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η, η' physics at KLOE

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New KLOE results on η, η' meson physics are presented.

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1. Introduction

The KLOE experiment [1] is situated at the Frascati factory DAΦNE which is an e^+e^- collider running mostly at $\sqrt{s}$ = 1019.5 MeV, corresponding to ϕ meson mass. The pseudoscalar mesons η, η' are accessible through electromagnetic decays of the produced ϕ mesons $\phi \rightarrow \eta\gamma$ and $\phi \rightarrow \eta'\gamma$ with branching ratios $1.30\cdot10^{-2}$ and $6.25\cdot10^{-5}$ respectively. KLOE has collected one of the largest sample of η mesons in the world, about 10^8, and approximately $0.5\cdot10^6$ of η' mesons.

2. $\eta - \eta'$ mixing and η' gluonium content [2]

The η' meson, being almost a pure SU(3)$_{flavour}$ singlet, is considered a good candidate to host a gluon condensate. 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 [3], 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. In the constituent quark model one can extract gluonium content together with η-η' mixing angle as described in [4]:

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

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

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 [5] and the new KLOE results on the ω meson [6] 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 1: gluonium content of the η' is confirmed at 3σ level. The new analysis and the results have been recently published in [2].

	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

Table 1: Output of the fit fixing or not the gluonium content to be zero.

3. η decays into four charged particles [7]

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 [8]. 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 [9]. CP violation can be introduced by a flavor-conserving, CP violating, 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 fb^{-1} of data. The main backgrounds after event selection are $\phi \to \pi^+\pi^-\pi^0$, other $\phi \to \eta\gamma$ decays and $\phi \to K^+K^-$. Backgrounds are reduced by setting a constraint on the sum of momenta of the two particles with highest momentum and opposite charge. After these cuts the background over signal ratio (B/S) is reduced by two order of magnitude and is approximately 1:1. For the selected events it is possible to reconstruct the invariant mass of the four tracks according to the mass hypothesis previously defined. To improve the resolution on the track momenta and on the energy of the neutral cluster a kinematic fit is performed imposing the four-momentum conservation and the cluster timing.

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 $BR(\eta \to \pi^+\pi^-e^+e^-) = (26.8 \pm 0.9_{Stat.} \pm 0.7_{Syst.}) \times 10^{-5}$ and $A_\phi = (-0.6 \pm 2.5_{Stat.} \pm 1.8_{Syst.}) \times 10^{-2}$ [7], see Fig. 1.

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. The analysis strategy is similar to the $\pi\pi ee$ one. Most of the background comes from continuum events and a small contribution is due to ϕ decays. The latter is subtracted from data 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. 2). From the fit we obtain 413pm31 events. This constitutes the first observation of this decay.

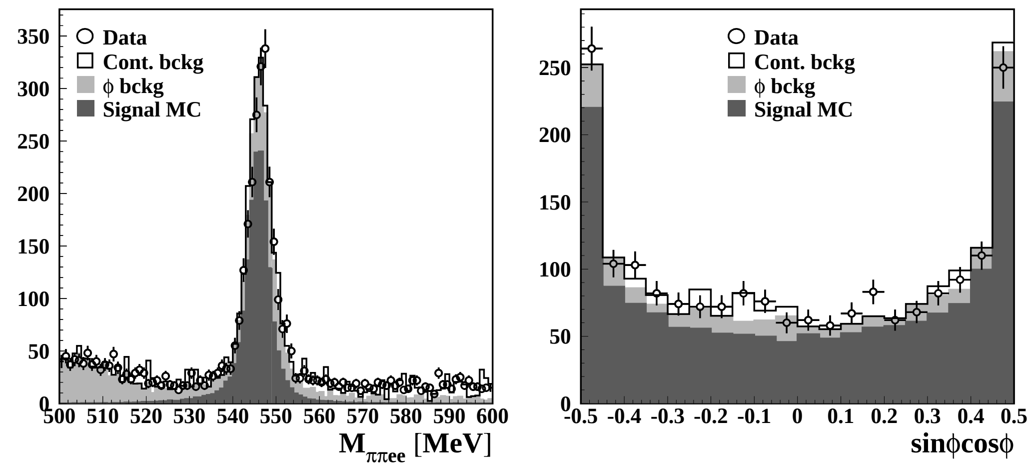

Figure 1: : $\eta \to \pi^+\pi^-e^+e^-$ analysis; $\pi^+\pi^-e^+e^-$ invariant mass and angular asymmetry distributions. Dots: data. The black histogram is the expected distribution, i.e. signal MC (dark gray), ϕ background (light Gray) and continuum background (white).

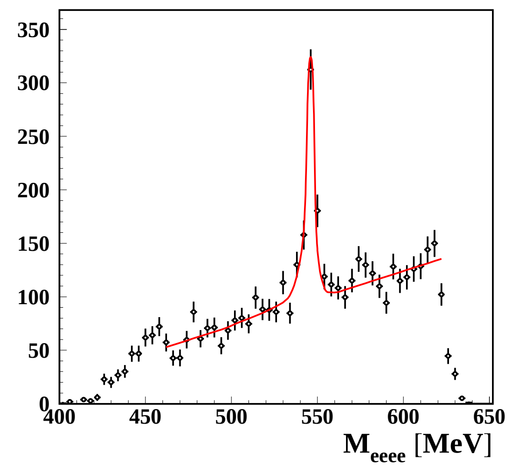

Figure 2: $\eta \to e^+e^-e^+e^-$ analysis; fit of the four electron invariant mass, M_{eeee}.

4. $\eta \to \pi^+\pi^-\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ decays, ratio $\Gamma_{\eta \to \pi^+\pi^-\gamma}/\Gamma_{\eta \to \pi^+\pi^-\pi^0}$

In the $\eta \to \pi^+\pi^-\gamma$ decay a significant contribution from the chiral anomaly responsible for $\eta \to \gamma\gamma$ decay is expected [10]. The chiral anomaly predicts exactly the values of the amplitudes for the non-resonant coupling at the chiral limit, however, the momentum dependence is not predicted and is modeled by many theoretical approaches. The distribution of the invariant mass of the pions ($m_{\pi\pi}$) was pointed out as an important observable in the effort to disentangle possible resonant contributions, e.g. from the ρ-meson. Several theoretical approaches have been developed to treat the contributions of the anomalies to the decay [11] [12] [13]. This decay has been measured in the 1970s with data samples of the order of 10^4 events [14] [15]. However the theoretical papers which tried to combine the two sets reported discrepancy in data treatment and as a consequence difficulty with obtaining consistent results. Therefore, since only few experimental data sets are available, to clarify the situation the results from experiments with large statistics are really needed [16]. Recently the CLEO collaboration published their results on the ratio of charged decays branching ratios $\Gamma_{\eta\to\pi^+\pi^-\gamma}/\Gamma_{\eta\to\pi^+\pi^-\pi^0} = 0.175\pm 0.007\pm 0.006$ which differ more than 3σ from old results. Our goal is to answer the above questions with a high statistics sample.

The analysis steps include selection of the high purity sample of $\eta\to\pi^+\pi^-\gamma$ and $\eta\to\pi^+\pi^-\pi^0$ decays. The main background is the decay $\phi\to\pi^+\pi^-\pi^0$ which mimics the event signature in the specific kinematical range when two photons' (one coming from eta and another from phi decay) invariant mass is around the π^0 value. In order to reduce the background contribution in the data the following steps, common for selection of both decays, are made in the analysis:

1. At least 2 neutral clusters must be found and at least one of them with energy > 250 MeV (the most energetic photon is assumed to be the one recoiling against the η in the $\phi\to\eta\gamma$ decay, γ_ϕ in the following). Two tracks (one positive and one negative) are selected based on the distance to the interaction point.

2. From two-body kinematics of $\phi\to\eta\gamma$ decay we can improve the information about the γ_ϕ and calculate its energy using angular information alone.

In order to select $\eta\to\pi^+\pi^-\pi^0$ decay two additional constraints are use:

3a Missing mass to the system $\phi-\pi^+-\pi^--\gamma_\phi$, MM, should be close to the π^0 mass: $|MM - m_{\pi^0}| < 10$ MeV

4a Opening angle $(\gamma^1_\eta,\gamma^2_\eta)$ in the π^0 rest frame should be larger than 2.7 rad.

The effect of the two constraints are presented in Fig. 3. One ends up with $4.22\cdot 10^6$ events in almost background-free sample with signal efficiency of 40 % and the background-to-signal ratio after the cuts of the level of 0.5%.

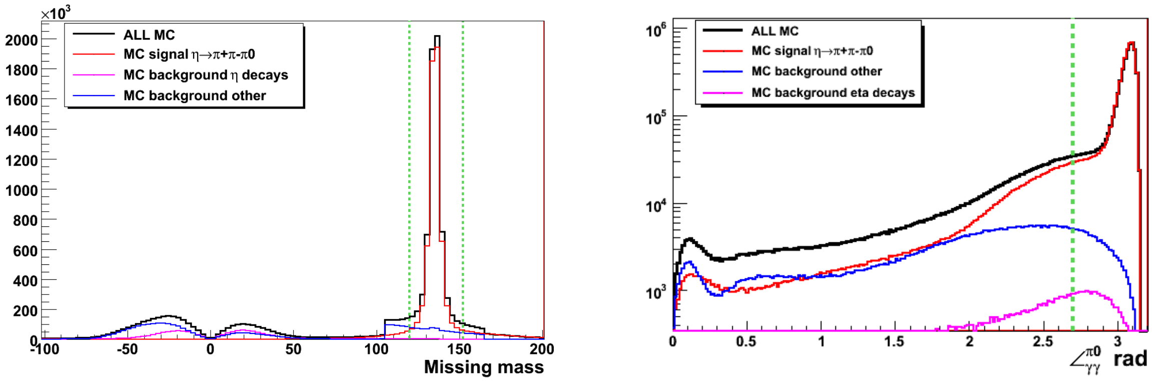

Figure 3: $\eta\to\pi^+\pi^-\pi^0$ selection: missing mass, MM, to the system $\phi-\pi^+-\pi^--\gamma_\phi$ (left) and the opening angle $(\gamma^1_\eta,\gamma^2_\eta)$ in the π^0 rest frame shown for signal and background MC.

To select $\eta\to\pi^+\pi^-\gamma$ decay one can calculate the four-momenta of γ_η using full event kinematics from $\phi\to\gamma\eta,\eta\to\pi^+\pi^-\gamma$ decay chain (with improved information about γ_ϕ) and use the opening angle (α) between the calculated γ_η and the original direction of the neutral cluster. If

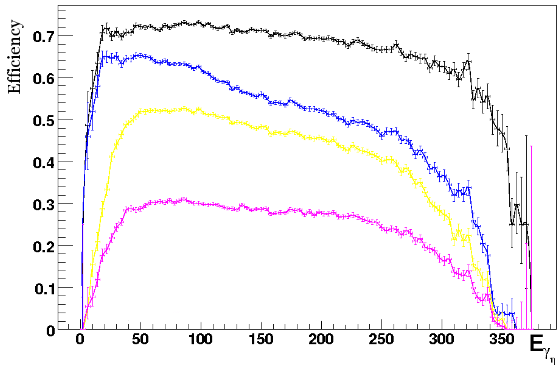

Figure 4: The signal ($\eta \to \pi^+\pi^-\gamma$) efficiency distribution in function of the energy of γ_η after different stages of the analysis. The final distribution (bottom-magenta) shows smooth behaviour in nearly whole range of the photon energy and corresponds to 28.3% overall efficiency.

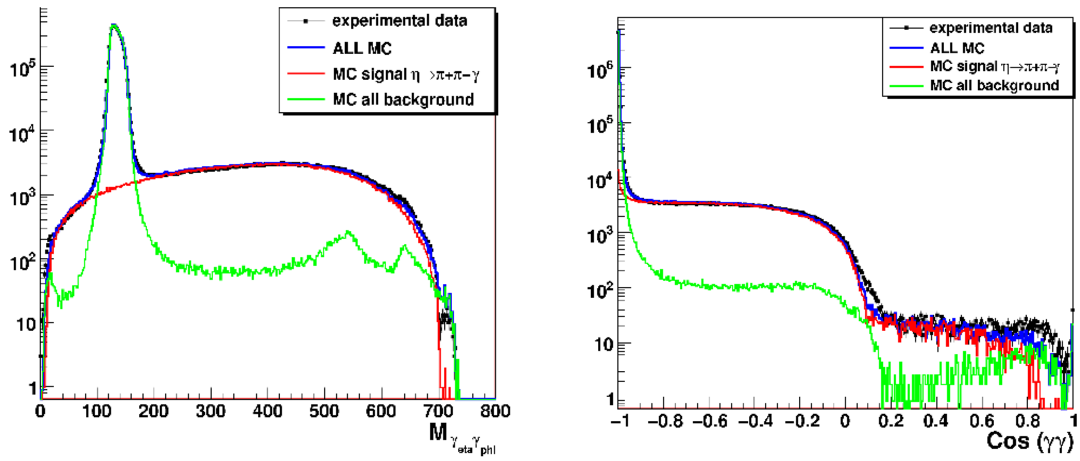

Figure 5: Invariant mass of two photons (left) and the cosine of the angle between γ_ϕ and γ_η calculated in the rest frame of π^0 (right). The experimental data (black points) are fitted simultaneously in both plots with signal (red line) and dominant background contributions (in green the sum of all MC backgrounds).

more than one cluster is present, the one with smaller α value is selected. Thereafter the following constraints were applied: $|E_\gamma - P_\gamma| < 10$ MeV on γ_η and $\angle(\alpha) < 0.2$ rad.

The applied constraints allow us to retain almost 30% of the signal while reducing signal-to-background ratio to 1:10. The efficiency distribution in function of the energy of γ_η (presented in Fig. 4) shows smooth behaviour near the whole kinematical range. The MC signal and all background contribution were compared with experimental data and all distribution showed very good agreement. Two of them are presented in Fig. 5: the cosine of the angle between γ_ϕ and γ_η calculated in the rest frame of π^0 (hypothetically assumed to be present in the event) (right) and the invariant mass of the two photons (left). They have been chosen to enhance the remaining differences between signal and background. For the background events (mostly remaining are events from $\phi \to \pi^+\pi^-\pi^0$ decay) there is very strong correlation at $cos(\gamma\gamma)$ =-1 (right) and at π^0 mass (left) while the signal is more uniformly distributed. These two distributions were simultaneously fitted with signal and background contributions to obtain the number of signal events in the plots, $0.61\cdot 10^6$. Combining this number with the number of the $\eta \rightarrow \pi^+\pi^-\pi^0$ events gives us preliminary ratio of branching ratios $\Gamma_{\eta \rightarrow \pi^+\pi^-\gamma} / \Gamma_{\eta \rightarrow \pi^+\pi^-\pi^0} = 0.2014 \pm 0.0004_{stat}$. Our number is in agreement with the old results from Thaler and Gormley and differs significantly from recent CLEO results as compared in Table. 2:

PDG08 Average		0.203 ± 0.008
LOPEZ (CLEO) 2007	859 events	$0.175 \pm 0.007 \pm 0.006$
THALER 1973	18k events	0.209 ± 0.004
GORMLEY 1970	7250 events	0.201 ± 0.006
Preliminary KLOE	611k events	0.2014 ± 0.0004

Table 2: Comparison of the existing results for the ratio $\Gamma_{\eta \rightarrow \pi^+\pi^-\gamma} / \Gamma_{\eta \rightarrow \pi^+\pi^-\pi^0}$. Recent results from CLEO differ significantly from PDG average and also disagree with our preliminary findings.

5. KLOE-2

Recently the interaction regions of DAFNE 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 leading to peak luminosities of the order of $5 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ which could in turn be translated to 800 pb^{-1} of integrated luminosity per month.

The KLOE-2 collaboration is preparing the KLOE detector for the new runs at upgraded DAFNE machine. In the first step aiming to integrate 5 fb^{-1} only small upgrades of the KLOE apparatus are foreseen. The second step will involve installation of several detector upgrades improving tracking capability, detection of photons coming from decays close to the interaction region and identification of $\gamma - \gamma$ processes. After the upgrades KLOE-2 can cover the physics program presented in [17] improving on systematics, thanks to the better detector, and on statistics thanks to an integrated luminosity ≥ 20 fb^{-1}.

For example, the unconventional forms of CP violation can be tested with higher precision using $\eta \rightarrow \pi^+\pi^-e^+e^-$ decays. More than 10^9 η's will be collected by KLOE-2 in few years of data taking. With this sample an asymmetry as small as 10^{-3} can be measured. KLOE has already put limits on the rates of $\eta \rightarrow \pi^+\pi^-$ [18] and $\eta \rightarrow \gamma\gamma\gamma$ [19] decays, two processes which are forbidden by invariance under P and C transformations. Using the full KLOE-2 statistics one can improve the above results by about two orders of magnitude; these will be among the most precise test ever done of P and C conservation in strong and electromagnetic interactions.

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