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# Jet physics at HERA

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## Abstract

Recent results obtained in jet physics in the H1 and ZEUS experiments at HERA are reviewed, including both photoproduction and deep inelastic scattering processes.

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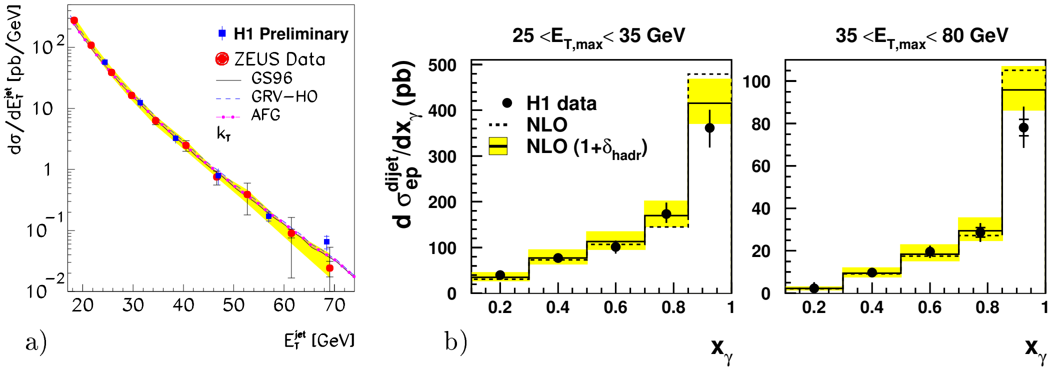


Figure 1. a) Transverse energy $E_T$ of photoproduced jets at HERA; b) $x_\gamma$ distribution of dijet events, where $x_\gamma$ is the fraction of the incoming photon energy given to the dijets.

# 1 INTRODUCTION

The excellent running conditions enjoyed by the H1 and ZEUS experiments during the years 1996-2000 have enabled a wide variety of studies of jet production to be performed. Jets of particles are the observed manifestation of the emission of high-energy quarks and gluons in the underlying parton scattering process. While the basic features of QCD are by now well understood, a variety of theoretical issues can be probed in these studies. These include:

1. the validity of perturbative methods, whether at lowest order (LO), next-to-lowest order (NLO) or higher;

2. the understanding of hadronisation effects, which are non-perturbative;

3. the parton density function (PDF) of the proton and the photon;

4. the relevance of BFKL amplitude evolution, which takes place at fixed values of $Q^2$, compared with the more normal DGLAP evolution at fixed Bjorken $x$, in evaluating the theoretical behaviour of the scattering amplitudes.

# 2 PHOTOPRODUCTION

Photoproduction can be studied at HERA when the exchanged photon in the *ep* collisions has only a small virtuality. When the entire photon takes part in the interaction with a parton in the proton, the process is known as 'direct'; when the photon acts as a source of quarks and gluons, one of which takes part in the parton interaction, the process is known as 'resolved'. Jets been observed in these processes up to high values of transverse energy $E_T$ (Fig. 1a). Good agreement is found with the NLO calculations of Frixione and Ridolfi, using a variety of photon PDFs. Scaling violations in jet photoproduction, giving a direct measurement of NLO QCD processes, have been observed by ZEUS and have been used to evaluate the QCD coupling constant $\alpha_s$. In dijet production (Fig. 1b), direct processes give rise to a peak at $x_\gamma \approx 1$, while lower values are dominated by resolved processes. Both H1 and ZEUS have made extensive measurements here, obtaining substantial but not perfect agreement with NLO QCD using the available photon PDFs.

# 3 DEEP INELASTIC SCATTERING

For most of the accessible kinematics at HERA, the deep inelastic scattering process should be described by perturbative QCD using the DGLAP evolution equations to relate cross sections at different $Q^2$. In the Breit frame the basic current jet is suppressed at high $E_T$ and QCD diagrams dominate (Fig. 2a). Recent results are well described by NLO QCD, over a wide range of $Q^2$, using a value of $\alpha_s$ in agreement with the best world values, and representing an excellent success for perturbative QCD. However jets at forward angles are not guaranteed to be described using this approach. The CASCADE Monte Carlo implements the CCFM theory

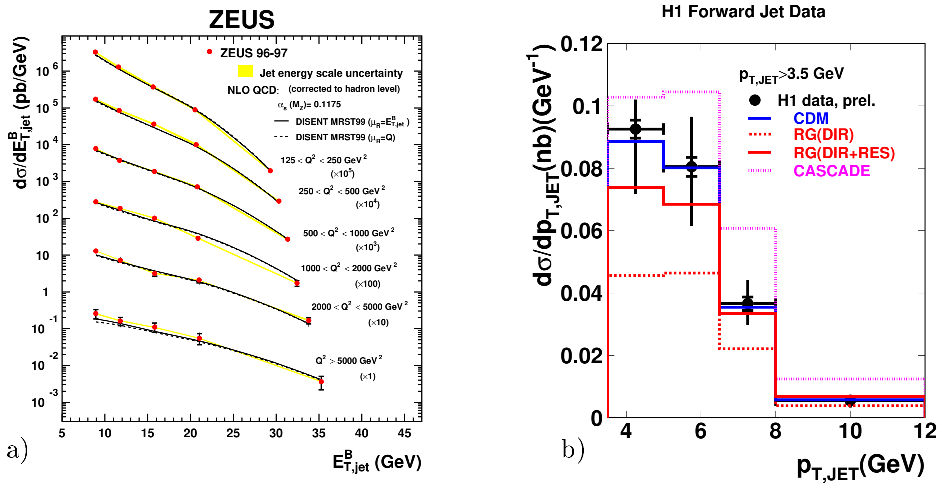


Figure 2. a) $E_T$ of jets in DIS at varying $Q^2$, compared with NLO QCD (DISENT) in the Breit frame; b) $E_T$ of forward jets compared with various models.

which includes BFKL evolution as well as DGLAP evolution. An alternative is the Colour Diple Model (CDM), implemented in the ARIADNE Monte Carlo; a simpler approach is RAPGAP, in which resolved processes can be included. In measurements of forward jets performed by H1, there is no evidence that the BFKL regime has yet been reached. RAPGAP fails without a resolved component, but otherwise CASCADE appears to give an inadequate description, and the CDM model works best.

The QCD coupling constant $\alpha_s$ has been extracted from fits to a number of different jet processes at HERA. Results are summarised in Fig. 3a), where $\alpha_s$ is seen to run as a function of the momentum scale of the process, namely $E_T$ or $Q$, and there is good agreement with the world average.

As $Q^2$ decreases through values around 1 GeV$^2$, a transition the photoproduction region is encountered. H1 have shown that a model based on HERWIG is able to describe the resolved part of the process for $Q^2 > 4.4$ GeV$^2$. However at $Q^2 \approx 1$ Gev$^2$, existing models do not work well (Fig. 3b). ZEUS have recently made first measurements of high energy prompt photons in DIS accompanied by jets (Fig. 4a). The jet distribution is described well by the NLO calculation of Kramer and Spiesberger.

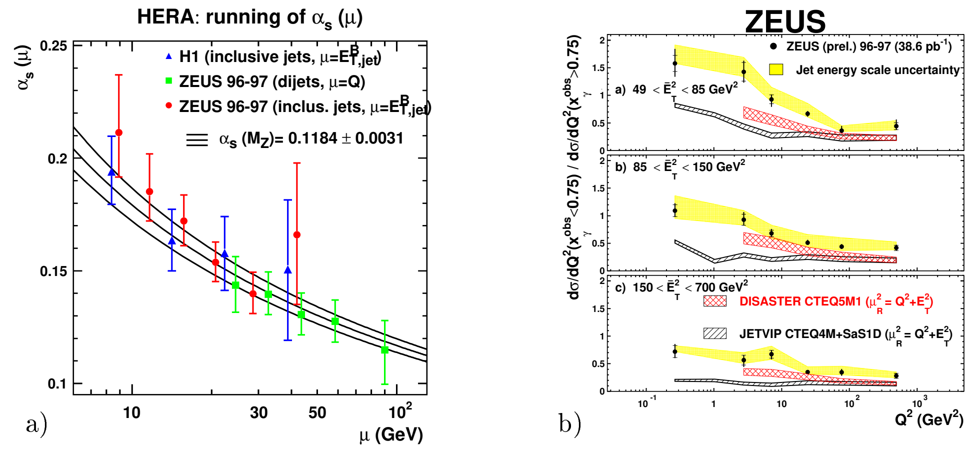


Figure 3. a) QCD coupling $\alpha_s$ from various HERA measurements, running as a function of the appropriate momentum scale in each case; b) 'resolved/direct' ratio as a function of $Q^2$, compared with DISASTER and JETVIP models.

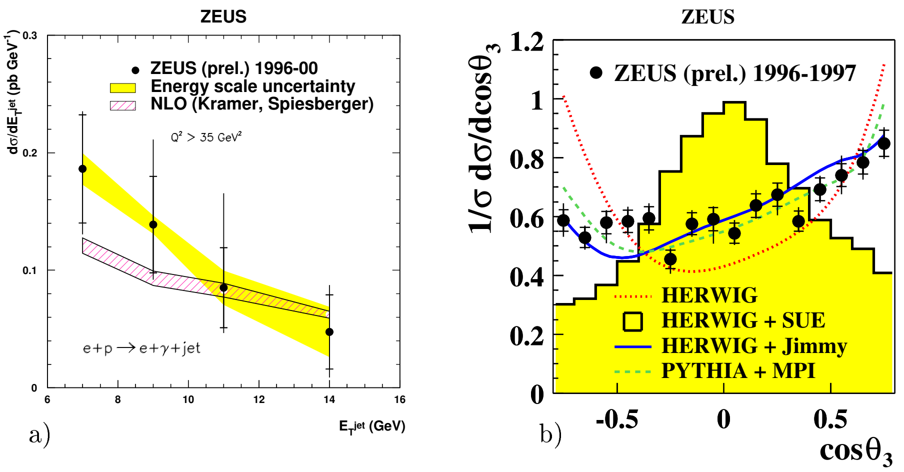


Figure 4. a) Transverse energy $E_T$ of a jet in DIS accompanied by a hard prompt photon; b) normalised plot of highest-energy jet angle in photoproduction, compared with HERWIG (default, soft underlying event model and multiparton interaction model) and PYTHIA (multiparton interaction models).

# 4 MULTIJETS

Studies have been made of the properties of events with more than two jets. Such final states can arise through higher-order QCD processes, but in photoproduction the question also exists whether the hadronic part of the photon-proton collision can give rise to soft underlying event effects or multiple parton interactions. This is expected to apply only at low transverse jet energies, and different models need to be considered. The situation is illustrated in Fig. 4b), using jet $E_T$ values down to 5 GeV,where with both HERWIG and PYTHIA a multiparton interaction model seems to describe the plotted jet angle best. However if cuts are applied to confine the data to high masses of the multijet system, default PYTHIA and HERWIG are found to be adequate. Similarly, H1 have found that the kinematics of a three-jet system in DIS is badly described by phase space, but well described by NLO QCD.

# 5 CONCLUSIONS

QCD has been studied extensively at HERA from many different perspectives by means of events containing final-state jets; further details of these results are available from the experiments' web pages. Over the entire range of processes and kinematics, NLO QCD gives an excellent description of the physics provided that the processes studied are sufficiently hard. The areas which require further study at present are those where perturbative diagrams combine with non-perturbative aspects of the various processes. Nevertheless, the area as a whole may be regarded as a spectactular success for QCD.