Physics Letters B 769 (2017) 166–170

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Unique prediction for high-energy J/ψ photoproduction: Color transparency and saturation

Dieter Schildknecht [a,b,*]

[a] Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany
[b] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, D-80805 München, Germany

ARTICLE INFO

Article history:
Received 9 November 2016
Accepted 26 March 2017
Available online 30 March 2017
Editor: G.F. Giudice

Keywords:
Vector meson production
Deep inelastic scattering
Color transparency
Saturation

ABSTRACT

Based on the color-dipole picture, we present a successful parameter-free prediction for the recent high-energy J/ψ photoproduction data from the Large Hadron Collider. The experimental data provide empirical evidence for the transition from color transparency to saturation.

Inspired by experimental data [1] on J/ψ photoproduction, $\gamma p \to J/\psi\ p$, at very high energies obtained at the Large Hadron Collider (LHC), we revive our predictions [2,3] on J/ψ production based on the color-dipole picture (CDP).[1] As depicted in Figs. 1 and 2, the total photoabsorption cross section and the forward production of quark-antiquark states, $\gamma^* p \to (q\bar{q})^{J=1}_{T,L} p$, of total spin $J=1$ at low values of $x \cong Q^2/W^2 \ll 1$ are represented by [3,4]

$$\sigma_{\gamma^*_{T,L}p}(W^2,Q^2) = \int dz \int d^2 r_\perp |\psi_{T,L}(r_\perp, z(1-z), Q^2)|^2 \times \sigma_{(q\bar{q})^{J=1}_{T,L}p}(\vec{r}_\perp\sqrt{z(1-z)}, W^2) \tag{1}$$

and

$$\left.\frac{d\sigma_{\gamma^*_{T,L}p\to(q\bar{q})^{J=1}_{T,L}p}}{dt}(W^2,Q^2)\right|_{t=0} = \frac{1}{16\pi}\int dz \int d^2 r_\perp \left|\psi_{T,L}(r_\perp, z(1-z), Q^2)\right|^2 \times \sigma^2_{(q\bar{q})^{J=1}_{T,L}p}(\vec{r}_\perp\sqrt{z(1-z)}, W^2). \tag{2}$$

In standard notation, $|\psi_{T,L}(r_\perp, z(1-z), Q^2)|^2$ denotes the probability for the photon of virtuality Q^2 to couple to a $(q\bar{q})^{J=1}_{T,L}$ state specified by the transverse size $\vec{r}_\perp$ and the longitudinal momentum partition $0 \le z \le 1$, and $\sigma_{(q\bar{q})^{J=1}_{T,L}p}(\vec{r}_\perp\sqrt{z(1-z)}, W^2)$ denotes the $(q\bar{q})$-dipole-proton cross section at the total $\gamma^* p$ center-of-mass energy W. The two-gluon coupling of the $q\bar{q}$ dipole state requires a representation of the $(q\bar{q})$-color-dipole cross section of the form [3,4]

$$\sigma_{(q\bar{q})^{J=1}_{T,L}p}(\vec{r}_\perp\sqrt{z(1-z)}, W^2) = \int d^2 l'_\perp \bar{\sigma}_{(q\bar{q})^{J=1}_{T,L}p}(\vec{l}^{\prime 2}_\perp, W^2)(1 - e^{-\vec{l}'_\perp\cdot\vec{r}_\perp\sqrt{z(1-z)}}). \tag{3}$$

Upon introducing the mass, M, of the $(q\bar{q})^{J=1}$ states, and upon applying the optical theorem to relate $(q\bar{q})^{J=1}p$ forward scattering to the $(q\bar{q})^{J=1}p$ total cross section, we identically reformulate the total photoabsorption cross section (1) in terms of the $(q\bar{q})p$ forward-production cross section (2), obtaining [5][2]

$$\sigma_{\gamma^*_T p}(W^2,Q^2) = \sqrt{16\pi}\sqrt{\frac{\alpha R_{e^+e^-}}{3\pi}} \int_{m_0^2} dM^2 \frac{M}{Q^2+M^2} \times \sqrt{\left.\frac{d\sigma_{\gamma^*_T p\to(q\bar{q})^{J=1}_T p}}{dt dM^2}\right|_{t=0}} \tag{4}$$

* Correspondence to: Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld, Germany
E-mail address: schild@physik.uni-bielefeld.de.

[1] Compare ref. [4] and the list of literature on the CDP quoted there.

[2] A correction related to the contributions due to a (small) real part of the $q\bar{q}$ forward-production amplitude is ignored in (4) and (5).

http://dx.doi.org/10.1016/j.physletb.2017.03.056
0370-2693/

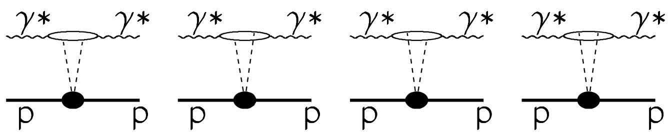

Fig. 1. The forward Compton amplitude.

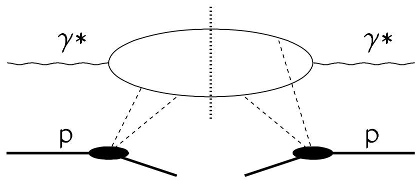

Fig. 2. One of the 16 diagrams for diffractive production. The vertical line indicates the unitarity cut corresponding to the diffractively produced final states, $(q\bar{q})^J$. Production of (discrete or continuum) vector states corresponds to $(q\bar{q})^J$ production with $J = 1$.

and

$$\sigma_{\gamma_L^* p}(W^2, Q^2) = \sqrt{16\pi}\sqrt{\frac{\alpha R_{e^+e^-}}{3\pi}}\int_{m_0^2} dM^2 \frac{\sqrt{Q^2}}{Q^2+M^2} \times \sqrt{\left.\frac{d\sigma_{\gamma_L^* p\to (q\bar{q})_L^{J=1}p}}{dtdM^2}\right|_{t=0}}. \tag{5}$$

The representations (4) and (5) explicitly relate the transverse and longitudinal total photoabsorption cross sections to the diffractive forward-production cross sections,

$$\left.\frac{d\sigma_{\gamma_{T,L}^* p\to (q\bar{q})_{T,L}^{J=1}p}}{dtdM^2}\right|_{t=0} = \left.\frac{d\sigma_{\gamma_{T,L}^* p\to (q\bar{q})_{T,L}^{J=1}p}}{dtdM^2}(W^2, Q^2, M^2)\right|_{t=0}, \tag{6}$$

of a continuum of $(q\bar{q})^{J=1}$ states of mass M. The lower limit m_0^2 in (4) and (5), via quark-hadron duality,[3] for the (dominant) contribution due to light quarks fulfills $m_0 < m_\rho$, where m_ρ is the ρ-meson mass, and $R_{e^+e^-} = 3\sum_q Q_q^2$, where the sum runs over the actively contributing quark flavors, and Q_q denotes the quark charge.

The representations (4) and (5) for the photoabsorption cross section explicitly demonstrate that low-x photoabsorption is due to the coupling of the photon to $(q\bar{q})^{J=1}$ (vector) dipole states that subsequently propagate and interact via coupling to two gluons with the gluon field in the nucleon. The massive $q\bar{q}$ continuum contains the low-lying vector mesons, $\rho^0, \omega, \phi, J/\psi, \Upsilon$ etc. followed by more massive $J = 1$ true continuum states, $X_{q\bar{q}}^{J=1}$, also diffractively produced via $\gamma^* p \to X_{(q\bar{q})}^{J=1} p$. For an appropriate magnitude of the kinematic variables, the $X_{(q\bar{q})}^{J=1}$ states appear as two-jet states with angular distribution characteristic for spin $J = 1$.

For quantitative predictions, $\bar{\sigma}_{(q\bar{q})_{T,L}^{J=1}p}(\vec{l}_\perp^{\,\prime 2}, W^2)$ in (3) must be specified. Agreement with experiment for the total photoabsorption cross section in (1), and, equivalently, in (4) and (5), then determines the diffractive (forward) production of vector states and allows for a parameter-free prediction of their photoproduction cross section (6). Indeed, for vector-meson production, specifically for J/ψ production,[4] we have [2,3]

$$\frac{d\sigma_{\gamma^* p\to J/\psi\, p}}{dt}(W^2, Q^2)\,|_{t=0} = \int_{\Delta M_{J/\psi}^2} dM^2 \int_{z_-}^{z_+} dz \frac{d\sigma_{\gamma^* p\to (c\bar{c})^{J=1}p}}{dt\, dM^2\, dz}(W^2, Q^2, z, m_c^2, M^2), \tag{7}$$

where

$$z_\pm = \frac{1}{2} \pm \frac{1}{2}\sqrt{1 - 4\frac{m_c^2}{M^2}}. \tag{8}$$

In (7), m_c denotes the mass of the charm quark, and $M^2 \equiv M_{c\bar{c}}^2$ denotes the mass squared of the $c\bar{c}$ state in the interval $\Delta M_{J/\psi}^2$ determined by the level spacing of the $c\bar{c}$ bound-state spectrum of states observed in e^+e^- annihilation.

Replacing the cross section for the open-charm continuum on the right-hand side in (7) by the cross section for $c\bar{c}$ production at threshold,

$$\frac{d\sigma_{\gamma^* p\to (c\bar{c})^{J=1}p}}{dt\, dM^2 dz}(W^2, Q^2, z, m_c^2, M^2) \longrightarrow \frac{d\sigma}{dt\, dM^2\, dz}\left(W^2, Q^2, z = \frac{1}{2}, M^2 = 4m_c^2 = M_{J/\psi}^2\right), \tag{9}$$

the integration in (7) simplifies to become [3]

$$\int_{4m_c^2}^{4m_c^2+\Delta M_{J/\psi}^2} dM^2 \int_{z_-}^{z_+} dz = \int_{4m_c^2}^{4m_c^2+\Delta M_{J/\psi}^2} dM^2 \sqrt{1 - \frac{4m_c^2}{M^2}} \equiv \Delta F^2(m_c^2, \Delta M_{J/\psi}^2), \tag{10}$$

where

$$\begin{aligned}\Delta F^2(m_c^2, \Delta M_{J\psi}^2) &\equiv \int_{4m_c^2}^{4m_c^2+\Delta M_{J/\psi}^2} dM^2 \sqrt{1 - \frac{4m_c^2}{M^2}} \int_0^1 dy \\ &= (4m_c^2 + \Delta M_{J/\psi}^2)\sqrt{\frac{\Delta M_{J/\psi}^2}{4m_c^2 + \Delta M_{J/\psi}^2}} \\ &\quad + 2m_c^2 \ln \frac{1 - \sqrt{\frac{\Delta M_{J/\psi}^2}{4m_c^2+\Delta M_{J/\psi}^2}}}{1 + \sqrt{\frac{\Delta M_{J/\psi}^2}{4m_c^2+\Delta M_{J/\psi}^2}}}.\end{aligned} \tag{11}$$

With (9) to (11), the cross section (7) becomes

$$\left.\frac{d\sigma_{\gamma^* p\to J/\psi p}}{dt}(W^2, Q^2)\right|_{t=0} \longrightarrow \frac{d\sigma}{dt\, dM^2\, dz}\left(W^2, Q^2, z = \frac{1}{2}, M^2 = 4m_c^2 = M_{J/\psi}^2\right) \times \Delta F^2(m_c^2, \Delta M_{J/\psi}^2). \tag{12}$$

The cross section for J/ψ electroproduction in (12) is accordingly represented by charm-quark pair production at threshold multiplied by the factor $\Delta F^2(m_c^2, \Delta M_{J/\psi}^2)$ of dimension $\Delta M_{J/\psi}^2$.

In refs. [2,3] we have evaluated the J/ψ-production cross section (12) upon specifying the dipole cross section in (3) by the ansatz

$$\bar{\sigma}_{(q\bar{q})_T^{J=1}p}(\vec{l}_\perp^{\,\prime 2}, W^2) = \bar{\sigma}_{(q\bar{q})_L^{J=1}p}(\vec{l}_\perp^{\,\prime 2}, W^2) = \sigma^{(\infty)}(W^2)\frac{1}{\pi}\delta(\vec{l}_\perp^{\,\prime 2} - \Lambda_{sat}^2(W^2)), \tag{13}$$

[3] Massless quarks are used in the derivation of (4) and (5).

[4] The generalization to Υ-production is straight forward.