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дубна

E2-85-380

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NUCLEON STRUCTURE FUNCTIONS FROM THE ANALYSIS OF THE EMC DEEP INELASTIC μp AND μd SCATTERING DATA

Submitted to "ЯФ"

1985

Introduction

The discovery[1] of an anomaly in the ratio of the structure function $F_2^{\mu N}$ measured on iron to the structure function $F_2^{\mu N}$ measured on deuterium ("EMC effect") has again confirmed the importance of the free nucleon structure study. Deep inelastic lepton scattering on hydrogen and deuterium is one of the best methods to perform these investigations.

In this paper we analyse the European Muon Collaboration (EMC) data on deep inelastic μp and μd scattering. A test of QCD and the quark-parton ideas on the free nucleon structure is the aim of our study. The QCD results are in a good qualitative agreement with a great number of data on lepton-hadron and hadron-hadron processes in a large kinematic region. After the early period of exultation following many years without a strong interaction theory, a hard time for a detailed quantitative verification of the theory is coming. Due to high statistics one of the main advantages of the muon scattering experiments is an accurate measurement of the Q^2 dependence of the nucleon structure functions or the deviation from Bjorken scaling over a large range.

We confront to the data also the scale-invariant (SI) models[4] of the strong interactions. A power in Q^2 scaling violation for the moments of the structure functions has been predicted in these models. From an analysis of the SLAC deep inelastic ep scattering data we had come to the conclusion[5] that it is impossible to distinguish between the logarithmic (form QCD) and power scaling violation. Available Q^2 in the present muon experiments, however, are an order of magnitude larger, and it is important to answer the question: Are these data capable to distinguish between different Q^2 dependences of the structure functions?

The early[6] EMC data (E =120, 280 GeV) were analysed in papers[7,8]. The test of QCD evolution equations and the determination of the mass scale parameter Λ were the main aim of these

investigations. In the present work the free nucleon structure functions are given in terms of quark distributions. For the latter simple analytic expressions are supposed. All free parameters associated with these distributions are found from a simultaneous fit to the data and the evolution equations for their moments. In this way one can get an information not only on the Λ value, but on the quark parton distributions, and use it in the analysis of other processes. Such an approach to the study of the nucleon structure seems more general to us.

1. Method of Analysis

The differential cross section of the muon nucleon scattering in the one-photon exchange approximation has the following form:

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

where Q^2 is the momentum transfer squared, $x = Q^2/2M\nu$ - the scaling variable, M - the nucleon mass, $y = \nu/E$, $\nu = E - E'$, E and E' are the muon initial and final energy, respectively. The information on the structure of the nucleon is contained in the two structure functions F_1, F_2 which are functions of variables x and Q^2.

The cross section can be expressed via the structure function F_2 and the ratio

$$R = \frac{\sigma_L}{\sigma_T}, \qquad (2)$$

where σ_T and σ_L are the transverse and longitudinal absorption cross sections of the virtual photon. The structure functions F_1, F_2 and R are related as follows:

$$2xF_1 = \frac{F_2\left(1 + 4M^2x^2/Q^2\right)}{1 + R}. \qquad (3)$$

We shall examine the data in the leading order (LO) approximation of QCD and scale-invariant models. In this approximation:

$$R = 0, \qquad (4)$$

and then there is a one-to-one correspondence between the directly measured cross sections and F_2. Note that we consider the EMC data for the proton and deuteron structure function F_2 which has been found assuming R equal to zero.

In the LO approximation of QCD and the models under consideration the structure functions F_2^p and F_2^d can be written in the form:

$$F_2^p(x,Q^2) = \frac{4}{9}xu_v(x,Q^2) + \frac{1}{9}xd_v(x,Q^2) + \frac{2}{9}xS(x,Q^2) + \frac{4}{9}xC(x,Q^2), \quad (5a)$$

$$\frac{1}{2}F_2^d(x,Q^2) = \frac{1}{2}\left(F_2^p(x,Q^2) + F_2^n(x,Q^2)\right) = \quad (5b)$$
$$= \frac{5}{18}x\left(u_v(x,Q^2) + d_v(x,Q^2)\right) + \frac{2}{9}xS(x,Q^2) + \frac{4}{9}xC(x,Q^2),$$

where

$$S = 6s, \quad C = 2c \quad (c = \bar{c}).$$

In Eqs. (5a,b) u_v, d_v, S and C are the valence u and d, strange and charm quark distributions in the free proton. Note that to obtain these expressions for F_2, the SU(3)-symmetry for the sea quarks and Eq. $c = \bar{c}$ are assumed. In Eq. (5b) the assumption that the deuteron is a system of two quasifree nucleons is also made. We note, however, that unless the origin of the "EMC effect" is cleared, this conjecture will remain questionable.

The distributions u_v, d_v, S and G satisfy the Lipatov-Altarelli-Parisi (LAP) evolution equations/9/. To solve these equations, it is necessary to know the quark and gluon distribution functions at some reference point $Q^2 = Q_0^2$. These quantities are connected with the dynamics of strong interactions at distances of a hadron-mass-scale magnitude. That is why these distributions cannot be calculated in the perturbative quantum field theory, and to choose them, different phenomenological assumptions are used. All the free parameters defining the distribution functions at Q_0^2 and the mass scale parameter Λ are determined simultaneously from the data fit by integrating the LAP equations. However, it is possible to solve these equations only numerically. This is not so convinient for applications.

In this paper we use the method suggested by Buras and Gaemers /10/. According to this method, analytic parameterizations are looked for the distribution functions reproducing, to an excellent accuracy QCD/11/ or SI model/4/ predictions for the moments of these distributions. The parametrizations in question are taken in the following form:

$$xu_v(x,Q^2) = \Gamma_u(\bar{s})\,x^{\eta_1(\bar{s})}(1-x)^{\eta_2(\bar{s})}, \quad (6a)$$

$$xd_v(x,Q^2) = \Gamma_d(\bar{s})\,x^{\eta_3(\bar{s})}(1-x)^{\eta_4(\bar{s})}, \quad (6b)$$

$$xS(x,Q^2) = A_s(\bar{s})\,(1-x)^{\eta_s(\bar{s})}, \quad (6c)$$

$$xC(x,Q^2) = A_c(\bar{s})\,(1-x)^{\eta_c(\bar{s})}, \quad (6d)$$

$$xG(x,Q_0^2) = A_G\,(1-x)^{\eta_G}. \quad (6e)$$

Criteria for this choice are quark counting rules, Regge-pole mechanism and simplicity. In Eqs. (6a-6d)

$$\bar{s} = \ln\frac{\ln Q^2/\Lambda^2}{\ln Q_0^2/\Lambda^2} \quad (7)$$

for the case of QCD, and

$$\bar{s} = \alpha_0 \ln Q^2/Q_0^2 \quad (8)$$

for the SI models. In these models the assumption that the running coupling constant $\alpha_s(Q^2)$ is tending to a small quantity α_0 (an ultraviolet stable zero of the Gell-Mann-Low function) at large Q^2:

$$\alpha_s(Q^2) \xrightarrow[Q^2 \to \infty]{} \alpha_0 \ll 1 \quad (9)$$

is made. If such a situation is possible in the theory, then one can use the perturbative methods, and in particular, to calculate the moments of the structure functions/4/. The asymptotic coupling constant α_0 is an unknown parameter for the models of this kind.

Coefficients $\Gamma_u(\bar{s})$, $\Gamma_d(\bar{s})$ in Eqs. (6a,6b) are found from the well known sum rules:

$$\Gamma_u(\bar{s}) = 2\,\frac{\Gamma(\eta_1(\bar{s}) + \eta_2(\bar{s}) + 1)}{\Gamma(\eta_1(\bar{s}))\,\Gamma(\eta_2(\bar{s}) + 1)}, \quad (10a)$$

$$\Gamma_d(\bar{s}) = \frac{\Gamma(\eta_3(\bar{s}) + \eta_4(\bar{s}) + 1)}{\Gamma(\eta_3(\bar{s}))\,\Gamma(\eta_4(\bar{s}) + 1)}. \quad (10b)$$

A_G in Eq. (6e) is fixed by the energy-momentum sum rule

$$\int_0^1 dx\, x\left(u_v + d_v + S + C + G\right) = 1 . \tag{11}$$

The exponents $\eta_i(\bar{s})$ in Eqs. (6a,6b) are taken to be linear functions of $\bar{s}$:

$$\eta_i(\bar{s}) = \eta_i(0) + G\eta_i' \bar{s} , \quad i = 1,\dots 4, \tag{12}$$

where

$$G = \frac{4}{33 - 2N_f} \tag{13}$$

for the case of QCD (N_f is a number of flavours), and $G = 1/3\pi$ for the SI model. The parameters $\eta_i \equiv \eta_i(0)$ determine the u_v and d_v distributions at some fixed value of $Q^2 = Q_0^2$ and are to be found from the data.

Taking into account the expressions (6a,6b) one can obtain the ratio of the moments of the valence quark distributions $R_n(\bar{s};\eta,\eta')$ at two different values of Q^2

$$R_n^{(q_v)}(\bar{s},\eta,\eta') \equiv \frac{\int_0^1 dx\, x^{n-1} q_v(x,Q^2)}{\int_0^1 dx\, x^{n-1} q_v(x,Q_0^2)} , \tag{14}$$

$$q_v = u_v, d_v,$$

in an explicit form. On the other hand, in the LO approximation of QCD and SI models the quantities $R_n^{(q_v)}$ are given as follows:

$$R_n^{(q_v)}(\bar{s}) = \exp\left(-G\gamma_n \bar{s}\right) , \tag{15}$$

where γ_n are known numbers /11/.

Therefore, the parameters η_i' are required to satisfy the following conditions for the first 20 moments:

$$\left| \exp(-G\gamma_n \bar{s}) - R_n^{(q_v)}(\bar{s};\eta,\eta') \right| \le \varepsilon_0 \exp(-G\gamma_n \bar{s}) \tag{16}$$

in the range $0 \le S \le S_{max}$. Here ε_0 is the accuracy which is required for approximate solutions of the equations for the moments. The X region in which these solutinns are correct depends on the number n of the moments taken into account in Eq. (16). One can show that n=20 is enough to reproduce, up to an accuracy 2-3%, the

numerical solutions of the LAP equations for u_v and d_v distribution functions in the region $X \le 0.8$, $5 \le Q^2 \le 200$ GeV^2.

There are experimental evidences /12/ that the see quark distributions are closed to zero in the range $X \gg 0.45$. Then, as it has been shown in Ref. (10) the functions xS and xC can be determined from their first two moments. As a result, the coefficients $A_s(\bar{s})$, $A_c(\bar{s})$ and exponents $\eta_s(\bar{s})$, $\eta_c(\bar{s})$ in Eqs. (6c,6d) can be represented as follows:

$$A_s(\bar{s}) = P_s\left(\frac{1}{\langle x \rangle_s} - 1\right) , \quad A_c = P_c\left(\frac{1}{\langle x \rangle_c} - 1\right) , \tag{17}$$

$$\eta_s(\bar{s}) = \frac{1}{\langle x \rangle_s} - 2 , \quad \eta_c(\bar{s}) = \frac{1}{\langle x \rangle_c} - 2 ,$$

where

$$P_s \equiv S_2(Q^2) , \quad P_c \equiv C_2(Q^2) ,$$
$$\langle x \rangle_s \equiv \frac{S_3(Q^2)}{P_s} , \quad \langle x \rangle_c \equiv \frac{C_3(Q^2)}{P_c} . \tag{18}$$

In Eq. (18) $S_n(Q^2)$, $C_n(Q^2)$ are the moments of the see quark distributions. Their relations with the moments $S_n(Q_0^2)$, $C_n(Q_0^2)$ and $G_n(Q_0^2)$ and all quantities needed for the calculations can be found in Refs.(10).

So, $A_s(\bar{s})$, $A_c(\bar{s})$, $\eta_s(\bar{s})$, $\eta_c(\bar{s})$ are known functions of the free parameters:

$$A_s(\bar{s}) = A_s(\bar{s}; \eta_i, A_s(0), \eta_s(0), \eta_G) . \tag{19}$$

Note that the assumption $A_c(0) = 0$ is used.

We emphasize that all the free parameters connected with the quark distributions (η_i , A_s , η_s ; η_i') and $\Lambda^2(\alpha_0)$ were determined by minimizing the following functional:

$$\chi^2 = \chi^2_{exp} + \frac{1}{\varepsilon^2}\chi^2_{th} , \tag{20}$$

where

$$\chi^2_{th} = \sum_{n=2}^{20} \sum_{i=1}^{N} \sum_{q=u,d} \left\{ \frac{\exp(-G\gamma_n \bar{s}) - R_n^{(q_v)}(\bar{s}; \eta, \eta')}{\exp(-\gamma_n G \bar{s})} \right\}^2, \qquad (21)$$

and χ^2_{exp} is the usual functional for the measured structure function F_2. In Eq. (20) ε^2 is a certain weight. Its value should be determined so that the solution obtained for η_i, η'_i should approximate, up to an accuracy 2-3%, the LO evolution equations for the moments in the EMC kinematic region.

Note that in papers/10/ the values of the parameters η_i, A_s (η_s, η_G being fixed) have been determined by fitting the data at some fixed value of $Q^2=Q_0^2$. Then, the parameters η'_i have been obtained by fitting the evolution equations for the moments. However, the range in x, for which there are statistically significant data, changes radically at different values of Q^2. That is why for determining of the free parameters we use all available data. This procedure ensures that the proper values of Λ (α_0) and the other free parameters are obtained.

2. Results of the Analysis

In this section we give the results of analysis of the EMC deep inelastic μp /2/ and μd /3/ data in the following regions (157 experimental points):

μp: $0.03 \leq x \leq 0.75$, $\quad 5.5 \leq Q^2 \leq 170$ GeV^2;

μd: $0.03 \leq x \leq 0.65$ $\quad 7 \leq Q^2 \leq 170$ GeV^2.

The values of F_2^p combined at all avialible incident muon energies (E_μ=120, 200, 240, 280 GeV) have been used.

We note once again, the analysis has been done in the LO approximation of QCD and scale invariant models. We have investigated different kinematic domains. To eliminate the complications associated with the charm threshold at small x, the data have also been fitted without the points for $x \leq 0.08$. Only the lowest Q^2 points of this region were used to constrain the low x behaviour of quark and gluon distributions. We have further analysed the data with a cut $W^2 \geq 21$ GeV^2 in order to reduce higher twist effects. The cuts $Q^2 \geq 10$, 27 GeV^2 were also used. The QCD and SI model predictions in these regions are more reliable. Moreover, the higher twist corrections become smaller with Q^2 increasing. A fit to the data in the region $x \geq 0.25$ was performed too. The advantage in using this region is that the sea quark and gluon contributions to the structure functions can be neglected.

We have chosen Q_0^2=5 GeV^2. However, the results of our analysis are not sensitive to the choice of Q_0^2. The parameter η_G connected with the gluon distribution at Q_0^2 was taken to have a fixed value in the range $3 \leq \eta_G \leq 10$. The correlation between η_G and Λ is discussed below. We note that the errors taken into account in all the fits are only statistical.

The results are given in Table 1 ($\eta_G = 5$, $N_f = 4$). In Table 2 there are presented the values of all free parameters associated with the free proton valence, sea and gluon distribution functions at Q_0^2= 5 GeV^2. The values of these parameters were found by minimizing the functional χ^2 (Eq. 20). The values obtained of the exponents η_i are closed to those based on the quark counting rules and Regge-pole mechanism.

The results given in Table 1 could be summerized as follows:

1. The values of χ^2_{exp} per degree of freedom are practically independent of the regions examined, but these values are rather large: 1.4-1.6. However, if the procedure suggested in Ref./2/ is performed and all statistical errors are increased by a scale factor, then the values obtained for χ^2_{exp}/D_F become close to one. For instance, χ^2_{exp}/D_F= 152/149 in the case of the whole x range and η_G= 5. Besides, the values of all free parameters remain unchanged. We note also that in the last/13/EMC tables for the values of F_2 the statistical errors are increased for all points. One can also add that there are many theoretical uncertainties up to now. These could affect the results of a proper quantitative test of QCD.

2. On the base of the EMC data it is impossible to distinguish between the logarithmic and power law in Q^2 of scaling violation.

3. The mean values of Λ^2 are consistent within one standard deviation. The corresponding Λ values are in the range:

$$64 \leq \Lambda \leq 105 \text{ MeV}.$$

However, the Λ value found from the fit to the data at $Q^2 \geq 27$ GeV^2 is much bigger: Λ = 276 MeV. In our opinion, this fact could be explained when next-to-LO and higher twist corrections will be taken into account.

4. The obtained valence quark distributions reproduce, up to an accuracy of 2-3%, the Q^2 dependence of the first 20 moments both for QCD and SI models for $5 \leq Q^2 \leq 200$ GeV^2 and up to an accuracy of 4-5% for $5 \leq Q^2 \leq 10^3$ GeV^2.

Note that the Λ values found in our fits are in agreement with the results of Ref./7/. However, in some cases these values are

Table 1. Results of analysis of EMC data

Kinematic region	χ^2_{exp}/D_F	Λ^2 (MeV^2)	Λ (MeV)	$\alpha_S(30)$	$\frac{\varepsilon_0(Q^2_{max}=200\,GeV^2)\%}{\varepsilon_0(Q^2_{max}=103\,GeV^2)\%}$
$0,03 \le x \le 0,75$ $5.5 \le Q^2 \le 170\,(GeV)^2$	237/147	0.0056±0.0025	75	0.17±0.01	3/4.5
$0.08 \le x \le 0.75$ $5.5 \le Q^2 \le 170\,(GeV)^2$	205/132	0.0041±0.0023	64	0.17±0.01	3/4.8
$W^2 \ge 21$	216/137	0.0065±0.0024	81	0.18±0.01	3.4/5
$Q^2 \ge 10\,(GeV)^2$	196/136	0.0110±0.0053	105	0.19±0.01	2.4/3.7
$Q^2 \ge 27\,(GeV)^2$	118/83	0.0760±0.0463	276	0.25±0.02	2.5/4.2
$x \ge 0.25$ $xS = xC = 0$	141/86	0.0097±0.0071	98	0.19±0.01	1.6/2
	Scale invariant model ($\eta_G=5$, $N_f=4$, $Q_0^2 = 5$ GeV^2)				
$0.03 \le x \le 0.75$ $5.5 \le Q^2 \le 170\,(GeV)^2$	240/148	-	-	0.19±0.01	3/5
$x \ge 0.25$ $xS = xC = 0$	137/86	-	-	0.19±0.02	1.6/2.1

Table 2. QCD, Values of all free parameters ($\eta_G=5$, $A_G=3.24$, $N_f=4$, $Q_0^2=5$ GeV^2)

Kinematic region		1	2	3	4	η_S	A_S
$0.03 \le x \le 0.75$	η_i	0.64±0.01	2.92±0.04	0.76±0.03	4.61±0.25	18.74±1.17	1.18±0.05
$5.5 \le Q^2 \le 170\,(GeV)^2$	η_i'	-1.24±0.05	4.62±0.11	-1.57±0.10	4.96±0.14		
$x \ge 0.25$	η_i	0.67±0.01	3.04±0.06	0.76±0.06	4.50±0.37	-	-
$xS = xC = 0$	η_i'	-1.30±0.06	4.69±0.12	-1.53±0.15	4.96±0.14		

in a considerable disagreement with the corresponding values of Λ obtained in paper[8].

Futher, the influence of the gluon distribution on the mass scale parameter Λ has been investigated. The results are given in Table 3.

Table 3. Influence of xG on Λ (whole x, Q^2 region)

η_G	χ^2_{exp}/D_F	Λ (MeV)
3	267/147	88
5	237/147	75
10	229/147	52

It is seen from the table that Λ decreases from 88 to 52 MeV with changing η_G from 3 to 10. However, the values of η_G in the range $5 \le \eta_G \le 10$ are more likely. The situation in the case of scale invariant models is the same.

The results on the study of the charm sea and Λ ($\alpha_s(Q^2)$) correlations are presented in Table 4.

Table 4. Influence of xC on $\alpha_s(Q^2)$

Kinematic region	$xC \neq 0$		$xC = 0$	
	χ^2_{exp}/D_F	$\alpha_s(30)$	χ^2_{exp}/D_F	$\alpha_s(30)$
All x, Q^2	237/147	0.17 ± 0.01	246/148	0.24 ± 0.01
$x \geqslant 0.08$	205/132	0.17 ± 0.01	216/134	0.21 ± 0.02
$Q^2 \geqslant 27$ GeV^2 ($x \geqslant 0.08$)	118/83	$0,25 \pm 0,02$	125/84	$0,29 \pm 0,03$

It is seen from this table that the values of χ^2_{exp}/D_F are practically unchanged if the fit is done neglecting the charm sea contribution to F_2. The values of $\alpha_s(xC \neq 0)$ and $\alpha_s(xC = 0)$ found from the fits in the data regions: $x \geqslant 0.08$; $Q^2 \geqslant 27$ ($x \geqslant 0.08$), where the contribution from xC is less important, coincide within two standard deviations. These values, however, are not in agreement if the whole x region is fitted. But for small x the Q^2 EMC re-

gion lies well above the charm threshold and, therefore, the charm contribution to F_2 should be taken into account.

Summary

The EMC deep inelastic μp and μd scattering data have been examined in the LO approximation of QCD and scale-invariant models. The free nucleon structure functions were parametrized in terms of quark distribution functions. For the latter simple analytic expressions were used. The value of $\Lambda(\alpha_0)$ and all the free parameters connected with the distribution functions have been found from a simultaneous fit to the experimental data and the Q^2 evolution for the moments. The distributions thus found approximate, up to an accuracy of 2-3%, the numerical solutions of the LAP equations in the EMC kinematic region. On the base of EMC data it is impossible to distinguish between the logarithmic (from QCD) and power (from SI models) scaling violation. Depending on the region examined and on the assumptions on theoretical uncertainties the following limits on the QCD mass scale parameter Λ and α_0 (SI models parameter) were found:

QCD: $52 \le \Lambda \le 276$ MeV,

$0.17 \le \alpha_s(30) \le 0.25$;

SIM: $0.18 \le \alpha_0 \le 0.25$.

It is well known that comparison of the Λ values obtained from different processes is only possible when next-to-LO corrections are taken into account. In this approximation, however, $R^{th} \neq 0$, and for that reason a fit to the cross sections data (not to F_2) is needed. Such a method has been applied by us[5] to the analysis of the SLAC ep scattering data.

The authors are grateful to I.A.Savin for support and interest in this work. We would like to thank also Yu.M.Kazarinov, A.V.Radyushkin, D.Bakalov, and G.Sultanov for useful discussions. One of the authors (D.S.) is thankful to T.Sloan who has kindly supplied us with the EMC data tables for F_2.

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Структурные функции нуклона из анализа данных ЕМС по глубоконеупругому μp- и μd-рассеянию

Излагаются результаты анализа данных ЕМС по глубоконеупругому μp- и μd-рассеянию в рамках главного логарифмического приближения КХД и масштабно-инвариантных /МИ/ моделей. Структурные функции выражаются через кварк-партонные распределения свободного нуклона. Все свободные параметры находятся из совместного фита экспериментальных данных и эволюционных уравнений для моментов этих распределений. Показано, что данные ЕМС не позволяют отличить логарифмического /КХД/ нарушения скейлинга от степенного /МИ модели/. Получены следующие границы для значений параметров Λ /КХД/ и a_0 /МИ модели/ в зависимости от рассматриваемой кинематической области и различных предположений о неопределенных в теории величинах: $52 \le \Lambda \le 276$ МэВ; $0,18 \le a_0 \le 0,25$.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1985

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Nucleon Structure Functions from the Analysis of the EMC Deep Inelastic μp and μd Scattering Data

The EMC deep inelastic μp and μd scattering data are analyzed. The analysis is done in the framework of the leading order approximation of QCD and scale invariant (SI) models. The free nucleon quark distributions are used to calculate the structure functions. All free parameters are found from a simultaneous fit to the experimental data and the evolution equations for the moments of these distributions. It is shown, that on the base of the EMC data it is impossible to distinguish between the logarithmic (from QCD) and the power low in Q^2 (from SI models) scaling violation. Depending on the region examined and on the assumptions about theoretical uncertainties the following limits on the values of Λ, the QCD mass scale parameter, and a_0, the SI models parameter, are obtained: $52 \le \Lambda \le 276$ MeV; $0.18 \le a_0 \le 0.25$.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1985