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High-p_T photon production at $p\bar{p}$ colliders*

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Abstract

It is demonstrated by consistent NLO calculations for isolated hadronic prompt photon production that previous discrepancies between NLO expectations for the direct-γ production rates at small p_T^γ ($\gtrsim$ 11 GeV) and isolated prompt photon data are removed. This is not only due to the use of experimentally confirmed steep small-x parton distributions, but also due to a consistent inclusion of isolated photonic fragmentation contributions in NLO.

Prompt photon production rates at high energy $p\bar{p}$ colliders are studied, among other reasons, in order to gain information on the gluon distribution $g(x,Q^2)$ of the proton. The high-p_T prompt photons are mainly due to the dominant Compton-like subprocess $gq \to \gamma q$ and, for small values of $x_T = 2p_T^\gamma/\sqrt{s}$, provide invaluable information on the small-x behavior of $g(x,Q^2)$. In practice, when measuring the prompt photon cross section at colliders [1-3], one introduces suitable isolation cuts designed to reduce the non-prompt photon background resulting, e.g., from the not yet satisfactorily measured photonic fragmentation functions $D^\gamma_{q,g}(z,\mu_F^2)$. This cut is charactarized by the opening angle 2δ of the photon isolation cone and an energy resolution parameter ϵ: If the total hadronic energy in the photon's isolation cone is less than ϵE_γ, with E_γ being the photon's energy, the photon is called isolated. A detailed description and discussion of the leading order (LO) calculations as well as of some estimates on the effects of the next-to-leading order (NLO) corrections, which are crucial for a meaningful theoretical analysis of recent data [1-3], can be found for example in [4].

The fully inclusive, i.e. non-isolated, total production cross section of one prompt photon, $ab \to \gamma X$, is generically of the form

$$\begin{aligned} d\sigma^\gamma_{ab} &= d\sigma_{dir} + d\sigma_{frag} = \sum_{f_a,f_b=q,\bar{q},g} \int dx_a dx_b f_a(x_a,\mu^2) f_b(x_b,\mu^2) \\ &\times \left[d\hat{\sigma}^\gamma_{f_a f_b}(p_\gamma, x_a, x_b, \mu^2, \mu_F^2) + \sum_{f=q,\bar{q},g} \int_{z_{min}}^1 \frac{dz}{z^2} d\hat{\sigma}^f_{f_a f_b}(p_\gamma, x_a, x_b, z, \mu^2, \mu_F^2) D^\gamma_f(z,\mu_F^2) \right] , \end{aligned} \tag{1}$$

where $z_{min} = x_T(e^\eta + e^{-\eta})/2$. The fragmentation scale is denoted by μ_F and the factorization scale μ, entering the parton distributions $f(x,\mu^2)$, has as usual been assumed to coincide with the renormalization scale entering $\alpha_s(\mu^2)$. The direct (dir) term in eq.(1) receives contributions from the one-photon inclusive subprocesses $f_a f_b \to \gamma X$ ($d\hat{\sigma}^\gamma_{f_a f_b}$) which in LO ($\alpha\alpha_s$) are derived from $gq \to \gamma q$ and $q\bar{q} \to \gamma g$, and in NLO ($\alpha\alpha_s^2$) from $gq \to \gamma qg$, $q\bar{q} \to \gamma gg$, $gg \to \gamma q\bar{q}$, etc. [5, 6]. The non-direct fragmentation ($frag$) dependent term in eq.(1), sometimes referred to as bremsstrahlung contribution [2, 4], receives contributions from the one-parton inclusive subprocesses $f_a f_b \to fX$ ($d\hat{\sigma}^f_{f_a f_b}$) which are derived from the LO (α_s^2) $2 \to 2$ and NLO (α_s^3) $2 \to 3$ parton-parton subprocess cross sections as given in [7] and [8], respectively. The produced parton $f = q, \bar{q}, g$ then fragments into a photon as described by the relevant photonic fragmentation function $D^\gamma_f(z,\mu_F^2)$ in LO (α/α_s) [9, 10] and HO ($\alpha/\alpha_s + \alpha$) [9] as we shall discuss in more detail below. It should be mentioned that the purely perturbative NLO (hard) direct contribution in eq.(1) depends, via the necessity of separating collinear singularities [4, 6, 11] on the fragmentation scale μ_F entering the non-direct fragmentation contribution in eq.(1) also via the fragmentation functions $D^\gamma_f(z,\mu_F^2)$.

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A realistic calculation of the contributions in eq.(1) to prompt photon production affords, however, an evaluation of the effects due to the isolation cut. In a theoretical study in LO this experimental criterion can be easily implemented into the calculation. Here the dominant contributions arise from hard $2 \to 2$ subprocesses for which the photon and the other final state particle, which will give rise to hadrons, are more or less back-to-back and thus separated from each other. The implementation of the isolation cut on the LO fragmentation contribution in eq.(1) is reflected merely in changing [4] the lower limit z_{min} of the z-integration in eq.(1) to $\max(z_{min}, 1/(1+\epsilon))$ and $\mu_F \to \mu_F(\delta, \epsilon)$.

In NLO, as mentioned above, important contributions to prompt photon production arise from the various possible 'direct' $2 \to 3$ processes $ab \to \gamma cd$. In contrast to the LO processes it is now possible kinematically that one of the final state partons carrying more energy than ϵE_γ happens to be inside the cone around the photon. Such contributions have to be excluded for the isolated cross section. Apart from a Monte Carlo program of Baer et al. [12] there exist two *analytical* calculations of the complete NLO corrections for the 'direct' (hard) part of *inclusive* prompt photon production, i.e. of the processes $ab \to \gamma cd$ [5, 6]. These calculations have been performed integrating over the *full* phase space of the outgoing unobserved particles c and d, and thus no longer allow for isolation cuts directly. Nevertheless they present the most convenient starting point for the treatment of the isolated 'direct' cross section since the latter can be written as the inclusive cross section minus a subtraction piece [4]:

$$d\sigma_{dir}^{isol} = d\sigma_{dir} - d\sigma_{dir}^{sub}(\delta, \epsilon) \quad , \tag{2}$$

$d\sigma_{dir}^{sub}$ being the cross section for producing a prompt photon which is accompanied by hadronic energy *more* than ϵE_γ inside the cone. The decomposition of $d\sigma_{dir}^{isol}$ in eq. (2) has several advantages: The inclusive cross section $d\sigma_{dir}$ is perturbatively well defined in itself in the sense that a complete cancellation of all poles has already taken place, i.e. infrared poles have cancelled between the virtual ($2 \to 2$) and the $2 \to 3$ NLO contributions and mass singularities have been factored into the initial state parton distributions and the photon fragmentation functions [5, 6].

In order to find a semi-analytical expression for $d\sigma_{dir}^{sub}$, one may assume that δ is small, i.e. that the cone around the photon, needed for isolating it, is rather narrow [11]. It turns out that the leading behavior of $d\sigma_{dir}^{sub}$ for small δ is logarithmic in δ which is a remnant of the final state collinear singularities arising in the calculation of $d\sigma_{dir}^{sub}$. One should also consistently keep terms constant with respect to δ, since these turn out to be of numerical relevance. They are furthermore needed since they contain the dependence on the factorization scheme which must be the same in the calculation of $d\sigma_{dir}^{sub}$ and $d\sigma_{dir}$. All remaining pieces in the subtraction cross section are suppressed by powers of δ^2 and are negligible. The only exception from this occurs when ϵ becomes very small. In this case the subtraction cross section is dominated by soft gluons being radiated into the cone which give rise to a logarithmic dependence on ϵ and eventually lead to an infrared divergence at $\epsilon = 0$ [4]. The reason for this is simple: A *completely* isolated cross section, with no hadronic energy at all in the isolation cone, is not a perturbatively well-defined quantity for a massless particle [4]. Although in reality ϵ is fixed by the experimental resolution, it is necessary to keep the contributions which are logarithmically dependent on ϵ in order to improve the accuracy of the approximation for the subtraction piece. Thus schematically we have the following structure of our approximated subtraction cross section:

$$d\sigma_{dir}^{sub} = A \ln \delta + B + C\delta^2 \ln \epsilon \quad , \tag{3}$$

where the coefficients A, B and C are functions of the kinematical variables. Note that A and B also depend on ϵ due to the isolation cuts. The contributing subprocesses to $d\sigma_{dir}^{sub}$ are the same as in the completely inclusive calculation ($d\sigma_{dir}$) [5, 6], namely $q\bar{q} \to \gamma gg$, $qg \to \gamma qg$, $gg \to \gamma q\bar{q}$, etc. Only the processes with (anti)quarks in the final state can lead to contributions to A and B whereas, as discussed above, only the first two subprocesses which involve gluon radiation can give $\ln \epsilon$ terms and contribute to C. The explicit result for $d\sigma_{dir}^{sub}$ can be found in ref. [11], where also the good accuracy of the small-cone approximation was proven over a wide range of the isolation parameters by comparing to a Monte-Carlo calculation.

In order to isolate the NLO fragmentation contribution, a procedure similar to that outlined above for the direct case can be followed [11]. For the NLO (α_s^3) partonic $2 \to 3$ subprocesses, the LO z-cut $\max(z_{min}, 1/(1+\epsilon))$ introduced above is in general no longer sufficient since a non-fragmenting parton from the $2 \to 3$ subprocess can also radiate into the cone around the photon, giving rise to additional hadronic energy accompanying the photon. If this happens we have to make sure that the sum of the energies of the fragmentation remnants, E_{frag}^{rem}, *plus* the energy of the additional non-fragmenting parton, E', be smaller than ϵE_γ. The required isolated NLO fragmentation contribution in eq.(1) can then be written as

$$d\sigma_{frag}^{isol} = d\sigma_{frag}^{z \geq 1/(1+\epsilon)} - d\sigma_{frag}^{sub}(\delta, \epsilon) \tag{4}$$

where $d\sigma_{frag}^{z \geq 1/(1+\epsilon)}$ is the NLO fragmentation cross section with the insufficient LO z-cut implemented which can be calculated using the program of [8], and $d\sigma_{frag}^{sub}$ is the fragmentation subtraction cross section

satisfying the conditions $E_{frag}^{rem} \leq \epsilon E_\gamma$ but $E_{frag}^{rem} + E' \geq \epsilon E_\gamma$ [11]. This latter subtraction term has been calculated in the small-cone approximation in [11] with its dominant and relevant contributions given by

$$d\sigma_{frag}^{sub}(\delta,\epsilon) = \epsilon\,[(A + A' \ln \epsilon) \ln \delta + B] \qquad (5)$$

with new coefficients A, A' and B as compared to eq.(3). Note that each cross section in eq.(4) vanishes for $\epsilon \rightarrow 0$, due to the constraint $z \geq 1/(1+\epsilon)$, and thus the fragmentation contribution is suppressed proportional to ϵ which explains the different structure of eq.(5) as compared to (3). The question about the appropriate isolation-parameter dependent fragmentation scale $\mu_F(\delta,\epsilon)$ can obviously not be answered unambiguously. One knows, however, that μ_F roughly controls the transverse size of the jet and thus merely kinematical considerations [4] point towards $\mu_F = \delta E_\gamma$. It has, however, been shown in [11] that the total isolated NLO cross section in eq.(1) is very insensitive to the specific choice of $\mu_F(\delta,\epsilon)$ since the μ_F-dependencies almost cancel in the differences in eqs.(2) and (4) for realistically small values of ϵ.

For our actual LO and NLO calculations [13] we use for the parton distributions $f(x,\mu^2)$ in eq.(1) the LO and HO GRV distributions [14], since the predictions for the steep small-x behavior of the structure functions as well as their predicted Q^2 dependence has, so far, been fully confirmed by recent HERA measurements [15]. The appropriate LO and HO fragmentation functions $D_{q,g}^\gamma(z,\mu_F^2)$ are taken, from [9], i.e., the ones relevant for inclusive prompt photon production. We furthermore use for our calculations of the isolated photon cross sections [2] $\delta = 0.7$ and $\epsilon = 2$ GeV$/p_T^\gamma$, although a commonly used fixed value of [4] $\epsilon = 0.15$ leaves our results essentially unchanged. In Fig.1 we present our LO and NLO results [13] for the isolated total prompt photon production cross section. To illustrate the importance of the fragmentation contribution $d\sigma_{frag} \sim D_f^\gamma$ in eq.(1) at small p_T^γ ($\lesssim$ 20 GeV), the 'direct' contribution in eq.(1) is shown separately in the insert. (The vertical bars indicate the scale ambiguity due to $p_T^\gamma/3 \leq \mu \leq p_T^\gamma$). It should be noted that this latter 'direct' NLO result (dash-dotted curve) is already in better agreement with the Tevatron data [2], in particular at small p_T^γ ($\lesssim$ 20 GeV) [16], than the result obtained with the older (flat) experimentally already disproved [15, 18] KMRS(B_0) parton distributions which is about 25% smaller [19]. It should be nevertheless emphasized that the separation into a direct and fragmentation contribution depends strongly on the factorization scale (μ_F) chosen, and their absolute values are factorization scheme dependent. Only the sum of both in eq. (1) is manifestly scheme invariant at a given perturbative order ($\mathcal{O}(\alpha\alpha_s^2)$).

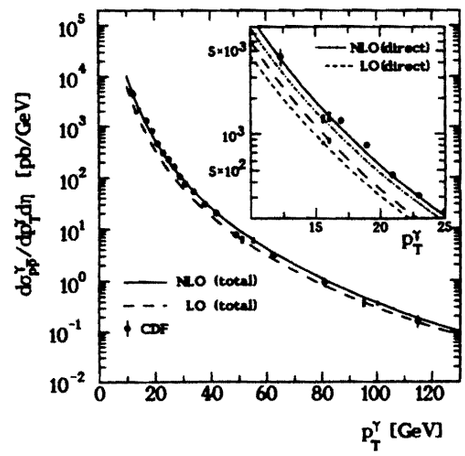

Figure 1. LO and NLO predictions [13] for isolated prompt photon production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV for $\eta = 0$, using the LO and HO GRV parton distributions [14] and fragmentation functions [9] in eq.(1) with $\mu = p_T^\gamma/2$ and $\mu_F = \delta p_T^\gamma$. These results are very similar (within 1%) to the ones obtained from averaging over the experimental rapidity range $|\eta| \leq 0.9$. The vertical bars illustrate the dependence of our results on the choice of scale: Upper edge ($\mu = p_T^\gamma/3$), lower edge ($\mu = p_T^\gamma$). The CDF data are taken from [2] and have an additional $\simeq$ 10% normalization uncertainty.

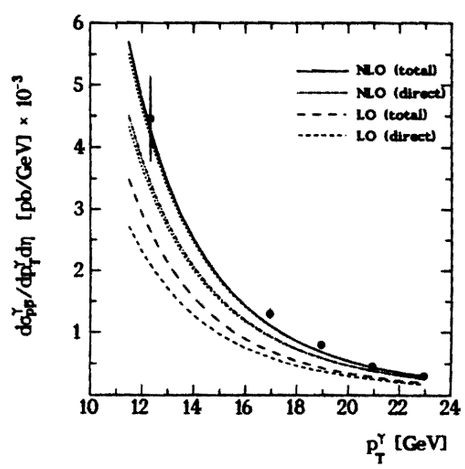

Figure 2. The LO and NLO GRV predictions of Fig.1 [13] shown on a linear scale in the small-p_T^γ region where the isolated fragmentation contributions are most important. The dotted curves result from using the NLO MRS(D'_) parton distributions [20].

In order to demonstrate more clearly the important change in shape caused by the isolated NLO fragmentation contribution in the small-p_T^γ region, we show the various LO and NLO contributions [13] on a linear scale in Fig. 2. As expected [19], the NLO results are insensitive to the specific choice of parton distributions.

The agreement between data and our *total* isolated

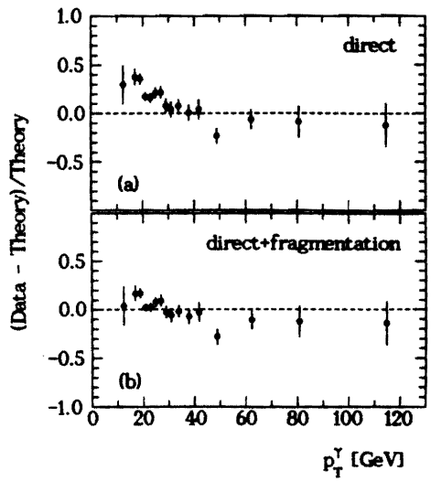

Figure 3. The isolated photon cross section data [2] compared to the NLO QCD predictions of Fig.1 [13]. The 'direct' contribution in eq.(1) is shown in (a), whereas the total (= direct + fragmentation) one is shown in (b).

predictions in Fig.1 [13] is seen better on a linear scale, as in Fig.3, where we show the default quantity (data − theory)/theory. It becomes clear from Fig.3(a) that the (factorization scheme dependent) isolated 'direct' contribution alone does *not* suffice to describe the data at $p_T^\gamma \lesssim 20$ GeV where the data appear to be significantly higher than theoretical expectations. However, the inclusion of the fragmentation contribution, Fig.3(b), appears to remove this discrepancy, taking into account the theoretically intrinsic ambiguities due to different choices of the scale μ in eq. (1) as shown in Figs. 1 and 2. Here, in Fig. 3, we have chosen $\mu = p_T^\gamma/2$ which is the favored choice obtained from the hadronic jet analysis of the CDF data [21].

Let us note that we find a similarly good agreement [22] between our total NLO results for the isolated prompt photon cross section and the D0 data [3]. It should be mentioned that the theoretical predictions as well as the data differ slightly from the ones for the CDF case since the D0 collaboration uses a different isolation criterion in restricting the hadronic energy inside a cone *annulus* of opening angles $\delta = 0.2$ and $\delta = 0.4$ [3].

We finally note that all our results are hardly changed if we use the simple asymptotic LO solutions for $D_f^\gamma(z, \mu_F^2)$, as parametrized by Owens [10]. The differences are immaterial due to the very similar shapes of $D_{q,g}^\gamma$ in the large-z region [9].

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References

[1] J. Alitti *et al.*, (UA2 Collab.), Phys. Lett. **B263** (1991) 544.
[2] F. Abe *et al.*, (CDF Collab.), Phys. Rev. Lett. **68** (1992) 2734; Phys. Rev. **D48** (1993) 2998; FERMILAB Pub-94/208-E.
[3] D0 Collaboration, J. Kotcher, talk presented at the *9th Workshop on Proton-Antiproton Collider Physics*, Tsukuba, Japan, 1993, FERMILAB-Conf-93/387-E; J. Womersley, *private communication.*
[4] E. L. Berger and J. Qiu, Phys. Lett. **B248** (1990) 371; Phys. Rev. **D44** (1991) 2002.
[5] P. Aurenche, R. Baier, A. Douiri, M. Fontannaz and D. Schiff, Phys. Lett. **140B** (1984) 87; P. Aurenche, R. Baier, M. Fontannaz and D. Schiff, Nucl. Phys. **B297** (1988) 661.
[6] L. E. Gordon and W. Vogelsang, Phys. Rev. **D48** (1993) 3136.
[7] B. L. Combridge, J. Kripfganz and J. Ranft, Phys. Lett. **70B** (1977) 234; J.F. Owens, E. Reya and M. Glück, Phys. Rev. **D18** (1978) 1501.
[8] F. Aversa, P. Chiappetta, M. Greco and J. Ph. Guillet, Phys. Lett. **B211** (1988) 465; Nucl. Phys. **B327** (1989) 105.
[9] M. Glück, E. Reya and A. Vogt, Phys. Rev. **D48** (1993) 116.
[10] J. F. Owens, Rev. Mod. Phys. **59** (1987) 465.
[11] L. E. Gordon and W. Vogelsang, Phys. Rev. **D50** (1994) 1901.
[12] H. Baer, J. Ohnemus and J. F. Owens, Phys. Rev. **D42** (1990) 61. It should be mentioned that this Monte Carlo approach does *not* include the full fragmentation contribution in NLO ($\alpha\alpha_s^2$). Therefore these results are not strictly independent of the chosen fragmentation scheme to order $\alpha\alpha_s^2$.
[13] M. Glück, E. Reya, L.E. Gordon and W. Vogelsang, Phys. Rev. Lett. **73** (1994) 388.
[14] M. Glück, E. Reya and A. Vogt, Z. Phys. **C53** (1992) 127.
[15] I. Abt *et al.*, (H1 Collab.), Nucl. Phys. **B407** (1993) 515; M. Derrick *et al.*, (ZEUS Collab.), Phys. Lett. **B316** (1993) 412.
[16] Such an enhancement effect in the small p_T^γ region, due to the steeper CTEQ1M parton distributions [17], has been recently observed in ref. [2]. It also applies to the UA2 data at $\sqrt{s} =$ 630 GeV [1] although there the discrepancy between the older (flat KMRS(B_0) distributions) 'direct' NLO expectations [2] and the small-p_T^γ ($\gtrsim$ 18 GeV) data is less pronounced.
[17] J. Botts *et al.*, (CTEQ Collab.), Phys. Lett. **B304** (1993) 159.
[18] P. Amaudruz *et al.*, (NMC), Phys. Lett. **B295** (1992) 159.
[19] Our NLO results in Fig.1 remain practically unchanged if the MRS(D'_) [20] parton distributions are used, since our results are at most 5 % larger.
[20] A. D. Martin, W. J. Stirling and R. G. Roberts, Phys. Lett. **B306** (1993) 145.
[21] S.D. Ellis, Z. Kunszt and D.E. Soper, Phys. Rev. Lett. **64** (1990) 2121.
[22] W. Vogelsang, work in preparation.