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Research Article

η_Q Meson Photoproduction in Ultrarelativistic Heavy Ion Collisions

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The transverse momentum distributions for inclusive $\eta_{c,b}$ meson described by gluon-gluon interactions from photoproduction processes in relativistic heavy ion collisions are calculated. We considered the color-singlet (CS) and color-octet (CO) components within the framework of Nonrelativistic Quantum Chromodynamics (NRQCD) in the production of heavy quarkonium. The phenomenological values of the matrix elements for the color-singlet and color-octet components give the main contribution to the production of heavy quarkonium from the gluon-gluon interaction caused by the emission of additional gluon in the initial state. The numerical results indicate that the contribution of photoproduction processes cannot be negligible for midrapidity in p-p and Pb-Pb collisions at the Large Hadron Collider (LHC) energies.

1. Introduction

Heavy quarkonium is a multiscale system which can probe all regimes of Quantum Chromodynamics (QCD) and present an ideal laboratory for testing the interplay between perturbative and nonperturbative QCD within a controlled environment. In recent years, many measurement reports have been published by ALICE collaboration [1, 2], CMS collaboration [3, 4], ATLAS collaboration [5, 6], and LHCb collaboration [7, 8] at the Large Hadron Collider (LHC) energies; several theoretical approaches have been proposed such as the color-singlet (CS) mechanism [9, 10], the color-octet (CO) mechanism [11, 12], the color evaporation mechanism [13, 14], the color-dipole mechanism [15–18], the mixed heavy-quark hybrids mechanism [19], the recombination mechanism [20–24], the photoproduction mechanism [25–31], the potential Nonrelativistic Quantum Chromodynamics (pNRQCD) approach [32–34], the transverse-momentum-dependent factorization approach [35], the transport approach [36–41], the k_T-factorization approach [42–45], the fragmentation approach [46–52], and the Nonrelativistic Quantum Chromodynamics (NRQCD) approach [53–67]. Among them, the NRQCD approach, which takes into account contributions of color-singlet component and color-octet components with the nonperturbative long-distance matrix elements (LDME), is the most successful in phenomenological studies. The long-distance matrix elements are process-independent and can be classified in terms of the relative velocity for the heavy quarks in the bound state. But, the heavy quarkonium production mechanism is still not fully understood.

In this study, we extend the hard photoproduction mechanism [68] to the heavy quarkonium production and investigate the production of inclusive $\eta_{c,b}$ meson in p-p and Pb-Pb collisions at the LHC. According to [69], the light $q\overline{q}$ contributions for heavy quarkonium production are negligible; therefore in this work we only consider the contributions of gluon-gluon processes caused by the emission of additional gluons, which is different from our previous work [26] based on the method developed in [70, 71]. In high energy collisions, the partons from the nucleus can emit high energy photons that can fluctuate into gluons and then interact with the partons of the other nucleus. Hence we consider that the hard photoproduction processes of a charged parton of the incident nucleon can emit a high energy photon in high energy nucleus-nucleus collisions.

The paper is organized as follows. In Section 2 we present the photoproduction of inclusive $\eta_{c,b}$ from gluon-gluon interactions at LHC. The numerical results for large-p_T $\eta_{c,b}$ meson production in p-p collisions and Pb-Pb collisions at LHC are given in Section 3. Finally, the conclusion is given in Section 4.

2. General Formalism

In relativistic heavy ion collisions, the production of η_Q mesons by the gluon-gluon (g-g) processes from the initial parton interaction can be divided into three processes: direct g-g processes, semielastic resolved photoproduction, and inelastic resolved photoproduction processes.

In direct processes, the parton (gluon) a of the incident nucleus A interacts with the parton (gluon) b of another incident nucleus B by the interaction of $gg \to \eta_c g$. The invariant cross section of large-p_T η_Q meson of the process ($A + B \to \eta_Q + X$) is described in the pQCD parton model on the basis of the factorization theorem and can be written as

$$\frac{d\sigma^{LO}_{AB\to\eta_Q X}}{dp_T^2 dy} = \int dx_a f_{g/A}\left(x_a, Q^2\right) f_{g/B}\left(x_b, Q^2\right) \cdot \frac{x_a x_b}{x_a - x_1} \frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow \eta_Q g\right), \quad (1)$$

where the variables x_a and $x_b = (x_a x_2 - \tau)/(x_a - x_1)$ are the momentum fractions of the partons, z_c is the momentum fraction of the final charmed-meson, $x_1 = (1/2)(x_T^2 + 4\tau)^{1/2}\exp(y)$, $x_2 = (1/2)(x_T^2 + 4\tau)^{1/2}\exp(-y)$, $x_T = 2p_T/\sqrt{s}$, $\tau = (M/\sqrt{s})^2$, and M is the mass of the η_Q meson; $f_{g/A}(x_a, Q^2)$ and $f_{g/B}(x_b, Q^2)$ are the parton distribution functions (PDF) for the colliding partons a and b carrying fractional momenta x_a and x_b in the interacting nucleons [72]:

$$f_{g/A}\left(x, Q^2\right) = R_A\left(x, Q^2\right) f_g\left(x, Q^2\right), \quad (2)$$

where $R_A(x, Q^2)$ is the nuclear modification factor [73] and $f_g(x, Q^2)$ is the gluon distribution function of nucleon.

According to NRQCD scaling rules [74, 75], the color-singlet as well as S-wave and P-wave color-octet components give the main contributions to the production process under consideration [76]:

$$\begin{aligned}\frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow \eta_Q g\right) &= |R(0)|^2 \frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow Q\overline{Q}\left[{}^1S_0^{[1]} g\right]\right) \\ &+ \left\langle O_S \right\rangle \frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow Q\overline{Q}\left[{}^3S_1^{[8]} g\right]\right) \\ &+ \left\langle O_P \right\rangle \frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow Q\overline{Q}\left[{}^1P_1^{[8]} g\right]\right).\end{aligned} \quad (3)$$

The subprocesses cross section of $[{}^1S_0^{[1]}]$, $[{}^3S_1^{[8]}]$, and $[{}^1P_1^{[8]}]$ state are, respectively, given by [77, 78]

$$\begin{aligned}\frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow Q\overline{Q}\left[{}^1S_0^{[1]}\right] g\right) &= \frac{\pi\alpha_s^3}{\hat{s}^2 M} \cdot \frac{P^2}{Q\left(Q - M^2 P\right)^2}\left[\left(P - M^4\right)^2 + 2M^2 Q\right], \\ \frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow Q\overline{Q}\left[{}^3S_1^{[8]}\right] g\right) &= \frac{\pi\alpha_s^3}{3M\hat{s}^2} \cdot \frac{\left(P^2 - M^2 Q\right)\left(19M^4 - 27P\right)}{M^2\left(Q - M^2 P\right)^2}, \\ \frac{d\hat{\sigma}}{d\hat{t}}\left(gg \longrightarrow Q\overline{Q}\left[{}^1P_1^{[8]}\right] g\right) &= \frac{2\pi\alpha_s^3}{M^3\hat{s}^2} \cdot \frac{1}{Q\left(Q - M^2 P\right)^3}\left[179M^4Q^3 + 217M^{10}Q^2 \right. \\ &- 27M^2P^5 + 54M^6P^4 - 27M^{10}P^3 + 135PQ^3 \\ &+ 103M^2P^2Q^2 - 212M^6PQ^2 - 124M^8P^2Q \\ &\left. + 43M^{12}PQ + 27P^4Q\right],\end{aligned} \quad (4)$$

where $M^2 = \hat{s} + \hat{t} + \hat{u}$, $P = \hat{s}\hat{t} + \hat{t}\hat{u} + \hat{u}\hat{s}$, and $Q = \hat{s}\hat{t}\hat{u}$. Here $\hat{s}$, $\hat{t}$, and $\hat{u}$ are the Mandelstam variables. $R(0) = [M_H^2\Gamma(H \to e^+e^-)/4\alpha^2 e_Q^2]^{1/2}$ is the wave function value of η_Q meson for the color-singlet state at the origin [79–84], where $M_H \approx 2m_Q$ is the mass of the heavy-quark pairs. The LDMEs of the color-octet components are used as follows:

$$\begin{aligned}\left\langle O_S \right\rangle &= \left\langle R_{\eta_Q}\left[{}^3S_1^{(8)}\right]\right\rangle = \frac{\pi}{6}\left\langle 0\left|O_8^{\eta_Q}\left[{}^3S_1\right]\right|0\right\rangle, \\ \left\langle O_P \right\rangle &= \left\langle R_{\eta_Q}\left[{}^1P_1^{(8)}\right]\right\rangle = \frac{\pi}{18}\left\langle 0\left|O_8^{\eta_Q}\left[{}^1P_1\right]\right|0\right\rangle.\end{aligned} \quad (5)$$

For the η_c meson they are [56]

$$\begin{aligned}&\left|R_{cc}(0)\right|^2 \approx 0.58\ \mathrm{GeV}^3, \\ &1.5 \times 10^{-3}\ \mathrm{GeV}^3 < \left\langle O_S^{\eta_c}\right\rangle < 5.3 \times 10^{-3}\ \mathrm{GeV}^3, \\ &\left\langle O_P^{\eta_c}\right\rangle = \frac{\pi}{18} \times 3 \times \left\langle O^{J/\psi}\left({}^3P_0^{[8]}\right)\right\rangle \\ &= \frac{\pi}{6} \times m_c^2 \times (1.7 \pm 0.5) \times 10^{-2}\ \mathrm{GeV}^3,\end{aligned} \quad (6)$$

and for η_b meson they are [85, 86]

$$\begin{aligned}|R_{bb}(0)|^2 &\approx 5.3\,\text{GeV}^3,\\ \langle O_S^{\eta_b}\rangle &\approx 0.01\,\text{GeV}^3,\\ \langle O_P^{\eta_b}\rangle &= \frac{\pi}{18}\times 3\times\left\langle O_8^{\gamma(1s)}\left({}^3P_0\right)\right\rangle\\ &= \frac{5\pi}{6}\times m_b^2\times(0.0121\pm 0.040)\ \text{GeV}^3,\end{aligned} \tag{7}$$

where m_c (m_b) is the mass of charm (bottom).

In the semielastic resolved photoproduction g-g processes, the parton (gluon) a from resolved photon of the incident nucleus A interacts with the parton (gluon) b of another incident nucleus B, and the cross section is given by

$$\begin{aligned}\frac{d\sigma^{\text{semi.}}_{AB\to\eta_Q X}}{dp_T^2dy} &= \int dx_a dx_b f_{\gamma/N}(x_a)\, f_{g/\gamma}\left(z_a, Q^2\right)\\ &\cdot f_{g/B}\left(x_b, Q^2\right)\frac{x_a x_b z_a}{x_a x_b - x_a x_2}\frac{d\hat{\sigma}}{d\hat{t}}(gg\longrightarrow\eta_Q g),\end{aligned} \tag{8}$$

where $f_{\gamma/N}(x_a)$ is the photon spectrum of the nucleus, and $f_{g/\gamma}(z_a, Q^2)$ is the parton distribution function of the resolved photon [87].

For p-p collisions, the photon spectrum function of a proton can be written as [88–90]

$$\begin{aligned}f_{\gamma/p}(x) &= \frac{\alpha}{2\pi x}\left[1+(1-x)^2\right]\\ &\cdot\left[\ln A_p - \frac{11}{6} + \frac{3}{A_p} - \frac{3}{2A_p^2} + \frac{1}{3A_p^3}\right],\end{aligned} \tag{9}$$

where x is the momentum fraction of photon, $A_p = 1 + 0.71\,\text{GeV}^2/Q^2_{\text{min}}$, with

$$\begin{aligned}Q^2_{\text{min}} &= -2m_p^2 + \frac{1}{2s}\left[\left(s+m_p^2\right)\left(s-xs+m_p^2\right)\right.\\ &\left.-\left(s-m_p^2\right)\sqrt{\left(s-xs-m_p^2\right)^2 - 4m_p^2 xs}\right].\end{aligned} \tag{10}$$

Here m_p is the mass of the proton and at high energies Q^2_{min} is given by $m_p^2x^2/(1-x)$.

For Pb-Pb collisions, the photon spectrum obtained from a semiclassical description of high energy electromagnetic collisions for low photon energies is given by [91, 92]

$$f_{\gamma/N} = \frac{2Z^2\alpha}{\pi\omega}\ln\left(\frac{\gamma}{\omega R}\right), \tag{11}$$

where ω is the photon energy, and $R = b_{\text{min}}$ is the nucleus radius.

In inelastic resolved photoproduction g-g processes, the parton (gluon) a' from resolved photon emitted by the charged parton a of the incident nucleus A interacts with the parton (gluon) b of another incident nucleus B, and the expression of the cross section is given by

$$\begin{aligned}\frac{d\sigma^{\text{inel.}}_{AB\to\eta_Q X}}{dp_T^2dy} &= \int dx_a dx_b dz_a f_{q/A}\left(x_a, Q^2\right) f_{\gamma/q}(z_a)\\ &\cdot f_{g/\gamma}\left(z'_a, Q^2_\gamma\right)\times f_{g/B}\left(x_b, Q^2\right)\\ &\cdot\frac{x_a x_b z_a z'_a}{x_a x_b z_a - x_a z_a x_2}\frac{d\hat{\sigma}}{d\hat{t}}(gg\longrightarrow\eta_Q g),\end{aligned} \tag{12}$$

where $f_{\gamma/q}(z)$ is the photon spectrum from the charged parton of the incident nucleus. In relativistic hadron-hadron and nucleus-nucleus collisions [69] we have

$$\begin{aligned}f_{\gamma/q}(x) &= \frac{\alpha}{\pi}e_Q^2\left\{\frac{1+(1-x)^2}{x}\left(\ln\frac{E}{m}-\frac{1}{2}\right)\right.\\ &\left.+\frac{x}{2}\left[\ln\left(\frac{2}{x}-2\right)+1\right]+\frac{(2-x)^2}{2x}\ln\left(\frac{2-2x}{2-x}\right)\right\},\end{aligned} \tag{13}$$

with x being the photon momentum fraction.

3. Numerical Results

In ultrarelativistic high energy nucleus-nucleus collisions, the equivalent photon spectrum obtained with a semiclassical description of high energy electromagnetic collisions for the nucleus is $f_{\gamma/N} \propto Z^2\ln\gamma$. At LHC energies, the Lorentz factor $\gamma = E/m_N = \sqrt{s_{NN}}/2m_N \gg 1$ becomes very important. Indeed, the equivalent photon spectrum function with Weizsäcker-Williams approximation for the proton is $f_{\gamma/p} \propto \ln A \propto \ln(s_{NN}/m_p^2)$, where m_p is the proton mass and $\sqrt{s_{NN}}$ is the centre-of-mass energy per nucleon pair. Since $\sqrt{s_{NN}}$ is very high, the photon spectrum function becomes very large. Therefore the contribution of η_Q meson produced by semielastic hard photoproduction g-g processes cannot be negligible at LHC energies. For the inelastic photoproduction processes, the equivalent photon spectrum function of the charged parton is $f_{\gamma/q} \propto \ln(E/m_q) = \ln(\sqrt{s_{NN}}/2m_q) + \ln(x)$, where m_q is the charged parton mass. Hence, the photon spectrum for the charged parton becomes prominent at LHC energies. The numerical results of our calculations for large-p_T η_Q mesons produced by the hard photoproduction gluon-gluon processes in relativistic heavy ion collisions are plotted in Figures 1 and 2.

In Figure 1 (Figure 2), we plot the contributions from the hard photoproduction gluon-gluon processes to the η_c (η_b) meson at midrapidity in p-p and Pb-Pb collisions at LHC energies. Compared with the production of the initial gluon-gluon interaction (the dashed line), the contribution of $\eta_{c,b}$ meson produced by semielastic hard photoproduction g-g processes (the dotted line) is not prominent in p-p collisions with $\sqrt{s_{NN}} = 7.0$ TeV and $\sqrt{s_{NN}} = 14.0$ TeV, but the contribution of inelastic photoproduction g-g processes (the dashed-dotted line) becomes evident in p-p collisions [see Figures 1(a), 1(b), 2(a), and 2(b)]. Indeed, for Pb-Pb

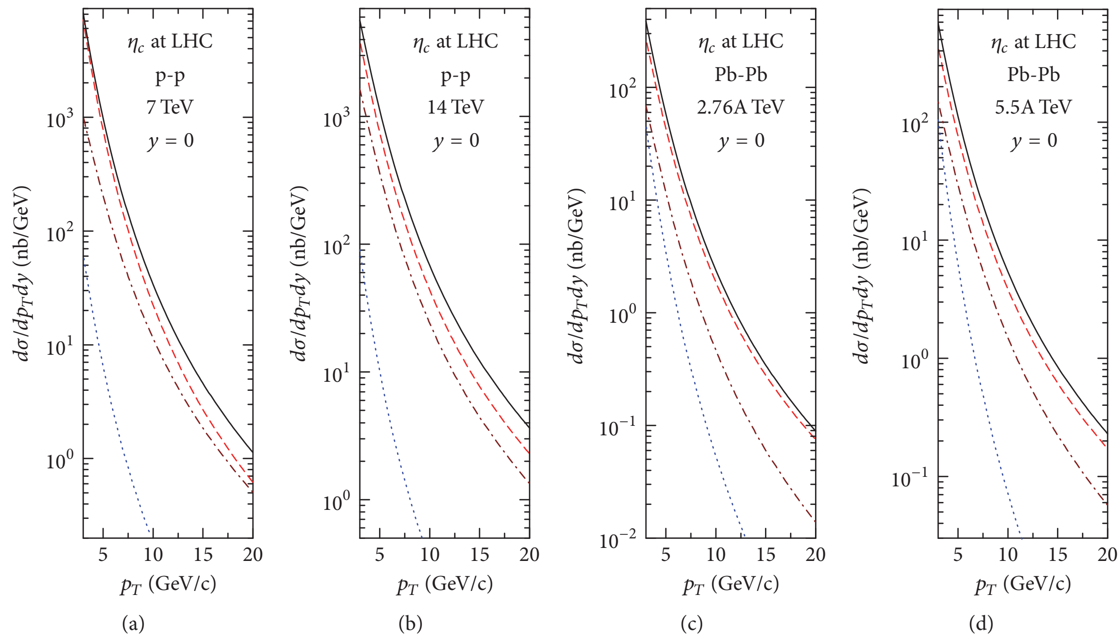

FIGURE 1: The invariant cross section of large-p_T η_c meson production from gluon-gluon interaction at midrapidity in p-p collisions ($\sqrt{s}$ = 7.0 TeV and $\sqrt{s}$ = 14.0 TeV) and Pb-Pb collisions ($\sqrt{s}$ = 2.76 TeV and $\sqrt{s}$ = 5.5 TeV) at the LHC. The dashed line (red line) is for the initial gluon-gluon interaction (LO), the dotted line (blue line) for the semielastic hard photoproduction g-g processes (semi.), the dashed-dotted line (wine line) for the inelastic hard photoproduction g-g processes (inel.), and the solid line (black line) for the sum of the above processes.

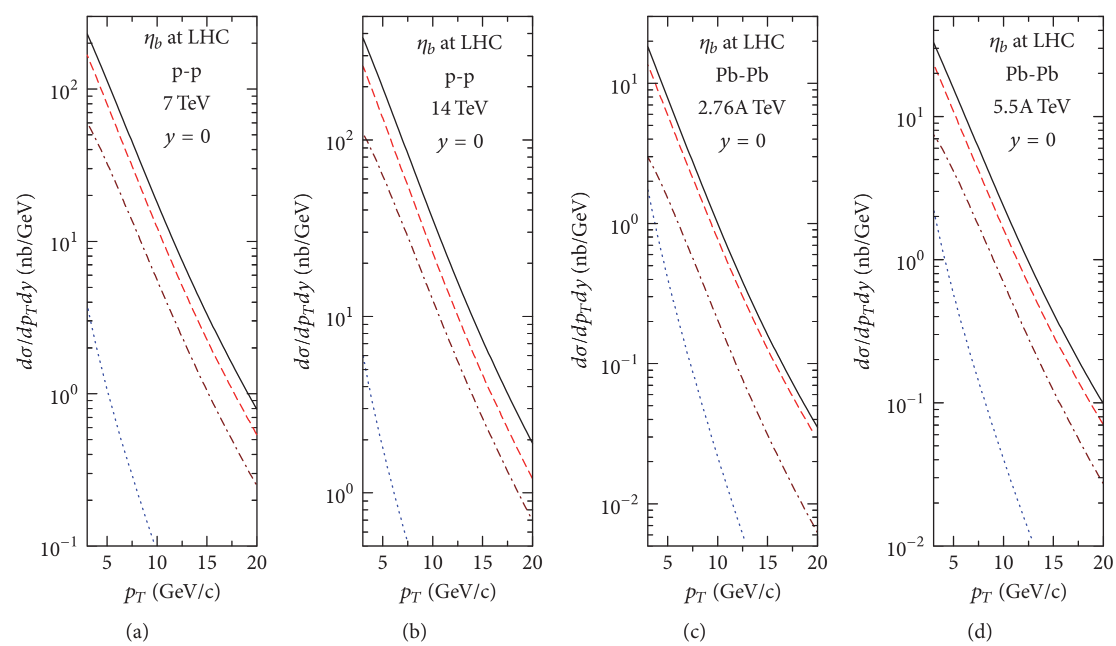

FIGURE 2: The same as Figure 1 but for large-p_T η_b meson production from gluon-gluon interaction at midrapidity in p-p and Pb-Pb collisions at the LHC.

collisions with $\sqrt{s_{NN}}$ = 2.76 TeV and $\sqrt{s_{NN}}$ = 5.5 TeV, the contribution of semielastic photoproduction g-g processes (the dotted line) and inelastic photoproduction g-g processes (the dashed-dotted line) cannot be negligible at LHC energies [see Figures 1(c), 1(d), 2(c), and 2(d)].

4. Conclusions

In summary, we have investigated the production of heavy quarkonium $\eta_{c,b}$ meson from the gluon-gluon interactions in p-p collisions and Pb-Pb collisions at LHC energies. The color-singlet and color-octet mechanisms have been used for heavy quarkonium production processes. At the early stages of relativistic high energy nucleus-nucleus collisions, the ultrarelativistic nucleus (charged parton) can emit hadron-like photons that can fluctuate into a gluon; then the gluon interacts with a gluon of the other incident nucleus by gluon-gluon interaction. Our results indicate that the contribution of $\eta_{c,b}$ meson produced by the hard photoproduction processes cannot be negligible in p-p and Pb-Pb collisions at LHC energies.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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