Isolated Photons in Deep Inelastic Scattering

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Photon radiation at large transverse momenta at colliders is a detailed probe of hard interaction dynamics. The isolated photon production cross section in deep inelastic scattering was measured recently by the ZEUS experiment, and found to be considerably larger than theoretical predictions obtained with widely used event generators. To investigate this discrepancy, we perform a dedicated parton-level calculation of this observable, including contributions from fragmentation and large-angle radiation. Our results are in good agreement with all aspects of the experimental measurement.

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Production of final state photons is a classical particle physics measurement, since its cross section can be computed in principle in the well-established framework of Quantum Electrodynamics. In turn, photon production cross sections were suggested as a probe of auxiliary quantities in particle physics, such as the measurement of the gluon distribution in the proton from isolated photon production at hadron colliders. With the advent of precise data on this observable (see \cite{1} for the most recent data), it was realized that the theoretical description of photons produced in reactions also involving final-state hadrons is less straightforward than expected, resulting in extensive theoretical discussion. For isolated photon production at hadron colliders, it turns out that effects from the fragmentation of a hadronic jet into a single, highly energetic photon \cite{2} and effects from the resummation of threshold and recoil corrections \cite{3, 4} had to be included to obtain a satisfactory description of experimental data. A very sensitive issue is the definition of isolated photons produced in association with hadrons, since a completely isolated photon is not an infrared safe observable in quantum chromodynamics (QCD). At present, this isolation is usually accomplished experimentally by admitting only a limited amount of hadronic energy inside a cone around the photon direction.

Recently, the ZEUS collaboration at DESY HERA reported a measurement \cite{5} of the inclusive production cross section for isolated photons in deep inelastic scattering (DIS). The normalization of the experimentally determined cross section turned out to exceed the cross section expected from the multi-purpose event generator programs HERWIG \cite{6} and PYTHIA \cite{7} by factors 7.9 and 2.3 respectively. Even after normalizing the total event rate, none of these programs was able to describe all kinematical dependencies of the measured cross section. Since the same event generator programs are used frequently to estimate photon production backgrounds for new particle searches in other collider environments, it appears to be very important to determine the origin of these large discrepancies. In a subsequent study \cite{11} the ZEUS measurement was analyzed in view of determining the photon distribution in the proton, relevant for electroweak radiative corrections at colliders.

By further analyzing the hadronic final state in isolated photon production in DIS, it is possible to define photon-plus-jet cross sections. In \cite{3, 4}, the isolated-photon-plus-one-jet cross section was also measured and found in good agreement with the theoretical prediction \cite{12}. This observation renders the discrepancy in the inclusive isolated photon cross section even more intriguing, since the inclusive cross section can in principle be obtained by summing all isolated-photon-plus-n-jet cross sections, starting with $n = 0$. To investigate the origin of the discrepancy, we performed a new calculation of the inclusive isolated photon cross section in DIS.

Production of photons in deep inelastic scattering is described by the leading order parton-level process

$$ q(p_1) + l(p_2) \rightarrow \gamma(p_3) + l(p_4) + q(p_5), $$

where $q$ represents a quark or anti-quark, and $l$ a lepton or anti-lepton. The measurable cross section for lepton-proton scattering $\sigma(ep \rightarrow e\gamma X)$ is obtained by convoluting the parton-level lepton-quark cross section $\sigma(eq \rightarrow e\gamma q)$ with the quark distribution functions in the proton. In the scattering amplitudes for this process, the lepton-quark interaction is mediated by the exchange of a virtual photon, and the final state photon can be emitted off the lepton or the quark. Consequently, one finds three contributions to the cross section, coming from the squared amplitudes for radiation off the quark ($QQ$) or the lepton ($LL$), as well as the interference of these amplitudes ($QL$). These were computed originally as part of the QED radiative corrections to deep inelastic scattering \cite{8}, where the final state photon remains unobserved. The $QL$ contribution is odd under charge exchange, such that it contributes with opposite sign to the cross sections with $l = e^-$ and $l = e^+$. The isolated photon rate in deep inelastic scattering is defined by imposing a number of kinematical cuts on the final state particles. In the ZEUS analysis (which combined three data samples: $38 \text{ pb}^{-1} e^+p$ at $\sqrt{s} = 300 \text{ GeV}$, $68 \text{ pb}^{-1} e^+p$ at $\sqrt{s} = 318 \text{ GeV}$ and $16 \text{ pb}^{-1} e^-p$ at $\sqrt{s} = 318 \text{ GeV}$), these were chosen as follows: virtuality of the process, as determined from the outgoing electron $Q^2 = -(p_4 - p_2)^2 > 35 \text{ GeV}^2$, outgoing electron energy $E_e > 10 \text{ GeV}$ and angle $139.8^\circ < \theta_e < 171.8^\circ$, outgoing
The only data constraining $D_{q \rightarrow \gamma}(z)$ come from final state photon radiation in electron-positron annihilation at LEP (some earlier evidence for the non-vanishing of $D_{q \rightarrow \gamma}(z)$ was obtained by the EMC experiment in deep inelastic muon-proton scattering). Using the method described in [13], the ALEPH collaboration has performed a direct measurement of $D_{q \rightarrow \gamma}(z)$ from the photon-plus-one-jet rate in $e^+e^-$ using a leading order (LO) theoretical calculation. In the method of [17], logarithms of $\mu_{F,\gamma}$ are not resummed, such that any cross sections computed with $D_{q \rightarrow \gamma}(z)$ of [13] are completely independent of $\mu_{F,\gamma}$. Next-to-leading order (NLO) corrections to the photon-plus-one-jet rate in $e^+e^-$ are known [18], and allow for a determination of $D_{q \rightarrow \gamma}(z)$ at NLO from the ALEPH data.

Several other parameterizations of photon fragmentation functions were proposed in the literature, based on models for the non-perturbative components [21]. These parameterizations incorporate a resummation of logarithms of $\mu_{F,\gamma}$, such that physical cross sections acquire a residual dependence on $\mu_{F,\gamma}$. Advantages and drawbacks of this resummation applied to different observables are discussed in [22]. The BFG parameterizations [21], yield a satisfactory description of the ALEPH data. Furthermore, a measurement of the inclusive photon spectrum in hadronic Z boson decays was made by the OPAL collaboration. The OPAL data are consistent with the ALEPH and BFG parameterizations.

In our calculation, we use the ALEPH leading order parameterization [13] as default, and the BFG (type I) parameterization [21], evaluated for $\mu_{F,\gamma}^2 = Q^2$ for comparison. The factorization scale $\mu_F^2$ for the parton distribution is $Q^2$ for the $QQ$ subprocess.

In the $LL$ subprocess (which is the only subprocess included in [11]), the final state photon is radiated off the lepton. Consequently, the momentum of the final state lepton can no longer be determined invariance four-momentum transfer between the lepton and the quark, which is in this subprocess given by $Q_{LL}^2 = -(p_1 - p_2)^2$, with $Q_{LL}^2 < Q^2 = Q_{QQ}^2 = -(p_1 - p_2)^2$. In principle, $Q_{LL}^2$ is unconstrained by the kinematical cuts, and the squared matrix element for the $LL$ subprocess contains an explicit $1/Q_{LL}^2$. The track requirement, implemented through a cut on the outgoing quark rapidity, enforces a minimum $Q_{LL}^2$, thus avoiding a singularity in the subprocess cross section. The cut has to be chosen in the choice of factorization scale $\mu_F^2$ in the $LL$ subprocess. In a leading order parton model calculation, $\mu_F^2$ should ideally be taken to be the invariant four-momentum transfer to the quark, i.e. $Q_{LL}^2$ for the $LL$ subprocess. Even applying the quark rapidity cut, $Q_{LL}^2$ can assume low values $Q_{LL}^2 \sim \Lambda_{QCD}^2$, where the parton model description loses its meaning. Because of the cuts, this kinematical region yields only a small contribution to the cross section. To account for it in the parton model framework, we introduce a minimal factorization scale $\mu_{F,min} = 1$ GeV, and choose for the $LL$ subprocess $\mu_F = \max(\mu_{F,min},Q_{LL})$, and for the $QL$ in-
This fixed factorization scale is an approximation to more elaborated procedures to extend the parton model to low virtualities \[24\], but sufficient in the present context. This procedure for the scale setting in the \( LL \) and \( QL \) subprocesses is similar to what is done in the related process of electroweak gauge boson production in electron-proton collisions \[25\]. The major difference to \[25\] is that the cross section for isolated photon production in DIS vanishes for \( Q^2 \rightarrow 0 \), while being non-vanishing for vector boson production. Consequently, in \[26\] the calculation of deep inelastic gauge boson production had to be supplemented by photoproduction of gauge bosons at \( Q^2 = 0 \), with a proper matching of both contributions at a low scale. This is not necessary in our case.

For the numerical evaluation of the cross sections, we use the CTEQ6L leading order parameterization \[26\] of parton distributions. Using the ZEUS cuts and the ZEUS composition of the data sample at different energies and with electrons and positrons, we obtain a theoretical prediction for the isolated photon cross section in DIS of 5.39 pb, to be compared to the experimental value of 5.64±0.58(stat.)\(^{+0.47}_{-0.72}\)(syst.). The total cross section is therefore well reproduced by our calculation.

We also computed the individual contributions to this cross section, which we list in Table I. It can be seen that the difference among the different beam energies and \( e^+ / e^- \) induced cross sections is about 6\%, thus justifying their combination into a single data sample. By decomposing the observed cross section into the \( QQ \), \( LL \) and \( QL \) contributions, we find that the \( QQ \) contribution yields only 53\% of the cross section, although the experimental cuts were designed to enhance this contribution relative to the others. Especially, by requiring the final state lepton and the photon to be found in different parts of the detector, any small-angle radiation off the lepton is suppressed, thus leaving only the (kinematically disfavored) large-angle radiation in the \( LL \) contribution. The still substantial magnitude of the \( LL \) contribution can be understood by the larger magnitude of the electric charge of the lepton compared with the quark. As expected, the \( QL \) contribution is very small. Finally, we observe that using the BFG (type I) parameterization \[21\] for \( D_{q \rightarrow \gamma} \) instead of the ALEPH parameterization \[13\] enhances the theoretical prediction only insignificantly by two per cent.

\begin{table}[h]
\begin{tabular}{|l|c|}
\hline
\( \sigma(ep \rightarrow e\gamma X) \) [pb] & \\
\hline
ZEUS & 5.64 ± 0.58 (stat.)\(^{+0.47}_{-0.72}\)(syst.) \\
Theory & 5.39 \\
e^+p (318 GeV) & 5.48 \\
e^+p (300 GeV) & 5.32 \\
e^-p (318 GeV) & 5.14 \\
QQ only & 2.87 \\
LL only & 2.39 \\
QL only & 0.13 \\
Theory using BFG \( D_{q \rightarrow \gamma} \) & 5.51 \\
\hline
\end{tabular}
\end{table}

FIG. 1: Rapidity distribution of isolated photons, compared to ZEUS data.

FIG. 2: Transverse momentum distribution of isolated photons, compared to ZEUS data.

FIG. 3: Dependence of isolated photon cross section on \( Q^2 \), as reconstructed from the outgoing electron. Data and theory are normalized to the total number of events, as in the experimental ZEUS measurement.
tions with normalized predictions from HERWIG and PYTHIA, it was found that none of these programs could describe all distributions: both reproduced only the shape of the $E_T,\gamma$-distribution correctly. HERWIG predicted a too soft $Q^2$-distribution, while PYTHIA yielded an incorrect $\eta_\gamma$-distribution. The approach suggested in [11], containing only the $LL$ subprocess, was found to yield a reasonable description of the $E_T,\gamma$-distribution, but failed on the $\eta_\gamma$-distribution [27]. Using our leading order calculation, we obtain differential cross sections in both shape and normalization. It should be noted that ZEUS does not provide a differential distribution in $Q^2$, but just normalized event counts binned in this variable.

Especially the $\eta_\gamma$-distribution, Figure 4 gives important insight into the discrepancies observed between the data and predictions from PYTHIA and HERWIG. In this distribution, the shapes of the $QQ$ and $LL$ contributions are considerably different. Comparing with the distributions obtained in [12] from the event generator programs, it can be seen that the shape of the $QQ$ contribution resembles the PYTHIA prediction, while the shape of the $LL$ contribution resembles the HERWIG prediction. This observation suggests that each program accounts for only one of the subprocesses appropriately: PYTHIA for only $QQ$ and HERWIG only for $LL$. The lack of photon radiation off quarks in HERWIG was already observed by the H1 collaboration in the study of photoproduction of isolated photons. The importance of both subprocesses for the shape of the $\eta_\gamma$-distribution shows clearly that the isolated photon cross section in DIS can not be described by the $LL$ subprocess only.

In this letter, we investigated the production of isolated photons in deep inelastic scattering in view of a recent ZEUS measurement of this observable. We found that photon radiation off quarks and leptons contribute about equal amounts to this observable, although radiation off leptons is restricted to large angles by the kinematical cuts. Since the photon isolation criterion admits some amount of hadronic activity around the photon direction, small angle radiation off quarks is kinematically allowed, and inherently contains a contribution from the non-perturbative quark-to-photon fragmentation function. Both these effects (large-angle radiation and photon fragmentation) are included in our fixed-order parton model calculation, while they are usually not accounted for in standard event generator programs. While the ZEUS collaboration could not describe their data with event generator predictions, we found that our calculation is in very good agreement with the ZEUS data both in normalization and in shape.

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