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Heavy Quark Production and Energy Loss

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Abstract

Heavy flavor research is a vigorous and active topic in high-energy QCD physics. Comparing theoretical predictions to data as a function of flavor provides a unique opportunity to tease out properties of quark-gluon plasma. We explicitly demonstrate this utility with energy loss predictions based on the assumption of 1) a weakly-coupled plasma weakly coupled to a high-p_T probe using pQCD and 2) a strongly-coupled plasma strongly coupled to a high-p_T probe using AdS/CFT; we find that while the former enjoys broad qualitative agreement with data, it is difficult to reconcile the latter with experimental measurements.

1. Introduction

Our goal as nuclear physicists is to quantitatively extract experimentally and understand theoretically the properties of nuclear matter; as part of this goal, we wish to compose the phase diagram of the strong force. This is an extremely immodest goal. For example, detailed first-principles calculations for the phase diagram of hydrogen, the most simple QED system, is contemporary research [1]. Nevertheless quark-gluon plasma (QGP) provides us with a unique opportunity to probe experimentally and theoretically the emergent, many-body physics of a non-Abelian gauge theory in a certain region of its phase diagram. We have a number of tools at our disposal for exploring the properties of QGP from experimental measurements, for example: low-p_T particles, electromagnetic probes, quarkonia, high-p_T light hadrons, and high-p_T heavy hadrons. Heavy flavor measurements and theory are an important piece in the puzzle we are trying to put together to form a consistent and coherent picture of heavy ion collision phenomena.

Unfortunately length limits the breadth of the coverage here of the fascinating and important aspects of heavy flavor research in high-energy QCD; we will focus on the physics we can learn from high momentum particles. High-p_T particles are especially interesting as they are the decay products of high-p_T partons, which are the most direct probe of the relevant degrees of freedom in a quark-gluon plasma (QGP) [2, 3]. One is able in principle to learn about QGP by making an assumption regarding the physics of the QGP and comparing the necessary theoretical consequences of those assumptions to data. One hopes to use this approach to falsify certain assumed descriptions of the plasma and add evidence for others. Just as one requires consistency of the entire picture of all data, one requires consistency of description of measurements associated with energy loss. It turns out that this consistency is quite hard to achieve, and, as a result,

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energy loss provides us with a valuable window through which to actually measure the physics of quark-gluon plasma. To explicitly demonstrate the power of this method we will take two extreme, generic assumptions regarding the medium and how it couples to high-p_T probes and compare the results to data.

Heavy flavor is especially interesting because of the additional experimental constraints it puts on energy loss calculations, and thus on the potential properties of quark-gluon plasma. In particular, an energy loss calculation, in a broad sense, results in a probability of a parton losing some of its initial momentum, $P(\Delta p_T \,|\, p_T,\, L,\, T,\, M_Q,\, R)$, where L is the pathlength the parent parton travels, T is the temperature of the plasma, M_Q is the mass (or effective mass) or the parent parton, and R is the representation (i.e. is the parent parton a gluon or quark). Unfortunately one cannot alter these parameters experimentally to test energy loss theories; rather one changes, for instance, the collision species, the $\sqrt{s}$ of the collision, or—as is especially useful for investigating heavy flavor—the mass of the measured hadron, and compares to theoretical predictions.

Qualitatively, one expects a simple ordering of the energy losses as one changes parent parton species, specifically[1]

$$\Delta E_b < \Delta E_c < \Delta E_{u,d,s} < \Delta E_g. \tag{1}$$

However, it is important to emphasize that *energy loss ordering does not necessitate an ordering of the nuclear suppression factors*, $R_{AA}(p_T)$, because R_{AA} involves a convolution over the fragmentation functions and, most important, the production spectrum. For approximately power law production of high-p_T partons, as predicted by pQCD, and fractional momentum loss $\epsilon = (p_{T,i} - p_{T,f})/p_{T,i}$, one can show that [5]

$$\frac{dN}{dp_T} \propto \frac{1}{p_T^{n+1}} \quad \Rightarrow \quad R_{AA} \approx \Big\langle \int d\epsilon (1-\epsilon)^n P(\epsilon) \Big\rangle, \tag{2}$$

where the angular brackets refer to averaging over the geometry. As one can see from Eq. (2), the softer the spectra the larger is n and thus the smaller R_{AA} for the same Δp_T. As seen in Fig. 1, the relative changes in production power laws n_Q for different parton species lead to a crossing in R_{AA} for different hadron species (as first noted in [6]).

The use of heavy flavor allows for an additional test of energy loss theory, and it turns out that by comparing to the centrality, center of mass energy, and especially flavor dependence of data yields a stringent constraint on the theory; see, for instance, a simultaneous description of pion and non-photonic electron suppression at RHIC precludes the possibility of pQCD-based radiative only energy loss [7].

2. Extracting Physics by Comparing to Data

2.1. *Strongly-coupled Medium Strongly Coupled to a Probe*

To begin our energy loss comparison to data using two extreme assumptions about the physics of the QGP, let's consider a strongly-coupled medium strongly coupled to the high-p_T probe. There are many reasons to believe that strong-coupling dynamics dominant the physics of the medium, and in particular, that AdS/CFT techniques provide valuable insight into these processes [3, 8]. For instance, running coupling calculations suggest that at $T \sim 250$ MeV—a not

[1] It's worth noting for the experts that this ordering is not strict in pQCD: because the formation time has mass dependence [4] there can be violations in the ordering in certain regions of phase space.