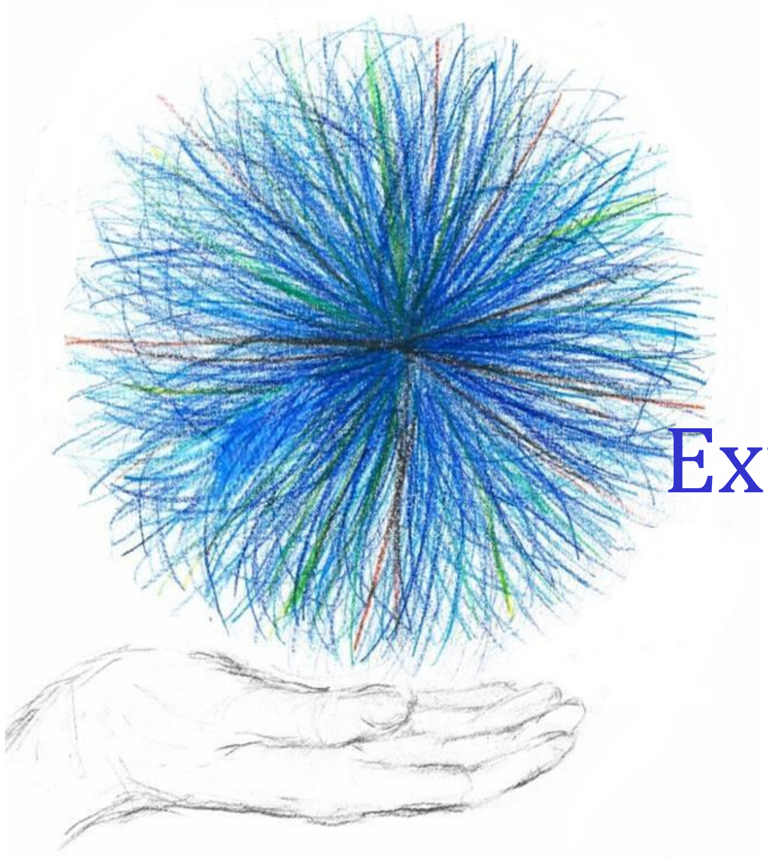


Exploring the bulk QGP properties with Bayes-DREENA

Magdalena Djordjevic, IPB

In collaboration with: Dusan Zigic, Stefan Stojku, Bojana Ilic, Jussi Auvinen, Lidija Zivkovic, Igor Salom, Marko Djordjevic and Pasi Huovinen

European Research Council

МИНИСТАРСТВО ПРОСВЕТЕ,
НАУКЕ И ТЕХНОЛОШКОГ РАЗВОЈА

Motivation

- Energy loss of high-pt 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 observable.
- Can be used with low-pt theory and experiments to study the properties of created QCD medium, i.e., for precision QGP tomography.

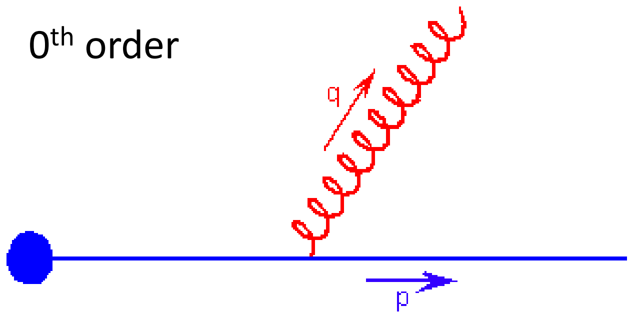
Energy loss in QGP

Energy loss in QGP

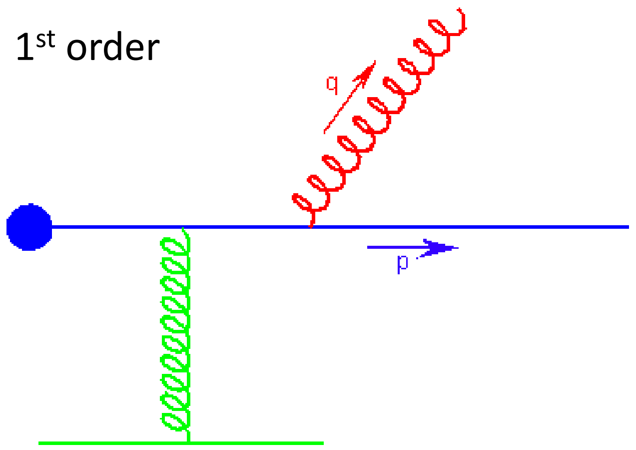
Radiative energy loss

Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:

0th order



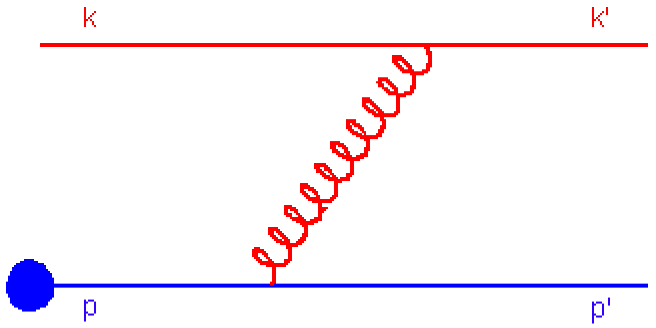
1st order



Collisional energy loss

Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:

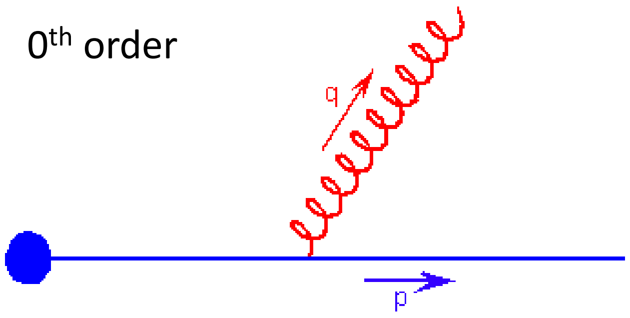
0th order

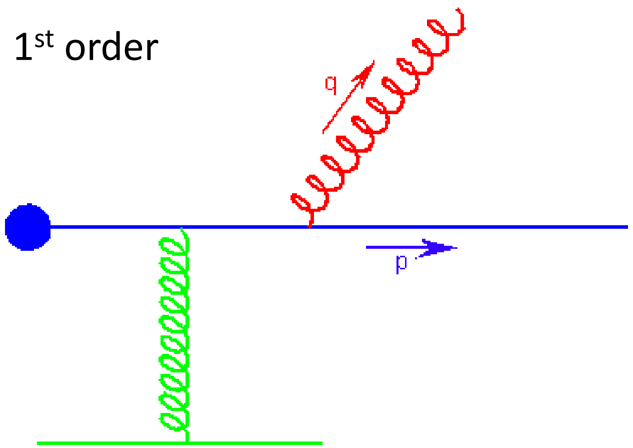


Energy loss in QGP

Radiative energy loss

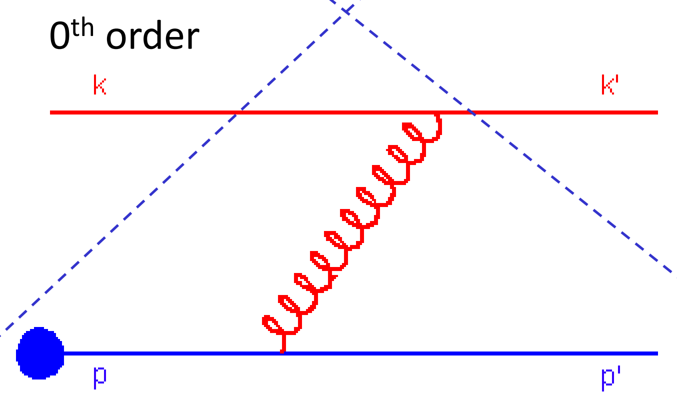
Radiative energy loss comes from the processes in which there are more outgoing than incoming particles:





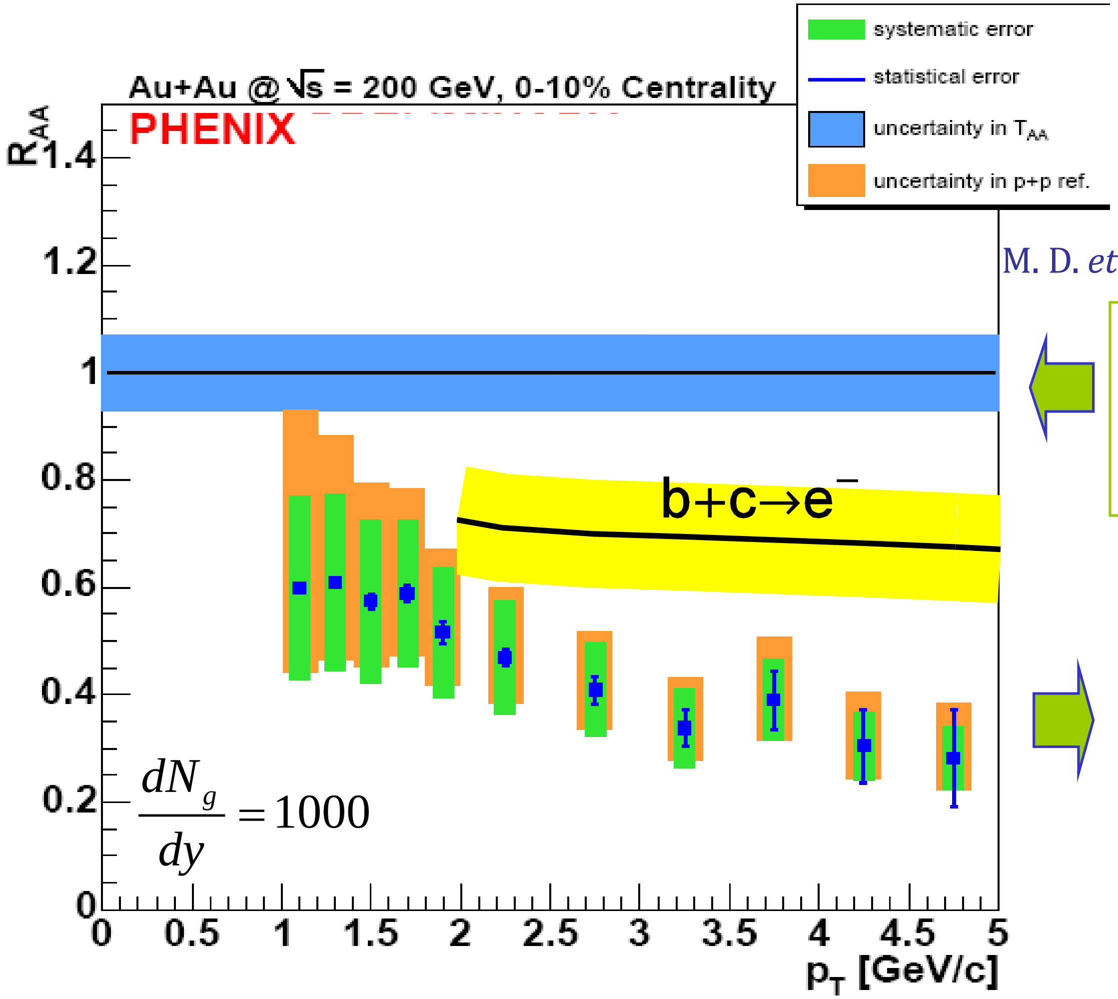
Collisional energy loss

Collisional energy loss comes from the processes which have the same number of incoming and outgoing particles:



Considered to be negligible compared to radiative!

Heavy flavor puzzle @ RHIC



M. D. *et al.*, Phys. Lett. B 632, 81 (2006)

Radiative energy loss predictions with $dN_g/dy=1000$

Disagreement!

Radiative energy loss cannot explain the single electron data as long as realistic parameter values are considered!

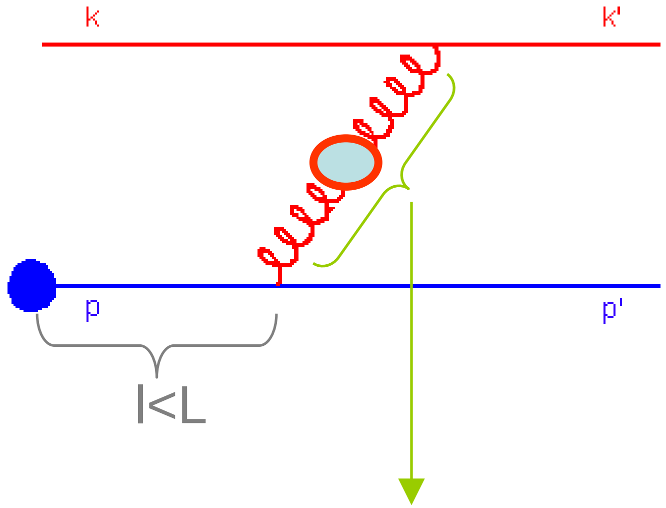
Does the radiative energy loss control the energy loss in QGP?

Is collisional energy loss also important?

Collisional energy loss in a finite size QCD medium

Consider a medium of size L in thermal equilibrium at temperature T.

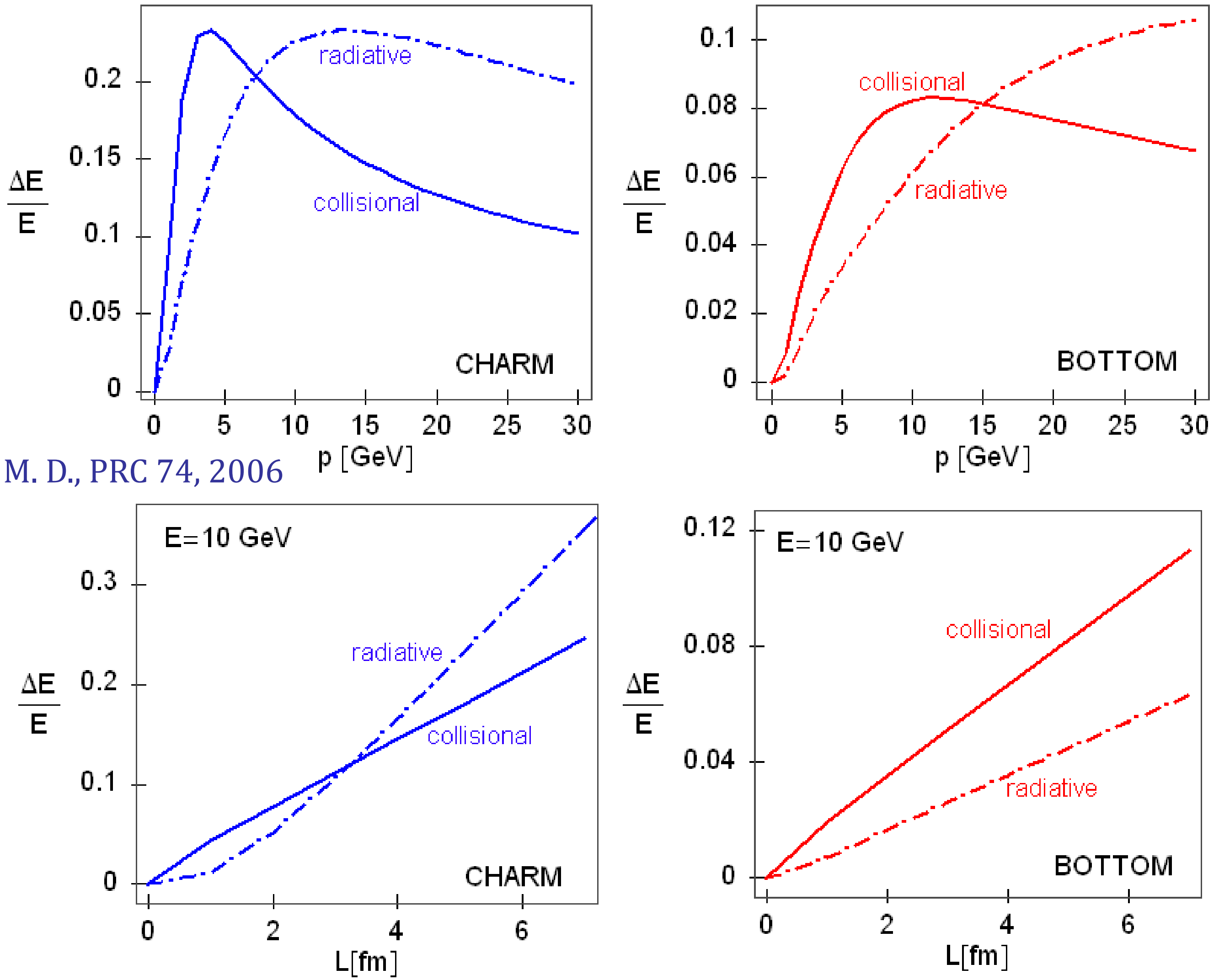
The main order collisional energy loss is determined from:



The effective gluon propagator:

$$D^{\mu\nu}(\omega,\vec{q}) = -P^{\mu\nu}\Delta_T(\omega,\vec{q}) - Q^{\mu\nu}\Delta_L(\omega,\vec{q})$$

M. D., Phys.Rev.C74:064907,2006



M. D., PRC 74, 2006

Collisional and radiative energy losses are comparable!

Non-zero collisional energy loss - a fundamental problem

Static QCD medium approximation (modeled by Yukawa potential).

→

With such approximation, collisional energy loss has to be exactly equal to zero!

↓

However, collisional and radiative energy losses are shown to be comparable.

←

Introducing collisional energy loss is necessary but inconsistent with static approximation!

↓

Static medium approximation should not be used in radiative energy loss calculations!

→

Dynamical QCD medium effects have to be included!

Our goal

Compute the light and heavy quark radiative energy loss in a dynamical medium of thermally distributed massless quarks and gluons.

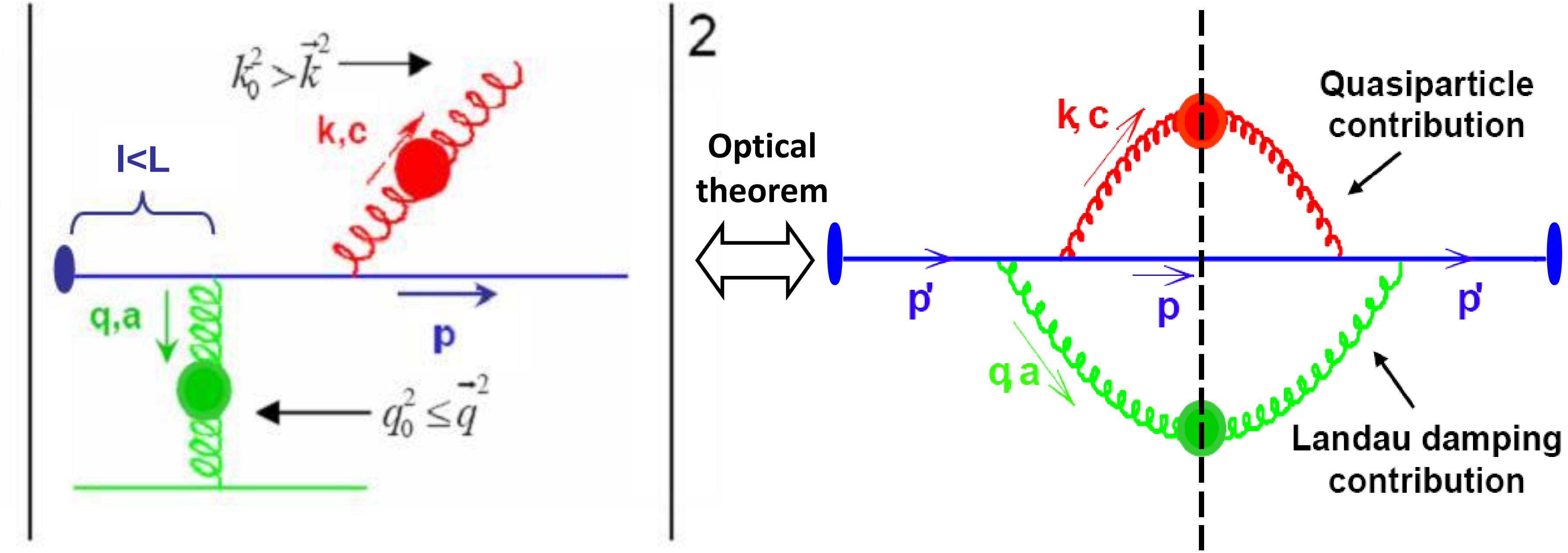
Why?

- Address the applicability of static approximation in radiative energy loss computations.
- Compute collisional and radiative energy losses within a consistent theoretical framework.

Radiative energy loss in a dynamical medium

Compute the medium-induced radiative energy loss for a heavy quark to the first (lowest) order in the number of scattering centers.

Consider the radiation of one gluon induced by one collisional interaction with the medium.



Consider a medium of finite size L, and assume that the collisional interaction has to occur in the medium.

The calculations were performed by using two Hard-Thermal Loop approach.

1-HTL gluon propagator:

$$iD^{\mu\nu}(l) = \frac{P^{\mu\nu}(l)}{l^2 - \Pi_T(l)} + \frac{Q^{\mu\nu}(l)}{l^2 - \Pi_L(l)}$$

Cut 1-HTL gluon propagator:

$$D^{>}_{\mu\nu}(l) = -(1+f(l_0))\Big(P_{\mu\nu}(l)\rho_T(l) + Q_{\mu\nu}(l)\rho_L(l)\Big)\,,$$

$$\rho_{L,T}(l) = \underbrace{2\pi\,\delta(l^2 - \Pi_{T,L}(l))}_{\text{Radiated gluon}} - \underbrace{2\,\mathrm{Im}\left(\frac{1}{l^2 - \Pi_{T,L}(l)}\right)\theta(1 - \frac{l_0^2}{\vec{l}^2})}_{\text{Exchanged gluon}}$$

For radiated gluon, the cut 1-HTL gluon propagator can be simplified to

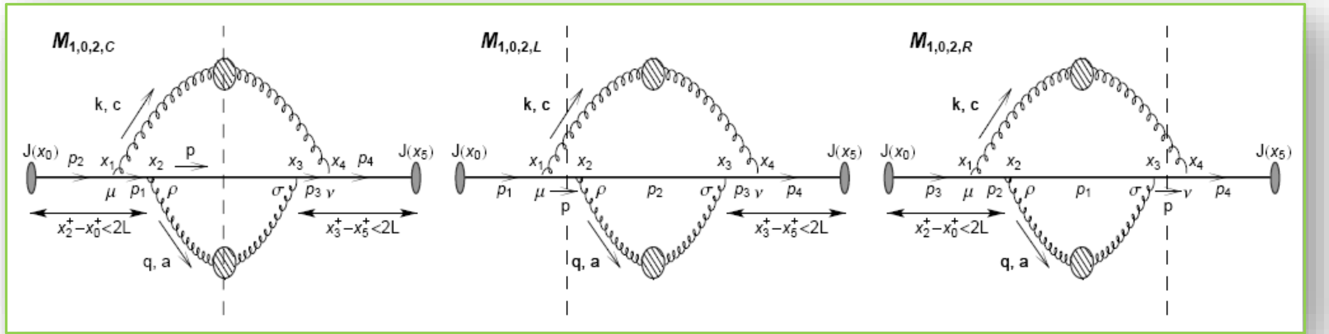
(M.D. and M. Gyulassy, PRC 68, 034914 (2003))

$$D^{>}_{\mu\nu}(k) \approx -2\pi\,\frac{P_{\mu\nu}(k)}{2\omega}\,\delta(k_0 - \omega) \qquad \omega \approx \sqrt{\vec{k}^2 + m_g^2}; \quad m_g \approx \mu/\sqrt{2}$$

For exchanged gluon, the cut 1-HTL gluon propagator cannot be simplified, since both transverse (magnetic) and longitudinal (electric) contributions will prove to be important.

$$D^{>}_{\mu\nu}(q) = \theta(1 - \frac{q_0^2}{\vec{q}^2})\,(1 + f(q_0))\,2\,\mathrm{Im}\left(\frac{P_{\mu\nu}(q)}{q^2 - \Pi_T(q)} + \frac{Q_{\mu\nu}(q)}{q^2 - \Pi_L(q)}\right)$$

More than one cut of a Feynman diagram can contribute to the energy loss in finite-size dynamical QCD medium:



These terms interfere with each other, leading to the nonlinear dependence of the jet energy loss.

M. D., Phys.Rev.C80:064909,2009 (highlighted in APS physics).

We calculated all the relevant diagrams that contribute to this energy loss.

Each individual diagram is infrared divergent due to the absence of magnetic screening!

The divergence is naturally regulated when all the diagrams are taken into account.

So, all 24 diagrams have to be included to obtain a sensible result.

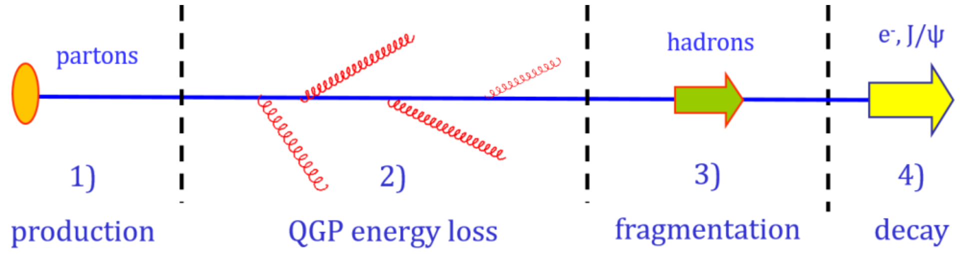
$$\frac{\Delta E_{\rm dyn}}{E} = \frac{C_R\alpha_s}{\pi}\frac{L}{\lambda_{\rm dyn}}\int dx \frac{d^2k}{\pi}\frac{d^2q}{\pi}\frac{\mu^2}{q^2(q^2+\mu^2)}\left(1-\frac{\sin\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}{\frac{(\mathbf{k}+\mathbf{q})^2+\chi}{xE^+}L}\right) \times 2\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi}\left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi}-\frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right),$$

The dynamical energy loss formalism

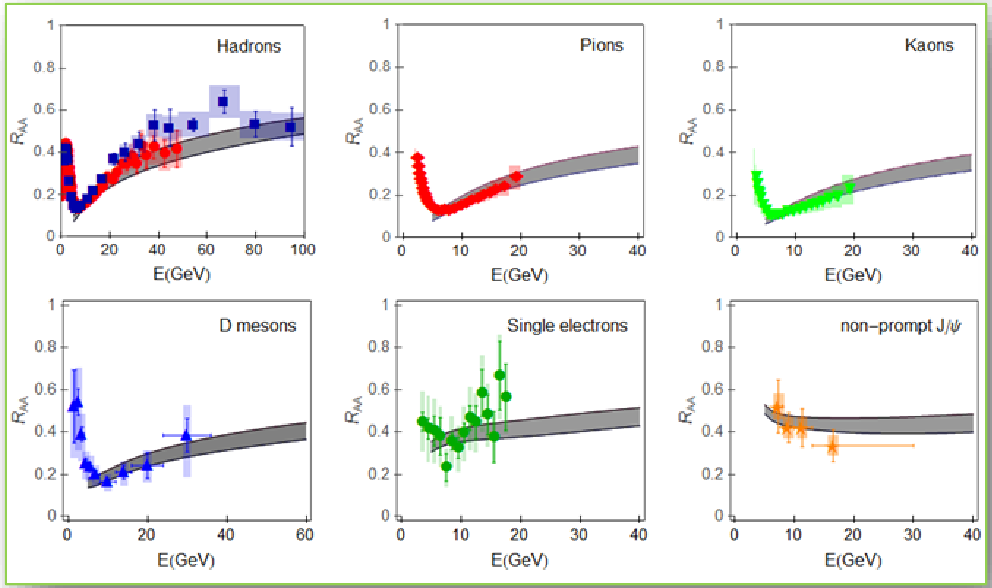
Has the following unique features:

- *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)).
- All ingredients necessary to accurately explain the data
  (B. Blagojevic and M.D, J.Phys. G42 (2015) 7, 075105).
- No fitting parameters in the model
- Temperature as a natural variable in the model.

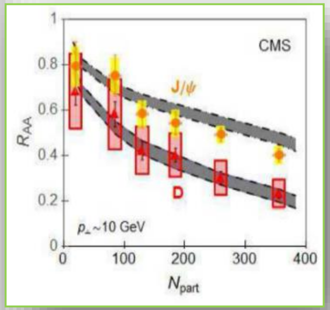
Numerical procedure

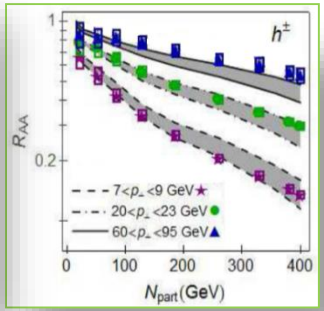


- Light flavor production
  Z.B. Kang, I. Vitev, H. Xing, PLB 718:482 (2012)
- Heavy flavor production
  M. Cacciari et al., JHEP 1210, 137 (2012)
- Path-length fluctuations A. Dainese, EPJ C33:495,2004.
- Multi-gluon fluctuations
  M. Gyulassy, P. Levai, I. Vitev, PLB 538:282 (2002).
- DSS and KKP fragmenation for light flavor
  D. de Florian, R. Sassot, M. Stratmann, PRD 75:114010 (2007)
  B. A. Kniehl, G. Kramer, B. Potter, NPB 582:514 (2000)
- BCFY and KLP fragmenation for heavy flavor
  M. Cacciari, P. Nason, JHEP 0309: 006 (2003)
- Decays of heavy mesons to single e and J/ψ
  M. Cacciari et al., JHEP 1210, 137 (2012)
- T=304MeV for LHC and T=221MeV for RHIC.
  M. Wilde, Nucl. Phys. A 904-905, 573c (2013) (ALICE)
  A. Adare *et al*., Phys. Rev. Lett. 104, 132301 (2010) (PHENIX)

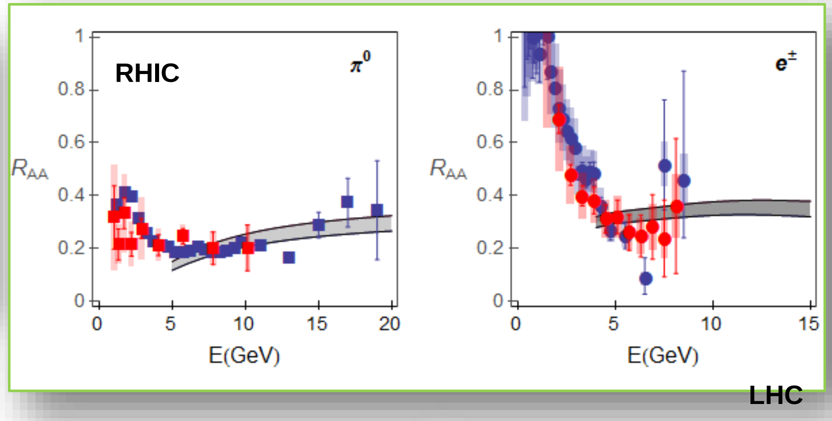


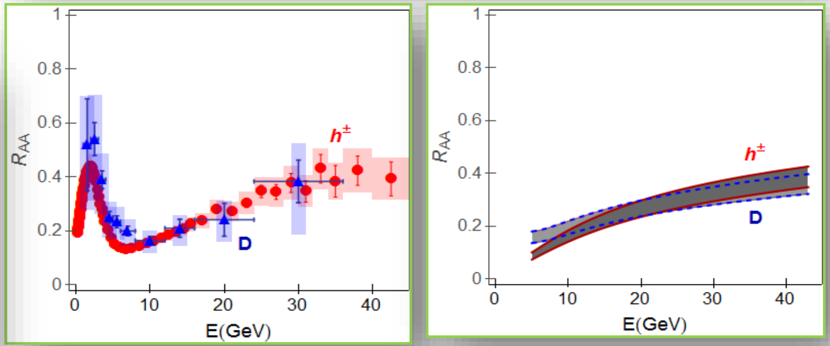
Explains high-pt R_{AA} data for different probes, collision energies, and centralities.





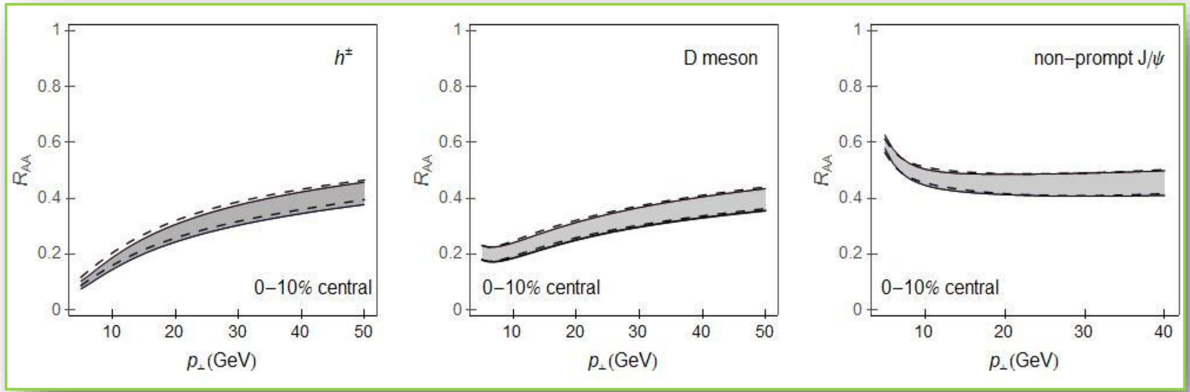
Resolved the longstanding “heavy flavor puzzles at RHIC and LHC”.

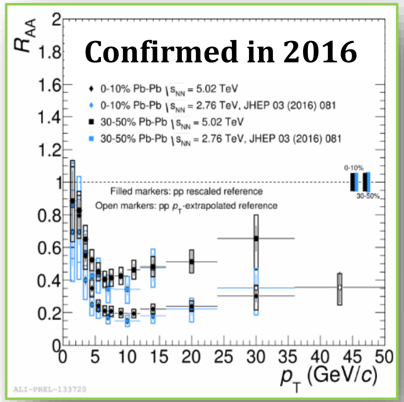




Clear predictive power!

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





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

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

Next Goal: 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.

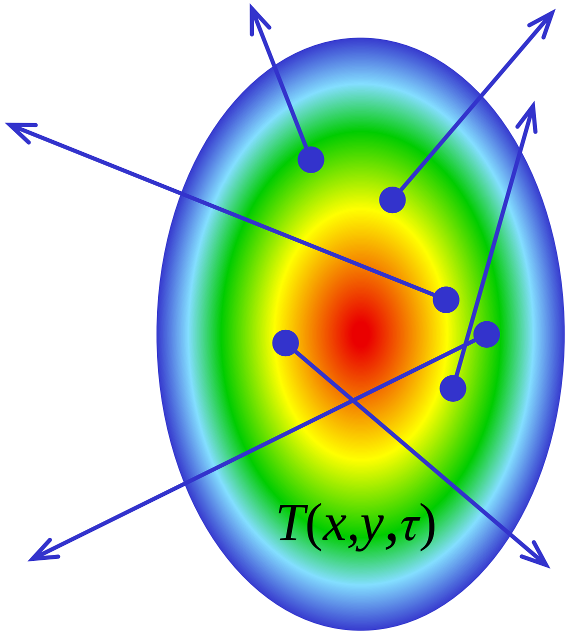
However, some important bulk QGP properties are known to be difficult to constrain by low-pt observables and corresponding theory/simulations.

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

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

erc European Research Council

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.

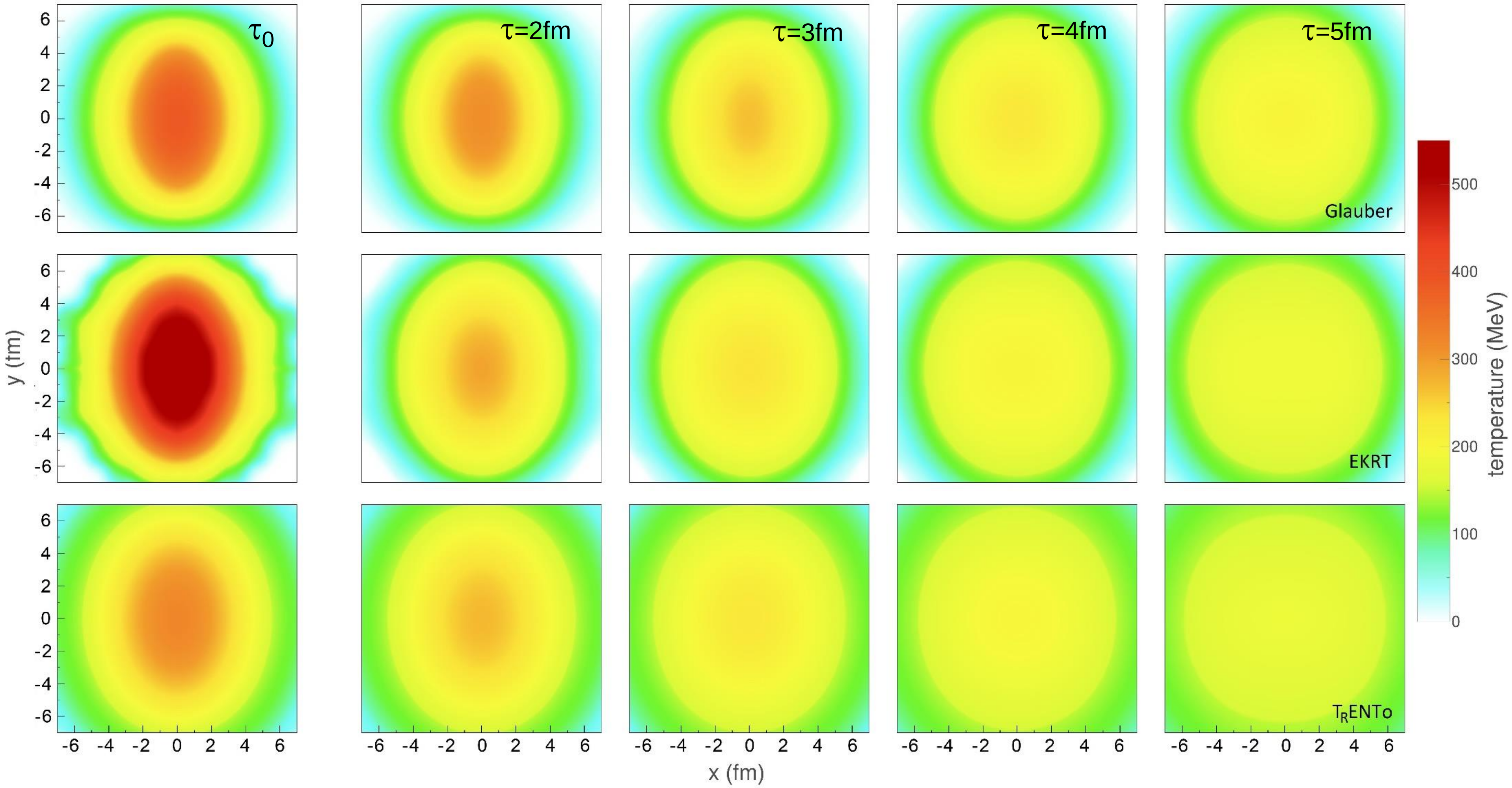
D. Zigic, I. Salom, J. Auvinen, P. Huovinen, M. Djordjevic Front.in Phys. 10 (2022) 957019

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

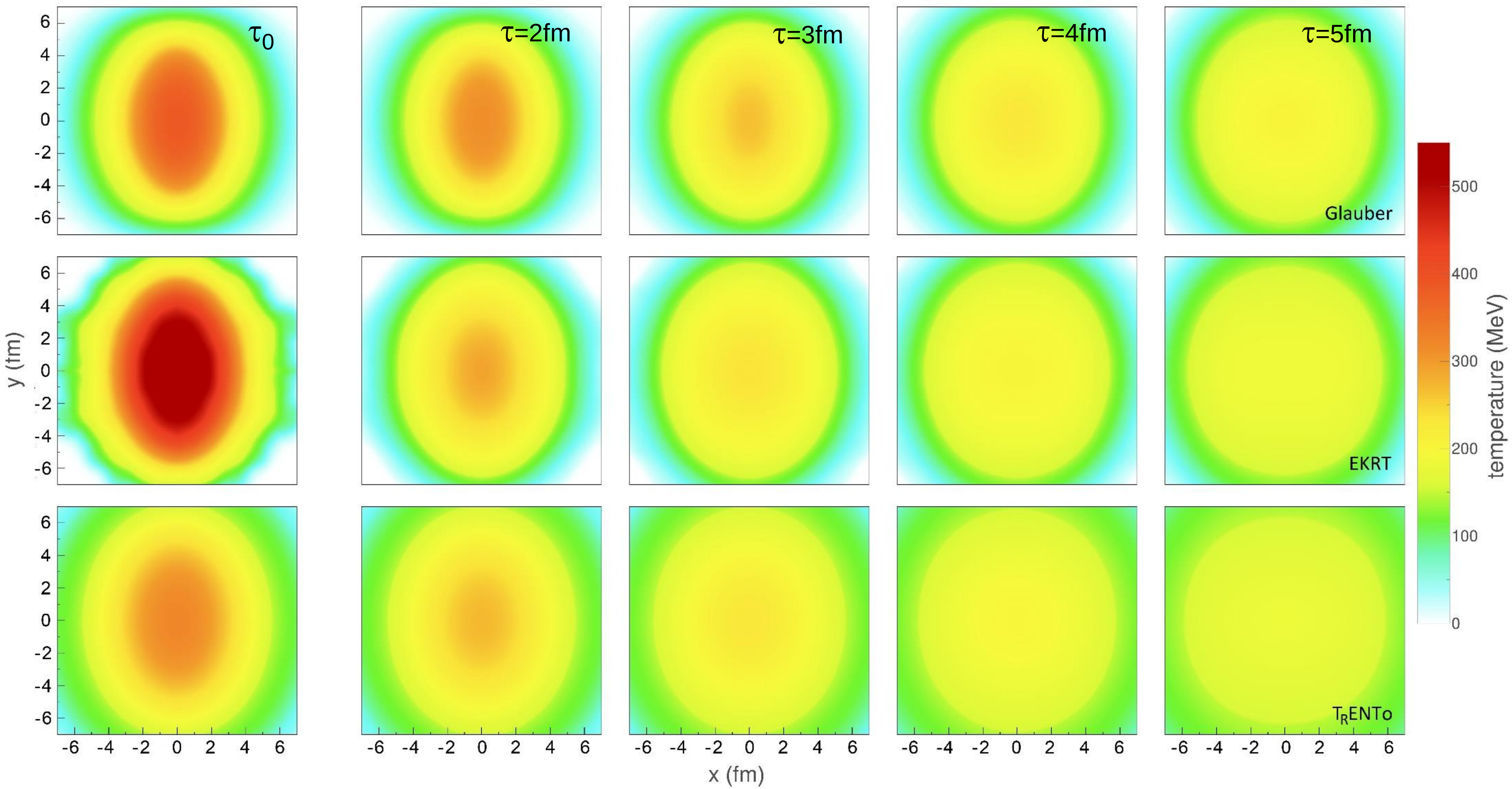
Are high-pt observables indeed sensitive to different T profiles?



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

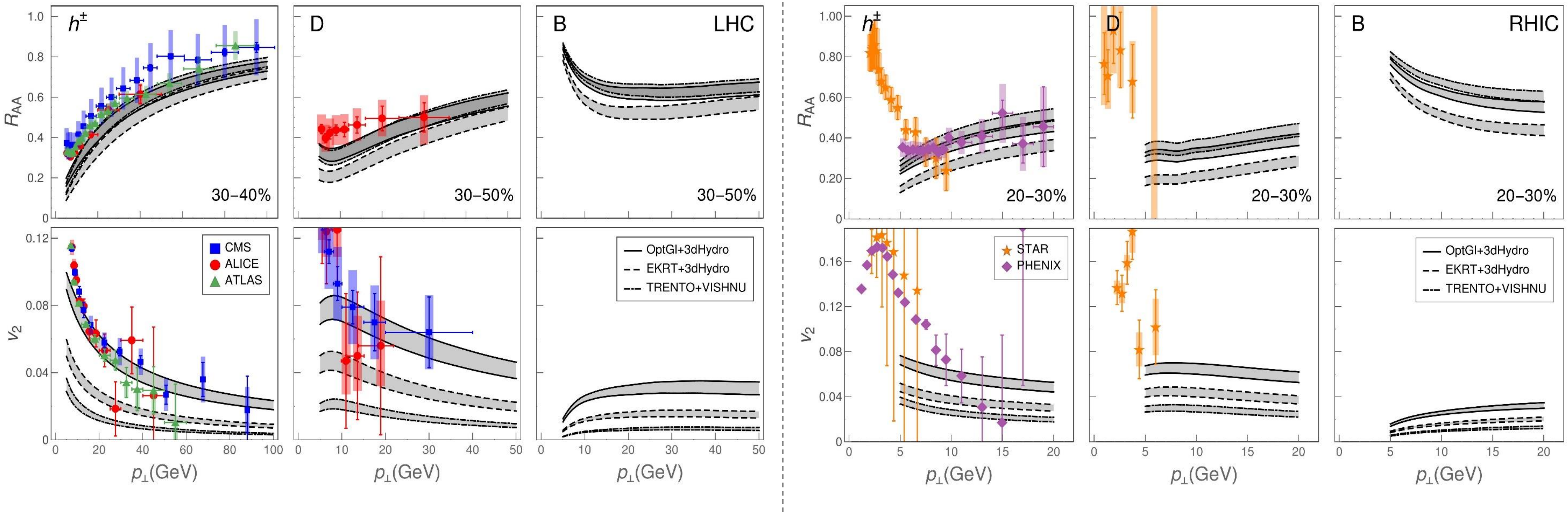
Qualitative differences



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

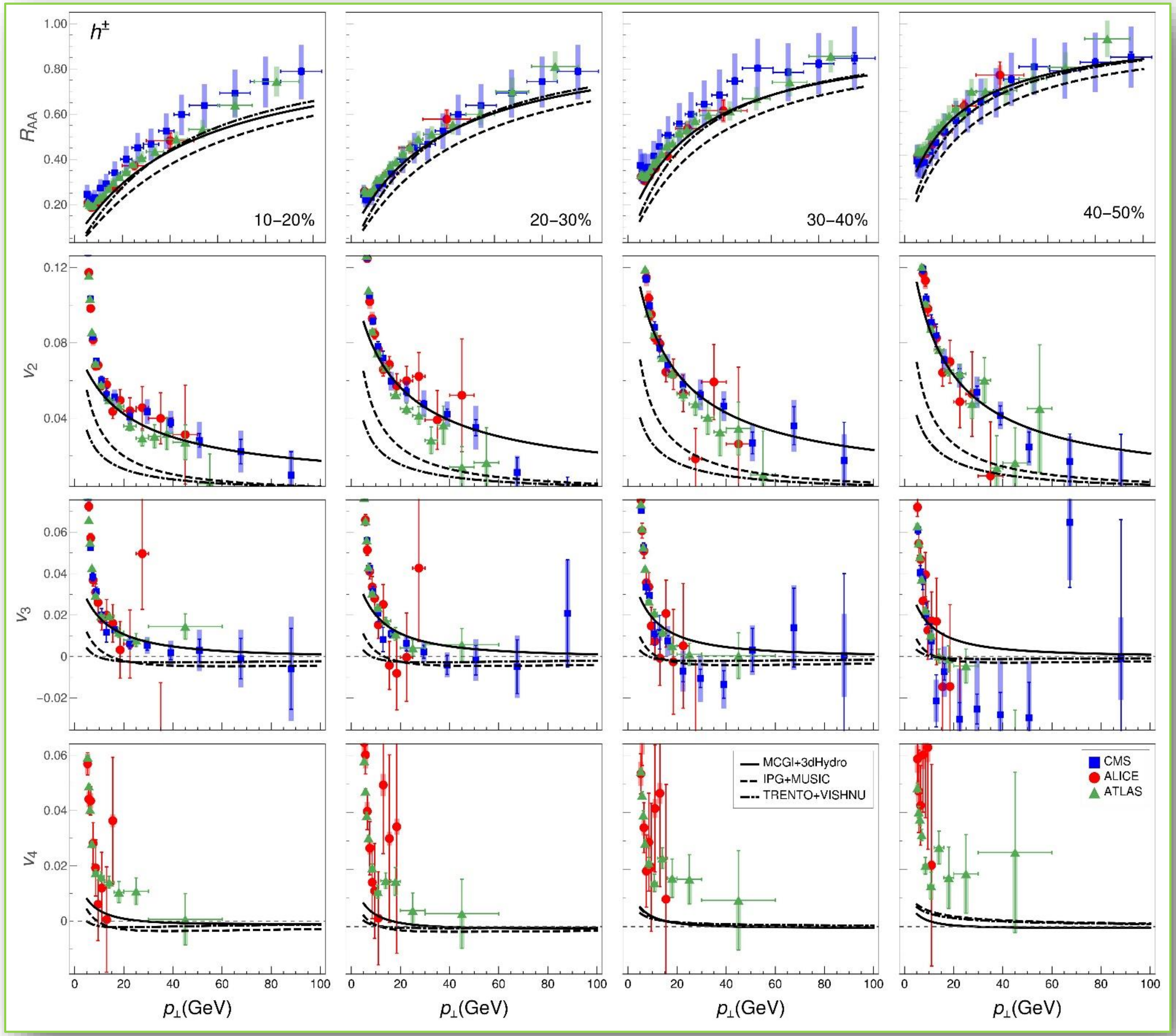
DREENA-A predictions

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



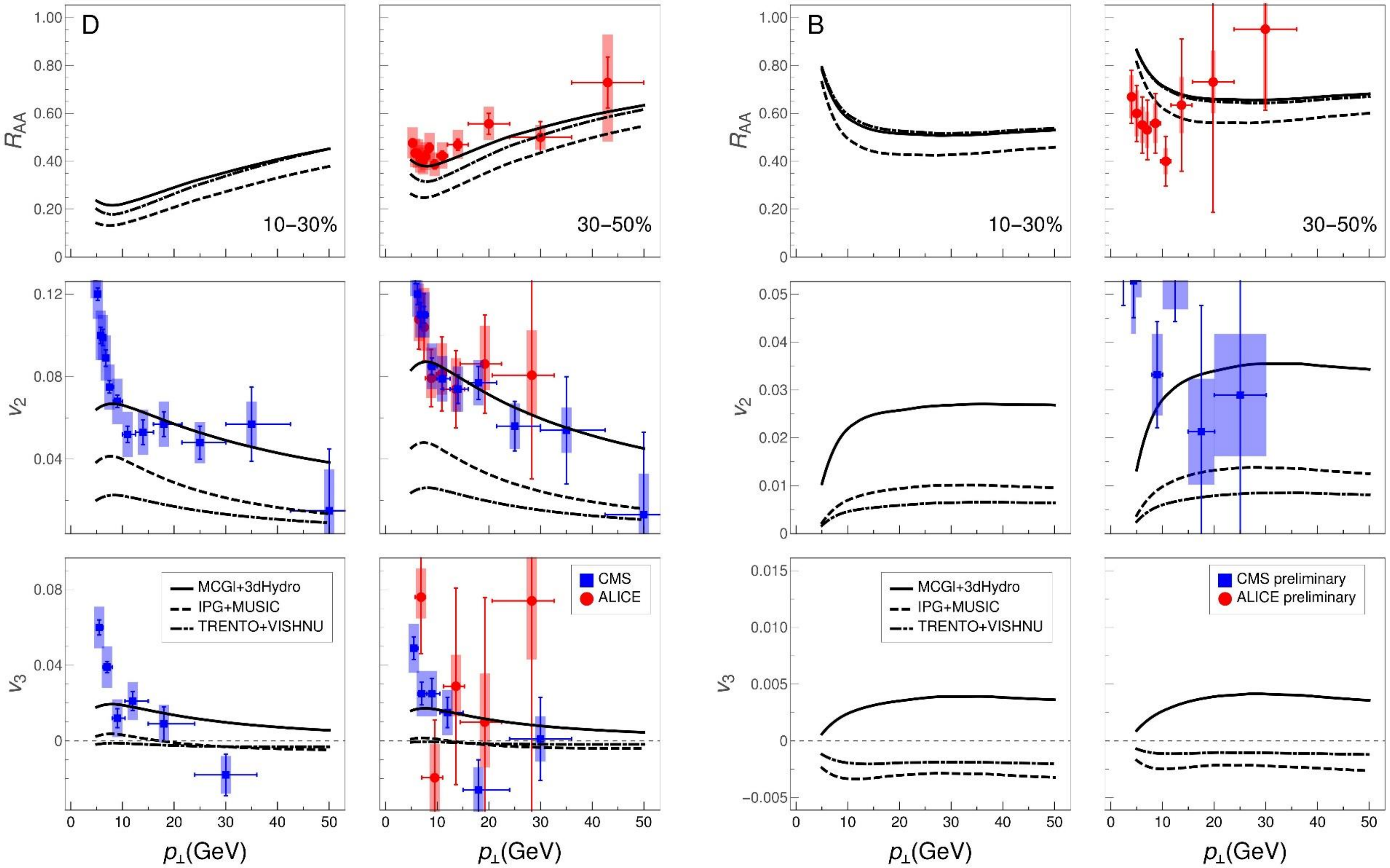
D. Zigic, J. Auvinen, I. Salom, P. Huovinen and MD, Phys.Rev.C 106 (2022) 4, 044909

- 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

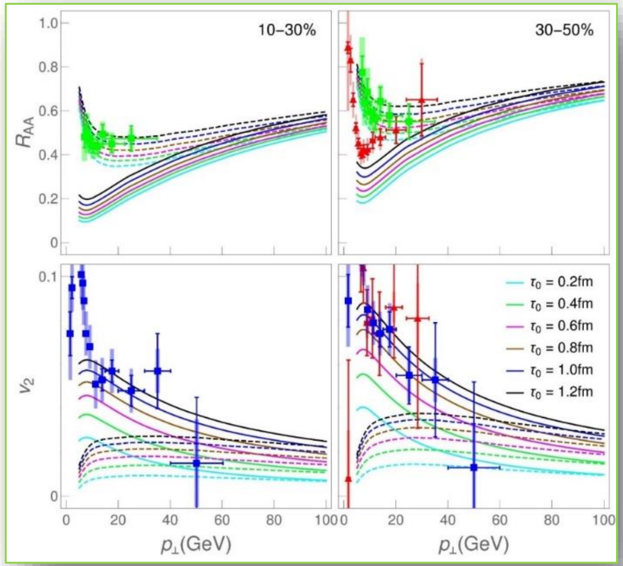


- Heavy flavor - even more sensitive to different medium evolutions!
- Upcoming high-luminosity data at RHIC and LHC will provide higher harmonics data with much larger precision.
  - Higher harmonics present a unique opportunity for precision QGP tomography.
- Adequate medium evolution should be able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

Exploring bulk QGP properties through DREENA

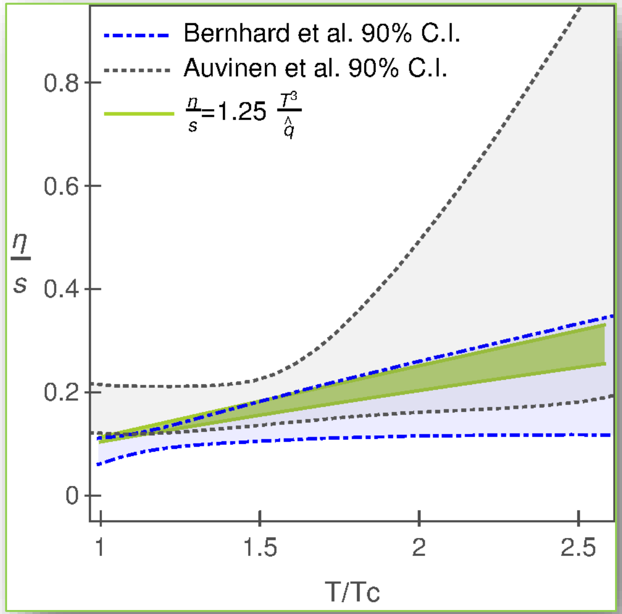
Constrained the early evolution of QGP

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



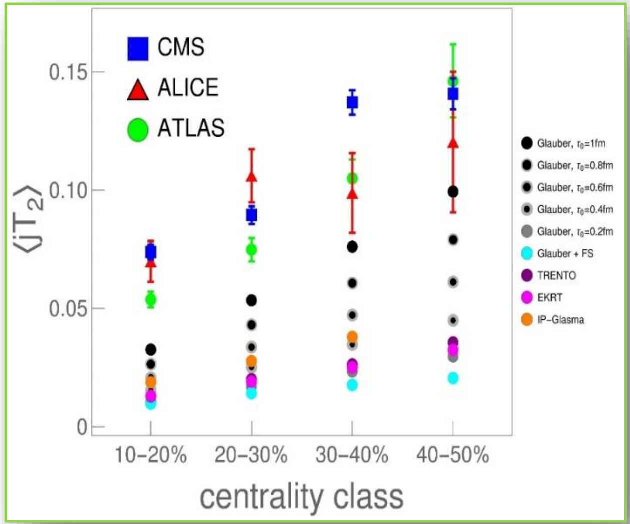
Constrained η/s from the dynamical energy loss $\hat{q}$

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



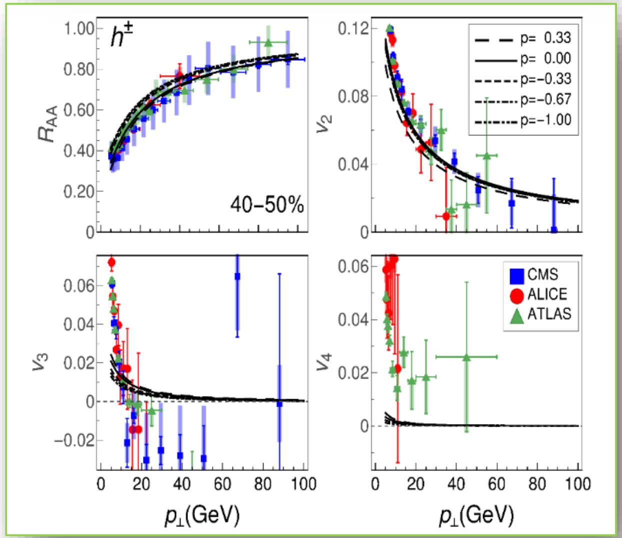
Proposed a new observable to constrain QGP anisotropy

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, arXiv: 2403.17817



Summary up to now

We have unified two separate fields of relativistic heavy ion physics:

- Energy loss of high-energy partons
- Relativistic hydrodynamics

We have developed an advanced numerical procedure (DREENA) that allows efficient generation of predictions for a wide range of observables and their comparison with data.

We have studied some significant QGP properties using this unique approach.

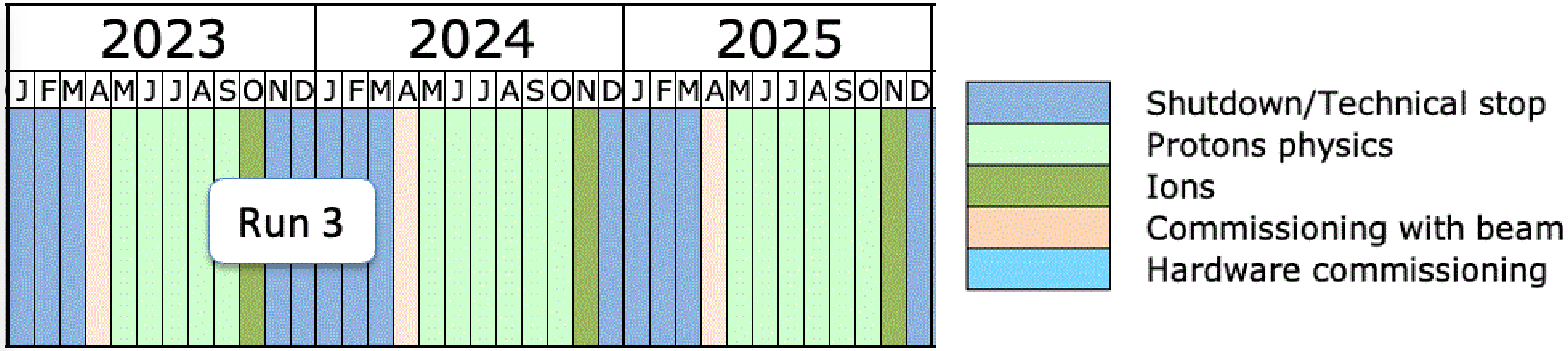
Significant project risk:

For the first time, we determined the properties of matter using low and high-energy data.

Significant scientific gain:

A large amount of high-energy data obtained through enormous scientific investments had not been utilized to determine the properties of QGP. Our tool enables optimal utilization of this valuable data!

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

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

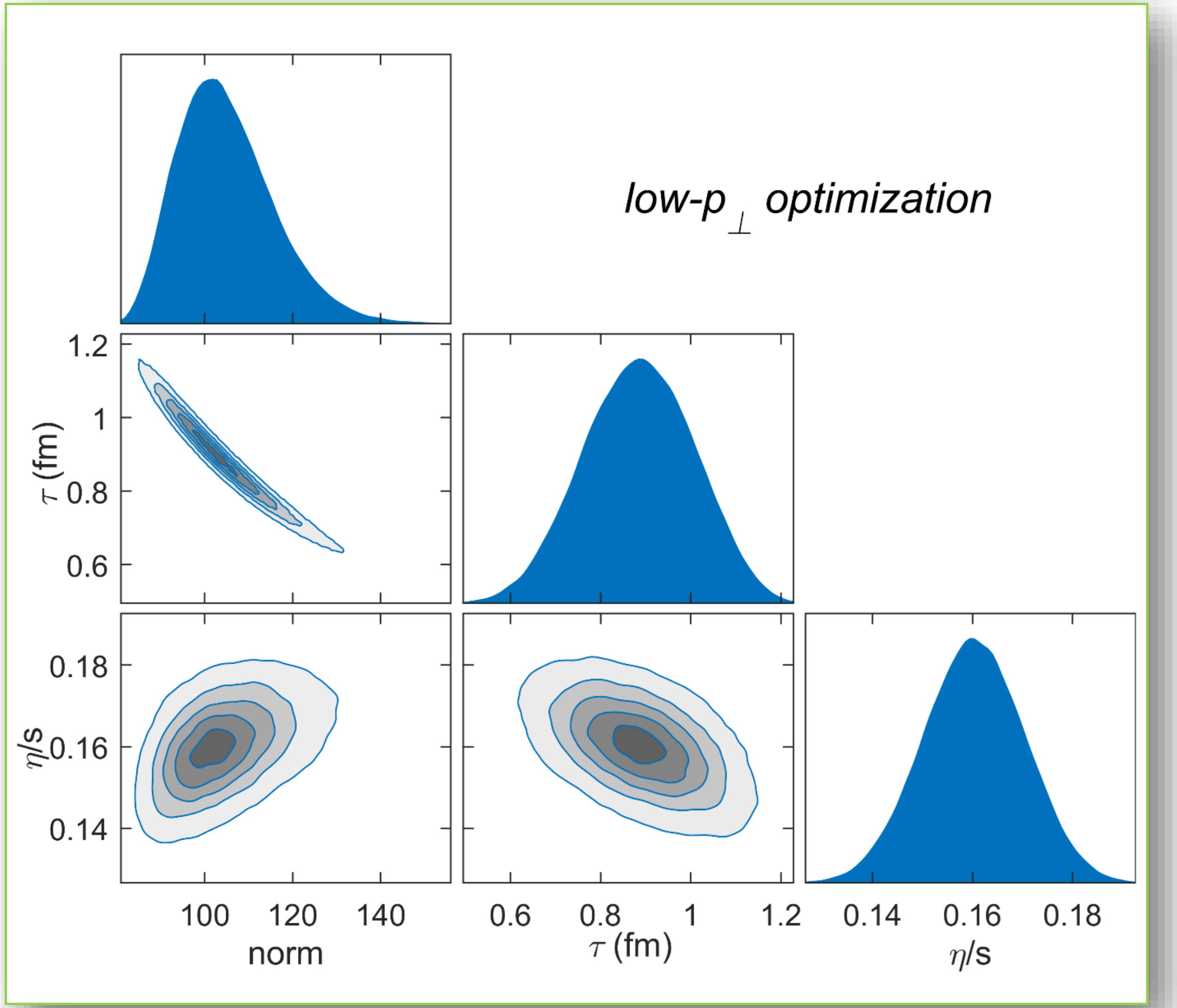
Bayesian inference (Hamiltonian Monte Carlo sampling)

- 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

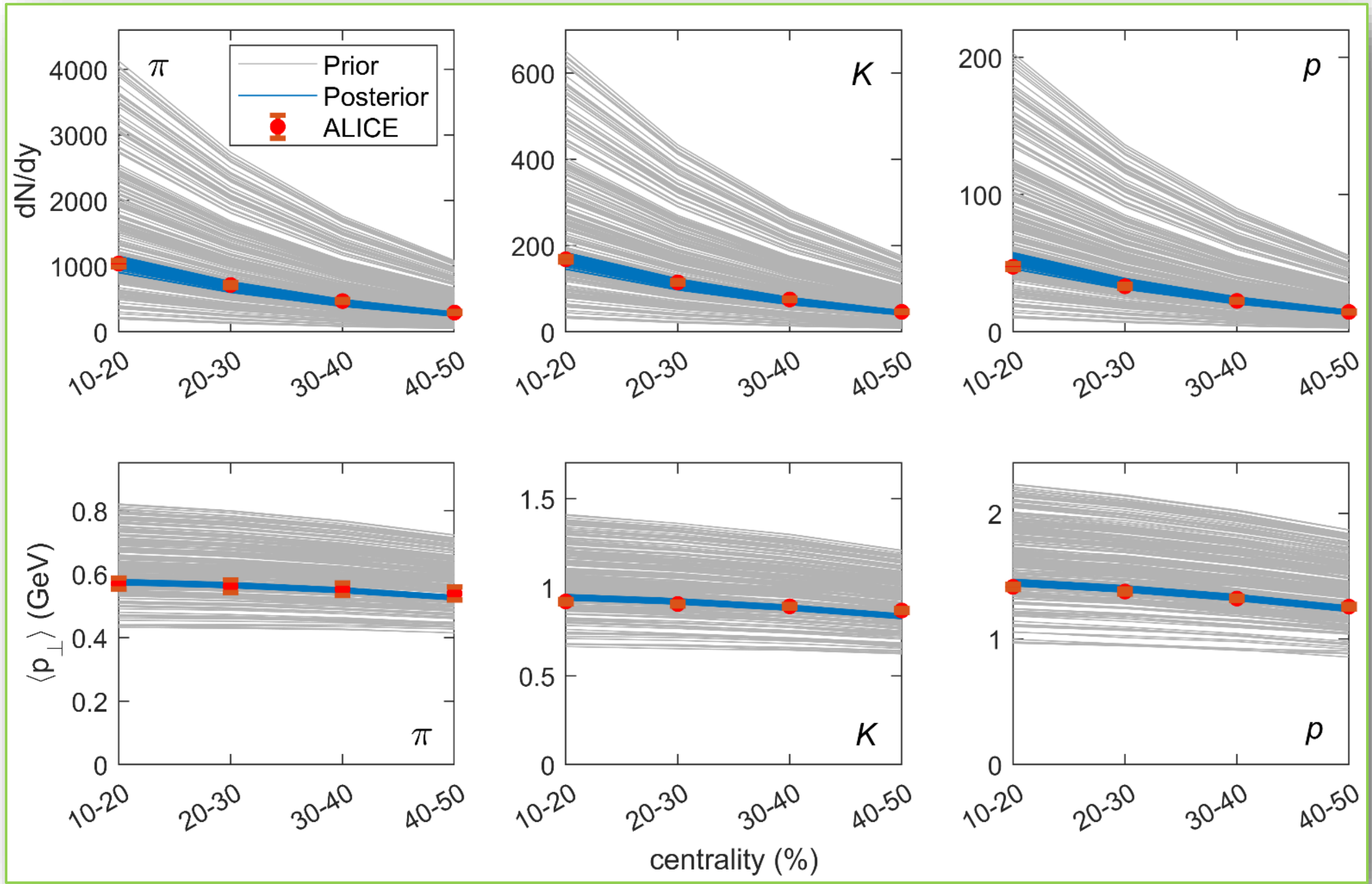
  All other parameters are as in PRC **108**, 044907 (2023).
- For each set of parameters, we run average medium evolutions with TRENTo+ VISHNew, to generate low-pt predictions and *T* profiles as an input for DREENA-A.
- Run DREENA-A with these *T* profiles to generate high-pt predictions.
- Statistical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

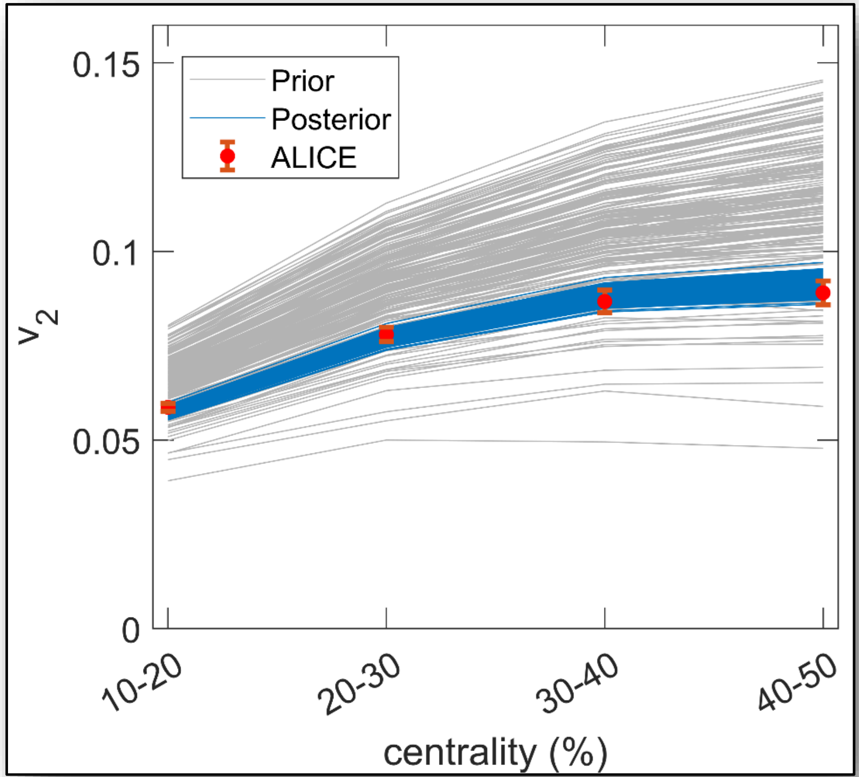
Marginal distribution of parameters obtained with Bayesian inference of low-pt data



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

Prior vs. posterior: low-pt data

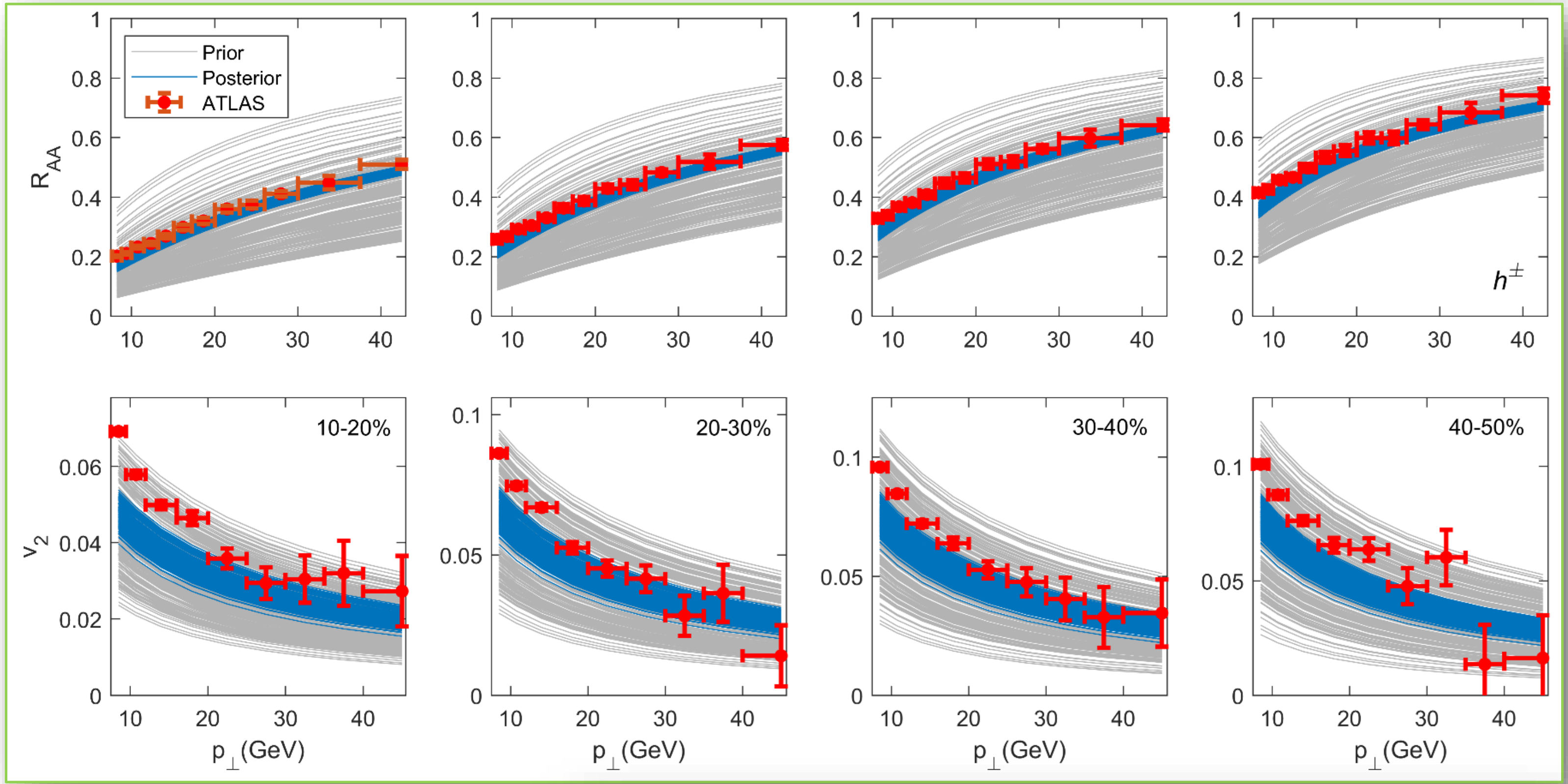




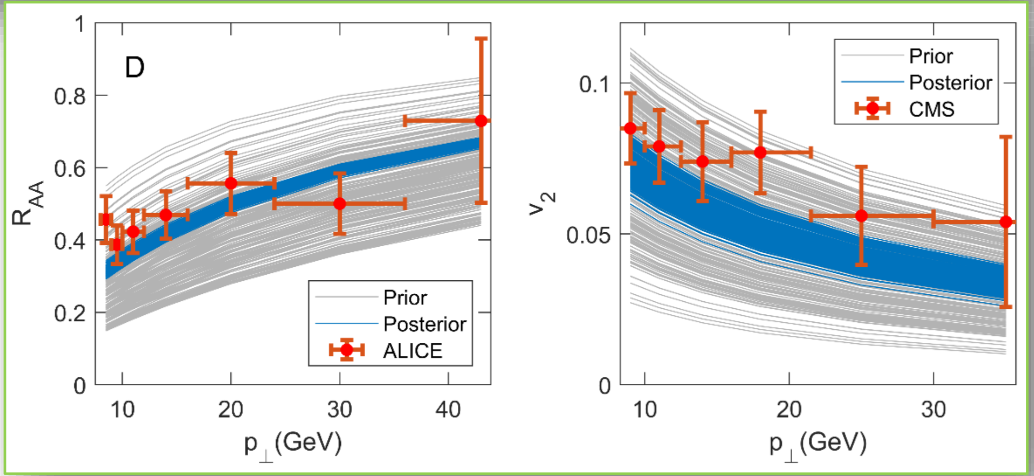
Very good agreement with low-pt data!

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

Prior vs. posterior: high-pt data

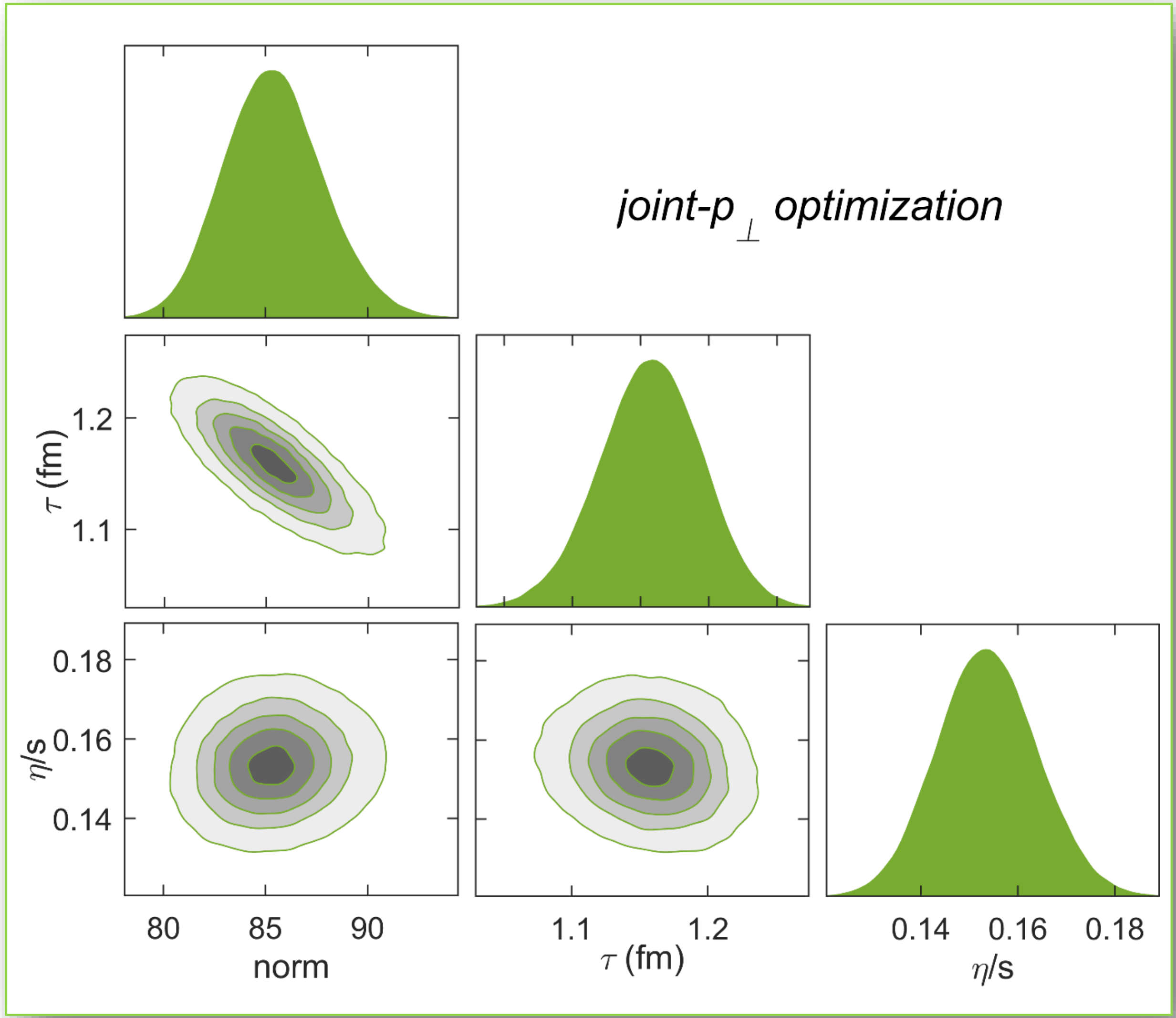


M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).



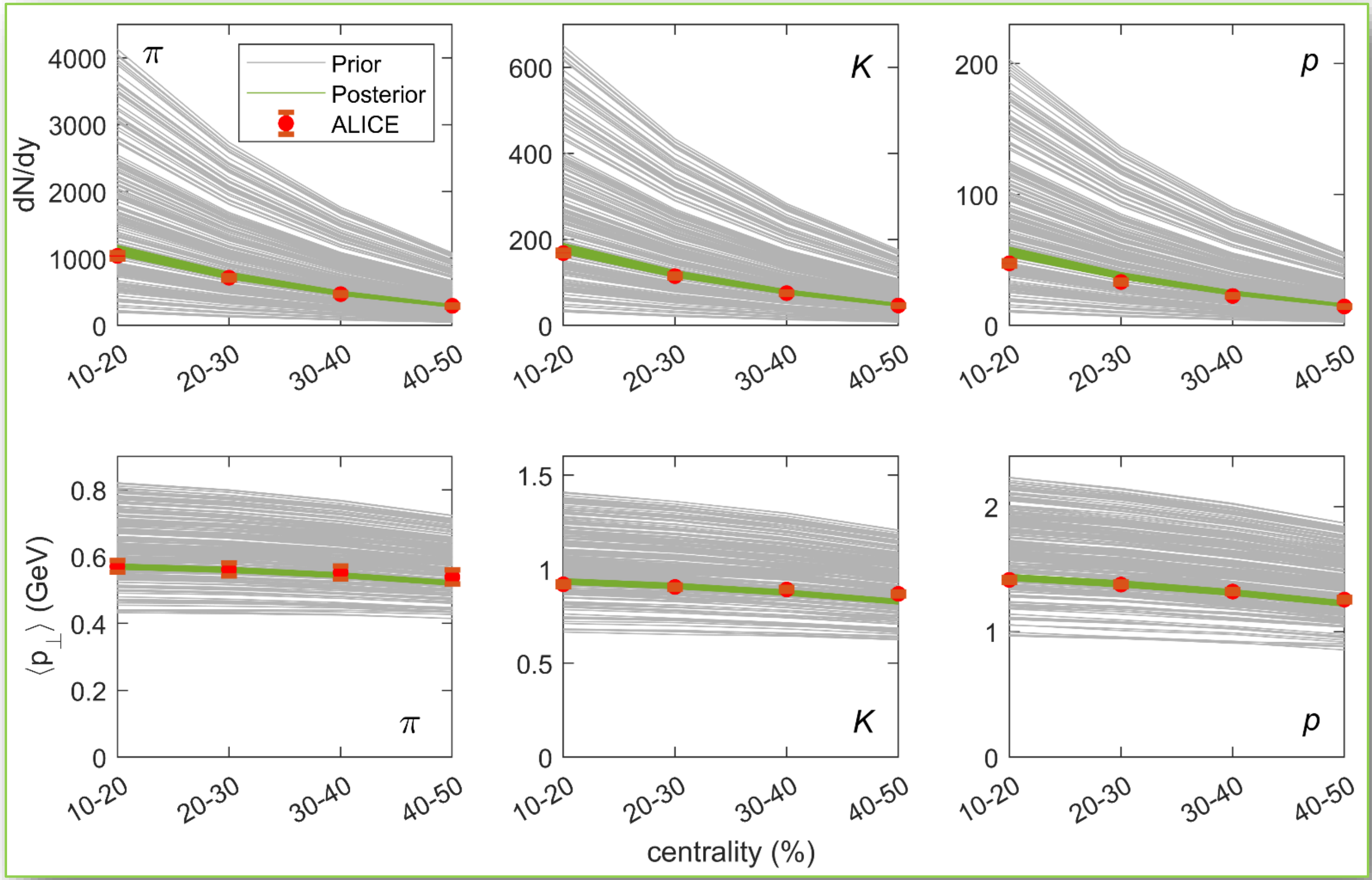
Suboptimal agreement with high-pt data, especially for v_2.

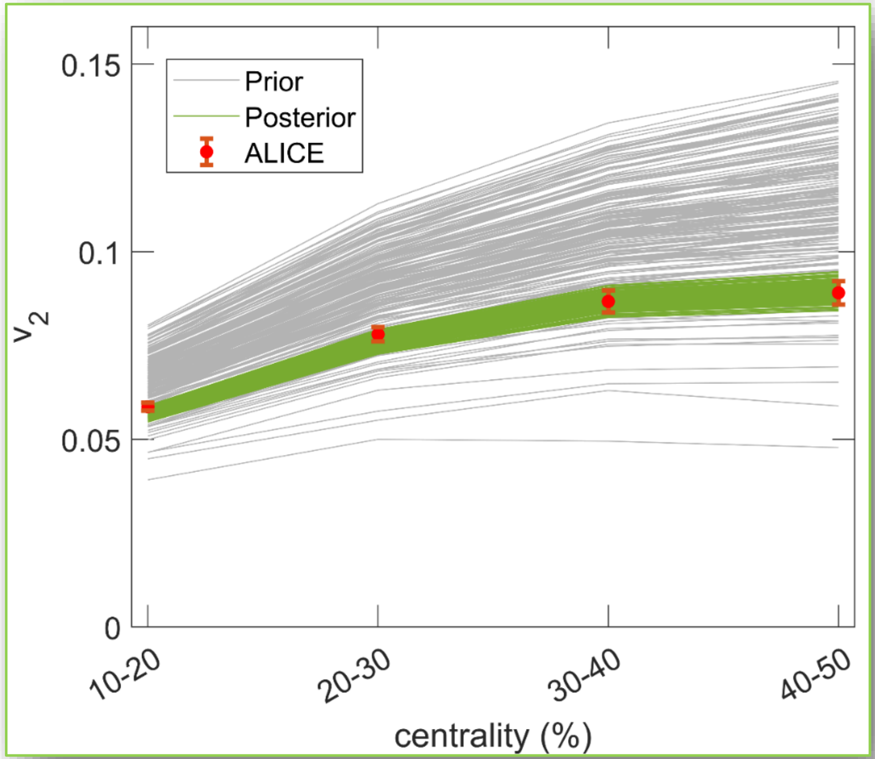
Marginal distribution of parameters obtained with Bayesian inference of both low-pt and high-pt data



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

Prior vs. posterior: low-pt data

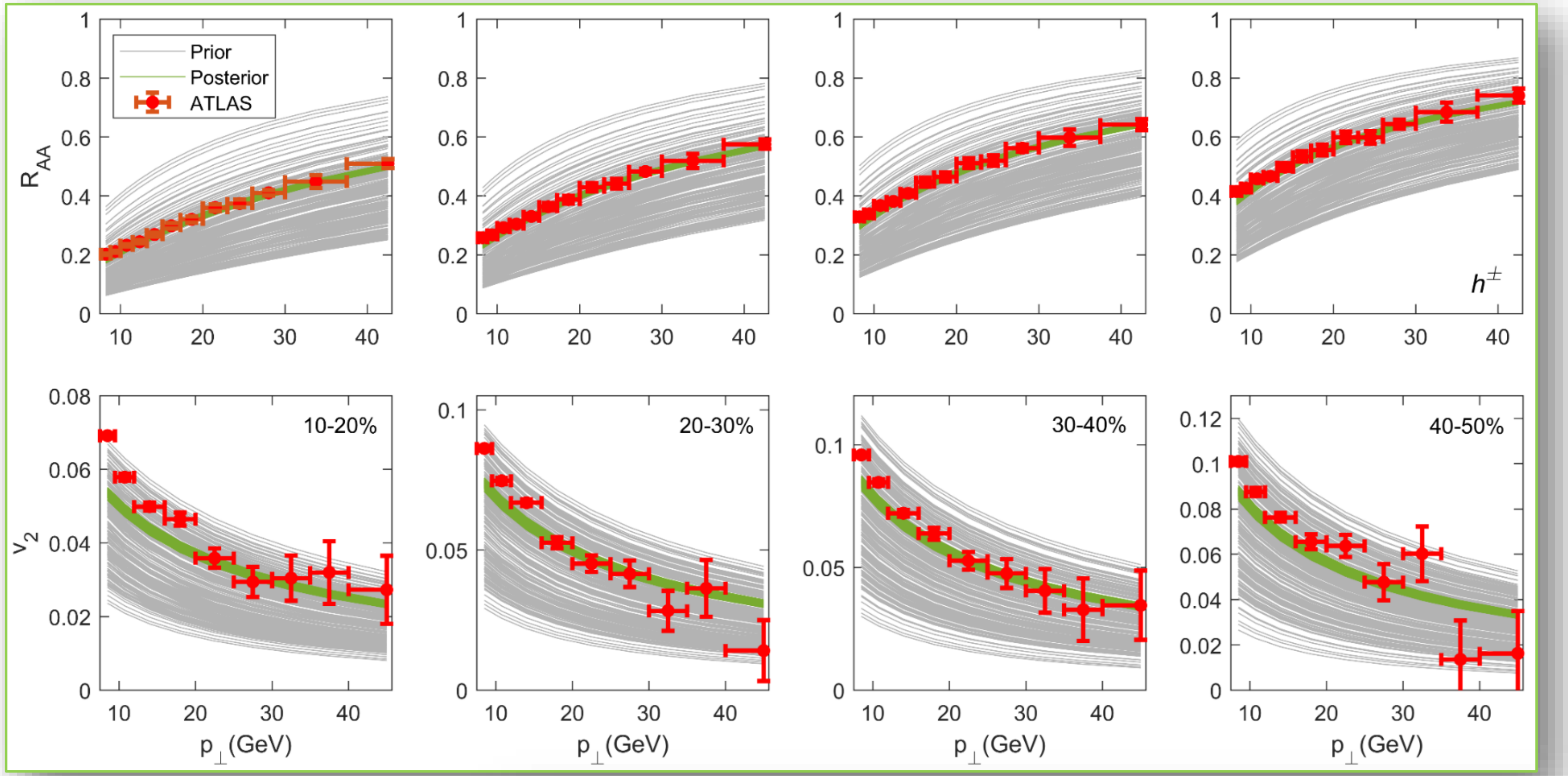




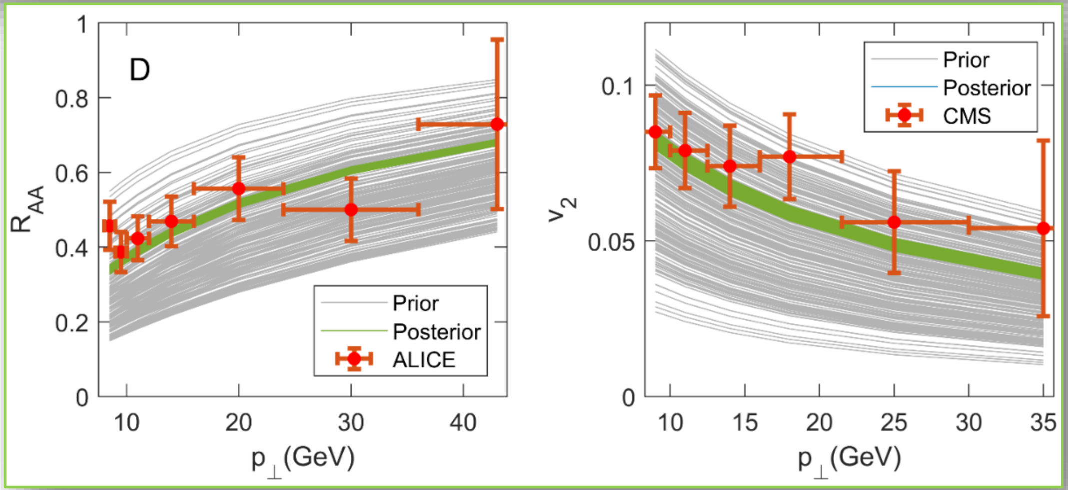
Very good agreement with low-pt data!

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

Prior vs. posterior: high-pt data



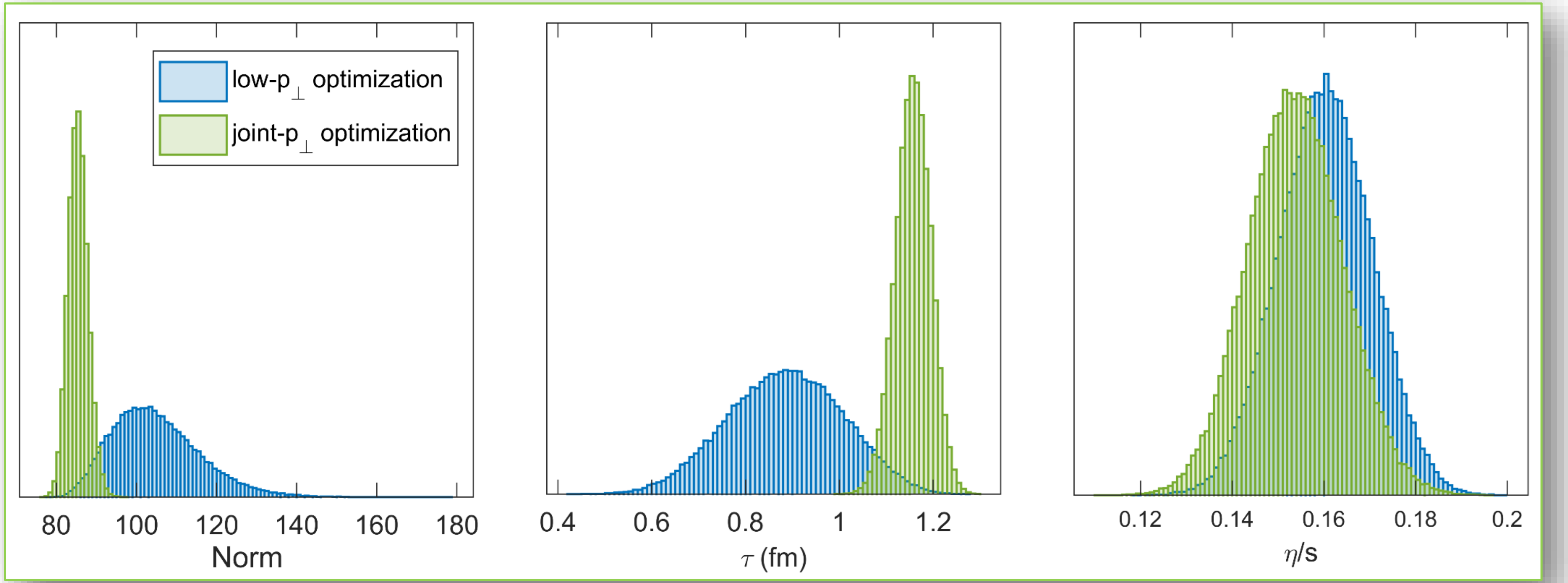
M. Djordjevic, D. Zigic, I. Salom, and MD, to be submitted (2024).



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!

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

INSTITUTE for NUCLEAR THEORY

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).