Photon Structure and the Hadronic Final State in Photoproduction Processes at ZEUS

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Advances in knowledge of the structure of the photon and tests of perturbative QCD have been made using the increased luminosity with the ZEUS detector at HERA. Events with a low photon virtuality and two high transverse energy jets have been studied. Measurements of inclusive dijet and multijet production are herein compared to Next-to-Leading-Order calculations. In order to analyse the structure of the photon, dijet production of quasi-real and virtual photons and dijet production containing \( D^{\pm\pm} \) mesons were measured.

1 Introduction

The study of dijet photoproduction at HERA allows one to perform tests of perturbative QCD (pQCD) and to place constraints on the structure of the photon. To Leading Order (LO) two types of processes contribute to jet photoproduction [1] - direct and resolved photon processes (see Fig. 1). In direct photon processes, the photon interacts directly in the hard sub-process, whereas for resolved photon processes, the photon resolves into a source of partons, one of which participates in the hard sub-process.

![Fig. 1](attachment:1-245223881365.jpg)

Fig. 1: Examples of LO direct photon (a) and resolved photon (b) and (c) processes.

The cross-section for resolved photon processes can be written in terms of the perturbatively calculable \( 2 \rightarrow 2 \) scattering cross-section, \( d\sigma_{ab\rightarrow cd} \), as,

\[
d\sigma_{\gamma p\rightarrow cd} = \sum_{ab} \int_{x_p} \int_{x_{\gamma}} f_{p/b}(x_p, \mu_p^2) f_{\gamma/a}(x_{\gamma}, \mu_{\gamma}^2) d\sigma_{ab\rightarrow cd}.
\]

The proton’s parton density function, \( f_{p/b} \), is experimentally constrained allowing the extraction of the parton density of the photon, \( f_{\gamma/a} \), a currently poorly known quantity.
Comparisons of data with pQCD calculations will be covered first followed by analyses of the structure of the photon.

2 Tests of pQCD in Dijet Photoproduction

The invariant mass of the dijet system, $M^{jj}$, is sensitive to the presence of new particles or resonances decaying into jets. The scattering angle in the centre-of-mass frame of the dijet system, $\cos\theta^*$, reflects the underlying parton dynamics, thereby providing a test of QCD. In direct photon processes, the dominant propagator is that of a quark in the $s$, $t$ and $u$ channels but is a gluon in the $t$ channel for resolved photon processes. The presence of the different propagators in the two processes is reflected in the angular dependence of the cross-section; the spin $-\frac{1}{2}$ quark yields a $(1 - |\cos\theta^*|)^{-1}$ and the spin $-\frac{1}{2}$ gluon yields a $(1 - |\cos\theta^*|)^{-2}$ dependence in the cross-section. This predicted (by pQCD) behaviour of the cross-section dependence on direct and resolved processes has been observed at HERA for $M^{jj} > 23$ GeV [2]. Consequently any deviation from the pQCD predictions for the cross-section for higher dijet invariant masses would also be an indication of the presence of decays from new particles or resonances.

Photoproduction events were defined by requiring $Q^2 < 4$ GeV$^2$ (corresponding to a median $Q^2 \approx 10^{-3}$ GeV$^2$) and the photon-proton centre-of-mass energy in the range, $134 < W < 277$ GeV. Differential cross-sections as a function of $M^{jj}$ and $|\cos\theta^*|$ for dijet masses above 47 GeV and $|\cos\theta^*| < 0.8$ were measured. Jet finding was performed using the $k_T$ clustering algorithm [3] requiring there to be at least two jets with $E_T > 14$ GeV and $-1 < \eta^{jet} < 2$. The measured cross-sections $d\sigma/d|\cos\theta^*|$ and $d\sigma/dM^{jj}$ using 41.3 pb$^{-1}$ are shown in Fig. 2 and compared to pQCD calculations [4].

![Fig. 2: Differential cross-sections, $d\sigma/d|\cos\theta^*|$ (left) and $d\sigma/dM^{jj}$ (right) compared to pQCD calculations. The ZEUS data points show statistical errors (thick bars) and statistical plus systematic errors (thin bars) with the error due to the energy scale displayed as a band.](image)

\[\text{All measurements presented in this paper were performed using the } k_T \text{ clustering algorithm}\]
The NLO calculations agree well in shape with the measured distributions for both $d\sigma/d|\cos\theta^*|$ and $d\sigma/dM^{JJ}$. The predictions using the GRV-HO photon structure function are closer in magnitude to the data compared to those from GS96.

3 Tests of pQCD in Multijet Photoproduction

Multijet production provides a test of pQCD predictions beyond leading order and additionally tests extensions to fixed order theories such as parton shower models. The three jet system can be visualised in the centre-of-mass frame by considering Fig. 3. Of interest are the angles $\theta_3$ and $\psi_3$. $\theta_3$ is the angle between the highest energy jet and the beam direction and is analogous to the scattering angle $\theta^*$ from the previous section. $\psi_3$ is the angle between the plane containing the three jets and the plane containing the highest energy jet and the beam direction.

By requiring $Q^2 < 1 \text{ GeV}^2$ and a photon-proton energy range, $134 < W < 269 \text{ GeV}$, photoproduction events are selected. These events are then required to have at least two jets with $E_{\text{jet}}^T > 6 \text{ GeV}$ and a third with $E_{\text{jet}}^T > 5 \text{ GeV}$ in a region of pseudorapidity, $|\eta_{\text{jet}}| < 2.4$. These jet requirements introduce a bias in the angular distributions by excluding those jets produced close the beam-line. The criteria; $M_{3J} > 50 \text{ GeV}$, $|\cos\theta_3| < 0.8$ and $2E_3/M_{3J} < 0.95$, reduce this bias.

The three jet invariant mass cross-section, $d\sigma/dM_{3J}$, is shown in Fig. 4 and compared with $O(\alpha_s^2)$ calculations from two pairs of authors, Harris & Owens [5] and Klasen & Kramer [6], showing good agreement with the data. The Monte Carlo models HERWIG and PYTHIA describe the shape well but lie 20-40% below the data. In Fig. 5, the angular distributions, $\cos\theta_3$ and $\psi_3$ are shown. These distributions show a difference from those obtained from phase space displaying a sensitivity to the QCD matrix elements. The $\cos\theta_3$ distribution is similar
to that of a Rutherford scattering form and is well predicted by the QCD calculations which account for the spin of the propagator. On consideration of the distribution in $\psi_3$, one can see a tendency for the three jet plane to lie near the plane containing the beam and the highest energy jet as predicted by the coherence property of QCD.

![ZEUS 1995–1996 Preliminary](image)

Fig. 5: Distributions for $\cos \theta_3$ (left) and $\psi_3$ (right). The statistical and systematic errors are as described previously.

## 4 High $E_T$ Dijet Cross-sections in Photoproduction

By choosing events with suitably high $E_T$ dijets, one can study the sensitivity of the cross-sections to the photon’s parton distribution, the proton’s being well constrained from previous experiments. This provides a measurement, in the range of the parton’s momentum fractions, $x_\gamma$, with a higher scale to those in $e^+e^-$ data. The current parameterisations of the parton density of the photon in the high $x$ region have large differences due to uncertainties in experimental measurements. In previous dijet measurements [8], a large excess of the measured cross-sections for $E_T^{jet} > 6$ GeV was seen over the NLO predictions for resolved enriched samples. This was attributed to possible contributions from non-perturbative effects such as multiparton interactions [7]. This effect should be reduced for increasing $E_T^{jet}$. To reconstruct $x_\gamma$ experimentally, we define the observable:

$$x_\gamma^{obs} = \frac{\sum_{jets} E_T^{jet} e^{-\eta^{jet}}}{2yE_e},$$

(2)

where the sum runs over the two highest $E_T$ jets and $yE_e$ is the initial photon energy. We can then define direct and resolved processes by cutting on $x_\gamma^{obs}$, such that direct
enriched requires $x_{\gamma}^{\text{obs}} \geq 0.75$.

Cross-sections are measured in two kinematical regions of the photon and proton centre-of-mass; the nominal region, $134 < W < 277$ GeV and the region $212 < W < 277$ GeV, which enhances the low $x_{\gamma}^{\text{obs}}$ events. The photon virtuality was again required to be less than 1 GeV$^2$. Asymmetric requirements on the jet transverse energy [4] of $E_T^{\text{jet1}} > 14$ GeV and $E_T^{\text{jet2}} > 11$ GeV in the region $-1 < \eta^{\text{jet}} < 2$ were chosen.

Fig. 6 shows the uncorrected $x_{\gamma}^{\text{obs}}$ distribution compared to HERWIG Monte Carlo predictions. There is good agreement in shape between the data and Monte Carlo without the requirement of multiparton interactions. For lower transverse energy jets ($E_T^{\text{jet}} > 6$ GeV [8]), there was a large excess at low $x_{\gamma}^{\text{obs}}$ which is not seen here.

Evidence of the non-requirement of multiparton interactions to describe the data can also be seen the distribution of transverse energy flow around the jets. Consideration of Fig. 7 demonstrates good agreement between data and Monte Carlo predictions. For high values of $\eta$, the region of disagreement in lower $E_T$ dijet studies [8], the agreement remains good. From this observation, coupled to the measurement of $x_{\gamma}^{\text{obs}}$, we conclude that no additional processes above the leading logarithm parton shower model is necessary to describe the event shapes.

Differential cross-sections with respect to the pseudorapidity of the second jet in bins of the pseudorapidity of the first jet are here presented. For the entire region in $W$, $d\sigma/d\eta_{\gamma}^{\text{jet}}$ is shown for the whole region in $x_{\gamma}^{\text{obs}}$ and for the direct enriched ($x_{\gamma}^{\text{obs}} \geq 0.75$) region in Fig. 8. The data is compared to NLO calculations from Klasen et al. [6] and Harris et al. [9] for the GS96 photon structure function and the GRV-HO structure function.
for Klasen et al.. Reasonable agreement between data and theory is seen in shape and magnitude for both regions of $x_{\gamma}^{\text{obs}}$. However, differences of the order of the systematic errors are seen between the two structure functions.

**Fig. 8:** Measured $d\sigma/d\eta_{\text{jet}}^{\text{ext}}$ in $134 < W < 277$ GeV in three regions of $\eta_{\text{jet}}^{\text{ext}}$ for all $x_{\gamma}^{\text{obs}}$ (circles) and for $x_{\gamma}^{\text{obs}} \geq 0.75$ (triangles) compared to NLO calculations. The data has statistical errors (thick bars), the sum of statistical and systematic errors (thin bars) and a band due to the uncertainty in the energy scale.

**Fig. 9:** Measured $d\sigma/d\eta_{\text{jet}}^{\text{ext}}$ in $212 < W < 277$ GeV in three regions of $\eta_{\text{jet}}^{\text{ext}}$ for all $x_{\gamma}^{\text{obs}}$ compared to NLO calculations. The data has statistical and systematic errors as described previously.
Fig. 9 shows \(d\sigma/d\eta_{2}^{jet}\) for the region of high \(W\) with all other cross-section definitions remaining the same. The cross-sections for the whole range of \(x_{Q}^{obs}\) are shown and compared to the calculations from Klasen et al. with the two previously mentioned structure functions. From these we see that this high \(W\) region leads to an increased sensitivity to the photon structure function particularly in the \(1 < \eta_{1}^{jet} < 2\) region. In the central region of pseudorapidity the measured cross-sections lie above the predictions.

The uncertainty from possible differences between the jets from final state particles and NLO partons due to higher order contributions and hadronizations is partly estimated using the leading logarithm parton shower Monte Carlo, HERWIG and PYTHIA. The estimator \((d\sigma/d\eta_{2}^{jet})_{\text{parton}}/(d\sigma/d\eta_{2}^{jet}) - 1\) for the narrower \(W\) region, \(212 < W < 277\) GeV is shown in Fig. 10 where the partons are those after the parton shower process. The uncertainties are compared with the experimental uncertainties for the measured \(d\sigma/d\eta_{2}^{jet}\). For low \(\eta_{2}^{jet}\) the estimator from the HERWIG model is large (smaller for PYTHIA) and comparable with the systematic uncertainties. The theoretical uncertainty is smaller than the experimental error in the other regions of \(\eta^{jet}\) being similar for HERWIG and PYTHIA.

Another uncertainty comes from the ambiguity of the renormalisation and factorisation scale, \(\mu\), and is estimated by Harris et al. [9] to be of the order of 10% by varying the scale; \(E_T/2\) to \(2E_T\), for the cross-sections in Fig. 8.
5 Real and Virtual Photons in Dijet Production

Whilst progress has recently been made in studying the parton distribution functions (PDFs) for quasi-real photons, little information exists for those of virtual photons with low statistics data from the PLUTO collaboration and studies of the photoproduction to deep inelastic transition region from the H1 collaboration [10] being the only published results. The expectation for the HERA data is that the contribution to the cross-section from resolved photon compared to direct photon processes should decrease with increasing photon virtualities. Therefore measurements of the evolution of the resolved photon component with $Q^2$ are expected to constrain the virtual photon PDFs and test pQCD.

As an estimator of $x^\text{obs}_\gamma$, $x^\text{meas}_\gamma$ was defined which is analagous to Eqn. 2 but uses calorimeter quantities; $y_J$ as an estimator for $y$, $E^\text{jet}_{\text{meas}}>5$ GeV and $-1.125<\eta^\text{jet}_{\text{meas}}<1.875$. Fig. 11 shows the $x^\text{meas}_\gamma$ distributions compared to HERWIG Monte Carlo predictions for three bins of $Q^2$. The normalistaion of direct and resolved processes were extracted from a two parameter fit to the measured distribution, being different for each range in $Q^2$. The agreement in shape for the virtual photon data is good but is poor for the quasi-real photon data due to non perturbative effects as mentioned in the previous section.

Using this data we can form the ratio of resolved enriched ($x^\text{meas}_\gamma<0.75$) to direct enriched ($x^\text{meas}_\gamma>0.75$) events and then compute the ratio of cross-sections,
\[ \sigma(x^0_{\gamma} < 0.75)/\sigma(x^0_{\gamma} > 0.75), \] as a function of \( Q^2 \). This ratio defined for dijet events, \( E_T^{\text{jet}} > 6.5 \text{ GeV} \) and -1.125 < \( \eta < 1.875 \), with 0.2 < \( y < 0.55 \) is shown in Fig. 12. From this figure we can see a general decrease in the ratio with increasing \( Q^2 \).

## 6 Charm in Dijet Photoproduction

Allied to the jets, a charm quark provides an additional hard scale (\( m_c > \Lambda_{\text{QCD}} \)) yielding a more reliable perturbative calculation. Two approaches for the calculation of charm are currently available, the so-called massive and massless schemes. The massive approach assumes only the three lightest quarks to be active flavours in the proton and photon. In the massless approach, the charm quark is treated as an additional active flavour. Massless calculations therefore predict, for a given factorisation scale, a larger resolved component compared to massive calculations. A measurement of \( x^0_{\gamma} \) will provide a method for the possibility of distinguishing the two schemes and probing the question of charm in the photon.

The charm quark itself cannot be directly tagged, consequently events are selected containing reconstructed \( D^{*\pm} \) mesons with \( p_T(D^*) > 3 \text{ GeV}/c \) and \(|\eta(D^*)| < 1.5\) in dijet photoproduction events. Before measuring a cross-section in \( x^0_{\gamma} \), we first consider the energy flow about the jet axis, Fig. 13. The jet profiles, calculated in the same way as described in Fig. 7, are split into low and high \( x^0_{\gamma} \) for three bins of \( \eta^{\text{jet}} \) for reconstructed jets; \( E_T^{\text{CAL,jet}} > 4 \text{ GeV} \). The HERWIG Monte Carlo without multiparton interactions provides a good description of the data even in the forward region where there was a discrepancy for inclusive dijets of this energy [8]. One can also see that the direct photon only Monte Carlo cannot describe the data at low values of \( \Delta \eta \) as can be seen in the \( x^0_{\gamma} < 0.75 \), 0 < \( \eta^{\text{jet}} < 1 \) bin. This excess energy flow in the rear direction is consistent with there being a photon remnant.

Fig. 14 shows \( d\sigma/dx^0_{\gamma} \) in the range \( Q^2 < 1 \text{ GeV}^2 \), 130 < \( W < 280 \text{ GeV} \) for jets with \(|\eta| < 2.4 \), \( E_T^{\text{jet1,2}} > 7.6 \text{ GeV} \) and at least one \( D^* \) meson, satisfying the criteria previously mentioned.
Fig. 14(a) shows the HERWIG Monte Carlo (normalised to the data) agreeing in shape with the measured cross-section. There is a peak at high $x_γ^{obs}$ consistent with LO-direct photon processes. There also exists a significant cross-section at low $x_γ^{obs}$ which cannot be described by LO-direct only and needs some component of LO-resolved photon processes. At the given scale the LO-resolved component is dominated by charm excitation processes of the form, Fig. 1(c). The required LO-resolved contribution is $45 \pm 5\text{(stat.)}\%$ (compared to the HERWIG prediction of 37%) of which 93% is from charm excitation processes.

Fig. 14(b) shows a comparison of the data with an NLO massive calculation [11]. This does not describe the low $x_γ^{obs}$ measured cross-section whilst describing the high $x_γ^{obs}$ region. Upon choosing extremes of the scale $\mu_R$ and the charm mass $m_c$, the prediction still fails to describe the data.

7 Summary and Conclusions

Sufficient data has now being collected by ZEUS to allow the comparison of pQCD with precise measurements; these comparisons show good agreement for dijet and multijet dynamics. With the increased precision the data can now differentiate between different photon structure function parameterizations and can be used to place constraints on its form.

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