FIRST MEASUREMENT OF THE DEEP–INELASTIC STRUCTURE OF PROTON DIFFRACTION

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ABSTRACT

A measurement is presented, using data taken with the H1 detector at HERA, of the contribution of diffractive interactions to deep–inelastic electron–proton (ep) scattering in the kinematic range $8.5\,\mathrm{GeV}^2 < Q^2 < 50\,\mathrm{GeV}^2$, $2.4 \cdot 10^{-4} < x < 7.5 \cdot 10^{-2}$. The diffractive contribution $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ to the proton structure function $F_2(x, Q^2)$ is evaluated as a function of the appropriate deep–inelastic scattering variables $x_{I\!P}$, Q^2, and β $(= \frac{x}{x_{I\!P}})$ using a class of deep-inelastic ep scattering events with no hadronic energy flow in an interval of pseudo-rapidity adjacent to the proton remnant direction. The dependence of $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ on $x_{I\!P}$ is measured to be $x_{I\!P}^{-n}$ with $n = 1.19 \pm 0.06(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})$ independent of β and Q^2, which is consistent with a factorisable diffractive interpretation. A first measurement of the deep–inelastic structure of the pomeron in the form of the Q^2 and β dependences of the factorised structure function $\tilde{F}_2^D$ is presented. For all measured β, $\tilde{F}_2^D(\beta, Q^2)$ is observed to be consistent with scale invariance.

1. Introduction

In recent measurements of deep–inelastic electron–proton (ep) scattering (DIS) at HERA a class of events has been observed with no hadronic energy flow between the direction of the outgoing proton and the hadronic system measured in the detector[1, 2]. This observation can be explained by the exchange of a colourless object between the proton and the virtual photon, which is then probed in the scattering process. Monte Carlo programs[3, 4] based on the assumption that these so–called rapidity–gap events are of diffractive origin and that the object probed in DIS is a pomeron were reported to reproduce the gross features of this class of events well[2, 5, 6].

In this paper we present a measurement of the triple–differential cross section $\frac{\mathrm{d}^3\sigma^D(ep \to epX)}{\mathrm{d}\beta\,\mathrm{d}Q^2\,\mathrm{d}x_{I\!P}}$, where β can be interpreted as the momentum fraction of the struck parton out of the colourless object (called pomeron henceforth for simplicity), Q^2 is the virtuality of the exchanged photon, $x_{I\!P}$ is the fraction of the proton's momentum carried by the pomeron, and t its virtuality. These quantities are defined as follows:

$$\beta = \frac{Q^2}{2q \cdot (P - P')} \qquad Q^2 = -q^2 \qquad x_{I\!P} = \frac{q \cdot (P - P')}{q \cdot P} \qquad t = (P - P')^2, \quad (1)$$

where q, P and P' denote the 4–momenta of the exchanged photon, the incident proton and the final state colourless remnant respectively. The Bjorken scaling variable $x = Q^2/(2q \cdot P)$ is equal to $\beta \cdot x_{\mathbb{P}}$. This cross section, which includes events where the proton dissociates, is related to a "diffractive structure function" $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$ by

$$\frac{\mathrm{d}^3\sigma^D_{ep\to epX}}{\mathrm{d}\beta\,\mathrm{d}Q^2\,\mathrm{d}x_{\mathbb{P}}} = \frac{4\pi\alpha}{\beta Q^4}\left[1 - y + \frac{y^2}{2(1+R)}\right] F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}}), \tag{2}$$

where y is the scaling variable given by $y = Q^2/(xs)$, and R denotes the ratio of the cross sections for longitudinally and transversely polarized photons. In this measurement R is taken to be 0, but since y is less than 0.43 for the present data sample, $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$ increases by at most 17% for $R \to \infty$.

Having measured $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$, we proceed to show that this function can be factorised into the product of a flux term proportional to $x_{\mathbb{P}}^{-n}$, and a function of β and Q^2 only. This behaviour is expected if the observed events are due to electron scattering off a pomeron that is emitted with a certain flux factor. We integrate $F_2^{D(3)}(\beta, Q^2, x_{\mathbb{P}})$ over a fixed range of $x_{\mathbb{P}}$, yielding a function $\tilde{F}_2^D(\beta, Q^2)$, which would in the above picture be proportional to the pomeron's structure function.

2. Event Selection and Kinematic Reconstruction

The data used for this measurement were taken with the H1 detector at the ep collider HERA in 1993, when 26.7 GeV electrons collided with 820 GeV protons, resulting in a centre–of–mass energy of $\sqrt{s} = 296$ GeV.

Charged particles are detected in central and forward tracking detectors that consist of drift chambers interspersed with multi–wire proportional chambers. The scattered electron is measured in the backward electromagnetic calorimeter (BEMC) with an energy resolution of $10\%/\sqrt{E/\mathrm{GeV}}$. The hadronic final state is measured with an energy resolution of $50\%/\sqrt{E/\mathrm{GeV}} \oplus 2\%$ in the liquid argon calorimeter (LAr), which covers a pseudorapidity range[a] of $-1.5 < \eta < 3.7$.

A "plug" calorimeter surrounding the forward beampipe detects particles in the region $3.5 < \eta < 5.5$. Particles in the pseudorapidity range $5.5 < \eta < 6.5$ may produce showers in the beampipe and dead material around it, so that shower particles can be detected by the forward muon detector (FMD), which consists of a set of drift chambers in front and behind a toroidal magnet.

Events for this analysis were selected first by requiring an electron candidate in the BEMC and a reconstructed vertex within 30 cm of the nominal interaction point. Further selection criteria to ensure good reconstruction of kinematical quantities are described in Ref. 6. Q^2 and y were reconstructed using the "Σ–method", which uses information from the scattered electron and the hadronic final state. It was required

[a] The polar angle θ is measured with respect to the direction of the outgoing proton (the "forward direction"), and related to the pseudorapidity η by $\eta = -\ln\tan\frac{\theta}{2}$.

that $0.03 < y < 0.7$ and $7.5\,\mathrm{GeV}^2 < Q^2 < 70\,\mathrm{GeV}^2$. 16366 events passed these cuts. Additional cuts were imposed to select events with a large rapidity gap, namely that the pseudorapidity η_{max} of the most forward energy deposition in the LAr above 400 MeV be $\eta_{max} < 3.2$, that less than 1 GeV be deposited in the plug calorimeter, and that at most one pair of hits be detected in the FMD[7], leaving 1723 events.

A comparison with a selection based solely on a cut $\eta_{max} < 1.8$ shows that $(21 \pm 4)\,\%$ of these large rapidity gap events do not pass the above cuts. $(7 \pm 3)\,\%$ of the events are rejected due to noise in the plug and background in the FMD, and Monte Carlo studies show that $(5 \pm 3)\,\%$ of the shortfall is due to "conventional" DIS events, therefore $(9 \pm 4)\,\%$ is attributed to proton dissociation. Accordingly the final cross sections are corrected for losses due to noise and proton dissociation by 16 %.

The mass M_X of the hadronic final state (excluding the proton or proton dissociative system) is calculated using LAr and BEMC calorimeter cells, with a resolution (determined from Monte Carlo) of 30 % for $M_X > 6\,\mathrm{GeV}$ which deteriorates to 100 % for $M_X \to 0.3\,\mathrm{GeV}$. β is determined from $\beta = M_X^2/(M_X^2 + Q^2)$, assuming $|t|$ to be negligible, and hence $x_{I\!P}$ by virtue of Eq. (1).

3. Measurement of $F_2^{D(3)}\,(\beta,\,Q^2,\,x_{I\!P})$ and Factorisation

To measure $F_2^{D(3)}\,(\beta,\,Q^2,\,x_{I\!P})$ as defined in Eq. (2), the events were binned in x, Q^2, and β. For each bin the background from "conventional" DIS as simulated by a combination of LEPTO[8] and ARIADNE[9], which implements the colour dipole model for gluon radiation, was subtracted. Acceptance, smearing and bin–centre corrections were derived from a Monte Carlo modelling $eI\!P$ scattering, namely RAPGAP[3], with an admixture of vector–meson electroproduction. Details, also concerning the evaluation of systematic errors, can be found in Ref. 7, as well as a table with the numerical values of $F_2^{D(3)}$. The result is shown in Fig. 1 for the different bins in β and Q^2.

$F_2^{D(3)}\,(\beta,\,Q^2,\,x_{I\!P})$ can be fitted with a function of the form $x_{I\!P}^{-n} \cdot F\,(\beta,\,Q^2)$, where the exponent n is measured to be $n = 1.19 \pm 0.06(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})$. This behaviour is consistent with the assumption of factorisation ($\chi^2/df = 32/46$ for the fit), and to be expected if the scattering process takes place between the electron and a pomeron out of the proton that is emitted with a flux factor $f_{I\!P/p}\,(x_{I\!P})$:

$$\frac{\mathrm{d}^3\sigma^D_{ep\to epX}}{\mathrm{d}\beta\,\mathrm{d}Q^2\,\mathrm{d}x_{I\!P}} = f_{I\!P/p}\,(x_{I\!P})\,\frac{\mathrm{d}^2\sigma_{eI\!P\to eX}}{\mathrm{d}\beta\,\mathrm{d}Q^2} = f_{I\!P/p}\,(x_{I\!P})\,\frac{4\pi\alpha}{\beta Q^4}\left[1 - y + \frac{y^2}{2}\right] F_2^{I\!P}\,(\beta,\,Q^2). \quad (3)$$

A comparison of Eqs. (2) and (3) shows that $F_2^{D(3)}\,(\beta,\,Q^2,\,x_{I\!P}) = f_{I\!P/p}\,(x_{I\!P})\cdot F_2^{I\!P}\,(\beta,\,Q^2)$, and that therefore $f_{I\!P/p}\,(x_{I\!P}) \propto x_{I\!P}^{-n}$ implies $F_2^{D(3)}\,(\beta,\,Q^2,\,x_{I\!P}) \propto x_{I\!P}^{-n}$.

Regge theory predicts $n = 2\alpha\,(\langle t\rangle) - 1 \approx 2\alpha\,(0) - 1$, where $\alpha\,(t)$ characterises the leading Regge trajectory for the observed process. Therefore the measured value of n corresponds to $\alpha\,(0) = 1.10 \pm 0.03 \pm 0.04$, consistent with a "soft" ($\alpha\,(0) \approx 1.08$) pomeron and inconsistent with the expected value of $\alpha\,(0) \approx 0.55$ for the exchange of

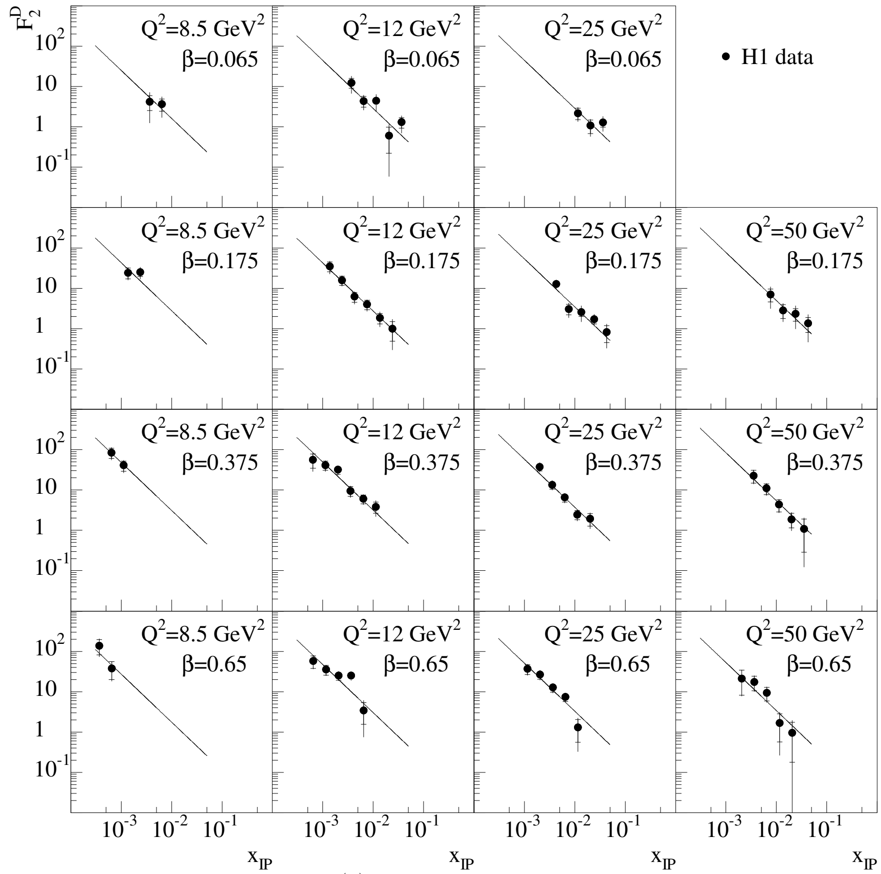

Fig. 1. The diffractive contribution $F_2^{D(3)}(\beta,\, Q^2,\, x_{I\!P})$ to the proton structure function F_2 as a function of $x_{I\!P}$ for different β and Q^2. The inner error bar is the statistical error, the full error shows the statistical and systematic error added in quadrature. Superimposed is the result of the fit establishing a factorisable dependence of the form $x_{I\!P}^{-n} \cdot F(\beta,\, Q^2)$. An overall normalisation uncertainty of 8% is not included.

meson trajectories like $f_2\,(1270)$, $\omega\,(783)$, $a_2\,(1320)$, or $\rho\,(770)$. A contribution from a harder pomeron ($\alpha\,(0) \approx 1.3 - 1.5$), especially at higher $|t|$, is however not excluded by the measurement.

4. Measurement of the Pomeron Structure Function

Having demonstrated that factorisation holds within experimental accuracy for the data presented here, it is possible to extract the pomeron's structure function from $F_2^{D(3)}$. However, the normalisation of the flux factor $f_{I\!P/p}$ is a matter of convention, and therefore we proceed to integrate $F_2^{D(3)}$ over a fixed range of $x_{I\!P}$, namely $3 \cdot 10^{-4} < x_{I\!P} < 5 \cdot 10^{-2}$, yielding a function $\tilde{F}_2^D$ given by

$$\tilde{F}_2^D\,(\beta,\, Q^2) = \int\limits_{3\cdot 10^{-4}}^{5\cdot 10^{-2}} F_2^{D(3)}\,(\beta,\, Q^2,\, x_{I\!P})\,\mathrm{d}x_{I\!P} = F_2^{I\!P}\,(\beta,\, Q^2) \int\limits_{3\cdot 10^{-4}}^{5\cdot 10^{-2}} f_{I\!P/p}\,(x_{I\!P})\,\mathrm{d}x_{I\!P}, \quad (4)$$

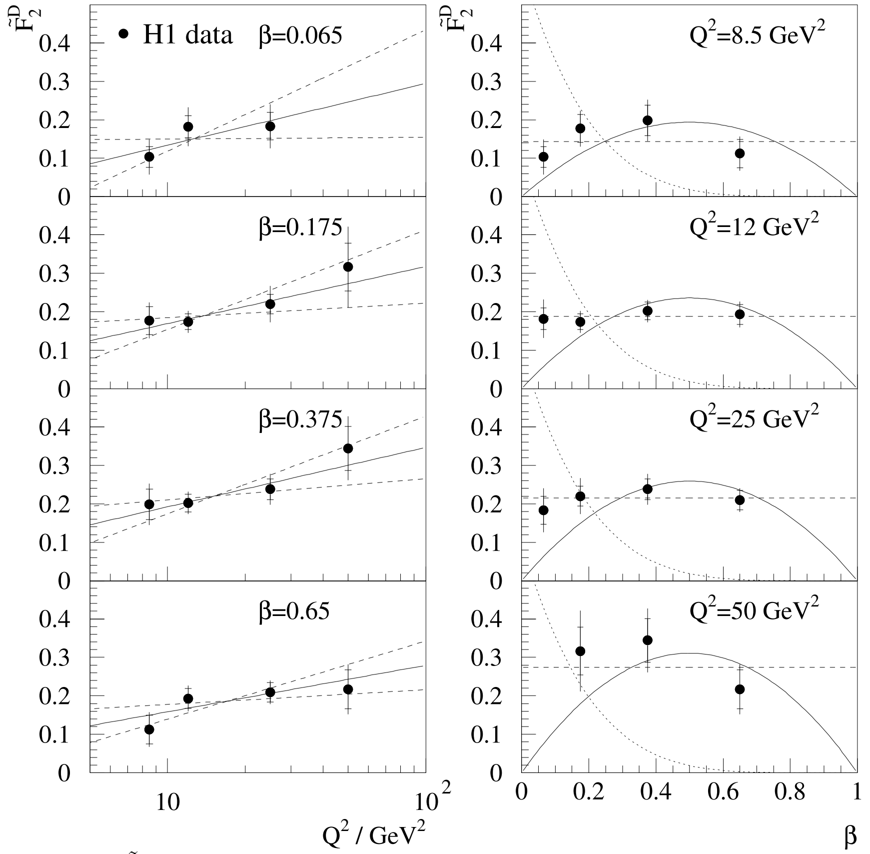

Fig. 2. Dependence of $\tilde{F}_2^D(\beta,\, Q^2)$ on Q^2 and β; superimposed on the Q^2 dependence are the results of fits at each β which assume leading logarithmic scaling violations; the best fit (continuous curve) and the curves corresponding to a change of ± 1 standard deviation (dashed curves) in the slope are shown; superimposed on the β dependence are the simplest $q\bar{q}$ expectation for $I\!P$ structure - $\beta(1-\beta)$ (continuous curve), and a constant dependence (dashed curve), for which the overall normalisations are determined from fits to the data; also displayed is a dependence of the form $(1-\beta)^5$ (dotted curve) with arbitrary normalisation. The overall normalisation uncertainty of 8% is not included.

which is unambigiously defined and proportional to a pomeron structure function $F_2^{I\!P}(\beta,\, Q^2)$. The experimental result for $\tilde{F}_2^D$ is shown in Fig. 2 as function of Q^2 and β. There is no evidence for any substantial Q^2 dependence of $\tilde{F}_2^D$. Deep (high Q^2) diffractive interactions are thus broadly of a scale invariant, and therefore point–like, nature. Furthermore, $\tilde{F}_2^D$ is observed to have little dependence on β with contributions throughout the measured range ($0.065 < \beta < 0.65$). Therefore the structure which is hit by the virtual photon carries only a fraction of the $I\!P$'s momentum, implying that the $I\!P$ has a sub–structure which may presumably be attributed to point–like partons.

A fit to the hypothesis of a linear $\log_{10} Q^2$ dependence of $\tilde{F}_2^D$ demonstrates that the data are consistent with zero slope to within 1 standard deviation (σ). The accuracy of this first measurement of the Q^2 dependence of $\tilde{F}_2^D$ is such that the possibility of "scaling violations", symptomatic of QCD, may be admitted. Furthermore, either they may be β dependent and thus characteristic of that observed for the structure function of a hadron such as the proton, or they may be insensitive to β and thus characteristic of the structure function of a "dressed" point–like field quantum such as the photon.

Also shown in Fig. 2 superimposed on the β dependence of $\tilde{F}_2^D$ is the expectation based on the simplest $q\bar{q}$ picture of deep–inelastic diffraction, namely a "hard" quark $\beta(1-\beta)$ dependence. There is a suggestion that the observed β dependence may exceed this simple $q\bar{q}$ expectation as $\beta \to 0$, which is naturally to be expected in any quantum chromodynamic interpretation which includes gluons as well as quarks. A fit assuming no dependence of $\tilde{F}_2^D$ on β is equally acceptable, whereas the ansatz of a soft dependence $(1-\beta)^5$ is ruled out.

5. Conclusions

The contribution of diffractive interactions to deep–inelastic ep scattering has been measured, and the corresponding structure function $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ has been evaluated, using a class of deep–inelastic ep scattering events with no hadronic energy flow in the forward direction. The dependence of $F_2^{D(3)}(\beta, Q^2, x_{I\!P})$ on $x_{I\!P}$ is measured to be $x_{I\!P}^{-n}$ with $n = 1.19 \pm 0.06(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})$ independent of β and Q^2, consistent with a factorisable diffractive interpretation. By integrating $F_2^{D(3)}$ over a fixed range of $x_{I\!P}$, yielding $\tilde{F}_2^D$, the deep–inelastic structure of the pomeron is measured. $\tilde{F}_2^D(\beta, Q^2)$ is observed to be consistent with scale invariance.

6. References

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