Conf-910551--3

ANL/HEP-CP--91-72

DE91 018539

ISOLATED PROMPT PHOTON PRODUCTION AT COLLIDER ENERGIES

EDMOND L. BERGER*

High Energy Physics Division

Argonne National Laboratory

Argonne, IL 60439

and

JIANWEI QIU†

Institute for Theoretical Physics

State University of New York,

Stony Brook, New York 11794-3840, U.S.A.

Abstract

We provide a consistent treatment of the isolated prompt photon cross section in QCD perturbation theory, showing that well behaved predictions can be derived for a wide range of isolation parameters.

(Paper presented by E. L. Berger. To be published in the Proceedings of Particles and Fields '91, Vancouver, Canada, August 18–22, 1991.)

*Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.

†SSC Fellow. Current address: Department of Physics and Astronomy, Iowa State University, Ames, IA 50011.

The goals of the study of prompt photon production at large transverse momentum (p_T) at collider energies include tests of perturbative quantum chromodynamics (QCD) and determination of the gluon density in nucleons at small values of Bjorken's $x \simeq x_T = 2p_T/\sqrt{s}$. In addition, isolated photons at large p_T may be signals for new physics processes.

In the QCD description of high energy hadron-hadron interactions, the observed photons can be produced directly through short-distance hard scattering at the parton level as well as through the long-distance fragmentation of quarks and gluons. In general, the inclusive cross section for prompt photon production at large transverse momentum has the following factorized form

$$E_\gamma \frac{d\sigma^{\rm tot}}{d^3p_\gamma}(A+B\to\gamma+X) = \sum_{i,j}\int_{x_a}^1 dx_1 f_{i/A}(x_1,\mu_f)\int_{x_b}^1 dx_2 f_{j/B}(x_2,\mu_f) \times \sum_{c=\gamma,q,g}\int_{z_{\rm min}}^1 \frac{dz}{z^2} D_{\gamma/c}(z,\mu_F)\,\hat\sigma_{ij,c}(p_c,x_1,x_2,z,\mu,\mu_f,\mu_F)\ , \tag{1}$$

where A and B refer to initial hadrons, i and j label the types of incident partons (gluons, quarks, and antiquarks), and c labels a final parton emerging from the short-distance process. The functions f and D are parton distribution and fragmentation functions. The parameters μ, μ_f, and μ_F are renormalization, initial state factorization, and fragmentation scales. $\hat\sigma_{ij,c}$ is a perturbatively calculable short-distance cross section for the subprocess $i+j\to c+X$; c may be a photon produced at short distances in the hard scattering, but it may also be a gluon or a quark.

To evaluate Eq. (1), we must compute $\hat\sigma_{ij,c}$, have sets of parton distributions f's and photon fragmentation functions D's, and determine the scales μ, μ_f, and μ_F. In principle, $\hat\sigma_{ij,c}$ can be calculated perturbatively in QCD perturbation theory. The f's and D's are nonperturbative functions, and they must be measured through a number of different experiments. If one's goal is to test perturbative QCD, one must know the non-perturbative functions well. Conversely, to extract the gluon density $f_{g/A}(x)$ and/or the fragmentation functions $D(z)$, one must demonstrate that perturbation theory is well understood. There are intrinsic theoretical uncertainties associated with the choices of the renormalization, factorization, and fragmentation scales. There are more prosaic uncertainties related to the imperfect determination of required parton distributions from other processes (notably deep inelastic lepton scattering), and in particular, to the lack of knowledge of the fragmentation functions which specify the probabilities for quarks and gluons to fragment into photons. Finally, experiments detect isolated photons at collider energies.[1] This experimental constraint must be imposed on theoretical calculations[2] in order to compare the theory with data. Imposition of the isolation cut threatens to make the theoretical calculation ill-defined since the possibility arises that infrared divergences will be introduced.

An isolation cone is defined to be a cone of opening angle δ, and whose axis is the direction of the observed photon. This definition can be converted into the isolation parameter R used in experiments; $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. When $\eta \simeq y = 0$, $R \approx \delta$. If the total hadronic energy, E_h, in a photon's isolation cone is less than ϵ times the photon's energy, E_γ, the photon is said to be *isolated.* In the CDF experiment[1] $\delta \simeq 40°$ and $\epsilon = 0.15$. In the ALEPH experiment[3] at LEP, $\delta = 20°$ and $E_h < 500MeV$ for $E_\gamma > 10GeV$.

It is convenient technically to treat the isolated cross section as the one photon inclusive cross section *minus* a subtraction term. The subtraction term is the cross section for photons with accompanying hadronic energy greater than ϵE_γ in the isolation cone. Because the one photon inclusive cross section is perturbatively well-defined, to study the behavior of the isolated cross section is to study the subtraction term.

The subtraction term should have a factorized form similar to that given in Eq. (1), but with a limited phase space. When the observed photons come from a fragmentation process, we must show how an isolation cut can be imposed on the nonperturbative quantities, the fragmentation functions. For photons produced through hard-scattering, we must address the possible noncancellation of infrared singularities due to the fact that the isolation cut restricts the phase space for integration of the momenta of soft gluons.

When a photon is produced through the fragmentation of a quark or a gluon, the event has the character of a photon accompanied by a hadronic jet in the direction of the photon. The fragmentation scale μ_F determines how much of the finite contribution of a diagram is included in the nonperturbative fragmentation functions and how much in the hard scattering part. Therefore, in calculating the isolated cross section, μ_F should be chosen so that the whole fragmentation jet falls within the isolation cone. The relationship between μ_F and the size of the fragmentation jet can be estimated best in terms of a transverse momentum cutoff scheme. When the transverse momentum between the photon and its accompanying partonic fragments is larger than μ_F, we attribute the contribution to hard scattering. Otherwise, we include the contribution in the fragmentation jet. We can estimate the relation between μ_F and the cone size δ as $\mu_F(\delta) \approx \delta\, p_q = \delta\, E_\gamma(1-z)/z$, with $z_{\min} < z < 1/(1+\epsilon)$, where p_q is the momentum of a quark accompanying the photon. It follows that $\mu_F(\delta)$ is of order δE_γ. The import of this discussion is that difficulties associated with the nonperturbative functions are effectively reduced to a choice of the fragmentation scale $\mu_F(\delta)$.

Hadronic energy may enter the isolation cone not only from the fragmentation process but also from the non-fragmenting final state quarks and/or gluons produced in the short-distance hard scattering. In any $2 \to \gamma + n$ partonic subprocess, with $n \geq 1$, it is possible for $n-1$ of the n final state partons to fall into the isolation cone. The other final state parton must have large p_T to balance the photon's transverse momentum. The subtraction term should include the part of the total cross section for which the non-fragmenting quarks and/or gluons within the cone carry total energy larger than ϵE_γ.

Up to the order $\alpha_s^2(\mu)$, we must consider only the $2 \to 3$ process with one photon in the final state. In this case, only one of the two final state partons (quark or gluon) can fall into the isolation cone of the photon. When ϵ is small, only soft gluons not quarks will produce a possible infrared divergence. The matrix element associated with soft gluon emission is proportional to $1/\omega^2$, where ω is the parton's energy. When combined with the $\omega d\omega$ phase space factor, the soft gluons yield a $\ell n \epsilon$ divergence. The leading behavior as ϵ goes to zero is

$$\hat{\sigma}_{2\to3}(p_\gamma, x_1, x_2, \delta, \epsilon) \approx \Gamma(p_\gamma, x_1, x_2, \delta, \epsilon)\, \hat{\sigma}_{2\to2}(p_\gamma, x_1, x_2)\,, \tag{2}$$

where $\hat{\sigma}_{2\to2}(p_\gamma, x_1, x_2)$ is the standard leading contribution from a $2 \to 2$ process with one photon in final state. When the isolation cone δ is small, the function Γ is given by

$$\Gamma(p_\gamma, x_1, x_2, \delta, \epsilon) = \left(\frac{\alpha_s}{\pi}\right) \sin^2\left(\frac{\delta}{2}\right) \ln\left(\frac{1}{\epsilon}\right) C(p_\gamma, x_1, x_2) + O(\epsilon^0)\,. \tag{3}$$

The function C is *positive* and of order *one*.

Equations (2) and (3) show that the subtraction term due to soft gluons is infrared divergent if we keep δ fixed and let ϵ go to zero. However, because of the energy resolution of the detector, ϵ can be small but never equal to zero. Consequently, the subtraction term in the definition of the isolated cross section is always perturbatively finite. For isolated cross sections measured in today's experiments, the factor $\Gamma(p_\gamma, x_1, x_2, \delta, \epsilon)$ is actually much *smaller* than *unity* because ϵ is not very small (for example, $\epsilon = 0.15$ for the CDF experiment), and because the factor $(\alpha_s/\pi)\sin^2(\delta/2)$ is *very* small. Therefore, soft gluons will not destroy the convergence of the perturbative calculation of the isolated cross sections. If ϵ is tiny, the QCD resummation technique for real soft gluons can improve the calculation through exponentiation of the subtraction term. The soft gluon contribution is infrared insensitive after resummation because $C > 0$.

We conclude[2] that the isolated prompt cross section can be calculated reliably in QCD perturbation theory. In addition, the isolated cross section is much less sensitive to photon fragmentation functions, enabling us to use high energy prompt photon data to determine the small x behavior of the gluon distribution.

Results of our numerical calculations are provided in Ref. 2, and further work[4] is nearing completion. As was noted in our paper[2] and in the contribution by Robert Harris,[5] there are systematic discrepancies between the theoretical curves and the data. The data appear to fall more steeply as a function of p_T, and theory tends to fall below the data in magnitude in the small p_T region. The discrepancies are indicative of two possible effects. First, in the small p_T region at collider energies, $x_T = 2p_T/\sqrt{s}$ is small. This is the "semi-hard" region where $\ell n x_T$ can be large and higher order contributions can be very important.[6] Second, a better understanding of the fragmentation contribution should also lead to improved agreement with data. Photons from the hard scattering diagrams tend to have a relatively shallow p_T distribution whereas those from fragmentation fall more steeply in p_T owing to the behavior of $D(z)$ and the $1/z^2$ factor in Eq. (1). In future work, efficient numerical programs must also be devised to include isolation restrictions in a fully accurate and consistent fashion.

References

1. UA2 Collab., R. Ansari et al., Phys. Lett. **176B**(1986)239; Z. Phys. **C41**(1988)395; UA1 Collab., C. Albajar et al., Phys. Lett. **209B**(1988)385; **209B**(1988)397; CDF Collab., R.M. Harris et al., Proceedings of the *Workshop on Hadron Structure Functions and Parton Distributions*, April 26-28 1990; Fermilab, ed by D.F. Geesaman *et al.*(World Scientific, Singapore, 1990), p. 278.
2. E.L. Berger and J.W. Qiu, Phys. Lett. **248B**, 371 (1990); Argonne report ANL-HEP-PR-90-104 (1990), to be published in Phys. Rev. D (1 Sept. 1991).
3. ALEPH Collaboration, D. Decamp *et al.*, CERN report CERN-PPE 91-89, June, 1991, submitted to Phys. Lett. B.
4. E.L. Berger, R.K. Ellis, and J.W. Qiu, to be published.
5. R.M. Harris, these proceedings.
6. J.C. Collins and R.K. Ellis, Fermilab report, FERMILAB-Pub-91/22T.