Photon structure as revealed in ep collisions

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Recent measurements of single inclusive jet and dijet production by the H1 and ZEUS experiments are reviewed. The results are compared to next to leading order QCD calculations. No large deviations are observed between the data and predictions based on photon parton distributions obtained from e^+e^- interactions.

1. Introduction

One of the main goals of the HERA collider is to probe the structure of the proton using a virtual photon radiated by the incoming electron (positron). There are however the kinematic regions in ep collisions where the partons in the proton probe the photon structure. The photon is the gauge boson and it is to our knowledge elementary. Only if photon interacts and the fluctuation time of photon to electron-positron pairs or quarks is much larger than the interaction time we can speak about the structure of the photon. The structure of the photon is therefore the part of the interaction dynamics. The hadronic structure of the photon was probed either by virtual photons in e^+e^- interactions or by virtual partons in ep collisions at HERA in photoproduction events where hard process occurs.

2. How to measure the photon structure

Events where jets with large transverse momentum E_T are produced can be used to probe the partonic structure of either the proton or the exchanged photon, depending on the dynamics of the process. As long as the transverse momentum E_T of the parton propagator entering the hard process is larger than the virtuality of the photon $Q^2 (E_T^2 > Q^2)$ the constituents of the photon are probed. This is fulfilled in photoproduction events, where $Q^2 \sim 0$. In the leading order (LO) of QCD the photon has two components, direct and resolved. In direct photon processes the photon interacts with a parton from the proton as a whole, whereas in resolved photon processes it behaves as a source of partons, which subsequently interact with partons from the proton. The variable which is used to separate the two processes is x_γ which measures the fraction of the photon momentum participating in the production of the dijet system. The resolved (direct) processes dominate at low (high) x_γ values. The x_γ is measured as:

$$x_\gamma = \frac{1.}{(2E_e y)}(E_{t,1}e^{-\eta_1} + E_{t,2}e^{-\eta_2}) \qquad (1)$$

where $E_{t,i}$ and η_i are the transverse momentum and pseudorapidity of two hard jets, E_e is the electron energy and y is the inelasticity. In the leading order QCD approximation to dijet photoproduction, the ep cross section may be written symbolically

$$\frac{d\sigma_{ep}}{dQ^2} = \gamma_{flux}(y, Q^2) \otimes PDF_\gamma(x_\gamma, Q^2, \mu) \otimes \otimes PDF_p(x_p, \mu) \otimes d\sigma_{ij}(\theta^*, Q^2, \mu) \qquad (2)$$

where γ_{flux} is the flux of photons, $PDF_\gamma, (PDF_p)$ are parton distribution functions of photon (proton) respectively, $d\sigma_{ij}$ is the cross section of the hard subprocess, x_p is the fraction of the proton momentum in the hard process, θ^* is the scattering angle of the jets in the dijet CMS system and μ represents the

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QCD renormalization and factorization scales. For direct processes the parton distribution functions (PDFs) of the photon are replaced by unity. The quark density functions used in the calculations were determined from measurements of the photon structure function F_2^γ in deep inelastic electron–photon scattering at e^+e^- colliders.

From the experimental point of view, results are obtained using particles momenta (tracks from charged particles) or energies (clusters) measured in detectors. The influence of the imperfect detector has to be taken out in order to get the measured experimental cross sections back to the jet cross section at hadron level.

There are two different approaches which has been used to gain the information about the parton distribution functions in the photon.

Extraction method was used e.g. in [1–4]. For the extraction of the effective photon parton distribution function, the measured dijet cross section was corrected to the level of the LO diparton cross section using the unfolding procedure. In this case the correlations between hadronic $(x_\gamma^{jet}, E_T^{jet})$ and the parton level variables (x_γ, p_T) are used to correct [2] for the fragmentation, higher order QCD and underlying energy effects. The effective parton distribution function of the photon is the fundamental, parton level quantity. The method is however experimentally difficult and is only applicable in LO of QCD.

The universality method (e.g. [5–8]) checks if existing parametrisations of PDF are adequate for the description of the dijet cross sections within next to leading order (NLO) of QCD. The most accurate QCD calculations, presently available at NLO [9,10], are expressed only at the parton level therefore the predicted cross sections have to be further corrected to the hadron level, by taking the ratios of cross sections at the hadron and parton level as given by Monte Carlo models. The application of hadronization corrections leads to the additional uncertainty.

The universality method has been used in the analyses which will be presented here.

[2]using LO Monte Carlo generators

3. High E_T dijet production

Measurements of the cross sections of dijets with high E_T have several motivations. At high E_T, where non-perturbative effects are less influential, jet cross sections directly reflect the underlying parton dynamics of the photon-proton collision. High E_T jets provide a natural hard scale for perturbative QCD calculations and offer a means of testing the validity of NLO perturbative QCD. The experiments at e^+e^- colliders covered the kinematic range 0.05< x_γ <0.8 and $\mu^2 = Q^2 < 500\ GeV^2$. In contrast to these experiments at HERA the scale extends up to $\sim 6000\ GeV^2$ and x_γ up to 1. Jets in photoproduction at HERA are directly sensitive to the quark and gluon content of the photon already in leading order. In addition data are sensitive also to the gluon densities of the proton at x_p up to 0.6, where the gluon densities from deeply inelastic scattering data have large uncertainties.

The advantage of requiring two high E_T jets lies in being able to determine x_γ from the formula (1). By selecting events with $x_\gamma < 0.75$ or > 0.75 , for example, one can divide the dijet events into subsamples in which the resolved and direct components dominate.

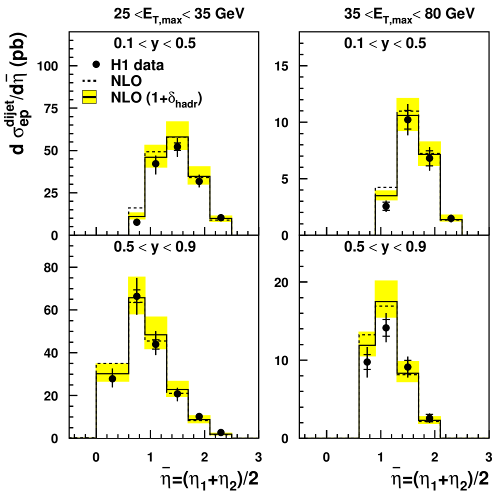

Figure 1. Differential ep cross section for dijet photoproduction as a function of $\overline{\eta}$ of the two highest E_T jets in two regions of $E_{T,max}$ and y. Grey band indicates the scale uncertaintes of the NLO prediction.

Analysis of dijet cross section was performed by both experiments H1 [11] and ZEUS [12]. The differential cross section $d\sigma/d\overline{\eta}$ (where $\overline{\eta} = (\eta_1 + \eta_2)$) measured by H1 is shown in Fig. 1 for two ranges of the jet maximal E_T, $E_{T,max}$, subdivided into two y regions to test the different domains of x_γ and x_p [3]. The good agreement between data and NLO QCD calculations (using CTEQ5M PDF for proton and GRV-HO PDF for photon) is observed taking into account the uncertaintes in the calculations related to the QCD scale variation. Currently, also at high x_p, the NLO calculations describe the data, which are however statistics limited.

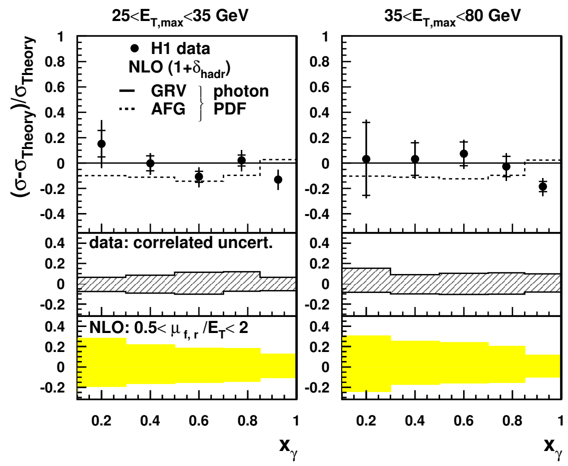

Figure 2. The x_γ dependence of the relative difference of the measured dijet cross section from the NLO prediction with hadronization corrections for two regions of $E_{T,max}$. GRV and AFG are used for photon PDFs.

The relative difference of data and NLO in $d\sigma/dx_\gamma$ for two regions of $E_{T,max}$ is presented in Fig. 2. NLO predictions are shown for both sets of photon PDFs, GRV and AFG. Within the uncertainites the NLO calculations describe the data well. The dominant source of uncertainties is the theoretical uncertainty related to the variation of the scale in NLO calculations.

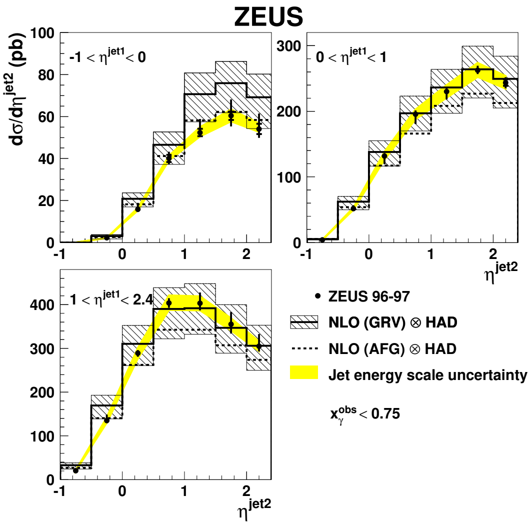

Figure 3. The measured cross section as a function of η^{jet2} for events with $x_\gamma < 0.75$ in three regions of pseudorapidity of the other jet.

The differential cross section measured by ZEUS collaboration [12] as a function of the pseudorapidity of one of the jets, in different regions of pseudorapidity of the other jet is shown in the region $x_\gamma < 0.75$ in Fig. 3. The NLO predictions give a good description of the data except for the jets produced in the backward region where the data are slightly bellow the uncertainty band. The $d\sigma/dx_\gamma$ distribution is compared in Fig. 4 with NLO predictions with GRV and AFG PDFs of the photon. The data are slightly below the prediction with GRV PDF for the lowest E_T^{jet1} bin and are slightly higher for high E_T^{jet1}. The predictions using AFG are similar in shape to those using GRV but are (10–15)% lower.

The asymmetric cuts were used in both H1 and ZEUS experiments to avoid the infrared sensitivities of NLO calculations [13]. ZEUS requires for the hardest jet E_T^{jet1} >14 GeV and second hardest jet E_T^{jet2} >11 GeV, while H1 demands 25 GeV and 15 GeV respectively. The slightly different conclusions by the two experiments can

[3]The lower right distribution in Fig. 1 corresponds to the region with lower x_γ and larger x_p.

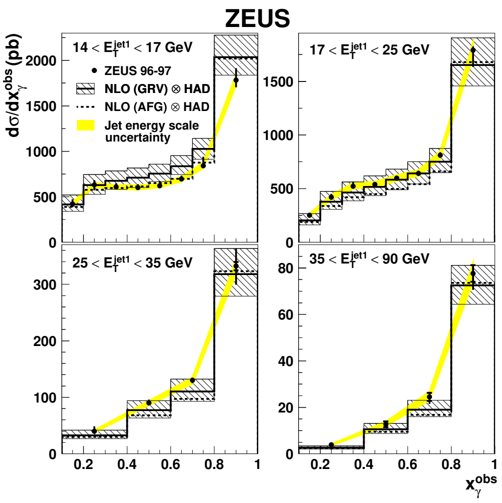

Figure 4. The measured cross section as a function of x_γ in four regions of E_T^{jet1} compared to NLO predictions with GRV and AFG photon PDFs.

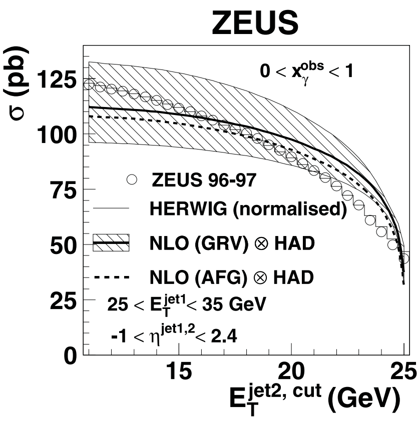

Figure 5. The measured cross section as a function of $E_T^{jet2,cut}$ for a fixed range of transverse energy jet E_T^{jet1} compared to NLO predictions and to the HERWIG MC model.

be at least partly understood by studying the dependence of the cross section to the cut on E_T^{jet2} between data and NLO calculations, see Fig. 5. With the cut on E_T of the second jet chosen by H1 the NLO lies closer to the data than with the choice of ZEUS. HERWIG MC model describes the E_T^{jet2} dependence of the data much better than NLO calculations indicating that NLO calculations should be improved significantly by including soft perturbative effects.

4. Inclusive jet production

Inclusive jet cross cross sections were measured by H1 [14] and ZEUS collaborations [15] demanding high E_T^{jet}, $E_T^{jet} > 17$ GeV (ZEUS) or 21 GeV (H1). In H1 analysis the data range was extended also to the region of lower E_T^{jet}, $5 < E_T^{jet} < 21$ GeV using another sample of data with tagged electron.

The differential cross section measured by ZEUS as function of E_T^{jet} is compared in Fig. 6 with LO and NLO predictions. The NLO calculations are in good agreement with the data within the two dominant errors, the jet energy scale (up to 2%) and the QCD scale uncertainty.

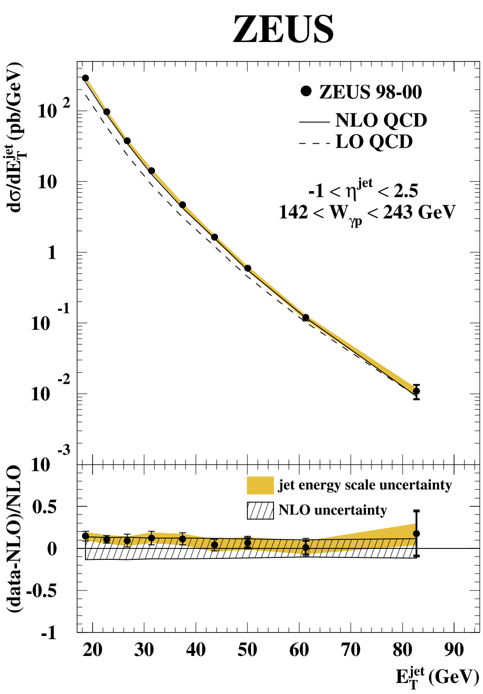

Figure 6. The measured cross section $d\sigma/dE_T^{jet}$ compared to LO and NLO QCD parton–level calculations corrected for hadronization effects.

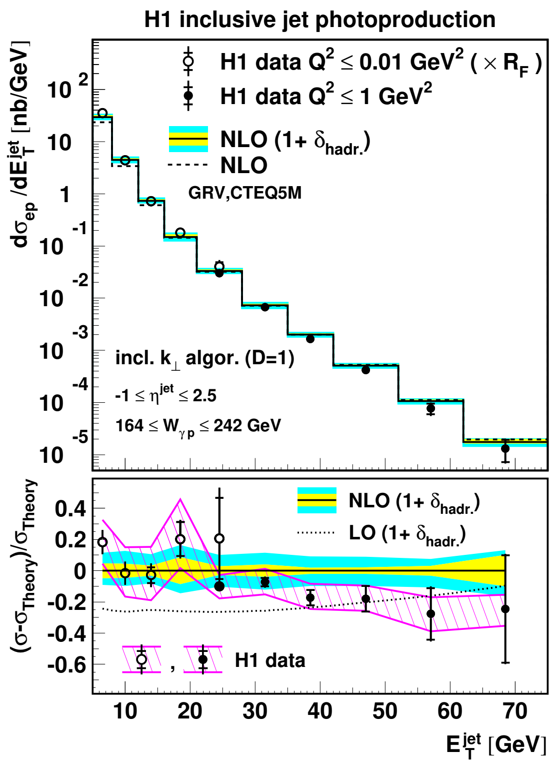

Figure 7. The differential cross section for inclusive jet production as a function of E_T^{jet} compared to NLO predictions.

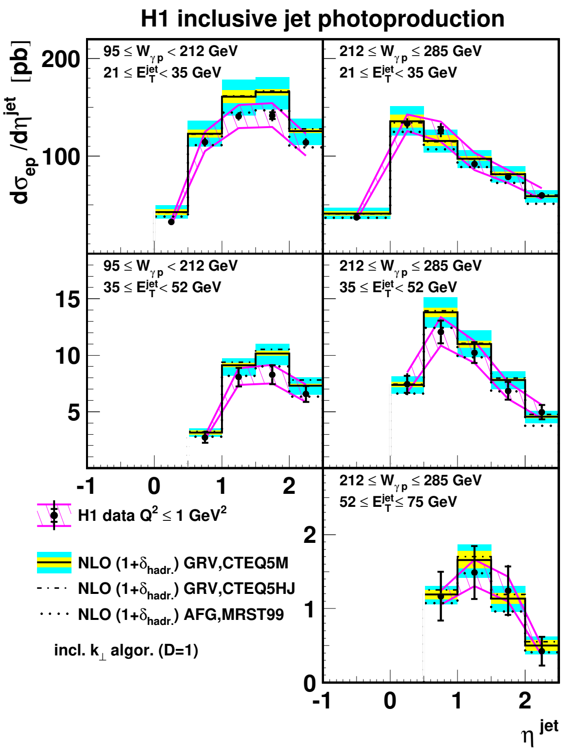

Figure 8. The differential cross section for inclusive jet production as a function of η^{jet} compared to NLO predictions.

A measurement of the inclusive jet cross section over the whole E_T^{jet} range was performed by combining of the "low" and "high" E_T^{jet} data sample by H1 and it is shown in Fig. 7. The analyses of both samples agree well in their domain of overlap. The measured cross section falls by more than 6 orders of magnitude and is well reproduced by the theoretical NLO prediction. In Fig. 8 the cross section is studied more differentially, $d\sigma/d\eta^{jet}$ is presented in two regions of the hadronic energy $W_{\gamma p}$ and three intervals of E_T^{jet}. NLO calculations using different combinations of photon and proton PDFs give good agreement with the data. The precision of the measurement and theoretical uncertainties do not allow to choose the best combination of PDFs.

5. Summary

The results of H1 and ZEUS experiments presented here demonstrate that we have achieved a good understanding of single inclusive jet production in γp at HERA. NLO calculations with photon PDFs obtained from $\gamma\gamma^*$ scattering are able to describe the data. The situation is however a little bit more complicated in the case of dijet analysis. The H1 and ZEUS experiments obtained seemingly contradictory conclusions - the agreement of data and theoretical NLO predictions obtained by H1 is not so perfect in ZEUS. This contradiction can be at least partly explained by the different dependence of the cross section to the cut E_T^{jet2} between data and NLO calculations. Since the experimental uncertainties are now smaller than the theoretical ones, the theoretical progress is needed in order to understand jet production at HERA. The current precision of the theoretical predictions does not allow to discriminate between the different photon PDFs using these data alone.

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