PROCEEDINGS OF SCIENCE

Hadron physics results at KLOE-2

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The KLOE/KLOE-2 Collaboration ended its data taking in 2018, about 20 years after the detector was turned on. In two different periods of data-taking about 8 fb^{-1} at the peak of the $\phi(1020)$ resonance have been collected. During the years many results of the study of the light mesons have been published. The analysis of this unique data sample continues and the results of the latest measurements concerning vector and pseudoscalar mesons and Dark Matter searches are presented in this paper.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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1. Introduction

The KLOE experiment has been carried on at the e^+e^- collider DAΦNE in Frascati. From 2001 to 2006 2.5 fb^{-1} of data at the peak of the $\phi(1020)$, plus 250 pb^{-1} off-peak have been collected. In 2008, a new interaction region has been installed in DAΦNE, to increase the luminosity, and from November 2014 to March 2018 a second data-taking campaign, the KLOE-2 experiment, has been carried out collecting 5.5 fb^{-1} of data at the peak of the $\phi(1020)$. The total KLOE+KLOE-2 data sample is the largest worldwide sample collected at a ϕ-factory, and it amounts to about 2.4×10^{10} ϕ mesons produced. The KLOE detector consisted of a large volume Drift Chamber surrounded by a hermetic Calorimeter, both immersed in an axial magnetic field of 0.52 T. The Drift Chamber, filled with a gas mixture of He - isobutane, provided a momentum resolution $\sigma_{p_t}/p_t = 0.4\%$ and a space resolution of 150 μm in the plane transverse to the beam line, and 2 cm along the beam direction. The Electromagnetic Calorimeter (EMC), made of Pb-scintillating fibers, was covering 98% of the whole solid angle, with energy resolution $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$ and time resolution $\sigma_t = 55\text{ps}/\sqrt{E(GeV)} \oplus 100$ ps. For the KLOE-2 data-taking the detector has been upgraded with the insertion of an Inner Tracker close to the DAΦNE Interaction Point (IP), made of four layers of cylindrical GEMs, and new small angle calorimeters, the QCALT (tungsten and scintillator tiles with SiPMs) as instrumentation of the quadrupoles, and the CCALT (LYSO crystals with SiPMs) to improve the acceptance for small angle particles. A tagging system for scattered electrons in $\gamma\gamma$ processes consisting of two different detectors was also installed: a High Energy Tagger (HET, scintillator hodoscopes readout by PMTs) placed after the first bending magnet of the machine, and a Low Energy Tagger (LET, LYSO crystal calorimeters with SiPMs) placed 1 m far from the IP.

2. $\eta \to \pi^0\gamma\gamma$

The rare decay $\eta \to \pi^0\gamma\gamma$ provides a good test of Chiral Perturbation Theory (ChPT), since the tree level contributions at $O(p^2)$ and $O(p^4)$ vanish because neutral mesons are involved, and the $O(p^4)$ contributions from kaon or pion loops are suppressed. Therefore it is directly sensitive to the $O(p^6)$ terms of the chiral lagrangian. The two most recent measurements of these decays have been performed with essentially the same detector, the Crystal Ball, at the AGS in Brookhaven, $Br = (2.21 \pm 0.24 \pm 0.47) \times 10^{-4}$ [1], and at MAMI in Mainz by the A2 Collaboration, $Br = (2.52 \pm 0.25) \times 10^{-4}$ [2]. These two values are significantly higher of the KLOE old result $Br = (0.84 \pm 0.27 \pm 0.14) \times 10^{-4}$ based on 68 signal events[3]. A sample of 1.7 fb^{-1} of KLOE data has been analyzed, looking for five prompt photon events from the decay $\phi \to \eta\gamma$ with $\eta \to \pi^0\gamma\gamma$. The main source of background is from the decay $\phi \to \eta\gamma$ with $\eta \to 3\pi^0$, that mimics five prompt photon events when photons are lost or are merged in the EMC. In Fig.1-left it is reported the final distribution of invariant mass of the four photons from η decay; a clear evidence of the signal is visible in correspondence to the η mass, superimposed to a large irreducible background. The yield of signal events is 1246 ± 133, which, normalzed to the very clean and abundant sample of seven prompt photon events from $\phi \to \eta\gamma$ with $\eta \to 3\pi^0$, gives:

$$Br(\eta \to \pi^0\gamma\gamma) = (0.99 \pm 0.11_{stat} \pm 0.24_{syst}) \times 10^{-4}$$

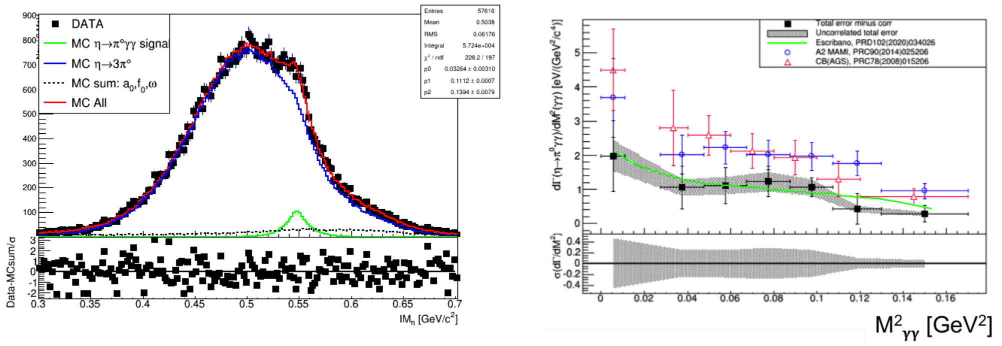

Figure 1: Left: Four photon invariant mass distribution, signal (green) and $\eta \to 3\pi^0$ background (blue), the red histogram is the sum of all the contributions. Right: differential decay rate as a function of the invariant mass of the two photons not coming from π^0, compared to previous experiments and to the latest theoretical prediction[4]; in gray the uncertainty band is shown.

This result is consistent with the old KLOE result, and confirms the discrepancy with the two measurements obtained with the Crystal Ball, now at level of four standard deviations. Also the differential decay rate has been obtained, by performing the analysis in bins of the invariant mass of the two photons not coming from the π^0; in Fig.1-right is compared with the same decay rate from refs.[1, 2]. The superimposed curve is a calculation based on Vector Meson Dominance and Linear Sigma Model[4].

3. $\phi \to \eta\mu^+\mu^-$

By measuring the invariant mass spectra of the lepton pairs produced in the Dalitz decays $V \to P\ell^+\ell^-$, the Transition Form Factors (TFF) at time-like momentum transfers can be determined. While the decay of $\phi \to \eta e^+e^-$ has been extensively studied, being the most recent result from KLOE in 2015 [5], for the decay into muon pairs only an upper limit on the branching fraction by the CMD-2 Collaboration exists, $Br < 9.4 \times 10^{-6}$ at 90% C.L.[6]. This decay, $\phi \to \eta\mu^+\mu^-$ can be studied at KLOE by selecting events with two charged tracks and two or six prompt photons from the $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$ decay channels, respectively. About 1.7 fb^{-1} of data are analyzed, and in Fig.2-left the invariant mass of the $\gamma\gamma$ pair is reported, showing a clear signal corresponding to the η mass. The second peak on the right is from the decay $\phi \to \eta\pi^+\pi^-$, that can also be studied with the same data sample, shifted with respect to the true η mass value due to the assumption of the wrong charged particle mass. In Fig.2-right the signal from the $\eta \to 3\pi^0$ decay is shown. From a fit to the peak region (Fig.3), the preliminary values of the branching fraction have been obtained: $Br(\phi \to \eta\mu^+\mu^-) = (5.65 \pm 0.11_{stat}) \times 10^{-6}$ for $\eta \to \gamma\gamma$ and $Br(\phi \to \eta\mu^+\mu^-) = (5.76 \pm 0.19_{stat}) \times 10^{-6}$ for $\eta \to 3\pi^0$. Only the statistical uncertainties are reported, the systematics are under evaluation. The

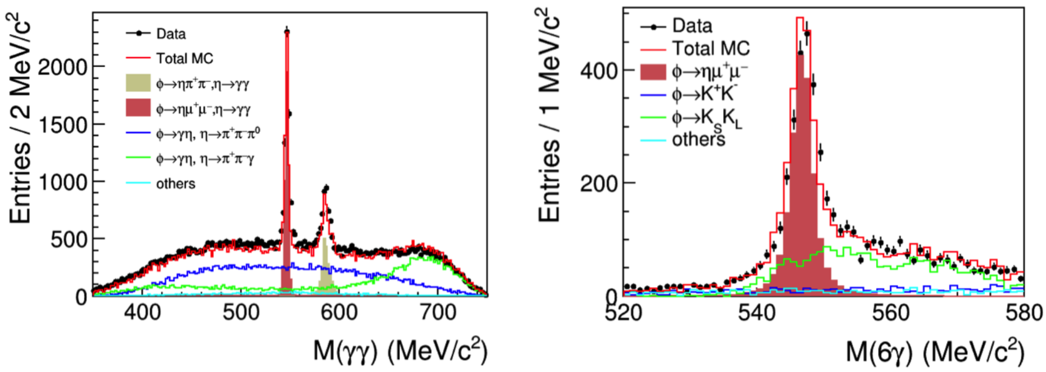

Figure 2: Left: Invariant mass of the $\gamma\gamma$ pair; right: invariant mass of the six prompt photons from $\eta \to 3\pi^0$.

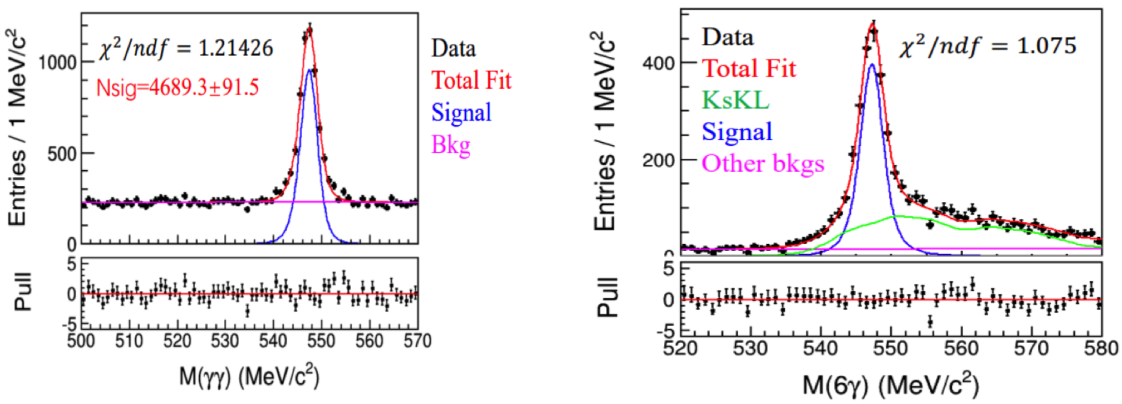

Figure 3: Fits to the $\gamma\gamma$ (left) and six photon (right) invariant masses.

TFF $F_{\phi\eta}(q^2)$ can be extracted from the $\mu^+\mu^-$ invariant mass distribution ($q^2 = M^2_{\mu\mu}$) according to:

$$\frac{1}{\Gamma(\phi \to \eta\gamma)} \frac{d\Gamma(\phi \to \eta\mu^+\mu^-)}{dq^2} = \left|F_{\phi\eta}(q^2)\right|^2 \frac{\alpha}{3\pi q^2} \sqrt{1 - \frac{4m_\mu^2}{q^2}} \left(1 + \frac{2m_\mu^2}{q^2}\right) \times$$
$$\times \left[\left(1 + \frac{q^2}{M_\phi^2 - M_\eta^2}\right)^2 - \frac{4M_\phi^2 q^2}{(M_\phi^2 - M_\eta^2)^2}\right]^{\frac{3}{2}}$$

The preliminary values of the form factor slope $\Lambda^{-2} = \frac{dF_{\phi\eta}}{dq^2}$ have been extracted: $\Lambda^{-2} = (3.01 \pm 0.10)$ GeV^{-2} for $\eta \to \gamma\gamma$ and $\Lambda^{-2} = (2.90 \pm 0.20)$ GeV^{-2} for $\eta \to 3\pi^0$.

4. Search for a leptophobic B-boson

Among the different models proposed for Dark Matter, there is the possibility of a new weakly coupled force interacting preferentially with quarks. The simplest model[7] is provided by a new gauge boson, called B-boson, not coupled to leptons, that in the mass range below 1 GeV would decay essentially to $\pi^0\gamma$. This energy range is accessible with the KLOE data by looking for 5 prompt photon events from $\phi \to \eta B$ and $\phi \to \eta\gamma$ with $\eta \to B\gamma$, both followed by $B \to \pi^0\gamma$. The first decay is studied with a sample of 1.7 fb^{-1} of KLOE data, using the $\eta \to \gamma\gamma$ final state; the background processes are $\phi \to a_0(980)\gamma$, and $\phi \to \eta\gamma$ with $\eta \to 3\pi^0$ with lost or merged photons. In Fig.4-left the $\pi^0\gamma$ invariant mass is shown, together with the background evaluated from a fit to the sidebands in a region of 5 σ, excluding the 1 σ central region, where $\sigma \sim 2$ MeV is the mass resolution. With the CL$_S$ method an exclusion region at the level of 10^{-7} for the coupling α_B of

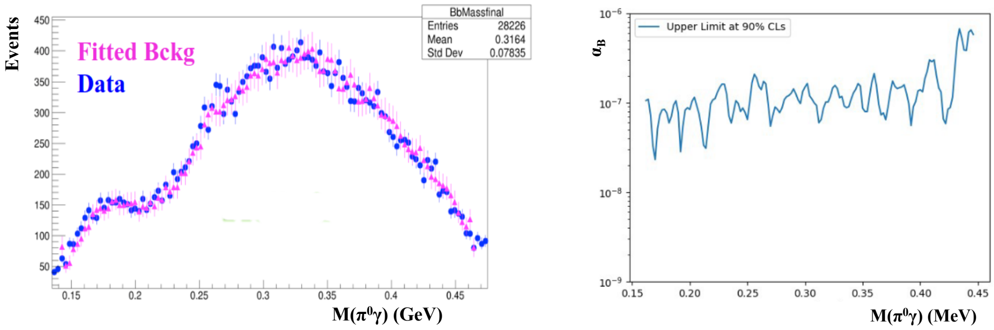

Figure 4: Left: $\pi^0\gamma$ invariant mass, data in blue, and background from sideband fit in magenta; right: upper limit on the coupling α_B as a function of the B-boson mass (preliminary).

the B-boson to quarks can be derived, as shown in Fig.4-right.

5. $\gamma\gamma \to \pi^0$

The HET, installed for the second phase of data-taking to detect the scattered electrons in $\gamma\gamma$ interactions, consisted of two scintillator hodoscopes read out with standard PMTs, placed after the first bending dipoles in each of the DAΦNE rings. The goal is to measure the π^0 width at few percent level, by detecting the π^0's produced in the process $e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-\pi^0$. The HET has been acquired asynchronously with respect to the central detector, and HET signals corresponding to 2.5 DAΦNE revolutions were recorded for each KLOE-2 trigger. The analysis is based on the comparison of the samples with the HET-KLOE coincidences (“A+”, accidental plus signal sample) and without coincidences (pure accidental,“A” sample). Events with signal on one of the two HET stations in a time window of 40 ns around the KLOE-2 trigger, and with two neutral clusters in the EMC, are selected. The number of π^0's is estimated from a simultaneous fit to several variables (see example in Fig.5), and it is normalized to radiative Bhabha scattering events. By combining the two HET stations, a statistical uncertainty of 6.5% can be reached on the π^0 width. The evaluation of the systematics coming from the different detector acceptance for signal events and for radiative Bhabha scattering is in progress.

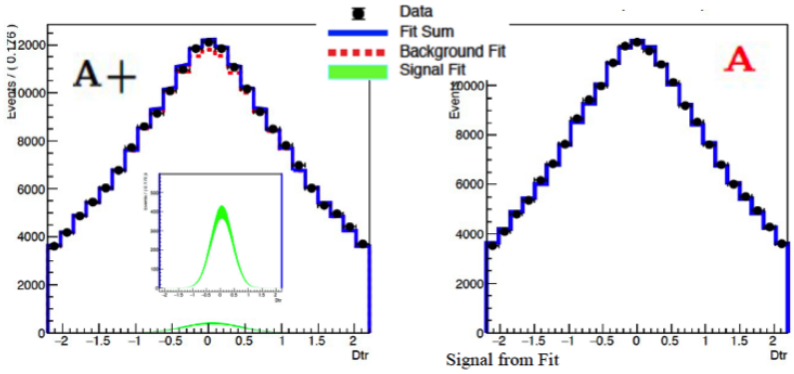

Figure 5: Example of simultaneous fit; the variable is the Time-of-Flight difference between the two clusters in the EMC. The green histogram represents the signal.

6. Conclusions

The KLOE/KLOE-2 Collaboration collected about 8 fb^{-1} of data at the peak of the $\phi(1020)$ resonance in two different data-taking periods. This is a unique worldwide data sample, from which many interesting physics processes have been studied in the past, and continue to be studied. In this paper the preliminary results on the latest analyses concerning light mesons and Dark Matter search have been presented.

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