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Data-driven analysis of the temperature dependence of the heavy-quark transport coefficient

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Abstract

By applying a Bayesian model-to-data comparison, our improved Langevin transport model simultaneously describes the D-meson nuclear modification factor R_{AA} and elliptic flow v_2 in heavy-ion collisions at both RHIC and LHC energies on an event-by-event basis. We extract the diffusion coefficients of charm quarks in a quark-gluon plasma medium and find the resulting spatial diffusion coefficient D_s is compatible with lattice QCD calculations.

Keywords: heavy quark, diffusion coefficient, Bayesian analysis

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1. Introduction

Heavy quarks (charm and bottom) serve as valuable probes to study the properties of the strongly-interacting quark-gluon plasma (QGP) created in ultra-relativistic heavy-ion collisions. During their propagation in the QGP medium, heavy quarks undergo multiple elastic and inelastic scatterings with light hadrons, lose energy, develop flow, and hadronize into heavy mesons. While the combination of perturbative QCD (pQCD) collisional and radiative energy loss might suffice to describe the heavy-meson suppression at high transverse momentum p_T, intermediate and low p_T phenomena like the large elliptic flow of D-mesons, comparable to that of light hadrons, are sensitive to non-perturbative effects. To take these and other unknown phenomena into account, most commonly-used models introduce additional parameters. Even taking into account the modified interaction between heavy quarks and the medium, the simultaneous description of the heavy meson nuclear modification factor R_{AA} and elliptic flow v_2 remains a significant challenge, in particular for those models based on Langevin transport.

By applying a Bayesian model-to-data analysis, we are able to calibrate the model parameters on experimental data and extract the physical properties of the medium associated with these parameters from the posterior distributions generated by the analysis. In this study we focus on the temperature dependence of charm quark diffusion coefficient. Using the results of the analysis, our improved Langevin framework simultaneously reproduces the experimental data of the D-meson R_{AA} and v_2 at both RHIC and LHC energies.

2. Modeling heavy flavor evolution in heavy-ion collisions

Our analysis utilizes the well-established improved Langevin approach developed by the Duke group [1]: The initial condition for the calculation is provided by a combination of the effective initial condition model T$_\mathrm{R}$ENTo [2] for the spatial distribution and a leading-order pQCD calculation for the momentum distribution of the heavy quarks [1]. T$_\mathrm{R}$ENTo – which is also used to generate the initial configuration of the QGP – has been shown to mimic the scaling behavior of the EKRT and IP-Glasma models [3].

The dynamics of the heavy quarks are described by a Langevin equation [4]. We adopt the improved

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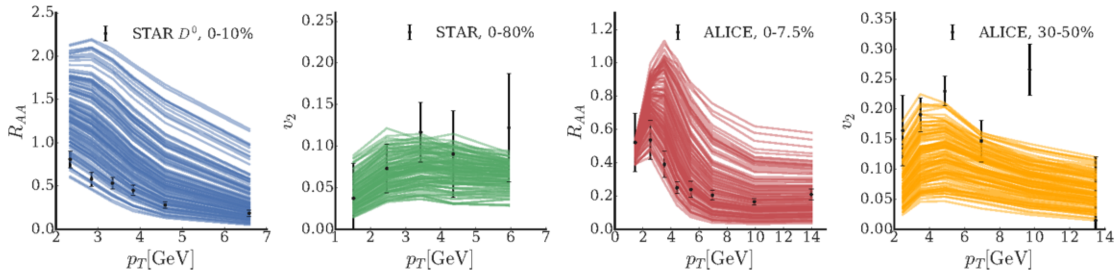

Figure 1: (color online) Improved Langevin model simulated observables (R_{AA} and v_2) of the 120 training inputs, compared with experimental data from STAR [15] and ALICE [16]

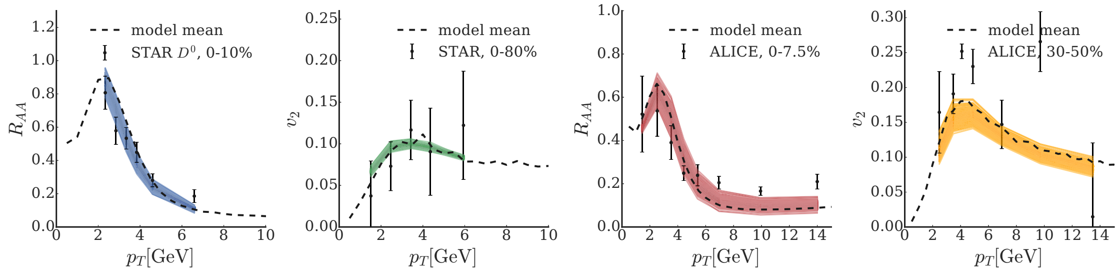

Figure 2: (color online) GP emulators predictions of 200 random input samples drawn from the posterior distribution, and Langevin calculation as taking the posterior distributions mean as parameters.

Langevin model [1], which incorporates both collisional and radiative energy loss, to describe the propagation of heavy quarks in the QGP medium:

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f_g} \tag{1}$$

The first two terms on the right hand side are the drag and thermal random forces known from the standard Langevin equation. They describe the collisional energy loss and are related to the momentum diffusion coefficient κ via $\eta_D(p) = \kappa/(2TE)$ and $\left\langle \xi^i(t)\xi^j(t') \right\rangle = \kappa\delta^{ij}\delta(t-t')$.

The third term $\vec{f_g} = -d\vec{p}_g/dt$ is the recoil force induced due to heavy quark emission of bremsstrahlung gluons. It is responsible for radiative energy loss. The higher twist mechanism for gluon emission probability is adopted [5, 6]. By relating the gluon diffusion coefficient and heavy quark diffusion coefficient through the color factors $\hat{q}_g = \hat{q}C_A/C_F = 2\kappa C_A/C_F$, κ is the only parameter in our improved Langevin model. In the literature, the spacial diffusion coefficient $D_s = 2T^2/\kappa$ is often used to characterize the coupling strength.

The evolution of the QGP medium is described by a boost-invariant (2+1)-dimensional viscous hydrodynamics model VISHN2+1 [7], which has be updated to handle event-by-event fluctuations and bulk viscosity corrections [8, 9]. It should be noted that all the parameters related to the bulk QGP matter have been calibrated to data on light hadrons by a prior Bayesian analysis [3].

The hadronization of heavy quarks into heavy mesons is described via a combined model of fragmentation and recombination. For the current study, we neglect any rescattering of heavy mesons inside the hadron gas, as it has been previously shown to be a relatively small correction [10].

To capture the non-perturbative effects of the heavy quark diffusion coefficient, we modify the leading-order pQCD calculation of $\hat{q}$ with a temperature-dependent Gaussian expansion around the critical temperature [11] to take into account its possible near T_c enhancement as suggested by [12, 13]:

$$\hat{q} = K_{\text{pre}}\left[1 + A_{\text{T}}e^{-(T-T_c)^2/2\sigma_{\text{T}}^2}\right] \cdot \hat{q}_{\text{pQCD}} \tag{2}$$

Under this configuration, the pQCD calculation is valid in the high temperature (perturbative) region, while at low temperature near T_c, the diffusion coefficient is modified. We note that this parameterization is not exclusive and alternative parameterizations could be applied as well. In this study we focus on charm quark evolution in heavy-ion collisions, but this framework would apply equally to bottom quarks.

3. Model-to-data comparison

A Bayesian model-to-data analysis can be used to simultaneously constrain multiple parameters of a computationally expensive model. First, a set of input parameters related to charm quark transport coefficients