Fluctuating open heavy flavour energy loss in a strongly coupled plasma with observables from rhic and the lhc

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Abstract. Heavy ion collisions at RHIC and at the LHC produce an enormous amount of energy that enables the nuclei and its constituent particles to melt, thus releasing gluons, quarks and antiquarks, travelling in different directions with different momenta. Studies of these collisions have shown that low transverse momentum observables describe a strongly coupled plasma (quark-gluon plasma), an almost perfect liquid that evolves hydrodynamically and flows with almost no viscosity [1, 2]. We make predictions for the suppression of these heavy quarks and thus describe the energy loss of the heavy quarks as they interact with the plasma; we show that these predictions are in good agreement with experimental data.

1. Introduction

One of the big questions of Physics is 'what happened shortly after the big bang?' Theory predicts that the early universe was composed of a hot mixture of particles (mainly weakly bound quarks and gluons) moving at nearly the speed of light [3]. Powerful particle accelerators can be used to recreate conditions of the early universe through colliding heavy ions. RHIC collides beams of ^{197}Au nuclei, each with a total energy of approximately 17TeV [4] while the LHC collides ^{208}Pb nuclei with a centre of mass energy of approximately 1000TeV [5].

Through these heavy-ion collision experiments, we can quantitatively extract the properties of nuclear matter and through some theoretical predictions, we can understand the properties of this nuclear matter better with the ultimate goal being to construct the phase diagram of nuclear matter [3]. This is a complicated task given that emergent phenomenon is not well understood practically, for example, we cannot predict the behaviour of a single water molecule (in a bucket of water) by simply applying Newton's laws and Maxwell's equations to it.

In these heavy-ion collisions, the temperatures of the material produced is in the order of a trillion Kelvin [3, 6, 7] and the best way of understanding it theoretically is yet to be known. This material is a new phase of matter called the quark-gluon plasma (QGP) [3] and is produced due to the very high temperatures. It is a state of strongly interacting matter where quarks and gluons are no longer confined to the colour-neutral hadrons [8]. In the formation of QGP, there has to be a phase transition and this comes as a natural consequence of the composite nature of hadrons in quantum chromodynamics (QCD) [3]. This phase transition has been found to be at a critical temperature $T_c \simeq 170MeV$, with an energy density $\epsilon_c \simeq 600MeV/fm^3$ [3, 9]. Hadronization starts to occur almost immediately after the collision, so the QGP has a very short lifetime (on the order of 4fm/c) at RHIC and on the order of 10fm/c at the LHC [3]. QGP can be understood better by looking at its coupling strength.

The interactions in Quantum Chromodynamics (QCD) are strong at low energy and decrease at high energy (asymptotic freedom) [10]. As a result, the strong interactions between quarks, antiquarks and gluons persist in the QGP and the dominant degrees of freedom in the QGP are thus light quarks, antiquarks and gluons [3]. Due to asymptotic freedom, the interaction strength weakens when large energies are exchanged in inter-particle collisions and interactions with a large momentum transfer can be treated in a perturbative way [11]. This asymptotic freedom regime is achieved when the temperature, $T \gg \Lambda_{QCD}$ (where $\Lambda_{QCD} \cong 200MeV$ is the QCD scale parameter) and the QGP is a weakly-interacting gas of slightly modifeid quarks and gluons that yields a plasma relatively transparent to hard probes[11] and calculations are performed using perturbative quantum chromodynamics (pQCD) [12, 13].

We're interested in the high transverse momentum particles because they are decay products of high transverse momentum partons and these are the most direct probe of the relevant degrees of freedom in a quark-gluon plasma [12, 14]. In the low momentum observables, QGP appears as a strongly coupled plasma that evolves hydrodynamically [15] and has almost no viscosity, making it the most perfect liquid observed. In this strong coupling regime, non-perturbative approaches such as AdS/CFT [16] need to be used to perform calculations and in this paper, we look at the energy loss of heavy flavour strongly-coupled to the medium.

Heavy flavour is more interesting because it puts more experimental constraints on the energy loss model and as a result, on the potential properties of the quark-gluon plasma [12]. It is important to compare our theoretical predictions to a wide range of experimental data, for example, by looking at the suppression of heavy flavour at different energies (i.e RHIC and the LHC) through the nuclear modification factor [13]. Some early results of the energy loss in the higher order strong coupling regime (AdS/CFT calculations) have shown favourable results of the measured nuclear modification factor $R_{AA}(p_T)$ of electrons from heavy flavour decay at RHIC [12, 17] but generally over-suppressed $R_{AA}(p_T)$ for D mesons at the LHC by a factor of approximately 5 [12, 18].

In this paper, we compute the nuclear modification factor ($R_{AA}(p_T)$) for bottom quarks at 5.5TeV and thus quantitatively describe the suppression of these heavy quarks at high transverse momentum.

2. Particle Geometry with the Optical Glauber Model

The Glauber model [19] is used to model the geometry of nuclei before a heavy-ion event. The Optical limit approximation of the Glauber model assumes that at high energies, the nucleons carry a sufficiently large momentum that they will be undeflected as nuclei pass through each other. As a result, for calculations, the nucleus is assumed to comprise of a smooth/continuous nucleon density (ρ). Assuming a spherical nuclei, the nucleon charge density (inside the nucleus) is given by the Woods-Saxon distribution [19]

$$\rho(r) = \frac{\rho_0}{1+e^{\left(\frac{r-R}{a}\right)}} \tag{1}$$

where ρ_0 is the nucleon density in the centre of the nucleus, $r = \sqrt{x^2 + y^2 + z^2}$, R is the nuclear radius and a is the "skin depth". For ^{208}Pb these parameters are; $R = 6.624 \pm 0.035 fm$ and $a = 0.549 \pm 0.008 fm$ respectively [20].

Perturbative QCD calculations are only valid for transverse momentum, $p_T \geq 1 GeV/c$ [21] and thus can't be used to determine the inelastic nucleon-nucleon cross section (σ_{inel}^{NN}) since the cross section involves processes with low momentum transfer (diffractive and elastic processes). As a result, the model takes in the experimental measured cross section data and this provides the only nontrivial beam-energy dependence for Glauber calculations. Table 1 gives the inelastic nucleon-nucleon cross section at collision energies appropriate for RHIC and the LHC.

Table 1: Values of the nucleon-nucleon inelastic cross section (σ_{inel}^{NN}) for collision-energies ($\sqrt{s}$) appropriate for RHIC and the LHC [20]

$\sqrt{s}(TeV)$	σ_{inel}^{NN} (mb)	σ_{inel}^{NN} (fm^2)
0.2	41.6 ±0.6	4.16
0.9	52.2 ±1.0	5.22
2.76	61.8 ±0.9	6.18
5.02	67.6 ±0.6	6.76
5.44	68.4 ±0.5	6.84
5.5	68.5 ±0.5	6.85

We consider two heavy-ions (target A and projectile B) colliding at relativistic speeds with impact parameter b. We focus on two flux tubes located at a displacement $(x - b/2, 0, 0)$ with respect to the center of the target nucleus and a displacement $(x + b/2, 0, 0)$ from the center of the projectile. During the collision these tubes overlap. The probability per unit transverse area of a given nucleon being located in the target/projectile flux tube is given by equation 2, while the joint probability per unit area of finding nucleons located in the respective overlapping target and projectile flux tubes is given by what is defined as the **thickness function** (equation 3).

$$T_{A/B}(x, y) = \int_{-\infty}^{\infty} \rho(x, y, z_{A/B}) dz_{A/B} \quad (2)$$

$$T_{AB}(b) = \int T_A \left(x - \frac{b}{2}, y \right) T_B \left(x + \frac{b}{2}, y \right) dxdy \quad (3)$$

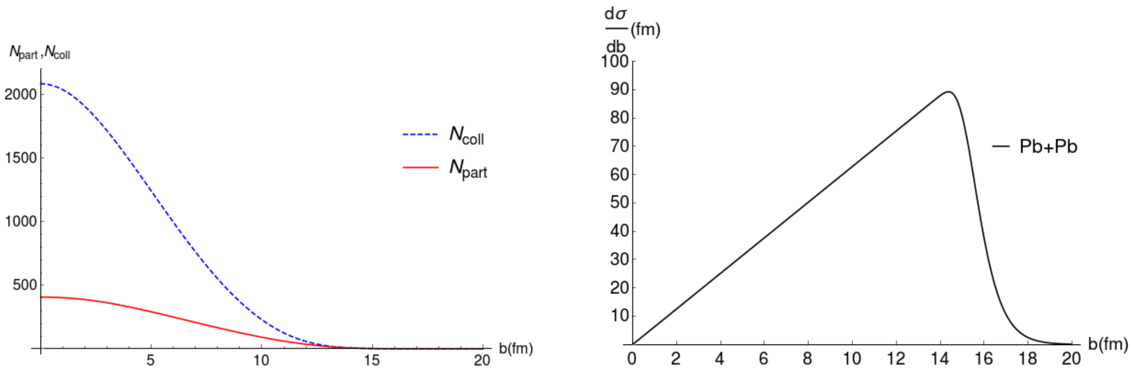
where $\rho(x, y, z_{A/B})$ is the probability per unit volume (normalised to unity), of finding a nucleon at a point $(x, y, z_{A/B})$ in the nucleus of projectile (A) or target (B).
We compute the total number of binary nucleon-nucleon collisions at impact parameter b (equation 4), the number of participants, which is the number of nucleons in the target and projectile nuclei that interacted at least once in a collision (equation 5) as well as the total geometric cross section (equation 7).

$$N_{coll}(b) = ABT_{AB}(b)\sigma_{inel}^{NN} \quad (4)$$

$$N_{part} = A \int T_A^-(1 - [1 + T_B^+]^B)dxdy + B \int T_B^+(1 - [1 + T_A^-]^A)dxdy \quad (5)$$

$$T_X^{\pm} = T_X\left(x \pm \frac{b}{2}, y\right) \tag{6}$$

$$\frac{d\sigma}{db} = 2\pi b(1 - [1 - T_{AB}(b)\sigma_{inel}^{NN}]^{AB}) \tag{7}$$



(a) N_{coll} and N_{part} as a function of impact parameter

(b) Total geometrical cross section as a function of impact parameter

Figure 1: Some geometric quantities in the optical limit of the Glauber model for Pb-Pb at 5.5TeV

3. Langevin Energy Loss

In the strong coupling regime, the dynamics of heavy quarks interacting with QGP is described by a stochastic differential equation known as the Langevin equation. In the fluid's rest frame, this equation is given by [22, 23]:

$$\frac{dp_i}{dt} = -\mu p_i + F_i^L + F_i^T \tag{8}$$

$$\mu = \frac{\pi\sqrt{\lambda}T^2}{2M_Q} \tag{9}$$

where p^i is the three-momentum of an on-shell heavy quark moving at constant velocity in a thermal bath, μ is the drag loss coefficient of a heavy quark, M_Q is the mass of the heavy quark in a plasma of temperature T and λ is the Hooft coupling constant. F_i^L and F_i^T are longitudinal and transverse momentum kicks with respect to the quark's direction of propagation. The energy loss model is described in detail in [23, 24] and is the first of its kind to include thermal fluctuations. The fluctuating momentum kicks are correlated as [24]

$$< F_i^L(t_1)F_j^L(t_1) > = \kappa_L \hat{p}_i\hat{p}_j g(t_2 - t_1) \tag{10}$$

$$< F_i^T(t_1)F_j^T(t_1) > = \kappa_T(\delta_{ij} - \hat{p}_i\hat{p}_j)g(t_2 - t_1) \tag{11}$$

where $\hat{p}_i = p_i/|\vec{p}|$ and g is a function only known numerically,

$$\kappa_T = \pi\sqrt{\lambda}T^3\gamma^{1/2} \tag{12}$$

$$\kappa_L = \gamma^2\kappa_T \tag{13}$$

The longitudinal direction of the heavy quark is the most important one for calculations of suppression observables and the detailed energy loss model is given by [24]. As mentioned earlier, our energy loss model requires the heavy quark to be moving at a constant velocity, as a result, we need to provide the quark with power to compensate for the momentum lost. Due to the restrictions around that power provided to the heavy quark, we end up with a speed limit on the heavy quark set-up given by,

$$\gamma < \gamma_{crit}^{sl} = \left(1 + \frac{2M_Q}{\sqrt{\lambda}T}\right) \sim \frac{4M_Q^2}{\lambda T^2} \tag{14}$$

4. Results

The main result of this paper is shown in Figure 3: which shows predictions for the nuclear modification factor ($R_{AA}(p_T)$) for bottom quarks at the LHC. We see a clear suppression of open heavy flavour at high transverse momentum for the various centrality classes studied, given with statistical uncertainties from the transverse momentum bins. It is also clear that the suppression is more pronounced for central collisions.

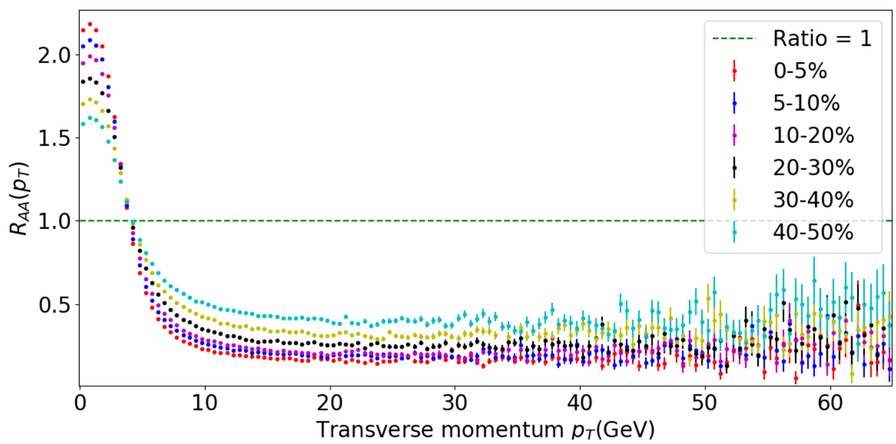


Figure 2: Nuclear modification factor ($R_{AA}(p_T)$) for bottom quark suppression at 5.5TeV

5. Conclusion and Outlook

Heavy flavour energy loss is crucial in understanding the properties of nuclear matter and thus trying to put together the phase diagram of nuclear matter. The Langevin energy loss model used in this paper is the first in the formulation of AdS/CFT correspondence to include thermal fluctuations and has been shown to be a success in computing several quantities from heavy ion collisions [15, 24, 25]. The results presented in this paper have shown that heavy flavour is largely suppressed for high transverse momentum.

The next steps of this work will be to look at the hadronization process decribed in [26] and compute predictions for the suppression of B mesons that these heavy quarks decay to, then compare the results to experimental data. Using this energy loss model, we will also look at the suppression of charm quarks and thus the suppression of D mesons. We will then be able to make predictions for higher energies of the upcoming runs of the LHC and potentially the FCC.

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