MEASUREMENT OF THE PROTON STRUCTURE FUNCTION F_2 IN
MUON-HYDROGEN INTERACTIONS AT 120 AND 280 GeV

The European Muon Collaboration

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ABSTRACT

The proton structure function F_2 has been measured in the range $2.5 \leq Q^2 \leq 170 \text{ GeV}^2$ and $0.03 \leq x \leq 0.65$. Scaling violation is clearly seen in the data. Results of fits to leading order QCD are presented, together with values of the scale-breaking parameter Λ .

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We present a measurement of the proton structure function F_2 in muon-proton scattering at incident energies of 120 and 280 GeV. The data correspond to muon fluxes of 2.6×10^{11} and 5.8×10^{11} respectively and represent a large increase in luminosity over previous muon experiments on hydrogen [1]. In the quark-parton model the structure functions scale, that is they are functions of x only. Violations of scaling have been observed in electron [2] and muon scattering [1, 3], in general agreement with the expectations of QCD [4]. This experiment considerably extends the range of Q^2 over which scaling violation has been measured on hydrogen*). Data extending to even larger Q^2 , taken with higher luminosity on an iron target, are presented in an accompanying letter [6].

The differential cross-section for inelastic muon-proton scattering, assuming one-photon exchange and neglecting the muon mass, is

$$\frac{d^2\sigma}{dQ^2 dx} = \frac{4\pi\alpha^2}{Q^4} \left[(1 - y - \frac{Mxy}{2E}) \frac{F_2}{x} + y^2 F_1 \right],$$

where Q^2 is the squared 4-momentum transfer from the muon, E is the beam energy, M the proton mass, $y = v/E$, where v is the energy transferred from the muon to the hadronic final state and x the Bjorken variable $Q^2/2Mv$. F_1 and F_2 are the proton structure functions. The relationship between F_1 and F_2 is conventionally expressed in terms of R , the ratio of σ_L to σ_T , as

$$\frac{2xF_1}{F_2} = (1 + \frac{4M^2x^2}{Q^2}) / (1 + R).$$

For this paper F_2 has been extracted using the above relationship with $R = 0.0$ and $R = 0.2$.

The experiment was performed in the muon beam of the CERN SPS using the EMC forward spectrometer shown in fig. 1, further details of which are already published [7]. Each μ^+ , incident on the 6m long hydrogen target, was measured in momentum to $\pm 0.3\%$ by a focussing spectrometer in the beam line

*) Preliminary results from these measurements have been presented previously [5].

and in position and direction by the scintillator hodoscopes BHA and BHB. Muons scattered from the target were detected and measured in the drift chambers W1-W5 and the proportional chambers P0-P3. Tracks detected in the drift chambers W6-7, which had penetrated the lead-iron-scintillator calorimeter, H_2 , and the 2 meter thick wall of magnetised iron, were identified as muons.

Five scintillation counter hodoscopes, H1V, H1H, H3V, H3H and H4 were used to form a trigger on a scattered muon. Signals from pairs of hodoscopes were fed into matrices of coincidence logic to select events in which a muon was observed (i) scattered through at least 0.5° , (ii) pointing back to the target in both views, and (iii) not excessively deflected in the vertical plane by the magnetised iron absorber. Condition (i) suppressed the high rate from low- Q^2 events, condition (ii) rejected most of the beam halo, while conditions (ii) and (iii) together imposed a cut-off at about 15 GeV in momentum, suppressing the contribution of muons from hadron decay accompanying a low- Q^2 event. The rate of false triggers from halo muons was rendered negligible by the use of the hodoscope arrays V1, V2 and V3 in anticoincidence.

Muon tracks were reconstructed by initially finding a track segment behind the absorber, and associating it with a track in W4, W5. Then by stepping back through W3, P3, P2, P1 and the chambers in front of the magnet the whole track was found. A quintic spline fit was used to determine the muon momentum, and the incident and scattered muon were fitted to a common interaction vertex. The muon tracks found were tested to ensure that the trigger was satisfied by the muon itself, and not, for example, by a combination of a muon and a produced hadron.

The beam flux used during the experiment was determined by counting the number of beam tracks reconstructed within a known time gate triggered randomly throughout the experiment. The selection criteria for beam track reconstruction were the same as those used for the normal triggers, and thus the flux normalisation was independent of the efficiency of the beam hodoscopes themselves and of the reconstruction method. This flux was in agreement with the one calculated from the rates of the counter hodoscope H5 downstream of the experiment.

To reduce background some cuts were applied to the data. Background events from the target end walls were eliminated by defining a 5.5 m fiducial length within the target. Inside this region the background, determined from separate runs with the target empty, was negligible ($< 3 \times 10^{-3}$). Muons with momenta below 42 GeV (20 GeV for the 120 GeV data) were rejected to avoid a residual contamination from hadron decay. In addition, the region $v < 20$ GeV ($v < 10$ GeV for the 120 GeV data) was removed because the poor resolution in v , due to the resolution in beam and scattered muon momentum, distorted the x dependence of F_2 .

The acceptance of the apparatus was determined by a Monte Carlo simulation of the experiment. Beam tracks were selected from the random-trigger events. Scattered muons were generated and weighted according to a trial parameterised input $F_2(x, Q^2)$, then tracked through the apparatus, taking account of multiple scattering and of hodoscope and chamber efficiencies. The experimentally measured resolutions, in angle ± 0.1 mr, in momentum $\Delta p/p = 7 \times 10^{-5} p$ (p in GeV) for 280 GeV data ($1.8 \times 10^{-4} p$ for 120 GeV data), were applied to determine the smearing in x and Q^2 . Radiative corrections were calculated according to Tsai [8], using the same trial function F_2 . The 'exact' formula, rather than the peaking approximation, was used for the inelastic radiative tails as well as the elastic tail. We have measured the yield of wide-angle bremsstrahlung at 120 GeV [9], which was in good agreement with these calculations. The Monte Carlo events, after experimental cuts, were compared with the data in bins of x and Q^2 to determine F_2 . The new F_2 was parameterised and the whole procedure was iterated to converge to the final F_2 which was independent of the starting function. The resulting values are to be interpreted as F_2 at the quoted x and Q^2 , not as an average over the bin.

The values of F_2 for the two assumptions $R = 0$ and $R = 0.2$ are given in Table 1. These data correspond to a total of 100K events at 120 GeV and 140K events at 280 GeV. For all data points presented the radiative corrections are $< 25\%$, the correction for the efficiency losses is $< 25\%$, the experimental smearing correction is $< 20\%$ and the acceptance is $> 5\%$. In fig. 2 we show F_2 obtained with $R = 0$. Because of systematic uncertainties, it is not possible to indicate any preference in the range $R \leq 0.2$. Further data at 200 and 240 GeV now being analysed will allow a determination of R . The errors in Table 1 are purely statistical. Besides an

overall normalisation error of $\pm 3\%$, the other sources of systematic error are a $\pm 0.4\%$ uncertainty in the beam energy calibration, $\pm 0.2\%$ in the spectrometer calibration, and errors in acceptance, resolutions, radiative corrections and efficiency losses. Fig. 3 shows our estimated total systematic error in F_2 , distributed about a parameterisation of the data.

The general behaviour of F_2 as shown in fig. 2 is such that at low x a rise with Q^2 is observed, at $x = 0.175$ F_2 is nearly constant and at large x a definite decrease of F_2 with Q^2 is seen. The pattern of scaling violation observed in earlier lepton nucleon scattering experiments [1, 2, 3, 10] is clearly established in this experiment. However, the data with their systematic errors as shown in fig. 3, allow the scaling violation to be rather small.

QCD fits in leading order [11-13] have been made according to the Altarelli-Parisi equations [14]. For the restricted range $x \geq 0.25$, where valence quarks are dominant, the structure function at a fixed $Q_0^2 = 4 \text{ GeV}^2$ was parameterized as $F_2 = Ax^\alpha(1-x)^\beta(1-\gamma x)$ and the data fitted using the non-singlet evolution equation. The relative normalisation between the 120 and 280 GeV data sets was left free and a shift of $(1 \pm 1)\%$ resulted. The fit is compared with the data in fig. 2 and the values obtained for Λ , the QCD scale breaking parameter, A , α , β and γ are given in Table 2 for both assumptions on R . These results for Λ were insensitive to the parameterisation of F_2 used (see Table 2 for fit with $\gamma = 0$) and to the choice of Q_0^2 . The systematic error on Λ was estimated by taking each component of the total systematic error separately into account for the fit and adding the differences in $\log \Lambda$ quadratically. Fits have also been made for $x \geq 0.35$ which gave a change in Λ of -43 MeV (for $R = 0$). Subtracting a Q^2 dependent sea contribution [15] changed Λ by $+29 \text{ MeV}$. Both exercises show that the change in Λ from the sea contribution is less than the quoted systematic error for $x \geq 0.25$.

To compare the results from the large x region with the data at small x a fit to $F_2 = B(1-x)^\delta(1-\epsilon x) + 1/2(F_2^p - F_2^n)$ has been made including all x . This was done by fixing Λ to 110 MeV and using a parameterisation of $F_2^p - F_2^n$ at $Q_0^2 = 30.5 \text{ GeV}^2$ with the gluon distribution $xG(x) = C(1-x)^5$, following Abbott et al. [11]. The parameter C was fixed by the momentum sum rule to 3.3 corresponding to a momentum fraction of 55% for the gluons. The number of flavours used in the Altarelli-Parisi equations was set to 3 and for $x = 0.03$ and

0.05 only the point at the lowest Q^2 was included in the fit to minimise the influence of the charm threshold. The result of this fit is shown in fig. 2 in the range $x < 0.25$, for which it is a reasonable description of the data.

For $x \geq 0.25$ this fit agreed within 2% everywhere with the other one.

In an attempt to explain the scaling violation of F_2 for $x \geq 0.25$ by higher twist [16] a fit of the form $F_2 = F_2(x)(1 + \frac{\mu^2}{Q^2(1-x)})$ was made with the result that $\mu^2 = (0.96 \pm 0.15) \text{ GeV}^2$ and $\chi^2 = 115$. This fit is less probable than the QCD fit.

In conclusion the proton structure function F_2 measured in this experiment shows scaling violation over the entire range $2.5 \leq Q^2 \leq 170 \text{ GeV}^2$ and $0.03 \leq x \leq 0.65$. It can be explained by leading order quantum chromodynamics with a scale breaking parameter $\Lambda = 110^{+58}_{-46} {}^{+124}_{-69} \text{ MeV}$ assuming $R = 0$.

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TABLE 1

THE PROTON STRUCTURE FUNCTION F_2 WITH STATISTICAL ERROR σ
EXTRACTED BY ASSUMING $R = 0.0$ and 0.2

x	Q ² GeV ²	Beam Energy GeV	R = 0.0		R = 0.2	
			F ₂	σ	F ₂	σ
0.030	2.5	120	0.2839	0.0090	0.2925	0.0093
	3.5	120	0.3034	0.0050	0.3212	0.0053
	4.5	120	0.3086	0.0051	0.3315	0.0055
	5.5	120	0.3307	0.0072	0.3601	0.0079
	5.5	280	0.3161	0.0142	0.3238	0.0145
	7.0	120	0.3501	0.0115	0.3884	0.0127
	7.0	280	0.3308	0.0060	0.3450	0.0063
	9.0	280	0.3381	0.0052	0.3601	0.0056
	11.5	280	0.3456	0.0053	0.3751	0.0060
	15.0	280	0.3411	0.0085	0.3781	0.0095
0.050	3.5	120	0.3195	0.0143	0.3242	0.0145
	4.5	120	0.3084	0.0089	0.3162	0.0092
	5.5	120	0.3143	0.0074	0.3267	0.0077
	7.0	120	0.3442	0.0058	0.3665	0.0062
	7.0	280	0.3702	0.0120	0.3752	0.0122
	9.0	120	0.3456	0.0094	0.3775	0.0103
	9.0	280	0.3364	0.0084	0.3432	0.0086
	11.5	280	0.3352	0.0067	0.3456	0.0069
	15.0	280	0.3473	0.0064	0.3671	0.0068
	20.0	280	0.3769	0.0077	0.4120	0.0084
0.080	27.0	280	0.3760	0.0228	0.4207	0.0255
	3.5	120	0.3160	0.0132	0.3176	0.0133
	4.5	120	0.3225	0.0091	0.3253	0.0092
	5.5	120	0.3353	0.0078	0.3397	0.0079
	7.0	120	0.3397	0.0060	0.3476	0.0062
	9.0	120	0.3406	0.0063	0.3543	0.0065
	9.0	280	0.3480	0.0089	0.3499	0.0090
	11.5	120	0.3547	0.0069	0.3777	0.0073
	11.5	280	0.3450	0.0067	0.3487	0.0068
	15.0	120	0.3657	0.0121	0.3995	0.0132
0.125	15.0	280	0.3530	0.0063	0.3597	0.0064
	20.0	280	0.3406	0.0059	0.3533	0.0061
	27.0	280	0.3578	0.0067	0.3830	0.0072
	36.0	280	0.3608	0.0114	0.3974	0.0126
	4.5	120	0.3309	0.0132	0.3322	0.0133
	5.5	120	0.3188	0.0105	0.3204	0.0105
	7.0	120	0.3349	0.0066	0.3375	0.0067
	9.0	120	0.3317	0.0076	0.3361	0.0078
	9.0	280	0.3728	0.0116	0.3736	0.0117
	11.5	120	0.3397	0.0070	0.3476	0.0072
0.175	11.5	280	0.3464	0.0082	0.3480	0.0082
	15.0	120	0.3286	0.0077	0.3426	0.0080
	15.0	280	0.3577	0.0076	0.3594	0.0076
	20.0	120	0.3527	0.0110	0.3790	0.0118
	20.0	280	0.3414	0.0069	0.3458	0.0070
	27.0	280	0.3304	0.0072	0.3384	0.0073
	36.0	280	0.3184	0.0078	0.3338	0.0081
	48.0	280	0.3233	0.0099	0.3504	0.0108
	65.0	280	0.3159	0.0280	0.3532	0.0313
	5.5	120	0.3217	0.0142	0.3227	0.0143
0.250	7.0	120	0.3026	0.0081	0.3038	0.0082
	9.0	120	0.3138	0.0081	0.3158	0.0081
	9.0	280	0.3129	0.0122	0.3127	0.0121
	11.5	120	0.3224	0.0074	0.3258	0.0075
	11.5	280	0.3509	0.0107	0.3518	0.0107
	15.0	120	0.3277	0.0089	0.3338	0.0091
	15.0	280	0.3206	0.0088	0.3220	0.0088
	20.0	120	0.3342	0.0102	0.3463	0.0106
	20.0	280	0.3124	0.0080	0.3140	0.0080
	27.0	120	0.3012	0.0144	0.3223	0.0154
0.250	27.0	280	0.3062	0.0083	0.3099	0.0083
	36.0	280	0.3046	0.0091	0.3108	0.0093
	48.0	280	0.2858	0.0095	0.2973	0.0099
	65.0	280	0.3053	0.0127	0.3293	0.0138
	7.0	120	0.2991	0.0077	0.2996	0.0077
	9.0	120	0.2875	0.0069	0.2882	0.0069
	9.0	280	0.2778	0.0153	0.2774	0.0153
	11.5	120	0.2967	0.0062	0.2980	0.0062
	11.5	280	0.2718	0.0081	0.2718	0.0081
	15.0	120	0.2734	0.0068	0.2757	0.0069
0.250	15.0	280	0.2826	0.0070	0.2825	0.0070
	20.0	120	0.2810	0.0072	0.2855	0.0074
	20.0	280	0.2881	0.0066	0.2886	0.0066
	27.0	120	0.2840	0.0095	0.2932	0.0098
	27.0	280	0.2810	0.0068	0.2824	0.0068
	36.0	120	0.2526	0.0138	0.2680	0.0147
	36.0	280	0.2625	0.0071	0.2649	0.0071
	48.0	280	0.2623	0.0076	0.2670	0.0077
	65.0	280	0.2477	0.0084	0.2567	0.0087
	90.0	280	0.2378	0.0113	0.2547	0.0121

TABLE 1 (Continued)

x	Q ² GeV ²	Beam Energy GeV	R = 0.0		R = 0.2	
			F ₂	σ	F ₂	σ
0.350	7.0	120	0.2175	0.0097	0.2178	0.0097
	9.0	120	0.2160	0.0076	0.2166	0.0076
	11.5	120	0.2260	0.0066	0.2267	0.0066
	15.0	120	0.2128	0.0072	0.2139	0.0072
	15.0	280	0.2120	0.0079	0.2126	0.0080
	20.0	120	0.2049	0.0072	0.2066	0.0072
	20.0	280	0.2170	0.0069	0.2174	0.0069
	27.0	120	0.2053	0.0087	0.2084	0.0089
	27.0	280	0.2155	0.0072	0.2166	0.0072
	36.0	120	0.2029	0.0118	0.2087	0.0122
	36.0	280	0.2098	0.0076	0.2109	0.0077
	48.0	120	0.1955	0.0172	0.2062	0.0182
	48.0	280	0.1952	0.0077	0.1970	0.0077
	65.0	280	0.1931	0.0085	0.1966	0.0086
	90.0	280	0.1622	0.0091	0.1679	0.0095
	125.0	280	0.2011	0.0162	0.2156	0.0174
0.450	9.0	120	0.1562	0.0087	0.1568	0.0087
	11.5	120	0.1390	0.0060	0.1398	0.0060
	15.0	120	0.1444	0.0068	0.1452	0.0068
	20.0	120	0.1512	0.0071	0.1522	0.0071
	20.0	280	0.1493	0.0069	0.1500	0.0069
	27.0	120	0.1382	0.0078	0.1396	0.0079
	27.0	280	0.1387	0.0065	0.1392	0.0065
	36.0	120	0.1510	0.0108	0.1536	0.0110
	36.0	280	0.1556	0.0077	0.1565	0.0077
	48.0	120	0.1273	0.0131	0.1314	0.0135
	48.0	280	0.1371	0.0073	0.1380	0.0073
	65.0	280	0.1287	0.0077	0.1302	0.0078
	90.0	280	0.1174	0.0084	0.1199	0.0086
	125.0	280	0.1244	0.0121	0.1296	0.0126
	170.0	280	0.1183	0.0233	0.1276	0.0252
0.550	11.5	120	0.0934	0.0060	0.0938	0.0060
	15.0	120	0.0860	0.0058	0.0864	0.0058
	20.0	120	0.0729	0.0052	0.0734	0.0052
	20.0	280	0.0840	0.0086	0.0840	0.0086
	27.0	120	0.0743	0.0062	0.0750	0.0062
	27.0	280	0.0890	0.0056	0.0894	0.0056
	36.0	120	0.0758	0.0080	0.0767	0.0081
	36.0	280	0.0888	0.0063	0.0893	0.0063
	48.0	120	0.0649	0.0098	0.0663	0.0100
	48.0	280	0.0611	0.0052	0.0615	0.0052
	65.0	280	0.0796	0.0066	0.0802	0.0067
	90.0	280	0.0791	0.0075	0.0803	0.0076
	125.0	280	0.0697	0.0093	0.0716	0.0095
	170.0	280	0.0615	0.0138	0.0648	0.0146
0.650	15.0	120	0.0500	0.0044	0.0496	0.0044
	20.0	120	0.0433	0.0042	0.0432	0.0042
	27.0	120	0.0370	0.0046	0.0371	0.0046
	36.0	120	0.0437	0.0064	0.0440	0.0064
	36.0	280	0.0519	0.0052	0.0517	0.0051
	48.0	120	0.0343	0.0072	0.0348	0.0073
	48.0	280	0.0441	0.0049	0.0441	0.0049
	65.0	280	0.0328	0.0045	0.0330	0.0045
	90.0	280	0.0431	0.0060	0.0435	0.0061
	125.0	280	0.0463	0.0078	0.0472	0.0079
	170.0	280	0.0228	0.0081	0.0236	0.0084

Table 2: Parameters of QCD fit for data points having $x \geq 0.25$

R	Λ [MeV]	Error Stat. Syst. [MeV]		A	α $Q_0^2 = 4 \text{ GeV}^2$	β	γ	χ^2 Stat. error only	Degrees of freedom
0.0	110	+58 -46	+124 -69	1.56	0.56	2.25	0.75	97	66
[0.0]	[109]			[1.32]	[0.48]	[2.77]	[0.0]	[98]	[67]
0.2	37	+36 -22	+84 -30	1.59	0.56	2.36	0.75	90	66

FIGURE CAPTIONS

Fig. 1 Schematic layout of the spectrometer

Fig.2 The proton structure function F_2 with statistical errors as measured at two different primary energies for $R = 0$. The curves are leading-order QCD fits. For the details in the different regions $x \geq 0.25$ and $x < 0.25$ see the text.

Fig. 3 Total excursions in F_2 allowed by a combination of all the systematic errors for 120 GeV and 280 GeV separately.

Fig. 1

Fig. 2

Fig. 3