Measurement of
\[ \Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0) \]
with KLOE experiment

The KLOE Collaboration

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Abstract

We report the measurement of the ratio $\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)$ analyzing a large sample of $\phi \rightarrow \eta\gamma$ decays recorded with the KLOE experiment at the DAΦNE $e^+e^-$ collider, corresponding to an integrated luminosity of $558\text{ pb}^{-1}$. The $\eta \rightarrow \pi^+\pi^-\gamma$ process is supposed to proceed both via a resonant contribution, mediated by the $\rho$ meson, and a non resonant direct term, connected to the box anomaly. The presence of the direct term affects the partial width value. Our result $R_\eta = \Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0) = 0.1838 \pm 0.0005_{\text{stat}} \pm 0.0030_{\text{syst}}$ is in agreement with a recent CLEO measurement, which differs by more 3 $\sigma$ from the average of previous results.

Key words: $e^+e^-$ collisions, $\eta$ decays
1 Introduction

The Chiral Perturbation Theory (ChPT) provides accurate description of interactions and decays of light mesons [1]. The decays $\eta \rightarrow \pi^+\pi^-\gamma$ and $\eta' \rightarrow \pi^+\pi^-\gamma$ are expected to get contribution from the anomaly accounted for by the Wess Zimino Witten (WZW) term into the ChPT Lagrangian [2]. Those anomalous processes are referred to as box anomalies which proceed through a vector meson resonant contribution, described by Vector Meson Dominance (VMD). According to effective theory [2] the contribution of the direct term should be present together with VMD. In case of $\eta \rightarrow \pi^+\pi^-\gamma$ the $\rho$ contribution is not dominant, this makes the partial width sensitive to the presence of the direct term, while in case of $\eta' \rightarrow \pi^+\pi^-\gamma$ the partial width is dominated by the resonance and the direct term effect should be visible in the dipion invariant mass distribution. The present world average of the $\eta \rightarrow \pi^+\pi^-\gamma$ partial width, $\Gamma(\eta \rightarrow \pi^+\pi^-\gamma) = (60 \pm 4)\text{ eV}$ [3], provides strong evidence in favour of the box anomaly, compared with value expected with and without the direct term, respectively $(56.3 \pm 1.7)\text{ eV}$ and $(100.9 \pm 2.8)\text{ eV}$ [2]. Recently CLEO [4] has measured the ratio $R_\eta = \Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0) = 0.175 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$, which differs by more than 3$\sigma$ from the average result of previous measurement [5,6], $R_\eta = 0.207 \pm 0.004$ [4]. We present a new measurement with the highest statistics and the smallest systematic error ever achieved.

2 The KLOE detector at DAΦNE

The KLOE experiment operates at the Frascati $\phi$-factory, DAΦNE, an $e^+e^-$ collider running at a center of mass energy of $\sim 1020\text{ MeV}$, the mass of the $\phi$ meson. The detector consists of a large cylindrical Drift Chamber (DC), surrounded by a lead-scintillating fiber electromagnetic calorimeter and a superconducting coil around the EMC provides a 0.52 T field. The drift chamber [8], 4 m in diameter and 3.3 m long, has 12,582 all-stereo tungsten sense wires and 37,746 aluminum field wires. The chamber shell is made of carbon fiber-epoxy composite with an internal wall of 1.1 mm thickness, the gas used is a 90%

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helium, 10% isobutane mixture. The spatial resolutions are $\sigma_{xy} \sim 150 \mu m$ and $\sigma_z \sim 2 mm$ and the momentum resolution is $\sigma(p_\perp)/p_\perp \approx 0.4\%$. The calorimeter [9] consists of a barrel and two endcaps, for a total of 88 modules, and covers 98% of the solid angle. The modules are read out at both ends by photomultipliers, both in amplitude and time. The readout granularity is $\sim (4.4 \times 4.4) \text{ cm}^2$, for a total of 2440 cells arranged in five layers. The energy deposits are obtained from the signal amplitude while the arrival times and the particles positions are obtained from the time differences. Cells close in time and space are grouped into calorimeter clusters and the cluster energy $E$ is the sum of the cell energies. The cluster time $T$ and position $\vec{R}$ are energy-weighted averages. Energy and time resolutions are $\sigma_E/E = 5.7%/\sqrt{E \text{ (GeV)}}$ and $\sigma_t = 57 \text{ ps}/\sqrt{E \text{ (GeV)}} \oplus 100 \text{ ps}$, respectively. The trigger [10] uses both calorimeter and chamber information. Data are then analyzed by an event classification filter [11], which selects and streams various categories of events in different output files.

3 Event selection

The analysis has been performed using 558 pb$^{-1}$ from the 2004-2005 data set at $\sqrt{s} \simeq 1.02$ GeV. Monte Carlo (MC) events are used to simulate the signal and the background. The signal is generated according to the matrix element quoted in [5]. All MC productions account for run by run variations of the main data-taking parameters such as background conditions, detector response and beam configuration.

The final state under study is $\pi^+\pi^-\gamma\gamma$, since at KLOE, the $\eta$ mesons are produced together with a monochromatic recoil photon ($E_\gamma = 363$ MeV) through the radiative decay $\phi \rightarrow \eta\gamma$. In the considered data sample about $\sim 25 \times 10^6 \eta$'s are produced. The main background comes from $\phi \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$ decaying to the same final state. Other backgrounds are $\phi \rightarrow \eta\gamma \rightarrow \pi^+\pi^-\pi^0 \rightarrow \pi^+\pi^-\gamma$ with one photon lost, and $\phi \rightarrow \eta\gamma, \eta \rightarrow e^+e^-\gamma$ when both electrons are mis-identified as pions.

As first step of the analysis, a preselection is performed, requiring at least two tracks with opposite charge pointing to the interaction point (IP) and at least two neutral clusters in time (not associated to any track), having energy $E_{cl} \geq 10$ MeV and polar angle in the range $(23^\circ - 157^\circ)$. Tracks are sorted according to the distance of the point of closest approach from the IP. The first two tracks are selected.

We require the most energetic cluster ($\gamma_\phi$) to have $E_{cl} > 250$ MeV and we identify it as the photon recoiling against the $\eta$ in the $\phi \rightarrow \eta\gamma$ decay. Moreover we ask for $\gamma_\phi$ inside the calorimeter barrel $(55^\circ - 125^\circ)$, to avoid effects of
cluster merging between barrel and end-caps of the calorimeter. Other cuts are imposed to clean up the sample; cut on cluster-track collinearity and identification by time of flight (TOF) are used to reject electrons. The cut effectively rejects Bhabha background and other processes with electrons in the final state. To select $\eta$ decays we exploit the $\phi \to \eta \gamma$ two body decay kinematic computing the $\gamma_\phi$ energy, using only the $\gamma_\phi$ polar angle:

$$\vec{p}_\phi = \vec{p}_\eta + \vec{p}_\gamma$$

$$E_{\gamma_\phi} = \frac{m_\phi^2 - m_\eta^2}{2(E_\phi - |\vec{p}_\phi|\cos\varphi)}$$

where $\varphi$ is the angle between the average $\phi$-meson momentum measured run by run with high accuracy and $\gamma_\phi$. This allows us to improve the energy measurement of the recoil photon to 0.1%. We can determine the direction of the photon from $\eta$ decay using $\phi$ and $\pi$-mesons information:

$$\vec{p}_{\gamma_\eta} = \vec{p}_\phi - \vec{p}_{\pi^+} - \vec{p}_{\pi^-} - \vec{p}_{\gamma_\phi}$$

The photon direction is compared with the direction of each neutral cluster, $\Delta \varphi = \varphi_{\text{clus}} - \varphi_{\gamma_\eta}$. If no cluster within $\Delta \varphi < 8.5^\circ$ is found the event is rejected. The cluster with the minimum value of $\Delta \varphi$ is selected for further analysis.

In order to reject the $\phi \to \pi^+\pi^-\pi^0$ background, the angle between the two photons in the $\pi^0$ reference frame, evaluated using the $\phi$ and the $\pi$-mesons momenta, is calculated and rejected with an angular cut $\phi_{\gamma\gamma} < 165^\circ$; in order to reduce the systematics the angle is evaluated in the transverse plane.$^1$

Finally we select events requiring $539.5$ MeV $< M_{\pi^+\pi^-\gamma} < 554.5$ MeV (fig. 1).

3.1 Normalization Sample: $\eta \to \pi^+\pi^-\pi^0$

The process $\phi \to \eta \gamma$ with $\eta \to \pi^+\pi^-\pi^0$ represents a good control sample, due to the similar topology. Moreover the ratio $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$ is not affected by the uncertainties on the luminosity, the $\phi \to \eta \gamma$ partial width and the $\phi$ production cross section cancel in the ratio. We use the same preselection as for the $\eta \to \pi^+\pi^-\gamma$ signal and calculate the missing four-momentum:

$$\mathbf{P}_{\text{miss}} = \mathbf{P}_\phi - \mathbf{P}_{\pi^+} - \mathbf{P}_{\pi^-} - \mathbf{P}_{\gamma_\phi}$$

where the variables in the formula represent the four-momenta of the $\phi$ meson and the products of the decays. For the $\eta \to \pi^+\pi^-\pi^0$ signal, the missing mass peaks at the $\pi^0$ mass value and we select events with $|M_{\text{miss}} - m_{\pi^0}| < 15$ MeV.

$^1$ The $\varphi$ angle of the cluster is measured with an angular resolution of 6 mrad using the position of the calorimeter cell. The polar angle is instead determined by the time difference of the cluster at each side of the barrel and is affected by larger systematics.
Fig. 1. The $\pi^+\pi^-\gamma\eta$ invariant mass distribution: Data-MC comparison. Dots are data, Magenta is MC signal $\eta \rightarrow \pi^+\pi^-\gamma$, Red is all MC background contribution. The remaining background is rejected very efficiently by using an angular cut applied to the two photons from the $\pi^0$ decay, $\phi_{\gamma\gamma} > 165^\circ$; the angle is evaluated in the transverse plane. Fig. 2 shows the distribution of the missing mass and $\phi_{\gamma\gamma}$. We select $N(\eta \rightarrow \pi^+\pi^-\pi^0) = 1115805 \pm 1056$, with a selection efficiency of $\varepsilon = 0.2276 \pm 0.0002$ and a background contamination of 0.65%.

Fig. 2. Left - missing mass spectrum around the $\pi^0$ mass. Right - angle between prompt neutral clusters in the $\pi^0$ rest frame evaluated in the transverse plane ($\phi_{\gamma\gamma}$).

4 Results

The total selection efficiency of the $\eta \rightarrow \pi^+\pi^-\gamma$ signal is $\varepsilon = 0.2131 \pm 0.0004$. Background contribution and the signal amount in the final sample are evaluated with a fit to the $E_{miss} - P_{miss}$ distribution of the $\pi^+\pi^-\gamma\phi$ system.
Table 1
Summary table of systematic uncertainties.

| Source of uncertainty                                      | Relative error |
|------------------------------------------------------------|----------------|
| \(\varphi^{\pi^+\pi^-\gamma} < 165^\circ \pm 2^\circ\)    | ±0.6%          |
| \(\Delta \varphi > 8.5^\circ \pm 2^\circ\)                | ±0.4%          |
| \(|M_{\pi^+\pi^-\gamma} - M_{\eta}| < 7.5\text{ MeV} \pm 2\text{ MeV}\) | ±0.6%          |
| \(|M_{\text{miss}} - M_{\eta}| < 15\text{ MeV} \pm 4\text{ MeV}\) | ±0.4%          |
| \(\varphi^{3\pi} > 165^\circ \pm 2^\circ\)                | ±0.1%          |
| \(E_{\text{miss}} > 10\text{ MeV} \pm 2\text{ MeV}\)      | ±0.1%          |
| \(E_{\phi} > 250\text{ MeV} \pm 4\text{ MeV}\)           | ±0.1%          |
| Preselection                                               | 1%             |
| Fit \(E_{\text{miss}} - P_{\text{miss}}\)                  | ±0.6%          |
| Total                                                      | 1.6%           |

with the shapes from remaining background and signal MC in the range \(|E_{\text{miss}} - P_{\text{miss}}| < 10\text{ MeV}\). We find \(N(\eta \rightarrow \pi^+\pi^-\gamma) = 204950 \pm 450\) with a background contamination of 10%. Combining our results we obtain the ratio:

\[
R_{\eta} = \frac{\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)}{\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)} = 0.1838 \pm 0.0005_{\text{stat}} \pm 0.0030_{\text{syst}}
\] (1)

to be compared with world average value \(\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0) = 0.202 \pm 0.007\) [3]. The systematic uncertainties due to analysis cuts have been evaluated by varying the cuts on all variables and re-evaluating the branching ratios. The relative variation for each source of systematic is in table 1. The total error is taken as the quadratic sum of all contributions.

Fig. 3. \(E_{\text{miss}} - P_{\text{miss}}\) distribution of the \(\pi^+\pi^-\gamma\) system: the fit is performed with the background and signal shapes from MC in the range \(|E_{\text{miss}} - P_{\text{miss}}| < 10\text{ MeV}\).
4.1 Dipion Invariant Mass

The $M_{\pi^+\pi^-}$ dependence of decay width has been parameterized in different approaches, in which VMD has been implemented in effective Lagrangians \[2,12\]. We present a preliminary comparison between dipion invariant mass, with the most simple approach \[12\]

$$\frac{d\Gamma(\eta \to \pi^+\pi^-\gamma)}{d\sqrt{s}} = A \left| 1 + \frac{3m_\rho^2}{s - m_\rho^2} \right|^2 k_\gamma^3 q_\pi^3$$

(2)

where $k_\gamma$ is the photon momentum in the $\eta$ rest frame and its expression is $k_\gamma = (m_\eta^2 - s)/2m_\eta$, while $q_\pi = \sqrt{s - 4m_\pi^2}/2$ represents the pion momentum in the dipion rest frame; $s$ is the $M_{\pi^+\pi^-}$ invariant mass squared. In fig. 4 we compare the observed $M_{\pi^+\pi^-}$ spectrum, background subtracted, with the theoretical prediction of eq. 2 corrected for acceptance and experimental resolution. The agreement with data is good; fits with more complex parameterizations are in progress.

Fig. 4. $M_{\pi^+\pi^-}$ distribution: dots are data; histogram is the prediction from eq. 2 corrected for acceptance and experimental resolution

5 Conclusions

Using a data sample corresponding to an integrated luminosity of 558 pb$^{-1}$, we select 204950 $\eta \to \pi^+\pi^-\gamma$ events and 1115805 $\eta \to \pi^+\pi^-\pi^0$ from the $\phi \to \eta\gamma$
decays. The corresponding width ratio is:

\[ R_\eta = 0.1838 \pm 0.0005_{\text{stat}} \pm 0.0030_{\text{syst}} \] (3)

Our measurement is in agreement with the most recent result from CLEO [4], which is \( R_\eta = 0.175 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}} \).

Combining our measurement with the world average value \( \Gamma(\eta \rightarrow \pi^+\pi^-\pi^0) = (295 \pm 16) \text{ eV} [3] \), we get \( \Gamma(\eta \rightarrow \pi^+\pi^-\gamma) = (54.2 \pm 0.3) \text{ eV} \), which is in agreement with the value expected taking into account the direct term [2], providing a strong evidence in favour of the box anomaly.

The preliminary measurement of the dipion invariant mass spectrum agrees with the simplest parametrization in Hidden Symmetry model as from [12].

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