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HIGHLIGHTS OF KLOE PHYSICS RESULTS[*]

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The KLOE experiment has collected an integrated luminosity of about 2.5 fb^{-1} up to the year 2006. Recent achievements in kaon physics as well as in light meson spectroscopy, based on the analysis of about 20% of the whole data sample are reviewed and presented in the following.

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1. Introduction: KLOE detector

The KLOE detector consists of a large volume cylindrical drift chamber [1], DC (3.3 m length and 2 m radius), surrounded by a calorimeter [2] made of lead and scintillating fibers, EMC. The detector is inserted in a superconducting coil producing a solenoidal field $B = 0.52\,\text{T}$. Large angle tracks from the origin ($\theta > 45°$) are reconstructed with momentum resolution of $\sigma_p/p = 0.4\%$. Photon energies and times are measured with resolutions of $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$ and $\sigma_t = 54\,\text{ps}/\sqrt{E(\text{GeV})} \oplus 50\,\text{ps}$.

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2. Kaon physics

Direct test of the Standard Model: $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$

The value of $R_K = \Gamma(K^+ \to e^+\nu_e)/\Gamma(K^+ \to \mu^+\nu_\mu) \equiv \Gamma(K_{e2})/\Gamma(K_{\mu 2})$, predicted in the Standard Model (SM), benefits from cancellation of hadronic uncertainties and it is known with a relative uncertainty of 0.04% [3]. Models with two Higgs doublets and lepton flavor violation [4] predict a deviation from the SM of the order of 1%. The main issue of this measurement is the discrimination of K_{e2} from $K_{\mu 2}$ events, which are about 5 orders of magnitude more frequent. The variables used to achieve this goal are:

- the lepton mass, $M_{\rm lep}$, evaluated from the measured momenta of the kaon and of the secondary track, assuming the neutrino is massless;
- the spread, $E_{\rm RMS}$, in the energy released by the particle traversing the layers of the EMC, different for electrons or muons.

Event counting is given by a likelihood fit of the distribution in $M^2_{\rm lep}$, $E_{\rm RMS}$: the number of signal events is 8090, from an integrated luminosity of 1.7 fb^{-1}. Fig. 1 (left panel) shows the K_{e2} peak over the $K_{\mu 2}$ tail. After correcting for efficiencies, particle identification, and radiative corrections, a value compatible with the SM is obtained:

$$R_K^{\rm exp} = 2.55(5)_{\rm stat}(5)_{\rm sys} \times 10^{-5}\,, \qquad R_K^{\rm SM} = 2.477(1) \times 10^{-5}\,.$$

The statistical error is dominated by the limited Monte Carlo (MC), sample of the background, whereas the particle identification gives the major contribution to the systematic error. Increasing MC statistics and refining the selection, a relative error of 1% is within reach with the full data sample.

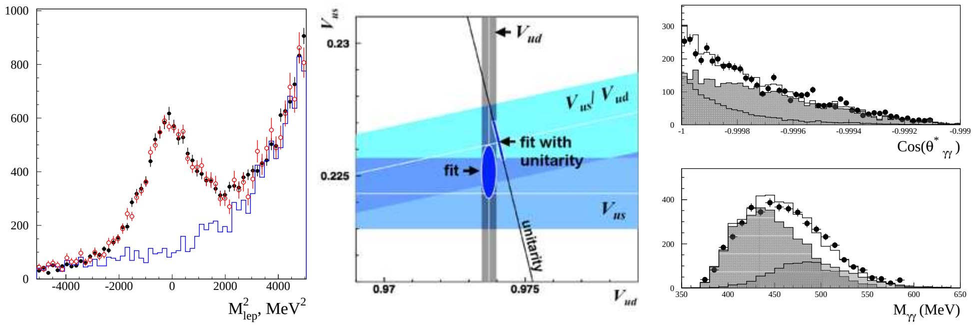

Fig. 1. Left: mass square of the secondary track, from data (full dots), K_{e2} (open dots) and $K_{\mu 2}$ (solid line) MC distributions. Middle: $V_{\rm us}$ *versus* $V_{\rm ud}$ correlation. Right: cosine of the opening angle (top) and invariant mass (bottom) distributions of the two photons in $K_{\rm S} \to \gamma\gamma$ events.

Extraction of $V_{\rm us}$

The most precise test of the CKM matrix unitarity is provided by the first row: $1-|V_{\rm ud}|^2-|V_{\rm us}|^2$, where $|V_{\rm ub}|\sim\mathcal{O}(10^{-5})$ is neglected, and $V_{\rm us}$ is extracted from kaon semileptonic decays using the following formula:

$$\Gamma\left(K_{\ell 3(\gamma)}\right)=|V_{\rm us}|^2\,|f_+(0)|^2\frac{C_K^2G_F^2M_K^5}{192\pi^3}\,S_{\rm EW}\,I_\ell(\{\lambda_\ell\})\,(1+\delta_\ell)\,. \qquad (1)$$

KLOE is measuring experimental observables needed in Eq. (1), in particular:

$\Gamma(K_{\ell 3(\gamma)})$: the semileptonic decay width evaluated from measuring branching ratios with radiative corrections and the kaon lifetime,

$I_\ell(\{\lambda_\ell\})$: the phase space integral, depending on the form factor slopes λ_ℓ of the specific leptonic final state, measured either from the momentum transfer $t\equiv(P_K-p_\pi)^2$ or from the neutrino spectrum.

The theoretical inputs are the form factor at $t=0$, $f_+(0)$, the Clebsch–Gordan coefficient, C_K, the electroweak perturbative corrections $S_{\rm EW}$, the isospin breaking and electromagnetic corrections, all included in δ_ℓ.

The $K^\pm$ semileptonic decays have been recently measured from an integrated luminosity of 410 pb^{-1}, using 4 data samples defined by different decay modes for the tagging kaon: $K^\pm_{\mu 2}$ and $K^\pm\to\pi^\pm\pi^0$. Signal count of $K^\pm\to\pi^0\ell^\pm\overset{(-)}{\nu}_\ell$ events is based on the likelihood fit of the mass of the secondary track. Averaging from the different data samples we obtain:

$$\begin{aligned}{\rm BR}(K^\pm_{e3}) &= (4.965\pm 0.038_{\rm stat}\pm 0.037_{\rm sys})\times 10^{-2},\\ {\rm BR}(K^\pm_{\mu 3}) &= (3.233\pm 0.029_{\rm stat}\pm 0.026_{\rm sys})\times 10^{-2}.\end{aligned}$$

The geometrical acceptance is evaluated using the KLOE average $\tau_{K^+}=12.384$ ns, for the charged kaon lifetime. This is measured using an integrated luminosity of 230 pb^{-1}, with two independent methods for extracting the K^+ proper time, t^*, which give consistent results:

- from the kaon track length, correcting for ionization energy losses, $\tau_{K^\pm}=(12.367\pm 44_{\rm stat}\pm 65_{\rm sys})$ ns,
- from the photon time of flight in the decay chain $K\to\pi^0X\to\gamma\gamma X$, $\tau_{K^\pm}=(12.391\pm 49_{\rm stat}\pm 25_{\rm sys})$ ns.

In the $K_{\rm L}\to\mu^\pm\overset{(-)}{\nu}_\mu\pi^\mp\equiv K_{L\mu 3}$ decay, the hadronic current is described by two functions, the vector, $\tilde{f}_+(t)$, and the scalar, $\tilde{f}_0(t)$, form factors:

$$J_\alpha^{\rm had}\sim f_+(0)\left[(P_K+p_\pi)_\alpha\,\tilde{f}_+(t)+(P_K-p_\pi)_\alpha\left(\tilde{f}_0(t)\frac{\Delta_{K\pi}}{t}-\tilde{f}_+(t)\frac{\Delta_{K\pi}}{t}\right)\right],$$

where $P(p)$ is the $K(\pi)$ four-momentum and $\Delta_{K\pi} = M_K^2 - m_\pi^2$. If both functions are expanded in powers of t up to t^2, there are two scalar and two vector λ slope parameters:

$$\tilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\,\frac{t}{m^2} + \frac{1}{2}\,\lambda''_{+,0}\left(\frac{t}{m^2}\right)^2 .$$

While this expansion for the vector form factor is consistent with predictions from a dispersive approach, there is a -99.96% correlation [6] between λ'_0 and λ''_0, making not meaningful any direct measurement of the two parameters, therefore, the linear approximation is used for the scalar form factor. From a combined fit of published $K_{\mathrm{L}e3}$ [5] and final $K_{\mathrm{L}\mu3}$ results we obtain:

$$\begin{aligned} \lambda' &= (25.6 \pm 1.5_{\mathrm{stat}} \pm 0.9_{\mathrm{sys}}) \times 10^{-3}\,, \\ \lambda'' &= (1.5 \pm 0.7_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}}) \times 10^{-3}\,, \\ \lambda_0 &= (15.4 \pm 1.8_{\mathrm{stat}} \pm 1.3_{\mathrm{sys}}) \times 10^{-3}\,, \end{aligned} \qquad \begin{pmatrix} 1 & -0.95 & 0.29 \\ & 1 & -0.38 \\ & & 1 \end{pmatrix} .$$

Using available KLOE experimental inputs, the quantity $|f_+(0)\,V_{\mathrm{us}}|$ is extracted and shown in the left panel of Table I. Where the muonic final state is measured, the lepton universality is tested using the formula:

$$\frac{g_\mu^2}{g_e^2} = \frac{|V_{\mathrm{us}} f_+(0)|^2_{\mu3}}{|V_{\mathrm{us}} f_+(0)|^2_{e3}} = \frac{\mathrm{BR}(K_{\mu3})}{\mathrm{BR}(K_{e3})}\,\frac{I_e(1+\delta_e)}{I_\mu(1+\delta_\mu)}\,. \tag{2}$$

TABLE I

Left panel: $|f_+(0)\,V_{\mathrm{us}}|$ values extracted using KLOE measurements: branching ratios, K_{L}, $K^\pm$ lifetimes and $K_{\mathrm{L}\ell3}$ slopes. Right panel: lepton universality tests.

mode	$\lvert f_+(0)\,V_{\mathrm{us}}\rvert$
K_{Le3}	0.21547(72)
$K_{L\mu3}$	0.21661(93)
K_{Se3}	0.21522(145)
$K^\pm_{e3}$	0.21465(137)
$K^\pm_{\mu3}$	0.21302(155)
average	0.21556(59)

mode	g_μ^2/g_e^2
$K_{L\ell3}$	1.0054(44)
$K^\pm_{\ell3}$	0.9924(54)
$K_{\ell3}$ average	1.0005(38)
$\tau \to \ell\nu_\ell\nu_\tau$	1.0005(41)
$\pi \to \ell\nu_\ell$	1.0034(30)
K, τ, π average	1.0019(21)

In the right panel of Table I, Eq. (2) is applied to K_{L} and $K^\pm$ semileptonic decays, averaged and compared with the values from τ and π pure leptonic decays. The average value from the three channels probes the universality of the charged current couplings of the leptons at the 0.002 level. Finally, using the $|\frac{V_{\rm us}}{V_{\rm ud}}|$ value extracted from $K_{\mu 2}$ decays [7], unitarity of the CKM matrix is verified to 1.5 standard deviations. Middle panel of Fig. 1 shows the correlation between $V_{\rm us}$ and $V_{\rm ud}$, with and without the unitarity constraint.

Test of Chiral Perturbation Theory: $K_{\rm S} \to \gamma\gamma$

The $K_{\rm S} \to \gamma\gamma$ decay is predicted with good accuracy to the order $\mathcal{O}(p^4)$ in Chiral Perturbation Theory; but the most precise measurement [8] to date differs about 30% from that prediction, suggesting for a sizeable $\mathcal{O}(p^6)$ contribution. KLOE selection of $K_{\rm S}$ events is based on the $K_{\rm L}$ interaction in the EMC and use of the quadrupole calorimeters to reject the $K_{\rm S} \to 2\pi^0$ background. Fig. 1 (right panel) shows cosine of the opening angle and invariant mass distributions of the two photons. The result is in agreement with the $\mathcal{O}(p^4)$ approximation:

$$\mathrm{BR}(K_{\rm S} \to \gamma\gamma) = \big(2.27 \pm 0.13(\mathrm{stat})^{+0.03}_{-0.04}(\mathrm{sys})\big) \times 10^{-6}\,.$$

3. Light hadron spectroscopy

Gluonium content in η'

From the selection of $\phi \to \eta'\gamma \to \pi^+\pi^- 7\gamma$ and $\phi \to \eta\gamma \to 7\gamma$ events, the ratio $R_\phi \equiv \frac{\Gamma(\phi\to\eta'\gamma)}{\Gamma(\phi\to\eta\gamma)}$ is measured. η, η' are known to be linear combinations of strange, $s\bar{s}$, nonstrange, $q\bar{q}$, quarks. Moreover, the η' could contain a gluonium component GG, so that

$$|\eta'\rangle = X_{\eta'}|q\bar{q}\rangle + Y_{\eta'}|s\bar{s}\rangle + Z_{\eta'}|GG\rangle\,, \qquad |\eta\rangle = \cos\varphi_P|q\bar{q}\rangle - \sin\varphi_P|s\bar{s}\rangle\,,$$

$$\begin{aligned} X_{\eta'} &= \cos\varphi_G \sin\varphi_P\,,\\ Y_{\eta'} &= \cos\varphi_G \cos\varphi_P\,,\\ Z_{\eta'} &= \sin\varphi_G\,, \end{aligned}$$

where φ_P and φ_G are the pseudoscalar and gluon–quark mixing angles.

A combined fit of the KLOE measurement $R_\phi \propto \cot^2\varphi_P \cos^2\varphi_G$ [9] with available measurements of $\frac{\Gamma(\eta'\to\rho\gamma)}{\Gamma(\omega\to\pi^0\gamma)}$, $\frac{\Gamma(\eta'\to\gamma\gamma)}{\Gamma(\pi^0\to\gamma\gamma)}$ and $\frac{\Gamma(\eta'\to\omega\gamma)}{\Gamma(\omega\to\pi^0\gamma)}$, either with the $Z_{\eta'} = 0$ constraint, Eq. (3), or leaving free $Z_{\eta'}$, Eq. (4), yields the following:

$$\varphi_P = (41.5^{+0.6}_{-0.7})^\circ\,, \qquad P_{\chi^2>\chi^2_{\rm obs}} = 0.01\,, \tag{3}$$

$$\varphi_P = (39.7 \pm 0.7)^\circ\,, \quad Z^2_{\eta'} = 0.14 \pm 0.04\,, \quad P_{\chi^2>\chi^2_{\rm obs}} = 0.49\,, \tag{4}$$

where a 3σ evidence is found for gluonium content in η', as shown in Fig. 2.

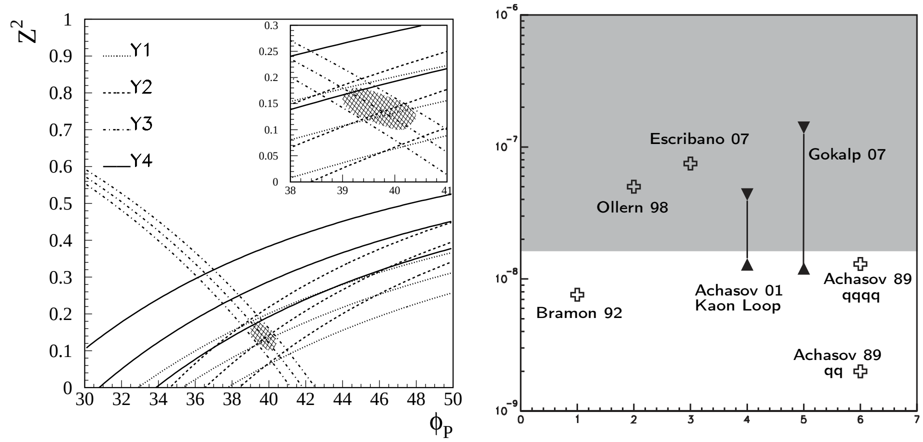

Fig. 2. Left panel: correlation $Z^2_{\eta'}$ *versus* φ_P, with constraints from $Y1 = \frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)}$, $Y2 = \frac{\Gamma(\eta' \to \rho\gamma)}{\Gamma(\omega \to \pi^0\gamma)}$, $Y3 = R_\phi$ and $Y4 = \frac{\Gamma(\eta' \to \omega\gamma)}{\Gamma(\omega \to \pi^0\gamma)}$ measurements. Right panel: scalar meson models excluded by the upper limit on the $\phi \to K\bar{K}\gamma$ decay.

Measurement of the η mass

Two precise measurements [10, 11] differ by 8 standard deviations. The analysis is based on 1.7×10^7 $\phi \to \eta\gamma \to 3\gamma$ events. A kinematic fit is applied to these events: the absolute energy scale is obtained rescaling the ϕ mass measured by KLOE with the precise value obtained by CMD-2 [12] and the interaction point is measured from Bhabha events [13]. The method is cross checked with $\phi \to \pi^0\gamma$ events. The result is the most precise to date:

$$m_\eta = (547.873 \ \pm\ 0.007 \ \pm\ 0.031)\,\mathrm{MeV}.$$

Charge conjugation asymmetries in the $\eta \to \pi^+\pi^-\pi^0$ decay

Study of the $\eta \to \pi^+\pi^-\pi^0$ Dalit plot density yields three C-violating observables: left–right A_{LR}, quadrant ($\Delta I = 2$ contribution) A_{Q}, and sextant ($\Delta I = 1$ contribution) A_{S} asymmetry. From the analysis of $\sim 1.4 \times 10^6$ $\eta \to \pi^+\pi^-\pi^0$ decays, we have values consistent with zero to the permil level:

$$\begin{aligned}
A_{\mathrm{LR}} &= \left(0.09 \pm 0.10(\mathrm{stat})^{+0.09}_{-0.14}(\mathrm{sys})\right) \times 10^{-2}\,,\\
A_{\mathrm{Q}} &= \left(-0.05 \pm 0.10(\mathrm{stat})^{+0.03}_{-0.05}(\mathrm{sys})\right) \times 10^{-2}\,,\\
A_{\mathrm{S}} &= \left(0.08 \pm 0.10(\mathrm{stat})^{+0.08}_{-0.13}(\mathrm{sys})\right) \times 10^{-2}\,.
\end{aligned}$$

Search for the $\phi \to (a_0(980) + f_0(980))\gamma \to K_S K_S \gamma$ decay

There many estimates in literature, but the process has never been observed. The $\phi \to K_S K_S \gamma \to 2(\pi^+\pi^-)\gamma$ process is analyzed, where the main background is the initial state radiation process $\phi \to K_S K_L \gamma$.

No events are found from background Monte Carlo sample, whereas 1 event in data is measured. From an integrated luminosity of $1.4\,\mathrm{fb}^{-1}$, of data collected between 2001 and 2005, the following upper limit is found:

$$\mathrm{BR}(\phi \to K\bar{K}\gamma) < 1.8 \times 10^{-8} \text{ at the 90\% CL.}$$

Fig. 2 shows the predictions of various theoretical models for the scalar mesons structure, excluded by this measurement. Sensitivity can be doubled with the full data sample.

4. Conclusions

In the last two years, the KLOE experiment is harvesting the fruits of a long campaign of data taking, simulation and analysis.

Kaon decays measurements allowed for tests of lepton flavor violation, unitarity of the CKM matrix, lepton universality and Chiral Perturbation Theory predictions.

Evidence of valence gluons in the η' to three standard deviations, precise η mass measurement, tests of charge conjugation invariance in the electromagnetic interactions and exclusion of structure hypotheses for the scalar mesons are obtained with ϕ decays.

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