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Charmonium spectrum and diffractive production in a light-front Hamiltonian approach

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Abstract

We study exclusive charmonium production in diffractive deep inelastic scattering and ultra-peripheral heavy-ion collisions within the dipole picture. The mass spectrum and light-front wavefunctions of charmonium are obtained from the basis light-front quantization approach, using the one-gluon exchange interaction plus a confining potential inspired by light-front holography. We apply these light-front wavefunctions to exclusive charmonium production. The resulting cross sections are in reasonable agreement with electron-proton collision data at HERA and ultra-peripheral nucleus collision measurements at RHIC and LHC. The charmonium cross-section has model dependence on the dipole model. We observe that the cross-section ratio of excited states to the ground state has a weaker dependence than the cross-section itself. We suggest that measurements of excited states of heavy quarkonium production in future electron-ion collision experiments will impose rigorous constraints on heavy quarkonium light-front wavefunctions, thus improving our understanding of meson structure, which eventually will help us develop a precise description of the gluon distribution function in the small-x regime.

Keywords:
charmonium, light front, meson production, dipole model

1. Introduction

Exclusive vector meson production processes are valuable probes of hadron structures [1] and provide insights to QuantumChromodynamics (QCD) in the high energy limit, where saturation dominates the gluon dynamics [1–3]. Models incorporating the saturation physics have been very successful in describing high precision electron-proton collision data collected at the Hadron-Electron Ring Accelerator (HERA) [4–8].

The diffractive DIS process can be effectively approximated by the scattering of a color dipole, a quark-antiquark pair, from the proton [9, 10]. The so called dipole picture has been very successful in explaining both exclusive and diffractive HERA measurements in the high-energy limit [11, 12], by employing some phenomenological vector meson light-front wavefunction (LFWF) [7, 11]. Such phenomenological models contain free parameters that weaken the predictive power of the diffractive heavy quarkonium production process.

Recently, a new description of heavy quarkonium system has emerged [13, 14] within the basis light-front quantization (BLFQ) approach [15–17]. The mass spectra for charmonium and bottomonium are obtained by diagonalizing a Hamiltonian within the BLFQ framework, with the one-gluon exchange interaction and a confining potential inspired by light-front holography [13]. The successful applications of the BLFQ formalism to the electron anomalous magnetic moment [16, 18], and to the positronium system [19, 20] have paved the way for the study of the heavy quarkonium system. The

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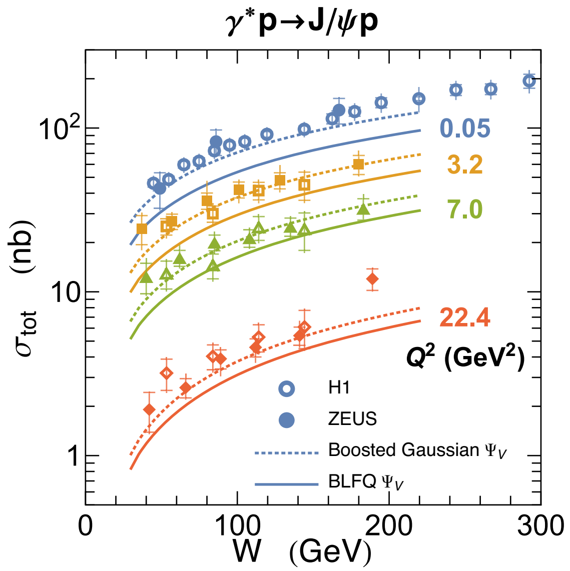

Figure 1: Predictions of the BLFQ LFWF (solid curves) and the boosted Gaussian LFWF (dashed curves) compared with the HERA experimental data of total J/Ψ cross section for different values of Q^2 and W [26, 27]. The inner bars indicate the statistical uncertainties; the outer bars are the statistical and systematic uncertainties added in quadrature.

LFWFs from the BLFQ approach, which arise from successful fits to the heavy quarkonia mass spectroscopy, show success in applications to decay constants and to additional observables such as charge form factors. Here we report predictions of the LFWFs obtained from the BLFQ approach and compare with selected experiment data on diffractive charmonium production, which were discussed in detail in Ref. [21].

2. Theoretical framework

The amplitude for producing an exclusive vector meson in diffractive DIS is calculated as follows in the dipole picture [11],

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

where Q^2 is the virtuality of photon, T and L denote the transverse and longitudinal polarization of the produced vector meson, and the momentum transfer being $t = -\vec{\Delta}^2$. $\vec{r}$ is the transverse separation between the quark and antiquark and z is the LF longitudinal momentum fraction carried by the quark respectively. $\vec{b}$ 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 vector meson respectively. The cross section is related to the amplitude as

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

Moreover, contributions from the real part of the scattering amplitude and skewedness correction should be taken into account, see Ref. [21] for details.

We employ the impact parameter dependent saturation (bSat) model [7] and the impact parameter dependent Color Glass Condensate (bCGC) model [8] for this study. We use five sets of parameters (bSat I-V) in the bSat model[11, 22] and three sets of parameters (bCGC I-III) in the bCGC model [23, 24]. The parameters for these dipole cross section parametrizations are summarized in Tables 1 and 2 in Ref. [21].

The heavy quarkonium mass spectrum and LFWFs are obtained by solving the eigenvalue equation of an effective light-front Hamiltonian, which combines the holographic QCD Hamiltonian [25] and the one-gluon exchange dynamics [13],

$$H_{\mathrm{eff}}|\psi_h\rangle = M_h^2|\psi_h\rangle, \quad (H_{\mathrm{eff}} \equiv P^+\hat{P}^-_{\mathrm{eff}} - \vec{P}^2_\perp)\,. \quad (3)$$

with

$$H_{\mathrm{eff}} = \frac{\boldsymbol{k}_\perp^2 + m_q^2}{z(1-z)} + \kappa_{\mathrm{con}}^4 \zeta_\perp^2 - \frac{\kappa_{\mathrm{con}}^4}{4m_q^2}\partial_z(z(1-z)\partial_z) - \frac{4\pi C_F \alpha_s}{Q^2}\bar{u}_s(k)\gamma_\mu u_{s'}(k')\bar{v}_{\bar{s}'}(\bar{k}')\gamma^\mu v_{\bar{s}}(\bar{k})\,, \quad (4)$$

where $C_F = \frac{4}{3}$, $Q^2 = -\frac{1}{2}(k'-k)^2 - \frac{1}{2}(\bar{k}-\bar{k}')^2$. The strong coupling constant α_s is fixed, $\alpha_s(M_{c\bar{c}}) \simeq 0.36$ and $\alpha_s(M_{b\bar{b}}) \simeq 0.25$. The effective quark mass m_q and the confining strength κ_{con} are determined by fitting the heavy quarkonium mass spectrum to the experimental measurements. The calculated spectra agree with the experimental values within a root-mean-square deviation of around 50 MeV for the states below the open flavor thresholds.

The heavy quarkonium LFWF from the BLFQ approach has several advantages over LFWFs from phenomenological models. First, it is constrained by a variety of observables. Second, it provides access to higher excited states without introducing additional assumptions. Moreover, it can be improved by including higher Fock sectors, e.g., the quark-antiquark-gluon sector.