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LIGHT HADRON PHYSICS AT KLOE AND KLOE-2*

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The recent results concerning the $\eta \to 3\pi$ decay, the study of the box anomaly in $\eta \to \pi^+\pi^-\gamma$, the search for signals of dark photons in the decay $\phi \to \eta e^+e^-$, and the η-meson production in $\gamma\gamma$ collisions are presented.

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Introduction. The KLOE Collaboration took data from 2001 to 2006 at the Frascati ϕ-factory DAΦNE, collecting about 2.5 fb^{-1} at the peak of the $\phi(1020)$, and 250 pb^{-1} off-peak, mainly at $\sqrt{s} = 1$ GeV. In 2008, the Accelerator Division of the LNF tested a new interaction scheme for DAΦNE, aiming to reach an increase of a factor of three in luminosity. Following the success of this test, a new data-taking campaign of the KLOE experiment (KLOE-2 in the following) with an upgraded detector has been proposed [1]. The DAΦNE commissioning started in 2010, but severe hardware failures lead to a long shutdown of the machine. The commissioning has been resumed at the end of 2011. In December 2012 began the planned shutdown for the installation of the new detectors in KLOE.

The KLOE-2 upgrade. As a first step of the detector upgrade, a tagger system for scattered leptons from the $\gamma\gamma$ processes had been installed before the commissioning start in 2010. It consists of two different devices: a Low Energy Tagger (LET), made of two calorimeters of LYSO crystals readout by SiPM, placed close to the interaction point (IP), to detect leptons with energy between 130 and 300 MeV, and a High Energy Tagger (HET) for leptons with $E > 400$ MeV, two scintillator hodoscopes readout by PMT, symmetrically placed after the first bending dipoles of DAΦNE.

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During the present shutdown, an Inner Tracker made of four layers of cylindrical triple GEM is being installed between the beam-pipe and the Drift Chamber, to improve the decay vertex resolution close to the IP, and the acceptance for low momentum tracks. Moreover, two Crystal Calorimeters (CCALT) will cover the low polar angle regions to increase the acceptance for γ and $e^{\pm}$ down to $10°$, and the focusing quadrupoles will be equipped with calorimeters (QCALT) made of tungsten and scintillator tiles.

η, η' decays. The radiative decays $\phi \to \eta\gamma, \eta'\gamma$ produce large samples of pseudoscalar mesons. KLOE collected about 100 millions of η mesons, easily identified by their recoil against a photon of $E = 363$ MeV. We have also about half a million of η' mesons identified through their decays into $\eta\pi^+\pi^-$ and $\eta\pi^0\pi^0$ and the subsequent η decays.

$\eta \to 3\pi$ decay. The $\eta \to 3\pi$ decay is isospin violating, and it is mainly induced by a QCD Lagrangian term proportional to the d and u quark mass difference. Once the amplitude for this decay is known, the measurement of the decay rate is suitable for a precise determination of the ratio of the light quark masses $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$, where $\hat{m} = \frac{1}{2}(m_d + m_u)$.

In a sample of 450 pb^{-1} of data, we selected about 1.3 millions of $\eta \to \pi^+\pi^-\pi^0$ events. The Dalitz plot (Fig. 1) is described in terms of $X = \sqrt{3}\frac{E_+ - E_-}{\Delta}$ and $Y = 3\frac{E_0 - m_0}{\Delta} - 1$ with $\Delta = m_\eta - 2m_\pm - m_0$. The Dalitz plot density is usually parametrized as a power expansion around $X = Y = 0$: $|A(X,Y)|^2 = 1 + aY + bY^2 + cX + dX^2 + eXY + fY^3$. From the result of the fit (Table I) [5], the following points can be emphasized: *(i)* c and e parameters are compatible with zero, as expected, since they are charge conjugation violating; *(ii)* the quadratic slope in Y does not agree with the Current Algebra prediction $b = a^2/4$; *(iii)* a large cubic term in Y is needed, the fit repeated by forcing $f = 0$ has χ^2 probability $\sim 10^{-6}$.

The Dalitz plot of $\eta \to 3\pi^0$ can be parametrized as $|A|^2 \propto 1 + 2\alpha Z$, where $Z = \frac{2}{3}\sum_{i=1}^{3}\left(\frac{3E_i - m_\eta}{m_\eta - 3m_\pi}\right)^2$. In the same data-set analyzed for the

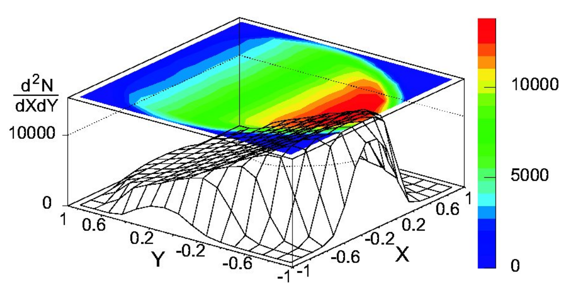

Fig. 1. Dalitz plot density for $\eta \to \pi^+\pi^-\pi^0$.

charged channel, we selected 6.5×10^5 fully neutral events. From the fit (Fig. 2), we get $\alpha = -0.0301 \pm 0.0035^{+0.0022}_{-0.0036}$ in agreement with the previous measurements [6].

TABLE I

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

a	$-1.090 \pm 0.005^{+0.008}_{-0.019}$
b	$0.124 \pm 0.006 \pm 0.010$
c	$0.002 \pm 0.003 \pm 0.001$
d	$0.057 \pm 0.006^{+0.007}_{-0.016}$
e	$-0.006 \pm 0.007^{+0.005}_{-0.003}$
f	$0.14 \pm 0.01 \pm 0.02$
$P(\chi^2)$	73%

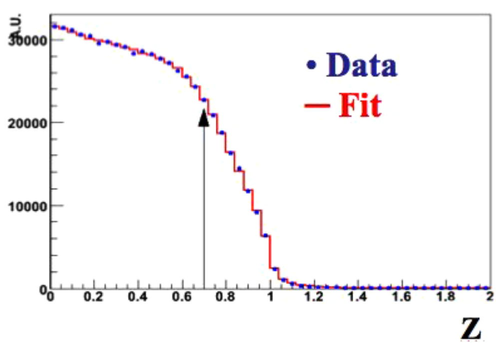

Fig. 2. Z distribution for $\eta \to 3\pi^0$, the arrow indicates the fit range, 0–0.7.

Recently, dispersive approaches to the $\eta \to 3\pi$ amplitudes have been proposed [7, 8]: the authors fixed the subtraction constants by fitting our measurement of $\eta \to \pi^+\pi^-\pi^0$, obtaining a good agreement with the measured Dalitz plot shape, and also reproducing the negative slope of the neutral decay. They derive $Q = 21.3 \pm 0.6$ and 23.1 ± 0.7, respectively.

A new analysis of the charged channel on the full KLOE data-set is in progress to reduce the systematic uncertainties. Also the decay $\eta' \to \pi^+\pi^-\pi^0$ can be related to $m_d - m_u$; at KLOE-2 with 5 fb^{-1}, we expect to collect about 8000 of such events.

$\eta \to \pi^+\pi^-\gamma$ decay. The decay $\eta \to \pi^+\pi^-\gamma$ proceeds through the box anomaly, a term of the Wess–Zumino–Witten Lagrangian of a higher order with respect to the triangle anomaly. Previous measurements date back to the 70s [3, 4]. The analysis of those two data-sets show some contradictions, in particular, concerning the need of a Contact Term (CT) beside the resonant one, dominated by a ρ exchange, to account for the box anomaly.

According to the Hidden Local Symmetry model [9], the value of the partial decay width is sensitive to the CT. Moreover, there is a 2–3 σ discrepancy between the old results and the CLEO one [2] (Table II).

TABLE II

Past measurements of $\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)}$.

Author	Value
CLEO [2] (2007)	0.175 ± 0.007 ± 0.006
Thaler [3] (1973)	0.209 ± 0.004
Gormley [4](1970)	0.201 ± 0.006

From a sample of about 560 pb^{-1}, we extracted 2×10^5 signal events (Fig. 3). We found $\frac{\Gamma(\eta\to\pi^+\pi^-\gamma)}{\Gamma(\eta\to\pi^+\pi^-\pi^0)} = 0.1838\pm0.0005\pm0.0030$ [10], favouring a sizeable contribution of the CT [9]. We fitted the $M_{\pi^+\pi^-}$ distribution (Fig. 4) according to the parametrization of Ref. [11], in which the decay width is factorized in a universal non-perturbative part (the pion form factor) and a process specific one $P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi} + \mathcal{O}(s^2_{\pi\pi})$, where $s_{\pi\pi} = M^2_{\pi\pi}$. We obtained $\alpha = (1.32\pm0.08\pm0.10)$ GeV^{-2} in agreement with WASA@COSY [12].

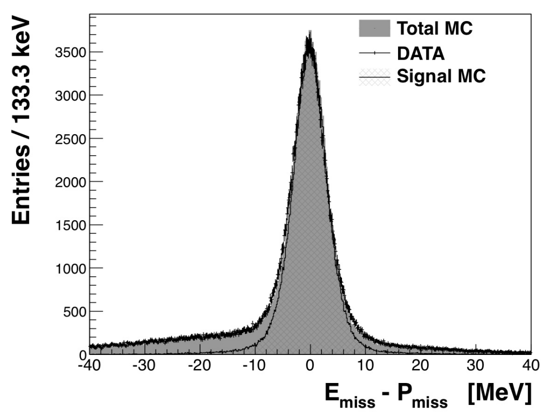

Fig. 3. $\eta \to \pi^+\pi^-\gamma$; $E_{\rm miss}$ and $p_{\rm miss}$ refer to the photon from the η decay, the signal is peaked at zero.

In the case of $\eta' \to \pi^+\pi^-\gamma$, also the $\pi\pi$ invariant mass distribution is expected to be sensitive to the CT [9]. The experimental data are contradictory: in 1997 Crystal Barrel claimed the evidence of the CT [13], while

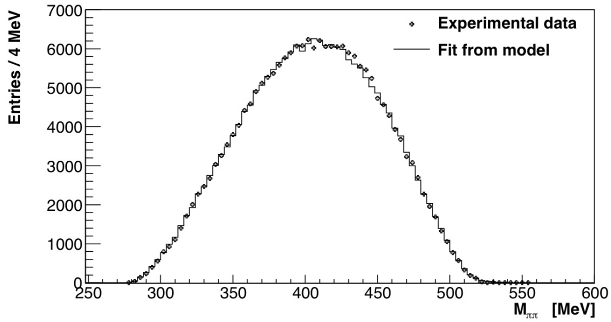

Fig. 4. $\eta \to \pi^+\pi^-\gamma$; $M_{\pi\pi}$ after background subtraction; the solid histogram is the fit result.

in 1998 the L3 data were well described in terms of resonant contribution only [14]. Then a high statistics measurement is desirable. At KLOE-2, with 5 fb^{-1}, $\sim 10^5$ $\eta' \to \pi^+\pi^-\gamma$ events are expected.

$\phi \to \eta e^+e^-$ decay. The Transition Form Factors (TFF) can be studied by means of the Dalitz decays, like $A \to B\ell^+\ell^-$. They are functions of the four-momentun squared $q^2 = m^2_{\ell^+\ell^-}$, and are usually parametrized as $F(q^2) = \frac{1}{1-\frac{q^2}{\Lambda^2}}$, where Λ is a characteristic mass that, according to Vector Meson Dominance (VMD), can be identified with the nearest vector meson. The dilepton invariant mass distributions of $\eta \to e^+e^-\gamma$ and $\eta \to \mu^+\mu^-\gamma$, measured by NA60 [15] and Crystall Ball@MAMI [16] are described by $\Lambda_\eta^{-2} = 1.92 \div 1.95$ GeV^{-2} in agreement with the VMD predictions $\Lambda_\eta^{-2} = 1.88$ GeV^{-2}. On the other hand, the slope of the TFF of $\omega \to \pi^0\mu^+\mu^-$, $\Lambda_\omega^{-2} = 2.24$ GeV^{-2} also measured by NA60, disagrees with the VMD expectation 1.68 GeV^{-2}. Concerning $\phi \to \eta e^+e^-$, there is only one low statistics measurement by SND, $\Lambda_\phi^{-2} = (3.8 \pm 1.8)$ GeV^{-2}, to be compared with the VMD expectation, $\Lambda_\phi^{-2} \simeq m_\phi^{-2} \simeq 1$ GeV^{-2}. We analyzed 1.5 fb^{-1} of data looking for $\phi \to \eta e^+e^-$ with $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^0\pi^0\pi^0$. The $m_{e^+e^-}$ spectra are shown in Fig. 5. The extraction of the TFF slope is still in progress.

We used the distributions of Fig. 5 to search for possible signals of dark forces (DF) mediators. In fact, it has been suggested that recent astrophysical observations, such as the excess of positrons between 10 and 100 GeV in cosmic rays by PAMELA, FERMI, ATIC, recently confirmed by AMS02; the 511 keV signal from the galactic core observed by INTEGRAL; and the annual modulation signal of DAMA/LIBRA could be explained in the framework of Dark Matter models that predict the existence of a vector boson (of mass $O(1$ GeV$)$) mediator of a new hidden gauge symmetry. This U-boson, should couple to Standard Model (SM) particles through a kinetic mixing with the photon. If the mixing parameter $\varepsilon = \sqrt{\frac{\alpha'}{\alpha_{\rm em}}} \sim 10^{-3}$–$10^{-4}$, the U-boson could be observable at KLOE by looking at the decays $\phi \to \eta U$, with $U \to \ell^+\ell^-$. There is no evidence of peaks in the spectra of Fig. 5, then by using the parametrization of Ref. [17], we evaluated the upper limit on the number of events of $\phi \to \eta U$ as a function of the $m_{e^+e^-}$. This translates into the exclusion plot on ε^2 shown in Fig. 6 [18]. To take into account the dependence on the TFF, we plotted the exclusion regions for the VMD expectation $b_{\phi\eta} = \Lambda^{-2} = 1$ GeV^{-2} and the SND value 3.8 GeV^{-2}. This result reduces the region of parameters that could explain the $(g-2)_\mu$ discrepancy between experiment and theory (light grey line in Fig. 6).

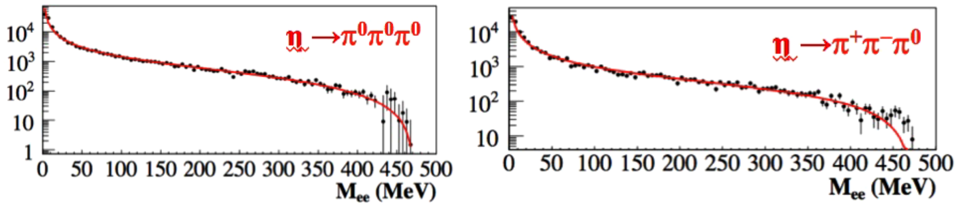

Fig. 5. e^+e^- invariant mass.

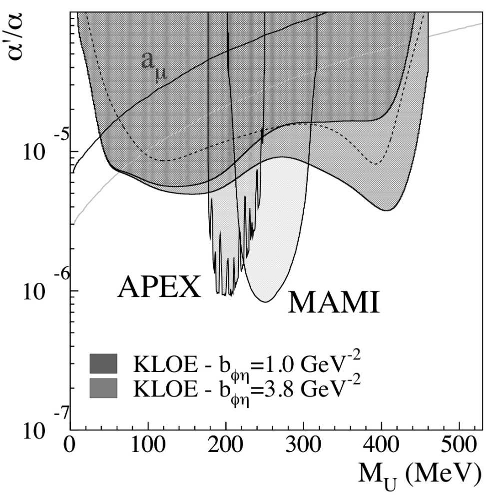

Fig. 6. Exclusion plot on $\varepsilon^2 = \frac{\alpha'}{\alpha_{\rm em}}$.

$\gamma\gamma$ physics. In $\gamma\gamma$ processes, $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$, $C = +1$ hadronic states can be produced. At the DAΦNE, final energy states with a single π^0 or η as well as the $\pi\pi$ one are accessible. With the KLOE data, we measured the two-photon width of the η meson by detecting events $e^+e^- \to e^+e^-\eta$, with $\eta \to \pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$. The scattered leptons were not detected because the taggers were not present, then in order to avoid the large background from ϕ decays, we analyzed the 250 pb^{-1} collected at $\sqrt{s} = 1$ GeV. In Fig. 7, the distributions of the missing mass with respect to $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$, respectively, are shown. By fitting these histograms, we obtained the cross sections $\sigma(e^+e^- \to e^+e^-\eta) = (34.5 \pm 2.5 \pm 1.3)$ pb and $\sigma(e^+e^- \to e^+e^-\eta) = (32.0 \pm 1.5 \pm 0.9)$ pb for the charged and neutral η decay channel, respectively. By combining them, $\sigma(e^+e^- \to e^+e^-\eta) = (32.7 \pm 1.3 \pm 0.7)$ pb, from which we extract the most precise measurement to date of the two-photon width: $\Gamma(\eta \to \gamma\gamma) = (520 \pm 20 \pm 13)$ eV [19].

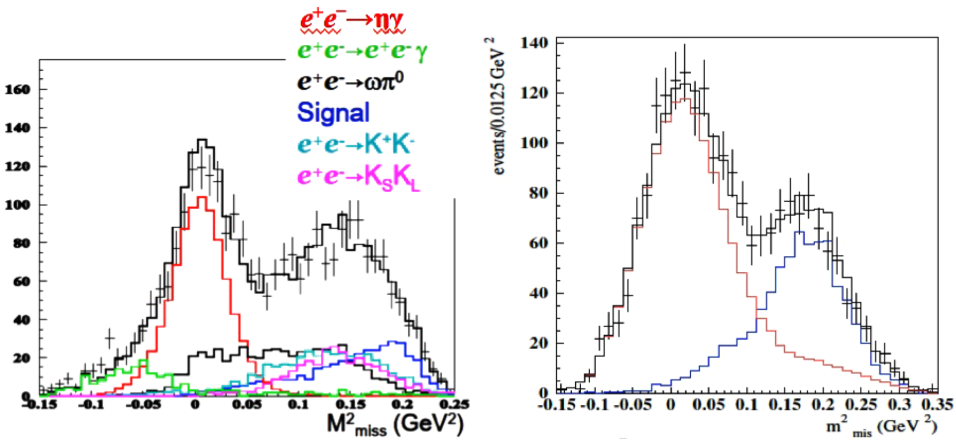

Fig. 7. Left: $\gamma\gamma \to \eta \to \pi^+\pi^-\pi^0$. Right: Dark grey/blue: $\gamma\gamma \to \eta \to \pi^0\pi^0\pi^0$; light grey/red: $e^+e^- \to \eta\gamma$ with $\eta \to \pi^0\pi^0\pi^0$.

At KLOE-2, we plan to measure $\Gamma(\pi^0 \to \gamma\gamma)$, which is known with 2.8% accuracy after the measurement by the PrimEx Collaboration. We will run mostly at the peak of the ϕ resonance, and by detecting the two scattered leptons in the HET, we will select $e^+e^- \to e^+e^-\pi^0$ with quasi-real photons ($q^2 \simeq 0$). We expect to collect about 10000 events in 5 fb^{-1} of data, in order to reach a 1% accuracy in $\Gamma(\pi^0 \to \gamma\gamma)$. Moreover, we plan to measure the $\pi^0\gamma^*\gamma$ TFF with a quasi-real photon, $q^2 \simeq 0$, and a virtual one, $|q^2| < 0.1$ GeV^2, by selecting events in which one of the leptons is detected in the HET and the other one at large angle in the KLOE main detector. This is a still unexplored q^2 region, important to check the TFF parametrizations. An accurate measurement of the TFF will also reduce the model dependence of the calculation of the light-by-light scattering contribution to $(g-2)_\mu$ which is dominated by the single π^0 exchange.

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