AdS/CFT predictions for correlations, suppression, and flow of heavy flavours at RHIC and LHC

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Abstract. We use two AdS/CFT based energy loss models to compute the suppression, flow, and azimuthal correlations of heavy quarks in heavy ion collisions at RHIC and LHC. The model with a velocity independent diffusion coefficient is in good agreement with **B** and **D** meson suppression data up to high transverse momentum. The partonic azimuthal correlations are compared with those from perturbative QCD based simulations, Ref. [1]. 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 broaded with similar efficiency, but with an order of magnitude more particles ending up in this momentum class. We thus propose heavy flavour momentum correlations as a distinguishing observable of weakly- and strongly-coupled energy loss mechanisms.

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 [2]. Both weak and strong coupling based approaches have had their respective successes in the past. For instance, measurements of the nuclear modification factor of pions, R^{π}_{AA}, show surprisingly consistent agreement with predicions from pQCD based models [3], 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, in natural units, $\frac{\eta}{s} \sim 0.1$ [4], which is in line with hydrodynamic inferences from collider data from LHC and RHIC [5].

Both frameworks show qualitative agreement with measurements of the nuclear modification factor of **D**-mesons, R^{D}_{AA} [3], suggesting they have attained sufficient maturity to investigate more differential observables.

In [1], the azimuthal correlations of heavy $q\bar{q}$ pairs in a weakly coupled plasma in Pb+Pb collisions (center-of-mass energy $\sqrt{s} = 2.76\text{TeV}$) were studied, both for a model using purely collisional energy loss and one additionally incorporating radiative corrections. These weak coupling based azimuthal correlations provide a secondary indicator for the momentum correlations of heavy quarks. We will compare these correlations with two different AdS/CFT based energy loss models, one having a velocity-*dependent* diffusion coefficient [6], and the other having a diffusion coefficient that is *independent* of the heavy quark's velocity [7]. Furthermore, we will probe the spectrum of their possible predictions (translated back to QCD) with two plausible [8] 't Hooft coupling constants ($\lambda_1 = 5.5$ and $\lambda_2 = 12\pi\alpha_s \approx 11.3$ with strong coupling $\alpha_s = 0.3$) where for λ_1, we also equate the QCD and $\mathcal{N} = 4$ super Yang-Mills (which is dual to the AdS_5 setting our calculations are performed in) temperatures, while λ_2 has the QCD temperature equated with the $\mathcal{N} = 4$ super Yang-Mills energy density instead.

The calculations will be performed at leading order for the same transverse momentum classes as in [1]. Additionally, we will consider momentum correlations that take initial momentum correlations into account. These correlations 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, and we thus argue that heavy flavour momentum correlations constitute a promising differentiator between weakly and strongly coupled plasmas.

Finally, we will compare our results with heavy flavour measurements from LHC and provide predictions for RHIC.

2. Energy Loss Model

2.1. Overview

The following will outline our computational procedure and its background. Subsequent to initializing the momenta of heavy quark pairs either to leading order with FONLL [9] or to next-to-leading order with aMC@NLO [10] using Herwig++ [11] for the showering, the production points of the heavy quarks are weighted by the Glauber binary distribution [6]. The particles are propagated through the plasma via the energy loss mechanism described in 2.2, either until the temperature in their local fluid cell drops below a critical threshold where hadronization is presumed to occur, or until the maximum time the VISHNU background [5] is calculated for has passed. If next-to-leading order initialization has been used, the heavy quarks are now hadronized. Finally, the heavy 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 [12]

$$\frac{dp_i}{dt} = -\mu p_i + F_i^L + F_i^T \tag{1}$$

where F_i^L and F_i^T are longitudinal and transverse momentum kicks with respect to the quark's direction of propagation and μ is the drag loss coefficient, given by $\mu = \pi\sqrt{\lambda}T^2/2M_Q$ [13] where M_Q is the mass of a heavy quark in a plasma of temperature T with 't Hooft coupling constant λ. The correlations of momentum kicks at time t_1 and t_2 are given by

$$\langle F_i^T(t_1)F_j^T(t_2)\rangle = \kappa_T(\delta ij - \frac{\vec{p}_i\vec{p}_j}{|p|^2})g(t_2 - t_1) \tag{2}$$

$$\langle F_i^L(t_1)F_j^L(t_2)\rangle = \kappa_L\frac{p_i p_j}{|p|^2}g(t_2 - t_1) \tag{3}$$

where the function g is only known numerically [6] and with

$$\kappa_T = \pi\sqrt{\lambda}T^3\gamma^{1/2} \tag{4}$$

$$\kappa_L = \gamma^2\kappa_T = \pi\sqrt{\lambda}T^3\gamma^{5/2} \tag{5}$$

$$\hat{q} = \langle p_\perp(t)^2\rangle\lambda \approx \kappa_T t/\lambda = \gamma(2\pi T^3\sqrt{\lambda})/v \tag{6}$$

where γ is the speed of the quark. It should be noted that this construction does not obey the fluctuation-dissipation theorem [6]. The computations based on this model will be labeled *D(p)*.

2.3. Development on energy loss model

The problem with the energy loss mechanism described in 2.2 is that, since the longitudinal momentum fluctuations grow as $\gamma^{\frac{5}{2}}$, our setup breaks down for high momenta, where in a perturbative QCD setting, Brehmstrahlung would restrict the momentum growth of the quark. Via a novel calculation presented in [7, 14, 15], we instead consider a stationary string in AdS_d hanging into a black hole horizon and calculate $s^2(t, a, d)$, the average transverse distance squared travelled by the string's free endpoint, where t is the time, d the dimension of the setup, and a parametrizes between a heavy quark for $a = 0$ and a light quark for $a = 1$. Crucially, $s^2(t, a, d = 3)$ can be determined analytically for small string lengths, which is identical to the asymptotically late time behavior of a string with arbitrary initial length. We thus find the asymptotically late time behavior of a string in d dimensions by

$$s^2(t \gg \beta, a, d) = s^2_{\text{small}}(t \gg \beta, a, d)$$
$$= (\frac{d-1}{2})^2 s^2_{\text{small}}(t \gg \beta, a, d = 3) = \frac{(d-1)^2}{8\pi\sqrt{\lambda}}\beta(1 - \frac{a}{2}) \quad (7)$$

where $\beta = T^{-1}$. At late times, the motion is diffusive, thus we can extract the diffusion coefficient

$$D(a, d) \sim \frac{1}{2}s^2(t \gg \beta, a, d) \quad (8)$$

which in AdS_5 for a heavy quark reads $2\beta/\pi\sqrt{\lambda}$. From this, we obtain

$$\kappa_T = 2T^2/D = \pi\sqrt{\lambda}T^2/\beta = \pi\sqrt{\lambda}T^3 \quad (9)$$
$$\hat{q} = \langle p_\perp(t)^2\rangle\lambda \approx \kappa_T t/\lambda = (2\pi T^3\sqrt{\lambda})/v \quad (10)$$

Requiring these fluctuations to obey the fluctuation-dissipation theorem (which the construction in 2.2 could not), we attain $\mu = \pi\sqrt{\lambda}T^2/2E$. The computations based on this model will be labeled *D=const*.

3. Leading Order Correlations

3.1. 2D correlations

In Fig. 1 and Fig. 2, the $\frac{d^2N}{d\phi dp_T}$ correlations in Pb+Pb collisions $\sqrt{s_{NN}} = 2.76$ TeV at $40 - 50\%$ centrality[1], are depicted for representative sections of the respective transverse momentum p_T. 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 [1], 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.

We compare our strong coupling azimuthal correlations to the weak coupling ones in Fig. 3. For $[10 - 20]$ GeV, our correlations are significantly more peaked at their initial back-to-back correspondence. At $[4 - 10]$ GeV, this observation still holds for the upper bound of our

[1] In Monte Carlo simulations of heavy ion collisions, the centrality quantifies the percentage of collisions that have a smaller impact parameter than the considered collision. In experimental heavy ion collisions, an estimator of the impact parameter has to be used, such as the charged particle multiplicity or the transverse energy of the collision (both inversely correlated with the impact parameter). For a detailed discussion, see [16].

$\lambda_1 = 5.5$

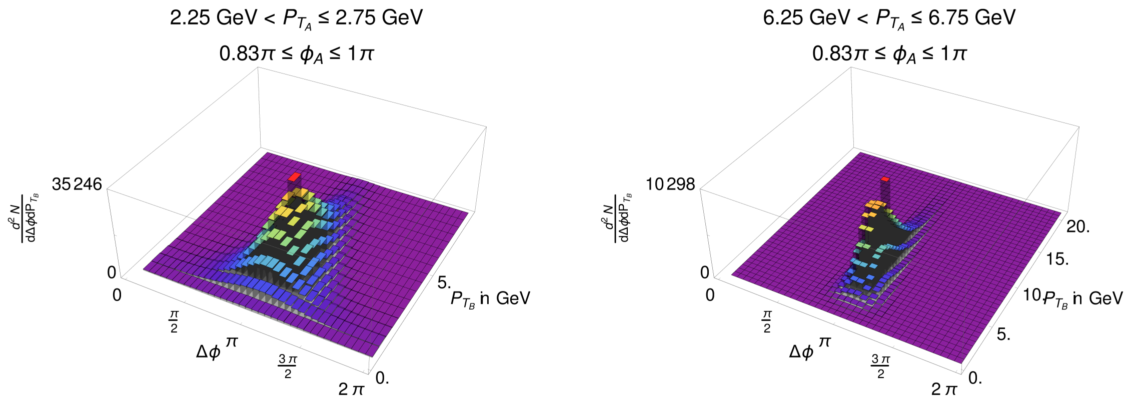

Figure 1: $\frac{d^2N}{d\phi dp_T}$ of $b\bar{b}$ pairs for $p_A = \{2.5, 6.5\}$ GeV in the $D(p)$ model

$\lambda_2 = 11.3$

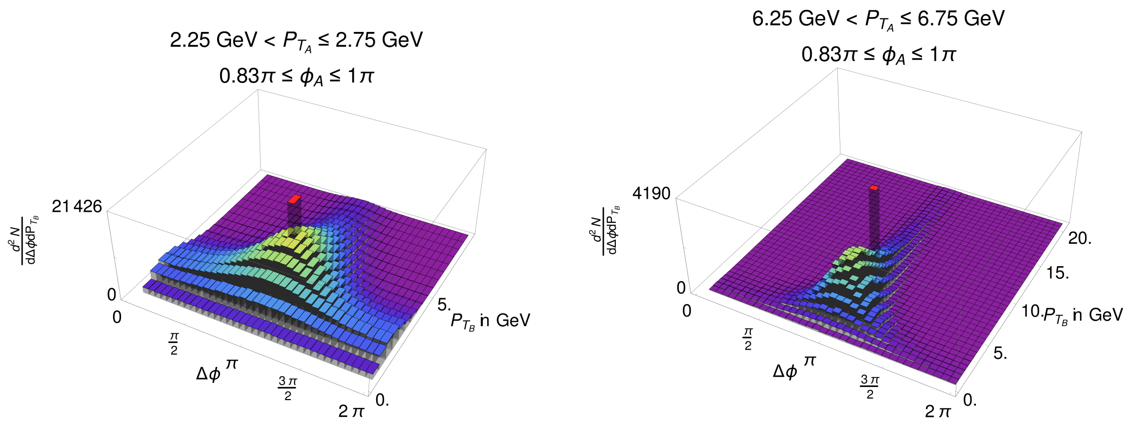

Figure 2: $\frac{d^2N}{d\phi dp_T}$ correlations of $b\bar{b}$ pairs for $p_A = \{2.5, 6.5\}$ GeV in the $D(p)$ model

parameters with $\lambda_1 = 5.5$, while the $\lambda_2 = 11.3$ bounded result is of similar magnitude, but with 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 similiar efficiency to the weak coupling results.

Of particular interest is the difference in momentum correlations the $[1-4]$ GeV range exhibits. At about an order of magnitude, this difference promises a distinguishing observable of weak- and strong-coupling energy loss in the medium, and should be investigated experimentally.

4. R_{AA} and v_2

We compare bottom and charm suppression predictions with data from CMS and ALICE (Fig. 4). While the agreement with CMS data for **B** meson suppression is comparable between the *D(p)* and *D=const* models, the comparison with ALICE data for **D** mesons shows the limited validity range of the *D(p)* model, whereas the *D=const* model remains consistent with data even for high-p_T. More fundamentally, for the *D(p)* model, the AdS/CFT picture naturally breaks down at $p_T \sim 100$ GeV [6]. For the *D=const* model, there is no such natural breakdown. Only

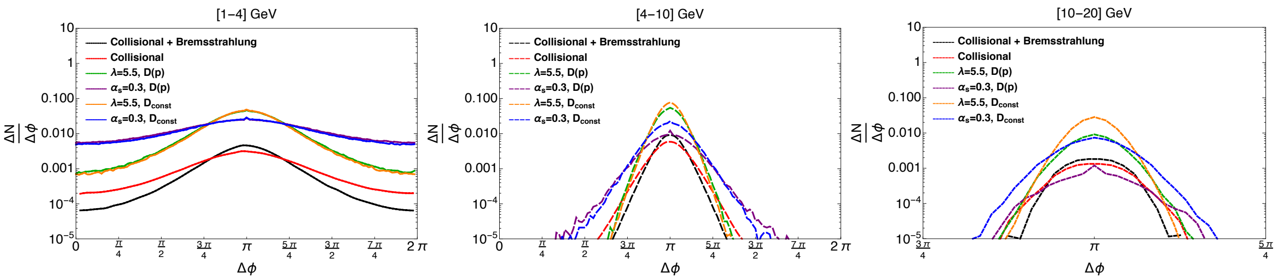

Figure 3: $\frac{dN}{d\phi}$ correlations for the specified classes.

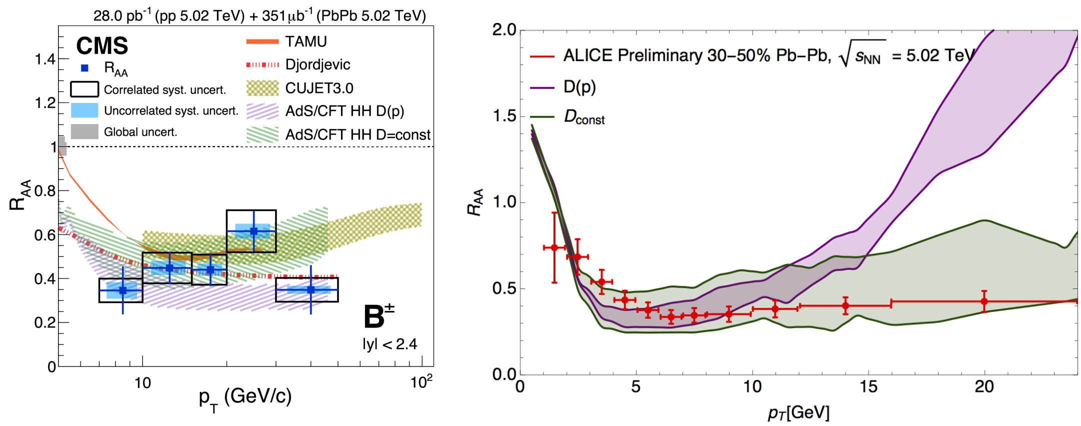

Figure 4: (Left) Comparison with R_{AA}^{B} data from CMS [17] with $\sqrt{s_{NN}} = 5.02$ TeV, |y| < 2.4. (Right) Comparison with R_{AA}^{D} data from ALICE [18] with $\sqrt{s_{NN}} = 5.02$ TeV, |y| < 0.5. The bands range from $\lambda = 5.5$ to $\lambda = 11.3$.

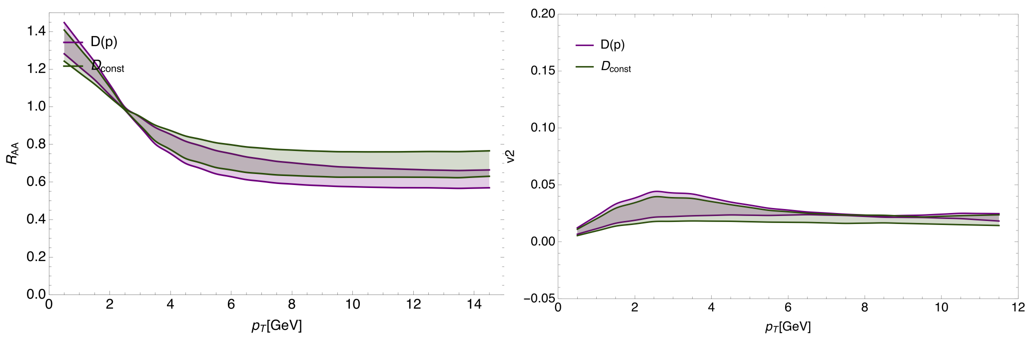

Figure 5: (Left) R_{AA}^{B} and (Right) v_2^B with $\sqrt{s_{NN}} = 200$ GeV, |y| < 1.0 and 10 − 40% centrality for future RHIC measurements. The bands range from $\lambda = 5.5$ to $\lambda = 11.3$.

for asymptotically large p_T *and* T is one guaranteed that the physics is perturbative.

In Fig. 5, we show our predictions for suppression and flow of **B** mesons at RHIC. **B** mesons are noticeably less suppressed than at the LHC, due to the substantially cooler medium in heavy collisions at RHIC.

The bands of our predictions range from $\lambda = 5.5$ to $\lambda = 11.3$ and account for statistical uncertainties. We note that, in particular for the high-p_T range of the **B** meson predictions in

Fig. 4 (left), our results' uncertainty is significant for high-p_T. This is due to the production spectrum of heavy quarks dropping as $\sim {p_T}^{-4}$. The aMC@NLO framework, at the time of writing, does not allow event generation weighted by p_T. In future work, we will use POWHEG's weighted event generation [19] to explore high-p_T phase space of our observables.

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 AdS/CFT based simulations; see Fig. 3 (left). Thus, bottom quark momentum correlations present an opportunity to distinguish between the energy loss mechanisms of the two frameworks.

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 the agreement with CMS data for **B** meson suppression is comparable between the *D(p)* and *D=const* models, the comparison with ALICE data for **D** mesons shows the limited validity range of the *D(p)* model. In contradistinction, the *D=const* model remains consistent with data even for high-p_T. The RHIC data exhibits decreased suppression compared with the LHC data, which can be understood from the lower temperatures of the medium at RHIC.

The high-p_T reach of recent results from the LHC Fig. 4, particularly CMS Fig. 4 (left), exposes the limited statistics of our simulations for high-p_T. In future calculations, we will migrate from aMC@NLO to POWHEG [19] to facilitate weighted event generation, which mitigate the issue of limited statistics at high-p_T.

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References

[1] Nahrgang M, Aichelin J, Gossiaux P B and Werner K 2014 *Phys. Rev.* **C90** 024907 (*Preprint* 1305.3823)
[2] Casalderrey-Solana J, Liu H, Mateos D, Rajagopal K and Wiedemann U A 2011 *Gauge/String Duality, Hot QCD and Heavy Ion Collisions* (*Preprint* 1101.0618)
[3] Horowitz W A 2013 *Nucl. Phys.* **A904-905** 186c–193c (*Preprint* 1210.8330)
[4] Gubser S S, Klebanov I R and Peet A W 1996 *Phys. Rev.* **D54** 3915–3919 (*Preprint* hep-th/9602135)
[5] Shen C, Heinz U, Huovinen P and Song H 2011 *Phys. Rev.* **C84** 044903 (*Preprint* 1105.3226)
[6] Horowitz W A 2015 *Phys. Rev.* **D91** 085019 (*Preprint* 1501.04693)
[7] Moerman R W and Horowitz W A 2016 (*Preprint* 1605.09285)
[8] Gubser S S 2008 *Nucl. Phys.* **B790** 175–199 (*Preprint* hep-th/0612143)
[9] Cacciari M, Frixione S, Houdeau N, Mangano M L, Nason P and Ridolfi G 2012 *JHEP* **10** 137 (*Preprint* 1205.6344)
[10] Alwall J, Frederix R, Frixione S, Hirschi V, Maltoni F, Mattelaer O, Shao H S, Stelzer T, Torrielli P and Zaro M 2014 *JHEP* **07** 079 (*Preprint* 1405.0301)
[11] Bahr M *et al.* 2008 *Eur. Phys. J.* **C58** 639–707 (*Preprint* 0803.0883)
[12] Moore G D and Teaney D 2005 *Phys. Rev.* **C71** 064904 (*Preprint* hep-ph/0412346)
[13] Herzog C P, Karch A, Kovtun P, Kozcaz C and Yaffe L G 2006 *JHEP* **07** 013 (*Preprint* hep-th/0605158)
[14] Hambrock R and Horowitz W 2017 *J. Phys. Conf. Ser.* **889** 012015
[15] Hambrock R and Horowitz W A 2017 *Nucl. Part. Phys. Proc.* **289-290** 233–236 (*Preprint* 1703.05845)
[16] Das S J, Giacalone G, Monard P A and Ollitrault J Y 2018 *Phys. Rev.* **C97** 014905 (*Preprint* 1708.00081)
[17] Sirunyan A M *et al.* (CMS) 2017 *Phys. Rev. Lett.* **119** 152301 (*Preprint* 1705.04727)
[18] ALICE Collaboration 2017 (*Preprint* ALI-PREL-128542)
[19] Alioli S, Hamilton K, Nason P, Oleari C and Re E 2011 *JHEP* **04** 081 (*Preprint* 1012.3380)