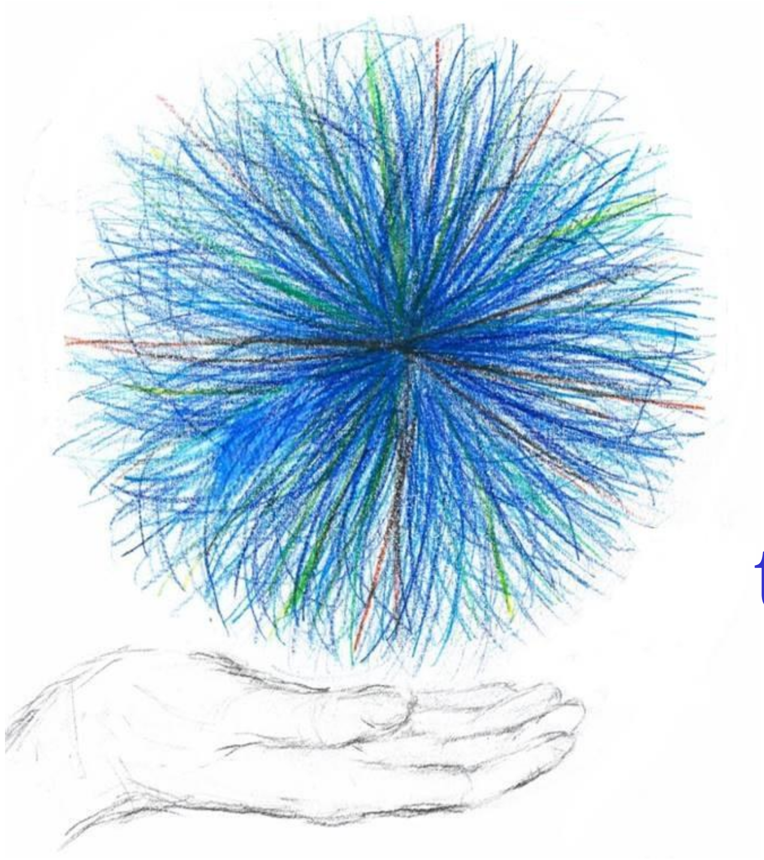


# Exploring bulk QGP properties through high-pt theory and data

Magdalena Djordjevic, IPB

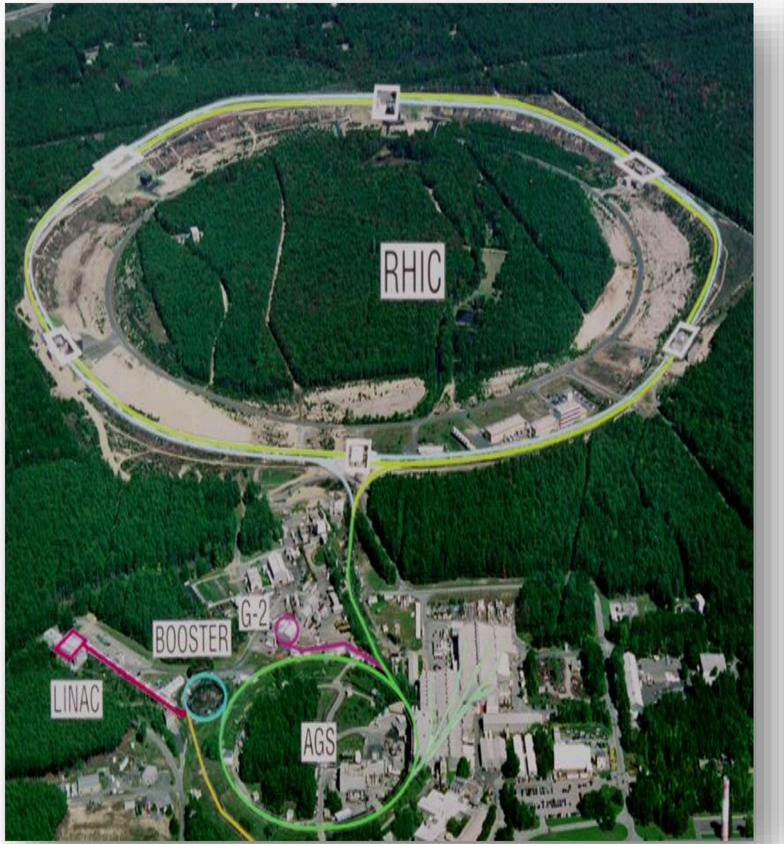
# Brief overview of Quark Gluon Plasma

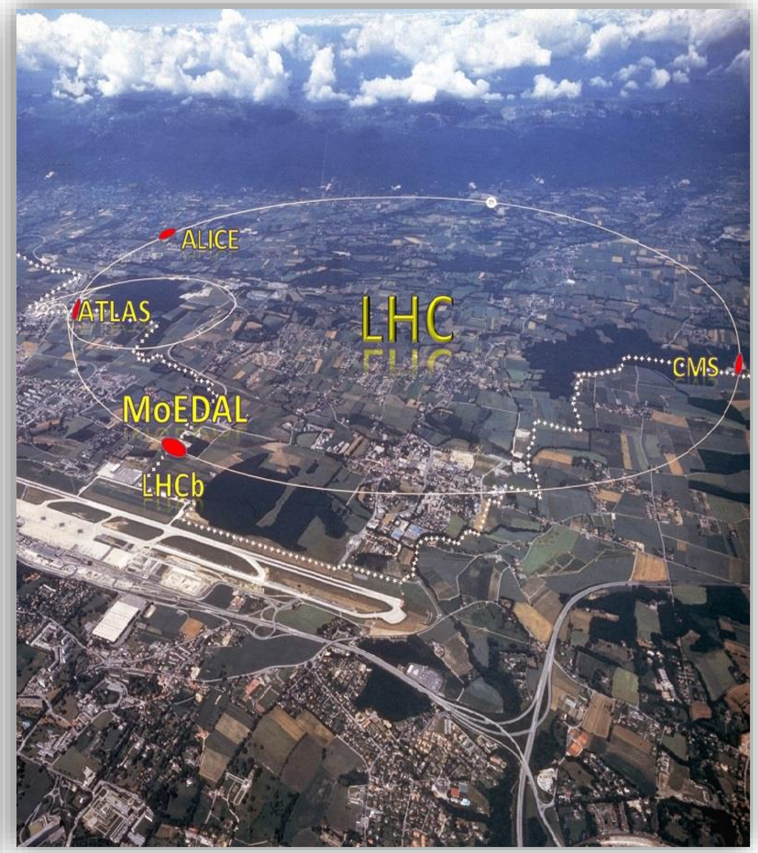
QGP is a new form of matter consisting of deconfined and interacting quarks, antiquarks and gluons. QCD predicts QGP to exist at extremely high energy densities.

One of the most important goals of high energy heavy ion physics is to form, observe and understand QGP.

↓

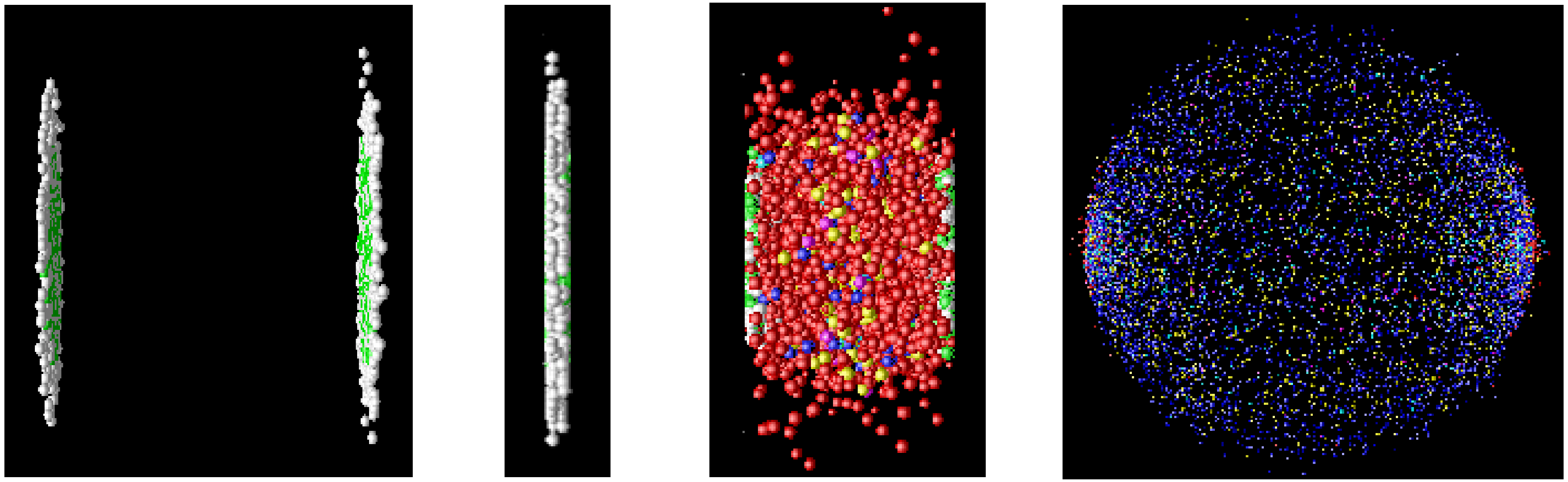
Ultra-Relativistic Heavy Ion Colliders (RHIC and LHC) at BNL and CERN.



# Scheme of relativistic heavy ion collisions

Simulation "VNI" (Geiger, Longacre, Srivastava)



Heavy ion acceleration

Collision

Quark-gluon plasma

Hadron Gas

To study the properties of QCD matter created at URHIC, we need suitable probes.

Low-pt particles are widely used to explore the properties of QGP.

QGP discovered at RHIC and LHC.

Current challenge: Understand QGP properties

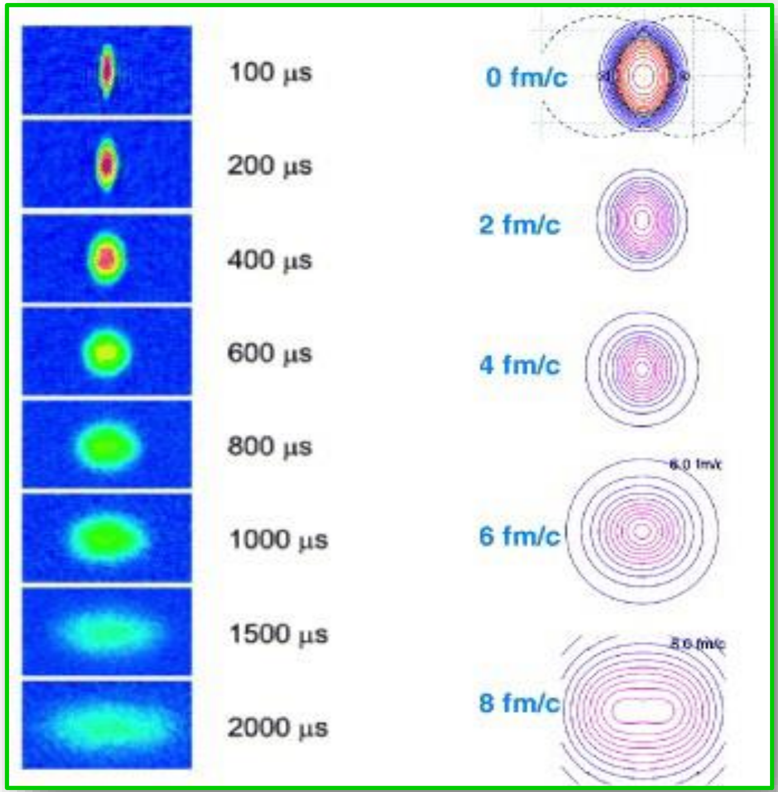
Expected: The QGP was anticipated to behave as a weakly interacting gas.

## Current paradigm:

- Strongly coupled system, i.e., nearly perfect fluid.
- Estimated η/*s* close to the lower bound conjectured by AdS/CFT.

Surprising connection between the hottest and coldest matter on Earth.

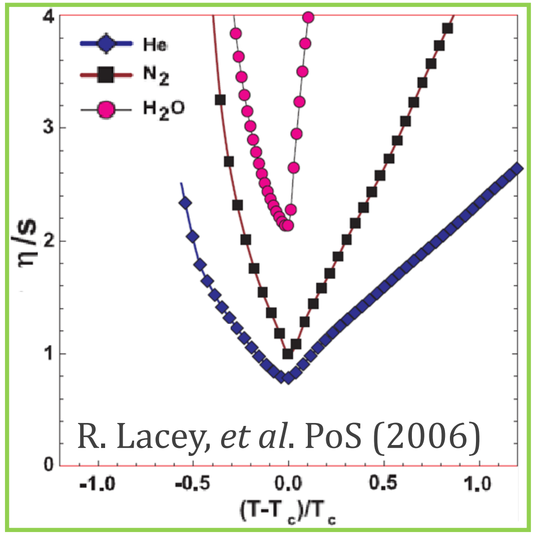
M. A. Lisa, *et al.*, New J. Phys. 13 (2011)




Ultracold Fermi gas $T \sim 10^{-6}$K

perfect fluid QGP simulation $T \sim 10^{12}$K

# Is QGP really perfect fluid?

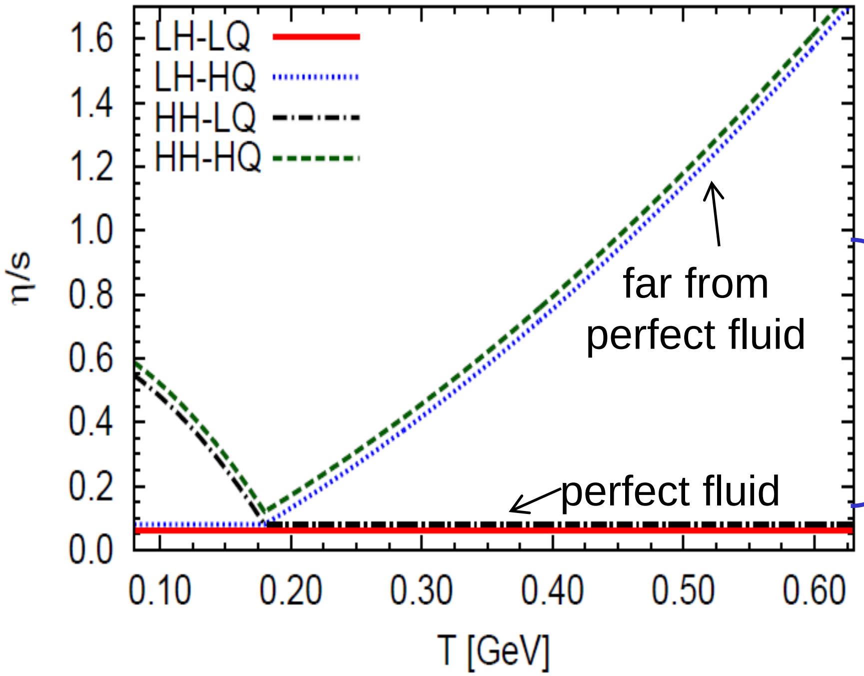



Origin of the low $\eta/s$ throughout QGP evolution unclear.

$\eta/s$ increases with T for all other substances.

The paradigm originates from the relativistic hydrodynamics.

H. Niemi *et al.*, PRL 106 (2011)



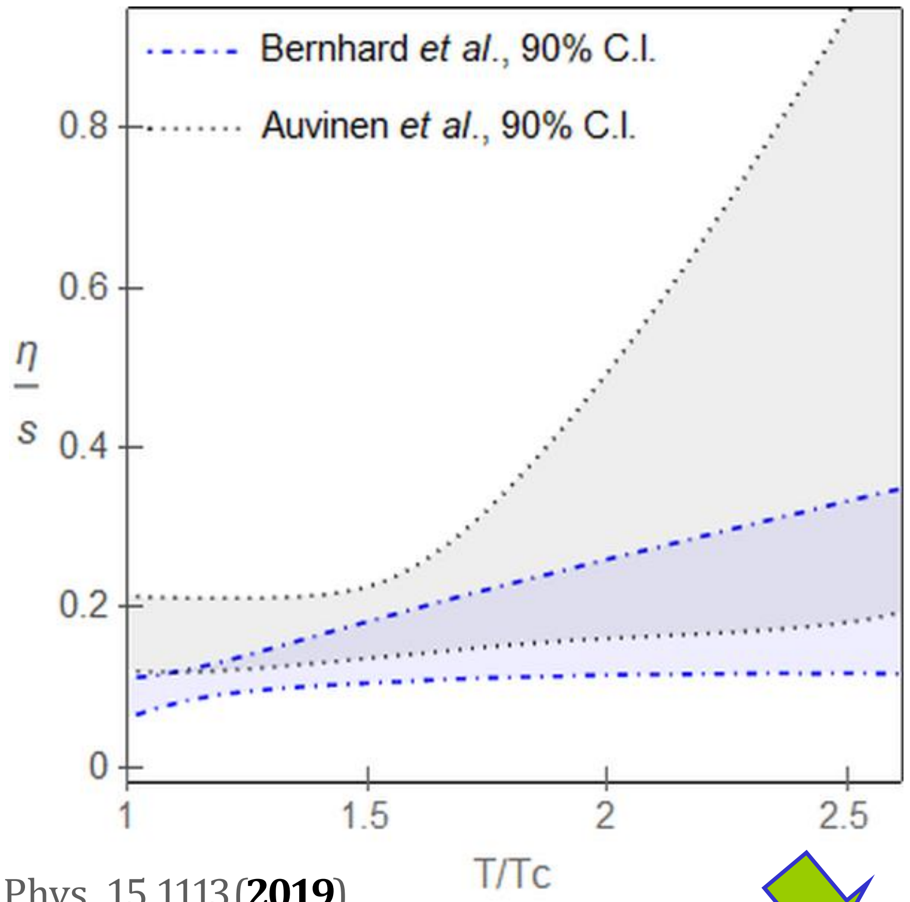

However, the predictions insensitive to even a large increase in $\eta/s$ not far away from the transition temperature ($T_c$).

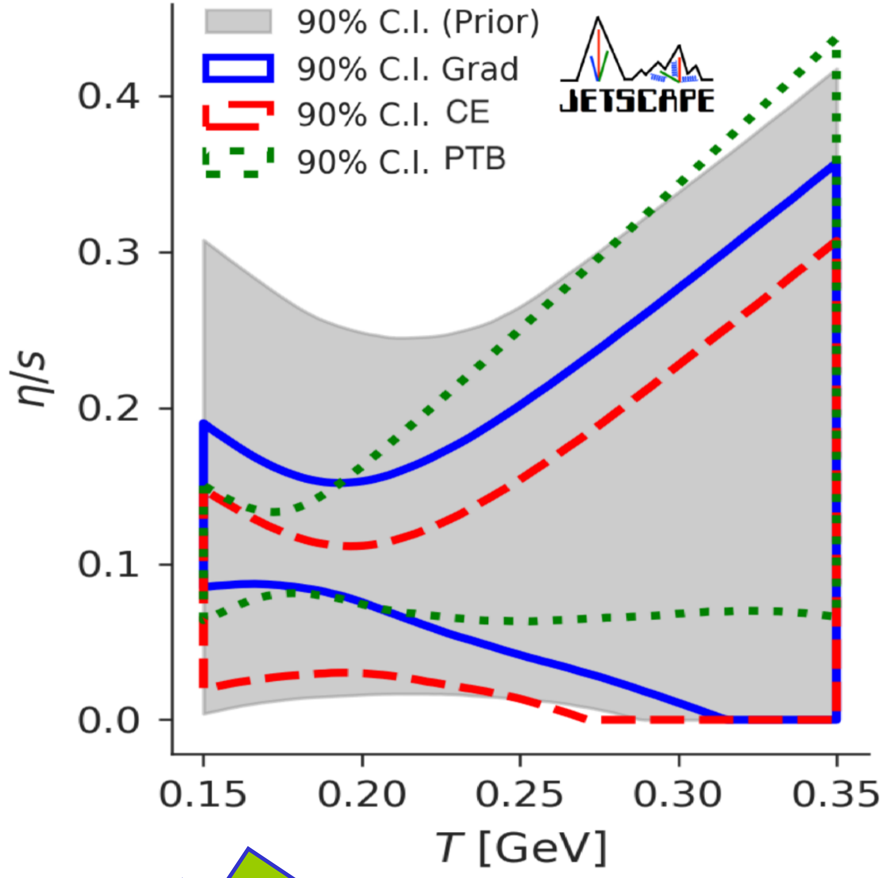
Similar insensitivity by other approaches, e.g.:
- hydro (PRC 94:024907,2016)
- parton transport (PRC 92:054902,2015)

## Perfect fluid too perfect ?

J. Nagle *et al.*, New J.Phys.13:075004,2011

Motivated by this, numerous state-of-the-art Bayesian statistical analyses were performed using viscous hydrodynamics models and low-pt data to constrain the bulk QGP properties:




**Blue:** Nature Phys. 15,1113 (**2019**)

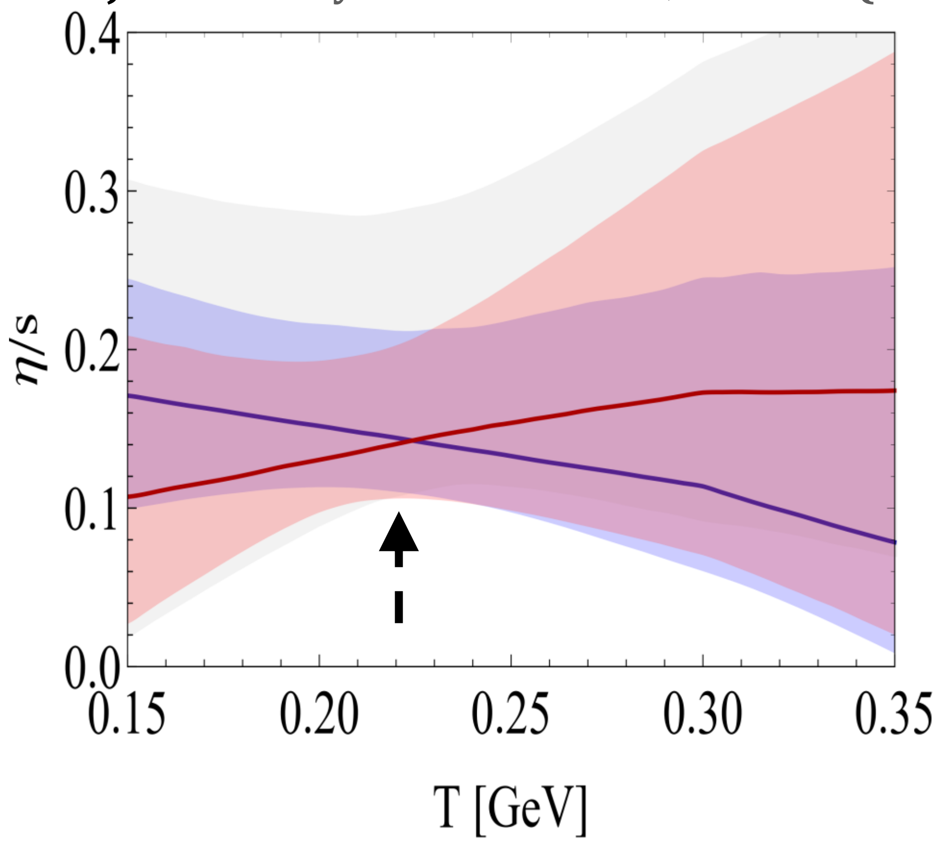
**Gray:** Phys. Rev. C 102,044911 (**2020**)

**JETSCAPE:** Phys. Rev. C 103, 054904 (**2021**)

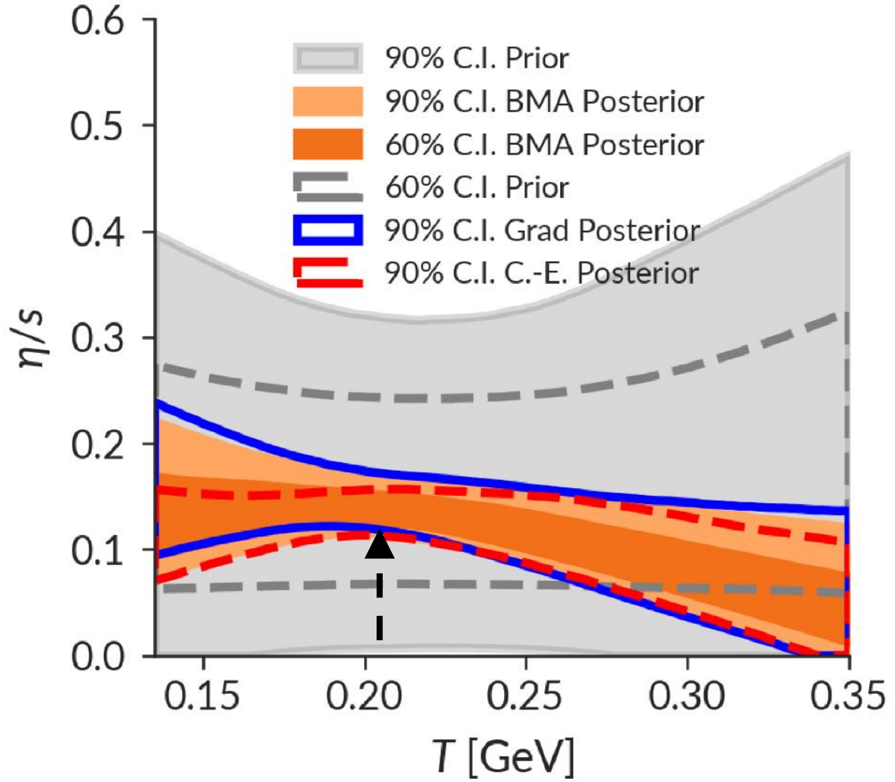
η/s is well constrained by Bayesian analyses in the low-$p_\perp$ sector in the temperature range $T_c \lesssim T \lesssim 1.5T_c$, but weakly constrained at larger temperatures.

# Latest Bayesian analyses suggest that minimum for η/s is not at $T_c$ and that that η/s may even decrease with T?!

**Trajectum:** Phys. Rev. Lett. 129, 232301 **(2022)**




**MUSIC:** Phys. Rev. C 109, 065207 (**2024**)




After almost 20 years of QGP discovery, the $\eta/s(T)$ dependence still remains a puzzle! This is one of the key questions about the properties of QGP to which we still do not know the answer!

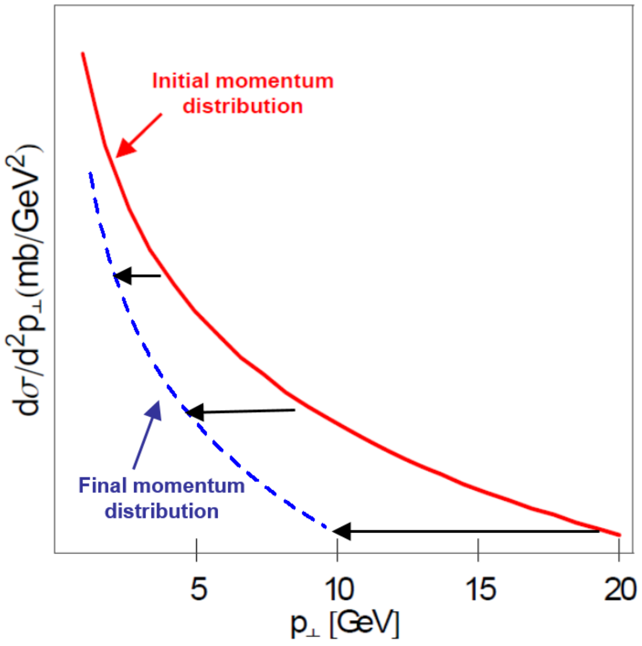
How to gain a new insight?

Relativistic hydrodynamics predictions → Low momentum data

# How to provide substantially new insight?

pQCD predictions → High momentum (pt) data

## The main idea: Use high pt data/theory




$$R_{AA} = \frac{\text{Final momentum distribution}}{\text{Initial momentum distribution}}$$

Wealth of precision high pt data available, or will soon become available - dawn of the high precision era (Run3 at the LHC and sPHENIX at BNL).

Angular *average* suppression

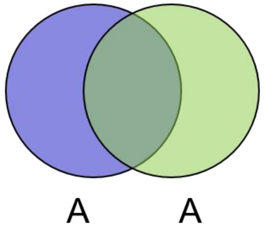
high pt hadron $R_{AA}$

Probes high *pt* parton interactions with QGP

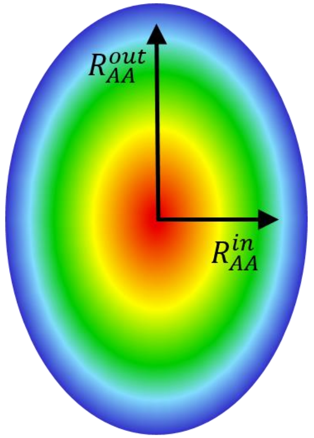
Angular *differential* suppression

high pt hadron $v_2$ and higher harmonics

Probes QGP evolution




Assymetric collision of two heavy ions

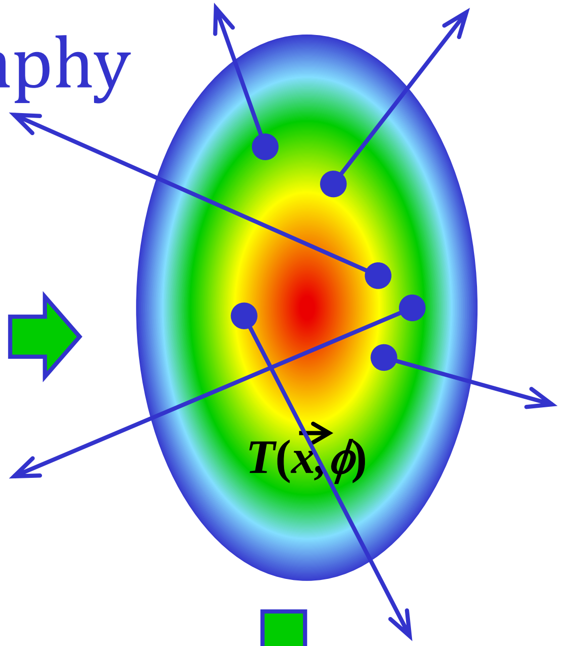



$$v_2 = \frac{R_{AA}^{in} - R_{AA}^{out}}{R_{AA}^{in} + R_{AA}^{out}}$$

# The main idea behind high-pt QGP tomography

Different *bulk* medium parameters lead to different $T(\vec{x},\phi)$

Directly probe $T$ profiles through high *pt* partons




Compare with high *pt* data for both *light and heavy* flavour probes

Infer $T(\vec{x},\phi)$ (i.e. $\eta/s(T)$) consistent with both low-*pt* and high-*pt* data

Note: Contribution to the energy loss is larger for higher $T$

Larger sensitivity for inferring $\eta/s$ at high $T$

In distinction to low pt data which are the least sensitive at high $T$

High *pt* theory/data – powerful complementary tool to constrain bulk QGP properties.

Performing Bayesian analyses with both low-pt and high-pt data may enable us to better constrain the QGP parameters and answer some of the key questions about the properties of this extreme form of matter.

While recognized as a milestone by the JETSCAPE collaboration, no decisive steps have been taken in this direction.

"The inclusion of jet observables and electromagnetic probes in the Bayesian analysis, while a major undertaking, would represent milestones with considerable potential to constrain the viscosities at higher temperature as well as the properties of the early stage in heavy-ion collision!"

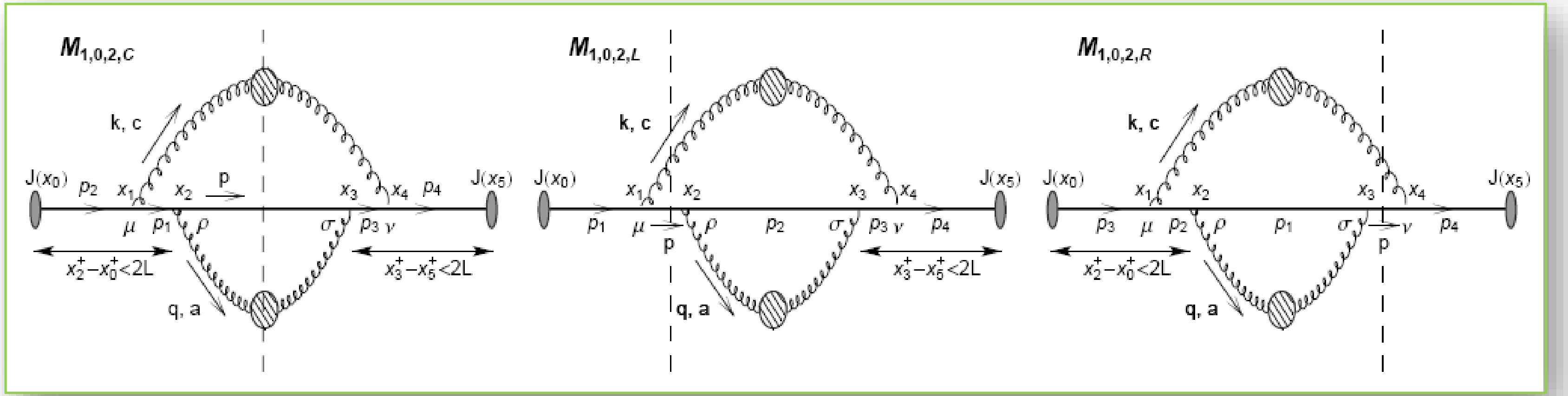
**JETSCAPE:** Phys. Rev. C 103, 054904 (2021)

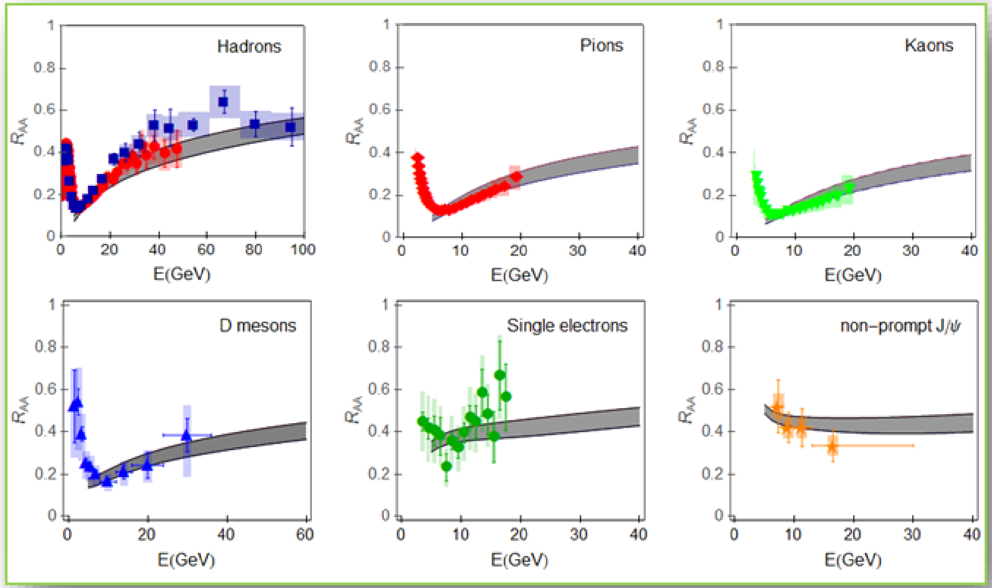
Within our ERC project, our group has made significant progress in this direction, and I will provide an overview of why this idea is important.

# The dynamical energy loss formalism

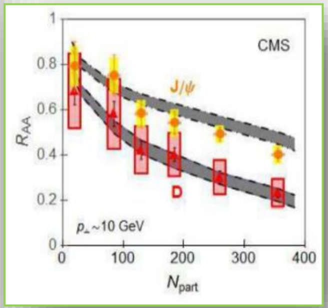
Has the following unique features:

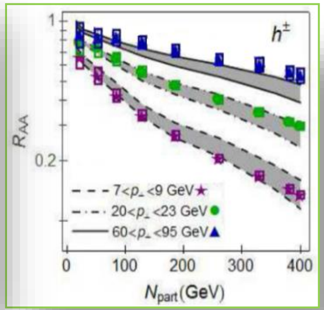
- *Finite size finite temperature* QCD medium of *dynamical* (moving) partons.
- Based on finite *T* field theory and generalized HTL approach.
- Same theoretical framework for both radiative and collisional energy loss.
- Applicable to both light and heavy flavor.
- Finite magnetic mass effects (M.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



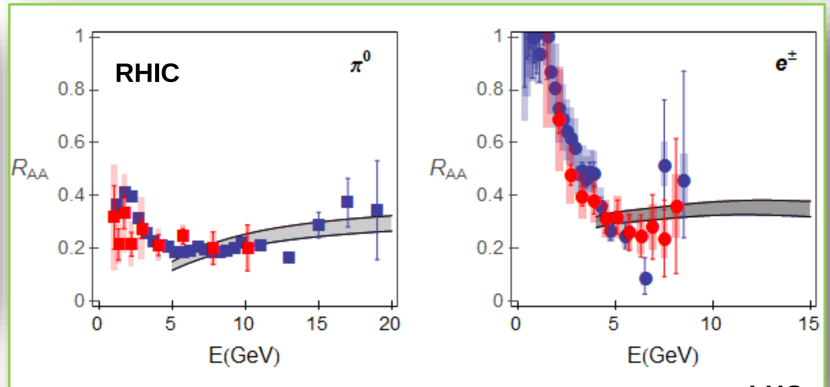



Explains high-pt $R_{AA}$ data for different probes, collision energies, and centralities.

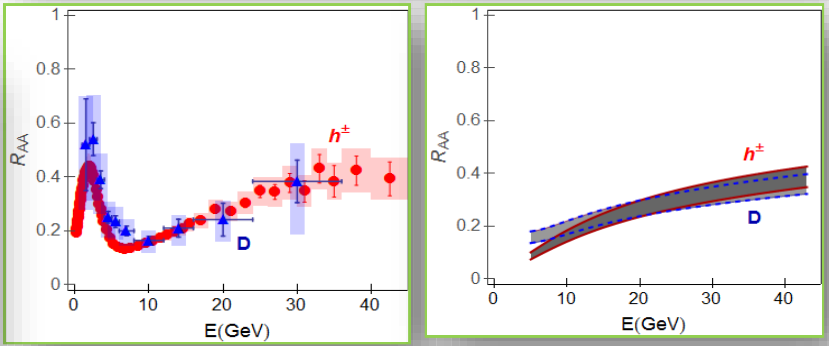



Resolved the longstanding "heavy flavor puzzles at RHIC and LHC".

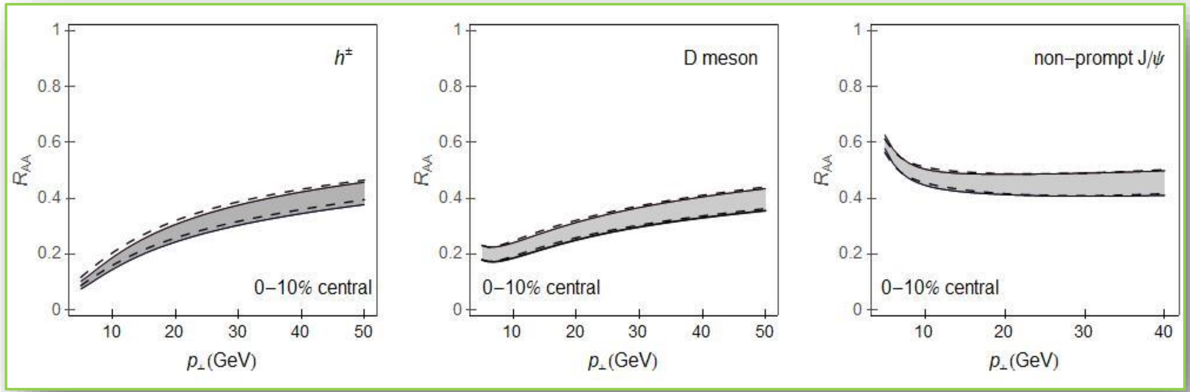


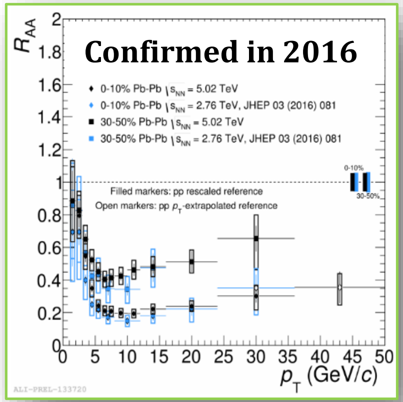

LHC




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!

# 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.

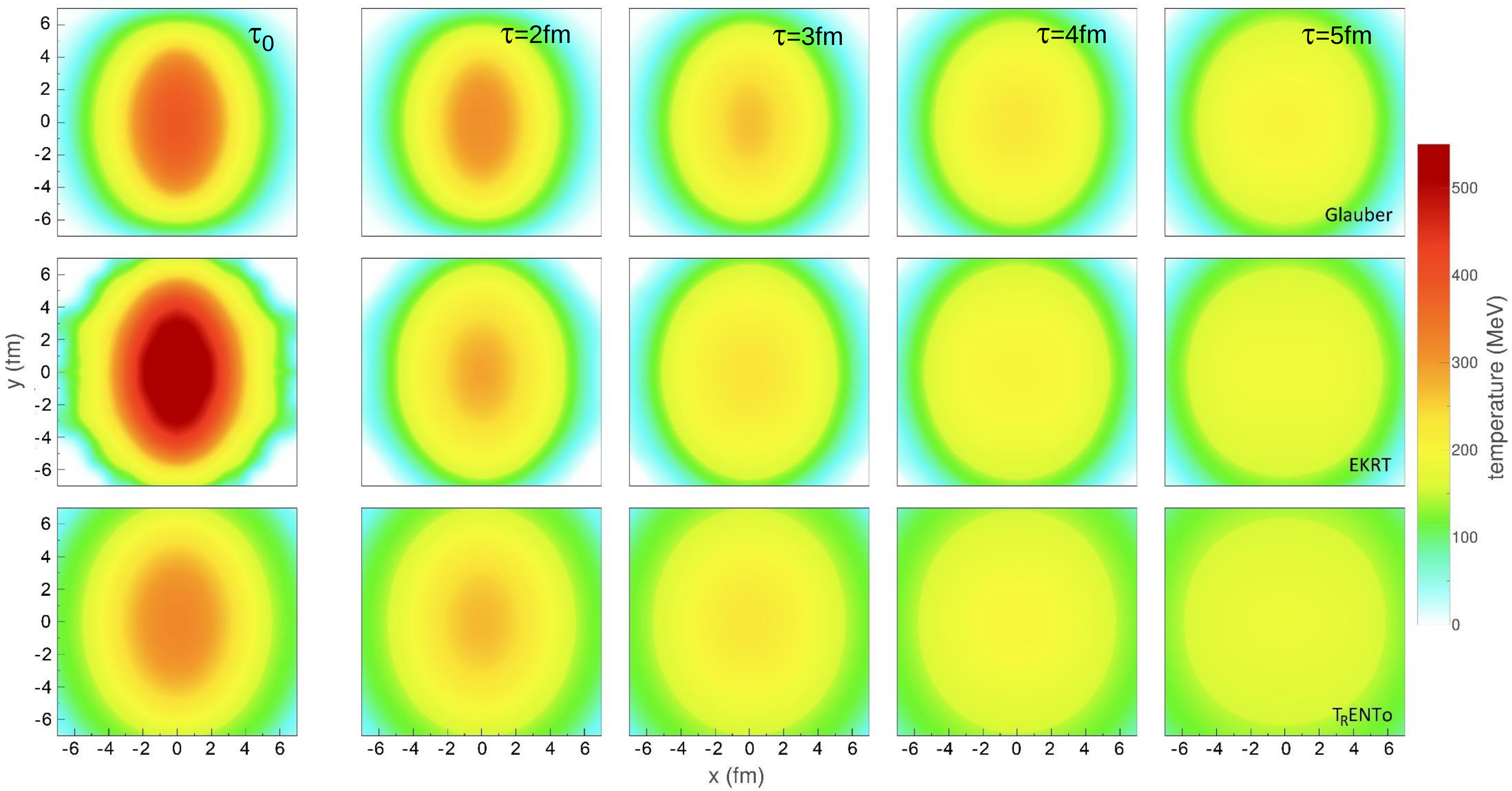
D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic Front. in Phys. 10 (2022) 957019

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

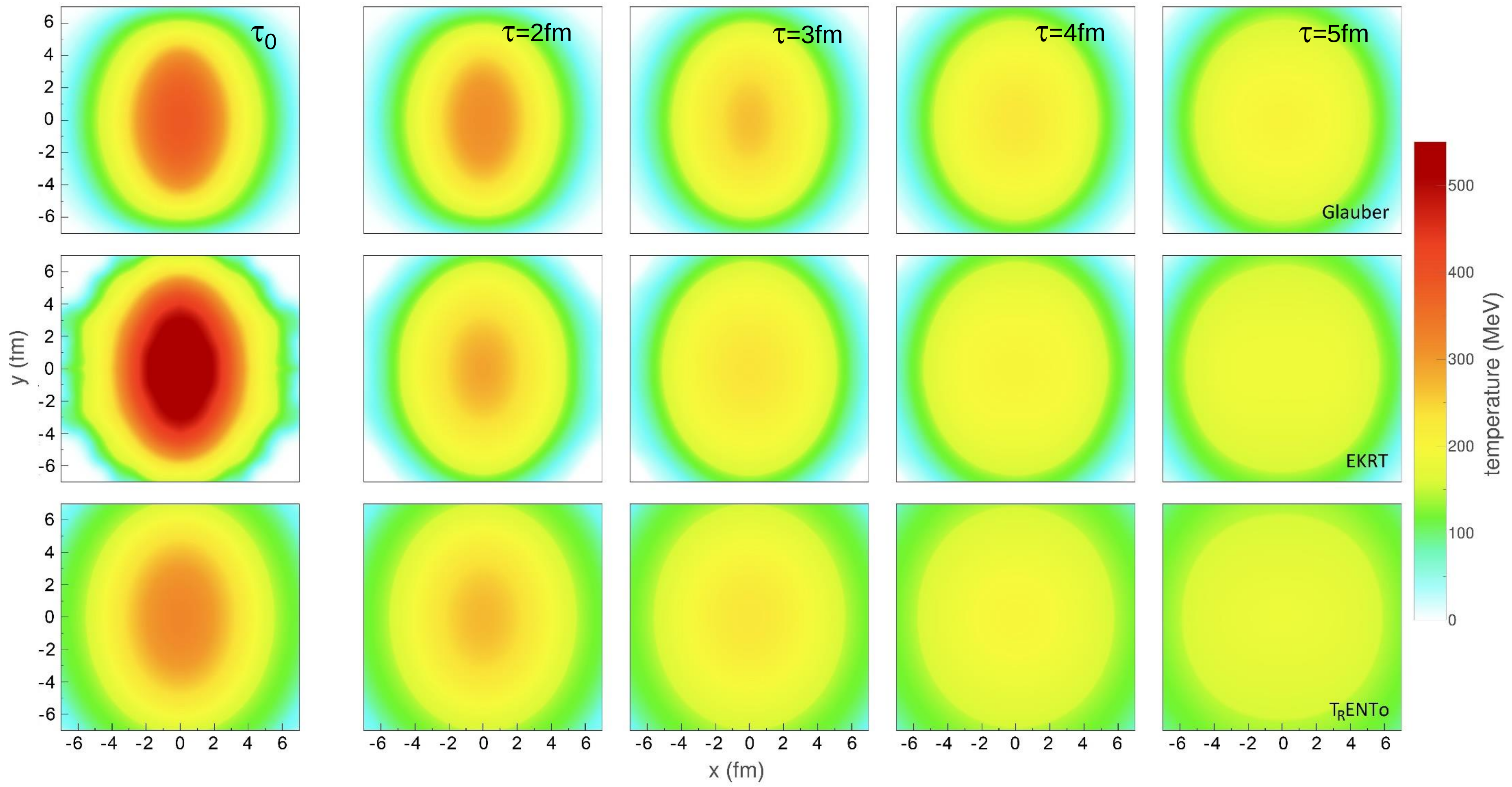
# Are high-pt observables indeed sensitive to different T profiles?




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

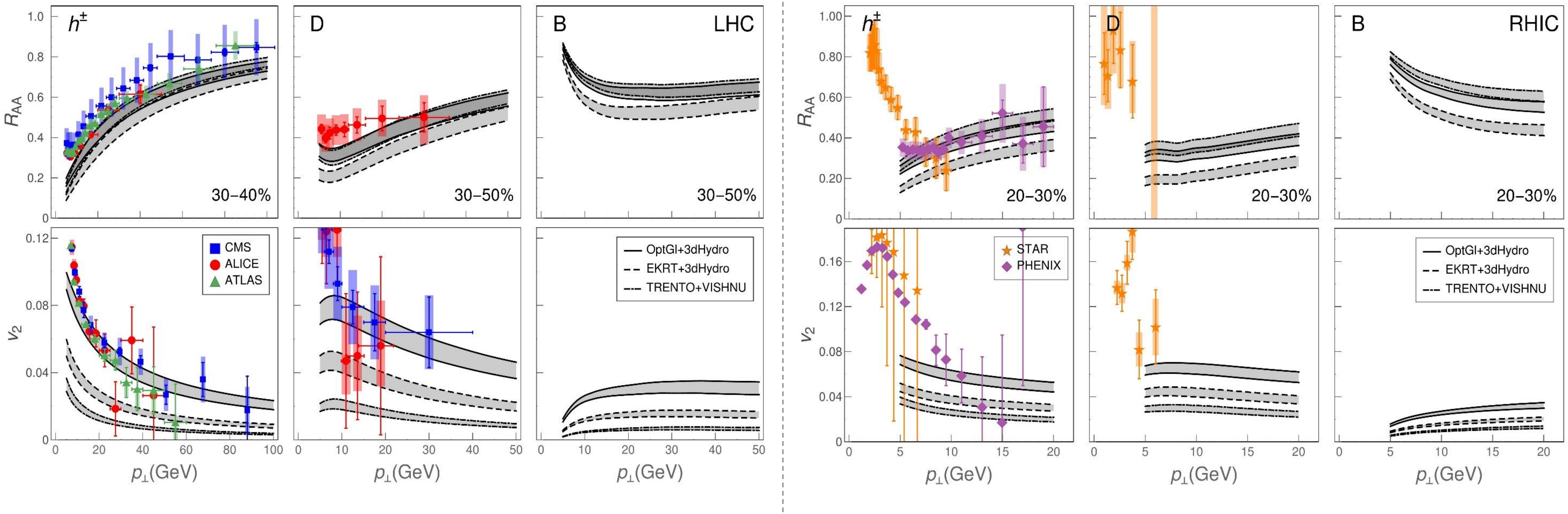
# Qualitative differences




- Largest anisotropy for Glauber ($\tau_0$=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

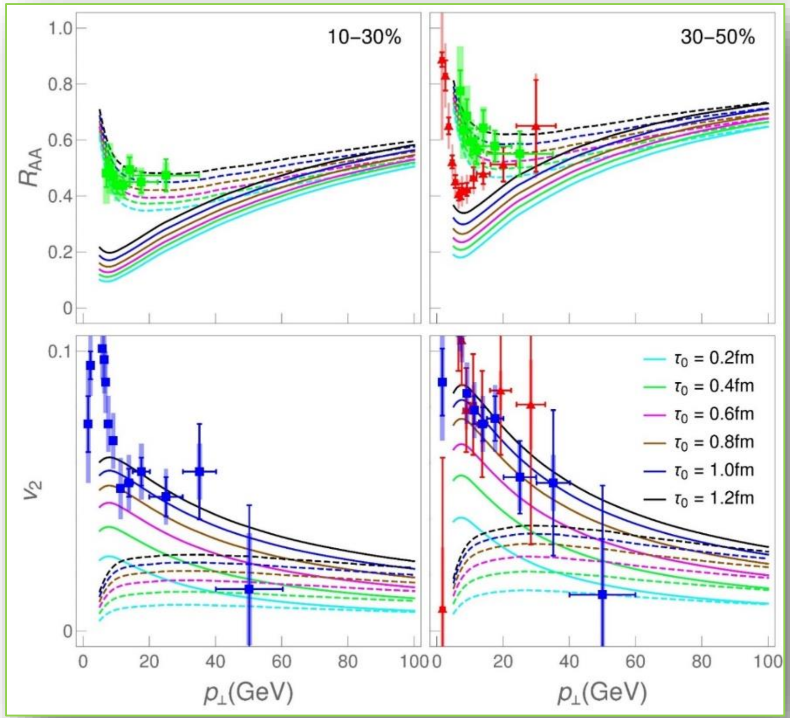



- 'EKRT' indeed leads to the smallest $R_{AA}$.
- Anisotropy translates to $v_2$ differences ('Glauber' largest, $T_R$ENTo lowest).
- High-pt predictions and data can differentiate between different *T* profiles.
- Additional (independent) constraint to low-pt data.

# Exploring bulk QGP properties through DREENA

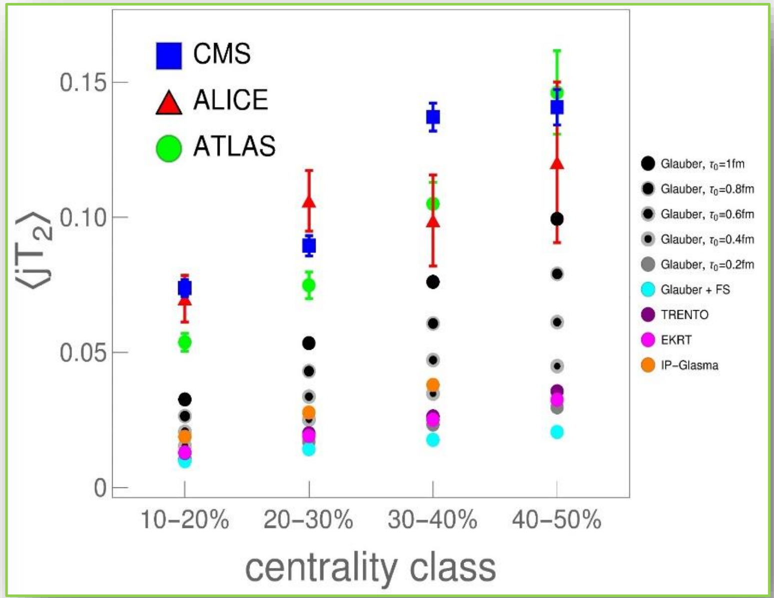
## Constrained the early evolution of QGP.

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



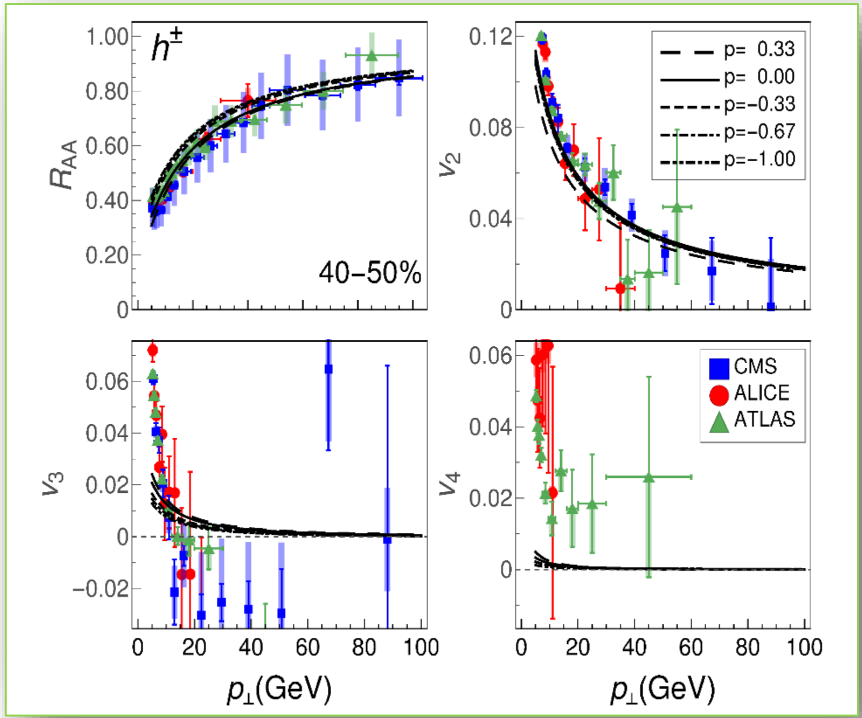

## Proposed a new observable to constrain QGP anisotropy

S. Stojku, J. Auvinen, L. Zivkovic, P. Huovinen, MD, Phys. Lett. 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, Phys. Rev. C **110**, 044906 (2024),



# 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)

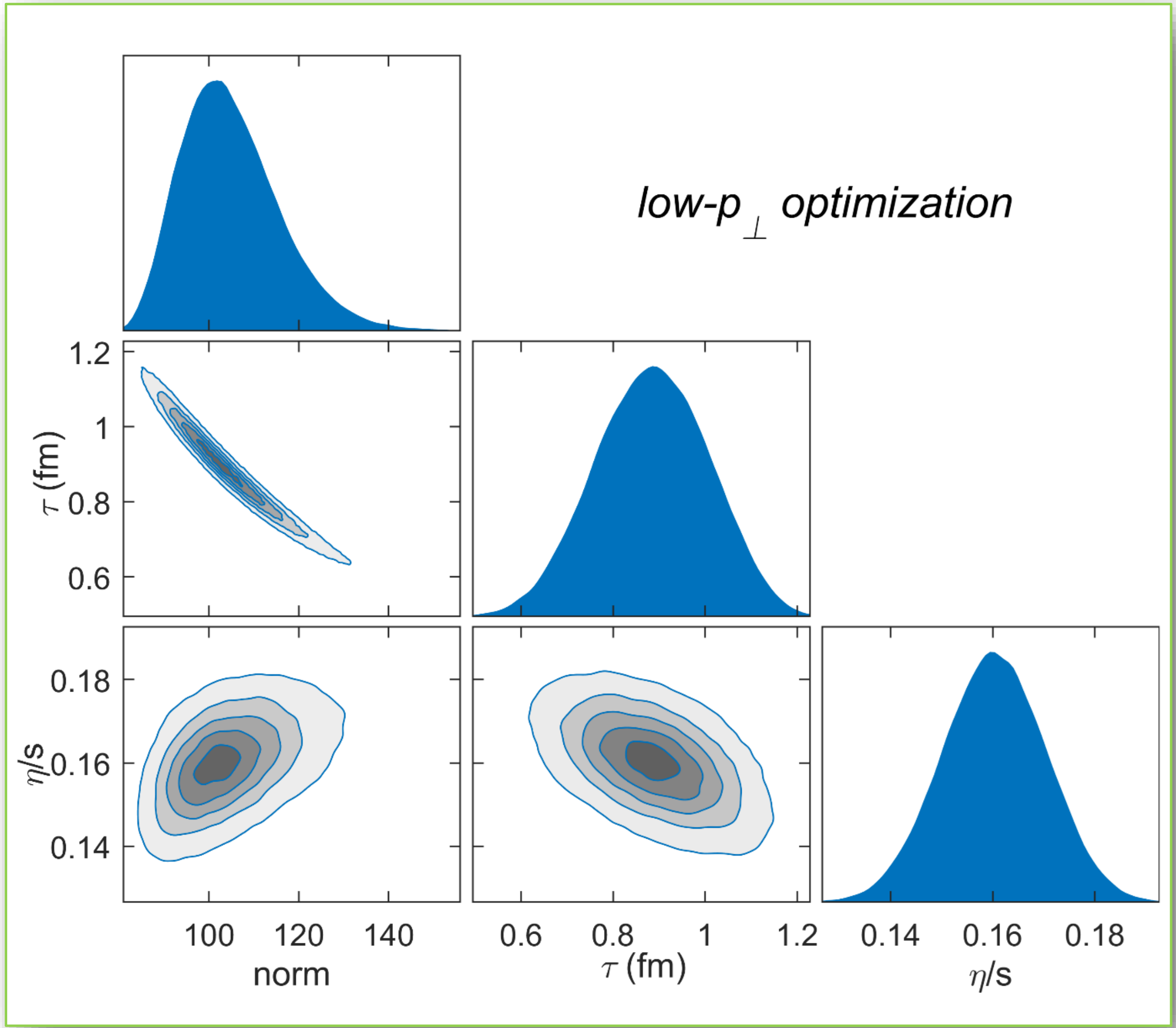
→
- Parameter posterior distributions.
- Low-pt and high-pt predictions compared with experimental data

- 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, $\tau$ and $\eta/s$ in the following ranges:
  - $\tau$: 0.2-1.3 fm
  - Constant $\eta/s$: 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.

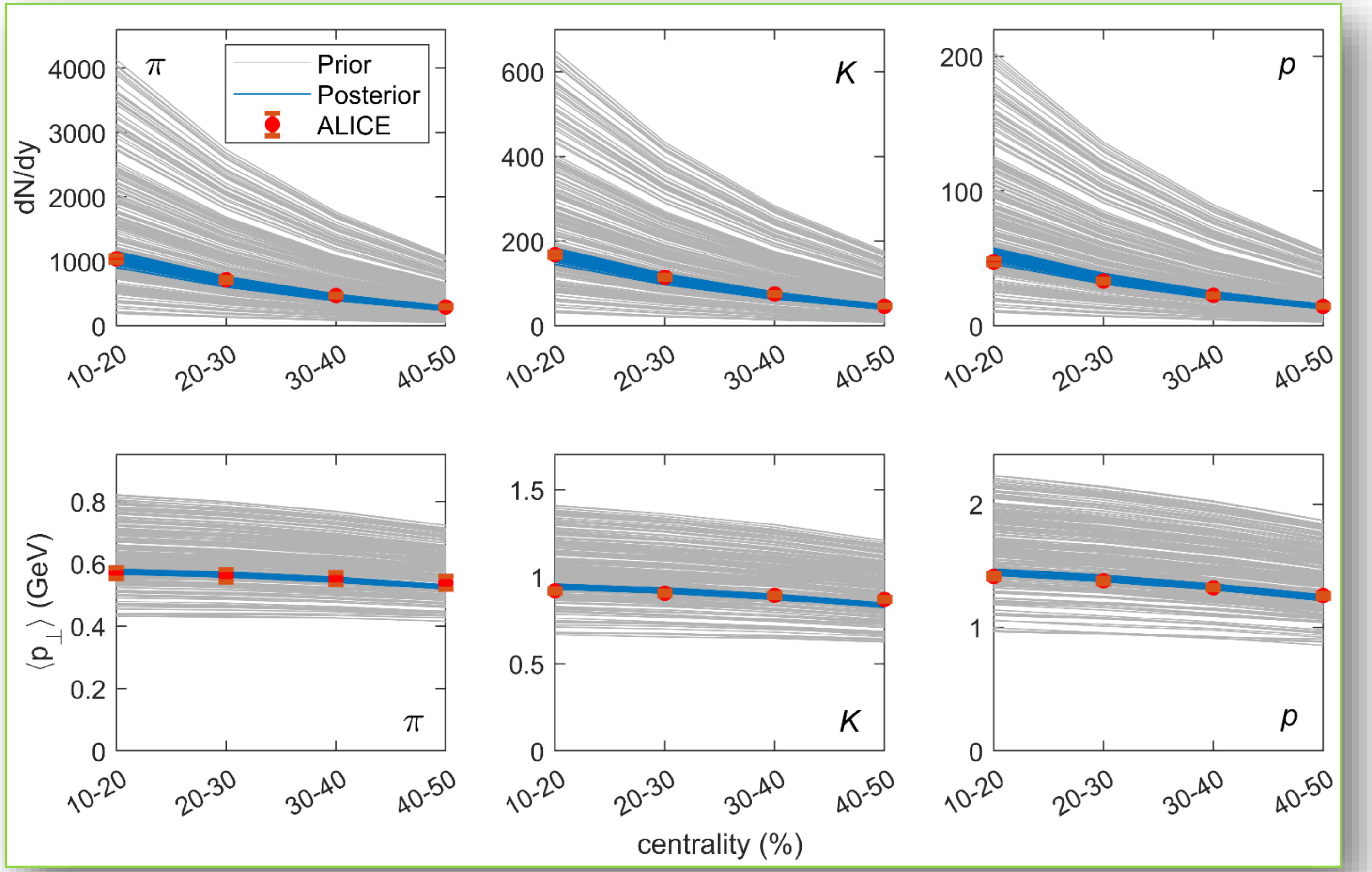
# Marginal distribution of parameters obtained with Bayesian inference of low-pt data

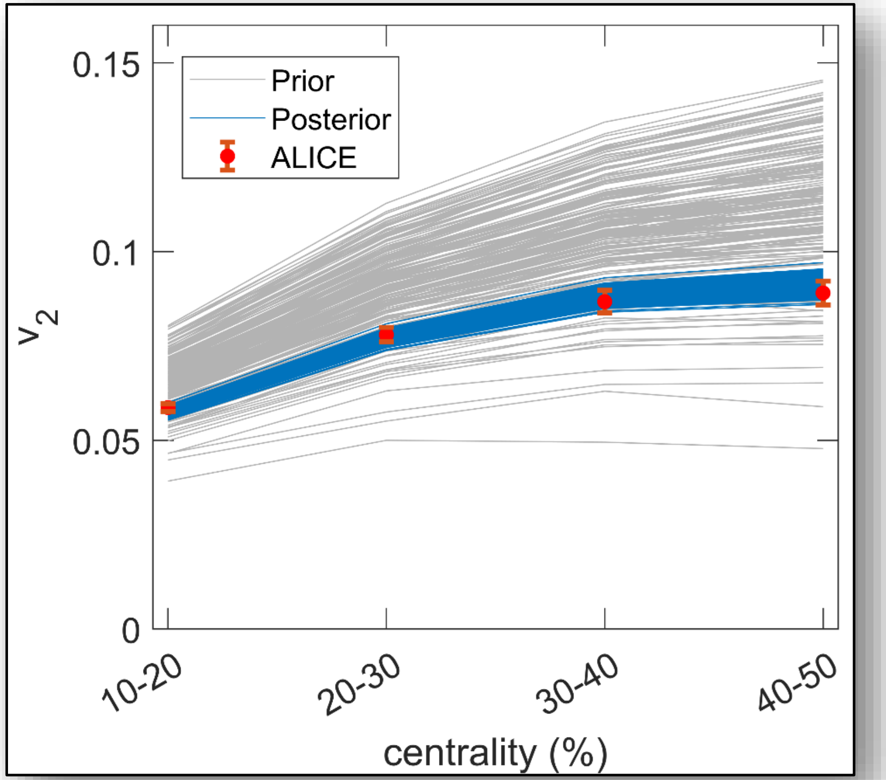





M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2025).

# Prior vs. posterior: low-pt data



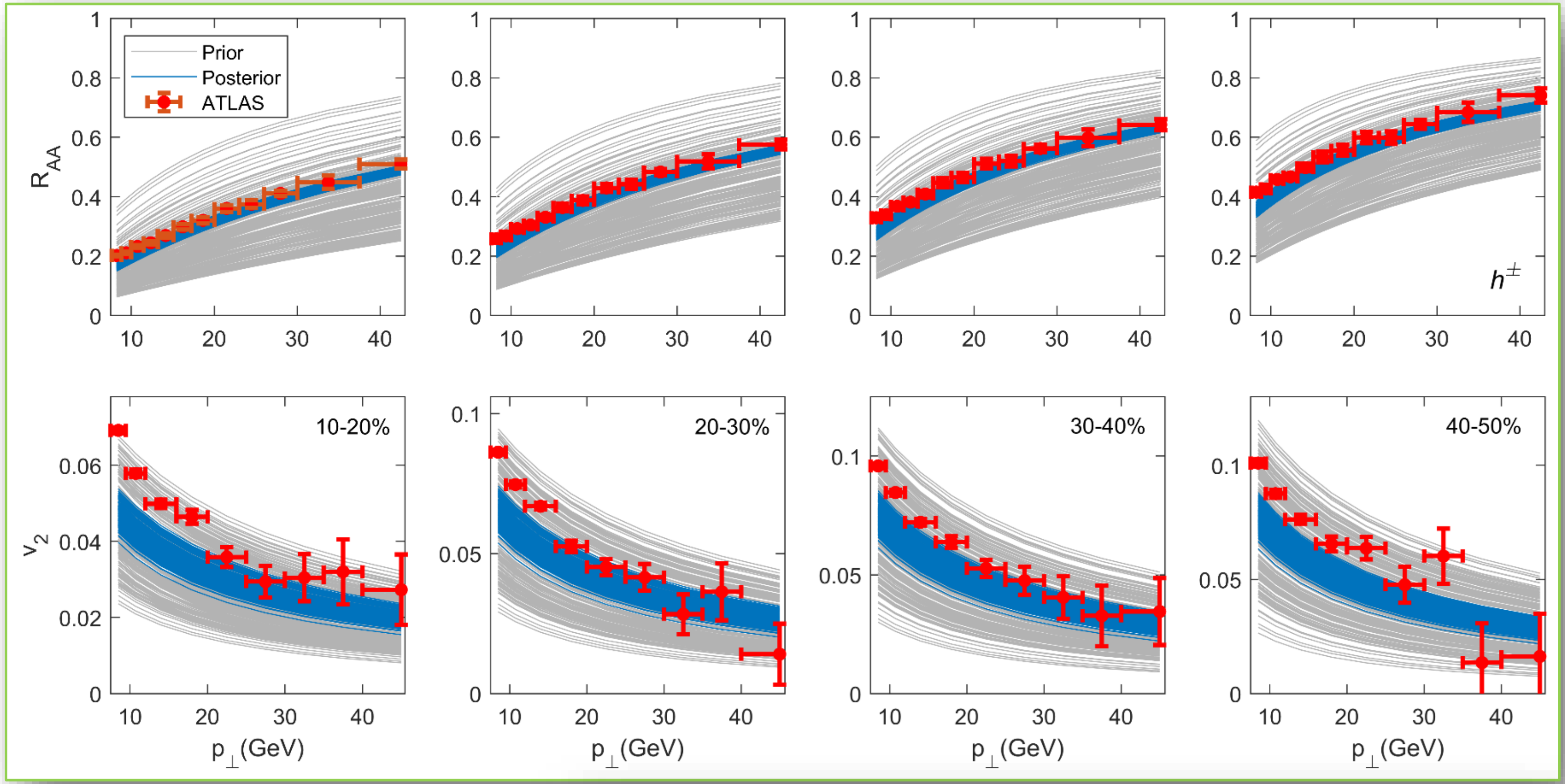




Very good agreement with low-pt data!



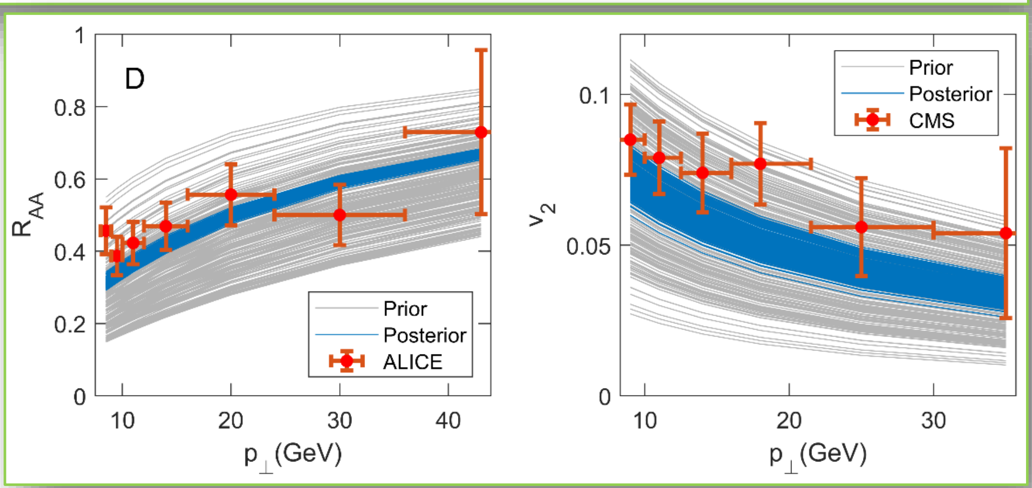
M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2025).

# Prior vs. posterior: high-pt data

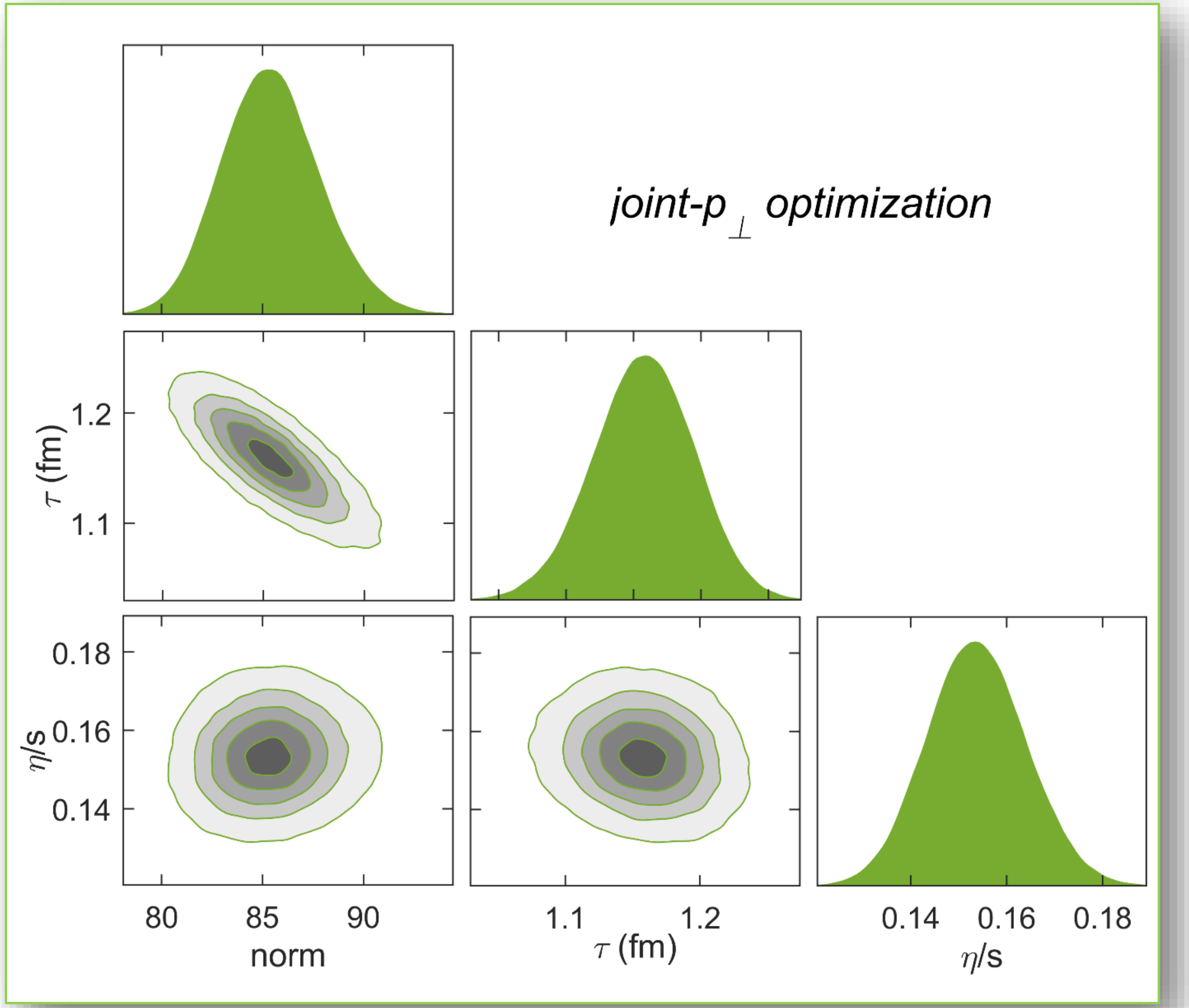



M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2025).

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

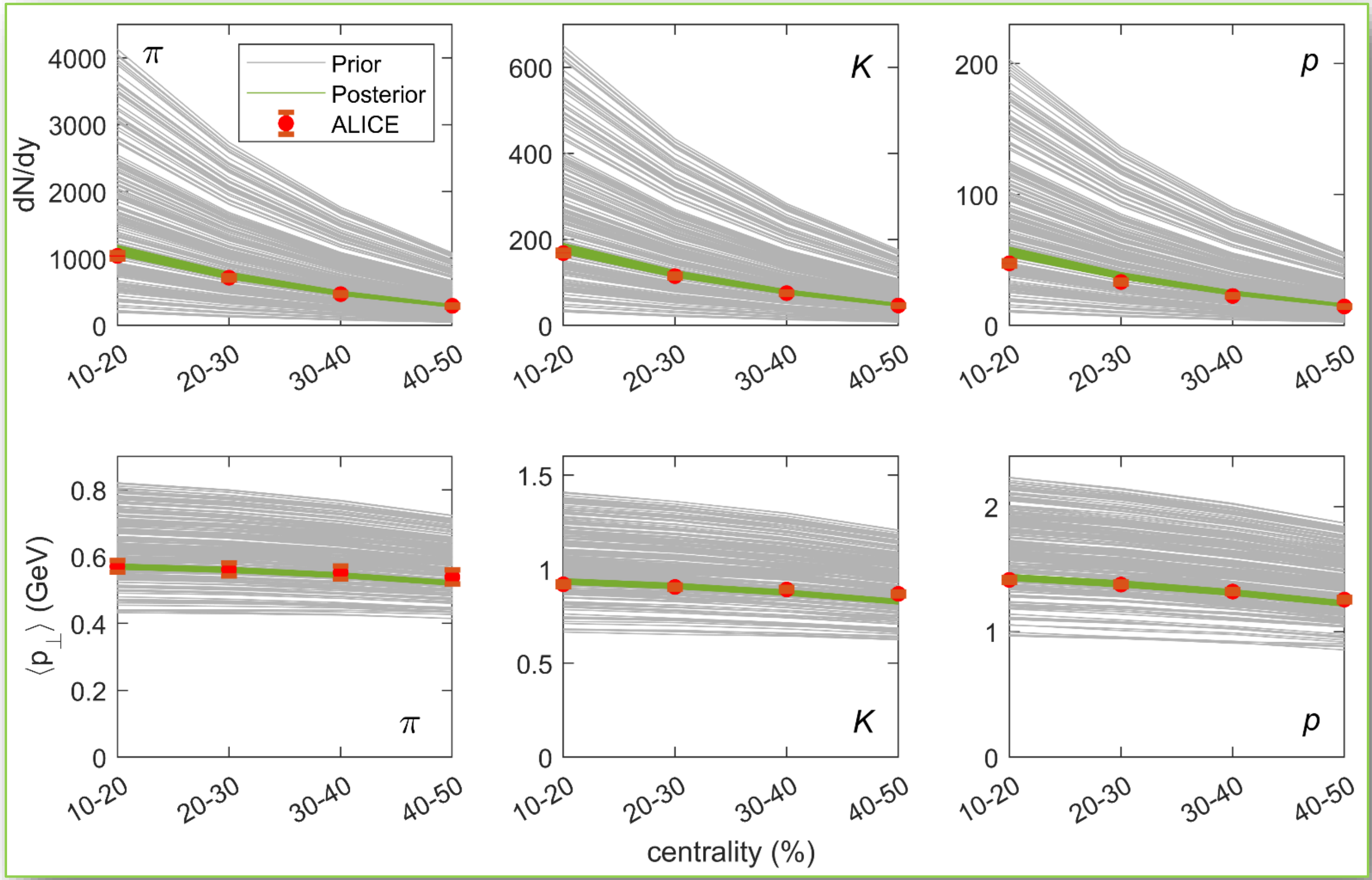


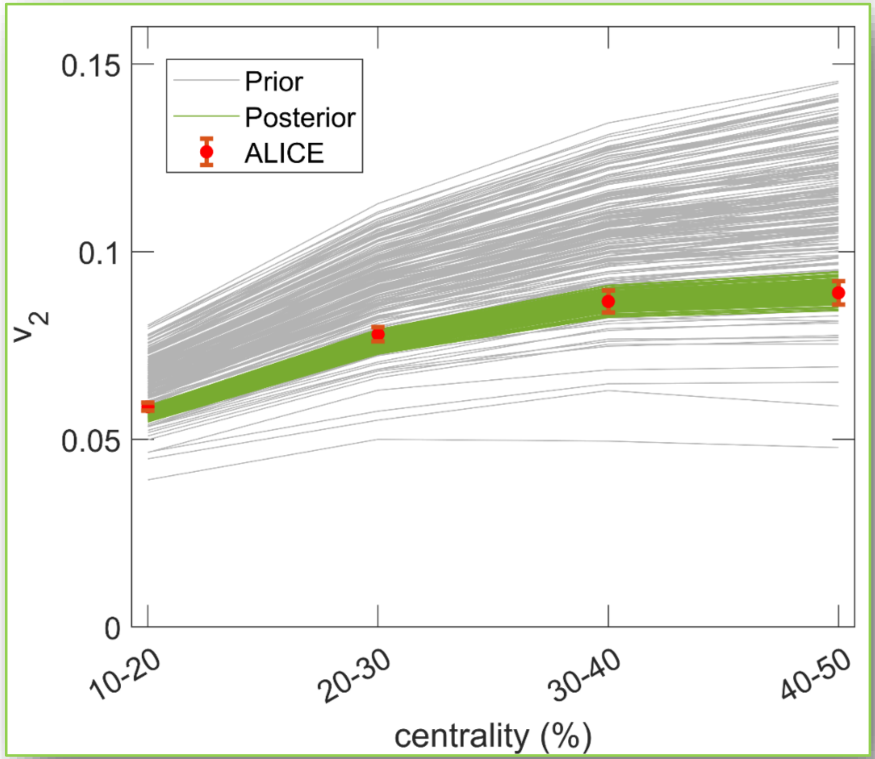
# Marginal distribution of parameters obtained with Bayesian inference of both low-pt and high-pt data




M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2025).

# Prior vs. posterior: low-pt data



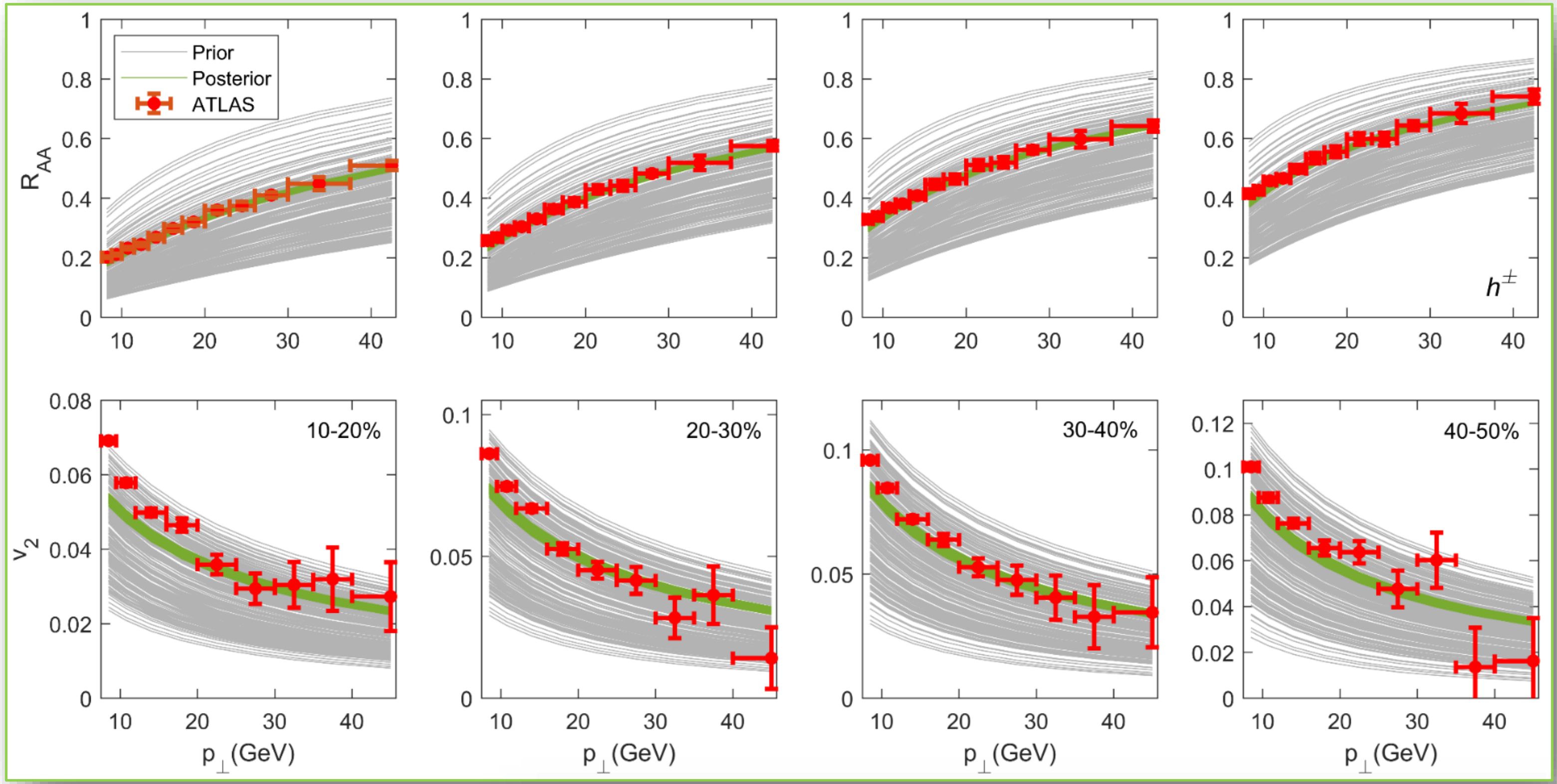




Very good agreement with low-pt data!

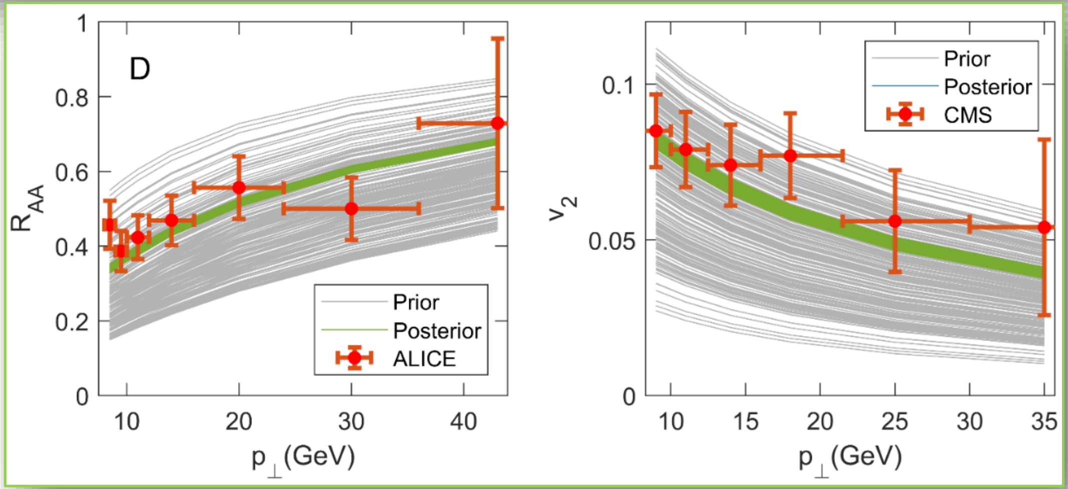


M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2025).

# Prior vs. posterior: high-pt data



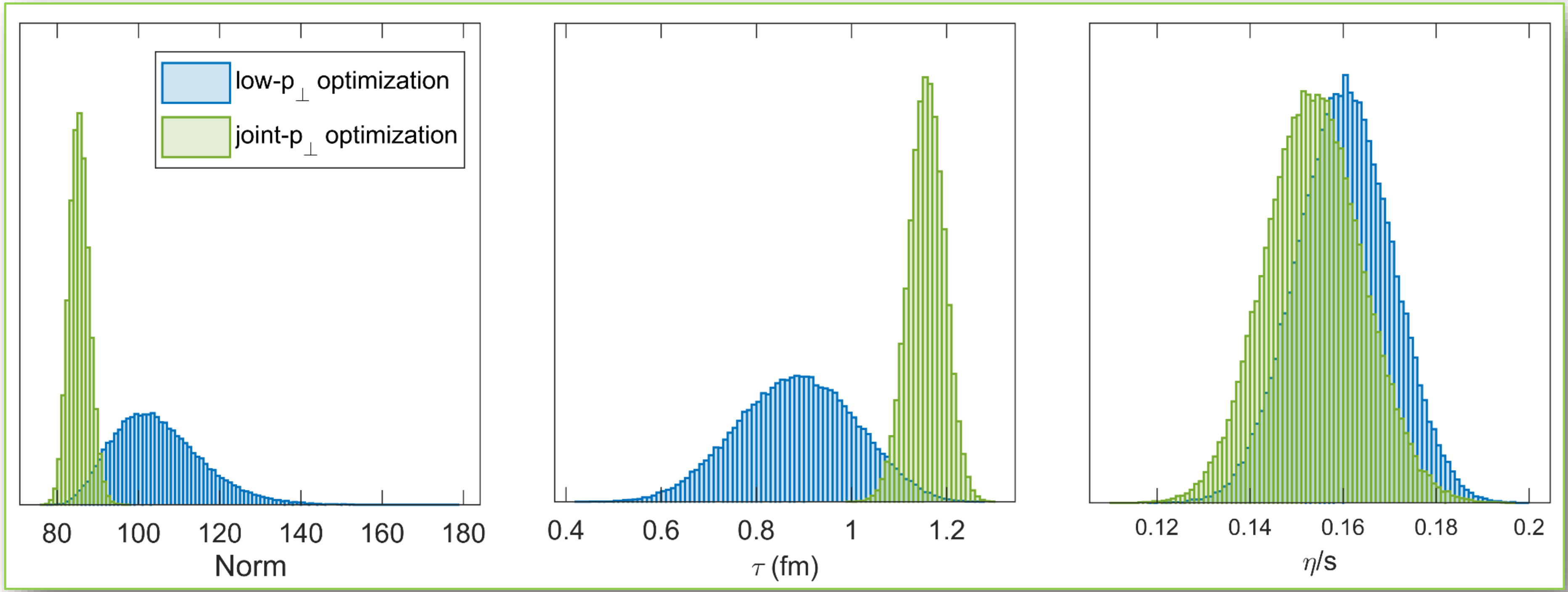

M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2025).




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 (2025).




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