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Low energy QCD and ChPT studies with KLOE

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Summary. — The KLOE experiment is situated at the ϕ factory DAΦNE in Frascati. ϕ radiative decays have been used to investigate the properties of the light scalar mesons $f_0(980)/a_0(980)$, whose structure is still controversial. Off-peak data allow to investigate $\gamma\gamma$ interaction with a consequent scalar/pseudoscalar meson production. From the large sample of the η and η' produced in $\phi \to \eta\gamma$ decay we have studied several η and η' decays relevant to η/η' mixing, η' gluonium content, CP violation searches and tests of ChPT. For the hadronic cross section, the pion form factor in the $M_{\pi\pi}$ invariant mass range (0.592–0.975) GeV has been determined and used in the evaluation of the hadronic contribution to the muon anomaly. The result confirms the 3-σ discrepancy between SM expectation and the measurement of the muon $(g-2)$ by the E821 experiment at the BNL.

PACS `13.25.Jx` – Decays of other mesons.
PACS `13.66.Bc` – Hadron production in e^-e^+ interactions.
PACS `14.40.Be` – Light mesons ($S = C = B = 0$).

1. – The nature of the scalar mesons

It is still controversial whether the light scalars are $q\bar{q}$ mesons, $qq\bar{q}\bar{q}$ states, or $K\bar{K}$ molecules. Here we describe the measurement of the couplings of the a_0 to $\eta\pi^0$ done at the KLOE detector [1] that together with our previous measurements [2,3] can be used to identify the nature of the scalars. We searched for $a_0(980)$ contribution in $e^+e^- \to \eta\pi^0\gamma$ with $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ [4]. A kinematic fit has been performed imposing the four-momentum conservation, the photon velocity and the invariant masses of both η and π^0. A combined fit (for the two η decay modes) to the $\eta\pi^0$ invariant mass distribution has been done with the "no-structure" (NS) [5] and the "kaon loop" (KL) [6] models after background subtraction. The results of the fit are shown in fig. 1 and table I.

It is interesting to note that both models give a large coupling of the $a_0(980)$ with the ϕ meson, indicating a sizable strange quark content in the $a_0(980)$. The branching ratios

$$BR(\phi \to \eta\pi^0\gamma) = (7.01 \pm 0.10_{\rm stat} \pm 0.20_{\rm syst}) \times 10^{-5}, \text{ with } \eta \to \gamma\gamma,$$
$$BR(\phi \to \eta\pi^0\gamma) = (7.12 \pm 0.13_{\rm stat} \pm 0.22_{\rm syst}) \times 10^{-5}, \text{ with } \eta \to \pi^+\pi^-\pi^0$$

are obtained normalizing to $\phi \to \eta\gamma$ decays. Results from both models give $R_\eta = BR(\eta \to \gamma\gamma)/BR(\eta \to \pi^+\pi^-\pi^0)$ compatible with PDG'08 value, confirming the consistency between the two samples.

Predictions on scalar mesons can be tested also from $\phi \to K^0\bar{K}^0\gamma$ decays. This decay is expected to proceed mainly through $\phi \to [a_0(980) + f_0(980)]\gamma \to K^0\bar{K}^0\gamma$. The $K^0\bar{K}^0$ pair is produced with positive charge conjugation and a limited phase space due to the small mass difference between the ϕ and the production threshold of two neutral kaons. The signature of this decay is provided by the presence of either 2 K_S or 2 K_L and a low energy photon. We select only the K_SK_S component, looking for double $K_S \to \pi^+\pi^-$ decay vertex, because of the clean topology. After the selection cut we found 5 candidate events in data whereas 3 events are expected from Monte Carlo background samples.

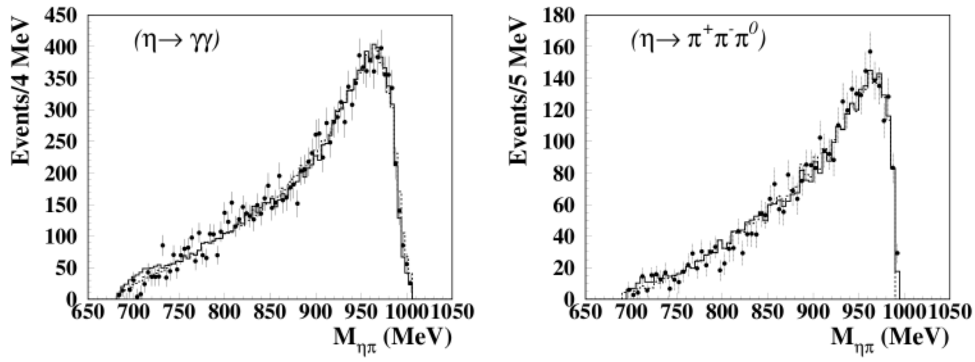

Fig. 1. – Fit results: points are data after background subtraction; histograms represent fit results (KL solid, NS dashed—differences between KL and NS models not appreciable on this scale).

This leads to: $BR(\phi \to K^0\bar{K}^0\gamma) < 1.9 \times 10^{-8}$ at the 90% CL [7]. Theory predictions for the BR spread over several orders of magnitude; several of them are ruled out by our result. Using the $a_0\, f_0$ couplings shown in table I, we may also obtain estimates for $BR(\phi \to K^0\bar{K}^0\gamma)$. These lie in the range 4×10^{-9}–6.8×10^{-8}, consistent with the above quoted upper limit, which excludes only the higher values.

2. – $\gamma\gamma$ physics at KLOE

The $\gamma\gamma$ coupling to scalar and pseudoscalar mesons brings information on meson's quark structure and can be measured directly in e^+e^- colliders via the reaction $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$. In fig. 2 left, the $\gamma\gamma$ flux expected at DAΦNE is shown. The question concerning $\sigma/f_0(600)$ meson has been debated for a long time. Our preliminary result, based on $240\,\mathrm{pb}^{-1}$ collected at $\sqrt{s} = 1\,\mathrm{GeV}$, shows a clear enhancement over estimated backgrounds at low $M_{4\gamma}$; see fig. 2, right [8]. We continue the analysis to better understand this effect and perhaps link it to the production of the σ.

TABLE I. – *Results from fit for $\phi \to a_0\gamma \to \eta\pi^0\gamma$ with KL and NS model.*

Fit parameter	KL	NS	PDG'08
M_{a_0} (MeV)	$982.5 \pm 1.6 \pm 1.1$	982.5(fixed)	
$g_{a_0K^+K^-}$ (GeV)	$2.15 \pm 0.06 \pm 0.06$	$2.01 \pm 0.07 \pm 0.28$	
$g_{a_0\eta\pi}$ (GeV)	$2.82 \pm 0.03 \pm 0.04$	$2.46 \pm 0.08 \pm 0.11$	
$g_{\phi a_0\gamma}$ (GeV^{-1})	$1.58 \pm 0.10 \pm 0.16$	$1.83 \pm 0.03 \pm 0.08$	
$BR(VDM) \times 10^6$	$0.92 \pm 0.40 \pm 0.15$	0	
R_η	$1.70 \pm 0.04 \pm 0.03$	$1.70 \pm 0.03 \pm 0.01$	1.729 ± 0.028
$(g_{a_0K^+K^-}/g_{a_0\eta\pi^0})^2$	$0.58 \pm 0.03 \pm 0.03$	$0.67 \pm 0.06 \pm 0.13$	
$P(\chi^2)$	10.4%	30.9%	
Γ_{a_0} (MeV)	105	80	50-100

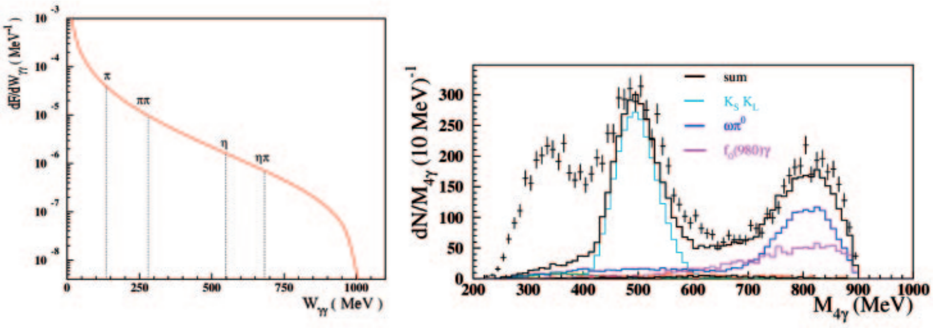

Fig. 2. – Left: $\gamma\gamma$ flux as a function of the $\gamma\gamma$ center-of-mass energy. Right: clear evidence of $e^+e^- \to e^+e^-\pi^0\pi^0$ events at low $M_{4\gamma}$ invariant mass.

We have investigated $\gamma\gamma$ processes also looking at the $e^+e^-\pi^+\pi^-\pi^0$ final state. The preliminary analysis shows evidence for a signal of ~ 600 events from process $\gamma\gamma \to \eta$.

3. – $\eta - \eta'$ mixing and η' gluonium content

The question of a gluonium component in the η' meson has been extensively investigated in the past but it is still without a definitive conclusion. The KLOE paper on $\eta-\eta'$ mixing [9], reporting a 3σ evidence of gluonium content in the η' meson, has triggered a large amount of discussion among theoreticians.

Therefore a new and more detailed study on this topic has been performed [10]. In the constituent quark model one can extract gluonium content together with η-η' mixing angle as described in [11]:

$$|\eta'\rangle = \cos\Psi_G \sin\Psi_P |q\bar{q}\rangle + \cos\Psi_G \cos\Psi_P |s\bar{s}\rangle + \sin\Psi_G |G\rangle,$$
$$|\eta\rangle = \cos\Psi_P |q\bar{q}\rangle - \sin\Psi_P |s\bar{s}\rangle,$$

where Ψ_P is the $\eta - \eta'$ mixing angle, $\mathrm{Z}_G^2 = \sin^2\Psi_G$ is the gluonium content and $|q\bar{q}\rangle = (|u\bar{u}\rangle + |d\bar{d} >)/\sqrt{2}$ and $|G\rangle = |\mathrm{gluonium}\rangle$.

In comparison to the previous fit five more relations were added to constrain the fit in the new approach, thus allowing an independent determination of more free parameters. In addition the BR values from PDG 2008 [12] and the new KLOE results on the ω meson branching ratios [13] were used. The fit has been performed both imposing the gluonium content to be zero or allowing it free. The results are shown in table II: gluonium content of the η' is confirmed at 3σ level.

4. – η decays into four charged particles

There are several theoretical reasons to study the $\eta \to \pi^+\pi^-e^+e^-$ decay. First, by using the virtual photon it is possible to probe the structure of the η meson in the time-like region of four-momentum transfer square, which is equal to the invariant mass squared of the lepton pair [14]. One may also compare the predictions of the branching ratio value based on Vector Meson Dominance model and the Chiral Perturbation Theory. Moreover, it would be possible to study *CP* violation beyond the prediction of the Standard Model [15]. *CP* violation can be introduced by a flavor-conserving, *CP* violating,

TABLE II. – *Output of the fit fixing or not the gluonium content to be zero.*

	Gluonium content forced to be zero	Gluonium content free
Z_G^2	fixed 0	0.115 ± 0.036
ϕ_P	$(41.4 \pm 0.5)^\circ$	$(40.4 \pm 0.6)^\circ$
Z_q	0.93 ± 0.02	0.936 ± 0.025
Z_s	0.82 ± 0.05	0.83 ± 0.05
ϕ_V	$(3.34 \pm 0.09)^\circ$	$(3.32 \pm 0.09)^\circ$
$m_s/\bar{m}$	1.24 ± 0.07	1.24 ± 0.07
χ^2/dof	14.7/4	4.6/3
P(χ^2)	0.005	0.20

four-quark operators involving two strange quarks together with combinations of other light quarks. It can be experimentally tested by measuring the angular asymmetry, A_ϕ, between pions and electrons decay planes in the η rest frame.

KLOE has studied the $\eta \to \pi^+\pi^-e^+e^-$ decay using $1.7\,\mathrm{fb}^{-1}$ of data [16]. After background rejection a fit of the sidebands of the four-track invariant distribution has been performed to obtain the background scale factors. Most of the background is due to ϕ decays, but there is still a non-negligible contribution from continuum events. Signal events have been counted in the η mass region, giving $BR(\eta \to \pi^+\pi^-e^+e^-) = (26.8 \pm 0.9_{\rm stat} \pm 0.7_{\rm syst}) \times 10^{-5}$ and $A_\phi = (-0.6 \pm 2.5_{\rm stat} \pm 1.8_{\rm syst}) \times 10^{-2}$, see fig. 3, left.

More recently KLOE has started studying the $\eta \to e^+e^-e^+e^-$ decay. This decay, together with the $\eta \to \mu^+\mu^-e^+e^-$, is interesting for the η meson form factor because there are only leptons in the final state. Most of the background comes from continuum events and a small contribution is due to ϕ decays. The latter is subtracted from data

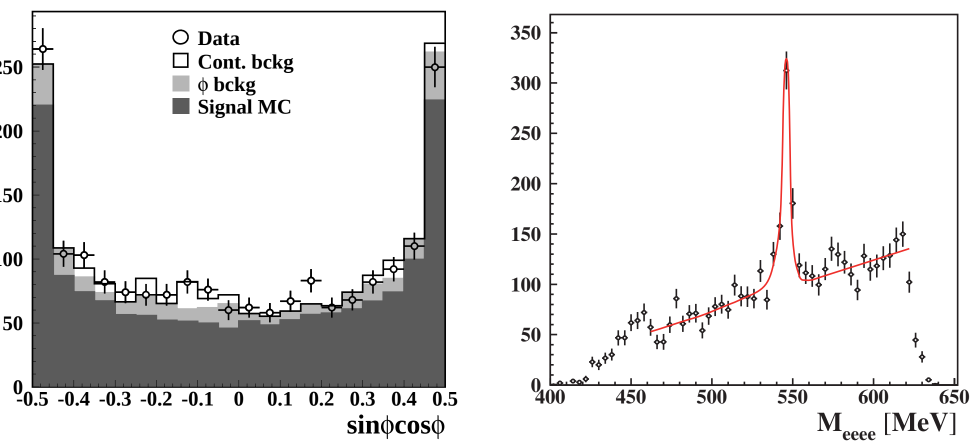

Fig. 3. – Left: $\sin(\phi)\cos(\phi)$ distribution for angle between $\pi^+\pi^-$ and e^+e^- planes. Dots: experimental data, black histogram is the combined MC distribution, *i.e.* signal (dark gray), ϕ background (light gray) and continuum background (white). Right: fit of the four-electron invariant mass, M_{eeee} in $\eta \to e^+e^-e^+e^-$ analysis.

TABLE III. – *Comparison of the existing results for the ratio* $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$.

PDG08 average		0.203 ± 0.008
LOPEZ (CLEO) 2007	859 events	$0.175 \pm 0.007 \pm 0.006$
THALER 1973 [22]	18k events	0.209 ± 0.004
GORMLEY 1970 [21]	7250 events	0.201 ± 0.006
KLOE Preliminary	611k events	$0.201 \pm 0.0006_{\mathrm{stat}\oplus\mathrm{syst}}$

using the MC spectrum. The number of events is obtained fitting the data distribution of the 4 electron invariant mass, M_{eeee}, with signal and background shapes (fig. 3, right). From the fit we obtain 413 ± 31 events. This constitutes the first observation of this decay.

5. – $\eta \to \pi^+\pi^-\gamma$

In the $\eta \to \pi^+\pi^-\gamma$ decay, a significant contribution from chiral box anomaly is expected [17]. The box anomaly accounts for the direct (non-resonant) coupling of three pseudoscalar mesons with the photon. The invariant mass of the pions ($m_{\pi\pi}$) is a good observable to disentangle this contribution from other possible resonant ones, *e.g.*, from the ρ-meson. However, the momentum dependence cannot be determined from chiral theory only because the kinematic range of the $\eta \to \pi^+\pi^-\gamma$ decay extends above the chiral limit, where the Weiss-Zumino-Witten term of the ChPT Lagrangian properly describes the direct coupling. Several theoretical approaches have been developed to treat the contributions of the anomalies to the decay [18-20].

The $\eta \to \pi^+\pi^-\gamma$ decay has been measured in 1970s [21, 22]. The analysis of the two data sets shows some contradiction. Theoretical papers trying to combine the two measurements have found discrepancies in data treatment and problems with obtaining consistent results [23]. Recently, the CLEO Collaboration published the measurement of the ratio of branching ratios, $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.175 \pm 0.007 \pm 0.006$, which differs by more than 3-σ from old results. We aim at the solution of the inconsistency of experimental data with precision measurements of the branching ratio and $m_{\pi\pi}$ invariant mass distribution.

The preliminary KLOE measurement of the ratio of branching ratios $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.201 \pm 0.0006_{\mathrm{stat}\oplus\mathrm{syst}}$ is in agreement with the old results from refs. [21, 22] while significantly differs from the recent CLEO results, as compared in table III.

6. – **Measurement of the** $\eta \to 3\pi^0$ **slope parameter** α

Using a clean sample of $\eta \to \pi^0\pi^0\pi^0$ decays we have measured the Dalitz Plot slope parameter obtaining $\alpha = 0.0301 \pm 0.0035(\mathrm{stat})^{+0.0022}_{-0.0035}(\mathrm{syst})$ [24] in agreement with other recent results of comparable precision. The above value is also consistent with the one obtained from the KLOE study of the $\eta \to \pi^+\pi^-\pi^0$ decay [25] using the theoretical correlations between the two decay modes. Our α measurement confirms the inadequacy of simple NLO ChPT computations and the need to take into account higher-order corrections.

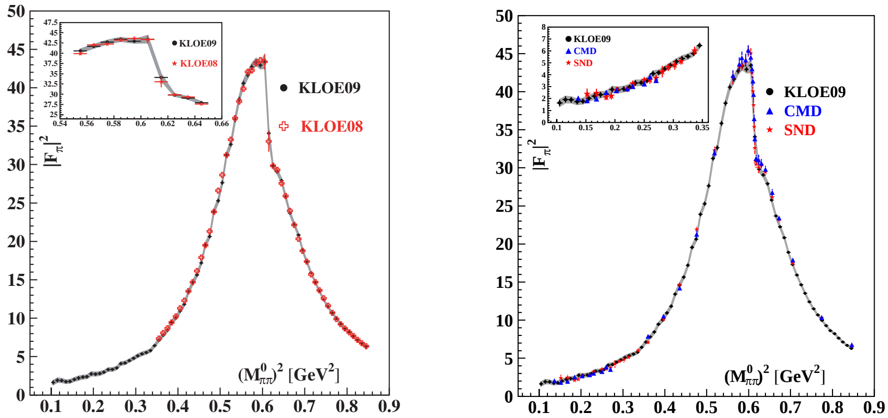

Fig. 4. – Pion form factor $|F_\pi|^2$ obtained in the present analysis (KLOE09) compared with the previous KLOE result (left) and results from the CMD and SND experiments (right). KLOE09 data points have statistical error attached, the superimposed band gives the statistical and systematic uncertainty (added in quadrature). Errors on KLOE08, CMD2 and SND points contain the combined statistical and systematic uncertainty.

7. – The measurement of the hadronic cross section

The published KLOE measurements [26, 27] of the hadronic cross section for the process $e^+e^- \to \pi^+\pi^-$ were based on initial-state-radiation (ISR) events with photon emitted at small angle, resulting in kinematical suppression of events with $M^2_{\pi\pi} < 0.35\,\text{GeV}^2$. To access the two-pion threshold, a new analysis is performed requiring events with photon at large polar angles ($50° < \theta_\gamma < 130°$), in the same angular region of the pions. The drawback of such acceptance cuts is a reduction in statistics of about a factor of five, as well as an increase of events with final-state-radiation (FSR) and from ϕ radiative decays. The uncertainty on the model dependence of the ϕ radiative decays to the scalars $f_0(980)$ and $f_0(600)$ together with $\phi \to \rho\pi \to (\pi\gamma)\pi$ has a strong impact on the measurement [28]. For this reason, the present analysis uses the data taken by the KLOE experiment in 2006 at a value of $\sqrt{s} = 1\,\text{GeV}$, about $5 \times \Gamma(\phi)$ outside the narrow peak of the ϕ resonance. This reduces the effect due to contributions from $f_0\gamma$ and $\varrho\pi$ decays of the ϕ-meson to a relative amount of 1%. The radiative differential cross section is obtained subtracting the residual background events and dividing by the selection efficiencies and the integrated luminosity.

The total cross section $\sigma_{\pi\pi}$ is obtained using [29]: $s \cdot \frac{\mathrm{d}\sigma_{\pi\pi\gamma_{\mathrm{ISR}}}}{\mathrm{d}M^2_{\pi\pi}} = \sigma_{\pi\pi}(M^2_{\pi\pi})\, H(M^2_{\pi\pi}, s)$, where H is the radiator function describing the photon emission in the initial state. This formula neglects FSR terms, which are however properly taken into account in the analysis. From $\sigma_{\pi\pi}$, the squared modulus of the pion form factor $|F_\pi|^2$ can be derived. Figure 4 shows $|F_\pi|^2$ as a function of $(M_{\pi\pi})^2$ for the new KLOE measurement (KLOE09) compared with the previous KLOE publication (KLOE08) and with results from CMD-2 [30, 31] and SND [32] experiments at the Novosibirsk collider. On the ρ-meson peak and above, the new analysis confirms KLOE08 data being lower than the Novosibirsk results, while below the ρ-peak the three experiments are in agreement.

The cross section, corrected for α_{em} running and inclusive of FSR, is used to determine the dipion contribution to the muon anomalous magnetic moment, $\Delta a_\mu^{\pi\pi}$:

$$\Delta a_\mu^{\pi\pi}((0.1\text{–}0.85)\,\text{GeV}^2) = (478.5 \pm 2.0_{\text{stat}} \pm 4.8_{\text{exp}} \pm 2.9_{\text{theo}}) \cdot 10^{-10}.$$

The evaluation of $\Delta a_\mu^{\pi\pi}$ in the range between 0.35 and 0.85 GeV^2 allows the comparison of the result obtained in this new analysis:
$\Delta a_\mu^{\pi\pi} = 376.6 \pm 0.9_{\text{stat}} \pm 2.4_{\text{exp}} \pm 2.1_{\text{theo}}$ with the previously published result by KLOE [27]:
$\Delta a_\mu^{\pi\pi} = 379.6 \pm 0.4_{\text{stat}} \pm 2.4_{\text{exp}} \pm 2.2_{\text{theo}}$, showing that these two independent analyses provide fully consistent contributions to the muon anomaly.

8. – KLOE-2

Recently the interaction region of DAΦNE accelerator has been modified allowing for a new beam-crossing scheme operating at larger crossing angle and reduced beam size in the interaction region. These modifications will allow for an increase of the luminosity by a factor 3-4. The KLOE-2 Collaboration is preparing the KLOE detector for the new runs at upgraded DAΦNE machine: e^+e^- taggers for $\gamma\gamma$ physics will be inserted first, then another upgrade with new inner tracker and small angle calorimeters will take place. After the upgrades KLOE-2 can cover the physics program presented in [33] improving on systematics, thanks to the better detector, and on statistics thanks to an integrated luminosity $\geq 20\,\text{fb}^{-1}$.

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