Jet Production at HERA: Progress and Problems

Marc Weber†

† Institut für Hochenergiephysik, Universtät Heidelberg, Schröderstraße 90, D–69120 Heidelberg, Germany

Abstract. This contribution reviews the measurements related to jet production at HERA which are available in '98. The reasons for the considerable progress achieved in the last years are summarized. The major difficulties and the limitations of these measurements as seen today are discussed.

1. What has been measured ?

One of the many fascinating topics of research at the electron–proton collider HERA is the study of multi–jet events. The application of jet algorithms to characterize the properties of multi–particle hadronic final states turned out to be a powerful and natural approach. Jet algorithms have been used intensively in the analysis of deeply inelastic scattering (DIS) and photoproduction processes.

In leading–order QCD, the cross section of multi–jet events in **DIS** is proportional to the strong coupling constant α_s and the parton density functions of the proton. Several determinations of α_s based on jets have been performed at HERA [1, 2, 3, 4] . There are (preliminary) extractions of the proton's gluon content in NLO [5]. This approach is more direct than determinations of the gluon density from inclusive structure function measurements, and it probes the gluon density at larger momentum fractions ξ. Events with a jet in the very forward (proton) direction of the detectors have been studied in attempts to search for signatures expected when the BFKL parton density evolution equations are valid at HERA [6].

In **photoproduction**, evidence for the partonic structure of the photon has been shown in studies of jet distributions [7]. In events with two reconstructed jets x_γ, the share of the photon's momentum entering the hard scattering process, can be calculated. From the measurement of dijet cross sections differential in x_γ and transverse jet energy, photon parton densities could be constrained, and the p_t dependence of the anomalous component of the real photon predicted by QCD could be confirmed [8]. Jet polar angle distributions for direct and resolved photons where measured to be sensitive to the spin of the corresponding gluon or quark propagators [9]. Also, LO effective parton densities were extracted [8].

Recently, the question of **virtual photon structure** has raised much interest. Evidence for virtual photon structure was found [10]. The structure of virtual photons is investigated as a function of the two scales, photon virtuality Q^2 and transverse jet energy squared in [11]. Again, the analysis in terms of jet related variables proved to be a convenient and natural approach.

2. Open problems and difficulties

The continuously increasing precision of the many results mentioned above was made possible by a variety of factors.

Most importantly, the luminosity provided by HERA was increased considerably reaching $\sim$ 33 pb^{-1} in '97. Also proton and photon parton densities were further constrained. Furthermore, the description of the hadronic final state by Monte Carlo models has much improved. New models like the LDC model or RAPGAP became available, and existing models (e.g. LEPTO) have been developed further. Also, the models' parameters were adjusted to the data [12].

Many analyses were only made possible by the advent of the second generation of the NLO programs MEPJET, DISENT, DISASTER and JETVIP [13]. These programs are able to calculate cross sections for (basically) all infrared safe variables. JETVIP covers DIS *and* photoproduction.

Due to this tremendous development, the limitations of many analyses became clearly visible. In the following part of this talk, I will discuss those limitations which I consider to be the major ones.

Table 1 illustrates the size of systematic errors in a recent determination of the strong coupling constant α_s from (2+1) jet events in DIS [3]. This example is chosen because in DIS at (relatively) high values of photon virtuality Q^2 – here Q^2 exceeds 200 GeV^2 – the hadronic final state is expected to be understood best. Nevertheless the uncertainties of the extracted value of $\alpha_s(M_Z) = 0.118 \pm 0.002\,(stat.)\ ^{+0.007}_{-0.008}\,(syst.)\ ^{+0.007}_{-0.006}\,(theor.)$ are considerable. It is important to note that both the purely experimental errors and the statistical errors are small compared to the *Monte Carlo model dependence*, the choice of parton densities and to the *uncertainties in the NLO calculations.*

2.1. Description of data by Monte Carlo models

Monte Carlo models are crucial to estimate and correct effects of detector acceptance and inefficiency. For comparisons of corrected data with NLO calculations, hadronization corrections are conventionally determined with MC models. The uncertainty of those corrections is estimated from the observed differences between alternative models.

Despite the progress mentioned above, considerable discrepancies between measured data distributions and the predictions of MC models remain in almost any analysis.

Table 1. Uncertainties in the extracted value of $\alpha_s(M_Z)$ compiled from [3] in per cent. Only the most relevant error sources are given.

statistical error	hadronic energy scale	model dependence	parton densities	renormalization scale dependence
+1.7	+2.5	+3.4	+4.2	+5.9
−1.7	−2.5	−5.1	−5.1	−4.2

Many –if not all– of these differences are due to the fact that the proton (and the photon) have structure. This gives rise to initial–state parton showers and to soft underlying events/multiple interactions. Furthermore, there are open questions in the modelling of the hadronization and of diffractive events. Of course, knowledge of the parton density functions also enters the predictions. There are further uncertainties in e.g. matching of the LO matrix elements and the parton showers. Many of these issues are addressed in the framework of the ongoing workshop *Monte Carlo models at HERA*.

2.2. Uncertainty of NLO predictions

Meanwhile various comparisons of experimental data with NLO calculations have been performed. In contrast to the many adjustable parameters of MC models, NLO calculations depend on assumptions for the value of the strong coupling constant, for the parton density functions and on the choice of renormalization and factorization scales only. Difficulties arise, however, due to the observation that the estimated renormalization scale uncertainties (with μ_R^2 set to Q^2) can be large and even be the largest individual error source.

It should also be noted that $O(\alpha_s^2)$ calculations are not expected to describe the data in phase space regions where multi–gluon radiation, as modelled by (initial–state) parton showers, is large. Thus, typically strict jet polar angle cuts are applied to the jets and regions at low parton momentum fraction ξ are avoided.

Thus it seems natural to compare the data with resummed calculations as presented in [14]. Unfortunately, due to the limited acceptance of detectors, in practice jet polar angle cuts are needed. It seems unclear if this makes resummation impossible.

3. Conclusions

In '98 a variety of precise analyses of events with (multi)–jet topologies is available. Many interesting physics issues have been addressed or even answered. Further progress depends critically on improvements of the Monte Carlo description of the data. Several analyses are dominated by uncertainties due to the renormalization scale dependence of NLO calculations. These two sources of error alone limit the precision of tests of the jet data in DIS to not much better than $\sim 10\%$.

While the improvement of the Monte Carlo models is ongoing, it also seems desirable to investigate the possibility of performing dedicated resummed calculations to try and overcome the limitations of NLO predictions.

Acknowledgments

It is a great pleasure to thank the organizers of the 3rd UK Phenomenology Workshop on HERA Physics in Durham for a highly instructive and well organized conference. In particular, I would like to thank the conveners of the *Jets and Fragmentation* working group for creating a lively atmosphere leading to many fruitful and inspiring discussions. This work was supported by the Bundesministerium für Forschung, Wissenschaft und Technologie under contract number 7HD27P.

References

Please note that due to lack of space this list of references corresponds to a rather personal selection and is not complete. I apologize for either only including the most recent results or the results which *in my view* best illustrate the text.

[1] H1 Collaboration, T. Ahmed et *al.*, Phys. Lett. **B346** (1995) 415.
[2] ZEUS Collaboration, M. Derrick et *al.*, Phys. Lett. **B363** (1995) 201.
[3] H1 Collaboration, C. Adloff et *al.*, DESY 98–075, to appear in Eur. Phys. Journal.
[4] H1 Collaboration, C. Adloff et *al.*, DESY 98–087, to appear in Eur. Phys. Journal.
[5] H1 Collaboration, *Measurement of Dijet Cross Sections in Deep-Inelastic Scattering at HERA and a Direct Determination of the Gluon Density in the Proton*, contributed paper to ICHEP98, Vancouver, Canada, July 1998.
[6] ZEUS Collaboration, J. Breitweg et *al.*, DESY 98–050, to appear in the Eur. Phys. Journal; H1 Collaboration, C. Adloff et *al.*, DESY 98–143, submitted to Nucl. Phys. B.
[7] H1 Collaboration, T. Ahmed et *al.*, Phys. Lett. **B297** (1992) 205; ZEUS Collaboration, M. Derrick et *al.*, Phys. Lett. **B297** (1992) 404.
[8] H1 Collaboration, C. Adloff et *al.*, Eur. Phys. J. **C1** (1998) 97.
[9] ZEUS Collaboration, J. Breitweg et *al.*, Eur. Phys. J. **C1** (1998) 109.
[10] H1 Collaboration, C. Adloff et *al.*, Phys. Lett. **B415** (1997) 418.
[11] H1 Collaboration, *Measurement of Dijet Cross–Sections at Low Q^2 and the Exctraction of an Effective Parton Density for the Virtual Photon*, to be submitted to Eur. Phys. Journal.
[12] See N. Brook et *al.*, Proc. of the Workshop '*Future Physics at HERA*', Eds. G. Ingelman, A. de Roeck and R. Klanner, Vol. 1 (1995/96) 614.
[13] E. Mirkes and D. Zeppenfeld, Phys. Lett. **B380** (1996) 205; S. Catani and M.H. Seymour, Nucl. Phys. **B485** (1997) 291; D. Graudenz, hep–ph/9710244; B. Poetter, DESY 98–071.
[14] S. Catani, B.R. Webber, Yu Dokshitser, Nucl. Phys. **B383** 419 (1992).