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Prompt photon production with associated jets at HERA

D.H. Saxon[a]

Dept of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland

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Abstract. We present the first observation of prompt photon production in deep inelastic scattering, by ZEUS, and make comparisons to NLO calculations and to Monte Carlos. New results are also presented on the photoproduction of prompt photons, by H1, with comparisons to calculations and to earlier data.

1 Introduction

Prompt photon production in ep scattering is the name given to photon radiation from the quark line. An isolated photon is thus a particle visible in the hadronic final state that is emitted directly from the hard process without the intervention of fragmentation. The signature in deep inelastic scattering is an isolated electron (at modest angles to the electron beam direction for moderate Q^2), an isolated photon somewhere in the detector and other hadronic, possibly jet, activity. In photoproduction ($Q^2 < 1$ GeV^2) the outgoing electron is unobserved and one sees an isolated photon, balanced in p_T by a jet.

The main backgrounds are as follows: γ radiation from the initial-state or final-state electron line (DIS only), γ from jet fragmentation and γ from π^0 or η decay. In the ZEUS DIS analysis (for $Q^2 > 35$ GeV^2) [1] initial state and final state electron radiation in DIS are minimised by demanding a large angular separation between the electron ($139.8° < \theta_e < 171.9°$) and the photon, observed in the rapidity range ($-0.7 < \eta < 0.9$).

The DIS process contains two hard scales (Q^2 and E_T^γ) and is thus hard for Monte Carlo to simulate. Comparisons are made to PYTHIA v6.206 [2] and HERWIG v6.1 [3]. In addition NLO ($O(\alpha^3\alpha_s)$) calculations are available by Kramer and Spiesberger, based on earlier work with Gehrmann-de Ridder [4]. This includes ISR, FSR, vertex diagrams and all interference effects. Predictions are made for ($e + \gamma +$ jet) including the effects of scale uncertainty.

Photoproduction results are presented by H1 [5] for ($-1.0 < \eta < 0.9$) and comparisons made to NLO calculations by Fontannaz, Guillet and Heinrich [6](see also [7]) and PYTHIA MC calculations, as well as to earlier ZEUS results on inclusive photons based on smaller luminosity [8]. The new ZEUS and H1 results use essentially the full 1996-2000 luminosity (over 100pb^{-1}) and combine e^-p and e^+p data at 820 and 920 GeV c.m. energy.

[a] For the H1 and ZEUS Collaborations

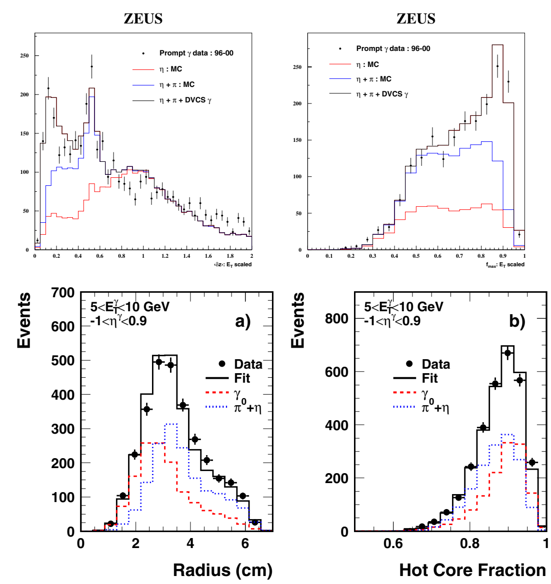

Fig. 1. Top row: Shower width measure, $\langle\delta Z\rangle$, and fraction of energy in highest calorimeter strip, f_{max} (for $\langle\delta Z\rangle < 0.65$ only), for ZEUS DIS data, together with fitted signal fractions based on photons from deeply virtual Compton scattering, reweighted to match the E_T distribution of the data, and Monte Carlo single π^0 and η signals. Bottom row: Shower radius and hot core fraction for H1 photoproduction, with fitted components for γ and for combined $\pi^0 + \eta$

2 Event selection and signal extraction

Both experiments quote results for $5 < E_T^\gamma < 10$ GeV. For photoproduction, the H1 γp energy range is $122 < W < 266$ GeV. The ZEUS DIS data are 31% at c.m. energy of 300 GeV and the rest at 318 GeV. Both experiments reconstruct the photon shower in the barrel calorimeter and demand that it is isolated in that the electromagnetic cluster constitutes 90% or more of the energy in a cone of $\Delta r = (\Delta\phi^2 + \Delta\eta^2)^{1/2} = 1.0$ centred on the shower.

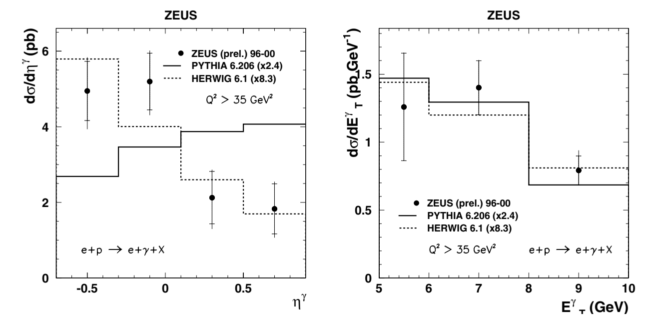

Fig. 2. Inclusive DIS photon rapidity and transverse energy distributions, compared to predictions of PYTHIA and HERWIG, rescaled by factors of 2.4 and 8.3.

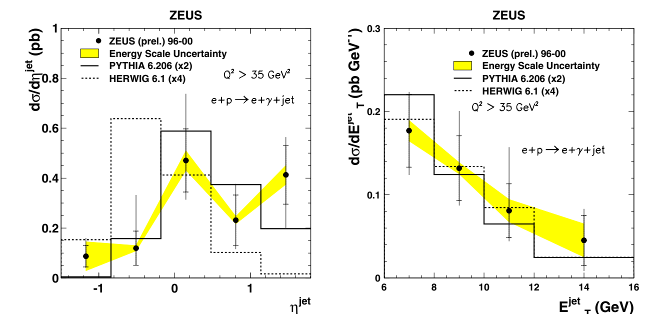

Fig. 3. Jet rapidity and transverse energy distributions, compared to predictions of PYTHIA and HERWIG, rescaled by factors of 2 and 4.

For prompt photon plus jet measurements, H1 use a k_T algorithm with $E_T^{\rm jet} > 4.5$ GeV and $-1.0 < \eta^{\rm jet} < 2.3$. ZEUS use cone jets of $\Delta r = 0.7$, $E_T^{\rm jet} > 6.0$ GeV and $-1.5 < \eta^{\rm jet} < 1.8$.

Such isolation cuts are not sufficient to separate the prompt-γ signal from the π^0 and η background. Further information on shower shape must be used. ZEUS take advantage of the 5 cm z-granularity and pointing geometry of the barrel electromagnetic calorimeter to define two measures of shower concentration (see figure 1). $\langle \delta Z \rangle$ is a measure of shower width. Prompt photons preferentially fill the one-strip peak at the far left of the plot. π^0's fill also the second peak and η's feed the continuum. The final prompt-photon signal is derived from the peak at high f_{max}, separately in each histogram bin for E_T^γ and η^γ, a method which reduces the sensitivity to errors in the shower shape fitting. H1 use a similarly motivated measure, using shower radius and the 'hot core fraction'. In their case the η/π^0 ratio is fixed (around 5%) by Monte Carlo studies and the prompt photon signal is extracted using a likelihood discriminator method based on MC shower shapes in two-dimensional $(E_T^\gamma, \eta^\gamma)$ bins.

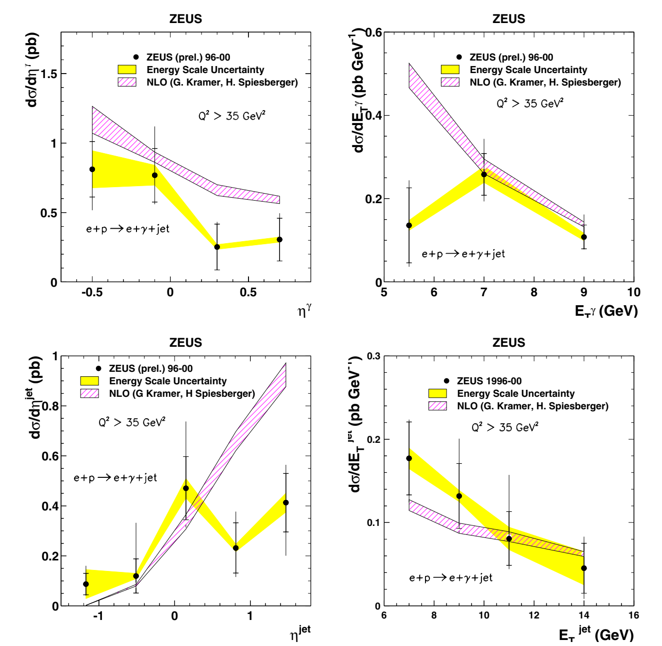

Fig. 4. Photon and jet rapidity and transverse energy distributions, for the final state (γ + 1 jet) compared to NLOQCD calculations by Kramer and Spiesberger.

3 Deep inelastic scattering results: ZEUS

Figure 2 shows ZEUS results on inclusive prompt photon production in deep inelastic scattering, compared to predictions from PYTHIA and HERWIG. Both describe the shape of the E_T distribution and HERWIG describes the rapidity distribution well. Both get the total cross section wrong by a substantial factor. The mean values of Q^2 found in data, PYTHIA and HERWIG are 87, 87 and 62 GeV^2, and the mean $x_{\rm Bj}$ are 0.0049, 0.0047 and 0.0017. One concludes that neither MC model is a good description of the inclusive data.

Demanding in addition that one and only one jet is observed in the rapidity and E_T range described above retains these features when comparing the photon distributions to the MC predictions. Figure 3 shows the information on the jet distributions. Again, both describe the shape of the E_T distribution well, but this time PYTHIA is preferred for the jet rapidity distribution.

Kramer and Spiesberger provide NLOQCD predictions for the final state (γ + 1 jet). Comparisons to data are made in figure 4, with the predictions shown as a band reflecting renormalisation scale uncertainty. Note that no multiplying factor is needed here to show the data and theory on the same graph. The total cross section is 1.9 standard deviations below the theory. The Q^2 and $x_{\rm Bj}$ are at a similar level of agreement. The E_T^γ slope is higher in the theory than in either data or Monte Carlo. Overall the level of agreement is better than for the Monte Carlos.

To summarise for prompt photons in deep inelastic scattering; the process has been observed for the first time, in inclusive photons and in (γ + 1 jet). Rapidity and transverse energy distributions have been measured and compared to the (differing) predictions of two Monte Carlos. Neither fits the data well. Comparisons of (γ + 1

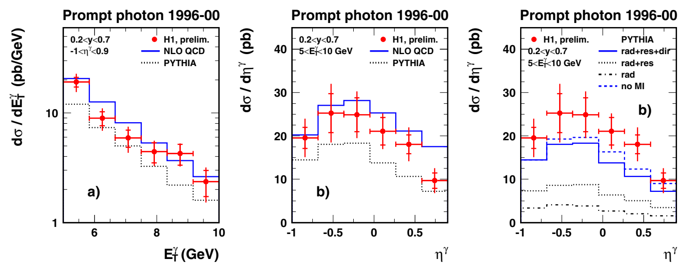

Fig. 5. Inclusive photon transverse energy and rapidity distributions, compared to NLOQCD (Fontannaz et al.) and PYTHIA. In the right hand graph the PYTHIA calculation is broken up into components - see text for details.

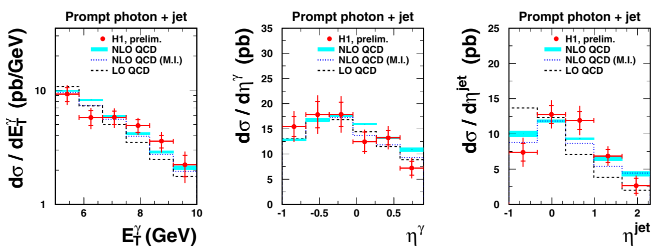

Fig. 6. Distributions for (γ +1 jet) compared to LO and NLO calculations (Fontannaz et al.): E_T^γ, η^γ and $\eta^{\rm jet}$. The effect of multiple interactions is estimated using PYTHIA.

jet) data with NLOQCD calculations show a fair measure of agreement.

4 Photoproduction results: H1

The H1 results on inclusive photoproduction are shown in figure 5, together with comparisons with NLOQCD calculations by Fontannaz, Guillet and Heinrich and with PYTHIA predictions. The agreement in normalisation and shape is excellent for NLOQCD, with PYTHIA maybe 30% lower. The H1 results are consistent with earlier ZEUS results, lying perhaps a little below ZEUS at negative rapidity.

The PYTHIA predictions for rapidity are also shown broken up into photons radiated from electron lines (rad), adding resolved photon processes (res), adding direct processes (dir) and (the highest line) removing multiple interactions (no MI). Multiple interactions reduce the cross-section for this process by spoiling the photon isolation.

For the final state (photon + 1 jet) H1 results are compared to LOQCD and NLOQCD predictions in figure 6. The NLO predictions include the uncertainty due to scale variation from $0.5E_T^\gamma$ to $2E_T^\gamma$. There are large negative corrections in going from LO to NLO at $\eta^{\rm jet} < 0$. The effect of adding multiple interactions is estimated from PYTHIA. One sees that the fit is improved at large η^γ.

One can investigate the fractions of direct and resolved photon contributions by calculating

$$x_\gamma = (E_T^{\rm jet} e^{-\eta({\rm jet})} + E_T^\gamma e^{-\eta(\gamma)})/2yE_e.$$

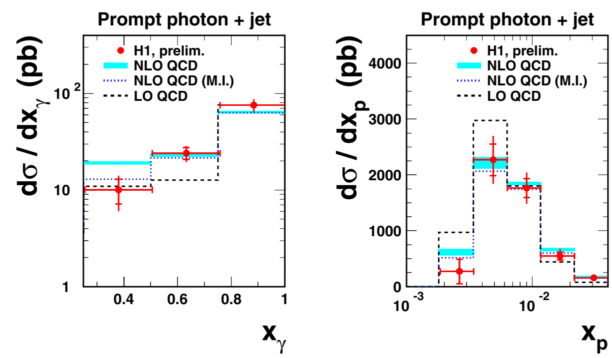

Fig. 7. x_γ and x_p distributions for (γ + 1 jet) final state compared to predictions of Fontannaz et al. as in previous figure.

This is plotted in fig 7(a) and compared to NLOQCD predictions. (Note the logarithmic scale.) The peak at $x_\gamma > 0.75$ shows that direct processes dominate, in good agreement with NLOQCD. Figure 7b shows the distribution in x_p, calculated as

$$x_p = (E_T^{\rm jet} e^{\eta({\rm jet})} + E_T^\gamma e^{\eta(\gamma)})/2E_p.$$

Again there is good agreement with NLOQCD.

In summary for photoproduction; H1 have made measurements for inclusive photons and for (γ +1 jet) final states. The results are compatible with earlier inclusive measurements by ZEUS, but have a somewhat larger rapidity range. NLOQCD calculations are in good agreement with the results. PYTHIA agrees well on the shape of distributions and is a little low in normalisation. Inclusion of multiple interaction effects, estimated using PYTHIA, further improves the agreement with NLOQCD.

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