STATUS AND PROSPECTS OF LOW x PHYSICS AT HERA*

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The status and future prospects of low x physics at HERA are presented.

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1. Introduction

One of the prominent early experimental results of HERA was the observation [1, 2] of a rapid rise of the structure function F_2 towards small x as depicted *e.g.* in Fig. 1. The rise is observed for $Q^2 > 1\,\mathrm{GeV}^2$ and accelerated for large momentum transfers Q^2. The rise persists for Q^2-values below 1 GeV^2 until the transition to photoproduction sets in. The low x limit is governed by large parton densities in a region where perturbative QCD (pQCD) is still deemed to be applicable ($Q^2 > \Lambda^2$). It is thus a particular interesting testing ground for the dynamics of QCD when more than one parton is involved. The high density of partons suggests to search for saturation effects. The low x limit is also important since $W^2 \approx Q^2(1-x)/x$ so that low x typically involves large energies W.

Below $1\,\mathrm{GeV}^2$ the cross section for the exchange of (quasi-)real photons, $Q^2 \approx 0$ is often described by vector meson exchange models, *i.e.* genuine hadronic processes.

2. Structure functions and gluon distribution

The measurement of the structure function F_2 constitutes to date the most precise map of the structure of the proton [3, 4] as shown in Fig. 1. The F_2-structure has been explored to the largest Q^2 and the smallest x, where $x = Q^2/(ys)$. The rise of the structure function towards low x is

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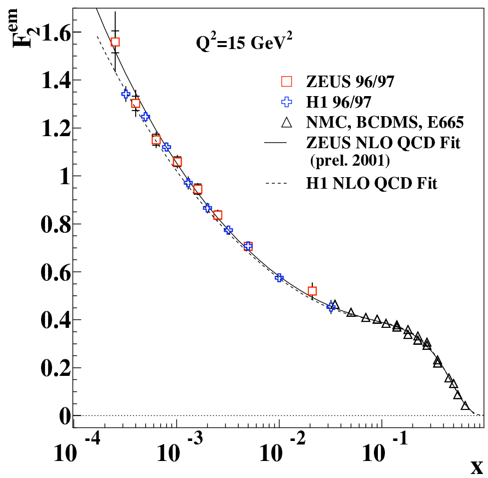

Fig. 1. The structure function F_2 measured at $Q^2 = 15$ GeV^2 at HERA and in fixed target experiments.

associated with the high density of gluons which dominate the production of sea quarks probed through the prevalent splitting process $g \to gg$ and subsequently $g \to q\bar{q}$. In the perturbative regime the structure functions are associated with parton densities, typically assumed to be described by terms $\propto x^b(1-x)^c$ with further corrections neglected here for simplicity. For small x (below 0.01) the dominant contribution for gluons is $xg(x,Q^2) \propto x^{b_g}$ with an exponent determined by experiment.

For small x the rate of generation of gluons is thus intimately related to the size of the strong coupling strength $\alpha_{\rm s}$. Attempts to determine the gluon density are thus correlated [3] with the measurement of the coupling strength as seen in Fig. 2. At the LHC even smaller x values will contribute significantly to the measured QCD cross sections and a precise knowledge of the gluon dependence is thus mandatory. The density–coupling strength correlations will be reduced once, in the same experiment, precision high x data become available, *i.e.* data from a region where the contribution of valence quarks decouples the two components. The measurement of the high x domain is one of the goals of the experimental programme at HERA II presently underway.

To date most perturbative descriptions of the partonic structure of the proton have been made using NLO calculations. NNLO calculations are becoming available [5, 6] and will thus improve the understanding of the structure of the proton together with forthcoming data from HERA II.

A major step forward will be made when precision data for the structure function $F_{\rm L} = 2F_2 - xF_1$ become available. $F_{\rm L}$ vanishes in the parton model and thus arises from the perturbative introduction of gluons. A measure-

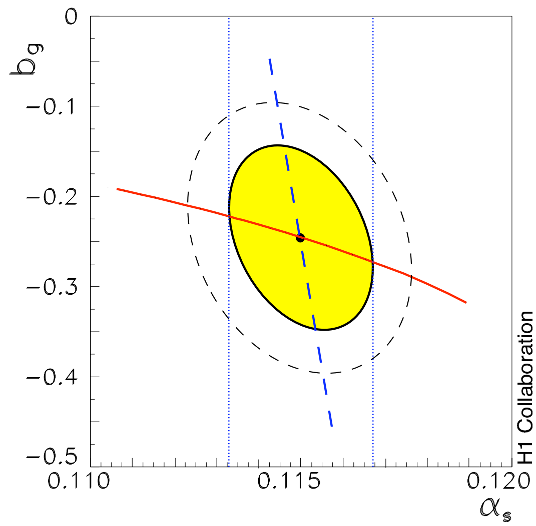

Fig. 2. Uncertainty of Gluon extraction. The vertical axis denotes the value of the coefficient b_g in the relation $xg(x, Q^2) \propto x^{b_g}$. Gluon distribution and strong coupling constant are thus correlated.

ment of F_{L} free of assumptions on the low x-extrapolation of F_2 necessitates measurements at various centre of mass energies and thus a variation of beam energies. With proton energies between 400 GeV and 920 GeV a 5-10% measurement of F_{L} is attainable. This precision is sufficient to shed light on the uncertainty presently existing in the behaviour of F_{L} where differences of up to 50% are seen depending on the details of the assumption (and calculation) [5].

3. The low x transition

It has been noted, *e.g.* in [7], that the low x behaviour of F_2 can be conveniently described by an ansatz $F_2 = c(Q^2)x^{-\lambda(Q^2)}$ for $x < 0.1$. In this region $c(Q^2)$ does not exhibit any significant Q^2 dependence, within the present experimental accuracy and λ is a function linearly rising with $\ln Q^2$. The simplicity of this ansatz only breaks down for $Q^2 < 1\,\mathrm{GeV}^2$. Unfortunately the present data in this region are not sufficiently precise to map the transition in all detail (Fig. 3). Pictorially speaking the transverse dimension of the probing virtual photon equals the size of the proton and it would thus be of interest to understand the details of the transition at this particularly high sensitivity.

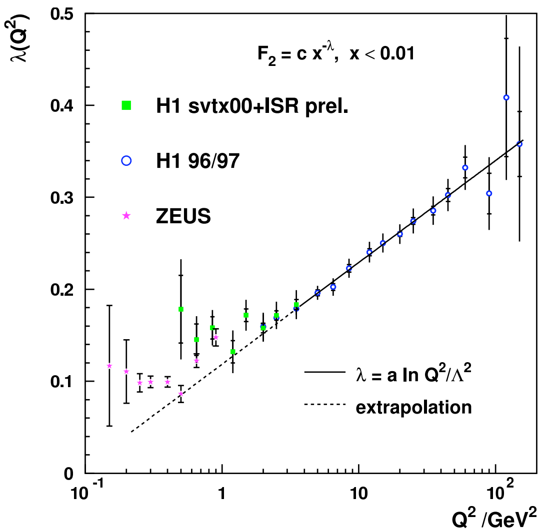

Fig. 3. The exponent λ of the parametrisation $F_2 = cx^{-\lambda}$ shown as a function of Q^2 as extracted from a measurement of the H1 and ZEUS data.

The dipole model describes the scattering of the virtual photon on the proton by a $\gamma \to q\bar{q}$ splitting long before the interaction with the proton, Fig. 4. Two characteristic time scales can be compared: the dipole formation $\propto 1/(xm_p)$ and the time to traverse the proton. For small x the interaction between the photon and the proton becomes a scattering of a single quark off a proton.

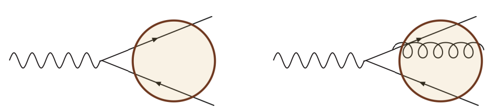

Fig. 4. The dipole formation $\gamma \to q\bar{q}$ proceeds well before the interaction of the quarks(s) with the proton. The emission of gluons from the propagation quarks (gluon evolution) improves the description of the data at high Q^2.

This picture, in a particular implementation [8], proves to be surprisingly successful and is able to describe a large variety of measurements as long as the size of the dipole varies with Q^2. With a determination of the model parameters in deep inelastic scattering both the photoproduction limit and transition to diffractive processes can be calculated. An extension of this model that includes the evolution of the gluon modifies the Q^2 dependence of the cross section [9] and leads to a significantly better description of the DIS data (Fig. 5). The dipole ansatz can be motivated using the Balitsky–Kovchegov non-linear evolution equations [10, 11].

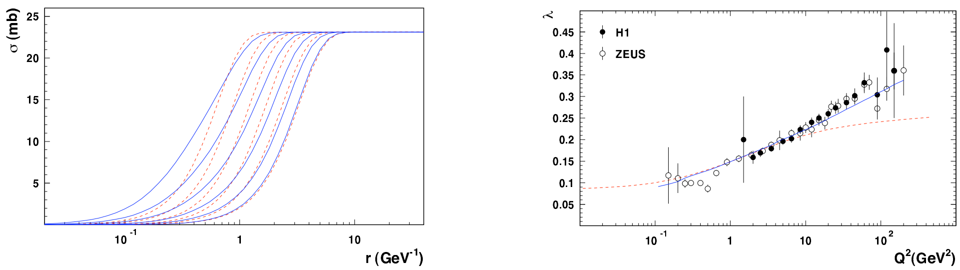

Fig. 5. The variation of the cross section as a function of the dipole size for various Q^2. The dashed line shows the behaviour of the cross section when gluon evolution is neglected. The high Q^2 behaviour of the cross section is significantly better described when the gluon is evolved (from Ref. [9]).

4. Forward production at HERA

Partons in the forward, *i.e.* proton, direction at HERA are of particular interest for tests of the low x evolution of QCD. They are generated in a region of phase space that is large enough to develop further characteristics that can be tagged experimentally (Fig. 6). Such cross sections have been measured (Fig. 6) using forward going π^0 which are indicative of forward parton production in conjunction with a hard scattering process.

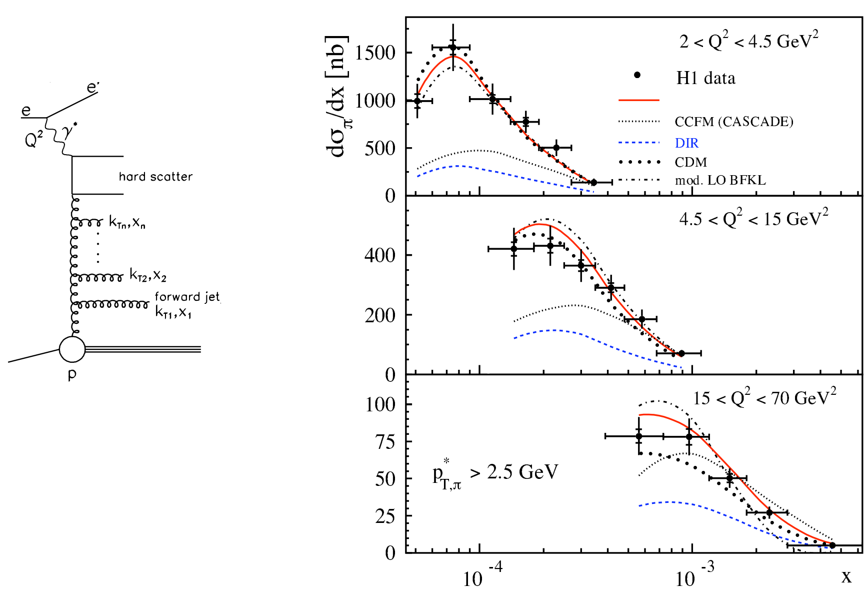

Fig. 6. The π^0 cross section and comparison to model assumptions for various Q^2 at HERA. The gluon-ladder indicates the emission of π^0s used to tag the jets.

The data have been compared to several calculations: while a calculation based on the plain DGLAP evolution falls short of describing the data both the CASCADE simulation and a simulation that includes resolved contributions from the photon vertex describe the data as does the CDM simulation. CASCADE implements un-integrated gluon distributions while the CDM simulation uses a colour dipole ansatz.

5. Future

Low x measurements have been in the focus of HERA QCD studies from the start and continue to be there at least until the F_{L} have been accomplished. An in-depth exploration of further facets of the low x transition would require a changed experimental set up and a modified interaction region that makes possible the exploration of the extreme forward and backward scattering regions. Two proposal have been elaborated: one based on the existing H1 detector and a new detector with emphasis on small angle scattering (Fig. 7). Both proposals [12,13] go beyond what has been sketched here and require an extended experimentation programme [14] reaching well beyond what is planned for HERA II.

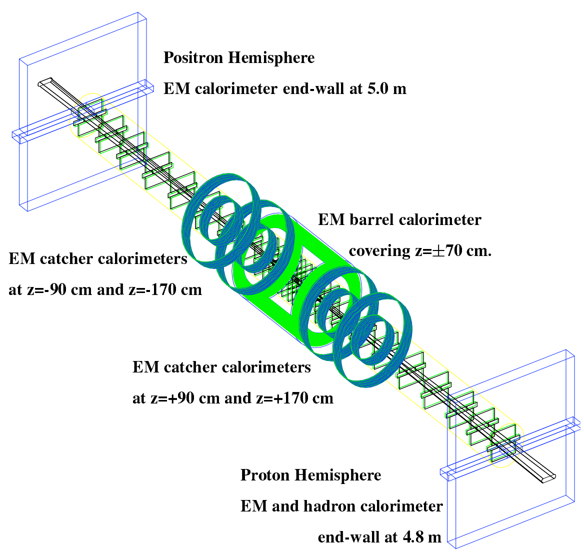

Fig. 7. Sketch of a dedicated new low x experiment at HERA (from Ref. [13]) with the components within approximately ± 6 m of the interaction point.

6. Conclusion

The proton constitutes *the* prime laboratory for QCD when succinctly probed with a well defined lepton. Today we have come a long way in understanding the basic properties of the structure. Yet the role of the gluon is still largely mysterious. New input will become available with the measurement of the structure function F_{L} at HERA and foreseeable progress in higher order calculations.

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