PROCEEDINGS OF SCIENCE

Update on hadron physics at KLOE/KLOE-2

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As a joint effort between DAΦNE and the KLOE-2 collaboration, the goal of reaching a total of 5 fb^{-1} integrated luminosity in the data-taking campaign has been achieved. The acquired large sample combined with the KLOE data set corresponds to more than 2.4×10^{10} ϕ and 3×10^{8} η mesons produced, which makes it the largest ϕ-meson sample ever collected in e^+e^- collisions. This allows precision measurements within the hadron physics program at KLOE/KLOE-2. The update on several ongoing analyses presented includes a status report on $\gamma\gamma$ physics, preliminary results on the B-boson search, a study of the $\eta \to \pi^0\gamma\gamma$ decay, and a measurement of the cross section for the $e^+e^- \to \pi^+\pi^-\pi^0$ process.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

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1. KLOE/KLOE-2 experiment

The ϕ-factory DAΦNE [1] located at LNF in Frascati, Italy, is a double storage ring e^+e^- collider operating at a center of mass energy $\sqrt{s} \sim 1020$ MeV, where ϕ mesons are produced nearly at rest. The KLOE detector consists of a large cylindrical drift chamber (DC), surrounded by a lead-scintillating fiber Electromagnetic Calorimeter (EMC). A 0.5 T magnetic field is provided by a superconducting coil. The EMC is composed of a barrel and two end-caps covering 98% of the solid angle. Energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$ and $\sigma_t = 57$ ps/$\sqrt{E(\mathrm{GeV})} \oplus 100$ ps, respectively. The DC is filled with a light gas mixture (90% helium, 10% isobutane) when operating. The position resolutions are $\sigma_{xy} \sim 150$ μm and $\sigma_z \sim 2$ mm. The momentum resolution is better than $\sigma_{p_\perp}/p_\perp \sim 0.4\%$ for large-angle tracks.

KLOE-2 is the upgraded version of the KLOE detector with several new detector parts implemented: The Quadrupole Calorimeter with Tiles (QCALT) [2] and the Crystal Calorimeter with Timing (CCALT) [2] are installed for increasing the acceptance for K_L decays and for low-energy photons from the interaction point (IP), respectively. The state-of-art Inner Tracker [3], based on a cylindrical GEM detector technology provides remarkable spatial and momentum resolutions for measuring tracks. Two new energy taggers LET [4] and HET [4] are installed aiming at $\gamma\gamma$ physics.

2. $\gamma\gamma$ physics

One of the distinctive features of the KLOE-2 experiment is the possibility to investigate two-photon physics in the space-like region at very low transferred momentum. To distinguish the signal from the background coming from ϕ decays and reach the level of precision needed to test QCD dynamics ($\sim 1\%$) [5], final state leptons coming from the $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ process must be tagged [6]. The leptons are scattered at very small angles while the π^0 produced by the fusion of the two quasi-real photons has to be detected in the KLOE calorimeter.

The DAΦNE radio-frequency is used to synchronize the HET and KLOE data acquisition, which is issued once per machine turn (325 ns) and independently recorded by the HET and KLOE, as it is used as start for the HET TDCs. The $\gamma\gamma \to \pi^0$ signal is expected in the coincidence window between HET and KLOE (1 turn of the machine) while the remaining buffer depth (about 1.5 turns), acquired together with the coincidence sample, is used to evaluate the amount of uncorrelated time coincidences between the two detectors. To evaluate the number of π^0 tagged events we perform

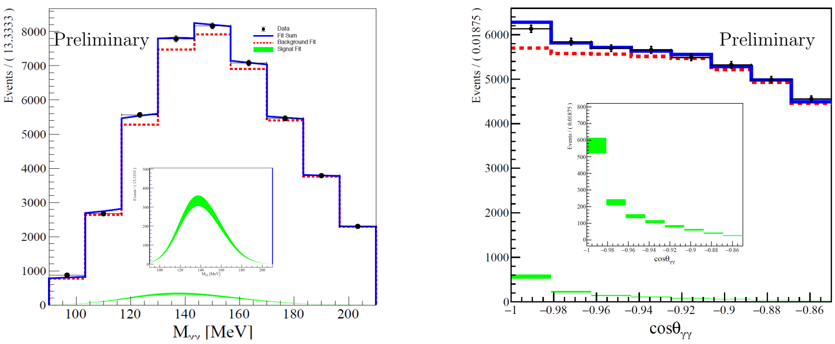

Figure 1: *Left*: Invariant mass of the $\gamma\gamma$ system. *Right*: Opening angle between the two photons.

multi-dimensional simultaneous likelihood fits on $M_{\gamma\gamma}$, $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/\mathrm{c}$, $\cos\theta_{\gamma\gamma}$ and $\mathrm{P}^{z}_{\gamma\gamma}$ variables for both coincidence and accidentals contained samples, where $P^{z}_{\gamma\gamma}$ is the longitudinal total momentum of the two photons, T and $R = \sqrt{x^2_{\mathrm{cl}} + y^2_{\mathrm{cl}} + z^2_{\mathrm{cl}}}$ are time and position of the cluster, by considering also the expected correlation between the longitudinal π^0 momentum and HET plastics. In these fits, the signal pdf is obtained from full simulation while accidental pdf is directly modeled from measured out-of-coincidence window data. The fit to this background sample is used to constrain the number of accidentals in the coincidence window fit.

Figure 1 shows the results of the fits performed on the coincidence sample (about 1.5 fb^{-1}) in the $M_{\gamma\gamma}$ and opening angle of the π^0 photons with a signal-enriching cut $|\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/\mathrm{c}| < 0.3$ ns. About 8% uncertainty on the signal counting has been reached. Additional data up to 3 fb^{-1} are currently being analysed. We are checking the reliability of the signal simulation and the effects of the kinematic fit on the reconstructed variables.

3. *B*-boson search

Among searches of exotic dark matter candidates, a new weakly-coupled force at the QCD scale interacting primarily with quarks is postulated [7]. Similar to the "dark photon" known as A' or U boson, which can couple the electroweak sector via kinetic mixing, a massive B boson can arise from the breaking of a new $U(1)_B$ gauge symmetry. The theory is given by the Lagrangian $\mathcal{L} \propto g_B \bar{q}\gamma^{\mu} q B_{\mu}$, where the B-field only couples to the baryon number. The gauge coupling constant g_B, which is universal for all quarks, and the baryonic fine structure constant $\alpha_B \equiv g^2/4\pi$ are defined. The B boson has the same quantum numbers and decay modes as the ω meson *e.g.* the leading decay $B \to \pi^0\gamma$ is expected for $m_{\pi} \lesssim m_B \lesssim 620$ MeV. Since the boson can be produced in various pseudoscalar meson decays *i.e.* $P \to B\gamma$, where $P = \pi^0, \eta, \eta'$, a particle with mass below 1 GeV is the suitable object to be detected at KLOE-2. So far, no evidence of the B boson has been found.

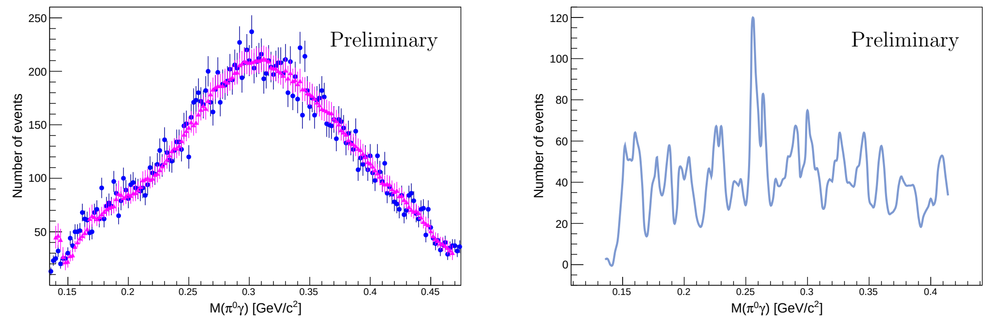

Figure 2: *Left*: invariant mass of the $\pi^0\gamma$ system. *Right*: number of excluded events at 90% CLs.

In this analysis, we use the data sample collected at KLOE, corresponding to an integrated luminosity of $\sim$ 1.7 fb^{-1}. We investigate the main signal channel $\phi \to \eta B(\pi^0\gamma)$[1] which has a five-photon final state. Events from the background channels $\phi \to a_0(\eta\pi^0)\gamma$ and $\phi \to \eta(3\pi^0)\gamma$ can

[1] $\eta \to B(\pi^0\gamma)\gamma$ can also be a suitable channel for the B-boson search.

be particularly harmful to the signal selection, where the latter can mimic the signal due to photon loss or cluster merging. Using energy-momentum conservation and the time-of-flight constraints of the neutral clusters, a kinematic fit is performed to suppress the backgrounds and enhance the resolution. No significant signal signature is found in the $\pi^0\gamma$ invariant mass spectrum (fig. 2 left). The upper limit on the number of signal events at 90% confidence levels gives the first constraint on the B boson, see (fig. 2 right).

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

The decay $\eta \to \pi^0\gamma\gamma$ is traditionally considered as the "Golden" mode to test Chiral Perturbation Theory (ChPT) [8, 9]. The theory implies that the first sizeable contribution comes at $O(p^6)$, and the corresponding coefficients involved are not precisely determined.[2] Several experiments have measured the branching ratio of the decay $\eta \to \pi^0\gamma\gamma$ [10–12], here indicated as $\mathcal{B}_{\pi\gamma\gamma} \equiv \mathcal{B}(\eta \to \pi^0\gamma\gamma)$. The preliminary KLOE result based on 450 pb^{-1} $\mathcal{B}_{\pi\gamma\gamma} = (8.4 \pm 2.7_{\text{stat}} \pm 1.4_{\text{syst}}) \times 10^{-5}$ [12] is found in tension with the PDG value $\mathcal{B}_{\pi\gamma\gamma} = (25.6 \pm 2.2) \times 10^{-5}$ [13].

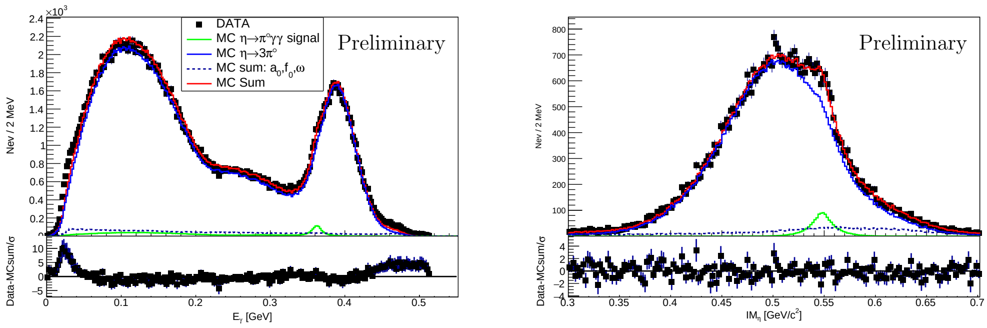

Figure 3: *Left*: Energy distributions of all five photons in the final state. The backgrounds $\phi \to \eta(3\pi^0)\gamma/a_0(\eta\pi^0)\gamma/f_0(\pi^0\pi^0)\gamma$ and $e^+e^- \to \omega(\pi^0\gamma)\pi^0$ are included in the plot. *Right*: Invariant mass of the η meson.

In this analysis, an independent and larger data sample corresponding to an integrated luminosity of $\sim$ 1.72 fb^{-1} is used, which is fourfold larger than the previous KLOE analysis. The signal process $\phi \to \eta(\pi^0\gamma\gamma)\gamma$ has a five-photon final state. The main background $\phi \to \eta(3\pi^0)\gamma$ has seven photons in the final state which can easily mimic the signal due to the loss of photons or merged clusters. By studying the cluster information, a multi-variable analysis [14] suppresses the merged clusters from $\eta \to 3\pi^0$. The kinematic fit with energy-momentum and time-of-flight constraints on the clusters is used to reject the backgrounds substantially, additional constraints on the η and π^0 masses are enforced in the fit to veto the $\phi \to a_0(\eta\pi^0)\gamma$ background. Backgrounds $\phi \to f_0(\pi^0\pi^0)\gamma$ and $e^+e^- \to \omega(\pi^0\gamma)\pi^0$, which have $2\pi^0$ intermediate states can mimic the signal in the same manner. We perform pseudo-χ^2 tests on the signal and background hypotheses to reject the $2\pi^0$ events. A good MC-data agreement is achieved after applying the kinematic fit. (fig. 3 left) shows distributions of all five photons in the final states for all normalized MC channels, where the monochromatic photons associated to the $\phi \to \eta\gamma$ decay peak at $\sim$ 363 MeV. Clear evidence of the

[2] At the tree-level, the amplitudes vanish at the lowest orders $O(p^2)$ and $O(p^4)$. The first non-trivial contribution is given at $O(p^4)$ from the loops that involve light hadrons, but is strongly suppressed by G-parity violation.

signal is seen in the invariant mass of the η-meson spectrum, see (fig. 3 right). The branching ratio $\mathcal{B}_{\pi\gamma\gamma} = (\mathbf{12.3} \pm \mathbf{1.4_{stat}}) \times \mathbf{10^{-5}}$ is obtained by using $3\pi^0$ normalization based on 7 photons events counting.[3] The result from this work is compatible with the previous KLOE analysis with a much higher signal acceptance $\sim 20\%$, and the accuracy is significantly improved thanks to larger statistics. More importantly, the latest preliminary KLOE result tends to agree with a recent theoretical prediction [8]. Studies on the systematic uncertainties and the invariant mass spectrum of the two photons not originating from π^0 are currently in progress.

5. $e^+e^- \to \pi^+\pi^-\pi^0$

Quantum field theory predicts a peculiar behaviour of the muon, that it can interact with virtual particles known in the Standard Model (SM) or beyond. Precise knowledge on the muon's anomalous magnetic moment $a_\mu \equiv (g_\mu - 2)/2$ should provide insight into potential new physics due to its heavier mass, about 200 times larger than for the electrons. The recent result from the Muon g-2 experiment at Fermilab [15] has confirmed the BNL [16] observation, its predecessor. The combined data gives a 4.2σ discrepancy compared to the SM prediction [17] with most of its uncertainties involving virtual hadrons. The three-pion channel $e^+e^- \to \pi^+\pi^-\pi^0$ accounts for the second largest contribution to the leading-order hadronic vacuum polarization with an uncertainty of $\sim 4.6\%$.

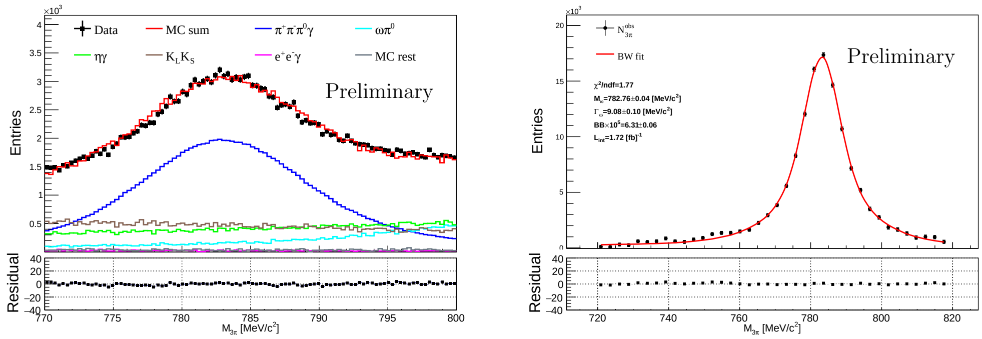

Figure 4: *Left*: The 3π invariant mass spectrum. The signal channel $e^+e^- \to \pi^+\pi^-\pi^0$ is presented in blue histogram. *Right*: The background-subtracted 3π mass distribution.

In data-driven analyses, comparing to the 2π data sets, less 3π data sets are available for the SM g-2 evaluations, and only a few have used the Initial State Radiation (ISR) [18]. The high luminosity provided by DAΦNE offers a unique opportunity of studying the 3π production in e^+e^- collisions, since the high statistics compensates the small ISR cross section. A ~ 1.72 fb^{-1} data sample collected at KLOE is used to obtain the cross section for $e^+e^- \to \pi^+\pi^-\pi^0$ in the energy range below 1 GeV. The MC distribution in the 3π mass spectrum is a result of smeared MC truth for the signal. A good agreement between the sum of all MC channels and the data is achieved after normalization, see (fig. 4 left). To extract ω mass, width of the resonance, and product of the branching ratio, we fit the background-subtracted 3π spectrum with a signal Breit-Wigner (BW)

[3]The stability is improved by studying 6-8 photon events, the variation of results from the analyses using different samples is at the level of few percent.

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model, the results are shown in (fig. 4 right). The preliminary results of the cross section have relatively small statistical uncertainty. Estimation of the systematic uncertainties is ongoing. A full model that includes ω-ϕ interference is currently under investigation and will replace the BW fit function.

6. Conclusion

We report the progress of several ongoing analyses within the hadron physics program using the KLOE and KLOE-2 data. Given the high statistics of the data collected with KLOE-2, the preliminary results of these analyses are expected to be improved.

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