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SCALAR MESONS COUPLINGS TO PIONS AND KAONS WITH KLOE*

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Investigations of the couplings of the scalar mesons $f_0(980)$ and $a_0(980)$ to pions and kaons are presented and discussed, from different analyses of an integrated luminosity of $\sim 400\,\mathrm{pb}^{-1}$ of KLOE data.

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1. Introduction

The main interest in the scalar mesons $a_0(980)$, $f_0(980)$ and $f_0(600)$ — known as $\sigma(600)$ [1] — lies in the possibility that they are not conventional $q\bar{q}$ mesons, but exotic structures such as $qq\bar{q}\bar{q}$ states [2] or $K\bar{K}$ molecules [3]. The KLOE experiment, working at the e^+e^- Frascati ϕ-factory DAΦNE [4], is perfectly suited for studying the properties of light scalar mesons through radiative ϕ decays:

f_0(980) produced in the $\phi \to f_0(980)\gamma \to \pi\pi\gamma$ decay chain, measured both in the $\pi^+\pi^-$ and in the $2\pi^0$ final states;

a_0(980) produced in the $\phi \to a_0(980)\gamma \to \eta\pi^0\gamma$ decay chain, analyzed with both $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to 2\gamma$ channels.

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In general, the branching fraction BR($\phi \to S\gamma$) [5], the couplings [6] to the $q\bar{q}$ pseudoscalar mesons and the $\phi S\gamma$ coupling [7], yield information upon the internal structure of the light scalar meson S. These quantities are extracted from the measurements discussed in the following.

1.1. DAΦNE and KLOE

DAΦNE is an e^+e^- collider operating at the center of mass energy $\sqrt{s} \sim 1.02\,\text{GeV}$, namely the ϕ meson mass. It has provided an integrated luminosity of about 2.5 fb^{-1} to the KLOE experiment up to year 2006. The KLOE detector consists of a large volume cylindrical drift chamber [8], DC (3.3 m length and 2 m radius), surrounded by a calorimeter [9] made of lead and scintillating fibers, EMC. The detector is inserted in a superconducting coil producing a solenoidal field $B = 0.52\,\text{T}$. Large angle tracks from the origin ($\theta > 45°$) are reconstructed with momentum resolution $\sigma_p/p = 0.4\%$. Photon energies and times are measured with resolutions of $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$ and $\sigma_t = 57\ \text{ps}/\sqrt{E(\text{GeV})} \oplus 100\ \text{ps}$.

1.2. Parametrizations of scalar meson exchange in ϕ decays

The Kaon Loop model (KL) is used because of the proximity of the $a_0(980)$, $f_0(980)$ masses to the $K\bar{K}$ threshold and because of the strong coupling of these mesons to kaons. This assumes [6] that the ϕ radiative decay proceeds through a virtual K^+K^- pair emitting the photon and subsequently annihilating into a scalar meson. This loop function damps the E_γ^3 behavior of the rate, typical of a radiative dipole transition, E_γ being the photon energy. The transition amplitude depends on the mass and the couplings to $\pi\pi$ and to KK of the scalar meson. The propagator includes the finite width corrections, relevant close to the $K\bar{K}$ threshold.

In the No Structure model (NS), the dynamics [7] of the scalar meson production is absorbed in the $g_{\phi S\gamma}$ coupling constant. The amplitude is described by a Breit–Wigner propagator with a mass dependent width, properly accounting for the analytical continuation under the $\pi\pi$ and KK thresholds, plus a complex polynomial describing a continuum background.

2. The $\phi \to f_0(980)\gamma \to \pi^+\pi^-\gamma$ analysis

This decay is searched for in $e^+e^- \to \pi^+\pi^-\gamma$ events [10], where competing processes with either an initial state (ISR) or a final state (FSR) radiation photon are more abundant. In particular, ISR is the dominant contribution for small photon polar angle, allowing the extraction of the $e^+e^- \to \pi^+\pi^-$ cross-section [11] at lower $\sqrt{s}$ values. The selection consists on the requirement of two tracks of opposite charge from the interaction region and a photon emitted at polar angles $45° < \theta < 135°$. This selection is

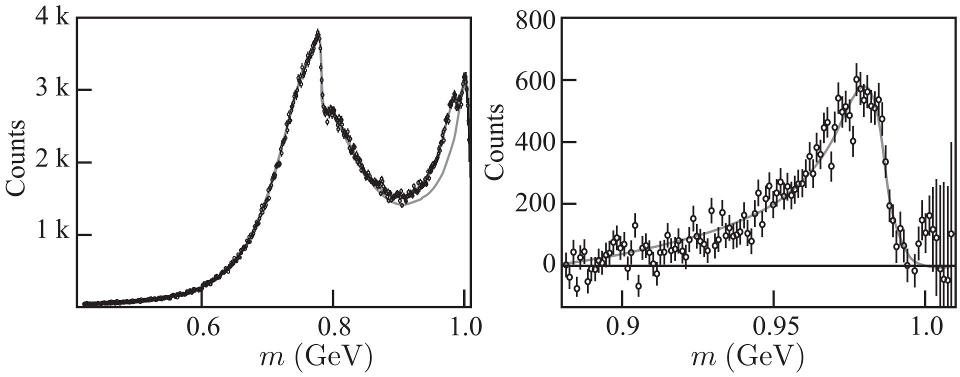

Fig. 1. Left: observed m spectrum compared with the fitting function with and without the $f_0(980)$. Right: the fitting function compared to the data spectrum in the $f_0(980)$ region, once ISR, FSR and $\rho\pi$ are subtracted.

applied to a total integrated luminosity $\mathcal{L} = 350$ pb^{-1} of data taken in 2001 and 2002, giving 6.7×10^5 events. Fig. 1 shows the $\pi^+\pi^-$ invariant mass, m, spectrum before and after the background subtraction. The m spectrum is fitted in the region $m \in [0.42, 1.01]$ GeV including the interference between the scalar meson exchange and the FSR amplitudes, $d\sigma_{\rm int}$, and the $\phi \to \rho^\pm\pi^\mp \to \pi^+\pi^-\gamma$ decay chain, $d\sigma_{\rho\pi}$:

$$\frac{d\sigma}{dm} = \frac{d\sigma_{\rm ISR}}{dm} + \frac{d\sigma_{\rm FSR}}{dm} + \frac{d\sigma_{\rho\pi}}{dm} + \frac{d\sigma_{S\gamma}}{dm} \pm \frac{d\sigma_{\rm int}}{dm}\,.$$

Both the KL and the NS models are satisfactory in describing the $f_0(980)$ structure, which appears to interfere destructively with FSR. The $f_0(980)$ results strongly coupled to kaons and to the ϕ, in both models. Fits show no sensitivity to the $\sigma(600)$ contribution, produced through the decay $\phi \to \sigma(600)\gamma \to \pi\pi\gamma$. Estimates of the parameters are shown in Table I and will be discussed together with results of the $\phi \to \pi^0\pi^0\gamma$ analysis.

3. The $\phi \to f_0(980)\gamma \to \pi^0\pi^0\gamma$ analysis

An analysis of this process with $\mathcal{L} = 16$ pb^{-1} of 2000 data is already published [12]. In the present contribution the analysis carried on $\mathcal{L} = 450$ pb^{-1} of data taken in 2001 and 2002 is described [13]. Main steps of the selection are the requirement of five photons from the interaction point and a kinematic fit imposing four-momentum conservation and π^0 masses, after a procedure of photon pairing to neutral pions. The efficiency of the selection on signal events is $\sim 50\%$, as evaluated from Monte Carlo, and the residual incoherent background contamination is $\sim 20\%$, mostly due to

$\phi \to \eta\gamma \to 3\pi^0\gamma$ events with lost or merged photons. Fig. 2 shows the Dalitz plot made up of the invariant masses of $\pi^0\pi^0$, $M^2_{\pi\pi}$, and of the two possible $\pi^0\gamma$ combinations, $M^2_{\pi\gamma}$. This is fitted with the coherent sum of the scalar term and the Vector Meson Dominance amplitudes, after folding with reconstruction efficiencies and with the probability for an event to migrate from a bin to another one, due to resolution or wrong photon pairing. The KL model used in this analysis consists of ten sets [14] of parameters, extracted from a combined fit of the 2000 KLOE measurement [12] and of the available $\pi\pi$, KK scattering data. The fit without the $\sigma(600)$ contribution does not yield an acceptable χ^2 value.

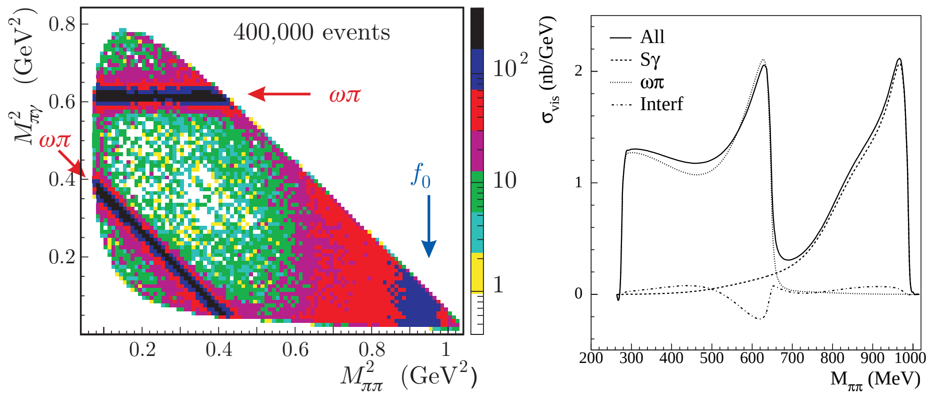

Fig. 2. Left: Dalitz plot in the $\pi^0\pi^0\gamma$ analysis after background subtraction. Right: $M_{\pi\pi}$ spectrum obtained from the KL fit result.

4. Comparison of results

For $\pi^+\pi^-\gamma$ and $\pi^0\pi^0\gamma$, the $f_0(980)$ parameters, extracted both for KL and for NS, are shown in Table I. The theoretical error for the neutral channel is related to theoretical model variants of the KL description. Results for the two models are summarized:

[KL] in both channels the $f_0(980)$ is strongly coupled to kaons;

[KL] the $\sigma(600)$ is required in the $\pi^0\pi^0\gamma$, the $\pi^+\pi^-\gamma$ data have not enough sensitivity;

[NS] both $\pi^+\pi^-\gamma$ and $\pi^0\pi^0\gamma$ are well described without the $\sigma(600)$;

[NS] the $\pi^0\pi^0\gamma$ fit exhibits a coupling to kaons weaker than $\pi^+\pi^-\gamma$.

Recent updates [14] for the KL model, related to the f_0–σ mixing and the $\sigma\pi\pi$ coupling, let us reduce the spread of parameters in the $\pi^0\pi^0\gamma$ analysis due to model dependence, preliminary values are shown in Table I (last column).

TABLE I

Comparison of the $f_0(980)$ parameters for both KL and NS models. The updated measurement of the $\pi^0\pi^0\gamma$ channel is also shown in the last column.

Model	Parameter	$\pi^+\pi^-\gamma$	$\pi^0\pi^0\gamma$	$\pi^0\pi^0\gamma$ update
KL	m_{f_0} (MeV)	$980 \div 987$	$976.8 \pm 0.3_{\rm fit}\,{}^{+0.9}_{-0.6}{}_{\rm sys} + 10.1_{\rm th}$	$984.7 \pm 1.9_{\rm th}$
	$g_{f_0K^+K^-}$ (GeV)	$5.0 \div 6.3$	$3.76 \pm 0.04_{\rm fit}\,{}^{+0.15}_{-0.08}{}_{\rm sys}\,{}^{+1.16}_{-0.48}{}_{\rm th}$	$3.97 \pm 0.43_{\rm th}$
	$g_{f_0\pi^+\pi^-}$ (GeV)	$3.0 \div 4.2$	$-1.43 \pm 0.01_{\rm fit}\,{}^{+0.01}_{-0.06}{}_{\rm sys}\,{}^{+0.03}_{-0.60}{}_{\rm th}$	$-1.82 \pm 0.19_{\rm th}$
	$\frac{g^2_{f_0K^+K^-}}{g^2_{f_0\pi^+\pi^-}}$	$2.2 \div 2.8$	$6.9 \pm 0.1_{\rm fit}\,{}^{+0.2}_{-0.1}{}_{\rm sys}\,{}^{+0.3}_{-3.9}{}_{\rm th}$	
NS	m_{f_0} (MeV)	$973 \div 981$	$984.7 \pm 0.4_{\rm fit}\,{}^{+2.4}_{-3.7}{}_{\rm sys}$	
	$g_{f_0K^+K^-}$ (GeV)	$1.6 \div 2.3$	$0.40 \pm 0.04_{\rm fit}\,{}^{+0.62}_{-0.29}{}_{\rm sys}$	
	$g_{f_0\pi^+\pi^-}$ (GeV)	$0.9 \div 1.1$	$1.31 \pm 0.01_{\rm fit}\,{}^{+0.09}_{-0.03}{}_{\rm sys}$	
	$\frac{g^2_{f_0K^+K^-}}{g^2_{f_0\pi^+\pi^-}}$	$2.6 \div 4.4$	$0.09 \pm 0.02_{\rm fit}\,{}^{+0.44}_{-0.08}{}_{\rm sys}$	
	$g_{\phi f_0\gamma}$ (GeV^{-1})	$1.2 \div 2.0$	$2.61 \pm 0.02_{\rm fit}\,{}^{+0.31}_{-0.08}{}_{\rm sys}$	

5. The $\phi \to a_0(980)\gamma \to \eta\pi^0\gamma$ analyses: $\eta \to 2\gamma$ and $\eta \to \pi^+\pi^-\pi^0$

Results from these decays are already published [15] using $\mathcal{L} = 16$ pb^{-1} of 2000 data.

In this contribution, results are obtained from $\mathcal{L} = 414$ pb^{-1} of data taken in 2001 and 2002. Both analyses share the requirement of five photons from the interaction point. The selection of also two tracks of opposite charge is less efficient, for $\eta \to \pi^+\pi^-\pi^0$ events, but leads to a selected sample with smaller background than in $\eta \to 2\gamma$ events.

The absence of a major source of interfering background allows to obtain the branching fraction directly from event counting. Table II shows the selection features and the branching fraction values for the two analyses.

TABLE II

Features of the two η decay channels.

	Signal efficiency	Background fraction	BR($\phi \to \eta\pi^0\gamma$) $\times 10^5$
$\eta \to 2\gamma$	40%	55%	$6.98(10)_{\rm stat}(23)_{\rm sys}$
$\eta \to \pi^+\pi^-\pi^0$	20%	15%	$7.12(13)_{\rm stat}(24)_{\rm sys}$

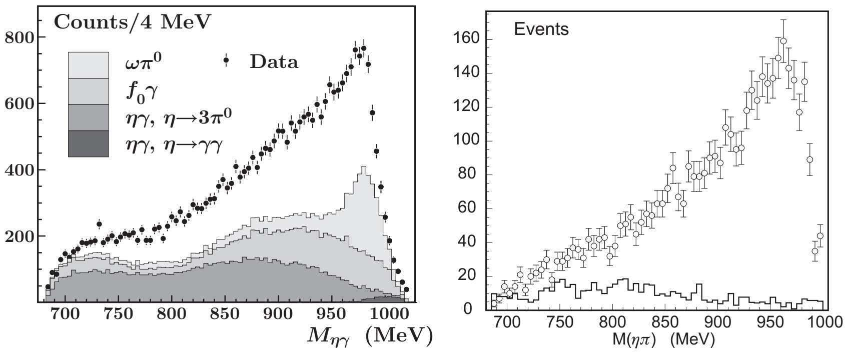

Fig. 3. Left: $M_{\eta\pi}$ spectrum from the $\eta\to2\gamma$ analysis. Right: $M_{\eta\pi}$ spectrum from the $\eta\to\pi^+\pi^-\pi^0$ analysis, where empty points are data and solid histogram is the background contamination, estimated from Monte Carlo.

Fig. 3 shows data spectra in the $\eta\pi$ invariant mass, $M_{\eta\pi}$, for the two η final states, with background shapes from Monte Carlo. The $a_0(980)$ parameters are extracted from a simultaneous fit of both $M_{\eta\pi}$ spectra and shown in Table III.

TABLE III

Best estimates of the parameters from the $\eta\pi^0\gamma$ combined fit.

Parameter	Kaon loop	No structure
m_{a_0} (MeV)	982.5 ± 3.0	982.5 (fixed)
$g_{a_0K^+K^-}$ (GeV)	2.15 ± 0.18	2.01 ± 0.29
$g_{a_0\eta\pi}$ (GeV)	2.82 ± 0.13	2.46 ± 0.14
$g_{\phi a_0\gamma}$ (GeV^{-1})	–	1.83 ± 0.09
confidence level	10.4%	30.9%

Table IV shows $a_0(980)$ and $f_0(980)$ couplings obtained from KLOE measurements with predictions from different hypotheses on the quark structure of these scalar mesons. The hypothesis of $q\bar{q}$, with $f_0(980)$ being a $s\bar{s}$ state, is as good as the $qq\bar{q}\bar{q}$ solution. However, the latter case provides a natural explanation for the $a_0(980)$–$f_0(980)$ mass degeneracy, otherwise left unsolved if $f_0(980)=s\bar{s}$ and $a_0(980)$ is the SU(2) isotriplet.

We made preliminary estimates of the $a_0(980)$ couplings assuming effective six-fermion interactions induced by instantons [16]. Using $f_0(980)$ couplings, pseudoscalar masses and mixing angles as input parameters, we found that the $g_{a_0K^+K^-}$ coupling increases from 2.01–2.15 to 2.1–2.5 (if the $qq\bar{q}\bar{q}$ structure is assumed) or 2.4–2.9 (if the $q\bar{q}$ structure is assumed).

TABLE IV

Predictions for $a_0(980)$ and $f_0(980)$ couplings according to different quark structures — where the $f_0(980)$ can be either a strange or a non-strange ($n = u, d$) quarkonium — compared with determinations from KLOE data.

	KLOE	$qq\bar{q}\bar{q}$	$q\bar{q}$ ($f_0(980) = s\bar{s}$)	$q\bar{q}$ ($f_0(980) = n\bar{n}$)
$g^2_{a_0K^+K^-}/g^2_{a_0\eta\pi}$	0.6–0.7	1.2–1.7	0.4	0.4
$g^2_{f_0K^+K^-}/g^2_{f_0\pi^+\pi^-}$	4.6–4.8	$\gg 1$	$\gg 1$	0.25
$g^2_{f_0K^+K^-}/g^2_{a_0K^+K^-}$	4–5	1	2	1

6. Conclusions

The 2001–2002 KLOE data set allowed for an extensive study of $a_0(980)$ and $f_0(980)$ couplings and resulted in:

- first clear evidence of $f_0(980) \to \pi^+\pi^-$ both in the mass spectrum and in the forward–backward asymmetry;
- accurate Dalitz plot analysis in the $\pi^0\pi^0\gamma$ final state yields the evidence of the $\sigma(600)$ meson;
- good agreement between $\eta\pi^0\gamma$ analyses with different systematics, the combined fit points to a sizeable strange quark content in the $a_0(980)$.

More detailed studies on scalar meson couplings are in progress, coming in particular from:

- the upper limit for the $\phi \to [f_0(980) + a_0(980)]\gamma \to K^0\bar{K^0}\gamma$ decay [17], for which the final result from the search for $\phi \to K_\mathrm{S}K_\mathrm{S}\gamma \to 2\pi^+2\pi^-\gamma$ events on the whole KLOE data sample is

$$\mathrm{BR}(\phi \to [f_0(980) + a_0(980)]\gamma \to K\bar{K^0}\gamma) < 1.7 \times 10^{-8} \text{ at } 90\% \text{ C.L.}$$

- a combined fit of both the neutral and the charged $\pi\pi\gamma$ final state;
- the search for the $\gamma\gamma \to \sigma(600) \to \pi^0\pi^0$ production [18].

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