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Meson decay studies with the KLOE detector at $DA\Phi NE$

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The KLOE experiment has been collecting data since april 1999 at the $DA\Phi NE$ collider in Frascati. A statistics of about 0.45 fb^{-1} has been analyzed. The latest results concerning the study of the ϕ radiative decays and of the kaon decays are illustrated in this paper.

1. Introduction

KLOE operates at DAΦNE, an e^+e^- collider also known as the Frascati ϕ factory; ϕ mesons are produced in small angle (25 mrad) collisions of equal energy electrons and positrons, giving the ϕ a small transverse momentum component in the horizontal plane, $p_\phi \sim 13\,\text{MeV}/c$. About 1.5% of ϕs decay into a photon and a scalar or a pseudo-scalar particle. This circumstance together with the intrinsic clean environment of an electron positron collider allows us to perform detailed studies of ϕ decays into $f_0\gamma$. Moreover due to the huge number of ϕ produced also η and η' decays have been investigated. The vast majority of ϕ decays, however, involve kaons in the final state. The main advantage of studying kaons at a ϕ factory is that ϕ mesons decay $\sim$49% of the time into charged kaons and $\sim$34% of the time into neutral kaons. K_L's and K_S's (or K^+'s and K^+'s) are produced almost back-to-back in the laboratory, with mean decay paths $\lambda_\text{L} \sim 340\,\text{cm}$, $\lambda_\text{S} \sim 0.6\,\text{cm}$, and $\lambda_\pm \sim 90\,\text{cm}$, respectively. One of the features of a ϕ factory is the the possibility to perform tagged measurements: the detection of a long-lived neutral kaon K_L guarantees the presence of a K_S of given momentum and direction and vice versa. The same holds for charged kaons.

The KLOE detector consists essentially of a drift chamber, DCH, surrounded by an electromagnetic calorimeter, EMC. The DCH [1] is a cylinder of 4 m diameter and 3.3 m in length which constitutes a large fiducial volume for K_L decays (1/2 of λ_L). The momentum resolution for tracks at large polar angle is $\sigma_p/p \leq 0.4\%$. The EMC is a lead-scintillating fiber calorimeter [2] consisting of a barrel and two endcaps which cover

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98% of the solid angle. The energy resolution is $\sigma_E/E \sim 5.7\%/\sqrt{\mathrm{E(GeV)}}$. The intrinsic time resolution is $\sigma_T = 54$ ps$/\sqrt{\mathrm{E(GeV)}} \oplus 50$ ps. A superconducting coil surrounding the barrel provides a 0.52 T magnetic field.

During 2002 data taking, the maximum luminosity reached by DAΦNE was $7.5 \cdot 10^{31}$ cm^{-2} s^{-1}. Although this is lower than the design value, the performance of the machine was improving during the years and, at the end of 2002, we could collect up to ~ 4.5 pb^{-1}/day. The whole sample (2001-2002) amounts to 450 pb^{-1}, equivalent to 1.4 billion ϕ decays. Recently, the machine has been upgraded and KLOE resumed its data taking in april 2004. Up to now (20^{th} of July) ~ 150 pb^{-1} has already been collected with peak luminosity of $8.4 \cdot 10^{31}$ cm^{-2} s^{-1}.

The tagging of K_L and K_S is the basis of each KLOE analysis for neutral kaons. Similar techniques have been developed also for charged kaons. The selection of $K_S \to \pi^+\pi^-$ decays provides an efficient tag for K_L decays. K_S's are instead tagged by identifying a K_L interaction, K_L-crash, in the calorimeter, which has a very distinctive signature given by a late ($\beta_K = 0.2$) high-energy cluster not associated to any track. In either case, reconstruction of one kaon establishes the trajectory of the other one with an angular resolution of 1° and a momentum resolution of ~ 2 MeV. Concerning the kaon physics, several analyses [3,4] have been already completed or are under completion at KLOE. We discuss only the two most advanced items in progress.

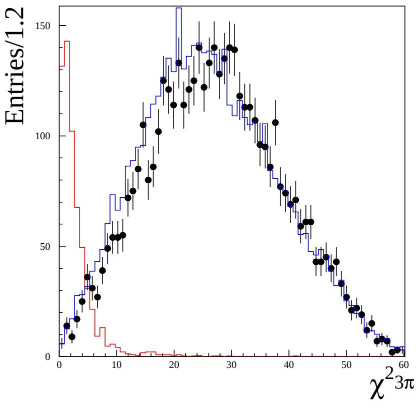
2. Direct search of $K_S \to 3\pi^0$

The decay $K_S \to 3\pi^0$ is a pure CP violating process. The related CP violation parameter η_{000} is defined as the ratio of K_S to K_L decay amplitudes: $\eta_{000} = A(K_S \to 3\pi^0)/A(K_L \to 3\pi^0) = \varepsilon + \varepsilon'_{000}$ where ε describes the CP violation in the mixing matrix and ε'_{000} is a direct CP violating term. In the Standard Model we expect η_{000} to be similar to η_{00}. The expected branching ratio of this decay is therefore $\sim 2 \cdot 10^{-9}$, making its direct observation really challenging. The best upper limit on the BR (i.e. on $|\eta_{000}|^2$) has been set to $1.5 \cdot 10^{-5}$ by SND [5] where, similar to KLOE, it is possible to tag a K_S beam. The other existing technique is to detect the interference term between $K_S K_L$ in the same final state which is proportional to η_{000}. The weighted average of the best published values [6,7] gives: $\eta_{000} = (0.08 \pm 0.11) + i \cdot (0.07 \pm 0.16)$. Apart from the interest in observing this decay directly, the large uncertainty on η_{000} limits the precision on CPT invariance test via the unitarity relation [8]. In the most general way, a neutral kaon state [9] is expressed as: $K_{S,L} = K_{1,2} + (\varepsilon \pm \delta) K_{2,1}$ where K_1 and K_2 are the two CP eigenstates and δ is a CPT violation parameter. The unitarity relation in this base can be written as:

$$(1 + i\tan(\phi_{sw}))(\Re(\varepsilon) - i\Im(\delta)) = \sum (A^*(K_S \to f) A(K_L \to f)/\Gamma_S) \quad (1)$$

where the sum runs over all the possible decay channels f, and $\tan(\phi_{sw}) = 2\Delta m_{S,L}/(\Gamma_S - \Gamma_L)$. According to ref. [10], the value of $\Im(\delta) = (2.4 \pm 5.0) \cdot 10^{-5}$ is limited by the measurement on η_{000}. Neglecting this term, the same analysis yields $\Im(\delta) = (-0.5 \pm 2.0) \cdot 10^{-5}$.

Our selection starts by requiring a K_L-crash tag and six neutral clusters coming from the interaction point, IP. A tight constraint on β and moderate requirements on energy and angular acceptance are applied in order to have a large control sample for the background,



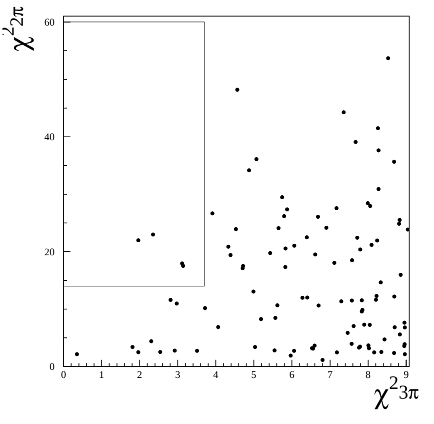


Figure 1. **Left:** Distribution of $\chi^2_{3\pi}$ with analysis cuts applied when $14 < \chi^2_{2\pi} < 40$; black dots (solid line) are data (MonteCarlo). The red line in the left is the MC distribution for BR($K_S \to 3\pi^0$) $= 10^{-5}$. **Right:** Distribution of events in $\chi^2_{2\pi}$ *vs* $\chi^2_{3\pi}$; 4 events are lies in the defined signal box.

while retaining large selection efficiency for the signal. On 450 pb^{-1} we have an initial sample of 39 k events dominated by $K_S \to 2\pi^0 +$ 2 fake γ. To reduce the sample, a kinematic fit which imposes K_S mass, K_L 4-momentum conservation and $\beta = 1$ for each γ is applied. Only the events with $\chi^2_{\text{fit}}/\text{ndf} < 3$ are retained for further analysis. However, this cut improves the rejection power only of a factor ~ 3 and, to better discriminate $2\pi^0$ *vs* $3\pi^0$ final state, we build two pseudo-χ^2 variables: $\chi^2_{3\pi}$, which is based on the 3 best π^0-mass estimates and $\chi^2_{2\pi}$, which selects 4 out of the 6 photons providing the best kinematic agreement with the considered decay. The sample selected by requiring $\chi^2_{2\pi}$ to be in a high acceptance region for the signal shows a contamination related to the production of fake K_L-crash followed by a $K_L \to 3\pi^0$ decay. These fake, late clusters are produced by the pions from $K_S \to \pi^+\pi^-$ interacting on the quadrupoles. To reduce it to a negligible amount we veto events with tracks coming from the IP. The distribution of $\chi^2_{3\pi}$ for the final selection is shown in Fig. 1 (left) for both MC and data, together with the expected distribution for the signal simulated with a branchin ratio of $1.4 \cdot 10^{-5}$, the previous limit for BR($K_S \to 3\pi^0$) [11]. A signal box region in the $\chi^2_{2\pi}$ *vs* $\chi^2_{3\pi}$ plane (see Fig. 1, right). With an efficiency $\varepsilon_{3\pi} = (22.6 \pm 0.8)\%$, we count 4 events for an expected background $N_b = 3.2 \pm 1.4 \pm 0.2$. Folding the proper background uncertainty, we quote the number of $K_S \to 3\pi^0$ decay to be below 5.8 at 90% C.L. In the same tagged sample, we count $3.8 \cdot 10^7$ $K_S \to 2\pi^0$ events used for normalization. We finally derive BR($K_S \to 3\pi^0$) $\leq 2.1 \cdot 10^{-7}$ at 90% C.L. which improves of a factor ~ 100 the previous measurement. This result can also be translated into a limit $|\eta_{000}| < 0.024$ at 90% C.L. which makes the contribution

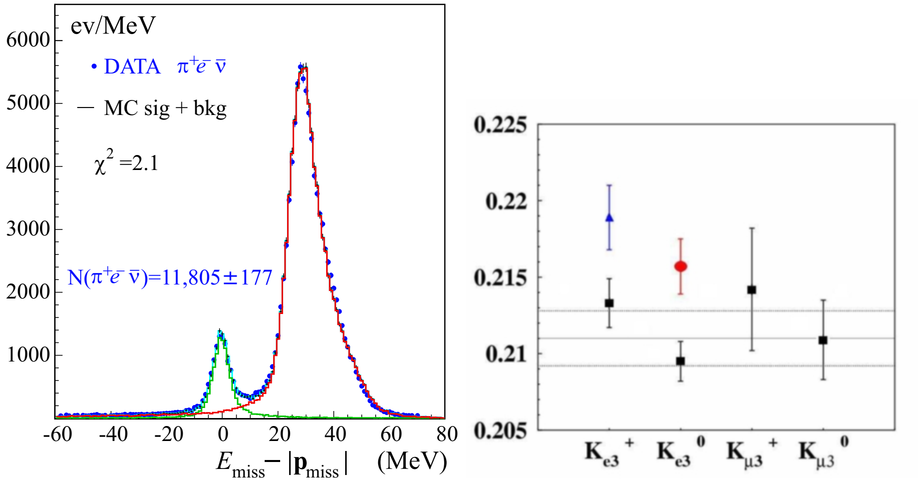


Figure 2. **Left:** $E_{\text{miss}} - |P_{\text{miss}}|$ distribution after time-of-flight cuts for the $\pi^+ e^- \overline{\nu}$ sample: dots are data, solid lines are MonteCarlo expectations. **Right:** evaluations of $|V_{us} f_+^{K^0\pi^-}(0)|$ from PDG 2002 numbers (squares), BNL-E865 (triangle), KLOE preliminar number from K_{e3} of the K_S (circle).

of the uncertainty for this decay negligible in the calculation of $\Im(\delta)$.

3. K_S semileptonic decays

The semileptonic charge asymmetries for $K_{S,L}$ are related to the CP, CPT violation parameters ε, δ as [9,12] : $A_{S,L} = \frac{\Gamma_s(\pi^+ e^- \overline{\nu}) - \Gamma_s(\pi^- e^+ \nu)}{\Gamma_s(\pi^+ e^- \overline{\nu}) + \Gamma_s(\pi^- e^+ \nu)} = 2\Re(\varepsilon) \pm 2\Re(\delta)$. A non zero value of $A_S - A_L$ would signal CPT violation either in the K_S-K_L mixing or in direct transitions violating the $\Delta S = \Delta Q$ rule. While A_L is measured with high precision [13] a measurement of A_S is still not existent. KLOE has already measured [14] the BR for the K_{e3} decay of the K_S using 17 pb^{-1} collected in 2000. A new measurement with the collected statistics of 450 pb^{-1} gives a first determination of A_S.

The $K_S \to \pi e \nu$ decays are selected, after K_L-crash tagging, by the presence of two oppositely charged tracks from a vertex close to the IP. Loose momentum and angular cuts, and the requirement of an upper cut on $M(\pi^+\pi^-)$, reject most of the $K_S \to \pi^+\pi^-$ background. The π and e assignments are made using time-of-flight so that the BR's to final states of each lepton charge can be measured independently. In Fig. 2 (left), the $E_{\text{miss}} - |P_{\text{miss}}|$ distribution, obtained by using the K_S momentum estimated from the K_L-tag, shows a pronounced peak around zero due to the neutrino. The number of signal events is obtained from a fit which uses the MC distributions for signal and background with their normalizations as free parameters. The generator used for the signal properly handles the final state emitted radiation through an infrared finite treatment. By normalizing to the number of $K_S \to \pi^+\pi^-$ events counted in the same tagged sample, we get the following preliminary values for BR($K_S \to \pi^+ e^- \overline{\nu}$) $= (3.54 \pm 0.05 \pm 0.04) \cdot 10^{-4}$ and BR($K_S \to \pi^- e^+ \nu$) $= (3.54 \pm 0.05 \pm 0.04) \cdot 10^{-4}$. Independent of charge, we get BR($K_S \to \pi e \nu$) $= (7.09 \pm 0.07 \pm 0.08) \cdot 10^{-4}$, which is consistent with our old measurement, improving of a factor 5 the statistical error. On the basis of these results, we derive also the first measurement ever done of the charge asymmetry for the K_S: $A_S = (-2 \pm 9 \pm 6) \cdot 10^{-3}$. This value is consistent with the much more precise A_L evaluations. With the 2 fb^{-1} expected from next running we could perform a consistency test of A_S with $2\Re(\varepsilon)$. We need instead at least 20 fb^{-1} to determine δ with a precision comparable to the one obtained by CPLEAR.

4. The determination of V_{us}

The determinations of $|V_{us}|$ and $|V_{ud}|$ provide the most precise test of CKM unitarity: ($|V_{ud}|^2 + |V_{us}|^2 = 1 - \Delta$). In PDG 2002 [11], $\Delta = 0.0042 \pm 0.0019$ shows a $2.2\,\sigma$ deviation from unitarity. In this test, $|V_{us}|$ account for 0.0011 of the error and is derived from the measurement of partial widths [15] in K_{l3} decays:

$$\Gamma(K_{l3}) \propto |V_{us} f_+^{K^0\pi^-}(0)|^2 I(\lambda_+, \lambda_0, 0)(1 + \delta_{SU2} + \delta_k) \tag{2}$$

where $f_+^{K^0\pi^-}(0)$ is the kaon form factor a $t = (P_k - P_\pi)^2 = 0$, $\lambda_{+,0}$ are the form factor slopes, I is the integral of the phase space and δ_{SU2}, δ_k are the isospin-breaking and electromagnetic radiative corrections; these corrections are of the order of $\sim 1 \div 2\%$. By measuring the BR(K_{l3}) in a photon inclusive way and correcting for the lifetimes the product $|V_{us}| f_+^{K^0\pi^-}(0)$ can be derived. The four evaluations of this quantity from published data are in good agreement as shown in Fig. 2 (right). On the other hands, the recent measurement of BNL-E865 [16] gives a discrepant value which is instead consistent with unitarity and the current determination of $|V_{ud}|$. Our preliminary measurement of the BR($K_S \to \pi e \nu$) allows us to obtain a new value of $|V_{us}| f_+^{K^0\pi^-}(0)$ in much better agreement with E865 and unitarity (see Fig. 2 (right)). The discrepancy between the K_S and K_L, $K^\pm$ determination of V_{us} calls for new measurements. In the longer term, KLOE should be able to determine all four K_{l3} BR's to much better than 1% and significantly improve the determinations of the lifetimes, as well as the form factors slopes.

5. Search for $\phi \to f_0\gamma$ in $\pi^+\pi^-\gamma$ events.

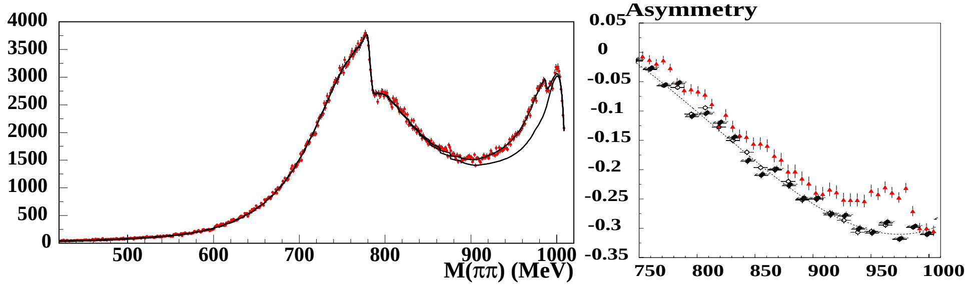
The ϕ radiative decays to scalar mesons, $\phi \to S\gamma$, give significant insight in the assessment of the nature of lower mass scalar mesons [17]. An overall fit of these data is in progress, with the aim of extracting the f_0 parameters taking into account all the possible interferences of the f_0 term with the other amplitudes.

The search for $\phi \to f_0(\to \pi^+\pi^-)\gamma$ is characterized by the presence of irreducible backgrounds due to the initial state radiation (ISR), to $e^+e^- \to \pi^+\pi^-\gamma$ (FSR) and $\phi \to \rho^\pm(\to \pi^\pm\gamma)\pi^\pm$. The f_0 events are searched for in the large photon angle region $45^o < \theta < 135^o$ to reduce ISR background. The f_0 signal appears as a bump in the $\pi^+\pi^-$ invariant mass $M_{\pi\pi}$ spectrum around 980 MeV. Fig.3 (left) shows the spectrum obtained at $\sqrt{s} = M_\phi$.

An overall fit to the spectrum has been done applying the following formula:

$$\frac{dN}{dM_{\pi\pi}} = \left[(\frac{d\sigma}{dM_{\pi\pi}})_{ISR} + (\frac{d\sigma}{dM_{\pi\pi}})_{FSR+f_0} + (\frac{d\sigma}{dM_{\pi\pi}})_{\rho\pi} \right] \times L \times \epsilon(M_{\pi\pi})$$

with L the integrated luminosity and $\epsilon(M_{\pi\pi})$ the selection efficiency as a function of $M_{\pi\pi}$. The f_0 amplitude is taken from the kaon-loop approach [17]. A forward-backward asymmetry $A = \frac{N^+(\theta>90^o)-N^+(\theta<90^o)}{N^+(\theta>90^o)+N^+(\theta<90^o)}$ is expected, due to the interference between FSR and ISR[18]. Fig.3 (right) shows the asymmetry as a function of $M_{\pi\pi}$ compared to the prediction based on the ISR-FSR interference alone. A significant deviation from the prediction is observed in the high mass region clearly due to the f_0 contribution.



M(ππ)(MeV)

Figure 3. *(left) $M_{\pi\pi}$ spectrum of $\pi^+\pi^-\gamma$. The upper (lower) curves are the result of the fit and the estimated background due to ISR, FSR and $\rho\pi$. (right) Forward-Backward asymmetry A as a function of $M_{\pi\pi}$. The curve and the black points are the Montecarlo expectations based on the interference between FSR and ISR only. The experimental data are reported as triangles.*

6. Dynamics of $\eta \to \pi^+\pi^-\pi^0$

The dynamics of the $\eta \to \pi^+\pi^-\pi^0$ decay has been studied with a Dalitz plot analysis. The conventional variables X and Y are defined as: $X = \sqrt{3}\frac{T_+ - T_-}{Q_\eta}, Y = \frac{3T_0}{Q_\eta} - 1$, where $Q_\eta = m_\eta - 2m_{\pi^+} - m_{\pi^0}$ and T_+, T_- and T_0 are the kinetic energies of the particles. The measured distribution has been fitted as: $|A(X,Y)|^2 \simeq (1 + aY + bY^2 + cX + dX^2 + eXY + ...)$. C-parity conservation prevents odd powers in X being present in the expansion: thus parameters c and e should be zero as confirmed by our fit. The results of the fit are shown in table 1 Efficiency is $\simeq 36$ % over the whole Dalitz plot. The evaluation of systematic effects is under completion.

Table 1
Fitted parameters $P(\chi^2) = 52$ of $\eta \to 3\pi$ Dalitz plot.

a	b	c
$-1.075 \pm .008$	$.118 \pm .009$	$-.0005 \pm .004$
d	e	f
$.049 \pm .008$	$-.004 \pm .01$	$.13 \pm .02$

7. Rare and forbidden η decays ($\eta \to \pi^0\gamma\gamma$,$\eta \to \pi^+\pi^-$,$\eta \to \gamma\gamma\gamma$)

The $\eta \to \pi^0\gamma\gamma$ decay is interesting to test the Chiral Perturbation Theory prediction for the branching ratio and $m_{\gamma\gamma}$ spectrum. [19]. The most accurate measurement for the branching ratio[20] is, infact, far from any theoretical prediction for this decay based on ChPT. Recently a new measurement has been performed [21] giving a much lower value than the previous one, with a larger error. All previous experiments were done at hadron machines, using mainly $\pi^-p \to \eta n$, and are largely dominated by $\pi^0\pi^0$ background and geometrical acceptance. KLOE can perform a measurement of competitive precision in a cleaner environment. Furthermore, it has different background topologies and experimental systematics. The signal is searched looking for a $\pi^0\gamma\gamma\gamma$ topology, where the further γ comes from $\phi \to \eta\gamma$. Five prompt clusters are required and an overall kinematic fit requiring π^0 mass is performed. The clusters energy must be greater than 30 MeV and azimutal angle bigger than 21° to reject fake clusters coming from machine background. The dominant background channel is $\eta \to 3\pi^0$ that has been reduced with several topological cut. With this selection we obtain an efficiency of 5.7%. To give an idea of the sensitivity, in fig.4 we compare our data together with MC prediction based on the $Br(\eta \to \pi^0\gamma\gamma)$ measured by [20] and [21]. It is evident that our data are incompatible with [20] and are marginally in agreement with [21]. The background simulation and the efficiency for the signal is still under study.

$\eta \to 3\gamma$ decay is C violating. It is a sensitive test of C violation in the strong and electromagnetic interactions. The KLOE result for the branching ratio is: $Br(\eta \to \gamma\gamma\gamma) \leq 1.6 \times 10^{-5}$ @90 % C.L. This limit is the experimental best limit for this decay. The expected branching ratio from the Standard Model is $\leq 10^{-12}$ [22], so any discovery of a larger decay rate would be a clear signal of Standard Model deviation.

$\eta \to \pi^+\pi^-$ decay is P and CP violating. This decay is allowed as a weak direct CP violating decay with a very low branching ratio: BR($\eta \to \pi^+\pi^-$)$\sim 10^{-27}$[23]. Therefore the detection of this decay at an accessible level would be a signal of P and CP violation not explainable in the Standard Model framework. The latest published [24] direct search of this decay has given the following 90% C.L. upper limit: $BR(\eta \to \pi^+\pi^-) < 3.3 \times 10^{-4}$. In KLOE the signal is searched in the M(η) region of the $\pi^+\pi^-$ invariant mass spectrum of $\pi^+\pi^-\gamma$ events selected according to the $f_0(980) \to \pi^+\pi^-$ analysis described before (see fig. 3). The signal efficiency is: ϵ_s=16.6%. The expected signal has a Gaussian shape with a mass resolution of 1.33 MeV. No signal is observed. The background is determined by

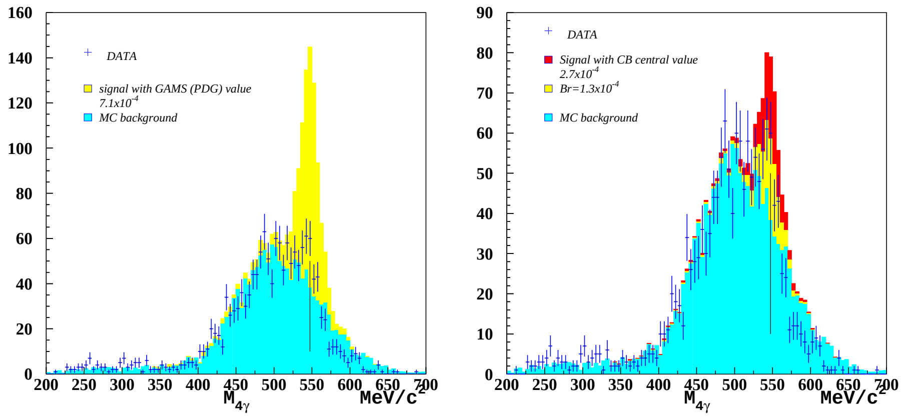


Figure 4. *M(4γ), the spectra expected from the GAMS[20] and Crystall Ball[21] measurement are shown. In the right plot we show also the expected spectrum for a Br $\simeq 1/2$ of C.B. result.*

fitting the theoretical model for $\pi^+\pi^-\gamma$ sample to the full spectrum. In order to determine an upper limit, we have added to this background a Gaussian function representing the signal multiplied by a constant N_s. We obtain: $N_s = -8 \pm 24$. The 90% confidence level upper limit on the number of events is obtained using the tables in [25]: $N_s < 32$. The branching ratio is $BR(\eta \to \pi^+\pi^-) = \frac{N_s}{\epsilon_s N_\eta}$ with N_η the number of η in the sample (1.43×10^7). The 90% C.L. upper limit is: $BR(\eta \to \pi^+\pi^-) < 1.3 \times 10^{-5}$. It improves by a factor ~ 30 the present best limit.

8. $\eta - \eta'$ mixing

The $\eta - \eta'$ system can be studied measuring the ratio:

$$R = \frac{\Gamma(\phi \to \eta'\gamma)}{\Gamma(\phi \to \eta\gamma)}$$

which had been measured previously by KLOE [26] using statistics collected in year 2000 and analyzing a chain with two charged pions and three photons in the final state. This ratio can be related to the pseudoscalar mixing angle in the flavor basis [27] , [28] and to the η' gluonic content [29,30]. This measurement was performed using about 120 signal events. From the newly collected statistics of year 2001-2002 we have analyzed a completely different final state, thus with different systematics and backgrounds, which proceeds via the decays: $\phi \to \eta'\gamma$; $\eta' \to \pi^+\pi^-\eta$; $\eta \to \pi^0\pi^0\pi^0$ and the decays $\phi \to \eta'\gamma$; $\eta' \to \pi^0\pi^0\eta$; $\eta \to \pi^+\pi^-\pi^0$. The final state is thus charachterized by two charged pions and seven photons, and has no physics background with the same topology in KLOE.

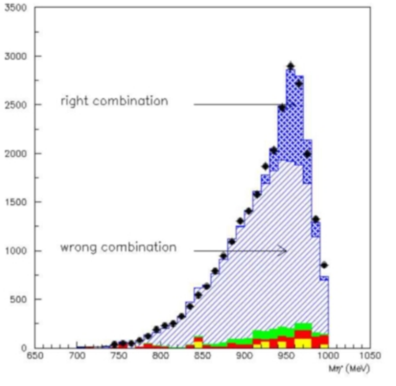


Figure 5. *The mass of all combinations of six photons and two tracks for $\phi \to \eta'\gamma$ candidate events. The contribution of right and wrong combinations for the signal, and from various $\phi \to K_s K_l$ decays (in green, yellow and red) is shown for Monte Carlo. Dots are data.*

After background subtraction (mainly from $\phi \to K_s K_l$ decays) we observe $3405 \pm 61 \pm 31$ $\phi \to \eta'\gamma$ events (see fig. 5). We normalize to the number of observed $\eta \to \pi^0\pi^0\pi^0$ decays in the same runs to obtain a preliminary measurement of the ratio of BR's :

$$R = (4.9 \pm 0.1_{stat} \pm 0.2_{syst}) \times 10^{-3}$$

where the systematic error is dominated by the knowledge of the intermediate BR's of the η'. This result compare favourably with our previous estimate [26] (which already dominates the world average [11]) but with considerably improved accuracy.

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