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J/ψ Production in Ultra-Peripheral pp Collisions through a Two-Photon Process *

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Using the photon spectrum of a high energy charged parton, we investigate the J/ψ production via the two photon interaction mechanism in ultra-peripheral pp collisions. It is shown that the contributions from the direct electromagnetic and the corresponding fragmentation processes are meaningful for the J/ψ productions in ultra-peripheral pp collisions at LHC energy.

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Ultra-peripheral collisions (UPCs) are such reactions that two ions interact through a cloud of photons, that have attracted growing interest recently.[1−5] Based on the method of Fermi, Weizsäcker and Williams[6,7] treated the moving electromagnetic fields of a charged nucleon as a flux of virtual photons. The number of photons surrounding the nucleus, and therefore, the intensity of the moving electromagnetic field, are proportional to the square of the nucleon number Z^2. Thus these kinds of interactions are important in heavy ions collisions, which provide unique opportunities for studying electromagnetic processes.

The purely electromagnetic interaction (two-photon interaction) is one of the main types of electromagnetic mechanisms of J/ψ production in UPCs, while the other one is the photonuclear interaction. There have been lots of studies in this area,[8−13] and all of them considered the whole nucleon as the source of photons. However, according to Kniehl,[14] under ultra-relativistic condition, a hadron can also be regarded as a beam of freely moving elementary constituents, which is the same as the quark-parton model. Therefore, the ultrarelativistic fermion can also emit photons described by[14,15]

$$f_{\gamma/f} = \frac{\alpha}{\pi} Q_{\rm q}^2 \Big\{ \frac{1+(1-x)^2}{x} \Big(\ln \frac{E}{m} - \frac{1}{2} \Big) + \frac{x}{2} \Big[\ln \Big(\frac{2}{x} - 2 \Big) + 1 \Big] + \frac{(2-x)^2}{2x} \ln \Big(\frac{2-2x}{2-x} \Big) \Big\}, \tag{1}$$

where α is the electromagnetic coupling parameter, $E(E \gg m)$, $Q_{\rm q}$ and m are the energy, the charge and the mass of the charged parton, respectively, and x denotes the photon energy in units of E. By using this photon spectrum function of charged partons, the photoproduction processes in heavy ion collisions have been investigated recently.[16,17]

In this work, we focus on the two-photon production mechanism of J/ψ in an ultra-peripheral pp collision by using the above photon spectrum function. Three processes are considered: direct double photons processes; resolved double photons processes; and direct and resolved mix photons processes. All of the processes include direct (non-fragmentation) and fragmentation contributions.

In a non-fragmentation direct double photons production of J/ψ, which is illustrated in Fig. 1(a), partons in each nucleon A and B emit a high-energy photon, respectively, then the photons interact with each other through the interaction of $\gamma\gamma \to J/\psi + X$. The cross section for such inclusive J/ψ production can be written as

$$\frac{d\sigma_{\rm dou.dir.pho.}}{dp_{\rm T}^2 dy} = \int dx_{\rm a} dx_{\rm b} dz_{\rm b} G_{\rm a/A}(x_{\rm a}, Q^2) G_{\rm b/B}(x_{\rm b}, Q^2) \cdot f_{q_\alpha}^{\gamma}(z_{\rm a}) f_{q_{\rm b}}^{\gamma}(z_{\rm b}) \frac{x_{\rm b} z_{\rm b} z_{\rm a}}{x_{\rm b} z_{\rm b} - x_2} \frac{d\hat{\sigma}}{d\hat{t}}(x_{\rm a}, x_{\rm b}, z_{\rm a}, z_{\rm b}). \tag{2}$$

In the corresponding fragmentation process (Fig. 1(b)), the two high-energy photons from partons of each nucleon A and B interact with each other and produce an intermediate particle. Then the particle splits into J/ψ and other particles. The cross section for each sub-process is

$$\frac{d\sigma_{\rm dir.res.mix.fra}}{dp_{\rm T}^2 dy} = 2 \int dx_{\rm a} dx_{\rm b} dz'_{\rm a} dz_{\rm b} dz_{\rm c} G_{\rm a/A}(x_{\rm a}, Q^2) \cdot G_{\rm b/B}(x_{\rm b}, Q^2) f_{q_\alpha}^{\gamma}(z_{\rm a}) G_{q'_\alpha/\gamma}(z'_{\rm a}, Q^2) f_{q_{\rm b}}^{\gamma}(z_{\rm b}) D_{\rm c}(z_{\rm c}) \cdot \frac{x_{\rm b} z_{\rm b} z_{\rm a}}{z_{\rm c}(z_{\rm c} x_{\rm b} z_{\rm b} - x_2)} \frac{d\hat{\sigma}}{d\hat{t}}(x_{\rm a}, x_{\rm b}, z_{\rm a}, z'_{\rm a}, z_{\rm b}, z_{\rm c}), \tag{3}$$

where y is the rapidity.

In a non-fragmentation double resolved process, which is plotted in Fig. 2(a), each parton of the incident nucleons A and B emits a high energy resolved photon, then each resolved photon emits another parton. The latter partons interact with each other through the interactions of

$$q\bar{q} \to J/\psi + X, \quad gg \to J/\psi + X, \quad gq \to J/\psi + X. \tag{4}$$

The cross section of such an inclusive J/ψ production

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process is

$$\frac{d\sigma_{\rm dou.res.pho.}}{dp_{\rm T}^2 dy} = \int dx_{\rm a} dx_{\rm b} dz'_{\rm a} dz_{\rm b} dz'_{\rm b} G_{\rm a/A}(x_{\rm a}, Q^2) \cdot G_{\rm b/B}(x_{\rm b}, Q^2) f^{\gamma}_{q_\alpha}(z_{\rm a}) G_{q'_\alpha/\gamma}(z'_{\rm a}, Q^2) f^{\gamma}_{q_{\rm b}}(z_{\rm b}) \cdot G_{q'_{\rm b}/\gamma}(z'_{\rm b}, Q^2) \frac{x_{\rm b} z_{\rm b} z_{\rm a} z'_{\rm b}}{x_{\rm b} z_{\rm b} x'_{\rm b} - x_2} \frac{d\hat{\sigma}}{d\hat{t}}(x_{\rm a}, x_{\rm b}, z_{\rm a}, z'_{\rm a}, z_{\rm b}, z'_{\rm b}). \quad (5)$$

In the corresponding fragmentation process (Fig. 2(b)), those partons from the emitted photons interact and produce a particle, which then splits into J/ψ and other particles. The cross section for each sub-process can be written as

$$\frac{d\sigma_{\rm dou.res.pho.fra}}{dp_{\rm T}^2 dy} = \int dx_{\rm a} dx_{\rm b} dz'_{\rm a} dz_{\rm b} dz'_{\rm b} dz_{\rm c} G_{\rm a/A}(x_{\rm a}, Q^2) \cdot G_{\rm b/B}(x_{\rm b}, Q^2) f^{\gamma}_{q_\alpha}(z_{\rm a}) G_{q'_\alpha/\gamma}(z'_{\rm a}, Q^2) f^{\gamma}_{q_{\rm b}}(z_{\rm b}) \cdot G_{q'_{\rm b}/\gamma}(z'_{\rm b}, Q^2) D_{\rm c}(z_{\rm c}) \frac{x_{\rm b} z_{\rm b} z_{\rm a} z'_{\rm b}}{z_{\rm c}(z_{\rm c} x_{\rm b} z_{\rm b} z'_{\rm b} - x_2)} \cdot \frac{d\hat{\sigma}}{d\hat{t}}(x_{\rm a}, x_{\rm b}, z_{\rm a}, z'_{\rm a}, z_{\rm b}, z'_{\rm b}, z_{\rm c}). \quad (6)$$

The corresponding figures for such processes are given in Fig. 5.

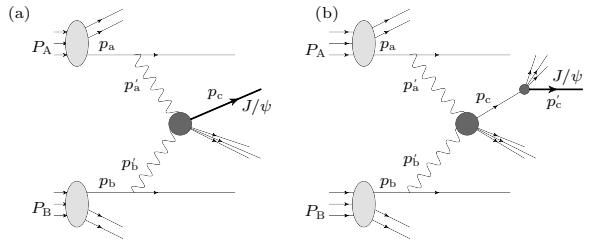


Fig. 1. The left figure corresponds to the non-fragmentation process and the right figure represents the fragmentation process. Here $p_{\rm a} = P_{\rm A} x_{\rm a}$, $p_{\rm b} = P_{\rm B} x_{\rm b}$, $p'_{\rm a} = p_{\rm a} z_{\rm a}$, $p'_{\rm b} = p_{\rm b} z_{\rm b}$, $p'_{\rm c} = p_{\rm c} z_{\rm c}$.

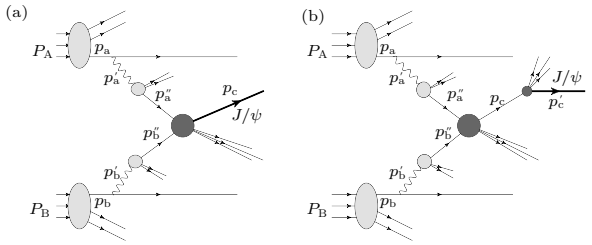


Fig. 2. The same as Fig. 1. Here $p_{\rm a} = P_{\rm A} x_{\rm a}$, $p_{\rm b} = P_{\rm B} x_{\rm b}$, $p'_{\rm a} = p_{\rm a} z_{\rm a}$, $p'_{\rm b} = p_{\rm b} z_{\rm b}$, $p''_{\rm a} = p'_{\rm a} z'_{\rm a}$, $p''_{\rm b} = p'_{\rm b} z'_{\rm b}$, $p'_{\rm c} = p_{\rm c} z_{\rm c}$.

As shown in Fig. 3(a), a non-fragmentation mixed process includes both direct and resolved processes. In such a process, nucleon A emits a high energy resolved photon, then the photon emits a parton which interacts with the parton emitted by nucleon B through the interaction of $\gamma g_\gamma \to J/\psi + X$ and $\gamma q_\gamma \to J/\psi + X$. The cross section for such an inclusive J/ψ production process is

$$\frac{d\sigma_{\rm dir.res.mix}}{dp_{\rm T}^2 dy} = 2\int dx_{\rm a} dx_{\rm b} dz'_{\rm a} dz_{\rm b} G_{\rm a/A}(x_{\rm a}, Q^2) \cdot G_{\rm b/B}(x_{\rm b}, Q^2) f^{\gamma}_{q_\alpha}(z_{\rm a}) G_{q'_\alpha/\gamma}(z'_{\rm a}, Q^2) f^{\gamma}_{q_{\rm b}}(z_{\rm b}) \cdot \frac{x_{\rm b} z_{\rm b} z_{\rm a}}{x_{\rm b} z_{\rm b} - x_2} \frac{d\hat{\sigma}}{d\hat{t}}(x_{\rm a}, x_{\rm b}, z_{\rm a}, z'_{\rm a}, z_{\rm b}). \quad (7)$$

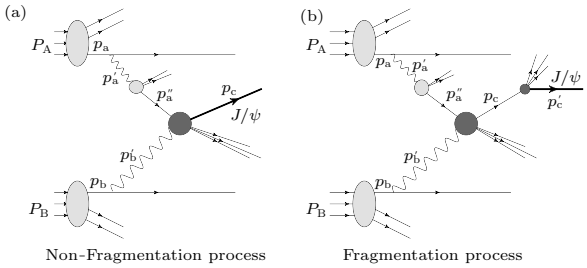


Fig. 3. The same as Fig. 1. Here $p_{\rm a} = P_{\rm A} x_{\rm a}$, $p_{\rm b} = P_{\rm B} x_{\rm b}$, $p'_{\rm a} = p_{\rm a} z_{\rm a}$, $p'_{\rm b} = p_{\rm b} z_{\rm b}$, $p''_{\rm a} = p'_{\rm a} z'_{\rm a}$, $p'_{\rm c} = p_{\rm c} z_{\rm c}$.

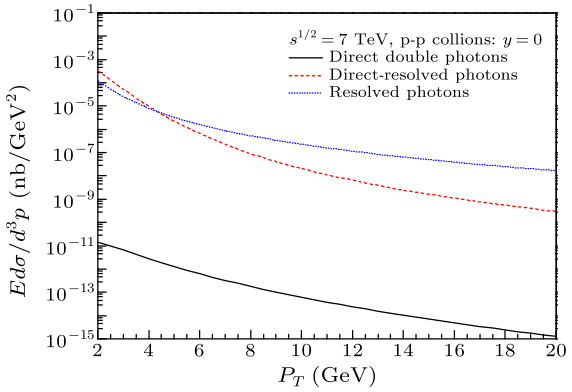


Fig. 4. Non-fragmentation processes of J/ψ production at $\sqrt{s} = 7$ TeV in ultra-peripheral pp collisions. The solid line, the dotted line and the dashed line represent the contributions from the direct photon processes, the mixed process, and the resolved photon process, respectively.

In the corresponding fragmentation process (Fig. 3(b)), a particle produced from the photon-parton interaction splits into J/ψ and other particles. The cross section for each sub-process can be written as

$$\frac{d\sigma_{\rm dir.res.mix.fra}}{dp_{\rm T}^2 dy} = 2\int dx_{\rm a} dx_{\rm b} dz'_{\rm a} dz_{\rm b} dz_{\rm c} G_{\rm a/A}(x_{\rm a}, Q^2) \cdot G_{\rm b/B}(x_{\rm b}, Q^2) f^{\gamma}_{q_\alpha}(z_{\rm a}) G_{q'_\alpha/\gamma}(z'_{\rm a}, Q^2) f^{\gamma}_{q_{\rm b}}(z_{\rm b}) D_{\rm c}(z_{\rm c}) \cdot \frac{x_{\rm b} z_{\rm b} z_{\rm a}}{z_{\rm c}(z_{\rm c} x_{\rm b} z_{\rm b} - x_2)} \frac{d\hat{\sigma}}{d\hat{t}}(x_{\rm a}, x_{\rm b}, z_{\rm a}, z'_{\rm a}, z_{\rm b}, z_{\rm c}). \quad (8)$$

The parton's momentum fraction is given in Fig. 5.

In all the above cross sections, $x_{\rm a}$, $x_{\rm b}$, $z_{\rm a}$, $z_{\rm b}$, $z'_{\rm a}$, $z'_{\rm b}$, $z_{\rm c}$ are the parton's momentum fractions. The variables $x_1 = 0.5(x_{\rm T} + \tau)^{1/2} e^{y}$, $x_2 = 0.5(x_{\rm T} + \tau)^{1/2} e^{-y}$, where $x_{\rm T} = 2p_{\rm T}/\sqrt{s}$, $\tau = M^2/s$, M is the mass of J/ψ, s is the square of energy in the center-of-mass system, and y is the rapidity. The functions $G_{\rm a/A}(x_{\rm a}, Q^2)$ and $G_{\rm b/B}(x_{\rm b}, Q^2)$ are parton distribu-

tions of nucleons,[16]

$$G_{i/\mathrm{A}}(x_i, Q^2) = R_{i/\mathrm{A}}(x_i, Q^2) p_{i/\mathrm{A}}(x_i, Q^2), \quad (9)$$

where $R_{i/\mathrm{A}}(x_i, Q^2)$ is the modification factor,[18] $p_{i/\mathrm{A}}(x_i, Q^2)$ are the parton distributions of protons,[19] $G_{q_\mathrm{a}/\gamma}(z_\mathrm{a}, Q^2)$ and $G_{q_\mathrm{b}/\gamma}(z_\mathrm{b}, Q^2)$ are the parton distributions of the resolved photon,[20] $f_\mathrm{q}^\gamma(z)$ is the photon spectrum from the quark, which is described in Eq. (1), while $D_\mathrm{c}(z_\mathrm{c})$ are the fragmentation functions, which describe the possibilities of gluon, quark and photon split into J/ψ.[21,22] The partonic differential cross sections $d\hat{\sigma}/d\hat{t}$ are chosen as Refs. [23,24] for non-fragmentation and fragmentation processes, respectively. Furthermore, we choose the long-distance non-relativistic QCD matrix elements as Ref. [25] for calculations in the partonic differential cross sections and the fragmentation functions.

Figure 4 presents the numerical results of non-fragmentation processes of J/ψ production at $\sqrt{s} = 7\,\mathrm{TeV}$ in ultra-peripheral pp collisions. The solid line, the dotted line and the dashed line shows the contribution from direct photon processes, the mixed process, and the resolved photon process, respectively. We can see that when $p_\mathrm{T} < 4\,\mathrm{GeV}$, the largest contribution comes from the mixed processes, and when $p_\mathrm{T} > 4\,\mathrm{GeV}$, the contribution from resolved photon processes becomes obvious.

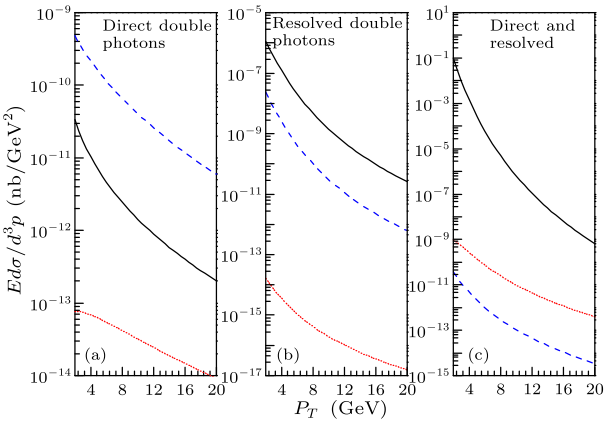


Fig. 5. The fragmentation processes of J/ψ production at $\sqrt{s} = 7\,\mathrm{TeV}$ in ultra-peripheral pp collisions. Fig. 2a, Fig. 2b and Fig. 2c corresponds to the direct double processes, the resolved double processes and mixed processes, respectively. The solid line, the dashed line and the dotted line represent the total contribution from gluon fragmentation, quark fragmentation and photon fragmentation, respectively.

Figure 5 presents the numerical results of the fragmentation processes of J/ψ production at $\sqrt{s} = 7\,\mathrm{TeV}$ in ultra-peripheral pp collisions. Figures 5(a)–5(c) correspond to the direct double processes, the resolved double processes and the mixed processes, respectively. In each figure, the solid line, the dashed line and the dotted line show the total contribution from gluon fragmentation, quark fragmentation and photon fragmentation, respectively. One can easily find that in direct double processes (Fig. 5(a)), the quark fragmentation contribution dominates, while in resolved and mixed processes (Figs. 5(b) and 5(c), respectively) the gluon fragmentation contribution dominates. By making a comparison among these three pictures, one can also find that the contribution from mixed processes dominates.

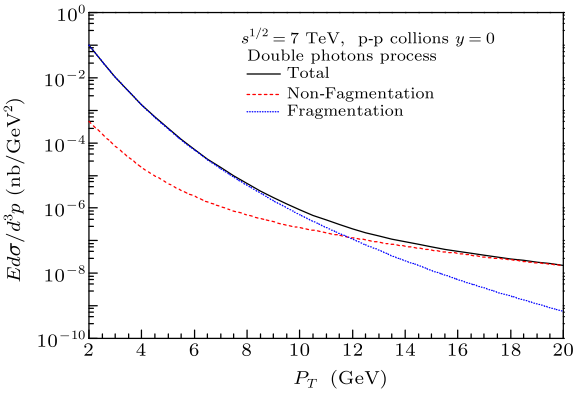


Fig. 6. Total contribution from fragmentation and non-fragmentation processes. The solid line represents the total non-fragmentation processes. The dashed line represents the total fragmentation processes.

Figure 6 presents the total contribution from fragmentation and non-fragmentation processes. The dashed line corresponds to the total non-fragmentation processes, the dotted line corresponds to the total fragmentation processes, and the solid line represents the sum of their contributions. It is easily concluded that in the range of $p_\mathrm{T} < 12\,\mathrm{GeV}$, the main contribution of J/ψ production via a two-photon mechanism comes from the fragmentation processes, while in the range of $p_\mathrm{T} > 12\,\mathrm{GeV}$, the contribution from the non-fragmentation processes is more obvious.

In summary, we have investigated the inclusive production of J/ψ via the two-photons mechanism using the photon spectrum of a high energy charged parton in an ultra-peripheral pp collision. Three processes are considered, which can be further divided into the direct or non-fragmentation process and the fragmentation process. The numerical results show that when $p_\mathrm{T} < 12\,\mathrm{GeV}$, the main contribution comes from the mixed fragmentation process and when $p_\mathrm{T} > 12\,\mathrm{GeV}$, the main contribution comes from the double resolved non-fragmentation process. Compared with the exclusive processes,[11–13] results from the two-photon processes of the charged partons are meaningful for the J/ψ production in the ultra-peripheral pp collisions.

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