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CAN THE NONRELATIVISTIC QUARK MODEL BE RECONCILED WITH DEEP INELASTIC SCATTERING RESULTS?

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Abstract

We define two quantities, which for high Q^2 tend respectively to Bjorken's and to Gottfried's sum. We elaborate a nonperturbative evolution model for such quantities, showing that at low Q^2 they have the same evolution and that at $Q^2 \sim 0$ they match the nonrelativistic quark model predictions about the axial charge and about the average quark isospin content of the proton.

I. INTRODUCTION

Several years ago two deep inelastic scattering (DIS) experiments [1,2] contradicted respectively the Ellis-Jaffe [3] and the Gottfried [4] sum rule, both based on naive assumptions - isoscalar sea and unpolarized strange sea - trivially satisfied by the non-relativistic quark model (NRQM). Moreover the value of the nucleon axial charge extracted from neutron beta decay is in contrast with the one resulting from NRQM calculation. Isospin symmetry implies that, as to the first moment of the isotriplet component of the polarized nucleon structure function, the NRQM prediction differs from the result of the Bjorken sum rule [5], consistent with recent experiments [6] provided radiative corrections [7,8] are taken into account. On the contrary the NRQM describes satisfactorily some static properties of light baryons, like masses and magnetic moments. This suggests that, as far as hadron structure functions are concerned, we can hope to reconcile the NRQM predictions with data by considering their evolution from low Q^2 - less than $(100 - 300\ GeV)^2$ - to Q^2 of order 4 to 10 GeV^2. This is in line with recent efforts of connecting the high-Q^2 and low-Q^2 descriptions of hadrons [9–12].

In the present article we limit ourselves to the isotriplet sector, therefore we consider the Bjorken sum and the Gottfried sum. For very high Q^2 these integral quantities consist almost exclusively in the leading twist contributions, corresponding to Feynman graphs with only one active quark. Since NRQM assumes approximate independence between constituent quarks, the predictions of this model are to be confronted with quantities which are low-Q^2 extrapolations of the leading twist contributions to the Bjorken or to the Gottfried sum. In the following we shall define these quantities, which we shall call respectively $B_0(Q^2)$ and $G_0(Q^2)$. Then we shall elaborate a model of nonperturbative evolution for $B_0(Q^2)$ and

$G_0(Q^2)$, showing that for very small Q^2 they match the NRQM predictions. In particular, at first, we shall propose a nonperturbative evolution model for $B_0(Q^2)$, suggesting two different mechanisms, according as Q^2 is greater or less than 0.5 GeV^2. Secondly we shall show that the model describes as well the evolution of $G_0(Q^2)$. Lastly we shall compare a consequence of our model with experimental data of the New Muon Collaboration, NMC [2].

Previously various attempts were done to explain the discrepancies of the NRQM predictions about isotriplet structure functions with respect to DIS data and, as regards the polarized structure function, also with respect to the Bjorken sum rule. The result of this rule, according to which the proton axial charge is predicted to be $g_A \simeq 1.2575$ instead of $\frac{5}{3}$, has been explained, in the framework of spontaneous chiral symmetry breaking [13], as a spin dilution due to a nonperturbative interaction between valence quarks and gluons [14]. By the way, spontaneous chiral symmetry breaking has been shown to produce the same effect of a Melosh [15] rotation, which therefore describes, in a modern terminology, the B_0 evolution from $Q^2 = 0$ to ∞. On the other hand the violation of the Gottfried sum rule - $G_0(Q^2 = 4\ GeV^2) = 0.240 \pm 0.020$ instead of the predicted value of $\frac{1}{3}$, as results from the NMC measurement - has been illustrated in different models, among which we recall the one by Sawicki and Vary [16], Ball and Forte [17](BF), Wakamatsu [18], Cheng and Li [19] and other authors quoted in refs. [16,17]. In particular BF start from the same viewpoint that we adopt in the present paper, although they use a different evolution model. It is also worth signalling some previous aprroaches relating the evolution of the polarized structure function to that of the unpolarized one [20–24].

Sect. 2 is devoted to the definition of the quantities whose evolution we shall study. In sect. 3 we present a model of nonperturbative evolution for $B_0(Q^2)$. In sect. 4 we show that by a plausible assumption the same model describes as well the evolution of $G_0(Q^2)$, then we compare our predictions with experimental results of the NMC. Sect. 5 is devoted to a short dicussion of the results and to a comparison with the BF model.

II. DEFINITIONS

The most natural way of defining $B_0(Q^2)$ and $G_0(Q^2)$ is to extend to any Q^2-value the limiting formulas of quark-parton model, valid at very large Q^2, i. e.,

$$B_0(Q^2) = \frac{1}{6}\int_0^1 dx[\Delta\hat{u}(x,Q^2) - \Delta\hat{d}(x,Q^2)], \tag{2.1}$$

$$G_0(Q^2) = \frac{1}{3}\int_0^1 dx[\hat{u}(x,Q^2) - \hat{d}(x,Q^2)], \tag{2.2}$$

$$\hat{q} = q_+ + q_- + \overline{q}_+ + \overline{q}_-, \qquad \Delta\hat{q} = q_+ - q_- + \overline{q}_+ - \overline{q}_-, \tag{2.3}$$

where $q = u$ ("up") or d ("down") and $+(-)$ denotes helicity parallel (antiparallel) to the nucleon spin. We relate the above defined quantities to those leading twist operators that contribute to the first moments of isotriplet unpolarized and polarized structure functions, i. e., respectively, to the isotriplet axial current and to the isotriplet scalar density:

$$B_0(Q^2)s_\mu \quad = \quad \frac{1}{6}C(Q^2) < p,s|\overline{\psi}\ \gamma_5\gamma_\mu T_3\psi|p,s>, \tag{2.4}$$

$$G_0(Q^2) \quad = \quad \frac{2}{3}C'(Q^2) < p,s|\overline{\psi}T_3\ \psi|p,s>; \tag{2.5}$$

s is the spin four-vector of the proton and C and C' are functions which in the perturbative regime - that is for Q^2 large enough - tend to the reduced Wilson coefficients in the operator product expansion, i. e.,

$$C(Q^2) \quad = \quad 1 - \frac{\alpha_s}{\pi} - 3.5833\ (\frac{\alpha_s}{\pi})^2 - 20.2153(\frac{\alpha_s}{\pi})^3 - (\sim 130)(\frac{\alpha_s}{\pi})^4 + ... \tag{2.6}$$

$$C'(Q^2) \quad = \quad 1 + (\sim 0.01)\alpha_s + ... \tag{2.7}$$

In such a regime the anomalous dimension of the isotriplet axial current vanishes, whereas the one of the isotriplet scalar density is nontrivial only to two loops. Therefore, to the extent that we limit ourselves to one-loop approximation and neglect the residual Q^2-dependence in the Wilson coefficients (which amount to a 10 % correction for B_0, 0.3 % for G_0), both quantities have no evolution. This is a consequence of the one-loop splitting function, corresponding to the elementary process $q \to qg$ for massless quarks, which does not create nor destroy quark-antiquark pairs and preserves flavour and helicity of the initial quark. As we shall see, B_0 and G_0 have, to a good approximation, the same evolution for low Q^2.

III. NONPERTURBATIVE EVOLUTION OF $\mathbf{B_0}$

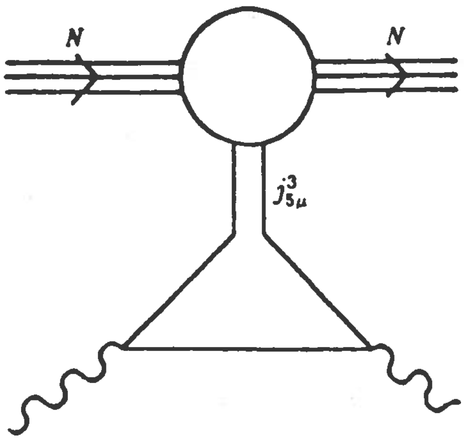
Let us consider the evolution of B_0. The component of the hadronic tensor corresponding to $j^5_{3\mu}$ - named $T^0_{\mu\nu}$ from now on - consists in the convolution over the proton state of the triangle electromagnetic anomaly, as shown in fig. 1. At infinitely large Q^2 the active quark - a current quark - is not dressed by strong interactions and therefore, according to Bjorken's sum rule, $B_0 = \frac{1}{6}g_A$, where g_A is the axial coupling constant derived from the neutron beta decay. At finite but large Q^2 gluon radiative corrections are taken into account, resulting in the reduced Wilson coefficient $C(Q^2)$ (see eq. (2.6)). At sufficiently small Q^2 (less than $Q_p^2 \sim 4\ GeV^2$) nonperturbative contributions become of some relevance. For $Q^2 < \Lambda^2_{\chi SB}$ ($\Lambda_{\chi SB} \simeq 1\ GeV$) spontaneous chiral symmetry breaking occurs and at these energy scales a very suitable effective lagrangian appears to be the one proposed by Manohar and Georgi [9](MG), who assume that for $\Lambda_c^2 < Q^2 < \Lambda^2_{\chi SB}$ (where $\Lambda_c \sim 100 - 300\ MeV$ is the confinement scale) the elementary objects are the constituent quarks and the (quasi) Goldstone bosons. The MG effective lagrangian is particularly appropriate for describing the nonperturbative evolution of the quantities in question, in that it ensures continuity with respect to the QCD lagrangian. In the original version also gluons were assumed as fundamental fields, but recently Glozman [25] has shown that they are by no means necessary at small Q^2, where they could even create some trouble in gluon polarization [26]. We shall assume this more recent version of the effective lagrangian.

As to the hadronic tensor $T^0_{\mu\nu}$, we assume, according to the MG lagrangian, that the active quark involved in the triangle anomaly is a constituent quark. As a check of this assumption we invoke the uncertainty principle. The collision of the spacelike photon with the active quark can be viewed as a t-channel annihilation of a photon into a quark-antiquark pair, whose offshellness is of order

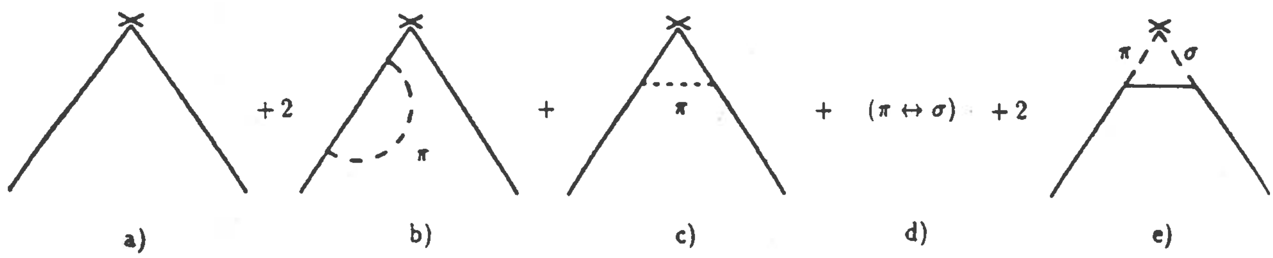
$$\Delta s = 4m^2 - q^2 = 4m^2 + Q^2, \tag{3.1}$$

$m \simeq 360\ MeV$ being the mass of the constituent quark. The larger Δs, the smaller the interaction time. For $\Delta s > 1\ GeV^2$, and therefore for $Q^2 > 0.5\ GeV^2$, the process is perturbative. By the way, the lower limit we obtain for Q^2 from the uncertainty principle nicely agrees with the MG apparently "perverse viewpoint" [9] of separating chiral symmetry breaking from confinement.

In order to determine the coefficient $C(Q^2)$ (eq. 2.4) in this interval of Q^2, we adopt the calculation by Peris [27], in the framework of a nonlinear sigma model (see also ref [28]). We have chosen a specific model in order to carry on calculations, however we believe our conclusions to be independent of the details. Peris determines the one-loop corrections to the axial coupling, using the linear sigma model as a regulator of the divergences of the nonlinear sigma model. The sum of these corrections - which consist in the vertex corrections and wavefunction renormalization, as shown in fig. 2 - is independent of any ultraviolet cutoff



[Fig.1] - The antisymmetric isotriplet component of the hadronic tensor.



[Fig.2] - Axial vertex and corrections due to nonlinear sigma model.

and in logarithmic approximation we have

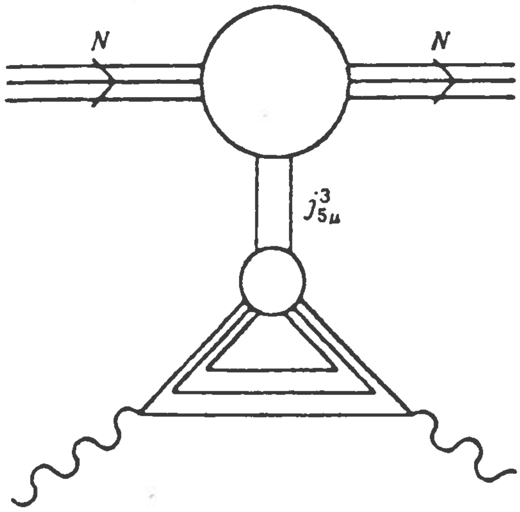
$$g'_A = 1 - \frac{g^2}{(4\pi)^2} \, log(\frac{m_\sigma^2}{m^2}), \qquad m_\sigma = 4\pi f_\pi \tag{3.2}$$

where $f_\pi = 93\ MeV$ and g is the pion-quark effective coupling constant, running from $\sqrt{\frac{4\pi m}{f_\pi}}$, for $Q^2 \leq \Lambda^2_{\chi SB}$, to 0 for $Q^2 \geq Q^2_p$. As a result Peris gets $g'_A \simeq 0.8$, in good agreement with the phenomenological value of the axial coupling constant, i. e., $g'_A = \frac{3}{5} g_A$.

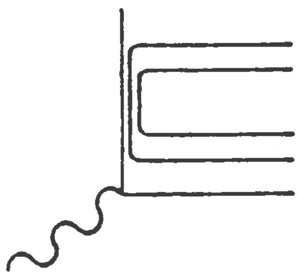
In our calculation also the corrections to the two electromagnetic vertices should be taken into account. However in logarithmic approximation they do not lead to any net contribution, as can be seen either by direct computation or invoking the Ward identity, owing to which the divergences of the vertex and wavefunction corrections compensate each other. Therefore for $0.5\ GeV^2 < Q^2 < \Lambda^2_{\chi SB}$ we have $C(Q^2) = g'_A$ and $B_0 = \frac{1}{6} g_A g'_A$, which, by the way, matches the perturbative QCD correction at $Q^2 = O(\Lambda^2_{\chi SB})$.

For Q^2 smaller than $0.5\ GeV^2$ the photon-quark collision lasts a sufficiently long time for the quark, before interacting with the photon, to evolve towards a more stable asymptotic state - a colour singlet - by emitting one or more quark-antiquark pairs. This suggests that the B_0 evolution depends on different degrees of freedom. In particular at scales of order Λ^2_c we assume - according to the Weinberg lagrangian [29], whose fundamental fields are light hadrons (see also [30]) - the active constituent quark to be dressed by the quark-antiquark pair(s), so as to form a virtual hadron (see figs. 3 and 4). Therefore the axial current consists of light hadrons instead of quarks. Since coupling of the axial current with light bosons is very unlikely (pion forbidden, ρ-meson weakly coupled), the most likely candidate hadron is the nucleon, for which the coupling constant to the axial current is g_A. By the way, three remarks are in order:

i) With respect to the axial current, the nucleon plays the same role in the Wein-



[Fig.3] - Corrections to the antisymmetric isotriplet component of the hadronic tensor at small Q^2.



[Fig.4] - Virtual dressing of the active quark at small Q^2.

berg lagrangian as the constituent quark in the MG lagrangian, since both are regarded as fundamental fermions in different regimes.

ii) The coupling constant g_A includes pion exchange corrections as well as the constant g'_A.

iii) The offshellness Δs of the nucleon is at least of 1 GeV^2, so that the (virtual) hadron is very short-lived and only the original active quark collides with the photon, such an interaction being kinematically very unlikely for one of the other two quarks.

From the preceding considerations it follows that at confinement scales the first moment of the leading-twist contribution to the isotriplet component of the polarized structure function becomes

$$B_0 = \frac{1}{6} g_A^2 \simeq \frac{1}{6} 1.59, \tag{3.3}$$

which almost equals the prediction by NRQM. The small discrepancy with respect to $B_0 = B_S = \frac{5}{18}$ is consistent with the slight mixing of irreducible $SU(2)_L \otimes SU(2)_R$ representations caused by interactions responsible for hyperfine baryon structure, that is, quark-gluon or quark-Goldstone boson [25] interaction. In this connection, multiplying B_S by the mixing angles found by LeYaouanc et al. [31] and Conci-Traini [32], we get values close to the result (3.3).

To summarize, B_0 has the following evolution:

i) it equals approximately the NRQM prediction for very small Q^2, of order Λ_c^2;

ii) it decreases down to $\sim \frac{1}{10} g_A^2$ for $0.5\ GeV^2 < Q^2 \leq \Lambda_\chi^2$;

iii) lastly it raises to $\frac{1}{6} g_A (1 - \frac{\alpha_s}{\pi})$ for $Q^2 \geq Q_p^2$.

We conclude this section with one more remark. The apparent paradox, according to which a low energy result (neutron beta decay) controls the high energy behaviour of a structure function, can be explained intuitively. The two situations involve either the charged or the neutral axial quark current, coupled respectively to the lepton charged current (via four-point interaction) and to a gamma pair (via axial anomaly); obviously leptons have no strong interactions, on the other hand at infinitely high Q^2 the quark triangle anomaly is not dressed by any gluon radiative corrections.

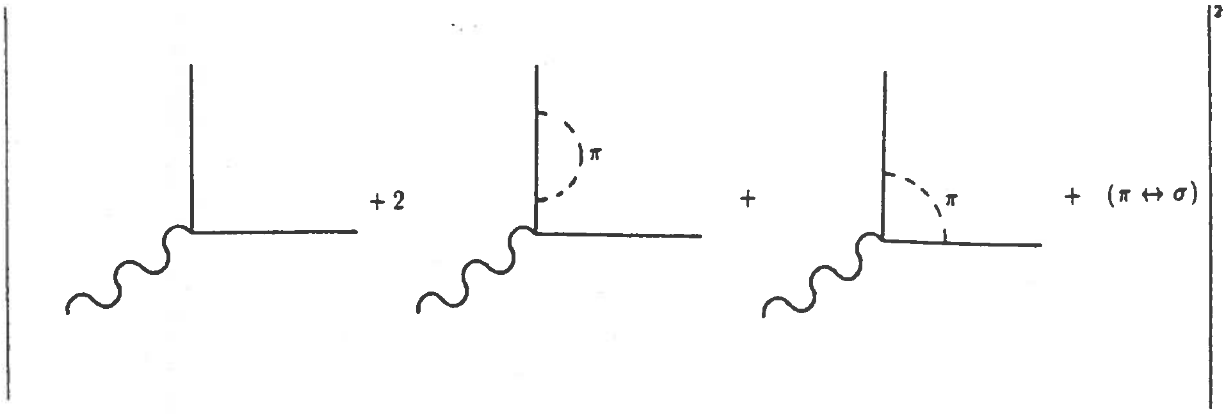
IV. EVOLUTION EQUATIONS FOR $\mathbf{B_0}$ AND $\mathbf{G_0}$

As is well-known, the hadronic tensor is often conveniently regarded as the elementary quark-photon cross section convoluted with parton distribution in the nucleon. Here we show that the elementary processes implicitly assumed for $T^0_{\mu\nu}$ in the preceding section describe as well the symmetric isotriplet leading-twist component of the hadronic tensor, which therefore has the same evolution for $Q^2 \leq Q_p^2$.

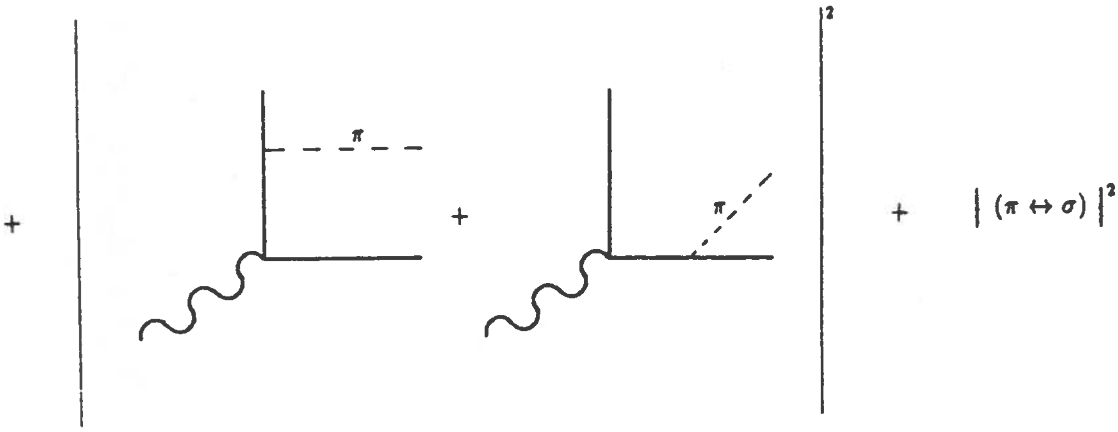
In particular for 0.5 $GeV^2 < Q^2 \leq Q_p^2$ the elementary processes corresponding to the vertex and wavefunction corrections of the axial current are represented in fig. 5. By the way, as regards the process represented in fig. 5c), it is worth noting that, after convolution with quark distribution in isotriplet combination, only the interference term - corresponding to the graph of fig. 2e - survives. As stressed by Eichten et al [20], the quark reverses its helicity after emitting the pion. Since the pion carries isospin 1, helicity and isospin changes are strictly correlated: as we are going to show, the model describes simultaneously the evolution of B_0 and G_0.

To this end we consider the evolution due to pion exchange of $\hat{q}_\pm(x, Q^2) = q_\pm(x, Q^2) + \overline{q}_\pm(x, Q^2)$. According to our preceding consideration, the following transitions are allowed:

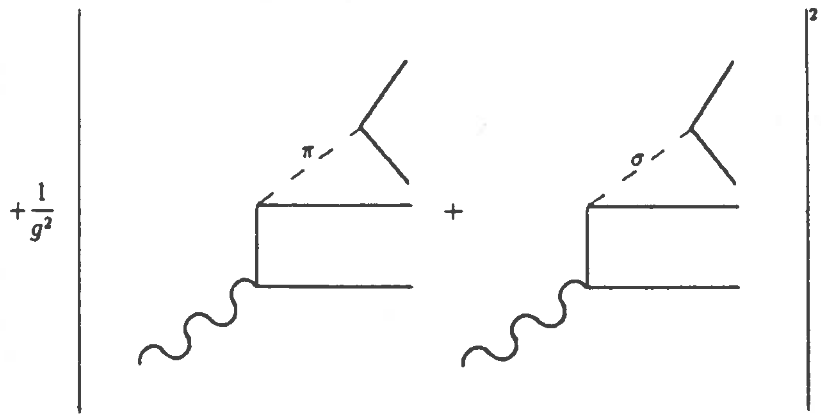
$$\pi^{\pm} exchange: \qquad u(\overline{u})_{+(-)} \longleftrightarrow d(\overline{d})_{-(+)}; \qquad (4.1)$$



a)



b)



c)

[Fig.5] - Graphic representation of the elementary cross section describing the nonperturbative evolution at not too small Q^2 of the isotriplet - symmetric and antisymmetric - components of the hadronic tensor.

$$\pi^0 exchange: \qquad u(\overline{u})_{+(-)} \longleftrightarrow u(\overline{u})_{-(+)}, \qquad d(\overline{d})_{+(-)} \longleftrightarrow d(\overline{d})_{-(+)}. \tag{4.2}$$

Then, a small change from Q^2 to $Q^2 + \Delta Q^2$ causes a change in quark densities described by a system of integrodifferential equations analogous to the Altarelli-Parisi one, i. e.,

$$\Delta\hat{u}_+ \simeq \Delta\sigma^{\pi^\pm} \otimes (\hat{d}_- - \hat{u}_+) + \Delta\sigma^{\pi^0} \otimes (\hat{u}_- - \hat{u}_+) + \ ....., \tag{4.3}$$

$$\Delta\hat{u}_- \simeq \Delta\sigma^{\pi^\pm} \otimes (\hat{d}_+ - \hat{u}_-) + \Delta\sigma^{\pi^0} \otimes (\hat{u}_+ - \hat{u}_-) + \ ....., \tag{4.4}$$

$$\Delta\hat{d}_+ \simeq \Delta\sigma^{\pi^\pm} \otimes (\hat{u}_- - \hat{d}_+) + \Delta\sigma^{\pi^0} \otimes (\hat{d}_- - \hat{d}_+) + \ ....., \tag{4.5}$$

$$\Delta\hat{d}_- \simeq \Delta\sigma^{\pi^\pm} \otimes (\hat{u}_+ - \hat{d}_-) + \Delta\sigma^{\pi^0} \otimes (\hat{d}_+ - \hat{d}_-) + \ ....., \tag{4.6}$$

where $\Delta\sigma$ is the variation of the elementary cross section $\sigma(\gamma Q \to \pi Q')$ (see fig. 5b) at changing the energy scale by ΔQ^2 and

$$\sigma \otimes q = \int_x^1 \frac{dy}{y} q(y, Q^2) \sigma(\frac{x}{y}), \tag{4.7}$$

ellipses indicating isosinglet contribution to the evolution of quark densities. Taking into account isospin invariance yields $\Delta\sigma^{\pi^\pm} = 2\Delta\sigma^{\pi^+} = 2\Delta\sigma^{\pi^-} = \Delta\sigma^{\pi^0} = \Delta\sigma^{\pi}$. Now we consider two different combinations of the four preceding equations, both in the isotriplet sector: take the differences between the first and the third equation and between the second and the fourth equation and consider both the sum and the difference of the two differences. If we take the first moments of the two integro-differential equations so obtained, recalling the definitions of B_0 and G_0, we get

$$\frac{\Delta B_0}{B_0} = \frac{\Delta G_0}{G_0} = -2\Delta\overline{\sigma}^{\pi}, \tag{4.8}$$

where $\overline{\sigma}^{\pi}$ is the first moment of the elementary cross section.

A comment is in order. In our model B_0 and G_0 have the same evolution in the interval $0.5\ GeV^2 < Q^2 < Q_p^2$, where, contrary to the perturbative regime, the evolution is nontrivial even to lowest order, since pion emission, unlike gluon emission, does not conserve the helicity nor the flavour of the quark.

If we take $Q^2 \leq \Lambda^2_{\chi SB}$ and $Q_0^2 = Q^2 + \Delta Q^2 \geq Q_p^2$, we get

$$2\Delta\overline{\sigma}^{\pi} = -[\overline{\sigma}^{\pi^{\pm}}(Q^2) + \overline{\sigma}^{\pi^0}(Q^2)] = -2[\overline{\sigma}^{\pi}(Q^2)] = -\frac{g^2(Q^2)}{(4\pi)^2} log(\frac{m_\sigma^2}{m_\pi^2}), \tag{4.9}$$

since, as explained in the preceding section, we assume $g = 0$ for $Q_0^2 \geq Q_p^2$. Substituting the first eq. (4.9) into eq. (4.8), and exploiting the smallness of $\overline{\sigma}^{\pi}(Q^2)$, we get

$$B_0(Q^2) \simeq B_0(Q_0^2)[1 - 2\overline{\sigma}^{\pi}(Q^2)], \tag{4.10}$$

which, owing to the third eq.(4.9), turns out to coincide with formula (3.2).

For $Q^2 < 0.5\ GeV^2$, as we have seen, the elementary cross section - corresponding to the amplitude represented in fig. 4 - consists in a quark emitting two quark-antiquark pairs before colliding with the photon. This process leads to a multiplicative, spin independent correction, since the quark is very unlikely to flip; indeed, the spin dependent interactions between constituent quarks are weak even in real nucleons, *a fortiori* they will be negligible in highly virtual ones. On the other hand pion emission by the active quark or by the quark-antiquark pairs influences in the same way polarized and unpolarized structure functions, as we have already seen above. Then we conclude that also for $Q^2 < 0.5\ GeV^2$ - and therefore for any $Q^2 < 4\ Q_p^2$ - B_0 and G_0 have the same evolution.

As a consequence we predict

$$\frac{B_0(Q^2)}{B_0(\Lambda_c^2)} = \frac{G_0(Q^2)}{G_0(\Lambda_c^2)}. \tag{4.11}$$

We can test this conclusion for $Q^2 = \overline{Q}^2 = 4\ GeV^2$. Assuming that for $Q^2 = \Lambda_c^2$ G_0 has the value predicted by the Gottfried sum rule and B_0 the value calculated according our model in the preceding section, i. e.,

$$G_0(\Lambda_c^2) = \frac{1}{3}, \qquad B_0(\Lambda_c^2) = \frac{1}{6}\, g'_A g_A, \tag{4.12}$$

and recalling the result of NMC about $G_0(\overline{Q}^2)$ and formulas (2.4) and (2.6) for $B_0(\overline{Q}^2)$ yields

$$\frac{B_0(\overline{Q}^2)}{B_0(\Lambda_c^2)} = 0.72, \qquad \frac{G_0(\overline{Q}^2)}{G_0(\Lambda_c^2)} = 0.71 \pm 0.08, \tag{4.13}$$

in good agreement with our prediction.

V. DISCUSSION

First of all we spend a few words on higher twists. As to the Gottfried integral, it is likely to coincide with G_0 for any Q^2, since it is quite unnatural that at small Q^2 higher twist contributions violate the Gottfried sum rule. On the contrary the Bjorken sum can be shown to vanish at $Q^2 = 0$, as follows from the Drell-Hearn-Gerasimov sum rule [33]. This is due to the negative polarization caused by resonances, like $\Delta(1232)$ [34], i. e., by higher twists.

Secondly a comparison with the BF model is in order. This model describes the non-perturbative evolution of the Gottfried sum, tacitly identified with G_0. That model differs substantially from the one presented in this article, in that it attributes the raising of G_0 towards small Q^2 exclusively to the interaction between quarks and (quasi-)Goldstone bosons, among which the pion plays the most important role, since it is by far the lightest one. Furthermore according to the BF calculation quark-pion interaction persists up to very large Q^2. That calculation is based on the use of the effective vertex functions [35] of quark-(quasi-)Goldstone interactions. While such vertex functions look suitable at small Q^2, where pseudoscalar bosons and constituent quarks can be regarded as elementary, it appears rather arbitrary to extrapolate these vertex functions to large Q^2, which correspond to too short time intervals for a boson to be formed from a current quark-antiquark pair. By the way the BF extrapolation is based on an asymptotic behaviour which is not easy to check (see ref. 36 of BF). Furthermore, in the BF model, at asymptotically large Q^2, when the pion nonperturbative correction vanishes, the Gottfried integral is predicted to raise again to the $SU(6)$-value.

Unfortunately the available data on the Gottfried and on the Bjorken sum do not allow to discriminate between the two models. More precise experiments, especially in the interval $(4 - 20)\ GeV^2$, would be useful in clarifying the question. Furthermore, in view of our above consideration on the Gottfried integral, a measurement of the isotriplet unpolarized component of the nucleon structure function at smaller Q^2 would be equally important.

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