A MEASUREMENT OF THE NUCLEON STRUCTURE FUNCTION FROM MUON–CARBON DEEP INELASTIC SCATTERING AT HIGH Q^2

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Deep inelastic scattering cross sections have been measured with the CERN SPS muon beam at incident energies of 120 and 200 GeV. Approximately 100 000 events at each energy are used to obtain the structure function $F_2(x, Q^2)$ in the kinematic region $0.3 < x < 0.7$ and $25\ \mathrm{GeV}^2 < Q^2 < 200\ \mathrm{GeV}^2$.

Over the past decade deep inelastic lepton scattering has been very fruitful for the investigation of the nucleon structure and for stimulating new theoretical ideas. Previous experiments [1] provided evidence for significant departures from Bjorken scaling [2] in the Q^2 region below 100 GeV^2.

In the limit of one-photon exchange, the inelastic lepton–nucleon cross section can be written as

$$\mathrm{d}\sigma/\mathrm{d}x\mathrm{d}Q^2 = (4\pi\alpha^2/Q^4)x^{-1}\{(1-y)+y^2/2(1+R) + (Q^2/2E^2)\,[(1+R)^{-1}-\tfrac{1}{2}]\}\,F_2(x,Q^2)\,, \quad (1)$$

where F_2 is the nucleon structure function and $R = \sigma_L/\sigma_T$ is the cross section ratio for longitudinal to transverse virtual photons.

In this letter we present new results on the nucleon

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structure function in the kinematic region $Q^2 > 25$ GeV^2 where higher twist effects [3], complicating the interpretation of the data are expected to be small. The high statistical accuracy of the data was provided by the high-intensity muon beam available at the CERN SPS.

The apparatus used for these measurements is shown in fig. 1. It is a magnetized iron torus with a 40 m long carbon target located in the central hole. The azimuthally symmetric magnetic field deflects scattered muons back towards the beam axis with a sagitta in the iron proportional to Q^2/E_{beam}. Twenty planes of scintillation counters, each with seven annular subdivisions detect those muons with a sagitta and hence Q^2 greater than a specified threshold. Trajectories of the scattered muons are measured in multiwire proportional chamber planes located after every 44 cm of iron. Alternate planes measure orthogonal track projections.

Interactions are recorded if the scattered muon is: (a) in coincidence with a beam muon; (b) unaccompanied by a halo track, and (c) transverses four consecutive scintillator planes at a radius of at least 44 cm from the spectrometer axis. The latter requirement introduces a Q^2 cut-off of ~ 20 GeV^2 at a beam energy of 120 GeV. No anticoincidence requirement is imposed downstream of the interaction point.

The efficiency of the scintillators, triggering electronics, and proportional chambers is continuously monitored in the data by exploiting the redundancy of the apparatus. These efficiencies are all typically $\geqslant 97\%$.

The calibration of the spectrometer energy measurement has been verified by using muon beams with energies of 120 and 200 GeV directly incident on the torus. The absolute calibration is confirmed to better than 1% and the resolution is measured as ±7% at these energies. From Monte Carlo calculations the resolution is found to be almost independent of energy above 20 GeV. Because of the focusing properties of the spectrometer the measurement errors on the energy tend to compensate the errors on the scattering angle. The resulting Q^2 resolution changes slightly with Q^2 varying from 6% at the highest Q^2 to 8% at the lowest Q^2. Since the data analysis requires a knowledge of muon energy loss in carbon and iron, and its energy dependence, these were measured in auxiliary studies. The results were in good agreement with existing calculations [4], which were then used in the determination of the incident and scattered energies.

The muon beam has already been described in detail elsewhere [5]. To summarize, it has an energy spread of ±4%, a profile at the target of $\sigma_x \sim \sigma_y \sim 2$ cm and a characteristic divergence of ±0.4 mrad. The energy of individual beam particles is measured to an accuracy of ±0.5% using a set of four scintillator hodoscopes together with one of the bending elements of the beam [6]. The muon beam is defined through the target by four hodoscope counters. The timing of all hodoscope cells is recorded with each event. The OR of the inner 48 elements of the first hodoscope in fig. 1 (radius = 42 mm) is used to define the beam signal in the trigger.

For the data reported below the beam intensity was $\sim 10^7$ μ/s. The absolute beam flux was determined by

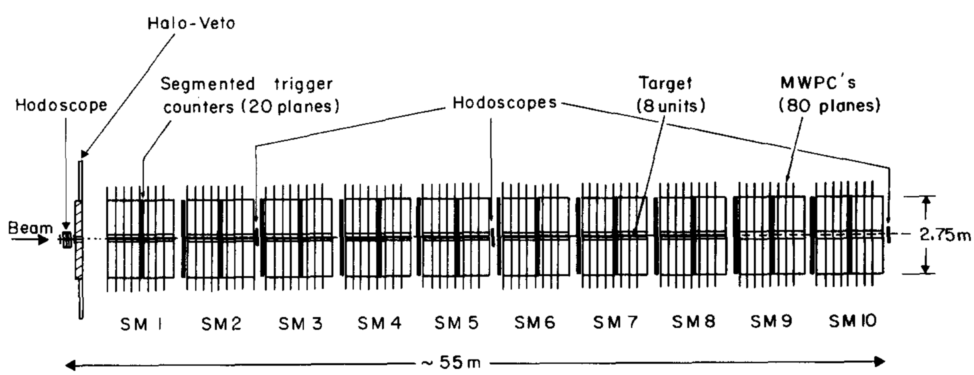

Fig. 1. Schematic view of the experimental set-up. Magnetized iron toroids with interspersed trigger counters and multiple wire proportional chambers are arranged in ten supermodules (SM 1–10). The last two supermodules do not contain target units. A wall of scintillation counters vetoes the halo muons.

two methods with different systematic limitations. In one method, the counting rate of individual elements of the first hodoscope (which are subject to very small dead time corrections) were added up and corrected for simultaneous multiple hits. In the other method we used the counting rate of the beam signal which is insensitive to simultaneous multiple hits. The dead time losses were estimated by using the time distribution of random hits in the individual hodoscope elements. Corrections to the primary measurements were typically <10% and the two methods agreed to 1%. Beam losses from the target were measured by the interaction vertex distribution along the target and correctly described by Monte Carlo calculations. The systematic error on the relative luminosity is estimated at ±2%. Further details of the apparatus, its calibration and resolution will be reported in a separate publication [7].

The results presented here are based on the analysis of most of the data taken in 1979 which constitute a small fraction of the available statistics. For the 200 GeV data, μ^+ and μ^- beams were used. The two polarities were compared for systematic differences in such variables as Q^2, momentum, and vertex position. No systematic trends were observed within the statistical accuracy and the two samples were combined in the structure function analysis. At the incident energy of 120 GeV only the positive beam polarity was used

From this sample reconstructed events were selected if the scattered muon had an energy of at least 15 GeV, emerged from the target volume, and produced the signature required by the electronic trigger. Reconstructed tracks were required to have at least four measured points on each projection and nine overall. The average number of overall points per track was 21. To check for proper functioning of the computer reconstruction program and the event selection procedure as well as to search for unexpected anomalies in the data, approximately 15000 analyzed events were visually inspected by physicists using computer displays. Possible errors in event selection were less than 0.5% and showed no bias to particular kinematic regions.

To obtain the muon scattering cross sections the detector acceptance was determined by Monte Carlo simulation. The calculation included beam phase space, energy loss in the target and spectrometer, multiple scattering, δ-rays associated with the muon track and hadronic showers from the interaction point. Also included were the small measured inefficiencies in the detector elements. Because of the focusing property of the detector the acceptance is rather uniform for most of the Q^2–x plane; typically it is 75% for $Q^2/Q^2_{max} > 0.1$ and $x > 0.3$. No data is used from a kinematic region with acceptance less than 28%. The correction for finite resolution is typically 5% and not more that 20% for $x < 0.7$. The acceptance calculation including resolution smearing effects, requires a knowledge of the shape of the cross section. An iterative approach was adopted in which a structure function was assumed and the results from the data used to correct the original assumption. Reasonable variations in the starting point affected the results of the first pass at the level of 5%. An additional pass was found to have converged at the level of 1%.

To extract the one-photon exchange cross section from the measured cross section, corrections for higher order processes must be applied. These radiative corrections were computed to first order in α as described

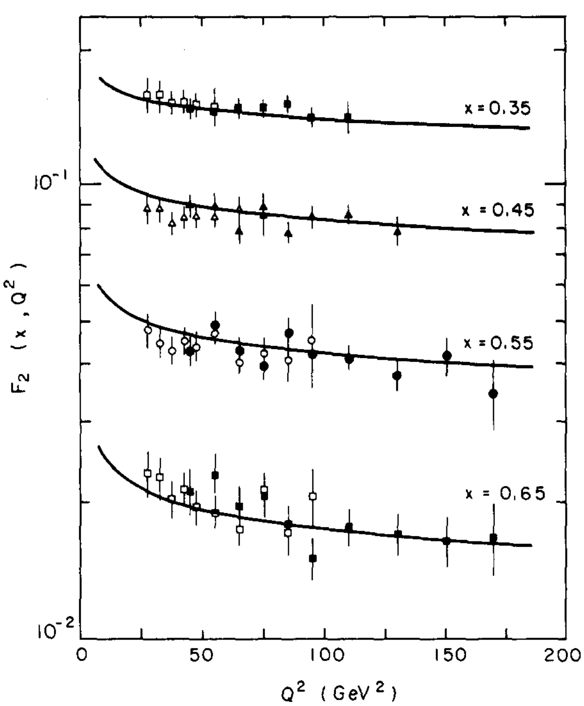

Fig. 2. $F_2(x, Q^2)$ measured with 120 GeV μ^+ (open symbols) and with 200 GeV μ^+/μ^- (closed symbols) using $R = 0$. The curves represent the best fit to the data with the Gonzalez–Arroyo et al. [10] parametrization with $\Lambda = 85$ MeV, $\alpha = 0.68$ and $\beta = 3.65$.

Table 1
F_2 structure function deduced from the 120 GeV data (average energy 113.1 GeV).

x	Q^2 (GeV^2)	F_2	Error on F_2	
			Stat	Syst
0.35	27.5	0.1599	0.0046	0.0129
	32.5	0.1612	0.0047	0.0099
	37.5	0.1544	0.0047	0.0071
	42.5	0.1556	0.0049	0.0067
	47.5	0.1528	0.0053	0.0066
	55.0	0.1526	0.0047	0.0118
0.45	27.5	0.0902	0.0030	0.0054
	32.5	0.0899	0.0031	0.0047
	37.5	0.0838	0.0030	0.0034
	42.5	0.0863	0.0032	0.0029
	47.5	0.0873	0.0037	0.0031
	55.0	0.0867	0.0028	0.0029
	65.0	0.0902	0.0036	0.0037
	75.0	0.0881	0.0044	0.0080
0.55	27.5	0.0486	0.0020	0.0034
	32.5	0.0458	0.0021	0.0029
	37.5	0.0441	0.0021	0.0021
	42.5	0.0462	0.0023	0.0019
	47.5	0.0449	0.0026	0.0019
	55.0	0.0480	0.0021	0.0017
	65.0	0.0415	0.0023	0.0015
	75.0	0.0435	0.0026	0.0018
	85.0	0.0418	0.0031	0.0027
	95.0	0.0460	0.0049	0.0082
0.65	27.5	0.0236	0.0013	0.0023
	32.5	0.0231	0.0014	0.0019
	37.5	0.0208	0.0014	0.0012
	42.5	0.0218	0.0015	0.0011
	47.5	0.0199	0.0016	0.0008
	55.0	0.0193	0.0012	0.0007
	65.0	0.0179	0.0013	0.0007
	75.0	0.0217	0.0018	0.0010
	85.0	0.0176	0.0019	0.0009
	95.0	0.0209	0.0026	0.0017

Table 2
F_2 structure function deduced from the 200 GeV data (average energy 192.0 GeV).

x	Q^2 (GeV^2)	F_2	Error on F_2	
			Stat	Syst
0.35	45.0	0.1459	0.0031	0.0067
	55.0	0.1435	0.0037	0.0073
	65.0	0.1464	0.0039	0.0054
	75.0	0.1462	0.0044	0.0044
	85.0	0.1491	0.0050	0.0046
	95.0	0.1398	0.0052	0.0048
	110.0	0.1402	0.0057	0.0098
0.45	45.0	0.0892	0.0024	0.0045
	55.0	0.0892	0.0029	0.0053
	65.0	0.0787	0.0027	0.0028
	75.0	0.0891	0.0033	0.0028
	85.0	0.0784	0.0033	0.0020
	95.0	0.0845	0.0039	0.0022
	110.0	0.0853	0.0032	0.0026
	130.0	0.0784	0.0039	0.0034
0.55	45.0	0.0429	0.0016	0.0028
	55.0	0.0485	0.0021	0.0033
	65.0	0.0428	0.0020	0.0019
	75.0	0.0397	0.0021	0.0016
	85.0	0.0469	0.0028	0.0020
	95.0	0.0421	0.0027	0.0015
	110.0	0.0411	0.0021	0.0013
	130.0	0.0378	0.0026	0.0011
	150.0	0.0417	0.0036	0.0019
	170.0	0.0346	0.0047	0.0038
0.65	45.0	0.0211	0.0011	0.0022
	55.0	0.0228	0.0014	0.0023
	65.0	0.0195	0.0014	0.0016
	75.0	0.0205	0.0015	0.0013
	85.0	0.0178	0.0016	0.0009
	95.0	0.0150	0.0015	0.0006
	110.0	0.0176	0.0014	0.0007
	130.0	0.0170	0.0017	0.0006
	150.0	0.0164	0.0020	0.0005
	170.0	0.0167	0.0028	0.0011

in ref. [8]. They were applied as a multiplicative factor in each Q^2–x interval. The correction averaged over each bin never exceeded 10%.

Fig. 2 and tables 1, 2 give the measurement of $F_2(x, Q^2)$ at beam energies of 120 and 200 GeV. The structure function values are reported at bin centres rather than as averages over the intervals. The values are calculated assuming $R = 0$. No correction for Fermi motion in the carbon target has been made. The errors shown in fig. 2 include, in addition to statistics, a systematic component based on a possible 2% luminosity error, a 7% error in the Monte Carlo correction, and a 0.5% error on the energy of the scattered muon. All sources are combined in quadrature.

Results from both incident muon energies are in good agreement. Data points from the Q^2–x region of overlap can be used directly to constrain the magnitude of R as can be seen from eq. (1). From a bin-by-bin comparison of the data we obtain a value of R

consistent with 0.0 ± 0.2 averaged over the kinematic region $0.3 < x < 0.7$ and $50 < Q^2 < 100$ GeV^2.

It is seen from these data that the Q^2 dependence of the structure function is very slight for $Q^2 > 25$ GeV^2. A fit to the data using the empirical formula [9]

$$F_2(x, Q^2) = A_1(1-x)^{A_2}$$

$$\times [1.0 + A_3 \ln(Q^2/3\ \mathrm{GeV}^2) \ln(0.25/x)] ,$$

gives a value of 0.12 ± 0.02 for the scaling violating term A_3 with a χ^2 of 1.1 per degree of freedom. Fixing this term to zero we obtain a worse fit to the data with a χ^2 of 2.1 per degree of freedom.

A more detailed description of the structure function $F_2(x, Q^2)$ can be obtained in the framework of QCD theory using the technique of Gonzalez-Arroyo et al. [10] to extract the QCD scale parameter Λ from the data. In this method, evolution equations of the Altarelli–Parisi type [11] are numerically integrated from a reference Q_0^2 value using a parametrization of the type:

$$F_2(x, Q_0^2) \propto x^{\alpha}(1-x)^{\beta} .$$

We have used the valence quark approximation (non-singlet case of ref. [10]) to fit F_2 in the x region 0.3–0.7 where the contributions from the sea quarks and the gluons are small [12] and have been neglected. The value of Λ obtained was $85\ ^{+60}_{-40}$ (statistical error), $^{+90}_{-70}$ (systematic error) MeV and was found to be independent of the reference Q_0^2 used. The inclusion of second-order terms in the fit lowered the value to $\Lambda = 32\ ^{+20}_{-15},\ ^{+30}_{-25}$ MeV [‡1].

The systematic errors on Λ are a quadratic superposition of systematic displacements due to the propagation of the errors on normalization and on the scattered muon energy. For instance a 2% increase of the 120 GeV data will displace the leading order value of Λ by +70 MeV. Fitting the two data samples independently we obtain values of Λ in agreement with the results of the fit to the combined data but with considerably larger errors. The value of Λ also depends on the value of R used. Changing R from zero to 0.1 will decrease Λ by 60 MeV in leading order.

For comparison we have used also the method of Buras and Gaemers [14] and obtained a value for $\Lambda = 136\ ^{+50}_{-40},\ ^{+90}_{-80}$ MeV which agrees within errors with the result of the previous analysis. The value of Λ can also be determined in a more direct way from the moments of F_2. In the Q^2–x region studied we have calculated the Nachtmann [15] moments with n from 4 to 7 (see table 3). A moment was accepted if the fraction determined by the data was at least 65% of the total. The uncertainty involved in the extrapolation is reflected on the errors quoted in table 3 by adding 20% of the unseen part of the moment in quadrature with the statistical errors. In the valence quark ap-

‡1 This value corresponds to the minimal subtraction (MS) scheme used in the renormalization procedure adopted by the authors in ref. [10]. For a detailed discussion of this point see ref. [13].

Table 3
Nachtmann moments for n = 4, 5, 6, 7 with 120 GeV and 200 GeV incident energy (systematic errors are not included, the values have been multiplied by 10^4).

E (GeV)	Q^2 (GeV^2)	n = 4	5	6	7
120	30.0	91.5 ± 6.2	37.8 ± 1.9	18.3 ± 0.9	9.87 ± 0.55
	40.0	87.1 ± 5.9	36.0 ± 1.8	17.4 ± 0.8	9.40 ± 0.52
	51.2	87.4 ∓ 6.0	35.8 ± 1.9	17.2 ± 0.8	9.20 ± 0.49
	65.0	–	34.9 ± 2.4	16.3 ± 0.9	8.53 ± 0.49
200	50.0	86.5 ± 5.8	36.4 ± 1.9	17.9 ± 0.9	9.79 ± 0.55
	70.0	83.1 ± 5.8	33.9 ± 1.7	16.2 ± 0.8	8.66 ± 0.46
	90.0	82.9 ± 5.7	33.4 ± 1.7	15.8 ± 0.8	8.32 ± 0.41
	110.0	82.1 ± 6.4	33.2 ± 1.9	15.7 ± 0.9	8.34 ± 0.48

proximation and in leading order this method gave an average value of $\Lambda = 80 ^{+130}_{-80}, ^{+100}_{-70}$ MeV.

Higher twist effects can be parametrized following Abbot et al. [3] as

$$F_2(x, Q^2) = F_2^{\mathrm{QCD}}\ [1 + \mu^2/(1-x)Q^2]\ .$$

and are expected to be small in the Q^2 range covered by this experiment. The inclusion of this term in the fits changes the value of Λ only slightly and gives a value for μ^2 of $\sim 0.17 \pm 0.6$ GeV^2 indicating that the fit is insensitive to this term. However, good fits to the data can also be obtained by fixing Λ and allowing the higher twist term to compensate for the change in Λ. A value of Λ of 400 MeV requires a negative higher twist contribution [16] with $\mu^2 \approx 1.5$ GeV^2 while $\Lambda = 10$ MeV can be compensated by a positive contribution with $\mu^2 = 1$ GeV^2.

In conclusion we have used several methods to extract from our data the parameter Λ characterizing the strength of the strong interaction. All methods gave consistent results which point to a value of Λ of approximately 100 MeV [‡2]. This value is lower than what has been found in the past by most deep inelastic scattering experiments [12,18–20] which relied on lower Q^2 data in their fits.

The apparatus for this experiment has been conceived and its construction directed by C. Rubbia. We acknowledge the help of many people, too numerous to be mentioned here individually, who contributed to the various stages of the experiment. In particular, we are indebted to the technical staff of our home institutions who participated in the construction and upkeep of the detector and to the Experimental Area Groups of the SPS division which ensured a flawless performance of the muon beam. Finally, we thank the EMC collaboration for giving us the measurement of the beam phase space.

‡2 Preliminary results of the EMC group also indicate a similar value of Λ [17].

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