THE STRUCTURE OF REAL PHOTONS AT HERA

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Inclusive jet cross sections for the reaction $e^+p \rightarrow$ jet + X for $\mathbf{Q}^2 < 1$ GeV^2 have been measured with the H1 detector at HERA. Differential cross sections as a function of η_{jet} and E_{Tjet} are in good agreement with NLO QCD calculations using different sets of photon parton density functions as input. Dijet cross sections of jets with high E_T were measured by both the ZEUS and H1 experiments in photoproduction. Comparisons of ZEUS data to NLO QCD calculations show that the theory underestimates the data for low x_γ, indicating possible inadequacies in the photon structure parametrisations. H1 data are in good agreement with the predictions of NLO QCD. The measurements were, however, made in different kinematic regions.

1 Introduction

In leading order (LO) QCD, two processes contribute to the photoproduction of jets at HERA: direct processes, in which the photon behaves as a point-like particle and resolved processes, where the photon acts as an object with structure. The quark densities in the photon are not strongly constrained for x_γ [a] values larger than 0.5 by e^+e^- experiments [1]. The photoproduction of jets at HERA is directly sensitive to the gluon content of the photon and the data are also sensitive to the parton densities of the proton at x_P values up to 0.6. Therefore one of the possible tools to investigate the structure of quasi–real photons, γ, is to measure the production of jets in γp interactions at HERA.
The production of high transverse momentum jets provides a hard scale which makes perturbative QCD calculations reliable and renders the results less sensitive to non–perturbative physics such as soft particle production and hadronisation.

2 Single inclusive jet production

The measurements of differential jet cross sections as a function of the jet transverse energy, E_T^{jet}, and pseudorapidity, η^{jet}, were analysed by experiment H1 [2]. The jet search was performed in the laboratory frame by applying

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[a] x_γ,(x_P) are the fractions of γ(proton) momentum in hard subprocesses.

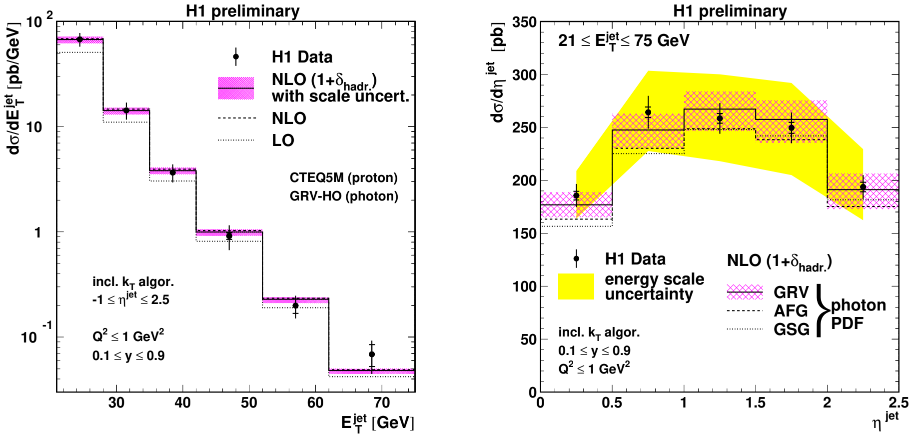

Figure 1. a) Differential inclusive cross section $d\sigma/dE_T^{jet}$ compared with QCD LO and NLO calculations. The full line indicates the NLO predictions with hadronisation corrections. b) Differential inclusive cross section $d\sigma/d\eta^{jet}$ compared with NLO QCD predictions with hadronisation corrections obtained by using different photon PDFs. The shaded band is the uncertainty due to the absolute energy scale of the jets and the hatched band is the uncertainty on the NLO QCD predictions obtained by varying the scale.

the longitudinal invariant k_T cluster algorithm [3]. The sample was defined with the cuts $E_T^{jet} > 21$ GeV and $-1 < \eta^{jet} < 2.5$. The HERWIG [4] and PYTHIA [5] Monte Carlo generators have been used to correct the data for detector effects.

The corrected differential e^+p cross section $d\sigma/dE_T^{jet}$ for jet production in the kinematic region defined by $Q^2 < 1$ GeV^2 and $95 < W < 285$ GeV is shown in figure 1a). The data are compared with QCD calculations, for both LO and NLO [6]. Hadronisation corrections, estimated using the Monte Carlo generators, are $\sim 5\%$ and are roughly constant with E_T^{jet}. On the same figure the theoretical uncertainty originating from the scale dependence is also shown. Within errors, the NLO QCD calculations describe the magnitude and the shape of the energy spectrum very well.

In figure 1b) the differential cross section $d\sigma/d\eta^{jet}$ is shown and compared with theory. The calculated cross sections using all three photon PDFs (GRV–HO, GSG–HO and AFG–HO) describe the data quite satisfactorily.

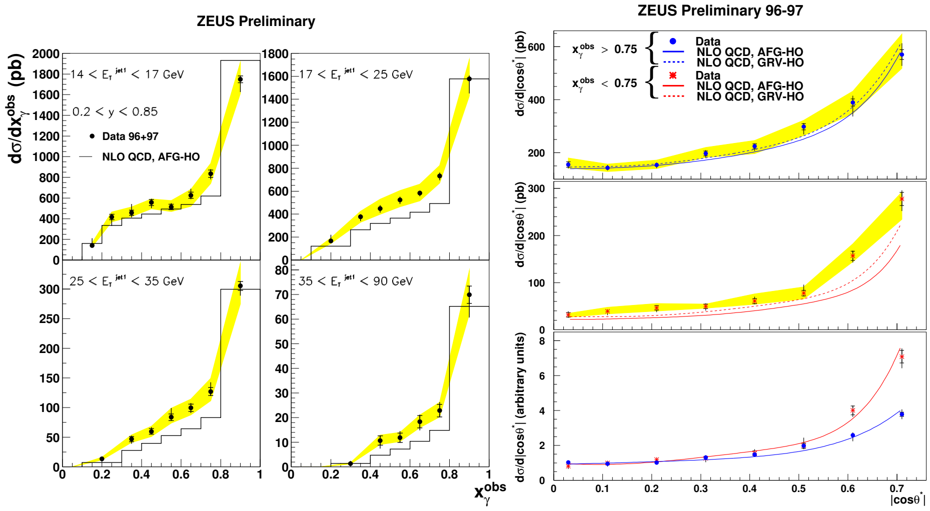

Figure 2. a) Differential cross sections in x_γ^{obs} in intervals of the transverse energy of the jet with higher E_T^{jet}, E_T^{jet1}. The energy scale uncertainty is shown as the band. b) Differential cross sections in $cos\theta^*$ for events with $x_\gamma^{obs} > 0.75$, $x_\gamma^{obs} < 0.75$ and both distributions, normalised to the content of the first three bins.

In order to compare the H1 results with previous ZEUS measurements, the differential cross sections were analysed in the same kinematic range [7],[8]. Within the errors, the measurements of the two experiments are in good agreement [2].

3 Dijet differential cross sections

The analysis was presented by the ZEUS experiment in [9]. The jets were found using the k_T cluster algorithm in the pseudorapidity region $-1 < \eta^{jet} < 2$ in the laboratory frame, with the transverse energy of the highest E_T jet, $E_T^{jet1} > 14$ GeV and the second–highest, $E_T^{jet2} > 11$ GeV. The cross section is given in the kinematic region $Q^2 < 1$ GeV^2 and $0.2 < y < 0.85$. The measured (and corrected for detector effects) differential cross section $d\sigma/dx_\gamma^{obs}$ [b] is shown in figure 2a) in four ranges of E_T^{jet1}. The effect of hadronisation (not shown

[b] The fraction of the photon's momentum participating in the hard proces x_γ^{obs} was defined as $x_\gamma^{obs} = \frac{\sum_{jets} E_{T,i} e^{-\eta_i}}{2yE_e}$.

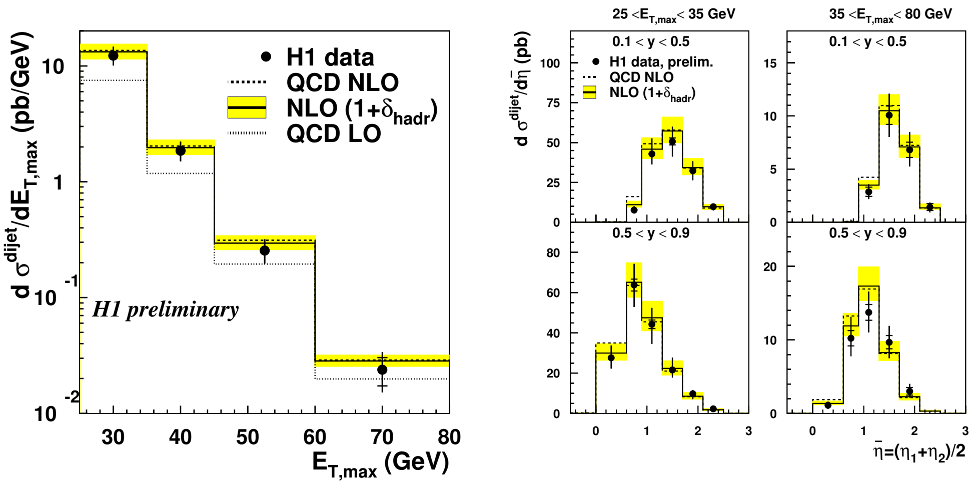

Figure 3. a) Differential ep cross section for dijet production as a function of the E_T of the highest E_T jet, $E_{T,max}$. The theoretical LO and NLO predictions use the CTEQ5M proton structure function and the GRV–HO photon structure function. NLO predictions are corrected to hadronisation (full line), and the grey band is the uncertainty of the theoretical prediction. b) Differential cross section as a function of $\overline{\eta}$ of the two highest E_T jets in two intervals of y and $E_{T,max}$.

here) has been found to be $\sim 10-15\%$. At high x_γ^{obs} where the contribution from direct processes dominates, the data are reasonably well described by NLO QCD calculations. However, at lower values, $x_\gamma^{obs} < 0.75$, the data are always above the NLO predictions. The angle between the dijet axis and the beam axis in the dijet CMS can be written as $\mathbf{c}os\theta^* = tanh((\eta^{jet1} - \eta^{jet2})/2)$. This variable is sensitive to the parton dynamics. For direct photon processes, where the propagator a is quark with spin 1/2, the angular dependence of the cross section is proportional to $(1-|cos\theta^*|)^{-1}$, for resolved processes where the gluon propagator with spin 1 dominates, to $(1-|cos\theta^*|)^{-2}$.
The measured cross section as a function of $|cos\theta^*|$ is shown in figure 2b) for $x_\gamma^{obs} > 0.75$ and $x_\gamma^{obs} < 0.75$. In this figure the additional cuts on the invariant mass of the dijets $M_{jj} > 39$ GeV and $0 < (\eta^{jet1} + \eta^{jet2})/2 < 1$ were applied. As observed before, the data in the high x_γ^{obs} region are well described by the NLO calculations and poorly in the low x_γ^{obs} region. The shapes of the measured distributions are well described by the theory for both regions in x_γ^{obs} (see the lowest plot of figure 2b)). Thus the parton dynamics of both

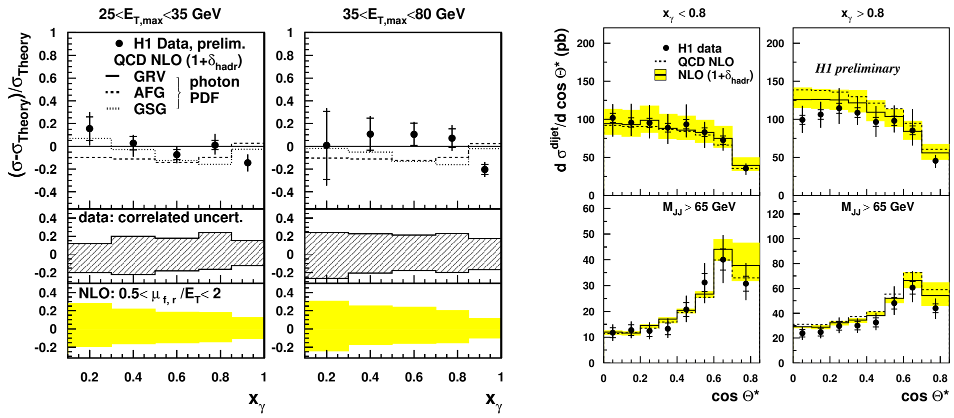

Figure 4. a) The relative difference of the dijet differential cross section as a function of x_γ to NLO predictions using 3 PDFs of the photon in two different $E_{T,max}$ regions. The correlated systematic error (hatched band) and the renormalisation and factorisation scale uncertainties of the NLO prediction (grey band) are shown in the two lowest plots. b) Differential cross sections as a function of $cos\theta^*$ are compared to NLO predictions with hadronisation corrections (full line).

x_γ^{obs} regions are well described, suggesting that the observed discrepancies may arise from inadequacies in the parameterisations of the photon PDF [9].

The dijet cross section in photoproduction was also studied by the H1 collaboration in [10]. The same jet algorithm was used as in previous analyses [2], [9]. The jet selection criteria require that the E_T of the two highest transverse energy jets are $E_{T,1} > 25$ GeV and $E_{T,2} > 15$ GeV. The pseudorapidity of jets is restricted to $-0.5 < \eta_{jet} < 2.5$. In figure 3a) the dijet cross section as a function of the E_T of the highest transverse energy $E_{T,1} = E_{T,max}$ is compared to NLO QCD calculations. The differential cross section $d\sigma/d\overline{\eta}$ is displayed for two different y regions and two different $E_{T,max}$ bins in figure 3b). An overall agreement between data and NLO QCD is observed, taking into account the uncertainties of the calculations and data points.
Figure 4a) displays the relative difference of the experimental and theoretical dijet cross sections $d\sigma/dx_\gamma$ as a function of x_γ for two regions of $E_{T,max}$. The data are compared to NLO calculations with three parametrisations of the photon structure. The predictions vary only little with photon PDF used. The lower part of the figure clearly demonstrates that the uncertainty of

the calorimetric energy (hatched band) together with the NLO uncertainties (shaded band) are much more important in this analysis than the difference induced by using different photon PDFs. The dijet cross section $d\sigma/dcos\theta^*$ is plotted in figure 4b) for $x_\gamma > 0.8$ and $x_\gamma < 0.8$ (upper two plots). Although the cut on the invariant mass M_{JJ} changes the shape of the distributions dramatically (see lower two plots in figure 4b)), the QCD calculations reproduce this behaviour nicely.

4 Conclusions

The measurement of the hadronic structure of the photon is an active field of research. The results of two experiments [2], [8,9] studying the single inclusive jet production are in good agreement [2]. In dijet production, however, the conclusions of the two experiments differ. ZEUS results [9] may indicate a possible inadequacy of the two photon structure functions used. On the contrary, the H1 data [10] agree well with NLO predictions using all available photon structure functions. In the two experiments, however, rather different kinematic regions were explored. In the future, cross sections in an identical phase space should be studied.

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