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RECENT RESULTS FROM THE KLOE EXPERIMENT

THE KLOE COLLABORATION*
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Recent results obtained by the KLOE experiment operating at DAΦNE, the Frascati ϕ-factory, are presented. They mainly concern neutral kaon decays including rare K_S decays, K_L lifetime, the radiative $\phi \to f_0\gamma$ decay and the measurement of the e^+e^- hadronic cross section using initial state radiation.

1. Introduction

DAΦNE, the Frascati ϕ factory, is an e^+e^- collider working at $W \sim m_\phi \sim 1.02$ GeV with a design luminosity of 5×10^{32} cm^{-2} s^{-1}. The ϕ mesons are produced, almost at rest, with a visible cross section of ~ 3.2 μb and decay into K^+K^- (K_SK_L) pairs with BR of $\sim 49\%$ ($\sim 34\%$). These pairs are produced in a pure $J^{PC} = 1^{--}$ quantum state, so that observation of a K_S (K^+) in an event signals (tags) the presence of a K_L (K^-) and vice-versa; highly pure and nearly monochromatic K_S, K_L, K^+ and K^- beams can be obtained. Neutral kaons get a momentum of $\sim$ 110 MeV/c which translates in a slow speed, $\beta_K \sim 0.22$. K_S and K_L can therefore be distinguished by their mean decay lengths: $\lambda_S \sim 0.6$ cm and $\lambda_L \sim 340$ cm.

The KLOE detector consists of a drift chamber, DCH, surrounded by an electromagnetic calorimeter, EMC. The DCH (Ref. 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 $\sigma_p/p \leq 0.4\%$.

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The EMC is a lead-scintillating fiber calorimeter (Ref. 2) consisting of a barrel and two endcaps which cover 98% of the solid angle. The energy resolution is $\sigma_E/E \sim 5.7\%/\sqrt{\mathrm{E(GeV)}}$. The intrinsic time resolution is $\sigma_T = 54$ ps$/\sqrt{\mathrm{E(GeV)}}\oplus 50$ ps. A super-conducting coil surrounding the barrel provides a 0.52 T magnetic field.

During 2002 data taking, the maximum luminosity reached by DAΦNE was 7.5×10^{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 collected $\sim$ 4.5 pb^{-1}/day. The whole data sample in the years 2001-2002 amounts to 450 pb^{-1}, equivalent to 1.4 billion ϕ decays. Recently, the machine has been upgraded and KLOE has resumed its data taking in April 2004. Up to know (5^{th} August, 2004) 180 pb^{-1} have already been collected with a peak luminosity of 8.4×10^{31} cm^{-2} s^{-1}.

2. Kaon physics

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 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 $\sim$ 2 MeV. Many analyses have been already completed or are under completion at KLOE (Ref. 3, 4, 5) but we will discuss here only the three most recent and advanced items.

2.1. *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} ($\sim 2\times10^{-3}$). The expected branching ratio of this decay is therefore $\sim 2\times10^{-9}$, making its direct observation really challenging. The best upper limit on the BR (i.e. on $|\eta_{000}|^2$) has been set to 1.5×10^{-5} by SND (Ref. 6) where, similarly to KLOE, it is possible to tag a K_S beam. The other existing technique is to detect the interference term between K_SK_L in the same final state which is proportional to η_{000}. The weighted average of the best published values (Ref. 7, 8) gives: $\eta_{000} = (0.07\pm0.11) + i(0.08\pm0.16)$. 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 (Ref. 9). In the most general way, a neutral kaon state (Ref. 10) 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:

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

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. 11, the value of $\Im(\delta) = (2.4 \pm 5.0) \times 10^{-5}$ is limited by the measurement on η_{000}. Neglecting this term, the same analysis yields $\Im(\delta) = (-0.5 \pm 2.0) \times 10^{-5}$.

The signal selection requires a K_L interacting with the calorimeter and six neutral clusters coming from the interaction point (IP). A first rejection of the huge background coming from the decay $K_S \to \pi^0\pi^0$ + 2 fake γ is obtained by applying a kinematic fit imposing as constraints the K_S mass, the K_L 4-momentum and $\beta = 1$ for each photon. Two pseudo-χ^2 variables are then built: $\chi^2_{3\pi^0}$ which is based on the three best π^0 mass estimates and $\chi^2_{2\pi^0}$ which selects four out of six photons providing the best kinematic agreement with the $K_S \to \pi^0\pi^0$ decay. A signal box is defined in the $\chi^2_{2\pi^0}$ vs $\chi^2_{3\pi^0}$ plane by optimising the upper limit in the Monte Carlo sample. Residual background comes from $K_S \to \pi^+\pi^-, K_L \to 3\pi^0$ events in which one of the two pions interacting with the quadrupoles produces a late cluster simulating a K_L-crash. This background is rejected by vetoing events with two charged tracks from IP.

With an efficiency $\varepsilon_{3\pi} = (22.6 \pm 0.8)\%$, we count 4 events for an expected background $N_b = (3 \pm 1.4_{\rm stat} \pm 0.2_{\rm syst})$. Folding the proper background uncertainty, we quote the number of $K_S \to 3\pi^o$ decay to be below 5.8 at 90% C.L. In the same tagged sample, we count 3.8×10^7 $K_S \to 2\pi^o$ events used for normalisation. We finally derive BR$(K_S \to 3\pi^o) \leq 2.1 \times 10^{-7}$ 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 of the uncertainty for this decay negligible in the calculation of $\Im(\delta)$.

2.2. *K_S semi-leptonic decays and V_{us}*

The semi-leptonic charge asymmetries for $K_{S,L}$ are related to the CP,CPT violation parameters ε, δ as (Ref. 10,12) : $A_{S,L} = \frac{\Gamma_s(\pi^+e^-\nu)-\Gamma_s(\pi^-e^+\nu)}{\Gamma_s(\pi^+e^-\nu)+\Gamma_s(\pi^-e^+\nu)} = 2\Re(\varepsilon) \pm 2\Re(\delta)$. 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 (Ref. 13), a measurement of A_S is still awaited for. KLOE has already measured (Ref. 14) the BR for the K_{e3} decay of the K_S using 17 pb^{-1} collected in 2000. A new measurement with the whole collected statistics gives a first determination of A_S. Moreover, a precise determination of $\Gamma_s(\pi e\nu)$ permits to evaluate V_{us}. The $K_S \to \pi e\nu$ decays are selected, after K_L tag, 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 techniques so that the BR's to final states of each lepton charge can be done

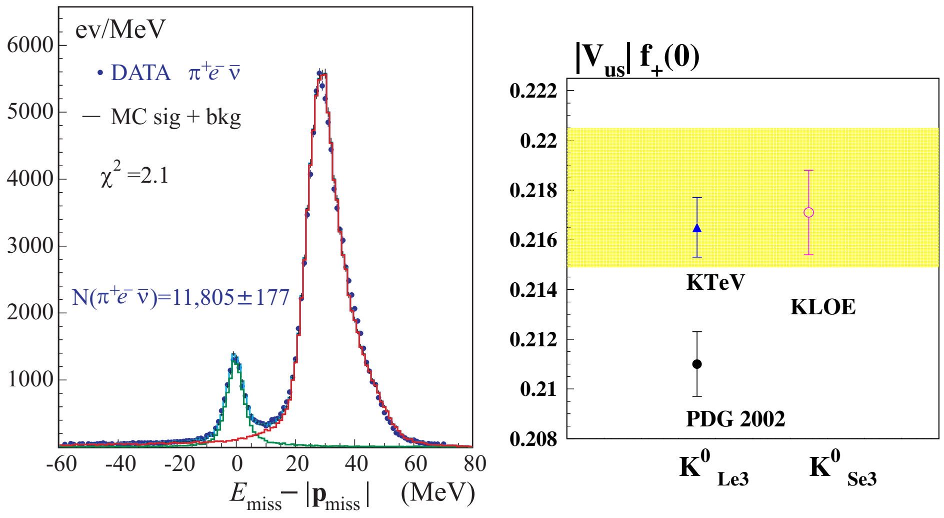

Fig. 1. **Left:** $E_{miss} - c|P_{miss}|$ distribution after time-of-flight cuts for the $\pi^+e^-\nu$ sample. Dots are data, solid lines are Monte Carlo expectations. **Right:** evaluations of $|V_{us}| \times f_+^{K^0\pi}(0)$ from K_{Le3} and K_{Se3} from PDG 2002 (full dot), KTeV (triangle) and KLOE (empty circle). The band is the prediction from unitarity and $|V_{ud}|$.

independently. In Fig. 1 (left), the $E_{miss}-|P_{miss}|$ 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 Monte Carlo distributions for signal and background having as free parameters their normalisations. The generator used for the signal properly handles the final state emitted radiation through an infrared finite treatment. By normalising to the number of $K_S \to \pi^+\pi^-$ events counted in the same tagged sample, we get the following preliminary values for $\mathrm{BR}(K_S \to \pi^+e^-\overline{\nu}) = (3.54{\pm}0.05_{\mathrm{stat}}{\pm}0.04_{syst}){\cdot}10^{-4}$ and $\mathrm{BR}(K_S \to \pi^-e^+\nu) = (3.54 \pm 0.05_{stat} \pm 0.05_{syst}) \cdot 10^{-4}$. Without considering the charge, we get $\mathrm{BR}(K_S \to \pi e\nu) = (7.09 \pm 0.07_{stat} \pm 0.08_{syst}) \cdot 10^{-4}$ which is consistent with our old measurement improving by 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: $A_S = (-2 \pm 9_{stat} \pm 6_{syst})10^{-3}$. 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.

2.2.1. $|V_{us}|$ *determination*

The determinations of $|V_{us}|$ and $|V_{ud}|$ provide the most precise test of CKM unitarity, the contribution of the error of $|V_{ud}|$ being at the level of $\sim 10^{-5}$. $|V_{us}|$ is proportional to the square root of the semileptonic BR of K mesons. In general we can write (Ref. 16):

$$|V_{us}| \times f_+^{K^0\pi}(0) = \left[\frac{128\pi^3 BR(K_S \to \pi e\nu)}{\tau_S G_\mu^2 M^5 S_{ew} I_K^e(\lambda_+, \lambda'_+)}\right]^{1/2} \times \frac{1}{1+\delta_{\rm em}^{Ke}} \tag{2}$$

where $f_+^{K^0}(0)$ is the normalisation of the kaon form factors at zero momentum transfer and $I_i(\lambda_+, \lambda'_+)$ is the integral of the phase space density, factoring out $f_+^{K^0\pi}$ and without radiative corrections. Radiative corrections at large scale of form factor and phase space density are contained in the term $\delta_{em}^{Ke} = 0.55 \pm 0.10$ (Refs. 20, 21). The short-distance electroweak corrections are included in the parameter S_{ew}. λ_+ and λ'_+ are the slope and curvature of the vector form factor $f_+^{K^0\pi}(0)$. In the extraction of V_{us} we use the values obtained by KTeV experiment from a quadratic fit (Ref. 22). We obtain: $|V_{us}^{K^0}| \times f_+^{K^0\pi}(0) = 0.2171 \pm 0.0017$. Fig. 1 (right) shows the product $|V_{us}^{K^0}| \times f_+^{K^0\pi}(0)$ as obtained from the KLOE preliminary measurement of the BR($K_S \to \pi e\nu$) as well as the recent result for K_{Le3} published by the KTeV collaboration (Ref. 23). In the same plot the $\pm 1\sigma$ band from $|V_{ud}|$ and unitarity is also shown where we assume $f_+^{K^0\pi}(0) = 0.961 \pm 0.008$ (Ref. 25). The possible violation of the unitarity in the first row of the CKM matrix which followed from the value for BR(K_{e3}) given in the PDG particle listings (Ref. 15) is clearly not there anymore.

2.3. *Measurement of K_L lifetime from $K_L \to 3\pi^0$ decay*

The accuracy on the $|V_{us}|$ determination from KTeV new measurements of the K_L semileptonic branching ratios (Ref. 23) is dominated by the error on the K_L lifetime. The PDG value rests on a single experimental value measured more than 30 years ago with an accuracy of $\sim 0.8\%$ (Ref. 17). KLOE is the ideal experiment to perform again such a measurement since the K_L are almost monochromatic,[a] with very low momentum ($\sim$ 110 MeV) and, therefore, a big fraction of them ($\sim$ 50%) decays inside the fiducial volume.

We have measured the K_L lifetime using the fully neutral decay $K_L \to \pi^o\pi^o\pi^o$ tagged by $K_S \to \pi^+\pi^-$ events. In this way the efficiency of the reconstruction of the K_L vertex is not biased by the selection of the tagging events. The position of the K_L vertex is measured using K_L flight direction and the positions and arrival times of the photons on the calorimeter (Ref. 5). Each photon determines the K_L decay length L_K up to a two-fold ambiguity, one easily discarded. The best value of L_K is taken as the energy-weighted average of the closest two L_K.

The accuracy of this method has been checked by comparing in the $K_L \to \pi^+\pi^-\pi^o$ decays the position of the K_L decay vertex from tracking with the $\pi^+\pi^-$ pair and the time of arrival of the π^0 photons. The $K_L \to \pi^+\pi^-\pi^o$ events are also

[a] ϕ mesons at DAΦNE are produced almost at rest with a small horizontal momentum of about 12 MeV.

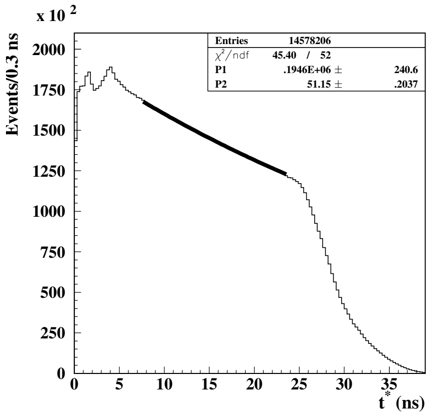

Fig. 2. K_L proper time distribution. The thick line shows the interval used in the fit.

used to measure the resolution on the vertex reconstructed with photons and the variation of the reconstruction efficiency with the decay path. $K_L \rightarrow \pi^o\pi^o\pi^o$ events are selected if there are at least three photons with energy greater than 20 MeV originating from the same decay vertex.

The background contamination, concentrated in the event sample with three and four detected photons, is dominated by $K_L \rightarrow \pi^+\pi^-\pi^o$ events with accidental clusters due machine background and by the CP-violating decay $K_L \rightarrow \pi^o\pi^o$. They are rejected using the same selection criteria used in the $\Gamma(K_L \rightarrow \gamma\gamma)/\Gamma(K_L \rightarrow \pi^o\pi^o\pi^o)$ analysis (Ref. 5). In Fig. 2 we show the K_L proper time distribution obtained with $\sim 15 \times 10^6$ $K_L \rightarrow \pi^o\pi^o\pi^o$ events. The distribution is fitted with an exponential inside a fiducial region, FR, ranging from 50 to 160 cm. Inside this interval the vertex reconstruction efficiency is flat to $\sim$ 0.3 %. The two peaks clearly visible at short values of $t^*(K_L)$ are due to the $K_L \rightarrow K_S$ regeneration in the beam pipe and in the inner wall of the drift chamber. The regeneration region is removed by the choice of FR. Variations of the fit result vs the FR choice are well within the statistical accuracy of the fit itself. Our preliminary result is $\tau_{K_L} = (51.15 \pm 0.20_{\rm stat} \pm 0.40_{\rm syst})$ ns. The systematic error is dominated by the uncertainties on the signal selection efficiency and the background contamination. Their knowledge is at present limited by the Monte Carlo statistics and contribute $\sim$ 0.7%. This error will decrease with the increasing of the generated Monte Carlo sample.

3. Non-kaon physics

Other than producing kaons, the ϕ meson decays $\sim$ 15% of the time in $\rho\pi$ and through radiative decays pseudoscalar (η, η') and scalar (f_0, a_0) mesons. Although many interesting analyses have been published (Ref. 19, 25, 26, 27) on these items,

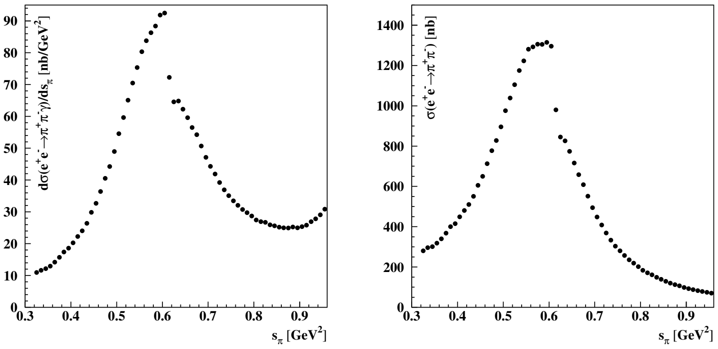

Fig. 3. Left: KLOE measurement of $d\sigma(e^+e^- \to \pi^+\pi^-\gamma)/ds_\pi$ for 140 pb^{-1} of 2001 data; the cross section is inclusive in θ_π and with $\sin\theta_\gamma < \sin 15^o$. Right: "bare" cross section for $e^+e^- \to \pi^+\pi^-$.

and their findings are being improved with the larger statistical sample available, we discuss here only two 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 $e^+e^- \to \pi^+\pi^-\gamma$ and the study of the $f_0(980) \to \pi^+\pi^-$ decay.

3.1. *Measurement of $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ and extraction of $\sigma(e^+e^- \to \pi^+\pi^-)$ below 1 GeV.*

The recent updated measurement of the anomalous magnetic moment of the muon, a_μ, by the E821 collaboration (Ref. 28) has led to renewed interest in accurate measurement of the hadronic cross section.

From the theoretical side, the hadronic contributions on a_μ, a_μ^{had}, cannot be evaluated in perturbative QCD but via a dispersion relation which integrates the hadronic cross section multiplied by an appropriate kernel. The process $e^+e^- \to \pi^+\pi^-$ below 1 GeV accounts for $\sim 70\%$ of the a_μ^{had} value and of its error. The most recent measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ by CMD-2 (Ref. 29), done with energy-scan of e^+e^- collisions, claim statistical (systematic) precision of 0.7% (0.6%) and imply a difference of $-2.7\,\sigma$ of the calculated value of a_μ with respect to the E821 measurement. Moreover, it gives also a rather strong disagreement with the value of a_μ^{had} obtained using τ-data (Ref. 30).

KLOE is determining in an original way this cross section as a function of s_π, the center of mass energy squared of the $\pi\pi$ system, in the region $0.3 < s_\pi < 1$ GeV^2. DAΦNE operates at fixed energy $W \sim m_\phi$, but Initial State Radiation (ISR) lowers the available beam energy for the di-pion system. We measure the cross section for the process $e^+e^- \to \pi^+\pi^-\gamma$ and use the PHOKHARA generator (Ref. 31) to relate $\sigma(\pi^+\pi^-\gamma)$ with $\sigma(\pi^+\pi^-)$. Complications from processes with final-state radiation are avoided by restricting the selection to events with small-angle photons ($\theta_\gamma < 15^o$) where ISR events completely dominate the sample. The γ's are not detected, but s_π and θ_γ are instead reconstructed by using DCH information on the π's. A description of the analysis strategy used can be found elsewhere (Ref. 32). The KLOE data shown in Fig. 3 provide an independent measurement (also from the systematic point of view) of this cross-section from CMD-2 data. We calculate the dispersion integral in the same region used by CMD-2 ($0.37 < s_\pi < 0.93$ GeV^2) to get: $a_\mu^{had} = (376.5 \pm 0.8 \pm 5.9) \cdot 10^{-10}$. This results is in good agreement with the CMD-2 number: $a_\mu^{had} = (378.6 \pm 2.8 \pm 2.3) \cdot 10^{-10}$ confirming the discrepancy of e^+e^- data with τ-data and with the measured value of a_μ.

3.2. *Search for $\phi \to$ f$_0$(980)γ in $\pi^+\pi^-\gamma$ events*

The scalar meson f$_0$(980) is produced at KLOE through the electric dipole radiative transition $\phi \to$ f$_0$(980)γ. The rate and the f$_0$ mass distribution depend crucially to the nature of this particle. The f_0 mass (980 MeV) is very close to the ϕ meson mass (1020 MeV) and the two $K\overline{K}$ thresholds ($2M(K^\pm) = 987.35$ MeV and $2M(K^0) = 995.34$ MeV) lie in between. The closeness of the masses and the position of the $K\overline{K}$ thresholds strongly affect the f$_0$ mass spectrum. Since the f$_0 \to K\overline{K}$ decay is kinematically suppressed, the final states available are $\pi^+\pi^-$ and $\pi^0\pi^0$. KLOE has already published a study of the $\phi \to \pi^0\pi^0\gamma$ process based on 17 pb^{-1} of the 2000 data sample (Ref. 25) where the f$_0$ signal is observed and analysed in the $M(\pi^0\pi^0)$ mass spectrum.

The analysis of the f$_0 \to \pi^+\pi^-$ requires much more statistics due to the presence of irreducible backgrounds with rates larger respect to the signal. These backgrounds are the ISR, and the process $e^+e^- \to \pi^+\pi^-\gamma$ either through the ϕ or through the ρ^0 tail (final state radiation, FSR in the following). A further lower rate background is due to the decay chain $\phi \to \rho^\pm\pi^\mp$ with $\rho^\pm \to \pi^\pm\gamma$. Since the ISR cross-section is peaked at small photon angles respect to the beam line, the f$_0$ events are searched in the large photon angle region $45^o < \theta < 135^o$.

Although in this region the ISR is still the dominant process, the f$_0$ signal appears as a bump in the $\pi^+\pi^-$ invariant mass M$_{\pi\pi}$ spectrum around 980 MeV. Fig. 4 shows the spectrum obtained from a 350 pb^{-1} data sample at $\sqrt{s} = M_\phi$. The spectrum is dominated by the radiative return to the ρ^0. The f$_0$ bump is clearly evident close to the high edge of the mass spectrum. 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 function of $M_{\pi\pi}$. The ISR and $\rho\pi$ contributions are parametrised according to Refs. (33, 34, 35). 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 (Ref. 36). The f$_0$ amplitude is described assuming that the ϕ decays to f$_0$ γ through a charged kaon loop.

A good fit of the whole spectrum is obtained with only seven free parameters as shown in Fig. 4. Of these parameters, four are due to the pion form factor entering

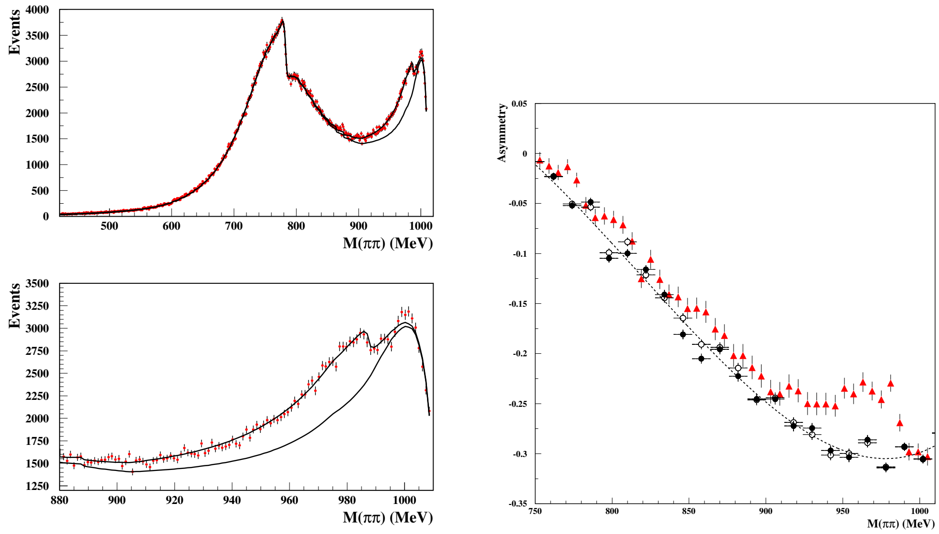

Fig. 4. **Left**: $M_{\pi\pi}$ spectrum of $\pi^+\pi^-\gamma$ events selected by requiring a photon at large angle. The upper (lower) curves are the result of the fit described in the text and the estimated background due to ISR, FSR and $\rho\pi$. (Lower) enlarged view of the region of the "f_0" signal. **Right:** forward-backward asymmetry A of $\pi^+\pi^-\gamma$ events as a function of $M_{\pi\pi}$. The curve and the full dots are the Montecarlo expectations based on the interference between FSR and ISR only. The experimental data are reported as triangles.

in the ISR term (Ref. 34), the other three are the usual parameters entering in the kaon-loop model for the scalars, namely the scalar mass and the two couplings g_{f_0KK} and $g_{f_0\pi\pi}$.
A clear evidence of the presence of the f_0 signal has been also obtained from the study of the charge asymmmetry of the $\pi^+\pi^-$ final state. A sizable 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 C-odd term coming from the interference between FSR and ISR. Fig. 5 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: this effect indicates that a C-odd interference term between the f_0 and the ISR is present with opposite sign respect the one between ISR and FSR.

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