Charm decay leptons in pA collisions within the CGC framework

Hirotsugu Fujii[1] and Kazuhiro Watanabe[2]

[1]University of Tokyo, Komaba, [2]Central China Normal University

Sep. 29, 2015, Quark Matter 2015

Abstract

We compute electron and muon distributions produced by the charm semileptonic decays in proton-lead collisions at the LHC within the Color Glass Condensate framework. High energy collisions at the LHC allow us to use open heavy flavor meson and quarkonium productions to access the small-x region of hadronic wavefunctions, where the nonlinear effects of the dense gluon system becomes manifest. Leptonic decay channels of heavy flavor quarks are valuable observables, but the information on the small-x gluons is convoluted with other kinematical factors and becomes relatively indirect there. In this presentation, we show electron and muon spectra from heavy-flavor decays at low-$P_\perp$ and their two-particle correlations, and discuss in which kinematical region the saturation effects are well reflected in the lepton distributions.

Introduction

The main objective of this study is to quantify to what extent the small-x gluon distribiuion in the target nucleus is reflected in heavy-quark-decayed lepton spectra which go through both the quark fragmentation process and the hadron semileptonic decay.

Heavy flavor production is one of the most important processes in high energy scattering to study the strong interaction. Recently, investigation of the so-called parton saturation in the nucleus through the heavy quark production has been worked on [1] since the LHC energy makes Bjorken's x value of the relevant gluons small ($\lesssim 10^{-5}$) even for the heavy flavor production.

Open heavy flavor productions (D, B) in pp and pA collisions are well described by the Color Glass Condensate (CGC) framework at mid rapidity at the LHC [1]. However, the RHIC and LHC experiments also study heavy quarks by detecting the decay leptons: e at mid and μ at forward rapidity. Importantly, the muon detection is the only relevant observable for the heavy flavor production at forward rapidities in the RHIC and LHC experiment setup. Then, we need to evaluate the leptonic decays from open heavy flavor mesons in order to study the saturation effects in the observed forward muon spectra.

We use the leading-order formula for the heavy quark pair production and supplement it with the generalized gluon distribution obeying the Balitsky-Kovchegov equation with running coupling constant (rcBK). The rcBK equation sums up the small-x quantum correction in terms of $\alpha_s \ln(1/x)$, and furthermore include important part of the next-leading-order (NLO) contributions. This approach has been sucessful in phenomenology, while the consistent NLO formulation is also desired.

Framework

- **Heavy quark pair production from the CGC**

  The quark pair ($q\bar{q}$) production cross section in pA collisions at leading order is given by "$k_\perp$-factorized" formula:

$$\frac{d\sigma_{q\bar{q}}}{d^2p_{q\perp}d^2p_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^4 C_F}\int \frac{d^2k_{2\perp}d^2k_\perp}{(2\pi)^4}\frac{\Xi(k_{1\perp},k_{2\perp},k_\perp)}{k_{1\perp}^2 k_{2\perp}^2}\,\varphi_{p,x_1}(k_{1\perp})\,\phi^{q\bar{q},g}_{A,x_2}(k_{2\perp},k_\perp). \tag{1}$$

  or Hybrid formula (collinear⊗CGC), which is valid at forward rapidity:

$$\frac{d\sigma_{q\bar{q}}}{d^2p_{q\perp}d^2p_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F}\int \frac{d^2k_\perp}{(2\pi)^2}\frac{\Xi_{\rm coll}(k_{2\perp},k_\perp)}{k_{2\perp}^2}\,x_1G(x_1,\mu)\,\phi^{q\bar{q},g}_{A,x_2}(k_{2\perp},k_\perp) \tag{2}$$

  where φ_{p,x_1} is the unintegrated gluon distribution function and x_1G is the usual collinear gluon distribution function with μ being the factorization scale. Ξ is the hard matrix elements and $\Xi_{\rm coll}$ is its collinear approximation taken on the proton side. Here x_1 (x_2) is the longitudinal momentum fraction carried by the incoming gluon in the proton (nucleus): $x_{1,2} = (\sqrt{m^2+p_{q\perp}^2}e^{\pm y_q} + \sqrt{m^2+p_{\bar{q}\perp}^2}e^{\pm y_{\bar{q}}})/\sqrt{s}$ for a quark pair with $p_q, p_{\bar{q}}$ in 2 → 2 kinematics. The 3pt. function of the nucleus $\phi^{q\bar{q},g}_{A,x_2}$ is approximated as

$$\phi^{q\bar{q},g}_{A,x_2}(k_{2\perp},k_\perp) = S_{A\perp}\frac{N_c k_{2\perp}^2}{4\alpha_s}F_{Y_2}(k_{2\perp}-k_\perp)F_{Y_2}(k_\perp) \tag{3}$$

  in the large N_c limit. $S_{A\perp}$ is the transverse size of target nucleus. $F_{Y_2}(k_\perp) \equiv \int dx_\perp^2 e^{-ik_\perp\cdot x_\perp}S_{Y_2}(x_\perp)$ is the Fourier transform of the fundamental dipole amplitude.

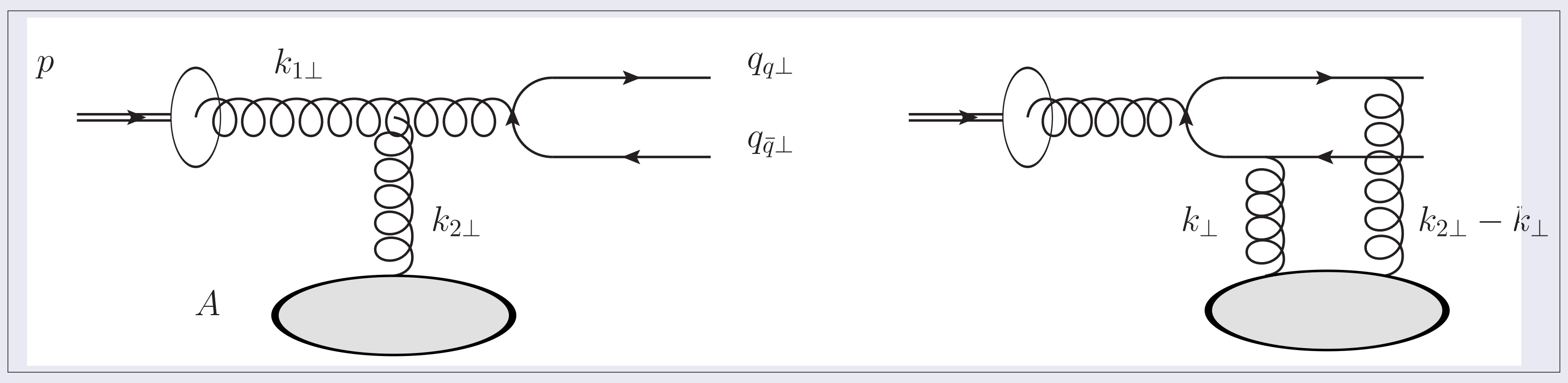

Figure: Leading order heavy quark pair production before/after scattering with the nucleus.

- **Leptons from heavy flavor semileptonic decay: $Q \to Xl\bar{\nu}$**

  Single meson production with open heavy flavor is obtained by convoluting the quark production cross-section with the fragmentation function:

$$\frac{d\sigma_Q}{d^2p_{Q\perp}dy} = Br_{q\to Q}\int dz\frac{D_q^Q(z)}{z^2}\frac{d\sigma_q}{d^2p_{q\perp}dy}, \tag{4}$$

  where we use Kartvelishvili's fragmentation function, $D_q^Q(z) = (\alpha+1)(\alpha+2)z^\alpha(1-z)$ and $Br_{q\to Q}$ is a branching ratio. Then the double differential cross section of lepton production from semileptonic decay $Q \to Xl\bar{\nu}$ is given by

$$\frac{d\sigma_l}{d^2p_{l\perp}dy_l} = \int dp_{Q\perp}dy_Q\,\mathcal{F}(p_l,p_Q)\,\frac{d\sigma_Q}{d^2p_{Q\perp}dy_Q}. \tag{5}$$

  Here $F(p_Q,p_l)$ is the probability for a heavy meson with momentum p_Q to decay with producing a lepton with momentum p_l in the laboratory frame, and is given by the following expression;

$$\mathcal{F}(p_Q,p_l) = \int d\phi\frac{d(p_{Q\perp}\cdot p_{l\perp})}{2p_{Q\perp}p_{Q\perp}\cdot p_{l\perp}}f\left(\frac{p_Q\cdot p_l}{M_Q}\right), \tag{6}$$

  where f is the lepton distribution in the rest frame of the heavy flavor meson and is defined by $f(E_l) = \omega\frac{E_l^2(M_Q^2-M_X^2-2M_QE_l)}{M_Q-2E_l}$, with the normalization constant ω. M_X is mass of the produced particle X, for which we assume $M_X = M_K = 0.497$ GeV in D decay ($M_Q = M_D = 1.86$ GeV) and $M_X = M_D = 1.86$ GeV in B decay ($M_Q = M_B = 5.28$ GeV).

Input: Unintegrated gluon distribution

The nonlinear effects are taken into account through the unintegrated gluon distribution ϕ.

In order to describe the energy (or x) dependence of the gluon distribution in the target, we use the rcBK equation for the fundamental dipole amplitude ($S_Y = 1 - N_Y$):

$$\frac{dN_Y(r_\perp)}{dY} = \mathcal{K}_{Bal}(r_\perp,r_{1\perp})\otimes\left[N_Y(r_{1\perp})+N_Y(r_{2\perp})-N_Y(r_\perp)-N_Y(r_{1\perp})N_Y(r_{2\perp})\right] \tag{7}$$

in Balitsky's prescription and with $r_\perp = r_{1\perp} + r_{2\perp}$ being the transverse size of the dipole. The initial condition for the rcBK equation at $x_0 = 0.01$ is constrained by global fit of HERA DIS data, being in the McLerran-Venugoaplan-model form:

$$S_{Y=0}(r_\perp) = \exp\left[-\frac{\left(r_\perp^2 Q_{s0,p}^2\right)^\gamma}{4}\ln\left(\frac{1}{r_\perp\Lambda}+e_c\cdot e\right)\right] \tag{8}$$

where $Y = \ln\frac{x_0}{x_2}$ is the evolution rapidity in association with gluon of the target nucleus. We fix $\Lambda = 0.241$ GeV and apply two parametrization sets listed here [3, 4].

set	$Q_{s0,\rm p}^2/\rm GeV^2$	γ	e_c
MV$^\gamma$	0.1597	1.118	1
MV^e	0.06	1	18.9

For the target nucleus, we replace the initial saturation scale by $Q_{s0,A}^2 = cA^{1/3}Q_{s0,p}^2$ with $c = 0.5$.

Setup for numerical calculations

- Quark mass: $m_c = 1.2 \sim 1.5$ GeV for charm and $m_b = 4.5 \sim 4.8$ GeV for bottom.
- We fix $\alpha_s = 0.2$ in the hard parts.
- Proton radius: $R_p = 0.8$ fm.
- One parameter in the Fragmentation function: $\alpha = 3.5$ (13.5) for D (B) meson.
- Saturation scale of nucleus: $Q_{s0,A}^2 = 3Q_{s0,p}^2$.
- Factorization scale in Hybrid formula: $\mu = \sqrt{m^2+p_\perp^2}$ with CTEQ6L PDF.

Note: We don't consider ($b \to c \to l$) channel since we assume this channel doesn't contribute to low $p_\perp$ spectrum.

Results

- **$p_\perp$ distribution of decay lepton at mid and forward rapidity in pp collisions**

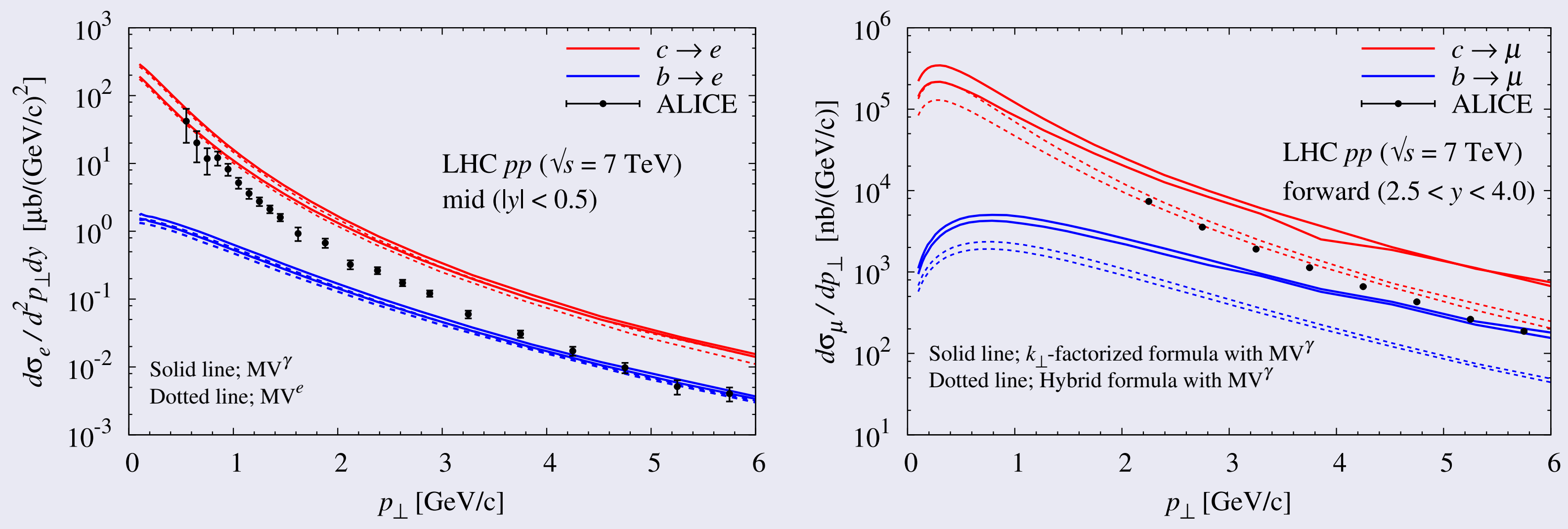

Figure: Differential cross section of leptons from heavy flavor semileptonic decay in pp collisions at the LHC. The band comes from the different values used for the quark mass.

- **Fractions of contributions from the CGC and Extended scaling regions**

  To quantify the saturation effects more precisely, we set two cutoff scales in $k_{2\perp}$ integration of the multipoint function ϕ in the integral: One is the saturation scale $Q_s(x)$ which is determined by the rcBK evolution, the other is the scale $Q_c(x) = Q_s^2(x)/\Lambda_{QCD}$ corresponding to the extended scaling region [4].

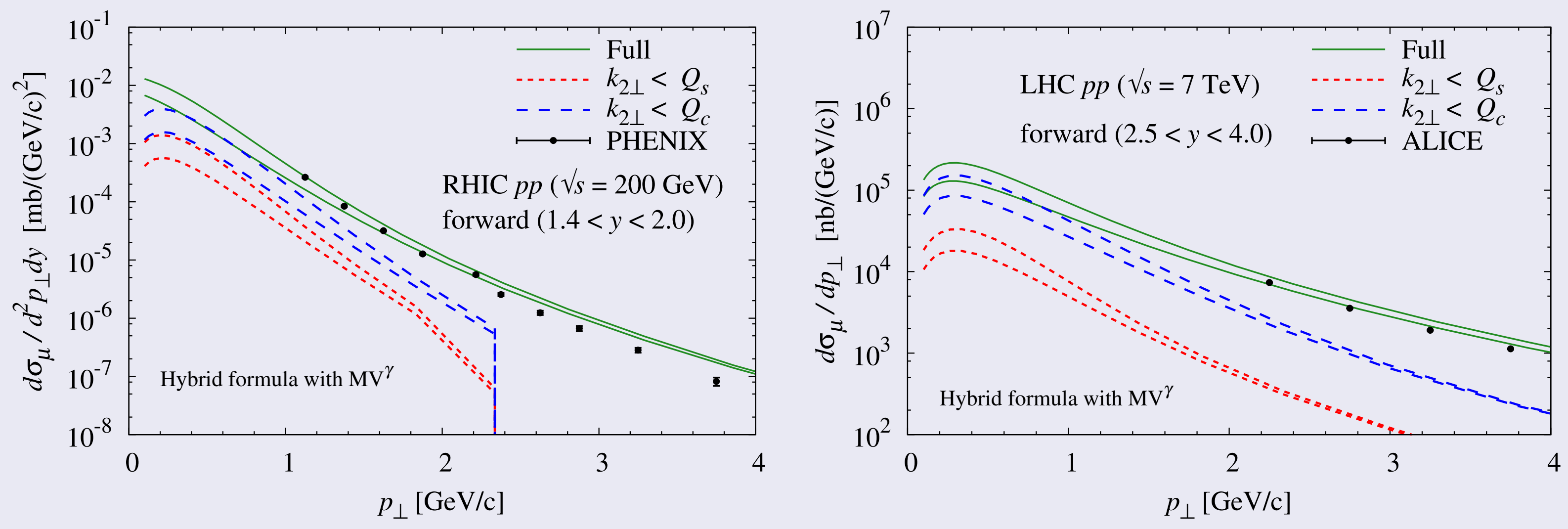

Figure: $p_\perp$ spectrum of charm lepton in pp collisions from the CGC ($k_{2\perp} < Q_s$) and up to the extended scaling region ($k_{2\perp} < Q_s^2/\Lambda_{QCD}$).

- **Nuclear modification factor**

  From the following definition $R_{pA}(p_\perp) = \frac{1}{A}\frac{d^3\sigma_{pA}/d^2p_\perp dy}{d^3\sigma_{pp}/d^2p_\perp dy}$, we obtain the relation $R_A = \sqrt{\frac{A}{(cA^{1/3})^\gamma}}R_p$ by supposing $R_{pA} \sim \frac{1}{A}\frac{\pi R_A^2 Q_{sA}^{2\gamma}}{\pi R_p^2 Q_{sp}^{2\gamma}} = 1$ at high $p_\perp$ for the charm quark production.

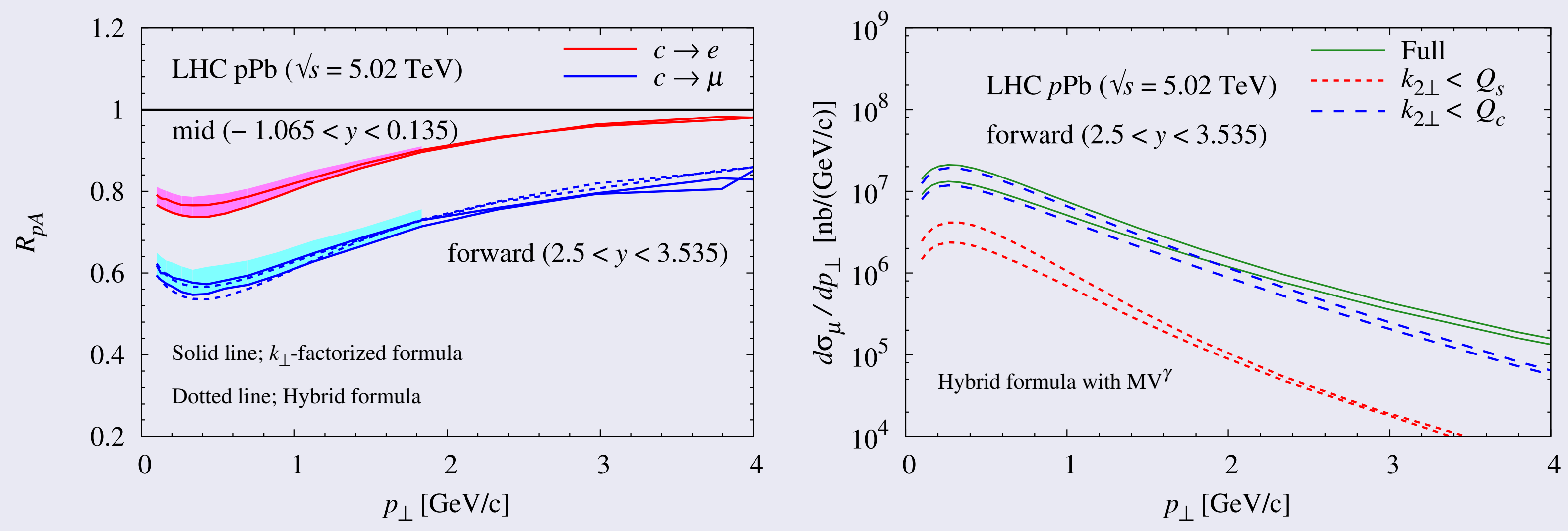

Figure: Left: Nuclear modification factor at the LHC. Filled color bands in left figure represent the uncertainty associated with quark mass and the initial condition of the rcBK in the $k_\perp$-factorized formula. Right: $p_\perp$ spectrum of charm lepton in pPb collisions

Summary

- We have evaluated the $p_\perp$ spectrum of the leptons from heavy flavor semileptonic decay, and separated the contribution fractions of the small-x gluons in the deep-saturated, and extended-scaling regions by setting kinematical cuts.
- The $p_\perp$ spectrum of the leptons reflects the information of small-x gluons in lower $p_\perp$ region. But for higher energies and for heavier nucleus, the kinematical window of the extended scaling region becomes wider toward higher $p_\perp$. ⇒ good opportunity at the LHC
- The nuclear modification factor R_{pA} of the leptons shows stronger suppresion at forward rapidities.
- Lepton yield at high $p_\perp$ becomes sensitive to extrapolation of the framework to high $p_\perp$; care is needed.

References

1. H. Fujii and K. Watanabe, Nucl. Phys. A **920**, 78 (2013) [arXiv:1308.1258 [hep-ph]].
2. J. P. Blaizot, F. Gelis and R. Venugopalan, Nucl. Phys. A **743**, 57 (2004) [hep-ph/0402257].
   H. Fujii, F. Gelis and R. Venugopalan, Nucl. Phys. A **780**, 146 (2006) [hep-ph/0603099].
3. H. Fujii, K. Itakura, Y. Kitadono and Y. Nara, J. Phys. G **38**, 124125 (2011) [arXiv:1107.1333 [hep-ph]].
4. T. Lappi and H. Mäntysaari, Phys. Rev. D **88**, 114020 (2013) [arXiv:1309.6963 [hep-ph]].
5. E. Iancu, K. Itakura and L. McLerran, Nucl. Phys. A **708**, 327 (2002) [hep-ph/0203137].

QUARK MATTER 2015

The XXVth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions