Exclusive $C = +$ charmonium production in $e^+e^- \rightarrow H + \gamma$ at B-factories within light cone formalism.

V.V. Braguta

1Institute for High Energy Physics, Protvino, Russia

In this paper the cross sections of the processes $e^+e^- \rightarrow H + \gamma, H = \eta_c, \eta_c', \chi_c0, \chi_c1,\chi_c2$ are calculated. The calculation is carried out at the leading twist approximation of light cone formalism. Within this approach the leading logarithmic radiative and relativistic corrections to the amplitudes are resummed. For the processes $e^+e^- \rightarrow \eta_c, \eta_c' + \gamma$ one loop radiative corrections are taken into account. It is also shown that one loop leading logarithmic radiative corrections calculated within light cone formalism for the processes under study coincide with that obtained by direct calculations of one loop diagrams within nonrelativistic QCD.

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I. INTRODUCTION

Theoretical approach to the description of hard exclusive processes, which is called light cone formalism (LC), is based on the factorization theorem [1,2]. Within this theorem the amplitude of hard exclusive process can be separated into two parts. The first part is partons production at very small distances, which can be treated within perturbative QCD. The second part is the hardronization of the partons at large distances. For hard exclusive processes it can be parameterized by process independent distribution amplitudes (DA).

The production of the charmonium meson $H$ in the process $e^+e^- \rightarrow H + \gamma$ at B-factories, is the simplest example of hard exclusive process. One can assume that the energy at which B-factories operate is sufficiently large so that it is possible to apply LC. Another approach to the calculation of the cross section of this process is nonrelativistic QCD (NRQCD) [3]. This approach is based on the assumption that relative velocity of quark-antiquark pair in charmonia is small parameter in which the amplitude of charmonium production can be expanded. LC has two very important advantages in comparison to the NRQCD. The first advantage is that LC formalism can be applied for light or heavy mesons if DA of this meson is known. From, NRQCD perspective this means that LC resums whole series of relativistic corrections to the amplitude under study. For NRQCD relativistic corrections are very important especially for the production of exited charmonia mesons. The second advantage is that within LC one can resum leading logarithmic radiative corrections to the amplitude in all loops. The main disadvantage of LC is that within this formalism it is rather difficult to control power corrections to the amplitude.

Within NRQCD the process $e^+e^- \rightarrow H + \gamma$ was considered in papers [4,5]. In paper [4] this process was considered at the leading order approximation in relative velocity and strong coupling constant. The authors of paper [5] took into account one loop radiative corrections. In addition to the radiative corrections the first order relativistic corrections to the process $e^+e^- \rightarrow \eta_c + \gamma$ were considered in paper [6].

The only process considered within LC is $e^+e^- \rightarrow \eta_c + \gamma$ [7,8]. The main drawback of these papers is that the authors used very simple model of DA of the $\eta_c$ meson, which doesn’t take into account relativistic motion in this meson. Recently, the leading twist DAs of charmonia mesons have become the object of intensive study [9-17]. The study of these DAs allowed one to build some models for charmonia DAs, that can be used in the calculation of different exclusive processes.

In this paper the leading twist processes $e^+e^- \rightarrow H + \gamma$ will be considered. Using helicity selection rules [18,20] it is not difficult to show that at the leading twist accuracy the mesons with longitudinal polarization and the following quantum numbers $H = \frac{1}{2} S_0, \frac{3}{2} P_1, \frac{3}{2} P_2, \frac{3}{2} P_3$ can be produced. So, in this paper the following processes will be considered:

$e^+e^- \rightarrow H + \gamma, H = \eta_c, \eta_c', \chi_c0, \chi_c1, \chi_c2$. To calculate the cross sections of these processes the model of DAs proposed in papers [11,12,13,14] will be used.

This paper is organized as follows. In the next section the amplitudes of the processes under consideration will be derived. Numerical results and the discussion of these results will be given in the last section of this paper.

*Electronic address: braguta@mail.ru
II. THE AMPLITUDE OF THE PROCESS \( e^+e^- \rightarrow H + \gamma \).

In this section the leading twist approximation for the amplitude of the processes \( e^+e^- \rightarrow H + \gamma \), \( H = \eta_c, \eta_c', \chi_0, \chi_{c1}, \chi_{c2} \) will be derived. The diagrams that contribute to the processes at the leading order approximation in the strong coupling constant are shown in Fig. 1. As was noted in the introduction, selection rules tell us that at the leading twist accuracy all produced mesons are longitudinally polarized. So, the polarization vectors of these mesons are proportional to the momentum of these mesons.

To calculate the amplitudes and the cross sections of the processes involved one needs the expressions for the following matrix element of the electromagnetic current \( J_\mu(0) \): \( \langle H(p)\gamma(k)|J_\mu(0)|0 \rangle \). For the production of the longitudinally polarized \( \eta_c, \eta_c', \chi_{c1} \) mesons it can be parameterized as follows

\[
\langle H(p)\gamma(k)|J_\mu(0)|0 \rangle = F_H \epsilon_{\mu \alpha \beta \gamma} q^\alpha p^\beta k^\gamma,
\]

where \( \epsilon^\gamma \) is the polarization vector of the final photon. It causes no difficulties to find the expression for the formfactor \( F_{H=\eta_c, \eta_c', \chi_{c1}} \) at the leading twist approximation

\[
F_{\eta_c, \eta_c', \chi_{c1}} = \frac{16\pi \alpha Q_c^2 f_{\eta_c, \eta_c', \chi_{c1}}}{s} \int\! d\xi \phi_{\eta_c, \eta_c', \chi_{c1}}(\xi, \mu) (1 - \xi^2),
\]

where \( Q_c \) is the charge of \( c \)-quark, the definitions of the constants \( f_{\eta_c, \eta_c', \chi_{c1}} \) and the DAs \( \phi_{\eta_c, \eta_c', \chi_{c1}}(\xi, \mu) \) can be found in the Appendix, \( \xi \) is the fraction of relative momentum of the whole meson carried by quark-antiquark pair, \( \mu \) is the characteristic scale of the process, \( s = (p + k)^2 \).

The expression for the production amplitude of the longitudinally polarized \( \chi_{0}, \chi_{c2} \) mesons can be written in the following form

\[
\langle H(p)\gamma(k)|J_\mu(0)|0 \rangle = F_H \left( (\epsilon q) k_\mu - (k q) \epsilon_\mu \right),
\]

where \( q = k + p \). The other designations are the same as were used in equation (1). The expression for the formfactor \( F_{H=\chi_{0}, \chi_{c2}} \) has the form

\[
F_{\chi_{0}, \chi_{c2}} = \frac{16\pi \alpha Q_c^2 f_{\chi_{0}, \chi_{c2}}}{s} \int\! d\xi \phi_{\chi_{0}, \chi_{c2}}(\xi, \mu) (1 - \xi^2),
\]

The constants \( f_{\chi_{0}, \chi_{c2}} \) and the DAs \( \phi_{\chi_{0}, \chi_{c2}}(\xi, \mu) \) can be found in the Appendix.

The cross section of the processes can be written in the following form

\[
\sigma_H = \frac{\alpha}{24} F_H^2 \left( 1 - \frac{M_H^2}{s} \right),
\]
It should be noted that the matrix elements of the processes under study were taken at the leading order approximation in $M_H^2/s$. The factor $1 - M_H^2/s$ in the cross section appeared due to the phase space of the final particles.

The expression of the formfactor $F_H$ depend on the DAs $\phi_H(\xi, \mu)$ of the charmonia mesons. If infinitely narrow distribution amplitudes $\phi_{\eta_c, \eta_c'}(\xi, \mu) = \delta(\xi)$, $\phi_{\chi_{c0, \chi_{c1}}}(\xi, \mu) = -\delta'(\xi)$ are substituted to formulas (2), (3), than NRQCD results for the amplitude will be reproduced [4]. If real distribution amplitudes $\phi_0(\xi, \mu)$ are taken at the scale $\mu \sim m_c$, than formulas (2), (3) will resum the relativistic corrections to the cross section up to $O(1/s^2)$ terms. To resum the relativistic and leading logarithmic radiative corrections simultaneously one must take the distribution amplitudes $\phi_H(\xi, \mu)$ at the characteristic scale of the process $\mu \sim \sqrt{s}$. The calculation of the cross sections will be done at the scale $\mu = \sqrt{s}/2$.

It is interesting to note that it is possible find the leading logarithmic radiative corrections at one loop level using formulas (2), (3) without calculation of one loop diagrams. Applying the approach proposed in paper [7] one gets the results

$$F_{\eta_c, \eta_c'} = \frac{16\pi\alpha Q_e^2}{s} \sqrt{\frac{\langle O \rangle_S}{m_c}} \left( 1 + C_f \frac{\alpha_s(s)}{4\pi} \log \left( \frac{\mu^2}{\mu_0^2} \right) \left( 3 - 2 \log 2 \right) \right),$$

$$F_{\chi_{c0}} = \frac{16\pi\alpha Q_e^2}{s} \sqrt{\frac{\langle O \rangle_P}{3m_c^2}} \left( 1 + C_f \frac{\alpha_s(s)}{4\pi} \log \left( \frac{\mu^2}{\mu_0^2} \right) \left( 1 - 2 \log 2 \right) \right),$$

$$F_{\chi_{c1}} = \frac{16\pi\alpha Q_e^2}{s} \sqrt{\frac{2\langle O \rangle_P}{m_c^2}} \left( 1 + C_f \frac{\alpha_s(s)}{4\pi} \log \left( \frac{\mu^2}{\mu_0^2} \right) \left( 3 - 2 \log 2 \right) \right),$$

$$F_{\chi_{c2}} = \frac{16\pi\alpha Q_e^2}{s} \sqrt{\frac{2\langle O \rangle_P}{3m_c^2}} \left( 1 + C_f \frac{\alpha_s(s)}{4\pi} \log \left( \frac{\mu^2}{\mu_0^2} \right) \left( 1 - 2 \log 2 \right) \right),$$

where $m_c$ is the pole mass of the $c$-quark, the definition of the NRQCD matrix elements $\langle O \rangle_S, \langle O \rangle_P$ can found in paper [3], $C_f = 4/3$. Note that in the above equations it was assumed that renormalization group evolution of the DAs begins at the scale $\mu_0 \sim m_c$ and ends at the scale $\mu \sim \sqrt{s}$. At the scale $\mu_0 \sim m_c$ the DAs are $\phi_{\eta_c, \eta_c'}(\xi, \mu) = \delta(\xi)$, $\phi_{\chi_{c0, \chi_{c1}}}(\xi, \mu) = -\delta'(\xi)$. Leading order NRQCD results [3] coincide with the results obtained in paper [4]. The one loop leading logarithmic radiative corrections for the $F_{\eta_c}$ coincide with the result of paper [7]. The one loop leading logarithmic radiative corrections for the $F_{\eta_c'}, F_{\chi_{c0}}, F_{\chi_{c1}}, F_{\chi_{c2}}$ coincide with the results of paper [8].

The result (2) for the production of the pseudoscalar mesons $\eta_c, \eta_c'$ can be improved since there exists expression for the one loop radiative correction to this amplitude [21, 22]. This expression can be written as follows [21]

$$F_{\eta_c, \eta_c'} = \frac{16\pi\alpha Q_e^2 f_{\eta_c, \eta_c'}}{s} \int_{-1}^{1} d\xi \frac{\phi_{\eta_c, \eta_c'}(\xi, \mu)}{(1 + \xi)} \left[ 1 + C_f \frac{\alpha_s(s)}{4\pi} \left( \log^2 \left( \frac{1 + \xi}{2} \right) - \log \left( \frac{1 + \xi}{1 - \xi} \right) \log \left( \frac{1 + \xi}{2} \right) - 9 + \left( 3 + 2 \log \left( \frac{1 + \xi}{2} \right) \right) \log \left( \frac{s}{\mu^2} \right) \right) \right],$$

In the above expressions it is assumed that the DAs $\phi_{\eta_c, \eta_c'}$ are $\xi$ even.

It is instructive to take the limit of zero relative velocity of quark-antiquark pair and compare it to the NRQCD result [3]. At leading order approximation in relative velocity expression (7) becomes

$$F_{\eta_c, \eta_c'} = \frac{16\pi\alpha Q_e^2}{s} \sqrt{\frac{\langle O \rangle_S}{m_c}} \left[ 1 + C_f \frac{\alpha_s(s)}{4\pi} \log \left( \frac{\mu^2}{\mu_0^2} \right) \left( 3 - 2 \log 2 \right) + C_f \frac{\alpha_s(s)}{4\pi} \log^2 2 + \log 2 - 9 + \log \left( \frac{s}{\mu^2} \right) \left( 3 - 2 \log 2 \right) \right].$$

The second term in equation (8) is due to renormalization group resummation of the leading logarithms in the DA. The last term is one loop radiative corrections to the hard part of the amplitude. The factorization scale $\mu$ separates long distance dynamic of the chamonium meson parameterized by DA from the small distance effects parameterized in the hard part of the amplitude. It is seen that $\mu$ dependence is canceled in the final answer, as it should be.

The authors of paper [3] obtained the following NRQCD expression for equation (8)

$$F_{\eta_c, \eta_c'} = \frac{16\pi\alpha Q_e^2}{s} \sqrt{\frac{\langle O \rangle_S}{m_c}} \left[ 1 + C_f \frac{\alpha_s(s)}{4\pi} \left( \log^2 2 + 3 \log 2 - 9 - \frac{\pi^2}{3} + \log \left( \frac{s}{m_c^2} \right) \left( 3 - 2 \log 2 \right) \right) \right].$$

(9)

It is seen that this expression is very similar to (8). Moreover one has one free parameter $\mu_0$ in expression (8), which can be used to adjust (8) to (9). However, expressions (8) and (9) seem to be a little bit different.
III. NUMERICAL RESULTS AND DISCUSSION.

To obtain numerical results for the cross sections of the processes under study the following numerical parameters are needed.

In this paper we are going to use the models of the charmonia DAs proposed in papers [11–13, 16]. For the strong coupling constant we use one-loop expression

$$\alpha_s(\mu) = \frac{4\pi}{b_0 \ln(\mu^2/\Lambda_{\text{QCD}}^2)},$$

where $b_0 = 25/3$ and $\Lambda_{\text{QCD}} = 0.2$ GeV.

In the calculation the following values of the constants $f_H$ will be used [23]:

$$f_{\eta_c} = 0.373 \pm 0.064 \text{ GeV},$$
$$f_{\eta'_c} = 0.261 \pm 0.077 \text{ GeV},$$
$$f_{\chi_{c0}}(M_{J/\Psi}) = 0.093 \pm 0.017 \text{ GeV},$$
$$f_{\chi_{c1}} = 0.272 \pm 0.048 \text{ GeV},$$
$$f_{\chi_{c2}}(M_{J/\Psi}) = 0.131 \pm 0.023 \text{ GeV} \quad (10)$$

The values of the constants $f_{\eta_c}, f_{\eta'_c}$ were calculated in paper [24]. The values of the constants of the $P$-wave charmonia mesons can be found in paper [10]. It should be noted that the constants $f_{\chi_{c0}}, f_{\chi_{c2}}$ depend on the renormalization scale. As it is seen from formulas (10) these constants are defined at the scale $\mu = M_{J/\Psi}$. The anomalous dimensions of these constants, which govern the evolution, can be found in paper [10].

There are different sources of uncertainty to the results obtained in this paper. The most important uncertainties can be divided into the following groups:

1. **The uncertainty in the models of the distribution amplitudes $\phi_H(x, \mu)$**, which can be modeled by the variation of the parameters of these models. The calculation shows that this source of uncertainty is not greater than 10%. So, it is not very important and it will be ignored.

2. **The uncertainty due to radiative corrections**. In the approach applied in this paper the leading logarithmic radiative corrections due to the evolution of the DAs and the strong coupling constant were resummed. For the processes $e^+e^- \rightarrow \eta_c, \eta'_c + \gamma$ one loop radiative corrections were taken into account. So, for last two processes radiative corrections are not very important and they will be ignored. As to the other processes considered in this paper radiative corrections to the results can be estimated as $\alpha_s(s) \sim 20\%$.

3. **The uncertainty due to the power corrections**. This uncertainty is determined by the next-to-leading order contribution in the $1/s$ expansion. One can estimate these corrections using the leading order NRQCD predictions [1], as it was discussed in paper [23]. Thus, for the processes $e^+e^- \rightarrow \eta_c, \eta'_c, \chi_{c0}, \chi_{c1}, \chi_{c2} + \gamma$ the errors due to this source of uncertainty are $\sim 3\%, 6\%, 50\%, 37\%, 60\%$ correspondingly.

4. **The uncertainty in the values of constants** [10]. The calculations show that, for the processes $e^+e^- \rightarrow \eta_c, \eta'_c, \chi_{c0}, \chi_{c1}, \chi_{c2} + \gamma$ the errors due to this source of uncertainties are $\sim 34\%, 60\%, 35\%, 35\%, 35\%$ correspondingly. Adding all these uncertainties in quadrature one gets the total errors of the calculation.

The results of the calculation are presented in Table III. Second column contains the results obtained in this paper. In the third, fourth and fifth columns the results obtained in papers [4], [5], [6] are shown. It is seen that the results obtained in this paper are in reasonable agreement with the results obtained within NRQCD.

| $H$ | $\sigma(e^+e^- \rightarrow H + \gamma)(\text{fb})$ | $\sigma(e^+e^- \rightarrow H + \gamma)(\text{fb})$ | $\sigma(e^+e^- \rightarrow H + \gamma)(\text{fb})$ | $\sigma(e^+e^- \rightarrow H + \gamma)(\text{fb})$ |
|-----|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| $\eta_c$ | $41.6 \pm 14.1$ | $82.0^{+21.4}_{-19.8}$ | $42.5 - 53.7$ | $68.0^{+22.2}_{-20.3}$ |
| $\eta'_c$ | $24.2 \pm 14.5$ | $49.2^{+10.4}_{-17.4}$ | $27.7 - 35.1$ | $42.6^{+10.9}_{-8.8}$ |
| $\chi_{c0}$ | $6.1 \pm 3.9$ | $13.3^{+3.4}_{-3.1}$ | $1.53 - 2.48$ | $1.36^{+0.26}_{-0.26}$ |
| $\chi_{c1}$ | $24.2 \pm 13.3$ | $13.7^{+3.4}_{-3.1}$ | $1.11 - 1.77$ | $10.9^{+3.7}_{-3.4}$ |
| $\chi_{c2}$ | $12.0 \pm 17.4$ | $5.3^{+1.6}_{-1.3}$ | $1.65 - 3.53$ | $1.95^{+1.85}_{-1.56}$ |

TABLE I: The cross sections of the processes $e^+e^- \rightarrow H + \gamma$, $H = \eta_c, \eta'_c, \chi_{c0}, \chi_{c1}, \chi_{c2}$. Second column contains the results obtained in this paper. In the third, fourth and fifth columns the results obtained in papers [4], [5], [6] are shown.
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Appendix A: Distribution amplitudes.

The leading twist distribution amplitudes needed in the calculation can be defined as follows:

for the pseudoscalar mesons $P = \eta_c, \eta'_c$:

$$\langle P(p) \bigg| \bar{Q}_\alpha^i(z, -z) Q_\beta^j(-z) \bigg| 0 \rangle = (\hat{p} \gamma_5)_{\beta \alpha} \frac{f_P}{4} \frac{\delta_{ij}}{3} \int_{-1}^{1} d\xi e^{i\xi(pz)} \phi_{\eta_c}(\xi; \mu),$$

for the $\chi_{c0}$-meson:

$$\langle \chi_{c0}(p) \bigg| \bar{Q}_\alpha^i(z, -z) Q_\beta^j(-z) \bigg| 0 \rangle = (\hat{p})_{\beta \alpha} \frac{f_{\chi_0}}{4} \frac{\delta_{ij}}{3} \int_{-1}^{1} d\xi e^{i\xi(pz)} \phi_{\chi_0}(\xi; \mu),$$

for the $\chi_{c1}$-meson:

$$\langle \chi_{c1}(p, \epsilon_{\lambda=0}) \bigg| \bar{Q}_\alpha^i(z, -z) Q_\beta^j(-z) \bigg| 0 \rangle = (\hat{p} \gamma_5)_{\beta \alpha} \frac{f_{\chi_1}}{4} \frac{\delta_{ij}}{3} \int_{-1}^{1} d\xi e^{i\xi(pz)} \phi_{\chi_1}(\xi; \mu),$$

for the $\chi_{c2}$-meson:

$$\langle \chi_{c2}(p, \epsilon_{\lambda=0}) \bigg| \bar{Q}_\alpha^i(z, -z) Q_\beta^j(-z) \bigg| 0 \rangle = (\hat{p})_{\beta \alpha} \frac{f_{\chi_2}}{4} \frac{\delta_{ij}}{3} \int_{-1}^{1} d\xi e^{i\xi(pz)} \phi_{\chi_2}(\xi; \mu),$$

The factor $[z, -z]$, that makes the above matrix elements gauge invariant, is defined as

$$[z, -z] = P \exp[ig \int_{-z}^{z} dx^\mu A_\mu(x)].$$

It is not difficult to show that the functions $\phi_{\eta_c}(\xi)$ and $\phi_{\chi_1}(\xi)$ are $\xi$-even. The normalization condition for these functions is

$$\int_{-1}^{1} \phi(\xi) d\xi = 1.$$

The functions $\phi_{\chi_0}(\xi)$ and $\phi_{\chi_2}(\xi)$ are $\xi$-odd and normalized according to

$$\int_{-1}^{1} \xi \phi(\xi) d\xi = 1.$$

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