Inelastic heavy quark and quarkonium ultra-incoherent photoproduction in ultra-peripheral collisions

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The inelastic heavy quark and quarkonium photoproduction through the ultra-incoherent photon channel in ultra-peripheral collisions is studied. Considering the ultra-relativistic hadrons as a beam of freely moving elementary constituents, the inclusive photoproduction cross sections for charm quark, bottom quark, J/ψ, and $\Upsilon(1S)$ are calculated by using the incoherent photon spectrum from the individual quarks in the nucleus. Comparing with the predictions of the coherent photon channel in the literatures, it is shown that the ultra-incoherent photon channel provides non-negligible contributions to the heavy quarks and heavy quarkonia photoproduction in ultra-peripheral collisions.

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I. INTRODUCTION

Ultra-peripheral collisions (UPCs) are such reactions that two ions do not interact directly with each other but interact via their photons cloud [1–4]. Based on the method of Fermi, Weizsäcker, and Williams [5], the moving electromagnetic fields of charged particles can be treated as a flux of photons. In an ultrarelativistic ion collider, these photons can interact with target nucleus in the opposing beam (photoproduction) or with the photons of the opposing beam (two-photon reactions). UPCs have been used to study many topics such as the determining of the nuclear parton distributions, small x physics, particle and particle pairs production, etc. [4]. At the CERN Large Hadron Collider (LHC) energies, the intense heavy-ion beams represent a prolific source of quasireal photons, hence it enables extensive studies of UPCs physics.

The UPCs cross sections are given by the convolution between the photon flux and other qualities related to the scattering process. In the calculations, an important function is the photon flux function or the equivalent photon spectrum, which has different forms in different processes. There are two types of photons emission process: coherent photon emission and incoherent photon emission [6]. In the first type, photons are coherently radiated by the whole nucleus, and the nucleus remains intact after the photon emitted. In the second type, photons are incoherently radiated by the individual constituents (protons or even quarks) inside the nucleus, and the nucleus, as a weakly bound system, will dissociate or excite after the photon radiated (see Fig. 1). There is a lot of research for these processes, and the ultra-incoherent photon emission mechanism has been used in the research of the two-photon process [7,8]. However, to our knowledge, this mechanism from the individual quarks has not been used in the research of photoproduction in UPCs. In this paper, we study the contributions of the ultra-incoherent channel to the heavy quarks and quarkonia photoproduction, and compare the results with the ones of the coherent channel in the literatures. For convenience, this type of photoproduction is denoted as ultra-incoherent (UIC) photoproduction in the present work. To avoid confusion, the terminology "coherent" or "incoherent" is always used to describe the photon emission types in this paper, which is different in many literatures where the "coherent" and "incoherent" usually refer to the case where the target nucleus remains intact or is allowed to break up after the scattering with photons.

This paper is organized as follows. Section II presents the ultra-incoherent photoproduction formulation. The ultra-incoherent photon spectrum is introduced. The direct-photon and resolved-photon processes are considered. Sections III and IV consider the ultra-incoherent photoproduction of heavy quarks and quarkonia in p-p and Pb-Pb collisions. For heavy quarks, the explicit formulas of the next-to-leading-order contributions are used in the calculations. For heavy quarkonia, some kinematics restrictions are considered, and the next-to-leading-order contributions are included with the K factor. The total cross sections are presented. In Sec. V, we present the conclusions.

II. THE ULTRA-INCOHERENT PHOTOPRODUCTION FORMULATION

Under the ultra-relativistic condition, a nucleon can also be regarded as a beam of freely moving elementary constituents [9], which is the same as the quark-parton model. The cross section of UPCs under the ultra-relativistic condition $A+B\rightarrow X_A+c+X$ can be presented as

$$\sigma=\int dx_a dx_b f_a(x_a,\mu^2)f_b(x_b,\mu^2)\times\hat{\sigma}(a+b\rightarrow a'+c+X'),\qquad(1)$$

where $f_a(x_a,\mu^2)$ and $f_b(x_b,\mu^2)$ are the parton distribution functions, $x_a=p_a/P_A$ and $x_b=p_b/P_B$ are the parton's momentum fractions, μ is the factorization scale. X_A is the residue of nuclear A after collision, or to be more precise, is the residue of nuclear A after the UIC photon emission. $\hat{\sigma}(a+b\rightarrow a'+c+X')$ is the cross section of UPCs subprocess in the parton level (see Fig. 1) and can be presented as

$$\hat{\sigma}(a+b\rightarrow a'+c+X')=\frac{(2\pi)^4\delta^4(p_a+p_b-p_{a'}-p_c-p_{X'})}{4\left[(p_a\cdot p_b)^2-p_a^2p_b^2\right]^{1/2}}\rho_{X'}\frac{d^3p_c}{(2\pi)^3 2E_c}\times|\mathcal{M}(a+b\rightarrow a'+c+X')|^2$$

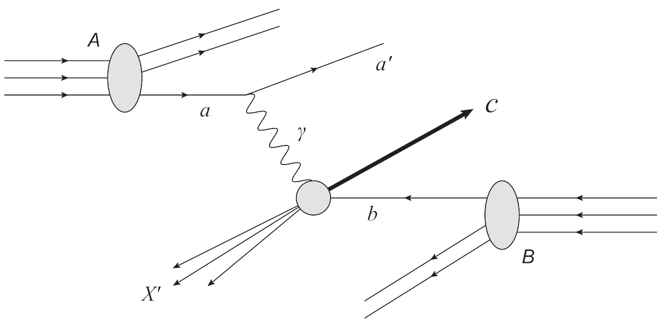

FIG. 1. The UPCs in the parton level under ultra-relativistic condition. a denotes the charged parton (quark) in nuclear A,b is the parton (quark or gluon) in nuclear B,a' is the scattered parton a,c is the final particle in which we are interested, and X' is the residue of b after scattering with the photon.

$$= \left[\frac{(q_\gamma \cdot p_b)^2 - q_\gamma^2 p_b^2}{(p_a \cdot p_b)^2 - p_a^2 p_b^2}\right]^{1/2} \frac{|\mathcal{M}(a \to \gamma + a')|^2}{Q_\gamma^2} \frac{d^3 p_c}{(2\pi)^3 2E_c}$$
$$\times \hat{\sigma}(\gamma + b \to c + X')$$
$$= \left[\frac{\alpha}{2\pi} e_i^2 P_{\gamma\leftarrow a}(y) \ln\left(\frac{Q^2_{\gamma\,\max}}{Q^2_{\gamma\,\min}}\right) dy\right] \hat{\sigma}(\gamma + b \to c + X'), \tag{2}$$

where $Q_\gamma^2 = -q_\gamma^2$, $P_{\gamma\leftarrow a}$ is the splitting function, $y = (q_\gamma \cdot p_b)/(p_a \cdot p_b)$. Therefore, the photon flux, or the UIC photon spectrum, provided by the quark a can be defined as [6,9,10]

$$f_{\gamma/a}(y) = \frac{\alpha}{2\pi} e_i^2 P_{\gamma\leftarrow a}(y) \ln\left(\frac{Q^2_{\gamma\,\max}}{Q^2_{\gamma\,\min}}\right)$$
$$= \frac{\alpha}{2\pi} e_i^2 \frac{1 + (1-y)^2}{y} \ln\left(\frac{Q^2_{\gamma\,\max}}{Q^2_{\gamma\,\min}}\right). \tag{3}$$

The UIC photoproduction, which is best treated as inclusive processes, can also provide additional correction to the central collisions. For instance, Ref. [11] has been used, Eq. (3), to study the inelastic dileptons, photons, light vector meson, and J/ψ production at LHC energies (after the scattering, the target nucleus is broken and the processes should be considered inelastic in this sense). These works show that the UIC photoproduction improves the contribution of massless and light final-state particles in the central collisions. However, the correction is not obvious for J/ψ due to its large mass [12]. In this paper, we present the calculations of the inelastic heavy quarks (charm and bottom) and heavy quarkonia [J/ψ and $\Upsilon(1S)$] UIC photoproduction in UPCs.

There are two kinds of photon contributions that should be considered: direct-photon contribution and resolved-photon contribution. For the direct-photon process, the high energy photons, emitted from quarks inside incoming nucleus A, interact with partons of target nucleus B directly, and the inclusive cross section can be obtained by inserting Eq. (3) into Eq. (1)

$$\sigma_{\mathrm{dir.}} = \int_{x_{a\,\min}}^1 dx_a \int_{x_{b\,\min}}^1 dx_b \int_{y_{\min}}^1 dy\, f_a(x_a,\mu^2)$$
$$\times f_b(x_b,\mu^2) f_{\gamma/a}(y) \hat{\sigma}(\gamma + b \to c + X'). \tag{4}$$

For the resolved-photon process, the high energy photon can split into a color singlet state with $q\bar{q}$ pairs and gluons. Due to this fluctuation, the photon interacts with the partons in B like a hadron, and the subprocesses are almost the purely strong interaction processes. Therefore $\hat{\sigma}(\gamma + b \to c + X')$ can be presented as

$$\int dx_a' f_{a_\gamma/\gamma}\left(x_a',\mu_\gamma^2\right) \hat{\sigma}(a_\gamma + b \to c + X'), \tag{5}$$

where $f_{a_\gamma/\gamma}(x_a',\mu_\gamma^2)$ is the parton distribution function in photon, $x_a' = p_{a_\gamma}/q_\gamma$, and the inclusive cross section is

$$\sigma_{\mathrm{res.}} = \int_{x_{a\,\min}}^1 dx_a \int_{x_{b\,\min}}^1 dx_b \int_{y_{\min}}^1 dy \int_{x'_{a\,\min}}^1 dx_a'$$
$$\times f_a(x_a,\mu^2) f_b(x_b,\mu^2) f_{\gamma/a}(y) f_{a_\gamma/\gamma}\left(x_a',\mu_\gamma^2\right)$$
$$\times \hat{\sigma}(a_\gamma + b \to c + X'), \tag{6}$$

where the center-of-mass energy of subprocess $\hat{s} = x_a x_b y s$ for thedirect photon case $\hat{\sigma}(\gamma + b \to c + X')$ and $\hat{s} = x_a x_b y x_a' s$ for the resolved photon one $\hat{\sigma}(a_\gamma + b \to c + X')$. The parton distribution function $f(x,\mu^2)$ can be presented as

$$f(x,\mu^2) = R(x)\left[\frac{Z}{A} p(x,\mu^2) + \frac{N}{A} n(x,\mu^2)\right], \tag{7}$$

where $R(x)$ is the nuclear modification function which is reflected the nuclear shadowing effect [13] [$R(x) = 1$ for p-p collisions], Z is the proton number, N is the neutron numberm and A is the nucleon number. $p(x,\mu^2)$ and $n(x,\mu^2)$ are the parton distributions of the proton and neutron [14], respectively. The parton distribution function in photon $f_{a/\gamma}(x,\mu_\gamma^2)$ can be found in Ref. [15], and we set $\mu_\gamma = \mu$ in our calculations. Since we consider the incoherent process, $Q^2_{\gamma\,\min}$ in Eq. (3) should be larger than $1/R^2$, where R is the size of the nucleon. However, in order to ensure the quark-parton model can be used for the UIC photon emission, we set $Q^2_{\gamma\,\min} = 1\,\mathrm{GeV}^2$ according to Refs. [6,7]. On the other hand, $Q^2_{\gamma\,\max}$ is expected to be smaller than the maximum virtuality $\hat{s} - M^2$ of the photon, and we set $Q^2_{\gamma\,\max} = (\hat{s} - M^2)/4$ [7,16] in this paper. Finally, the strong coupling constant is taken as the one-loop form

$$\alpha_S = \frac{12\pi}{(33 - 2n_f)\ln(\mu^2/\Lambda^2)} \tag{8}$$

with $n_f = 4$ and $\Lambda = 0.2$ GeV, and the electromagnetic coupling constant is chosen as $1/137$ in our calculations.

III. THE ULTRA-INCOHERENT PHOTOPRODUCTION OF C AND B QUARKS

Heavy quark production in UPCs has received much attention. Earlier studies have considered photoproduction of charm and bottom quarks as well as nuclear breakup and vector meson production. In Ref. [17], Klein, Nystrand, and Vogt presented the calculation for the production of top quarks via photon-gluon fusion, paralleled previous calculations of photoproduction in heavy ion collisions. By using the same coherent photon spectrum for a point charge Ze and considering the resolved-photon processes for the first time, these authors also calculated the photoproduction and two-photon production of charm and bottom quarks via photon-gluon fusion, gluon-gluon fusion, and quark-antiquark annihilation in Ref. [18]. On the other hand, Gonçalves and collaborators considered distinct theoretical scenarios, and presented their rigorous studies of heavy quarks photoproduction by using coherent photon spectrum [19].

In this section, we calculate the UIC photoproduction of inelastic charm and bottom quarks in p-p and Pb-Pb UPCs based on the scenario of Ref. [18]. For the direct-photon case the following parton-inclusive processes are considered:

$$\gamma + g \to Q + X, \quad \gamma + q \to Q + X, \quad \gamma + \bar{q} \to Q + X. \tag{9}$$

The exclusive parton subprocesses which contribute to these inclusive cross sections to order $\alpha_S^2\alpha_{em}$ are

$$\begin{aligned} &\gamma + g \to Q + \bar{Q}, \quad \alpha_S\alpha_{em}, \quad \alpha_S^2\alpha_{em},\\ &\gamma + g \to Q + \bar{Q} + g, \quad \alpha_S^2\alpha_{em},\\ &\gamma + q \to Q + \bar{Q} + q, \quad \alpha_S^2\alpha_{em},\\ &\gamma + \bar{q} \to Q + \bar{Q} + \bar{q}, \quad \alpha_S^2\alpha_{em}. \end{aligned} \tag{10}$$

At the leading-order (LO) of $\mathcal{O}(\alpha_S\alpha_{em})$, the cross section for the process $\gamma + g \to Q + \bar{Q}$ is

$$\begin{aligned} \hat{\sigma}(\hat{s},m_Q) = \frac{2\pi\alpha_{em}\alpha_S}{\hat{s}} e_Q^2 \bigg[&-(1+\rho)\beta \\ &+ \left(1 + \rho - \frac{\rho^2}{2}\right) \ln\left(\frac{1+\beta}{1-\beta}\right)\bigg], \end{aligned} \tag{11}$$

where $\rho = 4m_Q^2/\hat{s}, \beta = \sqrt{1-\rho}$. The explicit formulas for the next-to-leading-order (NLO) of $\mathcal{O}(\alpha_S^2\alpha_{em})$ subprocesses in Eq. (10) can be found in Refs. [20,21]. For the resolved-photon case the following parton-inclusive processes are considered:

$$\begin{aligned} &g_\gamma + g \to Q + X, \quad q_\gamma + \bar{q} \to Q + X,\\ &g_\gamma + q \to Q + X, \quad g_\gamma + \bar{q} \to Q + X,\\ &q_\gamma + g \to Q + X, \quad \bar{q}_\gamma + g \to Q + X,\\ &\bar{q}_\gamma + q \to Q + X. \end{aligned} \tag{12}$$

The exclusive parton subprocesses which contribute to these inclusive cross sections to order α_S^3 are

$$\begin{aligned} &g + g \to Q + \bar{Q}, \quad \alpha_S^2, \alpha_S^3,\\ &q + \bar{q} \to Q + \bar{Q}, \quad \alpha_S^2, \alpha_S^3,\\ &g + g \to Q + \bar{Q} + g, \quad \alpha_S^3,\\ &q + \bar{q} \to Q + \bar{Q} + g, \quad \alpha_S^3,\\ &g + q \to Q + \bar{Q} + q, \quad \alpha_S^3,\\ &g + \bar{q} \to Q + \bar{Q} + \bar{q}, \quad \alpha_S^3. \end{aligned} \tag{13}$$

TABLE I. Heavy quarks UIC photoproduction in p-p collisions.

p-p	Quark	$\sigma_{dir.}$	$\sigma_{res.}$	σ_{total}
$\sqrt{s} = 7$ TeV	charm	2.6576 μb	1.4763 μb	4.1339 μb
$\sqrt{s} = 14$ TeV	charm	4.6554 μb	3.2726 μb	7.9280 μb
$\sqrt{s} = 7$ TeV	bottom	0.0483 μb	0.0401 μb	0.0884 μb
$\sqrt{s} = 14$ TeV	bottom	0.1021 μb	0.1113 μb	0.2134 μb

At LO of $\mathcal{O}(\alpha_S^2)$, the cross section for the process $g + g \to Q + \bar{Q}$ is

$$\begin{aligned} \hat{\sigma}(\hat{s},m_Q) = \frac{\pi\alpha_S^2}{3\hat{s}} \bigg[&-\left(7 + \frac{31}{4}\rho\right)\frac{\beta}{4} \\ &+ \left(1 + \rho + \frac{\rho^2}{16}\right) \ln\left(\frac{1+\beta}{1-\beta}\right)\bigg], \end{aligned} \tag{14}$$

and for the process $q + \bar{q} \to Q + \bar{Q}$ is

$$\hat{\sigma}(\hat{s},m_Q) = \frac{8\pi\alpha_S^2}{27\hat{s}^2}(\hat{s} + 2m_Q^2)\beta. \tag{15}$$

As to the explicit formulas for NLO of $\mathcal{O}(\alpha_S^3)$, subprocesses in Eq. (13) can be found in Ref. [22].

In the heavy quark UIC photoproduction, $x_{a\,\min} = \hat{s}_{\min}/s$, $x_{b\,\min} = \hat{s}_{\min}/sx_a$, $y_{\min} = \hat{s}_{\min}/sx_ax_b$, $x'_{a\,\min} = \hat{s}_{\min}/sx_ax_by$, and $\hat{s}_{\min} = M^2$ in Eqs. (4) and (6), where $M = 2m_Q$ ($m_Q = m_c$ or m_b). The factorization scale μ is chosen as m_Q, where $m_c = 1.275$ GeV, $m_b = 4.18$ GeV [23]. Another choice in the literatures is $\mu = 2m_Q$ for the charm quark, which provides negative contribution at NLO in the charm quark UIC photoproduction, and is not considered in the present work. The total cross sections in p-p and Pb-Pb UPCs can be found in Tables I and II, where $\sigma_{total} = \sigma_{dir.} + \sigma_{res.}$.

Some features can be seen from these data:

(i) The relative contributions of resolved-photon processes become larger along with the increasing quark mass and $\sqrt{s}$. For instance, the resolved-photon contribution to the b quark is bigger than the direct-photon one in p-p collisions with $\sqrt{s} = 14$ TeV. The resolved-photon processes will dominate the UIC photoproduction at sufficiently large m_Q and $\sqrt{s}$.

(ii) Comparing with Ref. [18], for Pb-Pb UPCs with $\sqrt{s} =$ 5.5 NTeV, the result in the literature is about 24 times larger than our result for the c quark, and about 0.5 times than ours for the b quark. Although this is just a qualitative conclusion due to the different choice of parameters and parton distribution functions, it also means that the UIC mechanism contribution for the

TABLE II. Heavy quarks UIC photoproduction in Pb-Pb collisions.

Pb-Pb	Quark	$\sigma_{dir.}$	$\sigma_{res.}$	σ_{total}
$\sqrt{s} = 2.76$ NTeV	charm	27.1083 mb	12.1686 mb	39.2769 mb
$\sqrt{s} = 5.5$ NTeV	charm	47.1083 mb	28.3834 mb	75.4917 mb
$\sqrt{s} = 2.76$ NTeV	bottom	0.3465 mb	0.2307 mb	0.5772 mb
$\sqrt{s} = 5.5$ NTeV	bottom	0.7409 mb	0.6803 mb	1.4212 mb

heavy quarks photoproduction in UPCs becomes more obvious along with the increasing quark mass.

IV. THE ULTRA-INCOHERENT PHOTOPRODUCTION OF J/ψ AND $\Upsilon(1S)$

Heavy quarkonium production [24–26] involves both perturbative and nonperturbative aspects of quantum chromodynamics (QCD) and can be considered as proceeding in two steps. In the first step, heavy quark pair production in short distance can be studied by using the perturbative theory since the momentum transfers at least as large as the heavy quark mass. The second is the evolution of the heavy quark pair into the physical quarkonium state, which is nonperturbative over long distances with typical momentum scales such as the momentum of the heavy quarks $m_Q v$ and their binding energy $m_Q v^2$ in the bound-state rest frame. Since Bodwin, Braaten, and Lepage developed the factorization scheme based on the effective theory of nonrelativistic QCD (NRQCD) [27], the hadronization probability of a heavy quark pair into a quarkonium is described by the long-distance matrix elements (LDMEs). Another important development of NRQCD is the color-octet mechanism (COM) for the quarkonium production. In COM, the heavy quark pair is in an octet Fock state with a different angular momentum and spin states, and color-singlet mechanism (CSM), which is assumed that the heavy quark pair is in a color-singlet state and has the same spin and angular-momentum quantum numbers as the quarkonium, is naturally considered as the leading Fock state.

There is a lot of research for the photoproduction of heavy quarkonium in UPCs. In Ref. [28], Klein and Nystrand studied the exclusive vector meson production via photon-Pomeron or photon-meson interactions, and discussed the interplay between photoproduction and two-photon interaction. These authors also analyzed the quarkonium photoproduction in p-p collisions by using the photon spectrum associated with a proton and a photon-proton cross section for quarkonium production obtained by fitting the H1 and ZEUS data in Ref. [29]. Authors in Refs. [30,31] parametrized the cross section of $\gamma + N \to J/\psi + N$ by the QCD motivated formula, and studied elastic and large t rapidity gap vector meson production in ultra-peripheral proton-ion collisions. Gonçalves and Machado analyzed the possibility of using UPCs as a photon-photon/nucleus collision, and studied the production of vector mesons considering different QCD dynamics in Ref. [32]. They also presented their results for the inelastic quarkonium photoproduction in hadron-hadron interactions by using the semiclassical photon spectrum at LHC energies recently [33]. Lappi and Mäntysaari computed cross sections for diffractive J/ψ production in UPCs by using two different dipole models to HERA data in Ref. [34]. Authors in Ref. [35] investigated the exclusive photoproduction of J/ψ and the radially excited $\psi(2S)$ state off nucleons in p-p collisions according to the light-cone dipole formalism. The photon emission type in all of these above works are coherent.

In this section, we calculate the UIC photoproduction of inelastic J/ψ and $\Upsilon(1S)$ in p-p and Pb-Pb UPCs. The inclusive cross sections for direct-photon and resolved-photon processes can be found in Eqs. (4) and (6), where we replace $\hat{\sigma}$ as the integration of $\hat{t}$ [$\hat{t} = (p_c - q_\gamma)^2$ for the direct-photon case and $\hat{t} = (p_c - p_{a_\gamma})^2$ for the resolved-photon case]:

$$\hat{\sigma} = \int_{\hat{t}_{\min}}^{\hat{t}_{\max}} d\hat{t}\frac{d\hat{\sigma}_H}{d\hat{t}},$$
$$= \sum_{Q\bar{Q}} \int_{\hat{t}_{\min}}^{\hat{t}_{\max}} d\hat{t}\frac{d\hat{\sigma}_{Q\bar{Q}}}{d\hat{t}}\langle O^H[{}^{2S+1}L_J^{(1,8)}]\rangle, \tag{16}$$

where the quantity ${}^{2S+1}L_J$ represents the angular momentum quantum numbers of the $Q\bar{Q}$ pair in the Fock expansion. The superscript (1,8) refers to the color structure of the $Q\bar{Q}$ pair (color-singlet and color-octet). The short distance cross sections $d\hat{\sigma}_{Q\bar{Q}}$ correspond to the production of a $Q\bar{Q}$ pair in a particular color and spin configuration, while the LDMEs $\langle O^H[{}^{2S+1}L_J^{(1,8)}]\rangle$ corresponds to the hadronization probability of a heavy quark pair into a quarkonium ($Q\bar{Q}[{}^{2S+1}L_J^{(1,8)}] \to H$) [$H = J/\psi$ or $\Upsilon(1S)$]. The LO partonic cross sections $d\hat{\sigma}(Q\bar{Q})/d\hat{t}$ can be found in Refs. [36–38] for direct-photon processes, and Refs. [39–41] for resolved photon processes. Reference [42] presents a complete list for these partonic cross sections. The NLO fit results for the LDMEs $\langle \mathcal{O}^H({}^{2S+1}L_J^{(a)})\rangle$ can be found in Refs. [43,44]:

$$\begin{aligned}
\langle \mathcal{O}^{J/\psi}[{}^3S_1{}^{(1)}]\rangle &= 1.32\ \text{GeV}^3,\\
\langle \mathcal{O}^{J/\psi}[{}^1S_0{}^{(8)}]\rangle &= 4.50\times10^{-2}\ \text{GeV}^3,\\
\langle \mathcal{O}^{J/\psi}[{}^3S_1{}^{(8)}]\rangle &= 3.12\times10^{-3}\ \text{GeV}^3,\\
\langle \mathcal{O}^{J/\psi}[{}^3P_0{}^{(8)}]\rangle &= -1.21\times10^{-2}\ \text{GeV}^3,
\end{aligned} \tag{17}$$

and

$$\begin{aligned}
\langle \mathcal{O}^{\Upsilon(1S)}[{}^3S_1{}^{(1)}]\rangle &= 9.28\ \text{GeV}^3,\\
\langle \mathcal{O}^{\Upsilon(1S)}[{}^1S_0{}^{(8)}]\rangle &= 13.60\times10^{-2}\ \text{GeV}^3,\\
\langle \mathcal{O}^{\Upsilon(1S)}[{}^3S_1{}^{(8)}]\rangle &= 0.61\times10^{-2}\ \text{GeV}^3,\\
\langle \mathcal{O}^{\Upsilon(1S)}[{}^3P_0{}^{(8)}]\rangle &= -20.81\times10^{-2}\ \text{GeV}^3,
\end{aligned} \tag{18}$$

and the relations

$$\langle \mathcal{O}^H[{}^3P_J{}^{(8)}]\rangle = (2J+1)\langle \mathcal{O}^H[{}^3P_0{}^{(8)}]\rangle \tag{19}$$

are used.

Comparing with the heavy quarks case, the calculations for the heavy quarkonia UIC photoproduction should consider some addition restrictions [43]:

(i) Although the total cross section is also dominated by small values of p_T, the NRQCD factorization approach may not be valid in this region. Therefore, we set $p_{T\,\min} = M$, where $M = m_{J/\psi}$ or $m_{\Upsilon(1S)}$ [$p_T >$ 3 GeV for J/ψ and $p_T >$ 9 GeV for $\Upsilon(1S)$] for the calculations. All the p_T above are in the corresponding subprocess c.m.s. ($\gamma - b$ c.m.s. for direct-photon cases and $a_\gamma - b$ c.m.s. for resolved-photon ones).

(ii) The NRQCD prediction is broken down and the COM channels exhibit collinear singularities in the limit $z \to 1$, where $z = (p_c \cdot p_b)/(q_\gamma \cdot p_b)$. Therefore we set $z_{\max} = 0.9$ in order to screen the collinear singularities

TABLE III. Heavy quarkonia UIC photoproduction in p-p collisions.

p-p	Quarkonium	$\sigma_{\text{dir.}}$	$\sigma_{\text{res.}}$	σ_{total}
$\sqrt{s} = 7$ TeV	J/ψ	11.9874 nb	3.8007 nb	15.7881 nb
$\sqrt{s} = 14$ TeV	J/ψ	22.6687 nb	7.8352 nb	30.5039 nb
$\sqrt{s} = 7$ TeV	$\Upsilon(1S)$	0.0200 nb	0.0094 nb	0.0294 nb
$\sqrt{s} = 14$ TeV	$\Upsilon(1S)$	0.0454 nb	0.0230 nb	0.0683 nb

and exclude the elastic production which is due to the diffractive processes.

According to these restrictions, we have

$$\hat{s}_{\min} = M^2 + 2p_{T\min}^2 + 2\sqrt{p_{T\min}^4 + M^2 p_{T\min}^2}. \qquad (20)$$

For direct-photon cases,

$$\hat{t}_{\min} = M^2 - \hat{s}, \quad \hat{t}_{\max} = M^2 - z_{\max}^{-1} M_{T\min}^2, \qquad (21)$$

and for resolved-photon cases,

$$\hat{t}_{\min} = M^2 - \hat{s}, \quad \hat{t}_{\max} = M^2 - z_{\max}^{-1} x_a' M_{T\min}^2, \qquad (22)$$

where

$$M_{T\min}^2 = M^2 + p_{T\min}^2, \qquad (23)$$

and $x_a' > z$. On the other hand, since $\hat{t}_{\max} \leqslant 0$, one can find

$$x_a' \geqslant \frac{z_{\max} M^2}{M_{T\min}^2}. \qquad (24)$$

In the calculations, the factorization scale μ is chosen as $m_{J/\psi}$ and $m_{\Upsilon(1S)}$, respectively, where $m_{J/\psi} = 3.097$ GeV, $m_{\Upsilon(1S)} = 9.46$ GeV [23]. $x_{a\min} = \hat{s}_{\min}/s, x_{b\min} = \hat{s}_{\min}/s x_a$, $y_{\min} = \hat{s}_{\min}/s x_a x_b$, and $x_{a\min}' = \max[\hat{s}_{\min}/s x_a x_b y, z_{\max} M^2/M_{T\min}^2]$ in Eqs. (4) and (6). In order to include the NLO contributions, the LO results are multiplied by the K factor which can be found in Ref. [43]. Since the total cross section is dominated in the region of $p_T \to p_{T\min}$, we choose $K = 1.8$ for direct-photon processes and $K = 1.3$ for resolved-photon cases. The total cross sections in p-p and Pb-Pb UPCs can be found in Tables III and IV, where $\sigma_{\text{total}} = \sigma_{\text{dir.}} + \sigma_{\text{res.}}$.

Some features can be seen from these data:

(i) The numerical results are sensitive to the choices of $p_{T\min}$ since the total cross section is dominated in the small p_T region. For instance, the direct-photon results with $p_{T\min} = 1$ GeV will be about 8–10 times larger than the ones with $p_{T\min} = M$. However, the reliability of QCD perturbation theory and the NRQCD factorization approach is debatable in such a small p_T region. This is somewhat problematic. Nevertheless, we set $p_{T\min} = M$ for the present calculations. A more suitable choice for $p_{T\min}$ (and other parameters such as $z_{\max}$) needs to be studied by fitting the future experimental data.

(ii) Although the authors in Ref. [33] only considered the CSM by using the coherent photon spectrum, some useful features can also be found from the comparison of our results with theirs. It can be seen that our results for J/ψ are almost the same as the coherent ones in the literature for p-p UPCs. In contrast, the coherent results for J/ψ are about 20–30 times than ours for Pb-Pb UPCs. The reason is that the coherent photon emission mechanism is proportional to Z^2, whereas the UIC one is only proportional to A. As for $Z \gg 1$ the coherent part is dominant in the photoproduction (and also the two-photon reactions).

V. CONCLUSION

In this paper, we calculate the production cross section for inelastic heavy quarks and heavy quarkonia ultra-incoherent photoproduction in ultra-peripheral collisions. For the ultra-incoherent photon emission, photons are incoherently radiated by the individual quarks inside the nucleus. Since a proton can be regarded as a beam of freely moving elementary constituents under an ultra-relativistic condition in LHC, the ultra-incoherent photon spectrum can be obtained associated with the quark-parton model. There are two kinds of photon processes which should be considered. For the direct-photon process, the high energy photons interact with partons in the target nucleus directly. For the resolved-photon process, the high energy photon interacts with the partons in the target nucleus like a hadron since the photon can split into a color singlet state with $q\bar{q}$ pairs and gluons.

The ultra-incoherent photoproduction can provide an additional correction to the central collisions. However, this correction is meaningful for the light particles production (dileptons, photons, light vector mesons) but not obvious for heavy mass particles. Therefore we use this mechanism for the heavy quarks and heavy quarkonia photoproduction in the ultra-peripheral collisions. We calculate the inclusive production cross section for heavy quarks (charm and bottom) and heavy quarkonia [$J/\psi, \Upsilon(1S)$]. Comparing with the coherent photon channel results in the literatures, the ultra-incoherent photon channel provides meaningful contributions to the heavy quarks and heavy quarkonia photoproduction in p-p ultra-peripheral collisions. For the Pb-Pb case, the ultra-incoherent photon contributions are less than the coherent ones which

TABLE IV. Heavy quarkonia UIC photoproduction in Pb-Pb collisions.

Pb-Pb	Quarkonium	$\sigma_{\text{dir.}}$	$\sigma_{\text{res.}}$	σ_{total}
$\sqrt{s} = 2.76$ NTeV	J/ψ	102.2154 μb	25.6525 μb	127.8679 μb
$\sqrt{s} = 5.5$ NTeV	J/ψ	190.0469 μb	50.9759 μb	241.0228 μb
$\sqrt{s} = 2.76$ NTeV	$\Upsilon(1S)$	0.1353 μb	0.0536 μb	0.1889 μb
$\sqrt{s} = 5.5$ NTeV	$\Upsilon(1S)$	0.3049 μb	0.1373 μb	0.4421 μb

are proportional to Z^2. The ultra-incoherent photon channel provides non-negligible contributions to the heavy quarks and heavy quarkonia photoproduction in ultra-peripheral collisions, especially when Z is not much larger than 1.

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