We present here the predictions obtained from a calculation of the inclusive isolated photon production cross section in deep inelastic scattering. The results are compared with the cross section measurement of the ZEUS collaboration and found in good agreement with all aspects of it. Furthermore, a way of measuring the quark-to-photon fragmentation function in DIS is also briefly outlined.

1 Introduction

The ZEUS collaboration at DESY HERA reported recently a measurement of the inclusive production cross section for isolated photons in deep inelastic scattering (DIS). The normalization of the cross section obtained from the event generators HERWIG and PYTHIA was too high 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. A further attempt to describe the ZEUS measurement using the photon distribution in the proton was also considered in a subsequent study. However, it failed to describe the kinematical distribution correctly. To investigate the origin of these discrepancies, we performed a new calculation of the inclusive isolated photon cross section in DIS. In the following, we describe the parton level calculation and present the resulting predictions choosing the same kinematical constraints as in the experimental analysis. Finally we shall briefly mention the possibility of measuring the quark-to-photon fragmentation function in DIS events.

2 The inclusive isolated photon cross section

In the following, we outline major aspects of the parton-level calculation pointing out the presence of three different contributions depending whether the photon is radiated from a quark or a lepton. We will briefly discuss each contribution separately and in particular mention
that, when the photon is radiated off a quark, both hard photon radiation and quark-to-photon fragmentation contributions have to be taken into account.

2.1 The parton-level calculation

The leading order parton-level process corresponding to the inclusive production of an isolated photon in deep inelastic scattering is given by:

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

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 \( \hat{\sigma}(eq \rightarrow e\gamma q) \) with the quark distribution functions in the proton. In the scattering amplitudes for this process, the lepton-quark interaction is mediated by 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 \((QL)\). The \(Ql\) contribution is odd under charge exchange, such that it contributes with opposite sign to the cross sections with \( l = e^- \) and \( l = e^+ \).

In the \(QQ\) contribution, the photon can have different origins: the direct radiation off the quark and the fragmentation of a hadronic jet into a photon carrying a large fraction of the jet energy. When the radiation takes place at an early stage of the hadronization the quark and the photon are usually well separated from each other. However, when the photon is radiated somewhat later during the hadronization process, it can be emitted collinearly to the primary quarks giving rise to a collinear singularity. Both processes have to be considered. As physical cross sections are necessarily finite, this collinear singularity gets factorized into the fragmentation function defined at some factorization scale \( \mu_{F,\gamma} \), as usual. In the present calculation, we use the phase space slicing method to handle the collinear quark-photon singularity, as described in detail in [9,10].

The fragmentation contribution, besides absorbing the final state collinear singularity, describes non-perturbative physics effects. It is characterized by the process-independent quark-to-photon fragmentation function \([11]D_{q\rightarrow\gamma}(z,\mu_{F,\gamma})\), where \( z \) is the momentum fraction carried by the photon. This fragmentation function can not be calculated within perturbative methods. Instead it has to be measured experimentally. This function has, up to now, been directly determined only by the ALEPH collaboration at LEP. This determination was based on a comparison between the measured and the calculated \( e^+e^- \rightarrow \gamma + 1 \) jet rate at LEP. Other parametrizations of photon fragmentation functions were proposed in the literature, which a resummation of logarithms of \( \mu_{F,\gamma} \) is performed. In the calculation, for the quark-to-photon fragmentation function, we use the ALEPH leading order parametrization as default which does not incorporates any resummation of logarithms, and the BFG (type I) parametrization, evaluated for \( \mu_{F,\gamma}^2 = Q^2 \) for comparison.

The factorization scale \( \mu_F^2 \) for the parton distributions is \( Q^2 = -(p_1 - p_2)^2 \) for the \(QQ\) subprocess and kinematical constraints on \( Q^2 \) ensure the deep inelastic nature of the \(QQ\) process. In the \(LL\) subprocess, where the final state photon is radiated off the lepton, the situation is more complicated. It is described in detail in [3]. For the \(LL\) subprocess we choose \( \mu_F = \max(\mu_{F,\min},Q_{LL}) \), and for the \(QL\) interference subprocess \( \mu_F = \max(\mu_{F,\min},(Q_{LL} + Q_{QQ})/2) \) with \( Q_{LL}^2 = -(p_5 - p_1)^2 \) and \( \mu_{F,\min} = 1 \) GeV. To ensure the deep inelastic nature of the \(LL\) subprocess, the requirement of observing hadronic tracks is of crucial relevance as it implies that the proton disintegrates. As explained in this letter, the track requirement translated into parton-level variables corresponds to impose a minimal cut on the quark rapidity, \( \eta_q < 3 \), which we impose in our calculation.
2.2 The results

The isolated photon cross section 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, these were chosen as follows: virtuality of the process, as determined from the outgoing electron $Q^2 = -(p_1 - p_2)^2 > 35 \text{ GeV}^2$, outgoing electron energy $E_e > 10 \text{ GeV}$ and angle $139.8^\circ < \theta_e < 171.8^\circ$, outgoing photon transverse energy $5 \text{ GeV} < E_{T,\gamma} < 10 \text{ GeV}$ and rapidity $-0.7 < \eta_\gamma < 0.9$.

The photon, to be called isolated, is required to carry at least 90% of the energy found in a cone of radius $R = 1.0$ in the $\eta - \phi$ plane around the photon direction. This cone-based isolation procedure is commonly used to define isolated photons produced in a hadronic environment. A minimal amount of hadronic activity inside the cone has to be allowed in order to ensure infrared finiteness of the observable.

For the numerical evaluation of the cross section, we use the CTEQ6L leading order parametrization 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 $5.64 \pm 0.58 \text{ (stat.)}^{+0.47}_{-0.72} \text{ (syst.)} \text{ pb}$. The total cross section is therefore well reproduced by our calculation.

![Figure 1](image.png)

Figure 1: (a) Rapidity distribution and (b) transverse momentum distribution of isolated photons, compared to ZEUS data.

Using our leading order calculation, we obtain differential cross sections in $\eta_\gamma, E_{T,\gamma}$ which are shown in Figure 1. Both distributions are found in good agreement with the ZEUS data.

3 Conclusions and outlook

In this talk, we reported results concerning the production of isolated photons in deep inelastic scattering presented in 6. In this letter, we compare our predictions for the $\sigma(lp \rightarrow l\gamma X)$ with the ZEUS measurement of this cross section. We found that photon radiation off quarks and leptons contribute about equal amounts to this observable. Since the photon isolation criterion admits some amount of hadronic activity around the photon direction, small angle radiation off quarks and non-perturbative quark-to-photon fragmentation function contributions need to be considered. Both these effects (large-angle radiation and photon fragmentation) are included in our fixed-order parton model calculation, which yields good agreement with the ZEUS data both in normalization and in shape.

By further analyzing the hadronic final state in isolated photon production in DIS, one can define more exclusive observables like photon-plus-jet cross sections. In 16, we present the predictions obtained from calculating the $\gamma + (0 + 1)$-jet cross section differential in $z$. These predictions are obtained using the kinematical cuts appropriate for an H1 measurement specified.
in \cite{17} and defined using the $k_T$ exclusive jet algorithm \cite{18} in the laboratory frame. For this observable, besides the photon jet ($\gamma$) and the proton remnant (+1), no (0) further hadronic jet activity is present in the final state. Figure 2 displays the theoretical results as bin-integrated cross sections for three bins for two different values of the jet resolution parameter $y_{cut}$.

![Figure 2: Differential distribution in $z$ ($0.7 < z < 1$) of the $\sigma(\gamma + (0 + 1)$-jet) using the exclusive $k_T$ algorithm with (a) $y_{cut} = 0.1$ and (b) $y_{cut} = 0.001$ for the ALEPH (plain) and BFG (dashed) parametrizations of the quark-to-photon fragmentation function.](image)

For a given $y_{cut}$, the predictions for the $\gamma + (0 + 1)$-jet cross section obtained using different parametrizations shown in Figure 2 differ considerably; in particular for $0.7 < z < 0.9$. It appears therefore that this observable is highly sensitive on the photon FF and would be an appropriate observable to measure in view of extracting the quark-to-photon fragmentation function in DIS.

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