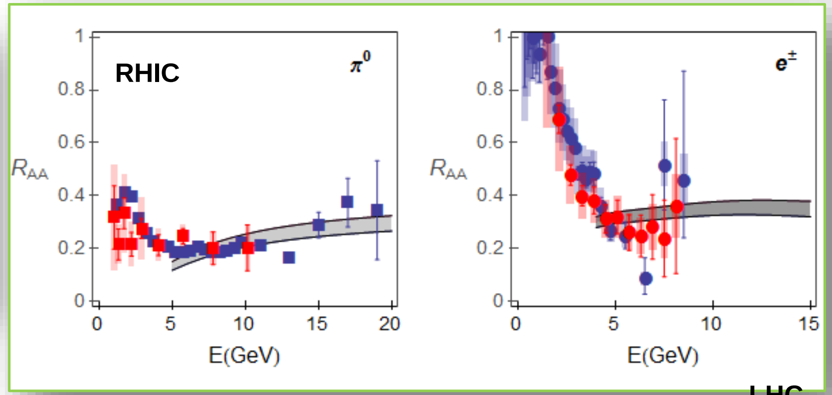


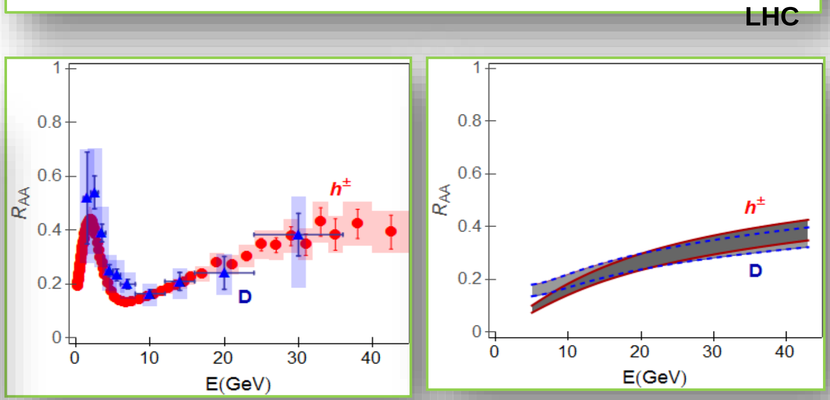
Explains high-pt R_{AA} data for different probes, collision energies, and centralities.





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

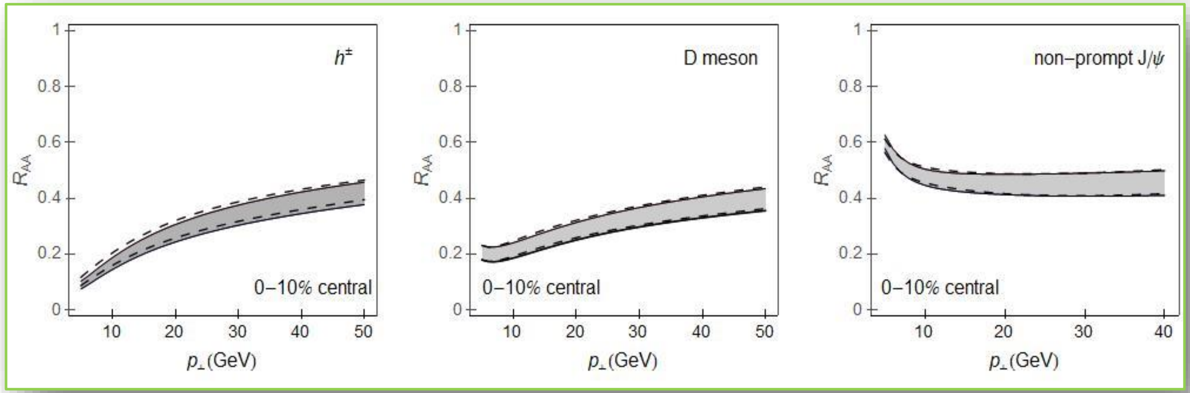


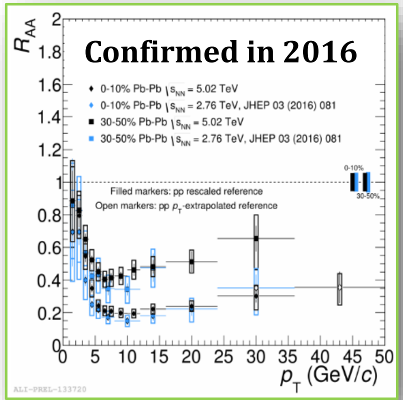


M.D., PRL 112, 042302 (2014)

Clear predictive power!

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





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

Part I: Can we use dynamical energy loss to constrain η/s?

- Low-$p_\perp$ observables are widely used to explore the bulk QGP properties.
- η/s is well constrained by Bayesian analyses in the low-$p_\perp$ sector in the temperature range $T_c \lesssim T \lesssim 1.5T_c$, but weakly constrained at larger temperatures.
- 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.
- Can we constrain η/s by using the dynamical energy loss?

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 $\hat{q}$ from the dynamical energy loss

- 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):

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

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

- In the fluid rest frame, weakly dependent on E!

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

- In the limit of $ET\rightarrow\infty$, reduces to the expression independent of jet energy: $x_{ME}=\mu_M/\mu_E$

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

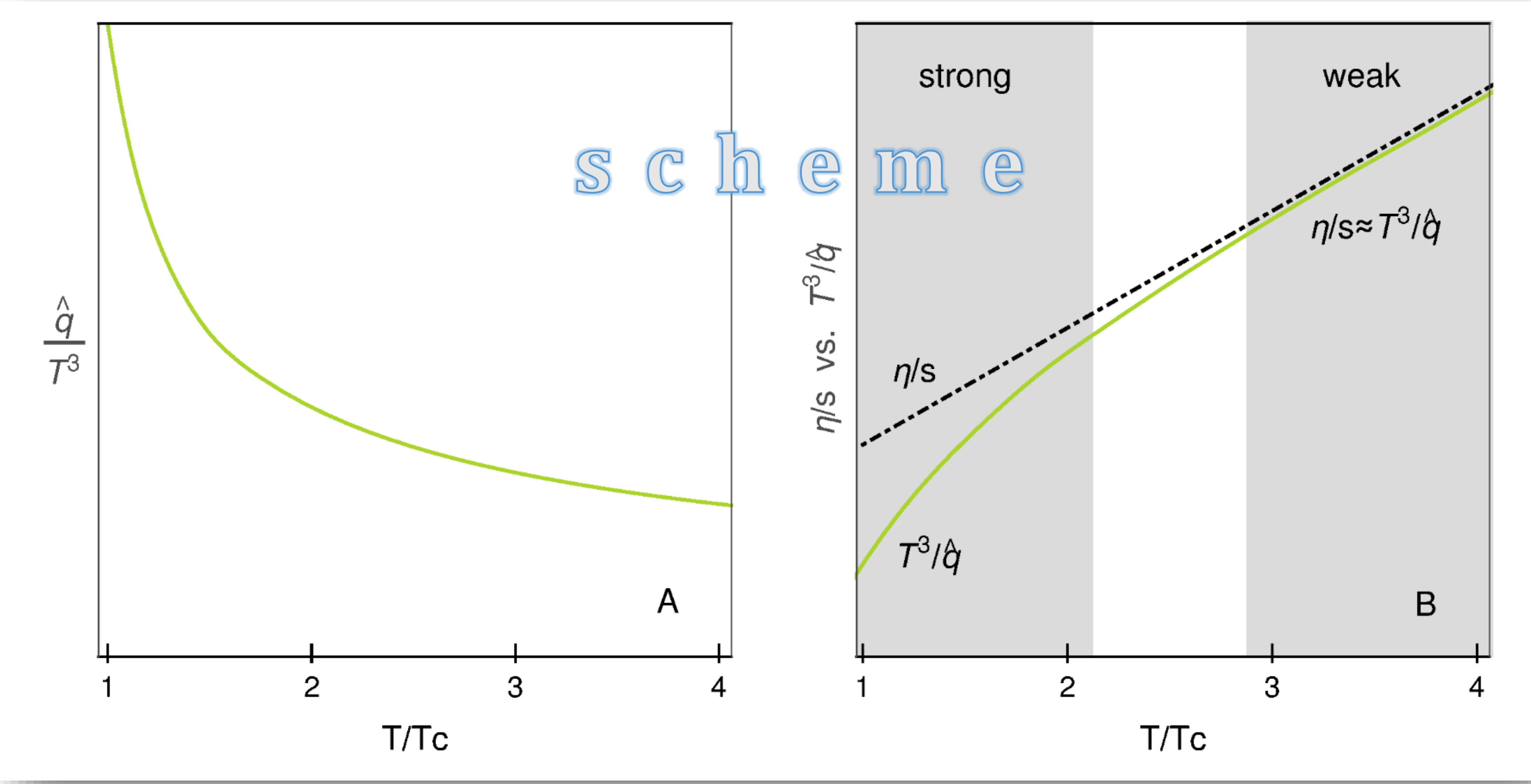
- **Expected behavior:** as a property of the medium $\hat{q}$ should be independent (or weakly dependent) on jet energy.

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

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.
- 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).
- In the weakly coupled regime (Majumder, Muller, Wang, PRL 99, 2007) $\eta/s \approx 1.25\frac{T^3}{\hat{q}}$.
- 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.



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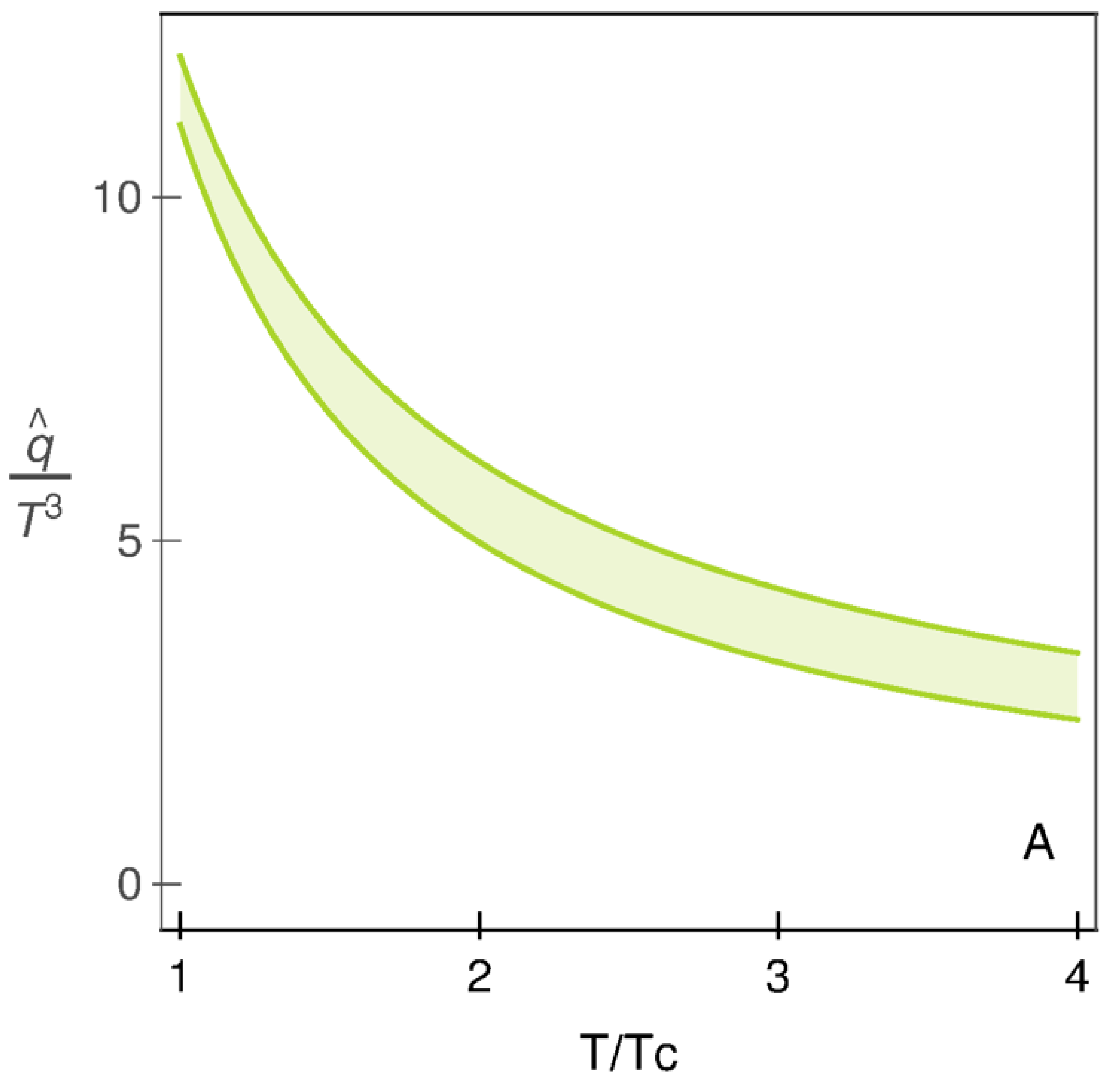


B. Karmakar, D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic and MD, PRC **108**, 044907 (2023).

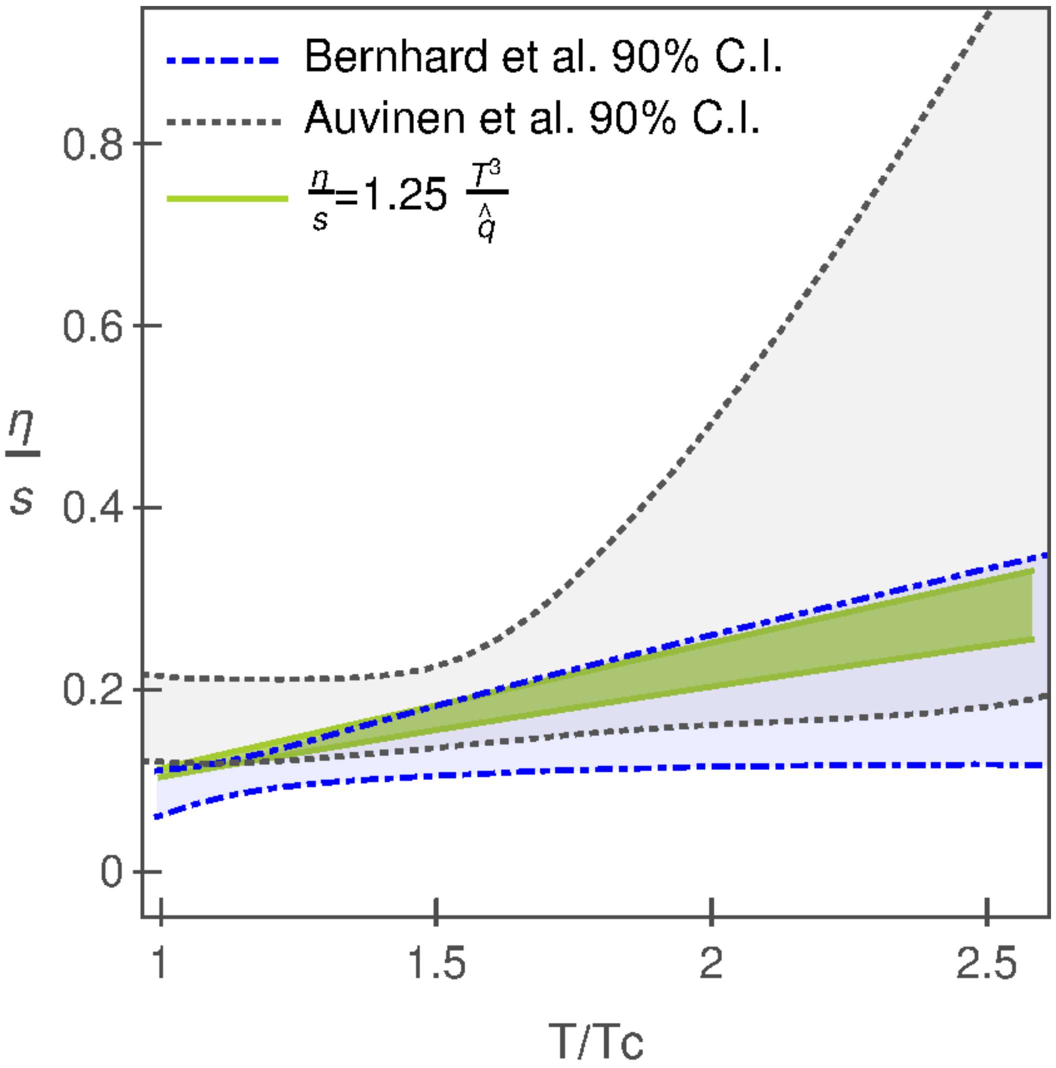
$\frac{\hat{q}}{T^3}$ shows expected behavior, i.e., enhanced quenching near *Tc*.

The enhancement arises from chromo-electric and chromo-magnetic interplay, absent in static models, underscoring dynamic medium importance in energy loss calculations.

Comparison with Bayesian analyses and Summary of Part I

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 our dynamical energy loss 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.

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

Part II: Inferring bulk QGP properties

Bulk QGP properties are traditionally explored by low-pt observables that describe the collective motion of 99.9% of QCD matter.

Rare high energy probes are, on the other hand, almost exclusively used to understand high-pt parton - medium interactions.

While high-pt physics had a decisive role in QGP discovery, it has been rarely used to understand bulk QGP properties.

However, some important bulk QGP properties are known to be difficult to constrain by low-pt observables and corresponding theory/simulations.

We advocate high-pt QGP tomography, where low- and high-pt physics jointly constrain bulk QGP parameters.

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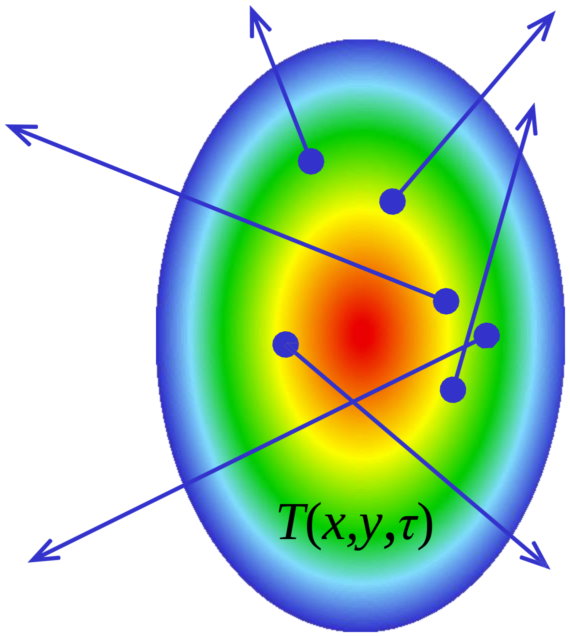


The main idea behind the QGP tomography

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

This energy loss depends on the temperature evolution of the QGP.

Temperature evolutions are different for different QGP parameters.

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.

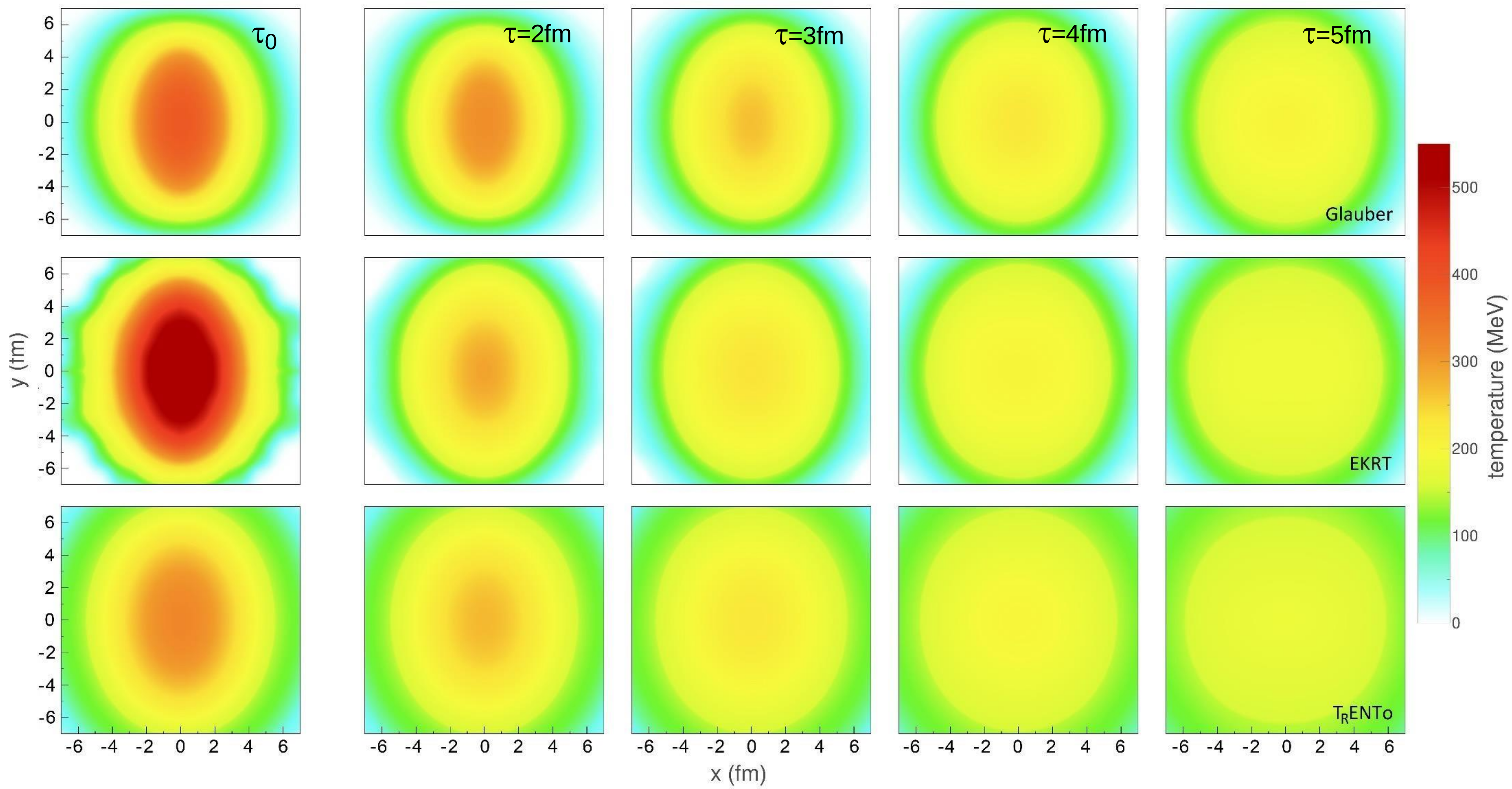
D.Zigic, I.Salom, J.Auvinen, P.Huovinen, M. Djordjevic Front.in Phys. 10(2022)957019

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

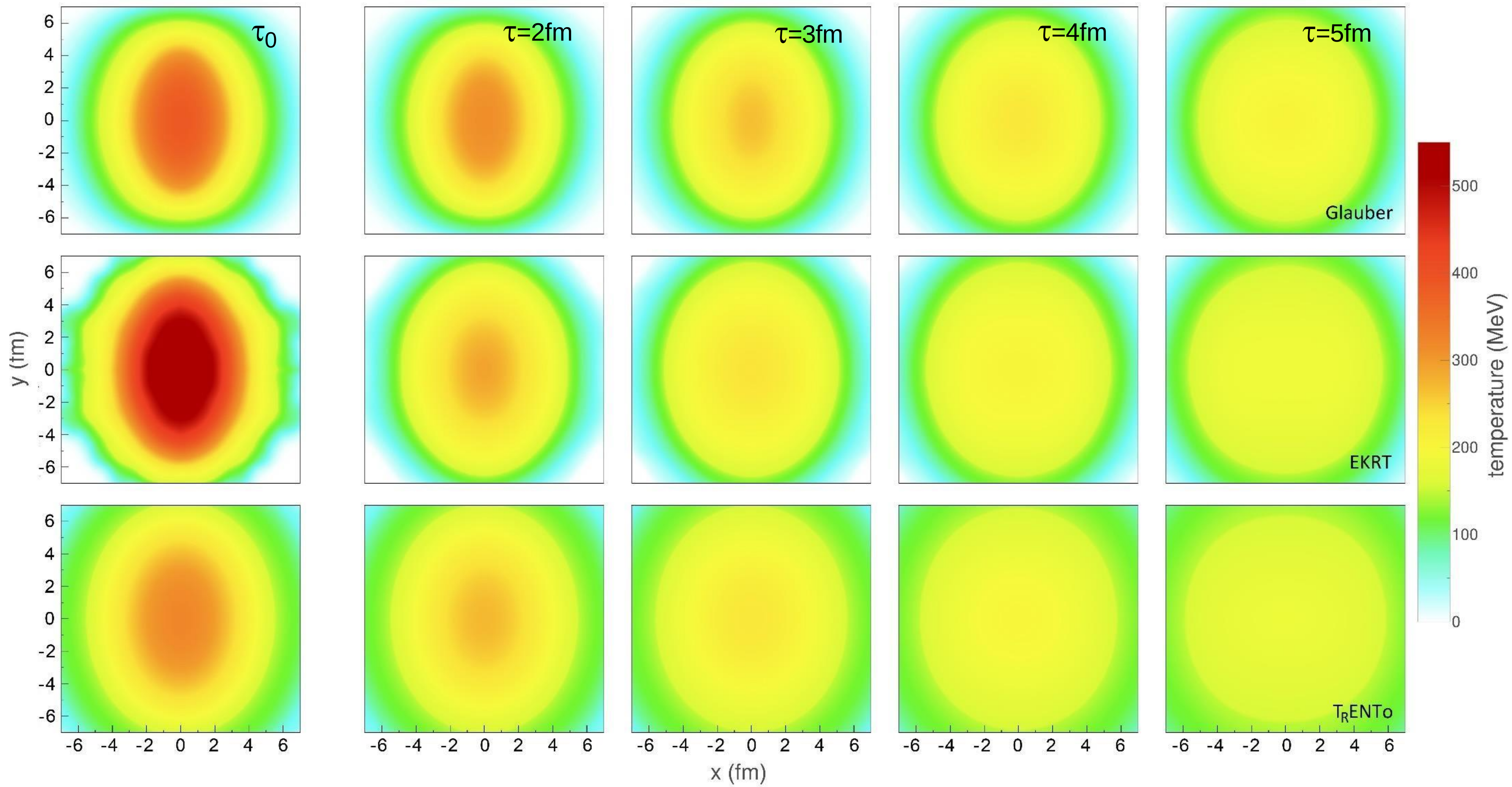
Are high-pt observables indeed sensitive to different T profiles?



All three evolutions agree with low-pt data. Can high pt-data provide further constraint?

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

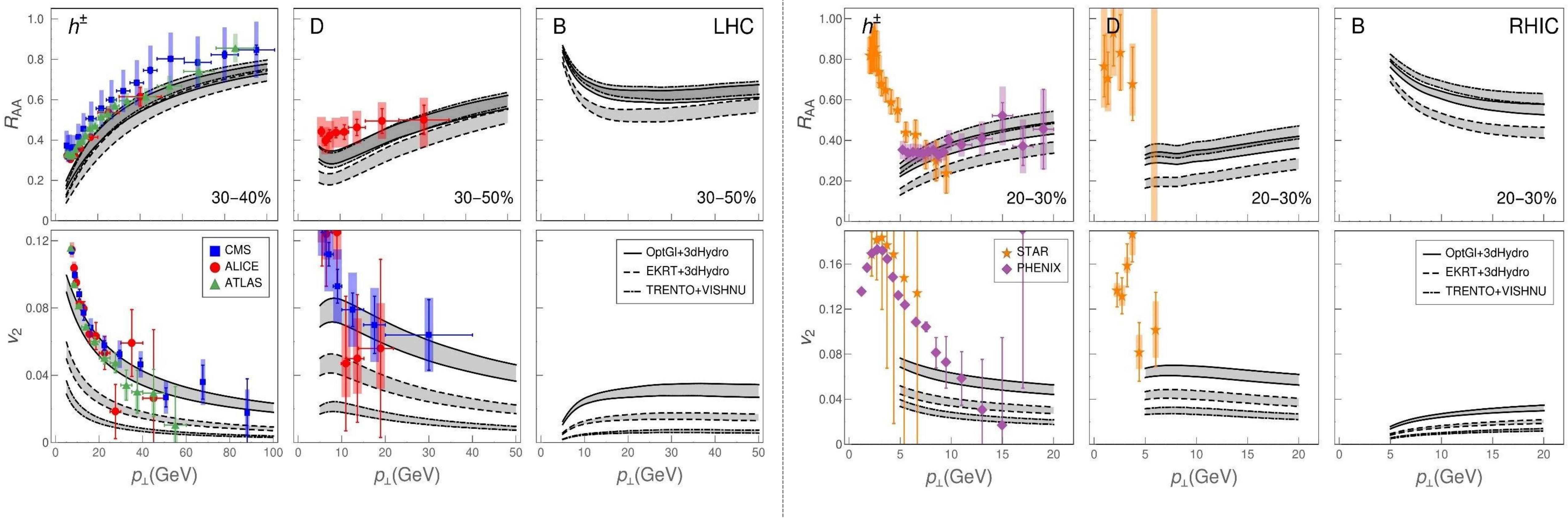
Qualitative differences



- Largest anisotropy for Glauber (τ_0=1fm) – expected differences in high-pt v_2.
- EKRT shows larger temperature - smaller R_{AA} expected.

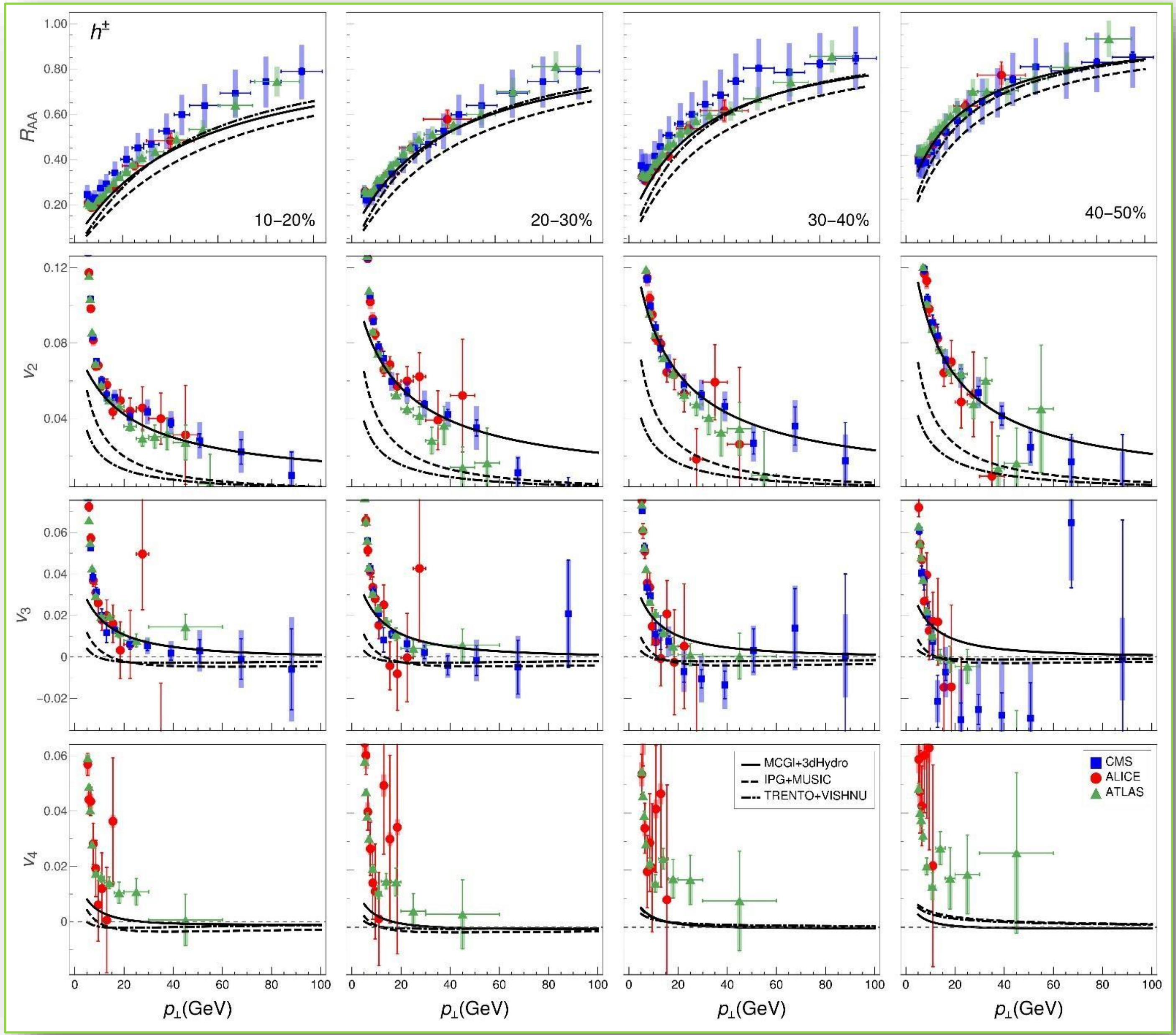
DREENA-A predictions

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



- 'EKRT' indeed leads to the smallest R_{AA}.
- Anisotropy translates to v_2 differences ('Glauber' largest, T_RENTo lowest).
- DREENA-A can differentiate between different *T* profiles.
- Additional (independent) constraint to low-pt data.

Importance of higher harmonics for QGP tomography



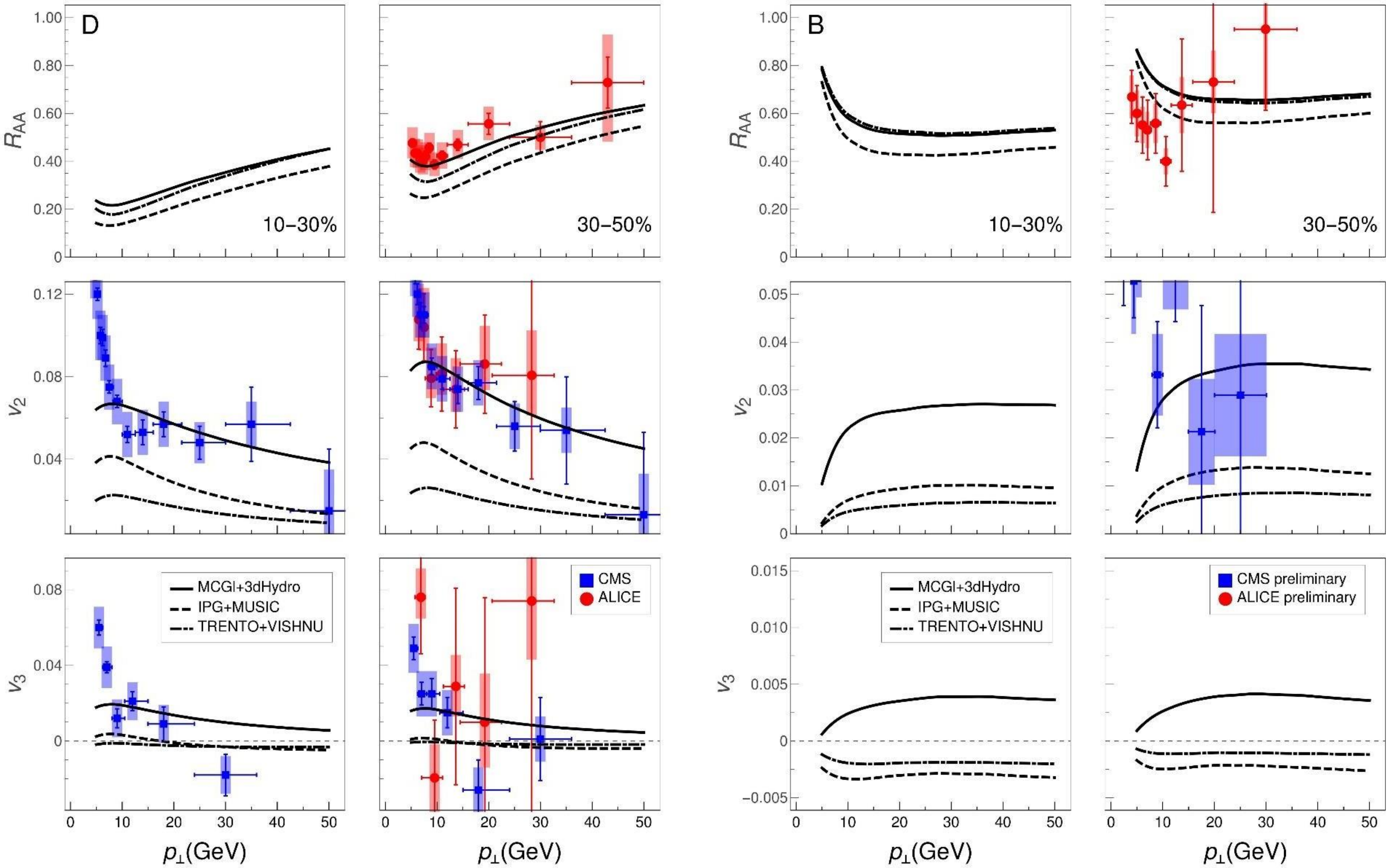
D. Zigic, J. Auvinen, I. Salom, P. Huovinen and MD, Phys.Rev.C 106 (2022) 4, 044909

- High-pt data are available up to the 7th harmonic (for ATLAS) and cover the pt region up to 100 GeV (for CMS).
- State of the art in the experimental sector, but theoretically not well explored!
- **Can higher harmonics be used for precision QGP tomography?**

- Higher harmonics can both qualitatively and quantitatively distinguish between different medium evolutions!
- Existent v_4 data are far above all model predictions – a possible v_4 puzzle!

Heavy flavor higher harmonics

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



- Heavy flavor - even more sensitive to different medium evolutions!
- Upcoming high-luminosity data at RHIC and LHC will provide higher harmonics data with much larger precision.
- Higher harmonics present a unique opportunity for precision QGP tomography.
- Adequate medium evolution should be able to all experimental data simultaneously, for both light and heavy flavor, at different centralities and collision energies.

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

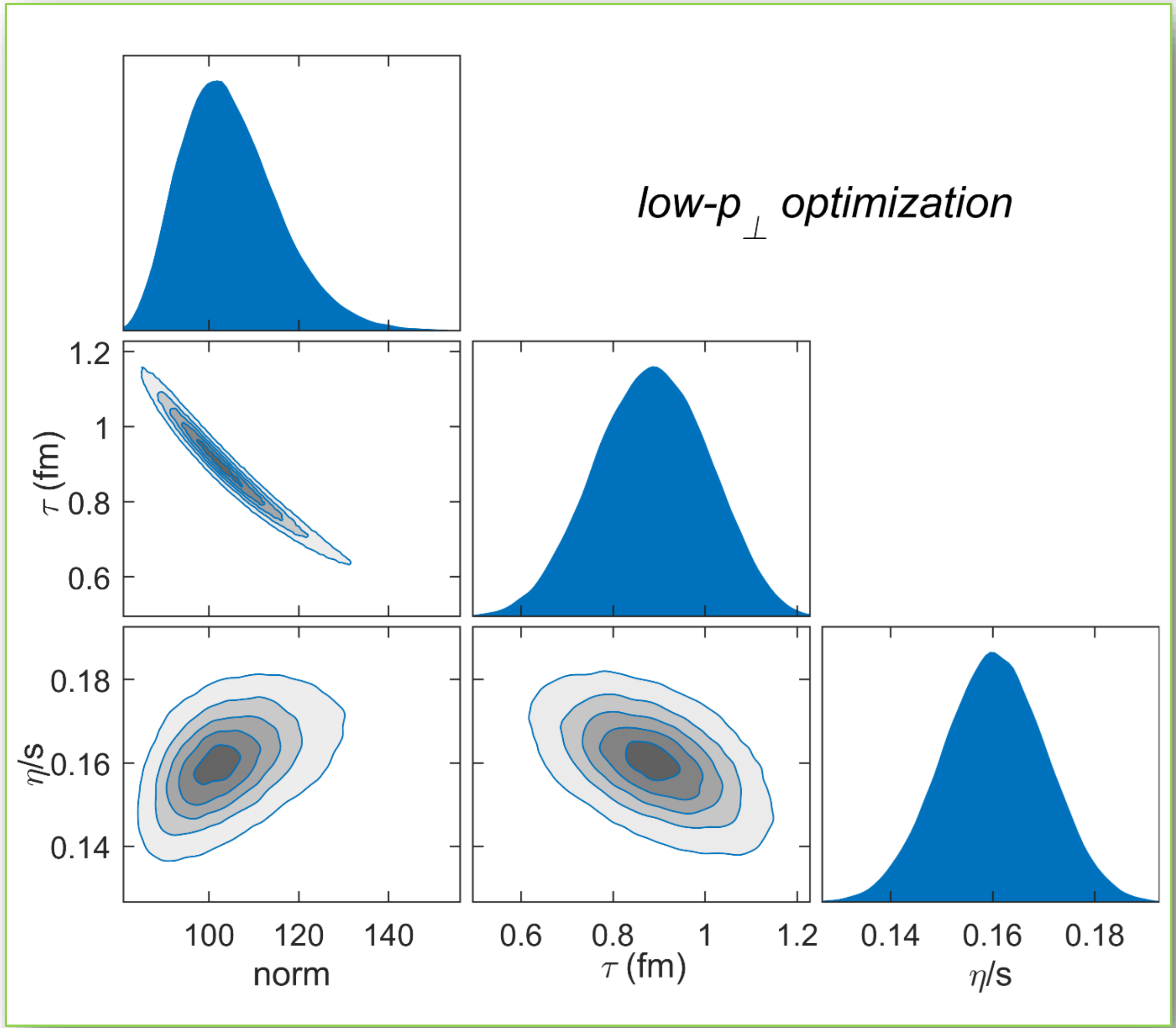
Bayesian inference (Hamiltonian Monte Carlo sampling)

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

- 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 ranges:
  - τ: 0.2-1.3 fm
  - Constant η/s: 0.02-0.2
  - Norm: 60-360

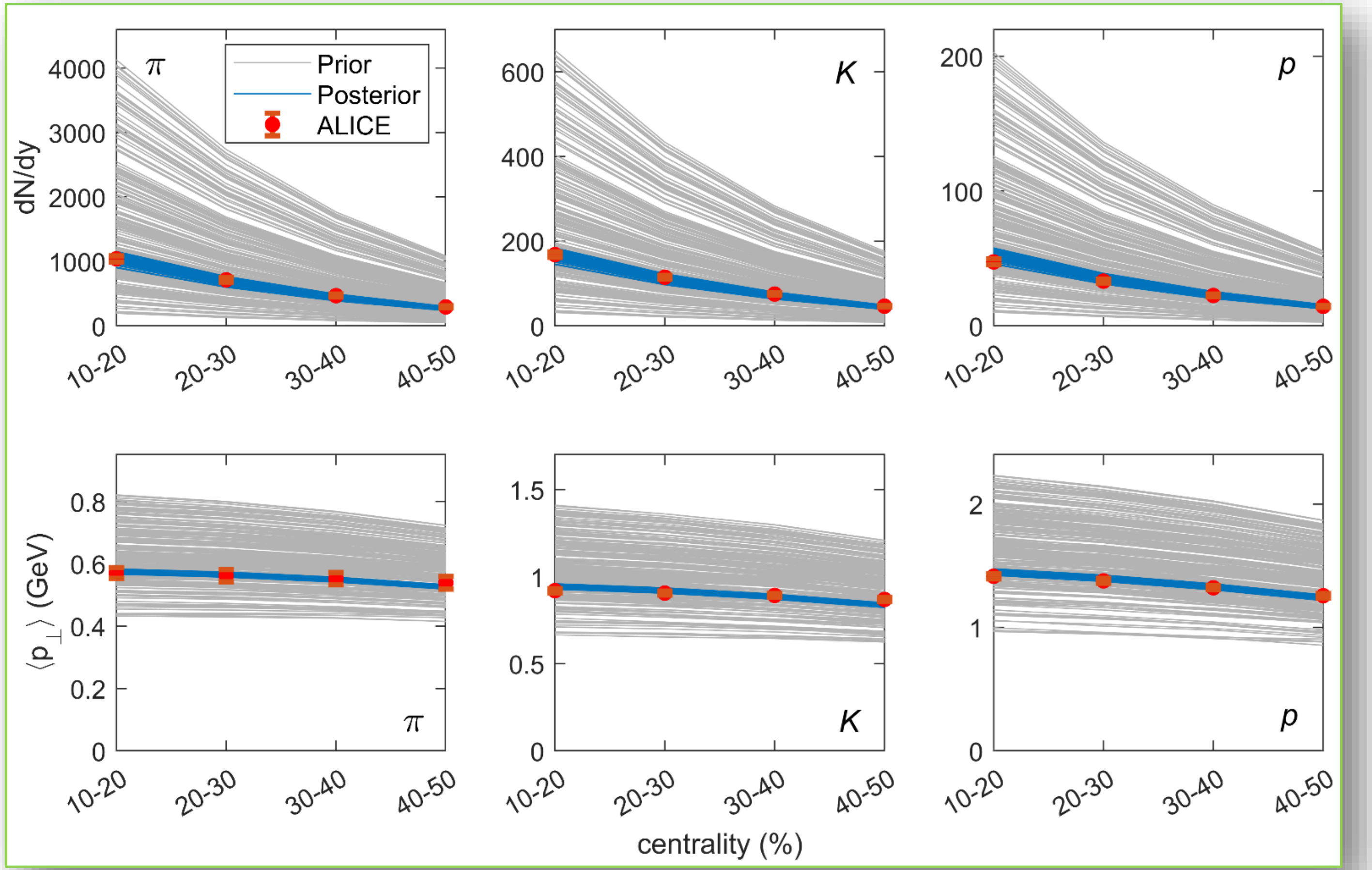
  All other parameters are as in PRC **108**, 044907 (2023).
- For each set of parameters, we run average medium evolutions with TRENTo+ VISHNew, to generate low-pt predictions and *T* profiles as an input for DREENA-A.
- Run DREENA-A with these *T* profiles to generate high-pt predictions.
- Statistical 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.

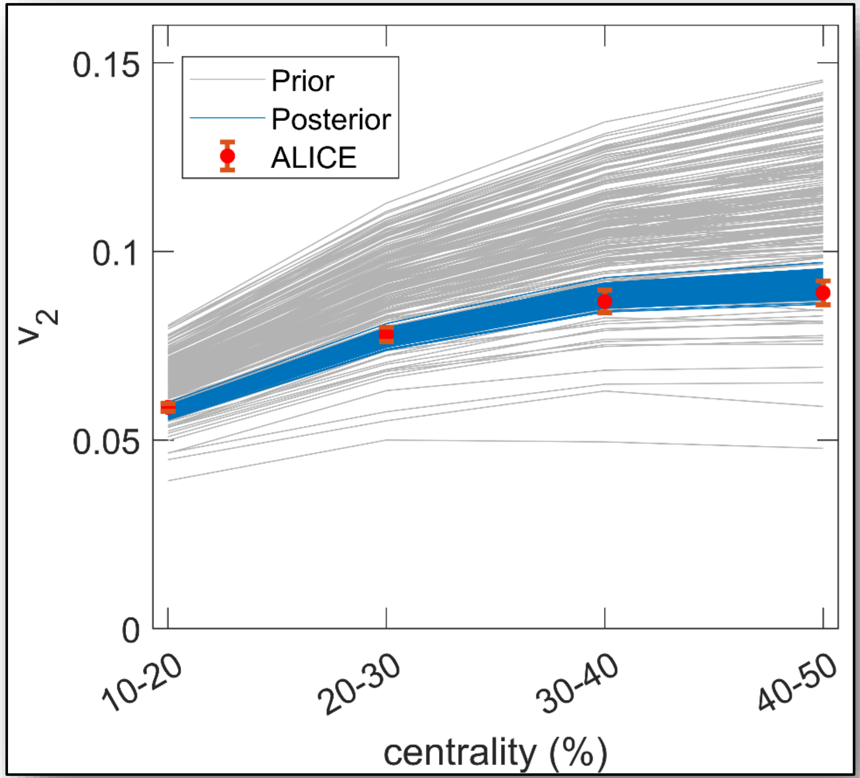
Marginal distribution of parameters obtained with Bayesian inference of low-pt data



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

Prior vs. posterior: low-pt data

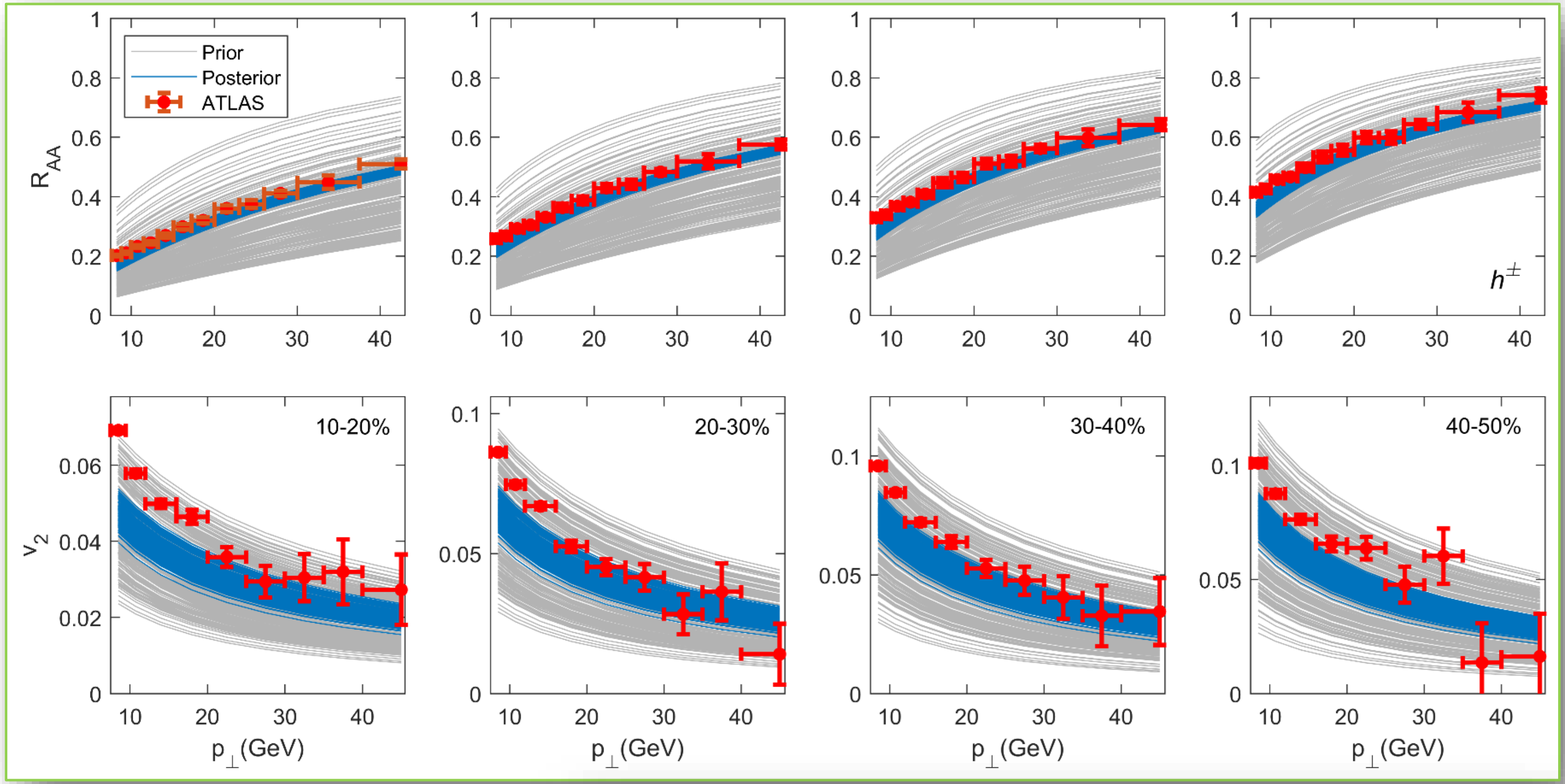




Very good agreement with low-pt data!

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

Prior vs. posterior: high-pt data



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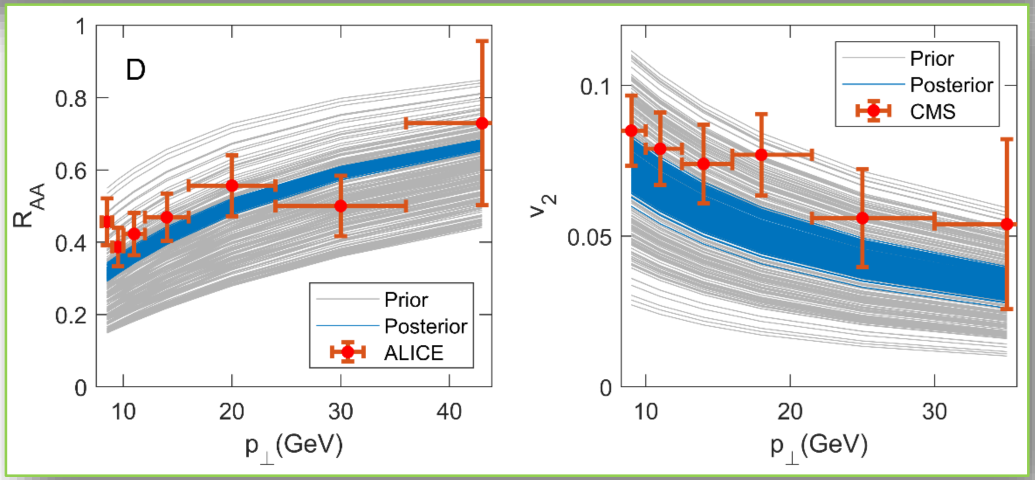
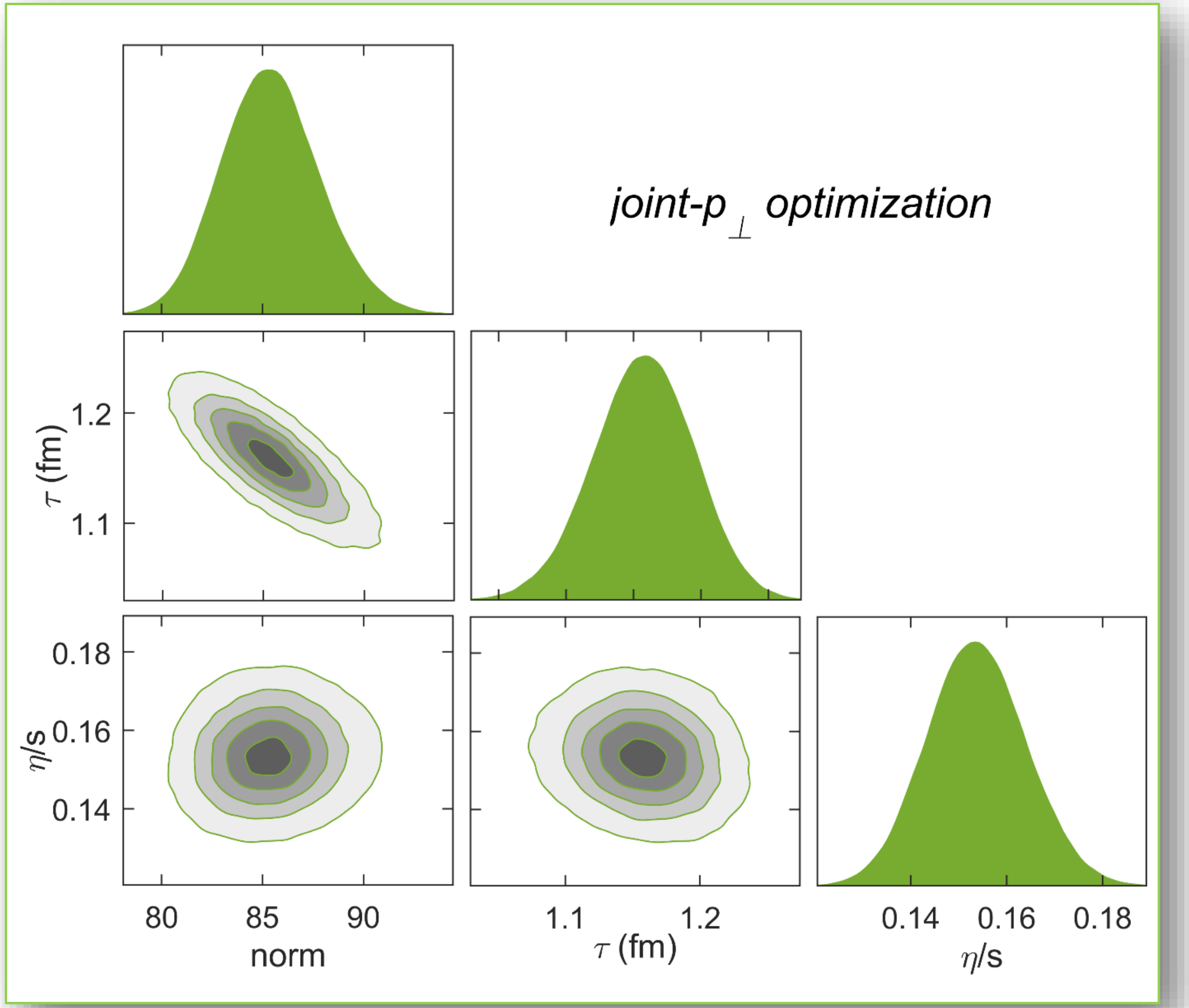


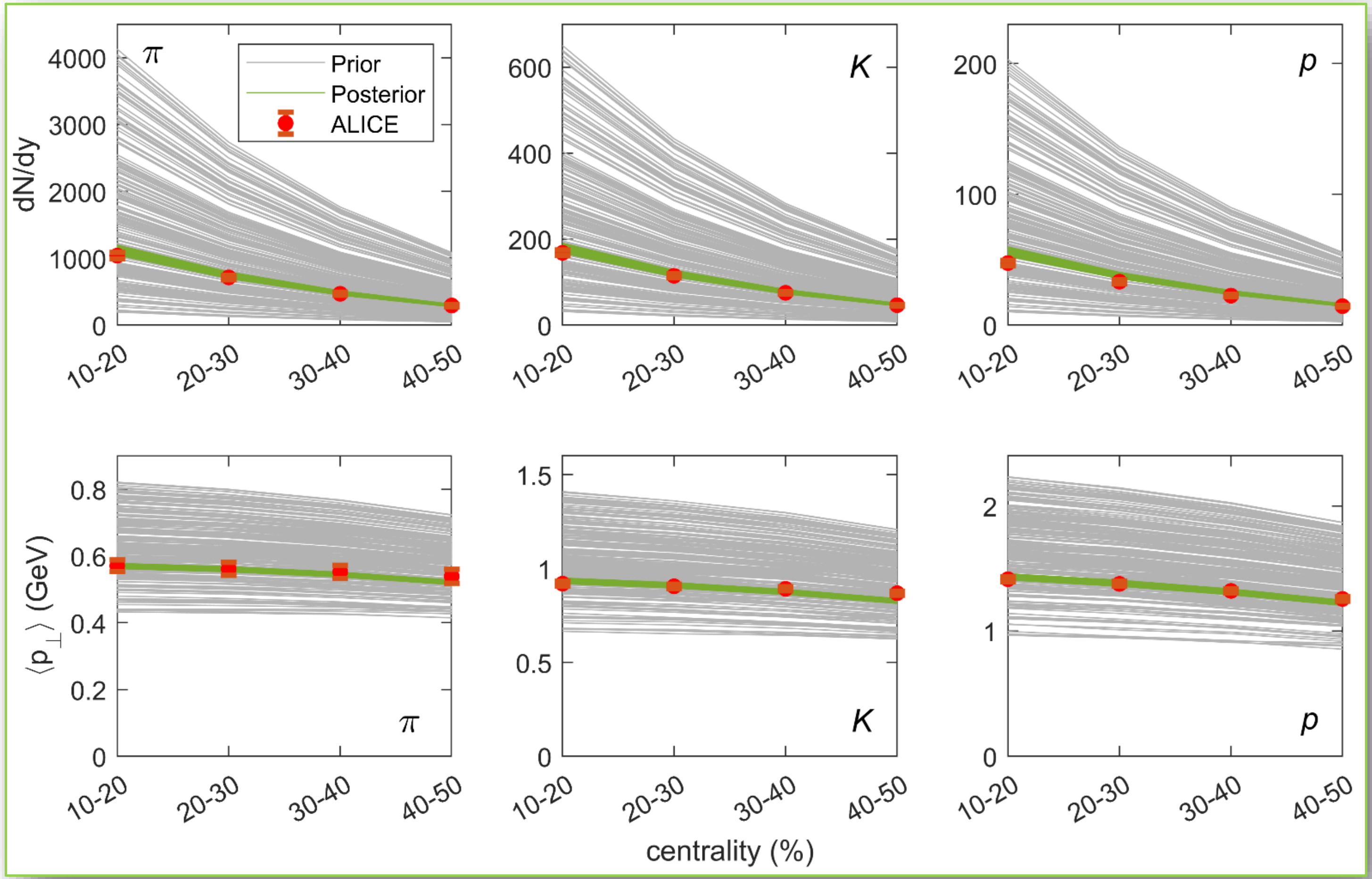
Suboptimal agreement with high-pt data, especially for v_2.

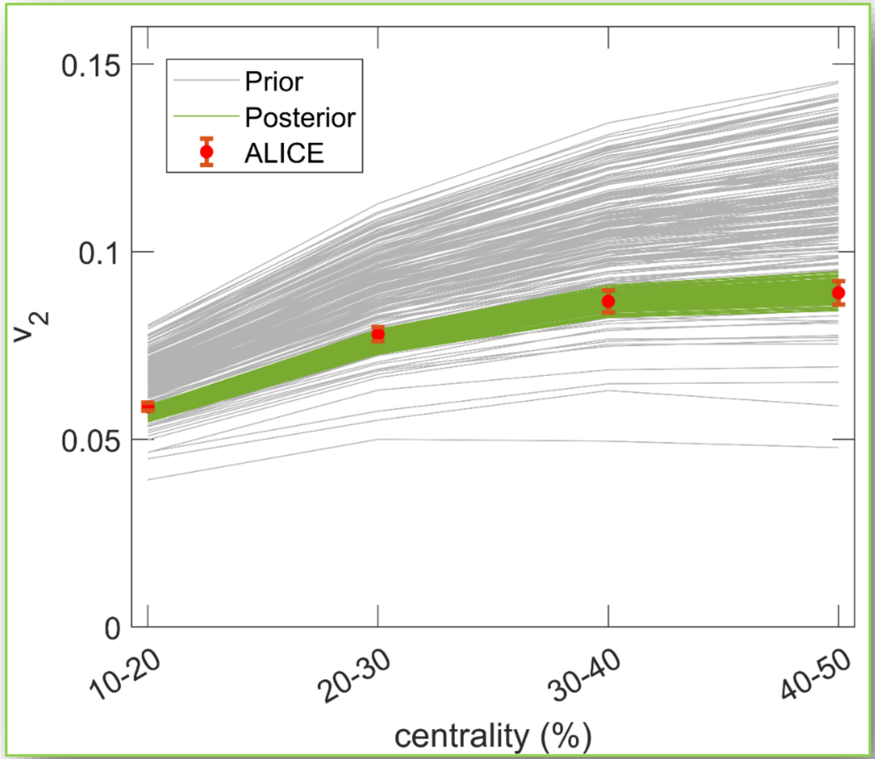
Marginal distribution of parameters obtained with Bayesian inference of both low-pt and high-pt data



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

Prior vs. posterior: low-pt data

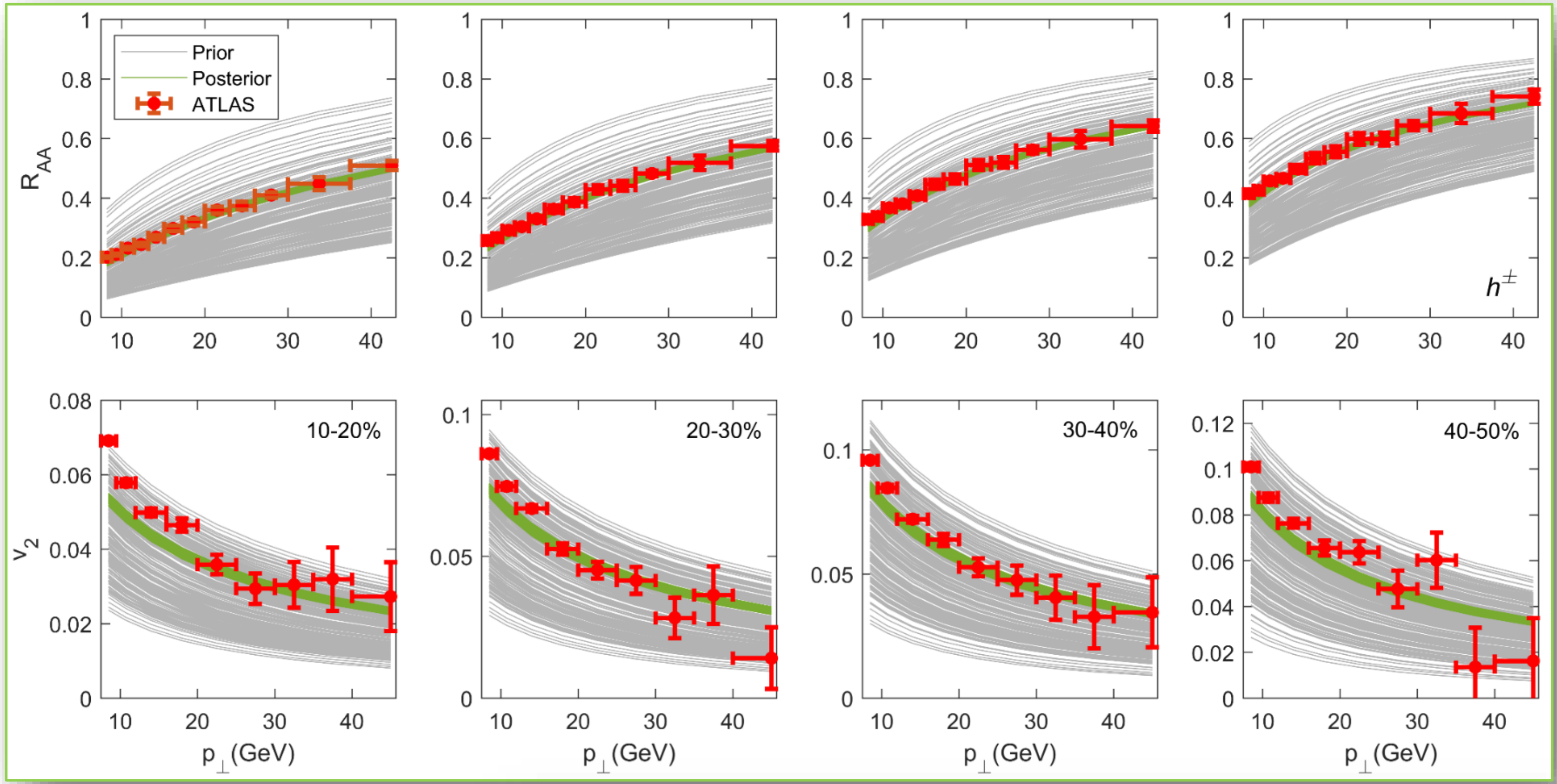


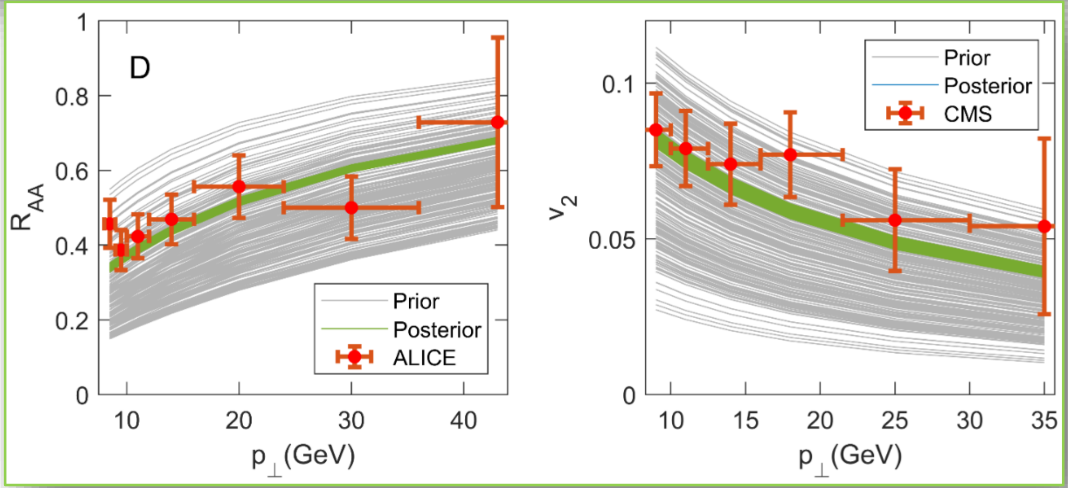


Very good agreement with low-pt data!

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

Prior vs. posterior: high-pt data



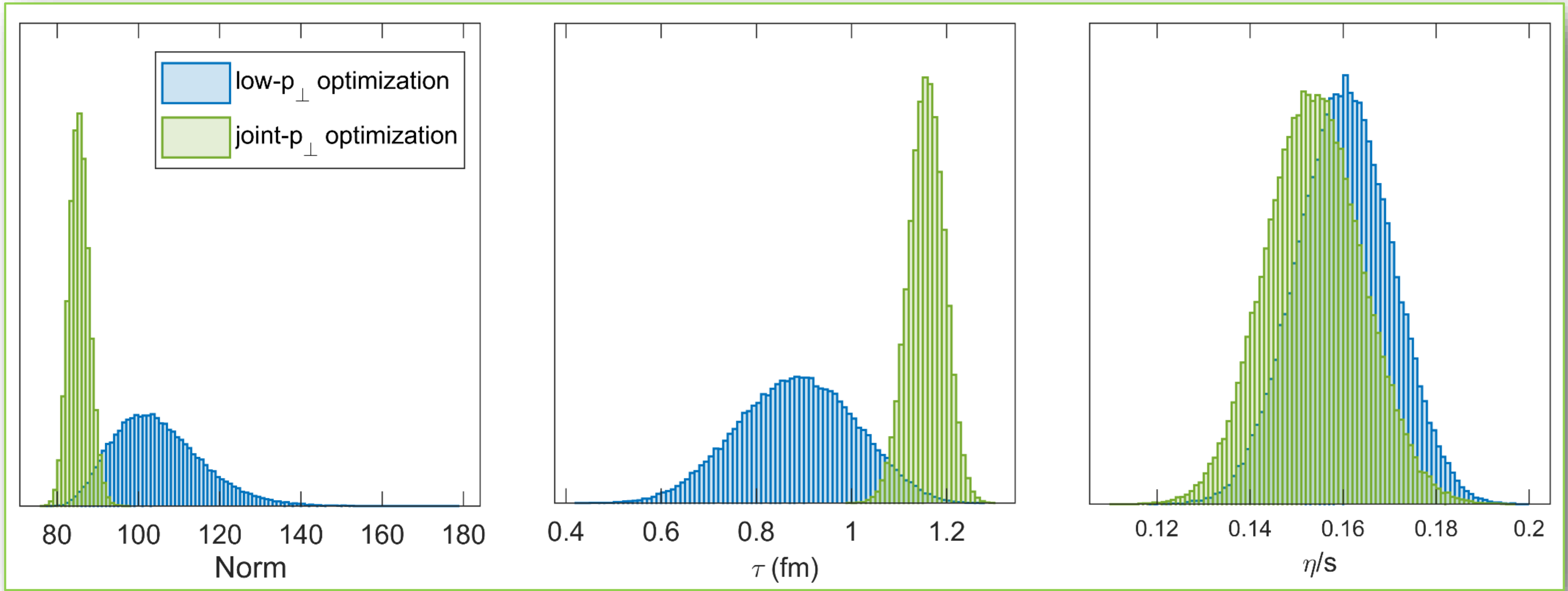


M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).

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!

Summary: Optimizing QGP Parameter Extraction

- Unifying low-pt and high-pt theory and data with advanced Bayesian statistics significantly improves constraints on QGP properties. High-pt data from RHIC and LHC were underutilized for this purpose, and this approach enables their optimal use.

What do we need from the experimental data at the LHC and RHIC in the high-precision era to accurately extract QGP parameters?

- Improved agreement between different experiments within the LHC.
  - Precise extraction of QGP parameters is challenging if the data from different experiments agree within large error bars.
- Precise measurements for high-pt D meson R_{AA}, v_2, and higher harmonics.
- Precise measurements for at least B meson high-pt R_{AA} and v_2 data.
  - Due to heavy mass (the dead cone effect), B mesons provide an independent variable, offering a much better constraint on QGP parameters. Models must simultaneously explain both low and high-pt data, and within high-pt data, they need to explain for both light and heavy flavor.

Conclusion: A joint effort between theorists and experimentalists will be essential to precisely extract the properties of this extraordinary new form of matter.

Canyon of river DREENA in Serbia

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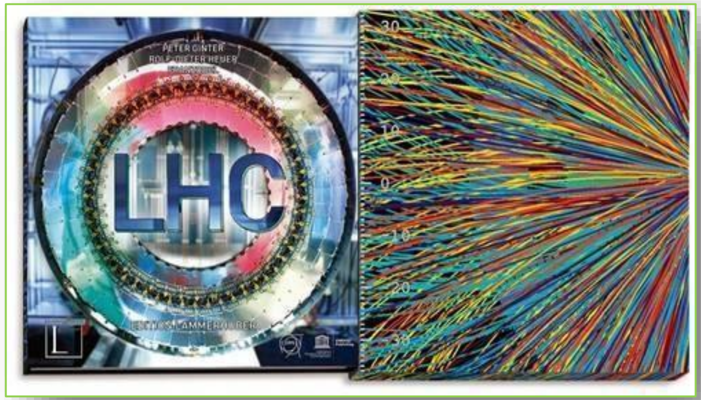
МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

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).

What next?



2023	2024	2024	2025
Au+Au	p-p	p+Au	Au+Au
Calibration	Ref. measurements for HI		High statistics

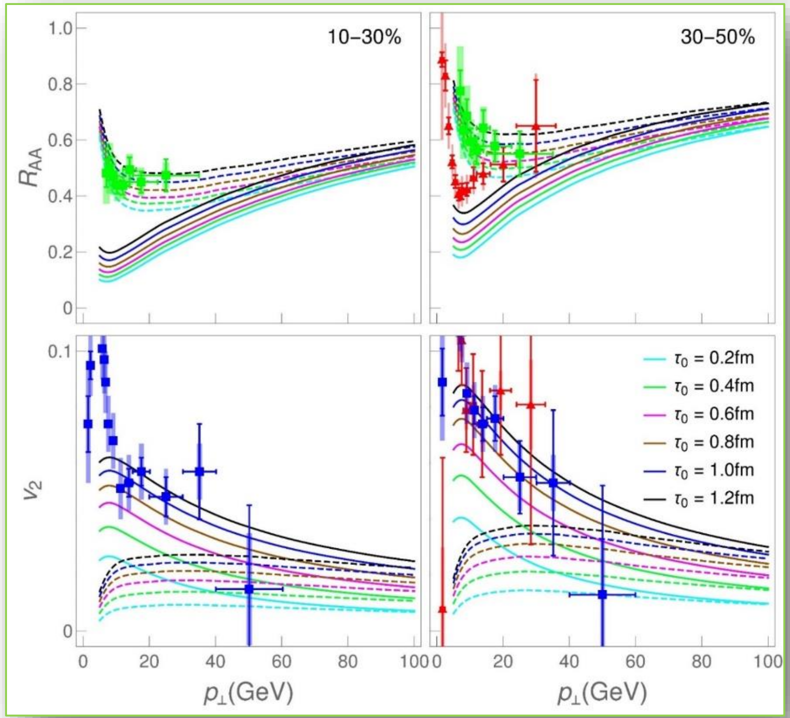
The beginning of the high-precision era at RHIC and LHC

DREENA can enable better utilization of the upcoming experimental data, as well as precise determination of the properties of this extreme state of matter.

Exploring bulk QGP properties through DREENA

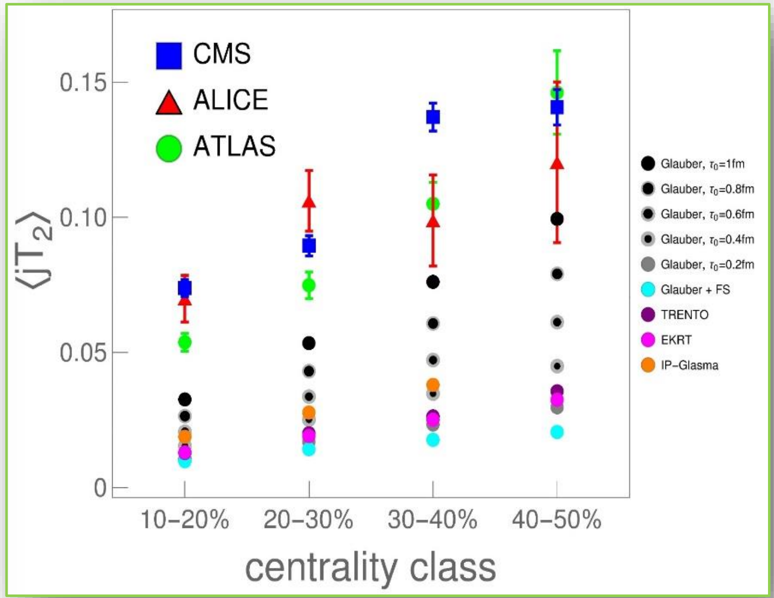
Constrained the early evolution of QGP.

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



Proposed a new observable to constrain QGP anisotropy

S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen, MD, Physics Letters B **835**, 137501 (2022).



Probed the shape of the QGP droplet with ebeDREENA

B. Karmakar, D. Zigic, P. Huovinen, M. Djordjevic, MD, and J. Auvinen, arXiv: 2403.17817 (PRC in press)