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Bayesian extraction of $\hat{q}$ with multi-stage jet evolution approach.

Ron Soltz for the JETSCAPE Collaboration*
Lawrence Livermore National Laboratory and Wayne State University
E-mail: soltz1@llnl.gov

The jet quenching or transverse diffusion coefficient, $\hat{q} = \langle(\Delta k_T)^2\rangle/L$, provides the primary metric that characterize the modification of hard jets in a QGP. A quantitative extraction of $\hat{q}$ from measurements requires sophisticated jet quenching theory, precise and extensive experimental data, as well as an advanced statistical framework that compares theory to data. Within the JETSCAPE collaboration we have developed a multi-stage approach of jet evolution, where the medium-modified parton showers at high virtuality scale are described using the DGLAP evolution and simulated with the MATTER event generator, while the in-medium elastic and inelastic scatterings of partons at low virtuality scale are described using a transport theory implemented with the LBT event generator. The transition from the DGLAP phase to the transport phase of jet modification, and its dependence on properties of the jet and the local medium, has previously only been approximately estimated. The goal of this work is to use the advanced statistical framework to determine this transition. To this end, a simplified version of the state-of-the-art JETSCAPE generator is embedded within a Bayesian analysis framework for a simultaneous calibration on jet quenching data at various centrality bins in 200 GeV Au-Au, 2.76 TeV Pb-Pb and 5.02 TeV Pb-Pb collisions, from which $\hat{q}$ is systematically extracted as functions of both jet energy and medium temperature. The dependence of $\hat{q}$ on the medium-induced virtuality scale is quantitatively explored for the first time. This virtuality, in combination with the local temperature and parton energy, serves as a crucial separation scale between the DGLAP region and the transport region for jet quenching. Its median value is determined to be 2.1 or 2.9 GeV for two different parameterizations of the jet quenching coefficient.

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*Speaker.

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1. Introduction

Studying the mechanisms for energy transport of hard partons in the quark-gluon plasma created in heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) is essential to fully probe the structure and dynamics of QGP. The jet quenching or transverse diffusion coefficient, $\hat{q} = \langle(\Delta k_T)^2\rangle/L$, provides the primary metric for evaluating energy-loss mechanisms for theoretical models of the jet-medium interaction. A recent study by the JET Collaboration performed a quantitative evaluation of $\hat{q}$ for several models compared to measurements of single inclusive hadron spectra at high p_T in central collisions at RHIC and the LHC. They determined a values of $\hat{q} \approx 1.2 \pm 0.3$ GeV^2/fm for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and $\hat{q} \approx 1.9 \pm 0.7$ GeV^2/fm for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [1].

Here we present new results from the JETSCAPE Collaboration, extending previous work by including non-central data from the LHC, allowing $\hat{q}$ to vary with temperature, and performing a simultaneous Bayesian extraction of $\hat{q}$ and a virtuality scale factor separating the transition between two energy loss models applicable to different domains of virtuality. The Modular All Twist Transverse-scattering Elastic-drag and Radiation (MATTER) model [2] is used to calculate splittings for partons with high virtuality, $Q^2 > \sqrt{\hat{q}E\hbar}$, where Q and E are the virtuality and energy of the parton. The splitting function includes both vacuum and medium-induced components, where the medium modification is treated as a perturbation based on the Higher Twist formalism [3]. The Linear Boltzmann Transport (LBT) model [4] describes the kinetic propagation of partons through a medium. It includes both elastic and inelastic components, where the latter is dominated by medium-induced gluon radiation that is also calculated using the Higher Twist formalism.

2. Jet Evolution and Statistical Models

We use the CTEQGL1 parameterizations [5] for the initial parton momentum distribution modified by the EPS09 [6] parameterizations of nuclear effects. The spatial distributions are sampled from the Monte-Carlo Glauber model [7]. The evolution of the heavy-ion medium is calculated using the 2D+1 viscous hydrodynamic model, VISHNU [8, 9, 10], run with MCGlauber initial nucleon distributions, a formation time, τ_0 =0.6 fm, and a shear viscosity to entropy ratio, η/s=0.08, which are appropriate the simultaneous description of soft hadronic spectra and elliptic flow at RHIC and the LHC. The hydrodynamic calculation provides the temperature, entropy, and flow velocity used to calculate the rescaled jet transport coefficient, $\hat{q} = \hat{q}_{\text{local}} \cdot p^\mu u_\mu / p^0$ [11] for the medium induced splitting function in MATTER, and inelastic scattering rate in LBT. For regions outside of the QGP regime ($\tau < 0.6$ fm and $T < 165$ MeV) we set $\hat{q} = 0$. Hadronization is handled by PYTHIA8 [12].

The temperature dependence of $\hat{q}$ is implemented with two parameterizations, given by Eq. 2.1 and Eq. 2.2. The implementation of Eq. 2.1 and Eq. 2.2 in our framework will be referred to as MATTER+LBT_1 and MATTER+LBT_2, respectively. Both incorporate the expected T^3 scaling with the density of scattering centers and appropriate color factors. The pre-factors are multiplied by a sum of two components designed to capture the anticipated temperature dependence for the MATTER and LBT stages of the jet evolution. In Eq. 2.1 the first term includes a logarithmic dependence on the parton energy scale appropriate to MATTER, with an overall scale factor, A, and an energy scale factor, B, which serves as a multiplier for the energy scale $\Lambda = 0.2$ GeV. The second term is motivated by the expected $\hat{q}$ dependence of LBT as expressed in Eq. 13 of [4], with an overall scale factor, C, and energy scale factor, D. When implementing this parameterization, an additional virtuality scale parameter, Q_0, is introduced to demarcate the transition from MATTER ($Q > Q_0$) to LBT ($Q < Q_0$). In Eq. 2.2, the parton virtuality replaces the energy for the first term, and the virtuality scale is included both as a scale factor, with $Q_0\Lambda$ replacing B, and as theta-function switch that turns off the first component for the LBT stage of the evolution when Q falls below Q_0. The full simulation is performed using the JETSCAPE framework [13].

$$\frac{\hat{q}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi} \left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{E}{\Lambda}\right) - \ln(B)\right]}{\left[\ln\left(\frac{E}{\Lambda}\right)\right]^2} + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2} \right\}. \tag{2.1}$$

$$\frac{\hat{q}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi} \left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{Q}{\Lambda}\right) - \ln\left(\frac{Q_0}{\Lambda}\right)\right]}{\left[\ln\left(\frac{Q}{\Lambda}\right)\right]^2} \theta(Q - Q_0) + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2} \right\}. \tag{2.2}$$

The parameters are determined using Bayes' theorem to extract the probability distribution for a set of model parameters from the conditional probability of the experimental values calculated by the model weighted by a prior distribution of the parameters,

$$f(\theta \mid \mathbf{Y}_E) \propto f(\mathbf{Y}_E \mid m(\theta)) f(\theta). \tag{2.3}$$

Y_E are the experimental measurements of the suppression factor R_{AA}. We use neutral pions from central and mid-peripheral $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions measured by PHENIX [14], charged-particle R_{AA} from central and mid-peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by ATLAS[15] and at $\sqrt{s_{NN}} = 5.02$ TeV by CMS[16]. The jet quenching model is m and the prior distribution of parameters if given by $f(\theta)$, where $\theta = A, B, C, D, Q_0$ for Eq. 2.1 and $\theta = A, Q_0, C, D$ for Eq. 2.2.

Because accumulating comparable statistical precision to the data with jet quenching calculation over the full parameter space is computationally expensive, we follow the work of Bernard *et al.* [17, 18] in employing Gaussian Process Emulators with Latin Hypercube Design sampling of parameters and Principal Component Analysis reduction of the parameter space. We generated 30,000 samples for calibration of the likelihood function, $f(\mathbf{Y}_E \mid m(\theta))$ and 100,000 draws to generate the posterior distribution $f(\theta \mid \mathbf{Y}_E)$ of the parameters. The prior distributions were assumed to be uniform for all parameters, with $A, C \in (0,2)$, $B, D \in (0,2)$, and $Q_0 \in (0,4)$.

3. Results

In addition to performing the analysis with the multi-stage MATTER+LBT model, we performed similar analyses using only MATTER and only LBT using the $\hat{q}$ parameterization in Eq. 2.1. Results for the median parameter values are shown in Table 1. As expected, for the MATTER-only model, the first term dominates the energy loss, $A \gg C$, and for the LBT-only model the second term is larger, $C > A$. For the multi-stage models, the two terms have similar magnitude when the $\hat{q}$ parameterization in Eq. 2.1 is used. The median value of Q_0 is 2.09 for Eq. 2.1 and 2.86 for Eq. 2.2.

The posterior distributions are shown in Fig. 1 for MATTER+LBT_1 and Fig. 2 for MATTER+LBT_2. We see better agreement with the LHC measurements for MATTER+LBT_2, whereas

Parameter	A	B	C	D	Q_0(GeV)
MATTER	0.378	1.75	0.0470	6.39	–
LBT	0.188	5.45	0.307	4.49	–
MATTER+LBT_1	0.135	2.50	0.146	2.77	2.09
MATTER+LBT_2	0.275	–	0.422	6.10	2.86

Table 1: Median values of the exacted parameters for different model and parameter setups.

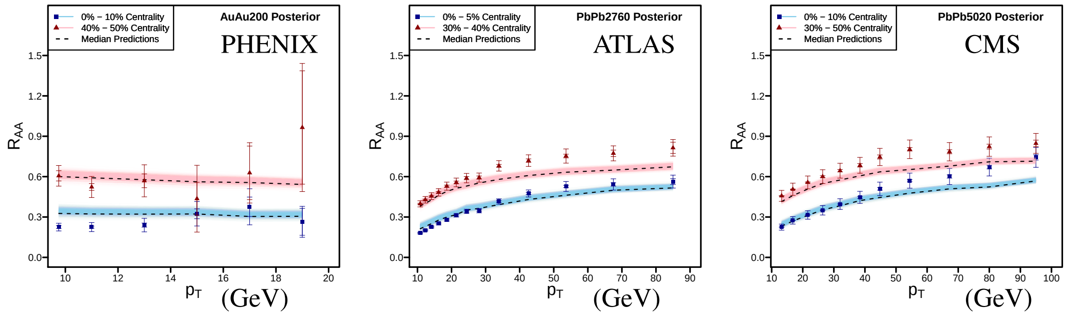

Figure 1: Emulator predictions for MATTER+LBT_1 of the single-inclusive hadron $R_{\rm AA}$ at RHIC and the LHC with the posterior distribution of the parameter space after calibration to data.

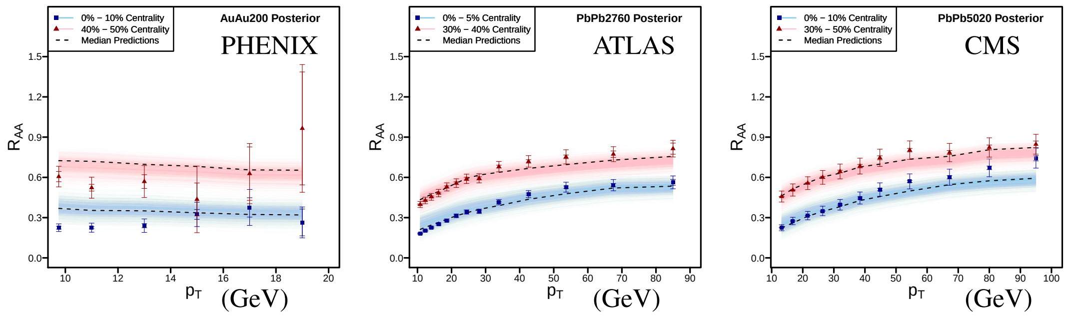

Figure 2: Emulator predictions for MATTER+LBT_2 of the single hadron $R_{\rm AA}$ at RHIC and the LHC with the posterior distribution of the parameter space after calibration to data.

the R_{AA} suppression at the LHC is slightly over-predicted by MATTER+LBT_1. The posterior parameter distributions are shown in Fig. 3. The parameter probability distributions show along the diagonal indicate all parameters to be well determined, largely due to the higher statistics results from the LHC. There is a significant anti-correlation between parameters A and C for MATTER+LBT_1, in which the two terms compete in both stages. When the first term is effectively removed by the theta-function in the LBT stage of MATTER+LBT_2, this anti-correlation disappears. All other parameter combinations appear to be uncorrelated.

Fig. 4 shows the 90% confidence regions for the temperature dependence of $\hat{q}$ for 100 GeV partons using Eq. 2.1 and Eq. 2.2. Both are consistent with the values determined by the JET Collaboration [1]. Eq. 2.2 yields a slightly stronger temperature dependence.

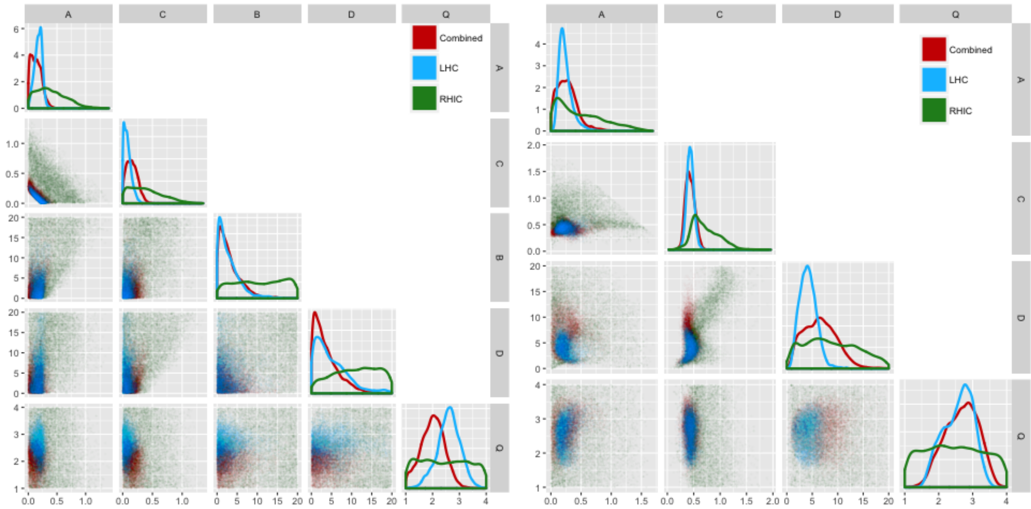

Figure 3: Posterior distribution of the 4-dimensional parameter space for $\hat{q}$ for parameterization in Eq. 2.1 (left) and Eq. 2.2 (right).

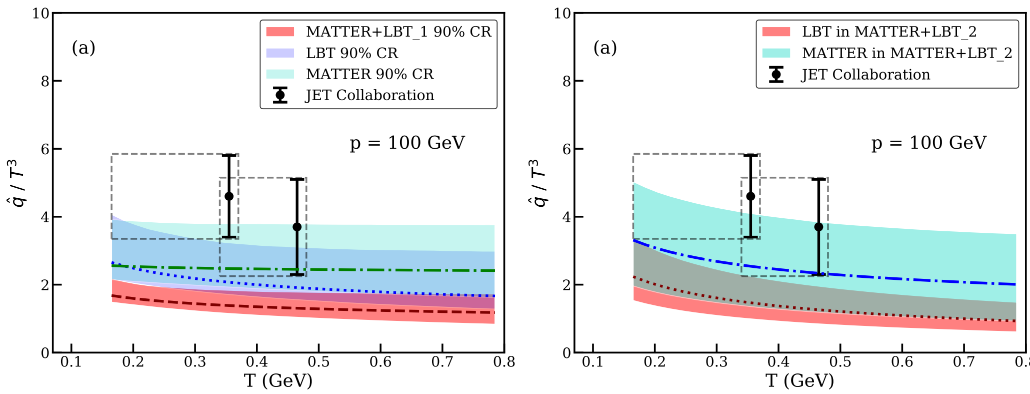

Figure 4: The (quark) jet transport parameter $\hat{q}$ as a function of medium temperature extracted from calibrating with $\hat{q}$ parameterization in Eq. 2.1 (left) and Eq. 2.2 (right).

4. Conclusion

We have performed the first Bayesian extraction of a temperature dependent $\hat{q}$ from a multi-stage jet energy loss model using the JETSCAPE framework by comparing to single inclusive hadron R_{AA} from central Au+Au collisions at RHIC and central and mid-peripheral collisions at the LHC. Our results are consistent with previous determinations of $\hat{q}$ by the JET Collaboration using single-stage models [1]. In addition, we have extracted values of the virtuality switching parameter, $Q_0 = 2.09$ and 2.86 GeV using two different parameterizations for $\hat{q}$.

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