Hadronic final states at HERA

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A selection of recent results on the analysis of hadronic final states in neutral current deep inelastic scattering (DIS) at HERA is presented. These measurements allow to test predictions of perturbative QCD as well as QCD-inspired description of non-perturbative phenomena over a large and unexplored kinematic range.

1. INTRODUCTION

Beyond the measurement of inclusive DIS cross-section in ep collisions at HERA, hadronic final states measurements are an essential tool to check the validity of QCD. Three types of measurements have been chosen here to illustrate the variety of tests which can be made. Asymmetries in the azimuthal angle of production of leading hadrons arise both from non-perturbative and perturbative QCD effects, and can be used to study the relative contribution from these two sources as well as the spin structure of perturbative QCD. Effects of a new regime of QCD dynamics, which could be governed by BFKL[1] instead of DGLAP[2] evolution equations, can be searched for in the measurements of jets or particle cross-sections, especially in the forward region. Finally the hadronization of partons can be studied using event shape variables and compared to recently developed theoretical formalism of power law corrections, where part of the evolution with Q^2 should be computable in perturbative QCD.

2. AZIMUTHAL ASYMMETRIES

In DIS processes, the azimuthal angle ϕ of an outgoing hadron is the angle between two planes: the lepton scattering plane, defined by the incoming and outgoing lepton, and the hadron production plane, defined by the exchanged virtual boson and the given hadron. In the hadronic centre-of-mass frame (HCM), the ϕ distribution of leading particles reflects the angular distribution of outgoing partons. Due to the polarisation of the exchanged virtual boson, the parton production cross-section should depend on ϕ as:

$$d\sigma/d\phi = A + B\cos\phi + C\cos 2\phi$$

A non-zero p_T in the scattering process (measured in the HCM frame) gives rise to azimuthal asymmetries (i.e. B or $C \neq 0$). The non-perturbative asymmetry, which comes from intrinsic k_T of partons in the proton, is expected to decrease with increasing p_T and Q^2. The term C associated to it, in particular, is negligible at high Q^2. The perturbative asymmetry, on the other hand, persists at high Q^2 and p_T, so that a $\cos 2\phi$ term in the high Q^2 region might unambiguously be attributed to perturbative QCD processes. The measurement of the ϕ distribution of leading particles in the HCM frame done by ZEUS[3] is based on $\mathcal{L} = 38$ pb^{-1} of data collected in 1996/1997. DIS events were restricted to the range $0.01 < x < 0.1$, $0.2 < y < 0.8$. Among tracks in the range $|\eta| < 1.75$ (lab), leading particles were selected by the cut $0.2 < z_h = P \cdot p_h / P \cdot q < 1.0$. In Fig. 1a are shown the differential ϕ distributions of charged hadrons for four values of the p_T cut, p_C, since the QCD predictions depend on this variable. The results are obtained by two methods which give similar results: a fit to the theoretical distribution corrected for detector effects (full line with shaded band), and a more traditional bin-by-bin correction. The low p_C distribution is dominated by the $\cos\phi$ term; as p_C increases, a clear $\cos 2\phi$ term appears, which provides the first evidence for a perturbative QCD contribution to the azimuthal asymmetry. In Fig. 1b the $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ terms (i.e. $B/2A$

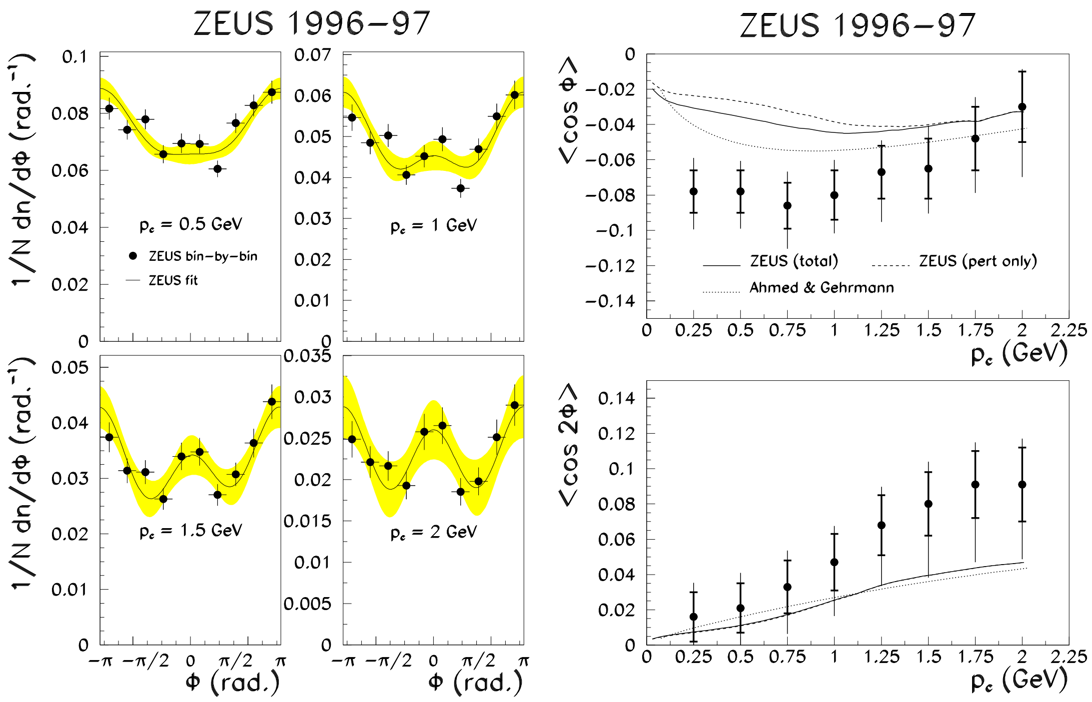

Figure 1. a) ϕ distributions of leading charged hadrons for four values of the p_T cut, p_C b) values of $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ as a function of p_C.

and $C/2A$) are shown as a function of p_C and compared with two LO QCD calculations. The first one, done by ZEUS (based on the calculation of Chay et al.[4]) includes an estimation of the non-perturbative contribution, and integrates over the whole kinematic range. The calculation of Ahmed & Gehrmann[5] is instead purely at leading order in α_s and computed at the mean values $\langle x\rangle = 0.022$ and $\langle Q^2\rangle = 750$ GeV^2 of the data, which explains the difference of the two predictions. The disagreement between data and LO QCD predictions for $\langle\cos\phi\rangle$ at low p_c could result from higher-order (HO) corrections, as indicated by DISENT[6] calculation. HO corrections to $\langle\cos 2\phi\rangle$ term are expected to be much smaller.

3. FORWARD PHYSICS AT LOW Q^2

The HERA collider has opened new regions of phase space where to test QCD. In DIS events with a hard jet of transverse energy $E_{T,jet}$, the relative magnitude of the two scales involved, Q^2 and $E^2_{T,jet}$, allows to distinguish between three kinematic regions: $Q^2 \gg E^2_{T,jet}$, $E^2_{T,jet} \approx Q^2$, and $Q^2 \ll E^2_{T,jet}$. The second region is of particular interest because there, all terms with $\log(Q^2/E^2_{T,jet})$ become small, so that the effects of DGLAP evolution are suppressed, and, instead, the effects of BFKL evolution should show up. However, alternative explanations (as higher-order QCD corrections, or a resolved photon component) to an eventual deviation of the data from calculation using DGLAP might also be considered. Three measurements will be presented here to illustrate the search for evidences of new QCD dynamics.

The inclusive π° production cross-section has been measured by H1[7] in the forward region, i.e. close to the proton remnant, which corresponds to central rapidity in the HCM frame. It is shown in Fig. 2 as a function of Bjorken-x, down to $x \approx 4\cdot 10^{-5}$. Particles were selected with $p^{\star}_{T,\pi} > 3.5$ GeV, $5° < \theta_\pi < 25°$ and $x_\pi = E_\pi/E_{proton} > 0.01$, for DIS events with $0.1 < y < 0.6$ and $2 < Q^2 < 70$ GeV^2 from

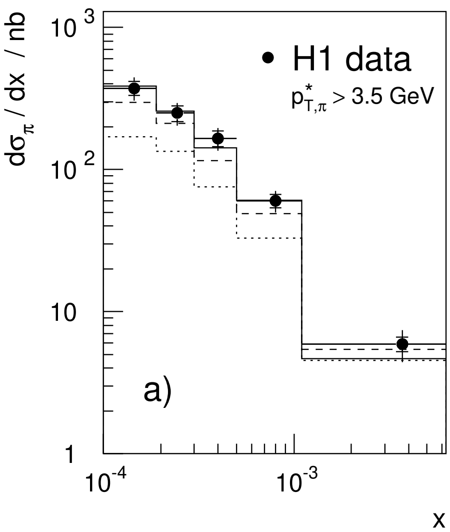

Figure 2. Inclusive π^0 production cross-section measured in the HCM frame as a function of x, compared to various models (see text).

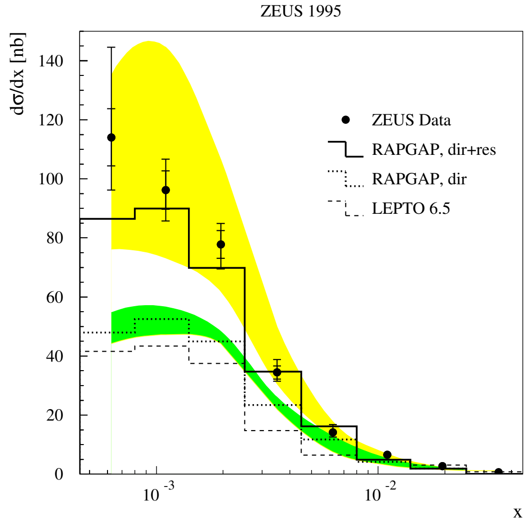

Figure 3. Forward jet cross-section function of x.

$\mathcal{L} = 5.8\ \mathrm{pb}^{-1}$ of data collected in 1996. The data show a strong rise of the cross section with decreasing x, similar to the rise of the inclusive DIS cross section. A standard LO DGLAP Monte-Carlo (LEPTO 6.5[8], dotted line) cannot describe data at low x. Inclusion of processes in which the virtual photon is resolved (RAPGAP 2.06[9], dashed line) improves the agreement with the data, but does not provide a satisfactory description in the full x range. A calculation based on the BFKL formalism[10] (full line) is in good agreement with the data, but the absolute normalization remains strongly affected by the scale uncertainty.

The ZEUS measurement[11] of the x–dependence of the forward jet cross-section is presented in Fig. 3. It is based on DIS events with $Q^2 > 10\ \mathrm{GeV}^2$, $0.1 < y$, from $\mathcal{L} = 6.4\ \mathrm{pb}^{-1}$ of 1995 data. Jets found using the cone algorithm with $R = 1$ were selected by the following cuts: $E_T > 5$ GeV, $\eta < 2.6$, $x_{jet} = E_{jet}/E_p > 0.036$ (lab), $p^Z_{jet} > 0$ (Breit), and corrected to the hadron level. Events were further restricted to the range $0.5 < E^2_{T,jet}/Q^2 < 2.0$ and $4.5{\cdot}10^{-4} < x < 4.5{\cdot}10^{-2}$. The LEPTO prediction is well below the data, whereas RAPGAP gives a good description of the cross section, however with a large uncertainty due to the factorization scale, which diminishes the significance of the agreement.

Finally H1[12] has recently done a measurement of the DIS jet cross-section at low Q^2 similar to ZEUS. A comparison of the data with DISENT NLO prediction, is shown in Fig. 4 as (NLO-Data)/Data as a function of x, for two η regions, ($0.5 < \eta < 1.5$ and $1.5 < \eta < 2.8$). In DIS events with $5 < Q^2 < 100\ \mathrm{GeV}^2$, $0.2 < y < 0.6$, from a sample of $\mathcal{L} = 30\ \mathrm{pb}^{-1}$ of data collected in 1996-1997, jets reconstructed using the inclusive k_T algorithm[13] in the Breit frame were selected by the following cuts: $E_T > 5$ GeV (Breit), $-1 < \eta < 2.8$ (lab). An additional cut $x_{jet} = E_{jet}/E_p > 0.035$ was applied. Data were corrected for detector effects and QED radiation, and compared with NLO calculation using DISENT, with a fixed choice of the factorization scale $\mu_F^2 = Q^2$, but with the renormalization scale μ_R^2 chosen either as E_T^2 or Q^2. When $\mu_R^2 = E_T^2$, the theoretical prediction shows significant deviation from the data in the forward region (right column) at low x, with difference increasing as x decreases. This is the same effect as observed

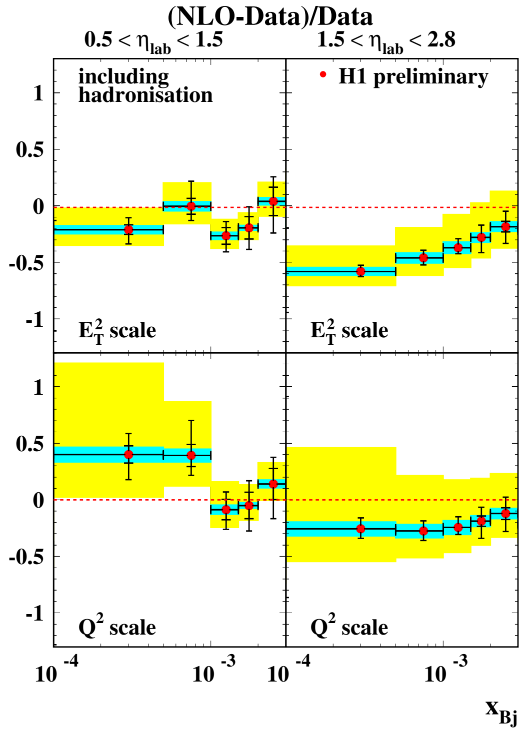

Figure 4. Relative difference (NLO-Data)/Data for the inclusive jet cross-section, function of x.

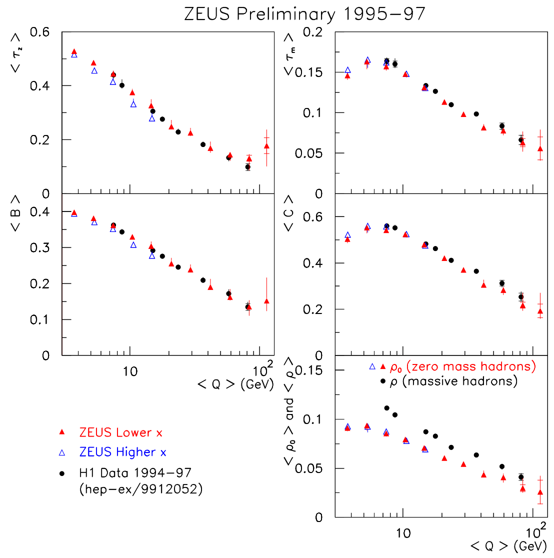

Figure 5. Comparison of ZEUS and H1 mean event-shape variables as a function of Q.

in Fig. 2 for π° production. When $\mu_R^2 = Q^2$, the data are described by the calculation for all values of x within the errors and uncertainties. However, the obtained renormalization scale uncertainties are up to three times as large as for $\mu_R^2 = E_T^2$.

4. EVENT SHAPES

Several infrared-safe event shapes variables can be studied in DIS at HERA: thrust τ and τ_C, jet broadening B, jet mass ρ and C parameter. Analyses rely on the observation of the hard scattered parton, as free as possible from the contamination of the proton remnant. In the simplest quark-parton model, this optimal separation is obtained in the Breit frame, where an incoming quark with momentum $Q/2$ collides head on with the space-like γ with momentum Q. The quark is then back-scattered into the current region, while proton fragments go to the remnant region. Thrust τ and jet broadening B are measured with respect to the Breit frame axis and are therefore specific to DIS; for the other variables, which can also be defined in e^+e^- experiments, the Breit frame permits the event shapes from the DIS spacelike process to be compared directly to their equivalent in the timelike e^+e^- process.

The Q^2 scale at HERA can be varied over four orders of magnitude, allowing a detailed study of event shapes evolution with Q^2. All mean event shapes decrease with increasing Q^2, due to the fact that the energy flow becomes more collimated along the event shape axis as Q^2 increases, a phenomenon also observed in e^+e^- annihilation experiments. This is shown in Fig. 5 where ZEUS results[14] are compared to H1 results[15]. ZEUS analysis is based on DIS events with $Q^2 > 10$ GeV^2 from $\mathcal{L} = 45$ pb^{-1} of data taken in 1995-1997, while H1 analysis makes use of DIS events with $50 < Q^2 < 10000$ GeV^2, from $\mathcal{L}$ =38 pb^{-1} of data taken in 1994-1997. ZEUS and H1 data show reasonable agreement in all variables, except the jet mass, where a different treatment of quark mass prescription accounts for the observed difference in the measurements. ZEUS results are binned in both x and Q, so that in some regions ZEUS has data points that are at similar Q but different x; in contrast H1 integrates over x.

The event shape dependence on Q can be understood in terms of perturbative QCD effects, due to the logarithmic change of the strong coupling constant $\alpha_s(Q) \propto 1/\ln Q$, and non-perturbative hadronization effects, decreasing with some power p of Q. Recent theoretical developments[16] suggest that leading corrections to perturbation theory can be parameterized without any assumptions on the details of the hadronization process, and predict the power p as well as the form and magnitude of the hadronization contributions as a function of a new parameter $\overline{\alpha}_{p-1}$. The scale dependence of any event shape mean $\langle F \rangle$ is written as the sum of two terms: one associated with the perturbative contribution, $\langle F \rangle^{\rm pert}$, which can be calculated from NLO programs such as DISENT, and the other related to the power corrections, $\langle F \rangle^{\rm pow}$, which can be parameterized as:

$$\begin{aligned}\langle F \rangle^{\rm pow} &= 1.61\ a_F \left(\frac{\mu_I}{Q}\right) \Bigg[\overline{\alpha}_0(\mu_I) - \alpha_s(Q) \\ &\quad -1.22 \left(\ln\frac{Q}{\mu_I} + 1.45\right) \alpha_s^2(Q)\Bigg]\end{aligned}$$

where a_F is a calculable coefficient depending on the observable F, μ_I is an infrared matching scale ($\mu_I = 2$ GeV), and $\overline{\alpha}_0$ is an universal, non-perturbative effective strong coupling below μ_I.

Results of two-parametric fits for each mean event shape, using this ansatz, are shown in Fig. 6 (H1) and Fig. 7 (ZEUS). The fits for different event shape variables yield a common value for the non-perturbative parameter $\overline{\alpha}_0 \simeq 0.5$ within 20%, supporting the notion of universal power corrections. However the spread of the strong coupling constant appears to be uncomfortably large and incompatible with the experimental uncertainties. A group of higher $\alpha_s(M_Z)$ values for those variables which do not make use of the boson axis can also be observed Possible explanations are missing higher order QCD corrections, expected to be different for each event shape variable, and/or incomplete knowledge of the power correction coefficients.

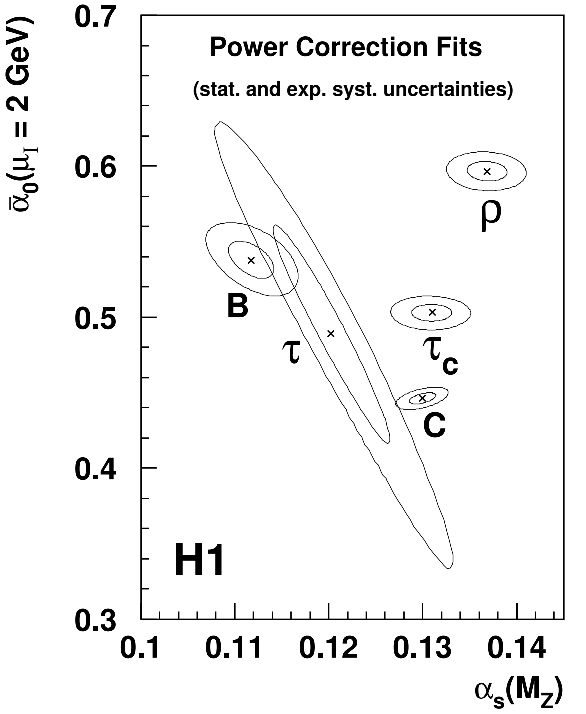

Figure 6. Contours showing H1 fitted values of $\overline{\alpha}_0(\mu_I)$ and $\alpha_s(M_Z)$

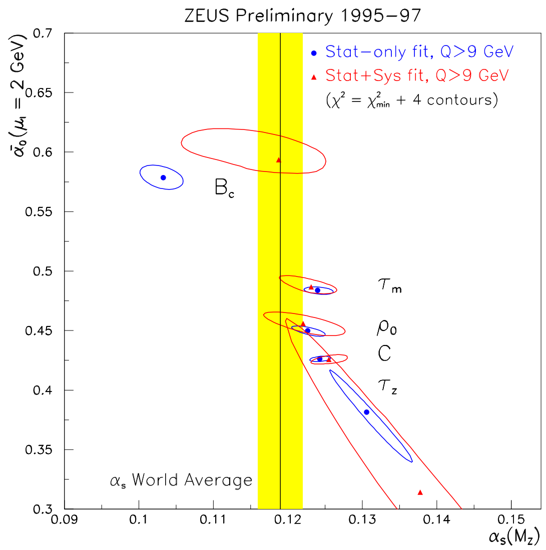

Figure 7. Contours showing ZEUS fitted values of $\overline{\alpha}_0(\mu_I)$ and $\alpha_s(M_Z)$

5. SUMMARY

Hadronic final states measurements at HERA have favoured great progress in the understanding of QCD dynamics, and largely extended the domain of validity of perturbative QCD calculations. Azimuthal asymmetries show general agreement with QCD predictions. The first measurement of $\langle \cos 2\phi \rangle$ provides a clear confirmation for a perturbative QCD effect predicted by theory. But if LO predictions qualitatively describe data, NLO calculations are probably still needed before a quantitative agreement can be reached. Concerning forward and particle jets measurements, data show significant deviations from standard NLO calculations, which use DGLAP evolution equations and take into account the direct component of the photon alone. Since several alternative modifications to this standard scheme (resolved photon, BFKL dynamics, choice of scale) give a better description of the data, however all with large uncertainties, an unambiguous interpretation of the present results will probably have to wait until higher order calculations based on the DGLAP equations, BFKL–type calculations and also a consistent treatment of resolved photon processes will be available. Finally event shapes measurements also show a general agreement with power corrections scheme, and support the concept of a universal $\overline{\alpha}_0 = 0.5 \pm 20\%$. However the spread in $\alpha_s(M_Z)$ exceeds what is allowed by experimental uncertainties. There also, further theoretical progress is needed in order to achieve a better common description of the different event shapes and to get a more coherent picture.

Acknowledgements

I wish to thank S. Narison and the organizing commitee for this fruitful meeting. I would also like to thank B. Foster, P. Schleper, and J. Terron for their help in preparing the presentation.

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