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Measurement of isolated photons accompanied by jets in deep inelastic *ep* scattering

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ABSTRACT

The production of isolated high-energy photons accompanied by jets has been measured in deep inelastic *ep* scattering with the ZEUS detector at HERA, using an integrated luminosity of 326 pb^{-1}. Measurements were made for exchanged photon virtualities, Q^2, in the range 10 to 350 GeV^2. The photons were measured in the transverse-energy and pseudorapidity ranges $4 < E_T^\gamma < 15$ GeV and $-0.7 < \eta^\gamma < 0.9$, and the jets were measured in the transverse-energy and pseudorapidity ranges $2.5 < E_T^{\text{jet}} < 35$ GeV and $-1.5 < \eta^{\text{jet}} < 1.8$. Differential cross sections are presented as functions of these quantities. Perturbative QCD predictions give a reasonable description of the shape of the measured cross sections over most of the kinematic range, but the absolute normalisation is typically in disagreement by 20–30%.

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1. Introduction

Events in which an isolated high-energy photon is observed provide a direct probe of the underlying partonic process in high-energy collisions involving hadrons, since the emission of such photons is unaffected by parton hadronisation. Processes of this kind have been studied in a number of fixed-target and hadron-collider experiments [1]. In *ep* collisions at HERA, the ZEUS and H1 collaborations have previously reported the production of isolated photons in photoproduction [2–6], in which the exchanged photon is quasi-real, and also in deep inelastic scattering (DIS) [7–9], where the virtuality Q^2 of the exchanged virtual photon is greater than 1 GeV^2. The analysis presented here follows a recent ZEUS inclusive measurement [9] of isolated photons in DIS.

Fig. 1 shows the lowest-order tree-level diagrams for high-energy photon production in DIS. Photons radiated by an incoming or outgoing quark are called “prompt”; an additional class of photons comprises those radiated from the incoming or outgoing lepton. In this Letter, the inclusive photon measurements in DIS by ZEUS are extended to include the requirement of a hadronic jet. By increasing the ratio of the prompt photon contribution relative to the lepton-radiated contributions, this measurement provides an improved test of perturbative QCD (pQCD) in a kinematic region with two hard scales, which are given by Q and by p_T^{jet}, the transverse momentum of the jet or, equivalently, the momentum transfer in the QCD scatter. In particular, the fraction of prompt processes is increased, and a class of jetless non-pQCD processes is excluded in which a soft photon radiated within the proton undergoes a hard scatter off the incoming electron [10]. Compared to a previous ZEUS publication on this topic [7], the kinematic reach extends to lower values of Q^2 and to higher values of the photon transverse energy, E_T^{γ}, and the statistical precision is much improved owing to the availability of nearly three times the integrated luminosity.

Leading-logarithm parton-shower Monte Carlo (MC) and perturbative QCD predictions are compared to the measurements. The cross sections for isolated photon production in DIS have been calculated to order $O(\alpha^3\alpha_s)$ by Gehrmann-De Ridder et al. (GKS) [11–13]. A calculation based on the k_T factorisation approach has been made by Baranov et al. (BLZ) [14].

2. Experimental set-up

The measurements are based on a data sample corresponding to an integrated luminosity of 326 ± 6 pb^{-1}, taken during the years 2004 to 2007 with the ZEUS detector at HERA. During this period, HERA ran with an electron/positron beam energy of 27.5 GeV and a proton beam energy of 920 GeV. The sample is a sum of 138 ± 2 pb^{-1} of e^+p data and 188 ± 3 pb^{-1} of e^-p data.[61]

A detailed description of the ZEUS detector can be found elsewhere [15]. Charged particles were tracked in the central tracking detector (CTD) [16] and a silicon micro vertex detector (MVD) [17] which operated in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The high-resolution uranium-scintillator calorimeter (CAL) [18] consisted of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. The BCAL covered the pseudorapidity range −0.74 to 1.01 as seen from the nominal interaction point. The FCAL and RCAL extended the range to −3.5 to 4.0. The smallest subdivision of the CAL was called a cell. The barrel electromagnetic calorimeter (BEMC) cells had a pointing geometry aimed at the nominal interaction point, with a cross section approximately 5×20 cm^2, with the finer granularity in the Z-direction.[62] This fine granularity allows the use of shower-shape distributions to distinguish isolated photons from the products of neutral meson decays such as $\pi^0 \to \gamma\gamma$.

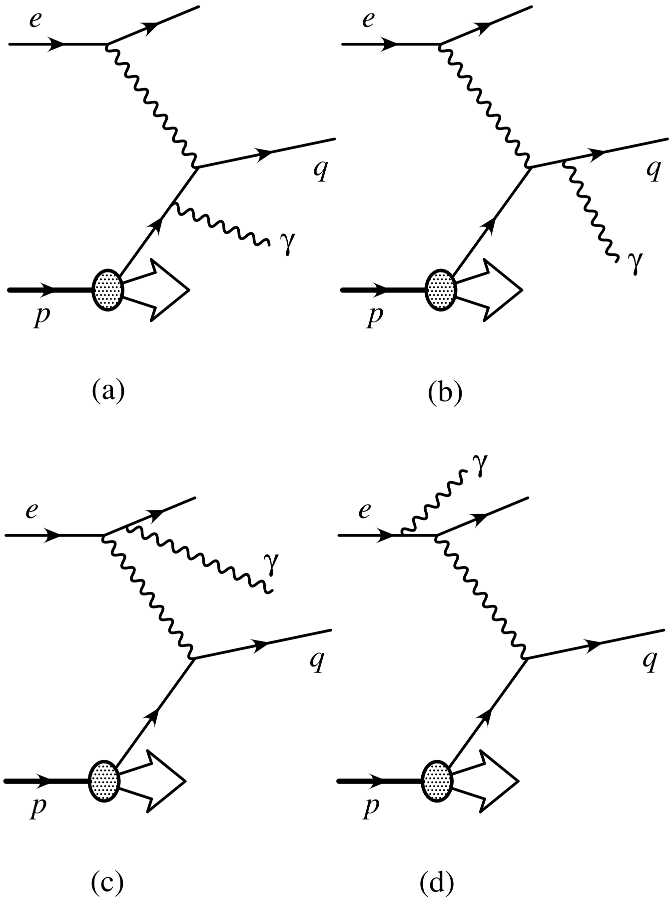

Fig. 1. Lowest-order tree-level diagrams for isolated photon production in *ep* scattering. (a)–(b): quark radiative diagrams; (c)–(d): lepton radiative diagrams.

The luminosity was measured using the Bethe–Heitler reaction $ep \to e\gamma p$ by a luminosity detector which consisted of two independent systems: a lead-scintillator calorimeter [19] and a magnetic spectrometer [20].

3. Event selection and reconstruction

A three-level trigger system was used to select events online [15,21,22] by requiring well isolated electromagnetic deposits in the CAL.

Events were selected offline by requiring a scattered-electron candidate, identified using a neural network [23]. The candidates were required to have a polar angle in the range $\theta_e > 140°$, in order to have a good measurement in the RCAL. To ensure a well understood acceptance, the impact point (X, Y) of the candidate

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[61] Hereafter “electron” refers to both electrons and positrons unless otherwise stated.

[62] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the “forward direction”, and the X axis pointing towards the centre of HERA. The coordinate origin is at the nominal interaction point.

on the surface of the RCAL was required to lie outside a rectangular region (± 14.8 cm in X and $[-14.6, +12.5]$ cm in Y) centred on the origin of coordinates. The energy of the candidate, E'_e, was required to be larger than 10 GeV. The kinematic quantities Q^2 and x were reconstructed from the scattered electron as $Q^2 = -(k-k')^2$ and $x = Q^2/(2P \cdot (k-k'))$, where k (k') is the four-momentum of the incoming (outgoing) lepton and P is the four-momentum of the incoming proton. The kinematic region $10 < Q^2 < 350\ \text{GeV}^2$ was selected.

To reduce backgrounds from non-ep collisions, events were required to have a reconstructed vertex position, Z_{vtx}, within the range $|Z_{\text{vtx}}| < 40$ cm and to have $35 < E - p_Z < 65$ GeV, where $E - p_Z = \sum_i E_i(1 - \cos\theta_i)$; E_i is the energy of the i-th CAL cell, θ_i is its polar angle and the sum runs over all cells [24]. The latter cut also removes events with large initial-state radiation and low-Q^2 (photoproduction) events.

Energy-flow objects (EFOs) [25] were constructed from calorimeter-cell clusters, associated with tracks when appropriate. Photon candidates were identified as trackless EFOs for which at least 90% of the reconstructed energy was measured in the BEMC. EFOs with wider electromagnetic showers than are typical for a single photon were accepted to allow evaluation of backgrounds. The reconstructed transverse energy of the photon candidate, E_T^{γ}, was required to lie within the range $4 < E_T^{\gamma} < 15$ GeV and the pseudorapidity, η^{γ}, had to satisfy $-0.7 < \eta^{\gamma} < 0.9$. The upper limit on the reconstructed transverse energy was selected to ensure that the shower shapes from the hadronic background and the photon signal remained distinguishable.

Each event was required to contain an electron, a photon candidate and at least one accompanying jet. Jet reconstruction was performed on all EFOs in the event, including the electron and photon candidates, using the k_T clustering algorithm [26] in the E-scheme in the longitudinally invariant inclusive mode [27] with the R parameter set to 1.0. The jets were required to have transverse energy, E_T^{jet}, above 2.5 GeV and to lie within the pseudorapidity, η^{jet}, range $-1.5 < \eta^{\text{jet}} < 1.8$. One of the jets found by this procedure corresponds to or includes the photon candidate. An additional accompanying jet was required; if more than one was found, that with the highest E_T^{jet} was used.

To reduce the background from photons and neutral mesons within jets, and from photons radiated from electrons or positrons, the photon candidate was required to be isolated from the reconstructed tracks and other hadronic activity. The isolation from tracks was achieved by demanding $\Delta R > 0.2$, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ is the distance to the nearest reconstructed track with momentum greater than 250 MeV in the η–ϕ plane, where ϕ is the azimuthal angle. Isolation from other hadronic activity was imposed by requiring that the photon candidate possessed at least 90% of the total energy of the reconstructed jet of which it formed a part.

A total of 6167 events were selected at this stage; the sample was dominated by background events. The largest source of background came from neutral current DIS events in which the scattered electron was detected in the RCAL, and one or more neutral mesons such as π^0 and η, decaying to photons, produced a photon candidate in the BEMC.

4. Theory

Two theoretical predictions are compared to the measurements presented in this Letter. In the approach of GKS [11–13], the contributions to the scattering cross section for $ep \to e\gamma X$ are calculated at order α^3, referred to here as LO, and $\alpha^3\alpha_s$, referred to here as NLO, in the electromagnetic and strong couplings. One of these contributions comes from the radiation of a photon from the quark line (called QQ photons; Fig. 1(a), (b)) and a second from the radiation from the lepton line (called LL photons; Fig. 1(c), (d)). In addition to QQ and LL photons, an interference term between photon emission from the lepton and quark lines, called LQ photons by GKS, is present. For the kinematic region considered here, where the outgoing photon is well separated from both outgoing electron and quark, the interference term gives only a 3% effect on the cross section. This effect is further reduced to $\approx 1\%$ when e^+p and e^-p data are combined, as the LQ term changes sign when e^- is replaced by e^+. The QQ contribution includes photon emission at wide angles from the quark as well as the leading $q \to q\gamma$ fragmentation term.

The GKS predictions use HERAPDF1.0 parton distribution functions for the proton [28] and the BFG parton–photon fragmentation functions [29]. For their NLO calculation, the authors quote an overall theoretical uncertainty of $(+4.3\%, -5.2\%)$ on their integrated cross section, rising to approximately $\pm 10\%$ at large negative jet rapidities. The uncertainty due to the choice of proton parton distributions is typically much less than 5%. The k_T factorisation method used by BLZ [14] takes into account the photon radiation from the lepton as well as the quarks. Unintegrated proton parton densities are used. This procedure gives a quark-radiated contribution that is enhanced relative to the leading-order collinear approximations. The uncertainties of up to 20% in the calculation are due mainly to the procedure of selecting jets from the evolution cascade in the factorisation approach.

In evaluating their predictions for the present data, both groups of authors have incorporated the experimental selections and photon-isolation procedure at the parton level. Hadronisation corrections were evaluated (see Section 5) to enable the predictions to be compared to the experimental data which are corrected to the hadron level.

5. Monte Carlo event simulation

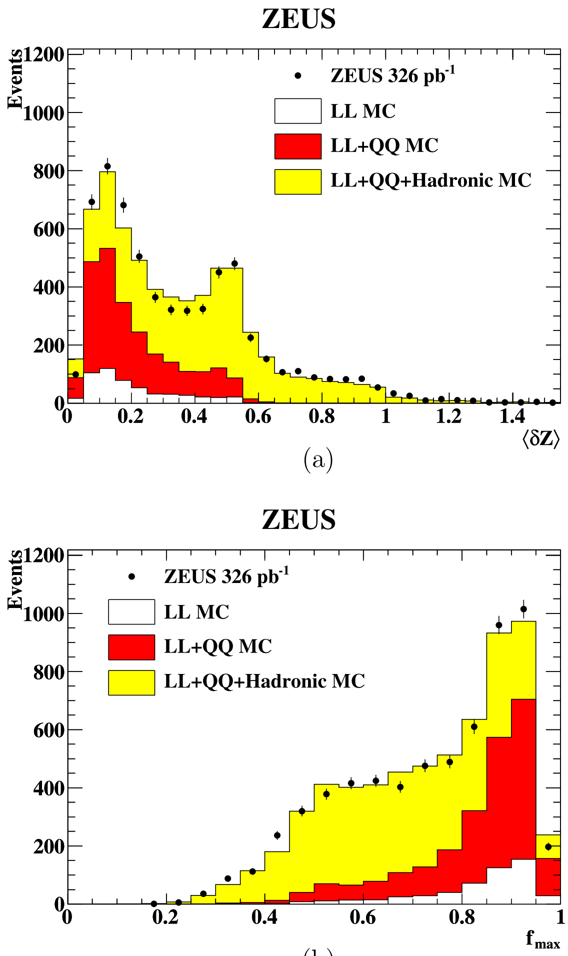
Monte Carlo event samples were generated to evaluate the detector acceptance and to provide signal and background distributions. The program Pythia 6.416 [30] was used to simulate prompt-photon emission for the study of the event-reconstruction efficiency. In Pythia, this process is simulated as a DIS process with additional photon radiation from the quark line to account for QQ photons. Radiation from the lepton is not simulated.

The LL photons radiated at large angles from the incoming or outgoing electron were simulated using the generator Djangoh 6 [31], an interface to the MC program Heracles 4.6.6 [32]; higher-order QCD effects were included using the colour dipole model of Ariadne 4.12 [33]. Hadronisation of the partonic final state was in each case performed by Jetset 7.4 [34] using the Lund string model [35]. The small LQ contribution was neglected.

The main background to the QQ and LL photons came from photonic decays of neutral mesons produced in general DIS processes. This background was simulated using Djangoh 6, within the same framework as the LL events. This provided a realistic spectrum of single and multiple mesons with well modelled kinematic distributions.

The generated MC events were passed through the ZEUS detector and trigger simulation programs based on Geant 3.21 [36]. They were reconstructed and analysed by the same programs as the data.

Hadronisation corrections to the theory calculations were evaluated using Pythia and Ariadne, and typically lowered the theoretical prediction by about 10% with typical uncertainties of a few percent. They were calculated by running the same jet algorithm



(a)

(b)

Fig. 2. Distribution of (a) $\langle \delta Z \rangle$, (b) f_{max}. The error bars represent the statistical uncertainties. The light shaded histogram shows a fit to the data of three components with fixed shapes as described in the text. The dark shaded histogram represents the QQ component of the fit, and the white histogram the LL component.

and event selections on the generated partons and on the hadronised final state in the MC events.

6. Extraction of the photon signal

The event sample selected according to the criteria described in Section 3 was dominated by background; thus the photon signal was extracted statistically following the approach used in previous ZEUS analyses [2–4,7,9].

The photon signal was extracted from the background using the lateral width of the BEMC energy-cluster comprising the photon candidate. This was calculated as the variable $\langle \delta Z \rangle = \sum_i E_i |Z_i - Z_{\text{cluster}}| / (w_{\text{cell}} \sum_i E_i)$. Here, Z_i is the Z position of the centre of the i-th cell, Z_{cluster} is the centroid of the EFO cluster, w_{cell} is the width of the cell in the Z direction, and E_i is the energy recorded in the cell. The sum runs over all BEMC cells in the EFO.

The global distributions of $\langle \delta Z \rangle$ in the data and in the MC are shown in Fig. 2(a). The MC distributions in LL and QQ have been corrected using a comparison between the shapes in $\langle \delta Z \rangle$ associated with the scattered electron in MC simulation of DIS and in real data. The $\langle \delta Z \rangle$ distribution exhibits a double-peaked structure with the first peak at ≈ 0.1, associated with the photon signal, and a second peak at ≈ 0.5, dominated by the $\pi^0 \to \gamma\gamma$ background.

As a check, an alternative method was applied in which the quantity f_{max} was employed instead of $\langle \delta Z \rangle$, where f_{max} is the fraction of the photon-candidate shower contained in the BEMC cell with the largest signal. The results (Fig. 2(b)) were consistent with the main analysis method and showed no significant systematic difference.

The number of isolated-photon events contributing to the data is illustrated in Fig. 2(a). It is determined for each cross-section bin by a χ^2 fit to the $\langle \delta Z \rangle$ distribution in the range $0 < \langle \delta Z \rangle < 0.8$, using the LL and QQ signal and background MC distributions as described in Section 5. By treating the LL and QQ photons separately, account is taken of their differing hadronic activity (resulting in significantly different acceptances) and their differing (η, E_T) distributions (resulting in different bin migrations due to finite measuring precision).

In performing the fit, the theoretically well determined LL contribution was kept constant at its MC-predicted value and the other components were varied. Of the 6167 events selected, 2440 ± 60 correspond to the extracted signal (LL and QQ). The scale factor resulting from the global fit for the QQ photons in Fig. 2(a) was 1.6; this factor was used for all the plots comparing MC to data. The fitted global scale factor for the hadronic background was 1.0. The maximum value of χ^2/n.d.f. of the fits in the cross section bins was 2.3 with a mean value of 1.5.

For a given observable Y, the production cross section was determined using

$$\frac{d\sigma}{dY} = \frac{\mathcal{A}_{\text{QQ}} \cdot N(\gamma_{\text{QQ}})}{\mathcal{L} \cdot \Delta Y} + \frac{d\sigma_{\text{LL}}^{\text{MC}}}{dY},$$

where $N(\gamma_{\text{QQ}})$ is the number of QQ photons extracted from the fit, ΔY is the bin width, $\mathcal{L}$ is the total integrated luminosity, $\sigma_{\text{LL}}^{\text{MC}}$ is the predicted cross section for LL photons from Djangoh, and $\mathcal{A}_{\text{QQ}}$ is the acceptance correction for QQ photons. The value of $\mathcal{A}_{\text{QQ}}$ was calculated using Monte Carlo from the ratio of the number of events generated to those reconstructed in a given bin. It varied between 1.0 and 1.5 from bin to bin. To improve the representation of the data, and hence the accuracy of the acceptance corrections, the Monte Carlo predictions were reweighted. This was done globally as a function of Q^2 and of η^γ, and bin-by-bin as a function of photon energy; the three reweighting factors were applied multiplicatively.

7. Systematic uncertainties

The significant sources of systematic uncertainty were taken into account as follows:

- the energy of the measured scattered electron was varied by its known scale uncertainty of ±2% [37], causing variations in the measured cross sections of up to ±5%;
- the energy of the photon candidate was similarly varied by ±2%, causing variations in the measured cross sections of up to ±5%;
- the modelling of the jets, and in particular the energy scale, was first studied for jets with $E_T^{\text{jet}} > 10$ GeV by selecting ZEUS DIS events having one jet of this type and no photon or other jets with $E_T^{\text{jet}} > 10$ GeV. Using the scattered electron, and requiring transverse-momentum balance, a prediction was made for the transverse energy of the jet, which was compared to the values obtained in the data and in the MC events. In this way, an uncertainty on the energy scale of ±1.5% was established for these jets. For jets with E_T^{jet} in the range [2.5, 10] GeV, DIS events were selected containing one jet in this range and one jet with $E_T^{\text{jet}} > 10$ GeV. Using the scattered

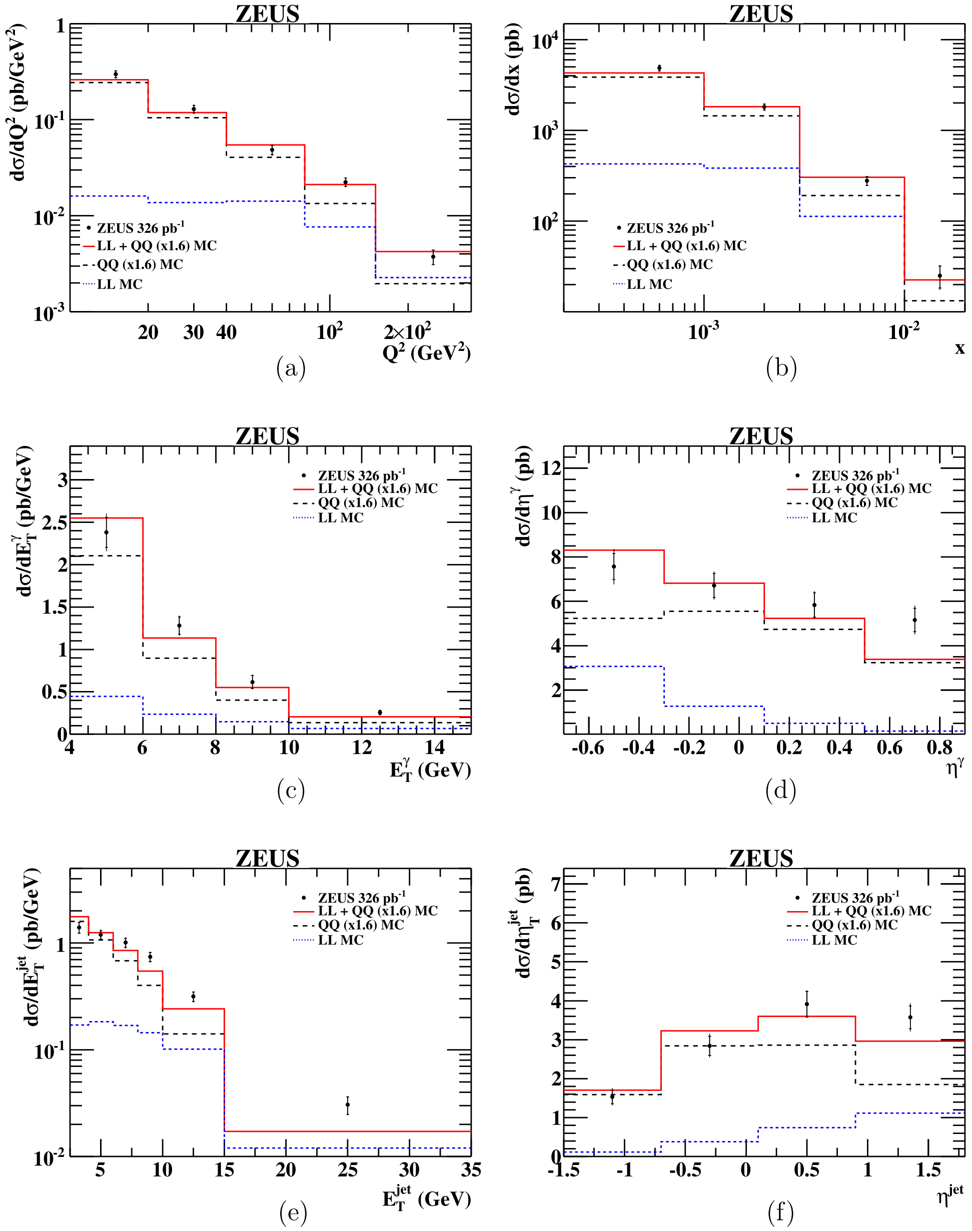


Fig. 3. Isolated photon differential cross sections in (a) Q^2, (b) x, (c) E_T^γ, (d) η^γ, (e) E_T^{jet}, and (f) η^{jet}. The inner and outer error bars show, respectively, the statistical uncertainty and the statistical and systematic uncertainties added in quadrature. The solid histograms are the reweighted Monte Carlo predictions from the sum of QQ photons from PYTHIA normalised by a factor 1.6 plus DJANGOH LL photons. The dashed (dotted) lines show the QQ (LL) contributions.

electron and the well measured high-energy jet, again requiring transverse-momentum balance, a prediction was made of the lower jet E_T^{jet} value, which was compared to the values obtained in data and in MC. In this way, the uncertainty on the jet energy scale was evaluated as ±4% and ±2.5% in the energy ranges [2.5, 6] and [6, 10] GeV, respectively. The resulting systematic uncertainty on the cross section was typically around ±2%, ranging to ±10% at the highest E_T^{jet} values.

Since the photon and jet energy scales were calibrated relative to that of the scattered electron, all three energy-scale uncertainties were treated as correlated. The three energy scales were simultaneously varied by the uncertainties described above, and the resulting change in the cross sections was taken as the overall systematic energy-scale uncertainty. Further systematic uncertainties were evaluated as follows:

- the dependence on the modelling of the hadronic background by ARIADNE was investigated by varying the upper limit for the $\langle \delta Z \rangle$ fit in the range [0.6, 1.0], giving variations that were typically ±5% increasing to +12% and −14% in the most forward η^γ and highest-x bins respectively;
- uncertainties in the acceptance due to the modelling by PYTHIA were accounted for by taking half of the change attributable to the reweighting as a systematic uncertainty; for most points the effect was small.

The background from photoproduction events at low Q^2 was found to be negligible. Other sources of systematic uncertainty were found to be negligible and were ignored [9,38]: these included the modelling of the ΔR cut, the track momentum cut, the cut on $E - p_Z$, the Z_{vtx} cut, the cut on the electromagnetic fraction of the photon shower, and a variation of 5% on the LL fraction.

Table 1
Measured differential cross-section $\frac{d\sigma}{dQ^2}$. The quoted systematic uncertainty includes all the components added in quadrature.

Q^2 range (GeV^2)	$\frac{d\sigma}{dQ^2}$ (pb GeV^{-2})
10–20	0.298 ± 0.024 (stat.) ± 0.019 (sys.)
20–40	0.129 ± 0.012 (stat.) ± 0.009 (sys.)
40–80	0.049 ± 0.005 (stat.) ± 0.004 (sys.)
80–150	0.0224 ± 0.0023 (stat.) ± 0.0011 (sys.)
150–350	0.0037 ± 0.0007 (stat.) ± 0.0002 (sys.)

Table 2
Measured differential cross-section $\frac{d\sigma}{dx}$. Details as in Table 1.

x range	$\frac{d\sigma}{dx}$ (pb)
0.0002–0.001	4869 ± 334 (stat.) ± 312 (sys.)
0.001–0.003	1811 ± 139 (stat.) ± 104 (sys.)
0.003–0.01	278 ± 31 (stat.) ± 13 (sys.)
0.01–0.02	25 ± 7 (stat.) ± 3 (sys.)

Table 3
Measured differential cross-section $\frac{d\sigma}{dE_T^\gamma}$. Details as in Table 1.

E_T^γ range (GeV)	$\frac{d\sigma}{dE_T^\gamma}$ (pb GeV^{-1})
4–6	2.38 ± 0.18 (stat.) ± 0.13 (sys.)
6–8	1.28 ± 0.10 (stat.) ± 0.06 (sys.)
8–10	0.62 ± 0.08 (stat.) ± 0.04 (sys.)
10–15	0.26 ± 0.03 (stat.) ± 0.02 (sys.)

These were found to generate systematic effects of at most 1–2% apart from a 2.5% effect in the highest-x bin.

Table 4
Measured differential cross-section $\frac{d\sigma}{d\eta^\gamma}$. Details as in Table 1.

η^γ range	$\frac{d\sigma}{d\eta^\gamma}$ (pb)
-0.7 to -0.3	7.6 ± 0.6 (stat.) ± 0.5 (sys.)
-0.3–0.1	6.7 ± 0.5 (stat.) ± 0.3 (sys.)
0.1–0.5	5.8 ± 0.6 (stat.) ± 0.3 (sys.)
0.5–0.9	5.2 ± 0.5 (stat.) ± 0.4 (sys.)

Table 5
Measured differential cross-section $\frac{d\sigma}{dE_T^{\text{jet}}}$. Details as in Table 1.

E_T^{jet} range (GeV)	$\frac{d\sigma}{dE_T^{\text{jet}}}$ (pb GeV^{-1})
2.5–4	1.40 ± 0.16 (stat.) ± 0.08 (sys.)
4–6	1.19 ± 0.11 (stat.) ± 0.10 (sys.)
6–8	1.01 ± 0.10 (stat.) ± 0.07 (sys.)
8–10	0.74 ± 0.07 (stat.) ± 0.05 (sys.)
10–15	0.32 ± 0.03 (stat.) ± 0.02 (sys.)
15–35	0.031 ± 0.006 (stat.) ± 0.003 (sys.)

Table 6
Measured differential cross-section $\frac{d\sigma}{d\eta^{\text{jet}}}$. Details as in Table 1.

η^{jet} range	$\frac{d\sigma}{d\eta^{\text{jet}}}$ (pb)
-1.5 to -0.7	1.53 ± 0.17 (stat.) ± 0.15 (sys.)
-0.7–0.1	2.84 ± 0.25 (stat.) ± 0.19 (sys.)
0.1–0.9	3.91 ± 0.33 (stat.) ± 0.14 (sys.)
0.9–1.8	3.57 ± 0.29 (stat.) ± 0.22 (sys.)

The major uncertainties were treated as symmetric and added in quadrature. The common uncertainty of 1.8% on the luminosity measurement was not included in the tables and figures.

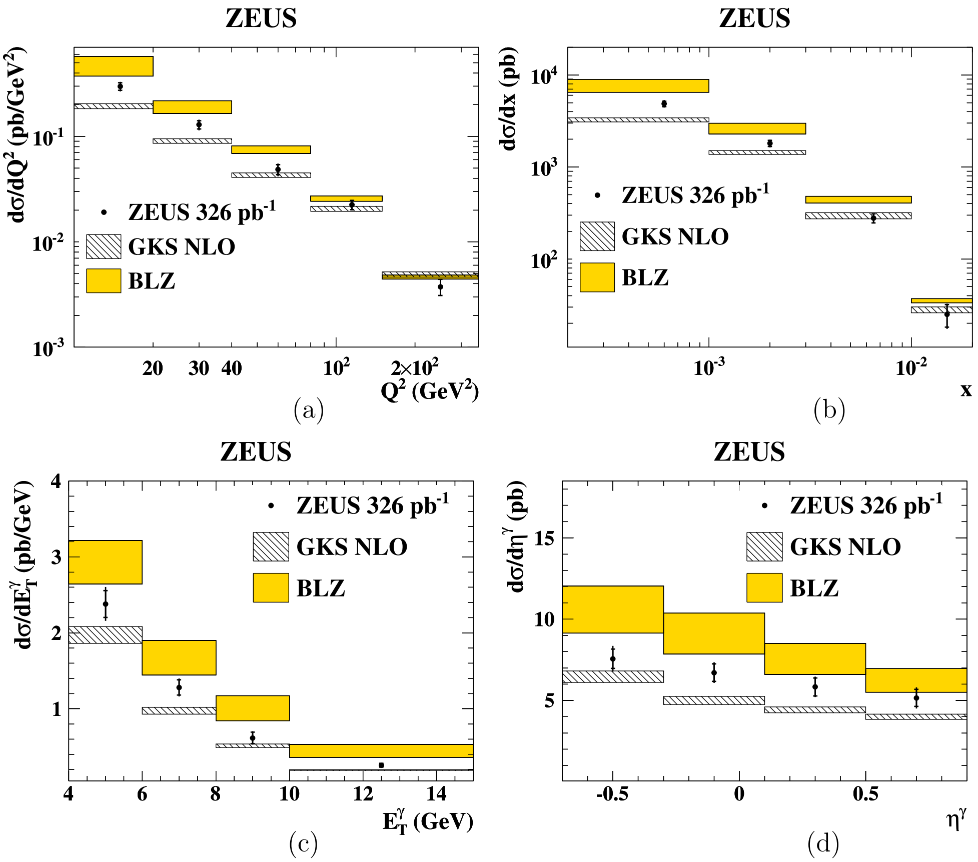
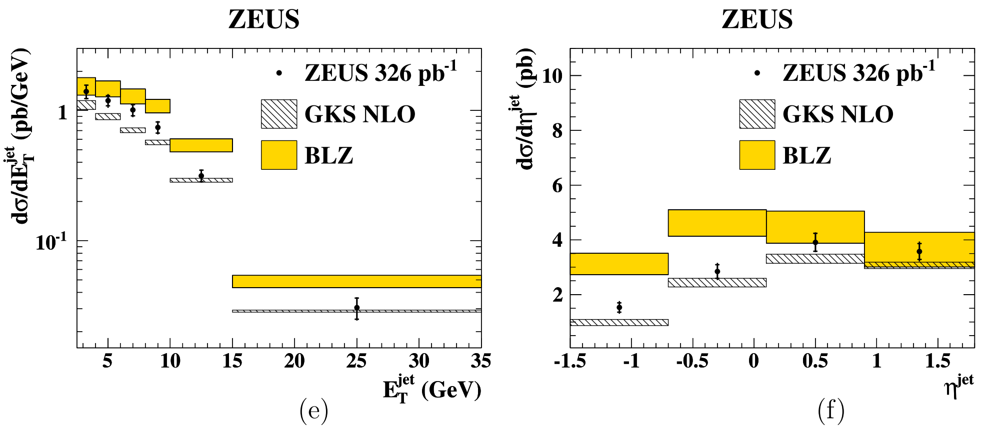


Fig. 4. Data points as shown in Fig. 3. Theoretical predictions from Gehrmann-De Ridder et al. (GKS) [39] and Baranov et al. (BLZ) [40] are shown, with associated uncertainties indicated by the shaded bands.



(e) (f)

Fig. 4. (*continued*)

8. Results

Differential cross sections in DIS for the production of an isolated photon and at least one additional jet, $ep \to e'\gamma + \text{jet}$, were measured in the kinematic region defined by $10 < Q^2 < 350$ GeV^2, $E'_e > 10$ GeV, $\theta_e > 140°$, $-0.7 < \eta^\gamma < 0.9$, $4 < E_T^\gamma < 15$ GeV, $E_T^{\text{jet}} > 2.5$ GeV and $-1.5 < \eta^{\text{jet}} < 1.8$ in the laboratory frame. The jets were formed according to the k_T-clustering algorithm with the R parameter set to 1.0, and photon isolation was imposed such that at least 90% of the energy of the jet-like object containing the photon belongs to the photon. No track with momentum greater than 250 MeV was allowed within a cone around the photon of radius 0.2 in η, ϕ.

The differential cross sections as functions of Q^2, x, E_T^γ, η^γ, E_T^{jet} and η^{jet} are shown in Fig. 3 and given in Tables 1–6. As expected, the cross section decreases with increasing Q^2, x, E_T^γ, and E_T^{jet}. The modest dependence of the cross section on η^γ and η^{jet} can be attributed to the LL contribution. The predictions for the sum of the expected LL contribution from DJANGOH and a factor of 1.6 times the expected QQ contribution from PYTHIA agree well with the measurements, and this model therefore provides a good description of the process.

The theoretical predictions described in Section 4 are compared to the measurements in Fig. 4. The predictions from GKS [39] describe the shape of all the distributions reasonably well, but the rise seen at low Q^2 and at low x is underestimated. The cross section as a function of η^γ and η^{jet} is underestimated by about 20%. This was also observed in the earlier inclusive photon measurement [9]. The theoretical uncertainties are indicated by the width of the shaded area. The calculations of BLZ [40] also describe the shape of the data reasonably well, but the predicted overall rate is on average too high by about 20%.

9. Conclusions

The production of isolated photons accompanied by jets has been measured in deep inelastic scattering with the ZEUS detector at HERA using an integrated luminosity of 326 pb^{-1}. The present results improve on earlier ZEUS results [7] which were made with an integrated luminosity of 121 pb^{-1} in a more restricted kinematic region. Differential cross sections as functions of several variables are presented within the kinematic region defined by: $10 < Q^2 < 350$ GeV^2, $E'_e > 10$ GeV, $\theta_e > 140°$, $-0.7 < \eta^\gamma < 0.9$, $4 < E_T^\gamma < 15$ GeV, $E_T^{\text{jet}} > 2.5$ GeV and $-1.5 < \eta^{\text{jet}} < 1.8$ in the laboratory frame. The order $\alpha^3\alpha_s$ predictions of Gehrmann-De Ridder et al. reproduce the shapes of all the measured experimental distributions reasonably well, as do the predictions of Baranov et al. However neither calculation gives a correct normalisation. The results presented here can be used to make further improvements in the QCD calculations.

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