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Inclusive photon production in proton-proton collisions

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Production of photons in proton-proton collisions is studied in the quark-parton-model context. The processes considered are $p+p\rightarrow\gamma+X$, $p+p\rightarrow\gamma+\gamma+X$, $p+p\rightarrow\gamma+$gluon jet $+X$, and $p+p\rightarrow\gamma+$quark jet $+X$. It is shown that the strong coupling constant and the gluon momentum-distribution function in the proton can be determined by measuring these cross sections.

I. INTRODUCTION

Deep-inelastic lepton-nucleon experiments[1] in which the short-distance structure of a nucleon is probed indicate that hadrons are made of a number of pointlike constituents.[2] This has been most successfully described by the quark-parton model (QPM)[3,4] where the pointlike particles are quarks and gluons. When the QPM is applied to hadron-hadron reactions one expects that the presence of partons will show up most evidently in the large transverse momentum phenomena. Those large-p_t processes are considered to be dominated by the large-angle scattering of quarks and gluons.

In this paper we would like to study a class of reaction, $p+p\rightarrow\gamma+X$ which provides a test of QPM and also serves to obtain information about the strong coupling constant α_s and gluon momentum-distribution functions. For this purpose we take the quark distributions obtained from deep-inelastic phenomena. Out of several proposed distribution functions we choose a modified Kuti-Weisskopf (MKW) function, following Tuan *et al.*[3,5] The functions are

$$\begin{aligned} u(x) &= 1.79(1-x)^3x^{-1/2}(1+2.3x)+0.1(1-x)^{7/2}x^{-1}\,,\\ d(x) &= 1.107(1-x)^{3.1}x^{-1/2}+0.1(1-x)^{7/2}x^{-1}\,, \qquad (1)\\ \bar{u}(x) &= \bar{d}(x)=s(x)=\bar{s}(x)=0.1(1-x)^{7/2}x^{-1}\,, \end{aligned}$$

where $x=$ (quark momentum)/(proton momentum). There are good reasons to believe[6] that strong interactions can be described by quantum chromodynamics (QCD), whose gauge group is $SU(3)_{\rm color}$. So we take the color gauge boson as our gluon.

In Sec. II, we compute the cross sections of three processes $p+p\rightarrow\gamma+\gamma+X$, $p+p\rightarrow\gamma+$gluon jet $+X$, $p+p\rightarrow\gamma+$quark jet$+X$ and show how to measure α_s and gluon distribution functions. In Sec. III, the inclusive process $p+p\rightarrow\gamma+X$ is considered and a discussion is given.

II. SEMI-INCLUSIVE PHOTON PROCESS

In the $p+p\rightarrow\gamma+X$ process, we assume that photons are produced via collision of partons. It is well known from deep-inelastic lepton-hadron scatterings that a proton has gluons besides valence and sea quarks as its pointlike constituents.[2] So the elementary scatterings to be considered are $q+\bar{q}\rightarrow\gamma+\gamma$, $q+\bar{q}\rightarrow\gamma+$gluon, and $q+$gluon$\rightarrow q+\gamma$ as shown in Fig. 1.

Let us consider the annihilation process first. The cross sections are

$$\frac{d\sigma}{dt'}(q+\bar{q}\rightarrow\gamma+\gamma)=\frac{2\pi}{3}\alpha^2 e_q^{\,4}\frac{1}{s'^2}\left(\frac{t'}{u'}+\frac{u'}{t'}\right), \qquad (2)$$

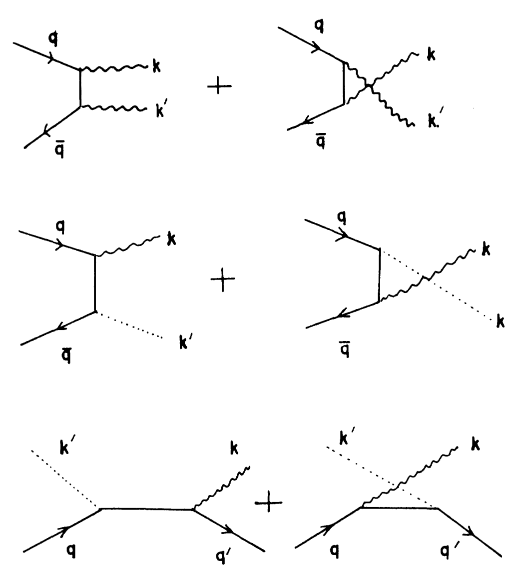

FIG. 1. Feynman diagrams of parton scatterings which produce photons. Quarks, gluons, and photons are denoted by solid, dotted, and wiggly lines, respectively.

$$\frac{d\sigma}{dt'}(q+\bar{q}\to\gamma+\text{gluon})=\frac{8\pi}{9}\alpha\alpha_s e_q^{\,2}\frac{1}{s'^2}\left(\frac{t'}{u'}+\frac{u'}{t'}\right), \tag{3}$$

where $s'=(q+\bar{q})^2$, $t'=(q-k)^2$, $u'=(\bar{q}-k)^2$ ($q,\bar{q}$, and k denote the momentum of the quark, antiquark, and outgoing photon, respectively. e_q denotes the quark charge in units of e). The strong coupling constant is g_s and $\alpha_s=g_s^{\,2}/4\pi$. Quark mass is neglected throughout this paper and the gluon is massless, following the QCD idea.

Now we calculate the cross section for the reaction $p+p\to\gamma+\text{gluon jet}+X$ by integrating over all quark-parton momentum distributions. For this we define two new variables,

$$\nu_1=p\cdot(k+k')=p\cdot(x_1p+x_2p')\simeq x_2\frac{s}{2}, \tag{4}$$

$$\nu_2=p'\cdot(k+k')=p'\cdot(x_1p+x_2p')\simeq x_1\frac{s}{2}, \tag{5}$$

where p, p', and k' denote the momentum of the incoming proton is x_1 and in the target is x_2. The differential cross section is

$$\begin{aligned}\frac{d^3\sigma}{dtd\nu_1d\nu_2}(\gamma+\text{gluon jet}+X)&=\frac{8\pi\alpha\alpha_s}{9}\frac{1}{s^2}\int_0^1\int_0^1 dx_1dx_2\left[\frac{x_1}{(x_1x_2)^2}\left(\frac{t}{u}\frac{x_1}{x_2}+\frac{u}{t}\frac{x_2}{x_1}\right)\delta\left(\nu_1-\frac{s}{2}x_2\right)\right.\\&\qquad\left.\times\,\delta\left(\nu_2-\frac{s}{2}x_1\right)D_1(x_1,x_2)\right]+(p\leftrightarrow p')\\&=\frac{4\pi\alpha\alpha_s}{9}\frac{1}{s}\frac{1}{\nu_1^{\,2}\nu_2}\left(\frac{t}{u}\frac{\nu_2}{\nu_1}+\frac{u}{t}\frac{\nu_1}{\nu_2}\right)D_1\left(\frac{2\nu_2}{s},\frac{2\nu_1}{s}\right)+(p\leftrightarrow p'),\end{aligned} \tag{6}$$

where $s=(p+p')^2$, $t=(p-k)^2$, $u=(p'-k)^2$, and

$$D_1(x_1,x_2)=(\tfrac{2}{3})^2u(x_1)\bar{u}(x_2)+(\tfrac{1}{3})^2d(x_1)\bar{d}(x_2)+(\tfrac{1}{3})^2s(x_1)\bar{s}(x_2). \tag{7}$$

We restrict ourselves to the special case of both the photon and the gluon jet coming out at 90° in the c.m. system. In this special case ($\nu_1=\nu_2$, $x_1=x_2$, $t=u$), we have

$$E_\gamma\left.\frac{d^3\sigma}{dE_\gamma d\cos\theta_\gamma\, d\cos\theta_{\text{jet}}}\right|_{\theta_\gamma=\theta_{\text{jet}}=90^\circ}=\frac{4\pi}{18}\alpha\alpha_s\frac{1}{E^2}D_1(x), \tag{8}$$

where $x=E_\gamma/E$, E = energy of a proton in the c.m. system, and E_γ = energy of the outcoming photon.

In a similar way we calculate the cross section for the process $p+p\to\gamma+\gamma+X$; the result for the two photons emerging at $\theta_{\text{c.m.}}=90°$ is

$$E_\gamma\left.\frac{d^3\sigma}{dE_\gamma d\cos\theta_\gamma\, d\cos\theta_{\gamma'}}\right|_{\theta_\gamma=\theta_{\gamma'}=90^\circ}=\frac{\pi}{6}\alpha^2\frac{1}{E^2}D_2(x), \tag{9}$$

where $x=E_\gamma/E$, and

$$D_2(x)=(\tfrac{2}{3})^4u(x)\bar{u}(x)+(\tfrac{1}{3})^4d(x)\bar{d}(x)+(\tfrac{1}{3})^4s(x)\bar{s}(x). \tag{10}$$

Comparing Eqs. (8) and (9) we can obtain α_s as a ratio of two measured cross sections, i.e.,

$$\alpha_s=\frac{3\alpha}{4}\frac{D_2(x)}{D_1(x)}\left[\left.\frac{d^3\sigma(\gamma+\text{gluon jet}+X)}{dE_\gamma d\cos\theta_\gamma\, d\cos\theta_{\text{jet}}}\right|_{90^\circ}\Big/\left.\frac{d^3\sigma(\gamma+\gamma+X)}{dE_\gamma d\cos\theta_\gamma\, d\cos\theta_{\gamma'}}\right|_{90^\circ}\right]. \tag{11}$$

Applying the particular distributions Eq. (1), one may notice that $D_2(x)/D_1(x)$ is a slowly varying bounded function having its value between $\frac{2}{9}(x\to 0)$ and $\frac{4}{9}(x\to 1)$. The measurement of α_s as a function of gluon jet momentum is very desirable because it provides a good test of present popular models of hadron interactions such as QCD, asymptotic freedom,[7] and QPM. These theories predict that α_s must be small at high momentum and approach zero logarithmically as a function of gluon momentum. Since we assumed α_s is small in deriving Eq. (11), the measurement of α_s using Eq. (11) becomes consistent only when α_s turns out to be small. At the same time experiments should also show the scaling behavior of the cross sections, i.e.,

$$E^2E_\gamma \frac{d^3\sigma}{dE_\gamma\, d\cos\theta_\gamma\, d\cos\theta_{\rm jet}}\bigg|_{\theta=90^\circ}$$

is a function of $x(E_\gamma/E)$ only.

Experiments measuring two outgoing particles at 90° in the c.m. system are especially suitable in the colliding-beam facilities such as CERN ISR and the future Fermilab colliding-beam facility. Experimentally, gluon jets may have different characters from quark jets which will be discussed shortly. On the average, a gluon jet will have zero baryon number and $SU(3)_{\rm flavor}$ singlet quantum numbers.[8]

Let us turn to the inverse Compton scattering $q+\text{gluon}\to q+\gamma$. The elementary cross section is

$$\frac{d\sigma}{dt'}=\frac{-\pi}{3}\alpha\alpha_s e_q^2\frac{1}{s'^2}\left(\frac{u'}{s'}+\frac{s'}{u'}\right), \tag{12}$$

where $s'=(q+k')^2$, $t'=(k'-k)^2$, $u'=(q-k)^2$ (q,k,k' are the momenta of incoming quark, photon, and gluon, respectively). The cross section for the process $p+p\to\gamma+\text{quark ket}+X$ is

$$\begin{aligned}\frac{d^3\sigma}{dtd\nu_1 d\nu_2}(\gamma+\text{quark jet}+X)&=\frac{-\pi}{3}\alpha\alpha_s\frac{1}{s^2}\int_0^1\int_0^1 dx_1dx_2\left[\frac{x_1}{(x_1x_2)^2}\left(\frac{u}{x_1s}+\frac{x_1s}{u}\right)\delta\left(\nu_1-\frac{s}{2}x_2\right)\right.\\&\qquad\left.\times\,\delta\left(\nu_2-\frac{s}{2}x_1\right)D_3(x_1,x_2)\right]+(p\to p')\\&=\frac{-\pi}{6}\alpha\alpha_s\frac{1}{s}\frac{\nu_2}{(\nu_1\nu_2)^2}\left(\frac{u}{2\nu_2}+\frac{2\nu_2}{u}\right)D_3\left(\frac{2\nu_2}{s},\frac{2\nu_1}{s}\right)+(p\to p'),\end{aligned} \tag{13}$$

where

$$D_3(x_1,x_2)=g(x_1)\{(\tfrac{2}{3})^2[u(x_2)+\bar u(x_2)]+(\tfrac{1}{3})^2[d(x_2)+\bar d(x_2)+s(x_2)+\bar s(x_2)]\}. \tag{14}$$

In the special case of both the photon and the quark jet emerging at 90° in the c.m. system, we have

$$E_\gamma\frac{d^3\sigma}{dE_\gamma\, d\cos\theta_\gamma\, d\cos\theta_{\rm jet}}\bigg|_{\theta_\gamma=\theta_{\rm jet}=90^\circ}=\frac{5\pi}{24}\alpha\alpha_s\frac{1}{E^2}D_3(x). \tag{15}$$

The information on gluon distribution can be obtained by comparing the gluon-jet case [Eq. (8)] and the quark-jet case [Eq. (15)]. The ratio between these two cross sections is

$$\frac{D_3(x)}{D_1(x)}=\frac{16}{15}\left[\frac{d^3\sigma(\gamma+\text{gluon jet}+X)}{dE_\gamma\, d\cos\theta_\gamma\, d\cos\theta_{\rm jet}}\bigg|_{90^\circ}\bigg/\frac{d^3\sigma(\gamma+\text{quark jet}+X)}{dE_\gamma\, d\cos\theta_\gamma\, d\cos\theta_{\rm jet}}\bigg|_{90^\circ}\right]^{-1}. \tag{16}$$

For the particular distributions of quarks [Eq. (1)], $D_3(x)/D_1(x)$ becomes simpler as a function of parton distributions,

$$\frac{D_3(x)}{D_1(x)}=\frac{[4u(x)+d(x)+7s(x)]g(x)}{[4u(x)+d(x)+s(x)]s(x)}. \tag{17}$$

Especially in the limiting cases $x\to0$ and $x\to1$, we have

$$\frac{D_3(x)}{D_1(x)}\bigg|_{x\to0}=\frac{2g(0)}{s(0)}, \tag{18}$$

$$\frac{D_3(x)}{D_1(x)}\bigg|_{x\to1}=\frac{g(1)}{s(1)}. \tag{19}$$

Using Eqs. (16)–(19), one can obtain gluon distribution functions from experimental measurements in the energy region where parton processes dominate and scaling behavior becomes evident.

We estimate the cross sections of the processes of Eqs. (8), (9), and (15) at $s=936$ GeV^2, $E_\gamma=2$ GeV to have rough numerical ideas. They are 0.02 nb, 3 nb, and 78 nb for $p+p\to\gamma+\gamma+X$, $\gamma+$"gluon jet"$+X$, and $\gamma+$"quark jet"$+X$, respectively. The cross section of events where a photon and a jet (gluon or quark) of a few GeV in momentum each emerges at large angles in the c.m. system is in the 1~100-nb range.

III. INCLUSIVE PHOTON PROCESS

The inclusive process $p+p\to\gamma+X$ was studied within QPM context by Bjorken *et al.*[9,10] In their paper the elementary parton scattering was $q+\bar q\to\gamma+\gamma$ and gluon effects were mentioned only. In this section

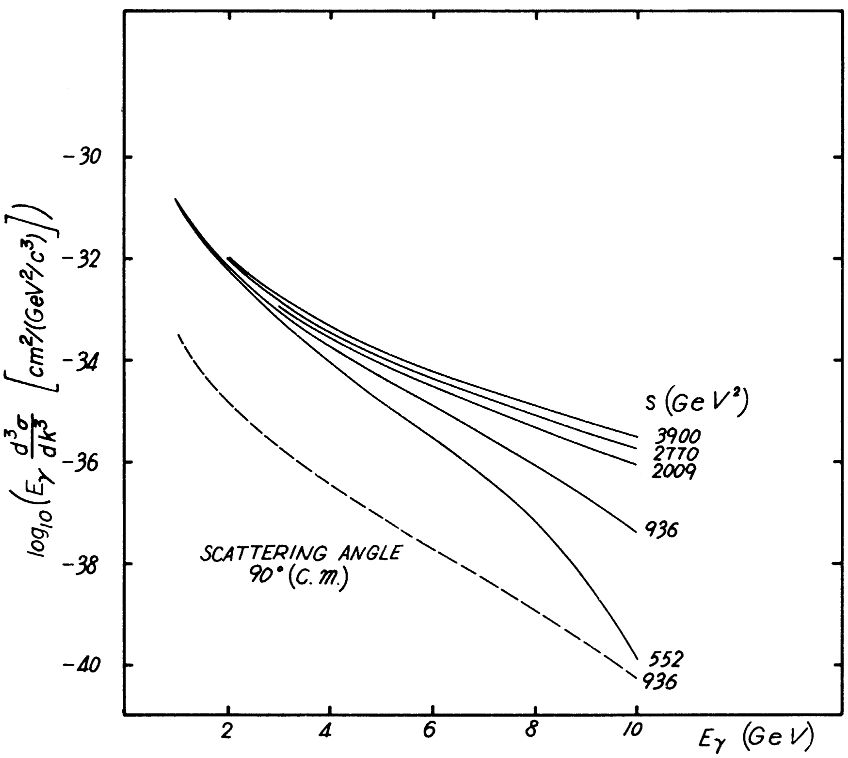

FIG. 2. The differential cross section $E\gamma(d^3\sigma/dk^3)$ of the inclusive process $p+p\to\gamma+X$ at various CERN ISR energies and $\theta_{\text{c.m.}}=90°$. The broken line represents the cross section without gluon effects at the energy $\sqrt{s}=30.6$ GeV.

we compute the one-photon inclusive cross section by adding the three parton processes we studied in Sec. II:

$$E_\gamma\frac{d^3\sigma}{dk^3}=\int_0^1\int_0^1 dx_1dx_2\frac{\delta(x_1x_2s+x_1t+x_2u)}{(x_1x_2s)^2}\left[\tfrac{8}{9}\alpha\alpha_s\left(\frac{x_1t}{x_2u}+\frac{x_2u}{x_1t}\right)D_1(x_1,x_2)+\tfrac{2}{3}\alpha^2\left(\frac{x_1t}{x_2u}+\frac{x_2u}{x_1t}\right)D_2(x_1,x_2)+\frac{\alpha\alpha_s}{3}\left(\frac{-x_1s}{u}+\frac{-u}{x_1s}\right)D_3(x_1,x_2)\right]+(p\longrightarrow p')\,. \tag{20}$$

In Fig. 2 the cross section in a special case when the photon is emerging at $\theta=90°$ in the c.m. system is shown as a function of photon energy. For the estimation we need the gluon distribution function[11] and the numerical value of α_s.[12,13] Here we take $g(x)=2(1-x)^3/x$ and $\alpha_s=0.32$, which are used in the $p+p\to l^++l^-+X$ case.[14] For the comparison with possible CERN ISR experiments, the c.m. energy is chosen as $\sqrt{s}=23.5$, 30.6, 44.8, 52.7, and 62.4 GeV. The cross section without gluons is also plotted for the energy $\sqrt{s}=30.6$ GeV so that one can see the effects of gluons. As can be seen clearly in the picture, this cross section is a few hundred times smaller. Gluon effects are dominating because α_s is larger than α and gluon distribution is assumed to be larger than antiquark distributions. The cross sections at other energies are not presented because the trend is almost the same.

It is well known that in present experiments the inclusive process shows p_t^{-8} behavior,[15,16] while one expects p_t^{-4} from parton-model calculations. At energies and transverse momentum higher than those reached by present experiments, one may hope that the parton processes become dominant.[17] Assuming this is the case also for photon inclusive processes, the measurement of α_s and gluon distributions mentioned in the previous section should be done at the energy range where thus far hypothetical p_t^{-4} behavior shows up.

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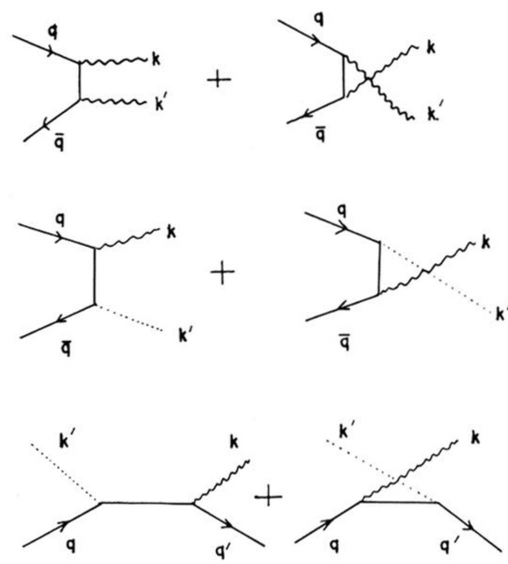

FIG. 1. Feynman diagrams of parton scatterings which produce photons. Quarks, gluons, and photons are denoted by solid, dotted, and wiggly lines, respectively.

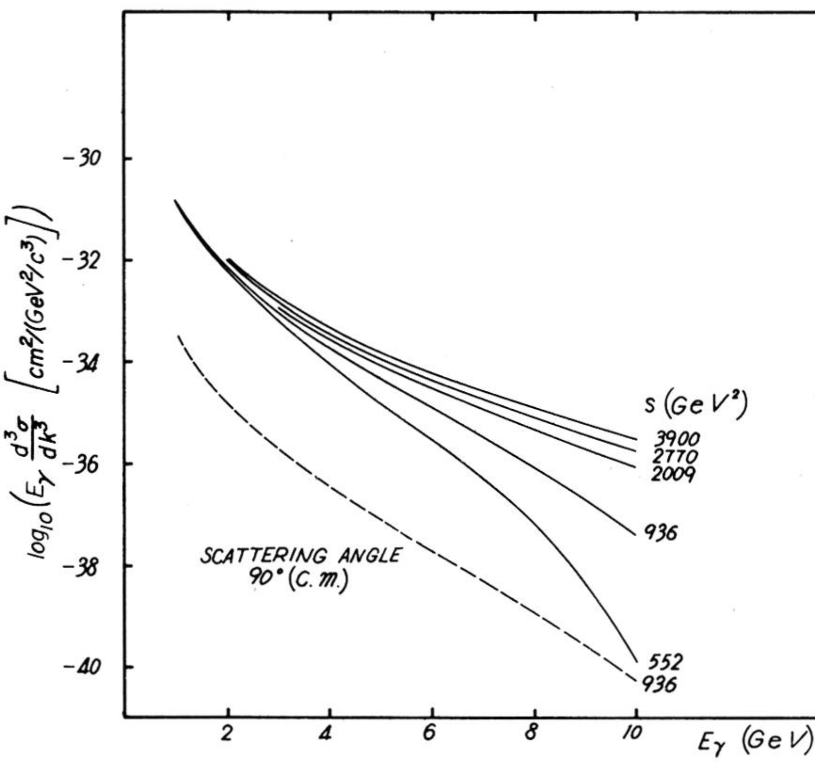

FIG. 2. The differential cross section $E\gamma(d^3\sigma/dk^3)$ of the inclusive process $p+p \rightarrow \gamma + X$ at various CERN ISR energies and $\theta_{c.m.} = 90°$. The broken line represents the cross section without gluon effects at the energy $\sqrt{s} = 30.6$ GeV.