Heavy Quark Energy Loss and Bulk Physics

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Abstract. We show that the low-p_T data and high-p_T data from RHIC and LHC give a contradictory picture of the relevant dynamics of a quark-gluon plasma. While the bulk observables imply a strongly coupled fluid best described by AdS/CFT the rare probes imply a weakly coupled gas best described using thermal pQCD. These conclusions are based on leading order theoretical calculations, and we speculate that more sophisticated calculations that include higher order effects might provide a resolution to the current puzzle.

1. Introduction

The goal of high-energy nuclear physics is the detailed understanding both theoretically and experimentally of the many-body dynamics of QCD. This goal is an immodest one: there are few examples of a detailed theoretical understanding of even many-body QED. However, there are many reasons to be interested in the emergent properties of QCD: the nuclear force is fundamental, the universe was in a state of quark-gluon plasma (QGP) a microsecond after the Big Bang, QCD is the only non-Abelian theory for which we have both experimental and theoretical access to many-particle physics, and it turns out that there appear to be surprising connections between QGP physics and disparate other fields of physics such as cold atoms and high temperature superconductivity.

Experimentalists can measure an enormous number of observables at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) as we attempt to tease out Nature's nuclear secrets. Broadly speaking, two of the most important classes of observables are those that are related to particles that have "low" transverse momentum, $p_T \lesssim 2$ GeV/c, and those that are related to particles with a large scale, such as heavy quarks and/or those with "high" transverse momentum, $p_T \gtrsim 5$ GeV/c.

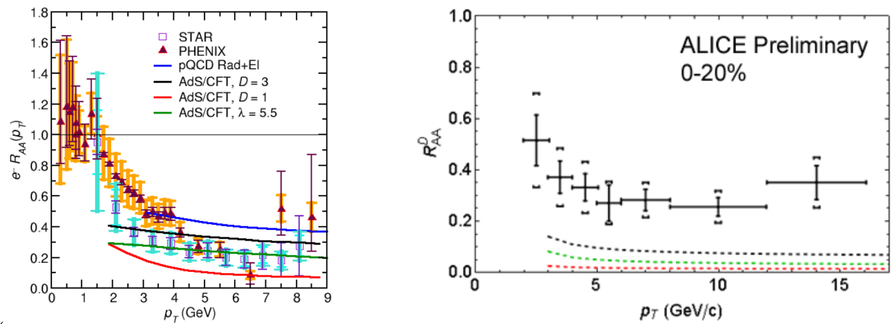
The consensus view of the community is that the low-p_T observables are well understood within a nearly perfect fluid paradigm [1]. Both naïve [2] and sophisticated, next-to-leading order [3] applications of pQCD predict a viscosity much larger than that suggested by the hydrodynamics models. On the other hand, leading order strong coupling calculations utilizing the AdS/CFT correspondence yield predictions within a factor of 2 of the measured QGP η/s [4]. The low-p_T observables thus exclusively suggest that the many-body dynamics of QGP at temperatures accessible at colliders is best understood as a strongly-coupled fluid.

It is natural then to ask: how do predictions of observables related to hard probes based on this strong-coupling paradigm compare to data?

2. Application of AdS/CFT to High-p_T Observables

In answering this question, we will assume that the high momentum particles are strongly coupled to a strongly coupled medium. Assuming all couplings are large corresponds to the not unreasonable assumption that any influence from weak coupling dynamics—from, say, running coupling in QCD—is small compared to those from the strong coupling dynamics.

Within this strong coupling paradigm the leading order calculation of the energy loss for a heavy quark is relatively straightforward [5, 6] and corresponds to a drag, $dp_T/dt = -\mu\, p_T$, $\mu = \pi T^2\sqrt{\lambda}/2M_Q$. We show in Fig. 1 that one may well describe the suppression of non-photonic electrons at RHIC using this energy loss model [7], but not simultaneously the suppression of D mesons at LHC. However this model only takes into account the mean heavy quark energy loss. As is shown in [8], fluctuations in the mean energy loss are large and grow quickly, $\propto \gamma^{5/2}$; we are currently working on quantifying the importance of these fluctuations in energy loss observables.



(a) (b)

Figure 1: (a) AdS/CFT predictions [7] for non-photonic electron decay products of heavy c and b quarks at RHIC [9, 10] and (b) D meson suppression predictions from AdS/CFT [11] at LHC [12].

It is less clear how to apply the AdS/CFT correspondence to the energy loss of light quarks and gluons. Nevertheless, although there are large uncertainties associated with the predictions, it appears that models based on naïve leading order calculations also overpredict the suppression; see Fig. 3 (a) and [13].

3. Appliction of pQCD to High-p_T Observables

On the other hand we may choose to assume that the high-p_T probe is weakly coupled to a weakly coupled QGP. In this scenario, the weak coupling to the plasma might be justified by the presence of a large scale in the problem, such as the quark mass or the transverse momentum of the probe. Assuming the medium is weakly coupled to itself is less justified. If one computes the running coupling at the first Matsubara frequency, then $g(2\pi T) \approx 2$, which is not much less than 1. Nevertheless we find that a comparison of predictions from an energy loss model [14, 15] based on these assumptions does an excellent job of qualitatively describing all single particle observables at both RHIC and LHC to within approximately a factor of 2, Fig. 2. We include here a new, very favorable comparison[1] between the WHDG energy loss model [14, 15] and the recent $R_{AA}^{B\to J/\psi}(N_{part})$ results from CMS [16].

It is worth emphasizing that the WHDG energy loss model includes both radiative and elastic energy loss, but is based on only the leading order in α_s contributions to these channels. The uncertainty estimates shown in Fig. 2 are due only to the rigorous extraction of the proportionality constant that we assume connects the thermalized QGP medium density and

[1] We wish to thank Zaida Conesa Del Valle and Andrea Dainese for fragmenting our B meson predictions to J/ψ mesons for the comparison with the CMS results.

the observed multiplicity [17]; we do not include theoretical uncertainty estimates for higher order effects. In particular, running coupling effects are very likely important, possibly leading to a more quantitative agreement with data [18]. The inclusion of running coupling and higher order corrections in collinearity, softness, and eikonality, also clearly very important [19, 20], are current works in progress.

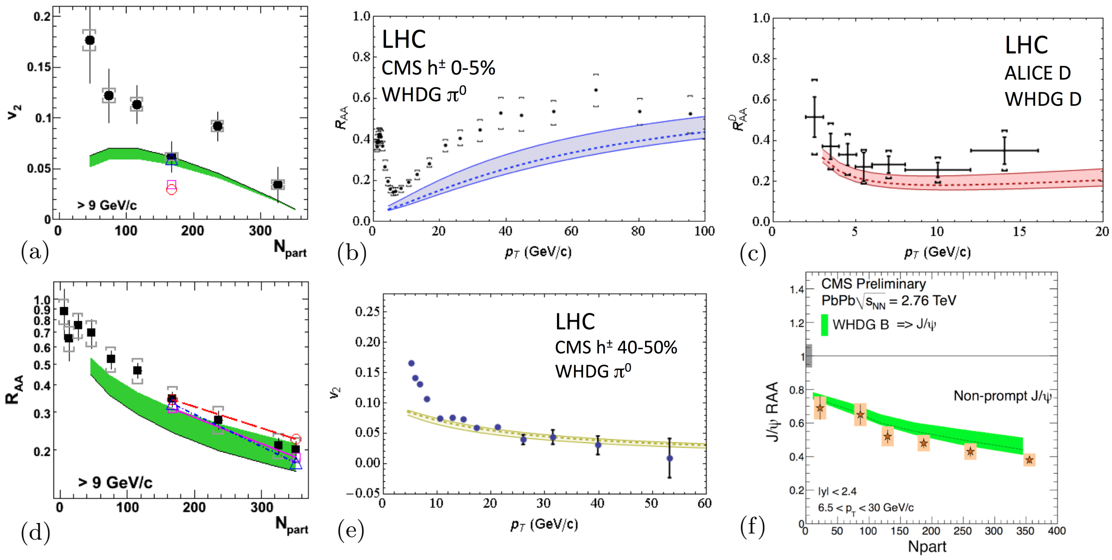


Figure 2: Constrained zero parameter WHDG predictions compared to data for (a) $v_2^{\pi^0}(N_{part})$ at RHIC [14, 21], (b) 0-5% centrality $R_{AA}(p_T)$ for light flavors at LHC [15, 22], (c) $R_{AA}^D(p_T)$ at 0-20% centrality at LHC [12, 13], (d) $R_{AA}^{\pi^0}(N_{part})$ at RHIC [14, 21], (e) $v_2(p_T)$ at LHC for light flavors at 40-50% centrality [13, 23], and (f) $R_{AA}^{B\to J\psi}(N_{part})$ at LHC [11, 16].

4. Towards a Hybrid AdS/CFT and pQCD Model

One would very much like to reduce the very large theoretical uncertainties associated with light flavor strong coupling energy loss, as shown, for example, in Fig. 3 (a). A better comparison between the light flavor energy loss and data might come from a calculation of the energy-momentum tensor associated with the high-p_T probe. There is an additional reason for investigating the energy-momentum tensor of probes in AdS/CFT: we show in Fig. 3 (b) the surprising sensitivity to the stopping distance on the off-shellness of the initial conditions of the high-p_T probe. One might hope to create a hybrid energy loss model that better approximates the relevant physics in a heavy ion collision by matching the results from pQCD from time $t = 0$ up to some finite time such as t_{therm} to a subsequent evolution using AdS/CFT methods. Matching the calculations in AdS/CFT and pQCD requires computing a gauge invariant observable in both regimes; the energy-momentum tensor seems a natural choice.

5. Conclusions

The inclusion of higher order corrections are necessary for a quantitative extraction of QGP properties within the paradigm of pQCD energy loss. However, it is important to recognize that this pQCD paradigm, which is shown here to be very successful in qualitatively describing the features of energy loss observables at RHIC and LHC, is in contradiction to the strong coupling paradigm implied by data associated with low-p_T observables. Naïve leading order applications of AdS/CFT techniques to energy loss observables leads to an oversuppression compared to

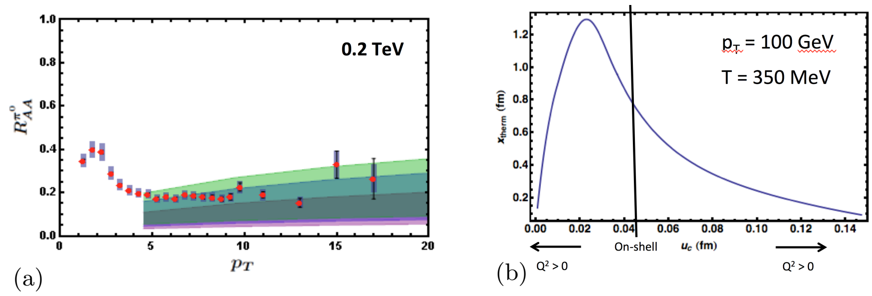


Figure 3: (a) Predictions from a simple Bragg peak model for AdS/CFT light flavor energy loss [13] compared to PHENIX data at RHIC [21]. (b) The stopping distance in AdS/CFT for light flavors depends strongly on the initial conditions.

data. Perhaps the success of the perturbative calculations is mainly due to a relatively correct description of the very early time physics. Then possibly a hybrid model in which 1) fluctuations in the AdS/CFT energy loss are included and 2) there is a better understanding of AdS/CFT initial conditions and light flavor energy loss will lead to a consistent description of high-p_T data within the AdS/CFT paradigm, and, therefore, we will have a consistent picture of the dynamics of QGP in heavy ion collisions.

References

[1] Heinz U, Shen C and Song H 2012 *AIP Conf.Proc.* **1441** 766–770 (*Preprint* 1108.5323)

[2] Danielewicz P and Gyulassy M 1985 *Phys.Rev.* **D31** 53–62

[3] Chen J W, Deng J, Dong H and Wang Q 2013 *Phys.Rev.* **C87** 024910 (*Preprint* 1107.0522)

[4] Kovtun P, Son D and Starinets A 2005 *Phys.Rev.Lett.* **94** 111601

[5] Gubser S S 2006 *Phys.Rev.* **D74** 126005 (*Preprint* hep-th/0605182)

[6] Herzog C, Karch A, Kovtun P, Kozcaz C and Yaffe L 2006 *JHEP* **0607** 013

[7] Horowitz W and Gyulassy M 2008 *Phys.Lett.* **B666** 320–323 (*Preprint* 0706.2336)

[8] Gubser S S 2008 *Nucl.Phys.* **B790** 175–199 (*Preprint* hep-th/0612143)

[9] Dion A (PHENIX collaboration) 2009 *Nucl.Phys.* **A830** 765C–768C (*Preprint* 0907.4749)

[10] Bielcik J (STAR Collaboration) 2006 *Nucl.Phys.* **A774** 697–700

[11] Horowitz W 2012 *AIP Conf.Proc.* **1441** 889–891 (*Preprint* 1108.5876)

[12] ALICE Collaboration 2012 *JHEP* **09** 112 (*Preprint* 1203.2160)

[13] Horowitz W and Gyulassy M 2011 *J.Phys.* **G38** 124114 (*Preprint* 1107.2136)

[14] Wicks S, Horowitz W, Djordjevic M and Gyulassy M 2007 *Nucl.Phys.* **A784** 426–442

[15] Horowitz W and Gyulassy M 2011 *Nucl.Phys.* **A872** 265–285 (*Preprint* 1104.4958)

[16] Mironov C (CMS Collaboration) 2013 *Nucl.Phys.* **A904-905** 194c–201c

[17] Adare A *et al.* (PHENIX Collaboration) 2008 *Phys.Rev.* **C77** 064907 (*Preprint* 0801.1665)

[18] Buzzatti A and Gyulassy M 2013 *Nucl.Phys.A904-905* **2013** 779c–782c

[19] Horowitz W 2008 (*Preprint* 0806.3092)

[20] Horowitz W and Cole B 2010 *Phys.Rev.* **C81** 024909 (*Preprint* 0910.1823)

[21] Adare A *et al.* (PHENIX) 2010 *Phys. Rev. Lett.* **105** 142301 (*Preprint* 1006.3740)

[22] Chatrchyan S *et al.* (CMS) 2012 *Eur. Phys. J.* **C72** 1945 (*Preprint* 1202.2554)

[23] Chatrchyan S *et al.* (CMS Collaboration) 2012 *Phys.Rev.Lett.* **109** 022301