Recent PQCD calculations of heavy quark production

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Abstract.
We summarize the results of a recent study of heavy quark production and attenuation in cold nuclear matter. In p+p collisions, we investigate the relative contribution of partonic sub-processes to D meson production and D meson-triggered inclusive di-hadrons to lowest order in perturbative QCD. While gluon fusion dominates the creation of large angle $D\bar{D}$ pairs, charm on light parton scattering determines the yield of single inclusive $D$ mesons. The distinctly different non-perturbative fragmentation of $c$ quarks into $D$ mesons versus the fragmentation of quarks and gluons into light hadrons results in a strong transverse momentum dependence of anticharm content of the away-side charm-triggered jet. In p+A reactions, we calculate and resum the coherent nuclear-enhanced power corrections from the final-state partonic scattering in the medium. We find that single and double inclusive open charm production can be suppressed as much as the yield of neutral pions from dynamical high-twist shadowing. Effects of energy loss in p+A collisions are also investigated in the incoherent Bertsch-Gunion limit and may lead to significantly weaker transverse momentum dependence of the nuclear attenuation.

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1. Introduction

A useful probe of the dense nuclear matter created in collisions of heavy nuclei at the relativistic heavy ion collider (RHIC) is one that is sensitive to dynamical scales and can be both cleanly measured experimentally and reliably calculated theoretically [1]. Because of color confinement, only hard probes, i.e. those with large momentum transfers, can be reliably calculated in the perturbation theory of Quantum Chromodynamics (QCD). Experimental measurements of inclusive particle suppression are now able to test jet quenching theory out to transverse momenta as large as $p_T \sim 20$ GeV [2]. On the other hand, typical dynamical scales of the nuclear matter produced in relativistic heavy ion collisions are on the order of hundreds of MeV, which is both much smaller than the scale of a hard probe and non-perturbative. Therefore, an ideal probe should be not only “hard” but also sensitive to this “soft” physics. Open charm production has a potential to satisfy these criteria because of the

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two distinctive scales of the open charm meson: the charm quark mass, \( m_c \sim 1.5 \) GeV, a relatively hard scale, and the binding energy, \( \sim M_D - m_c \sim \) hundreds MeV, which may be relevant to the fragmentation and dissociation of \( D \) mesons.

With this in mind, we present a baseline study of heavy quark production and the first results on heavy-quark-triggered large-angle correlations in elementary nucleon-nucleon reactions [1]. Next, we investigate the many-body QCD effects in single- and double-inclusive open charm production. Because of the quantitative importance of multiple scattering for inferring properties of the nuclear matter, the models of in-medium interactions should be subjected to experimental verification for heavy-flavor production. One may begin to gain confidence by applying the theoretical description of such effects to heavy ion collisions in simpler situations, such as proton-nucleus (p+A) scattering. In this case, plasma properties are not an issue and the main medium effect is, therefore, due to the multiple interactions in cold nuclei. The medium effects that we plan to investigate are also present in nucleus-nucleus (A+A) reactions during the interaction time \( \tau_{\text{int.}} = 2R_A/\gamma \ll \tau_{\text{eq.}} \ll \tau_{\text{QGP}} \) and cannot be neglected. Here \( R_A \) is the nuclear radius, \( \gamma \) is the Lorentz gamma factor of the nucleus, \( \tau_{\text{eq.}} \) is the equilibration time and \( \tau_{\text{QGP}} \) is the lifetime of the plasma.

We note that full technical details for the results presented in these proceedings are given in our complete manuscript [1].

2. \( D \) meson production and correlations in lowest order PQCD

A formal expansion for the differential cross section of heavy quark production can be written as follows:

\[
\frac{d\sigma}{dyd^2p_T} = (\alpha_s^2 A(m,p_T) + \alpha_s^3 B(m,p_T) + \cdots) + \left( \alpha_s^2 \sum_{i=2}^{\infty} a_i(\alpha_s \ln \mu/m)^i \right)
+ \alpha_s^3 \sum_{i=1}^{\infty} b_i(\alpha_s \ln \mu/m)^i + \cdots) G(m,p_T) + \cdots ,
\] (1)

where \( G(m,p_T) \to 1 \) when \( m/p_T \to 0 \), and power suppressed terms \( \sim (m/p_T)^n \) are not shown. In Eq. (1) \( A, B, a_i, b_i \) are coefficient functions and logarithms arise due to the new mass scale, \( m \). These are known to next-to-leading logarithm (NLL), but numerically, their contribution to the cross section is small up to \( p_T \sim 50 \) GeV [3]. Existing calculations of charm and bottom production [3] treat quarks as heavy, assuming \( \phi_{c,b/N}(x,\mu_f) \equiv 0 \). We here evaluate the differential cross sections for open charm production and open-charm-triggered di-hadron correlations in the Born approximation. We include the charm contribution from the nucleon wave-function explicitly [1], since this approach leads to a faster convergence of the perturbation series [4] and correspondingly smaller next-to-leading (NLO) order K-factors.

There is a direct relation between the absolute normalization of the cross section and the hardness of the non-perturbative \( D \) meson fragmentation. We compare in the left panel of Fig. [1] the calculated \( D^0 \) and \( D^+ \) cross sections to the Tevatron Run II \( \sqrt{s} = 1.96 \) TeV data [5]. We find that three different combinations \( (K_{\text{NLO}} = 1.5, r = 0.1), (K_{\text{NLO}} = 2, r = 0.2) \) and \( (K_{\text{NLO}} = 3, r = 0.4) \) yield little difference in the single inclusive charm meson spectrum. We note that for the same choice of the fragmentation parameter \( r = 0.1 \), a LO calculation with standard \( \phi_{c,N}(x,\mu_f) \neq 0 \) gives open charm cross sections similar to the ones from a NLO calculation that treats flavor as “heavy”.


Besides the inclusive spectra, we show our first results on charm meson-triggered away-side di-hadrons. The expectation for non-trivial $p_T^2$ dependence of such large-angle correlations is based on the very different behavior with respect to $z = p_{\text{hadron}}/p_{\text{parton}}$ of the fragmentation functions of partons into light hadrons compared to those of heavy quarks into charm and beauty meson \[^{[1]}\]. The insert in the right panel of Fig. 1 shows that while light hadrons favor soft decays of their parent partons, heavy quark fragmentation is very hard. For $z \approx 0.6-0.9$ there is more than an order of magnitude enhancement in the decay probabilities $D_D^{\pm}(z) + D_D^{\mp}(z)$ relative to $(1/N) \sum_{i=1,N}(D_\pi^{\pm}(i) + D_K^{\pm}(i) + D_p(i))$, where $i$ runs over the light and charm quarks, antiquarks and the gluon.

Triggering on a $D$ meson fixes the momentum of the charm quark much more reliably than does triggering on a light hadron \[^{[6]}\] in studying away-side correlations. The non-perturbative fragmentation, therefore, controls the yields of di-hadrons versus the associated momentum $p_T^2$ and the abundances of the different particle species. The right panel of Fig. 1 shows our prediction for the hadronic composition of the $D^0 + D^\pm$-triggered away-side jet. At transverse momenta significantly smaller than the trigger transverse momentum, $p_T^2 \ll p_T^1$, the away-side jet is dominated by pions, kaons and protons. At transverse momenta $p_T^2 \approx p_T^1$, the away-side jet is expected to be dominated almost completely by $\bar{D}^0$ and $D^-$ mesons. Since there is little sensitivity to the choice of $r$, our prediction is robust and can be used as a test of the production mechanism of heavy quarks.

### 3. Resummed QCD power corrections to open charm production

In the case of hadronic collisions there is indeed similarity with the DIS dynamics in the final-state rescattering of the struck, small $x_b$, parton from the nucleus, as shown in the left panel of Fig. 2. Such nuclear-enhanced power corrections are equivalent...
Implementing the normalization to no nuclear effect on a single nucleon as follows, we find \[1\]

dynamical shadowing corrections are important. The mechanism behind the reduction of the deep inelastic inclusive scattering cross section, as shown in Eq. (5), because of the rescaling of \( x \) to smaller versus larger values. Thus, initial-state multiple soft interactions without energy loss always lead to a Cronin effect, independently of whether they are treated as coherent or not. The derivations, summarized here, are critical to elucidating the dynamical origin of nuclear effects in high energy hadronic reactions. We have shown, through explicit calculation,
that such effects are process dependent and may change their sign. Therefore, these are not factorizable as a part of the parton distribution functions and fragmentation functions.

4. Energy loss in cold nuclear matter

In the presence of a nucleus, final-state rescattering of the struck small-\(x\) parton with its remnants exhausts the similarity between hadronic collisions, such as p+A and A+A, and DIS [6]. In \(\ell + A\) (DIS), the multiple interactions of the incoming leptons are suppressed by powers of \(\alpha^\text{em}/\alpha_s\) relative to the struck parton scattering. In contrast, in p+A and A+A the initial- and final-state scattering of the incoming quarks and gluons are equally strong. Nuclear modification, in particular jet energy loss associated with the suppression of particle production, cannot be neglected.

To illustrate the importance of energy loss, we study the nuclear modification of hadron production over a large range of center of mass energies and momentum fractions \(x_b\). We implement the presently well known incoherent limit of energy loss for asymptotic \(t = -\infty\) on-shell partons first derived in [8]. The double differential gluon intensity spectrum per scattering and the fractional energy loss \(\epsilon\) read:

\[
\frac{\omega dN_g^{(1)}}{d\omega d^2k} \propto \frac{\alpha_s}{\pi^2} \frac{q^2}{k^2(k - q)^2}, \quad \epsilon = \frac{\Delta E}{E} \propto \frac{L}{\lambda} = \kappa A^{1/3},
\]

where \(k\) is the transverse momentum of the radiative gluon, \(q\) is the transverse momentum transfer from the medium and \(\omega\) is the gluon energy. In Eq. (7) \(L/\lambda\) is the number of interactions and \(\kappa = 0.0175\) for minimum bias reactions implies that an average parton loses \(\sim 10\%\) of its energy in a large nucleus such as Au or Pb.

We first examine the results obtained by the CERN NA35 fixed target experiment with \(y_{cm} = 3\). It measured hadron production in d+Au reactions at \(\sqrt{s_{NN}} = 19.4\) GeV [10]. We take \(R_y(p_T)\), the ratio of hadron spectra in different rapidity

\[\text{Figure 2. Left panel from [1]: multiple coherent scattering of the out going partons in proton-nucleus reactions in the } t\text{-channel. We have denoted by } \rightarrow \text{ and } \\rightarrow | \text{ the long distance and contact propagators, respectively. We have indicated the lightcone positions, e.g. } y_i. \text{ Arcs show the momentum routing. Right panel from [1]: effects of rescaling of the momentum fraction } x \text{ illustrated on the example of the lowest order CTEQ6 parton distribution functions for valence and sea } u\text{-quarks. Gluons rescatter in the final-state to lowest order only in hadronic collisions and are included for completeness.}\]
Figure 3. Left panel from [1]: nuclear modification at three different rapidities $y - y_{cm}$ in $\sqrt{s_{NN}} = 19.4$ GeV d+Au collisions. Data is from NA35 [10]. Right panel from [1]: calculations of dynamical shadowing, with and without cold nuclear matter energy loss, are compared to the measured [11] $\pi^0$ suppression at $y = 4$ for d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

bins, and $R_{AA}(p_T)$,

$$R_{y}^{AB}(p_T) = \frac{d\sigma_{h}^{yAB}(y, p_T) / dy d^2 p_T}{d\sigma_{h}^{yAB}(y_{base}, p_T) / dy d^2 p_T}, \quad R_{AA}(p_T) = \frac{dN_{h}^{yAB}(y, p_T) / dy d^2 p_T}{T_{AB}(b)d\sigma_{h}^{yAB}(y_{base}, p_T) / dy d^2 p_T},$$

as measures of nuclear matter effects. The left panel of Fig. 3 shows this forward rapidity suppression of negative hadrons relative to the baseline $y - y_{cm} \approx -1.5$ production cross section. Dynamical shadowing calculations [6] give <5% effect at this energy in this rapidity range. Conversely, the implementation of energy loss in cold nuclear matter leads to much larger suppression at forward rapidity and significant improvement in the theoretical description of the data in Fig. 3.

In the other extreme, at $\sqrt{s} = 200$ GeV d+Au collisions at RHIC, the STAR collaboration observed a factor of 3 suppression of $\pi^0$ production at rapidity $y = 4$ [11]. The right panel of Fig. 3 shows that dynamical high-twist shadowing, constrained by the DIS data down to values of Bjorken $x_B \sim 10^{-4}$, underpredicts the nuclear attenuation by a factor of 2. Incorporating the same energy loss that we identified at much smaller center of mass energies, we observe very good agreement between theory and the data [1].

5. Numerical results

To illustrate the similarities and differences between massless and massive final-state partons, we carry out a comparative study of the effect of power corrections on single and double inclusive $\pi^0$ and $D$ meson production. The left panel of Fig. 4 shows the suppression of the low and moderate $p_T$ neutral pion cross section from high-twist shadowing relative to the binary scaled p+p result. The nuclear modification factor is shown for two different forward rapidities, $y_1 = 1.25, 2.5$, and three different centralities, $b = 3$ fm, $b_{min, bias} = 5.6$ fm, $b = 6.8$ fm, in $\sqrt{s} = 200$ GeV d+Au collisions at RHIC. At transverse momenta $p_{T_1} = 1.5$ GeV the suppression can be substantial, but disappears toward higher $p_{T_1}$ due to the power law nature of the effect. Coherent power corrections cannot fully account for the nuclear suppression measured by the
PHENIX experiment [12] and the discrepancy becomes larger at higher transverse momenta. The calculated suppression of $D^0 + D^+$ mesons (and equivalently, $\bar{D}^0 + D^-$ mesons), in deuteron-gold collisions at RHIC is also shown in the left panel of Fig. 4. It should be noted that the nuclear modification is very similar to or slightly larger than that for $\pi^0$. The reason for this similarity is that in both cases the dominant channel of hadron production is via quarks scattering on gluons, which have the same (large) color singlet coupling to the medium, $C_d = 9/4$ in Eq. (4). In addition, the typical momentum fraction, $z_1$, which enters in the determination of the hard scale, $\hat{t} \propto 1/z_1$, is slightly larger for the $D$ mesons. Preliminary PHENIX data on the modification of $\mu^-$ coming from the decay of heavy flavor at $y = 1.6$ in cold nuclear matter is provided as a reference [13]. Although the error bars are large, $D$ mesons seem to be suppressed as much as light hadrons.

Having investigated the largest dynamic range of measurements in proton(deuteron)-nucleus reactions accessible to perturbative QCD calculations in the previous section, we return to $D$ meson production and correlations at RHIC. We use the same fractional energy loss $\epsilon = \Delta E/E$ as in Fig. 3. Single inclusive $\pi^0$ and $D^0 + D^+$ suppression at rapidities $y_1 = 1.25, 2.5$ and minimum bias, central and peripheral d+Au collisions at RHIC are shown in the right panel of Fig. 4. In this case, very good agreement between the QCD theory incorporating cold nuclear matter effects and the PHENIX measurement of muons coming from the decay of light hadrons [12] is achieved. We find that the magnitude of the $D$ meson suppression is similar to that of pions. It is also comparable with the first forward rapidity results on heavy quark nuclear modification in d+Au reactions at RHIC [13]. Nuclear modification of inclusive two particle production is seen to follow closely that of single inclusive hadrons [1].

There are similarities between the calculations that only include resummed
nuclear-enhanced power corrections, left panel of Fig. 4 and the calculations that do not neglect energy loss in cold nuclear matter, right panel of Fig. 4. Both effects are generated through multiple parton scattering in the medium and lead to suppression of the rate of hard scattering [1]. In both cases single inclusive particle production and large angle di-hadron correlations are similarly attenuated. Like all nuclear many body effects, these increase with the centrality of the collision. The difference in the resulting nuclear modification is that high-twist shadowing arises from the coherent final-state scattering of the struck small-$x_b$ parton of the nucleus [7] and disappears as a function of the transverse momentum [8]. The energy loss considered here arises from the initial-state inelastic scattering of the incoming large-$x_a$ parton from the proton(deuteron) [8] and leads to a suppression which is much more $p_T$ independent, similar to final state energy loss applications [2].

6. Conclusions

In these proceedings, we summarized the results of the first perturbative QCD calculation of heavy meson triggered large-angle di-hadron yields [1] and showed how such measurements can provide information on the $D$ meson production mechanism and the non-perturbative fragmentation of heavy quarks. We identified multiple scattering effects that drive the cold nuclear matter attenuation of $D$ meson and light hadron production at forward rapidities, namely, high twist shadowing [6, 7] and parton energy loss [8, 9]. Our work demonstrates [1] how such effects can be independently constrained by DIS data (shadowing) and low energy $p+\Lambda$ measurements [10] where coherent power corrections are not important (energy loss). In the framework of the established QCD collinear factorization, our approach of incorporating dynamically generated and process-dependent nuclear effects is expected to give a more reliable description of particle production [11] in $p+\Lambda$ collisions. This work also provides the baseline for precision QGP tomography using heavy quarks as probes of the plasma away from midrapidity [1] where new experimental capabilities at RHIC and the LHC are expected to become available.

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