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LATEST RESULTS FROM KLOE AT DAΦNE

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KLOE Collaboration

The KLOE experiment has finished its data taking at the e^+e^- collider DAΦNE in Frascati. KLOE has collected 2.5 fb^{-1} at the peak of the ϕ resonance, and 250 pb^{-1} at $\sqrt{s}$ =1 GeV. The latest experimental results based on a sample of 450 pb^{-1} are presented in this paper: they mainly concern the neutral and charged kaon decays, and the radiative ϕ decays into scalar and pseudoscalar mesons.

Keywords: Kaon physics, light scalar mesons, pseudoscalar mesons.

1. Introduction

The ϕ is a pure $J^{PC} = 1^{--}$ state which decays mainly into a pair of kaons of opposite momentum (49.1% of cases in K^+K^- and 34.1% in K_LK_S) thus providing

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clean samples of tagged K_L, K_S, K^+, and K^- mesons, nearly monochromatic. A large number of η and η' and of light scalar mesons ($a_0(980)$, $f_0(980)$) is also produced via the radiative decays of the ϕ. In this paper are reported the most recent results of the KLOE experiment[1]. These results are based on a sample of about 450 pb^{-1} of the 2001-02 data, corresponding to $1.5\times10^9\phi$ produced. They concern various decay channels of neutral and charged kaons, with the extraction of the $|V_{us}|$ element of the CKM matrix (Sect. 2), the tests of the CPT symmetry and of the $\Delta S = \Delta Q$ rule (Sect. 3), the study of the dynamics of $f_0(980) \to \pi\pi$ (Sect. 4), a precise measurement of the η mass, and the evaluation of the $\eta - \eta'$ mixing angle (Sect. 5).

2. $|V_{us}|$ Measurement

From the first row of the CKM matrix, one can write: $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 1-\Delta$. $|V_{ud}|$ is well known from nuclear β decays[2] and $|V_{ub}|$ is very small ($O(10^{-5})$). The prediction of unitarity, $\Delta = 0$, can be tested at the permil level by extracting $|V_{us}|$ from the measurement of the semileptonic decay width of neutral and charged kaons. The inclusive semileptonic decay rates for $K_{\ell 3}$, where ℓ stands for e or μ, are given by:

$$\Gamma(K \to \pi\ell\nu(\gamma)) = Br(K_{\ell 3(\gamma)})/\tau_K \propto |V_{us}f_+(0)|^2 I_\ell S_{EW}(1+\delta_\ell) \tag{1}$$

where τ_K is the kaon lifetime, $f_+(0)$ is the form factor at zero momentum transfer, I_ℓ is the phase space integral that depends on the form factor slopes, S_{EW} is the short-range radiative correction, and δ_ℓ is the long-term electromagnetic correction. KLOE has measured almost all the experimental inputs to Eq. (1): $Br(K_{Le3})$, $Br(K_{L\mu 3})$, $Br(K_{Se3})$, $Br(K^\pm_{e3})$, the lifetimes of K_L and $K^\pm$, and the form factors slopes of K_{Le3}.

Dominant K_L decay modes: the dominant K_L branching ratios have been measured from a sample of $1.7\times10^7 K_L$ tagged by $K_S \to \pi^+\pi^-$. K_L decays into charged particles (K_{e3}, $K_{\mu 3}$, and $\pi^+\pi^-\pi^0$) have been selected by requiring two K_L decay tracks of opposite charge sign, forming a vertex in the drift chamber. The number of events of the different decay channels have been obtained from a fit of the distribution of $E_{miss} - p_{miss}$ in the $K_{\mu 3}$ hypothesis to the Monte Carlo (MC) distributions[3].

Concerning $K_L \to 3\pi^0$, events with at least three photons with $E > 20$ MeV have been selected. The K_L decay vertex is determined from the arrival times of the photons at the calorimeter.

By imposing the condition $\Sigma_i Br_i = 1$, including the rare decays from PDG, the branching ratios listed below have been obtained together with the lifetime value: $\tau_L = (50.72 \pm 0.17 \pm 0.33)$ ns[3].

$Br(K_L \to \pi e\nu(\gamma)) = 0.4007 \pm 0.0006 \pm 0.0014$
$Br(K_L \to \pi\mu\nu(\gamma)) = 0.2698 \pm 0.0006 \pm 0.0014$
$Br(K_L \to \pi^+\pi^-\pi^0(\gamma)) = 0.1263 \pm 0.0005 \pm 0.0011$
$Br(K_L \to 3\pi^0) = 0.1997 \pm 0.0005 \pm 0.0019$

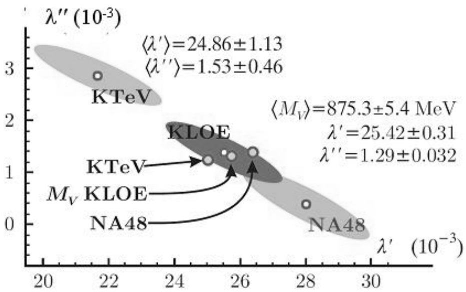

Fig. 1. Comparison of the KLOE slopes with the previuos measurements; the small points represent λ'_+ and λ''_+ obtained from the pole parametrization.

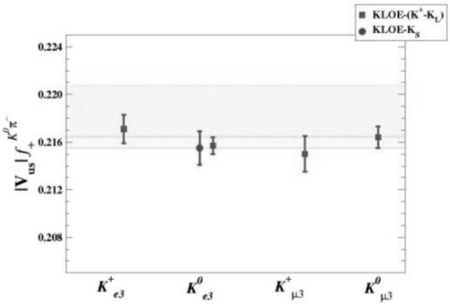

Fig. 2. KLOE measurements of $|V_{us} f_+(0)|$: the shaded region is the unitarity band.

KLOE also performed a direct measurement of τ_L with $K_L \to 3\pi^0$ events: $\tau_L = (50.92 \pm 0.17 \pm 0.25)$ ns[4]. By averaging $\tau_L = (50.84 \pm 0.23)$ ns is obtained.

Form factor slopes: the natural form of the transition form factor of $K_L \to \pi \ell \nu$ is given by the pole parametrization: $f_+(t) = f_+(0)\left[M_V^2/(M_V^2 - t)\right]$, where t is the squared momentum transfer. Its the Taylor expansion is:

$$f_+(t) = f_+(0)\left[1 + \lambda'_+ \frac{t}{m_\pi^2} + \frac{1}{2}\lambda''_+ \left(\frac{t}{m_\pi^2}\right)^2 + \ldots\right] \tag{2}$$

where $\lambda'_+ = (m_\pi/M_V)^2$ and $\lambda''_+ = 2\lambda'^2_+$ are the slope paremeters.
The momentum transfer distribution has been measured for a sample of $2\times10^6 K_{Le3}$ decays[5]. The fit to Eq. (2) gives the slope values $\lambda'_+ = (25.5 \pm 1.5 \pm 1.0) \times 10^{-3}$ and $\lambda''_+ = (1.4 \pm 0.7 \pm 0.4) \times 10^{-3}$, with a large correlation coefficient, $\rho(\lambda'_+, \lambda''_+) = -0.95$, as expected. The fit to the pole parametrization gives $M_V = (870 \pm 6 \pm 7)$ MeV. In Fig. 1 the KLOE slopes are compared to the NA48 and KTeV measurements[6]; the three small points indicate that the slopes obtained from the pole parametrization of the three experiments, agree better than the slopes from the quadratic fit.

Charged kaon semileptonic decays: $K^\pm \to \pi^0 \ell^\pm \nu$ events are tagged by $K^\mp \to \mu^\mp \nu$ and $K^\mp \to \pi^0 \pi^\mp$. The lepton identification is performed by means of time of flight (TOF). About 179000 $K^\pm_{e3}$ and 107000 $K^\pm_{\mu 3}$ events have been selected, which correspond respectively to $Br(K^\pm_{e3}) = (5.047 \pm 0.019 \pm 0.039)\%$ and $Br(K^\pm_{\mu 3}) = (3.310 \pm 0.016 \pm 0.045)\%$.

The charged kaon lifetime has been measured with a sample of 200 pb^{-1}, by using events tagged by $K^\mp \to \mu^\mp \nu$. A decay vertex has been searched for in the opposite side of the detector and $\tau_\pm = (12.367 \pm 0.044 \pm 0.065)$ ns has been obtained from the decay length of the $K^\pm$. The energy loss of the kaon along its flight path has been taken into account.

$|V_{us}|$ extraction: in Fig. 2 the KLOE results on $|V_{us} f_+(0)|$ are shown; they have been obtained by using the branching ratios and lifetimes quoted before, the

$Br(K_{Se3})$ reported in next section, and the K_S lifetime from PDG. The average slopes $\lambda'_+ = (25.42 \pm 0.31) \times 10^{-3}$ and $\lambda''_+ = (1.29 \pm 0.03) \times 10^{-3}$ from the pole parametrization of KLOE, NA48 and KTeV[6] have been used, together with the slope of the scalar form factor $\lambda_0 = (15.87 \pm 0.95) \times 10^{-3}$ average of KTeV and Istra+[7].

The average value is $< |V_{us} f_+(0)| >= 0.2160 \pm 0.0005$ (0.25% relative uncertainty); this result is in good agreement with the prediction assuming unitarity, $< |V_{us} f_+(0)| >= 0.2187 \pm 0.0022$ (shaded band of Fig. 2), obtained with $|V_{ud}| = 0.97377 \pm 0.00027$ from nuclear β decays[2] and $f_+(0) = 0.961 \pm 0.008$[8].

The ratio $|V_{us}|/|V_{ud}|$ can be extracted from the ratio of branching ratios: $\Gamma(K^+ \to \mu^+\nu(\gamma))/\Gamma(\pi^+ \to \mu +^{\nu} (\gamma)) \propto |V_{us}|^2/|V_{ud}|^2 f_K^2/f_\pi^2$. From the KLOE measurement $Br(K^+ \to \mu^+\nu(\gamma)) = 0.6366 \pm 0.0009 \pm 0.0015$[9], and using $f_K/f_\pi = 1.198 \pm 0.003^{+0.016}_{-0.005}$ from lattice calculations[10], one obtains $|V_{us}|/|V_{ud}| = 0.2294 \pm 0.0026$. A fit has been performed in the ($|V_{us}|$, $|V_{ud}|$) plane using the KLOE measurements of $|V_{us}|$ and $|V_{us}|/|V_{ud}|$, plus the already quoted values of $|V_{ud}|$ and $f_+(0)$. The result is: $|V_{us}| = 0.2242 \pm 0.0016$ (dominated by the theoretical uncertainty on $f_+(0)$) and $|V_{ud}| = 0.97377 \pm 0.00027$, with a $P(\chi^2) = 0.8$, in good agreement with unitarity as shown in Fig. 3.

3. K_S Semileptonic Decay and Charge Asymmetry

From a sample of 410 pb^{-1}, about 6500 events of both $K_S \to \pi^- e^+ \nu$ and $K_S \to \pi^+ e^- \bar{\nu}$ decays have been selected. The K_S presence is tagged by the tipical signature of a K_L interaction in the calorimeter; the e/π identification is performed by means of TOF, and this allows also the rejection of the $K_S \to \pi^+\pi^-$ background. After the TOF selection, the charge of the lepton in the final state can be assigned with negligible probability of misidentification. The amount of signal can be evaluated by fitting the distribution of $E_{miss} - p_{miss}$ to the MC expectations[11].

By normalizing to $K_S \to \pi^+\pi^-$, the following branching ratio have been measured: $Br(K_S \to \pi^- e^+ \nu) = (3.528 \pm 0.057 \pm 0.027) \times 10^{-4}$, $Br(K_S \to \pi^+ e^- \bar{\nu}) = (3.517 \pm 0.051 \pm 0.029) \times 10^{-4}$, and the total $Br(K_S \to \pi e \nu) = (7.046 \pm 0.077 \pm 0.049) \times 10^{-4}$. Then the first measurements of the K_S charge asymmetry has been obtained:

$$A_S = \frac{\Gamma(K_S \to \pi^- e^+ \nu) - \Gamma(K_S \to \pi^+ e^- \bar{\nu})}{\Gamma(K_S \to \pi^- e^+ \nu) + \Gamma(K_S \to \pi^+ e^- \bar{\nu})} = (1.5 \pm 9.6 \pm 2.9) \times 10^{-3} \tag{3}$$

The comparison of A_S with the asymmetry A_L of the K_L allows tests of CP and CPT. $A_S - A_L = 4[Re(\delta) + Re(x_-)]$ is sensitive to CPT violation either in mixing (δ) and in the decay amplitude with $\Delta S \neq \Delta Q$ (x_- parameter); by using $A_L = (3.322 \pm 0.058 \pm 0.057) \times 10^{-3}$ from KTeV[12] and $Re(\delta) = (3.0 \pm 3.4) \times 10^{-4}$ from CPLEAR[13], one gets $Re(x_-) = (-0.8 \pm 2.4 \pm 0.7) \times 10^{-3}$.

On the other hand $A_S + A_L = 4[Re(\varepsilon) + Re(y)]$, where ε is the usual CP violation parameter and $Re(y)$ is sensitive to the CPT violation in the $\Delta S = \Delta Q$ amplitude. Taking $Re(\varepsilon)$ from PDG (without assuming CPT), $Re(y) = (0.4 \pm 2.4 \pm 0.7) \times 10^{-3}$ has been obtained.

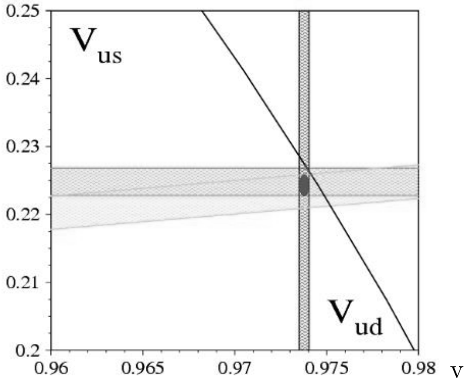

Fig. 3. Contraints on ($|V_{us}|$, $|V_{ud}|$) plane; unitarity is represented by the solid line.

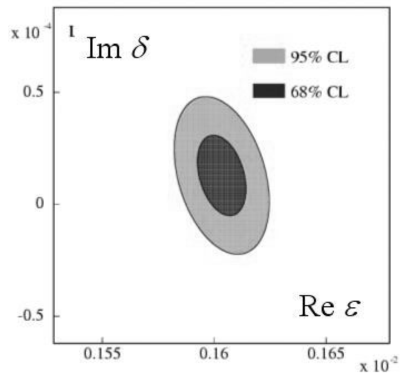

Fig. 4. $Re(\varepsilon)$ and $Im(\delta)$ from the BS relation.

Also a test of the $\Delta S = \Delta Q$ rule in CPT-conserving transitions can be performed through the quantity:

$$Re(x_+) = \frac{1}{2}\frac{\Gamma(K_S \to \pi e\nu) - \Gamma(K_L \to \pi e\nu)}{\Gamma(K_S \to \pi e\nu) + \Gamma(K_L \to \pi e\nu)} \tag{4}$$

With the KLOE results for $Br(K_L \to \pi e\nu)$ and τ_L, and τ_S from PDG, $Re(x_+) = (-0.5\pm3.1\pm1.8)\times10^{-3}$ is obtained. In all the three cases the KLOE results improve the uncertainties with respect to the previous CPLEAR measurements[13].

Another test of CPT can be performed by means of the Bell-Steinberger (BS) unitarity relation, that combines the information of the decay amplitudes of K_S and K_L to the same final states: $(1 + i\ tan\phi_{SW})[Re(\varepsilon) - iIm(\delta)] = 1/\Gamma_S \sum_f A^*(K_S \to f)A(K_L \to f)$. Most of the inputs to that relation have been measured by KLOE; in addition to A_S and to the other quantities reported above, important contributions are the following:

$Br(K_S \to \pi + \pi^-)/Br(K_S \to \pi^0\pi^0) = 2.2549 \pm 0.0059$[14]
$Br(K_L \to \pi + \pi^-) = (1.963 \pm 0.21) \times 10^{-3}$(see ref.(15))
$Br(K_S \to \pi^0\pi^0\pi^0) < 1.2 \times 10^{-7}$ at 90% C.L. $\Rightarrow$ $|\eta_{000}| < 0.018$ at 90% C.L.[16]

In Fig. 4 the correlation between the two parameters is shown; the central values are $Re(\varepsilon) = (160 \pm 1.3) \times 10^{-5}$ and $Im(\delta) = (1.2 \pm 1.9) \times 10^{-5}$, with an improvement of a factor about two with respect to the CPLEAR uncertainties[13].

4. Light Scalar Mesons

The scalar mesons $f_0(980)$ and $a_0(980)$ are not easily interpreted as ordinary $q\bar{q}$ mesons; alternative hypotheses have been proposed: $q\bar{q}q\bar{q}$ states or $K\bar{K}$ bound states. The branching ratios of $\phi \to f_0\gamma$ and $\phi \to a_0\gamma$, as well as the f_0 and a_0 mass shapes, are sensitive to the structure of these particles.

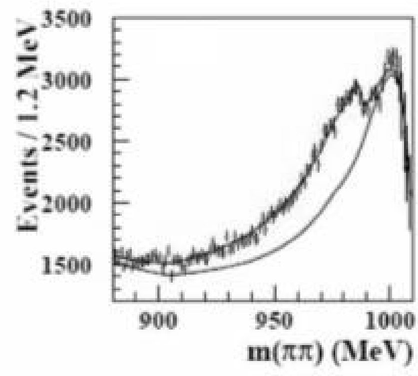

Fig. 5. $M_{\pi^+\pi^-}$ spectrum: the solid line is the contribution of ISR+FSR, the bump around 980 MeV is the f_0 signal.

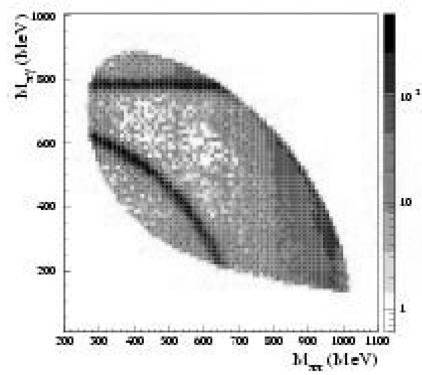

Fig. 6. Dalitz plot of $e^+e^- \to \pi^0\pi^0\gamma$.

The $f_0(980)$ is searched for in $\pi^+\pi^-\gamma$ and $\pi^0\pi^0\gamma$ final states. The search for $\phi \to f_0(\to \pi^+\pi^-)\gamma$ is characterized by the presence of high rate irreducible backgrounds due to the initial state radiation (ISR), and to $e^+e^- \to \pi^+\pi^-\gamma$, occuring either through the ϕ or through the ρ^0 tail (final state radiation, FSR)[17]. Since the ISR cross-section is peaked at small photon angles respect to the beam line, the f_0 events are searched for in the large angle region $45^o < \theta < 135^o$. The bump appearing in the $\pi^+\pi^-$ invriant mass spectrum around 980 MeV is the f_0 signal (Fig. 5).
In order to extract the relevant f_0 parameters, the $\pi^+\pi^-$ mass spectrum has been fitted to two different models: in the first one (called "No Structure", NS) the scalar is treated as a Breit-Wigner with energy dependent width[18]; in the second the coupling of the ϕ to the scalar occurs through a charged kaon loop[19]. The results of the fits are reported in Tab. 1. Both models well reproduce the experimental spectrum, without need of including the $\sigma(600)$ contribution, and show a large coupling of the f_0 to $K\bar{K}$.

Table 1. Fit results for $f_0(980) \to \pi^+\pi^-$ and $\pi^0\pi^0$

	$\pi^+\pi^-$			$\pi^0\pi^0$	
$f_0(980)$ param.	NS model[18]	Kaon Loop[19]		NS model	Kaon loop
m_{f_0} (MeV)	973 – 981	980 – 987		$984.7 \pm 0.4^{+2.4}_{-3.7}$	$976.8 \pm 0.3\ ^{+0.9}_{-0.6}$
$g_{\phi f_0\gamma}$ (GeV^{-1})	1.2 – 2.0			$2.61 \pm 0.02\ ^{+0.05}_{-0.02}$	
$g_{f_0\pi^+\pi^-}$ (GeV)	0.9 – 1.1	3.0 – 4.2		$1.31 \pm 0.01\ ^{+0.09}_{-0.03}$	$-1.43 \pm 0.01\ ^{+0.05}_{-0.02}$
$g_{f_0K^+K^-}$ (GeV)	1.6 – 2.3	5.0 – 6.3		$0.40 \pm 0.04\ ^{+0.62}_{-0.29}$	$3.76 \pm 0.04\ ^{+0.05}_{0.02}$

$e^+e^- \to \pi^0\pi^0\gamma$ is studied by looking for fully neutral events with 5 energy deposits in the calorimeter. In Fig. 6 the Dalitz plot for the selected sample of 1.5×10^5 events is reported. The two sharp bands correspond to $e^+e^- \to \omega(\to \pi^0\gamma)\pi^0$, while the structure close to the high $M^2_{\pi\pi}$ corner is due to $\phi \to f_0(\to \pi^0\pi^0)\gamma$. Also in this case the two models quoted above[18,19] well reproduce the Dalitz plot (Tab. 1).

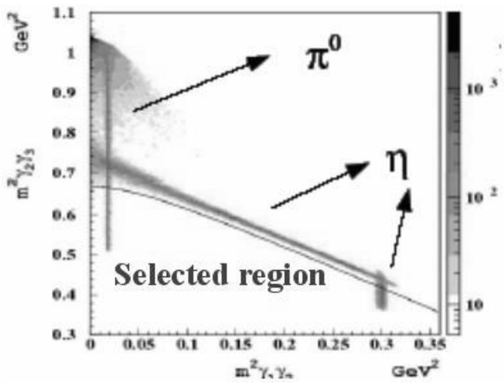

Fig. 7. Dalitz plot for 3γ events: the region below the solid line is selected for the measurement of the η mass.

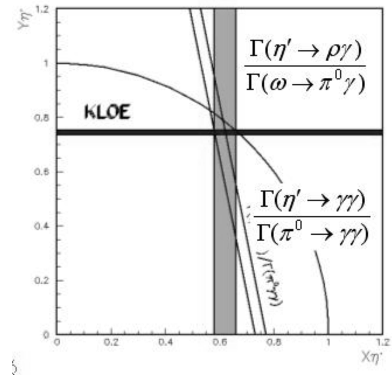

Fig. 8. η' gluon content: constraints on the $X-Y$ plane; the circle corresponds to $Z = 0$.

In the fit function a VDM calculation of the vector amplitude ($e^+e^- \to \omega\pi^0$) has been used, and the interference terms have been taken into account. The are differences with respect to the $\pi^+\pi^-$ final state: *(i)* the $\sigma(600)$ is now needed in order to reproduce the experimental data, and *(ii)* for the NS model a small f_0 to K^+K^- coupling is obtained.
By integrating the scalar part of the $\pi^0\pi^0$ invariant mass distribution one obtains: $Br(\phi \to S\gamma \to \pi^0\pi^0\gamma) = (1.07^{+0.01}_{-0.03} \pm 0.06) \times 10^{-4}$, where $S = \sigma(600)\ ,\ f_0(980)$.

5. Pseudoscalar Mesons

η mass: two recent measurements of the η mass show a large discrepancy, GEM collaboration at COSY obtained $M_\eta = (457.311 \pm 0.028 \pm 0.032)$ MeV[20] from $p + d \to^3 He + \eta$ with a missing mass technique, while NA48 measured $M_\eta = (547.843 \pm 0.030 \pm 0.041)$ MeV[21] by detecting $\eta \to \pi^0\pi^0\pi^0$ decays from $\pi^- + p \to \eta + n$.
KLOE selected 3 photon events, from $\phi \to \eta\gamma$ with $\eta \to \gamma\gamma$ and $\phi \to \pi^0\gamma$ with $\pi^0 \to \gamma\gamma$. A kinematic fit on the events has been performed by imposing the energy and momentum conservation (the ϕ momentum and the actual interaction point position are measured with large angle Bhabha scattering). In order to have a clean sample of events, the lower part of the Dalitz plot (Fig. 7) is selected; the η and π^0 masses are obtained from the peaks of the invariant mass distribution of the two lowest energy photons. The 2001-2002 data set has been divided into 8 periods and the average value of the η mass is $M_\eta = (547822 \pm 5 \pm 69)$ keV in agreement with the NA48 value. As a check of the absolute energy scale, the same analysis has been performed for the π^0 mass and $M_{\pi^0} = (134990 \pm 6 \pm 30)$ keV has been obtained, to be compared with the PDG value: $M_{\pi^0} = (134976.6 \pm 0.6)$ keV.

$\eta - \eta'$ mixing angle: KLOE has analyzed the decay chains $\phi \to \eta'\gamma\ \eta' \to \eta\pi^+\pi^-\ \eta \to \pi^0\pi^0\pi^0$, and $\phi \to \eta'\gamma\ \eta' \to \eta\pi^0\pi^0\ \eta \to \pi^+\pi^-\pi^0$, in order to measure the ratio $R = \Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$, that is related to the pseudoscalar mixing angle and to the η' gluonic content. The final state is characterized by two charged pions and seven photons. After background subtraction $3405 \pm 61 \pm 28$ $\phi \to \eta'\gamma$ events have been found. The normalization has been performed to the number of observed $\eta \to \pi^0\pi^0\pi^0$ decays to obtain the value $R = (4.79 \pm 0.09 \pm 0.20) \times 10^{-3}$, being the systematic error dominated by the uncertainties on the intermediate branching ratios of the η'. From that ratio, according to ref.(22), the pseudoscalar mixing angle in the flavor basis can be extracted: $\varphi_P = (41.4 \pm 0.4 \pm 0.9)^\circ$. The ratio R is in good agreement with the previous KLOE measurement $R = (4.7 \pm 0.5 \pm 0.3) \times 10^{-3}$ based on $\pi^+\pi^- + 3\gamma$ final state with 17 pb^{-1} of 2000 data.

If one allows the η' to have some gluonium content, then $|\eta' >= X|q\bar{q} > +Y|s\bar{s} > +Z|glue >$, and $X^2 + Y^2 < 1$. A consistency check can be done assuming $Z = 0$ and comparing the regions of the $(X,\ Y)$ plane allowed by the KLOE measurement $Y = cos\varphi_P$ and by other experimental constraints from $\Gamma(\eta' \to \rho\gamma)/\Gamma(\omega \to \pi^0\gamma)$ and $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\pi^0 \to \gamma\gamma)$. The overlap of the three regions gives $X^2 + Y^2 = 0.93 \pm 0.06$ (Fig. 8), compatible with no gluon content in the η'.

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