Jets in Photoproduction and at Low Q^2 at HERA

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Abstract. Recent H1 and ZEUS measurements of two and three jet cross sections in electron-proton interactions in the photoproduction region or at low photon virtuality, Q^2, are presented and compared to NLO QCD calculations. Phase space regions where data are not well reproduced by the NLO theory are pointed out. A recent ZEUS measurement of color dynamics sensitive to the underlying gauge group in QCD is presented.

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INTRODUCTION

The production of jets with high transverse momenta in electron-proton collisions is described within perturbative quantum chromodynamics (QCD) by the hard interaction of photons with partons inside the proton. Jet cross sections are successfully described by next-to-leading order (NLO) QCD calculations in most of the HERA kinematic range. However, regions of phase space have been observed for which NLO QCD predictions do not reproduce the data satisfactorily.

The measurement of jet production in the low Q^2 region, where Q^2 is the photon virtuality, is particularly suitable for the investigation of effects related to the photon structure. For $Q^2 \lesssim E_T^2$, where E_T is the transverse energy of the leading jet[1] (jets), the interaction can be conveniently described by the sum of two contributions. In the "direct photon" process the photon interacts as a whole with a parton from the proton, whereas in the "resolved photon" process it acts as a source of partons, which interact with partons from the proton. The parton distributions functions (PDF) of the photon are introduced in the latter case.

The dijet cross sections are often studied as a function of the variable x_γ defined as

$$x_\gamma = \frac{\sum\limits_{j=1,2} (E_j^* - p_{z,j}^*)}{\sum\limits_{\text{hadrons}} (E^* - p_z^*)} , \qquad (1)$$

where the sum in the numerator runs over the two leading jets and the sum in the denominator includes the full hadronic final state. Neglecting the masses of the partons and beam particles, the variable x_γ represents an estimate of the fraction of the photon four-momentum carried by the parton involved in the hard scattering.

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[1] E_T is assumed to be the hard scale of the process. In general, Q^2 should be smaller than the square of the renormalisation scale, μ_r^2, when introducing the resolved photon concept.

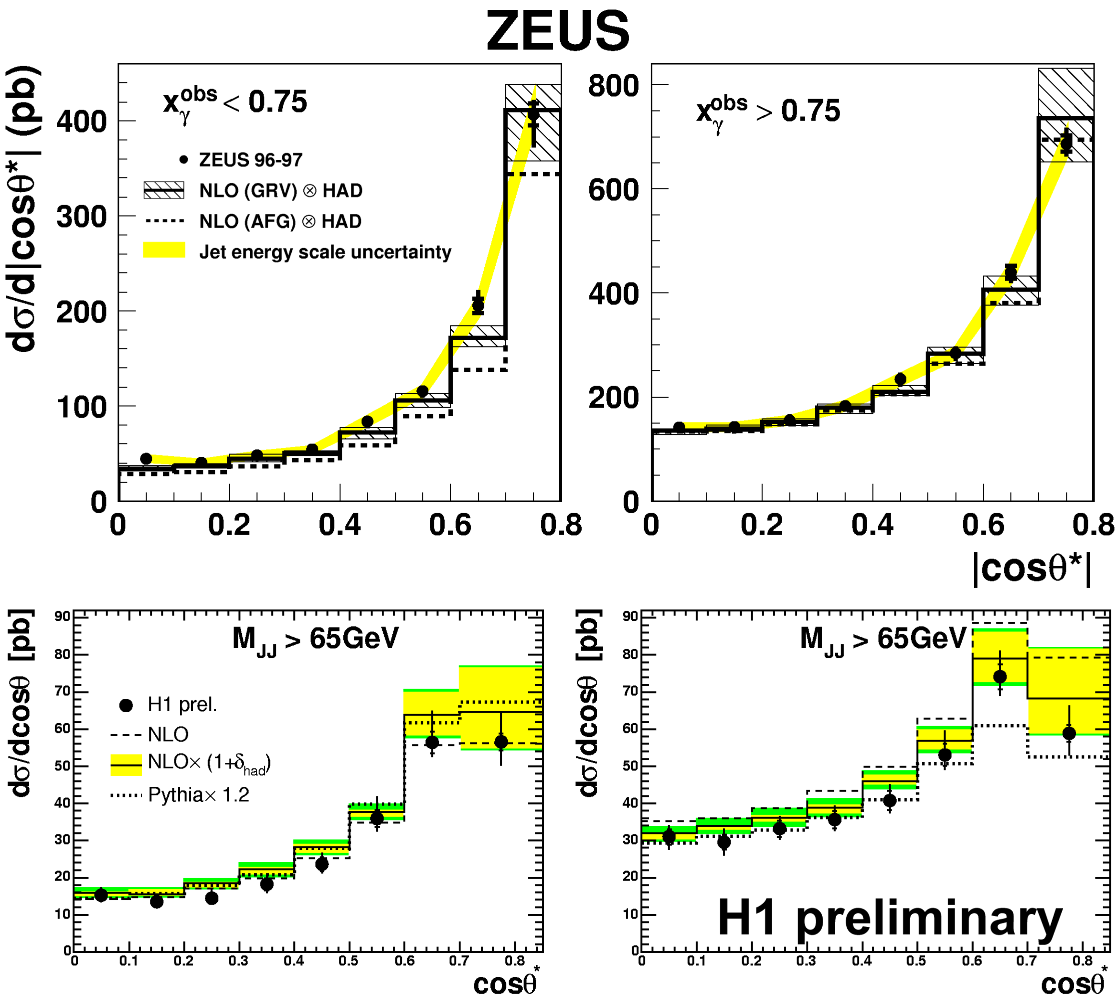

FIGURE 1. Cross section as a function of $|\cos\theta^*|$ measured by ZEUS (upper plots) and H1 (lower plots). The plots in the left column correspond to the region of $x_\gamma < 0.75$ ($x_\gamma < 0.8$), the plots in the right column to $x_\gamma > 0.75$ ($x_\gamma > 0.8$) for ZEUS (H1), respectively. Data are compared to the NLO predictions corrected for the hadronisation effects.

PHOTOPRODUCTION OF DIJETS

A published ZEUS measurement [1] as well as recent H1 preliminary results [2] of the measurement of dijet cross sections in the photoproduction region are compared with the NLO QCD predictions. As an example, dijet cross sections are shown in Fig. 1 as a function of $|\cos\theta^*|$, where θ^* denotes angle between the two leading jets in their centre-of-mass system. The phase space of the measurements is defined mainly by the cuts on E_T of the two leading jets ($E_{T\text{jet}1} > 14\,\text{GeV}$, $E_{T\text{jet}2} > 11\,\text{GeV}$ in the case of ZEUS and $E_{T\text{jet}1} > 25\,\text{GeV}$, $E_{T\text{jet}2} > 15\,\text{GeV}$ in the case of H1; see [1, 2] for further details about the event selection). The dijet cross section in Fig. 1 are shown for two different regions of x_γ. The data at low x_γ rise more rapidly at high $|\cos\theta^*|$ than those at high x_γ. This is consistent with a difference in the dominant propagators for direct (quark propagator) and resolved (gluon propagator) photon events[2].

Considering the theoretical and experimental uncertainties, the NLO predictions give a reasonable description of the data. This is also true for the photoproduction dijet cross sections plotted more differentially, e.g. as a function of E_T of the leading jet in different pseudorapidity regions [1, 2]. Due to the precision of these data, they are now used to constrain the mid- to high-x gluon distribution functions in the proton [3] as well as to constrain PDFs of the photon.

TRANSITION BETWEEN THE PHOTOPRODUCTION AND DIS

While dijet cross sections in the photoproduction region are quite well reproduced by the NLO QCD calculations, both H1 and ZEUS have reported significant discrepancies between the measurements and theory predictions of dijet cross section in the low Q^2 region, especially at low x_γ and for low E_T jets [4, 5]. The discrepancy is exemplified in Fig. 2, where dijet cross sections are shown triple differentially as a function of x_γ in different bins of Q^2 and E_T. In Fig. 2, the variable E_T denotes the transverse energies of the jets with the highest and the second highest transverse energy measured in the photon-proton centre-of-mass frame, so that each event contributes twice to the distributions, not necessarily in the same bin. The data are compared with the NLO QCD calculations: DISENT, JETVIP and NLOJET++. JETVIP denoted as "full" corresponds to the sum of the direct and resolved photon components, all the other predictions are just the direct photon contributions. NLOJET++ is run in two modes – either as the NLO QCD prediction for dijets (2 jet mode) or as the NLO QCD prediction for three jet production (3 jet mode). The latter can be compared to dijet cross section just in the region of $x_\gamma < 1$, where only events with at least three jets can contribute (see the discussion in [6]). Thus, NLOJET++ in the 3 jet mode calculates dijet cross section up to one order higher than the other NLO QCD programs mentioned above.

Fig. 2 illustrates that data are well reproduced by NLO QCD predictions at high x_γ, at high E_T or in the high Q^2 region. As we go to the low x_γ, low E_T and low Q^2 region, quite significant discrepancies are observed. The prediction of NLOJET++ in three jet mode and the prediction of JETVIP that includes also the resolved photon contributions get closer to the data, which indicates that higher order effects are probably missing in the theory predictions.

A similar conclusion has been drawn from the ZEUS measurement [5].

COLOR DYNAMICS IN PHOTOPRODUCTION

Recently, new ZEUS preliminary measurements of three jet cross sections have been presented [7] as a function of jet angular variables Θ_H, $\cos\alpha_{23}$ and $\cos\beta_{KSW}$, which

[2] More exactly, the resolved photon contributions are driven by both gluon and quark propagators, while the gluon propagator is absent in LO direct photon processes. The quark propagator is proportional to $(1-|\cos\theta^*|)^{-1}$ and the gluon propagator is proportional to $(1-|\cos\theta^*|)^{-2}$.

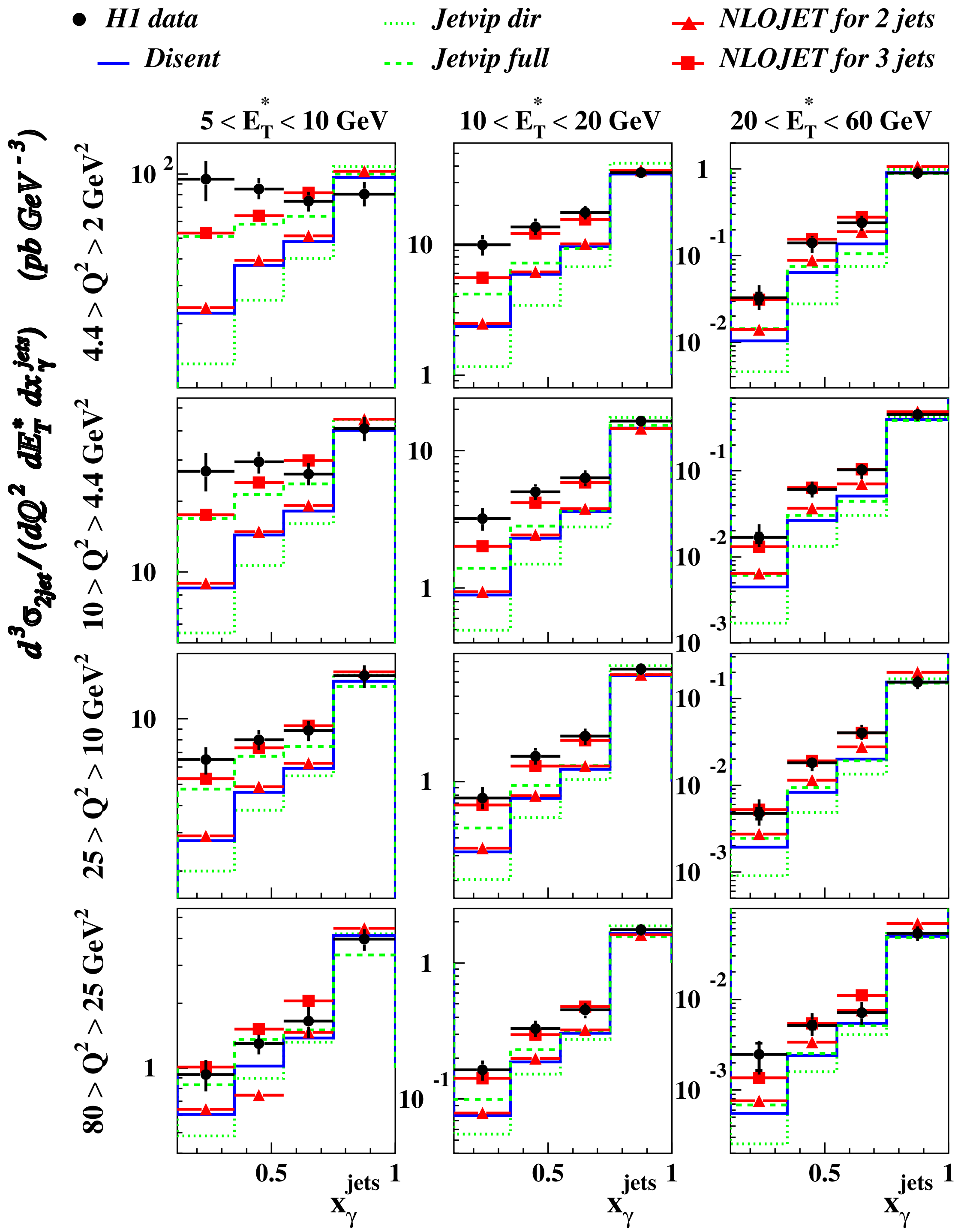

FIGURE 2. Triple differential dijet cross section $\mathrm{d}^3\sigma_{2\mathrm{jet}}/\mathrm{d}Q^2\mathrm{d}E_T\,\mathrm{d}x_\gamma$ with asymmetric E_T cuts (see [4] for details). The data are compared to NLO direct photon calculations using DISENT (full line) and JETVIP (dotted line), the sum of NLO direct and resolved photon contributions of JETVIP (dashed line) and the NLOJET++ predictions in 2-jet (triangles) and 3-jet (squares) mode. All calculations are corrected for hadronisation effects.

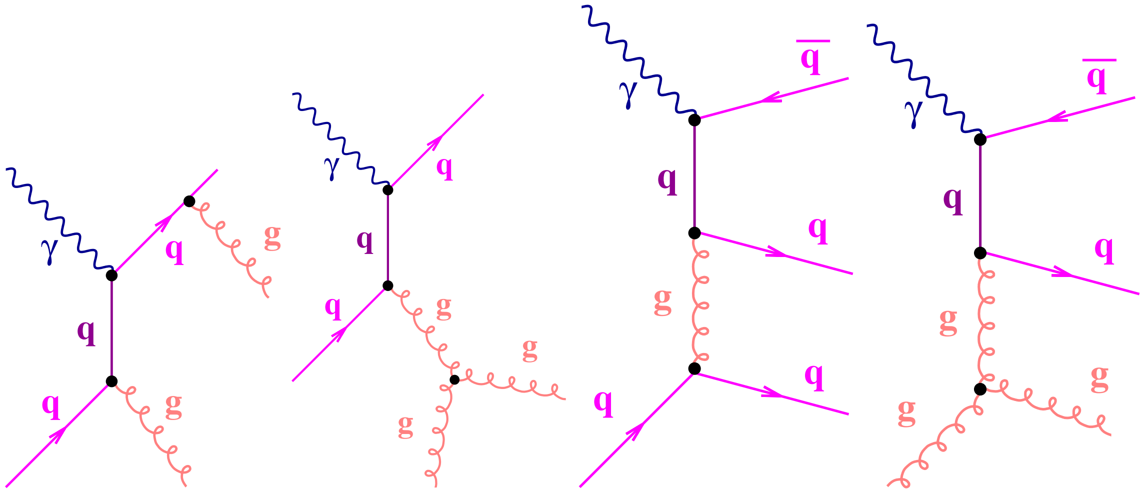

FIGURE 3. Examples of diagrams for the photoproduction of three jet events through direct photon processes in each color configuration.

are constructed from different combinations of planes and vectors defined by jets and the electron-proton beam. These variables are sensitive to different color configurations (i.e. to different combinations of color factors C_F, C_A and T_F) that correspond to four different types of diagrams for the photoproduction of three-jet events through direct photon processes (Fig. 3). The C_F, C_A and T_F color factors are a physical manifestation of the underlying group structure in QCD. They represent the relative strengths of the processes $q \to qg$, $g \to gg$ and $g \to q\overline{q}$ respectively. Due to different spins of quark and gluon, the color factors give rise to a specific pattern of angular correlations between the final state jets.

In Fig. 4, the color components have been combined in such a way as to reproduce the color structure of a theory based on the non-abelian group SU(N) for N=3 and in the limit of large N, the abelian group $U(1)^3$ and, as an extreme choice, a calculation with $C_F = 0$, $C_A = 3$ and $T_F = 1/2$. The data clearly disfavour the last example with $C_F = 0$ and a theory based on SU(N) in the limit of large N. On the other hand, no distinction between the SU(3) and $U(1)^3$ can be done from the presented angular distributions.

SUMMARY

Jet production in the region of $Q^2 < E_T^2$ in electron-proton collisions keeps providing us a precise and important information about the proton and photon structure that uniquely complements other measurements. On the other hand, the region of low x_γ, low E_T and low Q^2 (i.e. $Q^2 \sim 1\,\mathrm{GeV}^2$) is not satisfactorily described by the present theory. The measurement of angular correlations in three jet photoproduction is consistent with the admixture of color configurations as predicted by the SU(3) gauge group.

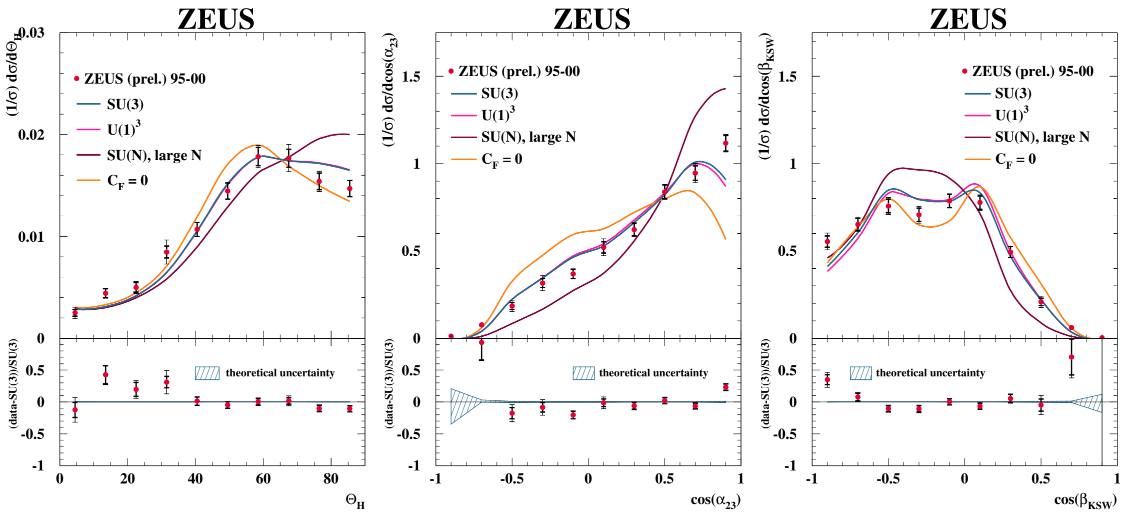

FIGURE 4. Normalised differential *ep* cross sections for three jet photoproduction integrated over $E_T > 14$GeV and $-1 < \eta < 2.5$ in the kinematic region defined by $Q^2 < 1\text{GeV}^2$, $0.2 < y < 0.85$ and $x_\gamma > 0.7$ as function of Θ_H, $\cos\alpha_{23}$ and $\cos\beta_{KSW}$. The data are compared to NLO QCD calculations for direct photon processes based on SU(3) (solid lines), U(1)^3 (dashed lines), SU(N) in the limit of large N (dot-dashed lines) and $C_F = 0$ (dotted line).

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