Jets in ep and γp Scattering at HERA*

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Recent jet physics results from ep and γp scattering at HERA will be reviewed covering cross-section measurements, the extraction of QCD parameters, the transition region from photoproduction to deep-inelastic scattering and the question of parton evolution in the proton.

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1. Introduction

Over the past few years, great progress has been achieved in the understanding of the hadronic final state and of jet production at HERA. This is, for example, expressed in the extremely good description of jet cross-sections at high values of the photon virtuality, Q^2, or the precise determinations of the strong coupling parameter, α_S, from jet data.

At present, our best knowledge is contained in next-to-leading (NLO) order QCD calculations which rely on collinear factorisation and the use of DGLAP evolution. However, for some observables the NLO precision does not seem to be sufficient - with many measurements now being dominated by theoretical uncertainties higher orders in the perturbative expansion are necessary. In addition, there are areas in jet physics at HERA which have not yet been succesfully addressed with standard approach of DGLAP-based factorisation, for example the question of the parton evolution scheme in forward jet production.

In this contribution, both the successes and the problems of jet physics at HERA will be reviewed, based on the most recent results.

2. Cross-section measurements in photoproduction and DIS

Both the H1 and ZEUS collaborations have used almost all of the HERA-I data sample of more than 80 pb^{-1} for the measurement of inclusive, two-

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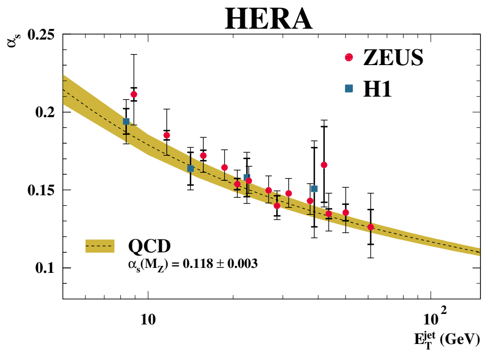

Fig. 1. Summary of HERA measurements of α_S in comparison to the world average (dark band). The running of the strong coupling is clearly demonstrated by the HERA data.

and three-jet cross-sections in the high-Q^2 regime of $Q^2 > 125$ GeV^2 or similar of DIS [1]. The data are corrected to hadron level using leading-order (LO) Monte Carlo (MC) generators and are compared to NLO QCD calculations which have been corrected to the hadron level. The description of the data by the theory is in general excellent; typically the data are described within ± 5 %, providing a handle on α_S and the PDFs.

Also in photoproduction the description of dijet cross-sections which have newly been measured by the H1 collaboration [2] by the NLO theory including resolved photon contributions is very good, making these data a candidate for further constraining the photon PDFs.

3. Extraction of α_S and the proton PDFs

The high quality of the theoretical description of the DIS and photoproduction jet cross-sections make these data ideal candidates for the extraction of the strong coupling parameter, α_S. For this enterprise, the dependence of the NLO cross-section on $\alpha_S(M_Z)$ is parametrized by a quadratic function, $\sigma_i^{theo} = A_i \cdot \alpha_S(M_Z) + B_i \cdot \alpha_S^2(M_Z)$, with the parameters A_i and B_i determined in a fit procedure individually for each observable i. Then, for each observable i, the measured cross-section is mapped onto σ_i^{theo}, leading to a value of $\alpha_S(M_Z)$ for each observable i. The various single values of $\alpha_S(M_Z)$ can then be combined or evolved to the relevant renormalisation scale in order to demonstrate the running of the QCD coupling. Figure 1 [3] summarizes the various determinations of α_S from jet measurements from both H1 and ZEUS. The data are consistent and agree very well with the world average [4] indicated by the brown band, demonstrating the running behaviour of the coupling. The most precise α_S measurements from HERA jets now have errors which are comparable to LEP results. The various HERA measurements have been used in [3] to derive a HERA average which is given as $\alpha_S(M_Z) = 0.1186 \pm 0.0011(\text{exp.}) \pm 0.0050(\text{theo.})$. The value is consistent with the world average, the error is dominated by theory.

Recently, jet measurements [5] in both photoproduction and DIS have been used by the ZEUS collaboration in their global QCD fits in addition to the inclusive structure function measurements with the specific aim of further constraining the gluon density of the proton at high fractional momenta x [6]. This technically challenging endeavour leads to a massive improvement on the gluon PDF around $x = 0.1$. A further benefit of the jet data is the improvement of the α_S determination from the global fit.

4. The transition from photoproduction to DIS

If the squared transverse energy of a parton, E_T^2, is smaller than the photon virtuality Q^2, the parton is able to probe the hadronic substructure of the photon. This effect is maximal for photoproduction and is more and more suppressed for more and more virtual photons in DIS. Figure 2 from a recent ZEUS measurement [7] shows the ratio R of the resolved over the direct contribution to the dijet cross-section over a wide range of photon virtualities from photoproduction to high-Q^2. It can be seen that even at high values of Q^2 of 100 GeV^2 or higher, the resolved component contributes significantly to the cross-section - an effect that is not accounted for by the direct-photon only NLO QCD calculations which are typically employed for DIS analyses. The concept of resolved contributions, on the other hand, works very successfully for the photoproduction regime where the data are well described by the NLO calculation which implements both direct and resolved photon contributions.

In a previous analysis [8] H1 tried to better understand the implications of the resolved photon structure and to evaluate the necessary amount of resolved contributions to the cross-section by studying the triple-differential cross-section $d^3\sigma/dE_T dQ^2 dx_\gamma$. Again, especially for $Q^2 < 10$ GeV^2 the data are undershot by the NLO prediction, even if the calculation incorporates the resolved photon component. In contrast, leading-order MC programs which incorporate parton shower algorithms and both longitudinally and transversely polarised resolved photons describe the data rather well, except for the highest x_γ values. So, in conclusion, there are clear indications for effects beyond direct NLO QCD - parton shower algorithms and resolved photon contributions are necessary to describe the data.

The H1 data have also been compared to the predictions of the CASCADE program which incorporates the CCFM evolution and thus uses an

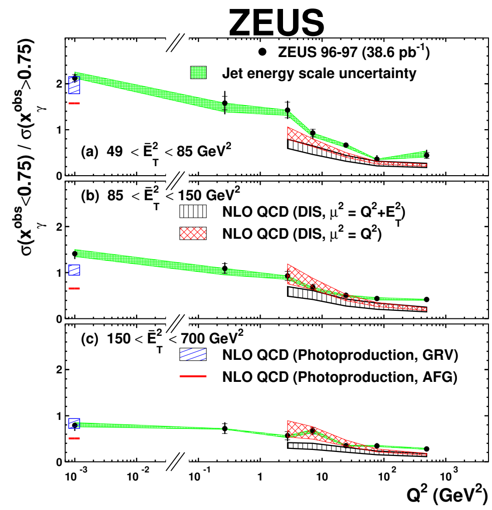

Fig. 2. The ratio of the resolved over the direct dijet cross-section as function of Q^2 in three regions of the mean dijet E_T.

unintegrated gluon density. Especially in the medium Q^2 region between 10 and 25 GeV^2 the data are described by CASCADE; this might be due to the fact that the unintegrated PDFs violate the strict k_T ordering of direct-photon DGLAP-type simulated events in much the same way that the ordering is violated in resolved events.

5. The question of parton evolution scheme

The problem of parton evolution in the proton is addressed by new analyses of forward jet events from both H1 [9] and ZEUS [10]. Figure 3 shows the H1 result which presents the data as function of x_{Bj} and compares them to various models and calculations. For both H1 and the very similar ZEUS result the fixed-order NLO calculation fails to describe the data at low x_{Bj} values; in the case of ZEUS however, who in contrast to H1 use Q^2 as renormalisation scale, the theoretical uncertainties on the predictions are huge. MEPS-type LO MC models also fail, although the inclusion of resolved contributions brings them rather close to the data (see line 'RG+DIR+RES' in figure 3). For the ZEUS result the best description of the data is achieved by the ARIADNE MC which implements the color dipole model and thus has similarity to the BFKL evolution scheme.

H1 has also measured the triple-differential cross-section in x_{Bj}, Q^2 and the transverse forward jet momentum p_T. Using the ratio of p_T^2 and Q^2

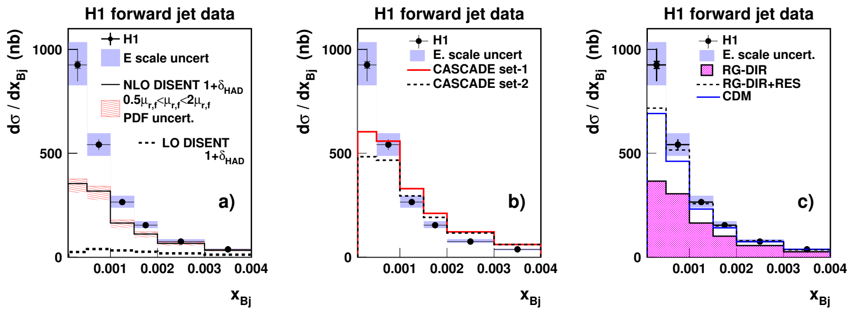

Fig. 3. H1 forward jet data [9], compared to fixed-order NLO calculations (left), to the CCFM model CASCADE (center), and to DGLAP-type LO MC models (right).

one can roughly adjust the type of evolution that is kinematically possible, between DGLAP-resolved dominated ($Q^2 < p_T^2$), DGLAP-direct ($Q^2 > p_T^2$) and BFKL-like ($Q^2 \sim p_T^2$). It turns out that both the CDM and the DGLAP models work rather well in the kinematical areas for which they are considered applicable; programs using the CCFM evolution have problems in correctly describing the shape of the distributions.

The H1 measurement is also the first to show, for a selection of forward jets plus a hard dijet system, a discrepancy in the quality of the data description between the CDM model and a direct+resolved DGLAP-based model, the latter failing to describe the data where the CDM does a good job. This is interpreted as an amount of k_T unordering in the resolved models that is not enough to account for the forward jet features, in contrast to the CDM.

All effects together clearly demonstrate that effects beyond the usual DGLAP-type direct-photon NLO picture are present; this has also been pointed out by a further ZEUS result [11]. The fact that both BFKL-like models (CDM) and models with resolved photon contributions give the best description of the data is indicative for a violation of k_T ordering in the process. However, the success of the resolved models might also be attributed to their partial simulation of higher orders in the perturbative expansion, mimicking parts of a more complete (not yet available) NNLO calculation.

The CASCADE program, which implements the CCFM evolution, does not give a clear message from all above mentioned measurements; in addition it depends strongly on the unintegrated gluon density. There seem to be, however, indications in the H1 result [9] that CCFM is able to describe the data at least in a specially designed (BFKL-like) phase-space.

6. Conclusion and outlook

The overview given so far is clearly not complete, missing, for example, measurements of inter-jet energy flow in photoproduction, the analysis of color dynamics in DIS and photoproduction or the measurement of subjet distributions from ZEUS [12]. However, it should have demonstrated that jet physics at HERA is at the same time a valuable laboratory for precision QCD tests and an exciting place to study open questions concerning, for example, the rôle of resolved photon contributions or the problem of the parton evolution in the proton.

So far, the analysis of HERA-II data has hardly begun, most analyses being restricted to about 80 pb^{-1} or less from the HERA-I period. With already close to 150 pb^{-1} from HERA-II and almost two more years of HERA running ahead, one can clearly expect improvements in statistical precision. But there is clearly hope to also improve both the systematic and the theoretical uncertainties. Since the latter are by now dominating many measurements, theoretical progress is of special importance in this field.

Finally it should be mentioned that the knowlegde gained in jet analyses at HERA is valuable for the physics program of the LHC, as was demonstrated in the HERA-LHC workshop.

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