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Multi-observable analysis of jet quenching using Bayesian inference with JETSCAPE[★]

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Abstract

The JETSCAPE Collaboration presents a new determination of the jet transport parameter $\hat{q}$ in the Quark-Gluon Plasma (QGP) using Bayesian Inference. This study expands on previous work by incorporating a comprehensive data set from inclusive hadron and jet yield suppression measurements at RHIC and the LHC. Utilizing Active Learning and other machine-learning approaches for computational efficiency, the analysis efficiently explores the parameter space and studies systematic dependencies across various kinematic and centrality ranges. The results highlight tensions in the extracted $\hat{q}$ values across different data sets, providing deeper insights into the physics of jet transport in the QGP.

Keywords: jet quenching, heavy-ion collisions, quark-gluon plasma, Bayesian inference

1. Introduction

Various theoretical frameworks have been developed for jet quenching in relativistic nuclear collisions. Comparisons between jet quenching models and experimental measurements provide valuable insights into the structure and dynamics of the Quark-Gluon Plasma (QGP). The jet transport coefficient $\hat{q}$, which characterizes the momentum transfer between an energetic parton and the QGP, has been constrained through comparisons between model predictions and experimental data [1]. However, current constraints on $\hat{q}$ show inconsistencies, primarily due to differing modeling assumptions, approximations, and data selection. This analysis introduces a new determination of $\hat{q}$ using the JETSCAPE framework [2], while addressing a key question: Is $\hat{q}$ a universal property of the QGP, with extracted values remaining consistent across different data sets?

In this analysis, the multi-observable nature and broad kinematic range of the data are utilized to examine the systematic sensitivity of the posterior distributions of $\hat{q}$ to the choice of observable and kinematic range [3–5]. If $\hat{q}$ is indeed a universal property of the QGP and the theoretical framework is accurate, the posterior distributions should remain consistent despite variations in observables or phase space coverage. Tensions observed in these distributions may indicate limitations in the theoretical formulation of $\hat{q}$ or in the bulk medium model used in the simulations, or stem from a lack of quantified theoretical uncertainties. Additionally, these tensions may suggest that interpreting $\hat{q}$ as an intensive property of the medium is not entirely correct.

2. Model and setup

This analysis employs a (2+1)-dimensional hydrodynamic model with parameters calibrated by Bayesian inference of soft-sector observables for the bulk medium evolution [6], producing bulk properties similar to those obtained in a separate JETSCAPE Bayesian analysis [7, 8]. Jet quenching is modeled within the JETSCAPE framework using the MATTER [9, 10] (for the high-virtuality stage) and LBT [11–14] (for the low-virtuality stage) models. The soft stage of the partonic shower is treated non-perturbatively using a hadronization model, as described in Ref. [15].

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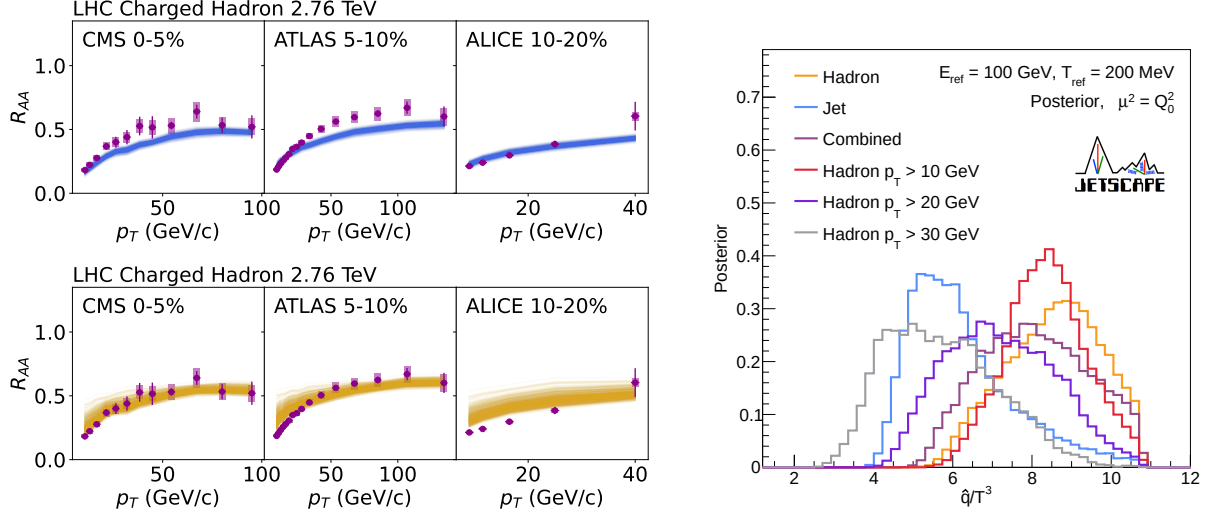


Figure 1: Left: Selected measurements of hadron R_{AA} at $\sqrt{s_{NN}} = 2.76$ TeV across various centralities (purple), compared with posterior distributions from the Combined calibration (upper panels, blue) and calibration using only hadrons with $p_T > 30$ GeV/c (lower panels, orange). Right: Posterior distributions of $\hat{q}/T^3$ for a quark with energy E_{ref} and virtuality Q_0^2 at temperature T_{ref} , calibrated with different datasets: combined (purple), jet-only (blue), hadron-only for all p_T (orange), and hadron-only with $p_T > 10$ GeV/c (red), $p_T > 20$ GeV/c (light purple), and $p_T > 30$ GeV/c (grey). Figures adapted from Ref. [5].

In this analysis, $\hat{q}$ is a quantity influenced by several scales including medium temperature T , parton energy E , and virtuality μ^2 . Its extraction also depends on the dynamical modeling of the thermal medium. Specifically, $\hat{q}$ is parametrized as $\hat{q}(\mu^2, T, E) = f(\mu^2)\hat{q}^{HTL}$, based on a hard thermal loop (HTL) calculation of $\hat{q}^{HTL}$, modulated by a virtuality-dependent term $f(\mu^2)$, which reduces energy loss for high-virtuality partons due to coherence effects [15, 16]. The full parametrization can be found in Ref. [5].

The Bayesian calibration incorporates all inclusive hadron and jet R_{AA} measurements from RHIC and the LHC for Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV, using data published before February 2022 [17–27]. This amounts to 729 data points. Since simulating the corresponding model calculations is computationally expensive, this analysis employs a machine-learning approach called Active Learning [28–31] for efficient selection of design points in parameter space for simulation and a Gaussian Process Emulator as a fast surrogate model. Despite these optimizations, the simulations required approximately 5.5 million CPU core-hours, using high-performance computing facilities provided by XSEDE [32].

3. Results and discussion

This section focuses on differential studies of the posterior distributions of $\hat{q}$, presented in terms of $\hat{q}/T^3$ for several choices of observable and phase-space coverage. Discussions of the posterior distributions for other model parameters are presented in Ref. [5]. The baseline calibration, denoted as “Combined,” incorporates the full set of inclusive hadron and jet R_{AA} data. In Fig. 1, the upper left panels show selected hadron and jet R_{AA} measurements compared to the posterior distributions from the Combined calibration (blue distributions). The lower left panels compare the same data with a calibration based solely on hadron R_{AA} data for $p_T > 30$ GeV/c.

When comparing the posterior distributions from these two sets of panels, it is essential to note that low- p_T hadron R_{AA} measurements have the highest precision data points among all the measurements, exerting strong constraints on the Combined posterior. This results in good agreement between the model and measurements at low- p_T ($p_T \lesssim 20$ GeV/c), while the model faces challenges at higher p_T . The lower left panels highlight this further: When the calibration is based only on hadron R_{AA} data for $p_T > 30$ GeV/c, the model performs better in this range but struggles at low- p_T . This calibration yields a broader 90% Credible Interval (CI) for high- p_T hadrons, reflecting lower measurement precision and sparser data points. These tensions highlight the importance of incorporating theoretical

uncertainties and addressing elements that are not yet included in the model. Potential improvements for low- p_T modeling could involve next-to-leading order (NLO) or non-perturbative corrections to $\hat{q}^{\text{HTL}}$, as well as accounting for nuclear shadowing effects.

The posterior distribution of $\hat{q}/T^3$ from the Combined analysis, evaluated for a reference quark energy and virtuality as a function of T , shows an increase as T decreases [5], consistent with previous studies [1]. The right panel of Fig. 1 presents the posterior distribution of $\hat{q}/T^3$ for a reference quark energy $E_{\text{ref}} = 100$ GeV and $\mu^2 = Q_0^2$, at a reference temperature $T_{\text{ref}} = 200$ MeV. The distributions are normalized to unit integral for comparison. To further understand the constraints on $\hat{q}$, we present distributions calibrated using only jet (blue) or hadron (orange) data sets. While the jet-only and hadron-only posterior distributions are consistent, with an overlap of 35.3%, the jet-only calibration tends to yield lower $\hat{q}/T^3$ values. The Combined distribution (purple) lies between the two, with more overlap with the hadron-only distribution.

To explore the origin of differences between jet-only and hadron-only calibrations, we further examine the $\hat{q}/T^3$ posterior distributions based on different hadron p_T ranges. Figure 1 (right panel) shows hadron-only calibrations for $p_T > 10, 20$, or 30 GeV/c. These p_T -selected hadron-only distributions interpolate between the p_T -integrated hadron-only and jet-only calibrations, with $p_T > 10$ GeV/c aligning more closely with the hadron-only calibration, and $p_T > 30$ GeV/c more consistent with the jet-only calibration. The approximate agreement between the hadron-only calibration for $p_T > 30$ GeV/c and the jet-only calibration is understandable since these two data sets probe similar partonic kinematics. However, the inconsistency with lower- p_T probes indicates that the model's description of partonic energy dependence in jet quenching may require refinement, as mentioned above.

4. Summary

The JETSCAPE Collaboration presents a new multi-observable determination of the jet transport coefficient $\hat{q}$, using all available inclusive hadron and jet suppression data from RHIC and the LHC. The QGP bulk medium and its evolution are modeled with parameters derived from a previous Bayesian calibration of soft observables. Virtuality-dependent jet quenching is implemented in a multi-stage model. The combined calibration of $\hat{q}/T^3$ using inclusive hadron and jet R_{AA} data shows good agreement with experimental data across a wide phase space, though tensions exist in certain regions. Further differential studies examine the interplay between hadron and jet R_{AA} data in constraining the posterior distributions. High- p_T hadron data (approximately $p_T > 30$ GeV/c) provide constraints consistent with jet R_{AA} data, probing similar partonic kinematics. However, discrepancies at lower p_T indicate that the model's description of $\hat{q}/T^3$ may not fully capture partonic energy dependence. This analysis builds on the previous JETSCAPE calibration of $\hat{q}/T^3$, representing a significant step toward a comprehensive multi-observable Bayesian calibration of jet quenching to better constrain fundamental transport properties of the QGP.

Acknowledgments

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