HADRON PHYSICS AT KLOE AND KLOE-2

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KLOE data allow to study many interesting processes related to light mesons. Several item have been investigated, among them we present the recently published search for the $U$ boson produced with $\eta$ meson and the last results on the dynamics of the $\eta \rightarrow \pi^+\pi^-\gamma$ decay. The KLOE-2 project aims to extend the KLOE program with detector upgrades and increased statistics: we describe the status of the art.

1 KLOE and DAΦNE

The $e^+e^-$ collider DAΦNE, designed to operate at the center of mass energy $\sqrt{s} \simeq 1.02$ GeV, the $\phi$ meson mass, has delivered to the KLOE experiment an integrated luminosity of about $2.5 fb^{-1}$ on peak of the $\phi$ meson and also about $240 pb^{-1}$ at $\sqrt{s} \simeq 1$ GeV. The KLOE detector consists of a large volume cylindrical drift chamber (DC), 3.3 m length and 2 m radius, surrounded by a calorimeter (EMC) made of lead and scintillating fibers. A superconducting coil produces an axial field $B = 0.52$ T. In the DC charged particle momenta are reconstructed with resolution $\sigma_p/p \simeq 0.4\%$, while in the EMC energy clusters are reconstructed grouping calorimeter cells close in space and in time with energy and time resolution of $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$ and $\sigma_t = 57 ps/\sqrt{E(GeV)} + 100$ ps.

1.1 $U$ Boson Search: $\phi \rightarrow \eta e^+e^-/\eta U$

In recent years several unexpected astrophysical observations have failed to find a common interpretation in terms of standard astrophysical or particle sources. All these unexpected observations can be interpreted assuming the existence of a light hidden sector interacting with Standard Model particles through the mixing ($\epsilon$) between a new gauge vector boson $U$, with mass lighter than $O$(GeV), and the photon. The $U$ boson can be produced at $e^+e^-$ colliders via different processes, we present the analysis of the process $\phi \rightarrow \eta U$, where the $\eta$ meson is tagged by the $\eta \rightarrow \pi^+\pi^-\pi^0$ channel. The Dalitz decay $\phi \rightarrow \eta \ell^+\ell^-$, having the same signature, is an irreducible background for the $U$ boson search. The SND and CMD-2 collaborations measured the branching fraction of $BR(\phi \rightarrow \eta e^+e^-) = O(10^{-4})$, which corresponds to a cross section of $\sigma(\phi \rightarrow \eta \ell^+\ell^-) \sim 0.7$ nb. For the signal the expected cross section is $\sigma(\phi \rightarrow \eta U) \sim 40$ fb, in the hypothesis of a mixing $\epsilon = 10^{-3}$ and a $\phi\eta\gamma$ transition form factor $|F_{\phi\eta}(m_{\ell}^2)|^2 = 1$. Even though the ratio between the overall cross section of the $\phi \rightarrow \eta U$ and $\phi \rightarrow \eta \ell^+\ell^-$ is not favorable to the signal, the di-lepton invariant mass should be different allowing to test the kinetic mixing parameter $\epsilon$. We searched for the $U$ boson in the $e^+e^-$ final state, because the

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*For an exhaustive list of references see the KLOE-2 paper*
channel $U \rightarrow e^+e^-$ allow to search the $U$ boson in a wider mass range and the $e^\pm$ are easily identified using TOF technique.

The $M_{ee}$ spectrum has been studied using an integrated luminosity of 1.5 fb$^{-1}$ of $\phi$ decays: about 14,000 $\phi \rightarrow \eta e^+e^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ candidates are present in the analyzed data set, with a negligible background contamination.

The background shape is extracted directly from our data. A fit is performed to the $M_{ee}$ distribution, after a bin-by-bin subtraction of $\phi \rightarrow \eta\gamma$ background and efficiency correction, using the following parametrization as from Vector Meson Dominance (VMD) model$^6$

$$\frac{dI(\phi \rightarrow \eta e^+e^-)}{dq^2} = \alpha \left|F_{\phi\eta}(q^2)\right|^2 \sqrt{1 - \frac{4m^2}{q^2}} \left(1 + \frac{2m^2}{q^2}\right) \chi^{3/2}(m_{\phi}^2,m_{\eta}^2,m_U^2)$$

with $q = M_{ee}$ and the transition form factor described by:

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

Free parameters of the fit are $\Lambda$ and an overall normalization factor. A good description of the $M_{ee}$ shape is obtained except at the high end of the spectrum see fig.(1.left), because of the contamination of a residual background from multi-pion events. The $\phi \rightarrow \eta U$ Monte Carlo signal has been produced according to Reece-Wang model$^7$, with a flat distribution of the $U$ mass, $M_U$. The sample has been used to evaluate the resolution on the $e^+e^-$ invariant mass as a function of $M_U$: resolution is $\sim 2$ MeV for $M_U < 350$ MeV and then improves to 1 MeV for higher values. The upper limit on $\phi \rightarrow \eta U$ has been reported in terms of the kinetic mixing parameter $\epsilon^2 = \alpha'/\alpha$, where $\alpha'$ is the coupling of $U$ boson to electrons and $\alpha$ is the fine structure constant. We include the opening $U \rightarrow \mu^+\mu^-$ threshold, in the hypothesis that the $U$ boson decay only to lepton pairs and assuming equal coupling to $e^+e^-$ and $\mu^+\mu^-$. The smoothed exclusion plot at 90% C.L. on $\alpha'/\alpha$, see fig.(1.right), is compared with existing limits from the muon anomalous magnetic moment $a_\mu$ and from recent measurement of MAMI$^8$ and APEX$^9$. The gray line is where the $U$ boson parameters should lay to account for the observed discrepancy between measured and calculated $a_\mu$ values. Our result improves existing limits in a wide mass range, resulting in an U.L. on $\alpha'/\alpha \leq 2 \times 10^{-5}$ @ 90% C.L. for $50 < M_U < 420$ MeV. Our result excludes that the existing $a_\mu$ discrepancy is due to $U$ boson with mass ranging between 90 and 450 MeV. Preliminary study for $U-$boson search looking at
$\eta \to \gamma \gamma$ and $\eta \to 3\pi^0$ looks promising and they should in principle allow to improve U.L. by a factor 2.

1.2 Light Mesons: $\eta \to \pi^+\pi^-\gamma$

The decays $\eta \to \pi^+\pi^-\gamma$ and $\eta' \to \pi^+\pi^-\gamma$ are expected to get contribution from the anomaly accounted for by the Wess Zumino Witten (WZW) term into the ChPT Lagrangian. Those anomalous processes are referred to as box anomalies which proceed through a vector meson resonant contribution, described by VMD. According to effective theory the contribution of the direct term should be present together with VMD. In case of $\eta \to \pi^+\pi^-\gamma$ the $\rho$ contribution is not dominant, this makes the partial width sensitive to the presence of the direct term. Recently CLEO has measured the ratio $R_\eta = \Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0) = 0.175 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$, which differs by more than 3$\sigma$ from the average result of previous measurements. We present a preliminary measurement with the highest statistics and the smallest systematic error ever achieved.

The final state under study is $\pi^+\pi^-\gamma$, since at KLOE, the $\eta$ mesons are produced together with a monochromatic recoil photon ($E_\gamma = 363$ MeV) through the radiative decay $\phi \to \eta\gamma$. In the considered data sample there are about $25 \times 10^6 \eta$'s. The main background comes from $\phi \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma\gamma$ decaying to the same final state. Other backgrounds are $\phi \to \eta\gamma \to \pi^+\pi^-\pi^0 \to \pi^+\pi^-3\gamma$ with one photon lost, and $\phi \to \eta\gamma, \eta \to e^+e^-\gamma$ when both electrons are mis-identified as pions. The process $\phi \to \eta\gamma$ with $\eta \to \pi^+\pi^-\pi^0$ represents a good control sample, due to the similar topology. Moreover the ratio $\Gamma(\eta \to \pi^+\pi^-\gamma)/\Gamma(\eta \to \pi^+\pi^-\pi^0)$ is not affected by the uncertainties on the luminosity, the $\phi \to \eta\gamma$ partial width and the $\phi$ production cross section cancel in the ratio. We use the same preselection as for the $\eta \to \pi^+\pi^-\gamma$ signal.

Concerning the control sample we select $N(\eta \to \pi^+\pi^-\pi^0) = 1190 \pm 10^3$, with a selection efficiency of $\varepsilon = 0.2277 \pm 0.0002$ and a background contamination of 0.65%; concerning the signal we select $N(\eta \to \pi^+\pi^-\gamma) = 204950 \pm 450$ with $\varepsilon = 0.2131 \pm 0.0004$ and a background contamination of 10%. Combining our results we obtain the ratio:

$$R_\eta = \frac{\Gamma(\eta \to \pi^+\pi^-\gamma)}{\Gamma(\eta \to \pi^+\pi^-\pi^0)} = 0.1856 \pm 0.0005_{\text{stat}} \pm 0.0028_{\text{syst}} \quad (3)$$

Our measurement is in agreement with the most recent result from CLEO, $R_\eta = 0.175 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$. Combining our measurement with the world average value of $\Gamma(\eta \to \pi^+\pi^-\pi^0) = (295 \pm 16) \text{ eV}$, we get $\Gamma(\eta \to \pi^+\pi^-\gamma) = (55 \pm 3) \text{ eV}$, which is in agreement with the value expected taking into account the direct term, providing a strong evidence in favor of the box anomaly.

The $M_{\pi^+\pi^-}$ dependence of decay width has been parametrized in different approaches, in which VMD has been implemented in effective Lagrangians. Recently a model independent method, based on ChPT and dispersive analysis, has been developed. In this approach, the relative strength between tree level and resonance contribution are not fixed. The function proposed to describe the partial width as function of $s_{\pi\pi} = m^2_{\pi\pi}$ is the following:

$$\frac{d\Gamma(\eta \to \pi^+\pi^-\gamma)}{ds_{\pi\pi}} = |A P(s_{\pi\pi})F(s_{\pi\pi})|^2 \Gamma_0(s_{\pi\pi}) \quad (4)$$

where $A$ is a normalization factor; $\Gamma_0(s_{\pi\pi}) = \frac{1}{32\pi^3m^2_{\pi}} \left( m^2_{\pi} - s_{\pi\pi} \right)^3 s_{\pi\pi} \sigma(s_{\pi\pi})^2$ with $\sigma(s_{\pi\pi}) = \sqrt{1 - 4m^2_{\pi}/s_{\pi\pi}}$; $F_V(s_{\pi\pi})$ is the pion vector form factor, the function $P(s_{\pi\pi}) = 1 + \alpha s_{\pi\pi}$ is reaction specific. For more details see Stoll's paper.

The $\alpha$ parameter was measured also by the WASA@COSY collaboration: $\alpha = (1.89 \pm 0.25_{\text{stat}} \pm 0.59_{\text{syst}} \pm 0.02_{\text{th}}) \text{ GeV}^{-2}$. Fig.2 shows the observed $M_{\pi^+\pi^-}$ spectrum, background
subtracted, compared with the theoretical prediction of eq. (4) with the value $\alpha = (1.31 \pm 0.08_{\text{stat}} \pm 0.40_{\text{syst}} \pm 0.02_{\text{th}})$ coming as output of the fit to the $M_{\pi\pi}$ shape, corrected for acceptance and smearing.

![Figure 2: Left: The $\pi^+\pi^-\gamma$ invariant mass distribution: Data-MC comparison. Dots are data, Magenta is MC signal $\eta \rightarrow \pi^+\pi^-\gamma$, Red is all MC background contribution; Right: Measured spectrum $m_{\pi\pi}$ (dots), histogram is the prediction from eq. (4) with $\alpha$ as from the output of the fit, corrected for acceptance and experimental resolution.](image)

1.3 KLOE-2

High statistic samples of light mesons produced at KLOE allowed to perform precision measurement and to look for very rare decays. A new DA$\Phi$NE interaction region, with large beam crossing angle and sextupoles for crab waist, improved the performance of the collider: a factor 3 in the luminosity has been gained. Minimal detector upgrade for first KLOE-2 run are already available as taggers to detect momentum of leptons in $e^+e^- \rightarrow e^+e^- \gamma^* \gamma^* \rightarrow e^+e^-X$. Work is in progress to insert an Inner Tracker, a 4 layers of cylindrical triple GEM, and new calorimeters around the beam pipe to increase acceptance for $\gamma$'s from interaction point. Nowadays a new data taking at KLOE-2 is waiting for stable run conditions.

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