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Heavy quark jet tomography of Pb + Pb at LHC: AdS/CFT drag or pQCD energy loss?

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ABSTRACT

We propose that the measurement of the transverse momentum dependence of the double ratio of the nuclear modification factors of charm and bottom jets, $R^c_{AA}(p_T)/R^b_{AA}(p_T)$, in central nuclear collisions at the LHC will provide an especially robust observable that can be used to differentiate Standard Model perturbative QCD predictions from recently proposed strong coupling string drag models derived using the AdS/CFT conjecture.

1. Introduction

Recent discoveries at RHIC [1–3] have led to suggestions [4] that the properties of strongly coupled quark gluon plasmas (sQGP) produced in ultra-relativistic nuclear collisions may be better approximated by string theoretic models inspired by the AdS/CFT gravity-gauge theory correspondence [5] than conventional Standard Model perturbative QCD (pQCD). Four main classes of observables have attracted the most attention: (1) Entropy production as probed by multiplicity distributions [6], (2) "Perfect" Fluidity [3] as probed by collective elliptic flow measurements [7–9], (3) Jet Quenching and Tomography as probed by high-p_T hadrons [10,11] and nonphotonic leptons [12,13], and (4) Dijet–Bulk Correlations as probed by two and three particle correlations [14,15].

Qualitative successes of recent AdS/CFT applications [4] to nuclear collision phenomenology include the analytic account for (1) the surprisingly small ($\sim 3/4$) drop [16] of the entropy density in lattice QCD calculations relative to Stefan–Boltzmann, (2) the order of magnitude reduction of the viscosity to entropy ratio η/s predicted relative to pQCD needed to explain the seemingly near perfect fluid flow of the sQGP observed at RHIC, (3) the unexpected large stopping power of high transverse momenta heavy quarks as inferred from heavy quark jet quenching and elliptic flow, and (4) the possible occurrence of conical "Mach" wave-like correlations of hadrons associated with tagged jets.

While quantitative and systematic comparisons of AdS/CFT gravity dual models with nuclear collision data are still incomplete and while the conjectured *double* Type IIB string theory ↔ conformal Supersymmetric Yang–Mills (SYM) gauge theory ↔ nonconformal, non-supersymmetric QCD correspondence remains under debate (see, e.g., [17]), the current successes provide strong motivation to seek more sensitive experimental tests that could help guide the theoretical development of novel theoretical approaches that may be needed to explain recent RHIC and soon LHC heavy ion data.

The aim of this Letter is twofold. First is to propose a robust observable that can more readily reveal the kinematic boundaries and reaction conditions where specific Standard Model weak cou-

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pling pQCD approximations may fail and where specific strong coupling AdS/CFT approximations may fail (or if they are applicable at all). Asymptotic freedom and the factorization theorems of QCD ensure that pQCD should apply above some hard scale $Q(A, \sqrt{s})$ that depends in general on both atomic number, A, and center of mass energy, $\sqrt{s}$. For jet production this scale is the greater of the gluon saturation scale $Q_s^2 \sim Q_0^2 \log(A\sqrt{s}/p_T)$, that defines a scale below which strong *initial state* nuclear modification of the parton distributions must be taken into account, and $\hat{q}L \equiv \int dz\, d\sigma\, \rho(z) q^2 \propto Q_s^2 \log^n(Q_s)$, below which strong *final state* nuclear modifications must be taken into account. For finite $A < 238$ and finite $\sqrt{s} < 10A$ TeV the numerical values of these scales remains uncertain. Second is to suggest this observable will discriminate between current pQCD and AdS/CFT dynamical models.

We start with the predicted nuclear modification factor, $R^Q_{AA}(p_T)$, of the transverse momentum distribution of identified heavy quark jets produced in central Pb + Pb reactions at 5.5A TeV at LHC. Specifically, we propose that the double ratio of identified charm and bottom jet nuclear modification factors R^c_{AA}/R^b_{AA} is a remarkably robust observable that can distinguish between a wide class of pQCD energy loss mechanisms and a recently proposed class of gravity "drag" models [18–22] of heavy quark dynamics. Similar tests can be performed at RHIC when identified jet flavor detector upgrades are completed [23]. The main advantage of LHC in comparison to RHIC is of course the much higher p_T kinematical range that will be accessible. The main advantage of RHIC is a better control of the initial state saturation physics because of extensive $d + A$ and $p + p$ control data at the same $\sqrt{s}$.

The current failure of pQCD based energy loss models [24–27] to account *quantitatively* for the recent RHIC data from STAR [12] and PHENIX [13] on the nonphotonic electron spectrum provides additional motivation to focus on heavy quark jet observables. Unlike for light quark and gluon jet observables, where pQCD predictions were found to be remarkably quantitative [11], heavy quark jet quenching, especially as inferred indirectly for bottom quarks, appears to be significantly underpredicted [24–27]. Current issues that cloud the pQCD based energy loss predictions are (1) the uncertainty in the initial state nuclear production of bottom to charm quarks, (2) the current controversy over the relative magnitude of elastic versus radiative loss channels [26,27], and (3) the possibility that short formation time nonperturbative hadronization effects may have to be taken into account [28,29].

The AdS/CFT correspondence has so far been applied to heavy ion jet physics in three ways. The first involves the calculation of the QCD Wilson line correlator that corresponds to the radiative transport coefficient $\hat{q}$ [30,31]. The second concentrates on estimating the heavy quark diffusion coefficient D [32] that is an input to a Langevin model of drag [33]. The third is a prediction of the heavy quark drag coefficient based on the gravity dual dynamics of a classical string in an AdS black brane background [19–21]. All three approaches remain under active debate (see, e.g., [21,34,35]).

We focus in this Letter on the third proposed AdS/CFT application that involves the most direct string theoretic inspired gravity "realization" of heavy quark dynamics [18–20]. A heavy quark in the fundamental representation is a bent Nambu–Goto string with one end attached to a probe brane and that trails back above the horizon of a D3 black brane representing the uniform strongly coupled SYM plasma heat bath. This geometry maps the drag force problem into a modern string theoretic version of the 1696 Brachistochrone problem and yields a remarkable, simple analytic solution for the string shape and momentum loss per unit time.

2. AdS/CFT compared to pQCD

Exploiting the AdS/CFT correspondence, the drag coefficient for a massive quark moving through a strongly-coupled SYM plasma in the $\lambda = g^2_{\text{SYM}} N_c \gg 1$, $N_c \gg 1$, $M_Q \gg T^*$ limit is given in [19–21] as

$$\frac{dp_T}{dt} = -\mu_Q\, p_T = -\frac{\pi\sqrt{\lambda}(T^*)^2}{2M_Q} p_T, \tag{1}$$

where T^* is the temperature of the SYM plasma as fixed by the Hawking temperature of the dual D3 black brane.

There exists a maximum momentum, or $\gamma_c \approx p_T^{\text{crit}}/M_Q$ beyond which Eq. (1) cannot be applied. Self consistency within the classical string picture requires a time-like boundary for the string worldsheet [21]. For constant velocity this limits heavy quark "speeds" to $\gamma < \gamma_c$, where

$$\gamma_c = \left(1 + \frac{2M}{\sqrt{\lambda}T^*}\right)^2 \approx \frac{4M^2}{\lambda(T^*)^2}. \tag{2}$$

The work of [19] relaxed the assumptions of infinite quark mass and constant velocity. The analytic form of Eq. (1) was found to well reproduce the full numerical results (most importantly μ_Q remained independent of p_T) but with M_Q no longer the bare quark rest mass. It is not clear how (2) is altered by propagation nonconstant in velocity. All the calculations in this Letter were based upon the infinite bare mass approximation of [20,21] with M_Q replaced with realistic quark masses.

While in the infinitely strongly coupled plasma dual the quasiparticle picture is not applicable, a similar "speed limit" arises for ordinary incoherent Bethe–Heitler (BH) radiative energy loss. Landau–Pomeranchuck coherence effects invalidate the linear in $E \approx p_T$ rise of the energy loss when the formation time, $\tau_E \sim E/M^2$, exceeds the mean free path, $\bar{\lambda} = 1/\rho\sigma \sim 1/\alpha_s T$ (in a Debye-screened ultrarelativistic plasma). The requirement that $\tau_E < \bar{\lambda}$ therefore limits the applicability of BH to $\gamma < \gamma_c^{\text{BH}} = M_Q/\alpha_s T$, similar to the AdS/CFT speed limit, Eq. (2), but with one less power of T^*/M_Q.

To get a sense of the p_T scale where the AdS/CFT approximation could break down, we will plot the momentum cutoffs from Eq. (2) for different SYM input parameters with two different assumptions for the mapping of QCD to AdS/CFT parameters, described in detail below. There is still additional ambiguity in the γ_c due to the time evolution of the QGP temperature. The smallest γ_c corresponds to the largest temperature; we take as the generous lower bound the extreme $T(\vec{x} = \vec{0}; \tau = \tau_0)$, shown as a '(' in the figures. For the largest γ_c we use T_c, show as a "]". To further emphasize the possibility of corrections in the drag model we gradually fade the curves from the "(" to the "]". Surprisingly the introduction of a thermal plasma in AdS/CFT results in an effective mass *smaller* than the bare mass; this will result in a reduction of the momentum reach of the drag formalism.

Applying Eq. (1) to LHC requires an additional assumption about how to map QCD temperature and coupling to the gedanken SYM world and its SUGRA dual. The "obvious" first prescription [36] takes $g_{\text{SYM}} = g_s$ constant, $T^* = T^{\text{QCD}}$, and $N_c = 3$. However it was suggested in [36] that a more physical "alternative" might be to equate energy densities, giving $T^* \simeq T^{\text{QCD}}/3^{1/4}$, and to fit the coupling $\lambda = g^2_{\text{SYM}} N_c \approx 5.5$ in order to reproduce the static quark–antiquark forces calculated via lattice QCD.

The string theoretic result for the diffusion coefficient used in the Langevin model is $D = 2/\sqrt{\lambda}\pi T^*$ [32]. This illustrates well the problem of connecting the T^* and λ of SYM to "our" QCD world. Using the "obvious" prescription with $\alpha_s = 0.3$, $N_c = 3$, one finds $D \sim 1.2/2\pi T$. However, $D = 3/2\pi T$ was claimed in [13,32] to fit PHENIX data somewhat better. Note that $D = 3/2\pi T$ requires an unnaturally small $\alpha_s \sim 0.05$ that is very far from the assumed $\lambda \gg 1$ 't Hooft limit.

We proceed by computing the nuclear modification factors, neglecting initial state shadowing or saturation effects. In order to correctly deconvolute such effects from the final state effects that we find below, it will be necessary to measure nuclear modification factors in $p + A$ as a function of (y, p_T) at LHC just as $d + A$ was the critical control experiment [1] at RHIC [2].

Final state suppression of high-p_T jets due to a fractional energy loss ϵ, $p_T^f = (1-\epsilon)p_T^i$, can be computed knowing the Q-flavor dependent spectral indices $n_Q + 1 = -\frac{d}{d\log p_T}\log(\frac{d\sigma_Q}{dy\,dp_T})$ from pQCD or directly from $p+p \to Q + X$ data. The nuclear modification factor is then $R_{AA}^Q(p_T) = \langle (1-\epsilon)^{n_Q}\rangle$, where the average is over the distribution $P(\epsilon; M_Q, p_T, \ell)$ that depends in general on the quark mass, p_T, and the path length ℓ of the jet through the sQGP. As in [26] we find n_Q from FONLL production cross sections [37], and we average over jets produced according to the binary distribution geometry and compute ℓ through a participant transverse density distribution taking into account the nuclear diffuseness. Given dN_g/dy of produced gluons, the temperature is found assuming isentropic Bjorken 1D Hubble flow. As emphasized in [26], detailed geometric path length averaging plays a crucial role in allowing consistency between π^0, η and heavy quark quenching in pQCD.

For AdS/CFT drag, Eq. (1) gives the average fractional energy loss as $\bar{\epsilon} = 1 - \exp(-\mu_Q \ell)$. Energy loss is assumed to start at thermalization, $\tau_0 \sim 0.6$–1.0 fm/c, and stops when the confinement temperature, $T_c \sim 160$ MeV, is reached. The exponentiated T^2 dependence in μ_Q leads to a significant sensitivity to the opacity of the medium, as well as to τ_0 and T_c.

To understand the generic qualitative features of our numerical results it is instructive to consider the simplest case of a geometric path average over a static, finite, uniform plasma of thickness L; then

$$R_{AA}^Q(p_T) = \frac{1 - e^{n_Q \mu_Q L}}{n_Q \mu_Q L} \approx \frac{1}{n_Q \mu_Q L}, \tag{3}$$

where the p_T dependence is carried entirely by the spectral index $n_Q(p_T)$.

Two implementations of pQCD energy loss are used in this Letter. The first is the full WHDG model convolving fluctuating elastic and inelastic loss with fluctuating path geometry [26]. The second restricts WHDG to include only radiative loss in order to facilitate comparison to [31]. Note that when realistic nuclear geometries with Bjorken expansion are used, the "fragility" of R_{AA} for large $\hat{q}$ reported in [38] is absent in both implementations of WHDG.

Unlike the AdS/CFT dynamics, pQCD predicts [24–26] that the average energy loss fraction in a static uniform plasma is approximately $\bar{\epsilon} \approx \kappa L^2 \hat{q} \log(p_T/M_Q)/p_T$, with κ a proportionality constant and $\hat{q} = \mu_D^2/\lambda_g$. The most important feature in pQCD relative to AdS/CFT is that $\bar{\epsilon}_{\text{pQCD}} \to 0$ asymptotically at high-p_T while $\bar{\epsilon}_{\text{AdS}}$ remains constant. $n_Q(p_T)$ is a slowly increasing function of momentum; thus R_{AA}^{pQCD} increases with p_T whereas R_{AA}^{AdS} decreases. This generic difference can be observed in Fig. 1, which shows representative predictions from the full numerical calculations of charm and bottom $R_{AA}(p_T)$ at LHC.

3. Double ratio of charm to bottom R_{AA}^Q

A disadvantage of the $R_{AA}^Q(p_T)$ observable alone is that its normalization and slow p_T dependence can be fit with different model assumptions compensated by using very different medium parameters. In particular, high value extrapolations of the $\hat{q}$ parameter proposed in [27] could simulate the flat p_T-independent prediction from AdS/CFT.

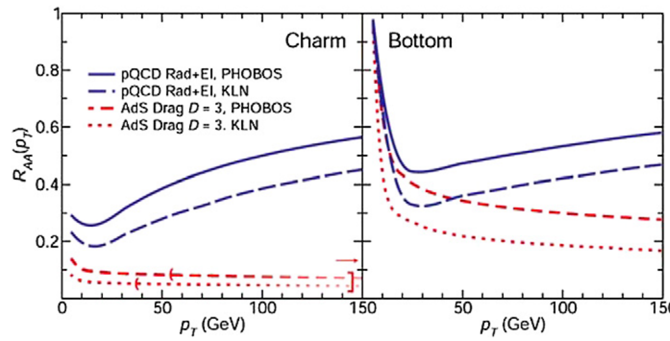

Fig. 1. (Color online.) $R_{AA}^c(p_T)$ and $R_{AA}^b(p_T)$ predicted for central Pb + Pb at LHC comparing AdS/CFT Eq. (1) and pQCD using the WHDG model [26] convolving elastic and inelastic parton energy loss. Possible initial gluon rapidity densities at LHC are given by $dN_g/dy = 1750$, from a PHOBOS extrapolation [39,40], or $dN_g/dy = 2900$, from the KLN model of the color glass condensate (CGC) [41]. The top two curves from pQCD increase with p_T while the bottom two curves from AdS/CFT slowly decrease with p_T. The AdS/CFT parameters here were found using the "obvious" prescription with $\alpha_{\text{SYM}} = 0.05$, $\tau_0 = 1$ fm/c, giving $D = 3/2\pi T$ (abbreviated to $D = 3$ in the figure). Similar trends were seen for the other input parameter possibilities discussed in the text. The "(" and "]" denote momenta after which possible string theoretic corrections may need to be considered; the curves' increasing transparency from "(" to "]" is meant to additionally emphasize this, see text.

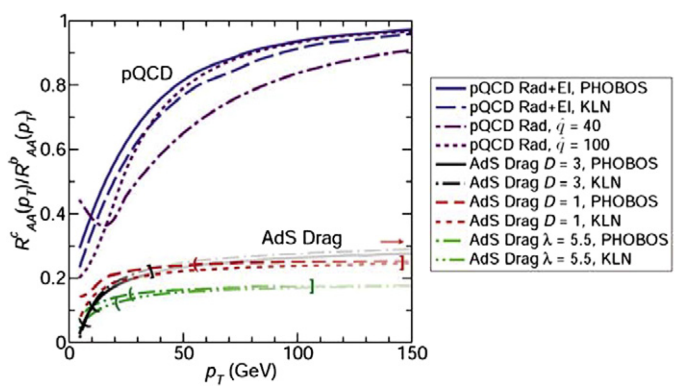

Fig. 2. The double ratio of $R_{AA}^c(p_T)$ to $R_{AA}^b(p_T)$ predictions for LHC using Eq. (1) for AdS/CFT and WHDG [26] for pQCD with a wide range of input parameters. The generic difference between the pQCD results tending to unity contrasted to the much smaller and nearly p_T-independent results from AdS/CFT can be easily distinguished at LHC. The "(" and "]" denote momenta after which possible string theoretic corrections may need to be considered; the curves' increasing transparency from "(" to "]" is meant to additionally emphasize this, see text.

We propose to use the double ratio of charm to bottom R_{AA} to amplify the observable difference between the mass and p_T dependencies of the AdS/CFT drag and pQCD-inspired energy loss models. One can see in Fig. 2 that not only are most overall normalization differences canceled, but also that the curves remarkably bunch to either AdS/CFT-like or pQCD-like generic results regardless of the input parameters used.

The numerical value of R^{cb} shown in Fig. 2 for AdS/CFT can be roughly understood analytically from Eq. (3) as,

$$R_{\text{AdS}}^{cb} \approx \frac{M_c}{M_b}\frac{n^b(p_T)}{n^c(p_T)} \approx \frac{M_c}{M_b} \approx 0.26, \tag{4}$$

where in this approximation all λ, T^*, L, and $n_c(p_T) \approx n_b(p_T)$ dependences drop out.

The pQCD trend in Fig. 2 can be understood qualitatively from the expected behavior of $\bar{\epsilon}_{\text{pQCD}}$ noted above giving (with $n_c \approx n_b = n$)

$$R_{\text{pQCD}}^{cb} \approx 1 - \frac{p_{cb}}{p_T}, \tag{5}$$

where $p_{cb} = \kappa n(p_T)L^2 \log(M_b/M_c)\hat{q}$ sets the relevant momentum scale. Thus $R^{cb} \to 1$ more slowly for higher opacity. One can see this behavior reflected in the full numerical results shown in Fig. 2 for moderate suppression, but that the extreme opacity $\hat{q} = 100$ case deviates from Eq. (5).

4. Conclusions

Possible strong coupling alternatives to pQCD in nuclear collisions were studied based on a recent AdS/CFT model of charm and bottom energy loss. The predicted nuclear modification factors, R^Q_{AA}, were found to be decreasing as a function of p_T, as compared to increasing as predicted from pQCD. We showed that the momentum dependence differences in the individual R^Q_{AA} can be masked by taking extreme energy loss extrapolations to LHC. However the double ratio R^{cb} revealed very generic behavior, insensitive to the input parameters and radically different for the two coupling limits. Of crucial importance is the momentum range over which pQCD and AdS/CFT drag are self-consistent. Certainly pQCD must apply for $p_T \to \infty$, but the scale below which non-perturbative effects become important is not yet well understood. Supposing that the AdS/CFT correspondence is relevant for heavy ion collisions, drag calculation momentum validity is limited from above. Since γ_c depends on M_Q but the hard pQCD scale does not there is likely a large region of p_T for which both approximations are applicable for bottom quarks. The disadvantage of studying the more robust R^{cb} observable is that the AdS momentum reach is limited by the much smaller charm quark mass; an overlapping momentum region of validity for both coupling limits may not exist for this observable. Further careful study of the "speed limit" and higher order corrections to the AdS/CFT result must be done in order to fruitfully compare R^c_{AA} and R^{cb} results to experiment. Or, turning this around, experiment might inform theory as to the correct scales for which these theoretical predictions give reliable results.

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