Heavy flavor production in pA collisions

H Fujii, F Gelis and R Venugopalan

1 Institute of Physics, University of Tokyo, Komaba, Tokyo 153-8902, Japan
2 CEA/DSM/SPhT, Saclay, 91191, Gif-sur-Yvette Cedex, France
3 Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract. Heavy quark production in high-energy proton-nucleus (pA) collisions is described in the framework of the Color Glass Condensate. $k_{\perp}$ factorization is broken even at leading order albeit a more general factorization in pA holds at this order in terms of 2, 3 and 4 point correlators of Wilson lines in the nuclear target. The $x$-evolution of these correlators is computed in the large $A$ and large $N$ mean field limit of the Balitsky-Kovchegov equation. We show results for heavy quark production at RHIC and LHC energies.

1. Introduction

Heavy flavor production in high energy processes is usually described in the collinear or $k_{\perp}$ factorization frameworks of perturbative QCD. Reactions with nuclear targets allow one to study new important features of multiple scatterings and parton saturation, which is characterized by the scale $Q_{sA}^2[1]$. For a large nucleus at higher energy, this scale can be large and comparable to the heavy quark mass $m_Q$, so that $\Lambda_{\text{QCD}}^2 \ll m_Q^2 \lesssim Q_{sA}^2 \ll s$. In this situation, realized at RHIC and definitely at future LHC, we can investigate saturation physics through heavy quark production with the generalized framework of the Color Glass Condensate (CGC) [2, 3, 4, 5, 6, 7].

In nucleus-nucleus collisions, heavy quarks are produced by initial hard interactions and subsequently propagate in the hot flowing medium which modifies the $p_{\perp}$ spectrum of the quarks and the quarkonium yield[8]. In order to quantify these in-medium effects in hot matter, proton/deuteron-nucleus (pA) collisions play a decisive role providing the baseline of the initial nuclear effects. Here, we will compute heavy quark production in high energy pA collisions using the CGC framework that incorporates both multiple scattering and small $x$ evolution effects.

2. Quark pair cross section in the large N limit

In pA collisions, which is a prototype of a dilute-dense system, the particle production cross-sections are known analytically to the leading order in the strong coupling constant
\(\alpha_s\) and the proton source \(\rho_p\), but to all orders in the dense nuclear source \(g^2\rho_A = O(1)[2]\). The cross-section of the quark pair production is written in the CGC framework as

\[
\frac{d\sigma_{qq}}{d^2p_\perp d^2q_\perp dy_p dy_q} = \frac{\alpha_s^2}{(2\pi)^6 C_F} \times \int_{k_\perp} \frac{\Xi(k_{1\perp}, k_{2\perp}, k_\perp)}{k_2^2} \phi_{A,y_2}^{q,q,g}(k_{2\perp}, k_\perp) \varphi_{p,y_1}(k_{1\perp}) , \tag{1}
\]

where \(k_{1\perp} = p_\perp + q_\perp - k_{2\perp}\), and \(k_{1,2\perp}\) and \(y_{1,2} = \ln(1/x_{1,2})\) are the momenta and rapidities of the gluons coming from the proton and the nucleus. A shorthand notation \(\Xi(k_{1\perp}, k_{2\perp}, k_\perp)\) stands for the matrix element squared, whose explicit form can be found in Refs. [2, 3, 4]. In the leading twist approximation on both the proton and nuclear sides, this \(\Xi\) reduces to the LO hard matrix element in the \(k_\perp\) factorization formalism [9]. The \(\varphi_{p,y_1}(k_{1\perp})\) is the \(k_\perp\)-dependent gluon distribution in the proton, which is related to the usual gluon distribution function via:

\[
\frac{1}{4\pi^2} \int_{Q^2} d^2k_\perp^2 \varphi_{p,y}(k_{1\perp}) \equiv x G_p(x, Q^2) . \tag{2}
\]

The multi-gluon correlations in the large nucleus are encoded in the expression (1) as the 3-point correlator (large \(N\))

\[
\phi_{A,y}^{q,q,g}(l_\perp, k_\perp) = \pi R_A^2 \frac{l_\perp^2 N}{4\alpha_s} S_Y(k_\perp) S_Y(l_\perp - k_\perp), \tag{3}
\]

where \(S_Y(k_\perp)\) is the Fourier transform of the forward scattering amplitude of the right-moving dipole \(S_Y(x_\perp) = (1/N)\text{tr}(\bar{U}(x_\perp)U(0))\), with

\[
\bar{U}(x_\perp) \equiv \mathcal{P}_+ \exp \left[ -ig^2 \int_{-\infty}^{+\infty} dz^+ \frac{1}{\nabla^2} \rho_A a(z^+, x_\perp) t^a \right] . \tag{4}
\]

Here \(t^a\) is the SU(\(N\)) generator in the fundamental representation.

On the proton side, the collinear approximation is more appropriate because the typical \(k_\perp\) should be small – \(O(\Lambda_{QCD})\) as long as \(x_1\) is not too small, especially in the forward rapidity (large \(x_1\)) region. As noted in Refs. [9, 2] the collinear limit on the proton side is well-defined thanks to a Ward identity: one obtains (see Fig. 1 (a))

\[
\frac{d\sigma_{qq}}{d^2p_\perp d^2q_\perp dy_p dy_q} = \frac{\alpha_s^2}{4(2\pi)^4 C_F} \times \int_{k_\perp} \frac{\Xi'(k_{2\perp}, k_\perp)}{k_2^2} \phi_{A,y_2}^{q,q,g}(k_{2\perp}, k_\perp) x_1 G_p(x_1, Q^2) , \tag{5}
\]

where \(k_{2\perp} = p_\perp + q_\perp\), and

\[
\Xi'(k_{2\perp}, k_\perp) \equiv \lim_{|k_{1\perp}| \to 0} \int \frac{d\theta_1}{2\pi} \frac{\Xi(k_{1\perp}, k_{2\perp}, k_\perp)}{k_1^2} . \tag{6}
\]

In this work, we numerically solve the Balitsky-Kovchegov (BK) equation for \(S_Y(k_\perp)\) [10, 11] with the McLerran-Venugopalan (MV) model [12] initial condition at \(x_0 = 0.01\,\), and compute the 3-point correlator \(\phi_{A,y_2}^{q,q,g}(k_{2\perp}, k_\perp)\) (Fig. 1 (b)). This prescription is justified in the large \(N\) and large \(A\) limit. For large-\(x\) extrapolation, see Ref. [4].
Heavy flavor production in pA collisions

In Fig. 2 (a), we show the single charm spectrum from eq. (5) with \( Q^2 s_A=2 \text{ GeV}^2 \) at \( x = 0.01 \) and the BK evolution with fixed \( \alpha_s=0.2 \). CTEQ6LO[13] is used for the proton. The \( D^0 \) spectrum is obtained after convolution with Peterson’s fragmentation function \( D(z) \) (\( \epsilon = 0.05 \) and \( z = p_{D\perp}/p_{c\perp} \)). Preliminary data are taken from STAR [14, 15]. We see that after the convolution the \( D^0 \) spectrum is a little harder at lower \( p_\perp \) than the data while it fits in the higher \( p_\perp \) region. Note that the b-quark contribution is not included in our calculation. Fig. 2 (b) presents the nuclear modification factor of \( Q^2 s_A=2 \text{ GeV}^2 \) to 0.22 GeV\(^2\) for D meson at \( \sqrt{s}=200 \) and 8500 GeV. In the latter case, results of the BK evolution with \( \alpha_s =0.1 \) and 0.2 are compared.

3. Open heavy flavor

In Fig. 2 (a), we show the single charm spectrum from eq. (5) with \( Q^2 s_A=2 \text{ GeV}^2 \) at \( x = 0.01 \) and the BK evolution with fixed \( \alpha_s=0.2 \). CTEQ6LO[13] is used for the proton. The \( D^0 \) spectrum is obtained after convolution with Peterson’s fragmentation function \( D(z) \) (\( \epsilon = 0.05 \) and \( z = p_{D\perp}/p_{c\perp} \)). Preliminary data are taken from STAR [14, 15]. We see that after the convolution the \( D^0 \) spectrum is a little harder at lower \( p_\perp \) than the data while it fits in the higher \( p_\perp \) region. Note that the b-quark contribution is not included in our calculation. Fig. 2 (b) presents the nuclear modification factor of \( Q^2 s_A=2 \text{ GeV}^2 \) to 0.22 GeV\(^2\) for D meson at \( \sqrt{s}=200 \) and 8500 GeV. In the latter case, results of the BK evolution with \( \alpha_s =0.1 \) and 0.2 are compared.

3. Open heavy flavor

In Fig. 2 (a), we show the single charm spectrum from eq. (5) with \( Q^2 s_A=2 \text{ GeV}^2 \) at \( x = 0.01 \) and the BK evolution with fixed \( \alpha_s=0.2 \). CTEQ6LO[13] is used for the proton. The \( D^0 \) spectrum is obtained after convolution with Peterson’s fragmentation function \( D(z) \) (\( \epsilon = 0.05 \) and \( z = p_{D\perp}/p_{c\perp} \)). Preliminary data are taken from STAR [14, 15]. We see that after the convolution the \( D^0 \) spectrum is a little harder at lower \( p_\perp \) than the data while it fits in the higher \( p_\perp \) region. Note that the b-quark contribution is not included in our calculation. Fig. 2 (b) presents the nuclear modification factor of \( Q^2 s_A=2 \text{ GeV}^2 \) to 0.22 GeV\(^2\) for D meson at \( \sqrt{s}=200 \) and 8500 GeV. In the latter case, results of the BK evolution with \( \alpha_s =0.1 \) and 0.2 are compared.

In Fig. 2 (a), we show the single charm spectrum from eq. (5) with \( Q^2 s_A=2 \text{ GeV}^2 \) at \( x = 0.01 \) and the BK evolution with fixed \( \alpha_s=0.2 \). CTEQ6LO[13] is used for the proton. The \( D^0 \) spectrum is obtained after convolution with Peterson’s fragmentation function \( D(z) \) (\( \epsilon = 0.05 \) and \( z = p_{D\perp}/p_{c\perp} \)). Preliminary data are taken from STAR [14, 15]. We see that after the convolution the \( D^0 \) spectrum is a little harder at lower \( p_\perp \) than the data while it fits in the higher \( p_\perp \) region. Note that the b-quark contribution is not included in our calculation. Fig. 2 (b) presents the nuclear modification factor of \( Q^2 s_A=2 \text{ GeV}^2 \) to 0.22 GeV\(^2\) for D meson at \( \sqrt{s}=200 \) and 8500 GeV. In the latter case, results of the BK evolution with \( \alpha_s =0.1 \) and 0.2 are compared.

In Fig. 2 (a), we show the single charm spectrum from eq. (5) with \( Q^2 s_A=2 \text{ GeV}^2 \) at \( x = 0.01 \) and the BK evolution with fixed \( \alpha_s=0.2 \). CTEQ6LO[13] is used for the proton. The \( D^0 \) spectrum is obtained after convolution with Peterson’s fragmentation function \( D(z) \) (\( \epsilon = 0.05 \) and \( z = p_{D\perp}/p_{c\perp} \)). Preliminary data are taken from STAR [14, 15]. We see that after the convolution the \( D^0 \) spectrum is a little harder at lower \( p_\perp \) than the data while it fits in the higher \( p_\perp \) region. Note that the b-quark contribution is not included in our calculation. Fig. 2 (b) presents the nuclear modification factor of \( Q^2 s_A=2 \text{ GeV}^2 \) to 0.22 GeV\(^2\) for D meson at \( \sqrt{s}=200 \) and 8500 GeV. In the latter case, results of the BK evolution with \( \alpha_s =0.1 \) and 0.2 are compared.

In Fig. 2 (a), we show the single charm spectrum from eq. (5) with \( Q^2 s_A=2 \text{ GeV}^2 \) at \( x = 0.01 \) and the BK evolution with fixed \( \alpha_s=0.2 \). CTEQ6LO[13] is used for the proton. The \( D^0 \) spectrum is obtained after convolution with Peterson’s fragmentation function \( D(z) \) (\( \epsilon = 0.05 \) and \( z = p_{D\perp}/p_{c\perp} \)). Preliminary data are taken from STAR [14, 15]. We see that after the convolution the \( D^0 \) spectrum is a little harder at lower \( p_\perp \) than the data while it fits in the higher \( p_\perp \) region. Note that the b-quark contribution is not included in our calculation. Fig. 2 (b) presents the nuclear modification factor of \( Q^2 s_A=2 \text{ GeV}^2 \) to 0.22 GeV\(^2\) for D meson at \( \sqrt{s}=200 \) and 8500 GeV. In the latter case, results of the BK evolution with \( \alpha_s =0.1 \) and 0.2 are compared.
4. Quarkonium

The J/ψ production cross-section is computed for $Q^2_{sA0}=2$ and 0.22 GeV$^2$ in the color evaporation model in Fig. 3, where we assume that the bound state formation takes place outside of the nucleus, and is thus not modified compared to pp. The J/ψ absorption in the target is not necessary. The cross-section is suppressed (enhanced) in the small (large) $p_{\perp}$ region at RHIC energy due to the multiple scattering of the pair (Fig. 3 (a))[16]. At forward rapidities $dN/dy$ is more suppressed due to the multiple scattering and saturation, which may be compared with the data[17]. Note that in the hatched region $y \lesssim 0.5$ in Fig. 3 (b), $dN/dy$ is largely determined by the larger $x_2$ part of $\phi_{A_{1/2}}^{qg}$, which is extrapolated from the MV model. In Fig. 3 (c), we show the suppressions of $dN/dy$ for the J/ψ and the charm quark at LHC energy. We expect that the difference between them represents the effect of the multiple scattering on the bound state formation. It is interesting to note that this difference depends on the rapidity $y$ only weakly.

![Figure 3](image)

**Figure 3.** (a) J/ψ spectrum for $Q^2_{sA0}=2$ and 0.22 GeV$^2$ at $\sqrt{s}=200$ GeV. (b) Nuclear modification factor of J/ψ and charm quark ($\alpha_s=0.1$ and 0.2). Hatched region corresponds to $x_2 \gtrsim 0.01$. (c) The same as (b) at $\sqrt{s}=8500$ GeV.

References

[1] For review, see Iancu E and Venugopalan R 2003 hep-ph/0303204, and references therein
[2] Blaizot J P, Gelis F and Venugopalan R 2004 *Nucl. Phys. A* **743** 57
[3] Fujii H, Gelis F and Venugopalan R 2005 *Phys. Rev. Lett.* **95** 162002
[4] Fujii H, Gelis F. and Venugoplan R 2006 *Nucl. Phys. A* **780** 146, and in preparation
[5] Kharzeev D and Tuchin K 2004 *Nucl. Phys. A* **735** 248
[6] Kharzeev D and Tuchin K 2006 *Nucl. Phys. A* **770** 40
[7] Albacete J and Kovchegov Yu V (these proceedings)
[8] Adler S S et al (PHENIX Collaboration) 2006 *Phys. Rev. Lett.* **96** 032301
[9] Gelis F and Venugopalan R 2004 *Phys. Rev. D* **69** 014019
[10] Balitsky I 1996 *Nucl. Phys. B* **463** 99
[11] Kovchegov Yu V 2000 *Phys. Rev. D* **61** 074018
[12] McLerran L and Venugopalan R, 1994 *Phys. Rev. D* **49** 2233; *ibid.* **49** 3352; *ibid.* **50** 2225
[13] Pumplin J, Stump D R, Huston J, Lai H L, Nadolsky P and Tung K 2002 *JHEP* **0207** 012
[14] Tai A (STAR Collaboration) 2004 *J. Phys. G: Nucl. Part. Phys.* **30** S809
[15] Adams J et al (STAR Collaboration) 2005 *Phys. Rev. Lett.* **94** 062301
[16] Fujii H and Matsui T 2002 *Phys. Lett. B* **545** 82; Fujii H 2002 *Nucl. Phys. A* **709** 236
[17] Adler S S et al (PHENIX Collaboration) 2006 *Phys. Rev. Lett.* **96** 012304