Hadronisation studies at HERA

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For the H1 and ZEUS collaborations

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Abstract

We discuss a selection of important recent H1 and ZEUS results on hadronic final states in deep-inelastic ep scattering at HERA.

1. Introduction

The unique kinematical reach of the ep collider HERA has enabled studies of deep-inelastic scattering (DIS) at values of Bjorken-x down to $x \sim 10^{-6}$ and (negative) momentum transfers Q^2 up to $\sim$ 30000 GeV^2. Measurements of $F_2(x, Q^2)$ are performed with ever increasing precision, allowing uniquely significant and successful tests of perturbative QCD (pQCD). Our understanding of the multitude of final states produced in these collisions is, however, much less profound. The low-x region, in particular, poses theoretical as well as experimental challenges.

The steep rise of F_2 is compatible with DGLAP evolution [1], when F_2 is fitted at some input scale, and then evolved in Q^2 by summing $\ln Q^2$ terms. At low x an alternative way to describe the evolution might be to sum $\ln(1/x)$ terms, as in the BFKL approach [2], which actually predicts directly the x-dependence of F_2. The CCFM equation [3] attempts to unify the two schemes. The present data on F_2 do not allow to determine unambiguously whether the BFKL mechanism is needed in the x-range covered by HERA. It is natural to expect that an answer to this question might only come from less inclusive studies of the hadronic final states. Some of these are described in the following sections.

Considerable experimental effort is also devoted to further our understanding (within pQCD or otherwise) of the current fragmentation region in DIS where, in Feynman's quark-parton model, particle production is due to the hadronisation of the colour field between a quark and the coloured proton remnant. In this region, conveniently analyzed in the Breit-frame, universal properties of the fragmentation process are looked for through comparison with e^+e^- data. Although no big surprises are to be expected (after all, universality is assumed in all presently successful Monte Carlo models), it has only recently been realized (see ref. [4] though) that the DIS dynamics at low-x, strongly affected by boson-gluon fusion (BGF) processes, leads to a significant (but apparent) breakdown of universality at not too large Q^2. This is borne out by the new ZEUS correlation studies. Their sensitivity to the BGF rate offers as yet unexploited opportunities to study the gluon distribution in the proton.

Not discussed in the written version of this talk is the intriguing—but largely unexplored—message contained in recent H1 and ZEUS data on leading protons and neutrons [5]. These data show interesting similarities with leading baryon production measured in soft hadron-hadron interactions. Particularly striking is the absence, within present accuracy, of any significant x and Q^2 (hence W) dependence of the production rates. This suggests a two-stage space-time picture: after the "fast" and hard interaction of the virtual probe with a parton in the proton, baryons are formed on a much longer time-scale as in soft collisions. It is tempting to speculate that a similar mechanism may occur in diffractive DIS interactions producing rapidity gaps.

2. Forward π^0's

After previous measurements of so-called "forward jets" [6] (see [7] for a recent review), H1 now presents [8] a new measurement of high transverse momentum π^0-mesons in DIS at low Bjorken-x. The measurement extends to small angles w.r.t. the proton remnant (forward region) and down to $x \approx 5{\cdot}10^{-5}$.

The analysis is based on 1996 data. The π^0-mesons are measured using the dominant decay channel $\pi^0 \rightarrow 2\gamma$. The π^0 candidates are selected in the region $5^\circ < \theta_\pi < 25^\circ$, where θ_π is the laboratory polar angle of the produced π^0. Candidates are required to have an energy of $x_\pi = E_\pi / E_{\rm proton} > 0.01$, with $E_{\rm proton}$ the proton beam energy in the lab frame, and a transverse momentum in the hadronic cms (hcms), $p_{T,\pi}$, greater than 2.5 GeV. Some results are shown in Fig. 1 for

$0.1 < y < 0.6$, $2 < Q^2 < 70\ \mathrm{GeV}^2$. The cross sections rise strongly towards small x. Interestingly, this rise is as fast as that of the inclusive *ep* cross section. The ratio of the two (Fig. 2) indeed exhibits no dependence on x.

The DGLAP prediction for pointlike $\gamma^\star p$ scattering only, represented by LEPTO [9], fails dramatically. Whether this is a sign of DGLAP breakdown, or a defect in the Monte Carlo implementation of the (backward) DGLAP evolution, remains to be clarified. Improvement is achieved by considering in addition processes where the virtual photon is resolved. This is implemented in RAPGAP [10]. Whether this mechanism is adequate to describe π^0 cross sections down to the lowest available x cannot as yet be decided due to large sensitivity to scales of this model.

The data are further compared with a calculation following the BFKL formalism in $\mathcal{O}(\alpha_s)$. Fragmentation functions are used to calculate the π^0-meson cross sections from the parton-level predictions [11]. The latter take into account "consistency conditions" as a way to include sub-leading corrections to the BFKL equation. The predictions are in good agreement with the data, except at lowest x (where BFKL effects are supposed to be most important!), the prediction being slightly low. Considering the relatively small uncertainties [11] in this calculation it is, at present, the best available approximation of QCD in the studied region of phase space. The fact that the π^0 cross section grows with about the same rate as the total $\gamma^\star p$ cross section, raises interesting questions as to the true origin of the F_2 rise.

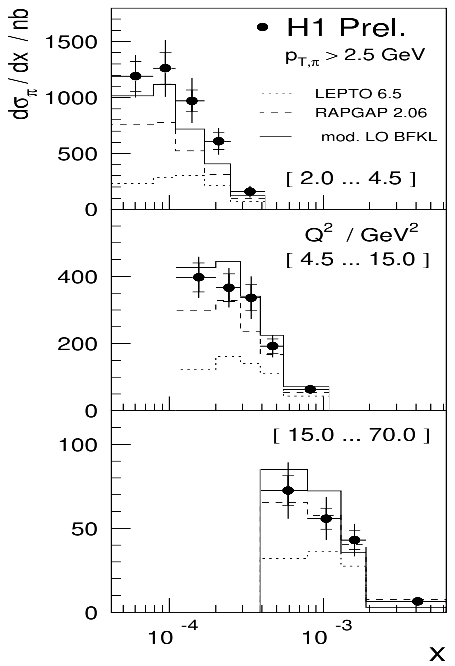

Figure 1. Inclusive π^0-meson cross sections as a function of x for $p_{T,\pi}$(hcms) $>$ 2.5 GeV, $0.1 < y < 0.6$, $5^\circ < \theta_\pi < 25^\circ$ and $x_\pi = E_\pi/E_{\mathrm{proton}} > 0.01$. RAPGAP (dir+res) and LEPTO are compared to the data. The prediction of the modified LO BFKL calculation [11] is also shown.

3. Breit-frame fragmentation studies

3.1. Single inclusive spectra

ZEUS has presented [12] a more detailed study than done previously [13] on charged particle spectra in the current hemisphere of the Breit-frame‡ as a test of quark fragmentation universality and of analytical calculations based on the modified leading log approximation (MLLA) which include coherence [14] and local parton hadron duality (LPHD). The basic assumption here is that the current region in DIS is analogous to a single hemisphere of e^+e^- annihilation.

The moments of the $\xi_p = \ln(1/x_p)$ distributions (hump-back spectra) have been investigated up to the 4th order. The mean, width, skewness and kurtosis were determined by fits of a "distorted Gaussian" to the data over a range of 3 ($Q^2 < 160\,\mathrm{GeV}^2$) or 4 ($Q^2 \geq 160\,\mathrm{GeV}^2$) units in ξ_p around the mean. This form is motivated by the MLLA predictions in ref. [15]. Here $x_p = 2p^{Breit}/Q$, with p the 3-momentum of a hadron in the Breit-frame.

‡ The ZEUS data on the target region are not discussed here.

Figure 3 shows the ξ_p-moments as a function of Q^2. The mean and width increase with increasing Q^2, whereas the skewness and kurtosis decrease. Similar fits performed on e^+e^- data [14] show a reasonable agreement with DIS results, consistent with universality in this observable.

The data are compared to the MLLA predictions of Ref.[16], using a value of $\Lambda = 175$ MeV, for different values of Q_0, the low transverse momentum cut-off. A comparison is also made with the predictions of [15] for the "limiting spectrum" ($Q_0 = \Lambda$). The MLLA predictions of the limiting spectrum [16] describe the mean well. However, both of the MLLA calculations predict a negative skewness which tends towards zero with increasing Q^2 for $Q_0 = \Lambda$, contrary to the measurements. For a range of Λ values, no single value gave a consistent description of all the moments.

ZEUS concludes that the MLLA+LPHD predictions do not describe the data. However, a similar moment analysis presented in [17], and taking into account the limitations of the massless assumptions of the MLLA predictions, finds that the "limiting" MLLA spectrum [16] agrees well with e^+e^- data for $3.0 < \sqrt{s_{ee}} < 133.0$ GeV (see further [14]).

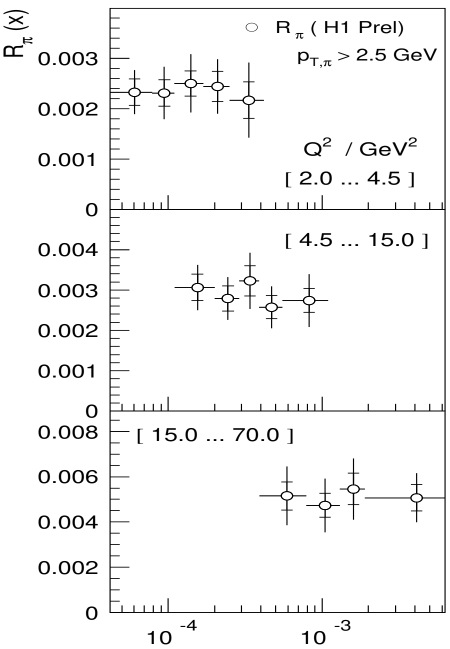

Figure 2. The rate of π^0-meson production in DIS as a function of x obtained by dividing the cross section shown in Fig. 1(a) by the inclusive ep cross-section in each bin of x and Q^2.

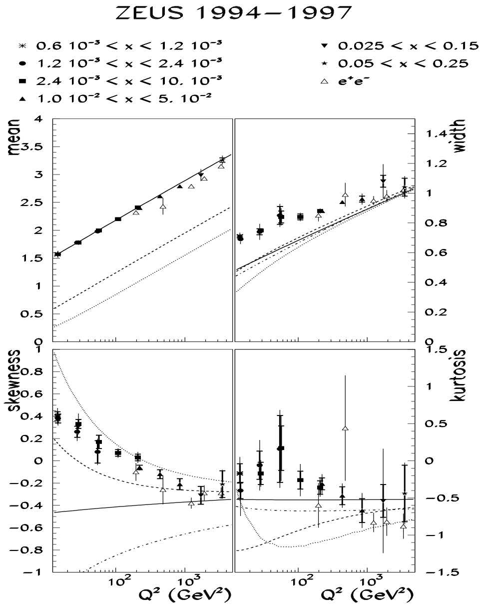

Figure 3. Evolution with Q^2 of the mean, width, skewness and kurtosis of the $\ln(1/x_p)$ distribution in the current fragmentation region. Data from e^+e^- and ep are shown together with the MLLA predictions of Dokshitzer *et al* [16] (full line $Q_0 = \Lambda$; dashed $Q_0 = 2\Lambda$; dotted $Q_0 = 3\Lambda$) and the limiting spectrum predictions of [15] (dash-dotted). The overlapping points are different x ranges in the same Q^2 interval.

3.2. Current-target correlations in the Breit frame

In attempting to verify fragmentation universality using DIS data, it should be realized that any dynamical correlation between the current and target§ hemispheres of the Breit-frame is bound to induce apparent universality violations. ZEUS [18] has studied for the first time such correlations, following [19]. As a measure of the correlation between charged particle multiplicity in the current and target regions, they consider the correlation coefficient κ:

$$\kappa = \sigma_{\rm c}^{-1}\sigma_{\rm t}^{-1}\,{\rm cov}(n_{\rm c}, n_{\rm t}), \tag{1}$$

$${\rm cov}(n_{\rm c}, n_{\rm t}) = \langle n_{\rm c} n_{\rm t}\rangle - \langle n_{\rm c}\rangle\langle n_{\rm t}\rangle, \tag{2}$$

where $\sigma_{\rm c}$ and $\sigma_{\rm t}$ are the standard deviations of the multiplicity distributions in these regions. At parton level, consideration of QCD-Compton (QCDC) and BGF processes allows to derive the relation [19]

$${\rm cov}(n_{\rm c}, n_{\rm t}) \simeq -A_1(Q^2)R_1(Q^2,x) - A_2(Q^2)R_2(Q^2,x), \tag{3}$$

where $A_1(Q^2)$ and $A_2(Q^2)$ are x-independent functions determined by the multiplicity of the outgoing partons. $R_1(Q^2,x)$ is the probability for back-to-back jet events and $R_2(Q^2,x)$ is the probability for an event without jets in the current region. Since $A_1(Q^2)$ and $A_2(Q^2)$ are positive [19], anti-correlations between current and target multiplicities are expected. At small fixed Q^2, ${\rm cov}(n_{\rm c}, n_{\rm t})$ is proportional to the BGF rate, as a function of x, and thus sensitive to the gluon density in the proton [19].

Fig. 4a shows the dependence of κ on Q^2; Fig. 4b that on x. Anti-correlations ($\kappa < 0$) are observed at all x and Q^2. According to eq. (3), this can be due to the $\mathcal{O}(\alpha_s)$ effects (QCDC and BGF). Their kinematics in the Breit frame can reduce the particle multiplicity in the current region and increase it in the target region. The influence from hadronisation is found to be relatively small.

The ZEUS result is totally different from what is seen eg. in e^+e^- annihilation, where small and positive correlations are measured [20, 21, 22, 23]. This fact can also explain differences between H1/ZEUS and e^+e^- data on mean charged multiplicities, the current region of DIS showing smaller mean at low Q^2 [24, 25, 12]. The magnitude of the anti-correlations increases with decreasing $\langle x\rangle$, as expected from the x-dependence of

§ The term "target-hemisphere" is actually quite misleading since only the central and current fragmentation regions in the $\gamma^\star p$ centre-of-mass are experimentally accessible.

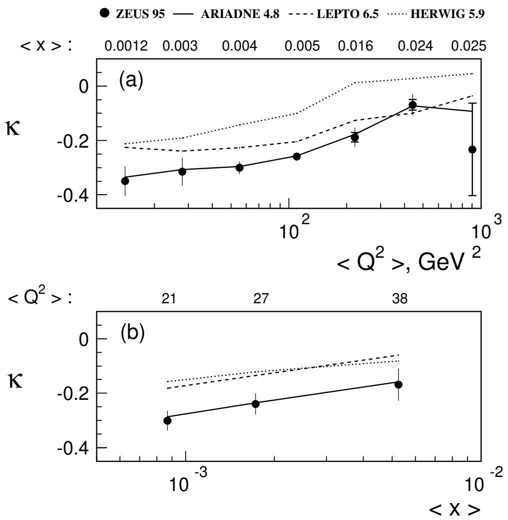

Figure 4. **(a)** shows the evolution of κ with predominant variation in Q^2 for corrected data and Monte Carlo predictions; **(b)** shows the same quantity when predominantly x varies.

the gluon density in the proton. The ARIADNE model agrees well with the data. This model also describes quite well dijet production in DIS [26]. LEPTO and HERWIG [27] do not reproduce the magnitude of the correlations. They also predict a lower dijet rate [26].

First results on two-particle angular correlations, measured in the current region of the Breit-frame, have also been obtained by ZEUS [18] (not shown). This data tests the validity of MLLA+LPHD at the level of 2-particle inclusive spectra. A comparison with DELPHI data reveals also for these observables sizeable differences, most likely related to the differences between the two types of processes already discussed.

References

[1] Yu.L. Dokshitzer, Sov. Phys. JETP 46 (1977) 641; V.N. Gribov, L.N. Lipatov, Sov. J. Nucl. Phys. 15 (1972) 438 and 675; L.N. Lipatov, Sov. J. Nucl. Phys. 20 (1975) 95; G. Altarelli, G. Parisi, Nucl. Phys. B126 (19977) 298.

[2] E.A. Kuraev, L.N. Lipatov, Y.S. Fadin, Sov. Phys. JETP 45 (1977) 199; Y.Y. Balitsky, L.N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 288.

[3] M. Ciafaloni, Nucl. Phys. B296 (1988) 49; S. Catani, F. Fiorani, G. Marchesini, Phys. Lett. B234 (1990) 339, Nucl. Phys. B336 (1990) 18; G. Marchesini, Nucl. Phys. B445 (1995) 49.

[4] K.H. Streng. T.F. Walsh, P.M. Zerwas, Z. Phys. C2 (1979) 237.

[5] H1 Coll., Eur. Phys. J. C6 (1999) 587; ZEUS Coll., Contrib. papers EPS-501 and EPS-538, this conf.

[6] H1 Coll., Nucl. Phys. B538 (1999) 3; ZEUS Coll., Eur. Phys. J. C6 (1999) 239.

[7] B. Potter, `hep-ph/9909320`.

[8] H1 Coll., Phys. Lett. B462 (1999) 440.

[9] G. Ingelman, A. Edin, J. Rathsman, Comp. Phys. Comm. 101 (1997) 108.

[10] H. Jung, Comp. Phys. Comm. 86 (1995) 147.

[11] J. Kwiecinski, A.D. Martin, J.J. Outhwaite, `hep-ph/9903439`.

[12] ZEUS Coll., DESY 99-041 (subm. to Eur. Phys. J. C).

[13] ZEUS Coll., Z.Phys. C67 (1995) 93; H1 Coll., Nucl. Phys. B504 (1997) 3 and B445 (1995) 3.

[14] W. Ochs, `hep-ph/9910319` and refs. therein.

[15] C.P. Fong, B. R. Webber, Phys. Lett. B229 (1989) 289; Nucl. Phys. B355 (1991) 54.

[16] Yu. Dokshitzer, V. Khoze,S. Troyan, Int. J. Mod. Phys. A7 (1992) 1875.

[17] S. Lupia, W. Ochs, Eur. Phys. J. C2 (1998) 307.

[18] ZEUS Coll., DESY-99-063 (in print) ; contrib. paper EPS-542, this conf.

[19] S.V. Chekanov, J. Phys. G25 (1999) 59; `hep-ph/9810477`.

[20] TASSO Coll., M. Althoff et al., Z. Phys. C29 (1985) 347; TASSO Coll., W. Braunschweig et al., Z. Phys. C45 (1989) 193; HRS Coll., M. Derrick et al., Phys. Rev. D34 (1986) 3304; Z. Phys. C35 (1987) 323.

[21] DELPHI Coll., P. Abreu et al., Z. Phys. C50 (1991) 185.

[22] Y. G. Xie (for the ALEPH Coll.,), XXI Int. Symp. on Multiparticle Dynamics, Wuhan, China, 1991, Eds. W. Yuanfong, L. Lianshou, (World Scientific, Singapore, 1992) p.172.

[23] OPAL Coll., R. Akers et al. Phys. Lett. B320 (1994) 417; M. Cuffiani (for the OPAL Coll.,) XXIV Int. Symp. on Multiparticle Dynamics, Vietri sul Mare, Selerno, Italy, 1994, Ed. A. Giovannini et al., (World Scientific, Singapore, 1995) p.37.

[24] H1 Coll., Nucl. Phys. B504 (1997) 3.

[25] ZEUS Coll.,Z. Phys. C67 (1995) 93.

[26] H1 Coll., C. Adloff et al., Eur. Phys. J. C5 (1998) 625; ZEUS Coll., paper No. 806 submitted to ICHEP98, July 1998.

[27] G. Marchesini et al., Comp. Phys. Comm. 67 (1992) 465.