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Color Octet Contribution to J/ψ Production at a Photon Linear Collider

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Abstract

We investigate J/ψ production at a Photon Linear Collider (PLC) in the framework of NRQCD factorization approach. It was shown that color octet contribution is dominating in charmonium production at PLC. The main fraction of J/ψ comes from the single and double resolved photon processes. Expected cross sections of charmonium states production are large enough even at $p_T > 5$ GeV to expect several hundreds of J/ψ's through the leptonic decays channel for a projected integral PLC luminosity of $50 fb^{-1}$

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1 Introduction

The nonrelativistic QCD (NRQCD) factorization approach, developed in the last few years, is the most successful method for the analysis of heavy quarkonium production and decay processes [1]. In the framework of this formalism cross section and decay rate of the process involving heavy quarkonium is factorized into the short distance part (coefficient functions) and the long distance one. For the cross section $\sigma(A+B\to H)$, where H stands for quarkonium, the formalism states:

$$\sigma(A+B\to H)=\sum_n \sigma(A+B\to Q\bar{Q}[n])\langle 0|\mathcal{O}^H[n]|0\rangle. \tag{1}$$

In (1) $\sigma(A+B\to Q\bar{Q}[n])$ is the cross section of the production of the heavy quark-antiquark pair state $[n]$. This part of cross section can be calculated perturbatively. The matrix element $\langle 0|\mathcal{O}^H[n]|0\rangle$ stands for the evolution of the state $[n]$ into the particular hadronic state H. It is defined by long distance dynamics and cannot be computed perturbatively. The long distance matrix elements scale as a power of v - the relative velocity of the heavy constituents in the quarkonium. So, in the NRQCD factorization approach (FA) the cross section of heavy quarkonium production is considered as a double series in the QCD coupling constant and the relative velocity v. The relative importance of long distance matrix elements in powers of v can be estimated using the NRQCD velocity scaling rules [2].

In the NRQCD factorization approach the quark-antiquark color octet intermediate states are allowed to contribute in heavy quarkonium production and decay processes in higher order. By such a way the Color Octet Mechanism (COM) takes into account the complete structure of the quarkonium Fock space while in the color singlet model (CSM) only the dominant Fock state is considered [3]. The shape of the p_T distribution of the ${}^3S_1^{(8)}$ octet state production cross section indicates that J/ψ and ψ' production at large p_T observed at the Tevatron (FNAL) can be explained in the framework of FA [4, 5].

Despite the obvious successes of the COM some problems remain unsolved. In particular, the theoretical predictions disagree with the J/ψ and ψ' polarization data at fixed target energies [6, 7] and the COM estimation for the yield ratio of χ_{c1} and χ_{c2} states remains too low [6]. These discrepancies indicate that higher twist corrections might contribute significantly in production of charmonium states at low p_T and should be considered equally with the COM contributions [8]. The latter underestimate the J/ψ photoproduction cross section at large values of z in H1 and ZEUS experiments at HERA ($z=E_{J/\psi}/E_\gamma$ in the proton rest frame)- the most problematic issue of the COM [9].

The NRQCD factorization approach has predictive power when the relative velocity v is small enough, allowing to describe with reasonable accuracy several experimental data by taking into account only a few lower order terms in powers of v. Hence it becomes necessary to check the universality of the FA, stating that the values of long distance matrix elements, extracted from the experimental data for different processes, should be the same. Unfortunately, due to the rather large theoretical uncertainties at the present time, the existing experimental data does not allow to extract the values of the long distance matrix elements with enough accuracy.

This has motivated us to look for processes with less theoretical uncertainties to test the color octet mechanism. The measurements of the J/ψ polarization in unpolarized hadron-hadron collisions and electroproduction [8, 10, 11, 12] can be used for these purposes as well as the asymmetries in J/ψ production [12]. Unlike hadron-hadron collisions, existing J/ψ photoproduction data can be explained within the CSM taking into account higher order QCD corrections [13]. Moreover, color octet contributions overestimate the experimental data drastically [9]. In this sense, the study of J/ψ production processes in non-hadron collisions can clarify the existing contradictory picture.

The collision of high-energy, high-intensity photon beams at a photon linear collider, obtained via Compton backscattering of laser beams off linac electron beams, should provide another possibility to investigate the heavy quark-antiquark bound states production processes. Based on a e^+e^- linear collider, the PLC will have almost the same energy and a luminosity, i.e. a c.m. energy of 500-1000 GeV and a luminosity of the order of $10^{33} cm^{-2} s^{-1}$ [14].

In the present paper we study J/ψ production at a photon linear collider. The color octet contribution in J/ψ production at PLC was calculated recently [15], where only the direct (unresolved) photon-photon collisions were considered. We will show that the resolved photon processes are more significant because there exist diagrams in lowest order of perturbative QCD leading to the subprocess cross section, non decreasing when the invariant mass of photon-photon system increases. In the next section we present all possible subprocesses in lowest order in perturbative QCD and fix the color octet long distance matrix elements needed. The numerical results are given in Sec. III. It is shown the that color octet contribution in resolved photon subprocesses is essential and the expected cross section of charmonium production is large enough even at high p_T (> 5 GeV) allowing to extract valuable information about color octet long distance matrix elements.

2 J/ψ Production Subprocesses and COM Parameters

For the calculation of the J/ψ production cross section at PLC we consider the following subprocesses: direct $\gamma\gamma$ collision, single and double resolved photon processes, when the heavy quark-antiquark pair is produced via hadronic components of the photon, which are described in terms of the photon structure functions [16].

To lowest order in α_{em} and α_S the following subprocesses contribute:

$$\gamma + \gamma \to (c\bar{c}) + \gamma(g) \tag{2}$$

$$\gamma + \gamma(g,q) \to (c\bar{c}) + g, q \tag{3}$$

$$\gamma(g,q) + \gamma(g,q) \to (c\bar{c}) + g, q \tag{4}$$

where $\gamma(g,q)$ denotes a gluon or quark component of the photon, $(c\bar{c})$ stands for any possible quark-antiquark state.

The cross section of J/ψ production in the NRQCD factorization scheme can be presented as

$$\sigma_{J/\psi} = \sigma(J/\psi)_{dir} + \sum_{J=0,1,2} Br(\chi_{cJ} \to J/\psi X)\sigma_{\chi_{cJ}} + Br(\psi' \to J/\psi X)\sigma_{\psi} \tag{5}$$

Here $Br((c\bar{c}) \to J/\psi X)$ denotes the branching ratio of the corresponding $(c\bar{c})$ state into J/ψ. To the production of each state of quarkonium both color octet and color singlet states contribute, as in the case of direct J/ψ production

$$\sigma(J/\psi)_{dir} = \sigma^{singl}_{J/\psi} + \sigma^{8}_{J/\psi} = \sigma(J/\psi)^{singl} + \sum \sigma(Q\bar{Q}[^{2s+1}L^8_J])\langle 0|\mathcal{O}_8^{J/\psi}(^{2s+1}L_J)|0\rangle \tag{6}$$

where the sum runs over the states ${}^3P^8_{0,1,2}$, ${}^1S^8_0$ and ${}^3S^8_1$. In the framework of the NRQCD FA velocity expansion we consider only the contribution of the dominant sets of color octet states in the direct production of S and P states of charmonium.

In direct $\gamma\gamma$ interaction in lowest order only the two states of heavy quark-antiquark pairs can be produced : $^3S_1$ color singlet (J/ψ) and $^3S_1$ color octet [15]. For the differential cross section of the singlet state production we have:

$$\frac{d\sigma_{\gamma\gamma}}{dt} = \frac{16M_{J/\psi}}{3}(\frac{2}{3})^4(4\pi)^2\alpha_S\alpha^2\langle\mathcal{O}_1^{J/\psi}(^3S_1)\rangle \frac{\hat{s}^2(\hat{s}-M_{J/\psi}^2)^2+\hat{t}^2(\hat{t}-M_{J/\psi}^2)^2+\hat{u}^2(\hat{u}-M_{J/\psi}^2)^2}{\hat{s}^2(\hat{s}-M_{J/\psi}^2)^2(\hat{t}-M_{J/\psi}^2)^2(\hat{t}-M_{J/\psi}^2)^2} \tag{7}$$

where $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the standard Mandelstam variables.

The differential cross section for the J/ψ production through color octet $^3S_1$ state can be obtained from (7) by the replacement [2]

$$\langle\mathcal{O}_8^{J/\psi}(^3S_1)\rangle \rightarrow \frac{4}{3}\frac{4\alpha}{9\alpha_S}\langle\mathcal{O}_1^{J/\psi}(^3S_1)\rangle$$

We calculated all possible subprocesses for single resolved photon reaction. Our results are in agreement with [9]. The subprocess for $(c\bar{c})$ states production in double resolved photon case are same as for J/ψ production in hadron-hadron collision and were calculated by Cho and Leibovich [5].

All color singlet long distance matrix elements are related to the radial quarkonium wave functions at the origin and their derivatives.We have used the Buchmüller-Tye wave functions at the origin, tabulated in [6]. The number of color octet long distance matrix elements can be reduced by using the NRQCD spin symmetry relations:

$$\langle 0|\mathcal{O}_8^H(^3P_J)|0\rangle = (2J+1)\langle 0|\mathcal{O}_8^H(^3P_0)|0\rangle, \tag{8}$$

$$\langle 0|\mathcal{O}_8^{\chi_{cJ}}(^3S_1)|0\rangle = (2J+1)\langle 0|\mathcal{O}_8^{\chi_{c0}}(^3S_1)|0\rangle. \tag{9}$$

These relations are valid up to order v^2.

After using these relations only three independent matrix elements remain - $\langle\mathcal{O}_8^{J/\psi}(^3S_1)\rangle$, $\langle\mathcal{O}_8^{J/\psi}(^3P_0)\rangle$ and $\langle\mathcal{O}_8^{J/\psi}(^1S_0)\rangle$, which give the main contribution to the direct J/ψ production cross section. The values of these parameters are extracted from the data of direct J/ψ production at CDF [5, 10]. We used the results of paper [10], where a more detailed numerical analysis was carried out:

$$\langle 0|\mathcal{O}_8^{J/\psi}(^3S_1)|0\rangle = 1.06 \pm 0.14^{+1.05}_{-0.59}\cdot 10^{-2}GeV^3, \tag{10}$$

$$\langle 0|\mathcal{O}_8^{J/\psi}(^1S_0)|0\rangle + \frac{3.5}{m_c^2}\langle 0|\mathcal{O}_8^{J/\psi}(^3P_0)|0\rangle = 3.9 \pm 1.15^{+1.46}_{-1.07}\cdot 10^{-2}GeV^3 \tag{11}$$

Further we will assume that $\langle 0|\mathcal{O}_8^{J/\psi}(^1S_0)|0\rangle = 3.5/m_c^2\langle 0|\mathcal{O}_8^{J/\psi}(^3P_0)|0\rangle$. For the indirect J/ψ production via the χ_{cJ} states decays we use the following value fitted from the CDF data [5]:

$$\langle\mathcal{O}_8^{\chi_{c1}}(^3S_1)\rangle = 9.8\cdot 10^{-3}GeV^3. \tag{12}$$

We would like to to mention that all these values contain large uncertainties (for more detailed analyses see [5, 10, 17]) and we use them only to estimate the expected cross sections of the production of different charmonium states at PLC.

[2]The additional factor 4/3 coming from different color factors of considered processes is omited in the paper [15].

3 Numerical Results

At PLC the energy distributions of the colliding photon beams are not monochromatic. One of the main characteristics of the Compton scattering process is the dimensionless variable x,

$$x = \frac{4E_b\omega_0}{m_e^2}\cos\theta/2.$$

Here E_b is the linac beam energy, ω_0 is the energy of the laser photons and θ is the angle between the directions of the electron and laser beams. The maximum energy of the obtained photon beam depends on x,

$$\omega_{max} = E_b\frac{x}{1+x},$$

and increases with increasing x. The value $x = 4.83$ is optimum for PLC to prevent e^+e^- pair creation in a collision of laser and backscattered photon beams [19]. In our calculations we use $x = 4.8$. This means that the maximum energy fractio carried by backscattered photon, ω_b/E_b, is about 0.83.

The luminosity distribution of the photon beam depends sensitively on the conversion distance due to non-zero angles of photon-electron beam scattering. The conversion distance is the distance from the laser and electron beam intersection point to the final interaction point. The luminosity distribution depends also on the electron beam size and shape. Assuming round Gaussian linac beams, the luminosity spectrum is characterized by a geometrical factor ρ, the ratio of the intrinsic transverse spread of the photon beam to that of the original one :

$$\rho = \frac{l\theta_0}{\sqrt{2}\sigma_e} = 3.61\sqrt{x+1}\left(\frac{l}{cm}\right)\left(\frac{E_b}{TeV}\right)^{-1}\left(\frac{\sigma_e}{nm}\right)^{-1}, \tag{13}$$

here l is the conversion distance and θ_0 is defined by the electron beam energy, $\theta_0 = m_e\sqrt{1+x}/E_b$. In fig.1 the spectral luminosities for unpolarized photon and electron beams are presented for different values of ρ are presented. The parameter k is the ratio of the number of electrons scattered on the laser beam to the number of electrons in each electron bunch . With ρ increasing the spectral density becomes narrower and more energetic photons dominate, meanwhile the total photon photon luminosity is decreasing. To achieve a maximum J/ψ production cross section the geometrical factor ρ should be as small as possible. However, in this case the transverse separation of the electron and the secondary photon beams becomes impossible and large background is expected from the process $e\gamma \to eZ \to eb\bar{b}$ with the subsequent decays of $b(\bar{b})$ quarks into J/ψ. Hence we use $\rho = 0.6$ which is small enough

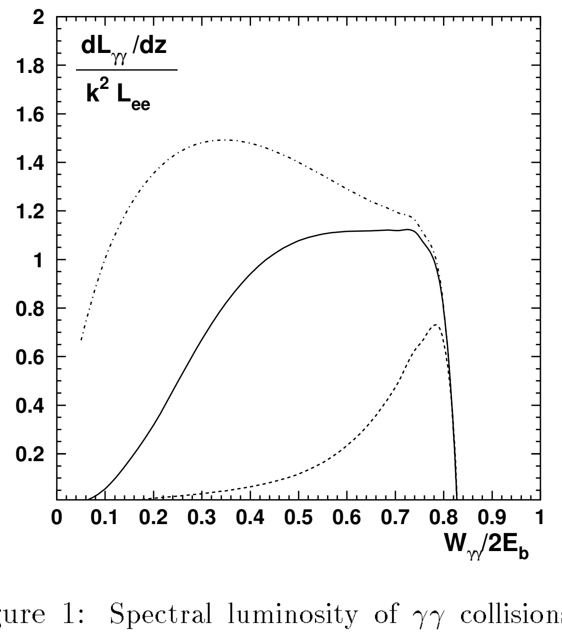

Figure 1: Spectral luminosity of $\gamma\gamma$ collisions; the dashed line corresponds to the value $\rho = 0$, the solid line to $\rho = 0.6$ and the dashed-dotted line $\rho = 2.4$.

to achieve an observable J/ψ production cross section (see below) as well as large enough to eliminate electron-photon collision background [20].

Table 1. J/ψ production cross sections in direct $\gamma\gamma$ interaction at PLC for $\sqrt{s_{e^+e^-}} = 500$ GeV and 800 GeV. The cross sections are calculated for two different values of the geometrical factor ρ =0 and 0.6.

ρ	$\sqrt{s}$=500 GeV		$\sqrt{s}$=800 GeV	
	singlet	octet	singlet	octet
0.	$2.79 \cdot 10^{-5} nb$	$2.71 \cdot 10^{-5} nb$	$1.21 \cdot 10^{-5} nb$	$1.18 \cdot 10^{-5} nb$
0.6	$1.74 \cdot 10^{-7} nb$	$1.69 \cdot 10^{-7} nb$	$3.10 \cdot 10^{-8} nb$	$3.00 \cdot 10^{-8} nb$

In Table I J/ψ production cross sections for two different values of the geometric factor, $\rho = 0$ and 0.6, are presented. We have used the color octet long distance parameters presented in the previous section. As one can see from table I, the total cross section of J/ψ production is decreasing with increasing e^+e^- collision energy. The reason for this is that the production of the $^3S_1$ state (singlet or octet) in direct $\gamma\gamma$ interaction falls off as $1/s^2$ with increasing photon-photon invariant mass. For $\rho = 0$ the luminosity of low energetic photons is higher than for large values of ρ and correspondingly the J/ψ production cross section is higher. The J/ψ production cross section in direct photon-photon collision for $\rho = 0.6$ is practically unobservable even at a high projected e^+e^- collider luminosity of $100 fb^{-1}$.

As for the resolved photon subprocess, unlike direct $\gamma\gamma$ collisions, there exist diagrams with only vector particles (gluon) in the t-channel in the lowest order of perturbative QCD. These diagrams result in a cross section of $(c\bar{c})$ pair production which is not decreasing with increasing $s_{\gamma\gamma}$.

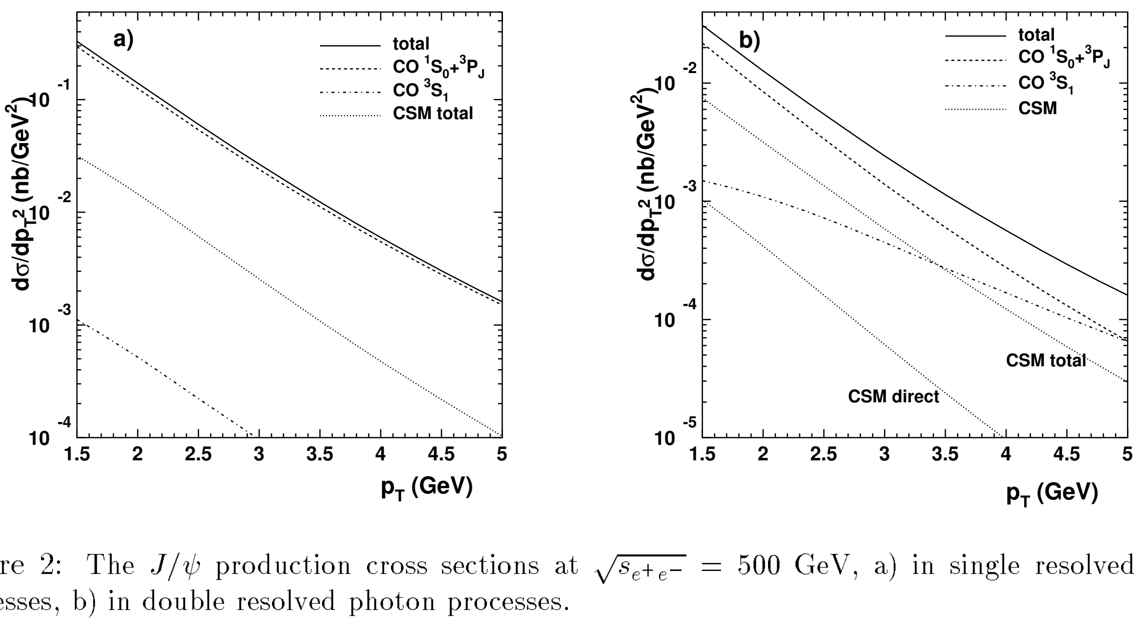

Figure 2: The J/ψ production cross sections at $\sqrt{s_{e^+e^-}} = 500$ GeV, a) in single resolved photon processes, b) in double resolved photon processes.

In fig.2 we present the direct J/ψ production cross sections through different $(c\bar{c})$-pair states for the single resolved (fig.2a) and double resolved (fig.2b) photon subprocesses. We have used $m_c = 1.5$ GeV for the charm quark mass and GRV [21] photon distribution functions evaluated at the factorization scale $Q^2 = \sqrt{p_T^2 + 4m_c^2}$. The QCD coupling constant α_S is normalized at the same scale. We present the numerical results for the cross sections of $1S_0$ and ^3P_J states production for $p_T > 1.5$ GeV in order to avoid the consideration of mass singularities and to deal with experimentally observable events. The J/ψ production cross sections in both single and double resolved photon processes are higher than in direct $\gamma\gamma$ collisions as can be seen when comparing fig.2 and table I. The color octet contribution is dominating in J/ψ production in the resolved photon case. At small values of $p_T < 5$ the color octet states $^1S_0$ and ^3P_J give main the contribution in direct J/ψ production. As in hadroproduction, the $^3S_1^{(8)}$ octet state becomes essential only at large values of p_T (> 5 GeV) in the double resolved photon processes, as can be seen from fig.2b.

Note that a nondecreasing cross section of J/ψ production, with increasing $\gamma\gamma$ invariant mass, can be obtained also in direct (unresolved) photon-photon reactions when considering higher order diagrams in pQCD with two-gluon exchange in the t-channel [22]. But the contribution to the total cross section of J/ψ production from such processes, $\sigma_{tot}(\gamma\gamma \to J/\psi X) \sim 2\cdot 10^{-2} nb$ [22], is smaller than color octet contribution in single and double resolved photon subprocesses, and decreases rapidly at large transverse momenta.

In fig.3 we present the direct J/ψ production total cross sections in dependence on the cut off value in p_T, for different angular cuts in laboratory frame (e^+e^- c.m.s. system). Fig.3a corresponds to $\sqrt{s_{e^+e^-}} = 500$ GeV and fig.3b to 800 GeV. The leading contribution in the cross sections with cuts $\cos\theta < \cos 30°$ or $\cos 45°$ comes from the double resolved photon processes, the contribution of single resolved photon subprocesses is negligible. In single resolved photon subprocesses ($c\bar{c}$) octet states are produced with large longitudinal momenta. As in the case of photon-proton collisions, color octet states are mainly produced at the kinematical endpoint $z = 1$, as in the case of J/ψ photoproduction [9]; here $z = (p_{\gamma_2}\cdot p_{J/\psi})/(p_{\gamma_2}\cdot p_{\gamma_1})$, where p_{γ_1} is unresolved photon momentum and p_{γ_2} is the momentum of the photon which splits into a flux of quarks and gluons. This means that the J/ψ carries almost the whole energy of the unresolved energetic photon and is produced at small angles relative to the beam direction.

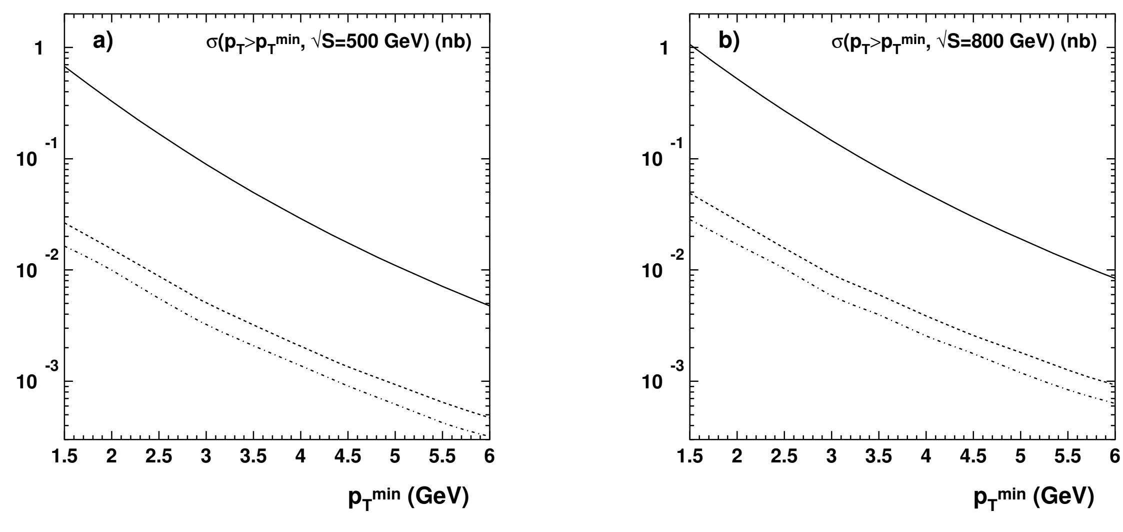

Figure 3: The J/ψ production cross section versus minimal p_T cut for different angular cuts. The solid line corresponds to the total cross section, the dashed line to $\cos\theta < \cos 30°$, and the dashed-dotted line to $\cos\theta < \cos 45°$; a) $\sqrt{s_{e^+e^-}} = 500$ GeV and b) $\sqrt{s_{e^+e^-}} = 800$ GeV.

The double resolved photon process is analogous to J/ψ hadroproduction. At large p_T the contribution from the $^3S_1^{(8)}$ color octet state dominates. Table II presents the integrated total cross sections and $^3S_1^{(8)}$ channel contribution for various p_T^{min} cuts. All cross sections are calculated at an angular cut off $\cos\theta < \cos 45°$. The cross sections are large enough to observe several hundred J/ψ events produced at $p_T > 7$ GeV through leptonic decay channels for the projected integral PLC luminosity of $\mathcal{L} = 50 fb^{-1}$. This would allow to extract the long distance matrix element $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ with sufficient accuracy [3].

Table II. The J/ψ production cross sections (total and through $^3S_1^{(8)}$ state), $\cos\theta < \cos 45°$.

p_T	5 GeV	6 GeV	7 GeV
total	$6.2 \cdot 10^{-4} nb$	$3.2 \cdot 10^{-4} nb$	$1.8 \cdot 10^{-4} nb$
$^3S_1^{(8)}$	$3.8 \cdot 10^{-4} nb$	$2.2 \cdot 10^{-4} nb$	$1.4 \cdot 10^{-4} nb$

Fig.4 presents the J/ψ production cross section resulting from the radiative decays of the χ_{cJ} state. The cross sections are calculated with an angular cut $cos\theta < cos 30°$. At subleading order in the relative velocity expansion, $O(v^5)$, only one color octet state, $^3S_1^{(8)}$, contributes to the production of χ_{cJ} (the corresponding color octet long distance parameter was extracted only from the Tevatron data [5]). The next corrections are already of order $O(v^9)$ [5]. In fig.4 the color octet (dashed-dotted line) and color singlet (dotted line) contributions to χ_{cJ} meson production are presented.

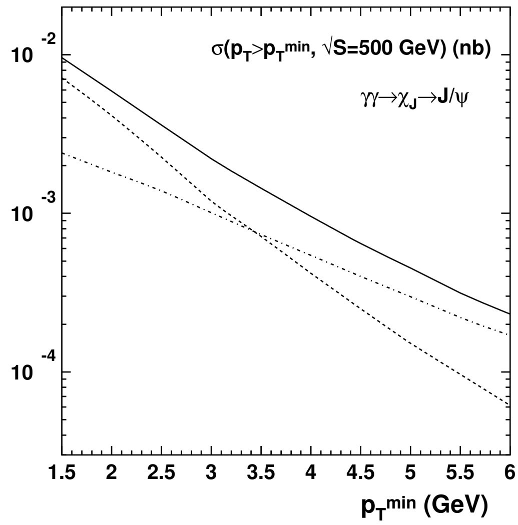

Figure 4: Cross section for J/ψ production resulting from radiative χ_{cJ} decay versus minimal p_T cut. The dashed curve corresponds to the color singlet cross section, the dashed-dotted line shows the $^3S_1^{(8)}$ contribution, the solid curve represents their sum.

4 Conclusions

In the present paper we consider J/ψ meson production at PLC. We calculated cross sections for the production of different color octet and color singlet heavy quark-antiquark states in direct and resolved photon processes. In the resolved photon subprocesses already at the lowest order of perturbative QCD the diagrams arise which lead to the non decreasing production cross sections for some quark-antiquark states with increasing photon-photon c.m.s. energy.

The contribution of color octet states to J/ψ production is dominating. It was shown that at large p_T ($p_T > 5$ GeV) the main contribution to J/ψ production comes from the $^3S_1^{(8)}$ state. The cross section is even at such values of transverse momentum large enough to observe several hundred J/ψ's through the leptonic decay channel at a projected PLC luminocity $50 fb^{-1}$. This should allow to extract the value of the corresponding matrix element. The cross section at smaller values of transverse momenta can also give valuable information about the color octet long distance matrix elements. The production cross section of J/ψ mesons through χ_{cJ} states was also calculated. It is worth mentioning that background

[3] We mean only statistical significance and do not take into account theoretical uncertainties

from b-quark decays are smaller or at same order as direct J/ψ production [23] but the analysis of possible backgrounds and ways of their rejection are subject of an additional study.

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