$J/\psi+c+\bar{c}$ photoproduction in e^+e^- scattering

Cong-Feng Qiao
CCAST (World Laboratory), P. O. Box 8730, Beijing 100080, China
and Department of Physics, Graduate School of the Chinese Academy of Sciences, YuQuan Road 19A, Beijing 100039, China

Jian-Xiong Wang
Institute of High Energy Physics, Academia Sinica, Beijing 100039, China
(Received 26 August 2003; published 30 January 2004)

We investigate the $J/\psi+c+\bar{c}$ photoproduction in e^+e^- collision at CERN LEP II energies. The physical motivations for this study are the following: (1) such a process was not considered in previous investigations of J/ψ photoproduction in e^+e^- interaction, and we show in this work that it is worthwhile to do so in order to make sound predictions for experimental comparison; (2) from recent Belle experiment results, the process with the same final states at the B factory has a theoretically yet unexplainable large fraction; hence it is interesting to see what may happen at other colliders; (3) the process can be measured with a high accuracy at the planned linear colliders; (4) it is necessary to take this process into consideration in elucidating the quarkonium production mechanism, especially in testing the universality of nonrelativistic QCD nonperturbative matrix elements. We find that the process concerned is really important at LEP experimental energies; within the theoretical uncertainties, it is of similar magnitude to the other color-singlet processes when the transverse momentum $p_T>1$ GeV. Nevertheless, to explain the recent DELPHI experimental result, the color-octet mechanism is still necessary, but with a shrunken contribution compared to previous analysis. It is found that the $J/\psi+c+\bar{c}$ photoproduction process cannot be mimicked by the simple fragmentation scheme.

DOI: 10.1103/PhysRevD.69.014015 PACS number(s): 14.40.Gx, 13.87.Fh

I. INTRODUCTION

Quarkonium physics is still an interesting research topic, while the first quarkonium state J/ψ was discovered about 30 years ago. Because of its approximately nonrelativistic nature, the description of the heavy quark and antiquark system is one of the simplest applications of QCD. The highly precise experimental results for quarkonium leptonic decays cause the heavy quarkonium to play a crucial role in investigations of various phenomena, such as measuring the parton distribution in hadron-hadron collisions, detecting the quark-gluon-plasma signal, and even new physics, etc. On the other hand, an interplay of perturbative and nonperturbative quantum chromodynamics (QCD) happens in quarkonium production and decays, which can therefore stand as probes in investigating the nonperturbative nature of QCD.

Quarkonium physics has experienced dramatic advances in recent years; among them the current focus in the field has been on the color-octet mechanism (COM) [1], triggered by the high-p_T J/ψ surplus production discovered by the Collider Detector at Fermilab (CDF) Collaboration at the Tevatron in 1992 [2–4]. The color-octet scenario was proposed based on a novel effective theory, nonrelativistic QCD (NRQCD) [5]. Having achieved the first step towards success in explaining the CDF data, the COM also has a strong impact on almost every aspect of quarkonium physics, and various efforts have been made to confirm this mechanism, or to fix the magnitudes of the universal NRQCD matrix elements. Although the theoretical framework seems to show qualitative agreement with experimental data, there are certain difficulties in the quantitative estimate of the color-octet contribution [6], in particular, in J/ψ and ψ' photoproduction at the DESY ep collider HERA [7–10,12], and J/ψ (ψ') polarization in large transverse momentum production at the Fermilab Tevatron [13–15], and more recently in B factories.

It is widely expected that the B factories will provide clearer information about quarkonium production. The B-factory experiments recently reported their measurements on prompt charmonium production at e^+e^- colliders at $\sqrt{s}=10.6$ GeV [16–18]. To one's surprise, both their inclusive and exclusive measurements have large discrepancies with theoretical calculations [19–24]. Among the puzzling features of the B-factory data, in particular, the total cross section of the exclusive $e^++e^-\rightarrow J/\psi+\eta_c$ process is found to be about an order of magnitude larger than theoretical predictions [22–24]. That is [18],

$$\sigma(e^++e^-\rightarrow J/\psi+\eta_c)\times\mathcal{B}(\eta_c\rightarrow\geqslant 4\ \text{charged}) = (0.033^{+0.007}_{-0.006}\pm0.009)\ \text{pb}. \tag{1}$$

The Belle Collaboration [18] also found a large cross section for J/ψ inclusive production along with an open charm pair, the same final state process that we are going to discuss,

$$\frac{\sigma(e^+e^-\rightarrow J/\psi+c\bar{c})}{\sigma(e^+e^-\rightarrow J/\psi+X)}=0.59^{+0.15}_{-0.13}\pm0.12, \tag{2}$$

which is far greater than theoretical expectations [19–21]. The new B-factory data, in some sense, pose a new ''crisis'' in the study of quarkonium physics. Therefore, to reveal the problems lying behind the prevailing quarkonium production mechanisms (models) is currently an urgent task, and possibly has a long way to go. Nevertheless, the Belle ''puzzle'' does not really mean the failure of QCD based quarkonium production mechanisms, like NRQCD and the color-singlet CS model. The "crisis" may stem from the unexplored higher-order contributions, for instance, and other yet unknown reasons within the framework of NRQCD.

The final establishment of NRQCD factorization as the correct theory of quarkonium production and decays still needs more tests. The universality of NRQCD matrix elements is one of the critical points to be verified. People have tried many ways to discover the universality of the COM at different colliders; so far there is still no decisive result either proving or disproving it.

Quarkonium photoproduction in e^+e^- collisions has been investigated by several groups [25]; and, very recently, based on leading order perturbative QCD analyses, Klasen *et al.* [27] find that the new DELPHI [28] data evidently favor the NRQCD formalism for J/ψ production, but rather the conventional color-singlet model [29], which is quite encouraging. Considering that the data accumulated at all four LEP detectors at CERN may still tell us more about quarkonium production in the future, we realize it is meaningful to investigate quarkonium photoproduction in more detail. We find that, although superficially the $\gamma+\gamma\rightarrow J/\psi+c+\bar{c}$ process stands as a subleading order process (in the sense of strong coupling in comparison with the resolved photon processes), its contribution to quarkonium production is not really necessarily minor compared to other processes within the CS prescription. In direct photon production, the process concerned here is obviously the leading-contribution process, since in experiment the $J/\psi+\gamma$ final state process is suppressed. In the case of resolved photon production, Ref. [27] finds that single resolved photon processes give the dominant contribution. The resolved processes in general are suppressed by the parton distribution probability, but may get compensation from the order of the coupling constant(s). To find whether direct or resolved processes dominate in J/ψ photoproduction at LEP, one needs to do a concrete calculation.

The remainder of the paper is organized as follows. In Sec. II, we give a description of our calculation procedure. In Sec. III, our numerical results are presented, where the theoretical calculation of $J/\psi+c+\bar{c}$ photoproduction at e^+e^- colliders is confronted with recent experimental results at LEP. Finally, we give our summary and conclusions.

II. PHYSICS MOTIVATION AND FORMALISM

As explained in the Introduction, we are going to add the process $\gamma+\gamma\rightarrow J/\psi+c+\bar{c}$ in e^+e^- scattering to the analyses of J/ψ inclusive production at LEP II. Here, the colliding photons can participate in the hard interaction either directly, or in resolved contributions through their hadronic components. As realized, both direct and resolved processes can be of the same order within the energy distribution range we are interested in [27]. In this sense, since the process we consider is perturbatively at subleading order relative to the resolved processes considered in [27], it looks negligible at first glance. However, the complexity of this process makes the order analyses nontransparent. Further, there is no obvious reason to disregard this process while taking color-octet processes into consideration. Therefore, to make an overall estimation of J/ψ photoproduction at LEP and draw conclusions without considering the new proposed process may run some risk, as shown in the next section. Of course, in the case of having enough events, as inspired by *B*-factory experiments, one may expect that the process concerned will be clearly distinguished from other processes. In addition, since the $J/\psi+c+\bar{c}$ final states have a relatively large invariant mass, it is easy to imagine that the resolved-photon contribution for this process will be less important than the direct one, which is confirmed by our numerical evaluation. We find in explicit calculation that the resolved-photon contribution is really negligibly small.

On the other hand, it is easy to attribute the $\gamma+\gamma\rightarrow J/\psi+c+\bar{c}$ process approximately to a simple fragmentation representation, where charmonium is produced via charm quark fragmentation. It is worthwhile to mention that the situation here is different from and more complicated than quarkonium production in, e.g., Z^0 decays, where the fragmentation mechanism works quite well, and the calculation can be greatly simplified by taking the fragmentation limit. Here, some "nonfragmenting" graphs are not negligible. Explicit numerical results given in the next section support this argument.

Generally speaking, in photon-photon collisions the interacting photons can either originate from the bremsstrahlung of high-energy electron-positron collision, beamstrahlung, or, theoretically, be obtained by Compton backscattering of laser light off linear acceleration (LINAC) electron beams, realizing photon-photon collision at a linear collider with approximately the same luminosity as that of the e^+e^- beams. In this work we will study only the first case and confront our result with the experimental data analyzed recently by the DELPHI Collaboration of the LEP II experiment at CERN.

The source of photons from electron-positron bremsstrahlung can be well formulated in the Weizsäcker-Williams approximation [30]:

$$f_{\gamma/e}(x)=\frac{\alpha_{e.m.}}{2\pi}\left[\frac{1+(1-x)^2}{x}\log(Q^2_{max}/Q^2_{min})+2m_e^2x\left(\frac{1}{Q^2_{max}}-\frac{1}{Q^2_{min}}\right)\right], \tag{3}$$

where $Q^2_{min}=m_e^2x^2/(1-x)^2$ and $Q^2_{max}=(E\theta)^2(1-x)+Q^2_{min}$ with $x=E_\gamma/E_e$, θ the experimental angular cut in order to ensure that the photon is real, and $E=E_e=\sqrt{s}/2$.

Our process of interest involves 20 Feynman diagrams. Ten are shown in Fig. 1 and the remaining ten are just their charge conjugates. It is evident that in this process the quarkonium can be formed in the CS configuration, which may be formulated coincidentally in both the CS model and the NRQCD description at leading order.

Calculation of the prompt J/ψ production rate is carried out by the standard procedure with the normalization of the spin projection operators for quarkonium production taken as

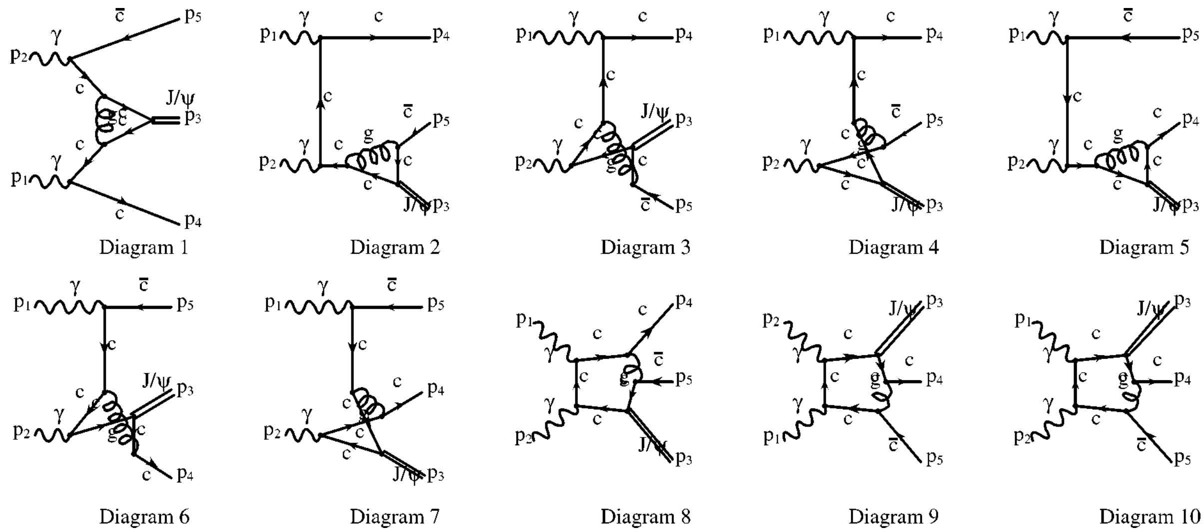

FIG. 1. Half of the Feynman diagrams of the discussed J/ψ producing subprocess $\gamma+\gamma\rightarrow J/\psi+c+\overline{c}$. The missing diagrams are the charge conjugates of the ones shown and can be simply obtained by flipping the fermion flow directions.

$$\mathcal{P}_{S,S_z}(P;q)=\sum_{s_1,s_2} v\left(\frac{P}{2}-q;s_2\right)\overline{u}\left(\frac{P}{2}+q;s_1\right)\times\left\langle\frac{1}{2},s_1;\frac{1}{2},s_2\middle|S,S_z\right\rangle, \tag{4}$$

where P, S, and S_z are, respectively, the quarkonium four-momentum, its spin, and the z component of the spin; q is the relative momentum of the heavy quarks; and s_1,s_2 represent their spins. In the nonrelativistic limit, for S-wave states, to leading order the covariant forms of the projection operators are very simple:

$$\mathcal{P}_{0,0}(P;0)=\frac{1}{2\sqrt{2}}\gamma_5(\not{P}+M), \tag{5}$$

$$\mathcal{P}_{1,S_z}(P;0)=\frac{1}{2\sqrt{2}}\not{\epsilon}^*(P,S_z)(\not{P}+M), \tag{6}$$

respectively, for the pseudoscalar and vector quarkonium states. Here $\epsilon^\mu(P,S_z)$ denotes the polarization vector of the spin-1 quarkonium state, and $M=2m_c$ is its mass. Here, m_c is the charm quark mass. The projectors (5) and (6) map a $Q\overline{Q}$ pair into the S-wave states. In our study we also repeat previous calculations, where J/ψ prompt production was considered; that is, the J/ψ coming from higher excited state feeddown is taken into consideration. For P-wave state production, to leading order one needs to expand the relative momentum of heavy quarks to first order. Of the spin projectors they are

$$\mathcal{P}^\alpha_{0,0}(P;0)=\frac{1}{2\sqrt{2}M}[\gamma^\alpha\gamma_5(\not{P}+M)+\gamma_5(\not{P}+M)\gamma^\alpha], \tag{7}$$

$$\mathcal{P}^\alpha_{1,S_z}(P;0)=\frac{1}{2\sqrt{2}M}[\gamma^\alpha\not{\epsilon}^*(\not{P}+M)+\not{\epsilon}^*(\not{P}+M)\gamma^\alpha], \tag{8}$$

respectively.

With the above spin projectors, the amplitudes for the $\gamma+\gamma\rightarrow J/\psi+c+\overline{c}$ process can be obtained; they are presented in the Appendix for reference and comparison. Nevertheless, the matrix element squared is too lengthy to be shown here. The whole calculation is evaluated by using the automatic Feynman diagram calculation (FDC) [31] package. Interested readers, who want to have the lengthy expressions and the corresponding FORTRAN program, are encouraged either to download directly from the website or write to us.

III. NUMERICAL RESULTS

As stated above, we perform calculation of the Feynman diagram algebra by a computerized program, where the spin projector method was built in, and which is more suitable for evaluating complicated processes. The Feynman diagram, analytic formulas, and FORTRAN source are generated by the FDC. This program was employed in the past in calculating the J/ψ electromagnetic production at electron-positron colliders [32], and in many other applications. In order to further assure the applicability of this program, in preparing this work we repeated several other independent processes and compared with the results given in the literature. The numerical calculation is performed in batches by a Monte Carlo subroutine also encoded in the FDC.

The overall differential cross section of J/ψ photoproduction can be obtained by the double convolution of the cross sections of parton-parton (photon-photon) to J/ψ processes, with the parton distribution functions photon distribution densities given schematically by

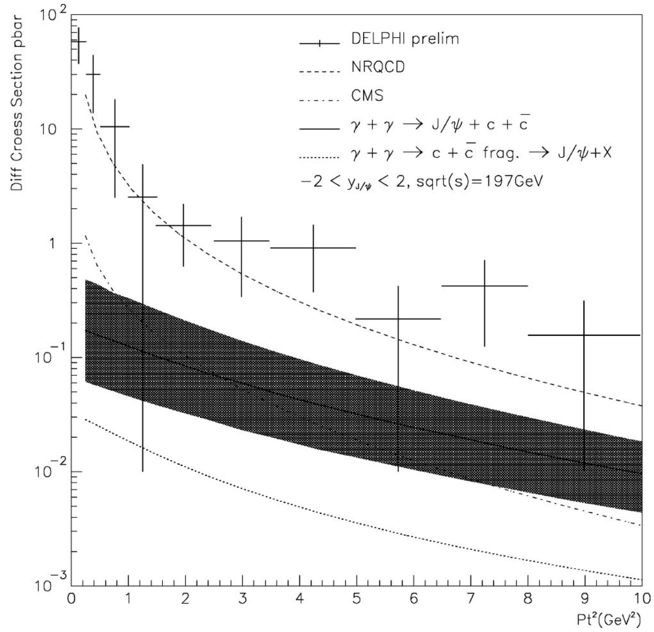

FIG. 2. The transverse momentum distribution of J/ψ photoproduction in the LEP II experiment. The results for the $\gamma+\gamma\to J/\psi+c+\bar{c}$ process are confronted with the central values in a previous study in Ref. [27] and the recent DELPHI experimental result [28]. The upper bound of the shaded band is obtained at the renormalization scale $r=0.5(M_T)$ and $m_c=1.4$, and the lower one at $r=2$ and $m_c=1.6$.

$$d\sigma=\int dx_1 dx_2 dt f_\gamma(x_1) f_\gamma(x_2) \sum_{i,j,k} \int dx_i dx_j \times f_{i/\gamma}(x_i) f_{j/\gamma}(x_j) d\sigma_{i+j\to\psi+k}(x_i,x_j). \quad (9)$$

Here, $f_\gamma(x)$ represents the photon density in e^+e^- collisions or at photon colliders, and $f_{i/\gamma}(x)(i,j=\gamma,g,u,d,s)$ denotes the Glück-Reya-Schienbein parton distribution functions in photon [33]. For direct photon-photon interaction, it is obvious that $f_{\gamma/\gamma}(x)$ will be a delta function.

In doing numerical calculations, the general parameters are taken as $\alpha=1/137.065$, $\langle\mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle=1.4\ \mathrm{GeV}^3$, $m_c=1.5\pm0.1$ GeV, $\Lambda_{QCD}^{(4)}=174$ MeV [26], and the strong coupling is running with the renormalization scale $\mu=m_T$. Here, $m_T=\sqrt{m_\psi^2+p_T^2}$ is the normally defined transverse mass of J/ψ. The factor $(J/\psi+\psi')=1.278$ is used to include the ψ' contribution. Taking the nonrelativistic limit, the J/ψ mass is taken to be twice the charm quark mass, and the open charm pair has the same mass as the charm quark in J/ψ, otherwise the gauge invariance will be broken. To retain consistency with other analyses, our choice of parameters is in accordance with that taken in Ref. [27]. For details of the choices, e.g., the magnitudes of color-octet matrix elements, readers are recommended to refer to the CTEQ5L fit used by [27].

In Fig. 2 we present our process versus other theoretical predictions [27] and the recent DELPHI experimental result [28], where to avoid nonphotoproduction processes the invariant mass of the $\gamma\gamma$ system is limited to $W\leqslant35$ GeV as in the experiment. The maximum angle ensuring a real photon in Eq. (2), θ_{max}, is taken to be 32 mrad. As shown in the figure, the previously considered leading order CS processes contribute less than the process we are considering here when the transverse momentum is larger than 1 GeV. When the transverse momentum is small we know the diffractive interaction process will make the leading contribution for J/ψ production. From the figure, the discrepancy between experimental data and color-singlet calculations is reduced after including the $\gamma+\gamma\to J/\psi+c+\bar{c}$ process, although the CS contributions still fall below the data even with the optimal choice of the errors. In drawing Fig. 2, the FDC was used to recalculate the NRQCD and CSM processes from [27] and numerical agreement with their results was obtained.

The results from the previous study appearing in the figure are taken only at the central values. We notice that there are large uncertainties remaining in both the previous analyses and our calculation, shown as the shaded band. The theoretical errors come mainly from the influence of scale dependence ($\mu=0.5m_T,m_T,2m_T$), the nonperturbative matrix element uncertainty, and the variation of the charm quark mass ($m_c=1.5\pm0.1$ GeV). The strong scale and mass dependence imply that the higher-order relativistic and radiative corrections will be large.

As shown in Fig. 2, the $\gamma+\gamma\to J/\psi+c+\bar{c}$ process cannot be reproduced by the fragmentation mechanism [11] (simply multiplying $\gamma+\gamma\to c+\bar{c}$ by 2.4×10^{-4}), even on the high-p_T side. This finding means that the nonfragmentationlike graphs existing in this process are not negligible in the high-energy and high-p_T limit. This characteristic suggests that B_c photoproduction and hadroproduction, with their similar topology of Feynman graphs, cannot simply be replaced by a fragmentation mechanism.

In Fig. 3 we present the invariant mass, angular, rapidity, and pseudorapidity distributions of the $\gamma+\gamma\to J/\psi+c+\bar{c}$ process. The invariant mass of colliding photons starts at 6 GeV as a physical requirement and ends at 35 GeV as imposed in the DELPHI experiment. The (pseudo)rapidity varies from -2 to 2 as also performed in the experiment.

To show the influence of the renormalization scale and charm quark mass, in Table I we present the dependence on them of the total cross section. Here, r means the fraction of the renormalization scale μ on the charmonium transverse mass. That is, $\mu=rm_T$, where p_T is the J/ψ transverse momentum. The total cross sections are obtained under the conditions $\sqrt{(10)}>p_T>1.0$ GeV, $W<35$ GeV, and $|\eta|<2$, where W and η are the final state invariant mass and J/ψ pseudorapidity, respectively.

It is evident that both the renormalization scale and the charm quark mass induce large uncertainties on the total cross section. Between them, the scale dependence is more important. Under the same physical cut and parameter input we find that the new process at linear colliders (LCs), e.g., TESLA, gives a total cross section of 0.41 pb at the central values of the scale and charm quark mass, which is larger

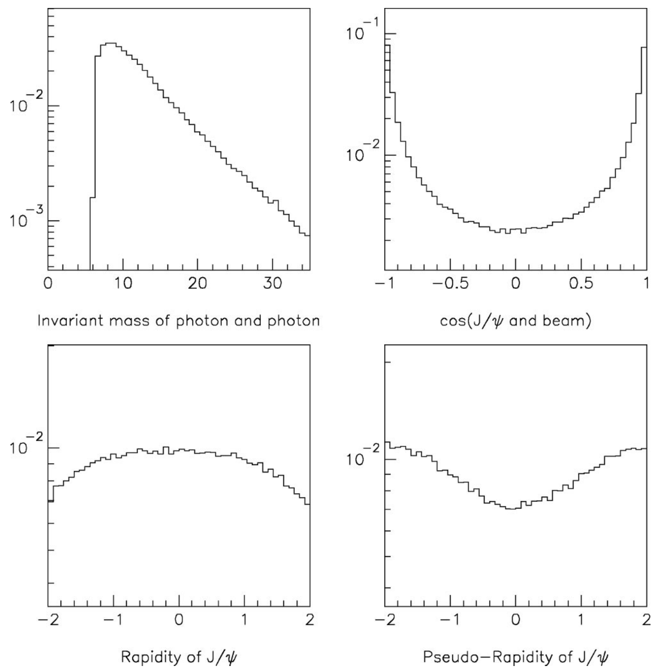

FIG. 3. From upper left to lower right, mass distribution $d\sigma/dM_{\gamma\gamma}$; angular distribution $d\sigma/d\cos\theta$; rapidity distribution $d\sigma/dy$; and pseudorapidity distribution $d\sigma/d\eta$.

than the total cross section at LEP as shown in Table I. This means that the new process can surely be measured with high accuracy at future LCs.

IV. DISCUSSION AND CONCLUSIONS

In this work we performed a calculation of the $\gamma+\gamma\to J/\psi+c+\bar{c}$ process of J/ψ photoproduction in e^+e^- interactions in LEP II experiments, which was not taken into consideration in previous analyses. We find that this process is quite large in photon-photon collisions at LEP. The importance of including this process lies in two aspects. (1) It is the dominant process among all the CS subprocesses with transverse momentum greater than 1 GeV. Since in the low-p_T region the diffractive interaction will be overwhelmingly large, to have a clear signal of it one needs to focus on the large-p_T area. (2) Considering the large uncertainties still remaining in the color-octet matrix elements, in attempting either to fix these uncertainties or to test the accuracy of QCD perturbative calculations, it is very necessary to include this new process.

The new process we considered is unique relative to other processes of J/ψ production in e^+e^- scattering. It is obviously necessary to obtain gauge invariance for the total amplitude. We performed a check and found that there is gauge invariance. It was also checked for other processes with the aim of giving us more confidence in our results. In practice, we performed the gauge invariance check in two different ways. At the amplitude level, we replaced the photon polarization vector(s) by the corresponding momentum, then reallocated the independent terms and numerically calculated the amplitude squared; in the other method, we did the replacement at the squared matrix element level and then evaluated it. In both cases a large cancellation happened, and up to the precision limit of the FORTRAN program they became zero.

TABLE I. Renormalization scale and charm quark mass dependence of the total cross section.

	$m_c=1.4$ GeV	$m_c=1.5$ GeV	$m_c=1.6$ GeV
$r=0.5$	0.82 pb	0.54 pb	0.37 pb
$r=1$	0.47 pb	0.31 pb	0.21 pb
$r=2$	0.30 pb	0.20 pb	0.14 pb

We found that the uncertainty induced by scale variation is quite large, which means the higher-order corrections could be big. The uncertainties remaining in the quarkonium nonperturbative matrix elements and charm quark mass are also sources of theoretical prediction errors.

We also compared the pure fragmentation result with our full calculation, and find that the situation of quarkonium production here differs from that in Z^0 decays, where the fragmentation scheme can almost reproduce the full Feynman diagram calculation results. It is noticed that, after considering our proposed process, the preliminary DELPHI data are still not explainable by the CSM alone, and the color-octet scenario is still necessary. Nevertheless, since large uncertainties remain in both CS and NRQCD analyses, quantitative conclusions for the universality of color-octet matrix elements are still hard to reach. In our opinion, to have a full next to leading order (NLO) calculation of prompt J/ψ production would be critical on this point and beyond. Although the present DELPHI data are just marginal for observing the $\gamma+\gamma\to J/\psi+c+\bar{c}$ signal, it would still be interesting for experimenters to see whether the accumulated LEP data are sufficient to find it. In any case, at LCs this new process should be observed with high precision. It is also noticed that in previous NLO calculations of J/ψ photoproduction at HERA [12,34], the similar order process $g+\gamma\to J/\psi(\psi')+c+\bar{c}$ was missing. Naive estimation tells us that the missing part there should not be so important as in the case of photon-photon interactions. A detailed investigation of this will be presented elsewhere.

ACKNOWLEDGMENTS

C.-F.Q. would like to thank J. P. Ma for discussions on related issues and ITP for their hospitality while part of this work was done. This work was supported in part by the National Science Foundation of China with Contracts No. 19805015 and No. 90103013 and by the Chinese Academy of Sciences under Project No. KJCX2-SW-N02.

APPENDIX

We give the matrix elements of the process $\gamma+\gamma\to J/\psi+c+\bar{c}$. Here, $\epsilon_1,\epsilon_2,\epsilon_3$ are the polarizations of initial photons and J/ψ, respectively; and $p_i\,(i=1,2,3)$ are their corresponding momenta.

$$M=c\overline{u}(p_4)(c_1\hat{p}_3\hat{\epsilon}_3\hat{p}_1\hat{\epsilon}_1+c_2\hat{p}_3\hat{\epsilon}_3+c_3\hat{\epsilon}_2\hat{p}_1\hat{p}_3\hat{\epsilon}_1+c_4\hat{\epsilon}_2\hat{p}_1\hat{\epsilon}_3\hat{\epsilon}_1+c_5\hat{\epsilon}_2\hat{p}_3\hat{\epsilon}_3\hat{p}_1\hat{\epsilon}_1+c_6\hat{\epsilon}_2\hat{p}_3\hat{\epsilon}_3\hat{p}_1$$
$$+c_7\hat{\epsilon}_2\hat{p}_3\hat{\epsilon}_3\hat{\epsilon}_1+c_8\hat{\epsilon}_2\hat{\epsilon}_1+c_{10}\hat{\epsilon}_2\hat{p}_3\hat{\epsilon}_1+c_{11}\hat{\epsilon}_2\hat{p}_3\hat{\epsilon}_3+c_{12}\hat{\epsilon}_2\hat{p}_3+c_{13}\hat{\epsilon}_2\hat{\epsilon}_3\hat{\epsilon}_1+c_{14}\hat{\epsilon}_2\hat{\epsilon}_3+c_{15}\hat{\epsilon}_2\hat{p}_1\hat{\epsilon}_1$$
$$+c_{16}\hat{\epsilon}_2\hat{p}_1\hat{\epsilon}_3+c_{17}\hat{\epsilon}_2+c_{18}\hat{\epsilon}_3\hat{p}_1\hat{\epsilon}_1+c_{19}\hat{\epsilon}_3\hat{\epsilon}_1+c_{20}\hat{\epsilon}_3+c_{21}+c_{22}\hat{p}_1\hat{\epsilon}_1+c_{23}\hat{p}_3\hat{p}_1\hat{\epsilon}_1+c_{24}\hat{p}_3\hat{\epsilon}_1$$
$$+c_{25}\hat{p}_3+c_{26}\hat{\epsilon}_1+c_{27}\hat{p}_1+c_{28}\hat{p}_3\hat{p}_1+c_{29}\hat{\epsilon}_3\hat{p}_1+c_{30}\hat{p}_1\hat{p}_3\hat{\epsilon}_3+c_{31}\hat{\epsilon}_2\hat{p}_1\hat{p}_3+c_{32}\hat{\epsilon}_2\hat{p}_1)v(p_5), \tag{A1}$$

where

$$c^2=\frac{4096\alpha^2\alpha_s^2\langle\mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle(J/\psi+\psi')\pi^4}{6561m_c},\quad c_i=\sum_{j=1,20}c_{i,j}y_j, \tag{A2}$$

$$\begin{aligned}
&y_1=[4x_3x_{10}(2m_c^2-x_8-2x_{10}+x_{15})]^{-1}, && y_2=[-2x_3(2m_c^2+x_{15})(4m_c^2+2x_{15})]^{-1},\\
&y_3=[2x_3x_8(2m_c^2+x_{15})]^{-1}, && y_4=[2x_3x_8(2m_c^2-x_2-2x_3+x_{14})]^{-1},\\
&y_5=[-2x_4(2m_c^2+x_{14})(4m_c^2+2x_{14})]^{-1}, && y_6=[2x_4x_8(2m_c^2+x_{14})]^{-1},\\
&y_7=[2x_4x_8(2m_c^2-x_2-2x_4+x_{15})]^{-1}, && y_8=[-x_8(2m_c^2+x_{15})(2m_c^2+x_{14}+x_{15}+2x_{19})]^{-1},\\
&y_9=[-x_8(2m_c^2+x_{14})(2x_1-x_2-x_8)]^{-1}, && y_{10}=[-x_2(2m_c^2+x_{14})(2x_1-x_2-x_8)]^{-1},
\end{aligned} \tag{A3}$$

$$\begin{aligned}
&x_1=p_1\cdot p_2,\ x_2=p_1\cdot p_3,\ x_3=p_1\cdot p_4,\ x_4=p_1\cdot p_5,\ x_5=p_1\cdot\epsilon_1,\ x_6=p_1\cdot\epsilon_2,\\
&x_7=p_1\cdot\epsilon_3,\ x_8=p_2\cdot p_3,\ x_9=p_2\cdot p_4,\ x_{10}=p_2\cdot p_5,\ x_{11}=p_2\cdot\epsilon_1,\ x_{12}=p_2\cdot\epsilon_2,\\
&x_{13}=p_2\cdot\epsilon_3,\ x_{14}=p_3\cdot p_4,\ x_{15}=p_3\cdot p_5,\ x_{16}=p_3\cdot\epsilon_1,\ x_{17}=p_3\cdot\epsilon_2,\ x_{18}=p_3\cdot\epsilon_3,\\
&x_{19}=p_4\cdot p_5,\ x_{20}=p_4\cdot\epsilon_1,\ x_{21}=p_4\cdot\epsilon_2,\ x_{22}=p_4\cdot\epsilon_3,\ x_{23}=p_5\cdot\epsilon_1,\ x_{24}=p_5\cdot\epsilon_2,\\
&x_{25}=p_5\cdot\epsilon_3,\ x_{26}=\epsilon_1\cdot\epsilon_2,\ x_{27}=\epsilon_1\cdot\epsilon_3,\ x_{28}=\epsilon_2\cdot\epsilon_3,
\end{aligned} \tag{A4}$$

$$\begin{aligned}
c_1=&[4x_{24}(4y_{10}+y_3+3y_4+3y_6+y_7+3y_8+4y_9)+4x_{21}(-y_3+y_4+y_6-y_7-y_8)\\
&+4x_{17}(2y_{10}+2y_4+2y_6+y_8+2y_9)],
\end{aligned} \tag{A5}$$

$$\begin{aligned}
c_2=&\{x_{26}[4x_8(-y_8-y_9)+8x_4(y_{10}+y_6+y_7+2y_9)+8x_3(-y_6-y_7-y_9)\\
&+4x_2(y_{10}-2y_6-2y_7)+8x_1(-y_{10}+y_6+y_7)+8(2m_c^2y_8-x_{10}y_8+x_{15}y_8)]\\
&+[8x_{24}x_{23}(3y_6+y_7+y_8)+8x_{23}x_{21}(y_6-y_7+y_8)+8x_{24}x_{20}(-y_3-3y_4+y_8)+8x_{21}x_{20}(y_3-y_4+y_8)\\
&+4x_{24}x_{16}(-y_{10}+3y_8-y_9)+4x_{21}x_{16}(y_{10}+y_8+y_9)+16(-x_{17}x_{20}y_4+x_{17}x_{23}y_6)]\},
\end{aligned} \tag{A6}$$

$$\begin{aligned}
c_3=&[4x_7(y_{10}-3y_3-y_4+y_6-y_7+y_9)+4x_{25}(-2y_{10}+y_3-y_4-y_6+y_7-3y_8-2y_9)\\
&+4x_{22}(2y_{10}+3y_3+y_4+y_6+3y_7+y_8+2y_9)+4x_{13}(y_{10}-2y_3-2y_7+y_9)],
\end{aligned} \tag{A7}$$

$$\begin{aligned}
c_4=&\{16m_c^2(-2y_3-2y_7+y_8)+[4x_8(-y_{10}+2y_3+2y_7-y_9)+4x_2(-y_{10}+3y_3+y_4-y_6+y_7-y_9)\\
&+4x_{15}(2y_{10}-y_3+y_4+y_6-y_7+3y_8+2y_9)+4x_{14}(-2y_{10}-3y_3-y_4-y_6-3y_7-y_8-2y_9)]\},
\end{aligned} \tag{A8}$$

$$c_5=4m_c(-y_1-y_{10}-y_2-y_3-y_4-y_5-y_6-y_7-y_8-y_9), \tag{A9}$$

$$\begin{aligned}
c_6=&[4x_{23}(y_{10}-4y_6-4y_7+3y_8-y_9)+4x_{20}(-3y_{10}-4y_6-4y_7-y_8-5y_9)\\
&+4x_{16}(-y_{10}-4y_6-4y_7+y_8-3y_9)],
\end{aligned} \tag{A10}$$

$$\begin{aligned}
c_7=&[4x_8(y_8+y_9)+8x_4(-y_{10}+y_6+y_7+y_8)+4x_3(2y_{10}+2y_3+2y_4+4y_6+4y_7+y_8+4y_9)\\
&+4x_2(4y_6+4y_7+3y_9)+4x_1(y_{10}-4y_6-4y_7-3y_9)+4(-7m_c^2y_8+5x_{10}y_8-5x_{15}y_8-3x_{19}y_8)],
\end{aligned} \tag{A11}$$

$$c_8=\{m_c^2[16x_7(y_{10}+4y_3-y_8+y_9)+96x_{25}y_8]+[8x_{25}x_2(-y_3+y_4-y_8)$$
$$+8x_{22}x_2(-y_{10}-3y_3-y_4-y_8-y_9)+8x_7x_{15}(y_3-y_4+y_8)+8x_7x_{14}(y_{10}+3y_3+y_4+y_8+y_9)$$
$$+8(3x_{13}x_{15}y_8+2x_{13}x_2y_3+3x_{14}x_{25}y_8-3x_{15}x_{22}y_8-3x_{25}x_8y_8-2x_7x_8y_3)]\}, \qquad (A12)$$

$$c_{10}=8m_cx_7(y_{10}+y_5+y_6+y_7+y_9), \qquad (A13)$$

$$c_{11}=m_c[8x_{23}(-y_5-y_6-y_7+y_8)+8x_{20}(y_1+y_2+y_3+y_4+y_8)+4x_{16}(y_{10}+y_8+y_9)], \qquad (A14)$$

$$c_{12}=\{x_{27}[4x_8(-y_8-y_9)+8x_4(2y_{10}-y_6-y_7)+8x_3(-y_{10}-3y_6-3y_7-3y_9)$$
$$+4x_2(y_{10}-6y_6-6y_7-4y_9)+8x_1(-y_{10}+3y_6+3y_7+2y_9)+8(2m_c^2y_8-x_{10}y_8+x_{15}y_8)]$$
$$+[8x_7x_{23}(-2y_{10}+2y_6+4y_7-3y_8)+8x_{25}x_{23}(y_6-y_7+y_8)+8x_{23}x_{22}(-y_6-3y_7+3y_8)$$
$$+8x_7x_{20}(y_{10}-3y_3-y_4+3y_6+3y_7+3y_9)+8x_{25}x_{20}(y_3-y_4-y_8)+8x_{22}x_{20}(3y_3+y_4+y_8)$$
$$+4x_7x_{16}(-y_{10}+6y_6+6y_7-y_8+3y_9)+4x_{25}x_{16}(-y_{10}-y_8-y_9)+4x_{22}x_{16}(y_{10}+y_8+y_9)$$
$$+16x_{23}x_{13}(y_7-y_8)-16x_{13}x_{20}y_3]\}, \qquad (A15)$$

$$c_{13}=\{m_c[12x_8(-y_8-y_9)+8x_4(y_{10}-2y_6-2y_7-y_8-y_9)+8x_3(y_1-2y_{10}-y_3-y_4-3y_6-3y_7-4y_9)$$
$$+4x_2(-3y_{10}-2y_5-8y_6-8y_7-2y_8-10y_9)+8x_{15}(4y_8+y_9)+24x_1(y_6+y_7+y_9)$$
$$+8(-3x_{10}y_8+x_{14}y_9+x_{19}y_8+x_9y_8)]+8m_c^3(7y_8+4y_9)\}, \qquad (A16)$$

$$c_{14}=\{m_c^2[64x_{23}(y_7-y_8)+16(-x_{16}y_8-4x_{20}y_3)]$$
$$+[16x_8x_{23}(-y_7+y_8)+8x_{23}x_2(y_{10}-3y_6-5y_7+3y_8-y_9)$$
$$+8x_{20}x_2(-2y_{10}+3y_3+y_4-4y_6-4y_7-4y_9)+4x_8x_{16}(y_8+y_9)+8x_4x_{16}(-2y_{10}+y_6+y_7)$$
$$+8x_3x_{16}(y_{10}+3y_6+3y_7+3y_9)+4x_2x_{16}(-2y_{10}-2y_6-2y_7+y_8-y_9)+8x_{23}x_{15}(-y_6+y_7)$$
$$+8x_{20}x_{15}(-y_3+y_4+2y_8)+4x_{16}x_{15}(y_{10}+y_8+y_9)+8x_{23}x_{14}(y_6+3y_7-3y_8)$$
$$+8x_{20}x_{14}(-3y_3-y_4-y_8)+4x_{16}x_{14}(-y_{10}-y_8-y_9)+8x_{16}x_1(y_{10}-3y_6-3y_7-2y_9)$$
$$+8(x_{10}x_{16}y_8+2x_{20}x_8y_3)]\}, \qquad (A17)$$

$$c_{15}=m_c[8x_7(y_1-2y_3+y_6-y_7)+8x_{25}(-y_{10}+y_2+y_3-y_4-y_6+y_7-2y_8-y_9)$$
$$+8x_{22}(-y_1+2y_{10}+2y_3-y_5+2y_7+y_8+2y_9)+8x_{13}(-y_3-y_7)], \qquad (A18)$$

$$c_{16}=m_c[8x_{23}(y_{10}-3y_6-3y_7+2y_8-y_9)+8x_{20}(-2y_{10}-3y_6-3y_7-y_8-4y_9)$$
$$+4x_{16}(-3y_{10}-2y_5-8y_6-8y_7+y_8-7y_9)], \qquad (A19)$$

$$c_{17}=(x_{27}\{m_c[8x_8(y_8+2y_9)+16x_4(-2y_{10}+y_6+y_7)+32x_3(y_6+y_7+y_9)+16x_2(-y_{10}+2y_6+2y_7+2y_9)$$
$$+16x_{15}(-y_8-y_9)+16x_1(y_{10}-2y_6-2y_7-y_9)+16(x_{10}y_8-x_{14}y_9)]+32m_c^3(-y_8-2y_9)\}$$
$$+m_c[16x_7x_{23}(y_6-y_7+y_8)+16x_{25}x_{23}(-y_6+y_7-y_8)+16x_{23}x_{22}(-y_5+2y_7-3y_8)$$
$$+16x_7x_{20}(-y_1+y_{10}+2y_3+y_9)+16x_{25}x_{20}(-y_2-y_3+y_4+2y_8)+16x_{22}x_{20}(y_1-2y_3)+8x_7x_{16}(y_{10}+y_8+y_9)$$
$$+8x_{25}x_{16}(y_{10}+y_8+y_9)+16x_{23}x_{13}(-y_7+2y_8)+16x_{20}x_{13}(y_3-y_8)+8(x_{13}x_{16}y_8-2x_{16}x_{22}y_8)]), \qquad (A20)$$

$$c_{18}=m_c[8x_{24}(4y_{10}+y_3+3y_4+3y_6+y_7+2y_8+4y_9)+8x_{21}(y_{10}+2y_4+2y_6-y_8+y_9)$$
$$+4x_{17}(5y_{10}+2y_2+3y_3+5y_4+5y_6+3y_7+3y_8+5y_9)], \qquad (A21)$$

$$
\begin{aligned}
c_{19}=&\{8m_c^2(5x_{17}y_8-4x_{24}y_8)+[16x_{24}x_2(2y_{10}+2y_6+y_7+y_8+2y_9)+8x_{21}x_2(y_{10}+2y_6+y_9)\\
&+4x_8x_{17}(-y_8-y_9)+16x_4x_{17}(-y_7-y_8)+8x_3x_{17}(-y_{10}-y_3-y_4-y_6-3y_7-y_8-y_9)\\
&+4x_2x_{17}(4y_{10}+4y_6-4y_7+y_8+3y_9)+8x_{17}x_1(y_6+3y_7+y_9)\\
&+8(-4x_{10}x_{17}y_8-x_{14}x_{24}y_8+3x_{15}x_{17}y_8-x_{15}x_{21}y_8-2x_{15}x_{24}y_8+3x_{17}x_{19}y_8+x_{24}x_8y_8)]\},
\end{aligned}\tag{A22}
$$

$$
\begin{aligned}
c_{20}=&(x_{26}\{m_c[8x_8(-y_8-2y_9)+16x_4(y_{10}+y_6+y_7+2y_9)+16x_{15}(y_8+y_9)+16x_1(-y_{10}-y_9)\\
&+8(-2x_{10}y_8+2x_{14}y_9+x_2y_{10})]+32m_c^3(y_8+2y_9)\}+m_c[16x_{24}x_{23}(3y_6+y_7-y_8)+16x_{24}x_{20}(-y_3-3y_4)\\
&+16x_{21}x_{20}(-2y_4+y_8)+8x_{23}x_{17}(5y_6+3y_7-3y_8-2y_9)+8x_{20}x_{17}(-2y_2-3y_3-5y_4-y_8-2y_9)\\
&+8x_{24}x_{16}(-3y_{10}-y_8-3y_9)+16x_{21}x_{16}(-y_{10}-y_9)+4x_{17}x_{16}(-5y_{10}-3y_8-9y_9)+32x_{21}x_{23}y_6]),
\end{aligned}\tag{A23}
$$

$$
\begin{aligned}
c_{21}=&(x_{26}\{32m_c^2x_7(y_{10}-2y_6+2y_7-2y_9)+[16x_8x_7(y_6-y_7+y_9)+32x_{25}x_2(y_6+y_9)\\
&+16x_{22}x_2(-y_{10}-2y_7)+32x_7x_{15}(-y_6-y_9)+16x_7x_{14}(y_{10}+2y_7)+16x_2x_{13}(-y_6+y_7-y_9)]\}\\
&+x_{27}\{m_c^2[32x_{17}(-y_8+y_9)+64x_{24}y_8]+[16x_{24}x_2(-3y_{10}-4y_6-2y_7-y_8-3y_9)+16x_{21}x_2(-y_{10}-2y_6-y_9)\\
&+16x_3x_{17}(y_{10}+y_6+y_7+y_9)+8x_2x_{17}(-3y_{10}-4y_6-3y_9)+8x_{17}x_{15}(-2y_8+y_9)+16x_{17}x_1(-y_6-y_7-y_9)\\
&+8(2x_{10}x_{17}y_8+x_{14}x_{17}y_9+2x_{14}x_{24}y_8+2x_{15}x_{24}y_8+x_{17}x_8y_8-2x_{24}x_8y_8)]\}\\
&+x_{28}\{m_c^2[32x_{23}(y_6-y_7+y_8)+32x_{20}(y_3-y_4+y_8)+16x_{16}(y_{10}+3y_8-y_9)]\\
&+[16x_{23}x_2(y_{10}+3y_7-y_8+y_9)+16x_{20}x_2(2y_{10}-y_3+y_6+3y_7+2y_9)+16x_4x_{16}(y_{10}+y_6+y_7+y_9)\\
&+8x_2x_{16}(4y_{10}+2y_6+6y_7-y_8+4y_9)+8x_{16}x_{15}(2y_8-y_9)+16x_{23}x_{14}(-y_7+y_8)+16x_{20}x_{14}(y_3+y_8)\\
&+8x_{16}x_{14}(y_{10}+y_8)+8(-2x_1x_{16}y_{10}-2x_{10}x_{16}y_8-2x_{15}x_{20}y_4+2x_{15}x_{23}y_6-x_{16}x_8y_8+2x_{20}x_8y_4-2x_{23}x_8y_6)]\}\\
&+[16x_7x_{23}x_{17}(-3y_7+y_8)+16x_{23}x_{22}x_{17}(y_7-y_8)+16x_7x_{20}x_{17}(-y_{10}+y_3-y_6-3y_7-y_9)\\
&+16x_{22}x_{20}x_{17}(-y_3-y_8)+16x_7x_{24}x_{16}(2y_{10}+3y_6+y_7+y_8+2y_9)+16x_7x_{21}x_{16}(y_6-y_7)\\
&+8x_7x_{17}x_{16}(y_{10}+2y_6-6y_7+y_8+y_9)+8x_{22}x_{17}x_{16}(-y_{10}-y_8-y_9)\\
&+16(x_{13}x_{16}x_{24}y_8-x_{13}x_{17}x_{20}y_4+x_{13}x_{17}x_{23}y_6-x_{16}x_{22}x_{24}y_8-x_{16}x_{24}x_{25}y_8+x_{17}x_{20}x_{25}y_4-x_{17}x_{23}x_{25}y_6)]),
\end{aligned}\tag{A24}
$$

$$
\begin{aligned}
c_{22}=&(x_{28}\{16m_c^2(y_{10}-y_3+y_4+y_6-y_7+y_8+y_9)+[8x_8(-y_{10}-y_4-y_6-y_9)\\
&+8x_2(-y_{10}+y_3-y_6-y_9)+8x_{15}(y_{10}+y_4+y_6+2y_8+y_9)+8x_{14}(-y_3-y_7-y_8)]\}\\
&+[8x_7x_{17}(y_{10}-y_3+y_6+y_9)+8x_{25}x_{17}(-y_{10}-y_4-y_6-2y_8-y_9)\\
&+8x_{22}x_{17}(y_3+y_7+y_8)+8x_{17}x_{13}(y_{10}+y_4+y_6+y_9)]),
\end{aligned}\tag{A25}
$$

$$
c_{23}=8x_{28}m_c(-y_2-y_3-y_7-y_8),\tag{A26}
$$

$$
\begin{aligned}
c_{24}=&\{x_{28}[4x_8(y_8+y_9)+16x_4(y_7+y_8)+8x_3(y_{10}+y_3+y_4+y_6+3y_7+y_8+y_9)\\
&+4x_2(y_{10}+2y_6+6y_7+2y_9)+8x_1(-y_6-3y_7-y_9)+8(-5m_c^2y_8+4x_{10}y_8-4x_{15}y_8-3x_{19}y_8)]\\
&+[16x_7x_{24}(-2y_{10}-2y_6-y_7-y_8-2y_9)+8x_7x_{21}(-y_{10}-2y_6-y_9)+4x_7x_{17}(-5y_{10}-6y_6-2y_7-y_8-5y_9)\\
&+8(-x_{13}x_{24}y_8+x_{17}x_{25}y_8+x_{21}x_{25}y_8+x_{22}x_{24}y_8+2x_{24}x_{25}y_8)]\},
\end{aligned}\tag{A27}
$$

$$
c_{25}=m_cx_{28}[16x_{23}(-y_7+y_8)+16x_{20}(y_2+y_3+y_8)+8x_{16}y_8],\tag{A28}
$$

$$c_{26}=(x_{28}\{m_c[8x_8(2y_8+y_9)+32x_4(y_7+y_8)+16x_3(y_{10}+y_4+y_6+2y_7+y_8+y_9)$$
$$+8x_2(y_{10}+2y_6+6y_7+2y_8+2y_9)+16x_1(-y_6-2y_7-y_9)+16(3x_{10}y_8-x_{14}y_8-4x_{15}y_8-3x_{19}y_8)]-112m_c^3y_8\}$$
$$+m_c[16x_7x_{24}(-3y_{10}-3y_6-y_7-2y_8-3y_9)+16x_7x_{21}(-y_{10}-2y_6-y_9)$$
$$+8x_7x_{17}(-4y_{10}-5y_6-3y_7-y_8-4y_9)$$
$$+16(-x_{13}x_{24}y_8+x_{17}x_{25}y_8+x_{21}x_{25}y_8+x_{22}x_{24}y_8+2x_{24}x_{25}y_8)]), \tag{A29}$$

$$c_{27}=\{m_cx_{27}[16x_{24}(3y_{10}+3y_6+y_7+y_8+3y_9)+16x_{21}(y_{10}+2y_6+y_9)+8x_{17}(4y_{10}+5y_6+3y_7+y_8+4y_9)]$$
$$+m_cx_{28}[16x_{23}(-y_6-2y_7+y_8)+16x_{20}(-y_{10}-y_6-2y_7-y_8-y_9)+8x_{16}(-y_{10}-2y_6-6y_7-y_9)]$$
$$+m_cx_{26}[16x_7(y_6-y_7+y_9)+16x_{25}(-y_6+y_7-y_8-2y_9)+16x_{22}(y_{10}-y_5+2y_7)+16x_{13}(-y_7+y_9)]\}, \tag{A30}$$

$$c_{28}=\{x_{27}[8x_{24}(3y_{10}+3y_6+y_7+y_8+3y_9)+8x_{21}(y_6-y_7)+4x_{17}(3y_{10}+4y_6+y_8+3y_9)]$$
$$+x_{28}[8x_{23}(-y_{10}-y_6-3y_7+2y_8-y_9)+8x_{20}(-2y_{10}-y_6-3y_7-y_8-2y_9)+4x_{16}(-3y_{10}-2y_6-6y_7+y_8$$
$$-3y_9)]+x_{26}[8x_7(y_6-y_7+y_9)+8x_{25}(-y_6+y_7-y_8-2y_9)+8x_{22}(y_{10}+y_6+3y_7+y_9)+8x_{13}(-2y_7+y_9)]\}, \tag{A31}$$

$$c_{29}=(x_{26}\{16m_c^2(-y_{10}+2y_6-2y_7+y_8+3y_9)+[8x_8(-y_6+y_7-2y_9)+16x_2(-y_6-y_9)+8x_{15}(2y_6+y_8+3y_9)$$
$$+8x_{14}(-y_{10}-2y_7)]\}+[8x_{23}x_{17}(y_6+3y_7-2y_8)+8x_{20}x_{17}(y_{10}+y_6+3y_7+y_8+y_9)$$
$$+8x_{24}x_{16}(-3y_{10}-3y_6-y_7-y_8-3y_9)+8x_{21}x_{16}(-y_6+y_7)+8x_{17}x_{16}(-y_{10}-y_6+3y_7-y_8-y_9)]), \tag{A32}$$

$$c_{30}=8x_{26}m_c(-y_5-y_6-y_7-y_9), \tag{A33}$$

$$c_{31}=8x_{27}m_c(y_{10}+y_5+y_6+y_7+y_9), \tag{A34}$$

$$c_{32}=(x_{27}\{16m_c^2(y_{10}+4y_7-y_8+y_9)+[8x_2(y_6-y_7)+8x_{15}(-y_{10}-y_6+y_7-y_8-y_9)$$
$$+8x_{14}(2y_{10}+y_6+3y_7+2y_9)-16x_8y_7]\}+[8x_7x_{16}(y_{10}+2y_7+y_9)+8x_{25}x_{16}(-2y_7+y_8)$$
$$+8x_{22}x_{16}(-3y_{10}-2y_6-4y_7-3y_9)+8x_{16}x_{13}(y_{10}+y_6+3y_7+y_9)]). \tag{A35}$$

---

[1] E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995).
[2] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **69**, 3704 (1992).
[3] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 572 (1997).
[4] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 578 (1997).
[5] G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. D **51**, 1125 (1995); **55**, 5853(E) (1997).
[6] C.F. Qiao, J. Phys. G **29**, 1075 (2003).
[7] M. Cacciari and M. Krämer, Phys. Rev. Lett. **76**, 4128 (1996).
[8] J. Amundson, S. Fleming, and I. Maksymyk, Phys. Rev. D **56**, 5844 (1997).
[9] P. Ko, J. Lee, and H.S. Song, Phys. Rev. D **54**, 4312 (1996); **60**, 119902(E) (1999).
[10] B.A. Kniehl and G. Kramer, Phys. Lett. B **413**, 416 (1997).
[11] E. Braaten, K. Cheung, and T.C. Yuan, Phys. Rev. D **48**, 4230 (1993).
[12] M. Krämer, Nucl. Phys. **B459**, 3 (1996).
[13] M. Beneke and I.Z. Rothstein, Phys. Lett. B **372**, 157 (1996); **389**, 769(E) (1996); M. Beneke and M. Krämer, Phys. Rev. D **55**, 5269 (1997).
[14] E. Braaten, B.A. Kniehl, and J. Lee, Phys. Rev. D **62**, 094005 (2000); B.A. Kniehl and J. Lee, *ibid.* **62**, 114027 (2000).
[15] Adam K. Leibovich, Phys. Rev. D **56**, 4412 (1997).
[16] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **87**, 162002 (2001).
[17] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **88**, 052001 (2002).
[18] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **89**, 142001 (2002).
[19] Peter Cho and Adam K. Leibovich, Phys. Rev. D **54**, 6690 (1996).
[20] S. Baek, P. Ko, J. Lee, and H.S. Song, J. Korean Phys. Soc. **33**, 97 (1998).
[21] F. Yuan, C.-F. Qiao, and K.T. Chao, Phys. Rev. D **56**, 321 (1997).
[22] E. Braaten and J. Lee, Phys. Rev. D **67**, 054007 (2003).
[23] K.Y. Liu, Z.G. He, and K.T. Chao, Phys. Lett. B **557**, 45 (2003).

[24] K. Hagiwara, E. Kou, and C.F. Qiao, Phys. Lett. B **570**, 39 (2003).

[25] J.P. Ma, B.H.J. McKellar, and C.B. Paranavitane, Phys. Rev. D **57**, 606 (1998); G. Japaridze and A. Tkabladze, Phys. Lett. B **433**, 139 (1998); C.F. Qiao, Phys. Rev. D **64**, 077503 (2001); M. Klasen, B.A. Kniehl, L.N. Mihaila, and M. Steinhauser, Nucl. Phys. **B609**, 518 (2001).

[26] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Eur. Phys. J. C **4**, 463 (1998).

[27] M. Klasen, B.A. Kniehl, L.N. Mihaila, and M. Steinhauser, Phys. Rev. Lett. **89**, 032001 (2002).

[28] S. Todorova-Nova, in *Datong 2001*, *Multiparticle Dynamics*, Proceedings of the 31st International Symposium on Multiparticle Dynamics (ISMD 2001), Datong, China, 2001, edited by B. Yuting, Y. Meiling, and W. Yuanfang, eConf. C010901, pp. 62–67, hep-ph/0112050; M. Chapkin, in *Hadron Spectroscopy*, edited by D. Amelin and A.M. Zaitsev, AIP Conf. Proc. No. 619 (AIP, Melville, NY, 2002), p. 803; Phys. Lett. B (to be published), hep-ph/0307049.

[29] J.H. Kühn, J. Kaplan, and E.G.O. Safiani, Nucl. Phys. **B157**, 125 (1979); C.H. Chang, *ibid.* **B172**, 425 (1980); B. Guberina, J.H. Kühn, R.D. Peccei, and R. Rückl, *ibid.* **B174**, 317 (1980); E.L. Berger and D. Jones, Phys. Rev. D **23**, 1521 (1981); R. Baier and R. Rückl, Z. Phys. C **19**, 251 (1983).

[30] S. Frixione, M.L. Mangano, P. Nason, and G. Ridolphi, Phys. Lett. B **319**, 339 (1993).

[31] J.X. Wang, http://www.ihep.ac.cn/lunwen/wjx/public_html/index.html; in *New Computing Techniques in Physics Research III*, Proceedings of AI93, Oberammergau, Germany (World Scientific, River Edge, NJ, 1994), pp. 517–522; in *Accelerator and Particle Physics*, edited by Y. Fujii (KEK, Tsukuba, Japan, 2001), pp. 108–121.

[32] C.H. Chang, C.F. Qiao, and J.X. Wang, Phys. Rev. D **56**, 1363 (1997); **57**, 4035 (1998).

[33] M. Glück, E. Reya, and I. Schienbein, Phys. Rev. D **60**, 054019 (1999); **62**, 019902 (2000).

[34] M. Krämer, J. Zunft, J. Steegborn, and P.M. Zerwas, Phys. Lett. B **348**, 657 (1995).