Meson Cloud, QCD Nucleon Correlator and Chiral Perturbation Theory

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Abstract

We introduce a model for nucleons with correlators that include the propagation of pseudo Goldstone bosons as well as the standard correlators for nucleons used in QCD sum rules. From the comparison with experimental nucleon magnetic dipole moments we estimate the probability of a pion cloud in a nucleon. The masses obtained from the sum rules are almost independent of the cloud contributions. We show that the model is consistent with chiral perturbation theory, and solves a long-standing problem on obtaining the leading non-analytic correction to the nucleon mass in QCD sum rules.

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1 Introduction

The concept of a meson cloud is very old in nuclear physics: the existence of the pion exchange interaction leads to a pion cloud which could affect the properties of nucleons. Although a main current goal of hadronic physics is to understand the properties of hadrons in terms of QCD, in recent years the study of deep inelastic scattering (DIS) has led to a great deal of interest in the nucleon’s meson cloud. The NMC/CERN experiments gave evidence for the violation of the Gottfried sum rule and the recent Fermilab/E866 Drell-Yan measurements show that for small Bjorken x the ratio \( \bar{d}(x)/\bar{u}(x) \), down to up sea quark distributions, is considerably larger than 1.0, while both perturbative and nonperturbative QCD calculations show that \( \bar{d}(x)/\bar{u}(x) \) for small x differs from unity only by about 1% isospin violations. It is likely that theoretical treatments with both QCD and Goldstone boson (GB) fields are most efficient in treating these sea quark problems as well as problems with the spin and strangeness content of the nucleon. The challenge is to do this consistently.

There have been many theoretical calculations of DIS using the concept of a meson cloud based on the one-pion interaction of nucleons (see Ref. for a review). It is obvious that if one only considers the \( \pi^+ \)-neutron system as an additional component of the proton, that there are more \( \bar{d} \) than \( \bar{u} \) sea quarks, but the \( \pi^- \Delta \) components tend to cancel this effect. A related model is the chiral quark model which has been used for flavor and spin properties of nucleons. As discussed in Ref., although these two models both introduce Goldstone bosons, in the chiral quark model these are fields internal to the confinement region, while the meson cloud model describes long-distance effects outside of the region of confined quarks. In lattice gauge calculations of the flavor-singlet axial coupling constant for the nucleon’s quark spin content gluonic effects were included by disconnected quark loops, which are interpreted as representing Goldstone bosons. In this method valence quark and GB effects are distinguished.

It was observed that the QCD sum rules for the nucleon mass are inconsistent with chiral perturbation theory. First, the quark condensates terms on the QCD side of the sum rules contain quark condensate terms which have been shown to introduce \( m_\pi^2 \ln(-m_\pi^2) \) terms, while the chiral perturbation theory expansion for the nucleon mass does not have such terms. Second, the leading non-analytic correction (LNAC) to the nucleon mass is a \( m_\pi^2/f_\pi^2 \) term, which is not found in QCD sum rules. By an analysis of the phenomenological correlator, given by a term with a pole at the nucleon mass and the continuum, it was shown that the chiral logs cancel; however, the LNAC term is not present so the QCD sum rules for the nucleon mass are not consistent with chiral perturbation theory. Virtual pions have also been included in QCD sum rule calculations of nucleon masses in nuclear matter. A chiral quark model was used to study pion-nucleon weak and strong coupling within
The model introduced in the present work uses the method of QCD Sum Rules in which hadronic systems are represented by local complex field operators, usually called currents, so that two-point functions can be used for defining correlators from which one can determine hadronic masses. Nonperturbative effects are treated via operator product expansions (O.P.E.) of the quark and gluon propagators using vacuum condensates, whose values are determined by fits to experiment as well as lattice gauge calculations. In this method short-distance effects are treated perturbatively and the condensates account for the medium-range and long-range QCD effects within the region of confinement.

The model introduced in the present work treats the nucleon correlator with a nucleon current that has a quark/gluon component and a component also involving a Goldstone boson field. The GB fields are included in the composite-field nucleon current, with no coupling to either hadrons or quarks and thereby represent the long-distance meson cloud effects. Thus the model differs from both the usual meson cloud and the chiral quark models. All internal meson exchange effects are assumed to be included in the condensates. For consistency, the coupling between the two currents is also not included, so the correlator has a standard QCD sum rule part and a QCD/GB part, with a GB propagator. There is a clear relationship between the present model of nucleons with a meson cloud and the usual QCD sum rule treatment. In the usual treatment states with a nucleon and a pion are in the continuum. In the present model the current explicitly contains pionic fields, so that the resulting continuum is modified. By doing this we are able to treat physical effects where explicit pion degrees of freedom are important, as in sea-quark distributions.

The goals of the present work are to estimate the probability of the meson cloud component by studying the properties of the nucleon, and to study the problem of consistency with chiral perturbation theory. This is similar to the problem of finding the correlator for hybrid hadrons, where the hybrid components of the nucleon and lowest hybrid baryon were estimated from the hadronic masses. In Sec. 2 we introduce the correlator using a standard form for the nucleon with no GB and derive the sum rules for the nucleon masses including a correlator with a GB. We find very small effects from the meson cloud correlator terms. In Sec. 3 we derive the sum rules for the neutron and proton magnetic dipole moments using a two-point correlator in an external electromagnetic field. From the sum rules found with this method compared to QCD sum rule calculations of Ref. without the cloud, we conclude that the GB component has roughly the same probability as the cloudless component. It should be noted that there is recent work on including instanton effects on the quark propagator that also modify the sum rules for the nucleon moments. In Sec. 4 we show that the model is consistent with chiral perturbation theory. The chiral logs cancel and the LNAC term appears as in hadronic models. The known value of the LNAC term from chiral perturbation theory can help determine the parameters of the model.
2 Correlator with Goldstone Boson Fields: Nucleon Masses

In this subsection we present our model of the pion cloud within the QCD sum rule method, which means that we introduce a correlator with explicit Goldstone boson fields. We apply this model correlator, a two-point function, to the estimate of the masses of nucleons. The composite field operator for the proton has the form

\[ \eta(x) = c_1 \eta^{p,o} + c_2 \eta^{p,\pi} + c_3 \eta^{p,K}, \]  

with constants \( c_j \) giving the meson cloud amplitudes. In Eq. (1) \( \eta^{p,o} \) is a standard proton field operator used in sum rules:

\[ \eta^{p,o}(x) = \epsilon^{abc} [u^a(x)^T C \gamma^\mu u^b(x)] \gamma^5 \gamma_\mu d^c(x), \]

where \( C \) is the charge conjugation operator, the \( u(x) \) and \( d(x) \) are quark fields labelled by color, \( \lambda_p \) is a structure parameter and \( v(x) \) is a Dirac spinor. The neutron operator, \( \eta^{n,o} \), is obtained from \( \eta^{p,o} \) by interchange of \( u \) and \( d \) quarks. The composite field operator \( \eta^{p,\pi} \) used in our present model is

\[ \eta^{p,\pi}(x) = \frac{1}{\sqrt{2} \lambda_\pi^2} \partial_\alpha \phi_\pi^+(x) \cdot \tau \gamma^\alpha \gamma^5 \eta^{N,o} + \partial_\alpha \phi_\pi^0(x) \gamma^\alpha \gamma^5 \eta^{p,\pi}, \]

where \( \phi_\pi(x) \) is the pion field and \( \lambda_\pi \) is a D=1 scale factor. From our experience with hybrid baryons and from the p-wave coupling of the pion one expects that \( \lambda_p^2 \ll \lambda_\pi^2 \). This simplifies the phenomenological form for the correlator and enables us to obtain sufficient sum rules to estimate the pion cloud part of the current. In the present work we do not consider the kaon cloud term which would enter through \( \eta^{p,K} \), defined similarly to Eq. (3) but with K fields and strange baryon composite operators. For estimates of strangeness in nucleons, which is a natural application of our model, this term must be included.

Our resulting model correlator for the proton with a pion cloud is

\[ \Pi^p(p) = i \int d^4 e^{ix-p} <0|T[\eta(x)\bar{\eta}(0)]|0> \]

\[ = c_1^2 i \int d^4 e^{ix-p} <0|T[\eta^{p,o}(x)\bar{\eta}^{p,o}(0)]|0> + (1 - c_1^2) i \int d^4 e^{ix-p} <0|T[\eta^{p,\pi}(x)\bar{\eta}^{p,\pi}(0)]|0> \]

\[ = c_1^2 \Pi^{(p,o)}(p) + (1 - c_1^2) \Pi^{(p,\pi)}(p). \]
An important aspect of the model is that the coupling of the $\eta^{p,\pi}$ and $\eta^{p,0}$ currents are not included. Only the long-range effects of the pion are included by the pion cloud contribution, and no pion-quark interactions are included in order to avoid the double counting of interactions given by the condensates. In a chiral quark model the pion-quark coupling would give both the coupling of the two currents and internal pionic forces. The present model assumes such internal interactions are given by QCD. Only external fields interact with the pion, giving the physics of the meson cloud.

The neutron correlator can be obtained from Eq. (4) with obvious isospin changes. The correlator $\Pi^{(p,\pi)}(x)$ for the propagation of a proton without the meson cloud is given in Ref. [21] and many other references.

Next we discuss the correlator with the pion cloud, $\Pi^{(p,\pi)}(p)$. From Eqs. (3,4) one finds for $\Pi^{(p,\pi)}(p)$

$$\Pi^{(p,\pi)}(x) = \frac{2}{3\lambda^2}\epsilon^{abc}\epsilon^{a'c'} G_{\alpha\beta}^\pi(x) \gamma_\alpha \gamma_\mu S_d^\gamma(x) \gamma_\mu \gamma_\beta$$

$$Tr[S_u^{a'}(x) \gamma_\mu C(S_s^{b'}(x))^T C_{\gamma'}]$$

$$+ 2[\pi^0 \rightarrow \pi^+ \text{ and } u \leftrightarrow d] + \text{[4-quark terms]},$$

where in the limit of zero pion mass

$$G_{\alpha\beta}^\pi(x) = \frac{1}{\pi^2 x^4} \left(\frac{4x_\alpha x_\beta}{x^2} - \delta_{\alpha\beta}\right).$$

In momentum space the pion cloud correlator is

$$\Pi^{(p,\pi)}(p) = -2\int \frac{d^4k}{(2\pi)^4} \frac{(\hat{p} - \hat{k})\Pi^{p,0}(k)(\hat{p} - \hat{k})}{(\hat{p} - k)^2}$$

$$= \hat{p}\Pi^{(p,\pi)}(p)_{\text{odd}} + \Pi^{(p,\pi)}(p)_{\text{even}},$$

with $\hat{p} = \gamma_\alpha p^\alpha$. We find after the Borel transform from $p^2$ to the Borel mass variable, $M_B^2$

$$\Pi^{(p,\pi)}(M_B^2)_{\text{even}} = 0$$

$$(2\pi)^4\Pi^{(p,\pi)}(M_B^2)_{\text{odd}} = \frac{1}{\lambda^2} \left[ \frac{15}{26} [12M_B^{10}E_4 - 5bM_B^6E_2 - 40a^2M_B^4E_1$$

$$+ 20m_o^2a^2M_B^2E_0] \right],$$

where the parameters for the quark condensate, gluon condensate and mixed condensate, respectively, are $a = -(2\pi)^2 < \bar{q}q >$, $b = < \bar{q}gG^2q >$ and $m_o^2 a = (2\pi)^2 < \bar{q}g \cdot G \bar{q} >$. For these parameters we take $a = 0.55 \text{ GeV}^3$, $b = 0.47 \text{ GeV}^4$ and $m_o^2 = 0.8 \text{ GeV}^2$. The scale factor $\lambda^2$ has a value in the range of $M_B^2/g_{\pi N}$ (see Sec. 4). The functions $E_n$ are $1 - \exp(-w)\sum_{k=0}^{n}w^k/k!$, with $w = s_o/M_B^2$, $s_o$ being the threshold parameter. In comparison with Eq. (8) for the meson cloud terms in the correlator, the usual(p,0) odd correlator is

$$(2\pi)^4\Pi^{(p,0)}(M_B^2)_{\text{odd}} = \frac{1}{25} (-4M_B^8E_2 + bM_B^6E_0 + 16a^2/3 - 4m_o^2a^2/(3M_B^2)).$$
The dependence of the correlators on the anomalous dimensions are not shown in Eqs. (8,9), since the result is not essentially changed if this is neglected. In fact it is obvious from Eqs. (8,9) that if $\lambda_p^2 << \lambda^2$, as expected, then the sum rules for the masses are independent of the pion cloud within the accuracy of the method.

3 Correlator with Goldstone Boson: Nucleon Magnetic Dipole Moments

For the calculation of the magnetic dipole moments of the proton and neutron we use the external field formalism, which is one way to avoid the problem of carrying out an operator product expansion in the momentum transfer variable. The coupling of a current $J^\Gamma$ to a nucleon is given by a two-point correlator in the external $J^\Gamma$ current [21]

$$\Pi^\Gamma(p) = i \int d^4 e^{ix\cdot p} <0|T[\eta(x)\bar{\eta}(0)]|0 > \Gamma .$$  \hspace{1cm} (10)

For the proton in an electromagnetic field, represented by the field tensor $F_{\mu\nu}$ the correlator is written as

$$\Pi^{F,p} = e(c_1^2 \Pi^{p,0}_{\mu\nu} + (1 - c_1^2)\Pi^{p,\pi}_{\mu\nu})F^{\mu\nu},$$  \hspace{1cm} (11)

with the two terms representing the correlator in the electromagnetic field without and with the meson cloud. Since at low momentum transfer the coupling of the photon to the pion does not contribute, the meson cloud correlator in the presence of the field in our model is given by

$$\Pi^{(p,\pi)}_{\mu\nu}(p) = -2 \int \frac{d^4 k}{(2\pi)^4} \frac{(\hat{p} - \hat{k})\Pi^{p,\sigma}_{\mu\nu}(k)(\hat{p} - \hat{k})}{(p - k)^2} \hspace{1cm} (12)$$

There are three covariants, and we write the correlator with and without meson clouds as

$$\Pi_{\mu\nu}(k) = [\sigma_{\mu\nu}, \hat{k}]\Pi^{F,odd}_{\sigma}(k) + i(k_{\mu}\gamma_{\nu} - k_{\nu}\gamma_{\mu})\Pi^{F,even}_{\nu}(k) + \sigma_{\mu\nu}\Pi^{F,\sigma}_{\nu}(k).$$  \hspace{1cm} (13)

For the two-point effective field treatment at low momentum momentum transfer $\Pi^F(x)$ can be evaluated using the operator product expansion (O.P.E.), since the variable $x$ is at short distance from the origin for large $p^\mu$. This is done by an O.P.E. of the quark propagator in the presence of the the $J^F$ current

$$S^F_q(x) = <0|T[q(x)\bar{q}(0)]|0 > \Gamma .$$  \hspace{1cm} (14)
There are three susceptibilities for the induced condensates: $\chi, \kappa$ and $\xi$, which are defined in Ref.[21]. For example, the quark condensate magnetic susceptibility, $\chi$, is defined as

$$
(2\pi)^2 \langle \bar{q}\sigma_{\mu\nu}q \rangle_F = -e_q\chi a F_{\mu\nu}.
$$

The QCD evaluation of the correlator in an electromagnetic field without a meson cloud gives[21]

$$
(2\pi)^4 \Pi_{\text{odd}}^{p,n,F}(k) = e_u k^2 \ln(-k^2) - e_u \chi a^2/(3k^4) + C_a/(3k^4)
$$

$$
(2\pi)^4 \Pi_{\text{even}}^{p,n,F}(k) = a[(e_u + e_d/2)/k^2 + (e_d\chi/3)(\ln(-k^2) - b/(24k^4))],
$$

with $C_a = (a^2/2)[e_d + 2e_d/3 - e_u(\kappa - 2\xi)] - e_u \chi a^2 m_n^2/8$. From Eqs.(8,16) we obtain the correlator for the nucleon with a pion cloud in an external electromagnetic field, giving

$$
(2\pi)^4 \Pi_{\text{odd}}^{p,\pi,F}(p) = \frac{\ln(-p^2)}{3 \cdot 2^8 \pi^2}[-e_u p^6 + 40 e_u \chi a^2 p^2/3 + 32 C_a]
$$

$$
(2\pi)^4 \Pi_{\text{even}}^{p,\pi,F}(k) = -\frac{\ln(-p^2)}{2^9 \cdot 3^3 \cdot 5\pi} \chi a[3^2 \cdot 2^4 e_d p^4 - 5 e_d b].
$$

For a rough estimate of the effect of the meson cloud, which is the goal of the present paper, we follow the prescriptions of Ref.[21]: For the odd term in the correlator multiply the p term by $e_d$ and subtract $e_u$ times the n term. Neglecting anomalous dimensions one finds

$$
-\frac{\lambda_N^2}{4} e^{-M_N^2/M_B^2}(e_d\mu_p - e_u\mu_n)/M_B^2 + \text{single poles} = (e_d^2 - e_u^2)[a^2/6M_B^2 + \Delta_d],
$$

where $\lambda_N^2 = (2\pi)^4 \lambda_N$ and the GB contribution is

$$
\Delta_d = \frac{1 - e_1^2}{c_1^2 \lambda_\pi^2} \frac{1}{2^7 3^2 \pi^2} [8a^2 M_B^2 E_0 - 6M_B^2 E_3 - 40 M_B^2 E_1 + 32 a^2 E_0 + 1/8 \chi a^2 m_0^2].
$$

Noting that with a value of $\chi a = -4$ GeV, which we obtain with our three-point treatment with nonlocal condensates[23], a value of $c_1^2$ about 0.5 reduces the neutron and proton magnetic dipole moments by about ten percent, improving agreement with experiment. From this we conclude that the component of the correlator with a pion cloud is roughly equal to that without. As we shall see in the next section, the known LNAC for the nucleon mass will help determine the scaling parameter, $\lambda_\pi$.

### 4 Consistency of Model With Chiral Perturbation Theory
In Ref. [12] it was shown that from the dependence of the quark condensates on the current quark masses and the Gell-Mann-Oakes-Renner relation [24] that the quark condensate has a $m_\pi^2\ln(-m_\pi^2)$ dependence on the pion mass. From this one can see from Eq. (3) that the standard QCD sum rule contains chiral logs that are not consistent with chiral perturbation theory [11]. Moreover, the LNAC term, which is proportional to $m_\pi^3/f_\pi^2$ [13] does not occur in the QCD sum rule form for the nucleon mass. In this section we show that both of these problems are solved in our model.

4.1 Chiral logarithms

In this subsection we show that by using the results of Ref. [14] our present model does not contain inconsistent chiral logarithms. We study the diagrams giving the LNAC in the next subsection. For simplicity let us take $c_1^2 = 0.5$. Using the observation from hybrid baryons [19] that $\lambda'_2 p < < \lambda_2 p$, as discussed in Sec. 2, the phenomenological side of the correlator, given by a dispersion relation has the form of a pole term and a continuum term,

\[ 2\Pi^{(\text{Phen})}(p) = -\lambda_2^2 \frac{\hat{p}}{p^2} + M_p^2 + \Pi^{(\text{cont})}(p), \]  

which is the same as the standard proton correlator except for a factor of two. As we saw in Sec. 2, the microscopic QCD side of the correlator has the form

\[ 2\Pi^{(\text{QCD})}(p) = \hat{p}(\Pi^{(p,0)\text{QCD}}(p)_{\text{even}} + \Pi^{(p,\pi)\text{QCD}}(p)_{\text{odd}}) + \Pi^{(p,0)}(p)_{\text{even}}. \]

Using the standard proton current [20] we recall that

\[ \Pi^{(p,0)\text{QCD}}(p)_{\text{even}} = <\bar{q}q>/p^2\ln(-p^2) - \frac{b}{18p^2} + \cdots \]  

\[ \Pi^{(p,0)\text{QCD}}(p)_{\text{odd}} = -\ln(-p^2)(\frac{p^4}{4} + \frac{b}{8}) + \cdots, \]

where by the ellipsis we mean four-quark condensates + higher dimensional terms. Making use of the $m_\pi$ expansion of the quark condensate from Ref. [12]:

\[ <\bar{q}q> = <\bar{q}q>o [1 - cm_\pi^2\ln(-m_\pi^2)] \]

where $c = \frac{3}{8\pi^2 f_\pi^2}$ and by the symbol $Q_o$ we mean the quantity $Q$ in the limit $m_\pi^2 \rightarrow 0$, one finds

\[ \Pi^{(p,0)\text{QCD}}(p)_{\text{even}} = [1 - cm_\pi^2\ln(-m_\pi^2)]\Pi^{(p,0)\text{QCD}}(p)_{\text{even}} + O(m_\pi^2) \]

\[ \Pi^{(p,0)\text{QCD}}(p)_{\text{odd}} = [1 + O(m_\pi^2)]\Pi^{(p,0)\text{QCD}}(p)_{\text{odd}}, \]

as was observed in Ref. [14]. For the pion cloud part of the correlator we observe that

\[ \Pi^{(p,\pi)}(x) = G_{\alpha\beta}(x)\gamma^\alpha \Pi^{(p,0)}(x)\gamma^\beta + m_\pi^2 \tilde{G}_{\alpha\beta}(x)\gamma^\alpha \Pi^{(p,0)}(x)\gamma^\beta, \]
where $\bar{G}_{\alpha\beta}$ is obtained from $G_{\alpha\beta}$ of Eq.(5) by an expansion of the pion propagator in powers of $m_\pi^2$, with the first term given by Eq(6). From Eq.(25) we observe that

$$\Pi^{(p,\pi)}(x) = \Pi^{(p,\pi)}(x) + O(m_\pi^2), \quad (26)$$

and does not contain any $m_\pi^2 \ln(-m_\pi^2)$ chiral log terms.

Therefore we conclude that in our model of the nucleon with a meson cloud

$$\Pi^{(P\text{hen})} = [1 - c m_\pi^2 \ln(-m_\pi^2)]\Pi^{(P\text{hen})}_0 + \cdots \quad (27)$$

and

$$\Pi^{(QCD)} = [1 - c m_\pi^2 \ln(-m_\pi^2)]\Pi^{(QCD)}_0 + \cdots \quad (28)$$

and our model the nucleon with pion cloud does not contain spurious chiral logarithms.

4.2 Leading Non-Analytic Correction

The leading non-analytic correction (LNAC) from chiral symmetry breaking can be found in chiral perturbation theory using the method described in Refs.\[25, 13\], with the Feynman-like diagrams of chiral perturbation theory given in Ref.\[26\]. The main idea is that if one has a broken symmetry, so that the Hamiltonian has the form

$$H = H_0 + mH_I, \quad (29)$$

with $m$ being the small parameter of the symmetry breaking, the mass of a hadron can be found from the relation

$$\frac{\partial^2 M^2}{\partial m^2} = \lim_{q_0 \to 0, q^2 \to 0,p \to 0} \int d^4x e^{iqx} < p|\theta(x^0)[H_I(x), H_I(0)]|p >, \quad (30)$$

including only connected diagrams, with $H_I = \int d^3x H_I$. The chiral symmetry breaking in QCD is

$$mH_I = \int d^3x m_a \bar{u}u + m_d \bar{d}d = m \int d^3x H_m. \quad (31)$$

In Ref \[13\] it is shown that the LNAC for the nucleon mass is given by the process illustrated in Fig. 1. The corresponding correction to the nucleon mass, $\Delta M_N = M_N - M_N^0$ was shown to be

$$\Delta M_N = -\frac{3g_\Lambda^2 m_\pi^3}{32\pi f_\pi^2} + \cdots = -15\text{MeV} + \cdots, \quad (32)$$
Fig. 1 Diagram giving LNAC to nucleon mass

which makes use of the result

$$< \pi^a | H_m | \pi^b > = \delta_{ab} \frac{m^2}{m} + \cdots . \quad (33)$$

The LNAC in the present model of QCD sum rules, after the chiral logs have been eliminated, are given by processes involving the pion cloud correlator. The lowest dimensional term is illustrated by the the diagram shown in Fig. 2. In the evaluation

Fig. 2 QCD process giving LNAC to nucleon mass

of the QCD sum rule diagram the $\pi$-N T-matrix evident in Fig. 1 is replaced by the traces over the quark propagators. The LNAC to the nucleon mass is found by equating the phenomenological expression for the Borel transformed correlator

$$\Pi^{(Phen)}(p) = \beta^2 \exp[-\frac{M_p^2}{M_B^2}] + continuum, \quad (34)$$

with $\beta^2 = (2\pi)^4 \lambda^2_p/4$ (see Eq. (2)), to the QCD expression with chiral symmetry breaking. Making use of Eq.(33), the Goldberger-Trieman relation ($g_{\pi N} = g_A M_N/f_\pi$), Eq.(8) and taking the nucleon and Borel masses $M_p, M_B = 1$ Gev, we find for the lowest-dimensional LNAC term

$$\Delta M_p = -\frac{em^3 g_A^2}{160\beta^2 f^2_\pi} \approx -20 MeV. \quad (35)$$
For the result of a LNAC of about 20 MeV, which is consistent with the chiral perturbations theory result, we have used a value of $\beta^2$ from Ref. [21], where it is pointed out that there is about a 50% uncertainty in the value, and have used $\lambda_2^2 = M_2^2/g_{\pi N}$ for the scale factor of the pion cloud model. Note that the gluon condensate process also contributes to the LNAC, with an opposite sign, cancelling about 10-20% of the term shown in Eq. [35].

Therefore, we have shown that the longstanding puzzle of the absence of the LNAC $m_2^2$ term in the QCD sum rule treatment of the nucleon mass can be explained in our model, with a correlator composed about equally of a conventional quark correlator and a meson cloud correlator. The known value of the LNAC for the nucleon mass can help determine the parameters of the model.

5 Conclusions

We have introduced a model for a nucleon in which Goldstone bosons are included in a QCD treatment. By only including the boson propagator and not interior quark-boson interactions we hope to account for long-distance effects which are difficult to calculate in a pure QCD treatment, and yet avoid introducing processes which are already treated by the nonperturbative QCD methods of QCD sum rules. With this model the nucleon mass sum rules are essentially not changed by the meson cloud terms, but from the treatment of magnetic dipole moments we conclude that within our model the correlators with and without the pion cloud are about equal. We have also shown that this model is consistent with chiral perturbation theory, and that the leading nonanalytic term found in chiral perturbation theory, but missing in previous treatments of the nucleon mass with QCD sum rules, is present in our model. The magnetic dipole moments and the LNAC for the nucleon mass can help determine the parameters of the model. Our future research with this model will include studies such as the spin and strangeness content of the proton, as well as the sea-quark distributions in the nucleon.

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