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The Inelastic Photon Content of the Proton

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Abstract

A radiatively generated photon distribution in the proton is considered in a model where it vanishes at a low resolution scale, $Q_0^2 = 0.25\text{GeV}^2$, where all other partons have a valence-like structure. The obtained photon distribution differs considerably from the commonly utilized distributions. A simple and accurate parametrization of the resulting photon distribution is presented in the range $10^{-5} < x < 1$ and $0.25 < Q^2 < 10^6\text{GeV}^2$. Some consequences for photon induced processes at high energy pp and ep colliders are discussed.

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Deep inelastic scattering processes involving proton beams are well described by the parton model where, usually, only quarks, antiquarks and gluons are considered as the parton constituents of the proton. This attitude is often kept even for processes such as $ep \rightarrow e\gamma X$, $pp \rightarrow \mu^+\mu^-X$, W^+W^-X , involving non - strongly interacting charged particles like $e^\pm$, $\mu^\pm$, $W^\pm$, etc. At very high energies, however, one may expect that the Weizsäcker - Williams [1] photons incoherently radiated off the light quark constituents should become increasingly relevant due to their typical logarithmic enhancement factor $\ln E^2/m_q^2$. At this level the photons may be included among the parton distributions of the proton. To determine their contribution one needs reliable information concerning the corresponding partonic distribution $\gamma_i^p(x, Q^2)$ where x denotes the momentum fraction of the 'inelastic' (i) photon within the proton and Q^2 the resolution scale at which the proton is probed.

A commonly used crude approximation, as utilized also in some recent publications [2-4], is:

$$\gamma_i^p(x, Q^2) = \frac{\alpha}{2\pi} \ln \frac{Q^2}{Q_0^2} \sum_q \int_x^1 \frac{dy}{y} P_{\gamma q} \left(\frac{x}{y} \right) [q(y, Q^2) + \bar{q}(y, Q^2)] \quad (1)$$

with

$$P_{\gamma q}(z) = e_q^2 \frac{1 + (1 - z)^2}{z} \quad (2)$$

where Q_0^2 is a typically low hadronic scale, e.g. $Q_0^2 = 1\text{GeV}^2$ in [2, 3] or $Q_0^2 = m_q^2$ with $m_q \simeq 0.3\text{GeV}$ in [4]. The equation underlying this approximation is the renormalization group (RG) equation:

$$\frac{d\gamma_i^p(x, Q^2)}{d \ln Q^2} = \frac{\alpha}{2\pi} \sum_q \int_x^1 \frac{dy}{y} P_{\gamma q} \left(\frac{x}{y} \right) [q(y, Q^2) + \bar{q}(y, Q^2)] \quad (3)$$

combined with the boundary condition

$$\gamma_i^p(x, Q_0^2) = 0 \quad . \quad (4)$$

One observes that (1) is a solution of this equation provided one neglects the Q^2 - dependence of $q(y, Q^2) + \bar{q}(y, Q^2)$ in eq.(3). For very low values of Q_0^2 combined with $Q^2 \gg Q_0^2$ this is obviously only a very crude approximation which deserves a closer scrutiny. For

this purpose one needs to specify the low resolution scale Q_0^2 in eq.(4) as well as the Q^2 - dependent quark distributions in eq.(3). A most natural choice for the latter is given by the quark distributions of [5] which are positive definite, i.e. physically meaningful, down to a very low resolution scale μ^2 , which is given by $\mu_{LO}^2 = 0.25\text{GeV}^2$ for the leading order (LO) distributions henceforth utilized in our present LO calculations. Following the ideas [6] underlying ref.[5] we identify Q_0^2 with μ_{LO}^2 , i.e. choose

$$Q_0^2 = \mu_{LO}^2 = 0.25\text{GeV}^2 \quad (5)$$

in eq.(4) specifying the boundary condition for $\gamma_i^p(x, Q^2)$.

The integration of eq.(3) subject to eqs.(4-5) is now straightforward¹ and yields a unique prediction for $\gamma_i^p(x, Q^2)$ which can be compared with the commonly utilized approximation provided by eq.(1). In fig. 1 we present a comparison of both predictions utilizing the same quark distributions [5] and the same value of Q_0^2 for both the exact and the approximate (eq.(1)) solutions of eq.(3). Also shown is the result obtained by setting $Q_0^2 = 1\text{GeV}^2$ in the approximate solution of eq.(3) which illustrates the sensitivity to the choice of the scale Q_0^2 .

A precise evaluation of $\gamma_i^p(x, Q^2)$ is significant for processes affected by this distribution such as e.g. Compton scattering at high energy ep colliders [7] or the scalar leptoquark production in pp and $p\bar{p}$ collisions considered in [4] to be discussed in some detail below. For this purpose we present a simple and accurate parametrization of $\gamma_i^p(x, Q^2)$ as obtained in LO by the integration of eqs.(3-5) utilizing the LO parton distributions of ref.[5]:

$$\frac{x\gamma_i^p(x, Q^2)}{\alpha} = \frac{s^{\alpha'}}{[\ln(1/x)]^a} (1 + A\sqrt{x} + Bx)(1-x)^C \exp(-D + \sqrt{D's^\beta \ln \frac{1}{x}}) \quad (6)$$

where

$$s = \ln \frac{\ln [Q^2/(0.232\text{GeV})^2]}{\ln [Q_0^2/(0.232\text{GeV})^2]} \quad (7)$$

¹Technically it is easiest to carry out this integration in the Mellin moment space utilizing the corresponding analytic Q^2 - dependent solutions for the quark distributions, eqs.(2.5) and (2.9) in [6], as well as the numerical Mellin inversion procedure described there.

with Q_0^2 given by eq.(5) and

$$\begin{aligned}
\alpha' &= 0.989 - 0.566 s, & B &= 3.219 - 1.535 s^{0.626}, \\
\beta &= 3.610 - 0.082 s, & C &= 3.966 + 0.261 s^{2.694}, \\
a &= -0.229 + 0.419 s^{2.404}, & D &= 0.831 + 0.814 s^{1.444}, \\
A &= -2.413 + 1.233 s^{0.969}, & D' &= 0.450 + 0.369 s^{0.887}.
\end{aligned} \tag{8}$$

This parametrization has been obtained for four flavors in eq.(3) and is valid for $10^{-5} < x < 1$ and $Q_0^2 < Q^2 < 10^6$. The averaged inaccuracy amounts to about 3 – 4% unless $x\gamma_i^p(x, Q^2)/\alpha$ is below about 10^{-4} , i.e. negligible.

In fig. 2 we study to what extent the results of ref.[2] for the various contributions to the production rate of charged heavy particles via $\gamma\gamma$ fusion ('elastic', 'semi - elastic' and 'inelastic'; cf. ref.[2], in particular eqs.(4-12) for details and sub - cross sections) at high energy pp colliders, e.g. $pp \rightarrow \gamma\gamma \rightarrow H^+H^-$, are modified if one substitutes the approximate photon spectrum (according to eq.(1) and setting $Q_0^2 = 0.25\text{GeV}^2$) by our $\gamma_i^p(x, Q^2)$ distribution (eq.(6)) throughout the calculation. Although our $\gamma_i^p(x, Q^2)$ distribution leads to somewhat larger cross sections for larger values of M_H as compared to the approximate results (the same holds for the production of other charged heavy particles, e.g. L^+L^- , $\tilde{\chi}^+\tilde{\chi}^-$, ...) there is no significant change in the conclusions of ref.[2], i.e. the $\gamma\gamma$ fusion cross sections are far below the competitive Drell - Yan production of charged heavy particles (cf. figs. 1, 2 of ref.[2]). Let us emphasize that the spectrum of the 'elastic', coherently radiated photons $\gamma_e^p(x, s)$ and therefore the 'elastic' contribution to $\gamma\gamma$ cross sections is not affected by the previous considerations and is well described [2] by the approximate analytic expressions in [8].

Let us now study the production of a scalar leptoquark (LQ) in pp collisions at $\sqrt{s} = 14\text{TeV}$ (LHC) in comparison with the results of [4]. In ref.[4] the $2 \rightarrow 1$ process $lq \rightarrow (lq)_{LQ}$, $l = e, \mu, \tau$, was implemented as the underlying production mechanism with the lepton l radiated off the photon considered as a lepton distribution in the proton. In contrast to this narrow width approximation we consider the full $2 \rightarrow 2$ process $\gamma q \rightarrow (lq)_{LQ}\bar{l}$. The total production cross section of a scalar leptoquark is then given by

$$\sigma(s) = 2 \int_{(M_{LQ}+m_l)^2/s}^1 dx_1 \int_{(M_{LQ}+m_l)^2/(x_1 s)}^1 dx_2 \gamma_i^p(x_1, M_{LQ}^2) q(x_2, M_{LQ}^2) \hat{\sigma}(x_1 x_2 s) \quad (9)$$

where

$$\begin{aligned} \hat{\sigma}(s) = \frac{\pi \alpha \alpha_{LQ}}{2s} & \left[v \bar{v} e_q (4 + e_q + 3e_q \Delta) + 4 v \bar{v} \Delta (1 + (1 + e_q)^2) \right. \\ & + 4(1 + e_q) \Delta \left(\frac{M_{LQ}^2}{s} (1 - e_q) - \left(1 - \frac{m_l^2}{s} \right) (1 + e_q) \right) \mathcal{L}_+ \\ & \left. + 2 \left(2(2e_q + 1) \frac{m_l^2}{s} \Delta + (1 - \Delta)^2 + \frac{M_{LQ}^4 - m_l^4}{s^2} \right) \mathcal{L}_- \right] \quad (10) \end{aligned}$$

utilizing the following definitions

$$\begin{aligned} \Delta &= \frac{M_{LQ}^2 - m_l^2}{s} \\ v &= \sqrt{1 - \frac{(M_{LQ} + m_l)^2}{s}} \\ \bar{v} &= \sqrt{1 - \frac{(M_{LQ} - m_l)^2}{s}} \\ \mathcal{L}_{\pm} &= \ln \left(\frac{1 + v \bar{v} \pm \Delta}{1 - v \bar{v} \pm \Delta} \right) . \quad (11) \end{aligned}$$

In fig. 3 we demonstrate the sensitivity of the predicted cross section to the considered photon distribution and leptoquark production mechanism.

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Figure Captions

Fig. 1 Comparison of our predictions (eqs.(3-5)) for $x\gamma_i^p(x, Q^2)/\alpha$ (solid lines) with the corresponding approximate results provided by setting $Q_0^2 = 0.25\text{GeV}^2$ in eq.(1) (dashed lines) for various representative values of x utilizing the quark distributions of ref.[5]. Also shown are the results obtained by setting $Q_0^2 = 1\text{GeV}^2$ in eq.(1) (dashed - dotted lines).

Fig. 2 'Elastic', 'semi - elastic' and 'inelastic' $\gamma\gamma$ cross sections for charged Higgs production at $\sqrt{s} = 14\text{TeV}$ distinguished by dashed, dashed - dotted and solid lines, respectively, utilizing our $\gamma_i^p(x, Q^2)$ distributions (eq.(6)) compared to the results obtained with the approximate photon spectrum according to eq.(1) using the quark distributions of ref.[5] and $Q_0^2 = 0.25\text{GeV}^2$. The bars demonstrate the dependence of the inelastic approximate result on Q_0^2 . Upper end: $Q_0^2 = 0.09\text{GeV}^2$, lower end: $Q_0^2 = 1\text{GeV}^2$ (as used in the original calculation of [2]). The scales of the parton distributions have been chosen as in [2] to be $\hat{s}/4$.

Fig. 3 Cross sections for scalar (eu - type) leptoquark production at $\sqrt{s} = 14\text{TeV}$ for all possible combinations of cross sections and photon spectra. Solid line: $2 \rightarrow 2$ cross section (eq.(9)) combined with our photon distribution (eq.(6)), dashed line: eq.(9) combined with the approximate photon spectrum (eq.(1) for $Q_0^2 = 0.25\text{GeV}^2$), dashed - dotted line: $2 \rightarrow 1$ cross section of ref.[4] combined with eq.(6), dotted line: same as before but combined with eq.(1). All results have been obtained by assuming $\alpha_{LQ} = \alpha$.

FIG. 1

FIG. 2

FIG. 3