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Magnetic moment of the ρ-meson in QCD sum rules: α_s-corrections

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Abstract: The magnetic moment μ of the ρ-meson is calculated in the framework of QCD sum rules in external fields. α_s-corrections are taken into account. Bare loop calculations (parton model) give: $\mu_{\text{part}} = 2.0$. The nonperturbative effects (operators of dimension 6) result in negative contribution, whereas perturbative corrections — positive one. The final answer is the same: $\mu = 2.0 \pm 0.3$.

Keywords: QCD, Sum Rules.

JHEP12(2003)061

Contents

1. Introduction

QCD sum rule technique is an effective model independent tool in the study of various characteristics of hadron states. This technique can be applied in particular to the investigation of the static properties of vector mesons.

Namely, in the study of photoproduction, scattering, etc. of the vector mesons the vector dominance hypothesis is used. In the framework of this hypothesis it is supposed that the interaction of real or virtual photon with hadrons proceeds in such a way that the photon first transforms into vector mesons ρ, ω, ϕ, which then undergo interaction with hadrons. In the consistent lagrangian formulation of vector dominance model it is assumed [1] (see [2] for review) that ρ-mesons are Yang-Mills vector bosons. In this hypothesis the ρ-meson magnetic moment is equal to 2 (in units $e/(2m_\rho)$), at least if strong interaction is neglected.

In paper [3] the ρ-meson formfactors were found at intermediate momentum transfer by QCD sum rules. By extrapolation of the ρ-meson magnetic formfactor to the point $Q^2 = 0$ (outside the applicability domain of the technique) it was found that the ρ-meson magnetic moment μ is close to 2. However, this result can not be considered as final, and direct calculation of the magnetic moment is the topical problem.

In our previous paper [4] the ρ-meson magnetic moment was calculated in the framework of QCD sum rules in external fields. This technique was developed in [5, 6]. The operators of dimension 6 were taken into account. As for α_s-corrections, they were neglected. However, since the discussed energy scale is approximately $1\,GeV^2$, α_s-corrections may give appreciable contribution.

This paper is devoted to the calculation of the α_s-corrections to the ρ-meson magnetic moment. It is organized as follows. First of all, we are going to remind the reader the basic points of the sum rule construction (section 2). In the section 3 we discuss in detail the perturbative contribution to the sum rule. In the section 4 we present the nonperturbative contribution. The results can be found in the section 5. The values obtained in some other approaches (Dyson-Schwinger equation based models [7, 8], relativistic quantum mechanics [9], light cone QCD sum rules [10]) are also presented.

In our paper u- and d-quarks are considered as massless.

2. Phenomenological part of the sum rule

Let us consider the correlator of two vector currents in the external electromagnetic field:

$$\Pi_{\mu\nu}(p) = i \int d^4x \, e^{ipx} \langle T(j_\mu(x) j_\nu^+(0)) \rangle_F \, . \tag{2.1}$$

Here subscript F denotes the presence of the external electromagnetic field with strength $F_{\rho\lambda}$ and j_μ is the vector current with ρ-meson quantum numbers: $j_\mu = \overline{u}\gamma_\mu d$. Its matrix element is

$$\langle \rho^+ | j_\mu | 0 \rangle = \left(\frac{m_\rho^2}{g_\rho} \right) e_\mu \, , \tag{2.2}$$

where m_ρ is the ρ-meson mass, g_ρ is the ρ-γ coupling constant, $g_\rho^2/(4\pi) = 1.27$, and e_μ is the ρ-meson polarization vector.

In the limit of weak external field we consider only linear in $F_{\rho\lambda}$ terms in the correlator $\Pi_{\mu\nu}$ (2.1):

$$\Pi_{\mu\nu} = \Pi^0_{\mu\nu} + i\sqrt{4\pi\alpha}\,\Pi_{\mu\nu\chi\sigma} F_{\chi\sigma} \, . \tag{2.3}$$

In order to find the ρ-meson magnetic moment we construct sum rule for the invariant function $\Pi(p^2)$ at certain kinematical structure of $\Pi_{\mu\nu\chi\sigma}$ (2.3).

The description of the kinematical structure choose and sum rule construction can be found in [4]. For the sake of consistency we present it here.

The electromagnetic vertex of the ρ-meson has the following general form [3]:

$$\begin{aligned}
\langle \rho(p+q, e^{r'}) | j^{el}_\chi | \rho(p, e^r) \rangle \; = \; -e^{r'}_\sigma e^r_\rho \Big(& \Big((2p+q)_\chi g_{\rho\sigma} - (p+q)_\rho g_{\chi\sigma} - p_\sigma g_{\rho\chi} \Big) F_1(-q^2) \, + \\
& + (g_{\chi\rho} q_\sigma - g_{\chi\sigma} q_\rho) F_2(-q^2) \, + \\
& + \frac{1}{m_\rho^2} (p+q)_\rho p_\sigma (2p+q)_\chi F_3(-q^2) \Big) \, .
\end{aligned} \tag{2.4}$$

In this expression $j^{el}_\chi = e_u \overline{u}\gamma_\chi u + e_d \overline{d}\gamma_\chi d$ is the electromagnetic current, $e_u \, , e_d$ are u- and d-quark charges and $F_1 \, , F_2 \, , F_3$ are electric, magnetic and quadrupole formfactors correspondingly. The ρ-meson magnetic moment μ is related to magnetic formfactor at $q^2 = 0$:

$$\mu = 1 + F_2(0) \, . \tag{2.5}$$

JHEP12(2003)061

Using (2.2) and (2.4), we obtain for the $\langle 0|j_\mu|\rho\rangle\langle\rho|j^{el}_\chi|\rho\rangle\langle\rho|j_\nu|0\rangle\epsilon_\chi$ transition:

$$
\begin{aligned}
-i\sum_{r,r'}\langle 0|j_\mu|\rho^{r'}\rangle\langle\rho^{r'}|j^{el}_\chi|\rho^r\rangle\langle\rho^r|j_\nu|0\rangle\epsilon_\chi = {} & i\frac{m_\rho^4}{g_\rho^2}\sum_{r,r'} e^{r'}_\mu e^{r'}_\sigma e^r_\rho e^r_\nu \epsilon_\chi \times \\
& \times\Big(\Big((2p{+}q)_\chi g_{\rho\sigma} - (p{+}q)_\rho g_{\chi\sigma} - p_\sigma g_{\rho\chi}\Big)F_1(-q^2) + \\
& + (g_{\chi\rho}q_\sigma - g_{\chi\sigma}q_\rho)F_2(-q^2) + \\
& + \frac{1}{m_\rho^2}(p+q)_\rho p_\sigma(2p+q)_\chi F_3(-q^2)\Big)\,. \qquad (2.6)
\end{aligned}
$$

Here $\epsilon_\chi-$photon polarization, r, r' are the ρ-meson polarization indices. Let us consider in this expression linear in q_σ terms. We sum over ρ-meson polarizations, retain the antisymmetric over χ,σ part, introduce the electromagnetic field $F_{\chi\sigma} = i(\epsilon_\chi q_\sigma - \epsilon_\sigma q_\chi)$ and obtain for (2.6):

$$
\begin{aligned}
-\frac{m_\rho^4}{2g_\rho^2}F_{\chi\sigma}\Big(&\Big(F_2+\frac{1}{2}F_1\Big)\frac{1}{p^2}\Big(p_\nu(p_\chi g_{\mu\sigma} - p_\sigma g_{\mu\chi}) - p_\mu(p_\chi g_{\nu\sigma} - p_\sigma g_{\nu\chi})\Big) + \\
&+\frac{1}{2}F_1\frac{1}{p^2}\Big(p_\nu(p_\chi g_{\mu\sigma} - p_\sigma g_{\mu\chi}) + p_\mu(p_\chi g_{\nu\sigma} - p_\sigma g_{\nu\chi})\Big) + \\
&+(F_2+F_1)(g_{\mu\chi}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\chi})\Big)\,.
\end{aligned}
$$

Formfactor F_3 does not give linear in q_σ contribution.

The ρ-meson magnetic moment μ is involved in the invariant functions at the kinematical structures $p_\nu(p_\chi g_{\mu\sigma} - p_\sigma g_{\mu\chi}) - p_\mu(p_\chi g_{\nu\sigma} - p_\sigma g_{\nu\chi})$ and $g_{\mu\chi}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\chi}$. We choose the structure

$$
p_\nu(p_\chi g_{\mu\sigma} - p_\sigma g_{\mu\chi}) - p_\mu(p_\chi g_{\nu\sigma} - p_\sigma g_{\nu\chi})\,. \qquad (2.7)
$$

In comparison with another one, (2.7) contains two additional powers of momentum in the numerator, which result in better convergence of the operator expansion series.

Using equalities (2.5) and $F_1(0) = 1$ one can see that $F_2(0) + 1/2F_1(0) = \mu - 1/2$.

Thus, one should calculate the invariant function $\Pi(p^2)$ at the structure (2.7) in $\Pi_{\mu\nu\chi\sigma}$.

In order to obtain the phenomenological part of the sum rule, one should saturate the dispersion relation for $\Pi(p^2)$ by the contribution of physical states. We use the simplest model of physical spectrum, which contains the lowest resonance and continuum. Phenomenological representation of Π has the form:

$$
\begin{aligned}
\Pi(p^2) &= \int ds\frac{\rho(s)}{(s-p^2)^2} + \cdots\,, \\
\rho(s) &= -\frac{m_\rho^4}{2g_\rho^2}\frac{1}{s}\Big(\mu - \frac{1}{2}\Big)\delta(s-m_\rho^2) + f(s)\theta(s-s_\rho)\,.
\end{aligned}
$$

Here dots mean the contributions of non-diagonal transitions (for example,

$$
\langle 0|j_\mu|\rho^\star\rangle\langle\rho^\star|j_\chi\epsilon_\chi|\rho\rangle\langle\rho|j_\nu|0\rangle,
$$

where $\rho^\star$ is the excited state with the same quantum numbers as ρ), function $f(s)$ represents continuum contribution and s_ρ is the continuum threshold for the ρ-meson.

JHEP12(2003)061

Retaining only the terms, which do not vanish after Borel transformation, we obtain:

$$\Pi(p^2) = -\frac{m_\rho^2}{2g_\rho^2}\frac{\mu-\frac{1}{2}}{(m_\rho^2-p^2)^2} + \frac{C}{m_\rho^2-p^2} + \int\limits_{s_\rho}^{\infty} ds \frac{f(s)}{(s-p^2)^2}\,, \tag{2.8}$$

where C appears due to non-diagonal transitions.

3. Perturbative contribution to the sum rule

Now we need to calculate $\Pi(p^2)$, basing on the operator product expansion in QCD. In this section we consider perturbative terms.

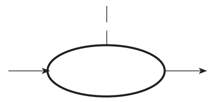

Figure 1: Loop diagram in the external electromagnetic field. Thick solid lines denote quarks, dashed line denotes the external field.

The loop diagram (figure 1) corresponds to the operator of the lowest dimension 2.

Its contribution to $\Pi(p^2)$ is equal to

$$-\frac{3}{16\pi^2}\int\limits_0^{\infty}\frac{ds}{(s-p^2)^2}\,.$$

The expressions for the quark propagator in the external electromagnetic field and in the external electromagnetic and soft gluon fields can be found in [5].

In order to improve the free-quark approximation, we calculate the α_s perturbation corrections corresponding to the diagrams in figure 2. We consider the integrals with respect to internal momenta in $D = 4-2\epsilon$ dimensions. For the calculation of the diagrams in figures $2e$ and $2f$ the following formula from the paper [11] is used:

$$\epsilon\int\frac{d^Dk\,d^Dq}{(2\pi)^{2D}}\frac{1}{k^2(p-k)^2q^2(q-k)^2(p-q)^2} =$$
$$= \int\frac{d^Dk\,d^Dq}{(2\pi)^{2D}}\left(\frac{1}{k^2(p-k)^4q^2(k-q)^2} - \frac{1}{k^2(p-k)^4q^2(p-q)^2}\right).$$

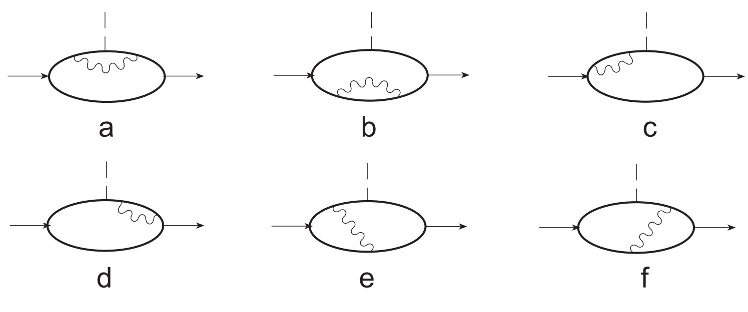

Figure 2: Perturbative corrections to the bare loop. Wave lines denote gluons.

In the limit $\epsilon \to 0$ these diagrams give the following contributions to the polarization operator:

$$A_a = \frac{\alpha_s}{2^6\pi^3 p^2}\left(\frac{4}{\epsilon} + 22 - 8\gamma_E\right) \qquad \text{(diagram in figure } 2a) ,$$

$$A_b = \frac{\alpha_s}{2^6\pi^3 p^2}\left(-\frac{4}{\epsilon} - 10 + 8\gamma_E\right) \qquad \text{(diagram in figure } 2b) ,$$

$$A_c = A_d = \frac{\alpha_s}{2^6\pi^3 p^2}\left(-\frac{4}{\epsilon} - 14 + 8\gamma_E\right) \qquad \text{(diagrams in figures } 2c,\ 2d) ,$$

$$A_e = A_f = \frac{\alpha_s}{2^6\pi^3 p^2}\left(\frac{4}{\epsilon} + \frac{44}{3} - 8\gamma_E\right) \qquad \text{(diagrams in figures } 2e,\ 2f) .$$

Here γ_E is the Euler constant.

In the sum

$$A_a + A_b + A_c + A_d + A_e + A_f = \frac{5\alpha_s}{24\pi^3 p^2}$$

the divergence $1/\epsilon$ cancels out. It is not by chance, since the diagrams in figure 2 correspond to the physically measurable process, and their total contribution can not include divergent term.

After adding the α_s-correction, we obtain for the perturbative (and bare loop) contribution to the polarization operator:

$$-\frac{3}{16\pi^2}\left(1 + \frac{10}{9}\frac{\alpha_s}{\pi}\right)\int\limits_0^\infty \frac{ds}{(s-p^2)^2} \,. \tag{3.1}$$

According to the quark-hadron duality, the continuum contribution in the interval of $P^2 = -p^2$ from s_ρ to infinity is determined by term (3.1) in this interval. Therefore, function f in (2.8) is: $f = -3/(16\pi^2)(1 + 10\alpha_s/(9\pi))$.

4. Contribution of dimension 6 operators

The contribution of the operators of dimension 6 was found in [4]. Here we remind the corresponding formulas.

The diagrams in figures 1, 2 correspond to the operator of the lowest dimension $F_{\rho\lambda}$. The operators of dimension 4 are absent. As was shown in [5], operator $\overline{q}(D_\mu\gamma_\nu - D_\nu\gamma_\mu)q$ has opposite with respect to the electromagnetic field C-parity and can not be induced by them, while operator $\epsilon_{\mu\nu\rho\lambda}\overline{q}\gamma_5\gamma_\rho D_\lambda q$ vanishes due to equation of motion for massless quarks.

Among the diagrams, corresponding to the vacuum expectation values of dimension 6 operators (there are five such vacuum expectation values), the dominating contribution appears from the no loop diagrams with hard gluon exchange. In our case such diagrams contain the vacuum expectation value $\langle\overline{q}\sigma_{\rho\lambda}q\rangle_F\langle\overline{q}q\rangle$ (figure 3). Their contribution to the polarization operator is equal to

$$\frac{2}{9}\frac{g^2\langle\overline{q}q\rangle^2\chi}{p^6} \,. \tag{4.1}$$

In this expression $g^2 = 4\pi\alpha_s$, the quark condensate magnetic susceptibility χ is negative.

JHEP12(2003)061

The contribution of the vacuum expectation value $\langle G^n_{\sigma\tau} G^n_{\sigma\tau}\rangle F_{\mu\nu}$ to $\Pi(p^2)$ is determined by the one-loop diagrams (figure 4) and, therefore, has numerically small factor. For this reason we disregard it.

There are three other vacuum expectation values of dimension 6 operators:

$$g\left\langle \overline{q}\Big(\Big(G^n_{\mu\lambda}D_\nu - \overleftarrow{D}_\nu G^n_{\mu\lambda}\Big) - \Big(G^n_{\nu\lambda}D_\mu - \overleftarrow{D}_\mu G^n_{\nu\lambda}\Big)\Big)\gamma_\lambda t^n q\right\rangle_F ,$$
$$\epsilon_{\mu\nu\rho\lambda} g\left\langle \overline{q}\left(G^n_{\rho\xi}D_\lambda + \overleftarrow{D}_\lambda G^n_{\rho\xi}\right)\gamma_\xi\gamma_5 t^n q\right\rangle_F \qquad (4.2)$$

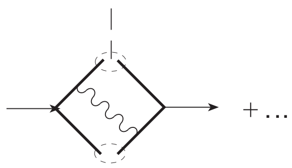

Figure 3: The diagrams, corresponding to the vacuum expectation value $\langle\overline{q}\sigma_{\rho\lambda}q\rangle_F\langle\overline{q}q\rangle$. Dots stand for permutations.

and

$$d^{ikl}g^3\left\langle\Big(G^i_{\mu\lambda}G^k_{\lambda\rho}G^l_{\rho\nu} - G^i_{\nu\lambda}G^k_{\lambda\rho}G^l_{\rho\mu}\Big)\right\rangle_F . \qquad (4.3)$$

Here D_μ is the covariant derivative, d^{ikl} are SU(3) structure constants, subscript F denotes the presence of the external field. Usually vacuum expectation values of such operators can be calculated by constructing the corresponding sum rules. But in our case this way is inapplicable because of their high dimension. However, the vacuum expectation values (4.2) are suppressed by the factor N_c^{-1} (N_c is the color number) as compared with $\langle\overline{q}\sigma_{\rho\lambda}q\rangle_F\langle\overline{q}q\rangle$, while (4.3) contains the factor g^3. So we can expect that they are rather small and disregard them.

Collecting the expressions (3.1) and (4.1), we find the operator product expansion part of the sum rule:

$$\Pi(p^2) = -\frac{3}{16\pi^2}\left(1+\frac{10}{9}\frac{\alpha_s}{\pi}\right)\int_0^\infty \frac{ds}{(s-p^2)^2} + \frac{2}{9}\frac{g^2\langle\overline{q}q\rangle^2\chi}{p^6} . \qquad (4.4)$$

Now we have both parts of required sum rule.

5. Results and discussion

After Borel transformation

$$\hat{B}(M^2) = \lim_{\substack{P^2,n\to\infty \\ P^2/n=M^2}} \frac{(P^2)^{n+1}}{n!}\left(-\frac{d}{dP^2}\right)^n , \qquad P^2 = -p^2 > 0$$

we equate the phenomenological (2.8) and operator product expansion (4.4) parts of the sum rule and obtain:

$$\mu - \frac{1}{2} + CM^2 = \frac{3g_\rho^2 M^2}{8\pi^2 m_\rho^2}\left(1+\frac{10}{9}\frac{\alpha_s(M^2)}{\pi}\right)\left(1-e^{-s_\rho/M^2}\right)e^{m_\rho^2/M^2} + \frac{2g_\rho^2 g^2\langle\overline{q}q\rangle^2\chi}{9m_\rho^2 M^2}e^{m_\rho^2/M^2} . \quad (5.1)$$

Here C appears due to nondiagonal transitions.

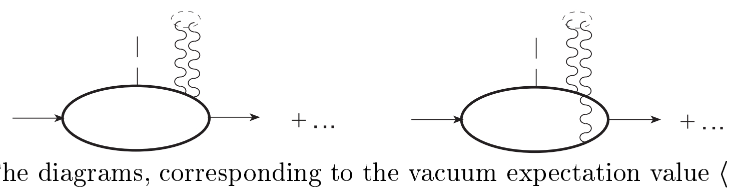

Figure 4: The diagrams, corresponding to the vacuum expectation value $\langle G^n_{\sigma\tau}G^n_{\sigma\tau}\rangle F_{\mu\nu}$.

We use the following values of parameters:

- $m_\rho = 0.77\,GeV$ – the ρ-meson mass,
- $g_\rho^2/(4\pi) = 1.27$ – the ρ-γ coupling constant,
- $s_\rho = 1.5\,GeV^2$ – the continuum threshold for ρ-meson,
- $g^2\langle\overline{q}q\rangle^2 = (0.28 \pm 0.09) \times 10^{-2}\,GeV^6$ – the quark condensate [12],
- $\chi(1\,GeV) = -(3.15 \pm 0.30)\,GeV^{-2}$ – the quark condensate magnetic susceptibility [13],
- $\Lambda_{QCD} = 0.2\,GeV$.

In (5.1) $\alpha_s(M^2) = 4\pi/(9\ln(M^2/\Lambda_{QCD}^2))$.

As was mentioned in [4], in order to obtain the ρ-meson magnetic moment in the parton model approximation one has to substitute the relation for g_ρ [14]

$$\frac{g_\rho^2 M^2}{4\pi^2 m_\rho^2}\left(1 - e^{-s_\rho/M^2}\right)e^{m_\rho^2/M^2} = 1$$

into the contribution of the bare loop and continuum (see (5.1)):

$$\mu_{part} - \frac{1}{2} = \frac{3g_\rho^2 M^2}{8\pi^2 m_\rho^2}\left(1 - e^{-s_\rho/M^2}\right)e^{m_\rho^2/M^2}\,.$$

It was obtained in this way:

$$\mu_{part} = 2\,.$$

This result agrees with the prediction of the vector dominance hypothesis.

Now let us analyze the whole equation (5.1). In order to find the value of the magnetic moment, we approximate the right-hand side of (5.1) $R(M^2)$ (see figure 5) by a straight line in the interval $0.9\,GeV^2 \leq M^2 \leq 1.4\,GeV^2$ and find it ordinate at zero Borel mass.

Thus we obtain the same result:

$$\mu = 2.0\,.$$

The operators of dimension 6 (term (4.1)) give less than 15% to this value.

The uncertainties in the values of the quark condensate and the quark condensate magnetic susceptibility result in the error about few percent in the value of the magnetic moment. Variation of the continuum threshold for the ρ-meson s_ρ in the reasonable limits gives the same effect.

Taking into account all uncertainties we obtain (in units $e/(2m_\rho)$):

$$\mu = 2.0 \pm 0.3\,. \tag{5.2}$$

This is our final result.

In [15] it was shown that the approximation procedure is correct (nonlinear terms can be safely neglected), when $CM^2/\mu \ll 1$. In our case $CM^2/\mu < 0.05$.

JHEP12(2003)061

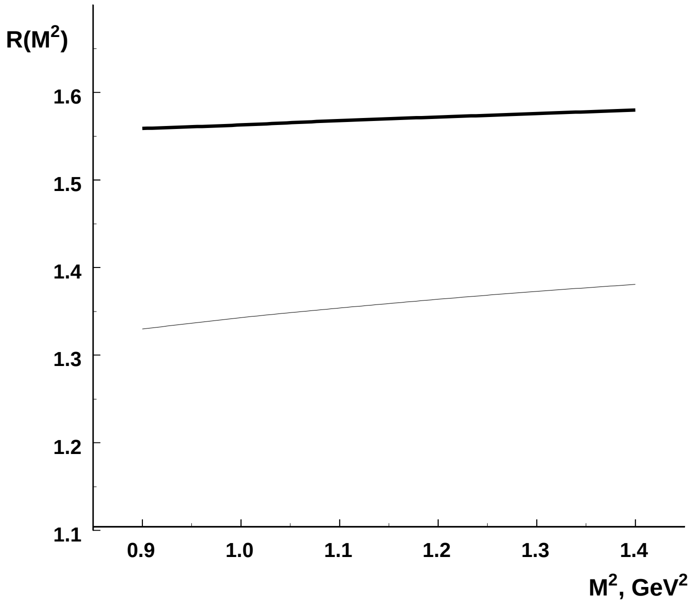

Figure 5: The right-hand side of equation (5.1) $R(M^2)$ as the function of M^2 (thick line). The same without α_s-corrections (thin line).

The value of the magnetic susceptibility $\chi = -(3.15 \pm 0.30)\, GeV^{-2}$ was obtained recently in [13] from the sum rule with account of α_s-corrections and new data for the resonances. The older value $\chi_{bel}(1\, GeV) = -4.4\, GeV^{-2}$ [16] decreases the value of the magnetic moment by 0.1.

Thus we see that in parton model (bare loop) approximation the ρ-meson magnetic moment $\mu_{part} = 2$. All accounted operator product expansion corrections are negative, i.e. nonperturbative interactions decrease this quantity. We obtain that the value of the magnetic moment (disregarding α_s-corrections) is equal to 1.7. On the other hand, the α_s-correction is quite appreciable (~ 0.3) in magnitude and positive (see figure 5). After taking into account both perturbative and nonperturbative terms, we obtain the value (5.2). It agrees with the vector dominance model prediction again.

The value of the ρ-meson magnetic moment was calculated in a number of papers within the Dyson-Schwinger equation based models. In [7] the value $\mu = 2.69$ was found. In [8] several results are compared, and the values of μ lie between 2.5 and 3.0. Relativistic quantum mechanics model gives [9] $\mu = 2.23 \pm 0.13$.

Recently the value of the magnetic moment was found in the light cone QCD sum rule technique [10]. In this technique the expansion over the twist of the operators is performed, and all nonperturbative effects are encoded in the wave functions. In [10] the asymptotic form $\psi(u) = 1$ of the twist 2 photon wave function $\psi(u)$ at the point $u = 1/2$ was used, and it was obtained (disregarding α_s-corrections): $\mu = 2.2 \pm 0.2$. This value and (5.2) do not contradict one another within the errors.

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