# Bayes-DREENA for QGP parameter inference from unified high and low-pt data Magdalena Djordjevic,

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МИНИСТАРСТВО ПРОСВЕТЕ, АУКЕ 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.





A realistic description for parton-medium interactions!

#### Suitable for QGP tomography!

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# Part I: Can we use dynamical energy loss to constrain $\eta/s$ ?

- Low- $p_{\perp}$  observables are widely used to explore the bulk QGP properties.
- $\eta/s$  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  $\eta$ /s to be very low Strongly coupled.
- QGP may behave as perfect fluid near  $T_c$  (soft regime), and  $\eta/s$  may increase at high temperatures (hard regime).
- Testing the soft-to-hard hypothesis is difficult: Anisotropy is weakly affected by the  $\eta/s$  at high temperatures.
- High- $p_{\perp}$  data/theory can serve as a complementary tool.
- Can we constrain  $\eta/s$  by using the dynamical energy loss?

# Constraining $\eta/s$ from the dynamical energy loss $\hat{q}$

#### **Dynamical energy loss:**



#### 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!  $\sqrt{6ET}$ 

$$\hat{q} = \int_{0}^{\sqrt{6DT}} d^{2}q \, q^{2} \cdot \frac{d\Gamma_{el}}{d^{2}q}$$

$$= C_{A}T\alpha(ET) \int_{0}^{6ET} dq^{2} \, q^{2} \left(\frac{1}{q^{2} + \mu_{M}^{2}} - \frac{1}{q^{2} + \mu_{E}^{2}}\right)$$

$$= C_{A}T\alpha(ET) \left(\mu_{E}^{2} \ln\left[\frac{6ET + \mu_{E}^{2}}{\mu E^{2}}\right] - \mu_{M}^{2} \ln\left[\frac{6ET + \mu_{M}^{2}}{\mu_{M}^{2}}\right]\right)$$

• 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).

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# What we expect from previous knowledge?

- Sensitive to the coupling strength in QGP: weak coupling enlarges  $\eta/s$  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<sub>1</sub> v<sub>2</sub>. (Liao&Shuryak, PRL 102, 2009).
- In the weakly coupled regime (Majumder, Muller, Wang, PRL 99, 2007)  $\eta/s \approx 1.25 \frac{T^3}{\hat{a}}$ .
- At large *T*, weakly coupled system.
- Near  $T_c$ , strongly coupled limit, and  $\frac{T^3}{\hat{q}}$  should significantly deviate from  $\eta/s$ .
- **Soft-to-hard boundary:** the transition region from strong to weak coupling.

 $\eta$ /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).



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



The enhancement arises from chromoelectric 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



- η/s shows surprisingly good agreement all the way to T<sub>c</sub> 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<sub>c</sub> 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: Can we use high-pt theory and data to extract the bulk QGP parameters through Bayesian statistics?

#### The main idea behind high-pt 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 <a href="http://github.com/DusanZigic/DREENA-A">http://github.com/DusanZigic/DREENA-A</a>

#### 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



# Formal framework for DREENA Bayesian inference



- Weassume 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 (2024).

# Prior vs. posterior: low-pt data



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

# Prior vs. posterior: high-pt data



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



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

### Prior vs. posterior: high-pt data



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



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





Established by the European Commission



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# A. Modeling the bulk evolution

- Initial entropy profiles are generated using TRENTo model.
- 10<sup>4</sup> 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\_data.
   S. Stojku, J. Auvinen, M. Djordjevic, P. Huovinen and MD, Phys. Rev. C 105 (2022) 2, L021901
- Onset time for hydrodynamics: τ<sub>0</sub>= 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).