THE KLOE-2 EXPERIMENT AT DAΦNE*

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The KLOE-2 experiment has finished its data-taking campaign at the DAΦNE collider, recording about 5.5 fb^{-1} of data. Together with the already collected events from the KLOE campaigns, the registered data represents the largest sample of ϕ-mesons acquired in a ϕ-factory. The article will cover the present status and plans of the experiment as well as the latest physics achievements of the collaboration.

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1. Introduction

The KLOE multi-purpose detector experiment operates in Frascati at the DAΦNE ϕ-factory. 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 superconductive coil providing a magnetic field of 0.5 T. The KLOE experiment collected 2.5 fb^{-1} at the ϕ-peak during its 2002 to 2005 campaign. Its continuation, KLOE-2, started on November 2014 and ended in 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 an inner tracker [3] and two calorimeters [4, 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. The full KLOE and KLOE-2 data sets present an invaluable and unique set to perform precise measurements and study low-energy hadron physics [7].

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2. $\gamma\gamma$ scattering

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 $\mathcal{O}(1\%)$ precision needed 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. KLOE-2 has the possibility to perform this measurement [8]. In order to reduce the background coming from ϕ-meson decays, two High Energy Tagger (HET) stations [9] are used to measure the deviation of the final-state leptons from their main orbit by determining their position and timing. Candidates of single-π^0 production from $\gamma\gamma$ scattering have been pre-filtered recording information on the hit in the tagger, trigger, DAΦNE operational parameters, clusters and tracks reconstructed in the KLOE central detector. After an event-by-event subtraction of the registered amount of accidentals, statistical evidence of correlated coincidence events between the tagger station hits and KLOE calorimeter clusters has been observed for the first time.

3. Running of the fine-structure constant $\alpha_{\rm em}$ below 1 GeV

The effective QED constant, $\alpha_{\rm em}$, is known [10–14] to increase with rising momentum transfer due to vacuum polarization (VP) effects. The VP effects can be implemented by making the fine-structure constant explicitly s-dependent ($s = q^2$): $\alpha_{\rm em}(q^2) = \frac{\alpha_{\rm em}(0)}{1-\Delta\alpha(q^2)}$. The correction $\Delta\alpha$ represents the sum of the lepton, the five lightest quarks, and the top-quark contributions: $\Delta\alpha(q^2) = \Delta\alpha_{\rm lep}(q^2) + \Delta\alpha^{(5)}_{\rm had}(q^2) + \Delta\alpha_{\rm top}(q^2)$. The value of

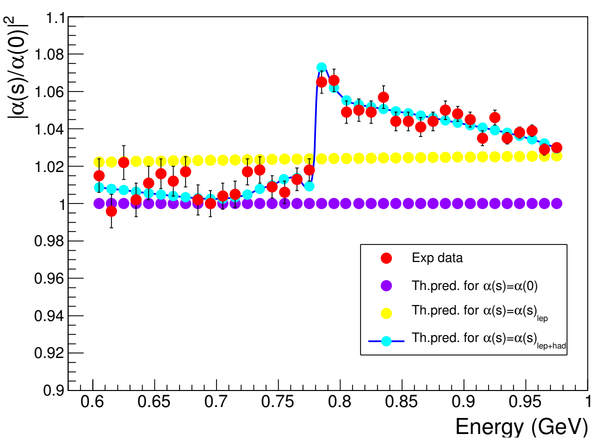

Fig. 1. (Colour on-line) The square of the modulus of the running $\alpha(s)$ in units of $\alpha(0)$ (dark grey/red points) compared with the prediction (grey/cyan) as a function of the di-muon-invariant mass. Theoretical expectations in the case of no running (black/violet) and only leptonic contribution (light grey/yellow) are also shown.

$\alpha_{\rm em}(s)$ in the time-like region can be extracted from the ratio of the differential cross section of $e^+e^- \to \mu^+\mu^-\gamma$, with a photon from the Initial State Radiation (ISR), and the corresponding cross section obtained from the Monte Carlo (MC) simulation with $\alpha_{\rm em}(s) = \alpha_{\rm em}(0)$ [15]: $\left|\frac{\alpha_{\rm em}(s)}{\alpha_{\rm em}(0)}\right|^2 = \frac{{\rm d}\sigma_{\rm data}(e^+e^-\to\mu^+\mu^-\gamma(\gamma))|_{\rm ISR}/{\rm d}\sqrt{s}}{{\rm d}\sigma^0_{\rm MC}(e^+e^-\to\mu^+\mu^-\gamma(\gamma))|_{\rm ISR}/{\rm d}\sqrt{s}}$. In Fig. 1, the ratio is compared to the theoretical predictions [16].

4. $K_{\rm S}$ semileptonic charge asymmetry

The charge asymmetries for the physical states $K_{\rm S}$ and $K_{\rm L}$ are defined as: $A_{\rm S,L} = \frac{\Gamma(K_{\rm S,L}\to\pi^-e^+\nu)-\Gamma(K_{\rm S,L}\to\pi^+e^-\bar{\nu})}{\Gamma(K_{\rm S,L}\to\pi^-e^+\nu)+\Gamma(K_{\rm S,L}\to\pi^+e^-\bar{\nu})} = 2\left[\Re\left(\varepsilon\right) \pm \Re\left(\delta\right) - \Re(y) \pm \Re(x_-)\right]$ with $\Re\left(\varepsilon\right)$ and $\Re\left(\delta\right)$ implying T and CPT violation in the K^0–$\bar{K}^0$ mixing, respectively. If CPT symmetry holds, then the two asymmetries are expected to be identical $A_{\rm S}=A_{\rm L}=2\,\Re,(\varepsilon)\simeq3\times10^{-3}$. Using 1.63 fb^{-1} of integrated luminosity collected by the KLOE experiment [17], about 7×10^4 $K_{\rm S}\to\pi^\pm e^\mp\nu$ decays have been reconstructed. The measured value of the charge asymmetry for this decay is $A_{\rm S} = (-4.9\pm5.7_{\rm stat}\pm2.6_{\rm syst})\times10^{-3}$ [18], which is almost twice more precise than the previous KLOE result [19]. The combination of these two measurements gives $A_{\rm S} = (-3.8 \pm 5.0_{\rm stat} \pm 2.6_{\rm syst}) \times 10^{-3}$ and, together with the asymmetry of the $K_{\rm L}$ semi-leptonic decay, from the KTeV Collaboration: $A_{\rm L} = (3.322 \pm 0.058_{\rm stat} \pm 0.047_{\rm syst}) \times 10^{-3}$ [20], provides significant test of the CPT symmetry.

5. Direct test of T and CPT symmetries in neutral kaon transitions

Comparing neutral meson transition rates between flavour and CP eigenstates allows direct and model-independent tests of time-reversal T and CPT symmetries [21, 22] to be performed. Quantum entangled kaon pairs are used to identify the initial state of a particle transition by the decay of its entangled partner, while the final state is tagged by semileptonic and hadronic decays into two and three pions. Two T-violating observables are determined as ratios of the rates of two classes of processes identified in the dataset $K_{\rm S}K_{\rm L} \to \pi^\pm e^\mp\nu, 3\pi^0$ and $K_{\rm S}K_{\rm L} \to \pi^+\pi^-, \pi^\pm e^\mp\nu$: $R_2(\Delta t) = \frac{P[K^0(0)\to K_-(\Delta t)]}{P[K_-(0)\to K^0(\Delta t)]}$, and $R_4(\Delta t) = \frac{P[\bar{K}^0(0)\to K_-(\Delta t)]}{P[K_-(0)\to\bar{K}^0(\Delta t)]}$. A deviation of the asymptotic level of these ratios from unity for large transition times would be a T-violation manifestation [21, 22]. Moreover CPT symmetry can be tested through the determination of the asymptotic level of the following double ratio $\frac{R_2^{\rm CPT}}{R_4^{\rm CPT}} = \frac{P[K^0(0)\to K_-(\Delta t)]P[K_-(0)\to\bar{K}^0(\Delta t)]}{P[\bar{K}^0\to K_-(\Delta t)]P[K_-(0)\to K^0(\Delta t)]} \stackrel{\Delta t \gg \tau_S}{=} 1 - 8\Re\delta_K - 8\Re x_-$, where the $\Re\delta_K$ and $\Re x_-$ are parameters violating the CPT symmetry in $K^0\bar{K}^0$

mixing and the $\Delta S = \Delta Q$ rule. This double ratio represents a robust CPT-violation sensitive observable [21, 22] which has never been measured to date. A percent level accuracy has been obtained on the double ratio measurement with 1.7 fb^{-1} KLOE data sample [23, 24].

6. Testing CP with BR($K_{\mathrm{S}} \to 3\pi^0$) upper limit

The Standard Model prediction for the branching ratio of the CP-violating decay $K_{\mathrm{S}} \to 3\pi^0$ is $\mathrm{BR}(K_{\mathrm{S}} \to 3\pi^0) \sim 1.9 \times 10^{-9}$. To improve present best upper limit $\mathrm{BR}(K_{\mathrm{S}} \to 3\pi^0) < 2.6 \times 10^{-8}$ at 90% C.L., which was set with 1.7 fb^{-1} of KLOE data searching for six photons coming from the IP and a K_{L}-crash [25], the analysis with KLOE-2 data has started. By using the full KLOE-2 statistics of 5 fb^{-1} and optimizing the background rejection, it will be possible to reach a sensitivity on the BR below 10^{-8}.

7. Determination of BR($K_{\mathrm{S}} \to \pi\mu\nu$)

Recent studies of B-meson decays have resulted in indications of lepton non-universality at the level of four standard deviations [26]. Open questions stand out to which extent the effect is observed in other systems. In neutral kaon physics, a unique test can be conducted by comparing semileptonic decays of K_{S} meson: $r_{\mu e} = \frac{\mathrm{BR}(K_{\mathrm{S}} \to \pi\mu\nu)}{\mathrm{BR}(K_{\mathrm{S}} \to \pi e\nu)}$. An analysis based on $L = 1.7$ fb^{-1} of KLOE data is ongoing and will be the first measurement to date that makes use of the direct detection of $K_S \to \pi\mu\nu$ decay channel.

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

The $\eta \to \pi^0\gamma\gamma$ decay is considered the golden mode of Chiral Perturbation Theory, since it is sensitive to higher order terms, particularly $\mathcal{O}(p^6)$, with $\mathcal{O}(p^2)$ being null for neutral mesons, and the order four terms suppressed by G-parity. The current PDG value of $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = (25.6 \pm 2.2) \times 10^{-5}$ corresponds to the Crystal Ball measurements [27, 28]. KLOE had measured a preliminary $\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = (8.4 \pm 3.0) \times 10^{-5}$, lower than the present PDG value. A new measurement using the full KLOE statistics and applying Multivariate Analysis algorithms to disentangle the background sources is being performed with the aim of improving the present experimental value.

9. $\eta \to \pi^+\pi^-$ limit

The $\eta \to \pi^+\pi^-$ decay is a P- and CP-violating process. According to SM, this decay can occur only through CP-violating weak interaction mediated by a virtual K^0_{S} meson and has a branching ratio $\mathrm{BR}(\eta \to \pi^+\pi^-) \leq 2 \times 10^{-27}$ [29, 30].

The collaboration already set the best upper limit on the branching ratio of the di-pion decay of the η meson by using $350\,\mathrm{pb}^{-1}$ of KLOE data: $\mathrm{BR}(\eta \to \pi^+\pi^-) \leq 1.3 \times 10^{-5}$ at 90% C.L. [31]. 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. A preliminary upper limit can be set from the invariant mass distribution in the region of the η mass, $\mathrm{BR}(\eta \to \pi^+\pi^-) < 6.3 \times 10^{-6}$ at 90% C.L. [32]. By using together the full KLOE/KLOE-2 sample, the limit is expected to decrease by a factor of about two.

10. Dark forces searches

The existence of an accessible portal to a hypothetical low-mass dark sector is among present hot topics of physics beyond the Standard Model searches. A new limit of the U boson has been extracted considering both $U \to \mu^+\mu^-, \pi^+\pi^-$ decays in the 500–1000 MeV mass region [33]. The combination of the two decays reduces the loss of sensitivity which affects the muon channel in the ρ–ω region thanks to the dominant hadron branching fraction of the $U \to \pi^+\pi^-$ decay channel. The KLOE-2 searches have been extended to a leptophobic B-boson [34]. The dominant decay channel for masses below 600 MeV, is $B \to \pi^0\gamma$. The reaction $\phi \to \eta\pi^0\gamma$ can be exploited for this purpose searching for an enhancement in the $\pi^0\gamma$-invariant mass [35].

11. Conclusions

A unique worldwide sample of data has been collected by the KLOE/KLOE-2 Collaboration at the DAΦNE ϕ-factory of the LNF in Frascati with a total luminosity of $8\ \mathrm{fb}^{-1}$ collected, corresponding to about 24×10^9 ϕ mesons produced. This sample is used to perform precise measurements in low-energy hadron physics, test of discrete symmetries and searches beyond SM.

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