

# Is It Hard Yet? The Qualitative Agreement of pQCD Energy Loss with RHIC and LHC Data

**W. A. Horowitz**

Department of Physics, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa

E-mail: [wa.horowitz@uct.ac.za](mailto:wa.horowitz@uct.ac.za)

**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 heavy ion physicists is to quantitatively extract experimentally and understand theoretically the properties of hot, dense nuclear matter; we wish to describe part of 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]. We have a number of tools at our disposal for exploring the properties of quark-gluon plasma (QGP) from experimental measurements; we will focus on some of the observables related to high transverse momentum (high- $p_T$ ) processes.

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 [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 by requiring consistency in the description of measurements associated with energy loss. It turns out that this consistency is quite hard to achieve, and, as a result, 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.

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) of the parent parton, and  $R$  is the representation (i.e. is the parent parton a gluon or quark). Unfortunately one cannot directly 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.

## 2. Extracting Physics by Comparing to Data

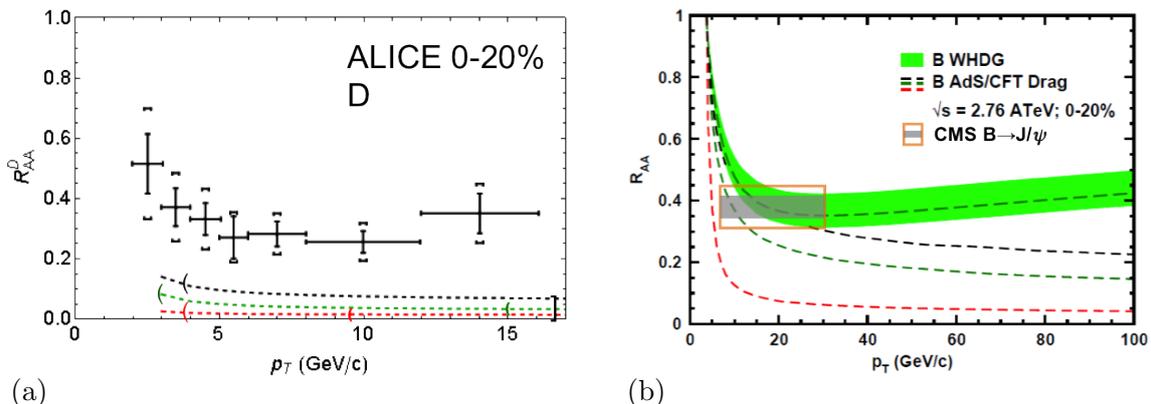
### 2.1. Strongly-coupled Medium Strongly Coupled to a Probe

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 dominate the physics of the medium, and in particular, that AdS/CFT techniques provide valuable insight into these processes [3, 4]. For instance, running coupling calculations suggest that at  $T \sim 250$  MeV—a not unreasonable placeholder for the QGP temperature— $g \sim 2$  and  $\lambda = g^2 N_c \sim 12 \gg 1$ ; it's worth noting that in phenomenological applications  $T$  is never large compared to  $\Lambda_{QCD}$ . Also, for  $T \gtrsim T_c$ , lattice calculations nontrivially deviate from the Stefan-Boltzmann limit, and in such a way that is reasonably well described using AdS/CFT [4]. Finally, the viscosity to entropy ratio extracted from hydrodynamics calculations [5] suggest  $\eta/s \sim 1/4\pi$ , which is readily explained by AdS/CFT [6].

There have been calculations of the energy loss of both light and heavy quarks using the AdS/CFT correspondence. For heavy flavor, the energy loss is a drag,  $dp_T/dt = -\mu p_T$ , where  $\mu = \pi \lambda^{1/2} T^2 / 2M_Q$  [7, 8]; this is similar to weakly-coupled energy loss in the Bethe-Heitler regime, but very different from the predictions of perturbative quantum chromodynamics (pQCD) in the deep Landau-Pomeranchuk-Migdal (LPM) region where  $dp_T/dt \sim -LT^3 \ln(p_T/M_Q)$  [9]. Comparison between AdS/CFT calculations and data are difficult because there is no unique mapping from the parameters of QCD to those of  $\mathcal{N} = 4$  SYM and  $\text{AdS}_5 \times S^5$ . Nevertheless, comparing over reasonable assumptions for parameter values in AdS/CFT yields a quantitative agreement between theoretical predictions and data for non-photonically electron suppression at RHIC [10–12]. But we see again the power of comparing theoretical calculations to a wide range of data when we attempt to simultaneously describe the suppression of heavy flavor at LHC. Keeping all parameters fixed and only changing the temperature of the medium (which we do according to the measured  $\sqrt{s}$  dependence of the multiplicity) we can calculate zero parameter predictions for LHC, shown in Fig. (1). While the  $B$  meson suppression is currently consistent with data within the large experimental and theoretical uncertainties, the AdS/CFT calculations significantly overpredict the suppression of  $D$  mesons. Before strong conclusions are drawn, however, it turns out that momentum fluctuations [13, 14] (especially longitudinal)—whose importance should only affect momenta parametrically large compared to the momenta at which the formalism breaks down, and were neglected in these calculations—likely play a significant role numerically.

One wants not only to simultaneously compare AdS/CFT predictions to data as a function of  $\sqrt{s}$  but also as a function of parton species. Unfortunately the theory of light flavor energy loss [18–20] is less well understood in AdS/CFT than for heavy quarks. Added difficulties arise in the light sector due to the lack of 1) an analytic solution for falling string configurations and 2) a good working definition for the energy lost by the probe (in principle one can exactly compute  $T^{\mu\nu}$  for the plasma and thus the energy lost by the probe, but this is an extremely difficult problem both in terms of the analytics and the numerics). Preliminary estimates, however, suggest that light flavor energy loss is also overpredicted by AdS/CFT: the thermalization time for light quarks in the medium is of the order of 3 fm; even when the 1D Hubble flow of the QGP is included the thermalization time is only increased to about 4 fm [21].

In addition to checking the flavor dependence, these AdS/CFT energy loss calculations may also be tested by changing collision species and looking at the suppression of heavy flavor at forward rapidities [22].



**Figure 1.** Comparison of (a)  $D$  [15] and (b)  $B$  [16] meson  $R_{AA}(p_T)$  for 0-20% centrality collisions at LHC to AdS/CFT heavy quark drag predictions constrained by RHIC data [11, 12, 17].

## 2.2. Weakly-coupled Medium Weakly Coupled to a Probe

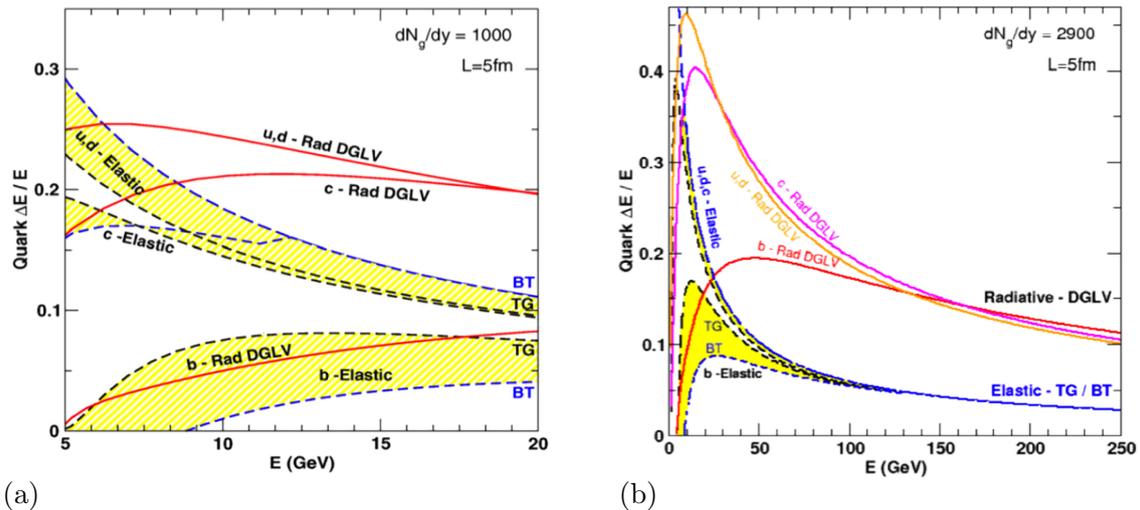
The assumption of the dominance of weakly-coupled dynamics in heavy ion collisions is also not unreasonable. For  $T \sim 250$  MeV,  $\alpha_s(2\pi T) = 0.3$ . Also, multi-loop thermal field theory is in good agreement with lattice data for thermodynamic properties of QCD at a few times  $T_c$ , albeit with large uncertainties [23]. Finally, numerically daunting parton cascade calculations show that including  $2 \rightarrow 3$  channels yields  $\eta/s \sim \text{few}/4\pi$  [24].

Continuing with the assumption of a weakly-coupled plasma coupling weakly to a probe, the medium is described by two scales: the Debye screening length, given in terms of the Debye mass  $\mu \sim gT$ , and a mean free path for gluons,  $\lambda_{mfp}^g \sim 1/g^2T$  (see [25] and references therein). When evaluated at temperature scales relevant for RHIC and LHC and with all the numerical coefficients, one finds<sup>1</sup> an ordering of scales  $1/\mu \ll \lambda_{mfp}^g \ll L$ , where again  $L$  is the pathlength travelled by the parent parton and is on the scale of the radius of the nucleus,  $L \sim R_A$ . Since  $1/\mu \ll \lambda_{mfp}^g$ , high- $p_T$  particles scatter off of well defined, separated medium quasi-particles. It is important to note however that for heavy quarks  $L/\lambda_{mfp} \sim 4$  (and similarly even for gluons), and therefore energy loss models that assume a large number of collisions (and that thus the central limit theorem holds), such as those using Langevin or rates methods, likely require large corrections.

In pQCD with its quasi-particle picture one can distinguish between two types of energy loss: elastic and inelastic, otherwise known as collisional and radiative, respectively. There is a long history of pQCD-based elastic energy loss calculations (see [12] and references therein); see [2] for a review of pQCD-based radiative energy loss calculations. Leading order estimates of the size of elastic energy loss yield  $dp_T^{el}/dt \sim -T^2 \ln(p_T/M_Q)$ . Naively, at asymptotically large energies intuition based on classical electromagnetism leads to the conclusion that  $\Delta E_{el} \ll \Delta E_{rad}$ , but this is based on a Bethe-Heitler estimate of radiative energy loss in which subsequent collisions with medium particles yield incoherently summable emissions. However, there is one more important scale to qualitatively understand radiative energy loss, the formation time,  $\tau_{form}$ , which characterizes the distance required for an emitted gluon to be resolved independently from the emitting parton. There is a large uncertainty in the size of  $\tau_{form}$  but for emissions of large energy gluons in QGP,  $\tau_{form} \gg \lambda_{mfp}^g$ , and a single gluon emission is thus produced from coherent scatterings off of multiple in-medium quasi-particles. This reduction in the amount of emitted radiation is known as the Landau-Pomeranchuk-Migdal, or LPM, effect [2]. In the LPM limit  $\Delta E_{rad} \propto -LT^3 \ln(p_T/M_Q)$ . With this reduction in radiative energy loss it is possible for

<sup>1</sup> For  $T_{RHIC} = 350$  MeV ( $T_{LHC} = 450$  MeV),  $1/\mu \simeq 0.3$  (0.2) fm and  $\lambda_{mfp}^g \simeq 0.8$  (0.7) fm.

elastic energy loss to be important even at asymptotically high energies. We will be using the Wicks-Horowitz-Djordjevic-Gyulassy (WHDG) model of convolved radiative and elastic energy loss [25] for explicit comparison to experimental data; in this calculation which uses thermal field theory methods for computing the elastic energy loss and the Djordjevic-Gyulassy-Levai-Vitev (DGLV) derivation for the radiative, the elastic energy loss remains a significant contributor to total energy loss even for 250 GeV/c partons at LHC; see Fig. (2).



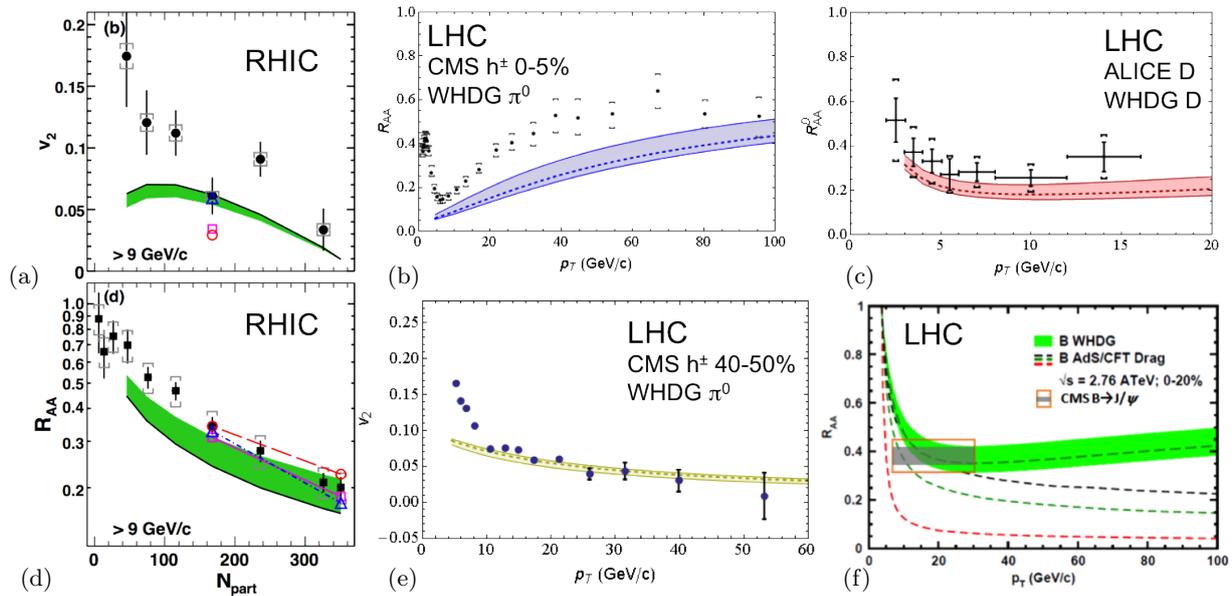
**Figure 2.** Elastic and radiative energy loss for gluons and light, charm, and bottom quarks travelling a distance  $L = 5$  fm through QGP at (a) RHIC and (b) LHC temperatures [12].

We would like to compare the WHDG model to as many observables as possible. Using the thermal field theoretic methods to relate  $\mu$  and  $\lambda_{mfp}^g$  to temperature, assuming that the temperature profile is proportional to the Glauber participant density, and that all couplings are approximately fixed at  $\alpha_s = 0.3$  there is only one free parameter in the theory, the proportionality constant relating the observed multiplicity to the entropy of the plasma. The PHENIX experiment rigorously extracted the best fit value of this parameter and its uncertainty, the rapidity density of gluons  $dN_g/dy = 1400_{-375}^{200}$  [26], by comparing to their  $R_{AA}^{\pi^0}(p_T)$  measurement in most central  $\sqrt{s} = 200$  AGeV collisions. Before immediately comparing to the multitude of data from RHIC and LHC, it is worth noting that the lack of precision and accuracy inherent in pQCD due to both the complicated nature of the theory and the relatively large size of its coupling constant: even NLO calculations of production rates in hadronic collisions tend to be correct only within a factor of 2 of the data [27, 28]. With this in mind, the agreement between the LO WHDG energy loss theory and data shown in Fig. (3) over a range of centralities, collision energies, measurements, and flavors is surprisingly good.

There are a number of directions in which these perturbative calculations can be improved. For instance one might try to model the energy loss using a parton cascade, which trades a better treatment of multiple gluon emission for a less accurate treatment of the quantum mechanical formation time effects [33]. Or one might attempt a NLO ansatz for running coupling along with a more careful treatment of production spectra and time evolution [34].

### 2.3. Direct Comparison of the Pictures

Although the high- $p_T$  physics evidence for a weakly-coupled plasma weakly coupled to a probe is strong and there are significant signs of disagreement between the predictions of a strongly-coupled plasma strongly coupled to a probe it is worth considering a measurement that shows



**Figure 3.** Constrained zero parameter WHDG predictions compared to data for (a)  $v_2(N_{part})$  at RHIC [25, 29], (b) 0-5% centrality  $R_{AA}(p_T)$  for light flavors at LHC [28, 30], (c)  $R_{AA}^D(p_T)$  at 0-20% centrality at LHC [15, 31], (d)  $R_{AA}^0(N_{part})$  at RHIC [25, 29], (e)  $v_2(p_T)$  at LHC for light flavors at 40-50% centrality [31, 32], and (f)  $R_{AA}^B(p_T)$  at 0-20% centrality at LHC [16, 17].

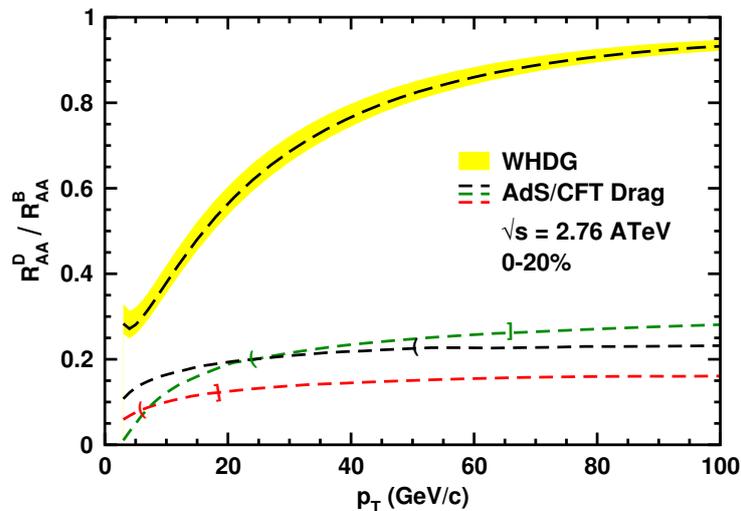
a qualitative difference between the two pictures. One may emphasize the different mass and momentum dependencies of the pQCD and AdS/CFT results by considering the double ratio of  $D$  to  $B$  meson  $R_{AA}$  as seen in Fig. (4). While the leading order AdS/CFT results are applicable (up to a speed limits indicated on the graph) the mass dependence of the energy loss remains; on the other hand the mass dependence drops out for the perturbative results at asymptotically large momenta.

### 3. Summary

We seek a coherent, consistent picture of the physics of QGP in our quest to understand its properties. The comparison of energy loss calculations to data provide a direct probe of the relevant degrees of freedom in a QGP and how this physics interacts with high- $p_T$  particles. As we have known since the first anisotropy and heavy flavor results from RHIC, a simultaneous description of multiple observables related to energy loss physics is very hard to achieve. In particular, despite successes at RHIC, predictions for LHC based on the strong coupling physics of AdS/CFT do not appear to describe the data, although possibly important physics was neglected. However, LO pQCD results give a rather good qualitative description of a suite of observables including pion and heavy flavor suppression and anisotropy from RHIC to LHC. Should we find that these tentative conclusions hold, it becomes a very interesting question of how the strong-coupling low- $p_T$  physics of the QGP medium as implied by hydrodynamics comparisons to data turn over to weak-coupling physics of the QGP medium as implied by the energy loss calculations.

### 4. Acknowledgments

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**Figure 4.** Comparison of the double ratio of  $D$  meson to  $B$  meson  $R_{AA}(p_T)$  for 0-20% centrality collisions at LHC using the pQCD-based WHDG energy loss model [25, 30] and a model based on AdS/CFT drag energy loss [11, 17].

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