Study of η-meson Decays at KLOE/KLOE-2

Xiaolin Kang
on behalf of KLOE-2 Collaboration
INFN-Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati (RM), Italy
E-mail: xiaolin.kang@lnf.infn.it

Abstract. Working at a ϕ-factory, KLOE/KLOE-2 has collected a very large and clean sample of η decays, which allow to perform a variety of precision measurements. This report presents the recent results on the η-meson decays from KLOE/KLOE-2 experiments, including the search of the C-violating decay $\eta \to \gamma\gamma\gamma$, the determination of the CP asymmetry in $\eta \to \pi^+\pi^-e^+e^-$, the precision measurement of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution, the search for the CP-violating decay $\eta \to \pi^+\pi^-$ and the precision measurement of $\mathcal{O}(p^6)$ dominated decay $\eta \to \gamma\gamma\pi^0$.

1. Introduction

After being discovered more than 50 years ago, the η and η' mesons are still included in the physics program of various experiments, because of their interesting properties. Both η and η' are eigenstates of parity P and G, charge conjugation C, and combined CP parity, ($I^G(J^{PC}) = 0^+(0^{-+})$). Therefore, both decays can serve as laboratories for the testing of conservation or breaking of these discrete symmetries. Moreover, as η is a pseudo-goldstone boson of the strong interaction gauge theory, its strong and electromagnetic decays are forbidden at tree level [1] and are particularly suitable to measure transition form factors, investigate decay dynamics and test different ChPT models. In addition, it is possible to search for new phenomena, such as light dark matter bosons, in rare or forbidden η decays [2, 3].

The KLOE/KLOE-2 experiments [4] were operated at DAΦNE, an e^+e^- collider running at a center of mass energy of $\sim$ 1020 MeV, the mass of the ϕ meson, at the INFN Frascati Laboratory. In March 2018 the KLOE-2 experiment completed its data taking campaign and collected 5.5 fb^{-1} of data. Together with the KLOE experiment, a total data sample of 8 fb^{-1} has been collected. Copious η mesons are produced via the radiative decay of the ϕ meson, $\phi \to \gamma\eta$, with a branching ratio of 1.3% [5]. The η mesons can be clearly identified by their recoil against a photon with monochromatic energy of 363 MeV. The KLOE/KLOE-2 data sample corresponds to 3.1×10^8 η mesons, which allow the accurate analysis of specific decays and to search for rare or forbidden ones.

2. Search for the forbidden decay $\eta \to \gamma\gamma\gamma$

The decay $\eta \to \gamma\gamma\gamma$ is forbidden by charge-conjugation invariance, if the weak interaction is not taken into account. KLOE has performed a search for this decay in the data sample collected in the years 2001 and 2002 with an integrated luminosity of 410 pb^{-1} and set the upper limit $\mathcal{B}(\eta \to \gamma\gamma\gamma) \leq 1.6 \times 10^{-5}$ at 90% confidence level (CL) [6], which is the most stringent result obtained to data.

Four isolated photons are required to select the candidate events. A kinematic fit imposing energy-momentum conservation and time-of-flight equal to the velocity of light is performed for the 4γ final states, and the χ^2 value is required to be less than 25. The dominant background is given by the process $e^+e^- \to \gamma\omega$, where the initial-state radiation of a hard photon is followed by the decay $\omega \to \gamma\pi^0(\gamma\gamma)$. In addition, $\phi \to \gamma\pi^0$, $\gamma f_0(\pi^0\pi^0)$ and $\gamma a_0(\eta\pi^0)$ also can mimic four-photon events because of the loss of photons, addition of photons from machine background or shower splitting. Those events can be rejected by requiring the invariant mass of any $\gamma\gamma$ pair to lay out of the π^0 mass range, (90,180)MeV.

8268 events survive the above cuts. In the decay $\phi \to \gamma\eta$, the recoil photon has an energy of 363 MeV in the rest frame of the ϕ, and it is also the most probable energetic photon (γ_{hi}) in the signal decay chain. Fig. 1-left shows the monte carlo (MC) simulated energy distribution of the γ_{hi}, $E(\gamma_{hi})$, for the signal. Fig. 1-right shows the $E(\gamma_{hi})$ distribution for the data sample. No peak is observed in the signal region, defined as $350 < E(\gamma_{hi}) < 379.75$ MeV. To estimate the background, polynomials are used to fit the $E(\gamma_{hi})$ sidebands, (280, 350) and (379.75,481.25) MeV. Neymans construction procedure is used to evaluate the upper limit, which gives the best upper limit to date, 1.6×10^{-5} @ 90% CL. By analysing the complete KLOE/KLOE-2 data sample, the upper limit is expected to reach 3.6×10^{-6} @ 90% CL.

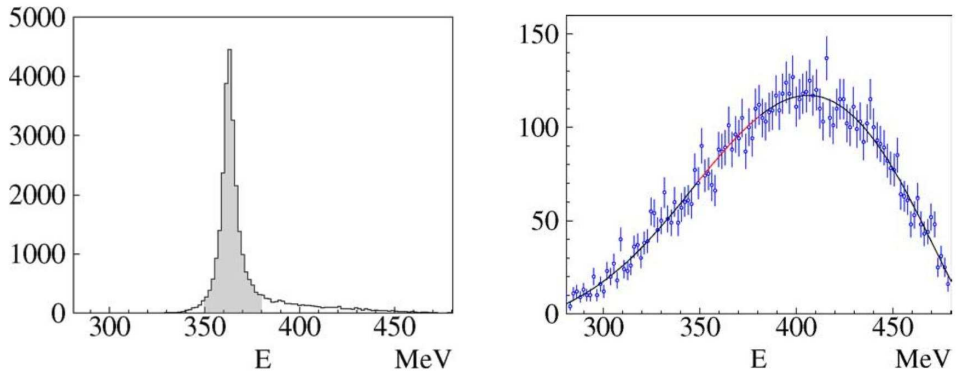

Figure 1. Distribution of the E(γ_{hi}) in the ϕ rest frame for the MC simulated signal (left) and data (right). The shaded interval is the signal region, the dots with error bars are KLOE data, the superimposed curve is the polynomial fit.

3. $\eta \to \pi^+\pi^-e^+e^-$

By comparing the precision measurement of the branching ratio of $\eta \to \pi^+\pi^-e^+e^-$ with the predictions from different theoretical approaches, such as Vector Meson Dominance model and ChPT, it is possible to probe the η meson's electromagnetic structure [7]. In addition, a possible CP-violating mechanism, not directly related to the most widely studied flavor changing neutral process, has been proposed for this decay [8]. This mechanism could induce interference between the parity-conserving magnetic amplitudes and the parity-violating electric amplitudes. Such CP-violation effect could be tested by measuring the polarization of the virtual photon and would result in an asymmetry in the angle ϕ between pions and electrons decay planes in the η rest frame, defined as

$$A_\phi = \frac{\int_0^{\pi/2} \frac{d\Gamma}{d\phi} d\phi - \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\phi} d\phi}{\int_0^{\pi/2} \frac{d\Gamma}{d\phi} d\phi + \int_{\pi/2}^{\pi} \frac{d\Gamma}{d\phi} d\phi} = \frac{N_{sin\phi cos\phi>0} - N_{sin\phi cos\phi<0}}{N_{sin\phi cos\phi>0} + N_{sin\phi cos\phi<0}}.$$

In the η decay this asymmetry is constrained by experimental [9] and SM [10] upper limits on the CP-violating decay $\eta \to \pi^+\pi^-$ at the level of $\mathcal{O}(10^{-4})$ and $\mathcal{O}(10^{-15})$, respectively.

KLOE has measured the $\phi \to \pi^+\pi^- e^+ e^-$ decay using a 1.73 fb^{-1} data sample collected at ϕ meson peak [11]. The main background sources are $\phi \to \pi^+\pi^-\pi^0$ events (with π^0 Dalitz decay) and $\phi \to \gamma\eta$ either with $\eta \to \pi^+\pi^-\pi^0$ (with π^0 Dalitz decay) or $\eta \to \pi^+\pi^-\gamma$ (with photon conversion on the beam pipe). Continuum background $e^+e^- \to e^+e^-(\gamma)$ events with photon conversions, split tracks or interactions with some material in the region of DAΦNE quadrupoles inside KLOE can also contaminate the signal and are studied using off-peak data taken at $\sqrt{s} = 1$ GeV. The $\pi^+\pi^- e^+ e^-$ invariant mass distribution, $M_{\pi\pi ee}$, is shown in Fig. 2-left. The background contribution is evaluated by performing a fit to the sidebands of the $M_{\pi\pi ee}$ invariant mass distribution with the shapes of the two background contributions obtained from MC. For the signal estimate, the η mass region, (535,555) MeV, is considered, counting the event number after background subtraction. The resulting number of signal events, $N_{\pi^+\pi^- e^+ e^-} = 1555 \pm 52$, is used to extract the branching ratio: $\mathcal{B}(\eta \to \pi^+\pi^- e^+ e^-(\gamma)) = (26.8 \pm 0.9_{stat} \pm 0.7_{syst}) \times 10^{-5}$.

The decay plane asymmetry A_ϕ has been evaluated for the events in the signal region after background subtraction. The obtained value is $A_\phi = (-0.6 \pm 2.6_{stat} \pm 1.8_{syst}) \times 10^{-2}$. This is the first measurement of this asymmetry. The distribution of the $sin\phi cos\phi$ variable is show in the right panel of Fig. 2.

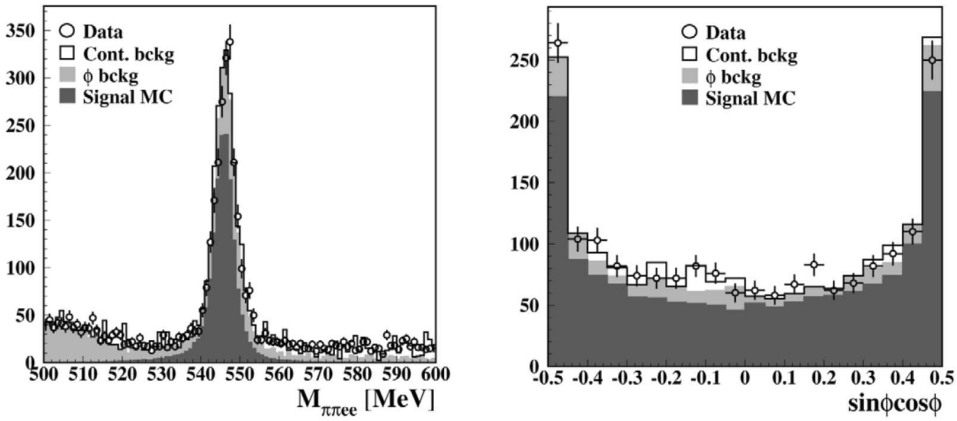

Figure 2. $\pi^+\pi^- e^+ e^-$ invariant mass spectrum around the η mass (left) and the $sin\phi cos\phi$ distribution in the signal region (right). The dots with error bars are data, the black histograms are the expected distributions obtained by the sum of the MC contribution to signal (dark grey), ϕ background (light grey) and continuum background (white).

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

The decay $\eta \to \pi^+\pi^-\pi^0$ is an isospin-violating process. Electromagnetic contributions to the process are expected to be very small and the decay is induced dominantly by the strong interaction via the u, d quark mass difference [12]. A precise study of this decay can lead to a very accurate measurement of $Q^2 = (m_s^2 - \hat{m}^2)/(m_d^2 - m_u^2)$, with $\hat{m} = (m_d + m_u)/2$, and thus put a stringent constraint on the light quark masses. The conventional decay amplitude square for $\eta \to \pi^+\pi^-\pi^0$ is parametrized as $|A(X,Y)|^2 = 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \ldots$, with $X = \sqrt{3}/Q_\eta(T_{\pi^+} - T_{\pi^-})$ and $Y = 3T_{\pi^0}/Q_\eta - 1$. T is the kinetic energy of the pions in η rest frame, $Q_\eta = m_\eta - m_{\pi^+} - m_{\pi^-} - m_{\pi^0}$ is the excess energy of the reaction, $m_{\eta/\pi}$ are the nominal masses from the Particle Data Group [5].

The Dalitz plot distribution has been recently studied by KLOE [13] with the world's largest signal sample of $\sim 4.7 \times 10^6$ events, based on 1.6 fb^{-1} ϕ data, improving the previous measurement [14]. From a fit to the Dalitz plot density distribution, shown in Fig. 3, we obtained

the most precise determinations of the parameters that characterize the decay amplitude. The results, together with a comparison with recent experimental measurements, are summarized in Table 1. This large statistics sample is also sensitive to the g parameter. As expected from C-parity conservation, the odd powers of X (c, e, h and l) are consistent with zero.

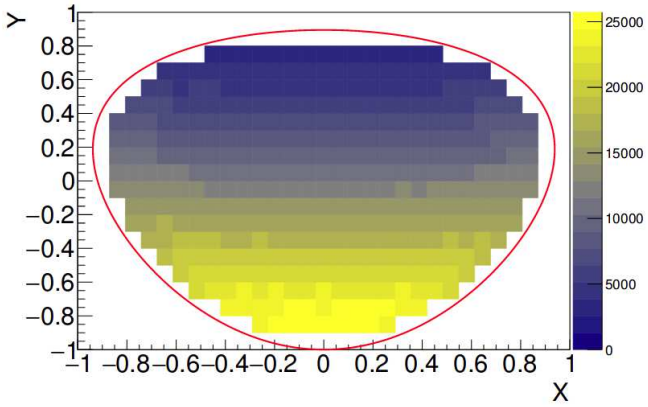

Figure 3. Dalitz plot for $\eta \to \pi^+\pi^-\pi^0$ in the data sample after background subtraction.

Table 1. Recent experimental measurement of the Dalitz plot parameters for $\eta \to \pi^+\pi^-\pi^0$.

	a	b	d	f	g
KLOE(16) [13]	-1.095 ± 0.004	0.145 ± 0.006	0.081 ± 0.007	0.141 ± 0.011	-0.044 ± 0.016
KLOE(16) [13]	-1.104 ± 0.004	0.142 ± 0.006	0.073 ± 0.005	0.154 ± 0.008	-
KLOE(08) [14]	-1.090 ± 0.020	0.124 ± 0.012	0.057 ± 0.017	0.14 ± 0.02	-
WASA [15]	-1.144 ± 0.018	0.219 ± 0.051	0.088 ± 0.023	0.115 ± 0.037	-
BESIII [16]	-1.128 ± 0.017	0.153 ± 0.017	0.085 ± 0.018	0.173 ± 0.035	-

In addition, we have also checked the C-parity conservation by measuring the left-right, quadrants and sextants charge asymmetries [17], which give the values $A_{LR} = (-5.0 \pm 4.5^{+5.0}_{-11}) \times 10^{-4}$, $A_Q = (+1.8 \pm 4.5^{+4.8}_{-2.3}) \times 10^{-4}$ and $A_S = (-0.4 \pm 4.5^{+3.1}_{-3.5}) \times 10^{-4}$, respectively. All of them are consistent with zero at the level of 10^{-4}.

5. Search for $\eta \to \pi^+\pi^-$

The decay $\eta \to \pi^+\pi^-$ violates both P and CP invariance. In the SM, this decay can proceed only via the CP-violating weak interaction, through mediation by a virtual K^0_S meson, with a branching ratio $\mathcal{B}(\eta \to \pi^+\pi^-) \leq 2 \times 10^{-27}$ [10]. By introducing the possible contribution of the CP-violating QCD θ term to this decay, the upper limit may reach the order of 10^{-17} [10]. While allowing a CP violation in the extended Higgs sector gives a slightly larger upper limit, a order of 10^{-15} [10]. Any detection of larger branching fractions would indicate a new source of CP violation in the strong interaction, beyond any considerable extension of the SM. With the first 350 pb^{-1} of data, KLOE searched for evidence of this decay, setting the best upper limit to date, $\mathcal{B}(\eta \to \pi^+\pi^-) \leq 1.3 \times 10^{-5}$ at 90% CL [9]. Using a data sample of 1.6 fb^{-1} collected at the ϕ meson peak, KLOE-2 is updating this result.

In this analysis, $\gamma\pi^+\pi^-$ final states are selected, contaminated by radiative Bhabha events γe^+e^-, $\gamma\mu^+\mu^-$ and $\rho(\pi\pi)\pi$ with one lost photon. A direction match between the missing

momentum of $\pi^+\pi^-$ and the selected γ is performed to reduce $\pi^+\pi^-\pi^0$ backgrounds. γe^+e^- backgrounds can be separated from the $\gamma\pi^+\pi^-$ signal by the different flight time inside the detector under different mass hypothesis for each charged track. While $\gamma\mu^+\mu^-$ events can be rejected using the so-called track-mass variable, computed assuming the ϕ decays to two particles of identical mass and a photon, shown in the left plot of Fig. 4.

The survived candidates are mainly $e^+e^- \to (\gamma)\gamma\pi^+\pi^-$. The $\pi^+\pi^-$ mass spectra, $M(\pi^+\pi^-)$, is used to look for the presence of η resonance, shown in the right plot of Fig. 4. No peak is observed in the distribution of $M(\pi^+\pi^-)$ in the vicinity of m_η. A Bayesian method is used to obtain the upper limit of the signal number. In the fit to $M(\pi^+\pi^-)$, the background is described by a third-order polynomial and the signal is described with the dedicated MC simulated shape. The preliminary upper limit on the branching ratio is determined to be 6.3×10^{-6} at 90% CL. With the whole KLOE and KLOE-2 data, the upper limit is expected to reach 2.7×10^{-6} @ 90% CL.

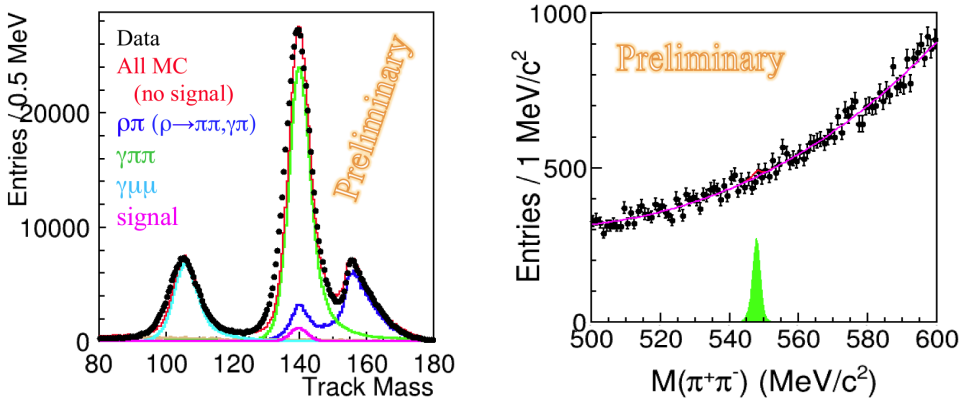

Figure 4. The track-mass distribution for different decay channels (left) and the $\pi^+\pi^-$ invariant mass spectrum between 500 and 600 MeV (right). The signal shape in arbitrary units.

6. The $\eta \to \gamma\gamma\pi^0$ decay

The doubly radiative decay $\eta \to \gamma\gamma\pi^0$ offers a unique window on pure p^6 terms of the Chiral Lagrangian, since there is no $\mathcal{O}(p^2)$ contribution, and the $\mathcal{O}(p^4)$ contribution is highly suppressed [18]. The branching ratio for this decay has been measured by several experiments in the past [5]. However, their results show large discrepancies. Using a data sample of 450 pb^{-1} of data, KLOE obtained the preliminary result $\mathcal{B}(\eta \to \gamma\gamma\pi^0) = (8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$ [19], which is around 2σ lower than the predictions from Chiral-loop, LσM and VMD [18, 20] and the latest result from Crystall Ball Collaboration at AGS [21] and A2 Collaboration at MAMI [22]. The experimental challenges of measuring this decay is the smallness of the rate for doubly radiative decays and the large rate of background contamination, in particular from $\eta \to 3\pi^0 \to 6\gamma$ decays with lost or merged photons. A correct estimation of the background is crucial for this analysis.

Reanalysis for this decay with more statistics is ongoing at KLOE-2, by performing kinematic fits under different signal or background hypothesis to suppress backgrounds. Furthermore, multi-variable analysis with cluster shape information is under tuning to separate single photon from merged photon. The final measurement is forthcoming.

Moreover, this decay also provides a probability for the search of a B boson at the QCD scale, via the decay chain $\eta \to \gamma B$, $B \to \gamma\pi^0$ [2].

7. Summary

The KLOE/KLOE-2 collaboration has achieved various precision measurements on η-meson decays, including the tests of discrete symmetries, studies of the decay dynamics and searches for rare decays using the KLOE data sample. In 2018 KLOE-2 has successfully completed its data taking at the ϕ-meson peak. The whole KLOE/KLOE-2 data sample amounts now to about 8 fb^{-1}. Ongoing analyses will produce more precise results in the next years.

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References

[1] B. M. K. Nefkens and J. W. Price, *Phys. Scripta* T **99**, 114 (2002).
[2] S. Tulin, *Phys. Rev.* D **89**, 114008 (2014).
[3] M. Reece and L. T. Wang, *J. High Energy Phys.* **0907**, 051 (2009).
[4] The KLOE Collaboration, The KLOE Detector Technical Proposal, LNF-93/002, 1993; S. Bertolucci (KLOE Collaboration), A Status Report of KLOE at DAΦNE, in Proc. 19th International Symposium on Lepton and Photon Interactions at High Energies, Stanford, USA, 1999, hep-ex/0002030.
[5] M. Tanabashi *et al.* (Particle Data Group), *Phys. Rev.* D **98**, 030001 (2018).
[6] A. Aloisio *et al.* (KLOE Collaboration), *Phys. Lett.* B **591**, 49 (2004).
[7] L. G. Landsberg, *Phys. Rept.* **128**, 301 (1985).
[8] D. N. Gao, *Mod. Phys. Lett.* **A 17**, 1583 (2002).
[9] F. Ambrosino *et al.* (KLOE Collaboration), *Phys. Lett.* B **606**, 276 (2005).
[10] C. Jarlskog, E. Shabalin, *Phys. Scr.* T **99**, 23 (2002); E. Shabalin, *Phys. Scr.* T **99**, 104 (2002).
[11] F. Ambrosino *et al.* (KLOE Collaboration), *Phys. Lett.* B **675**, 283 (2009).
[12] J. S. Bell and D. G. Sutherland, *Nucl. Phys.* B **4**, 315 (1968); R. Baur, J. Kambor and D. Wyler, *Nucl. Phys.* B **460**, 127 (1996); C. Ditsche, B. Kubis, and U. G. Meissner, *Eur. Phys. J.* C **60**, 83 (2009).
[13] A. Anastasi *et al.* (KLOE-2 Collaboration), *J. High energy Phys.* **1605**, 019 (2016).
[14] F. Ambrosino *et al.* (KLOE Collaboration), *J. High energy Phys.* **0805**, 006 (2008).
[15] P. Adlarson *et al.* (WASA-at-COSY Collaboration), *Phys. Rev.* C **90**, 045207 (2014).
[16] M. Ablikim *et al.* (BESIII Collaboration), *Phys. Rev.* D **92**, 012014 (2015).
[17] J. G. Layter, J. A. Appel, A. Kotlewski, W. Lee, S. Stein and J. J. Thaler, *Phys. Rev. Lett.* **29**, 316 (1972).
[18] L. Ametller, J. Bijnens, A. Bramon and F. Cornet, *Phys. Lett.* B **276**, 185 (1992).
[19] B. Di Micco *et al.* (KLOE Collaboration), *Acta Phys. Slov.* **56**, 403 (2006).
[20] R. Escribano, S. Gonzàlez-Solís, R. Jora and E. Royo, *arXiv:1812.08454 [hep-ph].*
[21] S. Prakhov *et al.* (Crystal Ball Collaboration at AGS), *Phys. Rev.* C **78**, 015206 (2008).
[22] B. M. K. Nefkens *et al.* (A2 Collaboration at MAMI), *Phys. Rev.* C **90**, 025206 (2014).