How sensitive are high-$p_T$ electron spectra at RHIC to heavy quark energy loss?

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In nucleus–nucleus collisions, high-$p_T$ electron spectra depend on the medium modified fragmentation of their massive quark parents, thus giving novel access to the predicted mass hierarchy of parton energy loss. Here we calculate these spectra in a model, which supplements the perturbative QCD factorization formalism with parton energy loss. In general, we find - within large errors - rough agreement between theory and data on the single inclusive electron spectrum in pp, its nuclear modification factor $R_{AA}$, and its azimuthal anisotropy $v_2$. However, the nuclear modification factor depends on the relative contribution of charm and bottom production, which we find to be affected by large perturbative uncertainties. In order for electron measurements to provide a significantly more stringent test of the expected mass hierarchy, one must then disentangle the $b$- and $c$-decay contributions, for instance by reconstructing the displaced decay vertices.

1. Introduction

The semi-leptonic decays of charmed and beauty mesons dominate the high-$p_T$ electron spectrum in $\sqrt{s_{NN}} = 200$ GeV hadronic collisions at the Brookhaven Relativistic Heavy Ion Collider (RHIC) up to $p_T \approx 20$ GeV, where the Drell–Yan contribution starts to become significant. At the 30 times higher center of mass energies of the CERN Large Hadron Collider (LHC), heavy quark decays are expected to dominate the electron spectrum up to $p_T \approx 30 - 35$ GeV, where $W$-decay contributions take over. In relativistic nucleus–nucleus collisions, such electron spectra are of great interest, since they are expected to give access to the medium modified fragmentation of their heavy quark par-
ents [1–4]. Models of strongly medium-enhanced fragmentation of light quarks and gluons [5–9] are favored by RHIC data, which show a strong suppression of high-$p_T$ hadron spectra and hadron-triggered correlation functions [10–13]. Establishing the dependence of this suppression on the mass and color charge of the parent parton provides a novel opportunity to further test the microscopic picture conjectured to underlie medium-induced high-$p_T$ hadron suppression [14]. This may also help to further constrain information about the density and collective dynamics of the QCD matter produced in heavy ion collisions, for which parton energy loss is considered to be a sensitive probe.

Preliminary RHIC data on single inclusive electrons in Au–Au collisions [15, 16] extend over a wider transverse momentum range, up to $p_T \sim 10$ GeV, than previously published results [17]. The purpose of this letter is to assess to what extent these spectra and their azimuthal asymmetry [18, 19] are in agreement with our current understanding of medium-induced parton energy loss, and how they can help us to access in more detail the microscopic mechanisms underlying high-$p_T$ hadron suppression. To this end, we determine the sensitivity of the nuclear modification factor for single electrons $R_{AA}(p_T)$ on uncertainties in the $b$- and $c$-benchmark cross sections, we quantify the possible contamination of $R_{AA}(p_T)$ from other hard processes (namely Drell–Yan), and we study its dependence on those properties of the nuclear matter, which are expected to induce the energy degradation of hard parent partons.

2. Uncertainties of the proton–proton benchmark

Heavy quark production in proton–proton collisions can be calculated in perturbative QCD via the collinear factorization approach [20–22]. In Fig. 1, we show the resulting electron spectrum for $\sqrt{s_{NN}} = 200$ GeV pp collisions at RHIC. This spectrum was obtained [23] by complementing a fixed-order plus next-to-leading-log-resummed (FONLL [24,25]) heavy quark $p_T$ distribution with proper fragmentation functions, describing the hadronization into heavy hadrons, and with the subsequent decay of the heavy hadrons into electrons. The Drell–Yan contribution, also shown in Fig. 1, is obtained using PYTHIA [26], with a Drell–Yan cross section rescaled such that the $e^+ e^-$ invariant mass distribution matches the one given by the NLO calculation in Ref. [27]. The curves in Fig. 1 reflect central values of a calculation, in which the Drell–Yan contribution to the single electron spectrum is about 10% at $p_T^e = 10$ GeV. This implies that neglecting the Drell–Yan contribution in computations of the nuclear modification factor of single electrons, one reduces $R_{AA}^{e}$ by up to 0.1. However, the theoretical uncertainties are large. At smaller transverse momenta $p_T^e$, on which we focus in this paper, Drell–Yan becomes even smaller (see Fig. 1), and will be neglected in what follows.
Fig. 1. (Color online) Contributions from semi-leptonic heavy quark decays and from Drell–Yan pairs to the single inclusive electron spectrum in proton-proton collisions at $\sqrt{s} = 200$ GeV, calculated with NLO accuracy.

In Fig. 2a, we compare the perturbative FONLL result for the single electron spectrum in $\sqrt{s} = 200$ GeV pp collisions [23] to data from the PHENIX collaboration at RHIC [28]. Upper and lower lines of the different decay contributions indicate theoretical uncertainties: they were estimated by varying the factorization and renormalization scales independently in the range $m_T/2 < \mu_F,\mu_R < 2m_T$ with the constraint $0.5 < \mu_F/\mu_R < 2$. In addition, we have varied quark masses around their central values $m_c = 1.5$ GeV and $m_b = 4.75$ GeV over the range $1.3 < m_c < 1.7$ GeV, $4.5 < m_b < 5.0$ GeV. These effects were then added in quadrature. The uncertainties related to the fragmentation picture, intrinsically ambiguous in the $p_T \lesssim m$ region, were not explicitly considered here, as they are not expected to be very large (see for instance [29]). Within errors, the comparison between FONLL predictions and experiment is fair, see Fig. 2a. However, the central value of the FONLL calculation under-estimates the central value of the measured electron yields by a factor 2–3. Thus, an ad hoc increase of the charm cross section by a factor of three, large but still at the borderline of the above-mentioned uncertainties, would bring the central values of experiment and theory into agreement (data not shown). This illustrates that there is only limited control over the proton–proton baseline, on top of which one aims at establishing medium effects. Another illustration of this is that the $b$-quark decay contribution may start dominating over the $c$ quark one at a transverse momentum as low as $p_T^e = 2.5$ GeV or as high as $p_T^e = 9.5$ GeV (see Fig. 2). This translates into a
significant uncertainty in $R_{AA}^e$, as we discuss now.

Fig. 2. (Color online) (a) Left: Comparison of the FONLL calculation of single inclusive electrons [23] to data from pp collisions at $\sqrt{s} = 200$ GeV [28]. Upper and lower lines are estimates of theoretical uncertainties, obtained by varying scales and masses, for details see text. (b) Right: The nuclear modification factor $R_{AA}^e$ of electrons in central Au–Au collisions for an opacity of the produced QCD matter characterized by the time-averaged BDMPS transport coefficient $\hat{q} = 14$ GeV$^2$/fm. The shaded band indicates the theoretical uncertainty of the perturbative baseline only. Red dashed and blue dotted curves show $R_{AA}^e$ for $c$-quark and $b$-quark decay contributions, respectively. Data taken from Ref. [15, 16].

3. The nuclear modification factor for single electrons in Au–Au collisions at RHIC

The medium-induced suppression of high-$p_T$ electrons in nucleus–nucleus collisions can be characterized by the nuclear modification factor $R_{AA}^e(p_T)$, which compares the production of electrons in AA collisions to an equivalent number of pp collisions,

$$R_{AA}^e(p_T) = \frac{d^2N_{AA\rightarrow e}/dp_T
dy\big|_{y=0}}{(N_{AA\text{coll}}) \ d^2N_{pp\rightarrow e}/dp_T
dy\big|_{y=0}}.$$ (3.1)
Here, $\langle N_{\text{coll}}^{AA} \rangle$ is the average number of inelastic nucleon–nucleon collisions in a given centrality class. We calculate $R_{\text{AA}}^{e}$ according to the model used successfully for the description of suppressed high-$p_T$ light-flavored hadron production [6,7]. To calculate $d^2N_{\text{medium}}^{AA\rightarrow e}/dp_Tdy$, we start from the FONLL spectrum of final state heavy quarks in pp collisions. The nuclear modification of parton distribution functions is expected to be at most a 10% effect and can be safely neglected in our calculation [14]. We calculate the medium-induced energy degradation of the partonic spectrum by means of quenching weights for massive quarks [2, 14], before fragmenting the energy-degraded partons in the vacuum according to FONLL fragmentation functions. This assumes that the interplay between quenching and hadronization can be neglected. Our treatment of medium effects is based on a realistic description of the collision geometry used to compute the in-medium path length and medium density on the parton-by-parton level [6, 7].

![Graph](image)

**Fig. 3.** (Color online) The nuclear modification factor for single electrons in central Au–Au collisions at RHIC. Curves indicate the suppression for different opacities of the produced matter. The shaded band indicates the theoretical uncertainty of the perturbative baseline for $\hat{q} = 14 \text{ GeV}^2/\text{fm}$.

The effect of parton energy loss on single inclusive spectra depends on the color charge and mass of the parent parton, its in-medium path length $L$, and the time-averaged squared momentum transfer from the medium to the partonic projectile, which is characterized by the BDMPS transport coefficient $\hat{q}$ [30]. Previous studies have shown that for $4 < \hat{q} < 14 \text{ GeV}^2/\text{fm}$, this model of parton energy loss accounts for the strength and approximate $p_T$-independence of light hadron suppression at RHIC [6, 7]. In Fig. 2b, we show the nuclear
modification factor (3.1) for \( \dot{q} = 14 \text{GeV}^2/\text{fm} \). For this large value of \( \dot{q} \), a calculation anchored on the FONLL perturbative baseline tends to over-estimate \( R_{AA}^e \). However, due to the sizable theoretical and experimental errors, claims about an inconsistency between theory and experiment are not supported by Fig. 2b. We observe that an experimental separation of \( b \)- and \( c \)-decay electrons would strongly enhance the sensitivity to the mass hierarchy of parton energy loss. Indeed, since the mass dependence of charm quark energy loss vanishes as a function of \( (m_c/p_{Tc})^2 \), the suppression of electrons from charm decays is comparable to that of light-flavored hadrons. In contrast, electrons from \( b \)-decays are much less suppressed due to the larger mass of their quark parents, see Fig. 2b and Ref. [31].

In Fig. 3, we compare the same data on the nuclear modification factor to central values of the parton energy loss model, calculated for different values of the transport coefficient \( \dot{q} \). By comparing Fig. 3 with the corresponding results for the nuclear modification factor \( R_{AA}^h \) for light hadrons [6,7], we find that for the experimentally favored range \( \dot{q} = 4 - 14 \text{GeV}^2/\text{fm} \), the difference between \( R_{AA}^e \) and \( R_{AA}^h \) is roughly 0.2. In general, the theoretical uncertainty in calculating the partonic baseline spectrum is comparable to the model-intrinsic uncertainty in determining \( \dot{q} \). For instance, the central value for \( \dot{q} = 10 \text{GeV}^2/\text{fm} \) lies within the perturbative uncertainty band of \( \dot{q} = 14 \text{GeV}^2/\text{fm} \). We also note that as \( \dot{q} \) increases, the suppression gradually saturates. This is due to the fact that at high opacity, particle production becomes surface biased, thereby decreasing the sensitivity of the nuclear modification factor on \( \dot{q} \) [7,32]. Since heavy quarks lose less energy than light quarks or gluons, this surface bias becomes important at higher values of \( \dot{q} \). Thus, if experimental and theoretical errors can be controlled, the measurement of the decay products of heavy quarks does have the potential to improve the characterization of the very opaque medium observed at RHIC [31].

Calculating in “minimum bias” (0–80 %) Au–Au collisions the angular dependence of the yield of heavy quark decay electrons with respect to the reaction plane, we can determine the azimuthal asymmetry, expected from parton energy loss in a spatially asymmetric medium [33,34]. This asymmetry is characterized by the so-called elliptic flow, which is the second harmonic coefficient \( v_2 \) in the Fourier decomposition of the angular dependence \( \phi \) with respect to the orientation \( \Psi_R \) of the reaction plane, \( dN^{AA\rightarrow e}/dp_T \, dp_T \, d\phi \propto 1 + 2 v_2(p_T) \cos[2(\phi - \Psi_R)] \) [35]. At low transverse momenta, other collective phenomena are expected to dominate \( v_2 \) for heavy quarks and their decay electrons [36–41]. However, for \( p_T > 2 \text{GeV} \), the azimuthal dependence of the energy loss of heavy quarks may be the dominant contribution to the observed asymmetry. As seen in Fig. 4, preliminary data in this kinematic regime show significant uncertainties, and our calculation favors a non-vanishing but small value for the high-\( p_T \) azimuthal asymmetry of electrons. In the presence of collective transverse flow effects, the BDMPS transport coefficient may be
sensitive to a combination of energy density and directed collective motion. This is expected to further increase high-$p_T$ $v_2^e$ \cite{34, 42}. Thus, our present study does not allow us to exclude values of $v_2^e$ which are somewhat larger than $v_2^e = 0.05$, but it strongly disfavors $v_2^e > 0.1$.

![Plot of azimuthal asymmetry of single inclusive electron spectrum](image_url)

Fig. 4. (Color online) The azimuthal asymmetry of the single inclusive electron spectrum in Au–Au collisions at 0-80% centrality, compared to our model of parton energy loss. Data taken from Refs. \cite{18, 19}.

4. Conclusions

Our study indicates that for the parameter range $\hat{q} = 4 - 14$ GeV$^2$/fm of the BDMPS transport coefficient favored by the suppression of light hadron spectra at RHIC, the nuclear modification factor $R_{e AA}$ of single electrons is $\sim 0.2$ larger than that of light-flavored hadrons. Thus, single electron spectra are in principle sensitive to the expected mass hierarchy of parton energy loss. Moreover, since massive quarks lose less energy than light ones in the medium, their spectrum starts being dominated by surface emission for higher medium densities only. Thus, single electron spectra may increase the experimental sensitivity to the properties of the produced matter in the region of high opacity.

However, to exploit these opportunities of single electron measurements in nucleus–nucleus collisions demands a significantly better control of the vari-
ous sources of uncertainties. The preliminary data available so far neither allow us to support claims of an inconsistency between theory and experiment, nor do they support yet the theoretically expected mass hierarchy of nuclear modification factors. Here, we have contributed to the generally needed assessment of uncertainties by characterizing the theoretical ones. In particular, we have established that uncertainties in the perturbative baseline are significant, and should not be neglected in calculations of the nuclear modification factor. If future experiments succeeded in disentangling the $b$- and c-decay contributions (e.g. by reconstructing the displaced decay vertices), this would remove a significant source of theoretical uncertainty, dramatically enhancing the experimental sensitivity to the mass hierarchy of parton energy loss, as can be seen from Fig. 2b. As an aside, we note that single electron spectra are not the only possibility to characterize the mass dependence of parton energy loss. Decay muons may provide another, as yet unexplored possibility. Also, topologically reconstructed $D$- and $B$-mesons provide an alternative and much more versatile access to the same information, which is particularly promising at the LHC [14, 43].

We finally emphasize that, although preliminary RHIC data favor high values ($\hat{\rho} = 14\text{ GeV}^2/\text{fm}$) of the BDMPS transport coefficient, significantly smaller densities given by $\hat{\rho} = 10\text{ GeV}^2/\text{fm}$ reproduce the data almost as satisfactorily, since their theoretical uncertainties largely overlap (see Fig. 3). The densities required in our calculation to obtain $R_{AA}^{p_T}(p_T = 10\text{ GeV}) = 0.4$ are not larger than those used previously [6, 7] for the characterization of light hadron suppression.

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