Heavy flavor electron \( R_{AA} \) and \( v_2 \) in event-by-event relativistic hydrodynamics

Caio A G Prado\(^1\), Mauro R Cosentino\(^{1,2}\), Marcelo G Munhoz\(^1\), Jorge Noronha\(^{1,3}\) and Alexandre A P Suaide\(^1\)

\(^1\) Instituto de Física, Universidade de São Paulo, C.P. 66318, 05315-970 São Paulo, SP, Brazil
\(^2\) Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Av. dos Estados 5001, Bairro Santa Terezina, 09210-508 Santo André, SP, Brazil
\(^3\) Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, USA

E-mail: caio.prado@usp.br mr.cosentino@gmail.com munhoz@if.usp.br noronha@if.usp.br suaide@if.usp.br

Abstract. In this work we investigate how event-by-event hydrodynamics fluctuations affect the nuclear suppression factor and elliptic flow of heavy flavor mesons and non-photonic electrons. We use a 2D+1 Lagrangian ideal hydrodynamic code \cite{1, 2} on an event-by-event basis in order to compute local temperature and flow profiles. Using a strong coupling inspired energy loss parametrization \cite{3} on top of the evolving space-time energy density distributions we are able to propagate the heavy quarks inside the medium until the freeze-out temperature is reached and a PYTHIA\cite{4} modeling of hadronization takes place. The resulting \( D^0 \) and heavy-flavor electron yield is compared with recent experimental data for \( R_{AA} \) and \( v_2 \) from the STAR and PHENIX collaborations \cite{5–7}. In addition we present predictions for the higher order Fourier harmonic coefficients \( v_3(p_T) \) of heavy-flavor electrons at RHIC’s \( \sqrt{S_{NN}} = 200 \text{ GeV} \) collisions.

1. Introduction

Central Au+Au collisions at RHIC and Pb+Pb at LHC exhibit a strong particle suppression when compared to \( p+p \) collisions as well as anisotropic flow. The suppression is usually related with jet quenching or energy loss of partons inside the quark-gluon-plasma (QGP) whereas the flow might be due to lumps of higher density inside the medium due to initial fluctuations. Furthermore while the QGP dynamics may affect differently the expansion of these high-density spots in comparison with the rest of the plasma it can affect higher harmonic orders of anisotropic flow such as \( v_3 \).

We aim to study these effects of the medium on the heavy quarks suppression during their evolution inside the QGP. In order to achieve this goal we performed computational simulations of the evolution of heavy quarks. The simulation consists of a sampled quark drawn from an initial condition energy density profile. The quark is then evolved inside the medium while the medium itself expands. The initial \( p_T \) distribution is given by First-Order Next-to-Leading Logs (FONLL \cite{8}) calculation. After evolution quarks reach the freeze-out temperature and hadronize. The resulting meson decays into electrons we can analyse and compare with experimental data of electron \( R_{AA} \) and \( v_2 \).
2. Simulation

This simulation takes for granted the factorization on QCD in order to follow a modular paradigm. This allows one to replace part of the calculation without affecting the other ones, for instance, one could change the energy loss model in order to study a different one. We can summarize the simulation with the following modules:

- Initial Conditions;
- Hydrodynamics;
- Energy loss model;
- Fragmentation;
- Meson decay.

Also, the simulation only takes into account the effects of the medium over the quark probes and not the other way around.

2.1. Initial Conditions

Initial conditions are constructed using a modified version of the PHOBOS Glauber Monte Carlo [9] code with default parameters, and selecting the appropriate centrality range. From the nucleons participants in the collision given by the PHOBOS simulation we can create an energy density profile for central rapidity by attributing gaussian distributions for each wounded nucleon and binary collision [10] with width given in terms of the inelastic nucleon-nucleon cross section [9]. The normalization factor which arises from this method is calculated by matching the maximum initial average temperature with literature values [11–14].

2.2. Hydrodynamics

The evolution of the medium is performed by an implementation of the Smoothed Particles Hydrodynamics (SPh) [1, 15] algorithm. We use a longitudinal expansion with boost invariance [16, 17] and set the initial transverse velocity to zero while also considering it to be independent of the rapidity. In addition we assume the baryon chemical potential to be zero. The equation of state eos s95n-v1 [18] is used in this work [2].

The evolution starts from $\tau = 1.0\text{fm/c}$ and we set the freeze-out temperature to 140 MeV [11, 12]. The smoothing SPh parameter is set to $h = 0.3\text{fm}$ in order to perform the simulation in a doable time while still preserving the important structures of the initial conditions. The evolution goes until the complete decoupling of the particles in the medium following the Cooper-Frye prescription [19]. The hydrodynamics is performed separately from the quark evolution.

2.3. Energy Loss Model

We draw quarks from the medium using the initial energy density profile as probability distribution for the initial position. From a FONLL calculation [8, 20, 21] we set the initial momentum of the quark with uniformly distributed $\varphi$ direction.

The quarks are propagated by a numerical integration of the energy loss over step distance. The integration is performed locally in the medium frame so Lorentz transformations are performed every step and this accounts for some quarks gaining energy while being pushed by the medium.

The parametrization used in these simulations for the energy loss is given by:

$$\frac{dE}{dx} \propto v \gamma(v)T^2, \quad (1)$$
where $v$ is the quark velocity, $\gamma(v)$ is the Lorentz factor and $T$ is the medium temperature. A similar expression is obtained by using AdS/CFT correspondence and a classical test string approximation to calculate the drag force on an external quark moving in a thermal plasma [3] and a Langevin simulation to describe the diffusion dynamics of heavy quarks in QGP [22].

The scale factor of the parametrization is fitted against experimental data, we use $D^0$ meson $R_{AA}$ for the charm quarks factor and the electron $R_{AA}$ for the bottom one.

2.4. Fragmentation, decay and output

After the propagation is performed and the quarks have reached the freeze-out temperature we use Peterson fragmentation function in order to hadronize the quarks which then decay into electrons using the semi-leptonic channels through PYTHIA8 [4].

The final output is the electron distribution after all quarks have hadronized and decayed. By analysing these electron spectra we can obtain heavy flavor electron $R_{AA}$ and $v_2$ in order to compare the results with experimental data.

3. Results

We now present some results that were obtained with the simulation. Figures 1 and 2 show the electron spectra for RHIC and LHC energies comparing both bottom and charm flavors with and without the energy loss. The ratio between them is the nuclear modification factor $R_{AA}$.

![Figure 1. Electron spectra for RHIC ($\sqrt{s_{NN}} = 200$ GeV) energy comparing charm and bottom flavors.](image1)

![Figure 2. Electron spectra for LHC ($\sqrt{s_{NN}} = 2.76$ TeV) energy comparing charm and bottom flavors.](image2)

We show the resulting $R_{AA}$ calculations for both RHIC and LHC energies in Figures 3 and 4. The simulation is performed separately for bottom and charm quark and in order to obtain the full $R_{AA}$ spectra we combine both results weighted by the FONLL cross section calculations. The spectra are compared with experimental data.

Also, in Figures 5 and 6 flow calculations for the RHIC energy. The results for $v_2$ are below the data which might be due to the energy loss model which we want to improve in order to obtain better results, also the $p_T$ range of the data is fairly limited in comparison with the available range for $R_{AA}$ spectra.

4. Conclusions

We implemented a 2D+1 Langrangian ideal hydrodynamic code on an event-by-event basis and evolved heavy quarks inside the expanding medium in order to obtain electron $p_T$ and $\varphi$
Figure 3. Electron nuclear modification factor for each quark flavor and the total one in comparison with experiment results for RHIC’

’s energy 200 GeV.

Figure 4. Electron nuclear modification factor for each quark flavor and the total one in comparison with experiment results for LHC’

’s energy 2.76 TeV.

Figure 5. Calculation of electron $v_2$ for RHIC energy.

Figure 6. Calculation of electron $v_3$ for RHIC energy.
spectra so we could calculate the nuclear modification factor $R_{AA}$ and the Fourier harmonic coefficients. Our framework is intentionally very modular so one could use it to test different models for energy loss, hydrodynamics or fragmentation, allowing for a comprehensive study of different aspects of the QGP phenomenology. We obtained $R_{AA}$ spectra for both RHIC and LHC energies.

References

[1] Andrade R P G and Noronha J 2013 *Phys. Rev. C* **88** 1–13 ISSN 0556-2813 URL http://link.aps.org/doi/10.1103/PhysRevC.88.034909
[2] Andrade R P G, Noronha J and Denicol G S 2014 *Phys. Rev. C* **90** 1–11 ISSN 0556-2813 URL http://link.aps.org/doi/10.1103/PhysRevC.90.024914
[3] Gubser S S 2006 *Phys. Rev. D* **74** 126005 ISSN 1550-7998 URL http://link.aps.org/doi/10.1103/PhysRevD.74.126005
[4] Sjostrand T, Mrenna S and Skands P 2008 *Comput. Phys. Commun.* **178** 852–867 ISSN 0010-4655 (Preprint 0710.3820) URL http://linkinghub.elsevier.com/retrieve/pii/S0010465508000441
[5] PHENIX Collaboration 2007 *Phys. Rev. Lett.* **98** 172301 ISSN 0031-9007 URL http://link.aps.org/doi/10.1103/PhysRevLett.98.172301
[6] STAR Collaboration 2007 *Phys. Rev. Lett.* **98** 192301 ISSN 0031-9007 URL http://www.ncbi.nlm.nih.gov/pubmed/17677616
[7] STAR Collaboration 2014 *Arxiv Prepr. arXiv1405.6348* 10 (Preprint 1405.6348)
[8] Cacciari M, Nason P and Vogt R 2005 *Phys. Rev. Lett.* **95** 1–4 ISSN 0031-9007 URL http://link.aps.org/doi/10.1103/PhysRevLett.95.122001
[9] Loizides C, Nagle J and Steinberg P 2014 *Arxiv Prepr. 1408.2549* 6 (Preprint 1408.2549) URL http://arxiv.org/abs/1408.2549
[10] Nonaka C and Bass S a 2007 *Eur. Phys. J. C* **49** 97–102 ISSN 14346044 (Preprint 0607018)
[11] Luzum M and Romatschke P 2009 *Phys. Rev. Lett.* **103** 262302 ISSN 0031-9007 URL http://link.aps.org/doi/10.1103/PhysRevLett.103.262302
[12] Luzum M, Gombeaud C and Ollitrault J Y 2010 *Phys. Rev. C - Nucl. Phys.* **81** 1–5 ISSN 05562813 (Preprint 1004.2024)
[13] Roy V and Chaudhuri a K 2011 *Phys. Lett. Sect. B Nucl. Elem. Part. High-Energy Phys.* **703** 313–317 ISSN 03702693 (Preprint 1103.2870) URL http://dx.doi.org/10.1016/j.physletb.2011.08.006
[14] Bhatt J R, Mishra H and Srekanth V 2011 *Phys. Lett. Sect. B Nucl. Elem. Part. High-Energy Phys.* **704** 486–489 ISSN 03702693 (Preprint 1103.4333) URL http://dx.doi.org/10.1016/j.physletb.2011.09.052
[15] Aguiar C E, Kodama T, Osada T and Hama Y 2000 *J. Phys. G Nucl. Part. Phys.* **27** 14 (Preprint 0006239) URL http://arxiv.org/abs/hep-ph/0006239
[16] Hwa R C 1974 *Phys. Rev. D* **10** 2260–2268 ISSN 05562821
[17] Bjorken J D 1983 *Phys. Rev. D* **27** 140–151 ISSN 05562821 URL http://link.aps.org/doi/10.1103/PhysRevD.27.140
[18] Huovinen P and Petreczky P 2010 *Nucl. Phys. A* **837** 26–53 ISSN 03759474 (Preprint 0912.2541) URL http://dx.doi.org/10.1016/j.nuclphysa.2010.02.015
[19] Cooper F and Frye G 1974 *Phys. Rev. D* **10** 186–189 ISSN 0556-2821 URL http://link.aps.org/doi/10.1103/PhysRevD.10.186
[20] Cacciari M, Greco M and Nason P 1998 *J. High Energy Phys.* **1998** 007–007 ISSN 1029-8479
[21] Cacciari M and Frixione S 2001 J. High Energy Phys. 2001 006–006 URL http://iopscience.iop.org/1126-6708/2001/03/006

[22] Akamatsu Y, Hatsuda T and Hirano T 2009 Phys. Rev. C 79 054907 ISSN 0556-2813 URL http://link.aps.org/doi/10.1103/PhysRevC.79.054907

[23] de Godoy D M and ALICE Collaboration 2014 Elliptic azimuthal anisotropy of heavy-flavour decay electrons in Pb-Pb collisions at SNN = 2.76 TeV measured with ALICE AIP Conf. Proc. vol 1625 pp 226–229 ISBN 9780735412620 URL http://scitation.aip.org/content/aip/proceeding/aipcp/10.1063/1.4901799