PROMPT PHOTON PRODUCTION AT LARGE p_T IN QCD BEYOND THE LEADING ORDER

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The results of the complete $O(\alpha_s^2)$ calculation of hadroproduction of prompt photons at large p_T are presented. Good agreement with ISR data is obtained.

In hadronic collisions, prompt photons are defined as real photons which are not decay products of known resonances. Quantum chromodynamics predicts that they should be produced rather abundantly at large p_T, with a rate comparable to single π^0 production [‡1], since the photon, like the quark or the gluon, participates directly in the hard scattering process. It is this property which makes the prompt photon production a very good testing ground for QCD. Several sets of data on proton–proton interactions have been collected covering the FNAL [3] and ISR [4,5] energy range [6] [‡2] with p_T as high as 12 GeV/c, while proton–antiproton data at both the ISR and SPS collider should be available in the near future [7]. A wide range of $\sqrt{s}$ and p_T will thus be covered, making the comparison with QCD quite meaningful. On the theoretical side, no full calculation beyond the leading logarithmic approximation exists yet. A study of the photon bremsstrahlung process $qq \to qq\gamma$ has been presented [8,9]: these terms were thought to be important for prompt photons in proton–proton collisions, however it turned out that they contribute at most by 30% of the Born term which is dominated by the QCD Compton diagrams (fig. 1a). The argument does not apply to the proton–antiproton or π^-–proton cases dominated at the lowest order by the annihilation of valence quarks and antiquarks (fig. 1b). On the other hand, the "π^2-terms" from one loop diagrams in the soft gluon limit as well as certain collinear gluon bremsstrahlung contributions have been estimated in ref. [10]. In this work the factorization is not properly implemented although the factorization scale is certainly a major factor for the absolute size and the shape of the cross section. Only a full, next to leading logarithm, calculation could resolve this problem. We present here the results of such a calculation.

Our main emphasis concerns the size and shape of the corrections in proton–proton and proton–antiproton reactions at large p_T. The cross section for the single inclusive point-like photon can be written as

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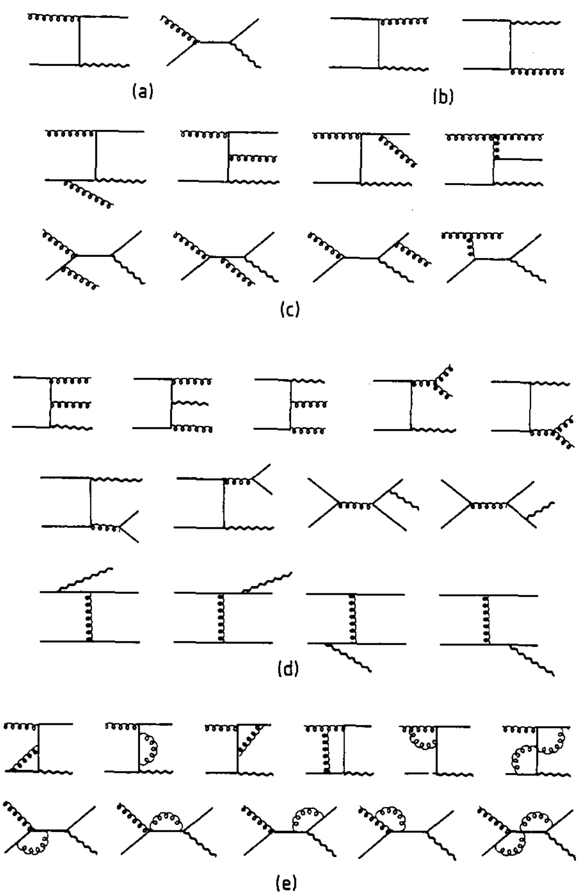

Fig. 1. Some Feynman diagrams contributions to $pp \to \gamma X$ up to $O(\alpha_s^2)$. The Born terms include (a) the QCD Compton diagrams, (b) the quark–antiquark annihilation diagrams; the real emission diagrams correcting (c) the QCD Compton process, (d) the annihilation process; (e) Virutal corrections to (a) except those contributing to wave function renormalization. The symmetrized diagrams for identical particles have not been shown. Wavy (curly) lines denote photons (gluons).

$$\frac{d\sigma}{dy\,d^2p_T}(h_1h_2 \to \gamma X) = \sum_{i,j} \frac{1}{\pi} \int dx_1\, F_{h_1,i}(x_1, Q_s^2)\, dx_2\, F_{h_2,j}(x_2, Q_s^2) \times \frac{1}{\hat{s}} \left(\frac{1}{v} \frac{d\sigma_{ij}}{dv}(\hat{s}, v)\, \delta(1-w) + \frac{\alpha_s(Q_c^2)}{2\pi}\, \theta(1-w) K_{ij}(\hat{s}, Q_c^2/\hat{s}, Q_s^2/\hat{s}, Q_d^2/\hat{s}, v, w) \right), \tag{1}$$

where the scaled variables v, w are related to the fractions of momenta x_i carried by the incoming partons via [11]

$$v = 1 - x_2 (p_T/\sqrt{s}) e^{-y}, \quad w = (1/vx_1)(p_T/\sqrt{s}) e^{y}. \tag{2}$$

The summation indices i,j run over quarks, antiquarks and gluons in the initial hadrons. The quantities $d\sigma_{ij}/dv$ are related to the Born cross sections and the K_{ij} contain the finite next-to-leading order corrections. The mass Q_s (Q_d) sets the scale breaking effects in the structure (fragmentation) functions. It is convenient to collect the many diagrams into four classes: $qg \to \gamma X$, $q\bar{q} \to \gamma X$, $qq \to \gamma X$ and $gg \to \gamma X$. The real diagrams pertaining to the first and second class, which also contribute to the Born term, are shown in fig. 1 which also displays the virtual diagrams for the QCD Compton scattering. The corresponding annihilation graphs are deduced in an obvious way. The qq and gg initial state contributions are obtained by selecting and/or crossing the diagrams of fig.. 1c,d. For a complete treatment one has to consider terms coming from the anomalous photon component arising from the collinear emission of the photon by a final state parton. They are written as

$$d\sigma^{ANOM}/dy\,d^2p_T = \sum_{i,j,k} \frac{1}{\pi} \int dx_1\, F_{h_1,i}(x_1, Q_s^2)\, dx_2\, F_{h_2,j}(x_2, Q_s^2) \times \frac{dx_3}{x_3} D_{k,\gamma}(x_3, Q_d^2) \times \frac{1}{\hat{s}} \frac{1}{v} \frac{d\sigma_{ij\to k}}{dv}(\hat{s}, v)\, \delta(1-w), \tag{3}$$

where the $d\sigma_{ij\to k}/dv$ are related to the Born terms for scattering of partons i and j to produce the parton k which emits the photon. Applying eq. (3) we do not distinguish between the photons which, in the experiment, are produced isolated or accompanied by other hadrons. It is in principle possible to distinguish between the two cases provided an appropriate method is used to regulate the collinear singularity [9].

the calculation is performed using the dimensional regularization method and the $\overline{MS}$ renormalization scheme (all partons are massless and on-shell). The algebraic manipulations are done with the help of

SCHOONSHIP [12] or REDUCE [13]. Since no parametrization beyond the leading order is yet available, we are using the leading logarithmic description of ref. [14] for the quarks and that of CDHS [15] for the gluon structure functions in the proton. As far as the quarks are concerned, it amounts to identifying the quark distributions $F_{\mathrm{p,q}}(x,Q^2)$ with the deep inelastic structure function, $F_2(x,Q^2) = \Sigma_{\mathrm{q}} e_{\mathrm{q}}^2 \times F_{\mathrm{p,q}}(x,Q^2)$, and this is legitimate provided one uses the factorization prescription of ref. [16], which incorporates the corrections to deep inelastic scattering in the definition of the quark distributions. The gluon structure function appears in first order of α_{s} in deep inelastic scattering, and therefore it is sensitive to the inclusion of corrections. The knowledge of its next to leading order parameterization thus would lead to more precise predictions for prompt photon production, especially in p–p and π^+–p collisions. For the fragmentation function of the quark into a photon we take the leading logarithm parametrization of ref. [17]. In our numerical application we are neglecting the photon component in the gluon, which is strongly suppressed at large p_{T} [2].

We display in fig. 2 the comparison between the data and our predictions including the $\mathrm{O}(\alpha_{\mathrm{s}}^2)$ corrections for prompt photons at 90° in the ISR energy range [5]. All predictions are given with the one loop strong coupling constant $\alpha_{\mathrm{s}}(Q_{\mathrm{c}}^2)$ evaluated for four flavors and $\Lambda_{\overline{\mathrm{MS}}} = 200$ MeV/c. The results for two choices of factorization scales are shown: the case (a), $Q_{\mathrm{c}}^2 = Q_{\mathrm{s}}^2 = Q_{\mathrm{d}}^2 = p_{\mathrm{T}}^2$ (dashed lines) giving a somewhat higher cross section than the case (b), $Q_{\mathrm{c}}^2 = p_{\mathrm{T}}^2$, $Q_{\mathrm{s}}^2 = Q_{\mathrm{d}}^2 = \hat{s}v(1-w) + Q_0^2$, $Q_0^2 = 5$ GeV^2 (solid lines). The latter scale which is related to the invariant mass, at the partonic level, of the system recoiling against the large p_{T} photon partly resums the large corrections which may appear at the edge of phase space. Another popular choice (c), $Q_{\mathrm{c}}^2 = Q_{\mathrm{s}}^2 = Q_{\mathrm{d}}^2 = 4p_{\mathrm{T}}^2$, leads at ISR energies to cross sections which are within a few percent the same as for case (b). One notes that both at $\sqrt{s} = 45$ GeV and $\sqrt{s} = 63$ GeV, the theoretical estimates fall below the data points for $p_{\mathrm{T}} \leqslant 5$ GeV/c. This is a consequence of our neglect of the effects of the primordial transverse momenta of the partons in the protons. It has been estimated in ref. [18] that accounting for this effect would raise the cross section by about 50% at $\sqrt{s} = 63$ GeV for a value of $p_{\mathrm{T}} = 4$ GeV/c, putting the predictions in better agreement with experiment. Such a correction factor rapidly decreases with p_{T}.

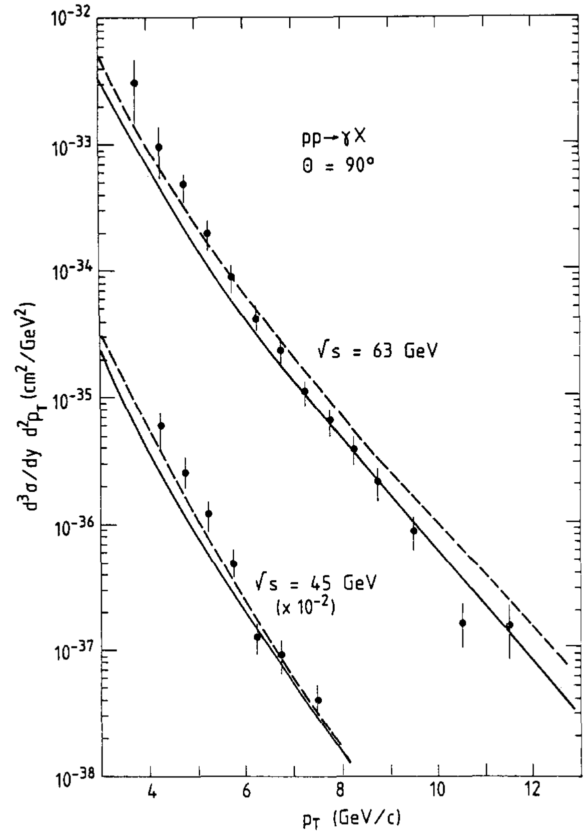

Fig. 2. The invariant cross section $\mathrm{d}\sigma/\mathrm{d}y\ \mathrm{d}^2p_{\mathrm{T}}|_{y=0}$ for pp → γX at two typical ISR energies. Fully corrected predictions [eqs. (1) and (3)] for two choices of scles: $Q_{\mathrm{c}}^2 = Q_{\mathrm{s}}^2 = Q_{\mathrm{d}}^2 = p_{\mathrm{T}}^2$ (dashed lines); $Q_{\mathrm{s}}^2 = Q_{\mathrm{d}}^2 = \hat{s}v(1-w) + Q_0^2$, $Q_{\mathrm{c}}^2 = p_{\mathrm{T}}^2$ (solid lines). The data are from ref. [5].

Fig. 3 shows the details of the corrections for pp → γX at 63 GeV and $\theta = 90°$, for the two choices (a) and (b) (fig. 3a and 3b, respectively). The solid lines represent the ratios C of the corrections, defined as the terms proportional to α_{s} in eq. (1), to the Born term [i.e. eq. (1) with $K_{ij} = 0$] the corrections are found to be positive, rather large and independent of p_{T} for $p_{\mathrm{T}} > 5$ GeV/c for the factorization scale p_{T}^2; they are smaller, p_{T}-dependent and negative at large p_{T} for the scale $\hat{s}v(1-w) + Q_0^2$, a pattern already observed in the hadron photoproduction calculation [19]. For the choice (c) the corrections C are of order one; for $p_{\mathrm{T}} > 6$ GeV/c, C is larger by 20% than for the choice (a). Although the corrections show a strong dependence on

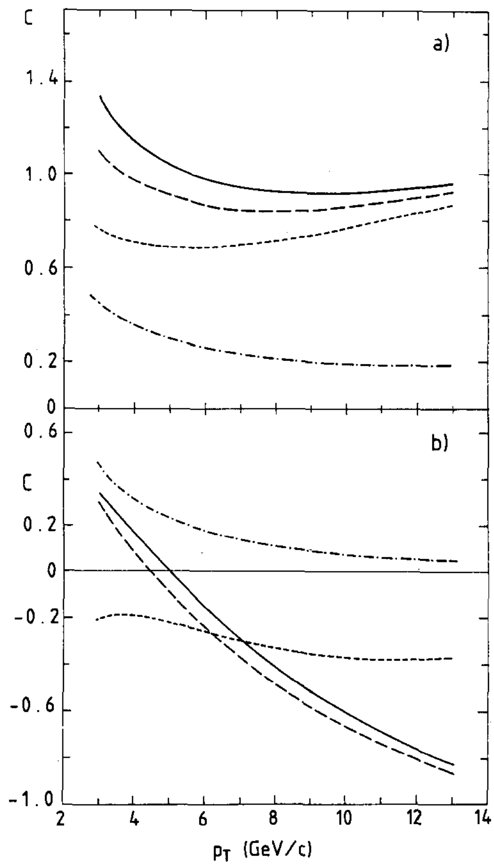

Fig. 3. The corrections normalized to the Born cross section for pp → γX at $\sqrt{s}$ = 63 GeV, y = 0 as a function of p_T. (a) $Q_c^2 = Q_s^2 = Q_d^2 = p_T^2$; (b) $Q_s^2 = Q_d^2 = \hat{s}v(1-w) + Q_0^2$, $Q_c^2 = p_T^2$. Assuming the partons distributions are defined beyond leading order as in ref. [16], the solid lines represent the $O(\alpha_s^2)$ corrections, the dashed lines the "singular" part of the $O(\alpha_s^2)$ corrections and the dash–dotted lines the anomalous part. The dotted lines are the $O(\alpha_s^2)$ corrections assuming the universal definition of the parton distributions [21].

the scales (a)–(c), the inclusion of the $O(\alpha_s^2)$ terms leads to relatively stable predictions for the p_T dependence of the cross sections in the ISR energy range. At $\sqrt{s}$ = 45 GeV the stability, even in magnitude, is evident from fig. 2. This is to be compared with the predictions for the choices (a)–(c) at the Born level, illustrated by the following ratios at p_T = 7 GeV/c: $[(a)/(b)]_{\rm Born}$ = 0.47 and $[(c)/(b)]_{\rm Born}$ = 0.27. At $\sqrt{s}$ = 63 GeV the comparison between the Born term and the fully $O(\alpha_s^2)$ corrected predictions for two values of p_T = 6 GeV/c (12 GeV/c) is as follows: $[(a)/(b)]_{\rm Born}$ = 0.70 (0.28) versus $[(a)/(b)]_{\rm full}$ = 1.47 (1.70), and $[(c)/(b)]_{\rm Born}$ = 0.47 (0.17) versus $[(c)/(b)]_{\rm full}$ = 1.04 (1.16). The shape of the invariant cross section however stays rather stable against the variation of the scales (a)–(c).

The dependence of the corrections on the choice of scales offers the interesting possibility of choosing the scales so as to minimize the size of the corrections or the sensitivity of the predictions [20].

In the kinematic range studied, it is found that the corrections for pp → γX are dominated by the ones to the QCD Compton process (i.e. the diagrams of fig. 1c,e); the terms due to class qq → γX in particular being at most at the 10% level. In order to further analyse the structure of the corrections we show as dashed lines the "singular" part, namely the terms of the form $a\delta(1-w) + b/(1-w)|_+ + c[\ln(1-w)]/(1-w)|_+$, which arise in the limit of soft unobserved partons. These terms follow closely the full corrections, suggesting that soft emission represents indeed the bulk of the corrections. It should be stressed that their sign is dependent on the choice of scales. The method for estimating the soft contributions proposed in ref. [10] leads to corrections of the form $C_\pi = a(\alpha_s/2\pi)\pi^2$ where the constant a, which is related to the color structure of the amplitude, is positive in the case of interest. Our results do not support such a conclusion as we find (i) that the sign of the corrections is not fixed but is essentially scale-dependent; (ii) that the full corrections give a pattern quite different from the "π^2-terms" alone; e.g. for $Q_c^2 = p_T^2$ the correction C_π is decreasing with p_T as $\alpha_s(p_T^2)$ giving $C_\pi \simeq 0.5$ at p_T = 12 GeV/c, whereas we find $C \simeq 1$ for the choice (a) in p–p collisions (fig. 3a).

In order to test the importance of knowing the higher order corrections to the structure functions we show the total corrections (dotted lines) under the assumption that our input parton distributions are "universal" [21]; the size of the corrections is reduced for both choices (a) and (b) of scales (fig. 3a,b). However it is expected that the fully corrected cross sections are less sensitive than the corrections with respect to the factorization prescription.

We now turn to the discussion of the anomalous component. For both scales it is smoothly falling to a rather small fraction which, when normalized to the full cross section, is less than 15% for $p_T \gtrsim 6$ GeV/c. The bremsstrahlung contributions from gq → γgq and

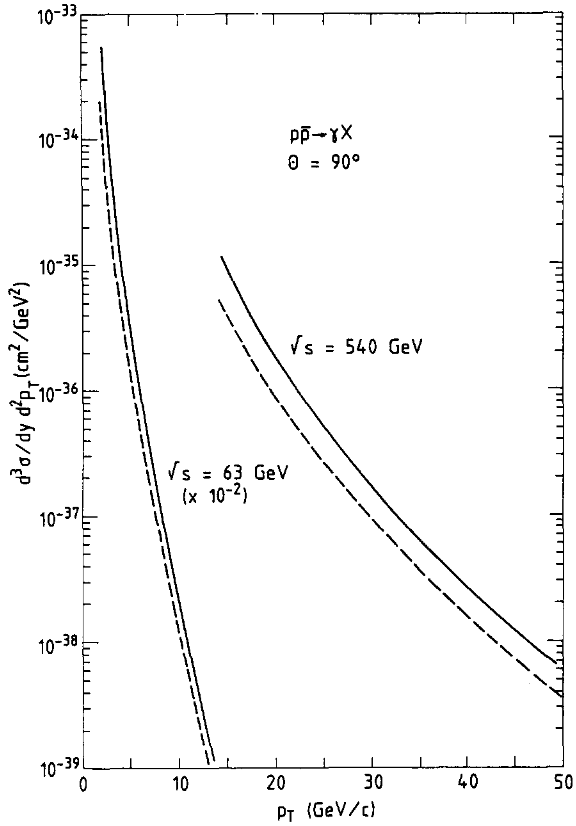

Fig. 4. The invariant cross section $d\sigma/dy\, d^2p_T$ for $p\bar{p}\to\gamma X$ at $\sqrt{s} = 63$ GeV and 540 GeV, $y = 0$. The scales are $Q_c^2 = Q_s^2 = Q_d^2 = p_T^2$. The dashed lines are the Born cross sections and the solid lines the fully corrected predictions.

$qq \to \gamma qq$ are comparable and an order of magnitude larger than those associated to $gg \to \gamma q\bar{q}$.

We show in fig. 4 the predictions for prompt photons at 90° in proton–antiproton collisions at $\sqrt{s} =$ 63 GeV and $\sqrt{s} = 540$ GeV. The curves are obtained with the choice $Q_c^2 = Q_s^2 = Q_d^2 = p_T^2$, and both the Born cross sections (dashed lines) and the fully corrected cross sections (full lines) are displayed. One notes a decrease of the correction at fixed x_T with increasing energy related to the decrease of $\alpha_s(Q_c^2)$ (e.g. at $x_T \simeq 0.2$, $C = 0.9$ at $\sqrt{s} = 63$ GeV and 0.5 and 540 GeV). In the range of energies studied, we observe that the QCD Compton process and its associated corrections dominate the cross section for $x_T = 2p_T/\sqrt{s}$ below 0.16 to 0.18 while the annihilation process takes over at larger x_T values [2]. Both subprocesses receive corrections of the same order of magnitude. We remark that, independent of energy, the ratio of the anomalous component is about 10% for $x_T \sim 0.1$ and decreasing at larger values. It is interesting to compare the predictions for $pp \to \gamma X$ and $p\bar{p} \to \gamma X$: the ratio $p\bar{p} \to \gamma X/pp \to \gamma X$ is increasing with p_T and at $\sqrt{s} = 63$ GeV, $p_T = 12$ GeV/c we find 3.4 at the Born level compared to 2.7 once the corrections are accounted for.

Concerning the predictions for collider energies at the lower end of the p_T spectrum we recal that $p_T = 15$ GeV/c corresponds to $x_T = 0.056$, a value below which the input structure functions are not reliable. It is encouraging to note that the isolated neutral particle yield (π^0 and γ) measured by the UA2 Collaboration [7] is of the same order of magnitude as our predictions in the x_T range above 0.1. It is the same range where good agreement is obtained for $pp \to \gamma X$ at ISR energies.

In conclusion, we find that the complete corrections of $O(\alpha_s^2)$ to prompt photons in proton–proton collisions enable us to get good agreement with the ISR data for $p_T > 4$ GeV/c. When next to leading order parametrizations of the quark and especially the gluon structure functions are available the numerical results of our QCD calculations would be strengthened.

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