Jet Physics at HERA

Oscar González
(On behalf of the H1 and ZEUS Collaborations)

Abstract

Analyses of jet production at HERA have become precise enough to perform QCD studies which are both competitive and complementary to those at e^+e^- and $p\overline{p}$ colliders. This report summarises some of the latest results on jet physics from the H1 and ZEUS Collaborations.

1 Introduction

The high-energy ep interactions at the HERA collider provide a powerful laboratory to test the prediction of Quantum Chromo-Dynamics (QCD). In this theory, the interactions between quarks and gluons produce partons with large transverse momenta, which fragment into hadronic jets.

In recent years the experimental uncertainties have been substantially reduced and the tools to compute the theoretical predictions have been refined so that more accurate QCD studies are possible with jet physics at HERA.

This report presents a selection of the latest results obtained by the H1 and ZEUS Collaborations at the HERA collider in both the photoproduction and deep inelastic scattering (DIS) regimes.

2 Photoproduction of Jets

The photoproduction of jets with high transverse energy is described by the hard interactions of real photons with the partons inside the proton. These interactions are separated into two classes: direct processes, in which the photon interacts as a point-like particle with a parton in the proton, and resolved processes, in which the photon has an hadronic structure and one of the partons in the photon scatters a parton in the proton. In order to separate these two processes, the variable x_γ is used. This quantity is the fraction of the photon's momentum which takes part in the interaction. It is expected that high values of x_γ, i.e. close to unitiy, are related to direct processes, whilst the resolved processes have a distribution on this variable at lower x_γ values.

2.1 The Internal Structure of the Photon

The study of dijet production in the photoproduction regime gives information on the partonic content of the photon as well as providing a test of the

QCD predictions. The variable x_γ is reconstructed from the transverse energies and pseudorapidities of the two jets with the highest transverse energies:

$$x_\gamma = \frac{1}{2\,E_\gamma}\left[E_{T,\mathrm{jet1}}\exp(-\eta_{\mathrm{jet1}}) + E_{T,\mathrm{jet2}}\exp(-\eta_{\mathrm{jet2}})\right] , \qquad (1)$$

where E_γ is the energy of the incoming quasi-real photon.

Measurements of dijet cross sections in the photoproduction regime are sensitive to both proton and photon parton distribution functions (pdfs), as shown in the analyses of the H1 and ZEUS Collaborations [1,2]. The data are reasonably well described by the next-to-leading order (NLO) QCD predictions. Due to the small uncertainties in the proton pdfs, well constrained by the DIS data, measurements of dijet photoproduction can be used to study the structure of the photon.

In order to use these data to precisely constrain the photon pdfs, a reduction of the theoretical scale uncertainties, possibly via the inclusion of higher orders, is needed [1,2]. At present, the data are only used to test the existing parameterisations.

Apart from testing the photon pdfs, dijet photoproduction has also been used to perform searches of high-mass resonances decaying into two partons, which are observed as a high-mass dijet system. In an analysis performed by the ZEUS Collaboration [3], no resonances are observed over the QCD background and upper limits on resonance production are presented. In this analysis, a 95% C.L. limit on the cross section for Z^0 photoproduction at HERA has been obtained for the first time, $\sigma_{e^+p\to e^+Z^0X} < 5.9\,\mathrm{pb}$, which is, however, well above the cross section of around $0.3\,\mathrm{pb}$ predicted by the Standard Model.

2.2 Multijet Photoproduction

The photoproduction of more than two jets per event is related to higher order interactions, but is also sensitive to multi-parton interactions (MPI), i.e. photon-proton collision in which more than one hard scattering is present at the parton level. The study of multijet production is sensitive to MPI, which at present cannot be described from first principles, but have to be modelled phenomenologically [4,5].

The ZEUS Collaboration has measured the production of four jets in γp interactions in order to study the sensitivity to multi-parton interactions [6]. In this analysis, the four-jet system is reduced to a three pseudo-jet system by combining the two jets with the lowest invariant mass in order to exploit the advantages of the variables used in the three-jet events studied previously [7].

The variable used to study the sensitivity to multi-parton interactions is $\cos\theta_3$, where θ_3 is the angle between the pseudo jet with the highest transverse energy and the beam in the four-jet rest frame. The $\cos\theta_3$ distribution is shown in Fig. 1 for the inclusive sample and for events in which the invariant mass of the four-jet system, m_{4J}, is greater than $50\,\mathrm{GeV}$. The inclusive

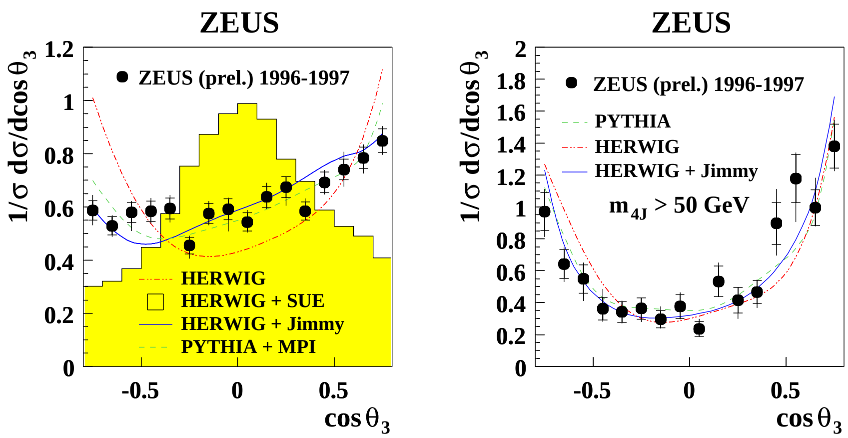

Fig. 1. The $\cos\theta_3$ distribution for the inclusive four-jet sample (left) and for the high-mass, $m_{4J} > 50\,\text{GeV}$, sample (right). The predictions of HERWIG and PYTHIA with and without including different models for MPI are shown

sample is not described without the inclusion of multi-parton interactions. However, the precision of the data is not yet high enough to distinguish between the two models considered, namely the PYTHIA+MPI [5] and the HERWIG+Jimmy [4] models. The soft underlying event in HERWIG is not able to describe the data in this kinematic region, indicating that the presence of a soft underlying event cannot account for the results.

For high m_{4J}, the sensitivity to multi-parton interactions becomes smaller and all models give a reasonable description of the data.

2.3 Inclusive Jet Photoproduction

Inclusive photoproduction of jets allows additional tests of QCD to be made with smaller theoretical uncertainties than in dijet production. On the other hand, the sensitivity to the partonic content of the photon is smaller and the present experimental and theoretical precision does not allow discrimination between different parametrisations of the photon pdfs.

The results by the H1 and ZEUS Collaborations [8] have been used to test the QCD predictions. NLO QCD calculations provide a very good description of the data, both in normalisation and shape, over several orders of magnitude.

3 Jet Physics in DIS

The study of jet production in DIS is complementary to jet photoproduction and provides direct access to the underlying parton dynamics. In this regime, the exchange boson is virtual so that the virtuality, Q^2, provides a second hard scale in addition to the transverse energy of the produced jets.

Jet production in DIS is particularly sensitive to QCD effects if the jets are produced with high transverse energy in the Breit frame [9]. In this frame, the exchanged virtual boson is purely space-like, with three-momentum $\boldsymbol{q} = (0,0,0,-Q)$. The production of jets with high energy in the transverse direction is only possible if hard partons are radiated. Thus, cross sections for producing high transverse energy jets in the Breit frame are directly proportional to the strong coupling constant, α_s, at the lowest order in the perturbative QCD expansion.

Measurements of jet cross sections in DIS have been compared to the theoretical predictions in order to test QCD predictions at HERA in widely different kinematic regions and parton configurations. Some of the results are described in the following sections.

3.1 Jet Cross Sections at Low Q^2 and at Forward Angles

The QCD studies performed by means of jet production in neutral current DIS at HERA focus on three topics: exploration of the low Q^2 region, forward- and multi-jet production and precise tests of QCD predictions.

In the first topic, recent results by the H1 Collaboration on the inclusive production of jets [10] in the region $5 < Q^2 < 100\,\mathrm{GeV}^2$ show that improved calculations, possibly by including higher order (e.g. NNLO) terms in the perturbative QCD expansion, are needed to understand low transverse energy jet production in DIS at low Q^2; in this kinematic region the data are porrly described by NLO QCD and the theoretical uncertainties are large.

This disagreement between data and NLO is particularly large for jets produced in the forward region, i.e. close to the proton remnant. In order to study the sensitivity to the evolution scheme, the H1 Collaboration has presented the results of a specific analysis [11] on forward jet production at HERA. The results are summarised in Fig. 2, where data are presented as a function of Bjorken x and compared to three different models. The prediction of the colour-dipole model as implemented in ARIADNE [12], which is close to the BFKL evolution scheme, describes the data well, whilst that of RAPGAP (RG) [13], using the standard DGLAP evolution, is only able to describe the data when a contribution from resolved virtual photons is added. The CASCADE program [14], which embodies the CCFM evolution equation, predicts a rate of forward-going jets which is too high. These conclusions are independent of the minimum transverse momentum of the selected jets used in the analysis.

3.2 Multijet Production in DIS

The production of more than two jets with high transverse energy in the Breit frame in DIS are related to higher powers of α_s in the perturbative

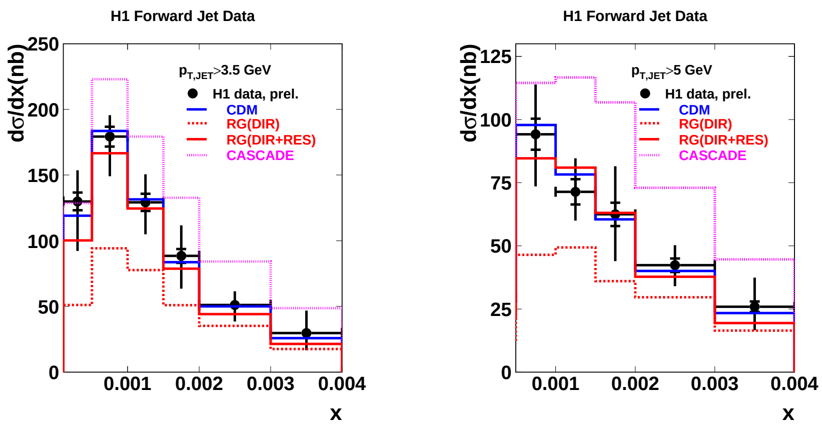

Fig. 2. Differential cross section for forward jet production as a function of Bjorken x for two regions of jet transverse momentum. Also shown are the predictions of several Monte Carlo models

QCD expansion. Thus, measurements of multijet production in DIS allow the realisation of tests of the QCD predictions to higher order in α_s. This is the aim of an analysis by the H1 Collaboration [15] which shows that the NLO QCD predictions provide a good description of the three-jet data over a large range in Q^2. Furthermore, the ratio of the three- to the two-jet cross section is well reproduced by NLO QCD. The leading-order (LO) QCD prediction is not able to describe the measured ratio as a function of Q^2. It should be noted that this type of observable allows the performance of precise QCD tests since some experimental and theoretical uncertainties cancel out in the ratio.

3.3 Precise Tests of QCD from Jet Production in DIS

Recent efforts to understand both the experimental and the theoretical aspect of the analyses of jet production in the Breit frame in DIS has been done in order to achieve the high possible precision in the QCD studies at HERA using jets. The knowledge of the jet energy scale at the 1%–2% level has been applied in precise measurements in kinematic regions in which the perturbative QCD predictions are well understood.

The most recent analysis [16] was performed by measuring inclusive jet production at high Q^2 in order to reduce the uncertainties associated to the low Q^2 region and those introduced by the additional cuts needed in dijet production in order to remove infrared-sensitive regions [17]. The data are well described over many orders of magnitude by NLO QCD calculations corrected by hadronisation effects. The differences between data and NLO

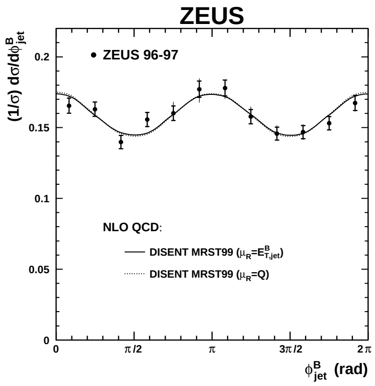

Fig. 3. The normalised differential cross section as a function of the azimuthal angle in the Breit frame for inclusive jet production. The NLO QCD predictions are shown for two choices of the renormalisation scale

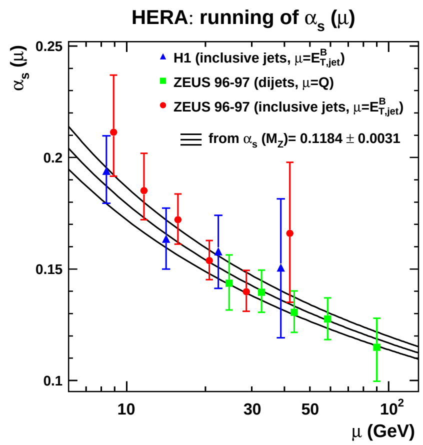

Fig. 4. Values of α_s as measured by H1 and ZEUS at different energy scales. The values are compared with the running predicted in perturbative QCD assuming the world average value for $\alpha_s(M_Z)$

QCD are of the same size as the theoretical uncertainties. This result provides a very precise test of QCD in describing jet production in DIS.

Figure 3 shows the distribution of the azimuthal angle of the jets in the Breit frame at $Q^2 > 125\,\mathrm{GeV}^2$, performed by the ZEUS Collaboration [18]. The measurements are well described by NLO QCD calculations, which predict a non-uniform distribution of the form $A + C\cos 2\phi$ [19]. This is the first time that the azimuthal asymmetry predicted in QCD has been observed in DIS using jets.

In addition to the realisation of precise tests of QCD, the HERA data have been used to determine α_s with a precision comparable to the best individual determinations in the world [16,20]. The measured values of α_s, obtained at different scales, presented in Fig. 4, display a running which is in good agreement with that predicted in QCD.

4 Conclusions

Jet studies at HERA allow precise tests of QCD predictions which are both competitive and complementary to those from other reactions.

With the present precision, jet studies at HERA provide results on several topics in QCD, including tests of perturbative QCD predictions beyond leading order, studies of the hadronic structure of the photon, studies of multijet and forward jet production and precise determinations of α_s.

In many of these analyses the uncertainties of the theoretical predictions are presently limiting the potential of jet physics at HERA.

References

1. H1 Coll., C. Adloff et al.: Eur. Phys.J. C **25**, 13 (2002)
2. ZEUS Coll., S. Chekanov et al.: Eur. Phys.J. C **23**, 615 (2002)
3. ZEUS Coll., S. Chekanov et al.: Phys. Lett. B **531**, 9 (2002)
4. J.M. Butterworth, J.R. Forshaw and M.H. Seymour: Z. Phys. C **72**, 637 (1996)
5. T. Sjöstrand and M. van Zijl: Phys. Rev. D **36**, 2019 (1987)
6. ZEUS Coll.: 'Multijets in photoproduction at HERA'. Contributed paper to the XXXIst International Conference on High Energy Physics, abstract 849 (Amsterdam, The Netherlands, 2002)
7. ZEUS Coll., J. Breitweg et al.: Phys. Lett. B **443**, 394 (1998)
8. ZEUS Coll., J. Breitweg et al.: Eur. Phys. J. C **4**, 591 (1998)
   ZEUS Coll.: 'Scaling violations in γp interactions at HERA'. Contributed paper to the XXXIst International Conference on High Energy Physics, abstract 843 (Amsterdam, The Netherlands, 2002)
   H1 Coll.: 'Measurement of single inclusive high E_T jet cross-sections in photoproduction at HERA'. Contributed paper to the XXXIst International Conference on High Energy Physics, abstract 1010 (Amsterdam, The Netherlands, 2002)
9. R.P. Feynman: *Photon-Hadron Interactions* (Benjamin, New York 1972)
   K.H. Streng, T.F. Walsh and P.M. Zerwas, Z. Phys. C **2**, 237 (1979)
10. H1 Coll., C. Adloff et al.: Phys. Lett. B **542**, 193 (2002)
11. H1 Coll.: 'Forward Jet production at HERA'. Contributed paper to the XXXIst International Conference on High Energy Physics, abstract 1001 (Amsterdam, The Netherlands, 2002)
12. L. Lönnblad: Comp. Phys. Comm. **71**, 15 (1992)
13. H. Jung: *The RAPGAP Monte Carlo for Deep Inelastic Scattering, version 2.08* (Lund University, 2002)
14. H. Jung and G.P. Salam: Eur. Phys. J. C **19**, 351 (2001)
    H. Jung: Comp. Phys. Comm. **143**, 100 (2001)
15. H1 Coll., C. Adloff et al.: Phys. Lett. B **515**, 17 (2001)
16. ZEUS Coll., S. Chekanov et al.: Phys. Lett. B **547**, 164 (2002)
17. M. Klasen and G. Kramer: Phys. Lett. B **366**, 385 (1996)
    S. Frixione and G. Ridolfi: Nucl. Phys. B **507**, 315 (1997)
    B. Poetter: Comp. Phys. Comm. **133**, 105 (2000)
18. ZEUS Coll., S. Chekanov et al.: DESY Report 02-171 (2002). Submitted to Phys. Lett. B
19. H. Georgi and H.D. Politzer: Phys. Rev. Lett. **40**, 3 (1978)
    J. Cleymans: Phys. Rev. D **18**, 954 (1978)
    G. Köpp, R. Maciejko and P.M. Zerwas: Nucl. Phys. B **144**, 123 (1978)
    A. Méndez: Nucl. Phys. B **145**, 199 (1978)
20. H1 Coll., C. Adloff et al.: Eur. Phys. J. C **19**, 289 (2001)
    ZEUS Coll., J. Breitweg et al.: Phys. Lett. B **507**, 70 (2001)