Abstract

We calculate open heavy-flavor (HF) transport in relativistic heavy-ion collisions by applying a strong-coupling treatment in both macro- and microscopic dynamics (hydrodynamics and non-perturbative diffusion interactions). The hydrodynamic medium evolution is quantitatively constrained by bulk and multi-strange hadron spectra and elliptic flow. The heavy quark (HQ) transport coefficient is evaluated from a non-perturbative $T$-matrix approach in the Quark-Gluon Plasma (QGP) which, close to the critical temperature, leads to resonance formation and feeds into the recombination of heavy quarks on a hydrodynamic hypersurface. In the hadronic phase, the diffusion of HF mesons is obtained from effective hadronic theory. We compute observables at RHIC and LHC for non-photonic electrons and HF mesons, respectively.

Keywords: Heavy Quark, Quark-Gluon Plasma, Heavy-ion Collisions, Non-perturbative Diffusion

1. Introduction

A deconfined state of nuclear matter has been predicted by large-scale numerical simulations of Quantum Chromodynamics (QCD) on the lattice [1,2]. Utilizing ultra-relativistic heavy-ion collision (URHIC) experiments, this new phase has been identified as a strongly coupled Quark-Gluon Plasma (sQGP) [3,4]. With the advent of LHC, the endeavor of characterizing the properties of sQGP has entered a new stage [5,6].

Heavy quarks, due to their large masses ($m_c \approx 1.3$ GeV for charm and $m_b \approx 4.2$ GeV for bottom), are produced in primordial hard collisions [7], and their number is expected to be conserved in the subsequent evolution of the medium. Through interactions with medium constituents, the spectra of HQs are modified, yet they may not fully thermalize. This makes them valuable probes of the hot and dense matter created in URHICs [8]. The suppression of non-photonic electrons ($e^\pm$) from HF decays measured in Au+Au ($\sqrt{s_{NN}} = 200$ GeV) at RHIC [9,10,11] is surprisingly large, and their elliptic flow [10,11] indicates a substantial collectivity of charm quarks. It is difficult to explain these results within perturbative QCD approaches [12,13,14,15] for HQ scattering in the QGP. They rather indicate the need for a non-perturbative treatment of HQ diffusion in the low- and intermediate-momentum region [16].

Here, we report on applications of our recently developed non-perturbative framework for open HF transport in medium [17] to $D$- and $B$-meson observables at LHC, and predict upcoming RHIC data for flavor-separated $e^\pm$ spectra.

2. Theoretical Framework: HQ Transport and Hadronization

The kinetics of HQs in the QGP can be described by Fokker-Planck dynamics, which in practice is simulated through relativistic Langevin diffusion [8]. The required transport coefficient is the HQ thermal relaxation rate,
meson masses are used: $\Gamma_{\eta}$ of the scattering rate, and thus consistent with the underlying transport coefficient $\delta^4$ are treated with resonance recombination [24, 17] with thermal light quarks on the pertinent hydro-hypersurface. Remaining heavy quarks found in Ref. [17]. Open Heavy-Flavor Observables hadronic phase until hydrodynamic kinetic freezeout at $T_{\text{kin}}$, the in-medium quark and meson masses are used: $m_q = 0.3$ GeV, $m_c = 1.7$ GeV, $m_b = 5.2$ GeV, $m_D = 2.1$ GeV and $m_B = 5.6$ GeV, with D- and B-meson widths of $\Gamma_{D,B} = 0.1$ GeV. After hadronization, the Langevin simulation resumes for D and B mesons in the hadronic phase until hydrodynamic kinetic freezeout at $T_{\text{kin}} = 110$ MeV.

3. Open Heavy-Flavor Observables

3.1. Flavor-separated non-photonic electrons at RHIC

The measured $e^+\nu$ nuclear suppression factor, $R_{AA}$, and elliptic flow, $v_2$, for Au+Au ($\sqrt{s_{NN}}=200$ GeV) collisions thus far are superpositions of open-charm and -bottom contributions [9] [10] [11]. In anticipation of experimental
Figure 2: (Color online) $D$-meson $R_{AA}$ (left panel) and $v_2$ (right panel) in Pb+Pb ($\sqrt{s_{NN}}=2.76$ TeV) collisions, compared to ALICE data \cite{28,29}. Our results for charm quarks, $D$ mesons after hadronization at $T_\text{c}$ and after hadronic diffusion at $T_{\text{kin}}$, are shown separately. The bands indicate the prevalent uncertainties in each case: shadowing (64.0%-77.6%) for $R_{AA}$ and charm-quark coalescence probability (50%-90%) for $v_2$.

Figure 3: (Color online) $B$-meson $R_{AA}$ (left panel) and $v_2$ (right panel) for Pb+Pb ($\sqrt{s_{NN}}=2.76$ TeV) collisions. No shadowing is assumed. The average $p_T$ of the CMS datum \cite{30} on non-prompt $J/\psi$ has been rescaled by $m_B/m_{J/\psi}$. Our results for charm- and bottom-separated $e^\pm$ \cite{25}, we present in Fig. 1 our pertinent predictions. The charm-$e^\pm$ $R_{AA}$ exhibits a flow bump at $p_T^c \approx 1.5$ GeV, which is a combined consequence of charm-quark thermalization in the QGP diffusion processes and the subsequent coalescence with thermal light quarks at hadronization \cite{17}. Note that, from a microscopic point of view, both processes are of identical origin (heavy-light quark $T$-matrix). At $p_T^c \approx 5$ GeV, the charm-$e^\pm$ suppression reaches 0.2-0.3. In accord with approaching thermalization in the suppression factor, the charm-$e^\pm$ also acquires substantial elliptic flow, reaching $\sim$8% at $p_T^c \approx 2$ GeV. Bottom electrons suffer less suppression, at least below $p_T^b \approx 5$ GeV, due to the larger $b$-quark mass. We also observe the bottom-$e^\pm$ $v_2$ to saturate at a significantly larger $p_T^b$ than for charm, as a result of the larger $m_b/m_q$ ratio that is operative in picking up light-quark $v_2$ through coalescence.

3.2. $D$ and $B$ mesons at LHC

Next, we apply our non-perturbative approach to the LHC. Toward this end, we employ FONLL pQCD \cite{26} $D_0$-meson and $B$-meson spectra in $\sqrt{s} = 2.76$ TeV $p+p$ collisions as our baseline, which yield good agreement with the ALICE $D_0$ spectrum \cite{27}. Assuming $\delta$-function fragmentation and folding with EPS09 shadowing \cite{28}, we obtain our initial HQ spectra for the Langevin simulations. The hydrodynamic medium evolution model has been tuned to available hadron data at the respective centralities, reproducing fairly well charged-hadron multiplicities, spectra and $v_2$ at $T_{\text{kin}}$ and $\Omega^-$ observables at $T_\text{c}$.

In Fig. 2 we display our calculated $D$-meson $R_{AA}$ and $v_2$ for central and semi-central collisions, respectively. The flow bump in the $c$-quark $R_{AA}$ at low $p_T$ is amplified via coalescence at the $D$-meson level. Diffusion of $D$ mesons in
the hadronic phase slightly reduces the $D$-meson $R_{AA}$ at high $p_T$, and increases the $v_2$ up to 20%. Our $D$-meson $R_{AA}$ appears to be systematically slightly too high but it reproduces the $p_T$-shape of the data [23] rather well, largely induced by the falling momentum-dependence of the non-perturbative $c$-quark relaxation rate [18][20]. The deviation from the data possibly indicates a missing radiative energy-loss contribution. For the $D$-meson $v_2$ we note that $c$-quark diffusion through the QGP only accounts for about half of its final value. Coalescence with light quarks and $D$-meson diffusion in hadronic phase cannot be neglected. Again, the apparent underprediction of the ALICE data, especially at higher $p_T$ where the the momentum-dependence of the elastic $c$-quark relaxation rate drops significantly, might call for an inclusion of radiative contributions. We note that such an assessment is only possible in the absence of phenomenological $K$-factors.

The $B$-meson results, shown in Fig. 3, show a substantial suppression of $R_{AA} \approx 0.4$ at $p_T > 10$ GeV, while the $v_2$, reaching up to 5%, indicates less collectivity (and thus less thermalization) than for $D$'s. The $B$-meson modifications also impact $J/\psi$'s via a so-called “non-prompt” feeddown. In this context it is interesting to quote the suppression of non-prompt $J/\psi$ of the CMS collaboration [30], which is $\sim 0.37 \pm 0.08$ at an average $p_T^{J/\psi} \approx 9.3$ GeV, in good agreement with our $B$-meson result at a correspondingly somewhat larger parent momentum.

4. Conclusions

We have evaluated heavy-flavor probes at RHIC and LHC within a non-perturbative framework for bulk evolution and microscopic interactions in the diffusion process [17]. Initial comparisons to $e^+\bar{e}^-$, $D$- and $B$-meson observables at RHIC and LHC are encouraging.

Acknowledgments.— This work was supported by the U.S. National Science Foundation (NSF) through CAREER grant PHY-0847538 and grant PHY-0969394, by the A.-v.-Humboldt Foundation, and by the JET Collaboration and DOE grant DE-FG02-10ER41682.

References

[1] Y. Aoki, G. Endrodi, Z. Fodor, S. D. Katz and K. K. Szabo, Nature 443 (2006) 675.
[2] A. Bazavov, T. Bhattacharya, M. Cheng, C. DeTar, H. T. Ding, S. Gotsheb, R. Gupta and P. Hegde et al., Phys. Rev. D 85 (2012) 054503.
[3] J. Adams et al. [STAR Collaboration], Nucl. Phys. A757 (2005) 102.
[4] K. Adcox et al. [PHENIX Collaboration], Nucl. Phys. A757 (2005) 184.
[5] B. Abelev et al. [ALICE Collaboration], Phys. Rev. Lett. 105 (2010) 252301.
[6] K Aamodt et al. [ALICE Collaboration], Phys. Rev. Lett. 105 (2010) 252302.
[7] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 94, 082301 (2005).
[8] R. Rapp and H. van Hees, R. C. Hwa, X.-N. Wang (Ed.) Quark Gluon Plasma 4, World Scientific, 111 (2010) [arXiv:0903.1096 [hep-ph]].
[9] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. Lett. 98 (2007) 192301.
[10] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 98 (2007) 172301.
[11] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 84 (2011) 044905.
[12] N. Armesto, M. Cacciari, A. Daniese, C. A. Salgado, and U. A. Wiedemann, Phys. Lett. B637 (2006) 362.
[13] P. B. Gossiaux and J. Aichelin, Phys. Rev. C 78 (2008) 014904.
[14] W. M. Alberico et al., Eur. Phys. J. C 71 (2011) 1666.
[15] J. Uphoff, O. Fochler, Z. Xu, and C. Greiner, Phys. Rev. C 84 (2011) 024908.
[16] H. van Hees, V. Greco and R. Rapp, Phys. Rev. C 73 (2006) 034913.
[17] M. He, R. J. Fries and R. Rapp, Phys. Rev. C 86 (2012) 014903.
[18] F. Riek and R. Rapp, Phys. Rev. C 82 (2010) 035201.
[19] M. He, R. J. Fries and R. Rapp, [arXiv:1204.4442 [nucl-th]].
[20] K. Huggins and R. Rapp, [arXiv:1206.6537 [hep-ph]].
[21] M. He, R. J. Fries and R. Rapp, Phys. Lett. B701 (2011) 445.
[22] M. He, R. J. Fries and R. Rapp, Phys. Rev. C 85 (2012) 044911.
[23] S. Borsanyi, G. Endrodi, Z. Fodor, A. Jakovac, S. D. Katz, S. Krieg, C. Ratti and K. K. Szabo, JHEP 1011 (2010) 077.
[24] L. Ravagli and R. Rapp, Phys. Lett. B655 (2007) 126.
[25] R. Nouicer, private communication (2011).
[26] M. Cacciari, M. Greco and P. Nason, JHEP 9805 (1998) 007; M. Cacciari, S. Frixione and P. Nason, JHEP 0103 (2001) 006.
[27] B. Abelev et al. [ALICE Collaboration], JHEP 1201 (2012) 128.
[28] B. Abelev et al. [ALICE Collaboration], [arXiv:1203.2160 [nucl-ex]].
[29] G. Ortona, these proceedings.
[30] S. Chatrchyan et al. [CMS Collaboration], JHEP 1205 (2012) 063.