The Color Octet Effect from $e^+e^- \to J/\psi + X + \gamma$ at B Factory

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We study the initial state radiation process $e^+e^- \to J/\psi + X + \gamma$ for J/ψ production at B factory, and find the cross section is 61% larger than it's Born one for color octet part and is about half as it's Born one for color singlet part. Furthermore, the color singlet and color octet signal are very clearly separated in it's E_γ spectra due to kinematics difference. We suggest to measure this E_γ spectra at B factory to determine the color octet effect.

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To study J/ψ production on various experiments is a very interesting topic since its discovery in 1974. It is a good place to probe of both perturbative and nonperturbative aspects of QCD dynamics. To describe the huge discrepancy of the high-p_T J/ψ production between the theoretical calculation based on color singlet mechanism[1] and the experimental measurement by the CDF collaboration at the Tevatron[2], color-octet mechanism[3] was proposed based on non-relativistic QCD(NRQCD)[4]. The factorization formalism of NRQCD provides a theoretical framework to the treatment of heavy-quarkonium production. The color singlet mechanism is straightforward from the perturbative QCD, but the color-octet mechanism depends on nonperturbative universal NRQCD matrix elements. So various efforts have been made to confirm this mechanism, or to fix the magnitudes of the universal NRQCD matrix elements. Although it seems to show qualitative agreements with experimental data, there are certain difficulties in the quantitative estimate of the color-octet contribution in J/ψ and ψ' photoproduction at HERA [5, 6, 7, 8, 9], $J/\psi(\psi')$ polarization in large transverse momentum production at the Fermilab Tevatron [10, 11, 12], and more recently in B-factories.

There are at least two kinds of uncertainty in the theoretical treatment of J/ψ production. One is from the QCD correction. It is difficulty to estimate the QCD correction effect up to a few times in various leading order calculation for J/ψ production. The uncertainty to fix the NRQCD matrix elements is quit large for the case in which color singlet effect is compatible with the color octet one such as in the measurement of the J/ψ production at B factory in BaBar and Belle experiments[13, 14]. There are a few examples shown that the NLO correction are quit large. It was found that the current experimental results on inelastic J/ψ phtonproduction[15, 16] are adequately described by the color singlet channel alone once higher-order QCD corrections are included[9]. Although ref[17] found that the new DELPHI [18] data evidently favor the NRQCD formalism for J/ψ production
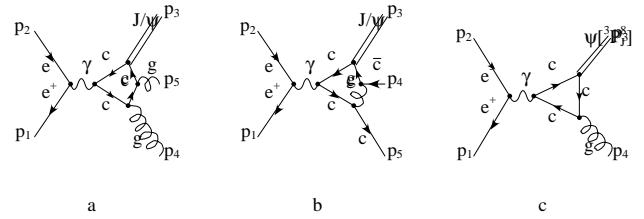
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FIG. 1: The typical Feynman diagrams for the $e^+e^- \to J/\psi X$, there are 6 diagrams for the $e^+e^- \to J/\psi gg$, 4 diagrams for $e^+e^- \to J/\psi c\bar{c}$ and 2 diagrams for each $e^+e^- \to \psi[^3P_J^8]g$, $J = 0, 1, 2$

$\gamma + \gamma \to J/\psi + X$, but rather the color-singlet model. It was also found by ref[19] that the QCD higher order process $\gamma + \gamma \to J/\psi c\bar{c}$ gives the same order and even bigger contribution at large p_T compare to leading order color singlet processes. ref[20] found that higher order process give large contributions.

The another uncertainty is from the hadronization of the color octet $J/\psi^{(8)}$ to the color singlet J/ψ and hadrons. The recent measurement of the J/ψ production at B factory in BaBar and Belle experiments[13, 14] show that the theoretical predication [21, 22] for $p^*_{J/\psi}$ spectra did not agree with experimental results, and gives the total cross section $\sigma(e^+e^- \to J/\psi + X) = 1.47 \pm 0.10 \pm 0.13pb$. It seems compatible with theoretical prediction[23, 24, 25] cover the range $0.8-1.7pb$, in which about $0.3pb$ from color singlet processes $e^+e^- \to J/\psi gg$ and $e^+e^- \to J/\psi c\bar{c}$, and $0.5 - 0.8pb$ from color octet processes $e^+e^- \to J/\psi^{(8)}g$. The color octet processes only contribute to the endpoint of $p^*_{J/\psi}$ spectra due to the kinematics of the two body final state. But the experiments did not observe the this signal. To explain this discrepancy, it is nature to think that $J/\psi^{(8)}$ have to hadronize into color singlet J/ψ and will lose it's energy such as the case when a quark jet hadronize into hadrons. Therefore there should be a hadronization possibility function $F(x, ...)$ for J/ψ production with momentum $p_{J/\psi} = x\ p_{J/\psi^{(8)}}$ and $\int_0^1 dx\ F(x, ...) = 1$. The universal NRQCD matrix elements treatment is just a first step approximation of $F(x, ...) = \delta(1 - x)$. The ref[26] tried on it for the J/ψ production at B factory

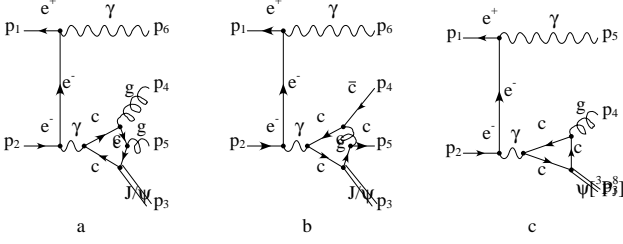FIG. 2: The typical Feynman diagrams for the $e^+e^- \to J/\psi X\gamma$, there are 12 diagrams for the $e^+e^- \to J/\psi gg\gamma$, 8 diagrams for $e^+e^- \to J/\psi c\bar{c}\gamma$ and 4 diagrams for each $e^+e^- \to \psi[^3P_J^8]g\gamma$, $J = 0, 1, 2$

and broadened the p^* spectra from color octet J/ψ.

Due to the above two kinds of uncertainty, the $p^*_{J/\psi}$ spectra from color octet $J/\psi^{(8)}$ is unknown, and meanwhile the higher order QCD effect for the color singlet J/ψ production is also unknown. So to confirm, to extract $J/\psi^{(8)}$ information from the measurement in B factory experiment become unavailable. However, we find a good way to determine the color singlet and color octet effect, i.e. to measure the E_γ spectra in the initial state radiation process $e^+e^- \to J/\psi + X + \gamma$, which could avoid the uncertainties from $J/\psi^{(8)}$ hadronization and QCD correction.

This QED higher order process is thought to be small at first glance. But there are already few examples in which QED higher order process could be very lager in certain case. It was found that there are large contributions to J/ψ production form QED processes such as $e^+e^- \to J/\psi\gamma$ and $e^+e^- \to J/\psi e^+e^-$ [27] due to enhancement from the t-channel peak. In the try to explain the double J/ψ production measured by Belle[28], ref[29] found that the high order QED process $e^+e^- \to J/\psi + J/\psi$ gives large contribution. Our numerical results show that $e^+e^- \to J/\psi X + \gamma$ gives larger cross section than $e^+e^- \to J/\psi + X$.

For the leading process $e^+e^- \to J/\psi + X$, the typical Feynman diagrams are shown in Fig.1. The color singlet processes $e^+e^- \to J/\psi gg$, $J/\psi c\bar{c}$ and color octet processes $e^+e^- \to \psi[^3P_J^8]g$, $J = 0, 1, 2$; $\psi[^1S_0^8]g$ were calculated in ref.[21, 22, 23, 24]. For the $e^+e^- \to J/\psi + X + \gamma$, there are $e^+e^- \to J/\psi gg\gamma$, $J/\psi c\bar{c} + \gamma$, $\psi[^1S_0^8]g\gamma$, $\psi[^3P_J^8]g\gamma$, $J = 0, 1, 2$, and the typical Feynman diagrams are shown in Fig.2.

To calculate this initial state QED radiation correction, we have to include two parts, One is the virtual correction plus soft photon emitted process, the another is the hard photon emitted process. A universal formula is easily obtained for the first part, i.e. virtual correction plus soft photon emitted one. It is[30]:

$$\sigma^{SV} = \sigma_0\left\{\frac{2\alpha}{\pi}\left[(\ln\frac{s}{m_e^2} - 1)(\ln\frac{2\delta\epsilon}{\sqrt{s}} + \frac{3}{4}) + \frac{\pi^2}{6} - \frac{1}{4}\right]\right\}. \quad (1)$$

Where the σ_0 is the Born cross section, the $\delta\epsilon$ is maximum energy of the emitted soft photon, s is the center

TABLE I: The numerical results for the color singlet and color-octet J/ψ production. The $p^*_{J/\psi} = \sqrt{p^2 - m^2_{J/\psi}}$ is the 3-momentum of J/ψ. $\delta\epsilon = 0.1$ is used. The cut $p^*_{J/\psi} > 2.0 GeV$ is used by the experiment to suppress the J/ψ from B decay. The result for color octet with cut condition $p^*_{J/\psi} > 2.0 GeV$ is not presented since it does not make sense in the case that the detail of $J/\psi^{(8)}$ hadronization procedure is unknown

	Born	Virtual+Soft	hard photon
$p^*_{J/\psi} > 2.0 GeV$			
$e^+e^- \to J/\psi gg(\gamma)$	0.158	-0.044	0.072
$e^+e^- \to J/\psi c\bar{c}(\gamma)$	0.102	-0.028	0.022
In total	0.270	-0.072	0.094
$p^*_{J/\psi} > 0 GeV$			
$e^+e^- \to J/\psi gg(\gamma)$	0.203	-0.056	0.099
$e^+e^- \to J/\psi c\bar{c}(\gamma)$	0.119	-0.033	0.029
In total	0.322	-0.089	0.128
$e^+e^- \to \psi[^3P_J^8]g(\gamma)$	0.143	-0.039	0.351
$e^+e^- \to \psi[^1S_0^8]g(\gamma)$	0.133	-0.037	0.094
In total	0.276	-0.076	0.445

mass energy of e^+e^- collider. In the above formula, the infrared divergence are canceled between the soft photon emitted process and virtual correction.

For both the Born processes and the hard photon emitted processes, We obtain the formula and Fortran source of the cross section, including the kinematics, by using our automatic Feynman diagram calculation program FDC[31]. The FDC was used in the calculation of $e^+e^- \to J/\psi\gamma$ and $e^+e^- \to J/\psi e^+e^-$ [27]. In ref[19] it was used in the calculation of $\gamma + \gamma \to J/\psi c\bar{c}$, and many other processes to repeat the calculation by ref[17]. In the Fortran source generated by FDC, it is very easily to check the gauge invariance by replacing the polarization vector of gluon or γ to it's momentum. All the possible gauge invariance are checked to be satisfied numerically in our calculation. Our analytic formula generated by FDC for $e^+e^- \to \psi[^3P_J^8]g$, $J = 0, 1, 2$; $\psi[^1S_0^8]g$ are checked with ref[21].

The numerical results are listed in Table. I and shown in Fig.3 and 4. In the numerical calculation, we use $m_c = 1.5$, $m_{J/\psi} = 3.0$, $\alpha = 1/137$ and the lowest-order formula for $\alpha_s^{(n_f=3)}(\mu)$. J/ψ matrix elements are chosen as $< J/\psi >= 1.4$. The universal NRQCD matrix elements for color octet J/ψ are chosen as that in ref[4],i.e, $< J/\psi^{(8)}(^3S_1) >= 0.0039$, $< J/\psi^{(8)}(^1S_0) >= 0.015$, $< \psi^{(8)}(^3P_J) >= (2J + 1)0.0043m_c^2$.

The renormalization scale μ dependent in the calculation are $\alpha_s = \alpha_s^{(3)}(10.6) = 0.188$ for Born processes and $\alpha_s = \alpha_s^{(3)}(\sqrt{(p_1 + p_2 - p_\gamma)^2})$ for hard photon processes. Where the p_1, p_2 and p_γ are the momentums for e^+, e^- and the emitted γ respectively. The hard photon processes are defined as $E_\gamma > \delta\epsilon$, i.e. the $\delta\epsilon$ is the minimum energy of the emitted photon. We have used different value of $\delta\epsilon = 0.5, 0.4, 0.3, 0.2, 0.1, 0.01 GeV$ to verify that

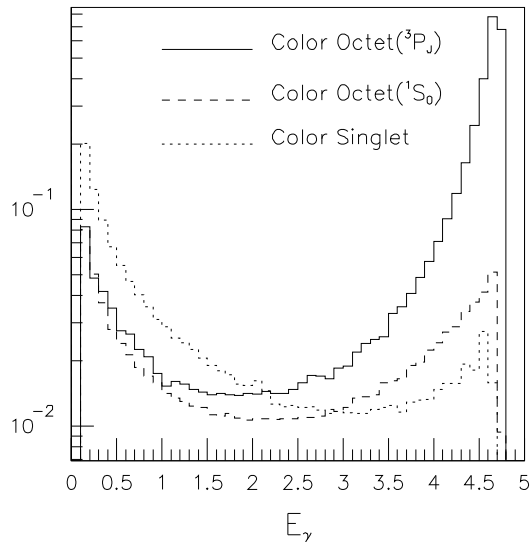FIG. 3: The differential cross section distribution vs the energy of emitted hard photon

FIG. 4: The differential cross section distribution vs the $cos(\theta)$ of the emitted hard photon and the beam

the Eq.1, which included only the leading term $\frac{1}{k}$ from the soft photon, is a good approximation when $\delta\epsilon$ is small enough. The numerical results show that the result of virtual + soft + hard is almost independent of $\delta\epsilon$. There is infrared divergence for the process $e^+e^- \to \psi[^3P_J^8]g(\gamma)$ when the energy of gluon approach to zero, but it can not happen since the gluon must hadronize into at least one pion. To apply the same cut condition used by the experiment[14] to suppress the background, the condition $\sqrt{(p_1 + p_2 - p_\gamma)^2} > m_{J/\psi} + 3m_\pi$ is applied to all the radiation processes.

There are other processes which may give compatible contributions from the perturbative order analysis, but the contributions form them are found too small so that they do not appeared in the above list. Such as $e^+e^- \to \psi[^3S_1^8]g\gamma$ is $1.2 \times 10^{-4}pb$. $e^+e^- \to J/\psi gge^+e^-$ with 48 Feynman diagrams are calculated and the result is $6.4 \times 10^{-4}pb$

In Fig.4, we find that most of the emitted photon go out with small angle to beam direction in both the color singlet and color octet processes. This is the t-channel enhancement effect which make the contribution of the QED correction large. In Fig.3, it very clearly shown that the color singlet processes mainly emit the photon with low energy ($E_\gamma < 1.0GeV$), meanwhile, the color octet processes mainly emit the photon with high energy ($E_\gamma > 4.0GeV$). The reason for this distribution is completely form the kinematics structure as shown in Fig.2. When the center mass energy go down from 10.6Gev to 5GeV, the cross section will increase about 4 times for $e^+e^- \to J/\psi gg$, about 51 times for $e^+e^- \to \psi[^3P_J^8]g$ and about 17 times for $e^+e^- \to \psi[^1S^0]g$, and the channel $e^+e^- \to J/\psi c\bar{c}$ will be closed. The above property was shown in the Fig. 5 in ref[23] and the Fig. 3 in ref[25].
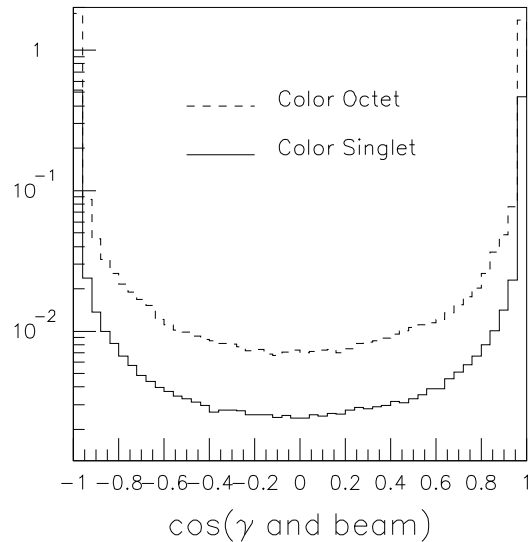
So that the remaining subprocesses will show this property after the photon emitting from the initial electron or positron. The peak in the small E_γ is well known from the soft photon effect. Based on the above analysis, it is very clear that the spectra in Fig.3 comes from the kinematics structure of the hard photon emitted processes. It is hardly be changed even if there is large QCD correction effects since the QCD correction appears only in the subprocesses and will not change the kinematics structure. So the ratio of the cross section for hard photon process to that for it's Born processes will be hardly changed by the QCD correction. In another side, the E_γ spectra can not be changed by the procedure of $J/\psi^{(8)}$ and gluon hadronization into J/ψ and hadrons since the hadronization procedure has no relation with it.

In the measurement of J/ψ production at B factory in BaBar and Belle experiments[13, 14], it was tried to separate the color singlet and color octet effects by measuring the spectra of $p^*_{J/\psi}$. The spectra show that the theoretical predication for color octet does not appear. It let us have to think about the detail of how the $J/\psi^{(8)}$ go through hadronization procedure. The ref[26] addressed on the problem, but the results is not predictive since the introduced shape function for $J/\psi^{(8)}$ is unknown. To avoid the uncentainties from $J/\psi^{(8)}$ hadronization and QCD correction, we find that to measure the E_γ spectra of the hard photon emitted J/ψ production process $e^+e^- \to J/\psi + X + \gamma$ in B factory experiment is a very clear and good way. This spectra is not changed by QCD correction, by the detail of $J/\psi^{(8)}$ hadronization. and will very clearly separate the color singlet and color octet signal. Another advantage is that the color octet cross section in the hard photon process is even 61% large than it's Born one.

Furthermore, It has been argued in the above that the ratio of the cross section of the hard photon process to it's Born one will be hardly changed by QCD correction and the detail of $J/\psi^{(8)}$ hadronization. As approximation, we have

$$
\begin{aligned}
\sigma(e^+e^- \to J/\psi + X) &= 0.233x + 0.2y, \\
\sigma(e^+e^- \to J/\psi + X + \gamma) &= 0.128x + 0.445y, \\
\sigma(e^+e^- \to J/\psi + X, color\ singlet) &= 0.233x, \\
\sigma(e^+e^- \to J/\psi + X, color\ octet) &= 0.2y.
\end{aligned}
\tag{2}
$$

where x and y represent the effects of QCD correction and uncertainty from the NRQCD matrix elements, and all the numerical values from the Table.I. The color octet and color singlet contributions can be extracted by solving Eq.2 when both the cross section $\sigma(e^+e^- \to J/\psi+X)$ and $\sigma(e^+e^- \to J/\psi + X + \gamma)$ be measured in the B factory experiment. In this way, the color octet cross section could not apply cut condition $p^*_{J/\psi} > 2.0 GeV$ since the $p^*_{J/\psi}$ spectra depends on $J/\psi^{(8)}$ hadronization. So how to suppress the background from B decay becomes a problem. However the measurement of the E_γ spectra will not suffer from this problem and the E_γ spectra fitting will fix the contributions from color singlet and color octet mechanism.

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