

# Fluctuations in Strong-Coupling Heavy Quark Energy Loss

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**Abstract.** We present recent and new results for observables related to heavy quarks from a strong-coupling energy loss model that includes fluctuations in the energy loss. We find that the inclusion of these next-to-leading order fluctuations yields results consistent with all measured data. Correlation measurements and bottom decays to electrons are potential future measurements that can distinguish between weak- and strong-coupling energy loss models.

## 1. Introduction

In high-energy nuclear physics, we seek a self-consistent theoretical framework that provides quantitative, falsifiable predictions that describe experimental data in order to extract quantitatively the properties of the region of the phase diagram of quantum chromodynamics (QCD) accessible to modern collider experiments. The mathematical tools used to understand this quark-gluon plasma (QGP) have broad applications in condensed matter physics at applied mathematics; the properties of the QGP may have important implications for the large scale structure of the universe.

Two obvious extreme assumptions about the properties of the QGP, for which it seems one has analytic theoretical tools to analyze, are that its constituents are slightly thermally modified versions of the quarks and gluons in the QCD Lagrangian, which can be probed using perturbative QCD (pQCD), or that the plasma is strongly-coupled, which perhaps can be understood with the methods of AdS/CFT.

AdS/CFT has had a number of successes in describing several aspects of the QGP: 1) the lattice calculation of the energy density as a function of temperature [1, 2], 2) the rapid hydrodynamization of the QGP [3, 4], and 3) the extremely small viscosity to entropy density ratio [4, 5, 6].

We aim in this proceedings to extend the application of AdS/CFT to heavy quark observables.

## 2. Heavy Quark Energy Loss in AdS/CFT

It was shown in [7] that the three-momentum  $p^i$  of an on-shell heavy quark moving at constant velocity in a strongly-coupled thermal bath of  $\mathcal{N} = 4$  SYM plasma evolves as:

$$\frac{dp_i}{dt} = -\mu p_i + F_i^L + F_i^T, \quad (1)$$



where the drag coefficient [8, 9, 10] of a heavy quark of mass  $M_Q$  in a plasma of temperature  $T$  with 't Hooft coupling  $\lambda$  is  $\mu = \pi\sqrt{\lambda}T^2/2M_Q$ . and the fluctuating momentum kicks are correlated as

$$\langle F_i^L(t_1)F_j^L(t_1) \rangle = \kappa_L \hat{p}_i \hat{p}_j g(t_2 - t_1) \quad (2)$$

$$\langle F_i^T(t_1)F_j^T(t_1) \rangle = \kappa_T (\delta_{ij} - \hat{p}_i \hat{p}_j) g(t_2 - t_1), \quad (3)$$

where  $\hat{p}_i = p_i/|\vec{p}|$ ,  $\kappa_T = \pi\sqrt{\lambda}T^3\gamma^{1/2}$ ,  $\kappa_L = \gamma^2\kappa_T$ , and  $g$  is a function known only numerically.

One may make a back of the envelope estimate for the momentum at which the fluctuations above become important [11], finding  $\gamma \lesssim \gamma_{crit}^{fluc} = \frac{M_Q^2}{4T^2}$ . There is a well-known speed limit for the heavy quark drag setup in which the derivation of Eq. (1) was performed [7, 12]:  $\gamma < \gamma_{crit}^{sl} = (1 + \frac{2M_Q}{\sqrt{\lambda}T})^2 \sim \frac{4M_Q^2}{\lambda T^2}$ . While the second speed limit is parametrically smaller than the first, the finite size of the coupling and mass lead one to conclude that the fluctuations must be taken into account, even at very small momenta (and that the latter speed limit is at extremely large momenta  $\mathcal{O}(100 \text{ GeV})$  for bottom quarks).

The implementation of the fluctuations in Eq. (1) are nontrivial for two reasons: first, the noise is *colored* and second, the fluctuations are *multiplicative*. For small enough momenta, both these issues can be overcome; see [11].

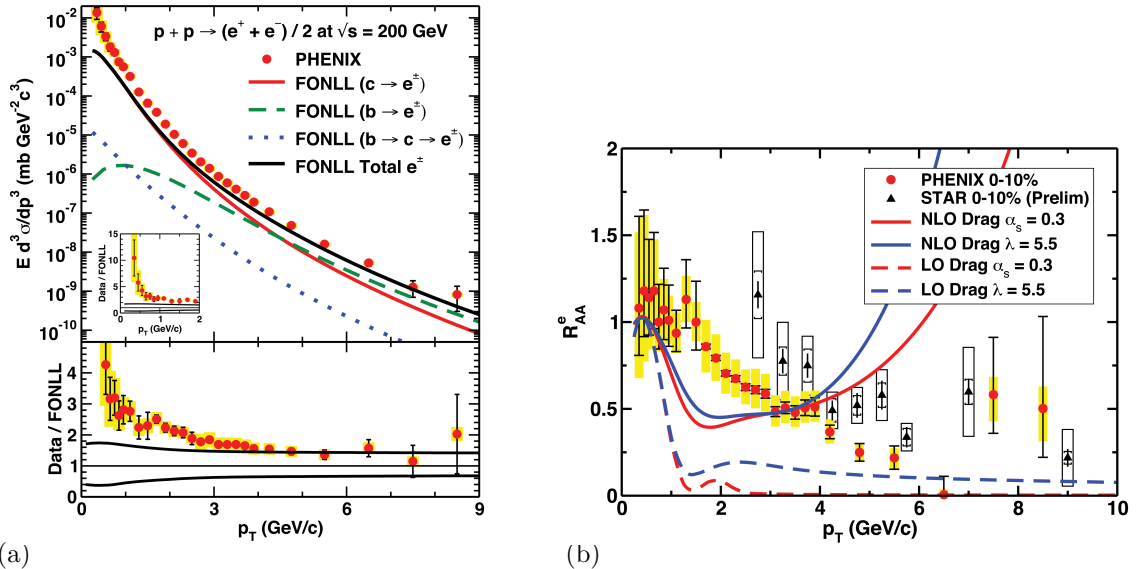


Figure 1: (a) FONLL predictions [13, 14, 15] for the spectrum of electrons from heavy flavor decay at RHIC compared to data from PHENIX [16]. (b) Strong-coupling energy loss predictions at leading (dashed) and next-to-leading order (solid) for two schemes (red, blue) of translating QCD parameters to  $\mathcal{N} = 4$  SYM parameters [11] compared to data from PHENIX [16] and preliminary data from STAR [17].

### 3. Strong-coupling Energy Loss Model Results

In order to compare with data from  $A + A$  collisions, we must first demonstrate that we have the production mechanism in  $p + p$  collisions under control. Fig. 1 (a) compares the spectrum of electrons from the decay of heavy flavor mesons from RHIC and from FONLL [13, 14, 15]. The spectra of open heavy quarks is readily available from an online generator [18], and the FONLL  $D$  and  $B$  meson fragmentation functions are well documented [15]. The decay of the

mesons to electrons in FONLL is not as well documented, and the results of this work [11] as shown in Fig. 1 (a) differ significantly from those shown in [16], with the results presented here diverging much more from the experimental results at low,  $p_T \lesssim 3$  GeV/c. Thus the comparison of electrons from  $A + A$  is restricted from above by the latter speed limit above and from below by the currently inaccurate production/fragmentation function mechanism.

Nevertheless, we show in Fig. 1 (b) the comparison of the strong-coupling energy loss model predictions for electrons from heavy flavor decay to RHIC data [16, 17], and then  $D$  and  $B$  meson suppression to LHC data [19, 20] in Fig. 2. The plots include both the leading and next-to-leading order predictions from AdS/CFT [11]. One of the subtleties involved in comparing the AdS/CFT calculations to data is the map between the parameters ( $\alpha_s$ ,  $N_c$ , and  $T$ ) in QCD and the parameters in  $\mathcal{N} = 4$  SYM. Two schemes for translating between the theories were proposed in [7]; we report the results of both schemes here as an attempt to provide a reasonable exploration of the parameter space. (One would hope that a theory dual to QCD would produce results somewhere between the predictions presented here.) In the range of applicability,  $3 \text{ GeV/c} \lesssim p_T^e \lesssim 4 \text{ GeV/c}$ , the theory and data agree for electron suppression. Similarly, in the range of  $p_T^D \lesssim 10 \text{ GeV/c}$  and for all current  $B$  meson measurements, the theory and data agree. In fact, the fast rise in  $R_{AA}$  for the observables for momenta above the scale set by the speed limit is precisely the sign of the calculation breaking down. A more correct treatment of the above equations would include autocorrelations, which would mitigate some of that spurious rapid rise. Additionally, a derivation of the energy loss that allowed the heavy quark to dynamically slow down (a highly non-trivial calculation) would include the Larmor-like energy loss experienced by accelerating probes in AdS/CFT [21, 22]. It is not yet known how much of a quantitative difference including this additional energy loss channel would make as a function of momentum, but an implementation of this improved energy loss theory would almost certainly compare more favorably with data.

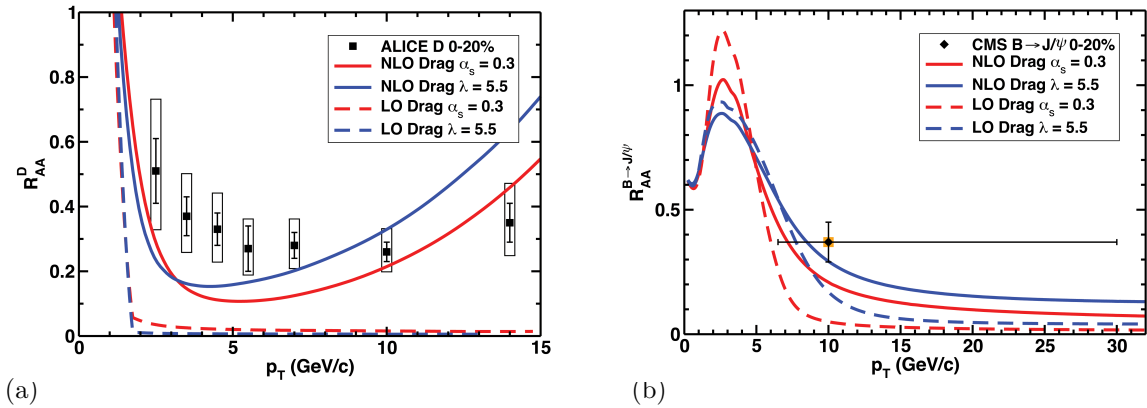


Figure 2:  $R_{AA}(p_T)$  predictions from AdS/CFT at leading (dashed) and next-to-leading (solid) order for two schemes (red, blue) of translating QCD parameters to  $\mathcal{N} = 4$  SYM parameters [11] compared to (a)  $D$  meson data from ALICE [19] and (b) non-prompt  $J/\psi$  mesons compared to data from CMS [20].

In Fig. 3 we show a novel result: the very large difference in predictions for bottom quark to electron  $R_{AA}(p_T)$  from the strong-coupling energy loss model presented here and the WHDG weak-coupling energy loss model [23, 24]. One can readily see that, even with the inclusion of the fluctuations in the strong-coupling energy loss, the AdS/CFT predictions are significantly more suppressed than those from pQCD.

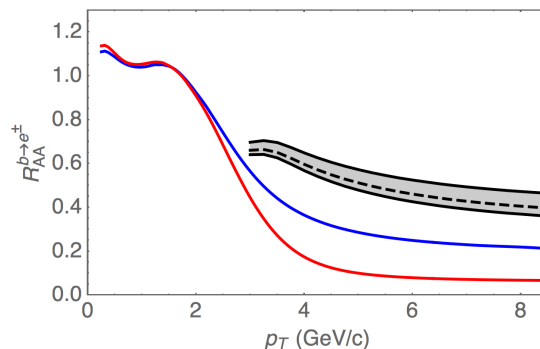


Figure 3:  $R_{AA}^{b \rightarrow e^\pm}(p_T)$  predictions from AdS/CFT at next-to-leading order for two schemes (red, blue) of translating QCD parameters to  $\mathcal{N} = 4$  SYM parameters [11] compared to predictions (black) from the WHDG energy loss model [23, 24] in 0-20% central PbPb collisions at  $\sqrt{s} = 2.76$  ATeV.

#### 4. Conclusions

We showed in these proceedings that a strong-coupling energy loss model including fluctuations can qualitatively describe the heavy flavor data measured at RHIC and LHC. Additionally, we provided a novel, falsifiable prediction for the suppression of electrons from bottom decay at LHC from both the AdS/CFT energy loss model presented here and from the pQCD-based WHDG energy loss model. Future correlations measurements of heavy flavor, such as the decays from  $b\bar{b}$  events, should provide even more insight into the energy loss mechanism at work in QGP.

#### 5. Acknowledgments

The author wishes to thank the South African National Research Foundation and SA-CERN for support.

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