Observation of Deep Inelastic ep Scattering with a Leading Proton

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Abstract. The H1 detector at HERA, upgraded with a forward proton spectrometer, has been used to measure the cross section for deep inelastic scattering in the kinematic range $2.6\,\mathrm{GeV}^2 \leq \mathrm{Q}^2 \leq 28.6\,\mathrm{GeV}^2$ and $10^{-3} \leq x \leq 10^{-2}$ with a leading proton in the energy range $580\,\mathrm{GeV} \leq \mathrm{E}'_\mathrm{p} \leq 740\,\mathrm{GeV}$. This class of events is described by a structure function $F_2^{LP\,(3)}$ very similar to the one for diffractive ep scattering. The shape of $F_2^{LP\,(3)}$ is well described by models based on meson exchange.

In 1995, H1 installed a forward proton spectrometer (FPS) to detect leading protons with energies between 500 and 760 GeV and scattering angles below 1 mrad. The FPS has been used to measure the cross section for the process $ep \to e'p'X$, where the scattered proton has an transverse momentum $p_\perp < 200\,\mathrm{MeV}$, in the deep–inelastic (DIS) regime. This cross section is parametrized by a structure function $F_2^{LP\,(3)}$ in analogy to the diffractive structure function $F_2^{D\,(3)}$ [1–3].

The present analysis uses the kinematic variables x, Q^2, and ξ or equivalently β, Q^2, and ξ that have been introduced for describing rapidity gap events. They are defined as follows:

$$Q^2 = -q^2 \qquad x = \frac{Q^2}{2P \cdot q} \qquad \xi = \frac{q \cdot (P - P')}{q \cdot P} \qquad \beta = \frac{Q^2}{2q \cdot (P - P')} = \frac{x}{\xi}.$$

Here q, P and P' are the 4-momenta of the virtual boson, the incident and the final state proton respectively. ξ may be interpreted as the fraction $x_{\pi/p}$ of the proton's four momentum carried by the exchanged object (here denoted as π), and β as the four momentum fraction $x_{q/\pi}$ of the π carried by the struck quark. The definition of ξ in terms of four–vectors is identical to that of the quantity $x_{\mathbb{P}}$ used in the diffractive analysis for events where the proton stays

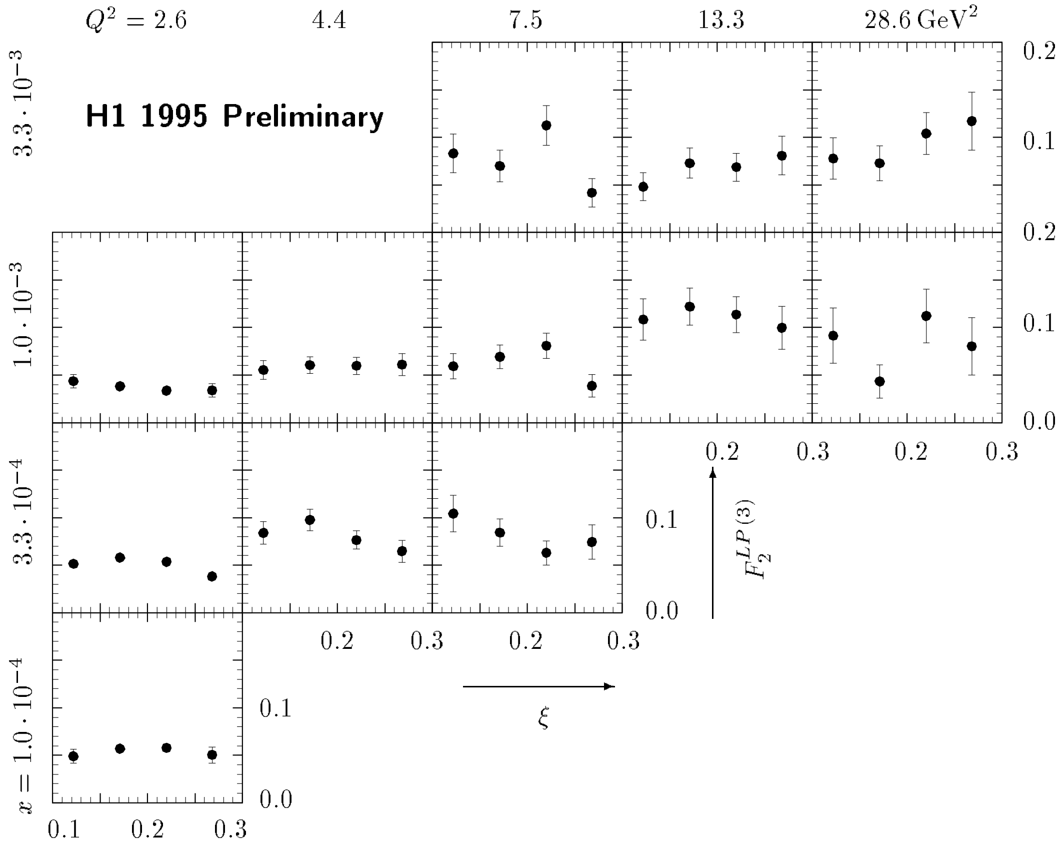

FIGURE 1. $F_2^{LP\,(2)}\,(x,\,Q^2,\,\xi)$ in bins of x and Q^2 as function of ξ.

intact. It is measured by the FPS via the relation $\xi = 1 - E'_p/E_p$, where E_p and E'_p are the energy of the beam and the scatterd proton.

The structure function $F_2^{LP\,(3)}$ for processes with a leading proton of transverse momentum $p_\perp < 200\,\mathrm{MeV}$ is defined as:

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}\xi} = \frac{4\pi\alpha^2}{x\,Q^4}\left(1 - y + \frac{y^2}{2}\right) F_2^{LP\,(3)}(x,\,Q^2,\,\xi),$$

where y is given by $y = Q^2/xs$, with s being the ep collision centre of mass energy squared.

The structure function $F_2^{LP\,(3)}$ was measured with data taken with the H1 detector [4,5] and the H1 FPS in 1995, when HERA operated with 27.5 GeV positrons and 820 GeV protons. The integrated luminosity was $L = 1.44\,\mathrm{pb}^{-1}$. The efficiency corrections were performed using the Monte Carlo generator RAPGAP [6] implementing a pion–exchange model and using the GRV–LO pion parton densities [7]. LEPTO 6.5 [8], a program implementing DIS with soft color interactions in the final state, was used as a cross-check. The measurement has been carried out in 12 $(x,\,Q^2)$–bins in the range $6\cdot10^{-5} < x < 6\cdot10^{-3}$ and $2\,\mathrm{GeV}^2 < \mathrm{Q}^2 < 50\,\mathrm{GeV}^2$, and 4 bins of ξ in the range $0.098 < \xi < 0.244$, corresponding to a β range of $2.5 \cdot 10^{-4} < \beta < 6 \cdot 10^{-2}$. The result of the measurement is shown in figure 1.

The data shows a weak ξ dependence, as expected for pion exchange. It also shows a logarithmic rise of $F_2^{LP\,(3)}$ with Q^2 and a tendency to rise with falling x. Both features are reproduced by the pion exchange model, but the overall normalization is too low by a factor of about 2. This could be due to contributions from additional Regge trajectories, or to an underestimate of the sea quark content in the pion parton densities. The LEPTO model describes the cross section in the lowest Q^2 bin, but fails to reproduce the rise of $F_2^{LP\,(3)}$ with Q^2. The ξ spectrum is in broad agreement with the data.

A key feature of pion exchange models is a factorization of the form

$$F_2^{LP\,(3)}(\beta,\, Q^2,\, \xi) = f_{\pi/p}(\xi) \cdot F_2^{\pi}(\beta,\, Q^2),$$

where $f_{\pi/p}(\xi)$ is the pion flux integrated over the appropriate t range and F_2^{π} is the pion structure function. To test this hypothesis independently of assumptions about the pion flux, to which contributions from other meson exchanges may have to be added, and about the pion structure, which has only been measured for $\beta > 0.2$, a fit of the data was performed to the form

$$F_2^{LP\,(3)}(\beta,\, Q^2,\, \xi) = r(\xi) \cdot (a \cdot \beta^b + c \cdot \beta^d \cdot \log Q^2), \tag{1}$$

with free parameters a, b, c, and d. The flux $r(\xi)$ was normalized at $\xi = 0.171$ to be 1, and fitted for the other three ξ bins, introducing three additional degrees of freedom. The χ^2/df of this fit is 52.9/41, corresponding to a confidence level of 10 % for the factorization hypothesis with this parametrization.

In models not based on the exchange of an intermediate object the meaning of β is not clear, and one might expect a factorization—if any—in terms of the variables x, Q^2, and ξ, if the behavior of the proton remnant is essentially independent of what happens in the current fragmentation region. To test this hypothesis, a fit of $F_2^{LP\,(3)}(x,\, Q^2,\, \xi)$ to the functional form (1) was performed, where β was replaced by x. The resulting $\chi^2/df = 53.1/41$ is similar to that for a factorization in β, Q^2, and ξ, so one cannot distinguish between these two hypotheses with the present precision of the data.

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