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Diffractive charmonium spectrum in high energy collisions in the basis light-front quantization approach

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ABSTRACT

Using the charmonium light-front wavefunctions obtained by diagonalizing an effective Hamiltonian with the one-gluon exchange interaction and a confining potential inspired by light-front holography in the basis light-front quantization formalism, we compute production of charmonium states in diffractive deep inelastic scattering and ultra-peripheral heavy ion collisions within the dipole picture. Our method allows us to predict yields of all vector charmonium states below the open flavor thresholds in high-energy deep inelastic scattering, proton–nucleus and ultra-peripheral heavy ion collisions, without introducing any new parameters in the light-front wavefunctions. The obtained charmonium cross section is in reasonable agreement with experimental data at HERA, RHIC and LHC. We observe that the cross-section ratio $\sigma_{\Psi(2s)}/\sigma_{J/\Psi}$ reveals significant independence of model parameters.

1. Introduction

Exclusive vector meson production in diffractive deep inelastic scattering (DIS) and deeply virtual Compton scattering (DVCS) are effective tools for studying Quantum Chromodynamics (QCD) [1]. At low x these processes are dominated by gluon saturation [2,3]. Models incorporating saturation physics successfully describe the high precision data harvested at the Hadron–Electron Ring Accelerator (HERA) [4–9] and are instrumental for deriving predictions for future experiments at the Large Hadron electron Collider (LHeC) [10] and the Electron–Ion Collider (EIC) [11]. Theoretical calculations often employ the dipole model [12,13] that relies on the separation of scales: in the proton rest frame, the lifetime of the virtual photon and the quarkonium formation time are much longer than the time scale of the interaction. The dipole model was used in Refs. [14,15] to describe both exclusive and diffractive HERA measurements at low x.

The largest theoretical uncertainty in the calculation of diffractive heavy quarkonium production in the dipole picture arises from poor knowledge of the heavy quarkonium light-front wavefunction (LFWF). In phenomenological applications, the LFWFs are simply educated guesses with several free parameters [7,14]. While such phenomenological models can be successful in explaining the experimental data, the presence of free parameters limits the predictive power. With electron–ion colliders on the horizon, where around 30% of total events are expected to be diffractive, finding well-constrained heavy quarkonium LFWFs based on the dynamics of QCD becomes important.

Fortunately, recent progress in the basis light-front quantization (BLFQ) approach [16–20] has paved an avenue for improving the understanding of the heavy quarkonium system. It has enabled the computation of the LFWFs for any heavy quarkonium state and thus calculate the corresponding diffractive cross sections. The BLFQ approach has been successfully applied to calculate the electron anomalous magnetic moment [18], and to study the positronium system [19,20]. Recently, some of us employed the light-front Hamiltonian formalism to obtain the mass spectra and LFWFs for charmonium and bottomonium [21]. This was achieved by diagonalizing an effective Hamiltonian that incorporates the one-gluon exchange interaction and a confining potential inspired by light-front holography [22,23]. The decay constants and the charge form factors for selected eigenstates calculated using these LFWFs are comparable to the experimental measurements as well as to results from Lattice QCD and Dyson–Schwinger Equation approaches. Compared to phenomenological LFWFs used in the literature, LFWFs from the BLFQ approach possess appealing merits. In particular, the BLFQ LFWFs arise from successful fits to the heavy quarkonia mass spectroscopy, show success in applications to decay constants and provide predictions for additional

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Table 1
Parameters of the initial gluon distribution in the bSat model in Eq. (5) determined from fits to F_2 data. Parameters of the bSat I–III are fitted to ZEUS data only [14]. Parameters of the bSat IV and V are fitted to combined HERA data [29].

Model	Q^2/GeV^2	N_f	$m_{u,d,s}$/GeV	m_c/GeV	μ_0^2/GeV^2	A_g	λ_g	χ^2/d.o.f.
bSat I	[0.25,650]	3	0.14	1.4	1.17	2.55	0.020	193.0/160 = 1.21
bSat II	[0.25,650]	3	0.14	1.35	1.20	2.51	0.024	190.2/160 = 1.19
bSat III	[0.25,650]	3	0.14	1.5	1.11	2.64	0.011	198.1/160 = 1.24
bSat IV	[0.75,650]	4	≈ 0	1.27	1.51	2.308	0.058	298.89/259 = 1.15
bSat V	[0.75,650]	4	≈ 0	1.4	1.11	2.373	0.052	316.61/259 = 1.22

quantities such as charge form factors all within the same formalism.

The main goal of this letter is to employ the theoretically sound and phenomenologically-constrained BLFQ wavefunctions to compute the diffractive cross sections for the heavy quarkonium production at low x using the dipole model to take into account the gluon saturation.

2. Background

In the dipole model, the amplitude for exclusive heavy quarkonium production in DIS can be calculated as [14]

$$\mathcal{A}_{T,L}^{\gamma^* p\to Ep}(x,Q,\Delta) = i\int d^2\boldsymbol{r}\int_0^1 \frac{dz}{4\pi} \times \int d^2\boldsymbol{b}\,(\Psi_E^*\Psi)_{T,L}(r,z,Q)\,e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\,\frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}}(x,r)\,, \quad (1)$$

where T and L denote the transverse and longitudinal polarization of the virtual photon (with virtuality Q^2) and the produced quarkonium, and $t=-\boldsymbol{\Delta}^2$ denotes the momentum transfer. On the right-hand side, $\boldsymbol{r}$ is the transverse size of the color dipole, z is the LF longitudinal momentum fraction of the quark, $\boldsymbol{b}$ is the impact parameter of the dipole relative to the proton and x is the Bjorken variable. Ψ and Ψ_E^* are LFWFs of the virtual photon and the exclusively produced quarkonium respectively. The cross section is related to the amplitude via

$$\frac{d\sigma_{T,L}^{\gamma^* p\to Ep}}{dt} = \frac{1}{16\pi}|\mathcal{A}_{T,L}^{\gamma^* p\to Ep}(x,Q,\Delta)|^2\,. \quad (2)$$

Furthermore, several phenomenological corrections are needed in order to describe the experimental data. For example, the contribution from the real part of the scattering amplitude is conventionally incorporated by multiplying the cross section by a factor $(1+\beta^2)$ [14], where β is the ratio of the real and imaginary parts of the scattering amplitude, and is calculated as [24]

$$\beta = \tan(\pi\lambda/2), \quad \text{with} \quad \lambda \equiv \frac{\partial \ln\left(\mathcal{A}_{T,L}^{\gamma^* p\to Ep}\right)}{\partial \ln(1/x)}. \quad (3)$$

The skewedness correction, which takes into account the fact that two gluons interacting with the dipole are carrying slightly different momentum fractions, will be specified in Sec. 2.1, since it has been implemented differently for different dipole models in the literature.

2.1. Dipole cross section parametrizations

There are many dipole cross section parametrizations available in the literature based on different theoretical considerations and inspired by the Golec-Biernat Wuesthoff (GBW) model [4]. For this study we employ two representative dipole parametrizations: the impact parameter dependent saturation model (bSat) [7] and the impact parameter dependent Color Glass Condensate model (bCGC) [9] to take advantage of their explicit impact parameter dependence, which is important in diffractive quarkonium production.

The bSat dipole model is based on the Glauber–Mueller formula [12] and assumes the dipole cross section as follows,

$$\frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}} = 2\left[1-\exp\left(-\frac{\pi^2}{2N_c}r^2\alpha_s(\mu^2)xg(x,\mu^2)T(b)\right)\right], \quad (4)$$

where $T(b)$ is the proton shape function, which is assumed to be Gaussian, $T_G(b)=\exp(-b^2/2B_G)/(2\pi B_G)$, with $B_G = 4$ GeV^{-2}. α_s is determined using LO evolution of the running coupling, with fixed number of flavors N_f. μ^2 is related to the dipole size r through $\mu^2 = 4/r^2+\mu_0^2$. The gluon density is determined using LO Dokshitzer–Gribov–Lipatov–Altarelli–Parisi evolution [25] from an initial scale μ_0^2, where the initial gluon density is,

$$xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^{5.6}. \quad (5)$$

In the bSat dipole model, μ_0, A_g and λ_g are parameters to be determined by the inclusive DIS data [26–28]. We use parametrizations given in Refs. [14,29] for this investigation, which we provide in Table 1. We follow the prescription in Ref. [14] for the skewedness correction in the bSat dipole model. $R_{\rm bSat}$ is assumed to be

$$R_{\rm bSat}(\delta_{bSat}) = \frac{2^{2\delta_{\rm bSat}+3}}{\sqrt{\pi}}\frac{\Gamma(\delta_{\rm bSat}+5/2)}{\Gamma(\delta_{\rm bSat}+4)} \quad \text{with}$$
$$\delta_{\rm bSat} \equiv \frac{\partial \ln\left[xg(x,\mu^2)\right]}{\partial \ln(1/x)}. \quad (6)$$

The obtained $R_{\rm bSat}$ is then applied multiplicatively to the gluon density function in Eq. (4). This prescription of the skewedness correction is also adopted in Refs. [29–32].

The bCGC dipole model is a smooth interpolation of the solutions of the Balitsky–Fadin–Kuraev–Lipatov equation [33] for small dipole sizes and the Levin–Tuchin solution [34] of the Balitsky–Kovchegov equation [35] deep inside the saturation region for larger dipoles,

$$\frac{d\sigma_{q\bar{q}}}{d^2\boldsymbol{b}} = 2\mathcal{N}(rQ_s,x) = 2\begin{cases}\mathcal{N}_0\left(\frac{rQ_s}{2}\right)^{2\left(\gamma_s+\frac{1}{\kappa_s\lambda_s\ln(1/x)}\ln\frac{2}{rQ_s}\right)} & : \quad rQ_s\le 2\\ 1-e^{-\mathcal{A}\ln^2(\mathcal{B}rQ_s)} & : \quad rQ_s>2\end{cases}, \quad (7)$$

with $Q_s \equiv Q_s(x) = (x_0/x)^{\lambda_s/2}Q_0$, where $Q_0 = 1$ GeV. γ_s, κ_s, λ_s are parameters to be determined by inclusive DIS data [26–28]. $\mathcal{A}$ and $\mathcal{B}$ should be evaluated by continuity conditions at $rQ_s = 2$. We use the parametrization by Soyez [36] and two parametrizations in Ref. [37] for this investigation, which we provide in Table 2. Note that different conventions were used for the impact parameter dependence in Refs. [36,37]. We follow the prescription in