B and D meson Suppression and Azimuthal Anisotropy in a Strongly Coupled Plasma at $\sqrt{s_{NN}} = 5.5$ TeV

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Abstract. We present predictions for the suppression and angular distribution of B and D mesons in $\sqrt{s} = 5.5$ TeV Pb+Pb collisions at the LHC for central, semi-central and peripheral collisions. We assume that the QGP produced at the LHC is strongly coupled and that the heavy quarks are strongly coupled to the QGP, and we employ the Langevin energy loss model with parameters from AdS/CFT. To account for the theoretical systematic uncertainties related to how the diffusion is computed across the two theories (i.e. QCD and $\mathcal{N} = 4$ SYM), we use a momentum dependent and momentum independent diffusion coefficient. We also estimate theoretical systematic uncertainties due to the mapping of parameters between the two theories, by using two sets of parameters; one where the temperature of the plasmas in the two theories is equated, and another where the energy densities of the plasmas are equated. We show that the $R_{AA}(p_T)$ increases with centrality and that the $v_2(p_T)$ is largest in semi-central collisions.

1. Introduction

Heavy-ion collisions have been successful in recreating the conditions of the early universe [1, 2], thus allowing us to probe and build our understanding of the hot-QCD matter that filled the universe shortly after the Big Bang. During a heavy-ion event, some of the incident partons experience hard perturbative interactions and result in the production of high-p_T particles [1]. These high-p_T particles are the most direct probe of the relevant degrees of freedom in a QGP [3]; they lose energy as they propagate through the QGP medium [4], and studying this energy loss allows us to measure the physics of QGP. In particular, we focus on heavy quarks (HQ) since they are produced very early in the collision and act as identifiable test particles (ideal probes), navigating the whole evolution of the QGP medium as they participate in and are affected by its dynamics, but remain conserved [5].

One way of conceptualising how high-p_T particles interact with the medium is via the weak coupling picture, tackled using pQCD techniques [6]. As the HQ propagate through the QGP medium, they scatter off the various constituents of the medium, leading to radiative and collisional energy loss [7, 8]. Weak coupling energy loss models have had success in describing RHIC and LHC data for both light and heavy flavoured particles [6].

In this paper, we will take the strong coupling view (i.e. the heavy quark is strongly coupled to a plasma that is also strongly coupled) to study this HQ energy loss. Since the relevant scale for HQ energy loss is the typical momentum transfer during interactions [7, 9] (which also informs the HQ diffusion in the QGP), weak coupling techniques can't be applied in processes involving a small momentum transfer since non-perturbative corrections become important, but are impossible to calculate using weak coupling techniques [10]. This regime where the momentum transfer is small, is the regime where QCD matter is strongly coupled [11], and we resort to AdS/CFT techniques to perform energy loss calculations [12, 13]. AdS/CFT energy loss has previously shown a massive over-suppression of high-p_T light/heavy flavour compared to data [3, 14]; however, more recent work [15, 16] shows a jet nuclear modification factor that is quantitatively consistent with preliminary CMS data.

In addition to the energy loss, the heavy quarks propagate through a 'different looking' medium depending on the angle in which they are produced; for example, the quark travels a different distance depending on its production angle for the various centrality classes, and experiences a different temperature profile. This difference in the medium results in the suppression of these heavy quarks having an azimuthal dependence, and we will also present results for this azimuthal dependence.

2. Langevin energy loss model

The energy loss model that we have employed was developed in [13] and a further discussion and application of the model can be found in [17, 18]. We obtain the production spectrum of the heavy quarks from FONLL calculations [19, 20] for $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 5.5$ TeV and $|y| < 1$. The heavy quarks are assumed to be produced in the transverse plane (with the production angles following a uniform distribution) at an initial time, t_0. This production procedure is described by the Optical Glauber model [21], and for our purposes, we have used ^{208}Pb nuclei and the corresponding parameters can be found in [22].

Once the heavy quark has been produced in the geometry, at thermalisation time ($t \sim 0.6$ fm/c), the hydrodynamic background forms and the heavy quark propagates through it while interacting with the medium. These hydrodynamic backgrounds (used for medium evolution) are generated by VISHNU 2+1D viscous relativistic hydrodynamics [23, 24]. Then the dynamics of the heavy quark interacting with the QGP medium (hydrodynamic background) as it propagates through it, are described by the Langevin equation,

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

in the fluid's rest frame, where p^i is the three-momentum of an on-shell heavy quark that is moving with constant velocity in the plasma and μ is the drag loss coefficient of a heavy quark [25]. The stochastic forces (diffusion terms) F_i^L and F_i^T are the longitudinal and transverse momentum kicks with respect to the quark's direction of propagation.

In computing the strongly coupled energy loss, we employ results from AdS/CFT [11, 12, 26]. However, there arise theoretical systematic uncertainties related to how the diffusion is computed across the two theories (i.e. QCD and $\mathcal{N} = 4$ SYM). In [25], it is shown that the diffusion coefficient grows as $\sim \gamma^{5/2}$ in the longitudinal direction, where γ is the Lorentz gamma factor. This result comes from forcing the heavy quark to move at a constant velocity by use of an external force, and the work of [27] suggests instead, that the diffusion coefficient should be momentum independent in the case where the heavy quark does not experience this forced motion. In order to account for these uncertainties, we use two different diffusion coefficients; one that is dependent on momentum, $D(p)$, and one that does not depend on the heavy quark momentum, $D = const$.

In the scenario where the diffusion coefficient is dependent on momentum, the drag (μ) and diffusion (D) are given by [13],

$$\mu = \frac{\pi\sqrt{\lambda}T^2}{2M_Q}, \qquad D = \frac{2T^2}{\kappa_L}, \tag{2}$$

where M_Q is the mass of the heavy quark in a plasma of temperature T, λ is the 't Hooft coupling constant, $\kappa_L = \pi\sqrt{\lambda}T^3\gamma^{5/2}$ is the mean squared longitudinal momentum transfer per unit time, and carries the momentum dependence of the diffusion. Note that this construction of parameters does not obey the fluctuation-dissipation theorem [13] and the transport scheme only leads to thermalization in the $p_T \to 0$ limit where the fluctuation-dissipation theorem is satisfied.

On the other hand, in the scenario where the diffusion coefficient does not depend on the heavy quark's momentum, the drag (μ) and diffusion (D) are given by [11, 27]:

$$\mu = \frac{\pi\sqrt{\lambda}T^2}{2E}, \qquad D = \frac{T}{M_Q\mu} = \frac{2T^2}{\kappa}, \tag{3}$$

where in this scenario, $\kappa = \pi\sqrt{\lambda}T^3$ does not contain a momentum dependence and E is the energy of the heavy quark in the local fluid rest frame. In this scenario, the momentum fluctuations are required to obey the fluctuation-dissipation theorem and the drag and diffusion are related by the Einstein relations.

The drag and diffusion coefficients in both the $D(p)$ and $D = const$ cases have a temperature and 't Hooft coupling dependence. The mapping of these parameters between the two theories (i.e. QCD and $\mathcal{N} = 4$ SYM) also introduces theoretical systematic uncertainties to our energy loss calculation. To account for these uncertainties, we have used two sets of parameters as outlined below [13, 28]:

(i) **Equal Temperature and Parameters (ET):** $T_{SYM} = T_{QCD}$, $\lambda = 4\pi \times 0.3 \times 3 \simeq 11.3$.

(ii) **Equal Energy Density and HQ Potential (EE):** $T_{SYM} = \frac{1}{3^{1/4}}T_{QCD}$, $\lambda = 5.5$.

The ET parameters compare QCD to $\mathcal{N} = 4$ SYM theory at the same temperature and the 't Hooft coupling is fixed by equating the coupling in the two theories. On the other hand, for EE parameters, the energy densities between the two plasmas (i.e. QCD and $\mathcal{N} = 4$ SYM plasma) are equated, resulting in the temperature relation given in (ii). The 't Hooft' coupling is then computed by comparing the static force between a quark and antiquark between the two theories, which yields $\lambda = 5.5$ [12]. Further discussions on the energy loss model and the various parameters we have employed can be found in [13, 17, 27, 29].

3. Results

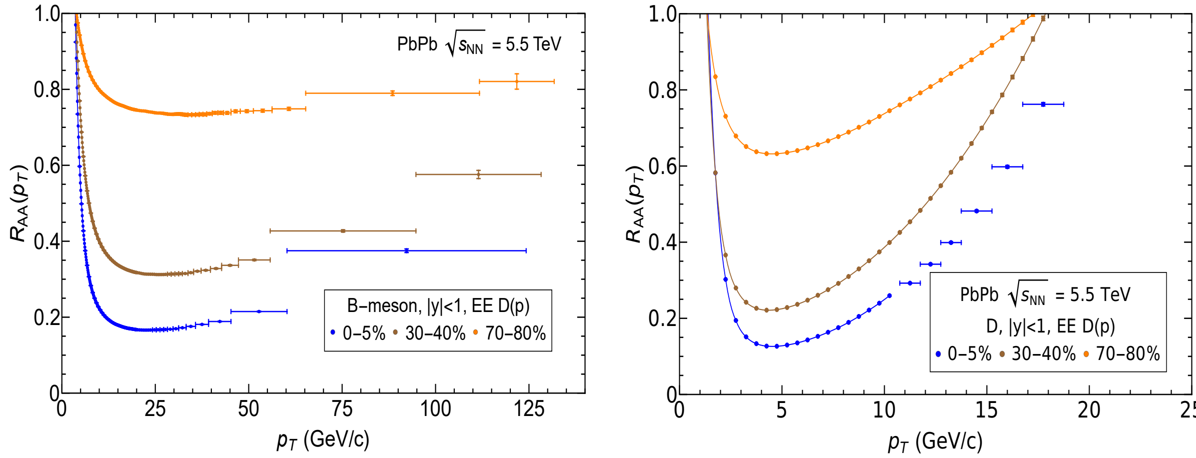
The results of this paper are the comparison of the nuclear modification factor, $R_{AA}(p_T)$, and the $v_2(p_T)$ for B and D mesons at $\sqrt{s_{NN}} = 5.5$ TeV, $|y| < 1$ for $Pb + Pb$ collisions in central, semi-central and peripheral collisions. The $R_{AA}(p_T)$ and $v_2(p_T)$ are defined as follows:

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T} \tag{4}$$

$$R_{AA}(p_T, \phi) = R_{AA}(p_T)\left[1 + 2v_2(p_T)\cos(2\phi)\right]. \tag{5}$$

The results will compare the four different scenarios discussed in the previous section, i.e. a momentum dependent and independent diffusion coefficients, $D(p)$ and $D = const$ respectively, as well as the ET and EE parameters. The horizontal bars represent the bin widths, while the vertical bars represent the statistical uncertainties.

In Figure 1, we show the centrality (a measure of how far apart the centres of two colliding nuclei are) dependence of $R_{AA}(p_T)$ for the EE, $D(p)$ parameters for B and D mesons. There is less suppression as we move from central to peripheral collisions (for both B and D mesons). This is due to the initial geometry of the colliding nuclei; in peripheral collisions, less QGP is produced and the heavy quarks spend less time in the QGP medium and lose less energy



(a) B mesons

(b) D mesons

Figure 1. *EE*, $D(p)$ $R_{AA}(p_T)$ at $\sqrt{s_{NN}} = 5.5$ TeV for centrality classes 0-5% up to 70-80%.

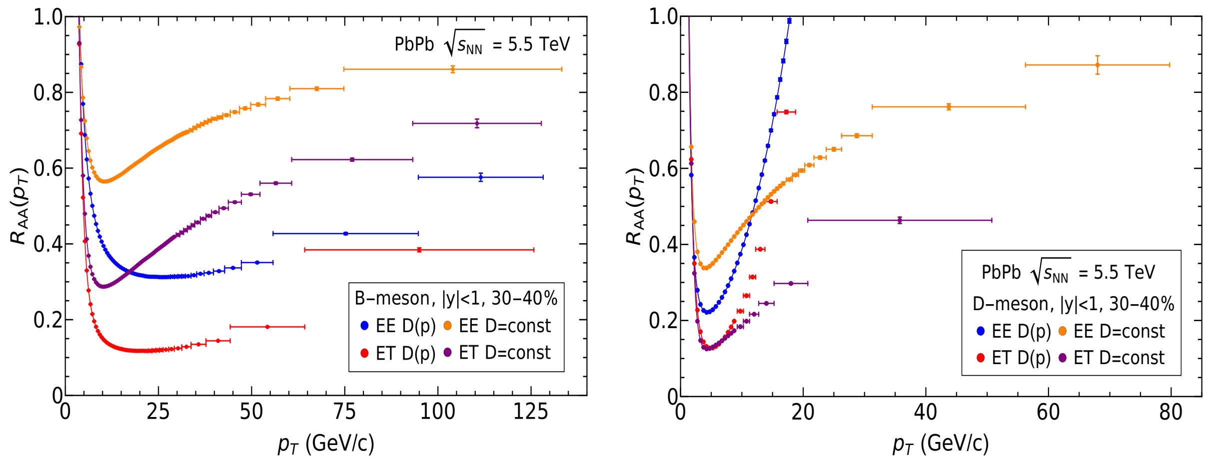
compared to central collisions. The centrality dependence for the rest of the other parameters behaves similarly and is discussed in [29] for B mesons.

We then compare the $R_{AA}(p_T)$ for the different parameters we have employed for B and D meson semi-central collisions in Figure 2. Notice that the models employing $D(p)$ parameters break down around $p_T \sim 15$ GeV/c for D mesons due to the fluctuations growing rapidly with p_T (this can also be seen in Figure 1 for the various centrality classes). These fluctuations are more pronounced for D mesons compared to B mesons due to the low mass of charm quarks, thus these parameters have a limit of $p_T \sim 15$ GeV/c for D mesons. Despite the rapidly growing fluctuations in the $D(p)$ case for B mesons, the models employing $D = const$ parameters show a stronger momentum dependence due to the drag being extracted from the fluctuation-dissipation theorem, which results in a μ that is inversely proportional to the energy of the heavy quark as shown in Equation 3.

The drag coefficient, μ, has the largest contribution to the energy loss, in the EE prescription, the 't Hooft coupling is smaller by ~ 2 and T is lower, so the drag for EE parameters is smaller compared to ET parameters and results in less suppression. This difference in μ between the two parameters is clearly reflected in our results shown in Figure 2 as the EE curves show a higher $R_{AA}(p_T)$ compared to ET curves for the same diffusion coefficient.

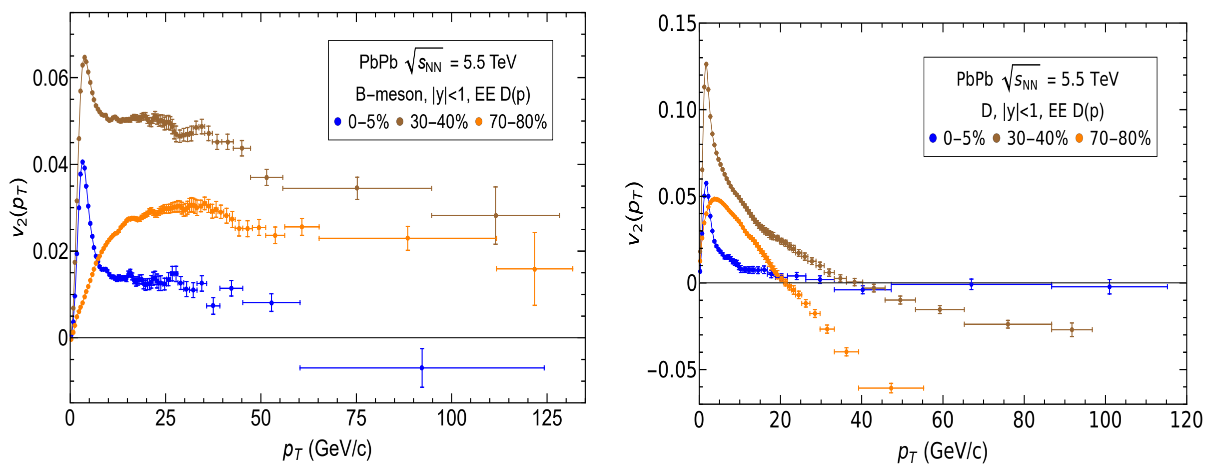
In Figure 3, we show the centrality dependence of the $v_2(p_T)$ for B and D mesons respectively. The $v_2(p_T)$ is low for central collisions and increases as we move up in centrality to semi-central collisions as a result of the increase in the geometrical asymmetry in the collision overlap region. The $v_2(p_T)$ is largest in semi-central collisions where the spatial anisotropy is largest and converts to a large momentum anisotropy and consequently large v_2. Generally, for the $D(p)$ scenario shown in Figure 3, the $v_2(p_T)$ is larger at low p_T for D mesons compared to B mesons at fixed centrality, and this is related to the strong fluctuations experienced by charm quarks due to their lower mass compared to bottom.

We have also shown the B and D meson comparison of the $v_2(p_T)$ predictions for each set of parameters for semi-central collisions (where we obtain the largest v_2) in Figure 4. Notice the anti-correlation of these $v_2(p_T)$ predictions to the $R_{AA}(p_T)$ results shown in Figure 2. We obtain the largest $v_2(p_T)$ for ET, $D(p)$ parameters, which corresponds to the $R_{AA}(p_T)$ and vice-versa. This anti-correlation is understood as follows: a larger energy loss implies that quarks are more sensitive to changes in geometry and thus results in a larger v_2.



(a) B mesons (b) D mesons

Figure 2. B and D-meson $R_{AA}(p_T)$ for various parameters at $\sqrt{s_{NN}} = 5.5$ TeV for the 30-40% centrality class.



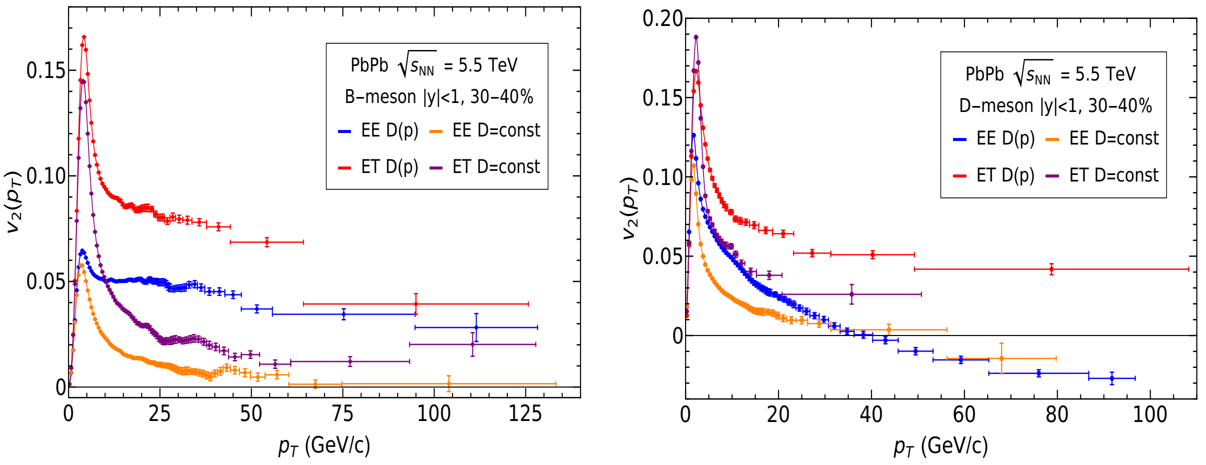
(a) B mesons (b) D mesons

Figure 3. *EE*, $D(p)$ $v_2(p_T)$ at $\sqrt{s_{NN}} = 5.5$ TeV for various centrality classes.

4. Conclusions

We have presented quantitative predictions for the $R_{AA}(p_T)$ and $v_2(p_T)$ for B and D mesons at $\sqrt{s_{NN}} = 5.5$ TeV for central, semi-central and peripheral collisions assuming a strongly coupled plasma and employing AdS/CFT techniques. These predictions have been made using four different sets of parameters to account for the theoretical systematic uncertainties due to the mapping of parameters in QCD and $\mathcal{N} = 4$ SYM.

We showed that the $R_{AA}(p_T)$ increases with centrality for both B and D mesons, which is expected as a result of the changing geometry with centrality. The model employing $D(p)$ parameters breaks down at high-p_T due to the growing fluctuations and is unreliable for D mesons for $p_T \gtrsim 15$ GeV/c, and *EE* parameters show less suppression compared to *ET* parameters due to the lower T and λ. We also showed that the $v_2(p_T)$ is largest in semi-central collisions where the geometrical asymmetry is largest, and is anti-correlated with the $R_{AA}(p_T)$. The peak in v_2 is larger for D mesons compared to B mesons, both for fixed centrality and fixed parameter



(a) B mesons

(b) D mesons

Figure 4. B and D-meson $v_2(p_T)$ at $\sqrt{s_{NN}} = 5.5$ TeV for the 30-40% centrality class.

set, which is a result of the lower mass of charm quarks that makes them more sensitive to the medium flow. A further discussion on B meson results at $\sqrt{s_{NN}} = 5.5$ TeV for other centralities and parameters can be found in [29].

One can also perform these calculations for other collision systems such as $Xe + Xe$ and this is left for future work. We would also like to incorporate pre-thermalisation energy loss effects (possibly following a pQCD approach), which could provide insights on the motion of the heavy quark prior the applicability of hydrodynamics.

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