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Second-order quantum-chromodynamic effect in J/ψ photoproduction

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Second-order quantum-chromodynamics (QCD) contributions are calculated for J/ψ photoproduction. We show that the measurement of the nonforward structure of the cross section $d\sigma/dt$ at large $-t$ (≥ 1 GeV^2) could be an excellent test for QCD.

The cross section of J/ψ photoproduction has been calculated to order α_s in quantum chromodynamics (QCD) by the photon-gluon-fusion mechanism.[1,2] The numerical result reproduces roughly the energy dependence of the cross section measured in the experiments.[3] This mechanism has also been supported from the experimental data of J/ψ production in hadron-hadron collisions for which the corresponding gluon-fusion mechanism was shown to give very consistent explanations.[4]

As far as the lowest-order graphs are concerned, the cross section for J/ψ photoproduction is forward, that is, $-t \simeq 0$, because by definition gluons must be nearly on-shell. This means that the higher-order QCD contributions give the cross section in the nonforward region.[5] Thus in this paper we calculate the nonforward structure of the cross section through order α_s^2 and show that the measurement of the slope of the cross section $d\sigma/dt$ at large $-t\,(\geq 1$ GeV$^2)$ could be an excellent test for QCD.

All of the order-α_s^2 graphs are given in Fig. 1, where (A)–(D) and (a)–(h) give the contributions from light-quark and gluon components in a target nucleon, respectively. The gauge invariance is easily proved for each of the sets of graphs (A) and (B), (C) and (D), and (a)–(h). Figure 2 gives the notation for momenta of particles.

The on-shell condition of the initial and final light quark or gluon determines the momentum fraction x, which is defined as $p = xP$, to be $x = q^2/2P\cdot q$, where $q\ (= p_- + p_+ - k)$ is the momentum transfer in the t channel. In the laboratory frame the cross section for the photoproduction of $c\bar{c}$ pairs is

$$\begin{aligned}\frac{d^2\sigma}{dt\,dW_c^2}(\gamma N\to c\bar{c}X) = \frac{\alpha\alpha_s^2}{4\pi M^2E^2|t|}\int_{M^2} dM_X^2\ \Sigma_0^2(W_c^2-4m_c^2)^{1/2}\\ \times\int d\Omega_{\vec{\Delta}}\,\frac{1}{(\Sigma_0^2\sin^2\varphi + W_c^2\cos^2\varphi)^{3/2}}\\ \times\Bigg\{2e_c^2\sum_{i=u}^{s} f_{i/N}(x)\,|\mathfrak{M}_A+\mathfrak{M}_B|^2 + 2\sum_{i=u}^{s} e_i^2 f_{i/N}(x)\,|\mathfrak{M}_C+\mathfrak{M}_D|^2\\ + \tfrac{2}{3}e_c^2 G_N(x)\Bigg[\sum_{j=a}^{f}|\mathfrak{M}_j|^2 + 2(\mathfrak{M}_a\mathfrak{M}_f^* + \mathfrak{M}_d\mathfrak{M}_a^* + \mathfrak{M}_f\mathfrak{M}_d^*)\\ + 2(\mathfrak{M}_b\mathfrak{M}_c^* + \mathfrak{M}_c\mathfrak{M}_e^* + \mathfrak{M}_e\mathfrak{M}_b^*)\Bigg]\\ - \tfrac{1}{12}e_c^2 G_N(x)\,2(\mathfrak{M}_a+\mathfrak{M}_d+\mathfrak{M}_f)(\mathfrak{M}_b^*+\mathfrak{M}_c^*+\mathfrak{M}_e^*) + \tfrac{3}{2}e_c^2 G_N(x)\,|\mathfrak{M}_g+\mathfrak{M}_h|^2\Bigg\},\qquad (1)\end{aligned}$$

where $e_i = (\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$, $e_c = \frac{2}{3}$, M is the nucleon mass, E is the photon energy, $t = q^2$, $\vec{\Sigma} = p_+ + p_-$, $\vec{\Delta} = p_- - p_+$, φ is the angle between $\vec{\Sigma}$ and $\vec{\Delta}$, $f_{i/N}(x)$ $(i = u, d, s)$, and $G_N(x)$ are the distribution functions of quarks and gluons, respectively, and $\mathfrak{M}_i$ $(i = A, \ldots, h)$ are invariant amplitudes of the graphs given in Fig. 1. Here the numbers 2, 2, $\frac{2}{3}$, $-\frac{1}{12}$, and $\frac{3}{2}$ are the QCD color factors stemming from the color summation of the final partons and the color average of the initial partons. Σ_0 is given by the relation $\Sigma_0 = (s + t - M_X^2)/2M$. The upper bound of M_X^2 is determined by the condition $\cos\theta \leq 1$, where θ is the angle between $\vec{\Sigma}$ and $\vec{k}$, as

$$M_X^2 = s + t - M[(W_c^2 + |t|)^2 + 4E^2W_c^2]/2E(W_c^2 + |t|).$$

We must remark here that the graph (D) in Fig. 1 causes a mass singularity of the type ln m^2 in the integral (1) at the configuration $\vec{k}/\!/\vec{p}\,'$, where $|\hat{u} - m^2|$ takes the minimum value $m^2(1 + W_c^2/|t|)$. Here m is the mass of the light quark and $\hat{u} = (p - \Sigma)^2$. It has not been proved whether this singularity remains or not when we introduce higher-order graphs than the ones included here. But fortunately the contributions coming from the graphs (C) and (D) do not seem to be large

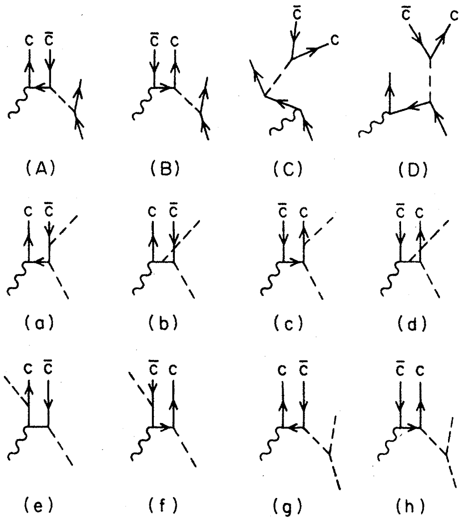

FIG. 1. Feynman graphs for $\gamma + N \to c\bar{c} + X$ up to order α_s^2. The notation in this and subsequent figures is solid lines for quarks, dashed lines for gluons, and wavy lines for photons.

because of the large mass of J/ψ in the denominator of the gluon propagator. In this paper we assume the approximate relation $p = xP$ only for the purpose of making our calculation simple. Then $|\hat{u} - m^2|$ has the minimum $(W_c^2 + |t|)^3/[4E^2|t| - (W_c^2 + |t|)^2]$, which is different from the correct minimum $m^2(1 + W_c^2/|t|)$ but takes much smaller values than 1 GeV^2 in the region of $|t| \ll E^2$ and $|t| < W_c^2$. In this approximation, in fact, we found that the graphs (C) and (D) do not give important contributions in the region of 1 $\mathrm{GeV}^2 \leq -t \leq 10$ GeV^2 and $E \geq 50$ GeV. Taking into account that the singularity is of a logarithmic type so that the contribution from the graph (D) does not depend so strongly on the minimum

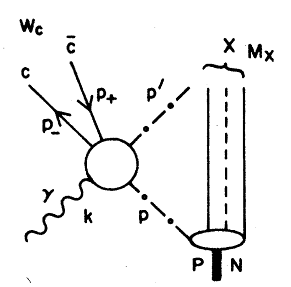

FIG. 2. The picture of the order-α_s^2 graphs to show the notation for momenta of particles. The nucleon labeled by N has the momentum P. The dash-dot lines denote quarks (or gluons) which have the momentum p and p'. Symbols p_- and p_+ denote momenta of charm quarks c and $\bar{c}$, and k is the one of photon. W_c is the invariant mass of the channel $c\bar{c}$ and M_X is the one of hadrons included in the anything X.

of $|\hat{u} - m^2|$, we can insist that our numerical results for $d\sigma/dt$ might not have a large contribution from the graph (D) and therefore are very reliable as far as $m \gtrsim 0.1-0.03$ GeV even when we treat this singularity correctly.

In the following step to connect Eq. (1) to J/ψ photoproduction, we use the same technique as in the photon-gluon-fusion model.[1,2] The $c\bar{c}$ pair produced in the reaction given in Fig. 1 will undergo some final-state interaction (which must include a color-rearrangement process if the $c\bar{c}$ pair is a color-octet state) and will turn into some charmonium state such as J/ψ, χ, etc., or into a pair of charmed particles. Then the J/ψ production, in general, comes from two components: the direct J/ψ production from the $c\bar{c}$ pair and the decays of the higher-mass states into the J/ψ state.[1] Thus we find that the cross section of the J/ψ production is associated with the direct production of all charmonium states from the $c\bar{c}$ pair. Because the contributions from the decays are due to charmonium states with masses less than $2m_D$ [m_D is the mass of $D(1.86)$], the cross section for J/ψ production is supposed to be given approximately by some fraction of the value obtained by integrating Eq. (1) over W_c^2 from $4m_c^2$ (m_c is the mass of the charmed quark) to $4m_D^2$.

We introduce the number N_D to express the cross section for J/ψ production as the above integral divided by N_D. As discussed above this number will be determined roughly by the probabilities of the direct productions of charmonium states and the branching ratio for the decays of the higher-mass states into J/ψ. Although we do not have enough knowledge about these, we can fortunately use the approximate value of N_D obtained from comparing the cross section calculated to order α_s with the experimental data of the total cross section. N_D has been known to be around 8 if we use $m_c = 1.5$ GeV and the power $n = 5$ in the following form for the gluon distribution function which we shall use: $G_N(x) = 0.5(n+1) \times (1-x)^n/x$.[6] As Jones and Wyld pointed out,[1] N_D depends strongly on m_c and n. Therefore we will mention later the dependences on m_c and n for our predictions calculated from Eq. (1).

Before proceeding to numerical calculations, we must specify the distribution functions $f_{i/N}(x)$ for the light quarks in the target nucleon. As will soon be found, our main prediction does not almost depend on these functions. So we use here only the Field-Feynman parametrization.[7]

We first temporarily choose the values $m_c = 1.5$ GeV and $n = 5$.[8] Figure 3 shows the numerical result of $d\sigma/dt$ for J/ψ photoproduction at the photon laboratory energy $E = 20$ GeV, where we

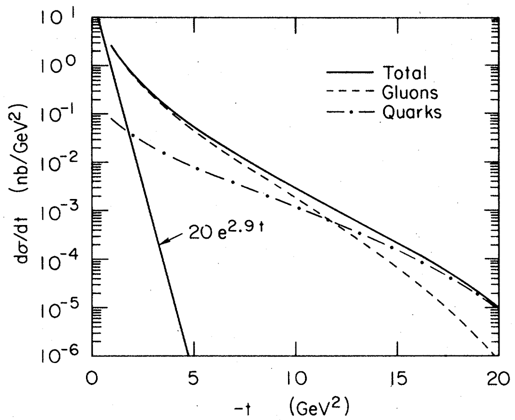

FIG. 3. The numerical result of $d\sigma/dt$ versus $-t$ for $\gamma+N\rightarrow\psi+X$ at $E=20$ GeV. Here we set $m_c=1.5$ GeV and $n=5$ in Eq. (2). A dashed line shows that contribution from gluons, a dash-dot line the one from quarks and a solid line is the total of them. At the same time we show the curve of $20e^{2.9t}$ nb/GeV^2 as the typical diffractive curve suggested by the experiment.[3]

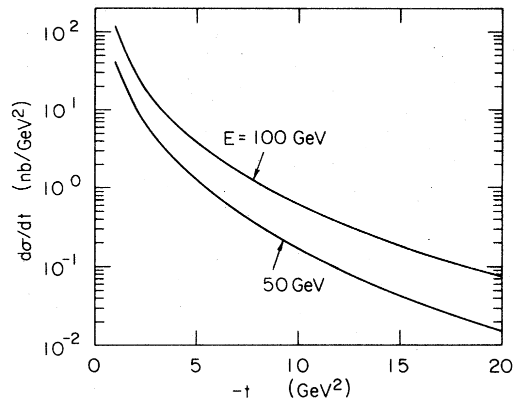

FIG. 4. The calculated curves of $d\sigma/dt$ versus $-t$ for $\gamma+N\rightarrow\psi+X$ at $E=50$ and 100 GeV.

take $N_D=8$ and $\alpha_s=(12\pi/25)\ln M_{J/\psi}^2/\Lambda^2$ $(=0.41)$ with $\Lambda=0.5$ GeV. The main pattern of the contributions from quarks and gluons is that the contribution from gluons dominates the cross section in the lower $-t$ region ($-t<15$ GeV^2) and the contribution from quarks emerges prominently at higher $-t$. In this figure we show the typical diffractive curve $20e^{2.9t}$ nb/GeV^2 which was suggested by the SLAC experiments.[3] Comparing the numerical result to this diffractive curve, we can predict that the slope of $d\sigma/dt$ should turn out to change very much apart from the diffractive curve around $-t=1$ GeV^2.

We have studied to what extent the above prediction depends on m_c and n, i.e., the form of $G_N(x)$ in the range 1.25 GeV $\leq m_c \leq$ 1.75 GeV and $3\leq n\leq 7$. The numerical results show a striking feature that the slope of $d\sigma/dt$ does not almost depend on m_c in the region $-t\leq 15$ GeV^2 where the gluon contribution dominates. On the other hand, the slope has a slight n dependence, but is not sufficiently large to be discriminated in experiments. Therefore we can conclude that the slope of $d\sigma/dt$ will be expected to reflect the significant feature peculiar to the higher-order interactions of QCD and irrelevant to the values of m_c and the form of $G_N(x)$ in the region $-t\leq 15$ GeV^2.

We finally discuss the energy dependence of the cross section $d\sigma/dt$ calculated to order α_s^2. Here we take the values $m_c=1.5$ GeV and $n=5$. In Fig. 4 we give the calculated curves of $d\sigma/dt$ versus $-t$ at $E=50$ and 100 GeV. This figure shows that the curves become flatter as E increases but the change of the slope does not strongly depend on E. This is supported also from our numerical result that the energy dependence is almost due to the phase space included in Eq. (1) and has a tendency similar to the total cross section calculated to order α_s in the photon-gluon-fusion model.

After we finished this calculation, we found the paper of the experimental data for the virtual photoproduction of elastic J/ψ events which have been measured by the European Muon Collaboration.[9] Although we cannot directly compare our results with this data, we can find the same tendency of the slope change at about $-t=1$ GeV^2 in it as we predict in this paper.

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[1]L. M. Jones and H. W. Wyld, Phys. Rev. D 17, 759 (1978); 17, 2332 (1978); see also H. Fritzsch and K. H. Streng, Phys. Lett. 72B, 385 (1978).
[2]M. Glück and E. Reya, Phys. Lett. 79B, 453 (1978);

T. Weiler, Phys. Rev. Lett. 44, 304 (1980).
[3]T. Nash *et al.*, Phys. Rev. Lett. 36, 1233 (1976); U. Camerini *et al.*, *ibid.* 35, 483 (1975).
[4]M. Glück, J. F. Owens, and E. Reya, Phys. Rev. D 17, 2324 (1978).
[5]As to J/ψ leptoproduction, an attempt to calculate the nonforward pattern of the cross section in QCD has been made by J. P. Leveille and T. Weiler, Phys. Lett. 86B, 377 (1979).
[6]M. B. Einhorn and S. D. Ellis, Phys. Rev. D 12, 2007 (1975).
[7]R. D. Field and R. P. Feynman, Phys. Rev. D 15, 2590 (1977).
[8]S. Brodsky and G. Farrar, Phys. Rev. Lett. 31, 1153 (1973).
[9]European Muon Collaboration, J. J. Aubert *et al.*, Phys. Lett. 89B, 267 (1980).