ISOLATED PROMPT PHOTON PLUS JET
PHOTOPRODUCTION AT HERA

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The cross section for photoproduction of a prompt photon in association with a jet is studied in Next-to-Leading Order at the DESY $e^p$ collider HERA. The effect of various cuts imposed on the cross section by the ZEUS collaboration including isolation cuts on the photon is examined. Comparisons with the ZEUS preliminary data using various parametrizations of the photon structure function is made, and good agreement is found. The preliminary data is not yet precise enough to make a distinction between various models for the photon structure function.

1 Introduction

It has long been anticipated that the DESY $e^p$ collider HERA would provide a good opportunity to study prompt photon production in photoproduction processes. Over the past few years various studies of this process have been performed with continuous improvements in their theoretical precision. In the most recent studies the inclusive cross section for producing a single photon was calculated fully in NLO with isolation effects incorporated. In an approximate but nevertheless very accurate analytic technique for including isolation effects in the NLO calculation, including the fragmentation contributions was used. This analytic technique is only applicable to single inclusive prompt photon production and cannot be applied when a jet is also observed.

The ZEUS Collaboration have begun analyzing prompt photon data and have first chosen to look for events with a jet balancing the transverse momentum ($p_T^γ$) of the photon. In order to compare with this data a new calculation is necessary which will be described in outline in the next section.

In all the previous studies of prompt photon production at HERA, one of the common themes was the possibility of using it for measuring the photon distribution functions, particularly the gluon distribution, $g^γ(x,Q^2)$ which is presently very poorly constrained by the available data. This latter fact is still true even with the availability of jet photoproduction data at both HERA

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1. Talk Presented at Photon'97, Egmond aan Zee, The Netherlands, May 10-14, 1997

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and TRISTAN. Prompt photon production is particularly attractive since it is dominated in Leading Order (LO) by the hard scattering subprocess $qg \rightarrow \gamma q$, resulting in a cross section which is very sensitive to the gluon distribution.

At HERA the situation is rather more complicated than at hadron colliders by two factors. Firstly there are two particles involved in the reaction, namely the quasi-real photon emitted by the electron which scatters at a small angle, as well as the proton. Both particles have distinct gluon distribution functions $g^\gamma$ and $g^p$, hence two different $qg$ initiated subprocess are present, $q^p g^\gamma \rightarrow \gamma q$ and $q^\gamma g^p \rightarrow \gamma q$. Since they contribute to the cross section in different regions of pseudo-rapidity, $\eta$, it has been proposed that this may provide a means of separating them experimentally, but this has proven to be very difficult experimentally. Secondly, there are two types of contributions to the cross section in photoproduction processes, usually labelled the direct and resolved contributions. In the former case the quasi-real photon participates directly in the hard scattering subprocess and gives up all its energy, while in the latter, resolved, case it interacts via its partonic substructure. Thus the resolved subprocesses are sensitive to the photon structure functions whereas the direct are not. Again it was proposed that they may be separated experimentally with suitable rapidity cuts. A study performed in [4] has shown that since the initial photon energy is not fixed but forms a continuous spectrum, then even this separation is not straightforward. Separation of resolved and direct processes is better achieved by tagging of the spectator jet from the resolved photon.

2 The Inclusive Photon Plus Jet Cross Section

In addition to the direct and resolved photon contributions to the cross section there are the non-fragmentation and fragmentation contributions. In the former case the observed final state photon is produced directly in the hard scattering whereas in the latter it is produced by long distance fragmentation off a final state parton. The fragmentation processes involve the fragmentation functions which require a non-perturbative input from experiment and have not been satisfactorily measured up to now.

The only direct non-fragmentation process contributing to the cross section in LO is the so called QCD Compton process

$$\gamma q \rightarrow \gamma q$$

and the direct fragmentation processes are

$$\gamma q \rightarrow gq \text{ and } \gamma g \rightarrow q\bar{q}.$$  

As discussed in many places (see eg. [5]) the photon fragmentation function is formally $O(\alpha_{em}/\alpha_s)$, thus although the hard subprocess cross sections in the
fragmentation case are $O(\alpha_{em}\alpha_s)$, after convolution with the photon fragmentation functions the process is $O(\alpha_s^2)$, the same as the the non-fragmentation part.

At NLO for the non-fragmentation part there are the virtual corrections to the LO Compton process plus the additional three-body processes

$$\gamma q \rightarrow \gamma g q \quad \text{and} \quad \gamma g \rightarrow \gamma q \bar{q}.$$ 

In addition there are $O(\alpha_s)$ corrections to the fragmentation processes to take into account, but in this calculation these processes are included in LO only. It has been shown in ref. [6] that the fragmentation contributions are not as significant here as at hadron colliders which generally have higher cms energies and are reduced drastically when isolation cuts are implemented. Thus ignoring NLO corrections to the fragmentation contributions while in principle inconsistent will not lead to a large numerical error.

In the resolved case, for non-fragmentation there are only the two processes

$$g g \rightarrow \gamma q \quad \text{and} \quad q \bar{q} \rightarrow \gamma g.$$ 

in LO. At NLO there are virtual and three-body corrections to these as well as other three-body processes, eg. $g g \rightarrow \gamma q \bar{q}$ etc. for a complete list of these plus the fragmentation processes see eq. [6].

The calculation was performed using the phase space slicing method which makes it possible to perform photon isolation exactly as well as to implement the jet definition. Details of the calculation can be found in ref. [11]. Following the ZEUS experiment, the cone isolation method is used, which restricts the hadronic energy allowed in a cone of radius $R_\gamma = \sqrt{\Delta \phi^2 + \Delta \eta^2}$, centred on the photon to be below the value $\epsilon E_\gamma$, where $E_\gamma$ is the photon energy. The fixed value $\epsilon = 0.1$ is used which corresponds to the value used in the ZEUS analysis.

The cone algorithm is used to define the jet. This defines a jet as hadronic energy deposited in a cone radius $R_J = \sqrt{\Delta \phi^2 + \Delta \eta^2}$. If two partons form the jet then the kinematic variables are combined to form that of the jet according to the formulae

$$p_J = p_1 + p_2,$$
$$\eta_J = \frac{\eta_1 p_1 + \eta_2 p_2}{p_1 + p_2},$$
$$\phi_J = \frac{\phi_1 p_1 + \phi_2 p_2}{p_1 + p_2}. \quad (1)$$

In the ZEUS analysis $R_\gamma = 1.0$ and $R_J = 1.0$ are chosen and we therefore use these values.
In order to estimate the flux of quasi-real photons from the electron beam the Weiszacker-Williams approximation is used. Thus the ‘electron structure function’ \( f_e(x_e, Q^2) \) is given by a convolution of the photon structure function \( f^γ(x_γ, Q^2) \) and the Weiszacker-Williams function

\[
f_{γ/e}(z) = \frac{\alpha_{em}}{2\pi} \left[ \frac{1 + (1 - z)^2}{z} \right] \ln \frac{Q_{max}^2(1 - z)}{m_e^2 z^2} - 2m_e^2 z^2 \left( \frac{1 - z}{m_e^2 z^2} - \frac{1}{Q_{max}^2} \right) \tag{2}\]

by

\[
f_e(x_e, Q^2) = \int_{x_e}^1 \frac{dz}{z} f_{γ/e}(z)f^γ \left( \frac{x_e}{z}, Q^2 \right). \tag{3}\]

The expression for \( f_{γ/e}(z) \) was taken from ref. Following the ZEUS analysis the value \( Q_{max}^2 = 1 \text{ GeV}^2 \) is used throughout.

3 Numerical Results

The numerical results presented in this section are obtained using the GS96\(^1\) photon distribution functions, the CTEQ4M\(^1\) parton distributions for the proton and the GRVLO\(^1\) fragmentation functions as standard. Futhermore the two-loop expression for \( α_s \) is used, four-flavours of quarks are assumed active and the factorization/renormalization scales are taken to be equal to the photon \( p_T \) \( (Q^2 = (p_T^2)^2) \). The maximum virtuality of the initial state photon is fixed at \( Q_{max}^2 = 1 \text{ GeV}^2 \) as chosen by the ZEUS Collaboration. Using the above parameters the fragmentation contribution constituted less than 20% of the cross section at \( p_T^γ = 5 \text{ GeV} \) before isolation and falls rapidly with increasing \( p_T^γ \). After isolation this figure is reduced by 85%. The higher order corrections enhances the cross section \( O(20\%) \) before isolation. Imposing the ZEUS \( p_T \), rapidity, and isolation cuts on the inclusive single photon cross section results in a drop in the cross section by more then a factor of 3 as shown in fig.1a. This severely reduces the accuracy of the measurement and makes it less likely that it will be useful in distinguishing between the available photon distribution function parametrizations. But as fig.1b shows if enough statistics can be accumulated in the negative rapidity region the possibility still exists to discriminate between the GRV\(^1\) and GS parametrizations.

Table 1 shows predictions for the resolved and direct contributions to the cross section in \( \text{pb} \) and their sum for various choices of parameters. In order to obtain a sample of direct events the ZEUS Collaboration have imposed the cut \( x_γ ≥ 0.8 \) on their data. This cut which is also imposed on the results in Table
1, favours the direct contributions since they contribute at \( x_\gamma = 1 \), but there is still a contribution from the resolved processes and hence some sensitivity to the photon distributions chosen. In addition the cuts \( 5 \text{ GeV} \leq p_T^\gamma \leq 10 \text{ GeV}, \ p_T^J \geq 5 \text{ GeV}, \ -1.5 \leq \eta^\gamma \leq 1.8, \ -0.7 \leq \eta^J \leq 0.8 \) and \( 0.16 \leq z = E_\gamma/E_e \leq 0.8 \) along with the isolation cuts and jet definitions discussed in section 2 are imposed.

The first column of numbers gives the results for the standard choice of parameters, while the 2nd and 3rd columns show the effect of changing the scales. The results show a remarkable stability to scale changes. This is in contrast to eg. the \( p_T^\gamma \) distribution which generally shows significant scale sensitivity. The 4th and 5th columns show the effect of changing the photon and proton distribution functions used respectively. In the latter case there is hardly any changes in the predictions, while in the former case the changes are very significant. Since with these cuts the cross section is mostly sensitive to the quark distributions in the photon at large-\( x \) then it may potentially be used to discriminate between the GS96 and GRV photon parametrizations which differ most significantly in this region. The preliminary experimental value given by the ZUES Collaboration of \( 17.1 \pm 4.5 \pm 1.5 \text{ pb} \) agrees remarkably well with the NLO theoretical predictions but the errors quoted are still too large to make
Table 1: Total $\gamma + \text{jet}$ cross section with HERA cuts (see text).

|     | STD  | $Q^2 = (p_T^\gamma)^2/4$ | $Q^2 = 4(p_T^\gamma)^2$ | GRVγ | MRSR1 |
|-----|------|--------------------------|--------------------------|------|-------|
| RES | 3.31 | 2.60                     | 4.95                     | 6.72 | 3.44  |
| DIR | 9.86 | 11.45                    | 8.18                     | 9.86 | 9.34  |
| SUM | 13.17| 14.05                    | 13.13                    | 16.58| 12.78 |

any distinction between GS and GRV.

4 Conclusions

A NLO calculation of isolated single photon plus jet production at HERA was presented and compared to the preliminary data from the ZEUS Collaboration and good agreement was found. The kinematic cuts chosen favour the direct contribution but there is still a significant sensitivity to the quarks distributions in the photon at large-$x$. At the moment the error in the data is still too large to distinguish between the GRV and GS96 photon distributions, but it is expected that accumulation of more data will soon remedy this situation.

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