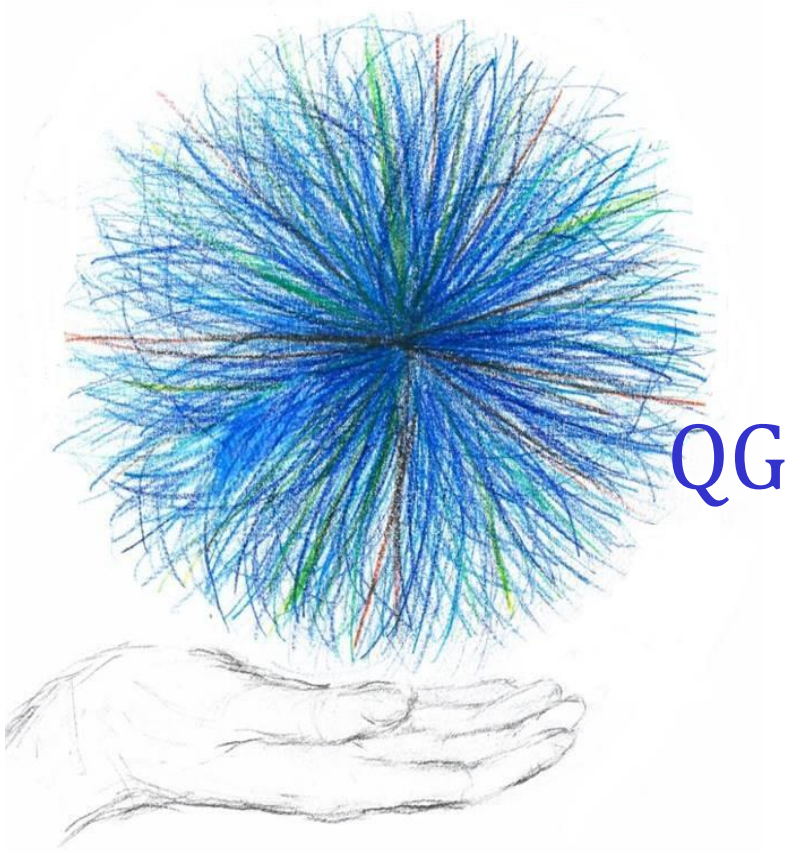


QGP tomography for exploring the bulk QGP properties

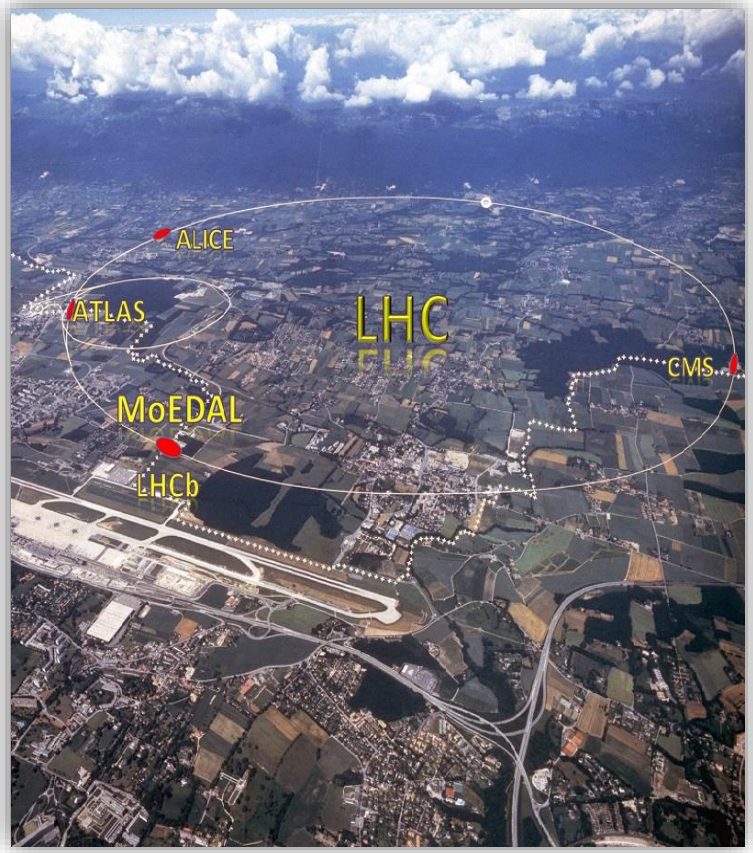
Magdalena Djordjevic,

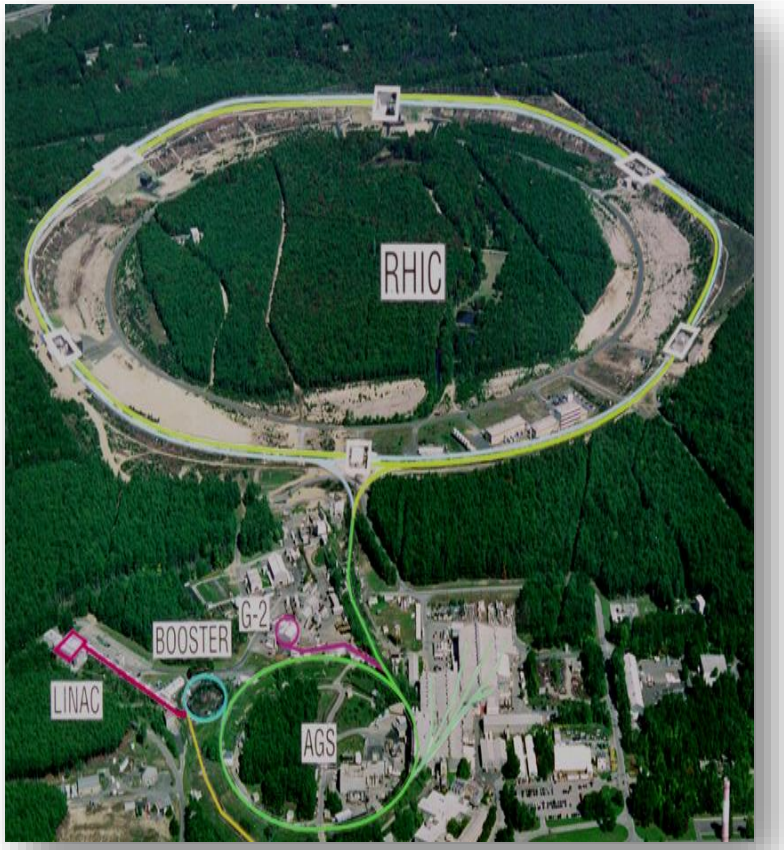
Brief overview of Quark Gluon Plasma

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.

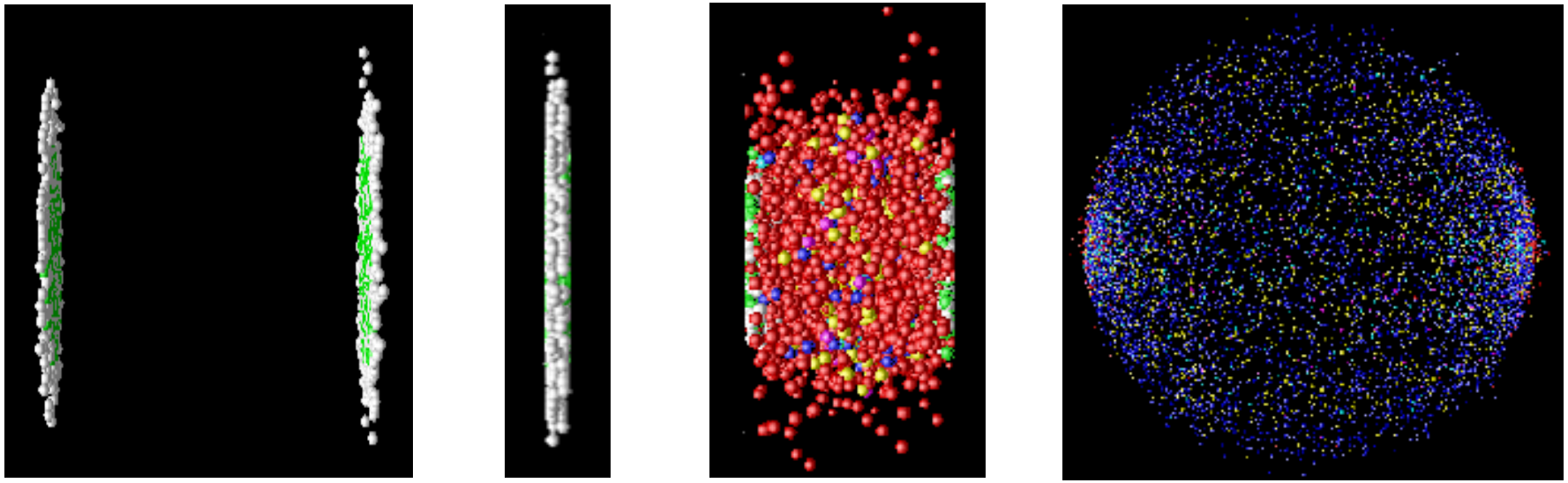
Ultra-Relativistic Heavy Ion Colliders (the LHC and RHIC) at CERN and BNL.





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 LHC and RHIC.

Current challenge: Understand QGP properties

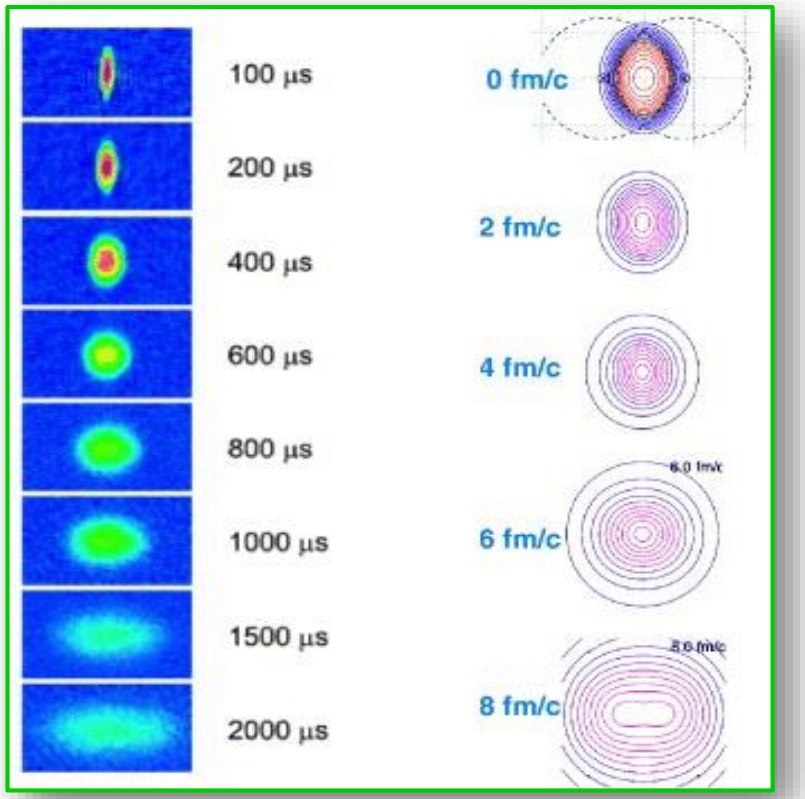
Expected: The QGP was anticipated to behave as a weakly interacting gas.

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.

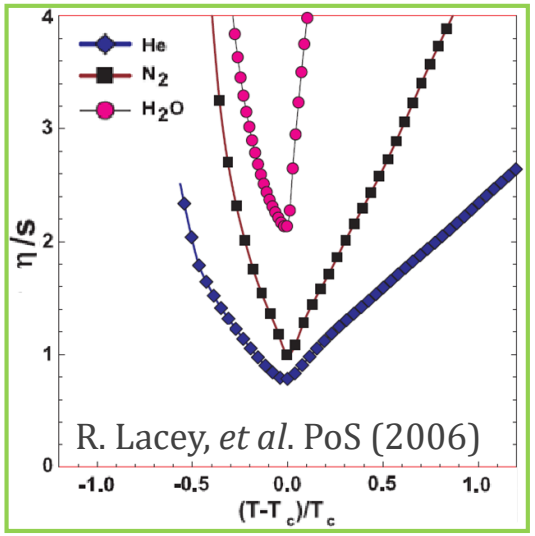
M. A. Lisa, *et al.*, New J. Phys. 13 (2011)



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

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

Is QGP really perfect fluid?

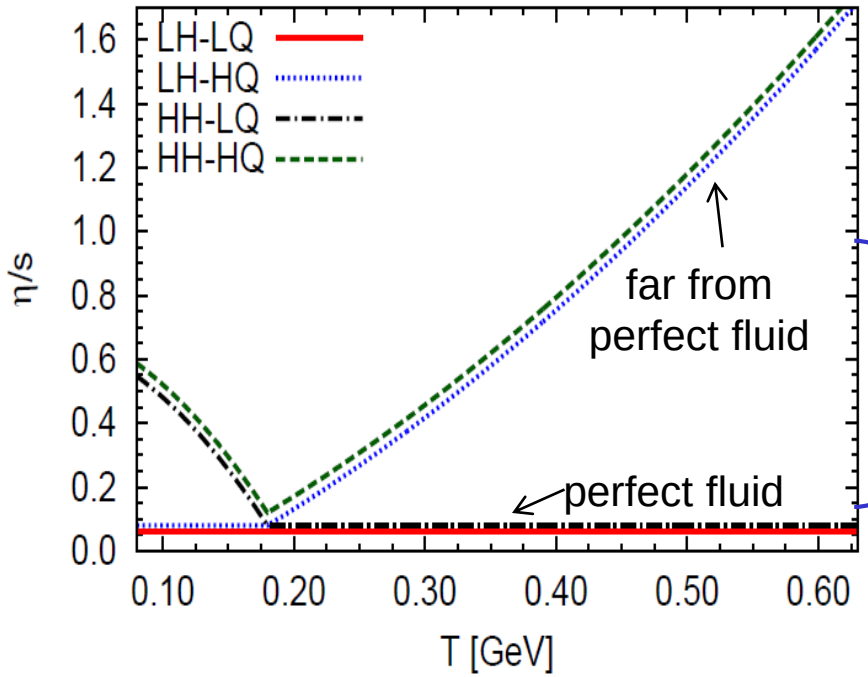


Origin of the low η/s throughout QGP evolution unclear.

η/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 η/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 ?

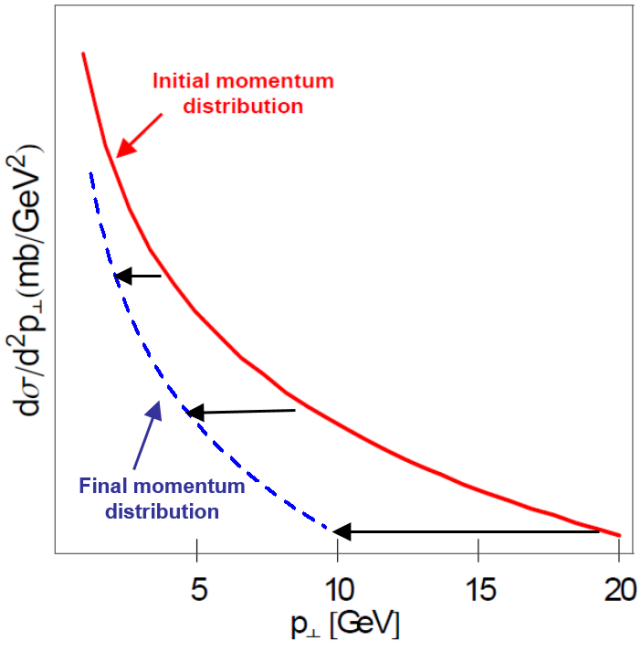
J. Nagle *et al.*, New J.Phys.13:075004,2011

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



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

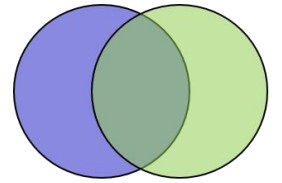
Wealth of precision high pt data available, or will soon become available - dawn of the high precision era (Run3 at the LHC and sPHENIX at BNL).

Angular *average* suppression
high pt hadron R_{AA}

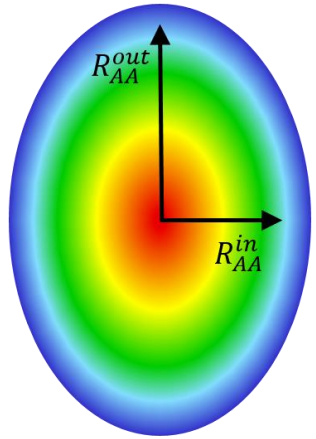
Probes high *pt* parton interactions with QGP

Angular *differential* suppression
high pt hadron v_2 and higher harmonics

Probes QGP evolution



Assymetric collision of two heavy ions

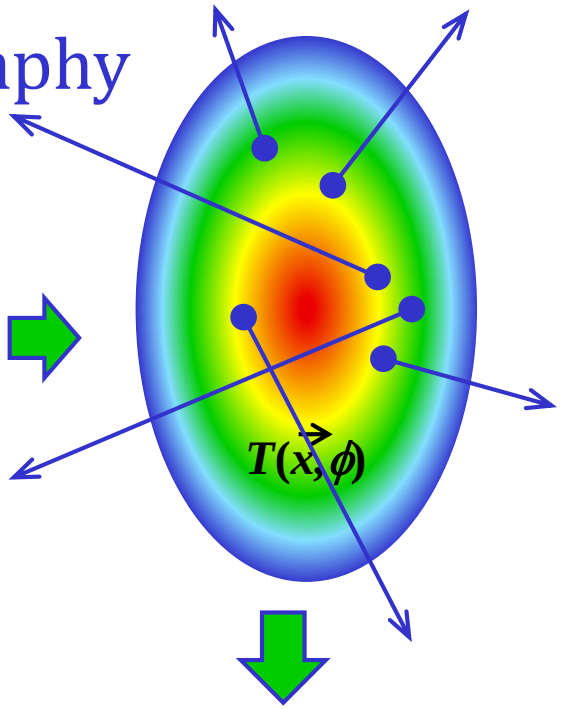


$$v_2 = \frac{R_{AA}^{in} - R_{AA}^{out}}{R_{AA}^{in} + R_{AA}^{out}}$$

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

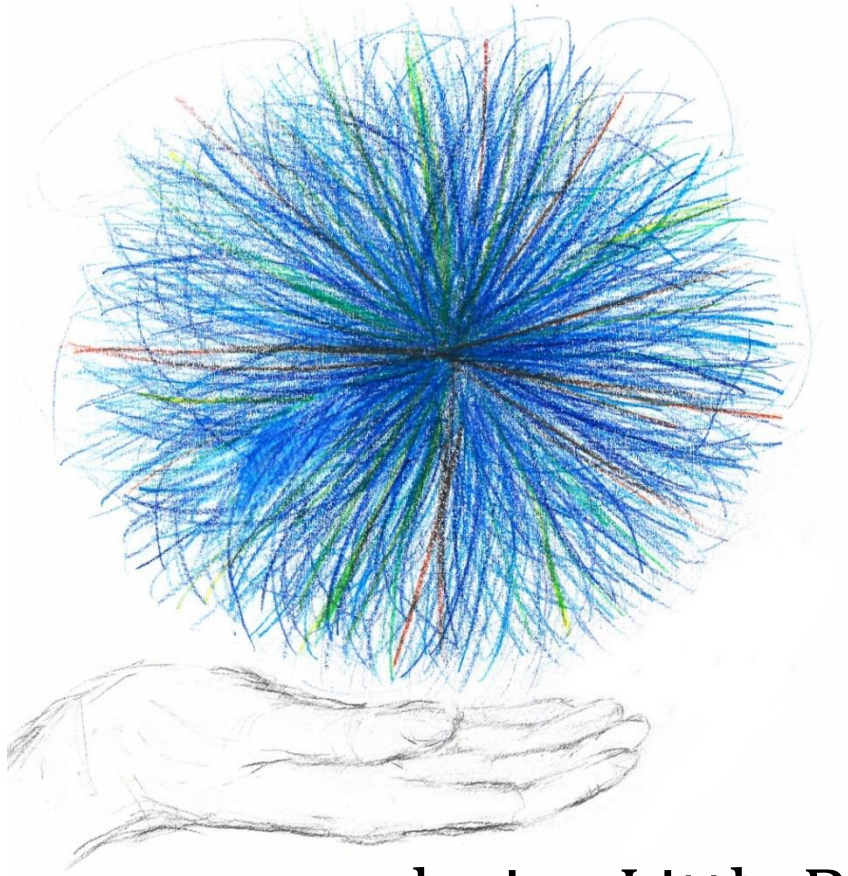
Infer $T(\vec{x},\phi)$ (i.e. $\eta/s(T)$) consistent with both low-*pt* and high-*pt* data

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

Larger sensitivity for inferring η/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.



About the project:

QGP Tomography

exploring Little Bangs at landmark experiments

ERC consolidator grant "A novel Quark-Gluon Plasma tomography tool: from jet quenching to exploring the extreme medium properties"

Total budget: 1356000 EUR

Duration: Sept 2017 – Sept 2023

PI: Dr. Magdalena Djordjevic, Institute of Physics Belgrade



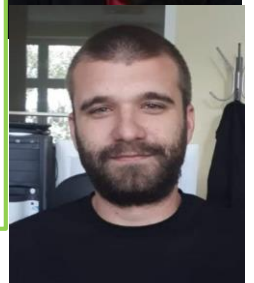


ERC team

- Team (besides the PI):
  - 3 Senior scientists
  - 3 Postdocs
  - 2 PhD students
  - 1 Consultant
- International group
  - Postdoc and senior scientist from Finland and India (bring expertise in relativistic hydrodynamics simulations, which did not exist in Serbia).
  - PI, 2 senior scientists, and one postdoc with significant (total >30 years) USA research experience.







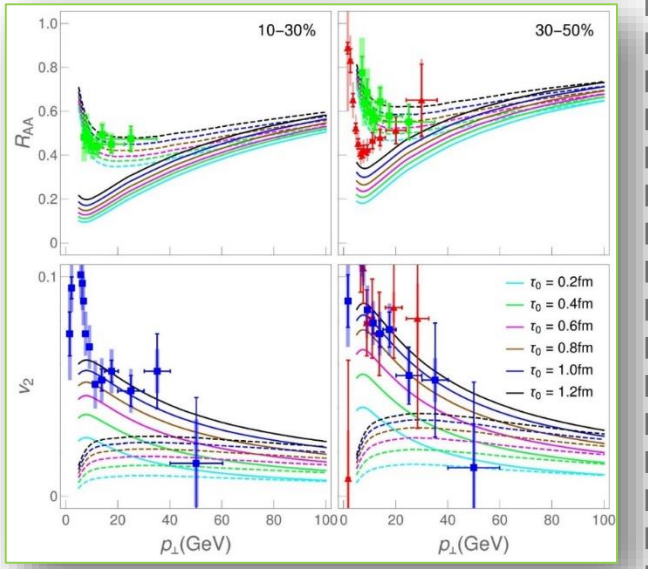
Results obtained during ERC grant

- Developed a tool, DREENA (publically available code), for exploring the properties of QGP through high-pt theory and data.
- Used DREENA framework to infer some crucial QGP properties.
- 21 papers published in high impact journals (3 in Physical Review C Rapid Communication, 2 in Physics Letters B, 9 in Physical Review C, 1 Journal of Physics G, and 3 in Nuclear Physics A,…).
- Research presented at 74 (27 plenary or invited) talks and 13 posters at major conferences (Quark Matter, Hard Probes, Initial Stages, Strangeness in Quark Matter...); 12 invited seminars (at MIT, BNL, Duke U, Yale U, etc.).
- Organized an international workshop, “Exploring Quark-Gluon Plasma through soft and hard probes“, SANU, Belgrade, May 2023.

Exploring bulk QGP properties through DREENA

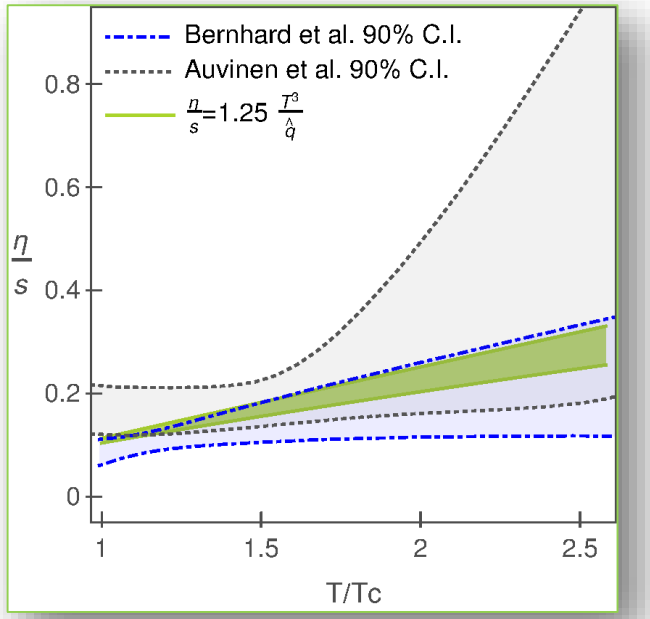
Constrained the early evolution of QGP

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



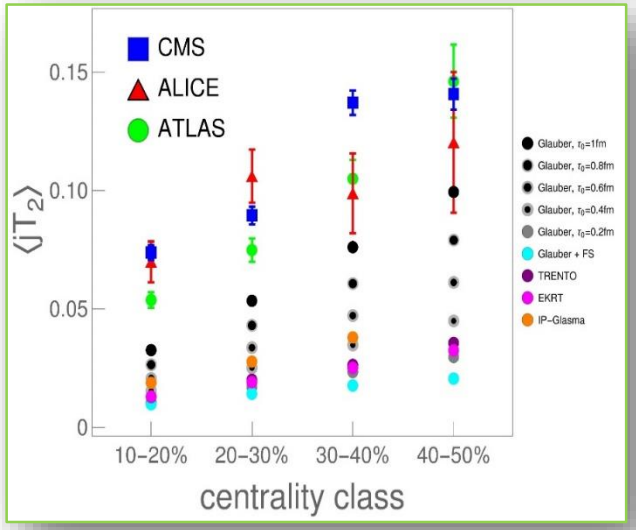
Constrained η/s from the dynamical energy loss $\hat{q}$

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



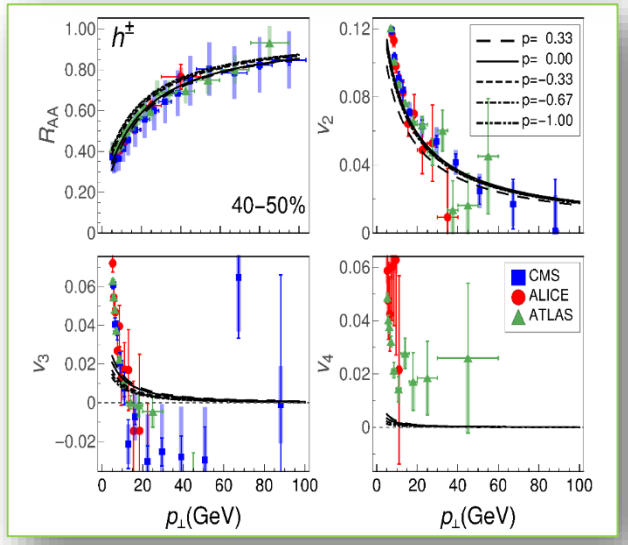
Proposed a new observable to constrain QGP anisotropy

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

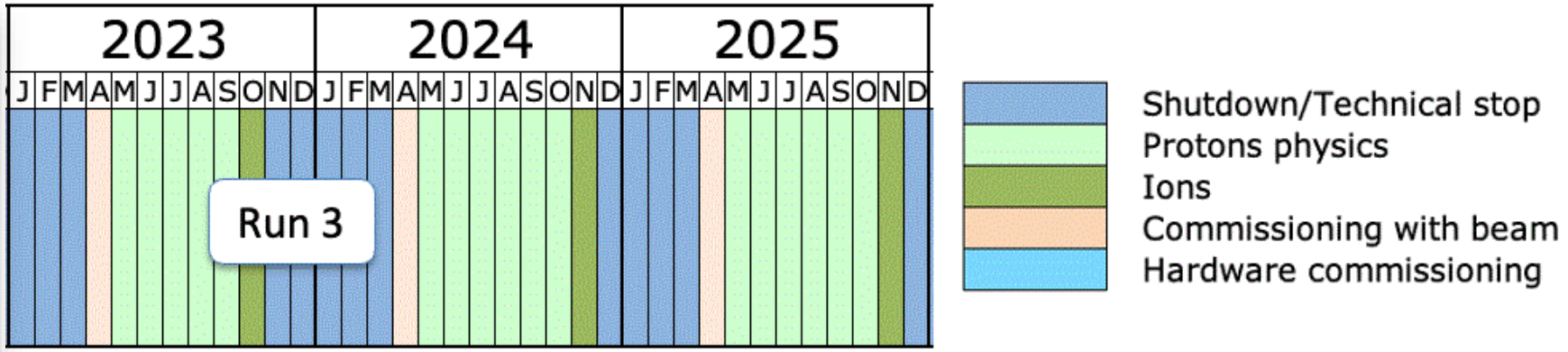


Probed the shape of the QGP droplet with ebeDREENA

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



What next?



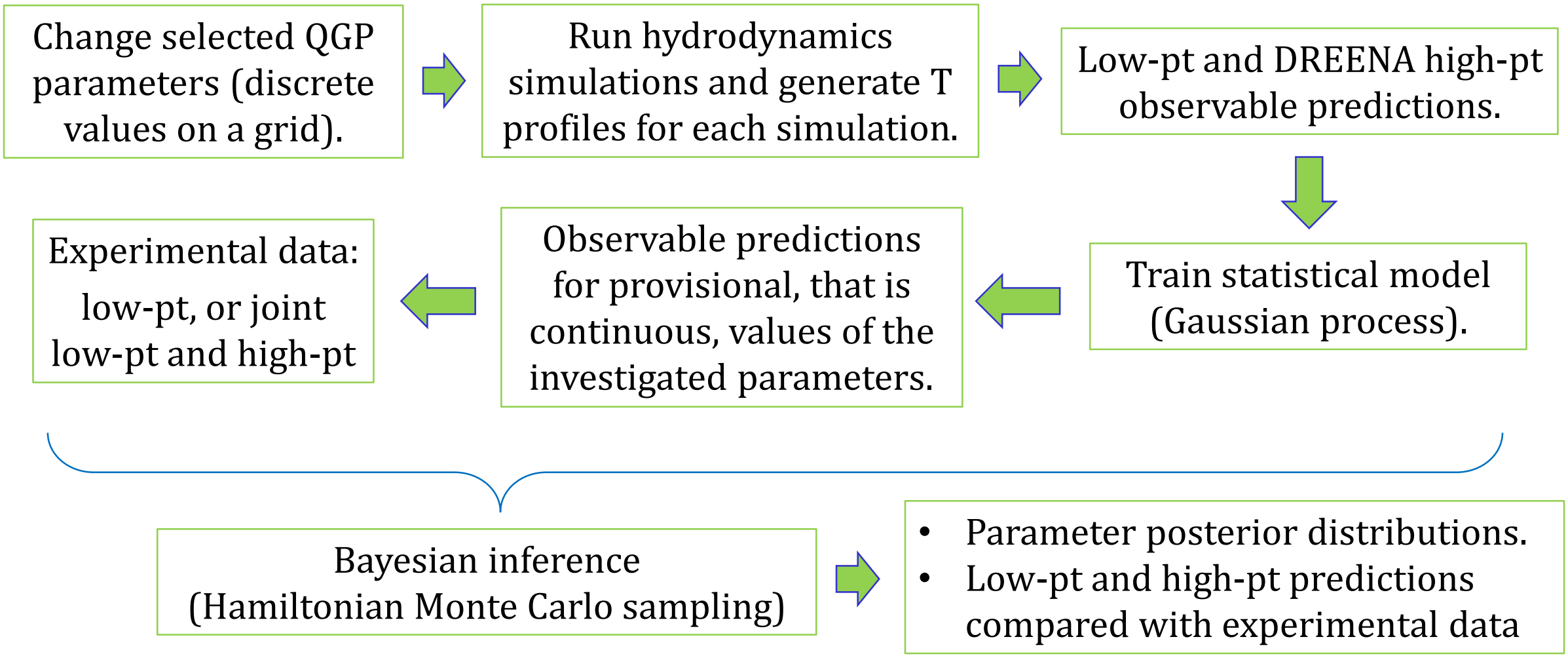
sPHENIX

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

Ongoing high-precision era at the LHC and RHIC.

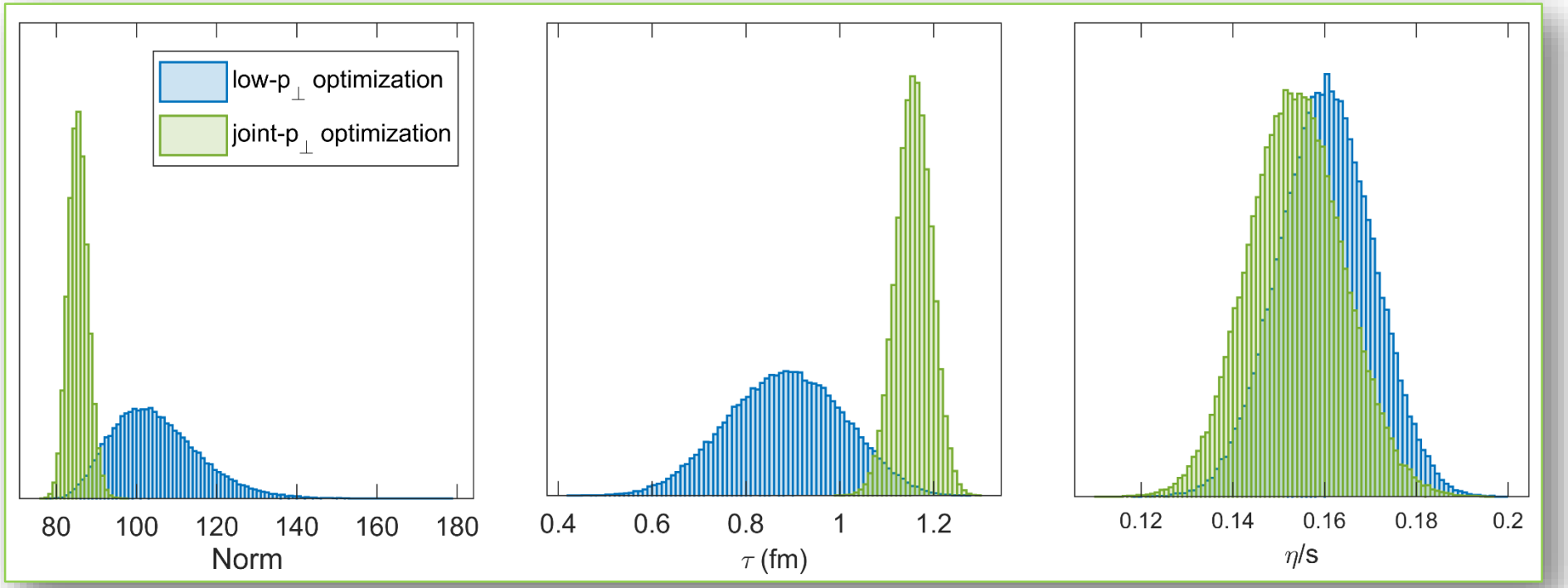
DREENA will enable better utilization of these large scientific investments, as well as precise determination of the properties of this extreme state of matter.

Our next goal: BayesDREENA



Preliminary results: Comparison of parameter distributions from low-pt and joint-pt Bayesian inferences with simple set of parameters

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!

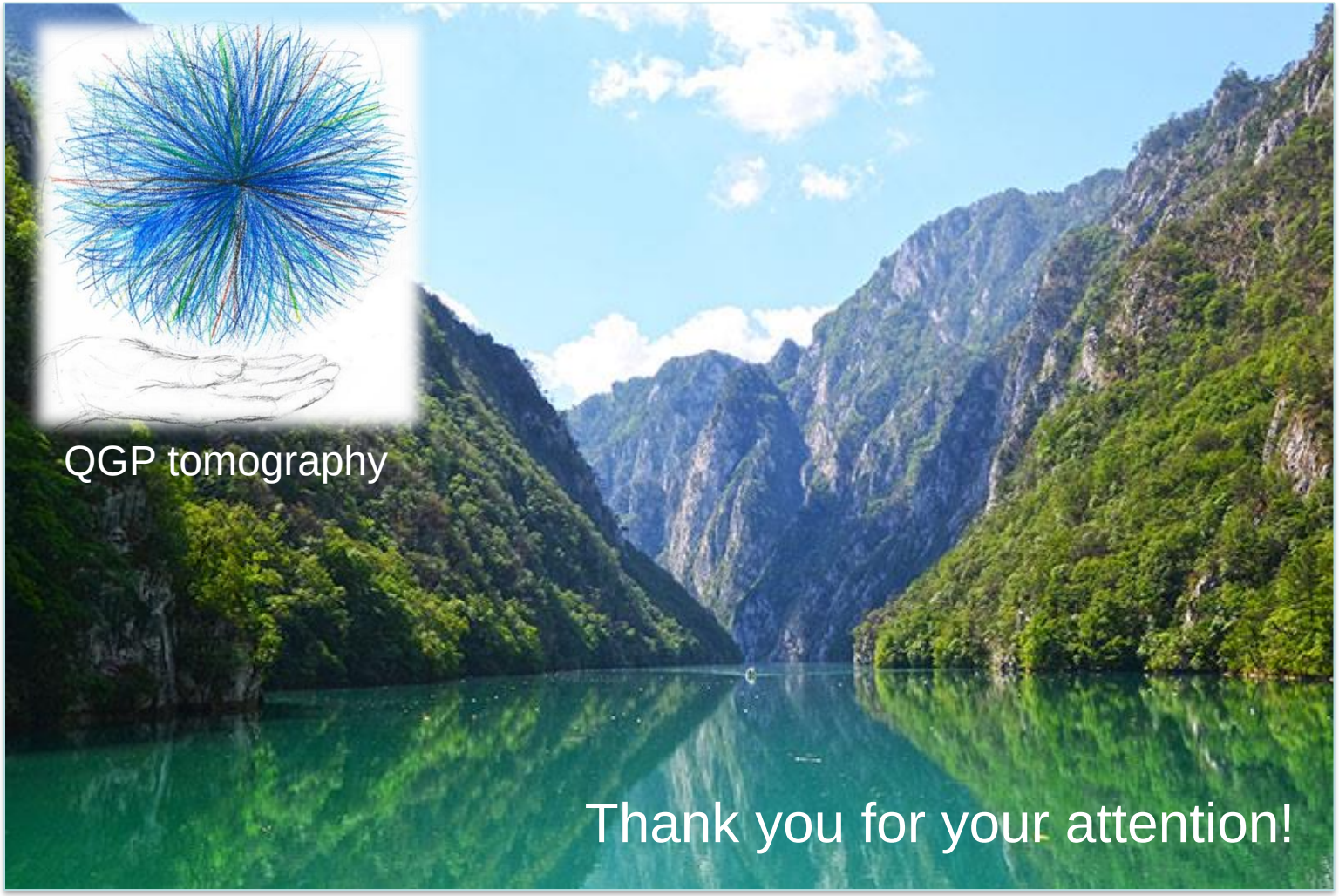
Summary: Optimizing QGP Parameter Extraction

- 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 Drina (DREENA) in Serbia

European Research Council
Established by the European Commission

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА