Recent results on hadron physics at KLOE-2

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Abstract. The KLOE-2 experiment at the Frascati $\phi-$factory ended its data-taking in March 2018 collecting more than 5 fb^{-1} at the ϕ peak. The new data sample, together with the KLOE one, corresponds to 2.4 $\times 10^{10}$ ϕ and 3.1×10^{8} η meson events. It represents the largest sample ever collected at the ϕ peak in e^+e^- colliders, allowing to study light mesons with unprecedented statistics. Recent results obtained with KLOE data on hadron physics e.g. – measurement of the running of the fine structure constant below 1 GeV, the combination of hadron cross section measurements with determination of $a_\mu^{\pi\pi}$, the new preliminary $\eta \to \pi^+\pi^-$ limit, and progress in $\gamma\gamma$ studies – will be presented.

1 Introduction

KLOE is a multi-purpose detector conceived to develop a wide-ranging physics program allowing to test fundamental symmetries of nature, search for processes beyond the Standard Model (SM), study rare meson decays and perform precise measurements in hadron physics. The experimental apparatus consists of a central detector made up of a large cylindrical drift chamber (DC) [1] and a lead-scintillating fiber electromagnetic calorimeter [2] surrounded by a magnetic field of 0.5 T. The KLOE experiment collected 2.5 fb^{-1} at the ϕ-peak running from 2002 to 2005, its continuation, KLOE-2, started on November 2014 and ended on March 2018 collecting more than 5 fb^{-1}, thanks to an upgraded beam crossing scheme of the DAΦNE collider. The KLOE detector has been also upgraded for the KLOE-2 run with the installation of a inner tracker [3, 4] and two calorimeters [5] close to the interaction region (IP) , in order to improve vertex reconstruction near IP and increase tightness of the detector. Moreover, two couples of energy taggers [6] have been installed along the machine layout to study $\gamma\gamma$ fusion.

KLOE and KLOE-2 full data sets (8 fb^{-1}) are invaluable to perform precise measurements and study low energy hadron physics.

In this paper most recent results on hadron physics obtained with the KLOE data and updates on the status of the $\gamma^*\gamma^* \to \pi^0$ search with KLOE-2 data sample will be presented.

2 Measurement of the running of the fine structure constant α

The precise knowledge of the running of α is very important since it involves low energy non-perturbative hadronic effects representing the major uncertainty and limitation of electroweak precision tests and the SM prediction of the the anomalous magnetic moment of the

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muon [7]. Vacuum polarization (VP) effects can be accounted for by redefining the fine structure constant in terms of the shift $\Delta\alpha(s)$ which is function of squared momentum transfer $s = q^2$: $\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)}$. The shift $\Delta\alpha(s)$ receives contributions from all leptons, lightest five quarks and from the top quark, whose contribution is negligible at low energies: $\Delta(s) = \Delta(s)_{\text{lep}} + \Delta(s)^{(5)}_{\text{had}} + \Delta(s)_{\text{top}}$. At low energy the hadronic contribution can be evaluated only through an experimental approach by means of dispersion relations. By using a sample of 1.7 fb^{-1}, the KLOE-2 Collaboration evaluated at 1% precision level the running of $\alpha(s)$ in the time-like region in the 0.6–0.9 GeV energy range. Figure 1 shows the measurement of square of the modulus of $\alpha(s)$ obtained from differential $\mu^+\mu^-\gamma(\gamma)$ cross section with initial state radiation (ISR) normalized to the MC *PHOKHARA* [11–14] undressed of all VP effects (bare cross section). The hadronic contribution to the photon propagator, with its characteristic $\rho - \omega$ interference structure, is clearly visible in the plot.

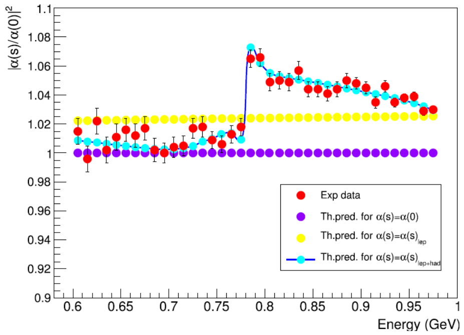

Figure 1. The square of the modulus of the running $\alpha(s)$ in units of $\alpha(0)$ (red points) [8] compared with the prediction (cyan) [9, 10] as a function of the dimuon invariant mass. Theoretical expectations in case of no running (violet) and only leptonic contribution (yellow) are also shown.

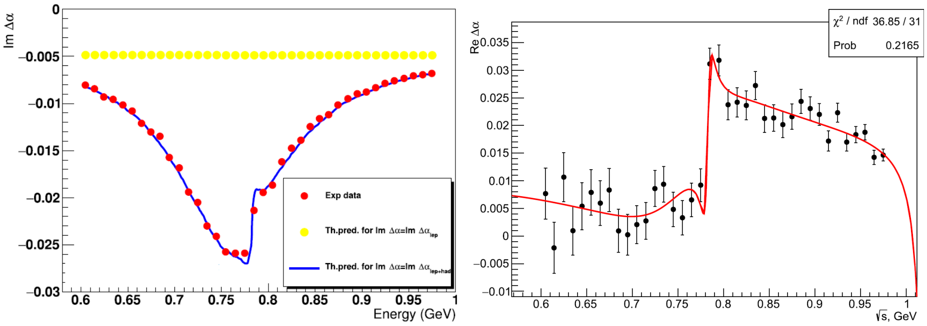

Figure 2. Left panel: $\text{Im}\,\Delta\alpha$(s) extracted from the KLOE data [8] compared with the values provided by *alphaQED* routine [9, 10] (without the KLOE data) for $\text{Im}\,\Delta\alpha = \text{Im}\,\Delta\alpha_{\text{lep}}$ (yellow points) and $\text{Im}\,\Delta\alpha = \text{Im}\,\Delta\alpha_{\text{lep}+\pi\pi}$ (blue solid line). Right panel: Re $\Delta\alpha(s)$ extracted by KLOE data (black points) with a fit (red line) [8]. Only statistical errors are shown.

In the time-like region of q^2, $\Delta\alpha(s)$ is a complex quantity with real and imaginary part given by $\text{Re}\,\Delta\alpha = \sqrt{|\alpha(s)/\alpha(0)|^2 - (\text{Im}\Delta\alpha)^2}$ and $\text{Im}\,\Delta\alpha = -\frac{\alpha}{3}\text{R(s)}$, respectively, with $\text{R}_{\text{had}}(s) = \frac{\sigma(e^+e^- \to \text{had})}{\sigma(e^+e^- \to \mu^+\mu^-)}$. Using the above measurement of $|\frac{\alpha(s)}{\alpha(0)}|^2$ and the pion form factor already measured by KLOE [15], real and imaginary part of $\Delta\alpha(s)$ have been extracted for the first time as shown in Figure 2. Figure 2 left panel shows Im$\Delta\alpha$(s) (red points) obtained from KLOE data in the hypothesis of $\pi^+\pi^-$ contribution only while right panel shows the real part of $\alpha(s)$ extracted from data. The red line is a fit performed using a sum of leptonic and hadronic contributions. The $\omega(782)$ and $\phi(1020)$ resonances have been parametrized as Breit-Wigner, while for the $\rho(770)$ resonance, the Gounaris-Sakurai parametrization [16] has been used; a non-resonant term has been also included in the fit. For the mass and the width of the ϕ, the ω width and the branching ratio product Br($\phi \to e^+e^-$)Br($\phi \to \mu^+\mu^-$), the PDG values [17] have been used. Assuming lepton universality and correcting for phase space, a branching ratio $\mathrm{Br}(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4 \pm 1.7) \times 10^{-5}$ is obtained, which is in good agreement with the PDG value $(9.0 \pm 3.1) \times 10^{-5}$. All the results show a clear contribution of the $\rho - \omega$ resonances to the photon propagator resulting in a more than 5σ significance of the hadronic contribution to the running of $\alpha(s)$.

3 KLOE Combined hadron cross section $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ and $a_\mu^{\pi\pi}$ contribution

The discrepancy between the calculated and measured values of the anomalous magnetic moment of the muon, a_μ, is one of the most powerful probe of physics beyond SM. The major source of uncertainty of the calculated value, a_μ^{SM}, originates from the hadronic VP contribution a_μ^{HVP} whose di-pion term $a_\mu^{\pi^+\pi^-}$ represents more than 70% of its total estimate. The a_μ^{HVP} contribution can be determined by a dispersion integral using the bare hadron cross section $\sigma^0(e^+e^- \to \text{had})$ with final state radiation correction included. The KLOE collaboration performed three precise measurements of the cross section $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ in 2008 [25], 2010 [26] and 2012 [27]. All three measurements are undressed of all VP effects, including FSR, overlapping in the energy range 0.6–0.95 GeV. These three KLOE $\sigma_{\pi\pi(\gamma)}$ measurements have been updated and then combined with consistent results [18]. To properly account of their correlations, statistical and systematic covariance matrices have been carefully constructed [18]. Data have been combined incorporating the energy dependent statistical and systematic uncertainties and corresponding correlations, using an iterative minimisation of a

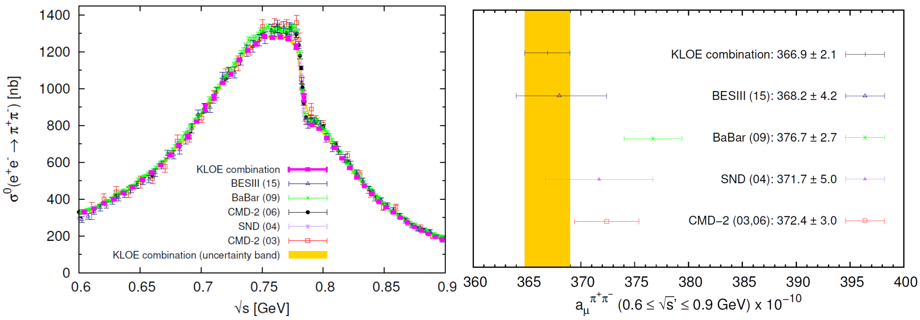

Figure 3. Left panel: the $\pi^+\pi^-$ cross section from the KLOE combination [18] compared with CMD-2 [19–21], SND [22], BaBar [23] and BESIII [24] data. The uncertainty on the KLOE combination is represented by the yellow band. Right panel: estimates of $a_\mu^{\pi^+\pi^-}$ from the KLOE combination [18], combined CMD-2 [19–21], SND [22], BaBar [23] and BESIII [24] in the 0.6–0.9 GeV range. The yellow band represents the KLOE combination uncertainty. All the uncertainties shown are the statistical and systematic uncertainties summed in quadrature.

linear χ^2 function [18]. Figure 3, left panel, shows the KLOE combined $\pi^+\pi^-$ cross section measurement compared with results obtained by CMD-2 [19–21] and SND [22] experiments by energy scan, and Babar [23] and BESIII [24] by radiative return. In Figure 3, right panel, the estimate of $a_\mu^{\pi^+\pi^-}$ from KLOE combined and all the above experiments is reported. In the overlapping region of all KLOE measurements, $0.10 < s < 0.95\,\mathrm{GeV}^2$, KLOE combined estimation of the contribution to muon magnetic moment anomaly is $a_\mu^{\pi^+\pi^-} = (489.8 \pm 5.1) \times 10^{-10}$ which is consistent with the CMD-2, SND and BESIII measurements within 1.5σ. The observed difference with the BaBar evaluation is below 3σ.

4 $\eta \to \pi^+\pi^-$ limit

The $\eta \to \pi^+\pi^-$ decay is a P- and CP-violating process. According to SM, this decay can occur only through a CP-violating weak interaction mediated by a virtual K_S^0 meson and has a branching ratio $\mathrm{Br}(\eta \to \pi^+\pi^-) \leq 2 \times 10^{-27}$ [28, 29]. This upper limit (UL) can increase of an order of magnitude by introducing a possible QCD-violating term contribution to the decay [28, 29] and reach 10^{-15} if a CP violation is allowed also in an extended Higgs sector [28, 29]. 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. The KLOE Collaboration already set the best UL on the branching ratio of the di-pion decay of the η meson by using $350\,\mathrm{pb}^{-1}$: $\mathrm{Br}(\eta \to \pi^+\pi^-) \leq 1.3 \times 10^{-5}$ at 90% CL [30]. A new preliminary limit has been extracted by the KLOE-2 Collaboration increasing the sample statistic to $1.6\,\mathrm{fb}^{-1}$ of KLOE data. The selection of $\phi \to \eta\gamma$, $\eta \to \pi^+\pi^-$ events requires one vertex with two opposite charged tracks reaching the KLOE EMC. The tracks are required to be at large polar angle $45^\circ < \theta < 135^\circ$ as well as the prompt photon in time in order to suppress ISR. The angle between the missing momentum of the di-pion system and the prompt photon direction has to be less than 0.03 rad to reject $\pi^+\pi^-\pi^0$ background. Main background contamination originates from radiative Bhabha, $\gamma\mu^+\mu^-$ and $\rho(\pi\pi)\pi$ with a lost photon. Time of flight techniques are used to separate γe^+e^- from selected $\gamma\pi^+\pi^-$ events 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 one photon, as shown in Figure 4 left panel. Candidates

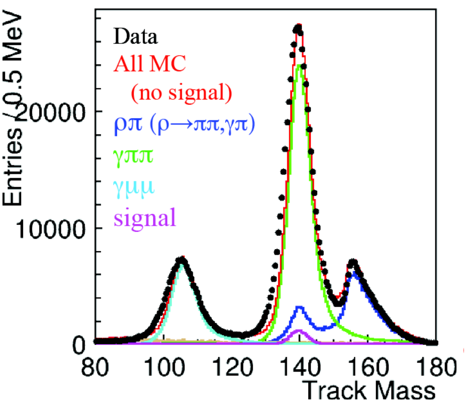

Figure 4. Left panel: track mass distributions. Data are shown in black, all MC background contributions in the hypothesis of no $\eta \to \pi^+\pi^-$ signal are in red ($\rho\pi$ in blue, $\gamma\pi^+\pi^-$ in green, $\gamma\mu^+\mu^-$ in cyan), while the signal is shown in violet. Right panel: $\pi^+\pi^-$ invariant mass distribution for data (black points). The curve is a third polynomial function with superimposed a MC signal shape in arbitrary units.

surviving the above selection are mainly $(\gamma)\gamma\pi^+\pi^-$ events. The η resonance should appear over the continuum $(\gamma)\gamma\pi^+\pi^-$ spectrum. No signal is observed around the η mass in the $\pi^+\pi^-$ mass spectrum as can be seen in the right panel of Figure 4. A limit on number of signal events is extracted by using a Bayesian method. The irreducible background is evaluated by a fit to the observed $\pi^+\pi^-$ mass spectrum with a third-order polynomial function, while the signal is described with a dedicated MC simulated shape. The preliminary UL on the branching ratio is 6.3×10^{-6} at 90% CL. With the whole KLOE /KLOE-2 data samples the upper limit is expected to reach 2.7×10^{-6}.

5 $\gamma\gamma$ studies

The precision measurement of the $\pi^0 \to \gamma\gamma$ width allows to gain insights into the low-energy QCD dynamics. A way to achieve the precision needed (1%) in order to test theory predictions is to study the π^0 production through $\gamma\gamma$ fusion in the $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-\pi^0$ reaction [31, 32]. One of the distinctive feature of the KLOE-2 experiment is the possibility to perform this measurement [32]. In order to reduce the background coming from ϕ-meson decays, two High Energy Tagger (HET) stations [6] are used to measure the deviation of final state leptons from their main orbit by determining their position and timing. The HET detectors have been installed in roman pots just at the exit of the DAΦNE dipole magnets, 11 m away from the IP, both on positron and electron sides. The HET sensitive area is made up of a set of 28 plastic scintillators. The measured time resolution of 550(1) ps gives the possibility to clearly identify the correct bunch crossing ($\Delta T_{bunch} \sim 2.7$ ns).

The HET counting rate is dominated by low angle radiative Bhabha whose effective cross section has been measured as a function of the data-taking period, in order to study the acceptance × efficiency of the detector, and for data-quality purposes. Data quality studies pointed out that the effective cross section is of the order of 10 mb with big instabilities for the scintillators closest to the beam. A sub-set of HET plastic scintillators, showing operational stability over a time scale of years, with effective cross section of about 1-2 mb, has been identified and used for the π^0 search.

The HET-KLOE coincidence data sample is dominated by time coincidences from independent events (accidentals), even at one-bunch-crossing level. Since the HET DAQ window is about 2.5 times larger than KLOE one, the sub-sample in the out-of-time window of the two detectors is continuously acquired at the same time of the coincidence sample and, thus, it can be correctly subtracted.

We have pre-filtered candidates of single-π^0 production from $\gamma\gamma$ scattering, recording information on the hit in the tagger, trigger, DAΦNE operational parameters, clusters and tracks reconstructed in the KLOE detector. Data are classified as single-arm (SA) or double-arm (DA) events. DA events are selected just requiring the time coincidence of the two HET stations within 12 ns, while for SA events, we select hits in one HET station and at least one bunch in KLOE associated with only 2 clusters in the KLOE EMC, in a time window of 30 ns around the trigger. Very loose kinematics cuts are applied to reconstructed data. By analysing a sample of 500 pb^{-1}, a statistical evidence of correlated coincidence events between the tagger station hits and KLOE calorimeter clusters has been observed for the first time, after a event-by-event subtraction of the registered amount of accidentals. New data reconstruction is ongoing in order to study in more detail the tagged sample.

6 Conclusions

The large data samples of light mesons collected by the KLOE/KLOE-2 experiments are invaluable to perform precise measurements in low energy hadron physics and test physics beyond SM. The first precise measurement of the running of $\alpha(s)$ below 1 GeV, and a more precise evaluation of the $a_\mu^{\pi\pi}$ contribution, through the combined KLOE hadron cross section measurements, have been recently published. The $\eta \rightarrow \pi^+\pi^-$ limit has been updated and progresses have been made on $\gamma^*\gamma^* \rightarrow \pi^0$ search using KLOE-2 data.

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