A HIGH-STATISTICS MEASUREMENT OF THE NUCLEON STRUCTURE FUNCTION $F_2(x,Q^2)$ FROM DEEP INELASTIC MUON-CARBON SCATTERING AT HIGH Q^2

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ABSTRACT

We present results from a high statistics study of the nucleon structure function $F_2(x,Q^2)$ in the kinematic range $x \geq 0.25$ and $Q^2 \geq 25$ GeV^2. The analysis is based on $1.3 \cdot 10^6$ reconstructed events recorded at beam energies of 120, 200 and 280 GeV. By comparing data taken at different beam energies, we find $R = \sigma_L/\sigma_T = (8 \pm 14(\text{stat.})^{+38}_{-35}(\text{syst.})) \cdot 10^{-3}$ independent of x in the range $0.25 \leq x \leq 0.7$ and 50 GeV^2 $\leq Q^2 \leq$ 150 GeV^2. The kinematic range of these data makes them well suited for quantitative tests of Quantum Chromodynamics (QCD). From a next-to-leading order nonsinglet fit, we find a QCD mass scale parameter $\Lambda_{\overline{MS}} = 220 \pm 20(\text{stat.})^{+90}_{-70}(\text{syst.})$ MeV.

We present new results on the nucleon structure function $F_2(x,Q^2)$ and $R = \sigma_L/\sigma_T$ measured in deep inelastic scattering of muons on an isoscalar carbon target. The data were collected with a high-luminosity spectrometer at the CERN SPS muon beam. The experimental apparatus is described in detail elsewhere [1]. Preliminary results obtained with the same set-up have been reported earlier [2].

The analysis presented here is based on $1.3 \cdot 10^6$ reconstructed events after kinematic cuts. Muon beams of 120, 200 and 280 GeV energy were used for this measurement. Beam polarities, kinematic ranges and data samples are summarized in Table 1. At present, the 280 GeV data represent only ⅓

TABLE I : The Data Sample

Beam energy (GeV)	Beam signs	Q^2 range (GeV)	x range	Number of events
120	μ^+/μ^-	25-115	0.25-0.8	600 000
200	μ^+/μ^-	42-200	0.25-0.8	600 000
280	μ^+ only	60-280	0.25-0.8	115 000

of the total statistics recorded at this energy. In view of the high statistical accuracy of these data, a large effort was invested in calibrating the apparatus, and in monitoring its performance, in order to reduce systematic errors to a similar level. As the most important systematic limitation of the experiment is the energy calibration of the incident and scattered lepton, special emphasis was put on calibrating the magnetic field in the iron toroids, where it is not measurable directly. A map of the magnetic excitation H was measured in the thin air gaps between individual discs of the iron toroids [1]. Inside the iron, it was converted into magnetic induction $B = \mu(H) \cdot H$ using accurately measured permeability curves for a large number of iron samples. The magnetic flux through the iron toroids and its dependence on the azimuth angle ϕ were verified with induction loops wound around various segments of the magnet. We estimate the uncertainty of the resulting field map to be smaller than $2 \cdot 10^{-3}$ over the entire magnet volume. The air gap magnet of the beam momentum spectrometer [1] was calibrated to an accuracy ranging from $1.5 \cdot 10^{-3}$ at 120 GeV beam energy to better than $1 \cdot 10^{-3}$ at 280 GeV.

To calibrate the luminosity of the experiment, the incident beam of $\approx 2.10^7$ μ/sec intensity was counted with a fast plastic scintillator hodoscope using two different methods [1] which normally agree to $\approx$ 0.5%.

The data were analyzed using a detailed Monte Carlo simulation of the experiment which takes into account

- the phase space of the incoming beam, including all correlation effects;
- efficiencies and resolution properties of all detectors in the apparatus;
- multiple scattering and energy loss of both incident and scattered muons [3], simulating the stochastic nature of energy losses due to ionization, bremsstrahlung, pair production and photonuclear effects;
- additional detector hits from hadronic shower punch-through close to the interaction vertex.

For each of the three beam energies, $3.5 \cdot 10^6$ events were generated and processed through exactly the same chain of reconstruction programs as the experimental data. From the reconstructed Monte Carlo events, fine-grain acceptance matrices in Q^2 and x which include all effects from resolution smearing are calculated to convert the experimental distributions into deep inelastic cross sections. The acceptance is typically 75% and is rather flat in the kinematic region $Q^2/Q^2_{max} > 0.2$, $x > 0.3$.

To extract the one-photon exchange cross section from the measured data, corrections must be applied for higher order processes. The radiative corrections used in this analysis are described in detail in refs. [5] and include

- lepton current processes up to order α^4,
- vaccum polarization by leptons and hadrons,
- hadron current processes up to order α^3,
- effects of weak-electromagnetic ($\gamma - Z^0$) interference [4].

They amount to at most 10% over the kinematic range of this measurement. The error on $F_2(x,Q^2)$ from uncertainties on these corrections is estimated to be smaller than 1%.

The structure functions at the three beam energies, assuming R = 0, are shown in Fig. 1. The comparison of F_2's measured at different beam energies allows to determine R and, in addition, provides a powerful cross-check of systematic errors. A variation of R affects mainly the region of large $y = \nu/E$, i.e. of low x and high Q^2. In contrast, errors on the relative normalization of the data sets are independent of any kinematic variable and a scale error on the momentum measurement of incident or scattered muons affects mainly the region of small y i.e. large x and small Q^2. Effects from these three different sources are therefore only weakly correlated and can be studied separately.

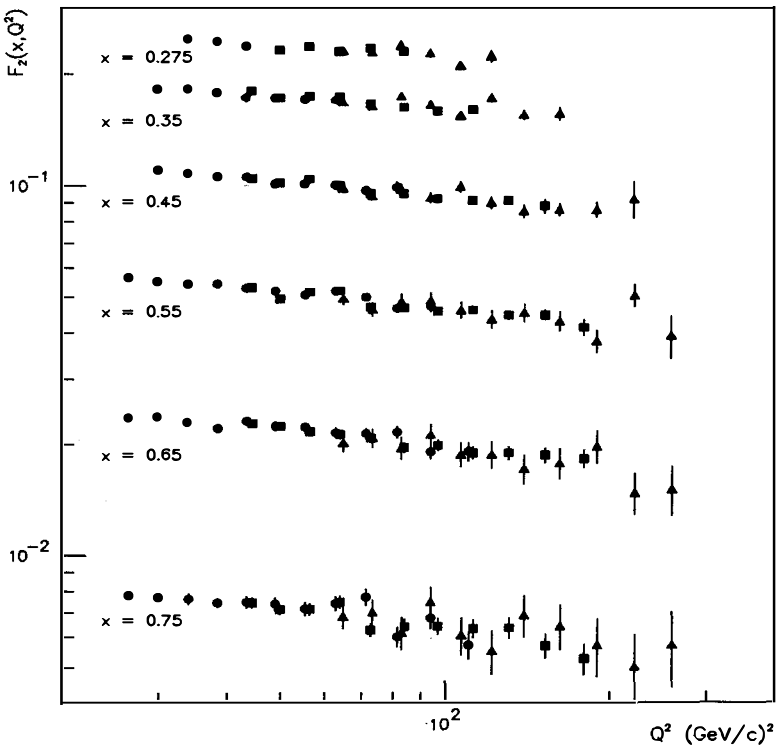

Fig. 1: The nucleon structure function $F_2(x,Q^2)$ measured at the three beam energies 120 (circles), 200 (squares) and 280 GeV (triangles). The 120 GeV data were multiplied by a factor 1.025 to adjust the relative normalization of the three data sets. Only statistical errors are shown.

While 200 and 280 GeV data are found to be in very good agreement, the data points at 120 GeV are 2.5% lower everywhere in the kinematic region of overlap. Therefore, they were multiplied by 1.025 for the further analysis. The systematic errors on all results presented below do not depend on the absolute normalization of the data but only on the relative normalization of the three data sets with respect to each other. We assume normalization uncertainties of ± 1.5% of both the 120 and 280 GeV data relative to the 200 GeV data. We then study the mutual agreement of the three data sets under variation of the overall calibration of the magnetic field. This is shown in the form of a χ^2 curve in Fig. 2 which exhibits a clear minimum at a recalibration factor $f_B = 1.0007 \pm .0008$, indicating that the calibration described above is indeed correct to 10^{-3}. We chose to retain the original calibration but assign to the magnetic field an asymmetric error $\Delta B/B = ^{+2}_{-1} \cdot 10^{-3}$.

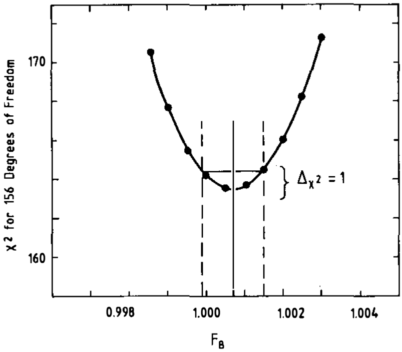

Fig. 2: The χ^2 of the three F_2 data sets with respect to each other as a function of a change in the overall calibration of the spectrometer magnetic field. The abscissa f_B is a global recalibration factor applied to the field map described in the text.

$R = \sigma_L/\sigma_T$ is also determined by minimizing the χ^2 of the three data sets with respect to each other. This is done separately in each bin of x but assuming R to be independent of Q^2 in the kinematic range of this analysis ($50\ GeV^2 \leq Q^2 \leq 150\ GeV^2$), as suggested by QCD calculations which predict only a weak (logarithmic) variation of R with Q^2 [6]. The result is shown in Fig. 3 and is clearly compatible with R = 0. Good agreement is also observed with the measurement by the European Muon Collaboration (EMC) on an iron target [7]. From our data, we find a mean value of $R = [8 \pm 14(stat.)^{+38}_{-35}(syst.)] \cdot 10^{-3}$ in the range $0.25 \leq x \leq 0.7$. We use R = 0 independent of Q^2 and x for the further analysis.

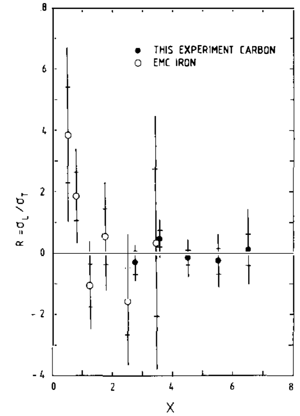

Fig.3: R = σ_L/σ_T as a function of x. Also shown is the measurement by the EMC collaboration on an iron target [7]. Inner error bars are statistical errors only, outer error bars are statistical and systematic errors added linearly.

Fig. 4 shows the final $F_2(x,Q^2)$ combined from the three data sets. To compare the observed deviations from Bjorken scaling to QCD predictions we show in Fig. 5 the logarithmic slopes $d\ell nF_2/d\ell nQ^2$, assumed to be independent of Q^2 and fitted to the data in bins of x. Data points with $y = \nu/E < 0.2$ were not used in these fits to reduce the sensitivity to the magnetic field uncertainty. Also shown in Fig. 5 are QCD predictions for different values of the QCD mass scale parameter Λ. They were obtained by a next-to-leading order computation in the $\overline{MS}$ renormalization scheme, using the Altarelli-Parisi evolution equations [8] and the x dependence of F_2 at fixed values of Q^2 from the data shown in Fig. 4. Within errors, the data are compatible with the QCD predictions for $\Lambda_{\overline{MS}}$ = 230 MeV. We consider this comparison the most stringent test of QCD in deep inelastic scattering because it does not require any parametrization of the structure function in x and Q^2. In the kinematic range of our data, it is also insensitive to assumptions on the gluon distribution.

We also did a flavour non-singlet, next-to-leading order QCD fit to our data, based on the method developed by Gonzales-Arroyo et al. [9]. This fit yields $\Lambda_{\overline{MS}} = 220\pm20(\text{stat.})^{+90}_{-70}(\text{syst.})$ MeV for a χ^2/DOF = 190/165 and is superimposed to the data in Fig. 4. Using other QCD fit programs or applying

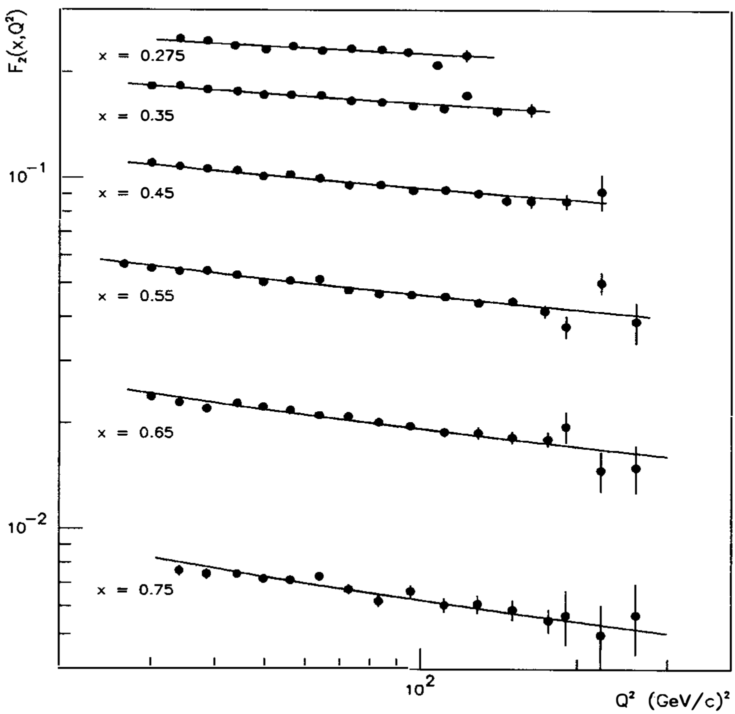

Fig. 4: The structure function $F_2(x,Q^2)$ combined for all beam energies assuming R = 0. Only statistical errors are shown. The solid lines represent the QCD fit described in the text.

more restrictive cuts in x or y changes Λ by less than 20 MeV; such effects are included in the estimate of the systematic error. Singlet fits under reasonable assumptions on the gluon distributions also give very similar values for Λ. We stress that these results are obtained in a kinematic region ($Q^2 \geq 25$ GeV^2) which is generally believed to be well described by perturbative QCD predictions and is not obscured by collective ("higher twist") effects from quark-quark interactions [10].

In conclusion, we have presented a new high statistics measurement of the nucleon structure function $F_2(x,Q^2)$ from deep inelastic muon-carbon scattering in the high Q^2($Q^2 \geq 25$ GeV^2) regime. Careful calibration of the experimental apparatus has allowed to reduce systematic uncertainties to a level close to the statistical accuracy of the data. $R = \sigma_L/\sigma_T$ is found to be compatible, within small

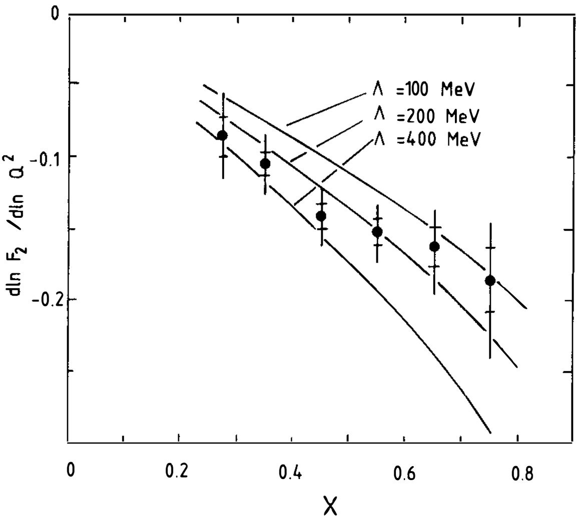

Fig. 5: Logarithmic slopes of the structure function $d\ell nF_2/d\ell nQ^2$ as a function of x, compared to QCD predictions for different values of Λ. Inner error bars are statistical errors only, outer error bars are statistical and systematic errors added linearly.

errors, with 0 in the kinematic range $0.25 \leq x \leq 0.7$. The pattern of scaling violations observed in the data is in good agreement with predictions from perturbative QCD for a mass scale parameter $\Lambda_{\overline{MS}}$ = 230 MeV.

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