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EVOLUTION OF NUCLEON STRUCTURE FUNCTIONS IN THE Q^2 RANGE BETWEEN
20 AND 10 000 GeV^2 FROM A NEW QCD ANALYSIS OF NEUTRINO DATA

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ABSTRACT

From the nucleon structure functions measured by the CHARM Collaboration in inclusive neutrino and antineutrino CC interactions we determined the QCD parameter $\Lambda_{\overline{\text{MS}}} = 310 \pm 140 \text{ (stat)} \pm 70 \text{ (syst)} \text{ MeV}$ using the Furmanski-Petronzio method.

With the same method we extrapolated the behaviour of the quark ($q + q$) and the gluon x -distributions up to $Q^2 = 10\,000 \text{ GeV}^2$ using perturbative QCD. The extrapolated structure functions are compared with recent results coming from the two jets differential cross section in proton-antiproton interactions at $\sqrt{s} = 540 \text{ GeV}$ and $Q^2 = 2000 \text{ GeV}^2$.

Deep inelastic scattering of muons and neutrinos allowed in recent years to explore the structure functions of the nucleon and the interpretation of their evolution in terms of QCD.

In particular, two calorimetric neutrino experiments at CERN [1,2] extracted from their data a full set of structure functions for the valence quarks, the singlet quarks, the sea quarks and the gluons.

The knowledge of nucleon structure functions in a Q^2 range between 1 and a few hundred GeV^2 can be used to determine the QCD scale parameter, $\Lambda_{\overline{\text{MS}}}$ and for extrapolating their behaviour to much higher Q^2 , on the basis of perturbative QCD, in order to compare it with the results of nucleon-antinucleon interactions at the energies presently reached by the CERN-SPS $p\bar{p}$ collider.

In this paper we will give the best value of $\Lambda_{\overline{\text{MS}}}$ and discuss how the extrapolation to large Q^2 can be performed using the singlet (F_2) and the gluon (G) structure functions extracted from the data of the CHARM experiment; we will also discuss the propagation of the uncertainties of our present picture of the nucleon at $Q^2 \sim 100 \text{ GeV}^2$ and how it will affect the validity of these predictions for $Q^2 \sim 10\,000 \text{ GeV}^2$.

We are aware of the following sources of uncertainty:

1. the uncertainty (both statistical and theoretical) on the value of the QCD parameter Λ ;
2. the uncertainty on F_2 and G as determined in the Q^2 range of present studies of deep inelastic neutrino scattering, 3-78 GeV^2 in the case of the CHARM Collaboration;
3. the validity of the perturbative expansion (e.g. effects of higher order terms, threshold for heavy quarks, etc.).

In this paper we will discuss the first two points.

The CHARM Collaboration has already published [1] a set of structure functions which was extracted from data of charged current interactions of neutrino and antineutrino wide band beams at the CERN SPS, using a model independent unfolding of experimental acceptance and resolution effects, based on the B-spline technique. The QCD fit to the data was performed using the

Furmanski-Petronzio method [3], that does not require any prior knowledge of the particular analytic form of the x -dependence of the structure functions at fixed Q^2 . This method gives an analytical solution of the Altarelli-Parisi equations in terms of a series of Laguerre polynomials, and it can be used directly to evaluate the extrapolation of structure functions to very high Q^2 .

In Ref. [1] we gave an estimation of the QCD scale parameter Λ and of its uncertainty as determined from a fit to non-singlet quarks and from a simultaneous fit to singlet, non-singlet and sea quark experimental distributions, in the leading order of perturbative QCD. We have now also determined a value of Λ in the modified minimal subtraction renormalization scheme from the non-singlet structure function alone and found

$$\Lambda_{\overline{\text{MS}}} = 310 \pm 140 \text{ (stat)} \pm 70 \text{ (syst) MeV} .$$

A global comparison of the Λ values determined from our experiment with those of other experiments is given in Table I [4]. In the following we show that the present large uncertainty on Λ does not very much influence the extrapolation of these structure functions to high Q^2 .

In principle, the result of the fit to the data produced by the Furmanski-Petronzio method can be used directly to extrapolate the evolution to higher Q^2 . However, the limited order of the polynomial ($n = 6$) used in the fit is not flexible enough to grant a reasonable behaviour of the structure functions in the x regions not restricted by experimental data (namely $x \sim 0$ and $x \sim 1$), and produces some unphysical behaviour in the extrapolation. Therefore we first determined F_2 and G at a reference Q^2 value in the centre of the range covered by our data (namely $Q^2 = 20 \text{ GeV}^2$) by the fit (see figure 1), and then imposed the conditions $G(x) \rightarrow 0$, for $x \rightarrow 1$ and $q(x) - \bar{q}(x) \rightarrow 0$ for $x \rightarrow 0$, and expanded the resulting curves in a polynomial of larger order ($n = 15$). These expansions are valid for $x \geq 0.0125$.

To evaluate the influence of the uncertainties on these reference functions, we also evaluated for each function the steepest and least steep curve compatible with the 68% confidence region of our experiment and conserving the integral of the central curve which is the global momentum carried by each component. As the error on the integral of F_2 including the overall normalization uncertainty is negligible, the global momentum carried by the gluon component is constrained by the momentum sum rule. Those curves (indicated as F_{2+} , F_{2-} and G_+ , G_-) are also shown in Fig. 1.

The result of the evolution of the structure functions from the reference value of $Q^2 = 20 \text{ GeV}^2$ to $Q^2 = 10\,000 \text{ GeV}^2$, for different values of x is shown separately for the singlet and the gluon distribution in Figure 2. Figure 3 summarizes to what extent the uncertainties on the structure functions at the low Q^2 reference value affect the distributions $F_2(x)$ and $G(x)$ at $Q^2 = 10\,000 \text{ GeV}^2$.

The $\overline{\text{MS}}$ evolution of the central distribution and of the two extreme distributions of $F_2(x)$ and $G(x)$ at the reference value of $Q^2 = 20 \text{ GeV}^2$ (see fig. 1) are shown separately in figure 3, assuming $\Lambda_{\text{QCD}} = 310 \text{ MeV}$. The evolution of the central distributions at $Q^2 = 20 \text{ GeV}^2$ are also shown for $\Lambda_{\text{QCD}} = 170$ and 450 MeV . The plot shows that the main uncertainty comes from the present error bands of the structure functions at low Q^2 and not from the error of Λ_{QCD} .

Recent results on proton structure functions at $Q^2 \sim 2000 \text{ GeV}^2$ have been published by the UA1 [5] and by the UA2 [6] Collaborations. They are determined from the two-jet differential cross section in proton-antiproton interactions measured at $\sqrt{s} = 540 \text{ GeV}$, using the expression:

$$d^3\sigma/dx_1 dx_2 d\cos\theta = [F(x_1)/x_1] [F(x_2)/x_2] d\sigma/d\cos\theta$$

where, under simplifying assumptions, $F(x)$ can be written as:

$$F(x) = G(x) + \frac{4}{9} (\bar{q}(x) + q(x))$$

and

$$d\sigma/d\cos\theta = K d\sigma/d\cos\theta \Big|_{\text{LO}}$$

K is a factor coming from higher order QCD corrections and is expected to be sensibly larger than 1 [7].

These results are presented in Fig. 4 assuming $K = 2$, as suggested in reference [7], together with the extrapolations at $Q^2 = 2000 \text{ GeV}$ from the CHARM structure function analysis. We note substantial agreement for $x > 0.1$. The singlet structure function alone ($\frac{4}{9} F_2(x)$) is also shown in figure 4 to demonstrate the need for gluons to describe the data. A similar extrapolation of structure functions measured by the CDHS Collaboration has been performed by the UA1 Collaboration [5]; within their uncertainties these extrapolations agree although the details differ considerably.

The UA1 point below $x = 0.1$ seems to be quite large with respect to the prediction derived from the neutrino experiments. It should be noted that the integral of this distribution is found to be $M_G + \frac{4}{3} M_q = 0.73$ for the CHARM structure functions, whereas the integral of the UA1 distribution seems to be sensibly higher. However, a 30% error on the absolute normalizations and the uncertainty on K has to be taken into account. The experimental points of UA2 are in better agreement with the values of $F(x)$ extrapolated to $Q^2 = 2000 \text{ GeV}^2$ from the CHARM neutrino data at $Q^2 = 20 \text{ GeV}^2$.

We conclude that, in spite of uncertainties in the structure functions at low Q^2 the extrapolation to high Q^2 of scaling violations observed in fixed target experiments is quite reliable (at least for $x > 0.01$) and qualitatively confirmed by experiments at present collider energies ($\sqrt{s} = 540 \text{ GeV}$), allowing stringent quantitative tests of perturbative QCD when a refined analysis of the collider data will be available. The dominant role of the gluon structure function for $x < 0.4$ is confirmed.

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FIGURE CAPTIONS

- Fig. 1 The structure functions $F_2(x)$ and $G(x)$ at a reference value of $Q^2 = 20 \text{ GeV}^2$ as determined by a fit of the data of the CHARM Collaboration [1] (continuous lines); also shown are $F_{2+}(x)$ and $G_+(x)$ (dashed lines), and $F_{2-}(x)$ and $G_-(x)$ (dotted-dashed lines), the steepest and least steep curve lying inside the 68% confidence region of the CHARM experiment, shown as a shaded area.
- Fig. 2 Evolution of the gluon and singlet reference structure functions in the range $20-10\,000 \text{ GeV}^2$ for various values of x , assuming $\Lambda_{\overline{\text{MS}}} = 310 \text{ MeV}$.
- Fig. 3 Variations on $G(x)$ and $F_2(x)$ at $Q^2 = 10\,000 \text{ GeV}^2$ caused by different values of $\Lambda_{\overline{\text{MS}}}$ ($\Lambda_{\overline{\text{MS}}} = 170 \text{ MeV}$: dashed lines, $\Lambda_{\overline{\text{MS}}} = 310 \text{ MeV}$: continuous lines, $\Lambda_{\overline{\text{MS}}} = 450 \text{ MeV}$: dotted-dashed lines) and by different initial conditions at $Q^2 = 20 \text{ GeV}^2$ ($G_+(x)$ and $F_{2+}(x)$ dotted lines, $G_-(x)$ and $F_{2-}(x)$ double dotted lines).
- Fig. 4 $F(x) = G(x) + \frac{4}{9} (q(x) + \bar{q}(x))$ at $Q^2 = 2000 \text{ GeV}^2$ as determined by the UA1 Collaboration (full points), UA2 Collaboration (open points), and extrapolated from CHARM structure functions (continuous line) and F_- (dotted line) and F_+ (dotted-dashed line). Also shown is the singlet contribution alone ($\frac{4}{9} F_2(x)$, dashed line) of the CHARM structure functions.

TABLE 1

Summary of Λ_{QCD} determinations *)

	Λ_{LO}	$\Lambda_{\overline{\text{MS}}}$
CHARM (1)	non-singlet 187^{+130}_{-110} MeV $F_2, F_3, \text{ sea } 190^{+70}_{-40}$ MeV	non singlet 310 ± 140 MeV
CDHS (2)	non-singlet 275 ± 80 MeV $F_2, \text{ sea } 180 \pm 20$ MeV	non singlet 250^{+150}_{-100} MeV
BFP (4)	$F_2 \quad 227 \pm 43$ MeV	
CCFRR (4)	$F_2 \quad 210 \pm 90$ MeV $F_3 \quad 133^{+90}_{-70}$ MeV	$F_2 \quad 240 \pm 100$ MeV $F_3, (\text{Abbot})^{(a)} \quad 194^{+220}_{-150}$ MeV $(\text{Devoto})^{(b)} \quad 300^{+295}_{-219}$ MeV

*) Only statistical errors are given

LO: leading order perturbative QCD

 $\overline{\text{MS}}$: modified minimal subtraction renormalization scheme(a) Abbot et al., Annals Phys. 125 (1980) 276(b) Devoto et al., Phys. Rev. B27 (1979) 508

Fig. 1

Fig. 2

Fig. 3

Fig. 4