PROCEEDINGS OF SCIENCE

Hadron Physics results at KLOE-2 experiment

Elena Perez del Rio for the KLOE-2 Collaboration[a,*]

[a] *Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, S. Łojasiewicza 11, 30-348, Kraków, Poland*

E-mail: elena.rio@uj.edu.pl

KLOE and KLOE-2 data (almost 8 fb^{-1}) constitute the largest sample ever collected at an electron-positron collider operating at the ϕ peak resonance. In total it corresponds to the production of about 24 billion of ϕ mesons whose decays include about 8 billion pairs of neutral K mesons and 300 million η mesons. A wide hadron physics program, investigating rare meson decays, $\gamma - \gamma$ interaction, dark forces and hadronic cross section, is thus carried out by the KLOE-2 Collaboration. The latest results and present analysis of the KLOE-2 collaboration are presented.

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1. The KLOE-2 detector setup

The KLOE-2 setup is a multi-purpose detector located in Frascati, Italy. It is designed for a broad physics program which includes, tests of fundamental symmetries of nature, search for processes beyond the Standard Model (SM), study rare meson decays and perform precise measurements in hadron physics [1, 2]. The experimental setup consists of a central tracking detector made up of a large cylindrical drift chamber (DC) [3] and a lead-scintillating fiber electromagnetic calorimeter [4] embedded in 0.5 T magnetic field. During the data campaign of 2002 to 2005, the KLOE experiment collected 2.5 fb^{-1} at the Φ-peak, later in the data campaign of 2014-2018, its continuation, KLOE-2, acquired more than 5 fb-1, thanks to an upgraded beam crossing scheme of the DAΦNE collider. For the KLOE-2 run, the setup was upgraded with the installation of a inner tracker [5, 6] and two new calorimeters [7] close to the interaction region (IP), to improve vertex reconstruction near IP and increase tightness of the detector. Also, to study $\gamma\gamma$ fusion, the experiment has been completed with two couples of energy taggers [8], which have been installed along the machine layout.

2. Analysis of the $\eta \to \pi^0\gamma\gamma$ decay

The $\eta \to \pi^0\gamma\gamma$ decay represents one of the golden tests of Chiral Perturbation Theory, since it is sensitive, both in the branching fraction (Br) and in the $M_{\gamma\gamma}$ spectrum, to the order p^6 term in the effective Lagrangian.[9, 10]. The 4 σ's tension between the Crystal Ball measurement [11] and the preliminary KLOE result [12] is being investigated at KLOE-2 with an independent and larger data sample, corresponding to 1.7 fb^{-1}.

The analysis selection is based in 5 and 7 prompt photon candidates in the final state. The $\phi \to \eta\gamma$ reaction, with a monochromatic photon is used to search for the rare η decay into $\pi^0\gamma\gamma$. Thus, the 5γ's from the η plus γ, final state is used to extract the signal events and then it is normalized to the fully neutral $\eta \to \pi^0\pi^0\pi^0$ sample, shown in Fig. 1 right, whose background is well under control and below 1%. The signal and background contributions are then extracted with a fit to the 4 γ's invariant mass with Monte Carlo distributions, shown in Fig. 1 left. A good agreement between data and MC is obtained, with the presence of a clear signal. The background rejection has been performed by means of kinematic fit with energy and momentum conservation constraints. A multivariate analysis (TMVA-BDT) has been also implemented.

The preliminary measurement of the $\eta \to \pi^0\gamma\gamma$ branching fraction is:

$$\mathrm{Br}(\eta \to \pi^0\gamma\gamma) = (1.21 \pm 0.13_{\mathrm{stat}}) \times 10^{-4} \tag{1}$$

This result agrees with the previous KLOE preliminary result at 1.2 σ level and is still in disagreement with the Crystal Ball measurement, with $\mathrm{Br}(\eta \to \pi^0\gamma\gamma) = (2.21 \pm 0.24_{stat} \pm 0.47_{syst}) \times 10^{-4}$ [13].

3. Dark Matter searches: B boson

The KLOE-2 collaboration continues contributing to the field of Dark Matter (DM) searches looking for a leptophobic mediator, as proposed in [14], using a total of 1.7 fb^{-1} acquired with the

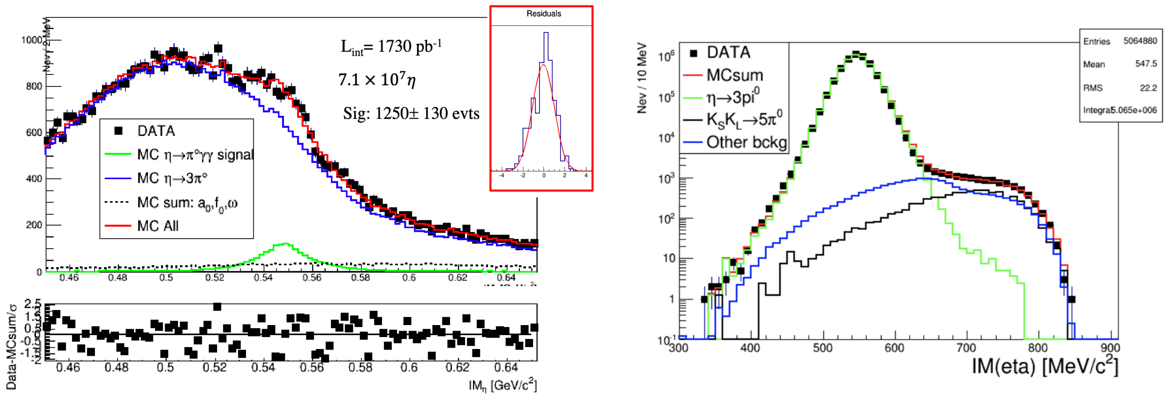

Figure 1: Data-MC comparison for $\eta \to \pi^0\gamma\gamma$ analysis: invariant mass distribution of the four photons assigned to η (left) and of the $\eta \to 3\pi^0$ normalization sample (right). Dots are data, while the different MC contributions are reported as solid lines. For the $4\,\gamma$'s fit, data-MC residuals are also shown.

KLOE detector. This new B-boson arises from a new baryonic force described by the Lagrangian:

$$\mathcal{L} = \frac{g_B}{3}\bar{q}\gamma^\mu q B_\mu \tag{2}$$

where g_B is the $U(1)_B$ coupling, estimated to be $g_B \lesssim 10^{-2} \times (m_B/100\text{ MeV})$ and B_μ the new gauge field that physically couples to baryon field. With quantum numbers $I^G(J^{PC}) = 0^-(1^{--})$, the B-boson decays in a similar way as the ω- and ϕ-meson. For masses below 600 MeV, the

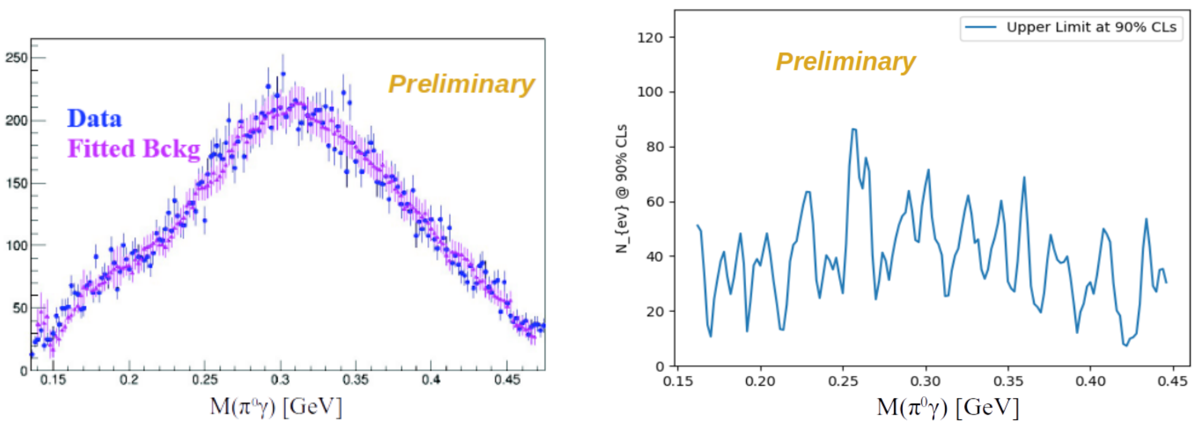

Figure 2: Left panel: Invariant mass of the $\pi^0\gamma$ system from the channel $\phi \to \eta B \to \eta\pi^0\gamma$. Blue solid dots correspond to data, magenta solid triangles are the extrapolated background from the side-bands fit. Right panel: Upper limit in the number of excluded events as a function of the B boson mass at the 90% C.L.

decay $B \to \pi^0\gamma$ becomes dominant and allows the KLOE detector to search for the B-boson in the 5γ's final state from the production channel $\phi \to \eta B$. The B-boson signal would show up as an enhancement in the $\pi^0\gamma$ invariant mass. Fig. 2 left panel shows the $\pi^0\gamma$ invariant mass from the decay $\phi \to \eta B$ with 1.7 fb^{-1} compared to the extracted background using a side-bands fit to the data. Since no signal is found, we proceed to establish a preliminary result on the upper limit as number of excluded events at 90% C.L. for the measured mass range, shown in Fig. 2 right panel.

4. Upper limit on the $\eta \to \pi^+\pi^-$ branching fraction

In the SM, the P- and CP-violating decay $\eta \to \pi^+\pi^-$ can proceed only through CP-violating weak interactions, with an expected branching fraction less than 2×10^{-27}. This limit can be raise to 1.2×10^{-17} if additionally a possible CP-violating term in the QCD Lagrangian and additional CP violation phases in the extended Higgs sector are considered. The observation of a branching fraction larger than this would be a signal of new sources of CP-violation and could help to explain the observed baryon asymmetry in the Universe [15].

The best upper limit on the branching fraction up to now was published by the KLOE collaboration on a data set of 350 pb$^-$1, Br($\eta \to \pi^+\pi^-$) $\lesssim 1.3 \times 10^{-5}$ at 90% confidence level (CL) [16]. A new recent limit was also set by the LHCb Collaboration, Br($\eta \to \pi^+\pi^-$) $\lesssim 1.6 \times 10^{-5}$ at 90% CL [17]. The newest analysis performed by KLOE-2 is based on an integrated luminosity of 1.61 fb^{-1} and sets the limit Br($\eta \to \pi^+\pi^-$) $\lesssim 4.9 \times 10^{-6}$ at 90% CL. Combined with the previous KLOE result [16] the new most precise limit is Br($\eta \to \pi^+\pi^-$) $\lesssim 4.4 \times 10^{-6}$ [15]. Using the full KLOE-2 statistical sample, the expected upper limit is Br ($\eta \to \pi^+\pi^-$) $\lesssim 2.7 \times 10^{-6}$ at 90% CL [15].

5. Study of the reactions $\phi \to \eta\pi^+\pi^-/\eta\mu^+\mu^-$

The $e^+e^- \to \eta\pi^+\pi^-$ decay, in the vector-meson dominance (VMD) model, is proceeded by ρ resonances and mainly via $\rho\eta$ intermediate state, which contributes to the total hadronic cross section. While the BaBar, CMD-2 and SND collaborations measured the cross section of this process in the energy region above 1.2 GeV [23], with the KLOE/KLOE-2 detector, it's possible to study this process in the low energy region. The specific interest of the decay $\phi \to \eta\pi^+\pi^-$ is motivated by the fact that it is double suppressed by $G-$parity and the OZI rule. The CMD-2 Collaboration set the upper limit of 1.8×10^{-5} at 90% of CL [24], while the VMD model predicts the branching fraction to be 0.35×10^{-6}. The same data sample can be also used to search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$, which has an upper limit of 0.94×10^{-5} [24] also set by CMD-2. A first

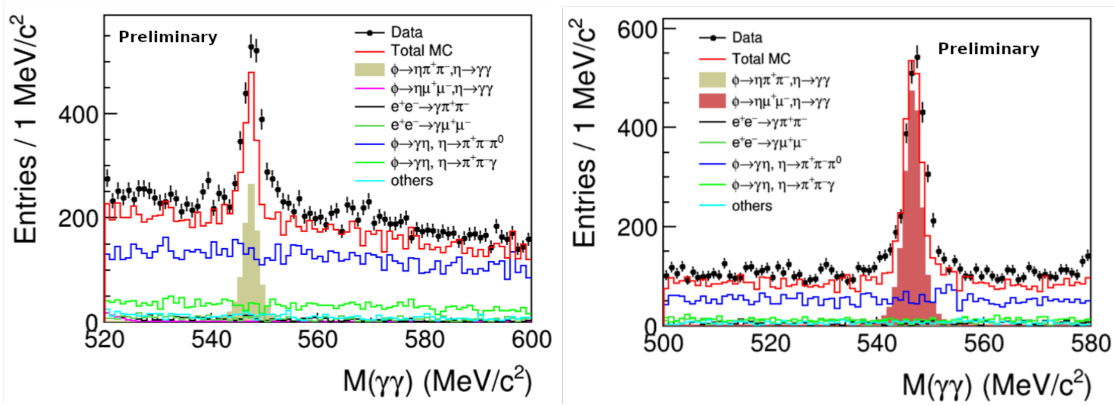

Figure 3: Invariant mass of $\gamma\gamma$ for $\gamma\gamma\pi^+\pi^-$ (left) and $\gamma\gamma\mu^+\mu^-$ (right). Black data points represent the experimental data. The different histograms show the background components evaluated from MC, full MC is the red line histogram. In the $\gamma\gamma\pi^+\pi^-$ (left) plot the MC signal is presented as the light yellow histogram, while MC signal for the $\gamma\gamma\mu^+\mu^-$ (right) process is shown in dark red filling.

760 pb^{-1} data sample has been used for the analysis of $\phi \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$ with $\eta \to \gamma\gamma$

or $\eta \to \pi^0\pi^0\pi^0$. Selected events are passed through a kinematic fit to improve the resolutions and further reject background. The resulting invariant masses are shown in Fig. 3, where clear peaks are observed around the η-meson signal mass in both spectra, which correspond to clear $\eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ decay signals with both $\eta \to \gamma\gamma$ and $\eta \to 6\gamma$ channels. This data represents the first measurement of the $\eta\mu^+\mu^-$ channel, which, as seen in the figure, has much less background contamination. These signal events will be used to extract a new and more accurate measurement of the branching fraction to compare directly to the VMD prediction.

6. π^0 production from $\gamma\gamma$ scattering

The precision measurement of the $\gamma\gamma \to \pi^0$ width would allow to give a close look at low-energy QCD dynamics. To test the predictions made by theory, a precision of $O(1\%)$ is needed. At KLOE-2, we can study the π^0 production through $\gamma\gamma$ fusion in the $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ reaction [18], where the 2γ's are virtual. To this purpose, two High Energy Tagger (HET) stations [19] have been used to detect leptons, which have been deviated from the nominal DAΦNE orbit. The measurement is performed in the low transferred momentum, q^2, in the space-like region in which the off-shellness of the photons has no impact on the measurement with respect other measurement of the width done with real photons. The HET acquisition system has been designed to register more than two turns of the machine, with a time window of the HET acquisition broader than the KLOE one. The $\gamma\gamma \to \pi^0$ signal is expected in the coincidence window between HET and KLOE while the remaining buffer depth is used to evaluate the amount of uncorrelated time coincidences between the two detectors (accidentals).

For the π^0 search a sub-set of HET plastic scintillators has been used, chosen for their operational stability over time scale of years. Candidates of single-π^0 production from $\gamma\gamma$ scattering have been pre-filtered. Data are labeled as single-arm (SA) or double-arm (DA) events. DA events are selected requiring the time coincidence of the two HET stations within 12 ns, while for SA events, we selected hits in one HET station and at least one bunch in the KLOE central detector associated with only 2 clusters in the calorimeter. Fig. 4 shows the projection, over $cos\theta_{\gamma\gamma}$, of the simultaneous fit on the KLOE-HET coincidence sample (A+ sample) in the $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$ vs $cos\theta_{\gamma\gamma}$ variables. The A+ sample contains both, accidentals (A sample) and $\gamma\gamma \to \pi^0$ signal. Accidental events coming from ϕ decays surviving selection are further rejected using MC data.

Using a sample of 3 fb^{-1}, on the electron side, we have evidence of correlated coincidence events between the tagger and the KLOE calorimeter, with a precision of about 10%.

7. Analysis of the reaction $e^+e^- \to \omega\gamma_{ISR}$

The hadronic cross section in the low energy mass range (*e.g.* below 1 GeV) can be measured with KLOE-2 data using the so-called initial-state radiation (ISR) technique, allowing to access the cross section at energies below M_Φ. This approach is used to study the $\pi^+\pi^-\pi^0$ final state below 1 GeV as a contribution to the hadronic cross section, which contributes with 4.6% to the uncertainty of the anomalous moment of the muon [25], as a test bench for the C-violating process $\phi \to \omega\gamma$. To this end, the KLOE full data-set of 1.7 fb^{-1}, has been analyzed looking for the $\pi^+\pi^-3\gamma$ final state [22]. The reconstructed events are passed through a global kinematic fit to improve the energy

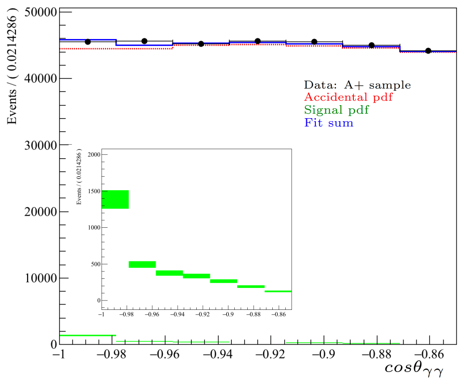

Figure 4: Results of the simultaneous fit of the KLOE-HET coincidence sample (A+), the fit projection on the $cos\theta_{\gamma\gamma}$ variable is shown. Data are the black points, the accidental amount is the red dashed line, the signal is in green while the blue line is the sum of the two fits. Insert is zoom of the signal extracted from the fit.

and time information, and the π^0 candidates are build from the best photon pair combination. The kinematics of the signal, as obtained from Monte-Carlo simulation, are then used to minimize the background contribution.

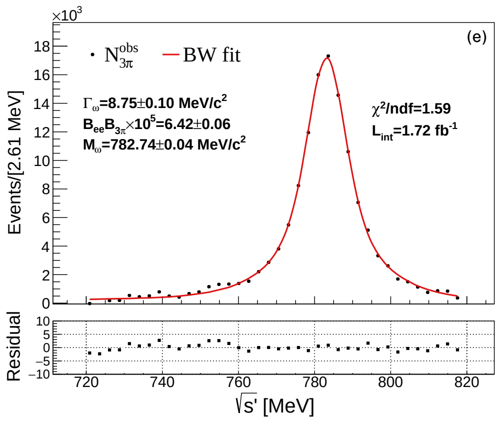

Figure 5: A Breit-Wigner distribution is fitted to the data to extract ω mass, total width and normalization related to branching fractions products. The bottom panel shows the residuals $((N_{Data} - N_{Fit})/\sigma_{Data})$ of the fit as a function of the invariant mass.

The resulting data distribution, background subtracted, is show in fig.5, where the preliminary results of the cross section fit are given. A reasonable agreement between data and Breit-Wigner cross section description is obtained. The measurement has comparable accuracy to the PDG fit/average, dominated by large systematic uncertainties, and it is useful in order to increase the precision on the fit parameters of low energy effective QCD models.

8. Conclusions

The KLOE/KLOE-2 data sample corresponds to 2.4×10^{10} ϕ mesons, the largest sample acquired in a ϕ-factory. The KLOE-2 collaboration has provided important results on decay dynamics together with limits on new physics. This contribution has presented: the most stringent UL on the $\eta \to \pi^+\pi^-$ decay, the preliminary results on the B boson search, a new dark leptophobic mediator, the preliminary result on the rare $\eta \to \pi^0\gamma\gamma$ decay and the current progress on the π^0 search, along with the studies of the $\phi \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$ and the study of the $e^+e^- \to \omega(\gamma_{IRS})$ reaction.

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References

[1] G. Amelino-Camelia and others, Eur. Phys. J. C **68**, 619-681 (2010)

[2] W. Krzemien and E. Perez del Rio, Int. J. Mod. Phys. A **34**, No. 25, 1930012 (2019)

[3] M. Adinolfi et al., Nucl. Instr. Meth. A **488**, 51 (2002)

[4] M. Adinolfi et al., Nucl. Instr. Meth. A **482**, 364 (2002)

[5] G. Bencivenni, D. Domenici, Nucl. Instr. Meth. A **581**, 221 (2007)

[6] A. Di Cicco, G. Morello, Phys. Pol B **46**, 73 (2015)

[7] F. Happacher, M. Martini, Acta Phys. Pol B **46**, 87 (2015)

[8] D. Babusci et al., Acta Phys. Pol B **46**, 81 (2015)

[9] J. Bijnens, Phys. Scripta **T 99** 34 (2002)

[10] E. Oset, J. R. Pelaez, L. Roca, Phys. Rev. **D 67** 073013 (2003)

[11] B. M. K. Nefkens *et al.*, Phys. Rev. **C 90** 025206 (2014)

[12] B. Di Micco *et al.*, Acta Phys. Slov. **56** 403 (2006)

[13] S. Prakhov *et al.*, Phys. Rev. C **78** 015206 (2008)

[14] S. Tulin, Phys. Rev. **D89**, 114008 (2014)

[15] D. Babusci et al., J. High Energ. Phys. **2020**, 47 (2020)

[16] F. Ambrosino et al., Phys. Lett. B **606**, 276 (2005)

[17] R. Aaij et al.,Phis Lett B **764**, 233 (2017)

[18] D. Babusci et al., Eur. Phys. J. C 72, 1917 (2012)

[19] D. Babusci et al., Acta Phys. Pol B 46, 81 (2015)

[20] H. Czyz, S. Ivashyn, Comput. Phys. Commun. 182 (2011)

[21] I. Agapov, G.A. Blair, S. Malton, L. Deacon, Nucl. Instrum. Meth. A 606, 708 (2009)

[22] B. Cao [KLOE-2], PoS **EPS-HEP2021** (2022), 409 doi:10.22323/1.398.0409

[23] R. R. Akhmetshin *et al.* (CMD-2 Collaboration), Phys. Lett. B **489** (2000) 125; M. N. Achasov *et al.* (SND Collaboration), Phys. Rev. D **97** (2018) 012008; J. P. Lees *et al.* (BaBar Collaboration), Phys. Rev. D **97** (2018) 052007.

[24] R. R. Akhmetshin *et al.* (CMD-2 Collaboration), Phys. Lett. B **491** (2000) 81.

[25] T. Aoyama *et al*, Phys. Rept. **887** (2020) 1-166