Four-point correlator constraints on electromagnetic chiral parameters and resonance effective Lagrangians

B. Ananthanarayan\textsuperscript{a} and B. Moussallam\textsuperscript{b}

\textsuperscript{a} Centre for High Energy Physics
Indian Institute of Science, Bangalore 560 012, India

\textsuperscript{b} Groupe de Physique Théorique, IPN
Université Paris-Sud, F-91406 Orsay Cédex, France

Abstract

We pursue the analysis of a set of generalized DGMLY sum rules for the electromagnetic chiral parameters at order $e^2p^2$ and discuss implications for effective Lagrangians with resonances. We exploit a formalism in which charge spurions are introduced and treated as sources. We show that no inconsistency arises from anomalies up to quadratic order in the spurions. We focus on the sum rules associated with QCD 4-point correlators which were not analyzed in detail before. Convergence properties of the sum rules are deduced from a general analysis of the form of the counterterms in the presence of electromagnetic spurions. Following the approach in which vector and axial-vector resonances are described with antisymmetric tensor fields and have a chiral order, we show that the convergence constraints are violated at chiral order four and can be satisfied by introducing a set of terms of order six. The relevant couplings get completely and uniquely determined from a set of generalized Weinberg sum-rule relations. An update on the corrections to Dashen’s low-energy theorem is given.

\footnote{Supported in part by IFCPAR contract 2504-1, by the European Union TMR network, Contract No. HPRN-CT-2002-00311 (EURIDICE) and by the Department of Science and Technology, Government of India.}
Contents

1 Motivation 3

2 Chiral calculation of the basic correlators 4
  2.1 Definition of the basic correlation functions 4
  2.2 Correlators at order $e^2 p^2$ 6
  2.3 Calculation of the one-loop photon contributions 9

3 Correlators from the minimal resonance Lagrangian 11
  3.1 $O(p^4)$ resonance Lagrangian 11
  3.2 Contributions proportional to $F_A^2$ and $F_V^2$ 13
  3.3 $G_V F_V$ contributions 15
  3.4 $G_A^2$ and $G_V^2 F_V^2$ contributions 17
  3.5 Contributions proportional to $c_d, \tilde{c}_d$ 17
  3.6 Comparison with the results of Baur and Urech 18

4 Short distance constraints 19
  4.1 OCD+OED counterterms 19
  4.2 Summary of the $\log \Lambda^2$ dependence 21

5 Beyond the $O(p^4)$ resonance Lagrangian 22
  5.1 Survey of $O(p^6)$ terms 22
  5.2 $\mathcal{L}_{\omega\rho\pi}$ constraints from $\langle VAP \rangle$ 24
  5.3 Linear contributions from $\mathcal{L}_{\omega\rho\pi}$ 25
  5.4 Quadratic contributions from $\mathcal{L}_{\omega\rho\pi}$ and consistency conditions for $\Pi_1, \Pi_2, \Pi_3$ 26
  5.5 Contributions from $\mathcal{L}_{\omega\rho\pi}$ and the consistency condition for $\Pi_8$ 28
  5.6 Contributions from $\mathcal{L}_{\omega\rho\pi}$ in the vector v/s tensor formalism and $\Pi_9$ 29

6 Numerical results 32
  6.1 Results for $K_1, ..., K_6$ 32
  6.2 An update on the corrections to Dashen’s theorem 32
  6.3 Uncertainties 34

7 Conclusions 34

A Vertices 34
  A.1 Vertices with pions 35
  A.2 Resonance vertices with $v_\mu$ sources: 36
  A.3 Vertices proportional to $F_A$ 36
  A.4 Vertices proportional to $F_V$ 37
  A.5 Vertices proportional to $G_V$ 37

B $b_1(1235)$ contributions 38
1 Motivation

Virtual photons play an important role in low energy QCD for isospin breaking phenomena and must also be taken into account in connection with precision experiments. The formalism for extending the framework of the standard ChPT[1, 2, 3] to include virtual photons at one-loop was developed, some time ago, by Urech[4]. Several extensions were later performed to accommodate leptons[5], to the weak non-leptonic sector[6], to the anomalous sector[7] as well as to the baryon sector[8]. The problem of the determination of the new set of low-energy coupling constants (LEC’s) which appear in Urech’s Lagrangian is of obvious practical importance in relation with radiative correction calculations. Many such calculations have been performed recently: low energy $\pi\pi$ or $\pi K$ scattering [9, 10, 11, 12, 13, 14, 15] pionic as well as pi-kaonic atoms [16, 17, 18], the set of semi-leptonic decays of the Kaon [19, 20], processes from the anomalous sector[21, 7], the problem of computing the hadronic contribution of the muon $g – 2$ from $\tau$ decay data[22], the theoretical prediction of the CP-violation ratio $\epsilon'/\epsilon$ for the Kaon[23, 24, 25] to mention just a few illustrative examples. Another important application of the electromagnetic low-energy couplings (LEC’s) is to the question of the chiral corrections to Dashen’s low-energy theorem[26] and the determination of the light quark masses (e.g. [27]). Interesting questions were raised recently concerning the proper definition of the quark masses in the presence of QED[28].

The problem of the determination of the EM-LEC’s was addressed in several papers some time ago[29, 30, 31] but the results remain incomplete and sometimes contradictory. In this paper, we continue the discussion started in ref.[31] (hereafter referred to as (I)). In (I) it was shown that the electromagnetic LEC’s obey integral sum rule representations which generalize the classic DGMLY sum rule[32] for the $\pi^+ – \pi^0$ mass difference. The integral representations have the form of convolutions involving a pure QCD $n$-point Green’s function with $n = 2, 3$ and $4$ together with the free photon propagator. These representations serve a number of purposes. For instance, they can be used to recover the chiral scale dependence of the LEC’s, to determine how these depend on the $\xi$ gauge parameter and, also, by studying the convergence properties, to determine which LEC’s are affected by short distance ambiguities. Finally, these representations can be used as a method to provide approximate determinations of these couplings.

This was exploited in (I) to discuss the set of couplings which are associated with 2- and 3-point Green’s functions. The method consists in constructing rational approximants to the Green’s functions, which is in the spirit of the large $N_c$ expansion[33]. The parameters of the rational functions are constrained by the chiral Ward identities, by physical input on resonance masses and couplings and by short-distance matching conditions. In the present paper, we address the more complicated case of the 4-point functions. The way of insuring that the Ward identities are satisfied is to start from a chiral Lagrangian including resonances. Such a Lagrangian was constructed in ref.[34] which uses the antisymmetric tensor formalism[2] to describe the vector and axial-vector resonances. This formalism is particularly convenient for discussing the ordinary LEC’s because one can assign a chiral order to each resonance field such that all the terms which are of order four, which include one multiplet of vector, axial-vector, scalar and pseudo-scalar resonances were listed in ref.[34]. It was shown in a subsequent paper[35] that if one imposes a number of short
distance matching conditions, the determination of the \(O(p^4)\) LEC’s becomes independent of the specific representation of the resonances in the chiral Lagrangian.

The Lagrangian of ref.\[34\] was employed by Baur and Urech\[29\] (BU) to discuss the electromagnetic LEC’s. For this application, however, one realizes by using the integral representation that the Green’s functions are needed under kinematical conditions which are different, in general, from those considered in\[35\] such that the Lagrangian of ref.\[34\] is no longer sufficient to ensure the proper short distance constraints. This deficiency manifests itself in the fact that the results of BU for the electromagnetic LEC’s fail to satisfy the correct scale dependence, which is an effect of leading order in \(N_c\). In this paper, we will show that a simple extension of the Lagrangian\[34\] to include a set of terms which are of chiral order six allows one to satisfy the short distance constraints in the chiral limit which are necessary for a consistent determination of the electromagnetic LEC’s and which are associated with the 2- and 3-point functions considered in\[31\] as well as the 4-point functions introduced in this paper. Finally, we will present estimates for the six LEC’s which are associated with these 4-point functions.

2 Chiral calculation of the basic correlators

2.1 Definition of the basic correlation functions

In the presence of a dynamical photon field \(F_\mu\) it is convenient to extend the source part of the QCD Lagrangian to include two spurion fields \(q_V, q_A\)\[4\]

\[
\mathcal{L}^{\text{sources}}_{\text{QCD}} = \bar{\psi}_L \gamma_\mu [l_\mu + q_L F_\mu] \psi_L + \bar{\psi}_R \gamma_\mu [r_\mu + q_R F_\mu] \psi_R - \bar{\psi}(s - i\gamma^5 p) \psi ,
\]

with

\[
l_\mu = v_\mu - a_\mu, \quad q_L = q_V - q_A, \quad r_\mu = v_\mu + a_\mu, \quad q_R = q_V + q_A .
\]

The number of light flavours is assumed to be \(N^0_F = 3\), and the sources in eq.(2) are traceless \(3 \times 3\) matrices. Originally\[4\], the spurions \(q_V, q_A\) were introduced only for the purpose of classifying the independent terms in the chiral Lagrangian and afterwards one would set \(q_A = 0, q_V = Q\). We will exploit here more general applications by considering the spurions on the same footing as the ordinary external sources. We note that renormalization will generate terms which are non-linear in the sources. Those which are quadratic in the spurion sources are of particular interest for our purposes and will be discussed in detail in sec.\[4\] It will also be argued that no difficulty arises in the definition of the generating functional in the presence of the \(q_V, q_A\) spurions up to quadratic order in the spurions. We now introduce a set of five correlation functions defined by taking two functional derivatives with respect to \(v_\mu\) or \(a_\mu\) and two derivatives with respect to the charge spurions \(q_V\) or \(q_A\). The first one is defined as follows

1) \(\langle A^a_\alpha A^b_\beta Q^d_A Q^d_A \rangle = \int d^4x d^4y d^4z \exp(iky) \frac{\delta^4 W(v_\mu, a_\mu, q_V, q_A)}{\delta a^a_\alpha(x) \delta a^b_\beta(y) \delta q^d_A(z) \delta q^d_A(0)}\) (3)

where \(W\) is the generating functional of connected Green’s functions. The remaining four

2) \(\langle A^a_\alpha A^b_\beta Q^V_V Q^d_V \rangle \)
are defined in an exactly analogous way. These correlators involve two Lorentz structures \( g_{\alpha\beta} \) and \( k_{\alpha}k_{\beta} \). For our purposes, we can restrict ourselves to the Lorentz structure proportional to \( g_{\alpha\beta} \) and we will consider the limit \( k \to 0 \). Before taking this limit, however, we must consider two possible kinds of singularities: a) \( 1/k^2 \) pion poles and b) \( \log(k^2) \) cuts due to pion loops. The latter singularities drop out in the leading large \( N_c \) approximation, which we will frequently invoke. A pion pole can appear only in one flavour structure of the fifth correlator \( <A_a^aV_b^bQ_c^cQ_A^d> \). Apart from this particular case, we can simply set \( k = 0 \), meaning that we restrict ourselves to constant vector and axial–vector sources. This leads to great simplification since all terms like \( \partial_{\mu}v_{\nu} \), \( \partial_{\mu}a_{\nu} \) etc... can be dropped in the chiral resonance Lagrangian. Similarly, the \( q_V \) and \( q_A \) sources can be taken as constant for the present applications.

From the definition, eq. (3) and the explicit expression of the terms linear in the sources eq. (1) we can easily see that the correlators introduced above can be represented as a convolution of an ordinary connected QCD 4-point Green’s function and the photon propagator. For example, one finds

\[
<A_a^aV_b^bQ_c^cQ_A^d> = \int d^4x d^4y d^4z \exp(iky) <0|T(A_{\alpha}^a(x)A_{\beta}^b(y)A_{\rho}^c(z)A_{\sigma}^d(0))|0> D_{\rho\sigma}^{\text{opt}}(z). \tag{5}
\]

Because of the short distance singularities, the integral over \( d^4z \) is expected to be divergent. The divergence is removed upon including the additional contributions stemming from the counterterms and one may use d-dimensional integration as a regularization method.

Let us now examine the flavour structure. The correlators depend on four flavour indices. At order \( e^2p^2 \) one can show by using the chiral Lagrangian that there are only four independent tensor structures. It will prove convenient to use the following basis

\[
e_1 = f^{tac}f^{tbd} + f^{tab}f^{tbc},
\]

\[
e_2 = \delta^{ac}\delta^{bd} + \delta^{ad}\delta^{bc},
\]

\[
e_3 = d^{tac}d^{tbd} + d^{tab}d^{tbc},
\]

\[
e_4 = f^{tab}f^{tcd}. \tag{6}
\]

Other tensor structures that arise in practical calculations can be expressed in terms of this basis by utilizing \( SU(3) \) trace identities. The following relations are useful

\[
d^{tab}d^{tcd} = \frac{1}{6}e_1 + \frac{1}{3}e_2 - \frac{1}{2}e_3
\]

\[
\delta^{ab}\delta^{cd} = \frac{1}{2}e_1 + \frac{3}{2}e_3. \tag{7}
\]

We can now expand the correlators over the flavour basis. The first four correlators are expanded over \( e_1, e_2, e_3 \) because of the permutation symmetry \( a \leftrightarrow b, c \leftrightarrow d \). For
instance, one has
\[
< A^a_\alpha A^b_\beta Q^c_A Q_A^d > = i g_{\alpha \beta} \sum_{j=1}^{3} < AAQ_A Q_A >_{j} e_j .
\] (8)

The expansion of the last correlator involves \( e_4 \) also,
\[
< A^a_\alpha V^b_\beta Q^c_A Q_A^d > = i g_{\alpha \beta} \sum_{j=1}^{4} < AVQ_A Q_A >_{j} e_j .
\] (9)

This expansion apparently generates sixteen independent flavour components. As we will see below there are only ten components which appear at the chiral order \( e^2 p^2 \) considered here.

### 2.2 Correlators at order \( e^2 p^2 \)

We start by computing the correlators defined above in the chiral expansion up to the order \( e^2 p^2 \). Setting the sources \( s \) and \( p \) equal to zero, the leading order Lagrangian collects the terms of order \( e^2 \) and \( p^2 \)
\[
\mathcal{L}^{(2)}_{\text{chir}} = \mathcal{L}^{e^2}_{\text{chir}} + \mathcal{L}^{p^2}_{\text{chir}}
\]
\[
\mathcal{L}^{e^2}_{\text{chir}} = C(q_L U^\dagger q_R U) ,
\] (10)

with
\[
D_\mu U = \partial_\mu U - i (r_\mu + q_R F_\mu) U + i U (l_\mu + q_L F_\mu) .
\] (11)

The photon is endowed with a small mass (which may be counted as \( O(p) \)) in order to regulate infrared divergences which can appear in the chiral limit. We will also need the following part of the chiral Lagrangian of order \( e^2 p^2 \)
\[
\mathcal{L}^{p^2}_{\text{chir}} = \frac{1}{2} K_1 F_0^2 \langle D_\mu U D^\mu U^\dagger \rangle (q_L q_L + q_R q_R)
\]
\[
+ K_2 F_0^2 \langle D_\mu U D^\mu U^\dagger \rangle (q_R U^\dagger q_R U)
\]
\[
+ K_3 F_0^2 \langle (D_\mu U q_L U^\dagger)^2 + (D_\mu U^\dagger q_R U)^2 \rangle
\]
\[
+ K_4 F_0^2 \langle D_\mu U q_L U^\dagger \rangle \langle D_\mu U^\dagger q_R U \rangle
\]
\[
+ K_5 F_0^2 \langle D_\mu U D^\mu U q_L q_L + D_\mu U D^\mu U^\dagger q_R q_R \rangle
\]
\[
+ K_6 F_0^2 \langle D_\mu U^\dagger D^\mu U q_L U^\dagger q_R U + D_\mu U D^\mu U^\dagger q_R U q_L U^\dagger \rangle
\]
\[
+ K_{12} F_0^2 \langle U D^\mu U^\dagger [\nabla_\mu q_R, q_R] + U^\dagger D^\mu U [\nabla_\mu q_L, q_L] \rangle
\]
\[
+ K_{13} F_0^2 \langle [\nabla_\mu q_R U, \nabla^\mu q_L U^\dagger] \rangle
\]
\[
+ K_{14} F_0^2 \langle [\nabla_\mu q_L, \nabla^\mu q_L + \nabla_\mu q_R, \nabla^\mu q_R] \rangle
\] (13)

where
\[
\nabla_\mu q_L = \partial_\mu q_L - i [l_\mu, q_L], \quad \nabla_\mu q_R = \partial_\mu q_R - i [l_\mu, q_R] .
\] (14)
For the next two correlators, only the first flavour structure appears at this chiral order to \( e_1 \). The last correlator has two non-vanishing flavour structures. The structure proportional to \( e_4 \) is the only one to receive a tree-level contribution from \( \mathcal{L}_{\text{chir}}^{(2)} \):

\[
< AVQAQV >_1 = F_0^2 \left[ 2K_{12}^r + 2K_{14}^r + \chi_4(M_\gamma, \mu) \right]
\]

\[
< AVQAQV >_4 = \frac{2C}{k^2} + F_0^2 \left[ -K_{13}^r + 2K_{12}^r + \chi_4(M_\gamma, \mu) \right].
\]
We now introduce a set of combinations of these correlator components which enjoy useful properties

\[ \Pi_1 = <AAQQ_A A>_1 - 2 <AVQ_A Q_V>_1 + <VVQ_A Q_A>_1 \]
\[ \Pi_2 = <AAQQ_V Q_V>_1 - 2 <AVQ_A Q_V>_1 + <VVQ_V Q_V>_1 \]
\[ \Pi_3 = <AAQQ_A Q_A>_3 \]
\[ \Pi_4 = <AAQQ_V Q_V>_3 \]
\[ \Pi_5 = <AAQQ_A Q_A>_2 - \frac{2}{3} <AAQQ_A Q_A>_3 \]
\[ \Pi_6 = <AAQQ_V Q_V>_2 - \frac{2}{3} <AAQQ_V Q_V>_3 . \]  
(20)

These six combinations are in one to one correspondence with the parameters \( K_{r1}^{\ast}, \ldots, K_{r6}^{\ast} \) which we intend to determine. One can show (see [31]) that they are independent of the gauge parameter \( \xi \), and we will show below that they get no contributions from the QCD counterterms. This last fact implies that the photon loop integral must be converging. Convergence must be understood in the sense that integration is to be performed in \( d \) dimensions and the limit \( d \to 4 \) is well defined.

In the leading large \( N_c \) approximation one has

\[ \Pi_5 = \Pi_6 = 0 \quad \text{(large } N_c \text{)} . \]  
(21)

This is not difficult to show. The graphs which are of leading order in \( N_c \) are the planar ones which involve a single fermion loop [33]. This implies that they involve a single trace over the flavour \( \lambda \) matrices. Furthermore, we are interested in four-point QCD correlators which are symmetric under permutation of the Lorentz indices \( \alpha, \beta \) as well as in the other two indices \( \rho \sigma \) (see eq. (5)). They must then have the following structure

\[ <A^a_\alpha A^b_\beta Q^c_\alpha Q^d_\beta> = i g_{\alpha\beta} \left( E\langle \{ \lambda^a, \lambda^b \} \{ \lambda^c, \lambda^d \} \rangle + F \langle \lambda^a \lambda^c \lambda^b \lambda^d + \lambda^a \lambda^d \lambda^b \lambda^c \rangle \right) \]
\[ = i g_{\alpha\beta} \left( 2(2E - F) \mathbf{e}_1 + \frac{4}{3}(2E + F)(\mathbf{e}_2 + \frac{3}{2} \mathbf{e}_3) \right) \]  
(22)

making use of relations (7), where \( E \) and \( F \) are arbitrary, and the same holds for the propagator with \( Q_A Q_A \) replaced by \( Q_V Q_V \). This proves relations (21). From these, one can recover the large \( N_c \) relations among the corresponding \( K_{r1}^{\ast} \) parameters

\[ K_3^{\ast} = -K_1^{\ast} \quad K_4^{\ast} = 2K_2^{\ast} \quad \text{(large } N_c \text{)} \]  
(23)

noted in refs. [4] and [30]. We will further consider the following three combinations

\[ \Pi_7 = <VVQQ_V Q_V>_1 - <VVQ_A Q_A>_1 \]
\[ \Pi_8 = <AVQ_A Q_V>_1 - <VVQ_V Q_V>_1 \]
\[ \Pi_9 = \lim_{k^2 \to 0} k^2 <AVQ_A Q_V>_4 \]  
(24)

From these combinations we will recover established results concerning the couplings \( C, K_1^{\ast}, \ldots, K_4^{\ast} \). \( \Pi_7 \) and \( \Pi_8 \) depend on the gauge. Convergence of the photon loop integral can
be established for \( \Pi_7 \) and \( \Pi_9 \) while for \( \Pi_8 \) it holds in the particular gauge \( \xi = 0 \) and in a limited sense, as we will discuss in more detail. This limitation affects the determination of \( K_{12}^r \). We will not attempt to estimate the coupling \( K_{14}^r \) which is a pure source term.

One further remark is in order. One usually expects the coupling constants in ChPT to be associated with QCD correlators which are order parameters, except for the pure source terms. Looking at eqs. (20) this, at first sight, seems sometimes not to be the case here. For instance, \( \Pi_3 \) is associated with the correlator \( < A^a A^b A^c A^d > \) which does not vanish in perturbation theory. However, this is simply due to the fact that the components \( < AVQA_Q >_3 \) and \( < VVVQV >_3 \) vanish at chiral order \( e^2 p^2 \), so one could equally well express \( \Pi_3 \) in terms of a correlator which does behave as an order parameter.

### 2.3 Calculation of the one-loop photon contributions

In this section, we will compute contributions to the generating functional \( W(v, a, q_V, q_A) \) arising from the chiral Lagrangian \( L^{(2)}_{\text{chir}} \). The use of the spurions \( q_V, q_A \) as sources gives rise to a simple diagrammatic method which we will in this section and the following ones. As there were some errors reported in related calculations in the past (see e.g. [36]) and we will, in fact, find some discrepancies with BU, we will present our calculations in some detail. Here, we will compute the functions \( \chi_i(M, \mu) \) which appear in eqs. (17). They arise from sets of one-loop diagrams containing one photon line and one pion line, the vertices being obtained from the leading order Lagrangian (10). The corresponding standard \( \xi \)-gauge massive photon propagator reads

\[
D_{F}^{\mu\nu}(p) = \frac{-i}{(p^2 - M_i^2)} \left\{ g^{\mu\nu} + (\xi - 1) \frac{p^\mu p^\nu}{(p^2 - \xi M_i^2)} \right\}. \tag{25}
\]

The list of the vertices which are effectively needed is displayed in the appendix. We remark here that these contributions are to be included both in the chiral expansion of the correlator as well as in the expression from the resonance Lagrangian since the latter includes the piece from eq. (10).

Let us now compute the contribution to \( < AAQ_AQ_A >_i \). A single diagram contributes, shown below

![Diagram](image)

The following conventions are used to represent the sources

- \( \bullet \) = \( q_A \) source
- \( + \) = \( a_\mu \) source
- \( \circ \) = \( q_V \) source
- \( \times \) = \( v_\mu \) source

The relevant vertices are listed in the appendix. One must keep in mind, for instance, that the coupling of one axial source to the pion does not contribute to our correlators. The
photon line which joins the two $q$-sources is not explicitly drawn. Each diagram is easy to interpret in terms of the integral representation eq. (5). We will first give the results in integral form, in order to display the integrands, in which we perform the replacement of $p_\alpha p_\beta$ by $p^2 g_{\alpha\beta}/d$. In integral form, this diagrams gives

$$<AAQ_AQ_A>_1 = -F_0^2 \int \frac{-i d^d p}{(2\pi)^d} \frac{\xi}{p^2(p^2 - \xi M_\gamma^2)}$$

and the other components $<AAQ_AQ_A>_i$ get no contributions. Next, we consider $<VVQ_VQ_V>_1$ and, again, there is a single diagram to compute shown below

which gives

$$<AAQ_VQ_V>_1 = -F_0^2 \int \frac{-i d^d p}{(2\pi)^d} \left\{ \frac{1}{p^2(p^2 - M_\gamma^2)} + \frac{\xi - 1}{d(p^2 - M_\gamma^2)(p^2 - \xi M_\gamma^2)} \right\}$$

and the other components vanish. One also finds that $<VVQ_VQ_V>_i$ receive no contribution from pions. Next we consider $<VVQ_AQ_A>_i$, in this case there are four diagrams

Calculating these diagrams, one finds that the last two cancel each other and the first two give the following integral

$$<VVQ_AQ_A>_1 = F_0^2 \left( 1 - \frac{1}{d} \right) \int \frac{-i d^d p}{(2\pi)^d} \frac{\xi - 1}{(p^2 - M_\gamma^2)(p^2 - \xi M_\gamma^2)}.$$

Finally, we have to compute $<AVQ_AQ_V>_i$. There are four diagrams in this case
Computing these diagrams gives
\[
< AVQ_A Q_V >_1 = - \frac{F_0^2}{k^2} \int \frac{-i \, d^d p}{(2\pi)^d} \left\{ \frac{1}{d} \frac{\xi}{p^2 (p^2 - \xi M^2)} - \frac{1}{2} \frac{1}{p^2 (p^2 - M^2)} \right\}
\]

\[
< AVQ_A Q_V >_4 = \frac{F_0^2 (1 - d)}{k^2} \int \frac{-i \, d^d p}{(2\pi)^d} \frac{1}{p^2} + < AVQ_A Q_V >_1
\]  
(29)

The \(1/k^2\) term is generated by the third and fourth diagrams and the integral vanishes in dimensional regularization. We can now compute the d-dimensional integrals and the divergences are removed using the chiral \(\overline{MS}\) prescription\[3\]. The results for the loop functions \(\chi_i(M, \mu)\) are collected below

\[
\chi_1(M, \mu) = \frac{1}{16\pi^2} \left[ \frac{M^2}{\mu^2} \log M^2 - \xi \log \mu \right]
\]

\[
\chi_2(M, \mu) = \frac{1}{16\pi^2} \left( \frac{1}{8} \right) \left[ 2(\xi + 3) \log M^2 - 2\xi \log M - \xi + 1 \right]
\]

\[
\chi_3(M, \mu) = \frac{1}{16\pi^2} \left( \frac{1}{8} \right) \left[ 6(\xi - 3) \log M^2 - 6\xi \log M + 6\xi - 1 \right]
\]

\[
\chi_4(M, \mu) = \frac{1}{16\pi^2} \left( \frac{1}{16} \right) \left[ 2(\xi - 3) \log M^2 - 2\xi \log M - 2\xi + 1 \right].
\]  
(30)

Using these results and those from the preceding section which display the contributions involving the chiral couplings \(K_i^r\) we can deduce the scale and gauge dependence of the latter. One finds that \(K_1^r, ..., K_6^r\) are independent of the gauge parameter \(\xi\) and the scale dependence is in agreement with the results of \[4, 17\]. The couplings \(K_1^{12}, K_1^{13}, K_1^{14}\) do depend on \(\xi\). Defining the beta functions \(\Sigma_i\) in the conventional manner

\[
\frac{dK_i^r(\mu)}{d\mu} = - \frac{1}{16\pi^2} \Sigma_i
\]  
(31)

one finds from eqs.\[39\]

\[
\Sigma_{12} = \frac{1}{4}(3 - 2\xi), \quad \Sigma_{13} = \frac{3}{4}(1 - \xi), \quad \Sigma_{14} = -\frac{3}{8}(1 - \xi).
\]  
(32)

These results agree with those of Urech in the special case \(\xi = 1\), and they reproduce the results presented in ref.\[31\] where a different set of correlation functions were employed.

### 3 Correlators from the minimal resonance Lagrangian

#### 3.1 \(O(p^4)\) resonance Lagrangian

Our starting point for determining the \(K_i^r\) parameters is the integral representation eq.(5) in terms of 4-point correlation functions. The first approximation that we make is to
consider the leading large $N_c$ limit. In this limit, it is an exact statement that QCD correlators can be expressed as a sum over tree graphs involving resonance propagators (see e.g. for a review of recent applications). The second approximation that we make is to restrict ourselves to contributions from a finite number of resonances. This is acceptable in our case because we consider combinations of correlators which fall off as powers for large momenta.

In order to guarantee the validity of chiral Ward identities one may compute the correlators starting from a chiral Lagrangian with resonances. In cases where the integrals can be shown to converge, imposing the convergence property generates a set of constraints for the parameters of the resonance Lagrangian which we will call consistency conditions. These conditions will be discussed in detail in the following. We begin with the resonance Lagrangian which was used by Baur and Urech

\[ \mathcal{L}_{res}^{(4)} = \mathcal{L}_{chir}^{(4)} + \mathcal{L}_{S,S_0}^{(4)} + \mathcal{L}_{V,A}^{(4)}. \] (33)

BU have used exactly the Lagrangian proposed by Ecker et al. (except for leaving out the $\pi'$ resonance multiplet) which we will call the minimal resonance Lagrangian. Let us recall the notation and formalism used in ref. The formalism that is used is one in which all resonances transform homogeneously under the non linear representation of the chiral group including the vector and the axial-vector resonances which are described as antisymmetric tensor fields. In this approach, all the resonance fields can be assigned a chiral order equal to two, such that the resonance Lagrangian of ref., contains all possible terms, for each resonance field, which are of chiral order four. The only terms of chiral order six which are present are the kinetic energy terms.

We recall here the details: in the scalar sector an octet $S$ and a singlet $S_0$ are considered and the Lagrangian involves two coupling-constants, $c_d$ and $\tilde{c}_d$,

\[ \mathcal{L}_{S,S_0} = \frac{1}{2} \langle \nabla^2 S \nabla S - M^2 S^2 + \frac{1}{2} \nabla^2 S_0 \partial_\lambda S_0 - M^2 S_0^2 \rangle + c_d \langle S \mu \mu \rangle + \tilde{c}_d S_0 \langle \mu \mu \rangle. \] (34)

Next, a nonet of vector and axial-vector resonances are considered and the minimal Lagrangian involves three coupling constants $F_A$, $F_V$, and $G_V$,

\[ \mathcal{L}_{V,A} = -\frac{1}{2} \sum_{R=V,A} \langle \nabla^2 R \partial_\lambda \nabla_\mu R_{\mu} - \frac{1}{2} M^2 R \mu R_{\mu} \rangle + \frac{F_A}{2\sqrt{2}} \langle A_{\mu\nu} f_{-\mu\nu} \rangle + \frac{F_V}{2\sqrt{2}} \langle V_{\mu\nu} f_{+\mu\nu} \rangle + \frac{iG_V}{2\sqrt{2}} \langle V_{\mu\nu} [u^\mu, u^\nu] \rangle. \] (35)

We will compute the basic correlators introduced in sec.1 first from this minimal resonance Lagrangian. It is convenient to keep using the $q_V$, $q_A$ source spurions at this level, introduced in association with the $v_\mu$ and $a_\mu$ sources, with the replacements $l_\mu \to l_\mu + q_L F_\mu$, $r_\mu \to r_\mu + q_R F_\mu$. The diagrammatic calculation is exactly equivalent to using the convolution representation eq. in which the QCD correlator is computed from the resonance Lagrangian. In principle, we should be able to reproduce the results of BU (who used a completely different approach to determine the $K_i$’s ). We follow their convention to
regularize the UV divergences in the chiral \(\overline{MS}\) prescription and we introduce a regularization scale \(\Lambda\). The various vertices needed in the calculation are collected in the appendix. We will use the photon propagator in a general \(\xi\) gauge as in eq. (25). Since the resonances are massive one can set the photon mass \(M_\gamma = 0\) in the following. Since the \(O(p^2)\) chiral Lagrangian is also part of the resonance Lagrangian, the pion contributions \(\chi_i(M_\gamma, \Lambda), i = 1, 2, 3, 4\) which we already computed (eqs. (30)) must be added to the resonance contributions.

### 3.2 Contributions proportional to \(F_A^2\) and \(F_V^2\)

We will now consider successively the contributions proportional to \(F_A^2\), \(F_V^2\), \(G_V F_V\), \(G_V^2\), \(G_V^2 F_V^2\) which are the only ones generated from the vector and axial-vector part of the resonance Lagrangian eq. (33). One easily sees, at first, that the following correlator components \(<AAQA_A>\) and \(<VVQVQ_1>\) get no contributions proportional to \(F_A^2\). Next, one finds that there are five diagrams which contribute to \(<VVQ_AQ_A>_1\), the relevant vertices can be found in appendix A. The diagram shown below is found to make a vanishing contribution

![Diagram](image.png)

as it is antisymmetric in the \(\alpha\ \beta\) indices. The remaining four diagrams are

![Diagrams](image2.png)

The result is of the following form

\[
<VVQA_A>_1 = F_A^2 \int \frac{-i\,d^d p}{(2\pi)^d} \sum_1^4 D_i(p),
\]

(36)

with the individual diagrams contributions to the integrand reading

\[
D_1 = (1 - \frac{1}{d}) \left(\frac{2 - d}{M_A^2(p^2 - M_A^2)} + \frac{6 - d}{(p^2 - M_A^2)^2} + \frac{4M_A^2}{(p^2 - M_A^2)^3}\right)
\]

\[
D_2 = (1 - \frac{1}{d}) \frac{-2}{(p^2 - M_A^2)^2}
\]
\[ D_3 = (1 - \frac{1}{d}) \left( \frac{2 - d}{M_A^2(p^2 - M_A^2)} + \frac{d - 1 + \xi}{p^2(p^2 - M_A^2)} \right) \]
\[ D_4 = (1 - \frac{1}{d}) \left( \frac{2(d - 2)}{M_A^2(p^2 - M_A^2)} - \frac{4}{(p^2 - M_A^2)^2} \right), \quad (37) \]

respectively. Next, we consider \( \langle AAQV \rangle \). A single diagram contributes (with a crossed one) which gives the same result as \( D_3 \) above. Finally, we turn to \( \langle AVQ_AQ \rangle \). There are three diagrams which contribute (and no crossed diagrams in this case), which are shown below.

These diagrams give
\[ \langle AVQ_AQ \rangle = F_A^2 \int \frac{-i d^d p}{(2\pi)^d} \left[ \frac{d + \xi - 1}{2p^2(p^2 - M_A^2)} - \frac{1}{(p^2 - M_A^2)^2} \right] \]
\[ k^2 \langle AVQ_AQ \rangle = F_A^2 \int \frac{-i d^d p}{(2\pi)^d} \frac{1 - d}{p^2 - M_A^2}. \quad (38) \]

Computing all the integrals, in summary, the following results are obtained
\[ \langle AAQ_AQ \rangle_{i_1} = 0 \]
\[ \langle AAQ_VQ \rangle_{i_1} = -\frac{3}{4} \frac{F_A^2}{16\pi^2} (1 + \xi) \left( \frac{1}{6} + \log \frac{M_A^2}{\Lambda^2} \right) \]
\[ \langle VVQ_AQ \rangle_{i_1} = \frac{3}{2} \frac{F_A^2}{16\pi^2} \left\{ 1 - \frac{1}{2} (\xi - 1) \left( \frac{1}{6} + \log \frac{M_A^2}{\Lambda^2} \right) \right\} \]
\[ \langle VVQ_VQ \rangle_{i_1} = 0 \]
\[ \langle AVQ_AQ \rangle_{i_1} = -\frac{3}{8} \frac{F_A^2}{16\pi^2} (1 + \xi) \left( \frac{1}{6} + \log \frac{M_A^2}{\Lambda^2} \right) \]
\[ k^2 \langle AVQ_AQ \rangle_{i_4} = \frac{3}{16\pi^2} \frac{M_A^2 F_A^2}{3} \left( \frac{2}{3} + \log \frac{M_A^2}{\Lambda^2} \right) + O(k^2). \quad (39) \]

There is a simple correspondence between the diagrams proportional to \( F_V^2 \) and those proportional to \( F_A^2 \) considered above so we give directly the results for the various components of the correlators
\[ \langle AAQ_AQ \rangle_{i_1} = -\frac{3}{4} \frac{F_V^2}{16\pi^2} (1 + \xi) \left( \frac{1}{6} + \log \frac{M_V^2}{\Lambda^2} \right) \]

14
\[<AAQ_VQ_V>_i^{F_V^2} = 0\]
\[<VVQA_QA>_1^{F_V^2} = 0\]
\[<VVQ_VQ_V>_1^{F_V^2} = \frac{3}{2} \frac{F_V^2}{16\pi^2} \left\{ 1 - \frac{1}{2} (\xi - 1) \left( \frac{1}{6} + \log \frac{M_V^2}{\Lambda^2} \right) \right\} \]
\[<AVQA_QV>_1^{F_V^2} = -\frac{3}{8} \frac{F_V^2}{16\pi^2} (1 + \xi) \left( \frac{1}{6} + \log \frac{M_V^2}{\Lambda^2} \right) \]
\[k^2 <AVQA_QV>_4^{F_V^2} = -3 \frac{M_V^2 F_V^2}{16\pi^2} \left( \frac{2}{3} + \log \frac{M_V^2}{\Lambda^2} \right). \]  

(40)

3.3 \(G_VF_V\) contributions

We have two diagrams which contribute to \(<AAQ_AQ>_1\) shown below.

![Diagram](attachment:image.png)

This results in the following integral for the correlator

\[<AAQ_AQ>_1 = 4 G_V F_V (1 - \frac{1}{d}) \int \frac{-i d^d p}{(2\pi)^d} \left( \frac{d - 2}{M_V^2 (p^2 - M_V^2)} + \frac{1 - d}{p^2(p^2 - M_V^2)} \right). \]  

(41)

Next we have one diagram contributing to \(<AAQ_VQ_V>_1\) which is non vanishing

![Diagram](attachment:image.png)

and which gives

\[<AAQ_VQ_V>_1 = 4 G_V F_V \int \frac{-i d^d p}{(2\pi)^d} \frac{1}{p^2(p^2 - M_V^2)}. \]  

(42)

The two correlators \(<VVQA_A>_1\) and \(<VVQ_VQ_V>_1\) are then found to get no contributions proportional to \(G_VF_V\).

Next, we consider \(<AVQA_Q>_i\). One first finds a set of 7 diagrams which contribute both to \(<AVQA_Q>_1\) and \(<AVQA_Q>_4\). The three diagrams drawn below give zero contribution
The next four diagrams are

Computing these four diagrams yields the following result for $<AVQAQV>_1$

$$<AVQAQV>_1 = G_V F_V (1 - \frac{1}{d}) \int -i \frac{d^d p}{(2\pi)^d} \left( \frac{-d}{p^2 (p^2 - M_V^2)} + \frac{2}{(p^2 - M_V^2)^2} \right),$$

these diagrams make an identical contribution also to $<AVQAQV>_4$. In order to get the full contribution to $<AVQAQV>_4$ we must also add the following two diagrams

These diagrams are slightly more complicated to compute because one must allow for a small momentum to flow through the $v_3$ source and expand the result in powers of $k^2$. One finds that the $k^2$ pole vanishes and then adding the constant contribution to that arising from the preceding four diagrams one finds that they cancel. In summary, the contributions proportional to $G_V F_V$ which are non vanishing read

$$<AAQAQA>_1^{G_VF_V} = \frac{3 G_V F_V}{16\pi^2} \left( \frac{1}{6} + \log \frac{M_V^2}{\Lambda^2} \right).$$

$$<AAQVQV>_1^{G_VF_V} = -\frac{3 G_V F_V}{16\pi^2} \left( \frac{1}{6} + \log \frac{M_V^2}{\Lambda^2} \right).$$

$$<AVQAQV>_1^{G_VF_V} = \frac{3}{2} \frac{G_V F_V}{16\pi^2} \left( \frac{1}{6} + \log \frac{M_V^2}{\Lambda^2} \right).$$
### 3.4 $G^2_V$ and $G^2_VF^2_V$ contributions

These contributions are simple because a single correlator component is found to be non-vanishing: $<AAQA_A>_1$ in the case of $G^2_V$ and $<AAQVQ_V>_1$ in the case of $G^2_VF^2_V$. There are three diagrams proportional to $G^2_V$ and a single one proportional to $G^2_VF^2_V$

After a small computation the following results are obtained,

\[
<AAQA_A>_1 = 4G^2_V(1 - \frac{1}{d}) \int \frac{-i d^d p}{(2\pi)^d} \left( \frac{2 - d}{M^2_V(p^2 - M^2_V)} + \frac{d - 1}{p^2(p^2 - M^2_V)} \right)
\]

\[
<AAQVQ_V>_1 = -4 \frac{G^2_VF^2_V}{F^2_0}(1 - \frac{1}{d}) \int \frac{-i d^d p}{(2\pi)^d} \frac{1}{(p^2 - M^2_V)^2}.
\]

In summary, the non-vanishing contributions proportional to $G^2_V$ read

\[
<AAQA_A>_1^{G^2_V} = -\frac{3G^2_V}{16\pi^2} \left( \frac{1}{6} + \log \frac{M^2_V}{\Lambda^2} \right)
\]

\[
<AAQVQ_V>_1^{G^2_VF^2_V} = \frac{3G^2_VF^2_V}{16\pi^2F^2_0} \left( \frac{7}{6} + \log \frac{M^2_V}{\Lambda^2} \right).
\]

### 3.5 Contributions proportional to $c_d$, $\tilde{c}_d$

The scalar singlet turns out to contribute only to $<AAQA_A>_2$ and the scalar octet to $<AAQA_A>_3$. The three Feynman diagrams to be computed are depicted below.
The dependence on the photon gauge parameter $\xi$ is found to cancel out, and the following results are obtained for the singlet and octet scalar contributions

\[ \langle AAQAQA \rangle_2 = 16c^2_d \left( 1 - \frac{1}{d} \right) \int \frac{-i d^d p}{(2\pi)^d} \frac{1}{p^2(M_{S0}^2 - p^2)} \]

\[ \langle AAQAQA \rangle_3 = 8c^2_d \left( 1 - \frac{1}{d} \right) \int \frac{-i d^d p}{(2\pi)^d} \frac{1}{p^2(M_S^2 - p^2)} . \]  

As before, we have replaced the term $p_\alpha p_\beta$ in the integrands by $p^2 g_{\alpha\beta}/d$. There are three additional tadpole diagrams. Let us quote the result for completeness

\[ \langle AAQAQA \rangle_{tad} = ig_{\alpha\beta} \left( \frac{8c^2_d}{M_S^2} d^{sab} s^{cde} + \frac{16c^2_d}{M_{S0}^2} \delta^{sab} \delta^{cde} \right) \int \frac{-i d^d p}{(2\pi)^d} \frac{3}{p^2} . \] 

Computing the integrals we obtain the following results for the scalar resonance contributions which are non vanishing

\[ \langle AAQAQA \rangle_2^{scal} = 12 \frac{c^2_d}{16\pi^2} \left( \log \frac{M_{S0}^2}{\Lambda^2} + \frac{1}{6} \right) \]

\[ \langle AAQAQA \rangle_3^{scal} = 6 \frac{c^2_d}{16\pi^2} \left( \log \frac{M_S^2}{\Lambda^2} + \frac{1}{6} \right) . \]

One notices that no dependence upon the gauge parameter $\xi$ appears except in some of the terms proportional to $F_A^2$ and $F_V^2$. This is to be expected because, quite generally, the part proportional to $\xi$ in the integral representation can be simplified by making use of chiral Ward identities and expressed in terms of 2-point Green’s functions. 

### 3.6 Comparison with the results of Baur and Urech

Up to this point we have used exactly the same resonance Lagrangian terms as Baur and Urech, and we are therefore in a position to check their results for the chiral parameters $K_{ir}$. Making use of the relations (15)-(19), for each resonance term contribution to the correlators (3)(4) we can solve for the $K_{ir}$’s which will then depend on the two scales $\mu$ and $\Lambda$. In ref. the values of the two scales have been taken to be equal. Following this convention for the sake of comparison, and using the results derived above, we reproduce the results of ref. for the parameters $K_{1r}^r,...,K_{6r}^r$.

We disagree, however, on a number of contributions which concern $K_{12r}$, $K_{13r}$, $K_{14r}$. Contrary to BU, we find that the following quantities are vanishing.

\[ K_{13FV}^{G_V} = K_{14FV}^{G_V} = K_{12G_V} = K_{13G_V} = K_{14G_V} = K_{13FV}^{G_V} = K_{14FV}^{G_V} = K_{13FV}^{G_V} = K_{14FV}^{G_V} = 0 . \] 

In the case of $K_{13r}^r$, $K_{14r}$ this follows from where it is shown that they can be obtained from 2-point correlators $\langle Q_V Q_V \rangle$ and $\langle QAQA \rangle$. Obviously, these can only pick up contributions proportional to $F_A^2$ and $F_V^2$, which is indeed what we recover here. Similarly, one can also obtain $K_{12r}$ from a correlator with three currents $\langle PQ_AQ_A \rangle$ which picks up no contribution proportional to $G_V^2$. 

18
4 Short distance constraints

We now need to determine the divergence structure in the integral representation of eq.(5) according to QCD. One way to proceed is to determine the necessary counterterms which are generated in QCD with a source term as in eq.(1), where $F_{\mu}$ is a dynamical (massive) photon. This QED-like sector differs from ordinary QED by the fact that we have replaced the charge matrix $Q$ by a vector ($q_{V}$) as well as an axial-vector ($q_{A}$) spurion source. We must consider this theory as a kind of effective theory and we assume that the divergences can be absorbed into a set of local Lagrangian terms. We will restrict ourselves to an expansion quadratic in the spurion fields. This represents an important simplification since, for instance, we will only need the free photon propagator and thereby avoid the problems of the photon propagator at higher order in the presence of axial couplings. Another restriction is that we will only consider contributions which are of leading order in $N_c$. Dimensional regularization together with the naive $\gamma_5$ prescription will be used.

4.1 QCD+QED counterterms

Let us consider QCD in the presence of dynamical photons and a source term of the form of eq.(1). The effective action is expanded to quadratic order in the spurions $q_{V}$ and $q_{A}$ and we drop the contributions which are subleading in $N_c$. We can then split the divergent terms in the effective action into two categories, (a) one which collects the graphs with an open quark line and, (b) one which collects the graphs with a closed quark loop (see fig. 1). The former ones are those which will prove to be of relevance to us.

Let us first consider the contributions in category (b). The graphs in this category, at any order in $\alpha_s$ (in QCD the three gluon vertex has dimension $p$, the four gluon vertex has

![Typical divergent diagrams quadratic in the spurion sources (a) with an open quark line (b) with a closed quark line.](image-url)
dimension zero), have dimensionality $p^4$. The corresponding local counterterms therefore must involve four derivatives. Examples of such terms are,

$$\langle \nabla^2 q_L \nabla^2 q_L + \nabla^2 q_R \nabla^2 q_R \rangle, \quad G_{\mu \nu} G^{\mu \nu} \langle \nabla_\rho q_L \nabla_\rho q_L + \nabla_\rho q_R \nabla_\rho q_R \rangle, \quad \text{etc...}$$

If we restrict ourselves to the correlator combinations $\Pi_i$, eq.(20) (from which the contribution proportional to $K_{14}$ drops out) then all the contributions from such counterterms also drop out or are suppressed in the large $N_c$ counting.

We are finally left with the contributions from the first category. Taking into account the structure of QCD, all graphs in this category have dimension $p$, implying that the counterterms must involve one derivative. Furthermore, they must involve two spurions of the same kind (either $q_L$ or $q_R$). One can form only two such independent terms

$$\mathcal{L} = \frac{i}{2} Z_2 \left\{ \bar{\psi}_L[q_L, \nabla^\mu q_L] \gamma_\mu \psi_L + \bar{\psi}_R[q_R, \nabla^\mu q_R] \gamma_\mu \psi_R \right\}$$

$$+ \frac{i}{2} Z_2' \left\{ \bar{\psi}_L q_L \gamma_\mu \psi_L + \bar{\psi}_R q_R \gamma_\mu \psi_R + h.c. \right\}$$

(52)

where

$$iD^\mu \psi_L = (i\partial^\mu + l_\mu + G_\mu) \psi_L, \quad iD^\mu \psi_R = (i\partial^\mu + r_\mu + G_\mu) \psi_R .$$

(53)

At order zero in the strong coupling constant one has the well known QED result

$$Z_2 = Z_2' = \frac{\mu_0^{-2\epsilon}}{16\pi^2} (-\xi)[\Gamma(\epsilon) + \log(4\pi)] + O(\alpha_s) .$$

(54)

Equality between $Z_2$ and $Z_2'$ need not hold beyond the lowest order.

Let us now discuss the contributions proportional to $Z_2$ and $Z_2'$ to our basic correlators $<L^a L_b Q^c L Q^d_L>$ in $N_c$. The first result is that the contribution proportional to $Z_2$ vanishes at leading order in $N_c$. This can be shown in a pedestrian way. Because of the conservation of chirality in one fermion loop graphs, the contributions concern only the correlators $<LLQ L Q>$ and $<RRQ R Q>$, it suffices to consider the former. For a given gluon field configuration $G_\mu(x)$ we can express the functional derivatives with respect to the sources in terms of exact fermion propagators $S_G(x, y)$ and we obtain the following expression

$$<L^a L_b Q^c L Q^d_L>_G = \frac{Z_2'}{32} \int d^4 x d^4 y \left[ -\delta(y) <\lambda^b \lambda^a \{ \lambda^c , \lambda^d \} > <\gamma^a P_L S_G(x, 0) \gamma^b P_L S_G(0, x) > 
-\delta(x) <\lambda^a \lambda^b \{ \lambda^c , \lambda^d \} > <\gamma^a P_L S_G(y, 0) \gamma^b P_L S_G(0, y) > 
+ <\lambda^b \lambda^a \{ \lambda^c , \lambda^d \} > <\gamma^a P_L S_G(x, y) \gamma^b P_L S_G(y, 0) [i\bar{\psi} + \gamma^\rho P_R] P_L S_G(0, x) > 
+ <\lambda^b \lambda^a \{ \lambda^c , \lambda^d \} > <\gamma^b P_L S_G(y, x) \gamma^a P_L S_G(x, 0) [i\bar{\psi} + \gamma^\rho P_R] P_L S_G(0, y) > \right] ,$$

(55)

where $P_L$ is the projector $P_L = 1/2(1 - \gamma_5)$ and the notation $\bar{\partial}$ means that the derivatives are acting on the right. There is another similar contribution coming from the hermitian conjugate part of the Lagrangian. Using the equation obeyed by the Dirac propagator

$$[i\bar{\psi} + \gamma^\rho P_R] P_L S_G(x, y) = P_R \delta^4(x - y) ,$$

(56)
we indeed find that the various terms in eq. (55) cancel each other. We have thus shown that the only relevant contributions from the counterterms are those proportional to $Z_2^2$. The calculation of these is performed by computing the functional derivatives according to the definition of eq. (3) and using the following result for the two-point correlators that appear

$$\int d^4x e^{ikx} \langle A_\alpha^s(x) A_\beta^t(0) >= iF_0^2 \delta^{st} \left( \frac{k_\alpha k_\beta}{k^2} - g_{o\beta} \right), \quad \int d^4x \langle V_\alpha^s(x) V_\beta^t(0) > = 0. \quad (57)$$

We find that the counterterms contribute to the following components of our basic correlators

$$\langle AAQA_Q A > |_1 = -Z_2 F_0^2,$$
$$\langle AAQV Q > |_2 = -Z_2 F_0^2,$$
$$\langle AVQA_Q V > |_3 = -\frac{1}{2} Z_2 F_0^2,$$
$$\langle AVQA_Q V > |_4 = -\frac{1}{2} Z_2 F_0^2. \quad (58)$$

There are no contributions to the other components.

### 4.2 Summary of the $\log \Lambda^2$ dependence

Let us consider the combinations of correlators $\Pi_i$ introduced in eqs. (20)-(24). In all these combinations the contribution from the coupling $K_{14}$ drops out. In the combinations $\Pi_1, \ldots, \Pi_6$ as well as $\Pi_7, \Pi_9$, the contributions from the renormalization parameter $Z_2$ also drops out, as is seen from using eq. (58). As a consequence, these quantities must be finite. More precisely, finiteness holds in the sense of dimensional regularization which was used to establish the form of the counterterms in the preceding section: one must compute the photon loop integral in $d$ dimensions and then take the limit $d \to 4$ which must be finite. From these eight combinations one can then determine the chiral couplings $K_{17}^r, \ldots, K_{67}^r$ as well as $K_{13}^r$ and $C$. The situation is different for $\Pi_8$ since, in that case, a contribution proportional to $Z_2$ is present. The integral is not finite in general. It is finite to zeroth order in the strong coupling $\alpha_s$ when the gauge parameter $\xi = 0$. This limitation affects the determination of the coupling $K_{12}^r$.

Let us examine how these finiteness conditions are satisfied when the relevant correlators are computed from the minimal resonance Lagrangian of eqs. (34), (35). Collecting the results presented in detail in sec. 5 we obtain the following dependence upon the regularization scale $\Lambda$

$$\Pi_1 \sim -\frac{3}{2} \log \Lambda^2 \left[ F_0^2 + F_A^2 - 2G_V^2 \right],$$
$$\Pi_2 \sim -\frac{3}{2} \log \Lambda^2 \left[ F_0^2 + F_V^2 - 4G_V F_V + 2G_V^2 \frac{F_V^2}{F_0^2} \right],$$
$$\Pi_3 \sim -\frac{6}{2} \log \Lambda^2 \left[ \epsilon_d \right],$$
$$\Pi_4 = 0$$

21
\[ \Pi_5 \sim -4 \frac{\log \Lambda^2}{16\pi^2} [3c_d^2 - c_d^2] \]
\[ \Pi_6 = 0 \]
\[ \Pi_7 \sim \frac{3 \log \Lambda^2}{4} \frac{1}{16\pi^2} [F_V^2 - F_0^2 - F_A^2] \]
\[ \Pi_8 \sim - \frac{3 \log \Lambda^2}{8} \frac{1}{16\pi^2} [F_V^2 - F_0^2 - F_A^2 + 4(G_V F_V - F_V^3)] \]
\[ \Pi_9 \sim - 3 \frac{\log \Lambda^2}{16\pi^2} [M_V^2 F_V^2 - M_A^2 F_A^2] . \] (59)

At this level, there is at first one consistency condition which is satisfied, but trivially so, since \( \Pi_4 \) is identically vanishing. In the sequel (sec.5.6) we will consider physically relevant interactions and attempt to satisfy the condition in a less trivial way. The consistency conditions for \( \Pi_7 \) and \( \Pi_9 \) can be satisfied and they generate the two Weinberg sum rule relations
\[ F_V^2 = F_0^2 + F_A^2, \quad M_V^2 F_V^2 = M_A^2 F_A^2 . \] (60)

These relations will be assumed to hold from now on. Furthermore, we will assume the following relation to hold,
\[ G_V F_V = F_0^2 \] (61)
which follows from imposing that the asymptotic behaviour of the vector form-factor of the pion
\[ \lim_{t \to \infty} t F_V^V(t) = 0 \] (62)
is satisfied. Using this, we observe that there are only two consistency conditions which are fulfilled, which are those associated with \( \Pi_7 \) and \( \Pi_9 \). The corresponding evaluation of \( \Pi_7 \) and \( \Pi_9 \) gives
\[ \Pi_7 = 3 \frac{F_0^2}{4} \frac{1}{16\pi^2} \left[ \log \frac{M_V^2}{M_A^2} + 2 - \frac{\log z}{z - 1} \right] \]
\[ \Pi_9 = 3M_V^2 \frac{F_0^2}{16\pi^2} \frac{1}{z - 1} , \] (63)
where \( z \) denotes the mass ratio
\[ z = \frac{M_A^2}{M_V^2} \] (64)
which one expects to be approximately equal to 2. We expect \( \Pi_5 \) and \( \Pi_6 \) to vanish as a result of the leading large \( N_c \) approximation. This condition is trivially satisfied for \( \Pi_6 \) and it can be imposed for \( \Pi_5 \) by setting \( 3c_d^2 = c_d^2 \).

5 Beyond the \( O(p^4) \) resonance Lagrangian

5.1 Survey of \( O(p^6) \) terms

In order to comply with the other consistency conditions, it is necessary to enlarge the resonance Lagrangian of eq. (33). Since this Lagrangian (for a given resonance content)
contains all terms of order $p^4$, it is natural to investigate terms of order six. Generally, let us designate a resonance building block by $R$ (which counts as $p^2$), a chiral building block by $\pi$ (which counts as $p$) and a source term by $J$ (which counts as $p^2$). In this schematic notation, there are four classes of terms of order $p^4$ which involve at least one resonance

$$RR, RJ, R\pi, R\pi\pi.$$  (65)

At order $p^6$ one can have the same terms but involving two more derivatives and, in addition, one can have terms formed from three, four as well as five building blocks

$$RRR, RR\pi, RRJ, RJ\pi, R\pi\pi, RJ\pi\pi, R\pi\pi\pi.$$  (66)

We will not attempt to classify and discuss all possible remaining terms in this work. We will simply consider (except in sec. 5.6) sets of terms of the form $RR\pi$. The first set will be labeled as $a_1\rho\pi$ and has the following form

$$L_{a_1\rho\pi} = i(G_1\eta^{\lambda\mu\rho\sigma}g^{\mu\rho\sigma\lambda} + G_2\eta^{\lambda\mu\rho\sigma}g^{\mu\rho\sigma\lambda} + G_3\eta^{\lambda\mu\rho\sigma}g^{\mu\rho\sigma\lambda}) < \nabla_{\mu_0}V_{\mu_1\lambda}, A_{\mu_2\lambda}u_{\mu_3}> $$

$$ + i(H_1\eta^{\lambda\mu\rho\sigma}g^{\mu\rho\sigma\lambda} + H_2\eta^{\lambda\mu\rho\sigma}g^{\mu\rho\sigma\lambda} + H_3\eta^{\lambda\mu\rho\sigma}g^{\mu\rho\sigma\lambda}) < [V_{\mu_1\lambda}, A_{\mu_2\lambda}]\nabla_{\mu_0}u_{\mu_3}> .$$  (67)

We will first show that by adding these terms to the minimal resonance Lagrangian we can reproduce the $<VAP>$ 3-point function constructed in ref. [31]. In addition, we will then show that it is possible to satisfy the consistency conditions associated with $\Pi_1$ and $\Pi_2$, and these provides a number of Weinberg-type sum rule relations. In an analogous way, we introduce an $a_0f_1\pi$ coupling (we assume nonet symmetry which reduces the number of couplings),

$$L_{a_0f_1\pi} = c_A\{S[\nabla^\mu A_{\mu\nu}, u^\nu]\}$$  (68)

which will allow us to satisfy the consistency condition on $\Pi_3$.

Finally, we will consider a set of terms of the type $\omega\rho\pi$ which contribute to $\Pi_4$. A calculation which is equivalent to an evaluation of this contribution was performed in ref. [7] using the vector, instead of the anti-symmetric tensor, formulation for the vector fields. A classification of the terms in this latter formulation was recently presented by Ruiz-Femenia et al. [41], we list below those of relevance to us,

$$L_{\omega\rho\pi} = \epsilon_{\mu\nu\rho\sigma} \left\{ d_3\{\nabla_\lambda V^{\mu\nu}, V^{\rho\lambda}\}u_\sigma + d_4\{\nabla_\sigma V^{\mu\nu}, V^{\rho\lambda}\}u_\lambda \right\} + \frac{c_5}{M_V}\{\nabla_\lambda V^{\mu\nu}, f_+^{\rho\lambda}\}u_\sigma + \frac{c_6}{M_V}\{\nabla_\sigma V^{\mu\lambda}, f_+^{\rho\lambda}\}u_\nu \right\} + \frac{c_7}{M_V}\{\nabla_\sigma V^{\mu\nu}, f_+^{\rho\lambda}\}u_\lambda \right\}. $$  (69)

In enabled them to reproduce the 3-point function $<VVP>$ as constructed in ref. [42]. The consistency condition on $\Pi_4$ is somewhat more complicated to satisfy in the anti-symmetric tensor than in the vector formalism. This will be explained in more detail below.

---

2 An extension was recently considered [40] which includes a $\pi'$ resonance multiplet and a corresponding resonance chiral Lagrangian was constructed. The result for the coupling constant combination $G_1 + G_2 + 2G_3$ which is needed in the following turns out to be unaffected by this extension.
5.2 $\mathcal{L}_{a_1\rho\pi}$ constraints from $< V A P >$

Let us examine the constraints on the six coupling constants of the $a_1\rho\pi$ Lagrangian which arise from the 3-point correlator $< V A P >$. This correlator is defined as follows

$$W_{\alpha\beta}(p, q) = \int d^4x d^4y e^{ipx + igy} < 0 | T (V_\alpha^1(x) A_\beta^2(y) P^3(0)) | 0 >. \quad (70)$$

Assuming an ansatz in terms of rational functions with a minimal number of resonance poles (i.e. one pion, one vector and one axial-vector resonance poles) it can be shown that this correlator is uniquely determined from a) the chiral Ward identities, b) the constraint to match the leading asymptotic scaling behaviour,

$$\lim_{\lambda \to \infty} W_{\alpha\beta}(\lambda p, \lambda q) = \frac{\langle \bar{u} u \rangle}{\lambda^2} \left\{ \frac{(p_\alpha + 2q_\alpha)q_\beta - q^2 g_{\alpha\beta}}{q^2 l^2} + \frac{(p^2 - q^2 - l^2) P_{\alpha\beta}}{2p^2 q^2 l^2} - \frac{Q_{\alpha\beta}}{p^2 q^2 l^2} \right\} \quad (71)$$

with $l^2 = (p + q)^2$,

$$P_{\alpha\beta} = p_\beta q_\alpha - p \cdot q g_{\alpha\beta}$$
$$Q_{\alpha\beta} = p^2 q_\alpha q_\beta + q^2 p_\alpha p_\beta - p \cdot q p_\alpha q_\beta - p^2 q^2 g_{\alpha\beta}, \quad (72)$$

and, finally, c) the asymptotic constraint on the vector form factor of the pion eq. [62].

More detailed analysis of asymptotic constraints related to this 3-point correlator were performed in ref. [33]. The result, for $< V A P >$, reads

$$W_{\alpha\beta}(p, q) = \langle \bar{u} u \rangle \left\{ \frac{(p_\alpha + 2q_\alpha)q_\beta - q^2 g_{\alpha\beta}}{q^2 l^2} + \frac{F(p^2, q^2, l^2) P_{\alpha\beta}}{(p^2 - M_V^2)(q^2 - M_A^2) l^2} + \frac{G(p^2, q^2, l^2) Q_{\alpha\beta}}{(p^2 - M_V^2)(q^2 - M_A^2) q^2 l^2} \right\} \quad (73)$$

with

$$F(p^2, q^2, l^2) = \frac{1}{2}(p^2 - q^2 - l^2) + M_V^2 - M_A^2$$
$$G(p^2, q^2, l^2) = -q^2 + 2M_A^2. \quad (74)$$

Let us compute the $V A P$ Green’s function from the resonance Lagrangian $\mathcal{L}_{\text{res}}^{(4)} + \mathcal{L}_{a_1\rho\pi}$. We find, for the $F$ and $G$ polynomials,

$$F(p^2, q^2, l^2) = p^2 \left[ \frac{F_0^2}{F_0^2} - \frac{F_V F_A}{F_0^2} (-2G_1 - G_2 - 2G_3 + H_1 + H_2) \right]$$
$$+ q^2 \left[ \frac{F_V^2 - 2G_V F_V}{F_0^2} - \frac{F_V F_A}{F_0^2} (G_2 + 2G_3 + H_1 + H_2) \right]$$
$$+ l^2 \left( \frac{-F_V F_A}{F_0^2} \right) [-G_2 - 2G_3 + H_1 + H_2 + 4H_3]$$
$$+ \frac{1}{F_0^2} \left[ M_V^2 F_A^2 - M_A^2 (F_0^2 - 2G_V F_V) \right]$$

$$G(p^2, q^2, l^2) = q^2 \left[ -\frac{2G_V F_V}{F_0^2} - \frac{2F_V F_A}{F_0^2} (-G_1 + H_1 + H_2) \right] + 2M_A^2 \frac{G_V F_V}{F_0^2}. \quad (75)$$
Let us first compare the constant terms in eqs. (75) and (74). Provided that the two Weinberg relations eq. (60) are satisfied together with the relation $G_V F_V = F_0^2$, one finds that the constant terms are in exact agreement. Next, the following three independent relations between the coupling constants $G_i$, $H_i$

\[
G_1 + G_2 + 2G_3 = \frac{F_A}{F_V} \\
H_1 + H_2 = \frac{F_A}{2F_V} - \frac{F_V}{2F_A} + G_1 \\
2H_3 = \frac{F_V}{2F_A} - G_1
\]

(76)

are found to be the necessary and sufficient conditions for the polynomials in eqs. (75) and (74) to be completely identical.

5.3 Linear contributions from $L_{\alpha_1,\rho\pi}$

Let us now return to the 4-point correlators and consider the contributions which are linear in the couplings of eq. (67). The couplings $H_i$ do not contribute because derivatives of the sources are involved. There are contributions to $<AAQ_AQ_A>_1$, $<AAQ_VQ_V>_1$ and $<AVQ_AQ_V>_1$ which we consider in turn. There is one kind of diagram relevant for $<AAQ_AQ_A>_1$

The upper vertex involves either $F_V$ or $G_V$. These diagrams give

\[
<AAQ_AQ_A>_1 = -4F_A(F_V - 2G_V)(1 - \frac{1}{d}) \int \frac{-i d^d p}{(2\pi)^d} \left[ \frac{(d - 2)G_2}{M_A^2 (M_A^2 - p^2)} + \frac{G_{123}}{(M_A^2 - p^2)(M_V^2 - p^2)} \right]
\]

(77)

where

\[
G_{123} \equiv G_1 + G_2 + 2G_3,
\]

(78)

denotes the combination which was determined from $<VAP>$. In the case of the correlator $<AAQ_VQ_V>_1$, there is again one kind of diagram which makes a linear contribution
and the result is very similar to the preceding one

\[
<AAQVQ_V> = -4F_A^2(1 - \frac{1}{d}) \int \frac{-i d^d p}{(2\pi)^d} \left[ \frac{(d - 2)G_1}{M_A^2(M_V^2 - p^2)} + \frac{G_{123}}{(M_A^2 - p^2)(M_V^2 - p^2)} \right].
\]

Next, in order to obtain \( <AVQ_AQ_V> \) one must calculate a set of five diagrams which are depicted below,

\[
<AVQ_AQ_V> = -F_AF_VG_{123}(1 - \frac{1}{d}) \int \frac{-i d^d p}{(2\pi)^d} \left[ \frac{d - 2}{(M_A^2 - p^2)(M_V^2 - p^2)} 
+ \frac{2M_A^2}{(M_A^2 - p^2)^2(M_V^2 - p^2)} + \frac{2M_V^2}{(M_A^2 - p^2)(M_V^2 - p^2)^2} \right]
\]

which is seen to be proportional to the coupling constant combination \( G_{123} \).

### 5.4 Quadratic contributions from \( L_{a_1,\rho \pi} \) and consistency conditions for \( \Pi_1, \Pi_2, \Pi_8 \)

We turn now to the contributions which are quadratic in the couplings \( G_i \). These concern only the two correlators \( <AAQ_AQ_A> \), \( <AAQ_VQ_V> \) and they are given respectively from the two kinds of diagrams depicted below.
The previous determinations of $F_s$ satisfied yields two Weinberg-type relations for $G$ existence of real solutions. Real solutions do exist for any value of the mass ratio $z$ we have used. Since these equations are quadratic, one could be concerned about the situation where chiral symmetry gets restored and one must have $z$ solutions provided

\[ \text{result for } <AAQ_A Q_A> \]

We can now collect all the contributions which involve the coupling constants $G_i$,

\[
<AAQ_A Q_A> \stackrel{G_i}{=} \frac{3 F_A (F_V - 2 G_V)}{16 \pi^2} \left[ -2 G_2 \left( \frac{7}{6} + \log \frac{M_A^2}{\Lambda^2} \right) + G_{123} \left[ \frac{1}{6} + \frac{z \log z}{z - 1} + \log \frac{M_V^2}{\Lambda^2} \right] \right] + 3 F_A \frac{G_{123}^2}{16 \pi^2} \left\{ \frac{4 G_2^2 \left( \frac{5}{3} + \log \frac{M_A^2}{\Lambda^2} \right)}{2} \right\} \]

\[ <AAQ_V Q_V> \stackrel{G_i}{=} \frac{3 F_A F_V}{16 \pi^2} \left[ -2 G_1 \left( \frac{7}{6} + \log \frac{M_V^2}{\Lambda^2} \right) + G_{123} \left[ \frac{1}{6} + \frac{z \log z}{z - 1} + \log \frac{M_V^2}{\Lambda^2} \right] \right] + 3 F_A \frac{G_{123}^2}{16 \pi^2} \left\{ \frac{4 G_2^2 \left( \frac{5}{3} + \log \frac{M_V^2}{\Lambda^2} \right)}{2} \right\} \]

\[ <AVQ_A Q_V> \stackrel{G_i}{=} \frac{3 F_A F_V G_{123}}{16 \pi^2} \left[ \frac{1}{6} + \frac{z \log z}{z - 1} + \log \frac{M_V^2}{\Lambda^2} \right] \]

Adding these contributions to those computed in sec. 5 it is now possible to satisfy the consistency conditions associated with $\Pi_1$, $\Pi_2$ and $\Pi_5$. Firstly one observes that the $\Lambda$ scale dependence drops out from the combination $\Pi_8$ automatically provided the first relation \[ \Pi_{123} \] holds for $G_{123}$. Requiring that the consistency conditions for $\Pi_1$ and $\Pi_2$ be satisfied yields two Weinberg-type relations for $G_1$ and $G_2$

\[
8 G_1^2 - \frac{4}{2} G_1 - 1 = 0
\]

\[
8 G_2^2 - \frac{4}{2} (2 - z) G_2 - 1 = 0
\]

The previous determinations of $F_V$, $F_A$, $G_V$ and of the combination $G_1 + G_2 + 2G_3$ have been used. Since these equations are quadratic, one could be concerned about the existence of real solutions. Real solutions do exist for any value of the mass ratio $z$ and, a priori, one has a set of four different solutions. By studying the behaviour as a function of $z$ we can reduce the multiplicity. We note that the Weinberg equations \[ \| \] have real solutions provided $z$ lies in the range $1 \leq z < \infty$. Firstly, let $z \to 1$: this corresponds to a situation where chiral symmetry gets restored and one must have $G_1 = G_2$ in this case.
This argument reduces the multiplicity to just two solutions, which we can write,

\[ G_1 = \frac{1}{4\sqrt{z}}(1 + \sigma\sqrt{1 + 2z}) \]
\[ G_2 = \frac{1}{4\sqrt{z}}(2 - z + \sigma\sqrt{(2 - z)^2 + 2z}), \quad \sigma = \pm 1. \]  

(86)

We can further reduce the multiplicity by observing the behaviour as \( z \to \infty \). In this limit, \( G_1 \) remains finite while in the case of \( G_2 \) only one solution remains finite corresponding to \( \sigma = 1 \). Correspondingly, the divergence in \( \Pi_1 \) is logarithmic for \( \sigma = 1 \) while it is linear for \( \sigma = -1 \). The solution with \( \sigma = 1 \), therefore, appears to be the most plausible choice. Using this solution, the following determinations are obtained for \( \Pi_1, \Pi_2 \) and \( \Pi_8 \)

\[ \Pi_1 = \frac{3}{2} \frac{F_0^2}{16\pi^2} \left\{ \log \frac{M_2^2}{M_V^2} + \frac{(z^3 - 5z^2 + 5z + 1) \log z}{(z - 1)^3} + \frac{z^3 - 2z^2 + 7z - 10}{2(z - 1)^2} - \frac{(z - 2)\sqrt{z^2 - 2z + 4}}{2(z - 1)} \right\} \]
\[ \Pi_2 = \frac{3}{2} \frac{F_0^2}{16\pi^2} \left\{ \log \frac{M_2^2}{M_V^2} - \frac{2z^2 \log z}{(z - 1)^3} + \frac{6z^3 - 7z^2 + 6z - 1}{2z(z - 1)^2} + \frac{\sqrt{2z + 1}}{2z(z - 1)} \right\} \]
\[ \Pi_8 = \frac{3}{8} \frac{F_0^2}{16\pi^2} \left( -\log \frac{M_2^2}{M_V^2} + \frac{(3z + 1) \log z}{(z - 1)^2} - \frac{4z}{z - 1} \right). \]  

(87)

5.5 Contributions from \( L_{a_0f_1\pi} \) and the consistency condition for \( \Pi_3 \)

By analogy with the preceding we now consider couplings which involve the scalar mesons of the type \( a_0f_1\pi \) which will contribute to \( <AAQ_AQ_A>_{2,3} \). There is only one Lagrangian term which matters, shown in eq. (68) (assuming nonet symmetry). The term in which the derivative acts on \( u_\nu \) does not contribute to our correlators nor to the physical decay amplitude which is discussed below. There are two kinds of diagrams which contribute to the relevant correlators

\[
\begin{array}{c}
\begin{array}{c}
\text{
\begin{array}{c}
\text{c} \\
\text{A}
\end{array}
\end{array}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{F} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{c} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{F} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{c} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{F} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{c} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{F} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{c} \\
\text{A}
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{F} \\
\text{A}
\end{array}
\end{array}
\]

Computing the diagrams gives

\[ <AAQ_AQ_A>_{3} = \left( 1 - \frac{1}{d} \right) \int \frac{-i d^d p}{(2\pi)^d} \left\{ \frac{8\sqrt{2} c_d c_A F_A}{(M_A^2 - p^2)(M_S^2 - p^2)} \right\}. \]  

28
5. Contributions from $MeV$ from ref.\cite{44}.

We can now add this result to the contribution (49) proportional to expression for the decay width is easily derived, $c$

Using the value

This result is in rather good agreement with the experimental one $\Gamma_{\exp}$ associated with the scalar mesons, $\Pi_3 = \langle AAQ_A Q_A \rangle_3 = \frac{6c_\omega^2 M_A^2}{16\pi^2(M_A^2 - M_S^2)} \left(1 - \frac{M_A^2}{M_A^2 - M_S^2} \log \frac{M_A^2}{M_S^2}\right)$.

We can compare the above determination of the coupling constant with experiment. Let us consider the decay process $f_1(1285) \to a_0(980) + \pi$. Using the Lagrangian above \cite{68}, the expression for the decay width is easily derived,

Using the value $c_d \approx 32$ MeV from ref.\cite{35}, $M_A = \sqrt{2}M_\rho$ (and physical masses in kinematical factors) one obtains

This result is in rather good agreement with the experimental one $\Gamma_{\exp}^{f_1 \to a_0 \pi} = 8.6 \pm 1.7$ MeV from ref.\cite{44}.

5.6 Contributions from $L_{\omega\rho\pi}$ in the vector v/s tensor formalism and $\Pi_4$

We discuss here contributions from $L_{\omega\rho\pi}$ eq.\cite{35} which are likely to be important and were also not accounted for in the minimal resonance Lagrangian. One faces a technical difficulty that the Lagrangian eq.\cite{69} involves the Levi-Civita $\epsilon$ tensor and this makes continuation to $d$ dimensional space ambiguous. One would therefore like to impose a stronger version of the consistency condition that the integral be finite in four dimensions. This condition is rather simple to enforce if one uses the vector formalism. Let us first briefly review what would be the result in this case and then we will show how to proceed in the case of the tensor formalism. An extensive study of resonance Lagrangian terms in the vector formalism can be found in ref.\cite{15}. In this formulation, the terms including the $\omega\rho\pi$ type couplings read (we use the same notation as \cite{35}),

$$L_{\omega\rho\pi}^V = -\frac{1}{4} (V_{\mu\nu} V^{\mu\nu} - 2m_V^2 V_{\mu} V^{\mu}) - \frac{1}{2\sqrt{2}} f_V \langle V_{\mu\nu} f^{\mu\nu}_+ \rangle + \frac{g_1^V}{2\sqrt{2}} e^{\mu\nu\alpha\beta} \langle \{u_\mu, V_\nu \} f_{+\alpha\beta} \rangle + \frac{g_2^V}{2} e^{\mu\alpha\beta} \langle \{u_\mu, V_\nu \} V_{\alpha\beta} \rangle,$$  

$$
+ \frac{4c_A^2 F_A^2 p^2}{(M_A^2 - p^2)(M_S^2 - p^2)} \right) \right) 
+ \frac{3c_A^2 F_A^2}{16\pi^2} \left( \frac{1}{6} + \log \frac{M_S^2}{\Lambda^2} + \frac{M_A^2}{M_A^2 - M_S^2} \log \frac{M_A^2}{M_S^2} \right) \right) 
+ \frac{3c_A^2 F_A^2}{16\pi^2} \left( \frac{1}{6} + \log \frac{M_S^2}{\Lambda^2} + \frac{M_A^2}{M_A^2 - M_S^2} \log \frac{M_A^2}{M_S^2} \right) \right).
\end{align}
\end{equation}

We can now add this result to the contribution \cite{49} proportional to $c_d^2$, and the consistency condition translates into a simple relation between the coupling constants $c_d$ and $c_a$

$$c_A F_A = \sqrt{2}c_d.$$

This allows one to obtain a consistent determination of the correlator component $\langle AAQ_A Q_A \rangle_3$

$$\Pi_3 = \langle AAQ_A Q_A \rangle_3 = \frac{6c_\omega^2 M_A^2}{16\pi^2(M_A^2 - M_S^2)} \left(1 - \frac{M_A^2}{M_A^2 - M_S^2} \log \frac{M_A^2}{M_S^2}\right).$$

We can compare the above determination of the coupling constant with experiment. Let us consider the decay process $f_1(1285) \to a_0(980) + \pi$. Using the Lagrangian above \cite{68}, the expression for the decay width is easily derived,

$$\Gamma_{f_1 \to a_0 \pi} = c_A p_{cm} (M_A^2 - M_S^2)^2 \frac{\sqrt{2}M_\rho}{8\pi M_{f_1}^2 F_0^2}.$$

Using the value $c_d \approx 32$ MeV from ref.\cite{35}, $M_A = \sqrt{2}M_\rho$ (and physical masses in kinematical factors) one obtains

$$\Gamma_{f_1 \to a_0 \pi} \approx 7.7 \text{ MeV}.$$  

This result is in rather good agreement with the experimental one $\Gamma_{\exp}^{f_1 \to a_0 \pi} = 8.6 \pm 1.7$ MeV from ref.\cite{44}.

5.6 Contributions from $L_{\omega\rho\pi}$ in the vector v/s tensor formalism and $\Pi_4$

We discuss here contributions from $L_{\omega\rho\pi}$ eq.\cite{35} which are likely to be important and were also not accounted for in the minimal resonance Lagrangian. One faces a technical difficulty that the Lagrangian eq.\cite{69} involves the Levi-Civita $\epsilon$ tensor and this makes continuation to $d$ dimensional space ambiguous. One would therefore like to impose a stronger version of the consistency condition that the integral be finite in four dimensions. This condition is rather simple to enforce if one uses the vector formalism. Let us first briefly review what would be the result in this case and then we will show how to proceed in the case of the tensor formalism. An extensive study of resonance Lagrangian terms in the vector formalism can be found in ref.\cite{15}. In this formulation, the terms including the $\omega\rho\pi$ type couplings read (we use the same notation as \cite{35}),

$$L_{\omega\rho\pi}^V = -\frac{1}{4} (V_{\mu\nu} V^{\mu\nu} - 2m_V^2 V_{\mu} V^{\mu}) - \frac{1}{2\sqrt{2}} f_V \langle V_{\mu\nu} f^{\mu\nu}_+ \rangle + \frac{g_1^V}{2\sqrt{2}} e^{\mu\nu\alpha\beta} \langle \{u_\mu, V_\nu \} f_{+\alpha\beta} \rangle + \frac{g_2^V}{2} e^{\mu\alpha\beta} \langle \{u_\mu, V_\nu \} V_{\alpha\beta} \rangle.$$  

$$
\end{equation}
where
\[ V_{\mu\nu} = \nabla_\mu V_\nu - \nabla_\nu V_\mu \, . \] (94)

In this description the consideration of short distance conditions imposes that chiral \( O(p^4) \) terms be added\(^{35}\) but these do not play any role for our calculation. Computing the correlator \( <AAQ_VQ_V>_3 \) from this Lagrangian, one finds

\[ <A_\alpha A_\beta Q_V Q_V>_3 = 8 \int \frac{d^4p}{(2\pi)^4} \frac{(p^2g_{\alpha\beta} - p_\alpha p_\beta)[p^2(g_1^V + 2g_2^V f_V) - M_V^2 g_1^V]^2}{p^2(M_V^2 - p^2)^3} \] (95)

The integral in eq.(95) can be defined in four dimensions without difficulty, it suffices that the following relation holds among the coupling constants

\[ g_1^V + 2g_2^V f_V = 0 \, . \] (96)

The result for the correlator then reads,

\[ <AAQ_V Q_V>_3^{\omega_{\pi\pi}} = \frac{F_0^2}{16\pi^2}(3\tilde{g}_V^2), \quad \tilde{g}_V = \frac{g_1^V M_V}{F_0} \, . \] (97)

The value of \( \tilde{g}_V \) was estimated in ref.\(^7\) from the \( \omega \rightarrow \pi\gamma \) decay rate, \( |\tilde{g}_V| = 0.91 \pm 0.03 \). Under the assumption of nonet symmetry (which is rather well satisfied experimentally for the vectors), one also has

\[ <AAQ_V Q_V>_2^{\omega_{\pi\pi}} = \frac{2}{3} <AAQ_V Q_V>_3^{\omega_{\pi\pi}} \, . \] (98)

From eqs.(97), (98) one can deduce an estimate, which is identical to the one performed in ref.\(^7\), for the combination of \( K_i \)’s which is involved in the radiative corrections to the process \( \pi^0 \rightarrow 2\gamma \).

Let us now reconsider the problem using the antisymmetric tensor formulation, i.e. starting from the Lagrangian of eq.(69). One has three kinds of diagrams to compute which are shown below

Evaluating these various diagrams we obtain \( <A_\alpha A_\beta Q_V Q_V>_3 \) in the form of the following four-dimensional integral

\[ <A_\alpha A_\beta Q_V Q_V>_3 = \int \frac{d^4p}{(2\pi)^4} \left\{ \frac{48 p_\alpha p_\beta}{M_V^4} \left( \frac{M_V F_V(d_3 + d_4)}{M_V^2 - p^2} - \sqrt{2}(c_5 + c_7) \right)^2 \right\} \] (99)

\[ + \frac{32(p^2g_{\alpha\beta} - p_\alpha p_\beta)}{M_V^2(M_V^2 - p^2)} \left( \frac{2M_VF_V d_3}{M_V^2 - p^2} - \sqrt{2}(c_5 - c_6) \right)^2 \right\} \, . \]
The integral in eq. (99) does not converge in four dimensions unless all the couplings \( c_i \) and \( d_i \) vanish identically. In order to remove the divergence, in this case, we introduce a more general set of resonance Lagrangian terms, which include four building blocks

\[
\mathcal{L}^{4bb} = (x_1 g^{i_0 i_1} g^{j_2 j_3} + x_2 g^{i_0 i_2} g^{j_1 j_3} + x_3 g^{i_0 i_3} g^{j_1 j_2}) (\{ f^{+ \lambda}_{\mu_0}, u_{\mu_1} \}\{ f^+_{\lambda_2}, u_{\mu_3} \})
\]

\[
+ \sqrt{2} (y_1 g^{i_0 i_1} g^{j_2 j_3} + y_2 g^{i_0 i_2} g^{j_1 j_3} + y_3 g^{i_0 i_3} g^{j_1 j_2}) (\{ V^\lambda_{\mu_0}, u_{\mu_1} \}\{ f^+_{\lambda_2}, u_{\mu_3} \})
\]

\[
+ (z_1 g^{i_0 i_1} g^{j_2 j_3} + z_2 g^{i_0 i_2} g^{j_1 j_3} + x_3 g^{i_0 i_3} g^{j_1 j_2}) (\{ V^\lambda_{\mu_0}, u_{\mu_1} \}\{ V^\lambda_{\mu_2}, u_{\mu_3} \}) .
\]

These terms generate the following additional contribution to the correlator

\[
\langle A_\alpha A_\beta Q_V Q_V \rangle^{4bb} = \int \frac{d^4 p}{(2\pi)^4} \left\{ 24 p^2 g_{\alpha\beta} \left( \frac{2x_{123}}{p^2} - \frac{F_V y_{123}}{p^2(M_V^2 - p^2)} + \frac{F_V^2 z_{123}}{p^2(M_V^2 - p^2)^2} \right) \right.
\]

\[
- 16 (p^2 g_{\alpha\beta} - p_\alpha p_\beta) \left( \frac{2x_{13}}{p^2} - \frac{F_V y_{13}}{p^2(M_V^2 - p^2)} + \frac{F_V^2 z_{13}}{p^2(M_V^2 - p^2)^2} \right) \left( \frac{2x_{13}}{p^2} - \frac{F_V y_{13}}{p^2(M_V^2 - p^2)} + \frac{F_V^2 z_{13}}{p^2(M_V^2 - p^2)^2} \right) \right\} .
\]

In this expression we have used the notation

\[
x_{123} = x_1 + 2x_2 + x_3, \quad x_{13} = x_1 + x_3 ,
\]

and similarly with \( y_i, z_i \).

The convergence constraint in four dimension can now be satisfied: it imposes \( c_5 + c_7 = 0 \) and determines the values of the six combinations of parameters which appear in eq. (100) in terms of \( d_3, d_3 + d_4 \) and \( c_5 - c_6 \). Collecting all the pieces, one finds that all the couplings drop out except \( d_3 \) and the correlator \( \langle A_\alpha A_\beta Q_V Q_V \rangle \) is then expressed as a convergent integral,

\[
\langle A_\alpha A_\beta Q_V Q_V \rangle \rangle \rangle \rangle = 128 M_V^2 F_V^2 d_3 \int \frac{d^4 p}{(2\pi)^4} \left( \frac{2p^2 g_{\alpha\beta} - p_\alpha p_\beta}{p^2(M_V^2 - p^2)^3} \right) .
\]

This expression is exactly analogous to the one obtained upon using the vector formalism and we write the final result in the same form,

\[
\Pi_4 = \langle AA Q_V Q_V \rangle = \frac{F_0}{16\pi^2} (3\bar{g}_{AT}^2), \quad \bar{g}_{AT} = 4F_V d_3/F_0 .
\]

The value of \( d_3 \) may be determined by enforcing asymptotic conditions concerning the \( \langle VVP \rangle \) correlator. Not all conditions can be satisfied at the same time if one uses a minimal resonance model \cite{12, 13, 16}. If one chooses to enforce the overall scaling behaviour one obtains \cite{11}

\[
d_3^{\text{scaling}} = \frac{F_0^2}{8M_V^2} - \frac{N_c M_V^2}{64\pi^2 F_V^2} .
\]

Numerically, this gives \( \bar{g}_{AT} \approx -0.58 \) which is somewhat smaller in magnitude than \( \bar{g}_V \). Alternatively, one may choose instead to impose that the \( \langle VVP \rangle \) correlator satisfies the VMD property, in which case one gets

\[
d_3^{VMD} = - \frac{N_c M_V^2}{64\pi^2 F_V^2} .
\]

If one uses this latter determination, one gets \( \bar{g}_{AT} \approx -0.93 \), i.e. the result from the antisymmetric tensor formalism becomes essentially identical to the one from the vector formalism.
6 Numerical results

6.1 Results for $K^r_1, ..., K^r_6$

| $10^4 K^r_1$ | $10^4 K^r_2$ | $10^4 K^r_3$ | $10^4 K^r_4$ | $10^4 K^r_5$ | $10^4 K^r_6$ |
|--------------|--------------|--------------|--------------|--------------|--------------|
| -4.44        | -1.73        | 4.44         | -3.46        | 13.31        | 5.19         |
| -6.8         | -2.7         | 6.8          | -5.5         | 20.3         | 8.2          |
| 1.97         | 1.97         | -1.97        | 3.93         | -1.97        | -1.97        |
| -0.35        | 0.35         | 0.35         | 0.69         | 0.35         | -0.35        |
| 0.4          | -0.4         | -0.4         | -0.7         | -0.4         | 0.4          |
| 0.11         | 0.11         | -0.11        | 0.21         | -0.11        | -0.11        |
| -2.71        | 0.69         | 2.71         | 1.38         | 11.59        | 2.77         |

$\rho, a_1$

$\rho, a_1$ (BU)

$\omega \rho \pi$

scalars

scalars (BU)

$b_1(1235)$

Table 1: Numerical results obtained for $K^r_i(\mu)$ with $\mu = 0.77$ GeV from the present work. The contributions associated with the $b_1(1235)$ are discussed in appendix B. The results from ref.[29] are also shown for comparison.

In the numerical applications we will simply use $M_V = 0.77$ GeV and $F_V = \sqrt{2}F_\pi$ (KSRF relation [47]), which corresponds to $z = 2$ (the same values were used by BU). We will also use $F_0 = F_\pi = 92.4$ MeV. The results for $K^r_i(\mu), ..., K^r_6(\mu)$ with $\mu = M_V$ are collected in Table 1. We show separately the contributions due to the scalars (terms proportional to $c_d$, with $c_d = 32$ MeV) and the contributions from the $\omega \rho \pi$ interactions (terms proportional to $\tilde{g}_{\omega \rho \pi}$, with $|\tilde{g}_{\omega \rho \pi}| = 0.93$). We find that this contribution can be significant for some of the couplings like $K^r_2$ or $K^r_4$. The contributions related to the scalars are rather small. In that case, our results agree on the magnitude but have a different sign from those of BU because of the extra contribution needed to ensure consistency. The largest contributions are those originating from the $a_1 \rho \pi$ sector. In that case our numerical results are in qualitative agreement with those of BU. We have also performed an estimate of the contributions associated with the $b_1$ meson (see appendix B) which turn out to be rather small.

6.2 An update on the corrections to Dashen’s theorem

A reliable evaluation of the electromagnetic part of the $K^+ - K^0$ mass difference is important for the determination of $m_u - m_d$. At leading order in the chiral expansion it is given by Dashen’s theorem [29]

$$(\Delta M^2_K)_EM = (\Delta M^2_\pi)_EM + O(e^2m_q) .$$

(107)

It was pointed out that the corrections of order $e^2m_s$ could be rather large [15] such that the right hand side could be modified by as much as a factor of two. Using Urech’s formalism one can compute explicitly these corrections which have the following form [4]

$$(\Delta M^2_K)_EM - (\Delta M^2_\pi)_EM = e^2M^2_K(A_1 + A_2 + A_3) + O(e^2M^2_\pi)$$

(108)
with
\[ A_1 = -\frac{1}{16\pi^2}[(3 + 2Z) \log \frac{M^2}{\mu^2} - 4] - 16ZL_5^r, \quad Z = \frac{C}{F_0^4} \]
\[ A_2 = -\frac{4}{3}(K_5^r + K_6^r) \]
\[ A_3 = 8(K_{10}^r + K_{11}^r) \].

As discussed in (I) (and also in [30]) the Urech couplings $K_{10}^r$, $K_{11}^r$ taken separately suffer from short distance ambiguities and depend on the gauge. The sum, however, is perfectly well defined and can be estimated from sum rules related to the correlators $<V^3V^3 - V^8V^8 - A^3A^3 + A^8A^8>$ and $<VAP>$, giving the following result [31]

\[ K_{10}^r + K_{11}^r = 3 \frac{1}{16}\frac{1}{16\pi^2}\left\{ \log \frac{M^2}{\mu^2} + Z_A - Z_V + 2 \log z \left[ \frac{(z + 1)^2}{2(z - 1)^3} + 1 \right] + \frac{2z(z - 3)}{(z - 1)^2} + \frac{1}{6} + 4Z_0^\mu \right\} \]  

(110)

with
\[ Z_A - Z_V = \frac{4M_\pi^2(F_\pi - F_K)}{F_\pi(M_\pi^2 - M_K^2)} + \frac{2F_\pi^2M_\rho(M_\rho - M_\phi)}{F_\pi^2(M_\pi^2 - M_K^2)} \log z - 2 \log z - 2 . \]  

(111)

The quantity $Z_A - Z_V$ is generated from flavour symmetry breaking at first order in the vector multiplet as well as the axial-vector multiplet and the computation takes into account Weinberg-type sum rule relations for the splittings of the masses as well as the coupling constants. The last entry in the expression (110), $Z_0^\mu$, is a contribution which should restore the scale dependence proportional to $C/F_0^4$. Since this effect is subleading in $N_c$, this term will be dropped here for consistency with previous approximations. Making use of the result eq. (110) and of the numerical values for $K_5^r + K_6^r$ shown in table 1 we find the following numerical values for the three corrective terms (which we give in units of the physical $\pi^+ - \pi^0$ mass difference, $\Delta M_{\pi}^2 = 1261.16$ MeV$^2$ )

\[ (\Delta M_K^2)_{EM} - (\Delta M_\pi^2)_{EM} = \Delta M_{\pi}^2 [0.59 - 0.34 + 1.25] . \]  

(112)

The new result with respect to (I) concerns $K_5^r + K_6^r$ and we find that this contribution goes in the sense of reducing the size of the correction. This is in qualitative agreement with the result of BU. However, the effect of the extra terms from $L_{a_1\rho\pi}$ included here is to reduce the magnitude of $K_5^r + K_6^r$ by approximately a factor of two as compared to BU. There is a clear indication for a sizable correction to Dashen’s theorem rather similar to that found in refs. [39, 30]. The origin of the different result obtain in ref. [29] can be traced, essentially, to the fact that their result for $K_{10}^r + K_{11}^r$ is ten times smaller than ours. This is due to two reasons 1) flavour symmetry breaking in the vector and the axial-vector multiplets was ignored in [29] such that $K_{10}^r$ was just set to zero and 2) the effect of the couplings from $L_{a_1\rho\pi}$ which they did not take into account is to strongly enhance the value of $K_{11}^r$. 

33
6.3 Uncertainties

One should keep in mind that there are uncertainties which are difficult to estimate quantitatively. These have two main sources. The first one is that we have used, at several places, large $N_c$ approximations a) in the treatment of the resonances, which are taken to be infinitely narrow and b) in the calculation of QCD n-point correlators in which only tree graphs were considered. The second source of uncertainty is that we have retained the contributions from the lightest resonances only. The usual experience with such approximations is that reasonable order of magnitudes should be obtained.

7 Conclusions

In this paper, we have considered a set of sum rules for the electromagnetic chiral parameters which involve QCD 4-point correlators in connection with the construction of a chiral Lagrangian with resonances. For our purposes, the resonance Lagrangian provides rational-type approximations for the QCD correlators obeying the chiral Ward identities.

We have shown that the resonance Lagrangian of order $p^4$ was not sufficient to ensure all the convergence conditions required by the sum rules. We have then shown that introducing a set of terms of order $p^6$, involving $a_1 \rho \pi$–type couplings renders it possible to satisfy these conditions in the sense of finiteness as a $d \to 4$ limit. The new coupling constants which appear were shown to obey non linear equations, we have argued that physical requirements select a unique solution.

Our investigation, however, was essentially limited to a set of terms with three building blocks. A more general investigation should be performed in the future. A more complete determination of the resonance Lagrangian would lead to much better estimates of the chiral coupling constants at this order[50] than those available at present. This would improve significantly the effectiveness of the chiral calculations at order $p^6$. There is also a limitation in the set of resonances which were included. In this regard, the role of tensor mesons should perhaps be investigated[51].

We have considered an application to the problem of the chiral corrections to Dashen’s low-energy theorem. We have found that the combination $K_5^r + K_6^r$ as determined here reduces the size of the correction which still remains rather large. One motivation for deriving estimates for each of the parameters $K_i$ is to improve the accuracy of radiative correction evaluations. In this context, further work is still needed because another set of parameters, $X_i$, is involved in the interesting case of the semi-leptonic decays[5]. Finally, a formal similarity can be noted between the sum rules considered here and those shown recently to hold for chiral parameters in the weak non-leptonic sector[52].

A Vertices

We list below the set of vertices which are needed in sec.2 and those needed sec.3 which are associated with vector and axial-vector resonances. The vertices represent derivatives of the action (times $i$) with respect to the various sources (with each source multiplied by $i$). It is not difficult to derive, in an analogous way, all the other relevant vertices.
A.1 Vertices with pions

\[ V = -F \partial_\lambda \pi^c(z) F^\lambda(z) \]

\[ V = i F f^{c\alpha}(x) F_\alpha(x) \delta(x - z) \]

\[ V = i F f^{b\beta}(y) F_\beta(y) \delta(y - z) \]

\[ V = i F f^{b\alpha}(x) g^{\alpha\beta} \delta(x - y) \]

\[ V = -f^{s\mu} \partial_\mu \pi^s(z) \pi^t(z) F_\mu(z) \]

\[ V = -f^{s\alpha} \partial_\alpha \pi^s(x) \pi^t(x) \]

\[ V = i g^{\alpha\beta} f^{ais} f^{bj\beta}(x) \pi^i(x) \pi^j(x) \delta(x - y) \]

\[ V = -i g^{\alpha\beta} f^{ais} f^{bj\beta}(x) \pi^i(x) \pi^j(x) \delta(x - y) \]
A.2 Resonance vertices with $v_\mu$ sources:

These vertices are the same for vector or axial-vector mesons:

\[ V = -f^{aij} R_{a\mu}^i(x) \partial^\lambda R_{\lambda}^{j\mu}(x) \]

\[ V = i f^{ail} f^{bjl} R_{a\mu}^i(x) R_{b\mu}^j(x) \delta(x - y) \]

A.3 Vertices proportional to $F_A$

\[ V = - F_A A_{\mu\nu}^c(z) \partial^\mu F^\nu(z) \]

\[ V = i F_A f^{ibe} A_{\beta\lambda}^i(y) F^\lambda(y) \delta(y - z) \]

\[ V = i F_A f^{iad} A_{\alpha\lambda}^i(x) F^\lambda(x) \delta(x) \]

\[ V = \frac{-E_A}{f} f^{dij} A_{\mu\nu}^i(0) \partial^\mu F^\nu(0) \pi^j(0) \]

\[ V = \frac{E_A}{f} f^{ijl} f^{abl} A_{\alpha\beta}^i(x) \pi^j(x) \delta(x - y) \]

Note that this vertex is antisymmetric in the Lorentz indices $\alpha\beta$ and will therefore not contribute here.
A.4 Vertices proportional to $F_V$

\[ V = F_V V_{\mu\nu}^c(z) \partial^\mu F^\nu(z) \]

\[ V = -iF_V f^{iac} V^i_{\alpha\lambda}(x) F^\lambda(x) \delta(x - z) \]

\[ V = -iF_V f^{iac} V^i_{\alpha\lambda}(x) F^\lambda(x) \delta(x - z) \]

\[ V = \frac{F_V}{F} f^{stc} V^s_{\mu\nu} \partial^\mu F^\nu \pi^t \]

A.5 Vertices proportional to $G_V$

\[ V = 2iG_V f^{act} V^t_{ab}(x) F^\nu(x) \delta(x - z) \]

\[ V = \frac{-2G_V}{F} f^{ast} V^s_{\alpha\mu}(x) \partial^\mu \pi^t(x) \]

\[ V = \frac{-2G_V}{F} f^{cst} V^s_{\lambda\mu}(z) \partial^\mu \pi^t(z) F^\lambda(z) \]

\[ V = \frac{-iG_V}{F_0} f^{stu} \int dv V^s_{\mu\nu}(v) \partial^\mu \pi^t(v) \partial^\mu \pi^u(v) \]

There are other potentially relevant vertices which are antisymmetric in $\alpha\beta$ and will thus not contribute for our purposes.
B  \( b_1(1235) \) contributions

We present here an estimate of the contributions associated with the \( b_1(1235) \) resonance. The physics of the \( b_1 \) meson is not as constrained as that of the \( a_1 \) meson by chiral symmetry, so in this section we will occasionally make some educated guesses. The order of magnitude of the \( b_1 \) effect should nevertheless be properly accounted for. The contributions are to the same correlator components as those from the \( \omega \rho \pi \) couplings. In principle, the convergence constraints should be applied to the sum. We will apply, however, these constraints separately to the \( b_1 \) for the purpose of obtaining an order of magnitude estimate.

We can write down a set of vertices in exact analogy with the \( a_1 \rho \pi \) vertices

\[
\mathcal{L}_{b_1\omega\pi} = (G_1^B g^{\rho\mu_1} g^{\rho\mu_3} + G_2^B g^{\rho\mu_2} g^{\rho\mu_1} + G_3^B g^{\rho\mu_3} g^{\mu_1\mu_2}) \langle \{ \nabla_{\mu_0} V_{\mu_1 \lambda}, B_{\mu_2}^\lambda \} u_{\mu_3} \rangle \\
+ (H_1^B g^{\rho\mu_1} g^{\mu_2\mu_3} + H_2^B g^{\rho\mu_2} g^{\mu_3\mu_1} + H_3^B g^{\rho\mu_3} g^{\mu_1\mu_2}) \langle \{ V_{\mu_1 \lambda}, B_{\mu_2}^\lambda \} \nabla_{\mu_3} u_{\mu_3} \rangle
\]

The only difference with the Lagrangian of eq.\((67)\) is that the commutator is replaced by an anticommutator on account of the fact that the \( b_1 \) meson is odd under charge conjugation. As a consequence, the contribution to the correlator \( \langle AAQ V Q \rangle_3 \) can be deduced simply from the results of sec.5.3

\[
\langle AAQ V Q \rangle_3^{b_1\omega\pi} = \frac{-3F_V^2}{16\pi^2} \left\{ - \left( G_1^B + G_2^B + 2G_3^B \right)^2 \left[ \log \frac{M_V^2}{M_B^2} + \frac{M_B^2 \log M_B^2}{(M_B^2 - M_V^2)^2} \right] \\
+ \frac{7M_V^2 - M_B^2}{6(M_V^2 - M_B^2)} \right\} + \frac{4}{M_B^2} \left( \log \frac{M_V^2}{M_B^2} + \frac{5}{3} \right)
\]

\((113)\)

Imposing a consistency condition on eq.\((113)\) enables one to express \( \langle AAQ V Q \rangle_3^{b_1\omega\pi} \) in terms of the combination

\[
\tilde{G}^B \equiv G_1^B + G_2^B + 2G_3^B
\]

and one obtains

\[
\langle AAQ V Q \rangle_3^{b_1\omega\pi} = \frac{3F_V^2}{16\pi^2} \left( \tilde{G}^B \right)^2 \left[ \frac{M_B^2 \log M_B^2}{(M_B^2 - M_V^2)^2} + \frac{3M_B^2 + M_V^2}{2(M_B^2 - M_V^2)} \right]
\]

\((116)\)

We must next try to determine the relevant combination of couplings \( \tilde{G}^B \) from experiment. The widths of the decays \( b_1^+ \to \gamma \pi^+ \) and \( b_1^+ \to \omega \pi^+ \) are known

\[
\Gamma_{b_1^+ \to \gamma \pi^+} = 227 \pm 59 \text{ KeV}, \quad \Gamma_{b_1^+ \to \omega \pi^+} = 142 \pm 9 \text{ MeV}
\]

\((117)\)

and their expressions in terms of the resonance Lagrangian coupling constants read

\[
\Gamma_{b_1^+ \to \gamma \pi^+} = \frac{\alpha(M_B^2 - M_V^2)}{24M_B} \left( \frac{F_V M_B^2}{3F_\pi M_V^2} \right)^2 \left( \tilde{H}^B \right)^2
\]

\[
\Gamma_{b_1^+ \to \omega \pi^+} = \frac{\rho_{\text{cm}}(M_B^2 - M_V^2)^2}{48\pi M_B^4 M_\omega^2 F_\pi^2} \left( 2M_B^2 M_V^2 \tilde{G}^B \right)^2 + \left( M_B^2 - M_V^2 \right) \tilde{H}^B + 2M_B^2 \tilde{G}^B \right)^2}
\]

\((118)\)
Here, we have introduced the notation

\[ \tilde{H}^B \equiv H_1^B + H_2^B + G_2^B + 2G_3^B \]  

(119)

Using these two pieces of information enables one to determine the combination of couplings that one needs, but there are several solutions due to the nonlinearity of the equations

\[ \tilde{H}^B = \pm 0.68 \quad \tilde{G}^B \equiv G_1^B + G_2^B + 2G_3^B = \pm 0.24, \pm 0.67 \]  

(120)

We can eliminate some of the solutions by using one more piece of experimental information concerning the \( D/S \) ratio in the decay \( b_1 \to \omega \pi \)

\[ \frac{f_D}{f_S} = 0.29 \pm 0.04 \]  

(121)

The \( S \) and the \( D \)-wave components of the decay amplitude \( b_1 \to \omega \pi \) (defined as in ref. [53]) are easily computed from our Lagrangian

\[ f_S = -\frac{\sqrt{4\pi}}{3M_B M_\omega F_\pi} \left( M_B^2 - M_\pi^2 \right) \left[ M_V (M_B + 2M_\pi) \tilde{G}^B + (M_B^2 - M_\pi^2) \tilde{H}^B \right] \]
\[ f_D = -\frac{\sqrt{8\pi}}{6M_B M_\omega F_\pi} \left( M_B^2 - M_\pi^2 \right) \left[ 2M_V (M_B - M_\pi) \tilde{G}^B + (M_B^2 - M_\pi^2) \tilde{H}^B \right] \]  

(122)

Using this result and the experimental one on the \( D/S \) ratio reduces the set of acceptable solutions for the coupling constants to

\[ (\tilde{G}^B, \tilde{H}^B) = \pm (0.24, 0.68) \]  

(123)

which give \( f_D/f_S = 0.28 \).

References

[1] S. S. Weinberg, Physica A 96 (1979) 327.
[2] J. Gasser and H. Leutwyler, Annals Phys. 158 (1984) 142.
[3] J. Gasser and H. Leutwyler, Nucl. Phys. B 250 (1985) 465.
[4] R. Urech, Nucl. Phys. B 433 (1995) 234 [arXiv:hep-ph/9405341].
[5] M. Knecht, H. Neufeld, H. Rupertsberger and P. Talavera, Eur. Phys. J. C 12 (2000) 469 [arXiv:hep-ph/9909284].
[6] G. Ecker, G. Isidori, G. Muller, H. Neufeld and A. Pich, Nucl. Phys. B 591 (2000) 419 [arXiv:hep-ph/0006172].
[7] B. Ananthanarayan and B. Moussallam, JHEP 0205 (2002) 052 [arXiv:hep-ph/0205232].
[8] U. G. Meissner and S. Steininger, Phys. Lett. B 419 (1998) 403 [arXiv:hep-ph/9709453].

[9] U. G. Meissner, G. Muller and S. Steininger, Phys. Lett. B 406 (1997) 154 [Erratum-ibid. B 407 (1997) 454] [arXiv:hep-ph/9704377].

[10] M. Knecht and R. Urech, Nucl. Phys. B 519 (1998) 329 [arXiv:hep-ph/9709348].

[11] B. Kubis and U. G. Meissner, Nucl. Phys. A 699 (2002) 709 [arXiv:hep-ph/0107199].

[12] B. Kubis and U. G. Meissner, Phys. Lett. B 529 (2002) 69 [arXiv:hep-ph/0112154].

[13] A. Nehme and P. Talavera, Phys. Rev. D 65 (2002) 054023 [arXiv:hep-ph/0107299].

[14] M. Knecht and A. Nehme, Phys. Lett. B 532 (2002) 55 [arXiv:hep-ph/0201033].

[15] A. Nehme, Eur. Phys. J. C 23 (2002) 707 [arXiv:hep-ph/0111212].

[16] H. Sazdjian, Phys. Lett. B 490 (2000) 203 [arXiv:hep-ph/0004226].

[17] J. Gasser, V. E. Lyubovitskij, A. Rusetsky and A. Gall, Phys. Rev. D 64 (2001) 016008 [arXiv:hep-ph/00103157].

[18] J. Schweizer, arXiv:hep-ph/0401048.

[19] V. Cirigliano, M. Knecht, H. Neufeld, H. Rupertsberger and P. Talavera, Eur. Phys. J. C 23 (2002) 121 [arXiv:hep-ph/0111042].

[20] A. Nehme, arXiv:hep-ph/0311113. V. Cuplov and A. Nehme, arXiv:hep-ph/0311274.

[21] L. Ametller, M. Knecht and P. Talavera, Phys. Rev. D 64 (2001) 094009 [arXiv:hep-ph/0107127].

[22] V. Cirigliano, G. Ecker and H. Neufeld, Phys. Lett. B 513 (2001) 361 [arXiv:hep-ph/0104267].

[23] V. Cirigliano, J. F. Donoghue and E. Golowich, Phys. Rev. D 61 (2000) 093001 [Erratum-ibid. D 63 (2001) 059903] [arXiv:hep-ph/9907341].

[24] V. Cirigliano, G. Ecker, H. Neufeld and A. Pich, Eur. Phys. J. C 33 (2004) 369 [arXiv:hep-ph/0303351].

[25] V. Cirigliano, A. Pich, G. Ecker and H. Neufeld, Phys. Rev. Lett. 91 (2003) 162001 [arXiv:hep-ph/0307030].

[26] R. F. Dashen, Phys. Rev. 183 (1969) 1245.

[27] H. Leutwyler, Phys. Lett. B 378 (1996) 313 [arXiv:hep-ph/9602366].

[28] J. Gasser, A. Rusetsky and I. Scimemi, Eur. Phys. J. C 32 (2003) 97 [arXiv:hep-ph/0305260].
[29] R. Baur and R. Urech, Nucl. Phys. B 499 (1997) 319 [arXiv:hep-ph/9612328].
[30] J. Bijnens and J. Prades, Nucl. Phys. B 490 (1997) 239 [arXiv:hep-ph/9610360].
[31] B. Moussallam, Nucl. Phys. B 504 (1997) 381 [arXiv:hep-ph/9701400].
[32] T. Das, G. S. Guralnik, V. S. Mathur, F. E. Low and J. E. Young, Phys. Rev. Lett. 18 (1967) 759.
[33] G. ’t Hooft, Nucl. Phys. B 72 (1974) 461.
[34] G. Ecker, J. Gasser, A. Pich and E. de Rafael, Nucl. Phys. B 321 (1989) 311.
[35] G. Ecker, J. Gasser, H. Leutwyler, A. Pich and E. de Rafael, Phys. Lett. B 223 (1989) 425.
[36] R. Baur and R. Urech, Phys. Rev. D 53 (1996) 6552 [arXiv:hep-ph/9508393].
[37] H. Neufeld and H. Rupertserberger, Z. Phys. C 68 (1995) 91, H. Neufeld and H. Rupertserberger, Z. Phys. C 71 (1996) 131 [arXiv:hep-ph/9506448].
[38] E. de Rafael, Nucl. Phys. Proc. Suppl. 119 (2003) 71 [arXiv:hep-ph/0210317].
[39] D. J. Gross and R. Jackiw, Phys. Rev. D 6 (1972) 477.
[40] V. Cirigliano, G. Ecker, M. Eidemuller, A. Pich and J. Portoles, arXiv:hep-ph/0404004.
[41] P. D. Ruiz-Femenia, A. Pich and J. Portoles, JHEP 0307 (2003) 003 [arXiv:hep-ph/0306157].
[42] B. Moussallam, Phys. Rev. D 51 (1995) 4939 [arXiv:hep-ph/9407402].
[43] M. Knecht and A. Nyffeler, Eur. Phys. J. C 21 (2001) 659 [arXiv:hep-ph/0106034].
[44] K. Hagiwara et al. [Particle Data Group Collaboration], Phys. Rev. D 66 (2002) 010001.
[45] J. Prades, Z. Phys. C 63 (1994) 491 [Erratum:ibid. C 11 (1999) 571] [arXiv:hep-ph/9302246].
[46] J. Bijnens, E. Gamiz, E. Lipartia and J. Prades, JHEP 0304 (2003) 055 [arXiv:hep-ph/0304222].
[47] K. Kawarabayashi and M. Suzuki, Phys. Rev. Lett. 16 (1966) 255, Riazuddin and Fayyazuddin, Phys. Rev. 147 (1966) 1071.
[48] K. Maltman and D. Kotchan, Mod. Phys. Lett. A 5 (1990) 2457, G. J. Stephenson, K. Maltman and T. Goldman, Phys. Rev. D 43 (1991) 860, J. F. Donoghue, B. R. Holstein and D. Wyler, Phys. Rev. D 47 (1993) 2089, J. Bijnens, Phys. Lett. B 306 (1993) 343 [arXiv:hep-ph/9302217], D. N. Gao, M. L. Yan and B. A. Li, Phys. Rev. D 56 (1997) 4115 [arXiv:hep-ph/9611297].

41
[49] J. F. Donoghue and A. F. Perez, Phys. Rev. D 55 (1997) 7075 [arXiv:hep-ph/9611331].
[50] J. Bijnens, G. Colangelo and G. Ecker, JHEP 9902 (1999) 020 [arXiv:hep-ph/9902437].
[51] D. Toublan, Phys. Rev. D 53 (1996) 6602 [Erratum-ibid. D 57 (1998) 4495] [arXiv:hep-ph/9509217].
[52] T. Hambye, S. Peris and E. de Rafael, JHEP 0305 (2003) 027 [arXiv:hep-ph/0305104].
[53] N. Isgur, C. Morningstar and C. Reader, Phys. Rev. D 39 (1989) 1357.