Properties of the quark-gluon plasma observed at RHIC and LHC

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Abstract. Puzzles and discoveries abound in the results from the Relativistic Heavy Ion Collider (RHIC) and from the relativistic heavy ion collisions at the Large Hadron Collider (LHC) including what seems to be the creation of the world's most perfect fluid and the stunning disappearance of large momentum particles into a dense, opaque quark-gluon plasma (QGP). Surprisingly, the methods of string theory appear to provide a better description of the QGP for observables associated with lower momentum particles while the completely opposite approach with an application of perturbative quantum chromodynamics (pQCD) works best for particles at the highest momenta. We discuss work attempting to bridge the divide between these two opposing descriptions of the properties of the QGP, the state of the universe a microsecond after the Big Bang.

1. Introduction

The great difficulty currently facing heavy ion physics is the apparent contradiction between the interpretation of low-p_T and high-p_T observables. A consensus has formed in which the distribution of low momentum particles is the result of rapid thermalization followed by nearly ideal hydrodynamic evolution. The best explanation of the early onset of thermalization [1] and nearly ideal fluid flow [2] is the existence of a strongly-coupled fluid best described by the methods of the AdS/CFT correspondence. On the other hand, naive application of the AdS/CFT correspondence to high-p_T probes yield results in contradiction with data. At the same time leading order pQCD predictions predicated on a weakly-coupled plasma weakly coupled to a high momentum probe [3] systematically describe the high-p_T data within a factor of 2 [4]; higher order correction seem likely to lead to an even better description of data [5]. Leading order [6] and sophisticated next-to-leading order [7] calculations based on the same weak-coupling perturbative picture of the plasma, though, yield a thermalization time and a viscosity to entropy ratio an order of magnitude larger than suggested by data. A hybrid strong-weak approach might reconcile these two pictures.

2. Energy Loss in AdS/CFT

2.1. Heavy Quarks

The now well-known leading order analytic energy loss formula for heavy quarks strongly-coupled to a strongly-coupled $\mathcal{N} = 4$ SYM plasma is

$$\frac{dp}{dt} = -\mu\, p, \text{ where } \mu = \frac{\pi\sqrt{\lambda}T^2}{2M_q}. \tag{1}$$

$\lambda = g^2 N_c$ is the 't Hooft coupling for the theory, T is the temperature of the plasma, and M_q is the mass of the heavy quark [8, 9]. The form of this energy loss is very different from that found assuming a probe weakly coupled to a weakly-coupled plasma: incoherent Bethe-Heitler bremsstrahlung energy loss [10] goes as

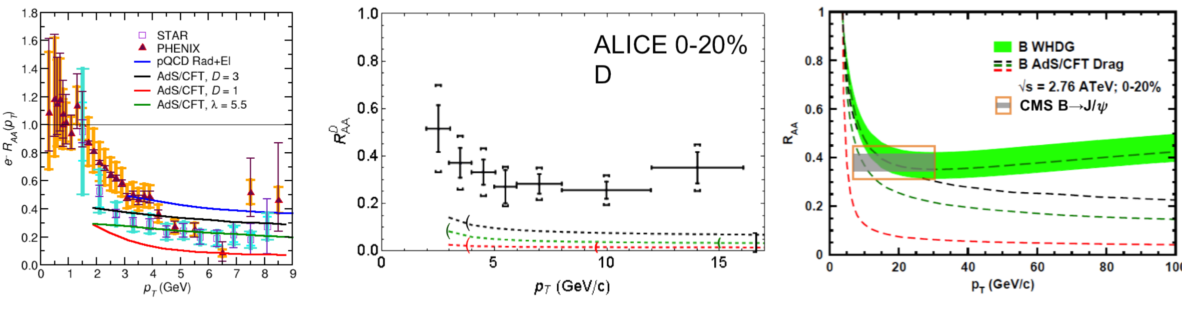
$$\left.\frac{dp}{dt}\right|_{BH} \sim -\frac{T^3}{M_q^2}\, p, \tag{2}$$

but the radiative energy loss in the deep-LPM regime is

$$\left.\frac{dp}{dt}\right|_{LPM} \sim -L\, T^3 \log(p/M_q), \tag{3}$$

where L is the length of the medium through which the heavy quark has passed [11].

Now $\mathcal{N} = 4$ SYM in the $N_c \to \infty$ and λ large and fixed limit is not QCD. However one hopes that the results from AdS/CFT can provide some useful insight into QCD processes. One of the complications of the dissimilarity of the two theories is that there is not a unique, reasonable mapping of the parameters in QCD to those in AdS/CFT. Using a set of these reasonable mappings, one finds a good description of the suppression of heavy quark decay fragments seen by RHIC experiments; see figure 1 (a). (A more detailed description of the model and parameters used to compute the figure can be found in [12].)



(a) (b) (c)

Figure 1: (a) AdS/CFT (and pQCD) predictions [12] for non-photonic electron decay products of heavy c and b quarks at RHIC [13, 14] and (b) D meson and (c) B meson suppression predictions from AdS/CFT [15] at LHC [16, 17]

Using this exact same set of mappings one may make predictions for D and B meson suppression at LHC, shown in figure 1 (b) and (c). As seen in (c), given the current uncertainties in the theoretical predictions and experimental measurements, the B meson predictions are consistent with data. The D mesons, however, as shown in (b), are falsifiably oversuppressed compared to ALICE data.

Previous calculations [12] included estimates of a "speed limit" for the applicability of the heavy quark drag calculations. Several independent lines of reasoning [18, 19] imply that the formalism does not apply to heavy quarks propagating faster than

$$\gamma \lesssim \gamma_{critical} = \left(1 + \frac{2M_q}{\sqrt{\lambda}T}\right)^2 \sim \frac{4M_q^2}{\lambda T^2}. \tag{4}$$

This speed limit is parametrically smaller than an estimate for the momenta at which the fluctuations in momentum loss become important [18],

$$\gamma_{fluc} \sim \frac{M_q^2}{4T^2}; \tag{5}$$

however, it turns out that numerically this latter speed limit is reached first. Efforts are underway to quantify the importance of momentum fluctuations in the suppression of high momentum heavy quarks.

2.2. Light Flavors

A critical test of any energy loss formalism is a simultaneous description of both heavy and light flavor suppression. The original calculations of light flavor energy loss require difficult numerics as the endpoints of the string are allowed to dynamically fall in the 5th dimension [20]. More recent work using an alternative setup yields a simple analytic solution [21]. However, it is not yet entirely clear what is the most appropriate setup in the AdS space to model light flavor energy loss. In the following, we will attempt to infer the physical consequences of the original light flavor energy loss calculation.

One of the first observations of the original setup was a generic Bragg peak in the energy loss such that the maximum stopping distance scaled as

$$\Delta x_{max} \sim \left(\frac{E}{\sqrt{\lambda}T}\right)^{1/3} \frac{1}{T}. \tag{6}$$

One can create a very naive energy loss model based on this maximum stopping distance [22]: assume that any light flavor created with $L < x_{max}$ gets out of the plasma unaltered while flavors created with $L > x_{max}$ are completely absorbed. There are large uncertainties in this model; in addition to the usual unknown mapping from QCD to AdS/CFT, one also does not know which single value of T to plug into Eq. (6). A maximal uncertainty band can be created by taking two extreme values for T: 1) the temperature at the point of creation at the moment of thermalization or 2) the transition temperature between the deconfined and confined phases of QCD matter. The predictions resulting from these two extremes are shown as a band in figure 2 () and (); the data at RHIC and LHC fall within the very large theoretical uncertainties.

Since the most naive calculation is not obviously falsified by the data, it is worth pursuing a more precise theoretical model. Preliminary investigations [25] show that results depend very sensitively on the "jet" prescription chosen, to the extent that one can even make the Bragg peak in the energy loss appear and disappear. Additional, large sensitivity comes from the precise initial string profile propagated from early times in the collision; see figure 2 (). It turns out that very little of the $2 \times \infty$ dimensions of the space of initial conditions has been explored. We will return to these issues later in this proceedings.

3. pQCD Energy Loss

One may also choose to determine the consequences of alternative picture of a weakly-coupled plasma weakly coupled to a high momentum probe. Jacksonian intuition suggests that at the

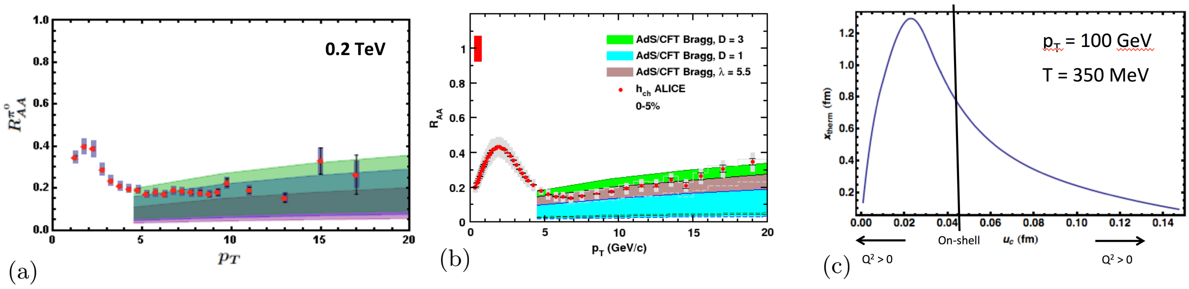


Figure 2: Predictions from a simple Bragg peak model for AdS/CFT light flavor energy loss [22] compared () to PHENIX data at RHIC [23] and () ALICE data at LHC [24]. () The stopping distance in AdS/CFT for light flavors depends strongly on the initial conditions.

GeV scale radiative energy loss dominates over collisional. However detailed calculations [26] show that the elastic energy loss is of the same order of magnitude as inelastic at the energy regimes applicable at RHIC and LHC; see figure 3. The PHENIX collaboration performed

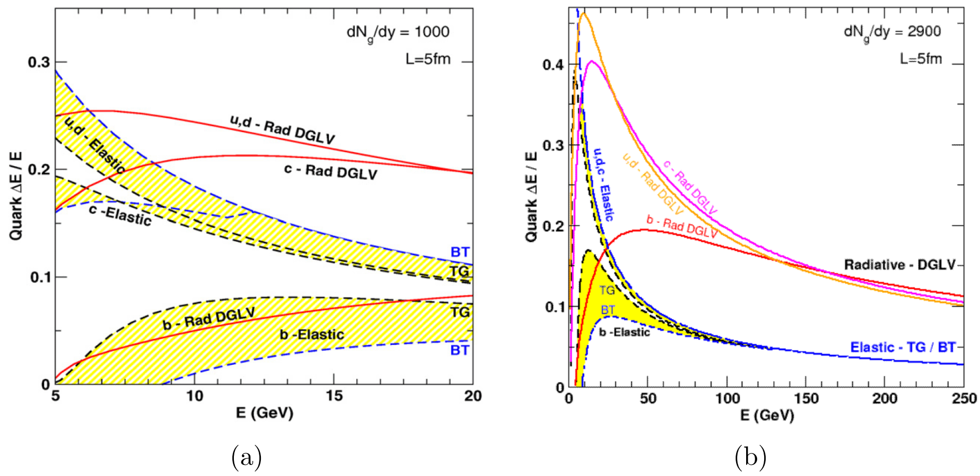


Figure 3: Comparison of magnitude of radiative and collisional energy loss in pQCD for (**??**) RHIC and (b) LHC [26]. Due to the LPM effect, elastic energy loss is the same order of magnitude as inelastic for all particle energies.

[27] a rigorous statistical analysis of the WHDG energy loss model [3] that incorporates both radiative and collisional energy loss in a reasonable geometric background that extracted the one free parameter in the calculation: the proportionality constant between the participant density and the number density of the color deconfined medium produced in heavy ion collisions. The value found by PHENIX corresponds to a central gluon rapidity density of $dN_g/dy = 1400^{+200}_{-375}$. Keeping the proportionality constant fixed, varying the medium density at different centralities and center of mass energies only by the measured multiplicities, the model robustly describes qualitatively a wealth of high-p_T observables; see figure 4, in which the theoretical uncertainty band is due only to the 1-σ range of values from the PHENIX proportionality constant extraction.

There are a very large number of sources of theoretical uncertainty not shown in the results above. Some of these sources of uncertainty include higher order contributions in: coupling α_s; collinearity, or k_T/xE, where k_T is the radiated gluon's perpendicular momentum, and

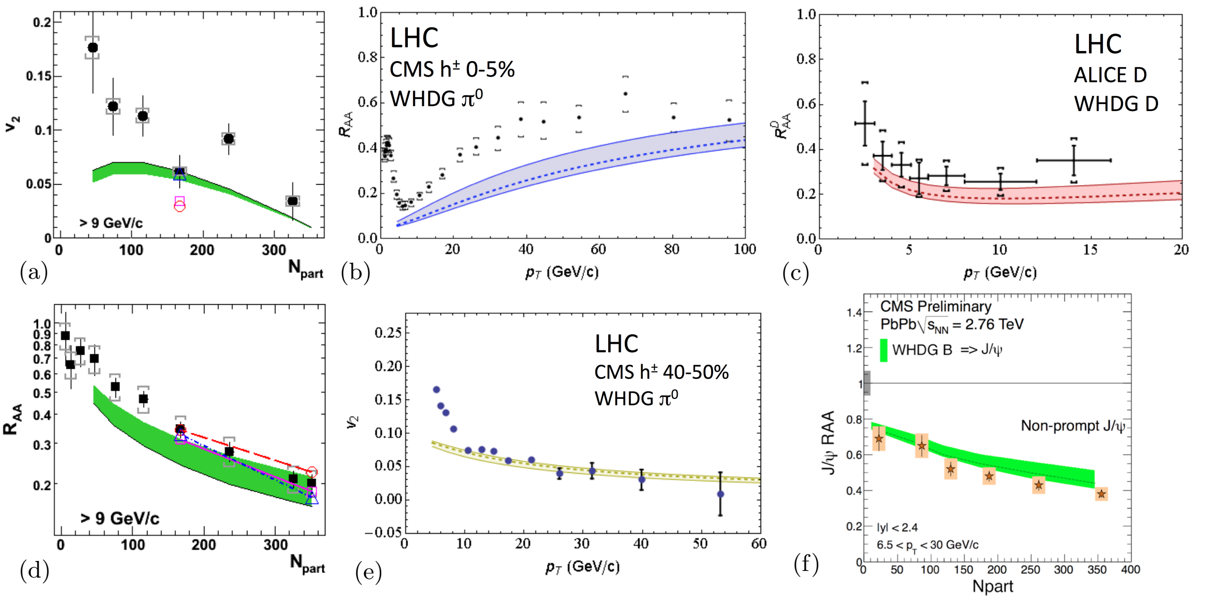


Figure 4: Constrained zero parameter WHDG predictions compared to data for (a) $v_2^{\pi^0}(N_{part})$ at RHIC [23, 3], (b) 0-5% centrality $R_{AA}(p_T)$ for light flavors at LHC [28, 29], (c) $R_{AA}^{D}(p_T)$ at 0-20% centrality at LHC [16, 22], (d) $R_{AA}^{\pi^0}(N_{part})$ at RHIC [23, 3], (e) $v_2(p_T)$ at LHC for light flavors at 40-50% centrality [30, 22], and (f) $R_{AA}^{B\to J\psi}(N_{part})$ at LHC [31, 15].

xE is the fraction of the leading parton's initial energy carried away by the emitted gluon; softness, x; quark mass to energy of the leading heavy quark, M_q/E; and opacity, the ratio of the mean free path to the pathlength, λ_{mfp}/L. An early attempt [32] to estimate the sensitivity of the calculation to higher order contributions in α_s varied the value of α_s from 0.2 to 0.4 and found a strong dependence of the suppression on the value of α_s chosen, not surprisingly as $dp/dt_{coll} \sim \alpha_s^2$ and $dp/dt_{rad} \sim \alpha_s^3$, although the amount of dependence absorbed by reevaluating the proportionality constant as α_s was varied was never explored. More recent work with a running coupling ansatz found in fact a better agreement with pion suppression as a function of p_T than the fixed coupling calculation [5]. Others showed that [33] pQCD calculations rather significantly violate the assumption of collinearity at RHIC and LHC energies and are very sensitive to the treatment of wide angle radiation. Predictions appear stable, i.e. not sensitive, once the proportionality constant is fixed for a given prescription for the treatment of the wide angle radiation [29]. However the inferred properties of the medium depend on the proportionality constant, which may vary by a factor of 3 due to the uncertainty in the treatment of wide angle radiation [33]; quantitative information regarding the medium therefore requires a detailed understanding of the higher order corrections in collinearity.

4. Discussion and Conclusions

How can we move forward to resolve the seeming contradiction between the weakly- and strongly-coupled pictures? How can we narrow down the theoretical uncertainties due to 1) the jet definition prescription and 2) the initial conditions in AdS space setup? We hope to address both of these issues simultaneously with a hybrid weak-strong energy loss model. Perhaps the early energy loss evolution is dominated by weak-coupling physics but later evolution, as the medium cools, is dominated by strong-coupling physics. We are in the process of creating a model that interfaces these two regimes by matching the finite time energy-momentum tensor of a high momentum colored object created in a heavy ion collision as calculated in pQCD to that calculated in AdS/CFT.

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