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ON A RELATION BETWEEN CROSS SECTION OF DEEP INELASTIC SCATTERING AND INCLUSIVE ANNIHILATION

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Abstract

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Arguments are presented that the available experimental data on structure functions of processes $ep \to eX$ and $e^+e^- \to p(\bar{p})X$ do not confirm the so called "reciprocity relation" obtained in the LLA approach of perturbation theory. It is also shown that the asymptotic relation of these processes obtained under more general considerations does not contradict the experimental data.

Аннотация

Петров В.А., Рютин Р.А. О связи сечений глубоконеупругого рассеяния и инклюзивной аннигиляции : Препринт ИФВЭ 98–59. – Протвино, 1998. – 18 с., 13 рис., библиогр.: 36.

Представлены аргументы в пользу того, что существующие экспериментальные данные по структурным функциям процессов $ep \to eX$ и $e^+e^- \to p(\bar{p})X$ не подтверждают так называемое "соотношение взаимности", полученное в ГЛП приближении теории возмущений. Показано также, что асимптотическая связь этих процессов, найденная из более общих соображений, не противоречит имеющимся экспериментальным данным.

Introduction

At present there exist a lot of experimental data on Deep Inelastic Scattering (DIS) $ep \to eX$ and Inclusive Annihilation (IA) $e^+e^- \to p(\bar{p})X$. These processes are important [1] for the investigation of such a fundamental phenomenon as confinment, and so for the verification of different kinds of models (QCD, Bag model, String model) and the first principles of quantum field theory (locality, causality e.t.c.)

The study of analytical properties and asymptotic behaviour of cross sections is of great significance. Two main relations between structure functions of DIS and IA have been obtained on this way. The former is the analytical continuation from the DIS--channel to the IA-channel (crossing), following from the basis of quanum field theory [2],[3],[4],[5], and the later is the so-called "reciprocity relation" [6], that was found in Leading Log Approximation (LLA) of the perturbation theory for QCD [7],[8] and for other models. Unfortunately, the number of articles on this theme has been noticeably reduced, also there were no discussions on a detailed experimental verification of some theoretical results. (see, however, [9]).

In the present paper, we try to retrieve the faults of previous papers and to show once again that any theoretical speculation must agree with experimental data. It is found by an elaborate analysis that some "hard-established" predictions have not been confirmed experimentally. In addition to this, we obtained a more general relation between structure functions of DIS and IA and compared it with the experimental results. The material on IA: ARGUS($\sqrt{Q^2} = 9.8\ Gev$) [10], TASSO ($\sqrt{Q^2} = 14, 22, 34\ Gev$) [11], TPC [12], HRS [13]($\sqrt{Q^2} = 29\ Gev$), TOPAZ ($\sqrt{Q^2} = 58\ Gev$) [14], OPAL [15], DELPHI [16] ($\sqrt{Q^2} = 91.2\ Gev$), and DIS: NMC [17], BCDMS [18], ZEUS [19], H1 [20], EMC [21], E665 [22], SLAC [23], and also the MRS parametrization [24] of structure functions are used here.

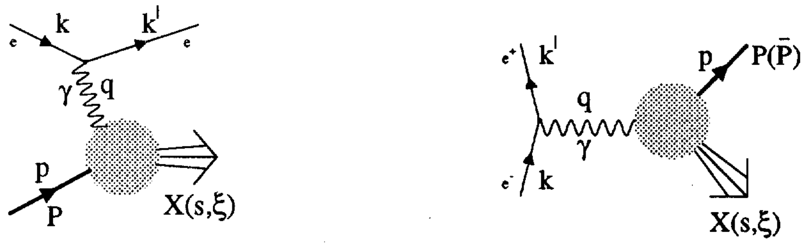

Fig. 1. Process of DIS. $s = (p+q)^2$ (the left figure). Process of IA. $s = (p-q)^2$ (the right figure).

1. On a relation of processes

Analytical continuation

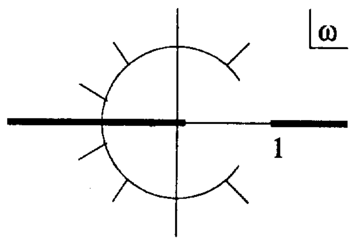

Fig. 2. Region of analyticity in ω, which follows from the perturbation theory, when anomalous thresholds are taken into account ($\omega = -q^2/(s-q^2)$, $\omega = x$ when $\omega > 0$).

Let us discuss in detail some approaches to the investigation of the crossing.

The earliest approach consists in using the expansion of T-product of currents near the "light cone" and in the assumption for F_i and $\bar{F}_i$ to be Q^2-independent, when Q^2 is high enough (scaling). Analytical properties derived from the perturbation theory are displayed in fig. 1. It is shown in [4] that there are two possibilities:

1. $F_i(x)$ can be analytically continued to $\bar{F}_i(x)$, and we have the crossing in the form:

$$\bar{F}(x) = -\Re\mathrm{e}\, F(x) + \rho(x) \quad , \tag{1}$$

where $\rho(x)$ can be expressed in terms of spectral functions of $F(x)$ in the annihilation region ($x > 1$) (fig. 1). The absence or presence of the cut along the real axis in this region determine two kinds of analytical continuation. The "simple crossing" [2] holds, when $\rho \equiv 0$, and looks as follows:

$$\bar{F}(x) = -F(x), \quad x > 1 \quad . \tag{2}$$

And we have to use (1), when $\rho \neq 0$. It is also pointed out in [4] that even if there is no cut, when $x > 1$, i.e. $\Im\mathrm{m}\, F(x) = 0$, then $\rho(x)$ is not necesserily equal to zero, and the following relation can exist:

$$\bar{F}(x) = -F(x) + \rho(x), \quad x > 1 \quad . \tag{3}$$

2. Nontrivial "scaling" holds separately for each process, but there is not any relation like analytical continuation.

The second way is to apply causality and spectrality only, without using the T-product expansion. The approach was studied in [3], and the essence of it is to get structure functions from the nonforward Compton amplitude (fig. 3). Selecting appropriate diagrams, which give the contributions to structure functions, and comparing the analytical expressions, we find the so-called "general crossing"

$$\overline{W}_2(s,q^2) = -\Re\mathrm{e}\, W_2(s,q^2) - \epsilon(s + M^2 - q^2)\cdot$$
$$\cdot\, \theta(s - s_0)\theta(q^2 - q_t^2) g(q^2, q^2, s, 0) \quad . \tag{4}$$

Here, $g(q^2, q'^2, s, t)$ is the triple discontinuity of the nonforward Compton amplitude on q^2,q'^2 and s at $t \neq 0$, which satisfies the relation

$$g(q^2, q'^2, s, t) = g(q'^2, q^2, s, t) \quad . \tag{5}$$

Let us note the fact that in this approach both the structure functions $\overline{W}$ and W can be expressed in terms of one spectral function g, in other words, there is a unified analytical function, and our structure functions are boundary values of it. Also, scaling is not implied, and (4) holds for any Q^2.

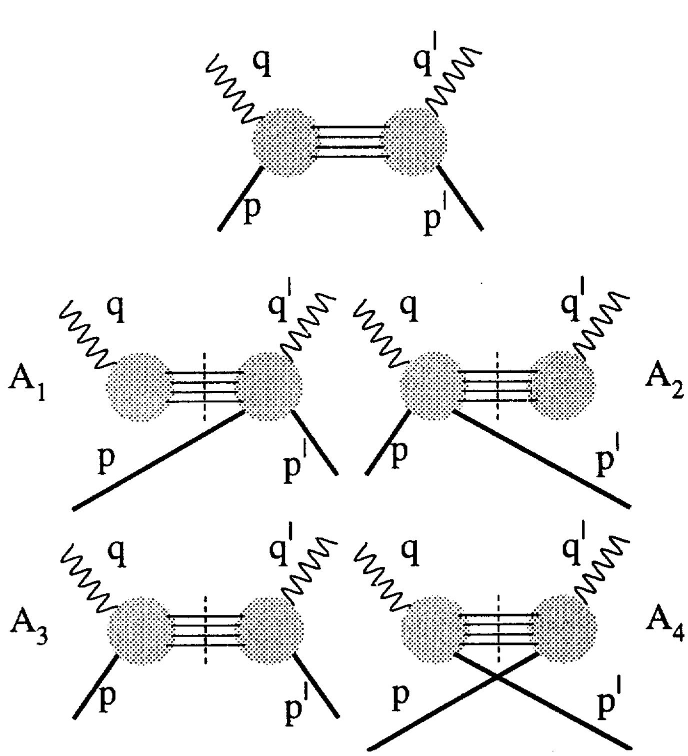

Fig. 3. Amplitude for $t = (q - q')^2 \neq 0$, $s = (q + p)^2 = (q' + p')^2$, $u = (q - p')^2 = (q' - p)^2$. Diagrams A_3 and A_4 give contributions to structure functions of DIS and IA correspondingly, when $t = 0$ ($q' = q$, $p' = p$). Structure functions are introduced as usual [2],[5],[6]: $F_2(x, q^2) = \nu W_2(x, q^2) = xW(x, q^2)$, the Callan-Gross relation [25] is assumed: $F_2(x, q^2) = 2xF_1(x, q^2)$; here, $x = Q^2/2M\nu$, $Q^2 = |q^2|$, $\nu = pq/M$, M is the proton mass. All this is correct for the structure functions of IA. It is convenient to use $z = 1/x < 1$ in the annihilation region.

The existence of such a unified analytical function of two complex variables was discussed in [26] from another viewpoint. By assuming the asymptotical behaviour of structure functions to be general enough for fixed s and $q^2 \to \pm\infty$, the following relation was obtained there:

$$\lim_{q^2 \to \infty} \frac{W(-q^2, s)}{\overline{W}(q^2, s)} = 1 \quad . \tag{6}$$

Since s is fixed, then this formula can be rewritten in the form:

$$\lim_{x \to 1} \frac{W(x, s)}{\overline{W}(x, s)} = 1 \quad . \tag{7}$$

The advantage of the relation in comparison with the crossing is that both stucture functions are taken in their physical regions. It enables us to verify (6), (7) experimentally, making some qualifications (see later). The "reciprocity relation" (see the next section) has also the lack of generality, because it was obtained by perturbative methods.

The "reciprocity relation"

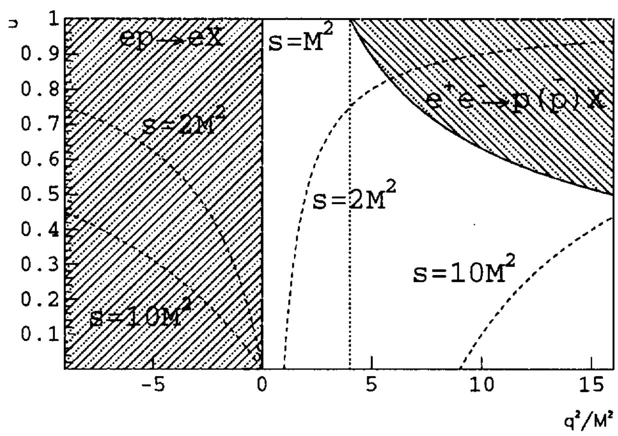

Fig. 4. Physical regions in variables q^2 and u, where $u = x$ (DIS), $u = z$ (IA). $s = const$- -curves are presented as dashed lines. At $s = M^2$ we get the straight line $u \equiv 1$. Dotted line shows $q^2 = 4M^2$.

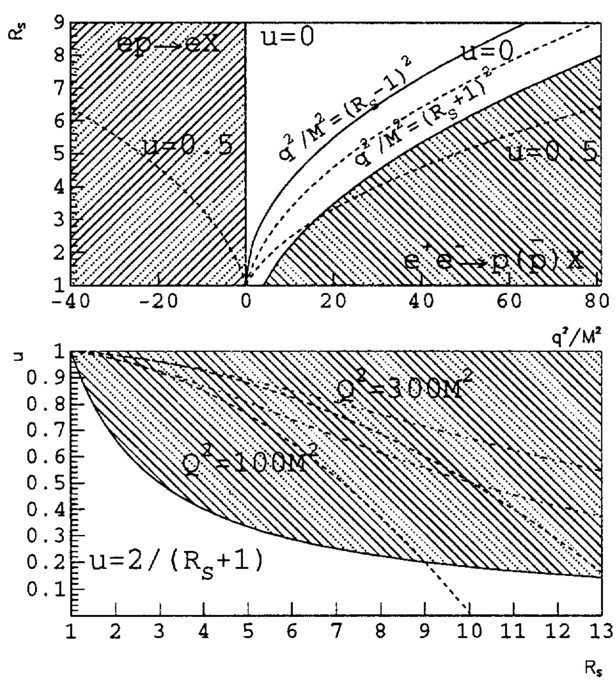

Fig. 5. Physical regions in variables s,q^2 (the top figure) and s, $u = x$ (DIS), $u = z$ (IA) (the bottom figure). Curves $u = const$ are presented as dashed lines in the top illustration, so one can see curves $Q^2 = const$ (dashed lines for IA and broken lines for DIS) and the shaded region of IA in the bottom one. $R_S^2 = s/M^2$

The "reciprocity relation", which connects DIS with IA in their physical regions (fig. 4, 5), was first obtained in [6] by the resummation of ladder graphs of the perturbation theory for the vector and the pseudoscalar models of interaction. It looks as follows:

$$\overline{W}(\frac{1}{x}, q^2) = xW(x, q^2) \quad , \tag{8}$$

where $\overline{W}$ and W are structure functions, which can be obtained from the amplitude of the Compton scattering of the virtual photon by a spinor particle. It has been emphasized that in the case of scattering the virtual photon by a virtual particle, the relation is the same for the pseudoscalar model, but it takes a more complicated form for the vector model:

$$\overline{W}_{virt}(\frac{1}{x}, q^2) = x \int\limits_0^1 \frac{d\gamma}{\gamma} W_{virt}(\frac{1}{\gamma}, q^2) \cdot æ(\ln(\gamma x)) \quad , \tag{9}$$

although, when $Q^2 \to \infty$, this formula goes to (8) with corrections of the order of $o(M^2/Q^2)$. One can find this relation for QCD in [7], [8].

There were many contradictory discussions on the "reciprocity relation" [27]-[33] after the publication of [6]. The majority of authors got their results by perturbative methods. For example, it was shown in [30] that (8) is violated, when $x \to 0$, because of some differences in mechanisms of DIS and IA reactions. Arguments were given in [27] based on the considerations of certain ladder graphs that (8) was valid only in the vicinity of $x \sim 1$ under condition that $W(x) \sim (1-x)^n$ for $x \to 1$. Nonleading logarithms were not taken into account in these papers.

Articles [28], [32] are devoted to the analysis of Nonleading Log Approximation. The role of nonperturbative effects, which violate the "reciprocity relation", was discussed in [31]. Taking the three last papers as a basis, one can conclude, that (8) may not exist in general. That is why all the computations have to be verified experimentally.

2. Experimental data analysis

Structure functions and cross sections

It is convenient to express (8) in terms of functions F_2 and $\bar{F}_2$, because these functions are directly related to differential cross sections of DIS and IA. It is known from the experimental work [17] that

$$\frac{d^2\sigma(x, Q^2, E)}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4} \cdot \frac{F_2(x, Q^2)}{x} \cdot$$

$$\cdot \left\{ 1 - y - \frac{Q^2}{4E^2} + (1 - \frac{2m^2}{Q^2}) \cdot \frac{y^2 + Q^2/E^2}{2(1 + R(x, Q^2))} \right\} \quad , \tag{10}$$

where α is the constant of fine structure, E,m are the initial energy (in the lab. frame) and the lepton (μ or e) mass, $y = \nu/E$, $R = \sigma_L/\sigma_T$ is the quantity, which characterizes the violation of the Callan-Gross relation [34]. Using (10), one can extract F_2. From the representation of the cross section in [2], we obtain the formula for $\bar{F}_2$:

$$\bar{F}_2(z,q^2) = \left[\frac{1}{\beta\sigma_h}\frac{d\sigma^{e^+e^-\to p+X}}{dz}\right]\frac{2\mathcal{R}}{(3-\beta^2)z^2} = \frac{1}{z}\overline{W}(z,q^2) \quad , \tag{11}$$

$$\mathcal{R} = \frac{\sigma_h}{\sigma_0} \quad , \tag{12}$$

$$\sigma_0 = \sigma_0(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3q^2} \quad , \tag{13}$$

where σ_h is the total cross section of process $e^+e^- \to$ hadrons, and $z = 1/x = 2pq/|q|^2$. Finally, we get the following expression for the "reciprocity relation":

$$F_2(x,q^2) = \frac{2z\mathcal{R}}{3-\beta^2}\cdot\left[\frac{1}{\beta\sigma_h}\frac{d\sigma^{e^+e^-\to p+X}}{dz}\right] = z^3\bar{F}_2(z,q^2) \quad . \tag{14}$$

The β-function is preserved to go easily from other experimental quantities to the functions presented in (14), although usually it is assumed to be equal to unity.

It is to be noted before the analysis that the experimental data on IA are collected only for a small number of Q^2 values, since the colliding energy is fixed, and we have to take the data from different accelerators and to average Q^2 values, because of the difficulty in finding the same ones for DIS and IA.

From visuality considerations and to demonstrate tendencies, we use interpolation functions. MRS-fit [24] is taken for $F_2(x,Q^2)$, and for IA we take a widespread parametrization:

$$\bar{F}_2(z,q^2) = Nz^a(1-z)^b(1+cz^d) \quad , \tag{15}$$

where N,a,b,c,d depending on q^2 were obtained by the computer analysis of experimental points.

The "reciprocity relation" violation

Let us start with the analysis. Structure functions F_2 and $\bar{F}_2$ are presented in the top left picture of each figure (6 - 12). In the top right picture we can see functions, which characterize the "reciprocity relation" (14) and must be directly compared.

Two bottom illustrations are also important in the analysis. The left one shows us the difference $\Delta_{EXP} = x^3\bar{F}_2 - F_2$ (i.e. the difference of corresponding interpolation curves) and the Next-to-Leading QCD-correction (Δ-QCD) for the nonsinglet part of structure functions. It can be calculated easily by using the evolution equation

$$Q^2\frac{\partial}{\partial Q^2}F_{NS}(x,Q^2) = K_{NS}(x,\alpha_s)\bigotimes F_{NS}(x,Q^2) \quad , \tag{16}$$

where $F_{NS} = F_{2,NS}; \bar{F}_{2,NS}$(the same is valid for K_{NS}),

$$f(x)\bigotimes g(x) = \int_x^1 \frac{dy}{y}f(\frac{x}{y})\cdot g(y) \quad ,$$

and so the correction to the kernel K_{NS} of this equation

$$\Delta K_{NS,2}(x) \equiv K_{NS,2}(x) - x\bar{K}_{NS,2}(\frac{1}{x}) =$$

$$= \left(\frac{\alpha_s}{4\pi}\right)^2 \cdot \left\{-4C_F^2[(-5 - x + \frac{6}{1-x})\ln x + \right.$$

$$+(3 + 3x - \frac{4}{1-x})\ln^2 x + 4\frac{1+x^2}{1-x}\ln x \ln|1-x|] +$$

$$\left. + b_0 C_F[-6\frac{1+x^2}{1-x}\ln x + 7(1+x) - 2\pi^2\delta(1-x)]\right\} \quad , \qquad (17)$$

($C_F = 4/3$, $b_0 = 23/3$), which was obtained in [32]. The right one gives us the possibility to study the behaviour of $x^3\bar{F}_2/F_2$ and to observe the violation of the "reciprocity relation" clearly. In addition it can be said, that the data for $\sqrt{Q^2} < 10$ *Gev* can be found in [9].

Let us consider each figure in detail. So, begin with fig. 6, where the data for $\sqrt{Q^2} = 9.8$ *Gev* are presented. It is to be noted that errors are much greater for IA than for DIS, therefore we have nothing particular to prove the truth of the "reciprocity relation". So, the interpolation curve tends to go up (the right bottom illustration) for the large x. The same can be said about figures 7, 8, 10, 11, where we see the violation more distinctly. Comparing the QCD-correction with the experimental result (curve in the left bottom illustration), we observe the noticeable differences in their behaviour, and the validity of the "reciprocity relation" seems to be doubtful. The situation is better in fig.9, since errors are not so large, the number of experimental points is enough for our purposes, and we can see once again the disagreement of (14) with the experimental data. In fig. 11 we take only the interpolation curve for DIS, and it is known, however, that Q^2-dependence of F_2 is slight, so the curve is taken exactly for $\sqrt{Q^2} = 58$ *Gev*, therefore errors are not so large, at least in the low-x region. Recent results from LEP at $\sqrt{Q^2} = 91.2$ *Gev* (fig. 12) provide us with just one more proof of the "reciprocity relation" violation.

In some papers [33] the authors tried to explain the fact of the violation and to obtain some improved relation. For example, it was shown in [33] that a scaling factor appeared of the order of $2 \div 4$, by which we can devide the right side of (14) (i.e. interpolation values in the right bottom pictures of fig. 6 -12). It was pointed out that the mechanisms of DIS and IA reactions were different, namely: in DIS everything took place in the limited region ("bag"); in IA this "bag" arose from the jet of partons, so this explanation led to the fact that the measured functions might differ from the functions, appearing in the initial "reciprocity relation". One can agree with the last statement. However, when using the data and introducing a correction coefficient, we will not get significant improvements in the low-x region. As to the region of x close to unity, agreement seems to exist for $\sqrt{Q^2} = 91.2$ *Gev*, but we cannot say anything particular.

Thus, taking as a basis all the experimental material, we make the following conclusions:

- The "reciprocity relation" is not valid for any value of x.
- There is some hope for it to be in agreement with the experimental data for x close to unity, when the use of the relation with the correction of the order of $2 \div 4$ is made, but this approach is not strict enough.

The next section shows, how to modify relation (8) by using the first principles of quantum field theory and to verify new relation experimentally.

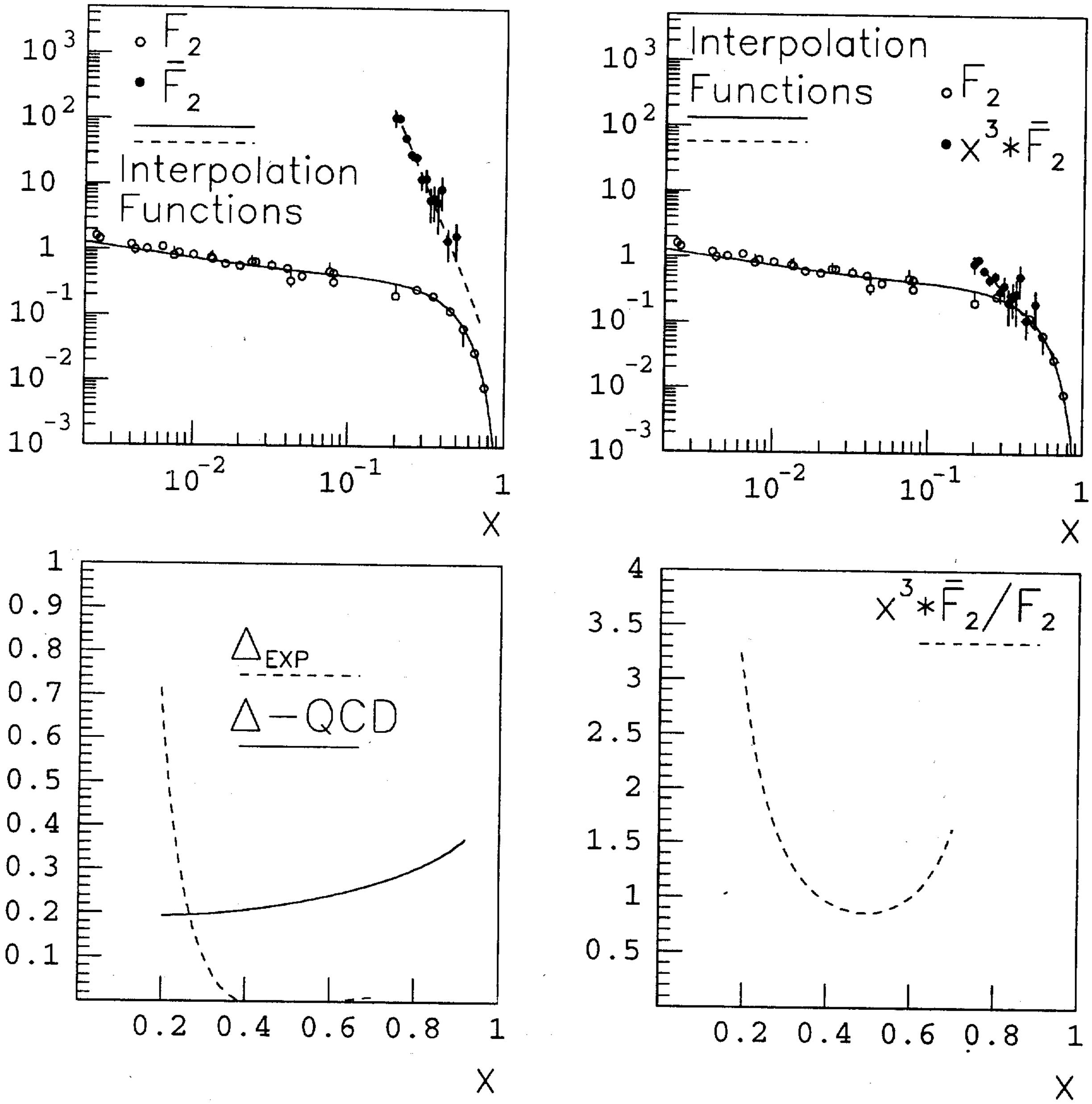

Fig. 6. Experimental data at $Q^2 = 96\ GeV^2$.

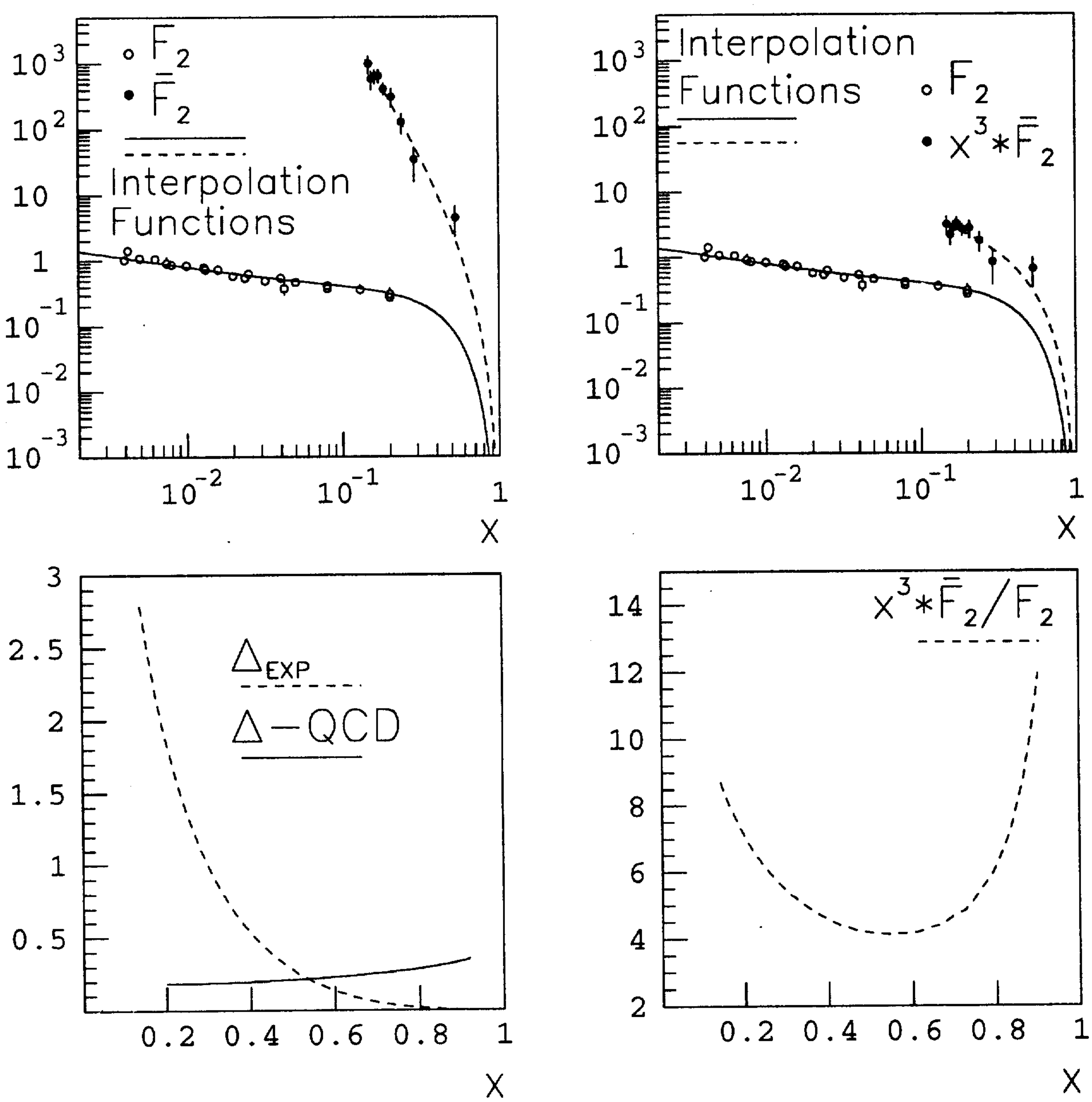

Fig. 7. Experimental data at $Q^2 = 196\ GeV^2$.

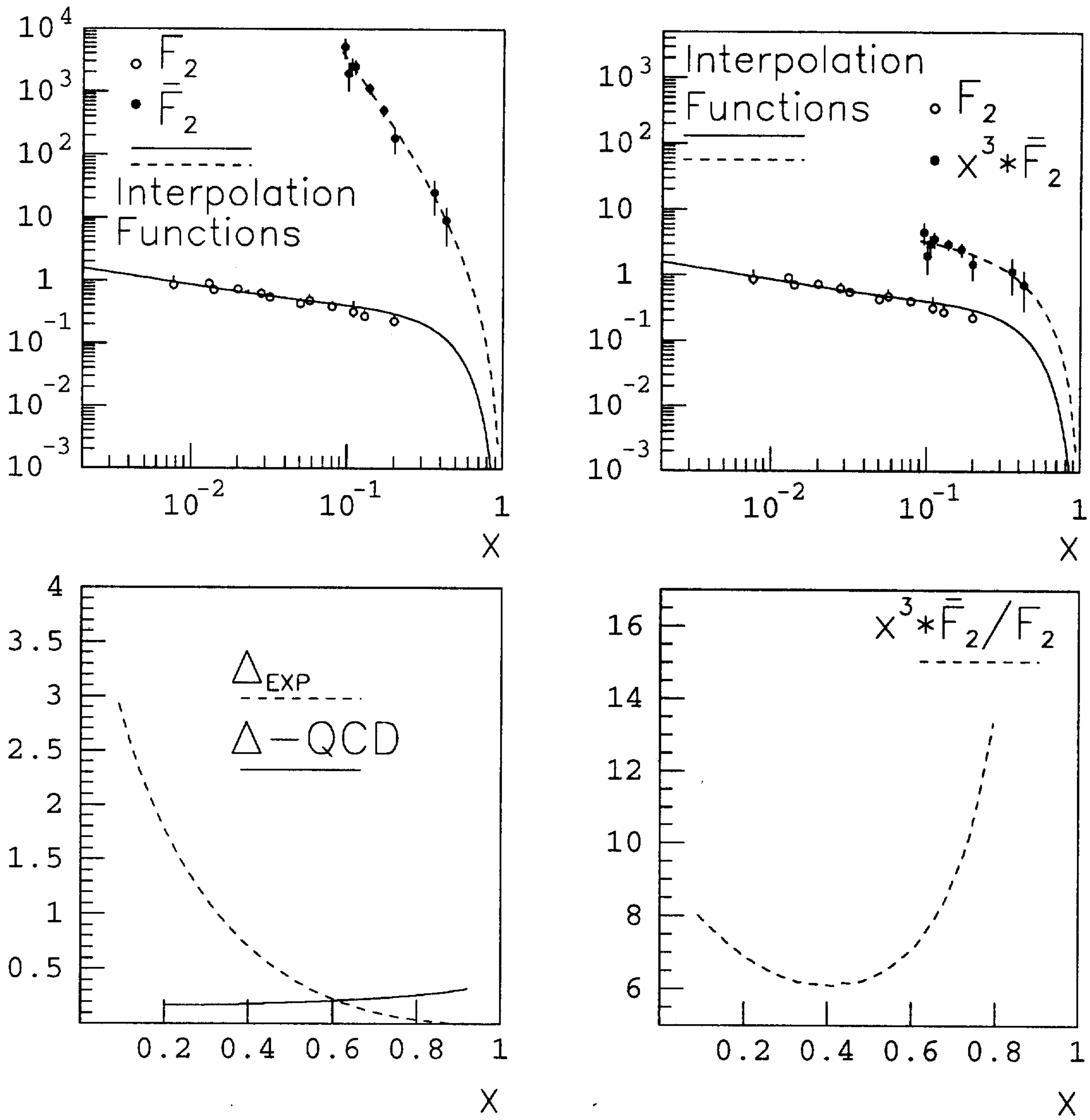

Fig. 8. Experimental data at $Q^2 = 484\ GeV^2$.

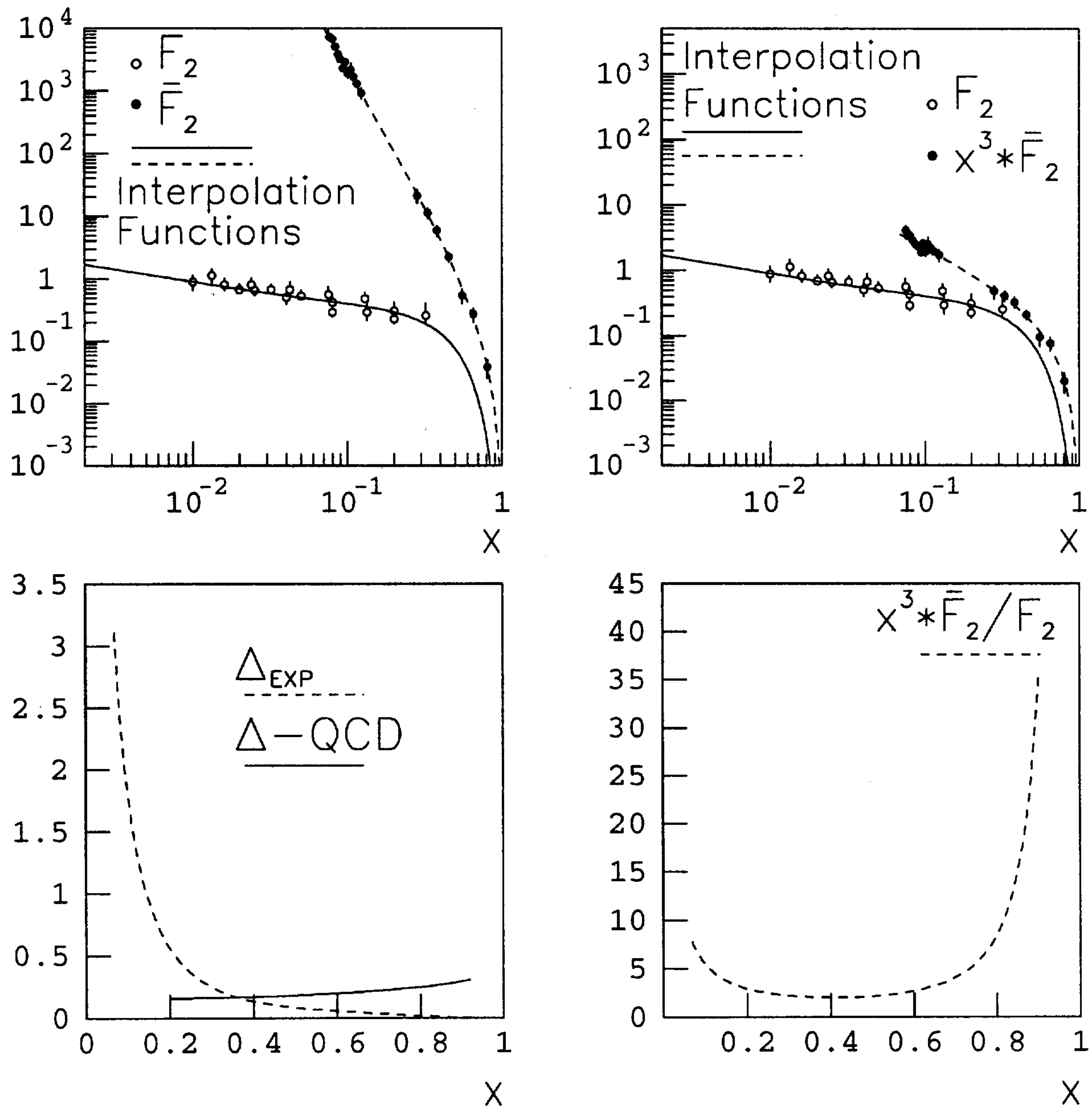

Fig. 9. Experimental data at $Q^2 = 841\ GeV^2$.

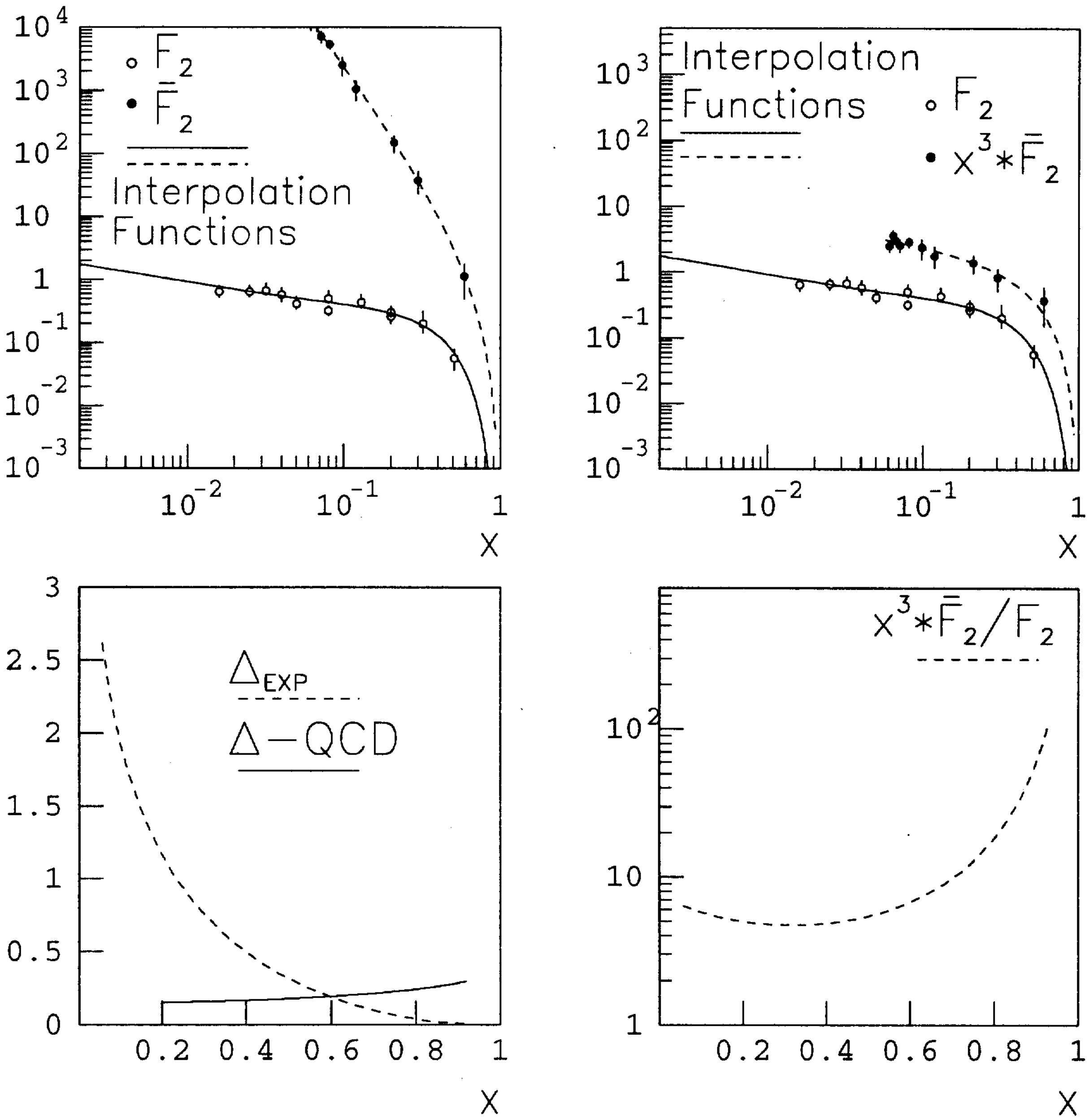

Fig. 10. Experimental data at $Q^2 = 1156\ GeV^2$.

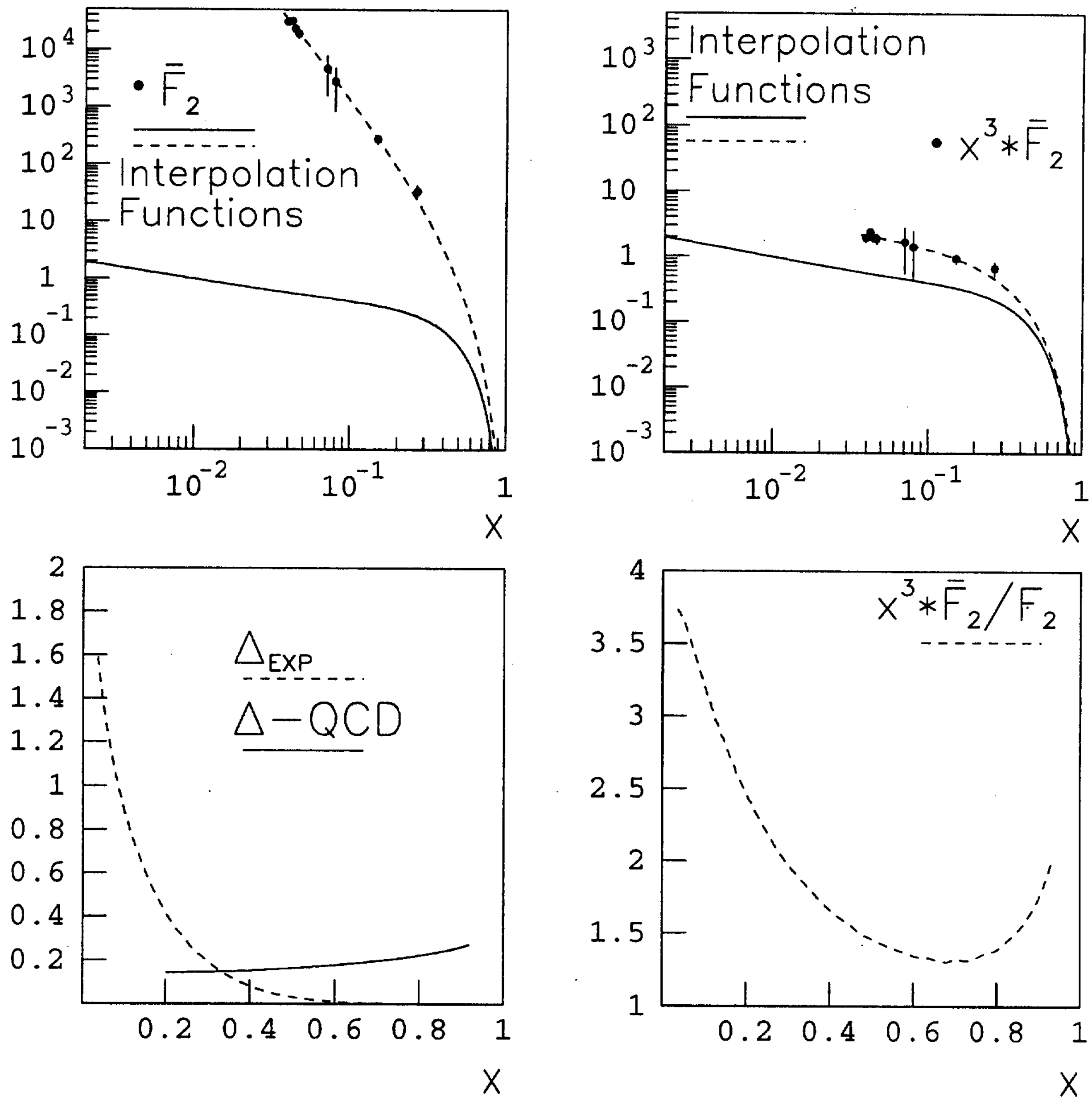

Fig. 11. **Experimental data at $Q^2 = 3364\ GeV^2$.**

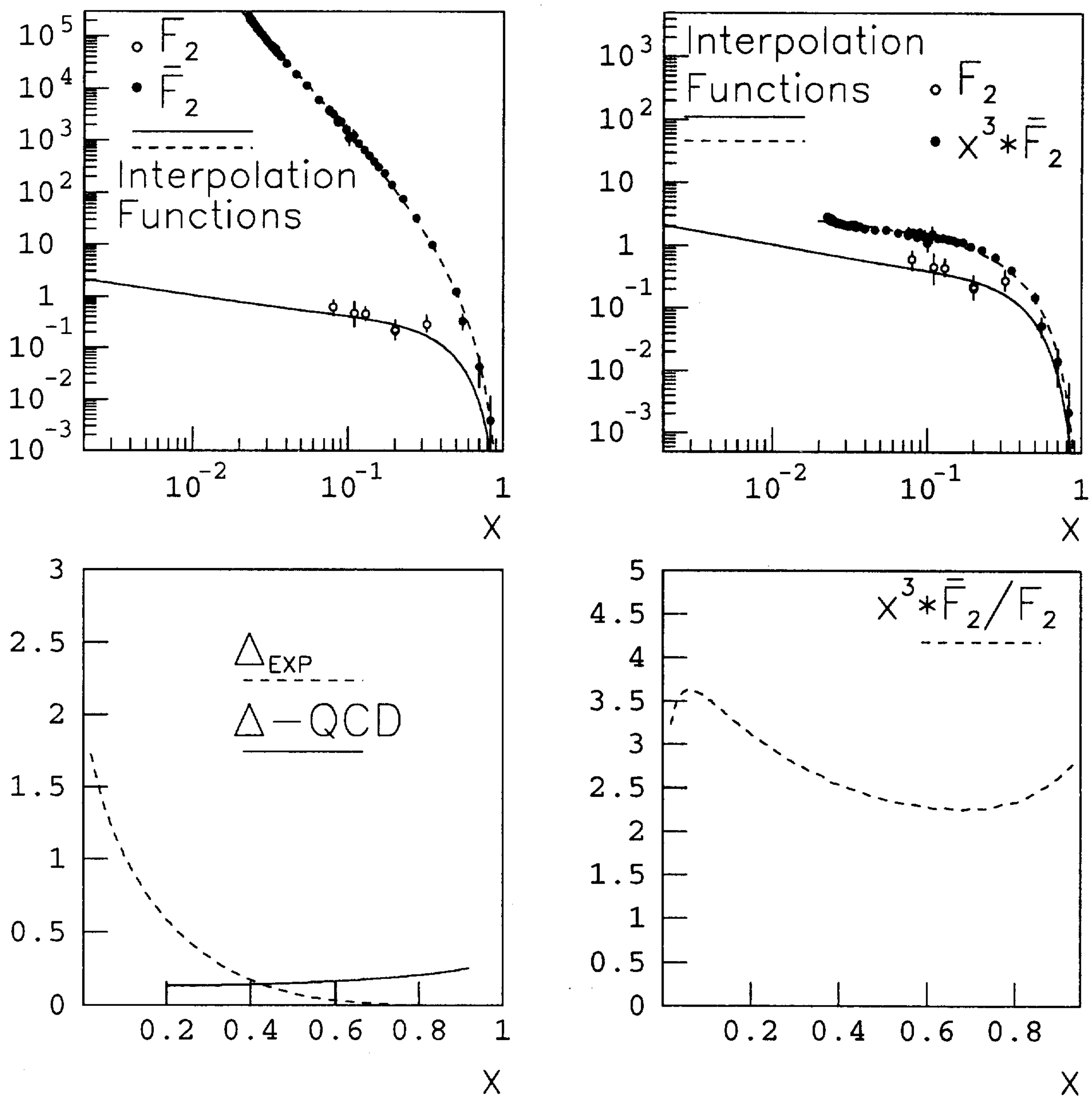

Fig. 12. Experimental data at $Q^2 = 8317\ GeV^2$.

Analysis of the modified relation

As has been noted above, relation (6), that holds at a fixed s, was found in [26]. It is necessary to have out here, what we are ultimately comparing. Let us do it, taking the model of partons as a basis. Using formula (10) and the representation

$$\frac{d^2\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4} \cdot \left[\sum_{i=1}^{N_f} e_{q_i}^2 (f_{q_i}(x,Q^2) + f_{\bar{q}_i}(x,Q^2))\right] \cdot$$

$$\cdot \left\{1 - y + \frac{y^2}{2}\right\} \quad , \tag{18}$$

we get

$$\frac{F_2}{x} = \sum_{i=1}^{N_f} e_{q_i}^2 (f_{q_i}(x,Q^2) + f_{\bar{q}_i}(x,Q^2)) \quad . \tag{19}$$

Comparing this expression with the similar one for the fragmentation functions of the parton model [35], [36]($N_C = 3$)

$$2z\bar{F}_1 \equiv z^2\bar{F}_2 = N_C \sum_{i=1}^{N_f} e_{q_i}^2 \left[\bar{D}_{q_i}^h(z) + \bar{D}_{\bar{q}_i}^h(z)\right] \quad , \tag{20}$$

we find that the following relation

$$\lim_{Q^2\to\infty} \frac{x^3(s,Q^2)\cdot\bar{F}_2(s,Q^2)}{3F_2(s,Q^2)} = 1 \tag{21}$$

must be investigated at the fixed s, i.e. functions F_2/x and $x^2\bar{F}_2/3$ are to be compared for $0 < x < 1$.

The main difficulty of the experimental verification of (21) is that we have to extract points for the fixed s (curves $s = const$ in fig. 4) from the existing data for different Q^2 and x. It reduces sharply the number of points. Nevertheless, we have enough data for our purposes, and there is a possibility of the verification, if the use of interpolation curves is made. Data are selected by simple rules: for DIS $s - M^2 = Q^2(1/x - 1) = const$ and for IA $s - M^2 = Q^2(1 - z) = const$.

The results are shown in fig.13. We conclude from this figure, that (21) can be regarded as a correct one, when Q^2 is high enough. Only the top left figure is an exception, where the last point is far above an expected value. However, Q^2 is not high enough, and if we take the point from the interpolation curve, then we will get the value approximately 1.5 times lower, so it is clear from a simple consideration of functions decreasing, when $Q^2 \to \infty$. Finally, it can be said that the experimental data do not contradict the modified relation. It is the another confirmation of the basic principles of quantum field theory.

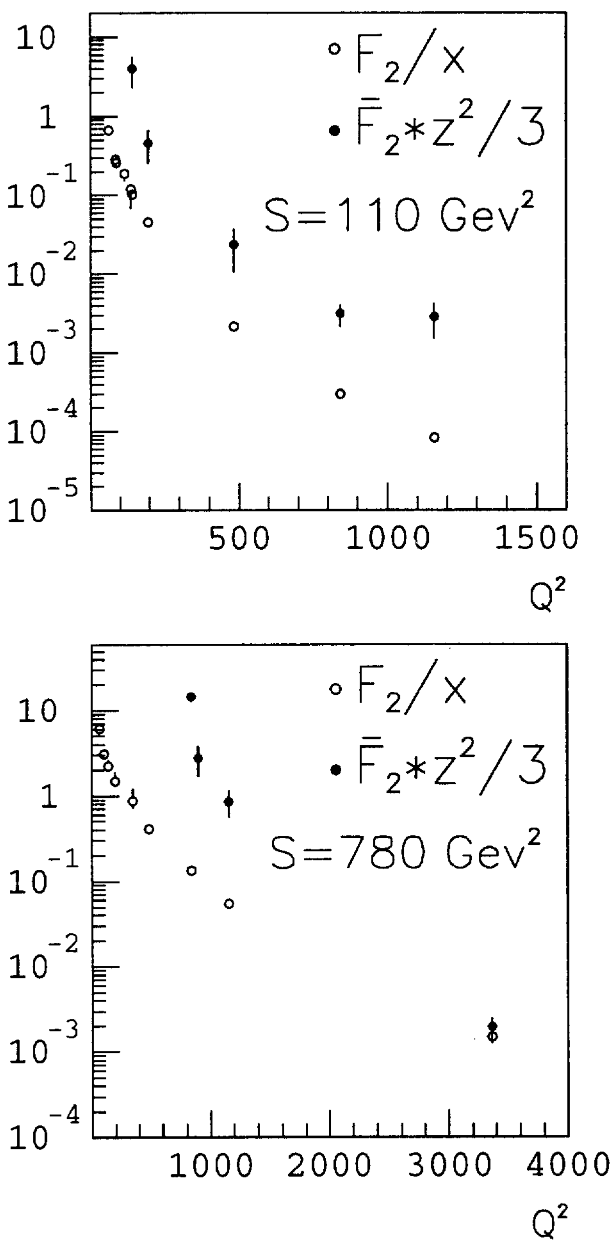

Fig. 13. **Experimental data at fixed** s**.**

3. Conclusions

Thus, we conclude from the above that:

- The "reciprocity relation", obtained in the LLA approach of perturbation theory, does not agree with the experimental data in the region $\sqrt{Q^2} < 91.2\ GeV$. As to its validity (when $\sqrt{Q^2} \geq 91.2\ GeV$) and the correction coefficient of the order of $2 \div 4$, this is only phenomenological evaluation, that is based on some additional assumptions.
- The study of the modified relation found from the basic principles of quantum field theory shows the possibility for it to be correct in the region, when Q^2 is high enough. To ascertain it finally, one must investigate the data in this region with better accuracy.

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