Proton spin in the valon model

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The valon model description of the proton is used to calculate contributions of the constituents of the proton to its spin. It is shown that the results of the model calculation agree rather well with the EMC results. It is conjectured that in probing the nucleon with high Q^2 one actually probes its valon structure. It is further conjectured that the valence quark contribution to the proton spin cancels out the sea contribution, and gluons almost exclusively carry the spin of the proton. Our results satisfy various theoretical constraints on the sea polarization.

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INTRODUCTION

The recent European Muon Collaboration (EMC) measurement [1] of the spin structure function for proton has found that $g_1^p(x)$ is small. The implication of this experiment led to the conclusion that the net quark contribution to the spin of the proton is almost zero.

The quark model has been very successful in describing static properties of the nucleon and according to which the proton spin is carried by its constituent quarks. On the other hand the QCD-parton model describes the nucleon as an infinite number of partons consisting of quarks, antiquarks, and gluons. To reconcile these two views, Hwa [2] suggested that the constituents in the quark model for the static nucleon are not the same objects as the quarks in the parton model and one can regard the former as a cluster of the latter without contradicting either view. Although the notion of a cluster is not new [3], but Hwa's approach is closely related to QCD. In this model cluster quantum numbers are the same as valence quarks' and the clusters have been called "valons." In this paper we adopt the valon point of view and calculate various contributions to the spin of the proton. We conjecture that the EMC experiment with high Q^2 and its conclusion can be interpreted as follows: the sea quark contribution to the spin of the proton cancels out the valence quark contribution. The prediction of the model for the gluon contribution is about 0.462, hence yielding the correct value of the spin of the proton. In this view we will show that the conclusion of the EMC data that quarks carry very little of the proton's spin is consistent with the model.

THE VALON MODEL

The valon is defined to be a dressed valence quark in QCD with the cloud of gluons and sea quarks which can be resolved by high Q^2 probes. In a scattering process the virtual emission and absorption of gluons in a valon become bremsstrahlung and pair creation. The structure function of a valon is determined by gluon bremsstrahlung and pair creation in QCD. At sufficiently low Q^2 the internal structure of a valon cannot be resolved and hence it behaves as a valence quark.

Let $G_{v/h}(y)$ describe the valon distribution in a hadron and $F^N(x,Q^2)$ denote the structure function of nucleon. Denoting the valon structure function by $f^v(z,Q^2)$, then the two structure functions are related by convolution theorem as

$$F^N(x,Q^2)=\sum_v \int_x^1 dy\, G_{v/n}(y) f^n(x/y,Q^2) , \tag{1}$$

where $f^v(z,Q^2)$ is described accurately by the leading-order results in QCD [2], and its moments expressed completely in terms of evolution parameter $S=\ln[\ln(Q^2/\Lambda^2)/\ln(Q_0^2/\Lambda^2)]$.

According to the valon picture of the nucleon, unpolarized parton distributions are given by [2,4] as

$$xu_v(x)=5.30324(1-x)^{3.244}x^{0.806} , \tag{2a}$$

$$xd_v(x)=1.908(1-x)^{3.574}x^{0.636} , \tag{2b}$$

$$xG(x)=0.6218(1-x)^{4.834}+1.7407(1-x)^{11.820} + 13.323(1-x)^{59.6905} , \tag{2c}$$

$$xu_{\rm sea}(x)=xd_{\rm sea}(x)=0.934e^{-5.6x}(1-x)^{2.59} , \tag{2d}$$

$$xs_{\rm sea}(x)=0.168e^{-5.6x}(1-x)^{2.59} , \tag{2e}$$

where $q_v(x)$, $G(x)$, and $q_{\rm sea}(x)$ refer to valence quark, gluon, and sea quark distributions in protons, respectively. These distributions are evaluated for $Q^2=10.7$ GeV^2 corresponding to the evolution parameter $S=2.052$.

SPIN-DEPENDENT STRUCTURE FUNCTIONS

Having determined the unpolarized parton distributions, our aim is now to obtain the spin dependent distributions. We adopt the method of Carlitz and Kaur [5] for valence quark polarization. Let $\Delta q(x)$ be the probability of finding a quark or antiquark with positive helicity and a momentum fraction x minus the corresponding

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probability of finding a quark or antiquark with negative helicity; that is, $\Delta q_i(x)=q_i^+(x)-\Delta q_i^-(x)$. We can write the valence quark spin distribution function $\Delta q_v(x)$ in terms of unpolarized distribution functions of $u_v(x)$ and $d_v(x)$ as

$$\Delta u_v(x,Q^2)=[u_v(x)-\tfrac{2}{3}d_v(x)]\cos\theta_D , \tag{3a}$$

$$\Delta d_v(x,Q^2)=-\tfrac{1}{3}d_v(x)\cos\theta_D , \tag{3b}$$

where $\cos\theta_D$ is the spin dilution factor [5] given by

$$\cos\theta_D=\{1+R(Q^2)[0.6218(1-x)^{4.834}+1.7407(1-x)^{11.820}+13.323(1-x)^{59.6905}]\}^{-1} . \tag{4}$$

The only parameter to be fixed is R which is used to satisfy the Bjorken sum rule:

$$\int_0^1 dx[u_v(x,Q^2)-\tfrac{1}{3}d_v(x,Q^2)]\cos\theta_d=1.258 \tag{5}$$

which gives $R=0.2145$. This value of R is rather large compared with other parametrizations [6]. In order to include QCD corrections, due to the axial U(1) anomaly, the matrix element of the axial vector current receives a gluon contribution. This term is the famous triangle diagram contribution to the axial vector current matrix element. Hence we redefine $\Delta q_v(x)$ as

$$\Delta q_v'(x)=\Delta q_v(x)-\left[\frac{\alpha_s\Delta g(x)}{2\pi}\right] . \tag{6}$$

This correction for the choice of $\alpha_s=0.25$ is about 10%. For the gluon polarization we take $\Delta g(x)=xG(x)$. One should, however, note that at present there is no experimental measurement of $\Delta g(x)$, so we need to deduce some phenomenological parametrization of $\Delta g(x)$. The hardest possible $\Delta g(x)$ that we can construct consistent with the inequality

$$|\Delta g(x)=(g^{\uparrow}-g^{\downarrow})(x)|\le g(x)=(g^{\uparrow}+g^{\downarrow})(x)$$

takes the form $\Delta g(x)=x^{\alpha}\Delta g(x)$ with $\alpha\ge 0$. In this parametrization also one can argue that spin-spin interactions lead to a saturation of gluon polarization at large x [6,9]. Integrating these will give the valence quark contribution to the spin of proton, with QCD corrections included:

$$\Delta u_v'=\int_0^1 \Delta u_v'(x)dx=0.995 , \tag{7}$$

$$\Delta d_v'=\int_0^1 \Delta d_v'(x)dx=-0.2632 , \tag{8}$$

$$\Delta q_v'=\int_0^1 [\Delta u_v'(x)+\Delta d_v'(x)]dx =0.7318 , \tag{9}$$

$$\Delta g=\int_0^1 \Delta g(x)dx=0.4619 . \tag{10}$$

Next we use the important constraint

$$\tfrac{1}{2}\sum_i \int_0^1 dx[\Delta q_i(x)+\Delta\bar{q}_i(x)]+\int_0^1 \Delta G(x)dx=\tfrac{1}{2}=\langle J_z\rangle , \tag{11}$$

where we have dropped the primes. Equation (11) can be written as

$$\tfrac{1}{2}=\tfrac{1}{2}\int_0^1 [\Delta u_v(x)+\Delta d_v(x)]dx+\tfrac{1}{2}\int_0^1 \Delta u(x)+\Delta\bar{u}(x)+\Delta d(x)+\Delta\bar{d}(x)+\Delta s+\Delta\bar{s}]_{\rm sea}+\int_0^1 \Delta g(x)dx . \tag{12}$$

The first and third integrals are obtained directly and their values are given by Eqs. (9) and (10). The second integral is the sea quark contribution to the spin of the proton. Equation (12) therefore requires that

$$\Delta q_{\rm sea}=-0.6557 . \tag{13}$$

Therefore, the net proton spin carried by quarks is

$$\tfrac{1}{2}(\Delta q_v+\Delta q_{\rm sea})=0.033 \tag{14}$$

which is consistent with the expected zero result.

Our value for $\int g_1^p(x)=0.1316$ which is in excellent agreement with the EMC measurement also indicating that the net quark contribution to the spin of proton is about zero in the valon model description; Fig. 1 represents its x dependence. The EMC measurement for $\int g_1^p(x)$ is

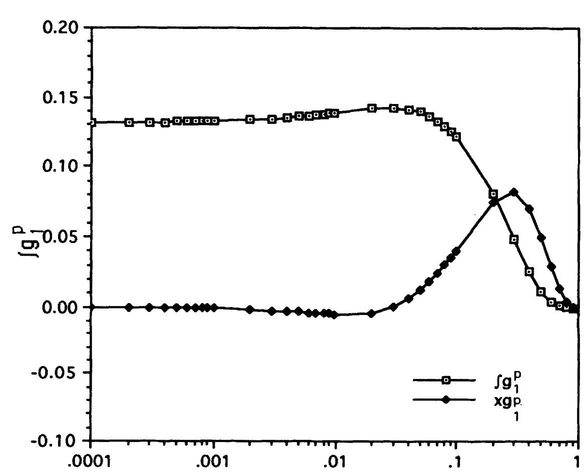

FIG. 1. Calculated values of xg_1^p and $\int g_1^p$ as a function of x.

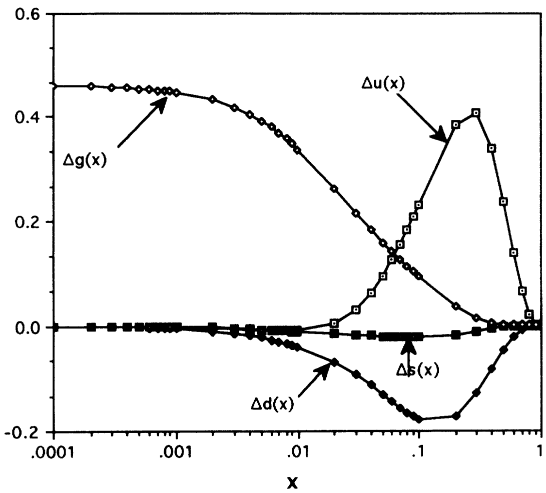

FIG. 2. Dependence on x of the polarized distribution functions $x\Delta u(x)$, $x\Delta d(x)$, $x\Delta s(x)$, and $\Delta g(x)$.

$$\int_0^1 g_1^p(x) = \tfrac{1}{2}\left[\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s\right] = 0.14 \pm 0.01 \ . \tag{15}$$

In Fig. 2 we have plotted the x dependence of the polarized distribution functions for u, v, s, and the gluon. Figure 3 shows the gluon distribution which is in agreement with the results of the NMC Collaboration results reported in [11]. In Fig. 4 we have shown valence quark polarization distributions. Figure 5 shows the variation of $x\Delta s(x)$ and finally Fig. 6 represents xg_1 for the neutron. Next we want to find each flavor sea quark contribution to the spin of the proton. SU(3) and hypron decay tell us that

$$\int_0^1 [\Delta u_{\text{tot}}(x) + \Delta d_{\text{tot}}(x) - 2\Delta s_{\text{tot}}(x)]dx = 0.67 \ . \tag{16}$$

Subtracting from this the valence contribution then we get the sea contribution

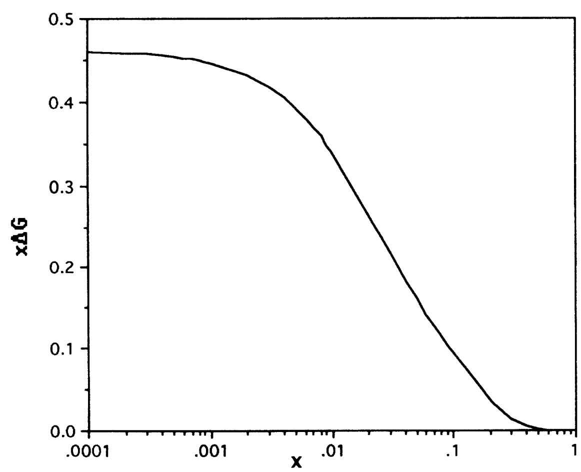

FIG. 3. Gluon distribution function.

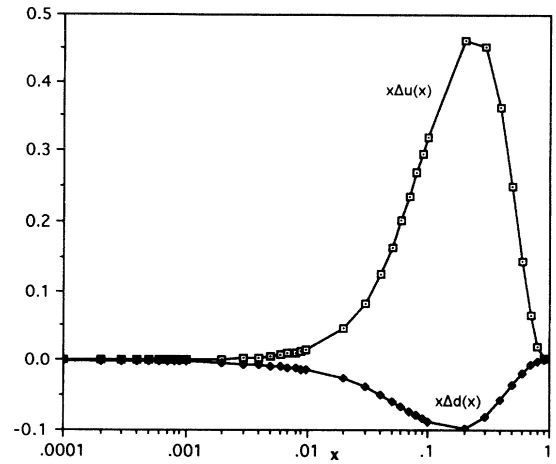

FIG. 4. Dependence on x of the polarized distribution functions $x\Delta u_v(x)$, $x\Delta d_v(x)$ of valence quarks.

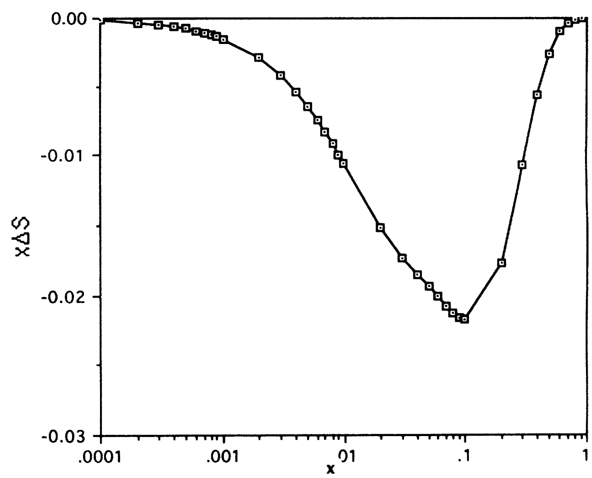

FIG. 5. Dependence on x of the polarized distribution functions $x\Delta s(x)$.

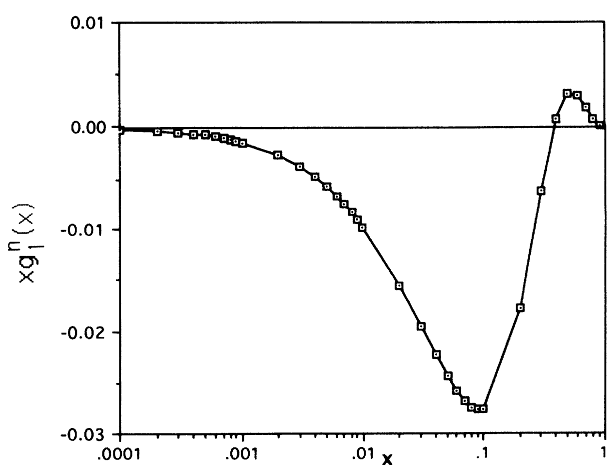

FIG. 6. Calculated values of $xg_1^n(x)$ for neutron vs x.

$$\Delta u_{\text{sea}} + \Delta d_{\text{sea}} - 2\Delta s_{\text{sea}} = -0.0719 \; . \tag{17}$$

We need two other combinations of Δq_{sea} to find Δu_{sea}, Δd_{sea}, and Δs_{sea}; instead we choose to use the prediction of our model and SU(2) flavor symmetry with respect to u and d; that is,

$$\int_0^1 [\Delta u(x) + \Delta d(x) + \Delta s(x)]_{\text{sea}} dx = -0.6557 \tag{18}$$

and $\Delta u_{\text{sea}} = \Delta d_{\text{sea}}$. From (17) and (18) we get

$$\Delta s_{\text{sea}} = -0.194 \quad \text{and} \quad \Delta u_{\text{sea}} = \Delta d_{\text{sea}} = -0.230 \; . \tag{19}$$

Do these agree with EMC data? From the data we have

$$\tfrac{1}{2}[\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s]_{\text{sea}} = -0.0665 \; ; \tag{20}$$

our prediction indicates that

$$\tfrac{1}{2}[\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s]_{\text{sea}} = -0.0748 \; . \tag{21}$$

Evidently, the agreement is excellent.

It seems natural to obtain the sea quark contribution to the spin of protons directly from their distributions, namely, from Eqs. (2d) and (2e). We take $\Delta q_{\text{sea}}(x) = -xq_{\text{sea}}(x)$. By integrating these functions we get

$$\begin{aligned} &\Delta \bar{u} = \Delta u = \Delta d = \Delta \bar{d} = -0.1090 \; , \\ &\Delta s = \Delta \bar{s} = -0.0196 \; , \end{aligned} \tag{22}$$

which means that total sea quark polarization is $\Delta q_{\text{sea}} = 4(-0.1090) + 2(-0.0196) = -0.4752$. With the QCD correction included this result becomes $\Delta q_{\text{sea}} = -0.585$ and an individual sea quark receives the asymmetries

$$\begin{aligned} &\Delta u_{\text{sea}} = \Delta d_{\text{sea}} = -0.2542 \; , \\ &\Delta s_{\text{sea}} = -0.075 \; . \end{aligned} \tag{23}$$

We can see that these results which are obtained directly from the valon model distribution functions for the sea quarks along with our ansatz that $\Delta q_{\text{sea}}(x) = -xq_{\text{sea}}(x)$ gives the following contribution to the $\int g_1^p(x)$:

$$\begin{aligned} \tfrac{1}{2}[\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s]_{\text{sea}} &= \tfrac{1}{2}[\tfrac{4}{9}(-0.2542) + \tfrac{1}{9}(-0.2542) + \tfrac{1}{9}(-0.075) \\ &= -0.0748 \; , \end{aligned} \tag{24}$$

which is exactly the value we obtained in Eq. (21). The value of $\Delta s = -0.075$ of Eq. (23) also meets the bound [7]

$$|s_z^s| = \left| \tfrac{1}{2}\int_0^1 dx \, \llcorner \, \Delta s + \Delta \bar{s} \, \lrcorner \right| \leq 0.036 \pm 0.15 \; . \tag{25}$$

In evaluating the polarization of the sea quark we chose $\Delta q_{\text{sea}} = -xq_{\text{sea}}$; however, usually it is determined by fitting the data. We have not chosen such a procedure, but if we take Eq. (13) as a guide, with a sea quark distribution of the form similar to Eqs. (2d) or (2e), one can achieve the same result. Let

$$x \Delta q_{\text{sea}}(x) = A e^{-5.6x}(1-x)^{2.59} \tag{26}$$

and considering the requirement of Eq. (13) that the integral of (26) must be equal to -0.6557 would yield $A = 5.6$, which is six times the value 0.934 of Eq. (2d), perhaps corresponding to six species of sea quarks and antiquarks.

Our prediction for $\int g_1^n(x) dx$ is equal to -0.07814 at $Q^2 = 10.7 \text{ GeV}^2$ whereas a combination of Spin Muon Collaboration (SMC) [12] and EMC data gives $\int g_1^n(x) dx = -0.08 \pm 0.04 \pm 0.04$, while the SLAC E142 [13] experiment measured at $Q^2 = 2 \text{ GeV}^2$ yields -0.022 ± 0.011. We have adjusted our calculation for the same Q^2 value as in the E142 experiment and obtained a value of -0.01.

We now make a short list of the comparison of our results with the experiment on the quark polarization contribution:

	Experiment	Model
$\Delta u = \Delta u_v + \Delta u_{\text{sea}}$	0.78 ± 0.06	0.7402
$\Delta d = \Delta d_v + \Delta d_{\text{sea}}$	-0.48 ± 0.06	-0.5174
Δs	-0.14 ± 0.06	-0.075
$2S_q$	0.16 ± 0.10	0.1478
$\int g_1^p(x)$	$0.125 \pm 0.01 \pm 0.015$	0.1316

where S_q is total contribution of quarks to the spin of proton. One can see that $S_z = (\frac{1}{2})\sum \Delta q_v + (\frac{1}{2})\sum \Delta q_{\text{sea}} + \sum \Delta g = 0.538$ which is consistent with the required 0.5.

Finally, we have attempted to calculate $\int g_1^p(x) dx$ using valon distributions. From the model we get the following distribution functions for the U and D valons in the proton:

$$U_p(y) = 7.98 y^{0.65}(1-y)^2 \; , \tag{27a}$$

$$D_p(y) = 6.01 y^{0.35}(1-y)^{23} \; . \tag{27b}$$

Since SU(6) symmetry breaking is present we build on this symmetry breaking and define $\Delta U(x) = \frac{5}{6}U(x) - \frac{1}{6}U(x)$ and $\Delta D(x) = \frac{1}{3}D(x) - \frac{2}{3}(x)$.

We found that the value of the integral $\int g_1^p(x)$ is

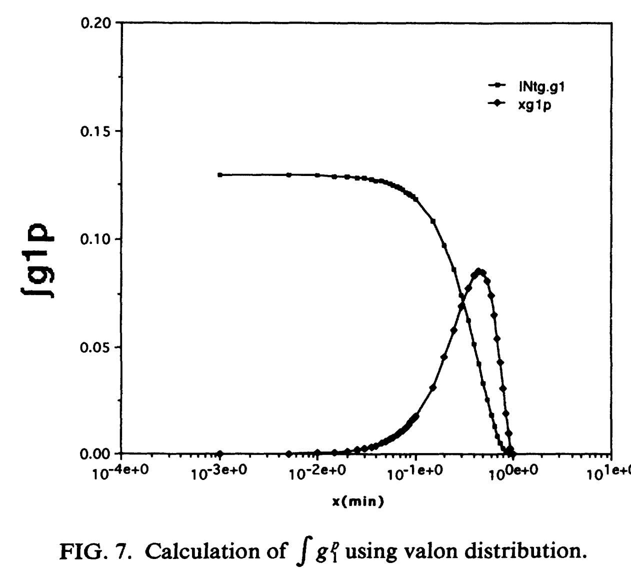

FIG. 7. Calculation of $\int g_1^p$ using valon distribution.

$$\int_0^1 g_1^p(x)dx = \frac{1}{2}\int_0^1 [\tfrac{4}{9}\Delta U(x) + \tfrac{1}{9}\Delta D(x)]dx$$
$$= 0.1296 \qquad (28)$$

which is in good agreement with both our parton based calculations and with the EMC measurements and serves as an additional test of the model. Figure 7 shows the results of the calculation using valon distributions. The valon distribution prediction for $\int g_1^n(x)$ is -0.036.

CONCLUSION

The picture discussed here implies that the sea is highly polarized. It appears that evidently the QCD correction, while being small for the valence quark polarization, is more significant for the sea quark polarization. In fact the QCD evolution suggests that this factor need not be small for large Q^2 [8–10]. This in turn suggests that the gluons in the proton must be polarized since in the valon picture the structure function of a valon is determined by gluon bremsstrahlung and quark-pair creation in the framework of QCD and a virtual gluon which produces a quark-antiquark pair must be polarized in order to transmit spin information to the sea. It is not unrealistic to conjecture that in probing a nucleon with high Q^2 it is indeed the valon structure that is being probed, although in addition to this there is a smearing on account of the momentum distribution of valons. Our results indicate that, while being in the range of experimental errors, there is a slight bump in $\int g_1^p(x)$ at around $x=0.02$ as shown in Fig. 1. It is also observed that the value of $xg_1^p(x)$ is negative for $x \leq 0.01$. This may be due to poor determination of unpolarized structure functions near $x \longrightarrow 0$ or a higher twist effect. The bag model also indicates such a feature for $g_1^p(x)$. With Q^2 still being large enough to be in the deep inelastic; the region of very low x, say $x<0.01$ is a new domain for investigation. It is clear that the leading-logarithmic approximation used for the structure function evolution must break down at some point since the number of partons increases without limit as x decreases leading to an unphysical blow-up of the cross section. For extremely small x values the large number of partons can no longer be considered as free. The interaction among them will be important and nonperturbative; confinement effects will play a role. This can be understood intuitively: since the softer the parton is the longer the wavelength becomes, eventually it can no longer fit into the bag of the proton and therefore it requires a field to keep them confined.

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