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RECENT RESULTS FROM THE KLOE EXPERIMENT AT DAΦNE*

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Recent results obtained by the KLOE experiment operating at the DAΦNE e^+e^- collider are presented. They include: the measurements of the branching ratios of the semileptonic kaon decays and the decay $K^+ \to \mu\nu(\gamma)$ and the related V_{us} determination, the study of the quantum interference in the channel $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$, the measurement of the total e^+e^- hadronic cross section using initial state radiation, the radiative decay $\phi \to f_0\gamma$ and the ratio $\mathrm{BR}(\phi \to \eta'\gamma)/\mathrm{BR}(\phi \to \eta\gamma)$.

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1. Introduction

The KLOE detector operates at DAΦNE, an e^+e^- collider working at the center of mass energy $W \sim m_\phi \sim 1.02$ GeV. The ϕ mesons are produced essentially at rest and decay to $K_\mathrm{S}K_\mathrm{L}$ (K^+K^-) $\sim 34\%$ ($\sim 49\%$) of the times. The K mesons are produced in a pure $J^{\mathrm{PC}} = 1^{--}$ coherent quantum state, so that observation of a K_S (K^+) in an event signals (tags) the presence of a K_L (K^-) and viceversa: highly pure, almost monochromatic, back-to-back K_S (K^+) and K_L (K^-) beams can be obtained. Moreover, K_S and K_L are distinguishable on the basis of their decay length: $\lambda_\mathrm{S} \sim 0.6$ cm and $\lambda_\mathrm{L} \sim 340$ cm.

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 ($\sim$1/2 of λ_L). The momentum resolution for tracks at large polar angle is $\sigma_p/p \leq 0.4\%$. The EMC [2] is a lead-scintillating fiber calorimeter consisting of a barrel and two endcaps, which cover 98% of the solid angle. The energy resolution is $\sigma_E/E \sim 5.7\%/\sqrt{E(\mathrm{GeV})}$. The intrinsic time resolution is $\sigma_T = 54\mathrm{ps}/\sqrt{E(\mathrm{GeV})}$. A superconducting coil surrounding the barrel provides a 0.52 T magnetic field. The present report is based on $\sim$500 pb^{-1} collected in earlier period; at present KLOE has about 2 fb^{-1} on disk.

2. Kaon physics

The kaons are produced from the decay of the ϕ in a coherent quantum state allowing study of the quantum interference and tagging techniques. The tagging techniques are the basis of all the KLOE analysis for kaons. Providing a well defined normalization sample, the tagging allows to perform measurements of absolute branching ratios.

The selection of $K_\mathrm{S} \to \pi^+\pi^-$ provides an efficient tag for K_L decays. K_S's are instead tagged by identifying a K_L interaction in the calorimeter, which has a very clear signature given by a late ($\beta_k = 0.2$) high energy cluster not associated with any track. Also for charged kaons a tagging technique has been developed. $K^\pm$'s are tagged by the identification of the 2-body decays $K^\mp \to \mu^\mp\nu$ and $K^\mp \to \pi^\mp\pi^0$.

We present here the study of the quantum interference in the channel $K_\mathrm{S}K_\mathrm{L} \to \pi^+\pi^-\pi^+\pi^-$ and we discuss the $|V_{us}|$ determination from the measurements of the semileptonic kaon branching ratios and from the two-body decay $K^+ \to \mu^+\nu(\gamma)$.

2.1. Quantum interference in the channel $K_{\rm L}K_{\rm S} \to \pi^+\pi^-\pi^+\pi^-$.

Test of quantum mechanics (QM) can be performed by studying the interference pattern of the decay $K_{\rm L}K_{\rm S} \to \pi^+\pi^-\pi^+\pi^-$. According to QM, the distribution of the difference of the decay times $I(\Delta t)$ of the two kaons shows a characteristic destructive interference which prevents the two kaons from decaying into the same final state at the same time. As suggested in Ref. [3, 4], a simple way to parametrize a possible deviation of QM is to introduce a decoherence parameter $\zeta_{\rm S,L}$ ($\zeta_{\rm S,L} = 0$ in QM) as follows:

$$I(|\Delta t|) \propto e^{-|\Delta t|\Gamma_{\rm L}} + e^{-|\Delta t|\Gamma_{\rm S}} - 2 \underbrace{(1-\zeta_{\rm S,L})}_{\substack{\text{decoherence}\\ \text{introduction}}} \cos(\Delta m|\Delta t|)e^{-\frac{\Gamma_{\rm S}+\Gamma_{\rm L}}{2}|\Delta t|} . \tag{1}$$

Selecting a pure sample of $K_{\rm L}K_{\rm S} \to \pi^+\pi^-\pi^+\pi^-$ and fitting Eq. (1) to data, KLOE has obtained the following preliminary result:

$$\zeta_{\rm S,L} = 0.043\,^{+0.038}_{-0.035}{}_{\rm stat} \pm 0.008_{\rm syst},$$

consistent with QM predictions. The result of the fit is shown in Fig. 1.

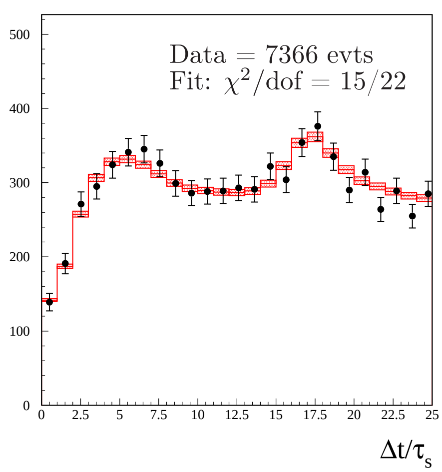

Fig. 1. Fit of the difference Δt of the decay times of $K_{\rm S} \to \pi^+\pi^-$ and $K_{\rm L} \to \pi^+\pi^-$. The full circles are data and the histogram is the result of the fit. The peak at $\Delta t \sim 17\tau_{\rm S}$ is due to the regeneration on the beam pipe.

2.2. $|V_{us}|$ determination

The most precise check on the unitarity of the CKM mixing matrix is provided by measurements of $|V_{us}|$ and $|V_{ud}|$, the contribution of V_{ub} being at the level of 10^{-5}. $|V_{us}|$ is proportional to the square root of the kaon semileptonic partial width. In general we can write for $|V_{us}| \times f_+^{K^0}(0)$ [10]

$$\left[\frac{192\,\pi^3 \Gamma}{G^2 M^2\, S_{\rm ew}\, I_i(\lambda'_+, \lambda''_+ \lambda_0)}\right]^{1/2} \frac{1}{1+\delta^i_{\rm em}+\Delta I_i/2}\,,$$

where i runs over the modes $K^{\pm,0}(e3)$, $K^{\pm,0}(\mu3)$, $f_+^{K^0}$ is the normalization of the form factors at zero momentum transfer and $I_i(\lambda'_+, \lambda''_+, \lambda_0)$ is the integral of the phase space density, factoring out $f_+^{K^0}$ and without radiative corrections. Short distance radiative corrections are in the universal term $S_{\rm ew}$ [11]. In addition long distance radiative corrections [12, 13] for form factor and phase space density are included in $\delta^i_{\rm em}$ and $\Delta I_i(\lambda)$. λ'_+ and λ''_+ are the slope and curvature of the vector form factor f_+. λ_0 is the slope of the scalar form factor. KLOE can measure all the experimental inputs to V_{us}: branching ratios, lifetimes, and form factors.

Concerning the neutral kaons, KLOE has measured the dominant $K_{\rm L}$ branching ratios by using the $K_{\rm L}$ beam tagged by $K_{\rm S} \to \pi^+\pi^-$ decays [6]. The resulting BR's are:

$$\begin{aligned}
{\rm BR}(K_{\rm L} \to \pi e \nu(\gamma)) &= 0.4007 \pm 0.0006 \pm 0.0014\,,\\
{\rm BR}(K_{\rm L} \to \pi \mu \nu(\gamma)) &= 0.2698 \pm 0.0006 \pm 0.0014\,,\\
{\rm BR}(K_{\rm L} \to 3\pi^0) &= 0.1997 \pm 0.0005 \pm 0.0019\,,\\
{\rm BR}(K_{\rm L} \to \pi^+\pi^-\pi^0(\gamma)) &= 0.1263 \pm 0.0005 \pm 0.0011\,,
\end{aligned}$$

after imposing the constraint $\sum {\rm BR}(K_{\rm L}) = 1$ (including BR's for other rarer decays taken from PDG04 whose sum amounts to about 0.0036). This allows an indirect measurement of the $K_{\rm L}$ lifetime $\tau_{\rm L}$ since the geometrical acceptance is a known function of $\tau_{\rm L}$. The $K_{\rm L}$ lifetime has been also measured directly [7], employing 10^7 $K_{\rm L} \to 3\pi^0$ events. The result is $\tau_{\rm L} = (50.92 \pm 0.17 \pm 0.25)$ ns, which together with that from the $K_{\rm L}$ BR measurements gives the KLOE average:

$$\tau_{\rm L} = (50.84 \pm 0.23)\,{\rm ns}\,.$$

KLOE has also measured the branching ratio of the decay $K_{\rm S} \to \pi e \nu(\gamma)$ using the $K_{\rm S}$ beam tagged by the interactions of $K_{\rm L}$'s in the electromagnetic calorimeter. The preliminary result is:

$${\rm BR}(K_{\rm S} \to \pi e \nu(\gamma)) = (7.09 \pm 0.05 \pm 0.05) \times 10^{-4}\,.$$

Concerning the charged kaons, KLOE has measured the branching ratios for the $K^{\pm}$ semileptonic decay by using four samples defined by different decay modes for the tagging kaon: $K^+_{\mu 2}$, $K^+_{\pi 2}$, $K^-_{\mu 2}$, and $K^-_{\pi 2}$. The analysis strategy can be found in Ref. [5]. The preliminary results, averaged over the four tag samples, are:

$$\begin{aligned} \mathrm{BR}(K^{\pm}_{e3}) &= (5.047 \pm 0.046 \pm 0.080) \times 10^{-2}\,, \\ \mathrm{BR}(K^{\pm}_{\mu 3}) &= (3.310 \pm 0.040 \pm 0.070) \times 10^{-2}\,. \end{aligned}$$

The BR's of the semileptonic K_{L} decays and the preliminary results on the semileptonic K_{S} and $K^{\pm}$ decays, allow five independent determinations of the observable $|V_{\mathrm{us}} f_+(0)|$. The results, obtained by using the values $\lambda'_+ = 0.0221 \pm 0.0011$, $\lambda''_+ = 0.0023 \pm 0.0004$ and $\lambda_0 = 0.0154 \pm 0.0008$, from KTeV [8] and ISTRA+ [9], are shown in Fig. 2, in which the new KLOE value of τ_{L} has been used to convert K_{L} BR's to partial widths. Averaging the five KLOE values gives $|V_{\mathrm{us}} f_+(0)| = 0.2170 \pm 0.0005$, with $\chi^2/\mathrm{dof} = 1.7/4$. The fractional uncertainty is about 0.25%.

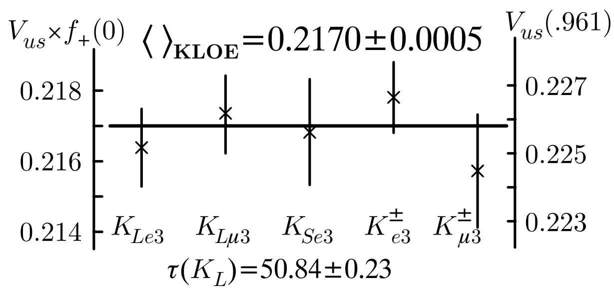

Fig. 2. $|V_{\mathrm{us}} f_+(0)|$ measurements. For K_{L} BR the KLOE τ_{L} has been used.

A precise estimate of $f_+(0)$, 0.961 ± 0.008, was first given in 1984 [14]. Recent lattice calculations [15] give $f_+(0)$ =0.960 ± 0.009, in agreement with Ref. [14]. Using the value from [14] and the average of our results for $|V_{\mathrm{us}} f_+(0)|$, we find $|V_{us}| = 0.2258 \pm 0.0022$.

KLOE has also measured the fully inclusive, absolute $K^+_{\mu 2}$ branching ratio by using $K^- \to \mu^- \nu$ events as tagging sample. The result is: $\mathrm{BR}(K^+ \to \mu^+ \nu(\gamma))$=$0.6366 \pm 0.0009_{\mathrm{stat}} \pm 0.0015_{\mathrm{syst}}$ [16], for an overall fractional error of 0.27%. Using recent lattice results on the decay constants of pseudoscalar mesons [17], we find $|V_{us}|$= 0.2223±0.0026. The fractional error of about 1% is dominated by the uncertainty in the f_K/f_π computation.

3. Non kaon physics

The ϕ meson decays $\sim 15\%$ of the time in $\rho\pi$ and through radiative decays in pseudoscalar (η, η') and scalar (f_0, a_0) mesons. We discuss here three items: the extraction of the hadronic cross section $\sigma(e^+e^- \to \pi^+\pi^-)$ below 1 GeV from the measurement of the non resonant process $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$, the study of the $f_0 \to \pi^+\pi^+$ and $f_0 \to \pi^0\pi^0$ decays and the measurement of the ratio $\mathrm{BR}(\phi \to \eta'\gamma)/\mathrm{BR}(\phi \to \eta\gamma)$.

3.1. Hadronic cross section

The recent measurement of the anomalous magnetic moment of the muon, a_μ, by the E821 collaboration [18] has led to new interest in the measurement of the cross section $e^+e^- \to$ hadrons at low energy. In fact, from the theoretical side, the hadronic contribution to a_μ, a_μ^{had}, cannot be evaluated at low energies in the perturbative QCD but via a dispersion integral. The process $e^+e^- \to \pi^+\pi^-$ below 1 GeV accounts for $\sim 70\%$ of a_μ^{had} and of its error. The most recent measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ has been performed by the CMD-2 experiment [19] via an energy scan with a total relative uncertainty of 0.9%. Using this measurement the Standard Model prediction of a_μ is 2.7σ away from the E821 measurement. Moreover, there is a significant disagreement with the a_μ value obtained using τ data [20].

KLOE has determined in an original way the cross section as a function of s_π, the center of mass energy squared of the $\pi\pi$ system, in the region $0.3 < s_\pi < 1\ \mathrm{GeV}^2$. DAΦNE operated at a fixed energy $W \sim m_\phi$, but Initial State Radiation (ISR) lowers the available beam energy for the di-pion system. KLOE has measured the cross section of the process $e^+e^- \to \pi^+\pi^-\gamma$ and has used the PHOKARA generator [21] to relate $\sigma(\pi^+\pi^-\gamma)$ to $\sigma(\pi^+\pi^-)$. Events with final state radiation are reduced by requiring the photons in a small polar angle region ($\theta_\gamma < 15°$) where ISR events dominate the sample. The photons are not detected, but s_π and θ_γ are reconstructed by using DCH information on the π's. A description of the analysis strategy used can be found in Ref. [22]. KLOE data are shown in Fig. 3. They can be used to evaluate a_μ^{had} in the same region used by CMD-2 ($0.35 < s_\pi < 0.93\mathrm{GeV}^2$), which turns to be:

$$a_\mu^{\mathrm{had}} = (374.6 \pm 0.8_{\mathrm{stat}} \pm 4.8_{\mathrm{syst+th}}) \times 10^{-10}$$

which is in good agreement with $\left(378.6 \pm 2.7_{\mathrm{stat}} \pm 2.3_{\mathrm{syst+th}}\right) \times 10^{-10}$ obtained by CMD-2 and confirms the discrepancy with the result obtained from the analysis of τ data and with the direct measurement of a_μ.

In order to investigate the low energy region down to the 2π threshold, which contributes $\sim 20\%$ to a_μ, a complementary analysis requiring a photon at large polar angle ($50° < \theta_\gamma < 130°$) is in progress.

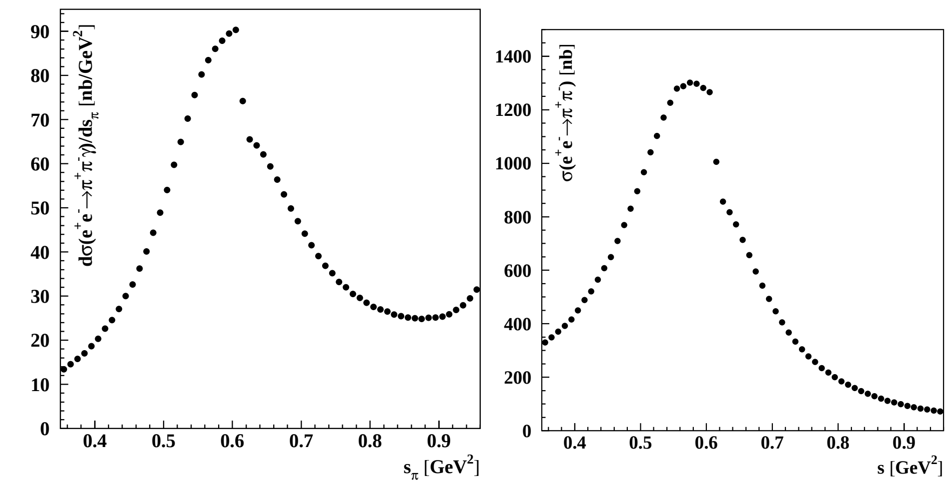

Fig. 3. Left: KLOE measurement for $d\sigma(e^+e^- \to \pi^+\pi^-\gamma)/ds_\pi$, inclusive in θ_π and with $\sin\theta_\gamma < \sin 15°$. Right: bare cross section for $e^+e^- \to \pi^+\pi^-$.

3.2. Search for $\phi \to f_0(980)\gamma$ in $\pi^+\pi^-\gamma$ and $\pi^0\pi^0\gamma$ events

The scalar meson $f_0(980)$ is produced at KLOE through the radiative decay $\phi \to f_0(980)\gamma$. The rate and the f_0 mass distribution depend crucially on the nature of this particle [23]. Since the $f_0 \to K\bar{K}$ decay is kinematically suppressed ($2M(K^\pm) = 987.35$ MeV and $2M(K^0) = 995.35$), the final states available are $\pi^+\pi^-$ and $\pi^0\pi^0$. The signal $f_0 \to \pi^+\pi^-$ is searched in $\pi^+\pi^-\gamma$ events with a photon at large polar angle. The search of this signal is characterized by the presence of a huge irreducible background due to the initial state radiation, 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 polar angle region $45° < \theta_\gamma < 135°$ to reduce ISR background. The f_0 appears as a bump in the $\pi^+\pi^-$ invariant mass $M_{\pi\pi}$ spectrum around 980 MeV. Fig. 4 shows the spectrum obtained at $\sqrt{s} = M_\phi$. An overall fit to the spectrum has been done by applying the following formula:

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

where L is the integrated luminosity and $\epsilon(M_{\pi\pi})$ is the selection efficiency as a function of $M_{\pi\pi}$. The FSR and f_0 amplitudes give rise to an interference term since the two pion state has the same quantum numbers in the two cases [24]. The f_0 amplitude is taken from the kaon-loop model [25].

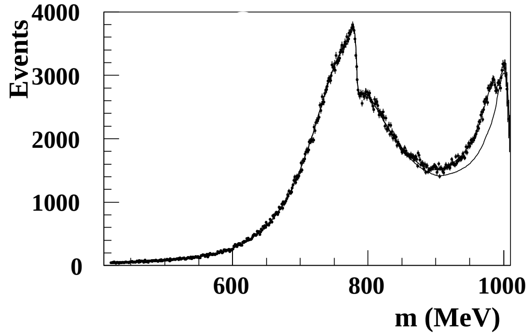

Fig. 4. $M_{\pi\pi}$ spectrum for $e^+e^- \to \pi^+\pi^-\gamma$. Data are compared with the fitting function (upper curve following the data points) and with the estimated non-scalar part of the function (lower curve). The fit uses the kaon-loop model for the f_0.

A forward–backward asymmetry $A = \frac{N^+(\theta>90°)-N^+(\theta<90°)}{N^+(\theta>90°)+N^+(\theta<90°)}$ is expected, due to the interference between FSR and ISR [26]. Fig. 5 shows the asymmetry as a function of $M_{\pi\pi}$ compared to the prediction based on ISR-FSR

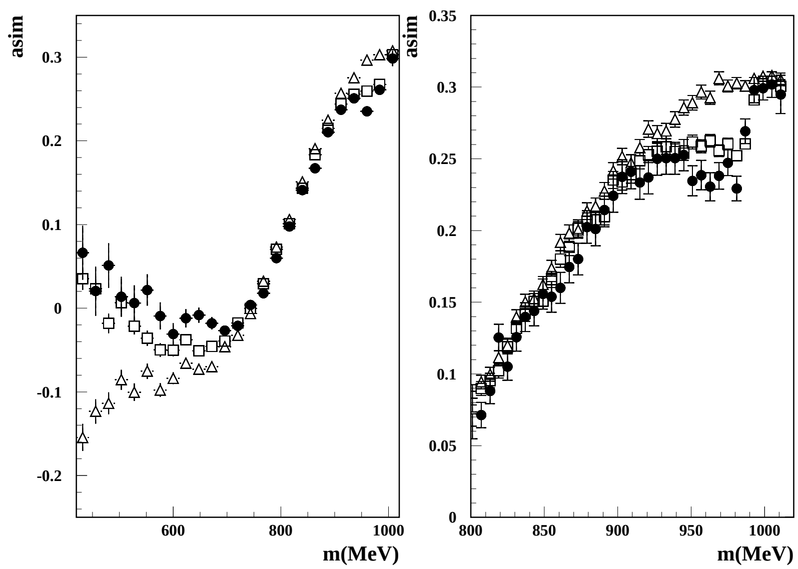

Fig. 5. Charge asymmetry data (full circles) compared to a simulation based on the non scalar part of the spectrum only (open triangles) and on the non-scalar part plus the f_0 part obtained from the kaon-loop amplitude (open squares). The plot on the right shows the detail of the comparison in the f_0 region.

interference alone. If the contribution of the f_0 is included, a significant improvement on the agreement between data and Monte Carlo prediction in the f_0 mass region and in the low mass region is observed.
The f_0 is also searched in the decay $\phi \to f_0\gamma$, $f_0 \to \pi^0\pi^0$ ($\pi^0\pi^0\gamma$ final state). The background is mainly due to $e^+e^- \to \omega\pi^0(\omega \to \pi^0\gamma)$ events which have a sizable interference with the signal. A 2-dimensional analysis $m^2_{\pi^0\gamma}$ *vs.* $m^2_{\pi^0\pi^0}$ is performed and the resulting Dalitz plot is shown in Fig. 6. The two bands on the left side of the plot are due to the $\omega\pi^0$ background while events on the right corner are due to the f_0 signal. In both the final states $\pi^+\pi^-\gamma$ and $\pi^0\pi^0\gamma$ the extraction of the f_0 parameters is in progress, using different theoretical models.

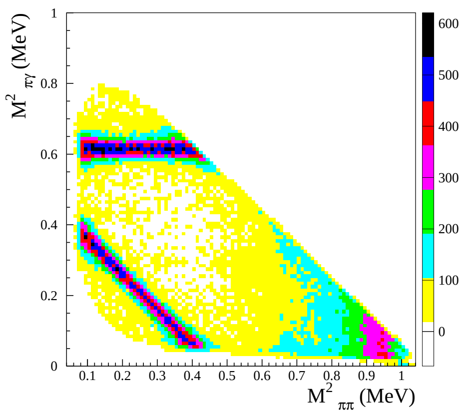

Fig. 6. Dalitz plot distribution ($m^2_{\pi^0\gamma}$ *versus* $m^2_{\pi^0\pi^0}$) of the $\pi^0\pi^0\gamma$ events.

3.3. η–η' mixing

The ratio of the BR's for the decays $\phi \to \eta'\gamma$ and $\phi \to \eta\gamma$ provides information on the $\eta - \eta'$ mixing angle and on the gluonium content of the η' [27, 28]. The η' is identified via the decays: $\phi \to \eta'\gamma$, $\eta' \to \pi^+\pi^-\eta$, $\eta \to \pi^0\pi^0\pi^0$ and $\phi \to \eta'\gamma$, $\eta' \to \pi^0\pi^0\eta$, $\eta \to \pi^+\pi^-\pi^0$. The final state is thus characterized by two charged pions and seven photons. KLOE has obtained the following preliminary result by counting the number of signals and normalizing to the number of observed $\eta \to \pi^0\pi^0\pi^0$ events:

$$\mathrm{BR}(\phi \to \eta'\gamma)/\mathrm{BR}(\phi \to \eta\gamma) = (4.76 \pm 0.08 \pm 0.20) \times 10^{-3}\,.$$

From this result an estimate of the mixing angle can be obtained:
$\phi_P = \left(41.3^{+2.0}_{-0.6}\right)^\circ$. The results are in agreement with the ones obtained analyzing the final state $\pi^+\pi^- + 3\gamma$ with the 2000 data [29].

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