PROCEEDINGS OF SCIENCE

Modeling coherence effects of gluon emission for heavy flavor studies

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Heavy quarks with large transverse momenta lose energy mainly through radiative processes. However, a Monte-Carlo implementation of gluon emission in an event-by-event fluctuating medium background is a non-trivial task. This is because the Landau-Pomeranchuk-Migdal (LPM) effect of the medium-induced bremsstrahlung introduces coherence over long distances that may be comparable to the typical expansion time scale or even the size of the QGP fireball. We have developed a new partonic transport model to implement the LPM effect approximately. The simulated in-medium bremsstrahlung spectra quantitatively agree with leading order theory calculations in a static medium and also display expected reduction in an expanding medium. Integrating the transport model into a multistage heavy-flavor dynamical model for heavy-ion collisions, we extract the heavy-quark transport coefficient by comparing to open heavy-flavor measurements at the LHC.

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1. Introduction

The coupling between heavy quarks and the quark-gluon plasma (QGP) is quantified by the heavy-flavor transport coefficient $\hat{q}$. The extraction of this quantity from heavy-ion collision experiments requires a dynamical modeling. A transport approach that couples heavy-flavor and medium evolution is suitable for this purpose. Often a semi-classical transport picture is employed in models using, e.g., (linearized) Boltzmann equations and Langevin equations. Though this picture may be justified at small transverse momentum (p_T) the high momentum propagation of a quark inside a QGP involves in-medium bremsstrahlung processes that are "non-local" in the semi-classical transport framework. This is because that the formation time (τ_f) of in-medium bremsstrahlung can be larger than the mean-free-path λ of the transport approach, and coherence effect from multiple-collisions leads to the QCD analog of the Landau-Pomeranchuk-Migdal (LPM) effect [1, 2]. Moreover, the fireball created in heavy-ion collisions expands fast with a time scale comparable to certain τ_f. As a result, a transport formulation based on local medium properties also starts to break down. We have developed a new partonic transport model to account for such effects and validate its prediction by comparing to theoretical results obtained in simplified scenarios. This transport model is integrated into a multi-stage model for the heavy-flavor propagation in heavy-ion collisions. Finally, we extract the energy and temperature dependence of the heavy quark transport coefficients $\hat{q}$.

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2. Modifications to a semi-classical partonic transport model

In an incoherent picture, the transport model includes both elastic collisions and inelastic collisions. We model processes involving a large momentum transfer ($q > Q_{\text{cut}}$) between hard parton and the medium by $2 \to 2$ and $2 \to 3$ matrix-elements computed in the vacuum, as the medium effects can be suppressed by using a $Q_{\text{cut}} \gg m_D$ in the weakly coupled limit. The small-q interactions are modeled by a diffusion equation plus diffusion induced $1 \to 2$ radiation processes. One advantage of this separation is its interpolating description from a diffusion picture to a scattering picture, which parametrizes essential dynamical modeling uncertainty. Another advantage is that one can include parametric corrections to the small-q diffusion coefficients to parametrize possible deviations of from the leading order results.

To approximately include the LPM effect, the incoherent transport simulation has to be modified accordingly [3]. Suppose during the time evolution, a parton bremsstrahlung event is sampled from the $2 \to 3$ or $1 \to 2$ radiation rates that are computed in the incoherence limit at time t_0. The the final state hard partons are not treated as independent objects immediately; instead, the daughter and the mother partons are kept being propagated under the influence of elastic transverse momentum broadening, which comes from both diffusion and large-q elastic scatterings. The momentum broadening also decreases the formation time τ_f until the time elapse since t_0 exceeds the formation time: $t - t_0 > \tau_f(t)$. When this happened, the incoherently sampled parton bremsstrahlung event is accepted with probability P,

$$P = b\frac{\tilde{\lambda}}{\tau_f(t)}. \tag{2.1}$$

Daughter partons from accepted events are then treated as independent objects, while rejected events are discarded without causing any physical effects. Here, $\tilde{\lambda} = m_D^2/\hat{q}_g$ is a gluon effective mean-free-path that can be defined for both diffusion and scattering processes. Acceptance P represents that in the leading-log (LL) picture of in-medium bremsstrahlung, the LPM effect reduces the radiation rate by $\tilde{\lambda}/\tau_f(t)$ comparing to the incoherent expectation. The factor b mimics the next-to-leading-log (NLL) corrections [4] to the LL picture,

$$b \approx 0.75\sqrt{\frac{\ln(1+Q_1^2/m_D^2)}{\ln(1+Q_0^2/m_D^2)}}. \tag{2.2}$$

This fixes the ambiguity from an undetermined scale in the LL results Q_0 by using the the NLL improved scale $Q_1^2 \sim \sqrt{2x(1-x)E\hat{q}} \sim m_D^2\tau_f(t)/\tilde{\lambda}$. In a transport model, Q_0 is a typical center-of-mass energy of the collisions between the hard partons and the medium partons $Q_0^2 \sim 6ET$. The only numerical factor 0.75 is obtained by matching the simulated spectra to the NLL solution for an asymptotically high energy parton.

In figure 1 (left), we present the simulation in of the above program in an infinite box and the comparison to the analytic solutions for the $q \to q+g$, $g \to g+g$ and $g \to q+\bar{q}$ splittings [4]. The model is able to reproduce the NLL solution in the region $\omega \gg T$. In the small ω region, the simulated result shows similar behavior as the incoherent radiation rate computed using Gunion-Bertsch matrix-element [5, 6]. Meanwhile, the modified transport model is able to capture qualitative feature of bremsstrahlung in an expanding medium. This is tested by comparing the simulated and theoretical computation of the reduction of radiation probability in an expanding medium to that in the static medium. The results are shown in figure 1 (right), which agrees with theoretical predictions in the region $\omega \gg T_0$.

Finaly, for heavy quark the massive kinematic is used and mass terms in the formation time is included $\tau_f = 2x(1-x)E/(k_\perp^2 + x^2M^2)$. The mass-effect in the matrix-elements is approximated by the "dead cone" factor, so that the acceptance probability in equation 2.1 is further suppressed by,

$$P_{\text{heavy}} \to P_{\text{light}} \times \left(\frac{k_\perp^2}{k_\perp^2 + x^2M^2}\right)^2. \tag{2.3}$$

The $k_\perp^2$ used here is the one after the elastic broadening from the multiple scattering.

3. Interfacing vacuum-radiation with transport model

Parton created at high p_T initially has a large virtuality $Q \sim p_T$ and undergoes vacuum radiation, while a semi-classical transport equation should be applied to almost on-shell particles. In the modified transport model, bremsstrahlung particles are allowed to have a finite in-medium virtuality upto the the momentum broadening that can be acquired from multiple collisions $Q_{\text{med}} \sim \sqrt{\int_0^{\tau_f} \hat{q}(t)dt}$. Such scales are significantly lower than the initial virtuality, but are still higher than the scale where one usually stops the vacuum shower. Currently, we use a simple prescription to interface the high-virtuality evolution and the transport equation of heavy quark. This is achieved by removing the gluon radiation off a heavy quark generated by vacuum parton shower, if the gluon

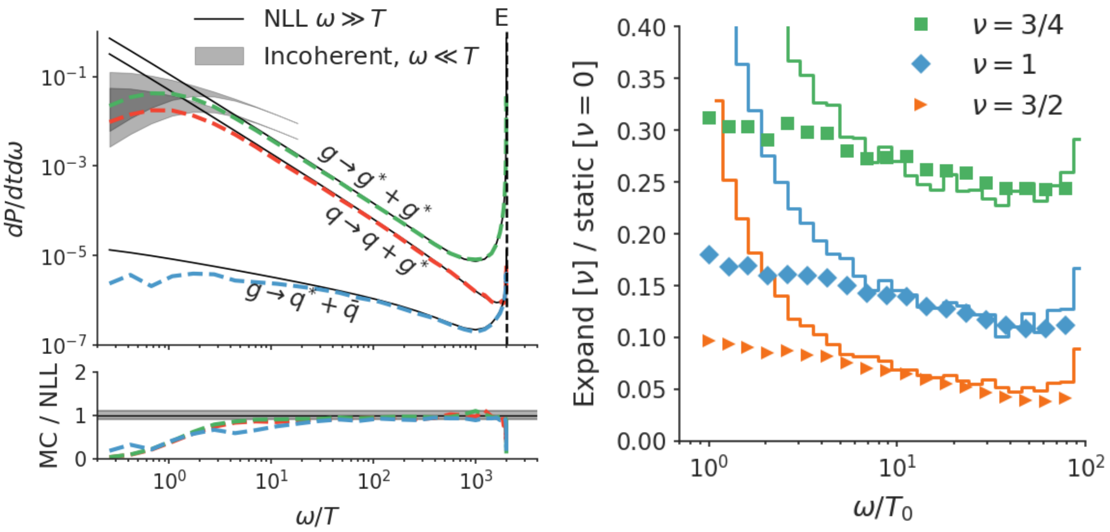

Figure 1: Left: a comparion of the simualted bremstrahlung rate for different channels in an infinite medium with analytic solution at the next-to-leading-log level from reference [4]. The original parton has 1 TeV energy, the medium temperature is 0.5 GeV, with a constant conpling constant $\alpha_s = 0.1$. Right: ratio between radiation probability in an expanding medium with temperature profile $T^3 = T_0^3(\tau_0/\tau)^{2-1/\nu}$ and that in an static medium with $T = T_0$. The symbols are calcualted from the theoretical formula in reference [7].

transverse momentum $k_\perp^2$ is comparable to $Q^2_{\rm med}$, with $Q_{\rm med}$ determined by performing elastic broadening. This way the vacuum shower is terminated at a low virtuality $Q \sim Q_{\rm med}$, where the processes are better treated by the modified transport equation.

4. Preliminary results for heavy quark $\hat{q}$ extraction

We apply such a model to extract the energy and temperature dependence of the heavy quark transport coefficient by comparing to data taken at the LHC energy. The above described heavy-flavor transport model is coupled to a hydrodynamic model for medium evolution. This 2+1D hydrodynamic based medium evolution model with optimized parameters are described in [8]. Below the pseudo-critical temperature, heavy quarks are hadronized using the model developed in [9].

The experimental dataset includes both D-meson R_{AA} and v_2 measured by the ALICE and the CMS Collaborations [10, 11, 12, 13, 14], plus the B-meson R_{AA} measured by the CMS Collaboration [15]. the statistical package to systematically calibrate model parameters to data are developed in [8]. The results are summarized in figure 2, where one can evaluate the global performance of the model. The extracted heavy flavor transport coefficient $\hat{q}$ is shown in figure 3, where the black-dashed lines show central predictions, and the dark- and light-red bands denote 60% and 90% credible intervals respectively. We also compare the results to the JET collaboration extraction for light quark $\hat{q}$ at $p = 10$ GeV [16] ($p \sim E$ for charm quark), and our extracted values are consistent with previous determination within uncertainty.

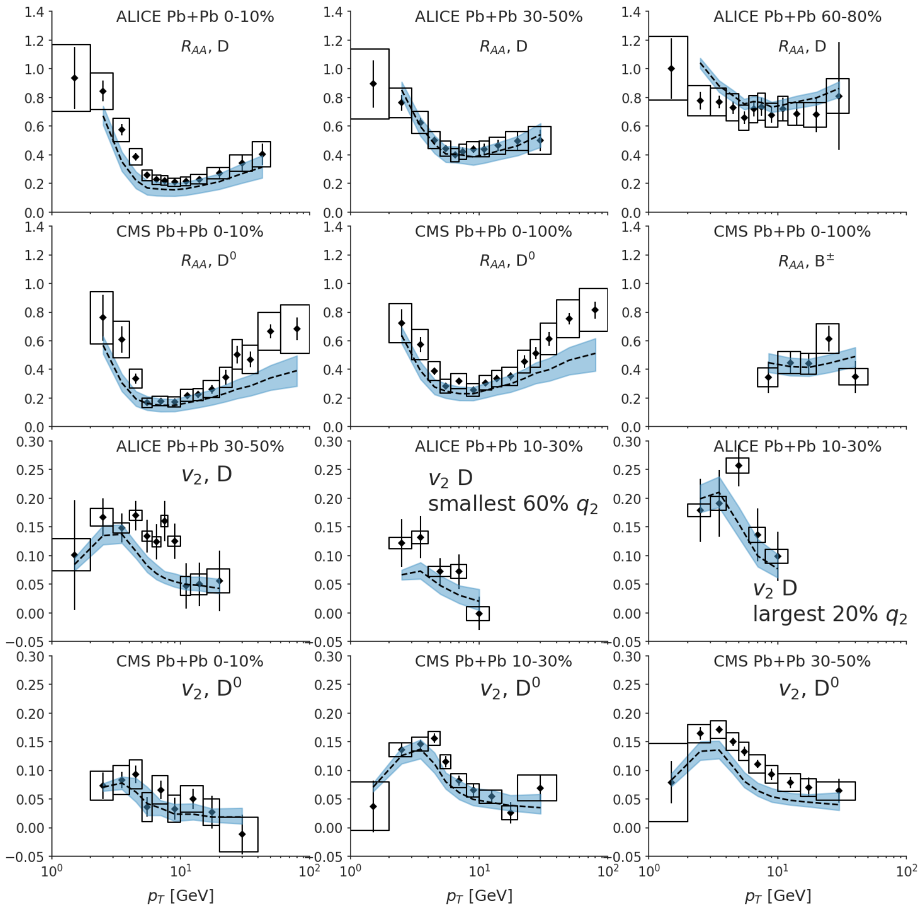

Figure 2: A comparison to the open heavy-flavor measurement at the LHC.

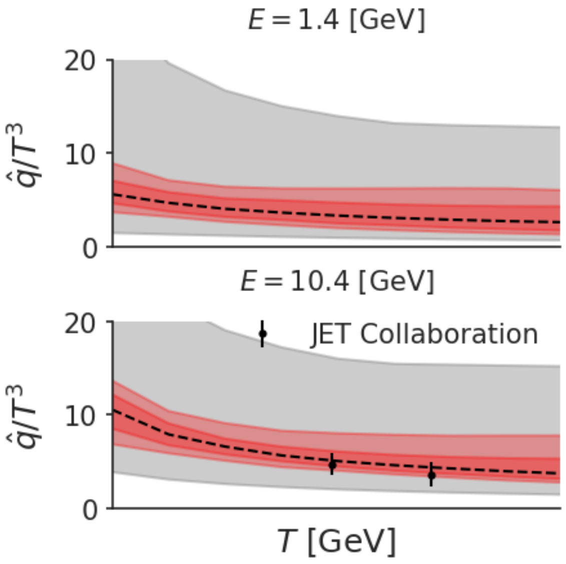

Figure 3: The extracted perturbative in-meidum coupling strength α_s evaluated at $Q = \mu\pi T$ (left), and the heavy-quark transport parameter $\hat{q}$ (right).

5. Summary

In summary, we have presented a new transport model with an improved treatment of the LPM effect, whose simulated results are comparable to theoretical calculations in simplified scenarios. The model is applied to heavy-flavor propagation in the heavy-ion collision. The interfacing between the initial high-virtuality evolution and the low-virtuality transport equation is chosen at a scale where the parton virtuality is comparable to the acquired in-medium transverse momentum broadening. Finally, by a systematic model-to-data comparison, we extracted the energy and temperature dependence of the heavy quark transport coefficients. At large momentum $p \gg M$, the results are consistent with the previous JET Collaboration extraction for light quark.

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