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# KLOE results on scalar and pseudoscalar mesons

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**Abstract** The data collected by the KLOE Collaboration at the Frascati ϕ-factory DAΦNE from 2001 to 2006 have been used for extensive studies in meson spectroscopy. The decays of the scalar mesons $a_0(980)$ and $f_0(980)$ into two pseudoscalar mesons have been exploited to measure the relevant parameters of those resonances. The radiative decays $\phi \to \eta\gamma$ and $\eta'\gamma$ have been used for the determination of the pseudoscalar mixing angle and to search for a possible gluonium content in the $\eta'$. The dynamics of the $\eta \to 3\pi$ decay has been studied and the Dalitz Plot parameters have been measured. The large amount of η mesons produced allowed also to study interesting rare η decays.

**Key words** $e^+e^-$ interactions, ϕ-factory, scalar mesons, pseudoscalar mesons

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## 1 Introduction

The KLOE experiment has been carried out at the Frascati ϕ-factory DAΦNE; its data taking ended in March 2006 with a total integrated luminosity of 2.5 $\text{fb}^{-1}$, corresponding to $8\times10^9$ $\phi(1020)$ mesons produced. The decays $\phi(1020) \to PP\gamma$, where P means a pseudoscalar meson, are dominated by the exchange of a scalar meson S in the intermediate state ($\phi \to S\gamma$, and $S \to PP$), thus they are suitable processes to study the $f_0(980)$ and $a_0(980)$, and also to look for a possible signal of the $\sigma(600)$. It is still controversial whether the light scalars are ordinary $q\bar{q}$ mesons, compact $qq\bar{q}\bar{q}$ states, or bound states of a K and a $\bar{K}$ mesons. The measurement of the branching ratios of $\phi(1020) \to PP\gamma$ and of the parameters of the scalar resonances (masses and couplings) are sentitive to their internal structure.

On the other hand large samples of η and $\eta'$ mesons are produced, through the decays $\phi \to \eta(\eta')\gamma$. With these decays a precise determination of the $\eta$–$\eta'$ mixing angle has been obtained, and the dynamics of the $\eta \to 3\pi$ has been studied.

Rare η decays, into $\pi^+\pi^-\gamma$, $\pi^+\pi^-e^+e^-$, and $e^+e^-e^+e^-$, have also been measured.

## 2 Light scalar mesons

The branching ratios of $\phi \to f_0(980)\gamma \to \pi\pi\gamma$ and of $\phi \to a_0(980)\gamma \to \eta\pi^0\gamma$ have been measured and the parameters of the scalar resonances have been extracted from a fit of the Dalitz plot or of the invariant mass distribution of the two pseudoscalars. Two phenomenological models have been used: the Kaon Loop (KL) one, in which the ϕ is coupled to the scalar through a loop of charged kaons[1], and the No Structure (NS) one, that assumes a point-like coupling of the scalar to the ϕ[2].

A sample of 450 $\text{pb}^{-1}$ of data has been used to study the $f_0(980)$ in the Dalitz plot of the process $e^+e^- \to \pi^0\pi^0\gamma$[3] (Fig. 1). The two bands are due to the non resonant process $e^+e^- \to \omega\pi^0$, with $\omega \to \pi^0\gamma$, while the region of high $M_{\pi\pi}$ is dominated by the $f_0$.

The results of the fit to the Dalitz plot are shown on Table 1. In the KL case the fit function includes the contribution of the $\sigma(600)$ with fixed parameters ($M_\sigma = 462$ MeV, $\Gamma_\sigma = 286$ MeV, $g_{\sigma K^+K^-} = 0.5$ GeV,

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and $g_{\sigma\pi^+\pi^-} = 2.4$ GeV) [1]. The interfering vector background ($e^+e^- \to \omega\pi^0$, and $\phi \to \rho^0\pi^0$ with $\rho^0 \to \pi^0\gamma$) is also included in the fit. If the σ(600) is excluded, the fit quality becomes very poor, $P(\chi^2) \sim 10^{-4}$.

The coupling $g_{\phi f_0\gamma}$ is a free parameter of the NS model. Moreover this model does not include explicitly the σ(600) contribution. The vector background has the same parametrization used for the KL.

The branching ratio is obtained from the integral of the scalar contribution only:

$$Br(\phi \to S\gamma \to \pi^0\pi^0\gamma) = (1.07^{+0.01}_{-0.03}\ {}^{+0.04}_{-0.02}\ {}^{+0.05}_{-0.06}) \times 10^{-4}, \quad (1)$$

where the first uncertainty is from the fit, the second one is systematic mainly due to event selection, and the last one is the model dependence.

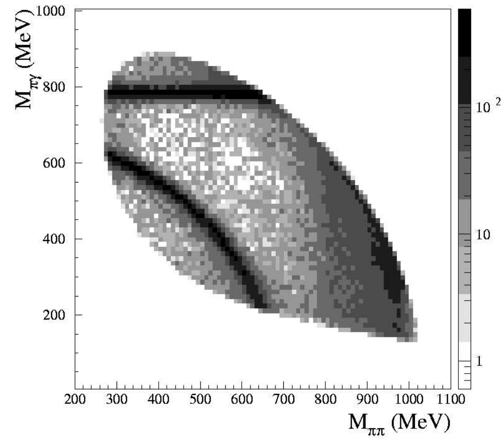


Fig. 1. Dalitz plot of $e^+e^- \to \pi^0\pi^0\gamma$.

Table 1. $f_0(980)$ parameters.

| | dalitz plot fit | | $M_{\pi^+\pi^-}$ fit | |
|---|---|---|---|---|
| | KL model | NS model | KL model | NS model |
| $M_{f_0}$/MeV | 984.7 | 984.7 | 983.7 | 973–981 |
| $g_{f_0K^+K^-}$/GeV | 3.97 | 0.40 | 4.74 | 1.6–2.3 |
| $g_{f_0\pi^+\pi^-}$/GeV | −1.82 | 1.31 | −2.22 | 0.9–1.1 |
| $g_{\phi f_0\gamma}$/GeV$^{-1}$ | – | 2.61 | – | 1.2–2.0 |
| $R_{f_0} = g^2_{f_0K^+K^-}/g^2_{f_0\pi^+\pi^-}$ | 4.8 | 0.09 | 4.6 | 2.6–4.4 |

The $f_0(980)$ has also been studied in $e^+e^- \to \pi^+\pi^-\gamma$ [3]; only a small fraction of $\pi^+\pi^-\gamma$ events originates from $\phi \to f_0\gamma$ with $f_0 \to \pi^+\pi^-$, the main contribution is given by events in which the photon is produced by either an initial state (ISR) or a final state (FSR) radiation.

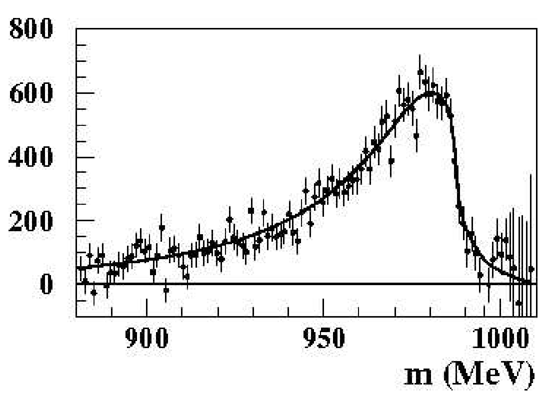


Fig. 2. $\pi^+\pi^-$ invariant mass distribution after the subtraction of ISR and FSR. The solid line is the KL fit.

The ISR component is suppressed by requiring the polar angle of the photon $\vartheta_\gamma > 45°$. The $\pi^+\pi^-$ invariant mass distribution has been fit to the differential cross-section ($m = M_{\pi^+\pi^-}$):

$$\frac{d\sigma}{dm} = \frac{d\sigma_{ISR}}{dm} + \frac{d\sigma_{FSR}}{dm} + \frac{d\sigma_{\rho\pi}}{dm} + \frac{d\sigma_{scalar}}{dm} \pm \frac{d\sigma_{scalar\otimes FSR}}{dm}. \quad (2)$$

The scalar contribution is parametrized according to both KL and NS models, and the last term can be either added (constructive interference) or subtracted (destructive one). The fit results for the KL model is shown in Fig. 2, and the $f_0$ parameters are listed in Table 1. Destructive interference between $f_0$ and FSR is preferred.

By integrating the scalar contribution, the following range for the branching ratio can be derived

$$Br(\phi \to f_0\gamma \to \pi^+\pi^-\gamma) = 2.1 \times 10^{-4} - 2.4 \times 10^{-4}, \quad (3)$$

which, as expected from isospin symmetry, is about twice the result of Eq. (1).

The $a_0(980)$ has been studied in $\phi \to \eta\pi^0\gamma$, by looking for the two final states corresponding to $\eta \to \gamma\gamma$ ($Br = 39.31\%$) and $\eta \to \pi^+\pi^-\pi^0$ (22.73%). Concerning the first decay chain, 29061 events have been selected in the analyzed sample of 450 pb$^{-1}$ with 38.5% efficiency; the irreducible background amounts to 55% of the final sample, and has been evaluated by

Monte Carlo (MC) and checked on control data samples. After the background subtraction the following branching ratio is obtained [4]:

$$Br(\phi\to\eta\pi^0\gamma)=(7.01\pm0.10_{\rm stat}\pm0.20_{\rm syst})\times10^{-5}. \quad (4)$$

The second decay chain is characterized by very low background, since there are no other processes with the same final state as the signal. 4181 events are selected, with 19.4% efficiency, and 15% total background, corresponding to

$$Br(\phi\to\eta\pi^0\gamma)=(7.12\pm0.13_{\rm stat}\pm0.22_{\rm syst})\times10^{-5}. \quad (5)$$

By combining the two results, $Br(\phi\to\eta\pi^0\gamma)=(7.06\pm0.22)\times10^{-5}$ is obtained.

A combined fit has been performed on the two $\eta\pi^0$ invariant mass distributions.

Among the free parameters there are also the branching ratio of the vector background and, as relative normalization, the ratio $R_\eta = Br(\eta\to\gamma\gamma)/Br(\eta\to\pi^+\pi^-\pi^0)$. In the NS fit also the $g_{\phi a_0\gamma}$ coupling is left free. The fit results are shown in Figs. 3 and 4 respectively, and the parameter values are listed in Table 2.

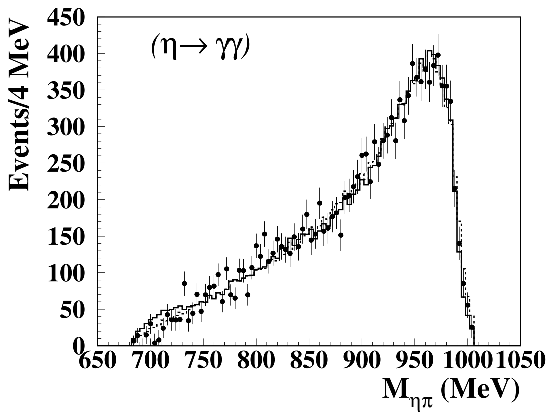


Fig. 3. $\eta\pi^0$ ($\eta\to\gamma\gamma$) invariant mass distributions after background subtraction. Points - data; solid histogram - KL fit result, dashed - NS fit.

Table 2. $a_0$ parameters from the combined fit of $M_{\eta\pi^0}$.

| fit parameters | KL model | NS model |
|---|---|---|
| $M_{a_0}$/MeV | 982.5±1.3±2.7 | 982.5 (fixed) |
| $g_{a_0K^+K^-}$/GeV | 2.15±0.05±0.17 | 2.01±0.07±0.28 |
| $g_{a_0\eta\pi^0}$/GeV | 2.82±0.04±0.12 | 2.46±0.08±0.11 |
| $g_{\phi a_0\gamma}$/GeV$^{-1}$ | 1.59±0.09±0.16 | 1.83±0.03±0.08 |
| $Br_{\rm vect}\times10^6$ | 0.92±0.40±0.15 | 0.1±4.0±0.1 |
| $R_\eta$ | 1.70± 0.04± 0.05 | 1.70±0.04±0.01 |
| $g^2_{a_0K^+K^-}/g^2_{a_0\eta\pi^0}$ | 0.58±0.03±0.06 | 0.67±0.12±0.13 |
| $P(\chi^2)$ | 10.4% | 30.9% |

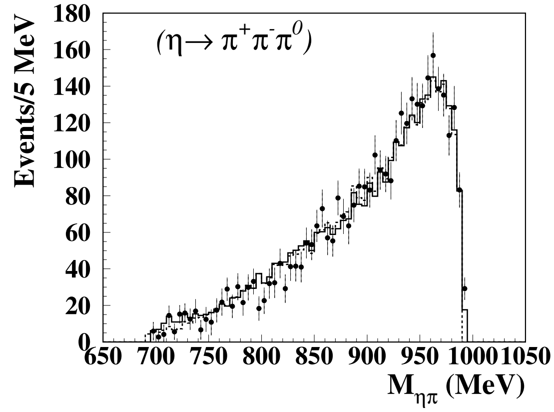


Fig. 4. $\eta\pi^0$ ($\eta\to\pi^+\pi^-\pi^0$) invariant mass distributions after background subtraction. Points - data; solid histogram - KL fit result, dashed - NS fit.

The decay $\phi\to K^0\bar{K}^0\gamma$ is dominated by the production of $f_0/a_0$ in the intermediate state. The $K_SK_S$ channel with both $K_S\to\pi^+\pi^-$ has been chosen. In 2.18 fb$^{-1}$ of data, 5 signal event have been found, with 3.2 background expected from MC, that corresponds to the limit: $Br(\phi\to K^0\bar{K}^0\gamma)<1.9\times10^{-8}$@90% C.L.

By using the couplings found in the $\phi\to\pi\pi\gamma$ and $\phi\to\eta\pi^0\gamma$ analyses, an expected range can be evaluated: $Br(\phi\to K^0\bar{K}^0\gamma)=4\times10^{-9}-6.8\times10^{-8}$, compatible with the upper limit.

## 3 η-η′ mixing angle and η′ gluonium content

The $\eta$-$\eta'$ mixing angle $\varphi_P$ in the quark flavour basis can be obtained from the measurement of the ratio $R=Br(\phi\to\eta'\gamma)/Br(\phi\to\eta\gamma)$. The decay

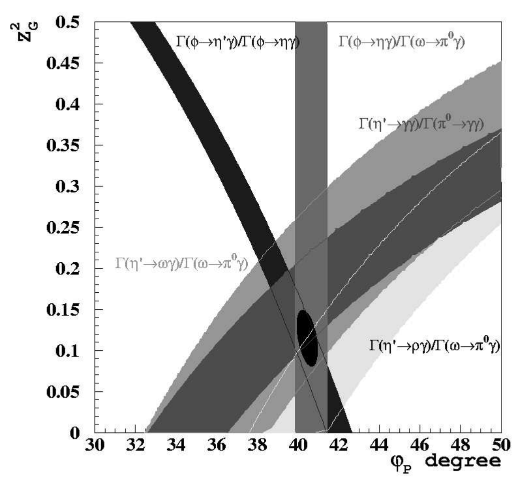


Fig. 5. $Z^2_{\eta'}$ vs $\varphi_P$, the black ellipse is the fit result (68% C.L.).

chains $\eta' \to \eta\pi^+\pi^-$ with $\eta \to 3\pi^0$ and $\eta' \to \eta\pi^0\pi^0$ with $\eta \to \pi^+\pi^-\pi^0$ have been chosen. $3407 \pm 75$ $\phi \to \eta'\gamma$ and $16.7\times 10^6$ $\phi \to \eta\gamma$ (with $\eta \to 3\pi^0$) events have been selected in a sample of 427 pb$^{-1}$, resulting in a ratio $R = (4.77 \pm 0.09 \pm 0.19) \times 10^{-3}$ from which the mixing angle $\varphi_P = (41.4 \pm 0.3 \pm 0.9)^\circ$ is derived [5].

If one allows for some gluonium content,

$$|\eta'\rangle = X_{\eta'}|q\bar{q}\rangle + Y_{\eta'}|s\bar{s}\rangle + Z_{\eta'}|G\rangle, \tag{6}$$

where $X_{\eta'} = \cos\varphi_G \sin\varphi_P$, $Y_{\eta'} = \cos\varphi_G \cos\varphi_P$ and $Z_{\eta'} = \sin\varphi_G$. From a fit performed by using the measured $R$, together with other eight experimental constraints [6], a non negligible $\eta'$ gluonium content has been found: $Z^2_{\eta'} = 0.12 \pm 0.04$ and $\varphi_P = (40.4 \pm 0.6)^\circ$ with $P(\chi^2)$ =21% (Fig. 5).

## 4 Dynamics of $\eta \to \pi\pi\pi$ decay

The $\eta \to 3\pi$ decay is induced by strong interactions via the u - d quark mass difference. Therefore a high statistics study is a good test of Chiral Perturbation Theory ($\chi$PT) [7]. The Dalitz plot of $\eta \to \pi^+\pi^-\pi^0$ (Fig. 6) contains $1.34\times 10^6$ events selected from a sample of 450 pb$^{-1}$.

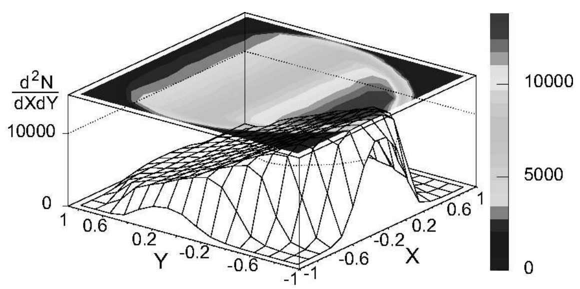


Fig. 6. Dalitz plot of $\eta \to \pi^+\pi^-\pi^0$.

It is usually parametrized as an expansion in powers of $X$ and $Y$ ($X = \sqrt{3}(E_+ - E_-)/Q$ and $Y = 3(E_0 - m_{\pi^0})/Q - 1$, where $Q = m_\eta - 2m_{\pi^\pm} - m_{\pi^0}$ and $E_+$, $E_-$, $E_0$ are the pion energies):

$$|A(X,Y)|^2 \propto 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3. \tag{7}$$

The coefficients have been determined with a fit (Table 3). The fit quality is good, $P(\chi^2)$ =73% [8]; the parameters $c$ and $e$ are compatible with zero, as expected since they violate charge conjugation, and a large cubic term in $Y$, $f$, has been found. A bad quality fit, with $P(\chi^2) \sim 10^{-6}$, is obtained by imposing $f = 0$.

The Dalitz plot of $\eta \to 3\pi^0$ is symmetric, the squared amplitude is described by only one slope parameter, $|A(Z)|^2 \propto 1 + 2\alpha Z$, where $Z = 2/3\sum_{i=1}^{3}[(3E_i - m_\eta)/(m_\eta - 3_\pi)]^2$ and $E_i$ are the pion energies. From the analysis of a sample of 450 pb$^{-1}$, $6.5\times 10^5$ events have been selected, and the slope parameter $\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}$ has been obtained, by using the KLOE value of the $\eta$ mass [9].

Table 3. Parameters of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot.

| | |
|---|---|
| $a$ | $-1.090 \pm 0.005 \pm^{+0.008}_{-0.019}$ |
| $b$ | $0.124 \pm 0.006 \pm 0.010$ |
| $c$ | $0.002 \pm 0.003 \pm 0.001$ |
| $d$ | $0.057 \pm 0.006 \pm^{+0.007}_{-0.016}$ |
| $e$ | $-0.006 \pm 0.007 \pm^{+0.005}_{-0.003}$ |
| $f$ | $0.14 \pm 0.01 \pm 0.02$ |

The slope parameter $\alpha$ can also been derived from an alternative parametrization of the $\eta \to \pi^+\pi^-\pi^0$ decay amplitude which takes into account the final state $\pi\pi$ rescattering [10]. From the Dalitz Plot analysis described above, the value $\alpha = -0.038 \pm 0.003^{+0.012}_{-0.008}$ has been obtained [8], in good agreement with the direct measurement.

## 5 Rare $\eta$ decays

The large sample of $\eta$ mesons produced at DAΦNE, about $10^8$ in 2.5 fb$^{-1}$, allows to study some interesting rare decay channels of this meson.

### 5.1 $\eta \to \pi^+\pi^-e^+e^-$

The $\eta \to \pi^+\pi^-e^+e^-$ decay mainly proceeds through the coupling of a pseudoscalar meson to virtual photons and vector mesons. The measurement of the branching ratio allows the comparison of different models based on Vector Meson Dominance and $\chi$PT [11]. Two previous measurements of this branching ratio exist, both based on low statistics datasets: the CMD-2 experiment at VEPP-2M obtained $Br(\eta \to \pi^+\pi^-e^+e^-) = (3.7^{+2.5}_{-1.8} \pm 3.0) \times 10^{-4}$ with 4 events [12], while the CELSIUS-WASA result is $(4.3^{+2.0}_{-1.6} \pm 0.4) \times 10^{-4}$ with 16 events detected [13].

This decay is also interesting as a probe of a $CP$ violation mechanism beyond the Standard Model [14]. According to this mechanism the interference between the electric and magnetic decay amplitudes would produce an asymmetry in the angle $\phi$ between the decay planes of the electron and the pion pairs in the $\eta$ rest frame:

$$A_\phi = \frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)}, \tag{8}$$

where $N$ means number of events. While in the SM $A_\phi$ is constrained to be $\mathcal{O}(10^{-15})$ and from the upper limit on the $CP$ violating process $\eta \to \pi^+\pi^-$, at most $A_\phi \sim \mathcal{O}(10^{-4})$ is expected, within this non-conventional mechanism larger values, $\mathcal{O}(10^{-2})$ can be predicted [14].

In Fig. 7 is shown the invariant mass ditribution of $\pi^+\pi^-e^+e^-$ obtained from a sample of 1.73 fb$^{-1}$ of analyzed data [15].

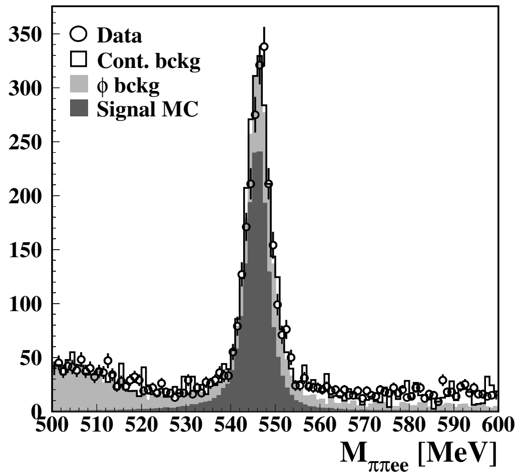


Fig. 7. $\pi^+\pi^-e^+e^-$ invariant mass distribution [15].

From a fit of this distribution with the expected shapes from MC, 1555±52 signal events have been obtained with a background of 368. The overall efficiency is $\varepsilon = 8.03 \pm 0.04\%$. This results translates into $Br(\eta \to \pi^+\pi^-e^+e^-) = (2.68 \pm 0.09 \pm 0.07) \times 10^{-4}$. From the distribution of the product sin$\phi$cos$\phi$, shown in Fig. 8, the first measurement of the plane asymmetry has been obtained:

$$A_\phi = (-0.6 \pm 2.5 \pm 1.8) \times 10^{-2}. \qquad (9)$$

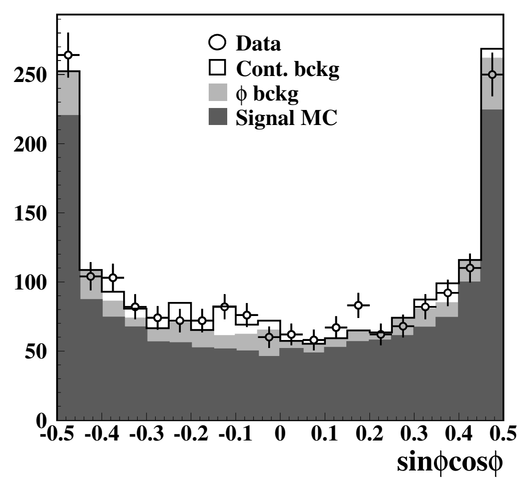


Fig. 8. sin$\phi$cos$\phi$ distribution for $\eta \to \pi^+\pi^- e^+e^-$ events [15].

### 5.2 $\eta \to \pi^+\pi^-\gamma$

This decay prodeeds through the box anomaly, accounted for by the Wess-Zumino-Witten term of the $\chi$PT Lagrangian. The box anomaly is a higher term that describes a direct coupling of three pseudoscalars to the photon. The study of the invariant mass of the pion pair or of the photon energy spectrum, provides a good tool to disentangle the box anomaly contribution from other possible resonant ones [16]. This decay has been measured in the 70's by Gormley et al. [17], $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.201 \pm 0.006$ and by Layter et al. [18], $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.209 \pm 0.004$. These two values are in good agreement, but the analysis of the photon spectra shows some contradictions [16]. Moreover a recent measurement by the CLEO Collaboration gave a lower value, $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.175 \pm 0.007 \pm 0.006$, marginally compatible with the old measurements.

From a sample of 1.2 fb$^{-1}$ of KLOE data, $6\times10^5$ events have been selected, and the preliminary ratio of branching ratios:

$$\frac{\Gamma(\eta \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \pi^+\pi^-\pi^0)} = 0.2014 \pm 0.004_{\rm stat} \qquad (10)$$

has been obtained, where the quoted uncertainty is only statistical. The study of the photon spectrum is in progress.

### 5.3 $\eta \to e^+e^-e^+e^-$

The double Dalitz $\eta$ decay in principle allows to access the transition form factors at time-like momenta of the virtual photons. This process has never been observed before, only an upper limit has been set by the CMD-2 Collaboration: $Br(\eta \to e^+e^-e^+e^-) < 6.9\times10^{-5}$@90% C.L. [12]. The theoretical predictions for this branching ratio are around $2.5 - 2.6 \times 10^{-5}$.

About 2 fb$^{-1}$ of KLOE data have been analyzed, the peak at the $\eta$ mass in the four electron invariant

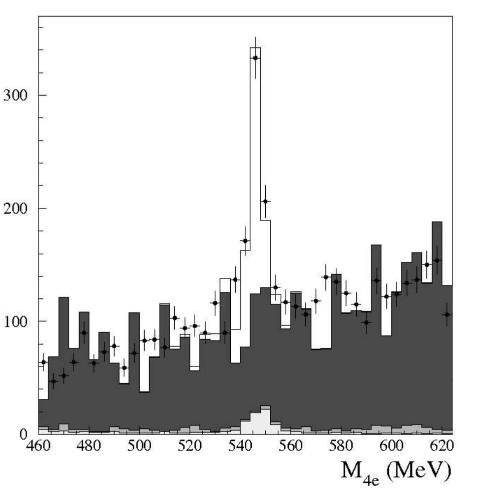


Fig. 9. Four electron invariant mass distribution: points are data, grey histograms represent bacgkround from MC.

mass distribution, shown in Fig. 9, represents the first observation of the $\eta \rightarrow e^+e^-e^+e^-$ decay.

From a fit of this distribution, using the expected background shape from the MC, $413 \pm 31$ $\eta \rightarrow e^+e^-e^+e^-$ events have been obtained. Work is in progress to evaluate the detection efficiency and the systematic uncertainties.

## 6 Future prospects: KLOE-2

A proposal for the continuation of the KLOE physics program with an upgraded detector, KLOE-2, at an upgraded DAΦNE, has been presented [19], considering the physics potential with an integrated luminosity of about 50 $fb^{-1}$ at the $\phi$ peak with the further possibility to increase the c.m. energy up to 2.5 GeV. Recently the DAΦNE interaction region has been modified, and a new scheme to increase the luminosity has been implemented. As a first step of the KLOE-2 project, in Mary 2010 a new data-taking will start, with the same KLOE detector with the minimal upgrade of the electron tagger for $\gamma\gamma$ physics [20].

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