On the coupling $g_{f_0K^+K^-}$ and the structure of $f_0(980)$

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Abstract. We use light-cone QCD sum rules to evaluate the strong coupling $g_{f_0K^+K^-}$ which enters in several analyses concerning the scalar $f_0(980)$ meson. The result is $6.2 \leq g_{f_0K^+K^-} \leq 7.8$ GeV.

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1 Introduction

The nature of light scalar mesons still needs to be unambiguously established \cite{12,20}. Their identification is made problematic since both quark-antiquark ($qq$) and non $qq$ scalar states are expected to exist in the energy regime below 2 GeV. For example, lattice QCD and QCD sum rule analyses indicate that the lowest lying glueball is a $0^{++}$ state with mass in the range 1.5-1.7 GeV \cite{3}. Actually, the observed light scalar states are too numerous to be accommodated in a single $qq$ multiplet, and therefore it has been suggested that some of them escape the quark model interpretation. Besides glueballs, other interpretations include multiquark states and quark-gluon admixtures.

Particularly debated is the nature of $f_0(980)$. Among the oldest suggestions, there is the proposal that confinement could be explained by the existence of vacuum quantum numbers and mass close to the proton mass \cite{4}. On the other hand, following the quark model and considering the strong coupling to kaons, $f_0(980)$ could be interpreted as an $ss$ state \cite{16,17,18}. However, this does not explain the mass degeneracy between $f_0(980)$ and $a_0(980)$ interpreted as a $(u\bar{u} - d\bar{d})/\sqrt{2}$ state. A four quark $qqq\bar{q}$ state interpretation has also been proposed \cite{9}. In this case, $f_0(980)$ could either be nucleon-like \cite{10}, i.e. a bound state of quarks with symbolic quark structure $f_0 = \langle u\bar{u} + d\bar{d} \rangle/\sqrt{2}$, the $a_0(980)$ being $a_0 = ss\langle u\bar{u} - d\bar{d} \rangle/\sqrt{2}$, or deuteron-like, i.e. a bound state of hadrons. If $f_0$ is a bound state of hadrons, it is usually referred to as a $K\bar{K}$ molecule \cite{11,12,13,14}. In the former of these two possibilities mesons are treated as point-like, while in the latter they should be viewed as extended objects. The identification of the $f_0$ and of the other lightest scalar mesons with the Higgs nonet of a hidden U(3) symmetry has also been suggested \cite{15}. Finally, a different interpretation consists in considering $f_0(980)$ as the result of a process in which strong interaction enriches a pure $qq$ state with other components, such as $|KK\rangle$, a process known as hadronic dressing \cite{6,16,17,18,19}; such an interpretation is supported in \cite{2,5,6,8,19,24}.

2 $g_{f_0K^+K^-}$ by light cone QCD Sum rules

In order to evaluate the strong coupling $g_{f_0K^+K^-}$, defined by the matrix element:

$$<K^+(p)K^-(p)|f_0(p + q) >= g_{f_0K^+K^-},$$

we consider the correlation function

$$T_\mu(p,q) = i \int d^4x e^{ipx} \langle K^+(q)|T[J^K_\mu(x)]J_\mu(0)|f_0(0)\rangle,$$

where $J^K_\mu = \bar{u}\gamma_\mu s\bar{s}$ and $J_{f_0} = ss$. The external kaon state has four momentum $q$, with $q^2 = M_K^2$. The choice of the $J_{f_0} = ss$ current does not imply that $f_0(980)$ has a pure $ss$ structure, but it simply amounts to assume that $J_{f_0}$ has a non-vanishing matrix element between the vacuum and $f_0$ \cite{19,24}. Such a matrix element, as mentioned below, has been derived by the same sum rule method.

Exploiting Lorentz invariance, $T_\mu$ can be written in terms of two independent invariant functions, $T_1$ and $T_2$: ...
Two variables \( p \) and \( q \) appear in the general strategy of QCD sum rules consists in representing \( T_\mu \) in terms of the contributions of hadrons (one-particle states and the continuum) having non-vanishing matrix elements with the vacuum and the currents \((J^K_\mu \text{ and } J^0_\mu)\) in the present case, and matching such a representation with a QCD expression computed in a suitable region of the external momenta \( p \) and \( p + q \).

Let us consider, in particular, the invariant function \( T_1 \) that can be represented by a dispersive formula in the two variables \( p^2 \) and \( (p + q)^2 \):

\[
T_1(p^2, (p + q)^2) = \int ds ds' \frac{\rho_{had}^0(s, s')}{(s - p^2)[s' - (p + q)^2]} .
\]

The hadronic spectral density \( \rho_{had}^0 \) gets contribution from the single-particle states \( K \) and \( f_0 \), for which we define current-particle matrix elements:

\[
\langle 0| J^K_\mu |p \rangle = M_{K} f_{K} \delta(s - M^2_{K}) \delta(s' - M^2_{K}) ,
\]

(4)
as well as from higher resonances and a continuum of states that we assume to contribute in a domain \( D \) of the \( s, s' \) plane, starting from two thresholds \( s_0 \) and \( s'_0 \).

Therefore, neglecting the \( f_0 \) width, the spectral function \( \rho_{had}^0 \) can be modeled as:

\[
\rho_{had}^0(s, s') = f_K M_K f_{f_0} g_{f_0K^+} \delta(s - M^2_{K}) \delta(s' - M^2_{f_0}) + \rho_{cont}(s, s') \delta(s - s_0) \delta(s' - s'_0) ,
\]

(5)
where \( \rho_{cont} \) includes the contribution of the higher resonances and of the hadronic continuum. The resulting expression for \( T_1 \) is:

\[
T_1(p^2, (p + q)^2) = \int_D ds ds' \frac{\rho_{had}^0(s, s')}{(s - p^2)[s' - (p + q)^2]} .
\]

We do not consider possible subtraction terms in eq. (3) as they will be removed by a Borel transformation.

For space-like and large external momenta \((p^2 > 0, -(p + q)^2 > 0)\), \( T_1 \) can be computed in QCD as an expansion near the light-cone \( x^2 = 0 \). The expansion involves matrix elements of non-local quark-gluon operators, defined in terms of kaon distribution amplitudes of increasing twist.

The first few terms in the expansion are retained, since the higher twist contributions are suppressed by powers of \( 1/(p^2) \) or \( 1/(-(p + q)^2) \). For the resulting expression for \( T_1 \), obtained to twist four accuracy, we refer to (21).

The sum rule for \( g_{f_0K^+} \) follows from the approximate equality of eq. (4) and the computation of \( T_1 \) in QCD. Invoking global quark-hadron duality, the contribution of the continuum in (1) can be identified with the QCD contribution above the thresholds \( s_0 \) and \( s'_0 \). This allows us to isolate the pole contribution in which the coupling appears.

3 Comparison with other results and conclusions

The various determinations of \( g_{f_0K^+} \) form a very complex scenario. A collection of experimental results is provided in table (1). In the case of KLOE Collaboration, two results are reported, corresponding to two different fits performed in the analysis of the data, indicated with (A)
Fig. 1. $g_{f_0 K+K^-}$ as a function of the Borel parameter $M_z^2$, varying: $1.05 \leq s_0 \leq 1.15\text{ GeV}^2$ and $0.7 \leq M_t^2 \leq 2.0\text{ GeV}^2$.

Table 1. Experimental determinations of $g_{f_0 K+K^-}$ using different physical processes.

| Collaboration | process | $g_{f_0 K+K^-}$ (GeV) | Ref. |
|--------------|---------|----------------------|-----|
| KLOE         | $\phi \to f_0 \gamma (A)$ | $4.0 \pm 0.2 \text{ (A)}$ | [32] |
|              | $\phi \to f_0 \gamma (B)$ | $5.9 \pm 0.1 \text{ (B)}$ |     |
| CMD-2        | $\phi \to f_0 \gamma$     | $4.3 \pm 0.5$            | [33] |
| SND          | $\phi \to f_0 \gamma$     | $5.6 \pm 0.8$            | [34] |
| WA102        | $pp \to D_s \to 3\pi$     | $2.2 \pm 0.2$            | [35] |
| E791         | $D_s \to 3\pi$            | $0.5 \pm 0.6$            |     |

and (B). The difference mainly consists in the inclusion of the $\sigma$ contribution in fit (B). Such a result is the one affected by the smallest uncertainty, and seems to point towards large values of $g_{f_0 K+K^-}$. Theoretical results also lie in a rather large range of values, from 2 GeV up to 7 GeV. For a detailed discussion we refer to [47], while an analysis based on experimental data can be found in [6]. The outcome of light-cone QCD sum rule analysis, reported here, is in keeping with a large value for the coupling. The uncertainty affecting the result is intrinsic of the method and does not allow a better comparison with data. However, the analysis confirms a peculiar aspect of the scalar states, i.e. their large hadronic couplings, thus pointing towards a scenario in which the process of hadronic dressing is favoured. However, since the most accurate experimental data stem from the investigation of $\phi \to f_0 \gamma$, it is mandatory to wait for the study of unrelated processes, namely the combined analysis of $D_s$ decays to pions and kaons, which could be performed, for example, at the B-factories.

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