

Heavy-flavor production from QCD evolution in dense matter

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Abstract

Calculations of heavy-flavor production in nuclear collisions are performed using a QCD evolution approach. The nuclear medium effects include initial-state power corrections from coherent scatterings, momentum broadening, and parton energy loss in the cold nuclear matter. In the final state, we considered both collisional energy loss in a dense QGP and the medium-modified heavy-flavor fragmentation functions, obtained from solving the modified DGLAP equation with SCET_G in-medium splitting functions. This framework is then applied to compute light- and heavy-flavor nuclear modification factors in small-system collisions (p -Pb and d -Au) and light-ion (O-O) collisions. Calculations are performed in two scenarios with and without the assumption of QGP formation to help the identification of QGP signatures in future experimental measurements in such collisions.

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I. Introduction

Using jet quenching, including the quenching of light and heavy-flavor hadrons production at large p_T , the quark-gluon plasma (QGP) has been identified in the final state of heavy-nucleus collisions. The large mass of heavy-flavors allows one to perform perturbative calculations down to intermediate to low transverse momentum, where hadron spectra receive sizable medium corrections from the QGP. There are increasing, yet inconclusive, pieces of evidence that final-state effects may also exist in small colliding systems such as d -Au and p -Pb collisions. One of the upcoming heavy-ion programs at RHIC and LHC is to use light-ion (oxygen-oxygen) collisions to study if the quark-gluon plasma (QGP) state of matter can exist in such small-sized systems. Heavy flavor probes will continue to be an important channel to probe any possible QGP effects. In small systems, QGP effects (if exist) are considerably reduced as compared to heavy-nucleus collisions. Therefore, both initial-state parton density modifications in the cold nuclear matter and final-state effects should be considered simultaneously to interpret the measured hadron modifications.

In this proceeding, we described a framework that includes both initial and final-state effects to study the heavy-flavor modifications in nuclear collisions. The predicted nuclear modification factors for D and B mesons in various systems in comparison to that of light mesons will be systematically tested in the upcoming light-ion programs at both RHIC and LHC.

II. Initial and final-state nuclear effects of heavy-flavor production

Before the hard collision, the parton from nucleus $A(B)$ undergoes multiple collisions with the nucleus $B(A)$, causing modifications of the parton densities in the cold nuclear matter. For low- x partons, these multiple collisions are coherent and lead to dynamical shadowing [1, 2], which effectively shifts the x variables of the partons by $\delta x/x \sim \mu^2 A^{1/3}/(-u)$ ($A \rightarrow B, u \rightarrow t$ for the other incoming parton). In the transverse direction, multiple collisions lead to transverse momentum broadening that we model by a Gaussian distribution [3]. Furthermore, we also considered energy loss of the incoming partons from the cold-nuclear-matter-induced soft gluon emissions [4]

$$x \frac{dN_{\text{IS}}}{dx d^2\mathbf{k}} = \frac{\alpha_s C_R}{\pi^2} \frac{L}{\lambda_g} \int_0^{\frac{\mu p^+}{4}} d^2\mathbf{q} \frac{\mu^2}{\pi(\mathbf{q}^2 + \mu^2)^2} \left[\frac{\mathbf{q}^2}{\mathbf{k}^2(\mathbf{k} - \mathbf{q})^2} - \frac{2(\mathbf{q}^2 - \mathbf{q} \cdot \mathbf{k})}{\mathbf{k}^2(\mathbf{k} - \mathbf{q})^2} \frac{\sin \frac{\mathbf{k}^2 L}{xp^+}}{\frac{\mathbf{k}^2 L}{xp^+}} \right]. \quad (1)$$

L is the path length of parton propagation before the hard collision. The CNM energy loss leads to an additional shift of the parton x variables.

The impact of these initial-state effects is shown on the left panel of figure 1 for nuclear modifications of the gluon and quark spectra from the hard collision. The Cronin effect and power correction strongly modify the shape of the spectra below $p_T = 10$ GeV (parton

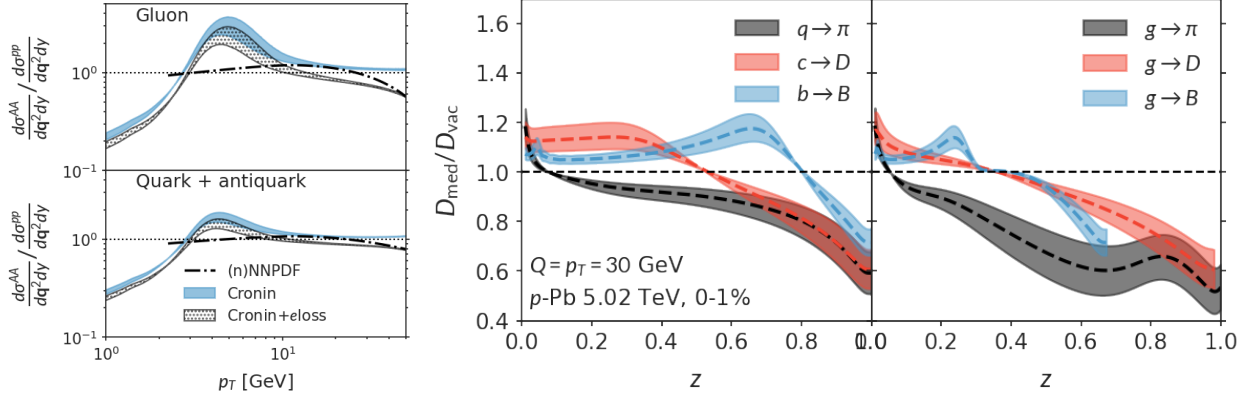


FIG. 1. Left: cold nuclear matter effects shown as the ratio of hard partonic spectra in Au-Au collisions to that in p - p collisions. Right: QGP effects shown as the ratio of the fragmentation functions modified in 0-1% high-multiplicity p -Pb collisions to those in the vacuum.

momentum); while the CNM energy loss suppresses spectra at large p_T . We also compare this dynamical initial-state effect model to the nuclear PDF calculations using the (n)NNPDF parametrization [5].

We then compute hadron production in light-ion and small-system collisions in two scenarios, depending on whether one assumes a near thermalized QGP forms in these systems. Without QGP formation, the parton spectra calculated with CNM effects are folded with vacuum fragmentation function to compute the production light-, D , and B -mesons. If there are QGP effects, we will include a collisional energy loss to the hard parton spectra, which are then folded with the medium-modified fragmentation functions. The collisional energy loss in the QGP is given by the hard-thermal-loop formula including running coupling effect [6]

$$\frac{dE_{\text{el}}}{d\Delta z} = \frac{C_R}{4} \left(1 + \frac{N_f}{6}\right) \alpha_s(ET) g_s^2 T^2 \ln\left(\frac{ET}{m_D^2}\right) \left(\frac{1}{v} - \frac{1-v^2}{2v^2} \ln \frac{1+v}{1-v}\right). \quad (2)$$

$v = p/E$ is the velocity of the parton in the rest frame of the QGP medium. The modified fragmentation function is obtained by evolving the light and heavy meson fragmentation function from an initial virtuality scale $Q_0 = 0.4$ GeV to $Q = p_T + \Delta E_{\text{el}}$ using the medium-modified DGLAP evolution equations [7]

$$\frac{\partial D_{h/i}(z, Q^2)}{\partial \ln Q^2} = \sum_j \int_z^1 \frac{dx}{x} D_{h/j}\left(\frac{z}{x}, Q^2\right) [P'_{ji}(x \rightarrow 1-x, Q^2) + d_{ji}(Q^2)\delta(1-x)]. \quad (3)$$

P'_{ji} are the in-medium QCD splitting functions obtained in SCET $_G$ [8, 9]. For evolutions involving heavy quarks, we consider medium modifications to both $Q \rightarrow Qg$ and $g \rightarrow Q\bar{Q}$ [9].

The nuclear modification of fragmentation functions in top 1% high-multiplicity p -Pb collisions at 5.02 TeV is shown on the right panel in figure 1. The bands correspond to the

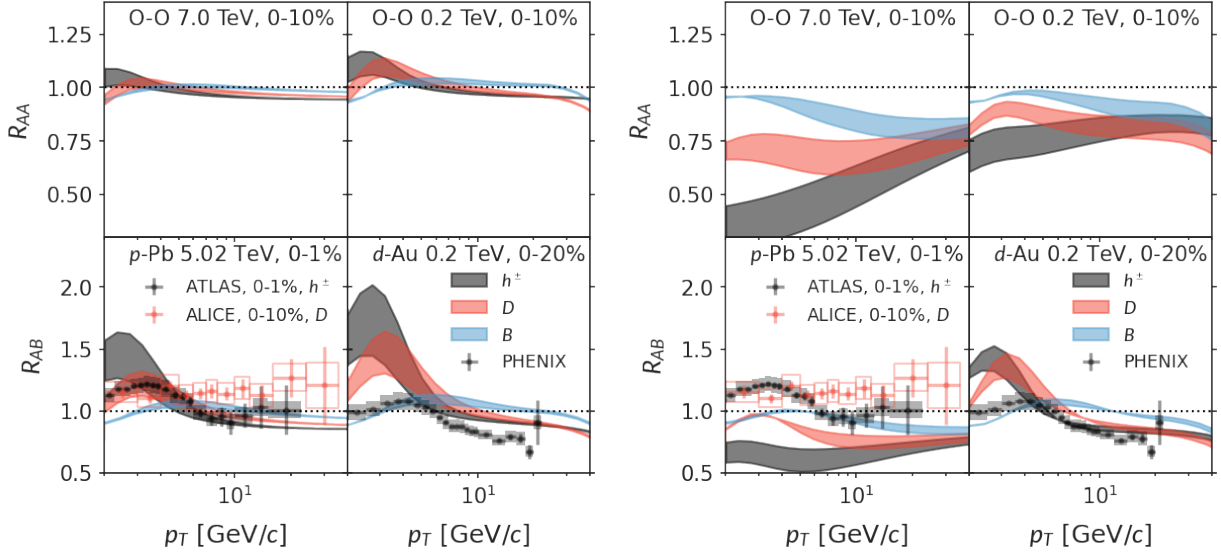


FIG. 2. Nuclear modification factor in light-ion (top rows) and small, asymmetric colliding systems (bottom rows). Left: calculations with only cold nuclear matter effect (without QGP formation). Right: calculations with both CNM and QGP effects. Experimental data are taken from ALICE, ATLAS, and PHENIX Collaborations [10–12].

use of $g_s = 1.8 \pm 0.2$ —a reasonable region to describe the jet quenching effects in large nucleus collisions at both RHIC and LHC [3]. We assume contributions from gluon to heavy-flavor mesons are zero at $Q = Q_0$, and $g \rightarrow D, B$ can only come from the perturbative evolution. It may underestimate the contribution from gluon fragmentation, and one should consider using non-perturbative heavy-flavor fragmentation function input in the future.

III. Results

Calculations of the nuclear modification factor of light, charm, and bottom mesons in O-O, p -A, and d -A are shown in figure 2. The scenario without (with) QGP formation is shown in the left (right) panel. In the scenario without QGP formation, asymmetry collisions such as p -Pb and d -Au receive strong cold nuclear matter corrections around $p_T = 3$ GeV for light hadron R_{AA} . The peak of the CNM modification moves to higher p_T for heavy mesons. At large p_T , the CNM energy loss can qualitatively describe light-hadron modifications in p -Pb. However, note that D -meson R_{AA} suggests an “enhancement” in high-multiplicity p -Pb events. The light-ion collisions are expected to have much smaller CNM effects and better experimental determination of centrality classes, i.e, a cleaner situation to study final-state effects.

With our assumption of the formation of a “near thermalized” QGP as described by hydrodynamics, final-state effects in both light-ion and small systems are strong at both LHC and RHIC energies. Such an assumption is strongly disfavored by LHC measurements in high-multiplicity p -Pb collisions. In O-O collisions, the final-state QGP quenching effects

are estimated to be 50%-25% for light hadrons at $p_T = 10$ GeV from LHC to RHIC energy and 20% to 10% even for bottom hadrons at $p_T = 10$ GeV. Of course, given the strong non-equilibrium effects that prevail the evolution of the medium produced in small and light-ion systems, we should not expect the density of the collision center to reach the equilibrium expectations for massless quarks and gluons as is used in this study. Therefore, our results should be understood as calculations with maximum QGP effects.

IV. Summary and outlook

To summarize, we studied the heavy-flavor production in light-ion and small-system collisions and provide predictions with and without QGP formation for the upcoming measurements at both RHIC and LHC. This QCD evolution approach of hadron production in nuclear collisions includes both final-state collisional energy loss and medium-modified DGLAP evolution and the initial-state cold nuclear matter effects. In order to identify the QGP effects in small systems, we find that future improvements in the calculation of CNM modifications are necessary. This motivates future works applying QCD evolution approach to treat initial-state in-medium calculations with better theoretical control.

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