A distinguishing observable of strongly- and weakly coupled plasmas:
NLO momentum correlations of $b\bar{b}$ pairs in heavy ion collisions at $\sqrt{s} = 2.76$ TeV

R Hambrock and WA Horowitz
Department of Physics, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
E-mail: roberthambrock@gmail.com, wa.horowitz@uct.ac.za

Abstract. We use an energy loss model sensitive to thermal fluctuations [1] to compute the azimuthal and momentum correlations of $b\bar{b}$ pairs traversing a strongly coupled plasma from Pb+Pb collisions at LHC ($\sqrt{s} = 2.76$ TeV). The azimuthal correlations are compared with those from perturbative QCD based simulations [2]. When restricted to leading order production processes, we find that the strongly coupled correlations of high transverse momentum pairs ($> 4$ GeV) are broadened less efficiently than the corresponding weak coupling based correlations, while low transverse momentum pairs (1 - 4 GeV) are broadened with similar efficiency, but with an order of magnitude more particles ending up in this momentum class. The strong coupling momentum correlations we compute account for initial correlations and reveal that the particle pairs suppressed from initially high momenta to the low momentum domain do not suffice to explain the stark difference to the weak coupling results in momentum correlations for 1 - 4 GeV. From this, we conclude that heavy quark pairs are more likely to stay correlated in momentum when propagating through a strongly coupled plasma than a weakly coupled one.

Keywords: Quark-Gluon Plasma, AdS/CFT Correspondence, Heavy Quarks

1 Introduction

The quark gluon plasma is of great interest since it represents our first case study of the emergent physics of the non-abelian gauge theory QCD. A key step in understanding this state of matter is identifying its relevant coupling strength. The perturbative techniques of QCD are only adequate in a weakly coupled plasma, with calculations for strongly coupled plasmas constrained to methods like AdS/CFT-based approaches or Resonance Scattering [3]. Both weak and strong coupling based approaches have had their respective successes in the past. For instance, experimental $R_{AA}^{\pi}$ measurements show surprisingly consistent agreement with predictions from pQCD based models [4], while AdS/CFT based calculations have fared strongly by predicting a global lower bound on the shear viscosity-to-entropy ratio of QGP-like systems of $\frac{\eta}{s} \sim 0.1$ [5], when taking natural units, which is in line with hydrodynamic inferences from collider data at LHC and at RHIC [6].
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Both frameworks show qualitative agreement with \( R_{AA}^{D} \) [4], suggesting they are attaining sufficient maturity to investigate more differential observables. We will argue that the momentum correlations of heavy quarks constitute a promising candidate as a differentiator between weakly and strongly coupled plasmas.

In [2], the azimuthal correlations of heavy \( q \bar{q} \) pairs in a weakly coupled plasma in Pb+Pb collisions (\( \sqrt{s} = 2.76 \text{ TeV} \)) were studied, both for a model involving purely collisional energy loss and one additionally incorporating radiative corrections. These weak coupling based azimuthal correlations provide a secondary indicator for the momentum correlations and we will compare them with computations from an AdS/CFT correspondence exploiting energy loss model sensitive to thermal fluctuations, the latter already having been introduced in [1]. As in [1], we will probe the spectrum of plausible [7] AdS/CFT based energy loss models with two plausible 't Hooft coupling constants (\( \lambda_1 = 5.5 \) and \( \lambda_2 = 12\pi\alpha_s \approx 11.3 \)) where for the former, temperature and the Yang-Mills coupling are equated, while for the latter constant, energy density and the coupling are equated.

The calculations will be performed for the same transverse momentum classes as in [2] and also both with leading order and next-to-leading order production processes used for the initialisation. Additionally, we will consider momentum correlations that take initial momentum correlations into account. These will provide evidence that heavy quarks traversing a strongly coupled plasma are more likely to stay correlated in momentum than they would if inside a weakly coupled plasma.

## 2 Energy Loss Model

### 2.1 Overview

The following will outline our computational procedure and its background. Subsequent to initializing the momenta of bottom quark pairs either to leading order with FONLL [8] or to next-to-leading order with aMC@NLO [9] using Herwig++ [10] for the showering, the production points of the bottom quarks are weighted by the Glauber binary distribution [1]. The particles are propagated through the plasma via the energy loss mechanism described in 2.2 until the temperature in their local fluid cell drops below the Tc threshold and hadronization was presumed to occur or 8.6fm had passed, being the maximum time of the VISHNU background [6]. Finally, the bottom quarks are binned pairwise according to their relative azimuthal angle and each particle’s final three-momentum.

### 2.2 Langevin Energy Loss

The stochastic equation of motion for a heavy quark in the fluid’s rest frame is [11]

\[
\frac{dp_i}{dt} = -\mu p_i + F^L_i + F^T_i
\]

where \( F^L_i \) and \( F^T_i \) are longitudinal and transverse momentum kicks with respect to the quark’s direction of propagation and with \( \mu \), the drag loss coefficient, being given by \( \mu = \pi\sqrt{\lambda T^2}/2M_Q \) [12] where \( M_Q \) is the mass of a heavy quark in a plasma of temperature \( T \) with 't Hooft coupling constant \( \lambda \). The correlations of momentum kicks are given by

\[
\langle F^T_i(t_1)F^T_j(t_2) \rangle = \kappa_T \delta_{ij} - \frac{\vec{p}_i \vec{p}_j}{|\vec{p}|^2} g(t_2 - t_1)
\]

\[
\langle F^L_i(t_1)F^L_j(t_2) \rangle = \kappa_L \frac{|\vec{p}_i|}{|\vec{p}|^2} g(t_2 - t_1)
\]
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$\lambda_1 = 5.5$

![Figure 1: $d^2 N/d\phi dp_T$ of $b\bar{b}$ pairs for $p_A = \{2.5, 6.5\}$ GeV at 40-50 centrality](image)

where $g$ is only known numerically [1] and with

$$\kappa_T = \pi \sqrt{\lambda T^3} \gamma^{1/2}$$

$$\kappa_L = \gamma^2 \kappa_T = \pi \sqrt{\lambda T^5/2}$$

As via Eqn. 5, the coupling of the longitudinal fluctuations to velocity grows as $\gamma^{5/2}$, thus growing significant extremely quickly [1]. For calculations without this scaling of the longitudinal fluctuations, see [13]. As reasoned in [1], the fluctuations are thus important to include for finite $\lambda \sim O(10)$, as is the case for our probing models, where $\gamma_{\text{crit}}^{\text{fluc}} = \frac{M_T^2}{\lambda T}$ is lower than the speed limit on a quark, $\gamma_{\text{crit}} = (1 + \frac{2M_Q}{\sqrt{\lambda T}})^2$ where $g(0) = 1$, since any kick will be fully correlated to itself. If the time scale of momentum kick correlations is small compared the time scale determined by the drag coefficient, we can model the colouring as white noise, hence treat $g$ as a Dirac delta [1]. By virtue of our requirement $\gamma < \gamma_{\text{crit}}^{\text{fluc}}$, it follows that $t_{\text{corr}} \mu \sim \frac{1}{\lambda} \sqrt{\gamma_T} \frac{T}{M_Q} < \frac{1}{\lambda} \sqrt{\gamma_T} \frac{\sqrt{\lambda T^5}}{\pi T} = 1$, and we may thus safely approximate the colouring as white noise.

3 Leading Order Correlations

3.1 2D correlations

In Fig. 1 and Fig. 2, the $d^2 N/d\phi dp_T$ correlations are depicted for representative sections of the respective $p_T$ classes. We observe that, for low $p_T$, we attain very efficient broadening of the angular correlations. For mid $p_T$, the angular correlations are much tighter, however with greater broadening of the momentum correlations, at least in absolute terms. For $\lambda_2 = 11.3$, both angular and momentum correlations are much weaker than for $\lambda_1 = 5.5$, given the larger consequent drag coefficient of the former.

3.2 Azimuthal correlations

In [2], at leading order, the weak coupling based computations exhibited very efficient broadening of initial azimuthal correlations for low $p_T$ $b\bar{b}$ pairs ($[4-10]$ GeV), which were washed out once NLO production processes were taken into consideration.

Both for mid- and high-$p_T$ ($[4-10]$ GeV and $[10-20]$ GeV respectively), the initial correlations survive to a large degree, both at leading order and at next-to-leading order, suggesting that they may still be observable in an experimental context.
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$\lambda_2 = 11.3$

![Diagram](image1)

Figure 2: $\frac{d^2N}{dp_T^2}$ correlations of $b\bar{b}$ pairs for $p_A = \{2.5, 6.5\}$ GeV at 40-50 centrality

![Diagram](image2)

Figure 3: $\frac{dN}{dp_T}$ correlations for the specified classes.

We compare our strong coupling azimuthal correlations to the weak coupling ones in Fig. 3. For $[10 - 20]$ GeV, our correlations are significant more peaked at their initial back-to-back correspondence. At $[4 - 10]$ GeV, this observation still holds for the upper bound of our parameters with $\lambda_1 = 5.5$, while the $\lambda_2 = 11.3$ bounded result is of similar magnitude but looser angular correlation than either the collisional or the collisional + Bremsstrahlung based results. In the $[1 - 4]$ GeV range, the azimuthal correlations are almost entirely washed out for $\lambda_2 = 11.3$, while for $\lambda_1 = 5.5$, they are broadened with similar efficiency to the weak coupling results.

3.3 Momentum correlations

What is striking about the low $p_T$ correlations ($[1 - 4]$ GeV) depicted in Fig. 3 is the order of magnitude difference between strong and weak coupling.

Naïvely, one may expect this to be caused by a more efficient suppression of high momentum particles in a strongly coupled plasma than a weakly coupled one. If we take initial momentum correlations into account Fig. 4, we find that the contribution of particles initially in a higher momentum class being suppressed down to $[1 - 4]$ GeV clearly do not suffice to account for the order of magnitude difference observed. In fact, the dominant portion of particles with low final transverse momentum had low transverse momentum initially too. On the one hand, this could be due to these particles ending up in other final momentum classes. From Fig. 3, it is clear they
do not end up in [4 − 10]GeV or [10 − 20]GeV. This only leaves [0 − 1]GeV and [20 − ∞]GeV, the latter being highly unlikely. A more plausible explanation is that in a weakly coupled plasma, $b \bar{b}$ pairs are much more weakly correlated in momentum and are thus more likely to end up in distinct momentum classes. Since this effect is observed in the low momentum domain, one may postulate that the momentum fluctuations in a weakly coupled plasma are more significant that in a strongly coupled plasma. Thus, it would be more likely for low momentum heavy quarks to receive momentum kicks that elevate them to higher momentum classes in the weakly coupled plasma.

4 Next-to-leading Order Correlations

4.1 Azimuthal correlations

As depicted in Fig. 5, the correlations for the [1 − 4]GeV class are entirely washed out, just as observed for the pQCD calculations in [2]. For mid- to high-$p_T$, while the peak around $\Delta \phi = \pi$ has been broadened, the computations suggest that this signal should still be observable in an experimental context. Unfortunately, we had no data from weak coupling calculations for a similar centrality to compare with.

5 Conclusion & Outlook

We have compared the azimuthal correlations predicted by pQCD and AdS/CFT based computations and found that, while the azimuthal correlations are qualitatively similar, the momentum correlations tell a different tale. In particular, the surprise of our findings is the large dissimilarity in low momentum correlations of the pQCD and
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![Figure 5: Final $\frac{dN}{d\phi}$ correlations for NLO initialization.](image)

AdS/CFT based simulations. Thus, bottom quark momentum correlations present an opportunity to distinguish between the energy loss mechanisms of the two frameworks.

Although stronger momentum fluctuations in the weakly coupled plasma have been identified as a plausible explanation for this disparity, it can only be verified by computing initial correlations for the weak coupling based correlations as well.

Furthermore, whether this order of magnitude difference in predictions for low $p_T$ correlations of heavy quarks exposes weaknesses in either or both of the frameworks cannot be declared until experimental data of bottom quark momentum correlations emerge. Strong coupling based approaches have fared better in the low momentum domain, where pQCD is restrained by uncertainties in the running coupling.

While discriminating initial momenta in the momentum correlation plots Fig. 4 is illuminating, producing these is impossible in the current paradigm of detectors, and thus their applicability is restricted to simulations. That being said, the integrated momentum correlations may constitute a potent experimental discriminator of strongly and weakly coupled plasmas and demand further investigation.

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