MENU 2007
11th International Conference
on Meson-Nucleon Physics and
the Structure of the Nucleon
September10-14, 2007
IKP, Forschungzentrum Jülich, Germany

PION SCALAR FORM FACTORS FROM J/ψ DECAYS

Timo A. Lähde
Department of Physics, University of Washington,
Seattle, WA 98195-1560, USA

Abstract

The description of the decays $J/\psi \to \phi\pi^+\pi^-$, $J/\psi \to \omega\pi^+\pi^-$, $J/\psi \to \phi K^+K^-$ and $J/\psi \to \omega K^+K^-$ in terms of the scalar form factors of the light pseudoscalar mesons is reviewed. Key features in these decays include the S-wave resonances σ and $f_0(980)$, which appear prominently in the new data from the BES collaboration. These resonances are dynamically generated by resummation of the s-channel unitarity loops, after which the formalism is matched to the NLO expressions for the scalar form factors in Chiral Perturbation Theory (ChPT). This allows for an estimation of several low-energy constants (LECs) of ChPT, in particular the OZI-suppressed L_4^r and L_6^r.

1 Introduction

The decays of the J/ψ into a vector meson, such as ϕ or ω, via emission of a pair of light pseudoscalar mesons may yield insight into the dynamics of the pseudo-Goldstone bosons of QCD [1–3], and in particular into the final state interaction (FSI) between $\pi\pi$ and $K\overline{K}$ pairs, which is an essential component in a realistic description of the scalar form factors (FFs) of pions and kaons. Recently, the BES collaboration has published data with high statistics on $J/\psi \to \phi\pi^+\pi^-$ and $J/\psi \to \phi K^+K^-$, as well as for $J/\psi \to \omega\pi^+\pi^-$ and $J/\psi \to \omega K^+K^-$ [4]. Additionally, a comprehensive partial-wave analysis (PWA) has been performed, which is particularly useful since a determination of the S-wave components of the $\pi\pi$ and $K\overline{K}$ invariant mass distributions is thus available.

A much more precise analysis in the spirit of Ref. [5] is thus possible, the key ingredient being a realistic treatment of the final state interaction (FSI) in the emitted pseudoscalar meson pair. It has been demonstrated in Ref. [6] that the FSI in the $\pi\pi - K\overline{K}$ system can be well described by a coupled-channel Bethe-Salpeter approach using the lowest order ChPT amplitudes for meson-meson scattering [7, 8]. In such an approach, the lightest resonances in the 0^{++} sector are of dynamical origin, i.e. they arise due to the strong rescattering effects in the $\pi\pi$ or $K\overline{K}$ system. Such dynamically generated states include the σ and $f_0(980)$ mesons, which are prominent in the BES data on the J/ψ decays in question [4].

The analysis of Ref. [9] uses the formalism introduced in Refs. [5, 6], which allows for a description of the scalar FFs which takes into account the final-state interaction (FSI) between pions and kaons up to $\sqrt{s} \sim 1.2$ GeV. At higher energies, a number of pre-existing scalar resonances such as the $f_0(1500)$ have to be accounted for, as well as the effects of multi-particle intermediate states, most importantly the 4π state. The scalar FFs may then be constrained by matching to the next-to-leading-order (NLO) chiral expressions. This allows for a fit of the large N_c suppressed Low-Energy Constants (LECs) L_4^r and L_6^r of ChPT to the dimeson spectra of the $J/\psi \to \phi\pi\pi$ and $J/\psi \to \phi K\overline{K}$ decays, using the Lagrangian model of Ref. [5].

2 Description of $J/\psi \to VPP$ decays

From the considerations of Ref. [5], the matrix elements for $\phi\pi^+\pi^-$ and ϕK^+K^- decay of the J/ψ are given, in terms of the strange and non-strange scalar operators $\bar{s}s$ and $\bar{n}n = (\bar{u}u + \bar{d}d)/\sqrt{2}$, by

$$\mathcal{M}_\phi^{\pi\pi} = \sqrt{\frac{2}{3}}\, C_\phi \, \langle 0|(\bar{s}s + \lambda_\phi \bar{n}n)|\pi\pi\rangle^*_{\mathrm{I}=0}, \tag{1}$$

$$\mathcal{M}_\phi^{KK} = \sqrt{\frac{1}{2}}\, C_\phi \, \langle 0|(\bar{s}s + \lambda_\phi \bar{n}n)|K\overline{K}\rangle^*_{\mathrm{I}=0}, \tag{2}$$

in terms of the $\pi\pi$ and $K\overline{K}$ states with $I = 0$, which are related to the physical $\pi^+\pi^-$ and K^+K^- states by the Clebsch-Gordan (CG) coefficients of the above expressions. In addition, the full transition amplitudes also contain the polarization vectors of the J/ψ and ϕ mesons. The matrix elements for $\omega\pi^+\pi^-$ and ωK^+K^- may be obtained by replacement of the labels in Eqs. (1) and (2) according to $\phi \to \omega$. The matrix elements of the scalar operators are referred to as the strange and non-strange $I = 0$ scalar FFs. The parameter λ_ϕ measures the relative strengths of the singly ($\bar{s}s$) and doubly ($\bar{n}n$) OZI-violating contributions to the $\phi\pi^+\pi^-$ decay.

In Ref. [5], ideal mixing in the $\phi - \omega$ system was used to relate the parameters for ω emission to those of the ϕ, which enables a simultaneous description of the $\phi\pi^+\pi^-$ and $\omega\pi^+\pi^-$ final states. The explicit relations are given by

$$C_\omega = \lambda_\phi C_\phi, \quad \lambda_\omega = \frac{\lambda_\phi + \sqrt{2}}{\sqrt{2}\lambda_\phi}, \tag{3}$$

such that the quantities to be determined from fits to the experimental spectra of Refs. [4] are C_ϕ and λ_ϕ. It is worth noting that in the limit $\lambda_\phi = 0$, the dimeson spectra for ϕ and ω emission are driven entirely by the strange scalar source $\bar{s}s$ and the non-strange scalar source $\bar{n}n$, respectively.

3 Matching of FSI to NLO ChPT

The constraints imposed by unitarity on the pion and kaon scalar FFs, the inclusion of the FSI via resummation in terms of the Bethe-Salpeter (BS) equation, the channel coupling between the $\pi\pi$ and $K\overline{K}$ systems, and the matching of the scalar FFs to the NLO CHPT expressions have all been elaborated in great detail in Refs. [5, 6]. Within that framework, the scalar FFs are obtained from the algebraic coupled-channel equation

$$\begin{aligned} \Gamma(s) &= [I + K(s)\, g(s)]^{-1} R(s) \\ &= [I - K(s)\, g(s)]\, R(s) \;+\; \mathcal{O}(p^6), \end{aligned} \tag{4}$$

where the expansion in the second line can be used for matching the FSI to the NLO ChPT expressions for the scalar form factors. In Eq. (4), the loop function $g(s)$ is divergent and requires a cut-off $q_{\max} \sim 1$ GeV, which can be fixed using the mass of the $f_0(980)$ resonance. The matching to ChPT implies that $R(s)$ is given by the NLO chiral expression for the scalar form factor with the unitarity loop contributions removed. Finally $K(s)$ denotes the (on-shell) LO chiral amplitude for $\pi\pi$ and $K\overline{K}$ scattering,

$$K_{11} = \frac{2s - m_\pi^2}{2f^2}, \quad K_{12} = K_{21} = \frac{\sqrt{3}s}{4f^2}, \quad K_{22} = \frac{3s}{4f^2}, \tag{5}$$

where the constant f is taken to equal the physical pion decay constant f_π, with the convention $f_\pi = 0.0924$ GeV. Consideration of Eq. (4) yields the defining relations for $R_i^n(s)$

$$\Gamma_i^n(s) = R_i^n(s) - \sum_{j=1}^{2} K_{ij}(s) g_j(s) R_j^n(s) + \mathcal{O}(p^6), \tag{6}$$

with $i = \pi, K$, illustrated in Fig. 3, such that only contributions up to $\mathcal{O}(p^4)$ are retained in the product KgR. The analogous expressions for the vectors $R_i^s(s)$ associated with the strange scalar FFs $\Gamma_i^s(s)$ can be obtained from the above relations by the substitutions $\Gamma_i^n \to \Gamma_i^s$ and $R_i^n \to R_i^s$.

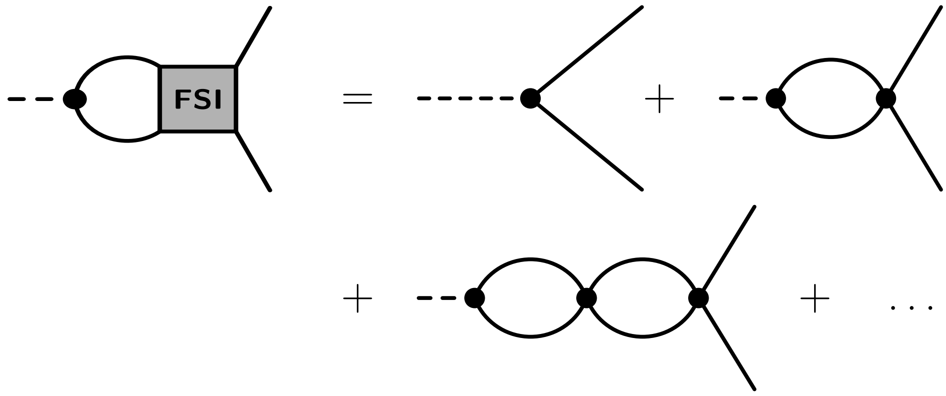

Figure 1: Resummation of unitarity loops in the s-channel for the pion and kaon scalar form factors. The leading term is given by the NLO ChPT expressions for Γ_i^n and Γ_i^s.

4 Fit Results

The results obtained in Ref. [5] involve a fit of the model parameters C_ϕ and λ_ϕ as well as the LECs L_4^r, L_5^r, L_6^r and L_8^r to the BES data on J/ψ decays to $\phi\pi^+\pi^-$, ϕK^+K^- and $\omega\pi^+\pi^-$. The main results are shown in Fig. 2, and the resulting pion scalar FFs are given in Fig. 3. The optimal value of λ_ϕ, which measures the OZI violation in the $J/\psi \to \phi\pi^+\pi^-$ decay, is $\lambda_\phi = 0.13 \pm 0.02$, which indicates a significant contribution to $\phi\pi^+\pi^-$ from the non-strange scalar FF, and a contribution to $\omega\pi^+\pi^-$ from the strange one. In particular, a realistic description of the $\omega\pi^+\pi^-$ spectrum close to the $K\overline{K}$ threshold requires an interplay between the non-strange and strange scalar FFs.

4.1 Determination of L_4^r and L_6^r

One of the main objectives of Refs. [5, 9] is the determination of the LECs L_4^r and L_6^r of ChPT. As discussed in Refs. [8, 10], where a set of standard estimates for the LECs of ChPT are given, L_4^r and L_6^r are expected, in terms of large N_c arguments, to vanish at some unknown scale in the resonance region of QCD, conventionally taken to be m_ρ or m_η. The values obtained from "Fit I" are $(0.84 \pm 0.06) \times 10^{-3}$ for L_4^r and $(0.03 \pm 0.16) \times 10^{-3}$ for L_6^r. These should be compared with the NNLO ChPT analyses of Refs. [11–13], where the L_i^r were extracted by fits to the available experimental data on K_{l4} decays. In that study, constraints on L_4^r and L_6^r were derived by requiring a

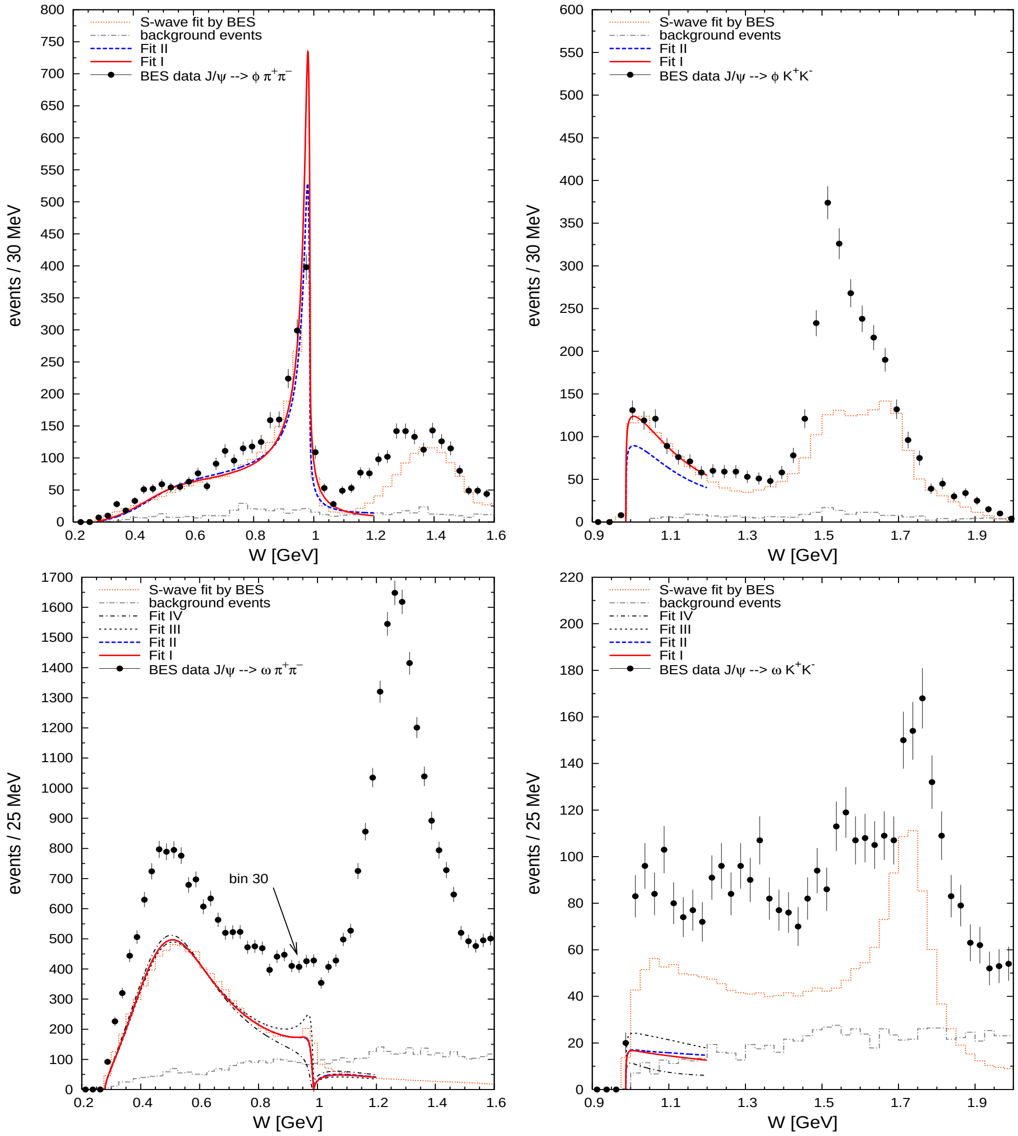

Figure 2: Fit results from Ref. [9] and BES data [4] for $J/\psi \to \phi\pi^+\pi^-$, $J/\psi \to \phi K^+K^-$ and $J/\psi \to \omega\pi^+\pi^-$. The case of $J/\psi \to \omega K^+K^-$ is left as a prediction. The direct S-wave contribution from the BES PWA and the estimated background are denoted by the dashed and dotted histographs, respectively. Note in particular the strong σ contribution and the conspicuous lack of $f_0(980)$ in $\omega\pi^+\pi^-$. The main result is given by the solid curves labeled "Fit I", the remaining fits II-IV are explained in Ref. [9].

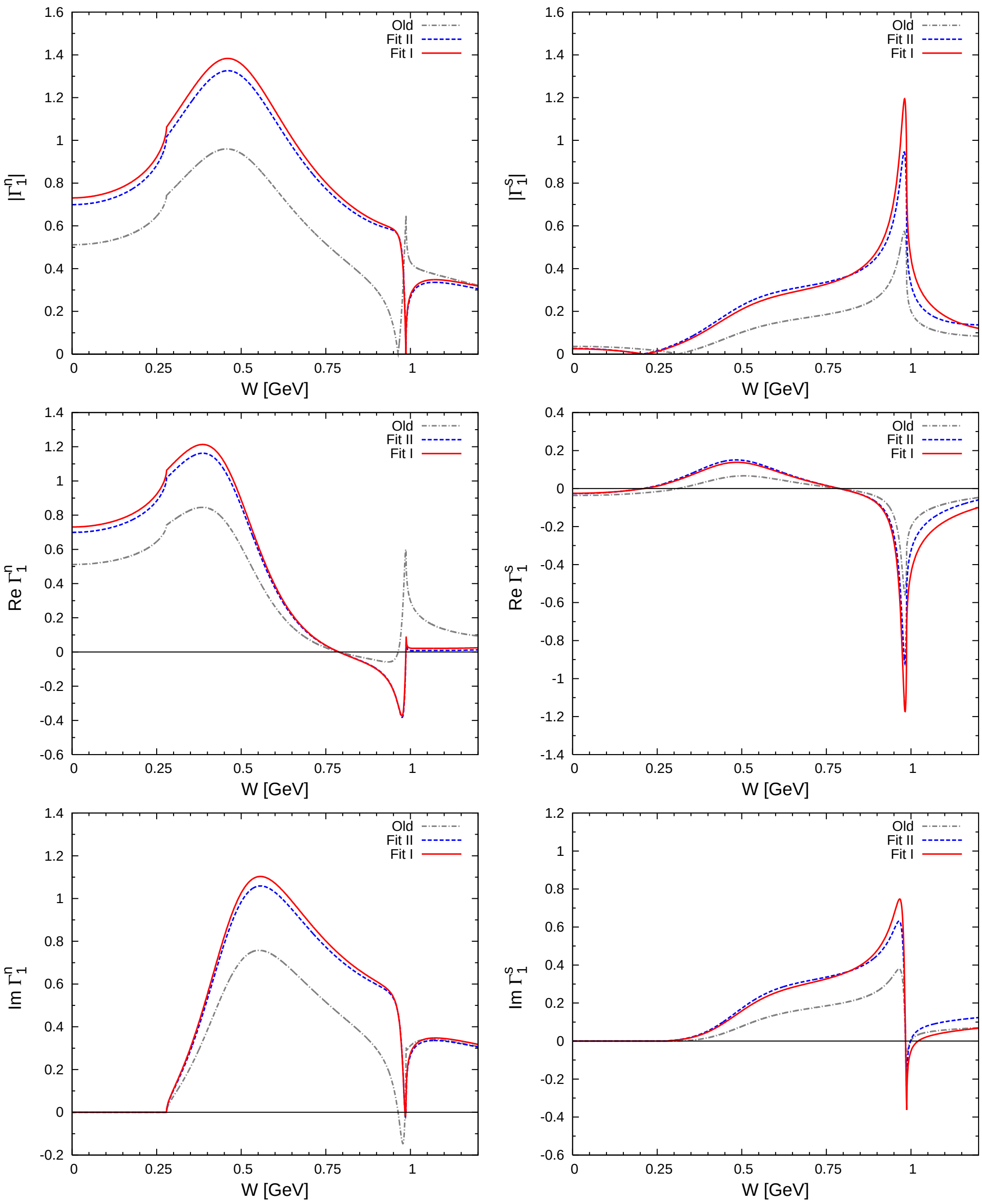

Figure 3: The non-strange and strange scalar FFs Γ_1^n and Γ_1^s of the pion. Moduli, real and imaginary parts are shown for the analysis of Ref. [9]. It should be emphasized that the FSI is identical for both FFs. The curves labeled "Old" show, for comparison, the scalar FFs obtained by Ref. [5]. The corresponding kaon FFs Γ_2^n and Γ_2^s can be found in Ref. [9].

properly convergent behavior of the chiral expansion up to NNLO for several quantities, such as the pseudoscalar meson masses and decay constants.

It was found that such a constraint can only be satisfied, within a NNLO ChPT analysis, in a rather small region centered around $L_4^r = 0.2 \times 10^{-3}$ and $L_6^r = 0.5 \times 10^{-3}$. Also of interest in this context is the analysis based on QCD sum rules in Ref. [14], where L_6^r was constrained to be positive and in the region $0.2 \times 10^{-3} \leq L_6^r \leq 0.6 \times 10^{-3}$. Also, a significantly positive value of $L_4^r = 0.4 \times 10^{-3}$ was obtained in Ref. [14], although with unknown error. Some updated results for the L_i^r are given in Ref. [15], and a recent analysis of $\pi\pi$ and πK scattering is presented in Ref. [16], where the preferred values of L_4^r and L_6^r were found to be compatible with zero.

Further recent determinations of the L_i^r include the analyses of Refs. [17, 18] and [19] in terms of the Inverse Amplitude Method (IAM) of Ref. [20]. In Ref. [19], a simultaneous fit to the $\pi\pi$ and $K\overline{K}$ partial wave amplitudes for $I = 0, 1, 2$ was performed using the complete NLO ChPT amplitudes, which yielded a value of L_4^r equal to $(0.2 \pm 0.1) \times 10^{-3}$. The analysis of Ref. [18] considered all two-meson scattering amplitudes including the $\eta\eta$ channel within the chiral IAM framework, which enabled the simultaneous extraction of the LECs L_1^r through L_8^r, the reported values of L_4^r and L_6^r being $(-0.36 \pm 0.17) \times 10^{-3}$ and $(0.07 \pm 0.08) \times 10^{-3}$, respectively.

Finally, Lattice QCD also offers the possibility of studying the LECs of ChPT via Partially Quenched (PQ) Lattice QCD and PQChPT. For a theoretical background, see Refs. [21–24], and some recent Lattice QCD results for the L_i^r can be found in Refs. [25–27].

4.2 Results for L_5^r and L_8^r

The values of L_5^r and L_8^r are much less controversial, as most studies are in reasonable agreement concerning their numerical values. In the previous work of Ref. [5] their values were kept fixed and were taken to coincide with those determined by the K_{l4} analysis of Ref. [13]. These values were quoted as $L_5^r = (0.65 \pm 0.12) \times 10^{-3}$ and $L_8^r = (0.48 \pm 0.18) \times 10^{-3}$, respectively. However, it turned out in Ref. [9] to be advantageous to let these parameters adjust themselves to their optimal values. The values so obtained are $L_5^r = (0.45 \pm 0.09) \times 10^{-3}$ and $L_8^r = (0.33 \pm 0.17) \times 10^{-3}$. Although they come out slightly smaller than the values of Ref. [13], it is encouraging to note that an optimal fit to data does not require extreme values of L_5^r and L_8^r.

The more recent fit in Ref. [15] has reported an updated set of LECs which compare slightly more unfavorably with the present values, namely $L_5^r = (0.91 \pm 0.15) \times 10^{-3}$ and $L_8^r = (0.62 \pm 0.20) \times 10^{-3}$. However, it should be kept in mind that Ref. [15] was not able to determine L_4^r and L_6^r at the same time. Moreover, the values for L_5^r and L_8^r obtained in Refs. [13, 15] are in much better agreement with the present results, than the NLO standard values $L_5^r = (1.4 \pm 0.5) \times 10^{-3}$ and $L_8^r = (0.9 \pm 0.3) \times 10^{-3}$ given in Ref. [10].

5 Conclusions

A good description of the σ and $f_0(980)$ resonances in the J/ψ decays studied by BES was achieved in terms of the scalar form factors of the light pseudoscalar mesons. The results are consistent with significant OZI-violation in the scalar sector of QCD, with a clear signal for a σ contribution to the $\phi\pi^+\pi^-$ final state, and hints at a possibly large value of the OZI-suppressed LEC L_4^r of ChPT. Further studies using the IAM method may yield improved insight into the latter issue.

Acknowledgments

This research was supported by the U.S. Department of Energy under grant DE-FG-02-97ER41014, and is part of the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3 - CT - 2004 - 506078 and DFG (SBF/TR 16, "Subnuclear Structure of Matter"). TL is grateful to Ulf-G. Meißner for a fruitful collaboration, and to B. Kubis and J.R Peláez for stimulating discussions, and acknowledges a travel stipend from the Mikael Björnberg memorial foundation.

References

[1] K. L. Au, D. Morgan and M. R. Pennington, Phys. Rev. D **35**, 1633 (1987); D. Morgan and M. R. Pennington, Phys. Rev. D **48**, 1185 (1993); Phys. Rev. D **48**, 5422 (1993).

[2] J. D. Weinstein and N. Isgur, Phys. Rev. Lett. **48**, 659 (1982); Phys. Rev. D **27**, 588 (1983); Phys. Rev. D **41**, 2236 (1990).

[3] G. Janssen, B. C. Pearce, K. Holinde and J. Speth, Phys. Rev. D **52**, 2690 (1995) [arXiv:nucl-th/9411021].

[4] M. Ablikim *et al.* [BES Collaboration], Phys. Lett. B **607**, 243 (2005) [arXiv:hep-ex/0411001]; Phys. Lett. B **598**, 149 (2004) [arXiv:hep-ex/0406038]; Phys. Lett. B **603**, 138 (2004) [arXiv:hep-ex/0409007].

[5] Ulf-G. Meißner and J. A. Oller, Nucl. Phys. A **679**, 671 (2001) [arXiv:hep-ph/0005253].

[6] J. A. Oller and E. Oset, Nucl. Phys. A **620**, 438 (1997) [Erratum-ibid. A **652**, 407 (1999)] [arXiv:hep-ph/9702314].

[7] S. Weinberg, Physica (Amsterdam) A **96**, 327 (1979).

[8] J. Gasser and H. Leutwyler, Annals Phys. **158**, 142 (1984); Nucl. Phys. B **250**, 465 (1985); Nucl. Phys. B **250**, 517 (1985); Nucl. Phys. B **250**, 539 (1985).

[9] T.A. Lähde and Ulf-G. Meißner, Phys. Rev. D **74**, 034021 (2006) [arXiv:hep-ph/0606133].

[10] J. Bijnens, G. Ecker and J. Gasser, in: *The Second DAΦNE Physics Handbook*, edited by L. Maiani, G. Pancheri and N. Paver (INFN-LNF publications, Frascati (Italy), 1995), Vol. 1, pp. 125-144 [arXiv:hep-ph/9411232].

[11] J. Bijnens, G. Colangelo and P. Talavera, JHEP **9805**, 014 (1998) [arXiv:hep-ph/9805389].

[12] J. Bijnens and P. Dhonte, JHEP **0310**, 061 (2003) [arXiv:hep-ph/0307044].

[13] G. Amorós, J. Bijnens and P. Talavera, Nucl. Phys. B **585**, 293 (2000) [Erratum-ibid. B **598**, 665 (2001)] [arXiv:hep-ph/0003258]; Phys. Lett. B **480**, 71 (2000) [arXiv:hep-ph/9912398].

[14] B. Moussallam, Eur. Phys. J. C **14**, 111 (2000) [arXiv:hep-ph/9909292]; JHEP **0008**, 005 (2000) [arXiv:hep-ph/0005245].

[15] G. Amorós, J. Bijnens and P. Talavera, Nucl. Phys. B **602**, 87 (2001) [arXiv:hep-ph/0101127].

[16] J. Bijnens, P. Dhonte and P. Talavera, JHEP **0405**, 036 (2004) [arXiv:hep-ph/0404150]; JHEP **0401**, 050 (2004) [arXiv:hep-ph/0401039].

[17] J. A. Oller, E. Oset and J. R. Peláez, Phys. Rev. D **59**, 074001 (1999) [Erratum-ibid. D **60**, 099906 (1999)] [arXiv:hep-ph/9804209].

[18] A. Gómez Nicola and J. R. Peláez, Phys. Rev. D **65**, 054009 (2002) [arXiv:hep-ph/0109056].

[19] F. Guerrero and J. A. Oller, Nucl. Phys. B **537**, 459 (1999) [Erratum-ibid. B **602**, 641 (2001)] [arXiv:hep-ph/9805334].

[20] T. N. Truong, Phys. Rev. Lett. **61**, 2526 (1988); Phys. Rev. Lett. **67**, 2260 (1991); A. Dobado, M. J. Herrero and T. N. Truong, Phys. Lett. B **235**, 134 (1990); J. A. Oller, E. Oset and J. R. Peláez, Phys. Rev. Lett. **80**, 3452 (1998) [arXiv:hep-ph/9803242].

[21] A. Morel, J. Phys. (France) **48**, 1111 (1987);
C. W. Bernard and M. F. L. Golterman, Phys. Rev. D **46**, 853 (1992) [arXiv:hep-lat/9204007]; S. R. Sharpe, Phys. Rev. D **46**, 3146 (1992) [arXiv:hep-lat/9205020].

[22] C. W. Bernard and M. F. L. Golterman, Phys. Rev. D **49**, 486 (1994) [arXiv:hep-lat/9306005]; S. R. Sharpe and N. Shoresh, Phys. Rev. D **62**, 094503 (2000) [arXiv:hep-lat/0006017]; Phys. Rev. D **64**, 114510 (2001) [arXiv:hep-lat/0108003].

[23] J. Bijnens, N. Danielsson and T. A. Lähde, Phys. Rev. D **70**, 111503 (2004) [arXiv:hep-lat/0406017]; Phys. Rev. D **73**, 074509 (2006) [arXiv:hep-lat/0602003].

[24] S. Dürr, Eur. Phys. J. C **29**, 383 (2003) [arXiv:hep-lat/0208051]; D. R. Nelson, G. T. Fleming and G. W. Kilcup, Phys. Rev. Lett. **90**, 021601 (2003) [arXiv:hep-lat/0112029].

[25] J. Heitger, R. Sommer and H. Wittig [ALPHA Collaboration], Nucl. Phys. B **588**, 377 (2000) [arXiv:hep-lat/0006026].

[26] F. Farchioni, I. Montvay and E. Scholz [qq+q Collaboration], Eur. Phys. J. C **37**, 197 (2004) [arXiv:hep-lat/0403014].

[27] C. Aubin *et al.* [MILC Collaboration], Phys. Rev. D **70**, 114501 (2004) [arXiv:hep-lat/0407028].