Kinematic distributions of the η_c photoproduction in ep collisions within the nonrelativistic QCD framework

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We study the η_c photoproduction in ep collisions in this paper. The short-distance coefficients for $c\bar{c}({}^1S_0^{[1]})$, $c\bar{c}({}^1S_0^{[8]})$, $c\bar{c}({}^3S_1^{[8]})$, and $c\bar{c}({}^1P_1^{[8]})$ photoproductions via both direct and resolved photons are evaluated at leading order in α_s expansion, where the color-singlet contribution is achieved for the first time. The dependence of the cross sections on the renormalization and factorization scales, and the charm quark mass is studied in this paper. As an interesting result, the color-singlet cross section is dominated by the resolved photoproduction, which is almost two orders of magnitude larger than the contributions from the direct photons. The resolved photoproduction also enhances the color-octet cross sections considerably. By including the contributions from direct and resolved photons, we find the color-singlet channel dominates the integrated cross section. Making use of different sets of long-distance matrix elements, we observe some apparently distinguishable predictions, which can be utilized to scrutinize the validity of these matrix elements. Moreover, we carefully analyze different kinematic distributions of the cross sections and find that, in high p_t regions, the color-singlet contribution is considerably suppressed comparing with the color-octet parts for most sets of long-distance matrix elements. This feature renders the η_c photoproduction process another laboratory to test the color-octet mechanism in nonrelativistic QCD.

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I. INTRODUCTION

In 2014, the η_c hadroproduction cross section was measured for the first time by the LHCb Collaboration [1,2], which opened a window for the study of the pseudoscalar quarkonia production. Under the assumptions of the heavy quark spin asymmetry, the J/ψ and η_c hadroproduction was studied comprehensively in Refs. [3–5], the first one of which considered the η_c measurement as a big challenge of nonrelativistic QCD (NRQCD) [6], while the latter two

reconciled the J/ψ and η_c hadroproduction data within the NRQCD framework. Unfortunately, when making use of the long-distance matrix elements (LDMEs) obtained in Refs. [4,5] in the J/ψ photoproduction, the theoretical results significantly overshoot the data [7]. Still, there does not exist any set of LDMEs which can describe all the data on charmonium production and polarization up to QCD next-to-leading-order (NLO). For some quarkonium production processes, the higher-order corrections in both α_s and v^2 expansion proved to be important, which might radically change the phenomenological results. Accordingly, we would expect the universality of the LDMEs be observed when higher precision calculations are completed. Recently, two-loop calculations for some quarkonium production and decay processes have been achieved by several theory groups [8–14]. There are also efforts made to find new approaches to improving the precision of the theoretical predictions, such

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as improving the convergence quality of the NRQCD expansions [15], and using fragmentation functions to achieve the dominant contributions at higher orders in high p_T regions [16–18].

In order to test NRQCD, it is also helpful to find such processes in which the color-octet (CO) mechanism dominates the quarkonium production. As a perfect example, inclusive J/ψ hadroproduction has been thoroughly investigated at QCD NLO in a series of theoretical papers [19–29]. As another example, the color-singlet (CS) J/ψ photoproduction undershoot the data [30], thus the CO mechanism is needed [31,32]. The J/ψ leptonproduction is also a good laboratory to test NRQCD. The QCD corrections to the CS J/ψ leptonproduction has been given in Ref. [33]. However, QCD NLO results for the CO processes are still lacking. Interestingly, even the QCD leading-order calculation of this process is not trivial. The first correct results were obtained as recently as in 2017 [34,35].

Thanks to its specific quantum numbers, the CS η_c is excluded from many processes at QCD leading order, and therefore considered to be suppressed. An interesting example is the η_c production in association with light hadrons in e^+e^- annihilation [36], where the CS contributions are negligible comparing with the CO ones. The η_c and η'_c hadroproduction are also studied in greater detail in Refs. [37,38]. As early as in 1999, the η_c photoproduction [39] and leptonproduction [40] in electron-proton (ep) collisions has been proposed to test the CO mechanism, because the CS η_c can be produced with at least two gluons emitted, which is suppressed by a factor of α_s^2 comparing to $c\bar{c}({}^1S_0^{[8]})$ production. Therefore the CO contribution is thought to dominate this process. However the CO LDMEs are suppressed relative to their CS counterpart. One may wonder whether the CS contribution is dispensable. Limited by the calculation capability at that time, the CS photoproduction and leptonproduction were not evaluated in Refs. [39,40]. Therefore, to make a solid conclusion, we need to complement this part and compare it with the CO contributions.

In this paper, we restudy the η_c photoproduction by including both the CS and CO processes. Section II gives a brief introduction to the NRQCD framework for the calculation of the η_c photoproduction. In this framework, the numerical results are evaluated and the phenomenological analyses are given in Sec. III. In Sec. IV, a brief summary and conclusion is presented.

II. η_c PHOTOPRODUCTION IN NRQCD FRAMEWORK

When the scattering angle of the electron is very small in ep collisions, the cross sections can be evaluated approximately by calculating the process of a proton interacting with a real photon [41–43], which carries a fraction (y) of

the momentum of the incident electron. This picture is known as the Weizsäcker-Williams approximation (WWA). Under this approximation, the η_c production cross section can be written as

$$d\sigma(e(k) + p(P) \rightarrow \eta_c(p) + X(p_X) + e(k')) = \int dy f_{\gamma/e}(y) d\sigma_{\gamma p \rightarrow \eta_c + X}(q = yk), \quad (1)$$

where q is the momentum of the incident photon, and $f_{\gamma/e}$ is the WWA photon distribution function, the form of which can be found in Ref. [43] and is presented explicitly as follows,

$$f_{\gamma/e}(y) = \frac{\alpha}{2\pi} \left\{ \frac{2m_e^2 y}{Q_{\max}^2} - \frac{2(1-y)}{y} + \frac{2(1-y) + y^2}{y} \ln \left[\frac{Q_{\max}^2 (1-y)}{m_e^2 y^2} \right] \right\}. \quad (2)$$

Here m_e is the electron mass, α is the fine structure constant, and $Q_{\max}$ is the maximum value of Q , which is determined by the experiment. Q is defined by

$$Q^2 = -(k - k')^2. \quad (3)$$

Note that X in Eq. (1) represents one or several particles.

Within the NRQCD framework, η_c can be produced via four intermediate $c\bar{c}$ states, namely ${}^1S_0^{[1]}$, ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^1P_1^{[8]}$, up to the relative order of v^4 , where v is the typical relative velocity of the c -quark in η_c . The cross section for the η_c photoproduction can thus be expressed as

$$d\sigma_{\gamma p \rightarrow \eta_c + X} = \sum_n d\hat{\sigma}_{\gamma p \rightarrow c\bar{c}(n) + X} \langle \mathcal{O}^{\eta_c}(n) \rangle, \quad (4)$$

where n runs over the four intermediate $c\bar{c}$ states, and $d\hat{\sigma}_{\gamma p \rightarrow c\bar{c}(n) + X}$ and $\langle \mathcal{O}^{\eta_c}(n) \rangle$ are the corresponding short-distance coefficient (SDC) and LDME, respectively. The SDCs can be evaluated perturbatively as expansions in the strong coupling, α_s , while the CO LDMEs in Eq. (4) are obtained through their correspondence with the LDMEs for the J/ψ production. The relations are given as

$$\begin{aligned} \langle \mathcal{O}^{\eta_c}({}^1S_0^{[8]}) \rangle &= \frac{1}{3} \langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]}) \rangle, \\ \langle \mathcal{O}^{\eta_c}({}^3S_1^{[8]}) \rangle &= \langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]}) \rangle, \\ \langle \mathcal{O}^{\eta_c}({}^1P_1^{[8]}) \rangle &= 3 \langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]}) \rangle. \end{aligned} \quad (5)$$

The CS LDME can be estimated by the approximate relation between it and the quarkonium wave function at the origin, $R(0)$, which is written as

$$\langle \mathcal{O}^{\eta_c}(^1S_0^{[1]}) \rangle \approx \frac{3}{2\pi} |R(0)|^2. \quad (6)$$

According to the parton model, the SDCs can be further factorized as SDCs for the $c\bar{c}$ production via the photon-parton fusion convoluted with the parton distribution functions (PDFs). Explicitly, we have

$$d\hat{\sigma}_{\gamma p \rightarrow \eta_c + X} = \sum_{i,n} \int dx f_{i/p}(x, \mu_f) \times d\hat{\sigma}_{\gamma i \rightarrow c\bar{c}(n) + X}(p_i = xP) \langle \mathcal{O}^{\eta_c}(n) \rangle, \quad (7)$$

where i runs over all possible species of partons whose momenta are denoted by p_i , and μ_f is the factorization scale.

The initial photon can interact directly with the parton, i , or also emit partons, which then interact with the parton, i , via strong interaction. The former and latter mechanism are named as direct and resolved photoproduction, respectively.

A. Direct photoproduction

In this subsection, we discuss the calculation of the contributions from the direct photons. In collinear factorization, to generate an η_c with nonzero transverse momentum (p_t), there are only five partonic processes at QCD LO. They are

$$\begin{aligned} \gamma + g &\rightarrow c\bar{c}(^1S_0^{[1]}) + g + g, \\ \gamma + g &\rightarrow c\bar{c}(^1S_0^{[8]}) + g, \\ \gamma + q(\bar{q}) &\rightarrow c\bar{c}(^1S_0^{[8]}) + q(\bar{q}), \\ \gamma + g &\rightarrow c\bar{c}(^3S_1^{[8]}) + g, \\ \gamma + g &\rightarrow c\bar{c}(^1P_1^{[8]}) + g, \end{aligned} \quad (8)$$

where q represents a light quark (u , d , or s).

The SDCs on the right-hand side of Eq. (7) can be expressed as

$$d\sigma_{\gamma i \rightarrow c\bar{c}(n) + X} = \frac{1}{2s_{\gamma i}N} |\mathcal{M}_{\gamma i \rightarrow c\bar{c}(n) + X}|^2 d\Phi, \quad (9)$$

where $s_{\gamma i} = (q + p_i)^2$, N synthesizes the spin, color, and symmetry average factors, $\mathcal{M}_{\gamma i \rightarrow c\bar{c}(n) + X}$ denotes the amplitude for the $c\bar{c}(n)$ production in the partonic process, and $d\Phi$ is the phase space which can be written as

$$d\Phi = (2\pi)^4 \delta^4(q + p_i - p - p_X) \frac{d^3p}{(2\pi)^3 2p_0} d\Phi_X, \quad (10)$$

where $d\Phi_X$ encapsulates the phase space for all the hadronic final-state particles other than the $c\bar{c}$. To accord

with the experiment, we express the cross sections in terms of the following two variables,

$$\begin{aligned} W^2 &= (q + P)^2 = 2q \cdot P = yS, \\ z &= \frac{P \cdot p}{P \cdot q} = \frac{p_i \cdot p}{p_i \cdot q}, \end{aligned} \quad (11)$$

where S is the squared invariant colliding energy of the ep system, and z is called the elasticity coefficient.

Substituting Eqs. (4), (7), and (9) into Eq. (1), we obtain the form of the cross section as

$$\begin{aligned} d\sigma &= \sum_{i,n} \int dx dy f_{i/p}(x, \mu_f) f_{\gamma/e}(y) \\ &\times \frac{1}{2s_{\gamma i}N} |\mathcal{M}_{\gamma i \rightarrow c\bar{c}(n) + X}|^2 \langle \mathcal{O}^{\eta_c}(n) \rangle d\Phi. \end{aligned} \quad (12)$$

Integrating over dx , replacing y by W , one can further reduce Eq. (12) into

$$\begin{aligned} d\sigma &= \frac{1}{8\pi s_{\gamma i}N} \sum_{i,n} \langle \mathcal{O}^{\eta_c}(n) \rangle f_{i/p}\left(\frac{s_{\gamma i}}{W^2}, \mu_f\right) f_{\gamma/e}\left(\frac{W^2}{S}\right) \\ &\times |\mathcal{M}_{\gamma i \rightarrow c\bar{c}(n) + X}|^2 \frac{dW}{W} \frac{dz}{z(1-z)} dp_i^2 d\phi_x, \end{aligned} \quad (13)$$

where $d\phi_x$ is defined as follows: $d\phi_x = 1$ for all the three CO processes, while for the CS process,

$$\begin{aligned} d\phi_x &= \frac{ds_{ab}}{2\pi} (2\pi)^4 \delta^4(p_X - p_a - p_b) \\ &\times \frac{d^3p_a}{(2\pi)^3 2E_a} \frac{d^3p_b}{(2\pi)^3 2E_b}. \end{aligned} \quad (14)$$

Here, p_a and p_b denote the momenta of the two final-state gluons, and $s_{ab} \equiv (p_a + p_b)^2$.

Summing over all the processes in Eq. (8), we obtain the η_c photoproduction cross section contributed by the direct photons.

B. Resolved photoproduction

The resolved photons emit partons, say light quarks and gluons, which carry a fraction, y' , of the photon momentum and interact with the partons from the protons. For each intermediate $c\bar{c}$ state, there are four partonic processes, namely,

$$\begin{aligned} g + g &\rightarrow c\bar{c}(n) + g, \\ g + q(\bar{q}) &\rightarrow c\bar{c}(n) + q(\bar{q}), \\ q(\bar{q}) + g &\rightarrow c\bar{c}(n) + q(\bar{q}), \\ q + \bar{q}(\bar{q} + q) &\rightarrow c\bar{c} + g, \end{aligned} \quad (15)$$

where the first and second initial parton come from the proton and photon, respectively.

Equation (7) in this case reduces to

$$d\sigma = \sum_{i,j,n} \int dx dy dy' f_{i/p}(x, \mu_f) f_{\gamma/e}(y) f_{j/\gamma}(y', \mu'_f) \times \frac{1}{2s_{ij}N} |\mathcal{M}_{ij \rightarrow c\bar{c}(n)+X}|^2 \langle \mathcal{O}^{n_c}(n) \rangle d\Phi, \quad (16)$$

where j denotes the parton emitted by the photon, the momentum of which, in the following, we denote as p_j , and s_{ij} is the squared invariant energy of the initial partons, namely $s_{ij} = (p_i + p_j)^2$. Note that μ'_f , the factorization scale for parton distribution of the photon, can be different from μ_f . Integrating over dx and replacing y by W , we obtain the final expression for the cross sections as

$$d\sigma = \frac{1}{8\pi s_{ij}SN} \sum_{i,j,n} \langle \mathcal{O}^{n_c}(n) \rangle \int \frac{dy'}{y'} f_{i/p}\left(\frac{s_{ij}}{y'W^2}, \mu_f\right) \times f_{j/\gamma}(y', \mu'_f) f_{\gamma/e}\left(\frac{W^2}{S}\right) |\mathcal{M}_{ij \rightarrow c\bar{c}(n)+X}|^2 \times \frac{dW}{W} \frac{dz}{z(1-z)} dp_t^2. \quad (17)$$

III. NUMERICAL RESULTS AND PHENOMENOLOGICAL ANALYSIS

The squared amplitudes for the processes listed in Eq. (8) are calculated automatically by the feynman diagram calculation package [44]. In our numerical calculations, we adopt the following parameter choices. $m_e = 0.5 \times 10^{-3}$ GeV, $m_c = 1.5$ GeV, and $\alpha = 1/137$. The renormalization scale (μ_r) and factorization scale are set to be $\mu_r = \mu_f = \mu'_f = \mu_0 \equiv \sqrt{4m_c^2 + p_t^2}$. Since HERA has stopped its running, we aim at new ep colliders such as the electron-ion collider. While the running energies of such colliders are not known yet, we set the energies of the incident beams according to the HERA experiment, namely the energy of the electron beams is 27.5 GeV and that of the proton beams is 920 GeV. The expression of the photon distribution function has been given in Eq. (2), where $Q_{\max}^2 = 0.5$ GeV² is chosen in our numerical calculation. We employ CTEQ6L1 [45] as the PDF for the protons. The PDF for the photons are taken from Ref. [46]. The CS LDME is computed according to

$$\langle \mathcal{O}^{n_c}(^1S_0^{[1]}) \rangle = \frac{3}{2\pi} |R(0)|^2 \approx 0.387 \text{ GeV}^3, \quad (18)$$

where the value of the wave function at the origin is taken from Ref. [47] as $|R(0)|^2 = 0.81$ GeV³. To obtain the value of α_s , the one-loop running equation is employed and its value at the Z_0 -boson mass is set to be $\alpha_s(M_Z) = 0.13$. In this paper, we calculate the differential cross section with respect to p_t^2 , W , and z . For the p_t^2 distribution, the ranges of W and z are constrained by $60 \text{ GeV} < W < 240 \text{ GeV}$

and $0.3 < z < 0.6$, respectively. In the calculation of the W and z distributions, the p_t is constrained by $p_t^2 > 4 \text{ GeV}^2$. The W distribution is calculated in the kinematic region, $0.3 < z < 0.6$, while the z distribution is calculated in the kinematic region, $60 \text{ GeV} < W < 240 \text{ GeV}$.

A. Scale dependence

First, we investigate the scale (μ_r , μ_f , μ'_f , and m_c) dependence of the integrated cross sections, where the integrations are carried out in the following kinematic region, $p_t^2 > 4 \text{ GeV}^2$, $60 \text{ GeV} < W < 240 \text{ GeV}$, and $0.3 < z < 0.6$, at the same time, compare the contributions from different channels. In order to compare their relative importance, the LDMEs should be multiplied. Here we employ the CO LDMEs given in Refs. [5,28]. For the sake of convenience, we list these LDMEs below,

$$\begin{aligned} \langle \mathcal{O}^{n_c}(^1S_0^{[8]}) \rangle &= 0.36 \times 10^{-2} \text{ GeV}^3, \\ \langle \mathcal{O}^{n_c}(^3S_1^{[8]}) \rangle &= 0.74 \times 10^{-2} \text{ GeV}^3, \\ \langle \mathcal{O}^{n_c}(^1P_1^{[8]}) \rangle / m_c^2 &= 6.0 \times 10^{-2} \text{ GeV}^3, \end{aligned} \quad (19)$$

where the relations in Eq. (5) have been used. Note that there is an inconsistency, i.e., the LDMEs extracted at QCD NLO are associated with the LO SDCs. This is because of the following considerations: (a) Under the NRQCD framework, the LDMEs are universal for all the processes. However, the NLO QCD corrections are always significant, and the behaviors of these corrections are different for different processes. Therefore, it is impossible to observe this universality at QCD LO. (b) It is shown in Ref. [31] that the NLO QCD corrections to the CS and CO J/ψ photoproduction in low p_t regions are not very large. For this reason, we can expect that our LO SDCs are very close to the NLO ones. Associated with the LDMEs extracted at QCD NLO, these LO SDCs can thus provide reasonable predictions.

For the direct photoproduction of η_c , although the SDC for the CS process is suppressed by a factor of α_s , comparing with the CO ones, the CS LDME is enhanced by some powers of $1/v$. Since for the charmonia, v^4 is approximated to be 0.1, one cannot naively conclude a CO dominance picture in the η_c photoproduction just from the analysis of the scaling. The renormalization scale (μ_r) dependence of the integrated cross section is presented in Fig. 1, where we have fixed the factorization scales, μ_f and μ'_f , at $\mu_f = \mu'_f = \mu_0$. The upper and mid plots display the contributions from the direct and resolved photons, respectively, while their summation is presented in the lower plot. From the upper plot of Fig. 1, we immediately realize that the direct CS contribution is one order of magnitude smaller than those from the $^1S_0^{[8]}$ and $^1P_1^{[8]}$ channels. This indicates that even the LDME is enhanced a lot, the SDC of the direct CS channel is highly suppressed, and therefore its

FIG. 1. The renormalization scale dependence of the cross sections. The upper and mid plots display the contributions from the direct and resolved photons, respectively. Their summation is given in the lower plot.

contribution is negligible. It is clearly shown that the $^3S_1^{[8]}$ channel is comparable with the CS one, which is also negligible. This is completely different from the η_c hadroproduction case, in which the $^3S_1^{[8]}$ channel dominates the CO η_c production. In contrast, the η_c produced via the resolved photons are dominated by the CS channel, which is enhanced by two powers of magnitude by the resolved photons, as we can see from the mid plot of Fig. 1. The inclusion of the contributions from the resolved photons completely change the relative importance of the four channel. Summing over the contributions from the direct and resolved photons, we find that the CS channel dominates the η_c photoproduction. This is actually not surprising. The large contribution of the CS η_c production via gluon-gluon fusion has already been known in the

studies of the η_c hadroproduction [3–5]. Our results indicate that the resolved photons enhance the $c\bar{c}(^3S_1^{[8]})$ production by an order of magnitude, contribute moderately to the $^1P_1^{[8]}$ channel, and slightly change the $^1S_0^{[8]}$ one. Nevertheless, the contributions from the $^1P_1^{[8]}$ channel, which nearly saturate the CO cross section, are much larger than that from the other two CO channels. This is partly due to the fact that $^1P_1^{[8]}$ bears a larger LDME. This feature can be exploited to impose new constraints on the LDMEs.

As μ_r varies from $0.5\mu_0$ to $2\mu_0$, The cross sections decrease by a factor of 2 to 3.

The factorization scale dependence of the integrated cross section is presented in Fig. 2. Here we set $\mu_f = \mu'_f$,

FIG. 2. The factorization scale dependence of the cross sections. The upper and mid plots display the contributions from the direct and resolved photons, respectively. Their summation is given in the lower plot.

FIG. 3. The charm mass dependence of the cross sections. The upper and mid plots display the contributions from the direct and resolved photons, respectively. Their summation is given in the lower plot.

and vary them simultaneously, during which μ_r is set to be $\mu_r = \mu_0$. As μ_f (along with μ_f') vary from $0.5\mu_0$ to $2\mu_0$, the cross sections increase by a factor of 2 or less.

In Fig. 3, we present the curves for the integrated cross sections with respect to charm quark mass (m_c), where not only the SDCs but also the LDMEs depend on m_c . Since all

the LDMEs are extracted at $m_c = 1.5$ GeV, we need to take the scaling rules,

$$\begin{aligned} \langle \mathcal{O}_{\eta_c}^{(2s+1)S_j^{[n]}} \rangle &\propto m_c^3, \\ \langle \mathcal{O}_{\eta_c}^{(2s+1)P_j^{[n]}} \rangle / m_c^2 &\propto m_c^3, \end{aligned} \quad (20)$$

are taken into account. As m_c varies from 1.3 GeV to 1.7 GeV, the integrated cross sections increase by a factor of 2 to 4.

B. The LDME dependence

In this subsection, we present the differential cross sections of the η_c photoproduction with respect to p_t^2 , W , and z . The contributions from both the direct photons and resolved photons are summed over. Since there are several sets of LDMEs available on the market, it is necessary and instructive to compare their corresponding predictions and see whether, just like in the J/ψ hadroproduction case, they work equally well also in the η_c photoproduction process. In the following discussions, we employ five different sets of LDMEs, taken from Refs. [18,23,25,28,29], respectively. They are listed in Table I, where the relations in Eq. (5) have been implemented. Each of them is independently obtained, and can describe the J/ψ yield data at the Tevatron and LHC. Note that the LDMEs for the J/ψ production are extracted also in Refs. [16,26], since the authors of the two references have updated their results in Refs. [18,29], respectively, we do not present results for the old version of the LDMEs in this paper.

The numerical results for different sets of LDMEs are given in Fig. 4. Although these LDMEs lead to almost equal results for the J/ψ hadroproduction, their prediction on the η_c photoproduction are completely different, which provides a good laboratory to scrutinize the validity of different sets of LDMEs. We can see that all the curves are above the CS ones. The LDMEs taken from Refs. [18,25] give the highest curves, which, in most of the kinematic regions, are almost twice of the CS ones. As p_t increases, the deviation between the CS curve and the NRQCD curves becomes greater, which is due to the fact that $c\bar{c}({}^1S_0^{[1]})$ production via parton-parton fusion is dominated by the next-to-leading power behavior in p_t , while $c\bar{c}({}^3S_1^{[8]})$ production is dominated by leading power behavior

TABLE I. The CO LDMEs for the η_c production obtained by different theory groups, where the relations between the LDMEs for the J/ψ and η_c production are employed.

References	Butenschon <i>et al.</i> [23]	Chao <i>et al.</i> [25]	Sun <i>et al.</i> [28]	Bodwin <i>et al.</i> [18]	Feng <i>et al.</i> [29]
$\langle \mathcal{O}_{\eta_c}({}^1S_0^{[8]}) \rangle (10^{-2} \text{ GeV}^3)$	0.056 ± 0.015	0.10 ± 0.04	0.36	-0.238 ± 0.121	0.059 ± 0.019
$\langle \mathcal{O}_{\eta_c}({}^3S_1^{[8]}) \rangle (10^{-2} \text{ GeV}^3)$	3.04 ± 0.35	8.9 ± 0.98	0.74	11.0 ± 1.4	5.66 ± 0.47
$\langle \mathcal{O}_{\eta_c}({}^1P_1^{[8]}) \rangle / m_c^2 (10^{-2} \text{ GeV}^3)$	-1.21 ± 0.21	1.68 ± 0.63	6.0	-0.936 ± 0.453	1.03 ± 0.31

FIG. 4. The p_t (upper), W (mid), and z (lower) distribution of η_c photoproduction employing different sets of LDMEs.

in p_t . This feature can help to distinguish the CS mechanism and NRQCD.

In order to scrutinize the behavior of each channel, we present their p_t^2 , W , and z distributions in Fig. 5, where the LDMEs given in Refs. [5,28] are employed. We also observe a sharp increase of the differential cross sections for $^1S_0^{[8]}$ production as z approaches the endpoint, $z = 1$. We should remember the fact that the perturbative expansion is invalid in the region $z \rightarrow 1$, where the cross sections suffer a divergence, $1/(1-z)$, and a more careful treatment should be implemented, which however is beyond the scope of this paper. To efficiently eliminate the effect of this unphysical divergence, we apply a kinematic cut, $0.3 < z < 0.6$, in presenting the p_t^2 and W distribution of the differential cross sections. From the lower plot of Fig. 4, we can see that in the region $0.3 < z < 0.6$, the z distribution of $c\bar{c}(^1S_0^{[8]})$ is not so sharp as in the region $z > 0.6$, to this end, we believe that the

FIG. 5. The p_t (upper), W (mid), and z (lower) distribution of η_c photoproduction for each channel.

divergence problem is reasonably mitigated by this cut. Accordingly, the relative importance of the different channels in the upper and mid plots of Fig. 5 is reasonable.

IV. SUMMARY

In this paper, we have calculated the η_c photoproduction in ep collisions at QCD LO, including not only the CO contributions, but also the CS ones for the first time. Contributions from both the direct and resolved photons are counted, and the dependence of the cross sections on the μ_r , μ_f , μ_f' , and m_c are carefully investigated. The inclusion of the contributions from the resolved photons is found to enhance the CS cross sections by two orders of magnitude. We find that, employing different sets of LDMEs, the CO results are generally much larger than the CS ones in high p_t regions. This feature may be utilized to test the CO mechanism. It is also found that different sets of LDMEs

lead to different phenomenological results, which enables this process to be an ideal laboratory to distinguish the variety of LDMEs on the market and impose new constraints on these LDMEs. We suggest that the future electron-proton and electron-nucleus colliders could measure the η_c production, which may offer a great help for the study of the quarkonium production mechanism.

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