Quarkonium production with soft gluon radiation in the CGC framework

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Kazuhiro Watanabe[1], Bo-Wen Xiao[1] & Feng Yuan[2]

[1]Central China Normal University, [2]Lawrence Berkeley National Laboratory

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Abstract

We study initial soft gluon radiation effect on quarkonium production at low transverse momentum in the color glass condensate (CGC) framework. In high energy pp (pA) collisions, the quarkonium production at forward rapidity can be described by adopting usual collinear pdf for dilute proton and the dipole gluon distribution function for dense proton (nucleus). The small-x quantum correction is embedded in the dipole amplitude which follows the BK equation with running coupling effect (rcBK). In the CGC framework, the parton saturation is expected to characterize the low-$p_\perp$ spectrum. Meanwhile, the initial soft gluon radiation also can affect the low-$p_\perp$ spectrum. Therefore, in order to study the parton saturation quantatively, both the small-x resummation and the low-$p_\perp$ resummation have to be considered simultaneously. In this presentation, we consider the Sudakov factor associated with the initial soft gluon resummation by following the Collins-Soper-Sterman (CSS) formalism. We will present some numerical results of quarkonium production at the LHC including both the small-x resummation and the low-$p_\perp$ resummation.

Introduction

Heavy quarkoniums production (J/ψ, Υ) can provide us a good opportunity to search the gluon saturation of hadron because quarkoniums are mainly produced in the gluon hard scattering. In fact, low $p_\perp$ spectrum of forward rapidity heavy quarkoniums produced in high energy pp (pA) collisions carries important information of the gluon saturation at small Bjorken's x. The so-called Cold Nuclear Matter effects including the saturation are important baseline to study the interaction with hot matter in AA collisions.

The saturation formula or Color-Glass-Condensate (CGC) framework [1] describes the wave function of hadron at high scattering energy which is cooperated with the hard scattering matrix elements for heavy quark pair production. Nonlinear Balitsky-Kovchegov equation in terms of small-x tells roughly that the saturated gluon has $k_\perp \sim 1$ GeV at the LHC. However, the LHCb experiments have found large broadening of $p_\perp$ distribution of Υ production compared to J/ψ. This large mean $p_\perp$ of Υ can't be described in early works [2] where only small x resummation has been considered. In this study, we solve this discrepancy by taking into consideration about the following two resummation effects simultaneously in the CGC framework [3]:

- Small-x: $\alpha_s N_c \ln\frac{1}{x} = \mathcal{O}(1) \to$ Balitsky-Kovchegov equation
- Low-$p_\perp$: $\alpha_s N_c \ln^2\frac{M^2}{p_\perp^2} = \mathcal{O}(1) \to$ Sudakov factor

with M being invariant mass of a quark and antiquark pair. It is clearly important to implement the low $p_\perp$ resummation for heavy Υ production in the CGC framework to obtain large $p_\perp$ broadening effect.

Heavy quark pair production with Sudakov factor in the CGC framework

The forward production cross section of a quark and antiquark pair with the Sudakov factor is implemented in the Hybrid formula [2] as

$$\frac{d\sigma_{q\bar{q}}}{d^2q_{q\perp}d^2q_{\bar{q}\perp}dy_q dy_{\bar{q}}} = \frac{\alpha_s^2}{16\pi^2 C_F}\int d^2l_\perp d^2k_\perp \frac{\Xi_{\rm coll}(k_{2\perp}, k_\perp - zl_\perp)}{k_{2\perp}^2}\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp) \quad (1)$$

where $\Xi_{\rm coll}$ is the hard matrix elements at leading order. x_1 (x_2) is the longitudinal momentum fraction of the dilute proton (the dense nucleus) carried by the incoming gluon. For quarkonium production, we find $x_{1,2} = \sqrt{M^2 + p_\perp^2}/\sqrt{s}e^{\pm Y}$ within $2 \to 1$ kinematics and $p_\perp = q_{q\perp} + q_{\bar{q}\perp}$ is transverse momentum of the pair. $Y = 1/2\ln((q_q^+ + q_{\bar{q}}^+)/(q_q^- + q_{\bar{q}}^-))$ is the pair rapidity. Here ϕ_{x_1,x_2} includes all the information of gluon distribution for incident proton and target nucleus and also initial soft gluon radiation:

$$\phi_{x_1,x_2}(k_{2\perp}, k_\perp, l_\perp) = \overline{S}_\perp F_{Y_g}(k_\perp) F_{Y_g}(k_{2\perp} - k_\perp + l_\perp) F_{\rm Sud}(l_\perp) \quad (2)$$

where we have assumed large N_c limit. We denote $\overline{S}_\perp = S_\perp \frac{N_c k_{2\perp}^2}{4\alpha_s}$ with $S_\perp = \pi R_A^2$ as the transverse area of target nucleus, the Fourier transform of the dipole amplitude as $F_{Y_g}(k_\perp) \equiv \int \frac{dx_\perp^2}{(2\pi)^2}e^{-ik_\perp \cdot x_\perp}S_{Y_g}(x_\perp)$, and the Fourier transform of the Sudakov factor as follows

$$F_{\rm Sud}(M, l_\perp) = \int \frac{d^2b_\perp}{(2\pi)^2}e^{-ib_\perp \cdot l_\perp}e^{-S_{\rm Sud}(M,b_\perp)}x_1 G\left(x_1, \frac{c_0}{b_\perp}\right), \quad (3)$$

where x_1G is the usual collinear gluon distribution function and $c_0 = 2e^{-\gamma_E}$ with γ_E the Euler-constant. The factorization scale is chosen as $\mu = \frac{c_0}{b_\perp}$.

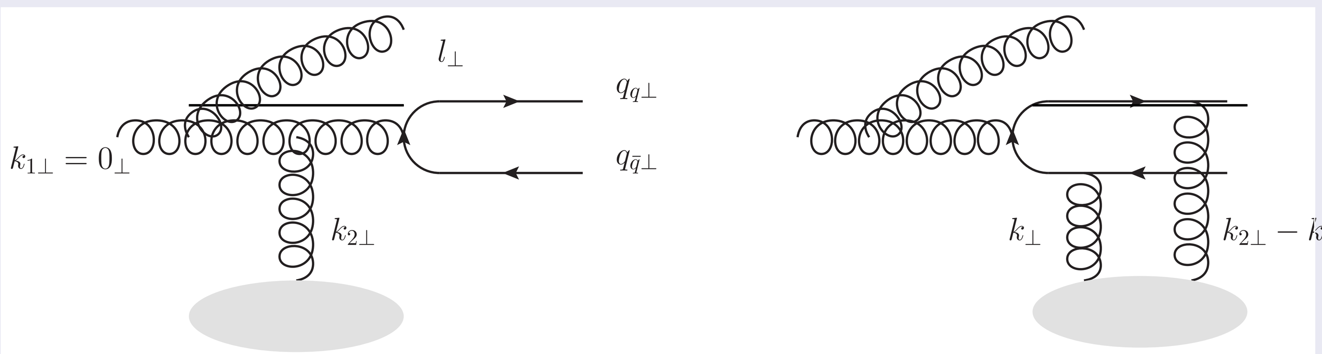

Figure: Typical diagrams of heavy quark pair production in pA collisions with initial soft gluon emissions

Quantum evolution for the gluon distribution functions

- **Target nucleus: Balitsky-Kovchegov equation in terms of $Y_g = \ln(x_0/x_2)$**

  We apply the rcBK equation in Balitsky's prescription to the fundamental dipole amplitude in the multipoint function ($S_{Y_g} = 1 - N_{Y_g}$):

$$\frac{dN_{Y_g}(r_\perp)}{dY_g} = \mathcal{K}_{Bal}(r_\perp, r_{1\perp}) \otimes \left[N_{Y_g}(r_{1\perp}) + N_{Y_g}(r_{2\perp}) - N_{Y_g}(r_\perp) - N_{Y_g}(r_{1\perp})N_{Y_g}(r_{2\perp})\right] \quad (4)$$

  where $r_\perp = r_{1\perp} + r_{2\perp}$ is the dipole transverse size. The initial condition of the rcBK is the so-called McLerran-Venugopalan model with modified anomalous dimension at $x_0 = 0.01$:

$$S_{Y_g=0}(x_\perp) = \exp\left[-\frac{(x_\perp^2 Q_{s,0}^2)^\gamma}{4}\ln\left(\frac{1}{|x_\perp|\Lambda} + e\right)\right]. \quad (5)$$

  By using this expression, global data fitting at HERA DIS provides a good initial condition; $Q_{s,0}^2 = 0.1597$ GeV^2 and $\gamma = 1.118$ with $\Lambda = 0.241$ GeV [4].

- **Incident proton: DGLAP evolution in terms of $c_0/b_\perp$**

  We adopt CTEQ6M PDF (NLO) for x_1G in numerical calculations.

Collins-Soper-Sterman formalism: Sudakov factor

Following the CSS formalism [5], the Sudakov factor is given by $S_{\rm Sud}(M, b) = S_{\rm perp}(M, b_*) + S_{\rm NP}(M, b)$ where $b_* = b/\sqrt{1 + (b/b_{\rm max})^2}$ is introduced to separate the perturbative part ($b \ll b_{\rm max}$) from the nonpertubative part ($b > b_{\rm max}$).

- **Perturbative part at small-b**

$$S_{\rm perp}(M, b) = \int_{c_0/b^2}^{M^2}\frac{d\mu^2}{\mu^2}\left[A\ln\left(\frac{M^2}{\mu^2}\right) + B\right] \quad (6)$$

  where the coefficient functions A and B have been calculated perturbatively : $A = \sum_{i=1} A^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$, $B = \sum_{i=1} B^{(i)}\left(\frac{\alpha_s}{\pi}\right)^i$. For the one loop correction, they are given by $A^{(1)} = C_A$ and $B^{(1)} = -(b_0 + \delta_{8c}/2)N_c$ where $b_0 = \left(\frac{11}{6}N_c - \frac{n_f}{3}\right)\frac{1}{N_c}$. We use the one-loop running coupling constant for the above expression.

- **Non-Perturbative part at large-b**

  For collinear/CGC framework,

$$S_{\rm NP}(M, b) = \exp\left[\frac{b^2}{2}\left(-g_1 - g_2\ln\left(\frac{M}{2Q_0}\right) - g_1g_3\ln(100x_1x_2)\right)\right] \quad (7)$$

  where $g_1 = 0.03$, $g_2 = 0.87$, and $g_1 \times g_3 = -0.17$ are obtained by the data fitting within the NRQCD factorization with $Q_0 = 1.6$ GeV and $b_{\rm max} = 0.5$ GeV is originally fixed in Ref. [6].

Results

To convert $q\bar{q}$ to quarkonium, we simply apply the color-evaporation-model (CEM):

$$\frac{d\sigma_{\mathcal{Q}}}{d^2p_\perp dY} = F_{q\bar{q}\to\mathcal{Q}}\int_{(2m)^2}^{(2M_h)^2} dM^2 \frac{d\sigma_{q\bar{q}}}{dM^2 d^2p_\perp dY}. \quad (8)$$

Through this study, we fix $m = 1.2$ GeV and $M_{h=D} = 1.864$ GeV for J/ψ production, and $m = 4.5$ GeV and $M_{h=B} = 5.280$ GeV for Υ, respectively. We choose $F_{q\bar{q}\to\mathcal{Q}}$, which includes any K-factor in association with higher order correction, to tune to the data with $\alpha_s = 0.3$, $R_p = 0.9$ fm, and $R_A = 8.5$ fm being fixed.

- **J/ψ in pp collisions**

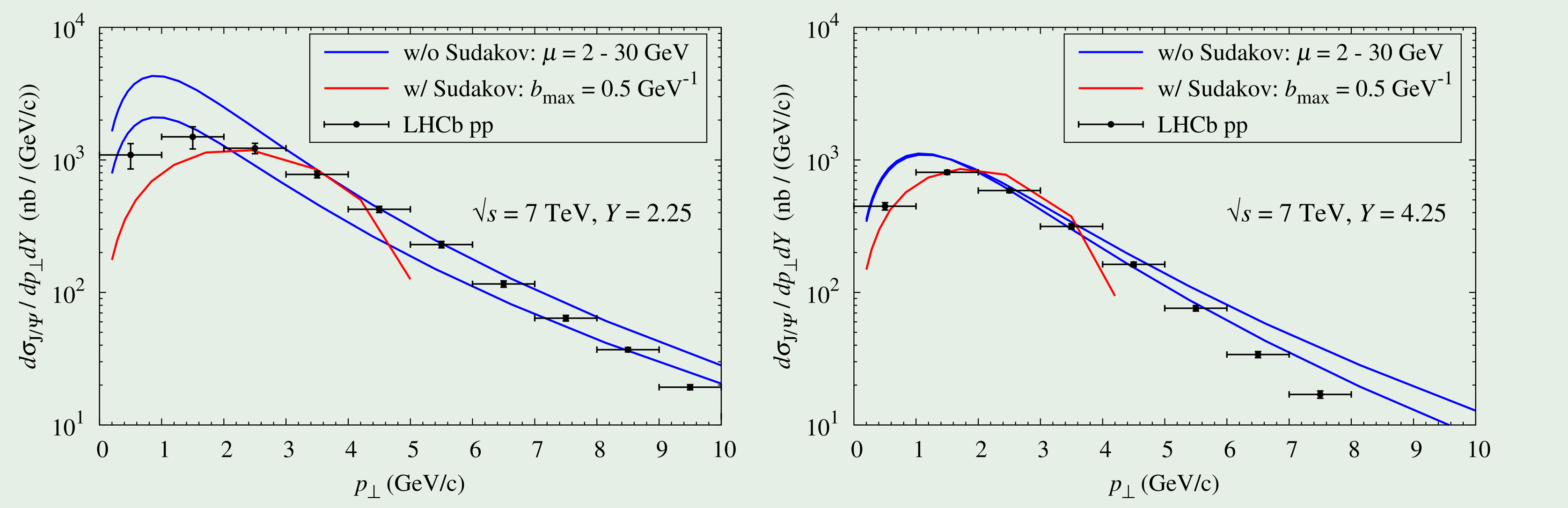

Figure: Double differential cross section of J/ψ as a function of $p_\perp$ for $Y = 2.25$ and 4.25 in pp collisions at $\sqrt{s} = 7$ TeV. Blue solid line is the result without the Sudakov factor and the uncertainty band is coming from a change of factorization scales ($2 < \mu < 30$ GeV) for the collinear gluon distribution function. Red solid line denotes the result of Eq. (1) at $b_{\rm max} = 0.5$.

- **Υ in pp collisions**

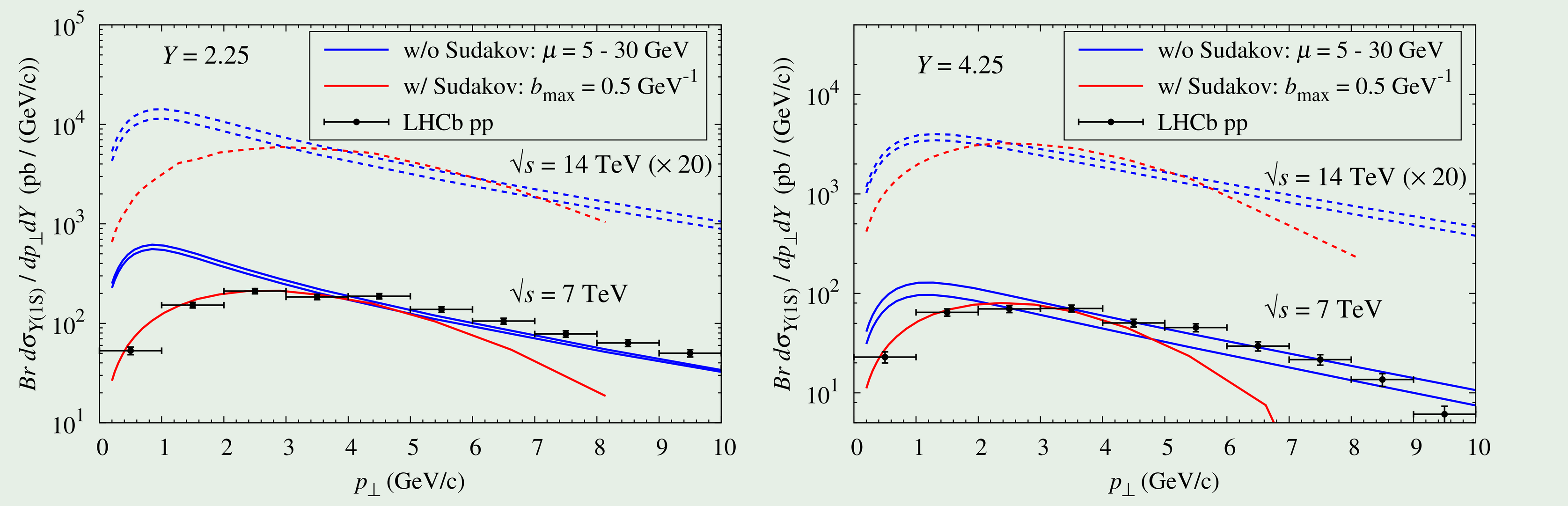

Figure: Double differential cross section of $\Upsilon(1S)$ multiplied by a branching ratio of $\Upsilon(1S)$ decay into a lepton pair as a function of $p_\perp$ for $Y = 2.25$ and 4.25 in pp collisions at $\sqrt{s} = 7$ TeV (solid lines) and 14 TeV (dotted lines).

- **Υ in pA collisions**

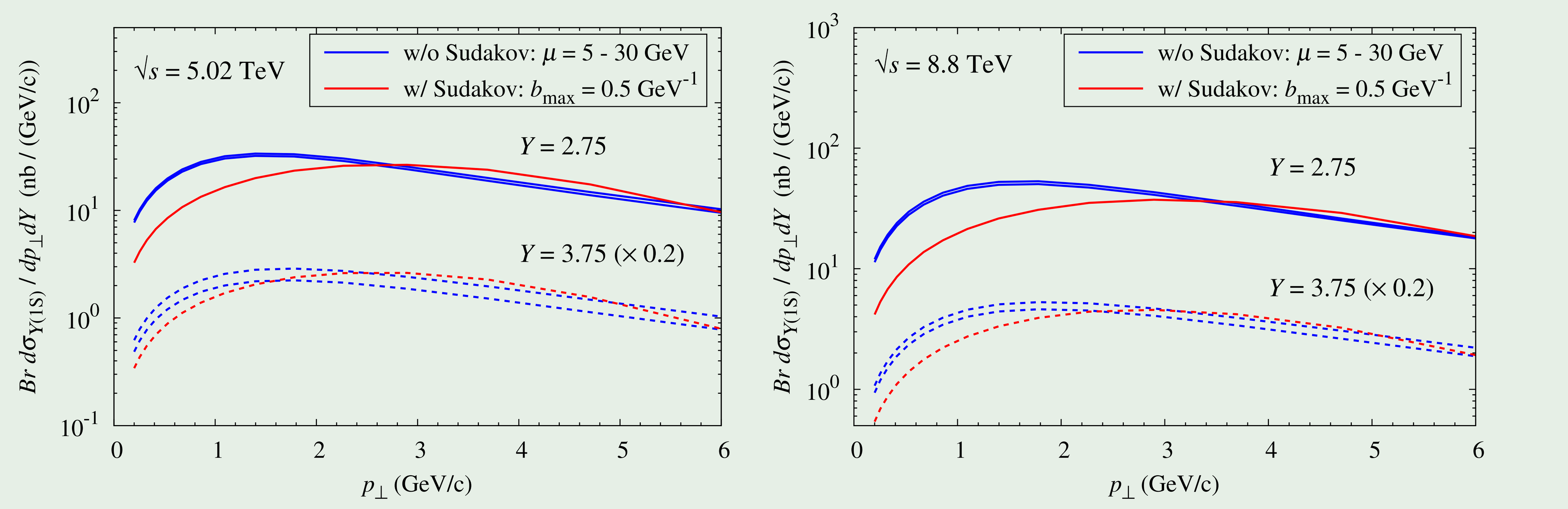

Figure: Double differential cross section of $\Upsilon(1S)$ in pPb collisions as a function of $p_\perp$ for $Y = 2.75$ (solid lines) and 3.75 (dotted lines) at $\sqrt{s} = 5.02$ TeV (Left) and $\sqrt{s} = 8.8$ TeV (Right).

Summary

- We have demonstrated both the small-x resummation and low-$p_\perp$ resummation are essential to understand the LHC data → The full NLO calculations are not completed in this study. Nevertheless NLO corrections are expected to be large.
- The Sudakov effect is small in J/ψ production but manifest in Υ production in pp collisions.
- The effect in pA collisions is less pronounced as compared to pp, since the saturation effect starts to dominate over the Sudakov effect.
- The large-$p_\perp$ broadening of quarkonium due to initial soft gluon emission could be found in the other model such as CGC+NRQCD framework.

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