JETS IN PHOTOPRODUCTION AND IN THE TRANSITION REGION TO DIS AT THE HERA COLLIDER

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For H1 and ZEUS collaborations

Recent results on jets in photoproduction and in deep-inelastic scattering at low Q^2 by the H1 and ZEUS collaborations are reviewed.

1 Introduction

The photon is probably the best known elementary particle. It is a quantum of the gauge field, and as such it is considered to be massless, charge-less and to couple point-like.

While interactions of photons with leptons are described by QED with high precision, interactions of photons with hadrons still bring surprises. This is caused by the fact, that in the same way, as the photon can fluctuate into an electron-positron pair, it can fluctuate into a pair of quark and anti-quark, which interact strongly. The photon then behaves as a hadron.

In Leading Order (LO), it is possible to distinguish between direct processes (the photon interacts electromagnetically) and resolved processes (the photon fluctuates into a partonic system, of which one of the partons then interacts). Beyond LO this classification becomes ambiguous.

2 Theoretical description of photon-proton interactions

Perturbative QCD calculations which aim to describe interactions of photons with protons use as an input parton density functions of the proton (obtained from global fits to DIS and hadron collision data) and of the photon (extracted from data on $\gamma\gamma$ collisions).

Depending on the way perturbative QCD is used, there are two groups of approaches.

Leading order plus Parton Shower (LO+PS) models combine LO matrix elements with parton showers re-summing the leading logarithmic contributions from all orders.[1] Hadronization is included using a QCD motivated phenomenological model and predictions are directly compared to data on hadron level.

Next-to-leading order (NLO) calculations use matrix elements up to a fixed order in α_S (for most processes up to α_S^2).[2,3,4] They provide predictions on parton level. Before comparing to data, NLO predictions are corrected for hadronization effects. These are estimated using LO+PS models discussed above.

3 Experimental conditions

Depending on how events are selected, we distinguish between tagged photoproduction (scattered electron is measured in downstream calorimeter, $Q^2 \leq 10^{-2}$ GeV^2), untagged photoproduction (electron is not observed in main detector, $Q^2 \leq 1$ GeV^2) and low Q^2 region (electron is measured in main detector, $Q^2 \geq 2$ GeV^2). The distribution of the center-of-mass energy of the γp system depends on the exact event selection; at HERA it extends up to 280 GeV.

The results are presented in the hadronic CMS (center-of-mass frame of γp system), for jet finding, an inclusive k_t algorithm is used[5] in the same frame.

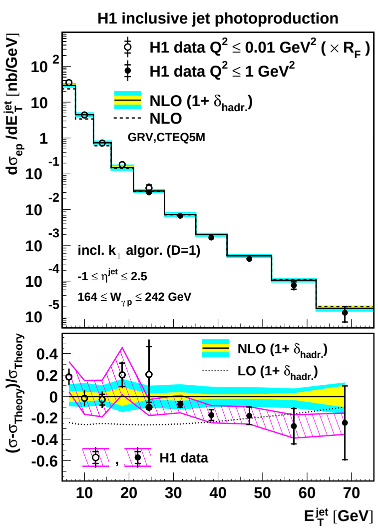

Figure 1. Cross section of inclusive jets in photoproduction as a function of E_T^{jet} from H1.

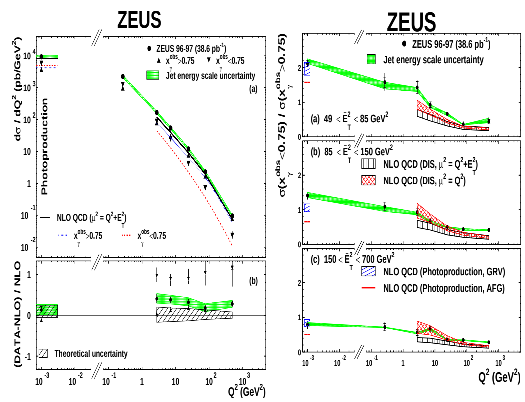

Figure 2. Dijet production in photoproduction and DIS from ZEUS as a function of Q^2, cross section (left), ratio between cross sections for resolved and direct event sample (right).

Before being compared to theory, data are corrected to hadron level, i.e. acceptance and effects due to the detector and the reconstruction software are corrected for. These corrections are calculated using LO+PS models together with a detailed detector simulation.

4 Inclusive jets

To check our understanding of jet production in photoproduction one can simply count the number of jets as a function of their transverse energy. The cross section of inclusive jets in the pseudo-rapidity range $-1 < \eta < 2.5$ has been measured by both H1 (Fig. 1) and ZEUS.[7,9]

One can see an excellent agreement between the NLO calculation and the data. Agreement extends down to low value of E_T (5 GeV), where hadronization corrections (including effects of the underlying event) become significant. The dominant experimental error is coming from the energy scale uncertainty, which is smaller then the renormalization scale uncertainty of the theory.

5 Dijets in photoproduction and at low Q^2 DIS

A measurement of inclusive jet production has clear advantages. Theoretical predictions are "safe", the measurement is least restrictive in phase space and offers good statistical precision. On the other hand, dijets allow to construct more differential quantities, for example x_γ^{obs}.[a] At parton level in LO this variable corresponds to the fractional photon energy of the parton "in" the photon entering the hard subprocess. Higher orders, hadronization and detector resolution smear-out the correlation, but still one expects for direct processes x_γ^{obs} to be close to one and significantly smaller than one for resolved processes.

In photoproduction ($Q^2 = 0$) a photon behaves part of the time as a hadron, which is manifested by the presence of its resolved part. On the other hand, in DIS, at high enough Q^2, the photon is point-like. What happens in the transition region?

ZEUS has presented the cross section on dijets in photoproduction and DIS (Fig. 2

[a] defined as $x_\gamma^{obs} = \sum_{jets}(E_j^* - p_z^*)/\sum_{hadrons}(E_j^* - p_z^*)$

left) in the hadronic CMS, in the pseudorapidity range $-3 < \eta^* < 0$ and for $E_T > 7.5$ (6.5) GeV.[10] While in photoproduction the cross section of dijet production is in agreement with NLO,[2] in DIS however, the NLO assuming only pointlike photon[4], underestimates the cross section.

Requiring $x_\gamma^{obs} > 0.75 (x_\gamma^{obs} < 0.75)$, it is possible to enhance direct (resolved) processes. The sample with predominantly direct processes is well described by NLO, while a discrepancy is observed at small x_γ^{obs}.

The same data are shown in Fig. 2 (right side) in the form of the ratio $R = \sigma(x_\gamma^{obs} < 0.75)/\sigma(x_\gamma^{obs} > 0.75)$. In this ratio correlated experimental and theoretical uncertainties partly cancel. We can see that the discrepancy between data and direct NLO extends up to rather high Q^2 values and is most remarkable at low E_T. A change of scale (using Q^2 instead of $Q^2 + E_T^2$), improves the agreement at low Q^2, but not at higher Q^2 values.

This result may be a hint that higher orders are needed in the perturbative calculation. At low Q^2, it is possible to include them effectively using the concept of resolved virtual photons.

H1 has measured the triple differential cross section of dijets as a function of Q^2, E_T and x_γ in DIS at low Q^2 in the region $-2.5 < \eta^* < 0$ and $E_T > 7$ (5) GeV.[8] The comparison of the data with NLO shows that NLO underestimates the cross section, the discrepancy being most clearly visible for low Q^2, E_T and x_γ. The inclusion of a resolved transverse virtual photon component in NLO reduces the discrepancy, but agreement with data is still not perfect.

The same data are compared to the LO+PS model of HERWIG[1] in Fig. 3. Again, direct processes alone underestimate the data and inclusion of transverse resolved photons improves the agreement. Including, in addition a contribution from resolved longitudinal photons yields an even better description..

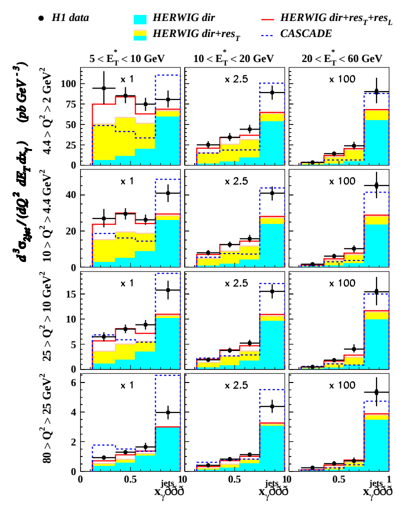

Figure 3. Triple differential cross section of dijet production in DIS from H1 compared to HERWIG and CASCADE

An alternative approach to modeling γp interactions is represented by the CASCADE model,[6] which is based on the CCFM evolution, with angle ordering instead of k_T ordering of the radiated gluons and using unintegrated parton densities of the proton. This model is in reasonable (but not perfect) agreement with the data. This is remarkable, as CASCADE does not use any concept of a resolved photon; low x_γ^{obs} events are produced by different evolution from the proton side.

6 Study of color dynamics in three jet events in photoproduction

Three jet events are interesting as they feel the triple gluon vertex. It would be nice to find three-jet observables sensitive to the structure of the gauge group behind the strong interaction.

ZEUS has measured cross sections of three-jet production as a function of angles θ_H, α_{23} and β_{KSW}. Jets with $-1 < \eta < 2.5$ and $E_T > 14$ GeV were selected.[11] They are ordered according to their E_T. Then θ_H is defined as the angle between the plane de-

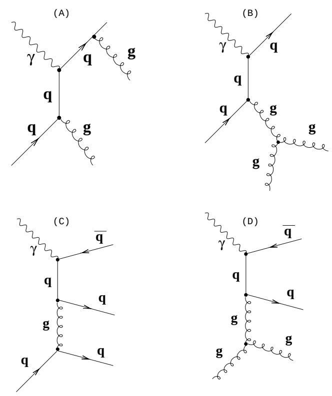

Figure 4. LO diagrams for direct three jet events

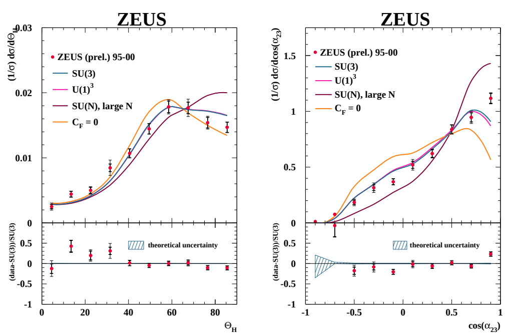

Figure 5. Cross section of direct three-jet photoproduction from ZEUS as a function of θ_H and $\cos\alpha_{23}$.

fined by the beam axis and jet 1 and the plane defined by jets 2 and 3, α_{23} is the angle between jets 2 and 3.

If predominantly direct events are selected ($x_\gamma > 0.7$), we have in LO four terms (see Fig. 4). Detailed analysis shows that cross sections plotted as a function of θ_H, α_{23} and β_{KSW} are sensitive to the presence of the triple gluon vertex. The shape of term B (triple gluon vertex in quark induced events) is different from the other three terms. [11]

A comparison of data with LO predictions[3] is shown in Fig. 5. There is very good agreement with SU(3) expectations. In addition, it is possible to rule out several exotic possibilities (like $SU(N)$ for large N, or $C_F = 0$). Current precision does not allow to distinguish between SU(3) and Abelian case, because SU(3) predicts only 10% probability for events with a triple gluon vertex in quark induced events.

7 Summary

Measured cross sections for inclusive jets in photoproduction are in excellent agreement with NLO. Study of dijets at low Q^2 show discrepancies between data and NLO, indicating the need for higher orders in the perturbative expansion. Inclusion of resolved longitudinal virtual photon component in low Q^2 DIS improves the description of the data.

Three-jet events are sensitive to the triple gluon vertex, allowing to study the gauge structure of the strong interaction. The data are in agreement with LO QCD predictions. Current precision does not allow to discriminate between SU(3) and the Abelian case.

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