Real photons produced from photoproduction in pp collisions

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We calculate the production of real photons originating from the photoproduction in relativistic pp collisions. The Weizsäcker-Williams approximation in the photoproduction is considered. Numerical results agree with the experimental data from Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC). We find that the modification of the photoproduction is more prominent in large transverse momentum region.

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Since photons do not participate in the strong interaction, the observation of prompt photons from the hadron collisions is a good method to test the perturbative Quantum Chromodynamics (pQCD). The application of pQCD for various hard scattering processes of the prompt photon production has been investigated [1–6]. It is necessary to identify different prompt photon sources in relativistic hadronic collisions. The hard scattering of partons is a well-known source of large transverse momentum ($P_T$) photons in high energy hadronic collisions. The prompt photons include direct photons and fragmentation photons [7–9]. The direct photons are those produced by the Compton scattering ($qg \rightarrow q\gamma$) and the annihilation of two partons ($q\bar{q} \rightarrow g\gamma$). The fragmentation photons are those produced by the bremsstrahlung emitted from final state partons ($ab \rightarrow (c \rightarrow x\gamma)d$). Previous works have studied the next-to-leading-order (NLO) contributions of the prompt photon production [10, 11], but the contributions of the photoproduction (higher-order) in the pp collisions are not researched clearly.

The photoproduction is an important concept in the $ep$ deep inelastic scattering (DIS) at Hadron Electron Ring Accelerator (HERA) [12–14]. In the $ep$ DIS, the electron interacts with the partons of the proton by exchanging a photon, a high energy photon emitted from the incident electron ($e \rightarrow e\gamma$) directly interacts with the proton by the interaction of $\gamma p \rightarrow X$ (photoproduction). Besides, the Heisenberg’s uncertainty principle allows the high energy photon for a short time to fluctuate into a quark-antiquark pair which then interacts with the partons of the proton (resolved photoproduction). In such interactions the photons emitted from the incident electron can be regarded as an extended object consisting of quarks and gluons. The photons are the so-called resolved photons ($\gamma_{\text{resolved}}$).

In this work, we study the large $P_T$ photons from the photoproduction mechanism by considering the Weizsäcker-Williams approximation in relativistic pp collisions. The charged partons of the incident proton can emit high energy photons ($q \rightarrow q\gamma$) and resolved photons ($q \rightarrow q\gamma_{\text{resolved}}$) in relativistic pp collisions [15–19], then the high energy photons or resolved photons interact with the partons of another proton by the subprocesses of $q\gamma \rightarrow q\gamma$, $q\bar{q} \rightarrow g\gamma$, $q\gamma \rightarrow g\gamma$, $q\gamma \rightarrow q\gamma$ and $g\gamma \rightarrow q\gamma$, here $q_\gamma$ denotes the parton of the resolved photon.

The prompt photons produced by the leading-order (LO) QCD Compton scattering, annihilation, and bremsstrahlung from final state partons have been discussed by previous works [1, 9, 10]. In this Letter we focus on the higher-order modification: the photoproduction. In the photoproduction, a parton $q_a$ of an incident proton $A$ emits a high energy photon ($q_a \rightarrow q\gamma$), then the photon interacts with a parton $q_b$ of another incident proton $B$ by the interaction of $\gamma p \rightarrow \gamma X$. The momentum transfer $Q^2$ in the deep inelastic collisions is large, so the perturbative factorization is applicable. The large $P_T$ photons produced by photoproduction (pho.) satisfy the following invariant cross section [15, 16]

\[
E \frac{d^2 \sigma_{\text{pho.}}}{d^3 P} = \frac{2}{\pi} \int_{x_{\text{amin}}}^{1} dx_a \int_{b_{\text{min}}}^{1} dx_b F_{q_a/A}(x_a, Q^2) \times F_{q_b/B}(x_b, Q^2) f_{\gamma/q_a}(z_a) \frac{x_a x_b z_a}{x_a x_b - x_a x_b} \times \frac{d\hat{t}}{d\hat{t}}(x_a, x_b, z_a, P_T),
\]

where $x_a$ and $x_b$ are the momentum fractions of partons, $F_{q_a/A}(x_a, Q^2)$ and $F_{q_b/B}(x_b, Q^2)$ are the parton distribution of the proton [20], we choose $Q^2 = 4P_T^2$ in the distribution [7]. $f_{\gamma/q_a}(z_a)$ is the photon spectrum from the quark $q_a$. The cross section of LO subprocesses $d\hat{t}/d\hat{t}$ is QED Compton scattering $q\gamma \rightarrow q\gamma$. The minimum values of $x_a$ and $x_b$ in the integral are

\[
x_{\text{amin}} = \frac{x_1}{1 - x_2},
\]

and

\[
x_{\text{bmin}} = \frac{x_a x_2}{x_a - x_1}.
\]

The momentum fraction $z_a$ of the photon emitted from the quark is

\[
z_a = \frac{x_b x_1}{x_a x_b - x_a x_2},
\]

where the variables are

\[
x_1 = \frac{1}{2} P_T e^y.
\]

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and
\[ x_2 = \frac{1}{2} x_T e^{-y}, \]  
(6)
and
\[ x_T = \frac{2 P_T}{\sqrt{s_{NN}}} \]  
(7)

here \( \sqrt{s_{NN}} \) is the total energy in the center-of-mass system, and \( y \) is the rapidity of the real photons.

The pQCD requests the QCD momentum transfer \( Q^2 > 1 \text{ GeV}^2 \) [19]. In the photoproduction high energy photons are bremsstrahlung from the charged particles, this is a pure QED process. Since the QCD coupling parameter \( \alpha_s(Q^2) \) does not depend on the QED momentum transfer \( q^2 \), the Weizsäcker-Williams approximation of the photoproduction is still valid for the charged partons of protons [18, 19]. Therefore the photon spectrum from the quark can be described by the Weizsäcker-Williams distribution

\[ f_{\gamma/q_a}(z_a) = \int_{q_{2\min}^a}^{q_{2\max}^a} dq^2 \frac{dN_q}{dz \, dq^2} = \frac{e_q^2 \alpha_{Pq} P_{q\rightarrow\gamma}(z_a)}{2\pi} \left[ \ln \left( \frac{(\sqrt{s_{NN}})^2}{4 m_q^2} \right) + \ln \left( \frac{x_a x_b (1 - z_a)}{z_a} \right) \right] \]

\[ -\frac{e_q^2 \alpha_{Pq}}{\pi} \left( \frac{1 - z_a}{z_a} - \frac{4 m_q^2}{x_a x_b s_{NN}} \right), \]
(8)

where \( e_q \) is the charge of the quark, \( \alpha \) is the electromagnetic coupling parameter, \( P_{q\rightarrow\gamma}(z_a) = (1 + (1 - z_a)^3) / z_a \) is the split function. The maximum momentum transfer \( q_{2\max}^a \) is determined by the experimental acceptance [12]. According to [19] we choose \( q_{2\max}^a = \hat{s}/4 \). By considering the Weizsäcker-Williams approximation, the kinematic limit of minimum momentum transfer \( q_{2\min}^a = (m_q z_a)^2 / (1 - z_a) \) is made such that the photon is close to being on its mass shell [13, 14]. Here \( m_q \) is the mass of the quark. The photoproduction contain higher-order QED coupling parameters, but the collision energies at RHIC (\( \sqrt{s_{NN}} = 200 \text{ GeV} \)) and LHC (\( \sqrt{s_{NN}} = 5500 \text{ GeV} \)) are large enough. Therefore the values of the term \( \ln ((\sqrt{s_{NN}})^2 / 4 m_q^2) \) in Eq. (8) enhance the modification of the photoproduction [15].

The QED Compton process \( (q_b \gamma \rightarrow q \gamma) \) can be written as [7]

\[ \frac{d\sigma}{d^2 \mathbf{t}}(q\gamma \rightarrow q\gamma) = \frac{\pi \alpha^2 e_q^2}{s^2} 2 \left( \frac{\hat{t}}{\hat{s}} - \frac{\hat{s}}{\hat{t}} \right), \]
(9)

where the Mandelstam variables are
\[ \hat{s} = x_a x_b z_a s_{NN}, \]
(10)
and
\[ \hat{t} = -x_a x_2 z_a s_{NN}. \]
(11)

The high energy photon emitted from the quark of the proton can fluctuate into a parton anti-parton pair in a short period of time \( \Delta t \). Besides the (anti-)quarks may emit gluons in the time \( \Delta t \). If, during such a fluctuation, one of the partons from the fluctuated photon interacts with partons of another incident proton. In such interaction the high energy photon is resolved [12–14]. In the resolved photoproduction, the parton \( q_a \) of the incident proton \( A \) emits a high energy resolved photon \( (q_{\text{resolved}} \rightarrow q_a \gamma_{\text{resolved}}) \), then the parton of the resolved photon \( (q_{\text{resolved}} \rightarrow q_a' \gamma'_{\text{resolved}}) \) interacts with the parton \( (q_b \) or \( q_b') \) of another incident proton \( B \) by the interaction of \( \gamma_{\text{resolved}} \rightarrow p \rightarrow \gamma X \). The corresponding invariant cross section of large \( P_T \) photons produced by resolved photoproduction (res. pho.) can be written as [15, 16]

\[ E \frac{d\sigma_{\gamma \rightarrow \gamma}}{d^3 p} = \frac{2}{\pi} \int_{x_{a_{\min}}}^{1} dx_a \int_{x_{b_{\min}}}^{1} dx_b \int_{z_{a'_{\min}}}^{1} d z_{a'}, \]

\[ \times F_{q_a/A}(x_a, Q^2) F_{q_b/B}(x_b, Q^2) f_{\gamma/q_a}(z_a) \]

\[ \times F_{q_a'/\gamma} (z_{a'}, Q^2) \frac{x_a x_b z_a z_{a'}}{x_a x_b z_a' - x_a z_{a'} x_2} \]

\[ \times \frac{d\hat{s}}{d\hat{t}}(x_a, x_b, z_a, z_{a'}, P_T), \]
(12)

where \( z_{a'} \) is the momentum fraction of partons from the resolved photon, and \( F_{q_a'/\gamma}(z_{a'}, Q^2) \) is the parton distribution of the resolved photon [21]. The minimum values of momentum fractions are

\[ x_{a_{\min}} = \frac{x_1}{1 - x_2}, \]
(13)

**FIG. 1.** The cross section of the real photon production in relativistic pp collisions at RHIC. The dash line is the sum of direct photons and fragmentation photons [15]. The dash dot line represents photons produced by the photoproduction and resolved photoproduction. The solid line is the sum of direct photons, fragmentation photons and photons from the photoproduction and resolved photoproduction. Data points are from PHENIX at RHIC [2].
and

\[ x_{b_{min}} = \frac{x_a x_2}{x_a - x_1}, \]

and

\[ z_{a_{\min}} = \frac{x_b x_1}{x_a x_b - x_a x_2}. \]

The variable \( z_a \) of the resolved photon is given by

\[ z_a = \frac{x_b x_1}{x_a x_b z_{a'} - x_a z_{a'} x_2}. \]

In the resolved photoproduction, the photon spectrum from the quark \( q_a \) can be written as

\[
f_{\gamma/q_a}(z_a) = \frac{e_q^2 \alpha P_f \gamma(\beta)}{2\pi} \left[ \ln \left( \frac{\sqrt{s_{NN}}}{2m_q^2} \right) + \ln \left( \frac{x_a x_b z_{a'}(1 - z_a)}{z_a} \right) \right] - \frac{e_q^2 \alpha}{\pi} \left( \frac{1 - z_a}{z_a} - \frac{4m_q^2}{x_a x_b z_{a'} s_{NN}} \right). \tag{17}\]

The cross section \( d\hat{\sigma} / d\hat{t} \) of the annihilation and Compton scattering \((q_a q_b \rightarrow g\gamma, q_a q_b \rightarrow g\gamma, q_a q_b \rightarrow q\gamma, g_a q_b \rightarrow q\gamma)\) are given by [1, 7]

\[
\frac{d\hat{\sigma}}{d\hat{t}}(q\bar{q} \rightarrow g\gamma) = \frac{\pi \alpha_s e_q^2}{s^2} \frac{8}{9} \left( \frac{\hat{u} + \hat{t}}{\hat{u}} \right), \tag{18}\]

and

\[
\frac{d\hat{\sigma}}{d\hat{t}}(qg \rightarrow q\gamma) = \frac{\pi \alpha_s e_q^2}{s^2} \frac{1}{3} \left( \frac{\hat{u}}{\hat{s}} - \frac{\hat{s}}{\hat{t}} \right), \tag{19}\]

where the strong coupling constant is

\[ \alpha_s = \frac{12\pi}{(33 - 2n_f) \ln(Q^2/\Lambda^2)}. \tag{20}\]

The large momentum variable is \( Q^2 = 4P_T^2 \) and the momentum scale is \( \Lambda_{LO} = 0.2 \text{ GeV} \) [7]. \( n_f \) is the flavor number. The Mandelstam variables in resolved photoproduction are

\[ \hat{s} = x_a x_b z_q z_q' s_{NN}, \tag{21}\]

and

\[ \hat{t} = -x_a x_2 z_q z_q' s_{NN}, \tag{22}\]

and

\[ \hat{u} = -x_b x_1 s_{NN}. \tag{23}\]

In Fig.1 and 2 we plot the contribution of prompt photons and photons produced from photoproductions for relativistic \( pp \) collisions at RHIC and LHC energies. Except the leading QCD Compton and annihilation subprocesses, the pure QED annihilation \( q\bar{q} \rightarrow \gamma\gamma \) (res.pho.) and QCD-induced gluon-photon coupling \( g\gamma \rightarrow g\gamma \) (pho.), \( g\gamma \rightarrow \gamma\gamma \) (pho.), \( g\gamma \rightarrow g\gamma \) (res.pho.) and \( gg \rightarrow \gamma\gamma \) (res.pho.) [23] are considered in the subprocesses. The correction factors to take into account the NLO effect of subprocesses of direct photons and fragmentation photons are \( K_{dir.\gamma} \) and \( K_{frac.\gamma} \). We evaluate these \( P_T \)-dependent \( K \) factors using the numerical program from Aurenche et al [11]. The authors of Ref. [10] have obtained \( K_{dir.\gamma}(10 \text{ GeV}) \sim 1.5 \) for RHIC and LHC and \( K_{frac.\gamma}(10 \text{ GeV}) \sim 1.8 \) at RHIC and 1.4 at LHC.

In Fig.1 the spectra of the photoproduction and resolved photoproduction (dash dot line) are compared with the spectra of direct photons and fragmentation photons (dash line). The numerical results show that the modification of photoproductions is not prominent in the relatively small \( P_T \) region. The modification of the photoproductions is weak in the relatively small \( 5 \text{ GeV} < P_T < 16 \text{ GeV} \) at RHIC energies. However, the photoproductions start playing an interesting role in large \( P_T \) region at LHC energies. The modification in the region of 20 GeV < \( P_T < 200 \text{ GeV} \) is almost 33% at LHC (Fig.2).

In conclusion, the photoproductions are very important in the \( ep \) deep inelastic collisions at HERA, we extend the photoproduction mechanism to the real photon production in the \( pp \) collisions at RHIC and LHC energies. Based on the Weizsäcker-Williams approximation, we derive the high energy photon spectrum from the charged partons, and study the cross section of the photoproduction and resolved photoproduction. The photon spectrum from the charged parton depends on the collision energies, and the photoproductions can produce large \( P_T \) photons at RHIC and LHC. The numerical results show that the photoproductions contribute an active modification for the direct photons and fragmentation photons production. The modification of photoproductions is weak in the relatively small \( P_T \), but becomes important in the large \( P_T \) region.

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