NIKHEF/00-14
YITP-00-33
RIKEN-BNL preprint
June 2000

Current Issues in Prompt Photon Production[†]

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Abstract

We give a brief account of recent theoretical developments in prompt photon production.

[†] Invited talk presented by W. Vogelsang at the "8th International Workshop on Deep-Inelastic Scattering" (DIS2000), 25-30 April 2000, Liverpool, UK

[‡] WV is grateful to RIKEN, Brookhaven National Laboratory and the U.S. Department of Energy (contract number DE-AC02-98CH10886) for providing the facilities essential for the completion of this work

CURRENT ISSUES IN PROMPT PHOTON PRODUCTION

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We give a brief account of recent theoretical developments in prompt photon production.

Prompt-photon production at high transverse momentum [1], $pp, p\bar{p}, pN \to \gamma X$, has been a classical tool for constraining the nucleon's gluon density, since at leading order a photon can be produced in the Compton reaction $qg \to \gamma q$. The 'point-like' coupling of the photon to the quark provides a supposedly 'clean' electromagnetic probe of QCD hard scattering. In the framework of QCD perturbation theory, the inclusive cross section is written in a factorized form:

$$\frac{d\sigma_{AB\to\gamma X}(x_T^2)}{dp_T} = \sum_{ab} \phi_{a/A}(x_a,\mu) \otimes \phi_{b/B}(x_b,\mu) \otimes \frac{d\hat{\sigma}_{ab\to\gamma c}\left(\hat{x}_T^2,\mu\right)}{dp_T} \,. \qquad (1)$$

For simplicity, we have integrated over the rapidity η of the prompt photon. In (1), $\phi_{a/A}(x_a,\mu)$ denotes the parton density for species a in hadron A, at factorization scale μ, x_a being the parton's momentum fraction. $d\hat{\sigma}_{ab\to\gamma c}/dp_T$ are the partonic hard-scattering functions, which have been calculated to next-to-leading order [2]. Hadronic and partonic scaling variables are $x_T^2 \equiv 4p_T^2/S$ and $\hat{x}_T^2 \equiv 4p_T^2/\hat{s}$, respectively, with $\hat{s} = x_a x_b S$.

Unfortunately, in experiment, one has to deal with a substantial background of photons from π^0 decay. In addition, high-p_T photons can be produced in jets, when a parton, resulting from a pure QCD reaction, fragments into a photon plus a number of hadrons. This inevitably introduces dependence on non-perturbative (parton-to-photon) fragmentation functions. So far, the latter are insufficiently known. Theoretical studies [3,4,5,6], based on predictions [3,7,8] for the photon fragmentation functions, indicate that the fragmentation component is in practice a subdominant, albeit non-negligible, effect. In the fixed-target regime, fragmentation photons are believed [5] to contribute at most 20% to the direct photon cross section. At collider energies, the fragmentation mechanism can easily produce about half or more of the observed photons [9,3,5]. Here an 'isolation' cut is imposed on the photon signal in experiment, in order to suppress the π^0 background. Isolation is usually realized by drawing a cone of fixed aperture in φ–η space around the photon, restricting the hadronic transverse energy allowed in this cone to a certain small fraction ε of the photon transverse energy. In this way, the fragmentation contribution, resulting from an essentially collinear process, is diminished [10], probably to a level of 15–20%, or less [4,5].

We mention that subtleties were observed [11,12,13] in the past concerning the factorizability of the *isolated* prompt photon cross section. While in [13] factorization was eventually proved to hold, it was also shown [13,12,11] that with isolation the NLO partonic hard scattering function has a Sudakov-type singular behavior at a certain point *inside* the physical region, requiring soft-gluon resummations in order to obtain a reliable theoretical result. It was also pointed out [10] that the (in practice [14]) small size of ε can give rise to potentially large logarithms of ε, associated with soft-gluon emission into the isolation cone. Further work on the fragmentation component is clearly needed. A recent suggestion [15] to refine isolation by allowing less and less hadronic energy the closer to the photon it is deposited, will, at least theoretically, eliminate the fragmentation component altogether and could potentially avoid some of the problems just mentioned. This isolation prescription has been applied in studies for prompt photon production at RHIC and LHC [16].

A pattern of disagreement between theoretical predictions and experimental data for prompt photon production has been observed in recent years [14,17,18], not globally curable by changing factorization and renormalization scales or by 'fine-tuning' the gluon density [5,19,6]. The most serious problems relate to the fixed-target data, where NLO theory dramatically underpredicts some data sets [17,18]. At collider energies, there is less reason for concern, but also here the agreement is not fully satisfactory. The mutual consistency of the various fixed-target data sets has been questioned in [6]. On the other hand, various improvements of the theoretical framework have been developed.

'Threshold' resummations for the inclusive prompt photon cross section have been performed in [20,21] and applied phenomenologically in [22,23]. As $\hat{s}$ approaches its minimum value at $\hat{x}_T^2 = 1$, corresponding to 'partonic threshold' when the initial partons have just enough energy to produce the high-p_T photon and the recoiling jet, the phase space available for gluon bremsstrahlung vanishes, resulting in corrections to $d\hat{\sigma}/dp_T$ as large as $\alpha_s^k \ln^{2k}(1 - \hat{x}_T^2)\,\hat{\sigma}^{\rm Born}$ at order α_s^k in perturbation theory. Threshold resummation [24,20,21] organizes this singular, but integrable, behavior of $d\hat{\sigma}/dp_T$ to all orders in α_s. It is

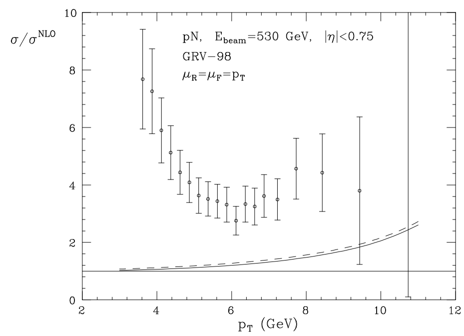

Figure 1: Threshold-resummed prompt photon cross section based on the formalisms of [20,(25)] (solid) and [21,(22)] (dashed), divided by the NLO cross section. Parton densities are from [26]. The E706 prompt photon data [17] are also shown in the same normalization.

carried out in Mellin-N moment space, where the logarithms are of the form $\alpha_s^k \ln^{2k}(N)\, \hat{\sigma}^{\rm Born}(N)$. Its application is particularly interesting in the fixed-target regime, since here the highest x_T are attained in the data, and since here the discrepancy between data and theory is largest. As seen from Fig. 1, one obtains a significant, albeit not sufficient, enhancement of the theory prediction. Also, a dramatic reduction of scale dependence is found [22]. One notices that the formalisms of [20,21], which differ in so far as the one of [20] resums at fixed photon rapidity, whereas the one of [21] applies to the cross section fully integrated over rapidity, yield very similar predictions in practice.

Valuable insight was gained in studies of direct photon production in which transverse smearing of the momenta of the initial partons was incorporated [19,27,28,29,30]. If, say, in the Compton process $qg \to \gamma q$ the initial partons have a non-zero k_T, the $\gamma\, q$ *pair* in the final state will acquire a net transverse momentum Q_T, which may make the process softer than it would be otherwise and result in an enhancement in the photon p_T spectrum. The first approaches [19,27,28] assumed Gaussian dependence on k_T and enjoyed phenomenological success in that they were able to bridge the large gaps between data and theory for appropriate choices of average $\langle k_T \rangle$, guided by values of dimuon, dijet and diphoton *pair* transverse momenta measured in hadronic reactions. On the other hand, it was clear that a more developed theoretical framework was required. For instance, as acknowledged already in [27], the physical origin for the parton k_T dependence should be thought of as initial-state gluon emission, so that Q_T takes the role of pair recoil against unobserved radiation. Ideally, the phenomenologically required k_T smearing would have to be understood in terms of a Q_T-resummation calculation, with perturbative as well as non-perturbative components, as familiar from the well-explored case of Drell-Yan dimuon production, where soft-gluon radiation gives rise to powers of large logarithms at small Q_T, which can be resummed to all orders. In the inclusive partonic prompt photon cross section $d\hat{\sigma}_{ab\to\gamma c}/dp_T$, such Q_T-logarithms will not be visible at any given order of perturbation theory; however, they will show up when considering $d\hat{\sigma}_{ab\to\gamma c}/d^2Q_T\, dp_T$ and can be resummed prior to Q_T integration. Attempts in this direction were first made in [29,30], where parton densities, unintegrated over parton transverse momentum, but constructed from the usual densities, were used. The 'double-logarithmic approximation' was employed in [29,30]. In [30], only small recoil effects were found when a strong ordering constraint was imposed.

In [31], a simultaneous resummation in both threshold and transverse momentum logarithms was achieved. The possibility of doing this had previously been pointed out in [32]. Contributions to the hard scattering function associated with threshold resummation are redistributed over soft gluon transverse momenta, simultaneously conserving energy *and* transverse momentum. Large logarithmic corrections in Q_T to $d\hat{\sigma}_{ab\to\gamma c}/d^2Q_T\, dp_T$ arising in the threshold region are resummed jointly with threshold logarithms. A further crucial and distinct feature of [31] is that it remains within the formalism of collinear factorization, which implies use of ordinary parton densities.

The possibility of joint resummation for singular behavior in Q_T and $1-\hat{x}_T^2$ is ensured by the factorization properties of the partonic cross section near threshold [33]. Singular Q_T behavior is organized in impact parameter b-space, where the logarithms exponentiate. Defining 'profile functions' in Q_T as

$$P_{ij}\left(N,\mathbf{Q}_T,Q,\mu\right) = \int d^2\mathbf{b}\, \mathrm{e}^{-i\mathbf{b}\cdot\mathbf{Q}_T}\, \exp\left[E_{ij\to\gamma k}\left(N,b,Q,\mu\right)\right] , \qquad (2)$$

where the resummed exponents $E_{ij\to\gamma k}$ can be found in [31] to NLL in both b and N, the resulting resummed cross section is given in terms of Mellin moments of the parton distributions and of the squared Born amplitudes $|M_{ij}|^2$ as

$$\frac{p_T^3 d\sigma^{(\mathrm{resum})}_{AB\to\gamma X}}{dp_T} = \sum_{ij} \frac{p_T^4}{8\pi S^2} \int_{\mathcal{C}} \frac{dN}{2\pi i}\, \tilde{\phi}_{i/A}(N,\mu)\tilde{\phi}_{j/B}(N,\mu) \int_0^1 d\tilde{x}_T^2 \left(\tilde{x}_T^2\right)^N$$
$$\times \frac{|M_{ij}(\tilde{x}_T^2)|^2}{\sqrt{1-\tilde{x}_T^2}} \int \frac{d^2\mathbf{Q}_T}{(2\pi)^2}\, \Theta\left(\bar{\mu}-Q_T\right) \left(\frac{S}{4{\mathbf{p}'_T}^2}\right)^{N+1} P_{ij}\left(N,\mathbf{Q}_T,\frac{2p_T}{\tilde{x}_T},\mu\right) , \qquad (3)$$

the recoil effect entering through $\mathbf{p}'_T = \mathbf{p}_T - \mathbf{Q}_T/2$. Eq. (3) reverts to the threshold-resummed cross section for $\mathbf{p}'_T \to \mathbf{p}_T$. Q_T is limited by the scale $\bar{\mu}$, to avoid going outside the region where the singularities in Q_T dominate.

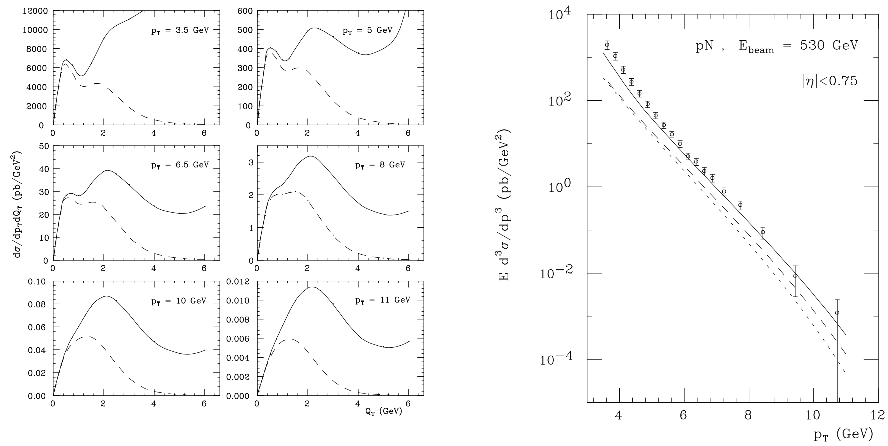

Figure 2: Left: prompt photon cross section $d\sigma_{\rm pN\to\gamma X}/dQ_T dp_T$ at $\sqrt{s} = 31.5$ GeV. Dashed lines are computed without recoil, solid lines are with recoil. Right: $Ed^3\sigma_{\rm pN\to\gamma X}/dp^3$. The dotted line represents the full NLO calculation, while the dashed and solid lines respectively incorporate pure threshold resummation (see [21] and Fig. 1) and the joint resummation of [31].

Cross sections computed on the basis of (3) are shown in Fig. 2 as functions of Q_T at fixed p_T. The kinematics are those of the E706 experiment [17]; see [31] for details of the calculation, in particular those regarding the evaluation of the b-integral in (2). The dashed lines are $d\sigma^{\rm (resum)}_{\rm pN\to\gamma X}/dQ_T dp_T$, with recoil neglected by fixing $\mathbf{p}'_T = \mathbf{p}_T$, thus showing how each Q_T contributes to threshold enhancement. The solid lines show the same, but now including the true recoil factor $(S/4\mathbf{p}'^{\,2}_T)^{N+1}$. The resulting enhancement is clearly substantial. For small p_T, the enhancement simply grows with Q_T, while for p_T above 5 GeV it has a dip at about $Q_T = 5$ GeV, which remains substantially above zero. This makes it difficult to confidently determine $\bar{\mu}$.

So far, the numerical results given in [31] are primarily to be regarded as illustrations, rather than quantitative predictions. This applies in particular to the resummed Q_T-*integrated* cross section, also shown in Fig. 2 for $p_T \geq 3.5$ GeV and $\bar{\mu} = 5$ GeV. Comparison with Fig. 1 demonstrates the size of the additional enhancement that recoil can produce and its potential phenomenological impact. Further work on the implementation of practical nonperturbative estimates and of matching procedures is required.

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