Jet and heavy flavor production in heavy-ion collisions

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Abstract

We review recent progress in the theoretical description of hard probes in heavy-ion collisions within the framework of Soft Collinear Effective Theory (SCET). Firstly, we consider the inclusive production of heavy flavor mesons and jets with a small radius parameter in proton-proton collisions. Secondly, we describe how in-medium effects can be incorporated consistently with the proton-proton baseline calculations. The in-medium interactions are described by Glauber gluon interactions. We present results for the nuclear modification factor R_{AA} which is most commonly used to study the quenching of hadron or jet production yields in heavy-ion collisions and we compare to recent data from the LHC.

Keywords: Jets, Heavy flavor mesons, Effective field theories

1. Introduction

In heavy-ion collisions at the LHC and RHIC, the quark-gluon plasma (QGP) can be reproduced which is predicted to have existed in the early stages of our universe. Highly energetic particles and jets traverse this hot and dense QCD medium and, hence, carry valuable information about its properties. In this work, we focus in particular on open heavy flavor production (*D*- and *B*-mesons) as well as inclusive jet production. In the past years, the experimental collaborations at the LHC and RHIC have provided high precision data for the nuclear modification factor R_{AA}, see for example [1, 2, 3, 4, 5, 6, 7].

In order to study the modification of open heavy flavor yields in heavy-ion collisions, we rely on recently developed techniques within Soft Collinear Effective Theory (SCET) [8, 9]. For brief overview of recent SCET developments in hadronic and nuclear collisions see [10]. In order to describe the in-medium interactions of energetic partons inside the QGP, additional Glauber modes are included at the level of the SCET Lagrangian [11, 12]. The corresponding effective theory for gluons and massive quarks propagating in the QGP

is referred to as $\text{SCET}_{M,G}$ [13]. Within this framework, it is possible to calculate the full collinear in-medium splitting functions which allows us to go beyond the traditional approach to parton energy loss [14, 15]. In this work, we present a novel implementation using these in-medium collinear splitting functions which is consistent with next-to-leading order (NLO) calculations used for the proton-proton (*pp*) baseline.

The second topic addressed in this work is the description of inclusive jet spectra. In the era of the LHC and RHIC, the measurement of jets in heavy-ion collisions and their theoretical description have received an increasing attention both from the theoretical [16, 17, 18, 19] and the experimental communities [5, 6, 7]. The cross section for jets crucially depends on the jet size parameter R. Typically, R is chosen in the range of $R \sim 0.2 - 0.4$ by the experimental analyses in order to avoid fluctuations in the heavy-ion background. The perturbative calculations exhibit a single logarithmic structure $\alpha_s^n \ln^n R$ which needs to be resummed to all orders [20, 21]. The results presented here for the *pp* baseline will eventually be the starting point for describing small-R jets in the medium.
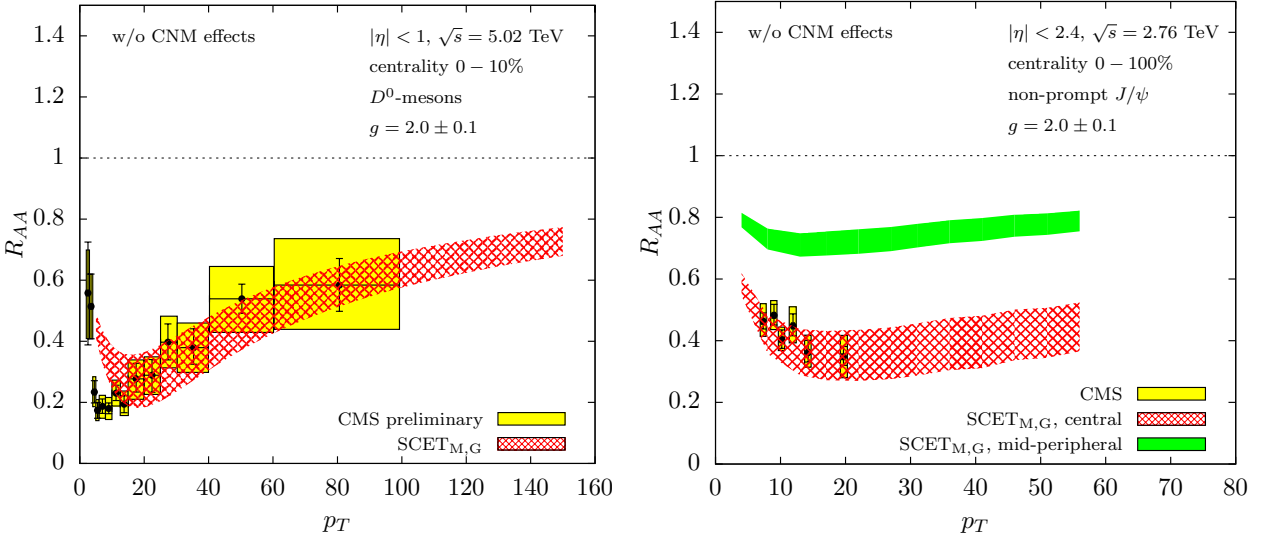
Figure 1: Suppression of D^0 mesons [3] (left) and non-prompt J/ψ which originate from B-hadrons [4] (right) in PbPb collisions at the LHC. The data was taken by the CMS collaboration. Our results obtained within SCET$_{M,G}$ are shown for central collisions (red hatched band) and for mid-peripheral collisions (green band). Here, we do not include Cold Nuclear Matter (CNM) effects.

2. Heavy flavor production

We calculate the pp baseline for open heavy flavor production using the Zero Mass Variable Flavor Number Scheme (ZMVFNS) at NLO and the fragmentation functions (FFs) of [22, 23]. We find a good description of the pp data even for relatively small transverse momenta $p_T \sim 5$ GeV. The part of the NLO cross section that describes the fragmentation of a parton i into a hadron H can schematically be written as

$$\sum_j \sigma_i^{(0)} \otimes \mathcal{P}_{i \to jk} \otimes D_j^H . \tag{1}$$

Here $\sigma_i^{(0)}$ is the leading-order production cross section for a parton i, $\mathcal{P}_{i \to jk}$ describes the splitting process $i \to jk$ and D_j^H is a non-perturbative fragmentation function. In the medium, we have to take into account both vacuum and medium induced parton emissions. The description of the splitting process gets modified as

$$\mathcal{P}_{i \to jk} = \mathcal{P}_{i \to jk}^{\text{vac}} + \mathcal{P}_{i \to jk}^{\text{med}} , \tag{2}$$

where $\mathcal{P}_{i \to jk}^{\text{med}}$ is the collinear in-medium splitting function which can be obtained from SCET$_{M,G}$. Using power counting techniques, we find that the required effective field theory including both finite quark masses and Glauber gluons describing the interaction with the medium is given by a direct sum of the massive vacuum

SCET Lagrangian [24] and the massless in-medium interaction terms [12]. See [13] for a more detailed discussion. To first order in opacity [14], we can compute the diagonal splitting process $Q \to Qg$ as well as the off-diagonal ones $Q \to gQ$ and $g \to Q\bar{Q}$ in the medium. In the soft emission limit, we recover the results obtained within the traditional picture of parton energy loss for massive quarks [15].

In Fig. 1, we present numerical results for the nuclear modification factor

$$R_{AA} = \frac{d\sigma_{\text{PbPb}}^H / d\eta dp_T}{\langle N_{\text{coll}} \rangle d\sigma_{pp}^H / d\eta dp_T} , \tag{3}$$

where $\langle N_{\text{coll}} \rangle$ is the average number of binary nucleon-nucleon collisions. On the left side, we present results using the new framework for D^0 mesons (hatched red band) and we find good agreement compared to the CMS data of [3] taken at $\sqrt{s} = 5.02$ TeV, $|\eta| < 1$ and $0 - 10\%$ centrality. Similarly, on the right side of Fig. 1, we show results for the suppression of non-prompt J/ψ which originate from B-hadrons and we compare to the CMS data of [4] ($\sqrt{s} = 2.76$ TeV, $|\eta| < 2.4$). Note that the non-prompt J/ψ data is not for fixed centrality but for minimum bias events. Therefore, we present our calculation for both central (hatched red band) and mid-peripheral collisions (green band). The experimental minimum bias results are dominated by central collisions and we find good agreement with our calculation