NLO QCD correction to $J/\psi(B_c)$ pair production in photon-photon collision

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Outline

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- Inclusive J/ψ production in photon-photon collision
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- Double $\eta_c, B_c, \Upsilon, \eta_b$ production in photon-photon collision
- References

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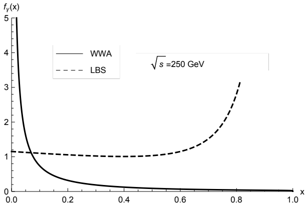

Figure: The WWA and LBS spectra at $\sqrt{s} = 250$ GeV.

The Weizsacker-Willimas approximation(WWA [1]):

$$f_\gamma(x) = \frac{\alpha}{2\pi}\left(\frac{1+(1-x)^2}{x}\log\left(\frac{Q^2_{\max}}{Q^2_{\min}}\right) + 2m_e^2 x\left(\frac{1}{Q^2_{\max}} - \frac{1}{Q^2_{\min}}\right)\right), \tag{1}$$

The laser back scattering(LBS [2]):

$$f_\gamma(x) = \frac{1}{N}\left(1 - x + \frac{1}{1-x} - 4r(1-r)\right), \tag{2}$$

where $r = \frac{x}{x_m(1-x)}$ and N is the normalization factor.

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Inclusive J/ψ production in photon-photon collision

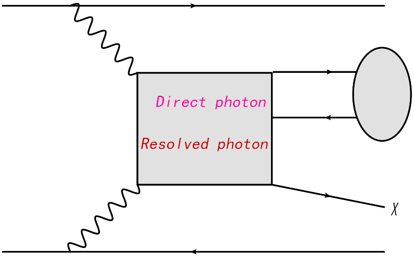

Figure: $e^+e^- \to e^+e^- + J/\psi + X$

In 2003, Inclusive J/ψ production in photon-photon collision had been observed at LEP II with the DELPHI detector [3], a clear signal from the reaction $\gamma\gamma \to J/\psi + X$ is seen.

$$\sigma(J/\psi + X) = 45 \pm 9(stat) \pm 17(syst)\ pb. \tag{3}$$

Various Cannels Contribute to Inclusive J/ψ Production

a) $\gamma + \gamma \to c\bar{c}[^3S_1^{[8]}] + g$ [4, 5, 6]

b) $\gamma + g \to c\bar{c}[^3S_1^{[1]}, ^1S_0^{[8]}, ^3S_1^{[8]}, ^3P_J^{[8]}] + g$ [7, 8, 9, 10]

c) $\gamma + q \to c\bar{c}[^1S_0^{[8]}, ^3S_1^{[8]}, ^3P_J^{[8]}] + q$ [8, 9]

d) $g + g \to c\bar{c}[^3S_1^{[1]}, ^3P_J^{[1]}, ^1S_0^{[8]}, ^3S_1^{[8]}, ^3P_J^{[8]}] + g$ [11, 12, 13, 14, 15, 8]

e) $g + q \to c\bar{c}[^3P_J^{[1]}, ^1S_0^{[8]}, ^3S_1^{[8]}, ^3P_J^{[8]}] + q$ [11, 14, 15, 8]

f) $q + \bar{q} \to c\bar{c}[^3P_J^{[1]}, ^1S_0^{[8]}, ^3S_1^{[8]}, ^3P_J^{[8]}] + g$ [11, 14, 15, 8]

g) $\gamma\gamma, \gamma g, gg, q\bar{q} \to c\bar{c}[^3S_1^{[1]}] + c + \bar{c}$ [16, 17, 18]

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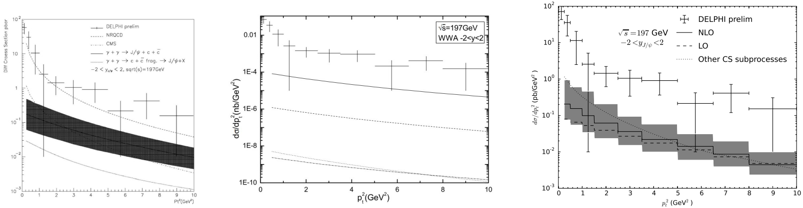
Color-Singlet Contribution



(a) (b) (c)

Figure: The p_t distribution of J/ψ photoproduction in the LEP II experiment. (a) Results for the $\gamma\gamma \to c\bar{c}[^3S_1^{[1]}] + c + \bar{c}$ [16] process are confronted with the central values in previous study in [6] and DELPHI experimental result [3]. (b) Results for the $\gamma\gamma, \gamma g, gg, q\bar{q} \to c\bar{c}[^3S_1^{[1]}] + c + \bar{c}$ process [17]. (c) NLO results for the $\gamma\gamma \to c\bar{c}[^3S_1^{[1]}] + c + \bar{c}$ process [18]

- CS are not adequate to explain the DELPHI data

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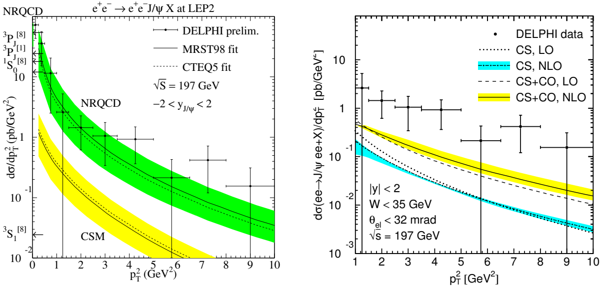

(a) (b)

Figure: The p_t distribution of J/ψ photoproduction in the LEP II experiment. (a) DELPHI [3] data is compared with the theoretical prediction of NRQCD and the CSM [6]. (b) NLO predictions of NRQCD and the CSM by using different LDMEs [19].

- CO results concluded differently in different LDMEs

Long distance matrix elements(LDME)

- The CO contributions are suppressed by v^8 in $\gamma + \gamma \to J/\psi + J/\psi$ process

$\langle \mathcal{O}^{J/\psi}(^1S_0^{[1]}) \rangle$	$1.32\ \text{GeV}^3$
$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]}) \rangle$	$(4.97 \pm 0.44) \times 10^{-2}\ \text{GeV}^3$
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]}) \rangle$	$(2.24 \pm 0.59) \times 10^{-3}\ \text{GeV}^3$
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]}) \rangle$	$(-1.61 \pm 0.20) \times 10^{-2}\ \text{GeV}^5$

Table: Fit results for the J/ψ CS and CO LDMEs [19].

- The CS mechanism dominate exclusive J/ψ production in photon-photon collision
- The signals are relative clean

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Double J/ψ production in photon-photon collision

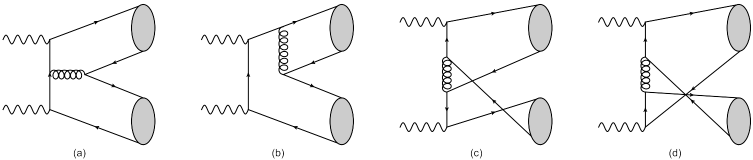

Figure: Typical LO Feynman diagrams for quarkonium-pair production via photon-photon fusion.

The standard form of quarkonium spin and color projection operator is adopted in our calculation [20]:

$$v(p_{\bar{Q}})\bar{u}(p_Q) = \frac{1}{4\sqrt{2}E(E+m_Q)}(\not{p}_{\bar{Q}} - m_Q)\,\not{\epsilon}_S^*(\not{P} + 2E)(\not{p}_Q + m_Q) \otimes (\frac{\mathbf{1_c}}{\sqrt{N_c}}) \qquad (4)$$

Typical NLO Feynman diagrams

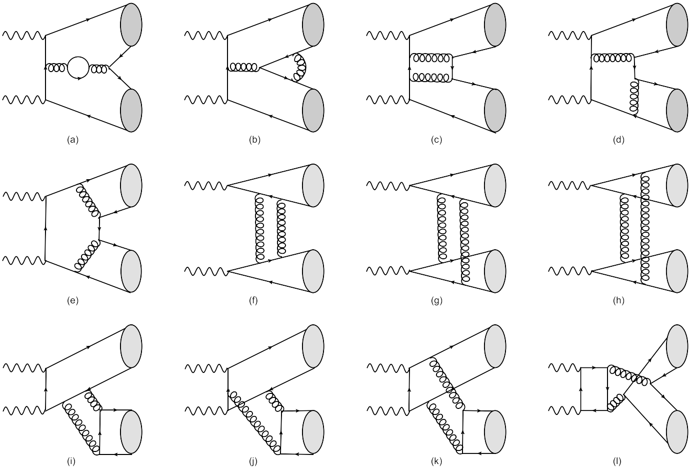

Figure: Typical NLO Feynman diagrams for quarkonium-pair production via photon-photon fusion.

NLO calculation

- Dimensional regularization is applied for UV and IR singularities
- The UV singularities are removed by renormalization
- The soft IR singularities are canceled with each other [21]
- No hard-collinear IR singularities due to massive charm quarks
- The Coulomb IR singularities vanish in the dimensional regularization [22]

$$\delta Z_2^{\rm OS} = -C_F \frac{\alpha_s}{4\pi}\left[\frac{1}{\epsilon_{\rm UV}} + \frac{2}{\epsilon_{\rm IR}} - 3\gamma_E + 3\ln\frac{4\pi\mu^2}{m_Q^2} + 4\right]$$

$$\delta Z_m^{\rm OS} = -3C_F \frac{\alpha_s}{4\pi}\left[\frac{1}{\epsilon_{\rm UV}} - \gamma_E + \ln\frac{4\pi\mu^2}{m_Q^2} + \frac{4}{3}\right]$$

$$\delta Z_3^{\overline{\rm MS}} = (\beta_0 - 2C_A)\frac{\alpha_s}{4\pi}\left[\frac{1}{\epsilon_{\rm UV}} - \gamma_E + \ln(4\pi)\right]$$

$$\delta Z_g^{\overline{\rm MS}} = -\frac{\beta_0}{2}\frac{\alpha_s}{4\pi}\left[\frac{1}{\epsilon_{\rm UV}} - \gamma_E + \ln(4\pi)\right]$$

Software Packages

- FeynArts [23]: generate Feynman diagrams
- FeynCalc [24]: Dirac algebraic calculation
- FeynCalcFormLink [25]: efficient Dirac trace
- FIRE [26]: tensor integrals reduction
- LoopTools [27]: numerically evaluate A0, B0, C0, D0 functions
- CUBA [28]: Monte Carlo phase space integrals

Numerical results at future e^+e^- Collider

$\sqrt{s}$ (GeV)	$\sigma_{J/\psi J/\psi}$(fb)	$\sigma_{\eta_c\eta_c}$(fb)	$\sigma_{\Upsilon\Upsilon}$(ab)	$\sigma_{\eta_b\eta_b}$(ab)
SuperKEKB	0.154(0.527)	0.361(0.152)	–	–
250 (WWA)	1.28(4.78)	2.18(1.15)	2.20(4.33)	1.89(1.10)
250 (LBS)	0.645(2.76)	1.10(0.597)	12.4(25.7)	9.55(5.66)
500 (WWA)	1.69(6.34)	2.90(1.52)	3.29(6.44)	2.80(1.63)
500 (LBS)	0.161(0.706)	0.280(0.152)	3.22(6.69)	2.47(1.46)

Table: The NLO(LO) total cross sections for quarkonium pair production via photon-photon fusion at future e^+e^- colliders.

- Luminosity(SuperKEKB) = $8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \approx 2.52 \times 10^4\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$ in 2025 [29]
- Typical luminosity(CEPC) = $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \approx 315\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$

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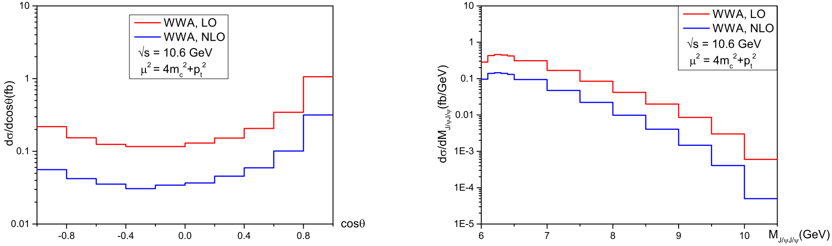
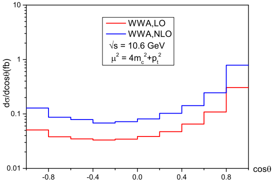
Numerical results at BELLE II



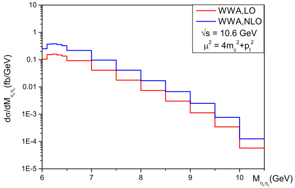
(a) (b)

Figure: The differential cross sections for charmonium-pair production. (a) J/ψ-pair production in bins of $\cos\theta$; (b) J/ψ-pair production in bins of $M_{J/\psi J/\psi}$.

Double $\eta_c, B_c, \Upsilon, \eta_b$ Production in Photon-photon Collision



(a)



(b)

Figure: The differential cross sections for η_c-pair production. (a) η_c-pair production in bins of $\cos\theta$; (b) η_c-pair production in bins of $M_{\eta_c\eta_c}$.

a) Double η_c events will be feasible at both SuperKEKB and CEPC
b) The cross section of bottomonium-pair production is $2 \sim 3$ magnitude smaller than charmonium-pair production
c) Double Υ, B_c, η_b may not feasible at CEPC

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Thank you for your time!

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