PROCEEDINGS OF SCIENCE

Hadron physics at KLOE and KLOE-2

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The KLOE experiment has collected 2.5 fb^{-1} at the peak of the ϕ resonance, at the e^+e^- collider DAΦNE in Frascati. A new beam crossing scheme, allowing for a reduced beam size and increased luminosity, is operating at DAΦNE. The upgraded KLOE-2 detector is successfully rolled in inside this new interaction region and is ready to acquire collision data.

Pseudoscalar production at the ϕ-factory associated to internal conversion of the photon into a lepton pair allows the measurement of the form factor F($q_1^2 = M_\phi^2, q_2^2 > 0$) of pseudoscalar mesons in the kinematical region of interest for the VMD model. The only existing data on $\phi \to \eta e^+ e^-$ are based on 213 events. At KLOE, with a sample of 1.5 fb^{-1}, a detailed study of this decay has been performed using the $\eta \to \pi^+\pi^-\pi^0$ final state. Simple analysis cuts provide about 14,000 signal events with very small residual background contamination. The e^+e^- invariant mass distribution has been used to set an upper limit on the process $\phi \to \eta U$, where U is a vector gauge boson, mediating dark forces. The resulting exclusion plot covers the mass range $5 < M_U < 470$ MeV, setting an upper limit on the ratio between the U boson coupling and the fine structure constants of $\alpha'/\alpha \leq 2 \times 10^{-5}$ at 90% C.L. for $50 < M_U < 420$ MeV [1].

Additionally, the measurement of the ratio $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$ using an integrated luminosity of 558 *picobarns*$^{-1}$ will be reported. The $\eta \to \pi^+\pi^-\gamma$ process is supposed to proceeds both via a resonant contribution, mediated by the ρ meson, and a non resonant direct term, connected to the box anomaly. The presence of the direct term affects the partial width value. The KLOE result $R_\eta = \Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.1856 \pm 0.0005_{stat} \pm 0.0028_{sys}$ is in agreement with a recent CLEO measurement, which differs by more 3σ from the average of previous results.

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1. The KLOE detector

The KLOE (**Klo**ng **E**xperiment) detector is installed at the interaction point (IP) of the electron and positron beams of the DAΦNE (**D**ouble **A**nnular ϕ-factory for **N**ice **E**xperiments) collider operating at the Laboratori Nazionali di Frascati (LNF). The KLOE detector consists of two main subsystems: an electromagnetic calorimeter and a large drift chamber. Energy and time resolutions for calorimeter are $\sigma_E/E = 5.7\%/\sqrt{E\ (\mathrm{GeV})}$ and $\sigma_t = 57\ \mathrm{ps}/\sqrt{E\ (\mathrm{GeV})} \oplus 100\ \mathrm{ps}$, respectively. For the drift chamber, the spatial resolutions are $\sigma_{xy} \sim 150\ \mu$m and $\sigma_z \sim 2$ mm, the momentum resolution is $\sigma(p_\perp)/p_\perp \approx 0.4\%$, while verticies are reconstructed with a spatial resolution of $\sim$ 3 mm.

2. Study of the $\phi \to \eta e^+e^-$ decay

The analysis of $\phi \to \eta\ e^+e^-$ decay is interesting from several point of view. The structure of ϕ and η mesons and underlying quark dynamics in the transition region can be extracted from e^+e^- invariant mass spectrum. By comparing the experimentally measured spectrum of the lepton pair with QED calculations for pointlike particles, it is possible to determine transition form factor in the time-like region of momentum transfer [2].

The only measurement of the form factor comes from the SND collaboration, and it is not in good agreement with predictions from the Vector Meson Dominance (VMD) framework [2, 3]. The form factor is often parametrized in one-pole approximation:

$$F_{\phi\eta}(q^2) = \frac{1}{1 - q^2/\Lambda^2}\,, \tag{2.1}$$

where $q = M_{ee}$ and Λ is a free parameter.

The theoretical calculation for Λ is 1.0 GeV (VMD), while the value measured by SND is 0.5±0.1 GeV [4]. Recently, other theoretical models provide different predictions [5, 6]. In this paper preliminary results of the investigation of the $\phi \to \eta\ e^+e^-$ decay at KLOE are presented.

The analysis of the $\phi \to \eta\ e^+e^-$ decay with subsequent $\eta \to \pi^+\pi^-\pi^0$, has been performed on 1.52 fb^{-1} of the KLOE dataset. The signal Monte Carlo (MC) simulation has been produced with $d\Gamma(\phi \to \eta\, e^+e^-)/dq$ weighted according to Vector Meson Dominance model [2], using the form factor parametrization from the SND experiment [4]. Data-MC corrections for cluster energies and tracking efficiency, evaluated with radiative Bhabha events and $\phi \to \rho\pi$ samples respectively, have been applied [1].

The first step of the analysis was preselection of events, that have to satisfy the following criteria:

1. two positive and two negative tracks with point of closest approach to the beam line inside a cylinder around the interaction point (IP), with transverse radius R=4 cm and length Z=20 cm;

2. two energy clusters in the calorimeter with $E > 7$ MeV not associated to any track, in an angular acceptance $|\cos\theta_\gamma| < 0.92$ and in the expected time window for a photon ($|T_\gamma - R_\gamma/c| < \mathrm{MIN}(5\sigma_t, 2\,\mathrm{ns})$);

3. best $\pi^+\pi^-\gamma\gamma$ match to the η mass with the pion hypothesis to assign $\pi^\pm$ tracks; the other two tracks are then assigned to $e^\pm$;

4. loose cuts on η and π^0 invariant masses ($495 < M_{\pi^+\pi^-\gamma\gamma} < 600$ MeV, $70 < M_{\gamma\gamma} < 200$ MeV).

After preselection, a clear peak corresponding to $\phi \to \eta e^+e^-$ events is observed in the distribution of the recoil mass to the e^+e^- pair (Fig. 1 (left)). The second peak at ~ 590 MeV is due to $\phi \to K_SK_L$, $K_S \to \pi^+\pi^-$ events with a wrong mass assignment. Events in the $535 < M_{\mathrm{recoil}}(ee) < 560$ MeV window are retained for further analysis.

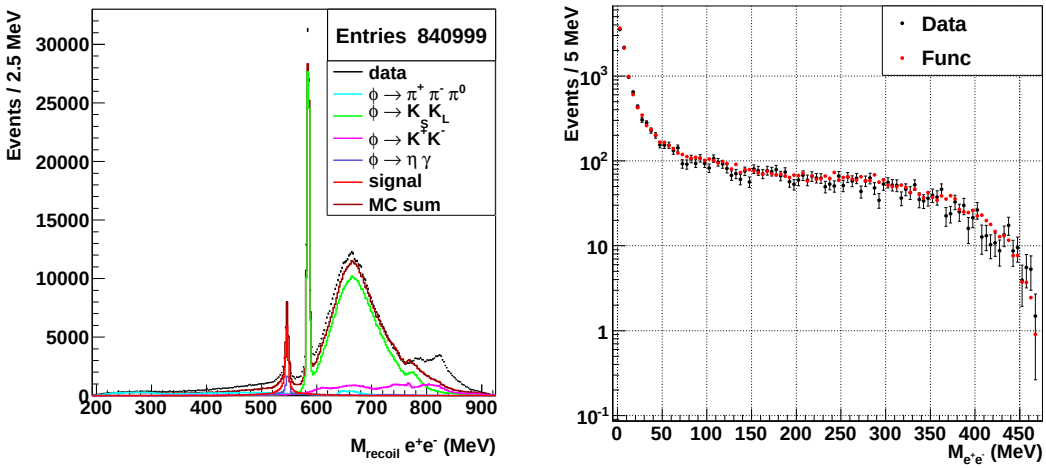

Figure 1: Recoiling mass against the e^+e^- pair for the data sample and MC events after preselection (left). Fit to the e^+e^- invariant mass distribution (right).

After all selection cuts, about 14,000 events was selected, with a background contamination less than 5%. The statistics is almost two orders of magnitude larger than in any previous measurement.

A fit to the invariant mass distribution was done using parametrizantion from Ref. [2].

Free parameters of the fit are Λ (reported in Eq. 2.1) and an overall normalization factor. Efficiency as a function of invariant mass of e^+e^- pair and smearing matrix were taken into account during fit procedure. The fit result is shown in Fig. 1 (right panel).

The statistical accuracy on Lambda is about 5%. The evaluation of systematic errors is in progress.

3. Searching of the dark matter in channel $\phi \to U\eta \to \eta e^+e^-$, with $\eta \to \pi^+\pi^-\pi^0$

The U boson is a postulated dark force mediator, that can mix with ordinary matter through a mixing with the photon. This particle can be observed at KLOE through the process $\phi \to \eta U$,

with U decaying into a lepton pair, while the η can be tagged by one of its main decays. An irreducible background due to the Dalitz decay of the ϕ meson, $\phi \to \eta\,\ell^+\ell^-$, is present. This decay has been studied by SND and CMD-2 experiments, which measured a branching fraction of $BR(\phi \to \eta\, e^+e^-) = (1.19 \pm 0.19 \pm 0.07) \times 10^{-4}$ and $BR(\phi \to \eta\, e^+e^-) = (1.14 \pm 0.10 \pm 0.06) \times 10^{-4}$, respectively [4, 7]. This corresponds to a cross section of $\sigma(\phi \to \eta\,\ell^+\ell^-) \sim 0.7$ nb, with a di-lepton mass range $M_{\ell\ell} < 470$ MeV. For the signal, the expected cross section is expressed by [8]:

$$\sigma(\phi \to \eta\, U) = \varepsilon^2\, |F_{\phi\eta}(m_U^2)|^2\, \frac{\lambda^{3/2}(m_\phi^2, m_\eta^2, m_U^2)}{\lambda^{3/2}(m_\phi^2, m_\eta^2, 0)}\, \sigma(\phi \to \eta\gamma)\,, \tag{3.1}$$

where $F_{\phi\eta}(m_U^2)$ is the $\phi\eta\gamma^*$ transition form factor evaluated at the U mass while the following term represents the ratio of the kinematic functions of the involved decays.[1] Using $\varepsilon = 10^{-3}$ and $|F_{\phi\eta}(m_U^2)|^2 = 1$, a cross section $\sigma(\phi \to \eta\, U) \sim 40$ fb is obtained. Despite the small ratio between the overall cross section of $\phi \to \eta U$ and $\phi \to \eta\,\ell^+\ell^-$, their different di-lepton invariant mass distributions allow to test the ε parameter down to 10^{-3} with the KLOE data set.

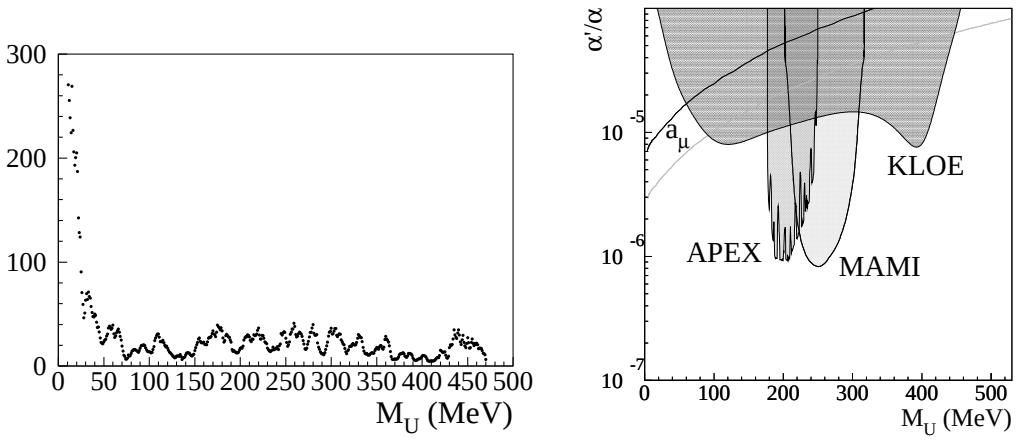

Figure 2: Upper limit at 90% C.L. on number of events for the decay chain $\phi \to \eta U$, $\eta \to \pi^+\pi^-\pi^0$, $U \to e^+e^-$ (left). Exclusion plot at 90% C.L. for the parameter $\alpha'/\alpha = \varepsilon^2$, compared with existing limits in our region of interest (right).

The $\phi \to \eta U$ MC signal has been produced according to Ref. [8], with a flat distribution of the U boson invariant mass, M_U. The analysed data sample is 1.5 $femtobarn^{-1}$.

In Fig. 2 (left panel) the exclusion plot at 90% C.L. on the number of events for the decay chain $\phi \to \eta U$, $\eta \to \pi^+\pi^-\pi^0$, $U \to e^+e^-$, is shown. Using Eq. (3.1) and taking into account the analysis efficiency, this result is then reported in terms of the parameter $\alpha'/\alpha = \varepsilon^2$, where α' is the coupling of the U boson to electrons and α is the fine structure constant. The opening of the $U \to \mu^+\mu^-$ threshold, in the hypothesis that the U boson decays only to lepton pairs and assuming equal coupling to e^+e^- and $\mu^+\mu^-$, has been included.

In right panel of Fig. 2 the smoothed exclusion plot at 90% C.L. on α'/α is compared with existing limits from the muon anomalous magnetic moment a_μ [10] and from recent measurements

[1] $\lambda(m_1^2, m_2^2, m_3^2) = [1 + m_3^2/(m_1^2 - m_2^2)]^2 - 4m_1^2 m_3^2/(m_1^2 - m_2^2)^2$.

of MAMI/A1 [11] and APEX [12] experiments. Our result greatly improves existing limits in a wide mass range, resulting in an upper limit on the α'/α parameter of $\leq 2\times10^{-5}$ @ 90% C.L. for $50 < M_U < 420$ MeV [1].

4. Analysis of $\eta \to \pi^+\pi^-\gamma$

In the final analysed sample, we find $N(\eta \to \pi^+\pi^-\gamma) = 204950 \pm 450$ with a background contamination of 10%. The total selection efficiency of the $\eta \to \pi^+\pi^-\gamma$ signal is $\varepsilon = 0.2131 \pm 0.0004$. Background contribution and the signal amount in the final sample are evaluated with a fit to the $E_{miss} - P_{miss}$ distribution of the $\pi^+\pi^-\gamma_\phi$ system with the shapes from remaining background and signal MC in the range $|E_{miss} - P_{miss}| < 10$ MeV. Combining our results we obtain the ratio:

$$R_\eta = \frac{\Gamma(\eta \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \pi^+\pi^-\pi^0)} = 0.1856 \pm 0.0005_{stat} \pm 0.0028_{sys}\,. \tag{4.1}$$

Our measurement is in agreement with the most recent result from CLEO [17], which is $R_\eta = 0.175 \pm 0.007_{stat} \pm 0.006_{syst}$. Combining our measurement with the world average value $\Gamma(\eta \to \pi^+\pi^-\pi^0) = (295 \pm 16)$ eV [13], we get $\Gamma(\eta \to \pi^+\pi^-\gamma) = (55 \pm 3)$ eV, which is in agreement with the value expected taking into account the direct term [14], providing a strong evidence in favour of the box anomaly. The $M_{\pi^+\pi^-}$ dependence of decay width has been parameterized in different approaches, in which VMD has been implemented in effective Lagrangians [14, 15]. We have fit it using a model independent approach [16], with a function:

$$\frac{d\Gamma}{ds_{\pi\pi}} = |AP(s_{\pi\pi})F_V(s_{\pi\pi})|^2\,\Gamma_0(s_{\pi\pi})\,, \tag{4.2}$$

where the normalization parameter A has the dimension of mass^{-3} and where

$$\Gamma_0(s_{\pi\pi}) = \frac{1}{3\cdot 2^{11}\cdot\pi^3 m^3}\,\left(m^2 - s_{\pi\pi}\right)^3\, s_{\pi\pi}\,\sigma(s_{\pi\pi})^3$$

collects phase-space terms and the kinematics of the absolute square of the simplest gauge invariant matrix element (for point-particles).

The term $P(s_{\pi\pi})$ is reaction specific and, for the decay of light mesons, it is expected to be perturbative:

$$P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi} + \mathscr{O}\left(s_{\pi\pi}^2\right) \tag{4.3}$$

Fit results are reported in Fig. 3, and the preliminary value obtained for the alpha parameter is:

$$\alpha_{KLOE} = (1.31 \pm 0.08 \pm 0.02) GeV^{-2} \tag{4.4}$$

The systematic uncertainties evaluation is in progress.

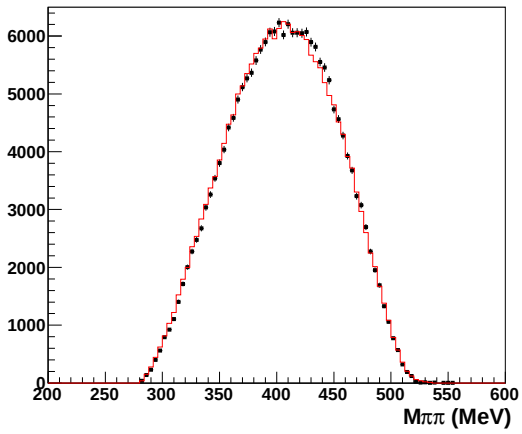

Figure 3: $M_{\pi^+\pi^-}$ distribution. Dots are data, fit function is marked with red color. Distribution is corrected for acceptance and experimental resolution.

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