



Transport properties of QGP within a Bayesian holographic QCD model

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Abstract

Using a holographic QCD model calibrated through Bayesian inference, we calculate key transport coefficients of the quark-gluon plasma (QGP)—including the drag force, jet quenching parameter, heavy quark diffusion coefficient, and shear and bulk viscosities—within a finite temperature and finite density Einstein–Maxwell–dilaton framework, with the phenomenological analysis presented here focused on zero chemical potential. Posterior parameter distributions at the 68% and 95% credible levels, as well as the maximum a posteriori (MAP) estimates, are employed to quantify uncertainties. Our findings indicate that the diffusion coefficient within the Bayesian credible regions aligns with lattice QCD results for $T \sim 1.2T_c$ to $2T_c$, and is consistent with ALICE experimental measurements near T_c . The jet quenching parameter derived from the posterior ensemble is compatible with RHIC and LHC data, while the extracted viscosity trends are consistent with representative phenomenological and holographic results. These results demonstrate the utility of Bayesian-calibrated holography for constraining the non-perturbative transport properties of QCD matter.

Keywords Holographic QCD · Jet quenching parameter · Diffusion coefficient

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1 Introduction

The study of high-energy nuclear collisions provides essential insights into the properties of the quark-gluon plasma (QGP), a strongly interacting state of matter believed to have existed shortly after the Big Bang. Among the most informative observables are jet quenching phenomena, characterized by the suppression of high-energy partons traversing the medium, and the transport coefficients governing the medium’s response—such as shear viscosity, bulk viscosity, and diffusion coefficients [1–5]. The jet quenching parameter $\hat{q}$ quantifies the transverse momentum broadening of energetic partons per unit length, serving as a critical probe of the medium density and coupling strength [6]. Various theoretical models have been developed to calculate this parameter [7–12].

Shear viscosity η measures the ability of a system to restore equilibrium after being subjected to a shear-mode perturbation. On a microscopic level, the ratio of shear viscosity to entropy density, η/s , is closely related to the interaction strength between particles in the system. Typically, a stronger interaction corresponds to a smaller η/s ratio. In the weak coupling regime, perturbative QCD calculations show that $\eta \propto 1/(\alpha_s^2 \ln \alpha_s)$ [13], where α_s is the strong coupling constant. When the coupling is strong, lattice QCD

simulations reveal that η/s for a pure glue plasma remains small, typically in the range 0.1–0.2 [14, 15]. Furthermore, studies based on the AdS/CFT correspondence [16–18] led to the conjectured lower bound for η/s as $1/(4\pi)$ [19], a value closely aligned with that employed to fit the elliptic flow v_2 data obtained at RHIC [20–22]. Therefore, it is widely recognized that the matter produced at RHIC and LHC behaves as a strongly coupled, nearly “perfect” fluid.

Bulk viscosity ζ , like shear viscosity, characterizes how quickly a system returns to equilibrium under uniform expansion. In the perturbative regime, ζ is very small, with its leading dependence on the strong coupling constant α_s expressed as $\zeta \propto \alpha_s^2 / \ln(1/\alpha_s)$ [23]. However, studies using various approaches—such as lattice QCD [24, 25], the linear sigma model [26], the Polyakov-loop linear sigma model [27], and the real scalar model [28]—demonstrate that the ratio ζ/s rises sharply near the critical temperature T_c . This enhancement of bulk viscosity near the phase transition corresponds to the peak observed in the trace anomaly around T_c , reflecting a highly non-conformal equation of state [29] in this region. These microscopic insights are further elucidated through complementary studies, using distinct collision systems and probes [30–39]. These approaches provide a multi-scale perspective on QCD matter evolution under extreme conditions.

In strong coupling scenarios, perturbative QCD is inadequate for describing the medium’s behavior [40, 41], leading researchers to employ lattice QCD methods to study the static equilibrium properties of this matter. Additionally, there is a non-perturbative approach known as the AdS/CFT correspondence [16, 18, 42–46] that provides a new perspective for investigating the dynamical properties of the QGP under strong coupling conditions. This correspondence establishes a connection between $\mathcal{N} = 4$ $SU(N_c)$ super-Yang-Mills theory and type IIB string theory in a combined $AdS_5 \times S^5$ space, offering a powerful tool for analyzing strongly interacting gauge theories when the number of colors N_c is large and the ’t Hooft coupling is also substantial. The original form of this duality linked asymptotically AdS space to a conformal gauge theory at absolute zero temperature. However, since the properties of the QGP are closely tied to temperature, researchers have sought to extend this duality to encompass holographic models that describe the QGP at non-zero temperatures. This extension has been explored through both top-down [47–51] and bottom-up [52–60, 60–69] approaches, leading to in-depth investigations in various studies.

One of the intriguing features of QCD is the confinement–deconfinement phase transition, which is strongly coupled in the vicinity of the crossover region [70–74]. These phenomena can be explored through the AdS/CFT correspondence and the development of various related holographic dual models [75–79]. Among the holographic

models tailored for QCD, those constructed within the framework of Einstein–Maxwell–dilaton (EMD) gravity are particularly noteworthy [80–89]. In early studies [90, 91], the authors aimed to construct a five-dimensional gravity theory with black-hole solutions to mimic the properties of QCD, introducing an ansatz for the dilaton field potential. These studies indicate that bottom-up holographic models can effectively capture the properties of sound speed and shear viscosity in the quark-gluon plasma.

Within the framework of the AdS/CFT correspondence, a heavy quark is modeled as a fundamental string attached to a flavor brane. The endpoint of the string corresponds to the quark in the boundary field theory, while the string itself represents the gluonic field surrounding the quark. The resistance encountered by a quark moving through the plasma is reflected in the momentum flux carried from the trailing end of the open string into the deeper bulk region [67, 92–110].

In this study, we extend a holographic QCD model with Bayesian inference to compute the drag force, jet quenching parameter, heavy quark diffusion coefficient, and viscosities in a finite temperature and finite density framework, while the phenomenological results shown below focus on zero chemical potential. Employing posterior parameter distributions at the 68% and 95% credible levels, together with the maximum a posteriori (MAP) estimate, we compare our results with lattice QCD, experimental data, and perturbative predictions, thereby providing a comprehensive analysis of the transport properties of the QGP [110–133].

Machine learning is increasingly being applied in high-energy physics [134–154] and gauge/gravity duality studies [62–64, 68, 69, 88, 155–166]. Recently, substantial research efforts are being directed toward extracting the temperature-dependent shear and bulk viscosities of the quark-gluon plasma (QGP) through large-scale model-to-data comparisons combined with Bayesian inference in high-dimensional parameter spaces. These efforts also aim to quantify uncertainties arising from variations in other aspects of the theoretical model [167–172]. Building on a holographic model that captures temperature and chemical potential dependence across QCD phases [68, 69], previous work calculated the heavy quark potential, Schwinger effect, and transport coefficients [173–177] and performed Bayesian inference [172]. In this paper, we further analyze QGP transport coefficients within this Bayesian-calibrated holographic framework.

The paper is organized as follows: Sect. 2 provides a brief review of the holographic QCD model based on EMD gravity developed in [68, 69]. Section 3 discusses the drag force experienced by a heavy quark in motion in this holographic framework. In Sect. 4, we calculate the diffusion coefficient of the heavy quark. Section 5 is devoted to the jet quenching parameter. Section 6 presents the temperature dependence of the bulk viscosity, and Sect. 7 investigates the temperature dependence of the shear viscosity with higher-order

derivative corrections. Section 8 presents the overall summary and conclusions of the article.

2 Holographic model via Einstein–Maxwell–Dilaton gravity

We first review the five-dimensional EMD system of our model [68, 69, 172]. This system comprises a gravitational field $g_{\mu\nu}$, a Maxwell field A_μ , and a dilaton field ϕ . In the Einstein frame, its action is given by

$$S_E = \frac{1}{16\pi G_5} \int d^5x \sqrt{-g} \left[R - \frac{f(\phi)}{4} F^2 - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) \right]. \quad (1)$$

Here, R is the Ricci scalar, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the Maxwell field strength, $f(\phi)$ is the gauge kinetic function, $V(\phi)$ is the dilaton potential, and G_5 is the five-dimensional Newton constant. The explicit forms of $f(\phi)$ and $V(\phi)$ are determined self-consistently from the equations of motion (EOMs).

We propose the following metric ansatz

$$ds^2 = \frac{L^2 e^{2A(z)}}{z^2} \left[-g(z) dt^2 + \frac{dz^2}{g(z)} + d\vec{x}^2 \right], \quad (2)$$

where z is the holographic radial coordinate in the fifth dimension and the AdS_5 space radius L is conventionally set to one, i.e., $L = 1$.

To obtain analytical solutions, we specify parametric forms for $A(z)$ and $f(\phi)$. We take the warp factor

$$A(z) = d \ln(az^2 + 1) + d \ln(bz^4 + 1), \quad (3)$$

and the form of the gauge kinetic function $f(z)$ as

$$f(z) = e^{cz^2 - A(z) + k}. \quad (4)$$

$A(z)$ is chosen to reproduce the entropy behavior and constrain the temperature dependence of the model. The function $f(z)$ controls the baryon density response of the model and is constrained by the baryon number susceptibility. The constant k corresponds to an overall constant rescaling of the Maxwell term near the conformal boundary. Such a constant prefactor does not change the gauge-invariant content and can be absorbed into a field redefinition of the bulk gauge potential. Then, we can derive

$$g(z) = 1 - \frac{1}{\int_0^{z_h} dx x^3 e^{-3A(x)}} \times \left[\int_0^z dx x^3 e^{-3A(x)} + \frac{2c\mu^2 e^k}{(1 - e^{-cz_h^2})^2} \det G \right], \quad (5)$$

$$\phi'(z) = \sqrt{6 \left(A'^2 - A'' - \frac{2A'}{z} \right)}, \quad (6)$$

$$A_t(z) = \frac{\mu \left(e^{-cz^2} - e^{-cz_h^2} \right)}{1 - e^{-cz_h^2}}, \quad (7)$$

and the dilaton potential as

$$V(z) = -\frac{3z^2 g e^{-2A}}{L^2} \times \left[A'' + A' \left(3A' - \frac{6}{z} + \frac{3g'}{2g} \right) - \frac{1}{z} \left(-\frac{4}{z} + \frac{3g'}{2g} \right) + \frac{g''}{6g} \right]. \quad (8)$$

The determinant G is given by

$$\det G = \left| \begin{array}{cc} \int_0^{z_h} dy y^3 e^{-3A(y)} & \int_0^{z_h} dy y^3 e^{-3A(y) - cy^2} \\ \int_{z_h}^z dy y^3 e^{-3A(y)} & \int_{z_h}^z dy y^3 e^{-3A(y) - cy^2} \end{array} \right|.$$

The Hawking temperature and entropy of this black-hole solution are given by the following formulas,

$$T = \frac{z_h^3 e^{-3A(z_h)}}{4\pi \int_0^{z_h} dy y^3 e^{-3A(y)}} \left[1 + \frac{2c\mu^2 e^k \left(e^{-cz_h^2} \int_0^{z_h} dy y^3 e^{-3A(y)} - \int_0^{z_h} dy y^3 e^{-3A(y) - cy^2} \right)}{(1 - e^{-cz_h^2})^2} \right], \quad (9)$$

$$s = \frac{e^{3A(z_h)}}{4G_5 z_h^3}. \quad (10)$$

For the subsequent calculation of probe observables, we employ the metric in the string frame

$$ds_s^2 = \frac{L^2 e^{2A_s(z)}}{z^2} \left(-g(z) dt^2 + \frac{dz^2}{g(z)} + dx_1^2 + dx_2^2 + dx_3^2 \right), \quad (11)$$

where $A_s(z) = A(z) + \sqrt{\frac{1}{6}} \phi(z)$.

There are three undetermined parameters a , b , and d in $A(z)$, and two parameters c and k in $f(z)$, along with the Newton constant G_5 , yielding a six-dimensional parameter space.

The six parameters $\theta = (a, b, c, d, k, G_5)$ used in our model are taken from Ref. [172]. That work employs a Bayesian

analysis within the EMD framework, constrained by lattice QCD data for the thermodynamic quantities (S/T^3 , χ_2^B , C_s^2) at zero chemical potential [178, 179], to determine the posterior distribution of the model parameters. The specific analytical procedure is as follows: first, the parameter inference framework is established based on Bayes' theorem:

$$P(\theta|\text{data}) \propto P(\text{data}|\theta)P(\theta) \quad (12)$$

Within the Bayesian framework, the posterior distribution $P(\theta|\text{data})$ describes the probability distribution of the model parameters θ after incorporating the observed data. The prior distribution $P(\theta)$ represents the initial belief or existing knowledge about θ before observing the data. The likelihood function $P(\text{data}|\theta)$ quantifies the plausibility of observing the current data given specific values of θ . Here, "data" specifically refers to lattice QCD data, including S/T^3 , χ_2^B , and C_s^2 , while θ corresponds to the six parameters in the EMD model.

Regarding the prior distribution $P(\theta)$, the parameter set $\theta = (a, b, c, d, k, G_5)$ for the EMD model was assigned prior ranges based on existing research [69, 172]. Following these ranges, we generated 300 parameter samples using the Latin Hypercube Sampling (LHS) [180, 181] method. These parameters were then substituted into the EMD model to compute the corresponding values of S/T^3 , χ_2^B , and C_s^2 . Subsequently, the results were subjected to dimensionality reduction via Principal Component Analysis (PCA) [182]. Finally, a Gaussian Process emulator [183] was constructed based on the 300 parameter sets and their corresponding PCA-reduced outputs. This emulator will be used to construct the likelihood function in subsequent steps (Table 1).

Furthermore, for the likelihood function $P(\text{data}|\theta)$, we adopt a Gaussian form:

$$P(\text{data}|\theta) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{[y_i(\theta) - y_i^{\text{lattice}}]^2}{2\sigma_i^2}} \quad (13)$$

The term y_i^{lattice} represents the lattice QCD results, while $y_i(\theta)$ is the prediction from the EMD model, which is approximated by a Gaussian emulator to enhance computational efficiency. Here, σ_i encompasses the uncertainties

from both the lattice QCD data and the Gaussian emulator. Finally, by sampling the posterior distribution via the Markov Chain Monte Carlo (MCMC) [184, 185], we obtained the posterior distributions for the EMD model parameters. The corresponding 95% credible intervals and the Maximum a Posteriori (MAP) estimates are presented in Ref. [172] (Table 2).

3 Heavy quark drag force

In the holographic trailing-string approach, when a heavy quark moves through a strongly coupled medium at a constant velocity v in some direction (for example, in the x direction), it is represented by the endpoint of an open string attached to the boundary, while the remainder of the string trails into the bulk and develops an induced worldsheet horizon. As the quark moves at the boundary, it loses energy and momentum through the drag force $F_{\text{drag}} = \frac{dp_x}{dt}$, which can be computed through the conserved momentum flux along the trailing string [111]. For this EMD background, Ref. [176] shows that the heavy quark drag force is given by

$$F_{\text{drag}} = \frac{dp}{dt} = \frac{dE}{dx} = -\pi_x^1 = -\frac{1}{2\pi\alpha'} \frac{L^2 e^{2A_s(z_s)} v}{z_s^2}, \quad (14)$$

where $\sqrt{\lambda} = \frac{g_{\text{YM}}^2 N_c}{4\pi} = \frac{L^2}{\alpha'}$ is the 't Hooft coupling. Following Ref. [176], the only additional parameter, α' , is fixed to 2 by matching the high-temperature behavior to NLO perturbative results. z_s is the radial location of the string worldsheet horizon [111], which is obtained as the numerical solution of the following equation [176]

$$g(z_s) - v^2 = 0. \quad (15)$$

The drag force in the AdS/Schwarzschild background can be obtained as follows [94],

Table 1 The prior parameter ranges for the EMD model [172]

Parameter	Prior	
	Min	Max
a	0.110	0.310
b	0.005	0.031
c	-0.280	-0.205
d	-0.240	-0.110
k	-0.910	-0.770
G_5	0.375	0.430

Table 2 In the 2+1 flavor QCD system, the distributions of the EMD model parameters (a, b, c, d, k, G_5) after Bayesian inference, including the maximum a posteriori values and the 95% credible intervals [172]

Posterior 95% CL			
Parameter	Min	Max	MAP
a	0.229	0.282	0.252
b	0.019	0.027	0.023
c	-0.261	-0.231	-0.245
d	-0.143	-0.127	-0.135
k	-0.871	-0.808	-0.843
G_5	0.388	0.406	0.397

$$F_{\text{drag}}^{\text{SYM}} = -\frac{\pi T^2 \sqrt{\lambda}}{2} \frac{v}{\sqrt{1-v^2}}. \quad (16)$$

In Fig. 1, we examine the drag force as a function of temperature in the 2+1 flavor system at zero chemical potential and with the quark velocity set to $v = 0.3$. The gray region in Fig. 1a represents the range of drag force within the 95% credible interval, with the red curve showing the temperature dependence at the MAP values. In Fig. 1b, the gray region represents the corresponding 68% credible interval. The figure clearly shows that the drag force increases with temperature, indicating stronger medium-induced momentum loss in a hotter plasma.

In Fig. 2, the variation of drag force with velocity in the 2+1 flavor system at the critical temperature $T_c = 0.128$ GeV

and zero chemical potential is presented. The gray region in Fig. 2a represents the range of drag force within the 95% credible interval, while the red curve shows the change in drag force with velocity at the MAP values. In Fig. 2b, the gray region represents the range of drag force within the 68% credible interval, with the red curve again depicting the change in drag force with velocity at the MAP values. The figure clearly indicates that the drag force increases with velocity, suggesting that in the 2+1 flavor system, the resistance faced by a moving quark increases as its velocity rises. This trend is consistent with the stronger momentum flux flowing down the trailing string at larger velocity.

According to Eq. (14), we evaluate the momentum loss rate and, equivalently, the energy loss per unit length, which allows us to study the relation between energy loss and momentum within the Bayesian analysis. Figure 3 illustrates the

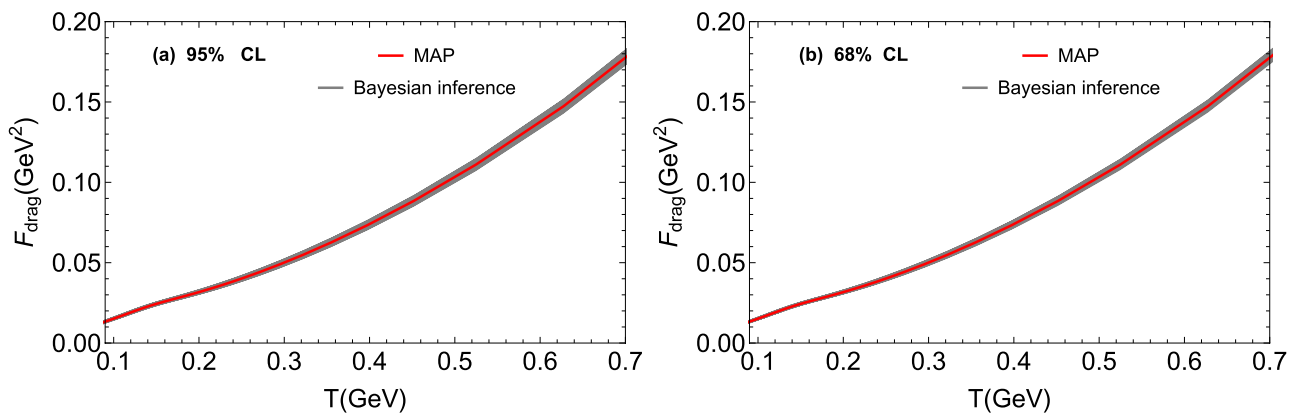


Fig. 1 (Color online) In a 2+1 flavor system at zero chemical potential with the quark velocity set to $v = 0.3$, the drag force as a function of temperature is shown. **a** The gray area represents the variation of drag force with temperature at the 95% credible interval; **b** the gray

area represents the variation of drag force with temperature at the 68% credible interval. The red curve shows the variation of drag force with temperature at the MAP values

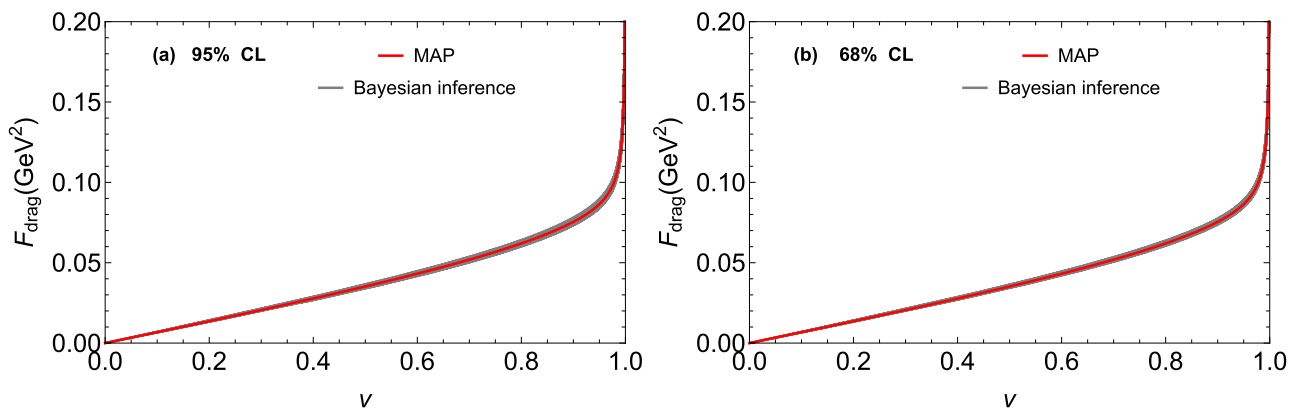


Fig. 2 (Color online) In a 2+1 flavor system at zero chemical potential and at the critical temperature $T_c = 0.128$ GeV, drag force as a function of velocity is investigated. **a** The gray area represents the variation of drag force with velocity at the 95% credible interval; **b**

the gray area represents the variation of drag force with velocity at the 68% credible interval. The red curve shows the variation of drag force with velocity at the MAP values

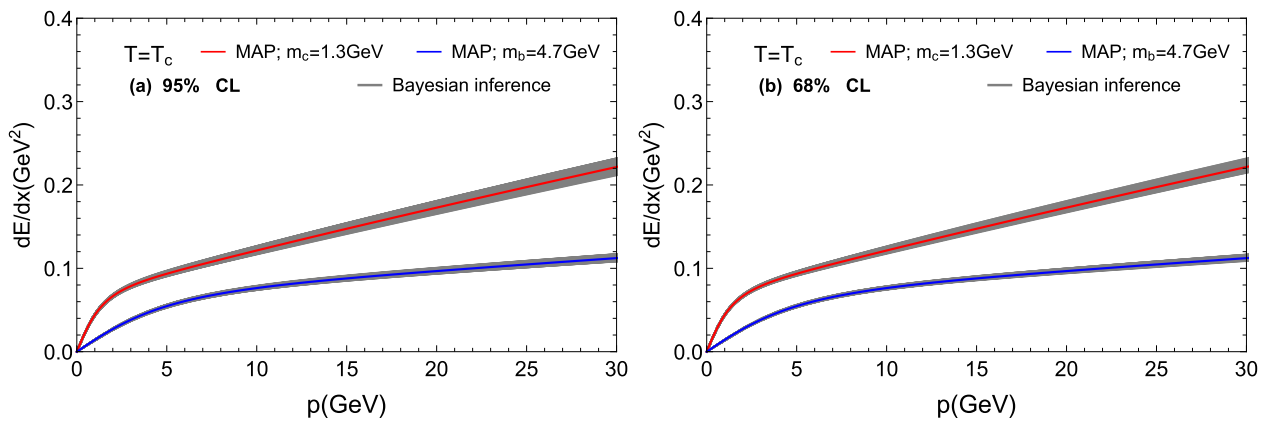


Fig. 3 (Color online) Energy loss of the bottom quark ($m_b = 4.7$ GeV) and charm quark ($m_c = 1.3$ GeV) as a function of momentum p (in GeV) at temperature $T = T_c$. **a** The gray area represents the relationship between energy loss and momentum at the 95%

credible interval. **b** The gray area represents the relationship between energy loss and momentum at the 68% credible interval. The red and blue curves show the results at the MAP values

corresponding behavior for the bottom quark ($m_b = 4.7$ GeV) and charm quark ($m_c = 1.3$ GeV) in a 2+1 flavor system at zero chemical potential and temperature $T = T_c$ [38, 39]. Figure 4 shows the analogous relation for the bottom and charm quarks in a 2+1 flavor system at zero chemical potential and temperature $T = 2T_c$, where the light-colored area represents the range of energy loss within the 68% and 95% credible intervals, and the curves indicate the energy loss value at the MAP values. Figure 3a and b represent the 95% and 68% credible intervals, respectively, and the same applies to Fig. 4. From Figs. 3 and 4, it is evident that energy loss increases with momentum. The mass of the quarks also affects energy loss; lighter quarks undergo larger energy loss. Additionally, a comparison between Figs. 3 and 4 shows that temperature has

a more significant impact on energy loss than quark mass, with higher temperatures leading to increased energy loss.

4 Heavy quark diffusion coefficient

In the AdS/Schwarzschild background, the drag force relation in Eq. (16) can be rewritten as [94]

$$F_{\text{drag}}^{\text{SYM}} = -\frac{\pi T^2 \sqrt{\lambda}}{2m} \frac{vm}{\sqrt{1-v^2}} = -\eta_D p, \quad (17)$$

where m denotes the mass of the heavy quark, η_D is the drag coefficient, and $p = \frac{vm}{\sqrt{1-v^2}}$ is the momentum. The diffusion time t_{SYM} is given by [94]

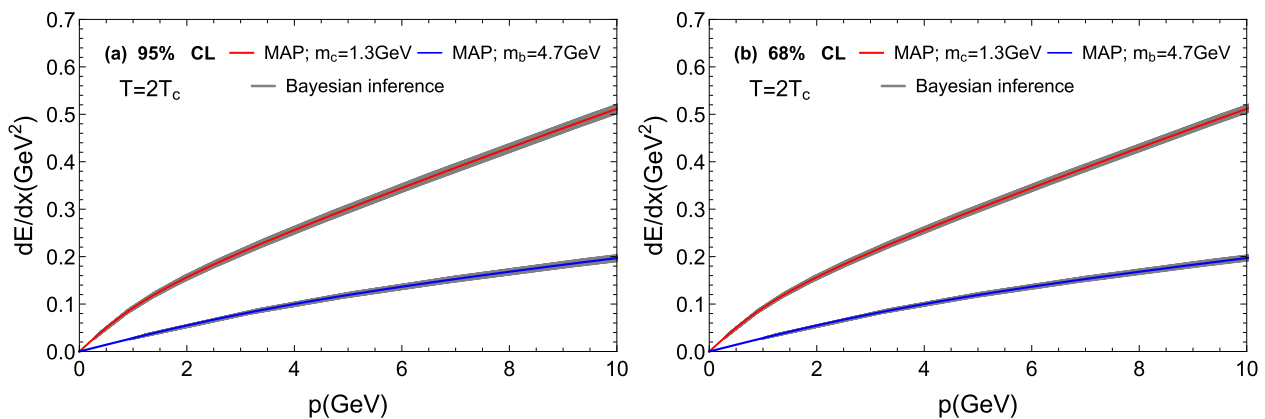


Fig. 4 (Color online) Energy loss of the bottom quark ($m_b = 4.7$ GeV) and charm quark ($m_c = 1.3$ GeV) as a function of momentum p (in GeV) at temperature $T = 2T_c$. **a** The gray area represents the relationship between energy loss and momentum at the 95%

credible interval. **b** The gray area represents the relationship between energy loss and momentum at the 68% credible interval. The red and blue curves show the results at the MAP values

$$t_{\text{SYM}} = \frac{1}{\eta_D} = \frac{2m}{\pi T^2 \sqrt{\lambda}}, \quad (18)$$

and the diffusion coefficient D_{SYM} can be expressed as [94]

$$D_{\text{SYM}} = \frac{T}{m} t_{\text{SYM}} = \frac{2}{\pi T \sqrt{\lambda}}. \quad (19)$$

Eq. (14) can be rewritten as

$$F_{\text{drag}} = -\frac{e^{2A_s(z_s)} \sqrt{1-v^2}}{\pi^2 T^2 z_s^2} \frac{\pi T^2 \sqrt{\lambda}}{2m} \frac{vm}{\sqrt{1-v^2}}, \quad (20)$$

The diffusion time t is

$$t = \frac{2m}{\pi T^2 \sqrt{\lambda}} \frac{\pi^2 T^2 z_s^2}{e^{2A_s(z_s)} \sqrt{1-v^2}}. \quad (21)$$

The diffusion coefficient D can be represented as

$$D = \frac{T}{m} t = \frac{2}{\pi T \sqrt{\lambda}} \frac{\pi^2 T^2 z_s^2}{e^{2A_s(z_s)} \sqrt{1-v^2}}. \quad (22)$$

From Eq. (19) and Eq. (22), we can deduce

$$\frac{D}{D_{\text{SYM}}} = \frac{\pi^2 T^2 z_s^2}{e^{2A_s(z_s)} \sqrt{1-v^2}}. \quad (23)$$

From Fig. 5, it can be observed that in the 2+1 flavor system with a quark velocity of $v = 0.3$ and zero chemical potential, the ratio of the diffusion coefficient to its conformal value in $\mathcal{N} = 4$ SYM theory increases with temperature. This growth indicates that the diffusive properties of the system become increasingly aligned with the behavior predicted by conformal field theory at higher temperatures. The figure

also shows that under zero chemical potential, this ratio ultimately trends toward 1 as the temperature rises. The gray area in the graph represents D/D_{SYM} within the 68% and 95% credible intervals, while the red curve indicates the D/D_{SYM} result at the MAP values.

We compared the spatial heavy quark diffusion coefficient, normalized by $2\pi T$, with estimates from lattice QCD, ALICE experiments, and next-to-leading-order (NLO) perturbative predictions, as depicted in Fig. 6. It can be seen that our model's 68% and 95% posterior bands together with the MAP curve largely fall within the error bars of the lattice data for $N_f = 2 + 1$ [186]. The gray uncertainty band represents the computed results using the posterior parameters within the 68% and 95% credible intervals, while the red curve corresponds to the result obtained from the MAP parameter set. The uncertainty in the gray band originates from the range of the posterior parameters. Because the present extraction is performed at fixed $v = 0.3$ rather than in the strict static limit $v \rightarrow 0$, the comparison with lattice and phenomenological determinations should be interpreted as semi-quantitative. Our results are also in very good agreement with the results from the ALICE experiment [187]. At high temperatures, our values of $2\pi TD$ are consistent with the NLO perturbative predictions [188]. Additionally, our Bayesian inference overlaps with the Duke hydro/transport model [189].

5 Jet quenching parameter

We now turn to the study of the jet quenching parameter. This quantity characterizes transverse momentum broadening and medium-induced energy loss for energetic partons traversing the hot dense medium. In Ref. [176], the authors

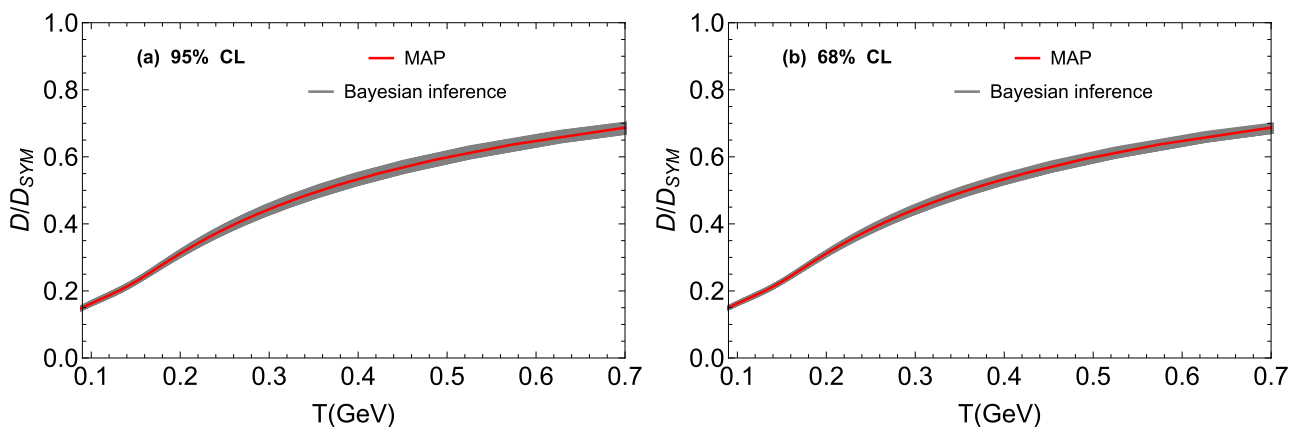


Fig. 5 (Color online) In the 2+1 flavor system at zero chemical potential, with the quark velocity set to $v = 0.3$, the variation of the scaled diffusion coefficient D/D_{SYM} with temperature is shown. **a** The gray area represents the variation of D/D_{SYM} with temperature at

the 95% credible interval; **b** the gray area represents the variation of D/D_{SYM} with temperature at the 68% credible interval. The red curve shows the variation of D/D_{SYM} with temperature at the MAP values

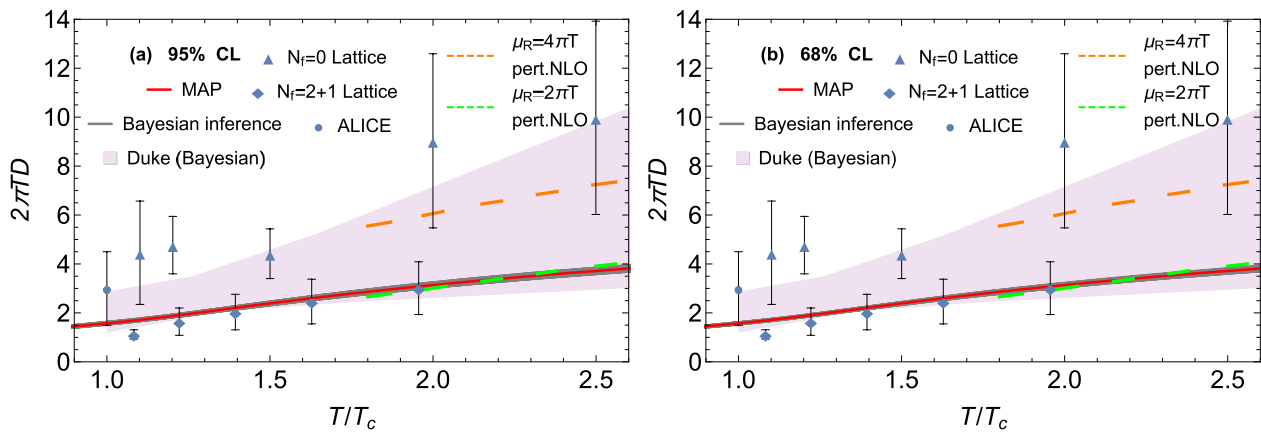


Fig. 6 (Color online) Scaled diffusion coefficient $2\pi TD$ as a function of T/T_c , with the quark velocity set to $v = 0.3$. The lattice data in the figure are results from Ref. [186]. The results of ALICE are from Ref. [187]. The orange dashed line represents the next-to-leading-order perturbative calculation with the renormalization scale set to $\mu_R = 4\pi T$, while the green dashed line represents the next-to-leading-order perturbative calculation with the renormalization scale

set to $\mu_R = 2\pi T$ [188]. The pink region represents Bayesian inference results from the Duke hydro/transport model [189]. The red curve and gray area represent the results of our model. **a** The gray area represents the variation of $2\pi TD$ with T/T_c at the 95% credible interval; **b** the gray area represents the variation of $2\pi TD$ with T/T_c at the 68% credible interval. The red curve shows the variation of $2\pi TD$ with temperature at the MAP values

conducted a detailed study on the temperature-dependent behavior of $\hat{q}$ within this model.

According to Ref. [8], the relationship between the jet quenching parameter and the adjoint light-like Wilson loop is given by the equation

$$\langle W^A[C] \rangle \approx \exp \left(-\frac{1}{4\sqrt{2}} \hat{q} L^- L'^2 \right), \quad (24)$$

where $W^A[C]$ is the Wilson loop in the adjoint representation, and C is a rectangular contour of size $L' \times L^-$. The quark and antiquark are separated by a small L' and propagate along L^- .

The expectation value of the Wilson loop is dual to the classical value of the string Nambu-Goto action under the appropriate string configuration. The $\hat{q}$ can be obtained as [176]

$$\hat{q} = \frac{1}{\pi \alpha' \int_0^{z_h} \frac{dz z^2 L^{-2} e^{-2A_s(z)}}{\sqrt{g(z)(1-g(z))}}}. \quad (25)$$

For $\mathcal{N} = 4$ supersymmetric Yang-Mills theory, in the large N_c and large λ limit, Eq. (25) reduces to the analytic expression [8]

$$\hat{q}_{\text{SYM}} = \frac{\pi^{3/2} \Gamma(\frac{3}{4})}{\Gamma(\frac{5}{4})} \sqrt{\lambda} T^3, \quad (26)$$

where Γ denotes the Gamma function. The finite 't Hooft coupling correction to this jet quenching parameter was obtained in Ref. [190], and the jet quenching parameter was

found to be reduced due to worldsheet fluctuations by a factor $(1 - 1.97\lambda^{-1/2})$.

To obtain the jet quenching parameter in the holographic QCD model, we performed numerical calculations at various temperatures with zero chemical potential. The resulting curves are illustrated in Fig. 7. It can be observed that the jet quenching parameter increases with temperature, indicating stronger transverse momentum broadening in a hotter medium. This trend is consistent with the expectation that jets traversing a higher-temperature plasma encounter more effective scattering centers. The posterior bands obtained in our model are consistent with the experimental results from RHIC and LHC [4].

In Fig. 8, we depict the curve of $\hat{q}/T^3$ as a function of temperature. The gray area in the figure represents the 68% and 95% credible intervals, while the red curve indicates the MAP values. We observe that the curve reaches a peak above the phase transition temperature and then approaches the value in the pure AdS background. This behavior is distinctly different from the pure AdS background result, where $\hat{q}/T^3$ remains constant at all temperatures. This indicates that dynamical holographic QCD encodes new features related to the deconfinement phase transition. In Fig. 9, we present the scaled jet transport parameter $\hat{q}/T^3$ as a function of the initial temperature T for an initial quark jet with energy $E = 10$ GeV in the most central A + A collisions, with an initial time of $t_0 = 0.6$ fm/c, extracted by the JET Collaboration from experimental data on hadron suppression [4]. We compare the temperature dependence of $\hat{q}/T^3$ with this result, and it can be observed that our model's Bayesian inference is in good agreement with the HT-BW extraction and is compatible with most phenomenological results at low temperatures.

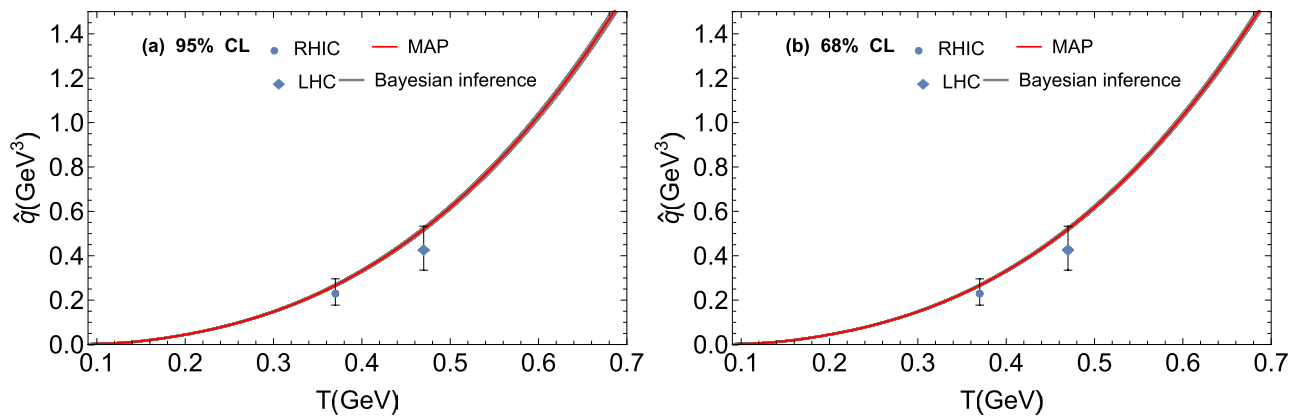


Fig. 7 (Color online) Relationship between the jet quenching parameter and temperature in the holographic model at zero chemical potential. Error bars represent experimental values from RHIC and LHC [4]. **a** The gray area represents the variation of jet quenching param-

eter with temperature at the 95% credible interval; **b** the gray area represents the variation of jet quenching parameter with temperature at the 68% credible interval. The red curve shows the variation of jet quenching parameter with temperature at the MAP values

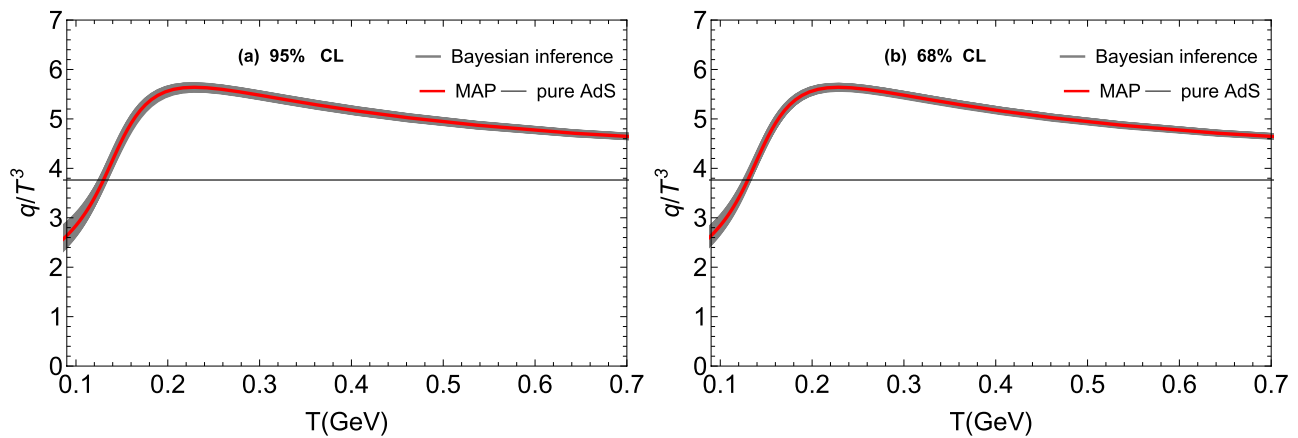


Fig. 8 (Color online) Relationship between $\hat{q}/T^3$ and temperature T at zero chemical potential. **a** The gray area represents the variation of $\hat{q}/T^3$ with temperature at the 95% credible interval; **b** the gray area

represents the variation of $\hat{q}/T^3$ with temperature at the 68% credible interval. The red curve shows the variation of $\hat{q}/T^3$ with temperature at the MAP values

Figure 10 shows the ratio of the jet quenching parameter in the holographic QCD model to $\hat{q}_{\text{SYM}}$. It can be observed that at lower temperatures, the jet quenching parameter $\hat{q}$ is below $\hat{q}_{\text{SYM}}$. This implies that, at lower temperatures, the quenching effect of the medium on high-energy jets predicted by the holographic QCD model is weaker than the theoretical prediction in the AdS/Schwarzschild background. However, as the temperature increases, the ratio of $\hat{q}$ to $\hat{q}_{\text{SYM}}$ first grows, indicating an intensification of the quenching effect, and then starts to decrease after reaching a certain threshold, suggesting a relative weakening of the quenching effect, ultimately approaching 1. This indicates that at higher temperatures, the quenching effect predicted by the holographic QCD model tends to converge to the theoretical prediction in the AdS/Schwarzschild background.

The parameter λ (equivalently, α') is the only new parameter in the paper. At the end of this section, we include Fig. 11 to illustrate two λ -sensitive quantities, namely the jet quenching parameter $\hat{q}$ and the diffusion coefficient. As shown in the figure, increasing the value of λ leads to an enhancement of $\hat{q}$, while the diffusion coefficient decreases as λ increases.

6 Bulk viscosity

This section focuses on the temperature-dependent behavior of bulk viscosity. We briefly review how to extract the bulk viscosity from a graviton-dilaton system and present the results graphically. In four-dimensional field theory, extracting bulk viscosity using the Kubo formula is a viable approach. The

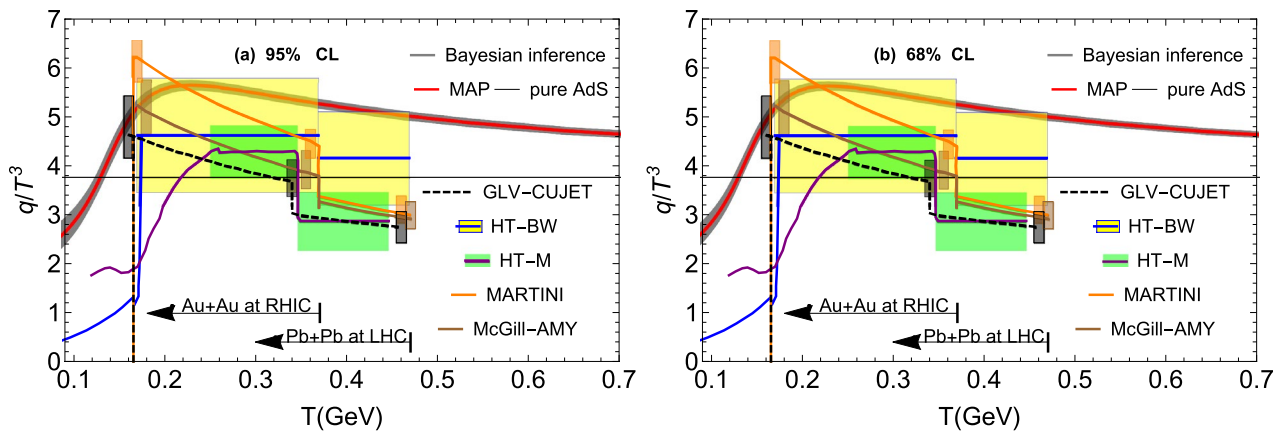


Fig. 9 (Color online) Relationship for $\hat{q}/T^3$ at zero chemical potential with temperature T . The plot (HT-BW and HT-M) of the scaled jet transport parameter $\hat{q}/T^3$ as a function of the initial temperature T for an initial quark jet with energy $E = 10$ GeV in the most central A+A collisions, with an initial time of $t_0 = 0.6$ fm/c, extracted by the JET

Collaboration from experimental data on hadron suppression [4]. **a** The gray area represents the variation of $\hat{q}/T^3$ with temperature at the 95% credible interval; **b** the gray area represents the variation of $\hat{q}/T^3$ with temperature at the 68% credible interval. The red curve shows the variation of $\hat{q}/T^3$ with temperature at the MAP values

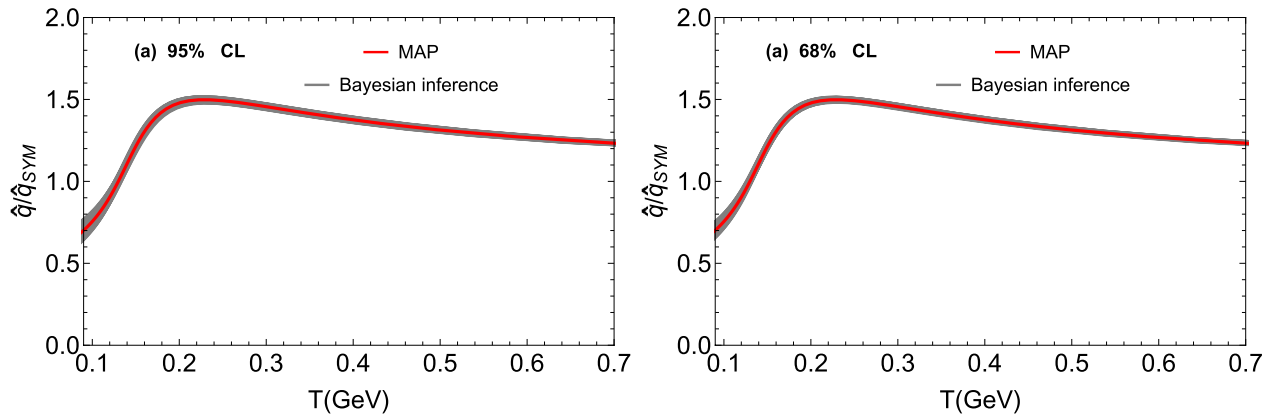


Fig. 10 (Color online) Ratio of the jet quenching parameter in the holographic QCD model to $\hat{q}_{\text{SYM}}$ at zero chemical potential. **a** The gray area represents the variation of $\hat{q}/\hat{q}_{\text{SYM}}$ with temperature at the 95% credible interval; **b** the gray area represents the variation of

$\hat{q}/\hat{q}_{\text{SYM}}$ with temperature at the 68% credible interval. The red curve shows the variation of $\hat{q}/\hat{q}_{\text{SYM}}$ with temperature at the MAP values. The unit of T is GeV

Kubo formula relates transport coefficients, such as bulk viscosity, to the retarded Green's functions of the stress-energy tensor. Specifically, the bulk viscosity (ζ) can be expressed as

$$\zeta = \frac{1}{9} \lim_{\omega \rightarrow 0} \frac{1}{\omega} \text{Im} G_{T_i^i T_j^j}^R(\omega), \quad (27)$$

where $G_{T_i^i T_j^j}^R$ is the retarded Green's function of the trace of the spatial stress-energy tensor. According to the holographic dictionary, the Green's function of the stress tensor can be extracted through metric perturbations (e.g., $g_{\mu\nu} \rightarrow g_{\mu\nu} + h_{\mu\nu}$). When applying the Kubo formula, we choose the spatial momentum to satisfy $\vec{q} = 0$ and assume that $h_{\mu\nu}$ depends only on time t and the holographic

coordinate z , i.e., $h_{\mu\nu} = h_{\mu\nu}(t, z)$. These metric perturbation components should include h_{xx} , h_{yy} , and h_{zz} . We impose spatial rotational symmetry, which allows us to identify the metric perturbations in the three spatial directions as $h_{xx} = h_{yy} = h_{zz}$. Following this reasoning, the bulk viscosity can be extracted from the retarded Green's function of the scalar mode. The imaginary part of the retarded Green's function $G^R(\omega)$ is related to the conserved flux $\mathcal{F}(\omega)$ via

$$\text{Im} G^R(\omega) = -\frac{\mathcal{F}(\omega)}{4\pi G_5}. \quad (28)$$

For the metric of Eq. (2), the conserved flux takes the form:

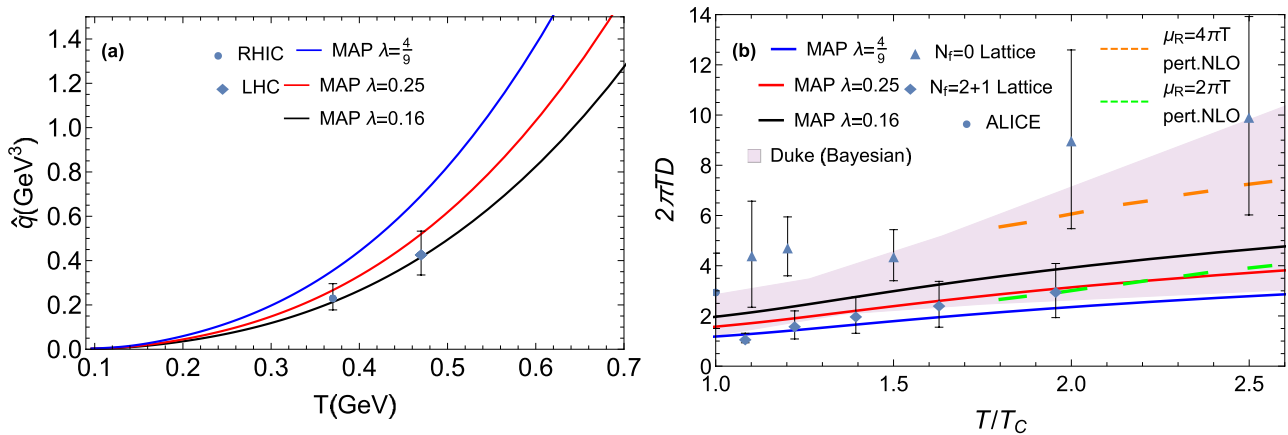


Fig. 11 (Color online) Two λ -sensitive quantities: **a** the jet quenching parameter $\hat{q}$ and **b** the diffusion coefficient D

$$\mathcal{F}(\omega) = \frac{L^3 e^{3A(z)} g(z)}{4z^2 (A' - 1/z)^2} \left| \text{Im}(h_{xx}^* h'_{xx}) \right|. \quad (29)$$

We fix this residual gauge freedom by choosing the dilaton (radial) gauge, i.e., we use the background scalar to parametrize the holographic direction, which is equivalent to setting $\delta\phi = 0$. With this gauge fixing, the physical scalar mode is entirely captured by the metric fluctuation h_{ii} , and its equation of motion decouples from the remaining perturbations. This procedure follows the standard treatment used, e.g., in Ref. [91] for the computation of bulk viscosity. A notable feature of the perturbation equations of motion is that the equation for the h_{xx} component decouples completely from h_{zz} and h_{rr} . The equation of motion for the perturbation h_{xx} takes the form:

$$h''_{xx} + h'_{xx} \left[3 \left(A' - \frac{1}{z} \right) + \frac{g'}{g} \right] + h_{xx} \left[\frac{\omega^2 z^2 e^{-2A}}{L^2 g^2} - 2 \frac{g'}{g} \left(A' - \frac{1}{z} \right) - 3 \left(A'' - \frac{1}{z^2} \right) - 3 \left(A' - \frac{1}{z} \right)^2 \right] = 0. \quad (30)$$

The temperature dependence of the bulk-viscosity-to-entropy-density ratio is shown in Fig. 12. The pronounced peak of bulk viscosity around T_c could have important consequences for particle spectra and flow observables. In this figure, the gray band displays results derived from posterior parameters within the 95% credible interval, while the red curve is obtained from the MAP parameter estimate. The breadth of the gray band directly reflects the uncertainty propagated from the posterior parameter distribution. It can be observed that the model aligns well with the 90% CL of the JETSCAPE Bayesian model [191] at higher

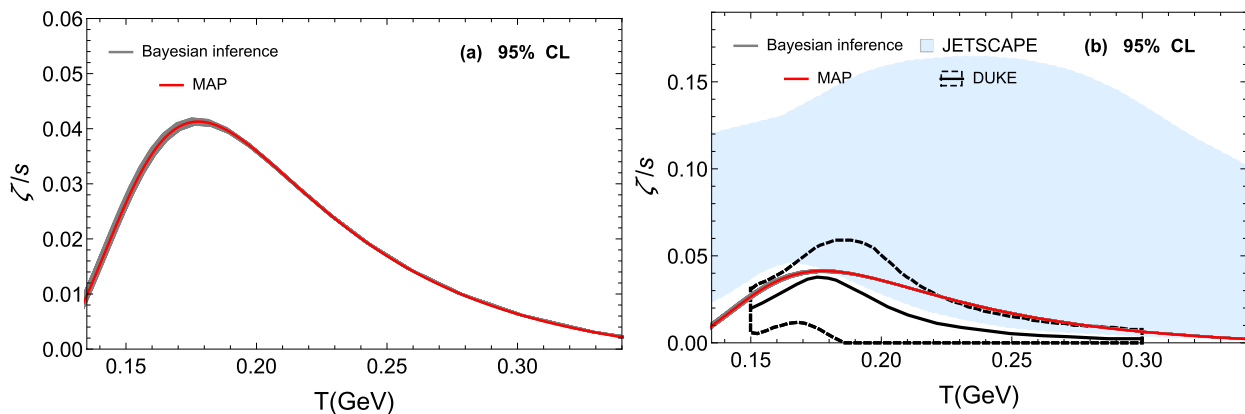


Fig. 12 (Color online) Relationship between ζ/s and temperature T at zero chemical potential. The gray region corresponds to the 95% credible interval. The red curve depicts the temperature dependence of the bulk-viscosity-to-entropy-density ratio based on the MAP val-

ues. The blue region represents the 90% CL of the JETSCAPE Bayesian model [191], and the black dashed lines and curves indicate the results from the Duke University team [169]

temperatures, as well as with the findings from the Duke University team [169].

7 Shear viscosity with higher derivative corrections

The shear viscosity coefficient has been extensively studied in the context of Einstein gravity, demonstrating a universal ratio to entropy density $\eta/s = \frac{1}{4\pi}$. Currently, the shear viscosity coefficient has also been studied in some other models [192–195]. To introduce temperature dependence in the η/s ratio, higher derivative gravitational corrections must be incorporated into Einstein gravity [196]. To obtain this temperature dependence, we introduce higher-derivative corrections in the following form:

$$S = \frac{1}{16\pi G_5} \int d^5x \sqrt{-g} \left[R - \frac{f(\phi)}{4} F^2 - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) + \beta e^{\gamma\phi} R_{\mu\nu\lambda\rho} R^{\mu\nu\lambda\rho} \right]. \quad (31)$$

The parameter β is a small dimensionless coupling. To compute the shear viscosity coefficient, it is necessary to introduce off-diagonal metric perturbations h_{xy} to obtain the two-point Green's function of the energy-momentum tensor. The shear viscosity can be calculated via the Kubo formula:

$$\eta = \lim_{\omega \rightarrow 0} \frac{1}{\omega} \text{Im} G_{xy,xy}^R(\omega). \quad (32)$$

As noted in [196], η/s depends solely on the background metric at the $\mathcal{O}(1)$ level. Therefore, we do not consider the

$\mathcal{O}(\beta)$ corrections to the ratio arising from deformations of the background metric. Following the argument in [196], the calculation of the shear-viscosity-to-entropy-density ratio at the $\mathcal{O}(\beta)$ level can be expressed as:

$$\frac{\eta}{s} = \frac{1}{4\pi} \left[1 - \frac{\beta L^2}{c_0} \left(e^{\gamma\phi_h} + \gamma \frac{\phi'(z_h)}{A'(z_h) - \frac{1}{z_h}} e^{\gamma\phi(z_h)} \right) \right], \quad (33)$$

Here, $c_0 = \frac{L^2 e^{2A_h}}{z_h^2} \frac{1}{2g'(z_h)(A'(z_h) - \frac{1}{z_h})}$. When $\beta = 0.01$ and $\gamma = -\sqrt{0.3448}$, Fig. 13 shows the functional dependence of the η/s ratio on T/T_c . It can be observed that the η/s ratio exhibits a dip near $T = 1.2T_c$.

The temperature corresponding to this minimum value almost coincides with the temperature corresponding to the peak of the bulk viscosity. Near the transition region, the trace anomaly exhibits a pronounced peak and the speed of sound c_s^2 reaches a minimum, reflecting the strong breaking of conformal symmetry in QCD. These features enhance the interaction strength, which naturally drives η/s toward its minimum. This behavior is consistent with general expectations in strongly coupled gauge theories, where η/s approaches the KSS bound in the vicinity of the transition.

In Fig. 13, the blue band represents the results computed using posterior parameters at the 95% credible interval, while the black curve illustrates the functional dependence of the η/s ratio on T/T_c at the MAP value. The uncertainty associated with the blue band originates from the range of the posterior parameters. We emphasize that this band does not include any additional uncertainty associated with the

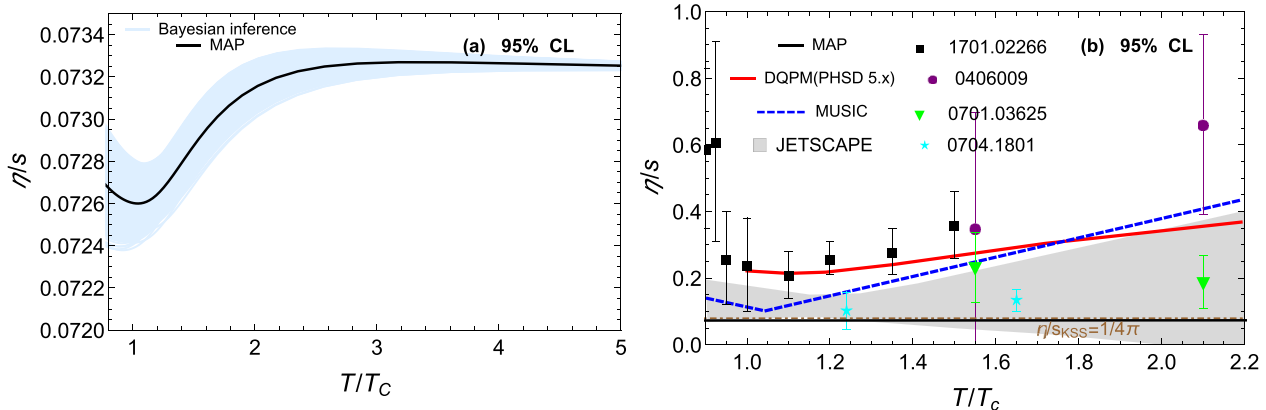


Fig. 13 (Color online) Functional dependence of the η/s ratio on T/T_c . The blue band represents the 95% credible interval, while the black curve shows the functional dependence of the η/s ratio on T/T_c at the MAP value. The symbols correspond to the LQCD (lattice QCD) results for pure SU(3) gauge theory: (black squares) [192], (green triangles and magenta circles) [14], and (cyan stars) [193]. The gray dash-dotted line represents the Kovtun–Son–Starinets (KSS) bound, $(\eta/s)_{\text{KSS}} = 1/(4\pi)$ [19]. The gray band denotes

the model-averaged results from the Bayesian analysis of heavy-ion experimental data [191]. The red curve corresponds to the results from the DQPM (Dynamical QuasiParticle Model) [194], while the blue dashed line shows the parameterization of η/s employed in the MUSIC hydrodynamic simulations [195]. **a** Magnified view in the vicinity of the dip near $T \approx 1.2 T_c$. **b** Wide-temperature-range view including all comparison data sets

fixed higher-derivative couplings β and γ . Figure 13a displays a magnified view of the results shown in Fig. 13b, where our findings are compared with various model predictions [14, 19, 191–195].

8 Summary

In this work, we performed a comprehensive investigation of the transport properties of the quark–gluon plasma using a five-dimensional Einstein–Maxwell–dilaton (EMD) holographic model whose parameters are fully constrained by Bayesian inference. In contrast to previous holographic studies that rely on specifically chosen potentials or phenomenological inputs, our model incorporates the complete posterior distributions inferred from lattice QCD thermodynamics, thereby enabling a systematic and statistically controlled quantification of theoretical uncertainties for all transport observables. This Bayesian holographic framework provides a unified and non-perturbative approach to studying the strongly coupled dynamics of QCD matter.

We calculated several key transport coefficients—namely the heavy quark drag force, the spatial diffusion coefficient, the jet quenching parameter, and the bulk and shear viscosities—at finite temperature, within a framework that also accommodates non-zero chemical potential. These observables probe complementary aspects of the QGP and jointly capture the interplay between thermal effects, nonconformality, and strong coupling.

The drag force was shown to increase monotonically with both temperature and quark velocity, consistent with a medium whose color charge density and interaction strength grow with temperature. The Bayesian uncertainty band demonstrates that this trend is robust against variations in the EMD model parameters and exhibits quantitative agreement with expectations from strongly coupled dynamics. Because the worldsheet horizon depends sensitively on the background metric, the drag force serves as a stringent probe of the gravitational dual and directly reflects the non-conformal structure encoded in the metric deformation.

For the diffusion coefficient, we demonstrated that the scaled quantity D/D_{SYM} approaches unity at high temperature, indicating an emergent conformal behavior of the plasma in the $T \gg T_c$ regime. Near the transition region, however, the diffusion coefficient deviates substantially from its conformal value, signaling strong non-perturbative effects. Remarkably, our Bayesian credible intervals align well with lattice QCD calculations, ALICE experimental estimates, and next-to-leading-order perturbative predictions at high temperatures. This agreement demonstrates the predictive power of the Bayesian EMD model, although the present comparison should be interpreted with some caution

because the extraction is performed at fixed velocity rather than strictly in the static limit.

The jet quenching parameter exhibits a pronounced peak slightly above the phase transition temperature. This behavior mirrors that found in earlier holographic studies but is now obtained with statistically meaningful uncertainty quantification. The peak provides direct evidence of enhanced transverse momentum broadening near T_c , where the medium’s color interaction strength is maximal. The magnitude and temperature dependence of $\hat{q}$ derived from our model agree well with phenomenological extractions from RHIC and LHC data, as well as with the HT-BW and HT-M Bayesian extractions from the JET Collaboration.

The viscosities further illuminate the role of strong coupling in the transition region. Consistent with the non-conformal equation of state, we find a sharp peak in the bulk viscosity near T_c , accompanied by a minimum in the shear viscosity. The near coincidence of these extrema indicates that the rapid change in the trace anomaly around the phase transition significantly alters the dissipative properties of the medium. Once higher-derivative corrections are included, η/s acquires a temperature dependence with a well-defined dip, consistent with expectations from hydrodynamic modeling and with Bayesian extractions of $\eta/s(T)$ from the JETSCAPE and Duke analyses. These results highlight that the EMD model—despite its relative simplicity—captures the essential dynamics underlying both conformal and non-conformal transport effects.

Taken together, our findings demonstrate that a Bayesian-calibrated holographic EMD model can consistently and simultaneously describe a wide range of transport coefficients across a broad temperature interval relevant to heavy-ion collisions. The ability to reproduce lattice QCD thermodynamics, match experimental constraints, and quantify theoretical uncertainties represents a significant advancement over traditional holographic approaches. Two limitations should nevertheless be kept in mind: the quantitative phenomenological comparisons shown here are restricted to $\mu_B = 0$, and the shear-viscosity analysis does not propagate uncertainty from the fixed higher-derivative couplings. This work therefore provides a robust and predictive non-perturbative framework for studying QCD matter and offers valuable insights into the microscopic mechanisms governing jet energy loss, heavy quark dynamics, and viscous transport in the strongly coupled quark–gluon plasma. In the future, our results can be used as inputs to transport models, such as the Linear Boltzmann Transport model, to compute observables like R_{AA} , v_2 , and others [197–199].

Author Contributions All authors jointly participated in the conception and design of the study. Specific contributions are as follows: Xun Chen proposed the core research concept and constructed the computational program framework; Li-Qiang Zhu performed critical modifications and optimizations to the program framework; Bing Chen was

responsible for program debugging, numerical computations, and data analysis of the results; De-Fu Hou and Xu-Rong Chen jointly carried out the verification and review of the research findings. The first draft of the manuscript was written by Bing Chen, and all authors provided important feedback on successive revisions of the paper. All authors have reviewed and approved the final version for submission.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

AI-assisted coding conflict of interest: The authors used DeepSeek to assist with the translation and polishing of portions of the text during the preparation of this manuscript. All code logic, algorithmic choices, and numerical computations were designed and verified by the authors. The AI tool did not generate any simulation results or interpret the physical phenomena. The authors have thoroughly validated all outputs and assume full responsibility for the accuracy and integrity of the computational results presented.

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