Eur. Phys. J. A **31**, 446–450 (2007)
DOI 10.1140/epja/i2006-10183-8

THE EUROPEAN PHYSICAL JOURNAL A

Special Article – QNP 2006

Recent KLOE results on hadron physics

C. Bini[a]

Università "La Sapienza" and INFN Roma, Roma, Italy

Received: 25 October 2006
Published online: 19 February 2007 –

Abstract. The KLOE experiment at the Frascati e^+e^- collider DAFNE has completed this year its data taking. An integrated luminosity of $2.7\,\mathrm{fb}^{-1}$ has been collected mostly at the ϕ-resonance peak. A wide experimental program is in progress. The detection of ϕ radiative decays allows to study the properties of the lowest-mass scalar and pseudoscalar mesons and to obtain information on their structure. The main results are reviewed together with the prospects for low-energy e^+e^- physics at Frascati.

PACS. 13.66.Bc Hadron production in e^-e^+ interactions – 14.40.-n Mesons

1 The KLOE experiment at DAFNE

The Frascati e^+e^- collider DAFNE has been working since 1999 at a center-of-mass energy $\sqrt{s} \sim m_\phi = 1019.4\,\mathrm{MeV}$. In this last year it has reached an instantaneous luminosity of $1.5 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ that is the highest luminosity ever reached by any e^+e^- collider in this energy region. DAFNE has two experimental regions: one is occupied by the KLOE experiment; in the other one the FINUDA and DEAR experiments have been run in different times.

The KLOE experiment has collected in 5 years an integrated luminosity of $2.7\,\mathrm{fb}^{-1}$: $2.5\,\mathrm{fb}^{-1}$ at the ϕ peak (corresponding to 6×10^9 ϕ decays) and $0.2\,\mathrm{fb}^{-1}$ at a slightly lower center-of-mass energy, $\sqrt{s} = 1\,\mathrm{GeV}$, out of the ϕ-resonance region. The detector consists of a very large cylindrical drift chamber [1] around the interaction region, a hermetic calorimeter [2] done with scintillating fibers and lead surrounding the chamber and a superconducting solenoid providing a $0.6\,\mathrm{T}$ magnetic field. The whole detector is about 4 m long and has a radius of about 3 m. The drift chamber allows the tracking of charged particles and the measurements of their momenta. The calorimeter measures energy, position and time of neutral particles (photons, K_L) and, due to its excellent timing capabilities, provides also a good particle identification of charged particles (electrons *vs.* muons *vs.* pions).

Table 1. Main ϕ decay channels together with their branching ratios.

Channel	Branching ratio
K^+K^-	49.2%
$K^0\overline{K^0}$	34.0%
$\rho\pi + \pi^+\pi^-\pi^0$	15.3%
$\eta\gamma$	1.3%
$\pi^0\gamma$	0.125%
$\eta'\gamma$	6.2×10^{-5}
$\pi^0\pi^0\gamma$	1.1×10^{-4}
$\eta\pi^0\gamma$	8.3×10^{-5}

The main decay channels of the ϕ-resonance are summarised in table 1. It can be seen that a ϕ-factory is mostly a kaon factory but, even if at a lower rate, it is also a factory of η ($\sim 1\%$), η' (few $\times10^{-5}$) and, through the $\pi\pi\gamma$ and $\eta\pi\gamma$ radiative decays, a factory of scalar mesons, $f_0(980)$, $f_0(600) \to \pi\pi$ and $a_0(980) \to \eta\pi$. A large amount of $\pi^+\pi^-\gamma$ events are also observed. The large majority of them are due to the initial-state radiation that allows to study the $e^+e^- \to \pi^+\pi^-$ cross-section from the two-pion threshold up to the ϕ mass. However, a small fraction of these events is due to the decay chain $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$. In the following the results obtained by KLOE concerning

[a] e-mail: `cesare.bini@roma1.infn.it`; On behalf of the KLOE Collaboration: F. Ambrosino, A. Antonelli, M. Antonelli, C. Bacci, P. Beltrame, G. Bencivenni, S. Bertolucci, C. Bini, C. Bloise, V. Bocci, F. Bossi, D. Bowring, P. Branchini, S.A. Bulychjov, R. Caloi, P. Campana, G. Capon, T. Capussela, F. Ceradini, S. Chi, G. Chiefari, P. Ciambrone, S. Conetti, E. De Lucia, A. De Santis, P. De Simone, G. De Zorzi, S. Dell'Agnello, A. Denig, A. Di Domenico, C. Di Donato, S. Di Falco, B. Di Micco, A. Doria, M. Dreucci, G. Felici, A. Ferrari, M.L. Ferrer, G. Finocchiaro, C. Forti, P. Franzini, C. Gatti, P. Gauzzi, S. Giovannella, E. Gorini, E. Graziani, M. Incagli, W. Kluge, V. Kulikov, F. Lacava, G. Lanfranchi, J. Lee-Franzini, D. Leone, M. Martini, P. Massarotti, W. Mei, S. Meola, S. Miscetti, M. Moulson, S. Müller, F. Murtas, M. Napolitano, F. Nguyen, M. Palutan, E. Pasqualucci, A. Passeri, V. Patera, F. Perfetto, L. Pontecorvo, M. Primavera, P. Santangelo, E. Santovetti, G. Saracino, B. Sciascia, A. Sciubba, F. Scuri, I. Sfiligoi, T. Spadaro, M. Testa, L. Tortora, P. Valente, B. Valeriani, G. Venanzoni, S. Veneziano, A. Ventura, R.Versaci, G. Xu.

the ϕ radiative decays to scalars and pseudoscalar mesons are presented and discussed. A review of the kaon physics done at KLOE can be found in ref. [3], and the first KLOE results on the $\pi^+\pi^-$ cross-section below the ϕ peak obtained using the initial-state radiation can be found in ref. [4].

2 Results on scalar mesons

Standing at the ϕ-resonance energy, the lowest mass $I = 0$ (the $f_0(980)$ and the controversial $f_0(600)$ or σ) and $I = 1$ (the $a_0(980)$) scalar mesons are accessible through ϕ radiative decays. In particular the $\pi^+\pi^-\gamma$ and $\pi^0\pi^0\gamma$ final states are sensitive to the $I = 0$ sector and the $\eta\pi^0\gamma$ to the $I = 1$ sector. The nature of these scalar mesons is still today controversial. In fact it is hard to describe their spectrum and their properties as standard $q\bar{q}$ states. Several hints suggest a 4-quark, $qq\overline{qq}$ structure [5,6]. For what concerns the two almost mass degenerate states $f_0(980)$ and $a_0(980)$, whose mass is very close to twice the kaon mass, the possibility that they are $K\overline{K}$ molecules has been also considered [7,8].

The KLOE data on ϕ radiative decays are interesting essentially for two reasons:

1. the possibility to estimate the coupling of the scalar mesons to the ϕ that is an almost pure $s\bar{s}$ quark state, either directly [9] or through a kaon loop [10];
2. the possibility to look for the presence of the σ in the mass spectra.

The extraction of these information from the data is not straightforward since a huge unreducible background is present at least for the $\pi\pi$ channels. A fit of the mass spectra has to be done in any case using a parametrisation for the signal and for the background and including in a proper way the interference between the different amplitudes. In the end one has to take into account several unknown parameters and it is not easy to obtain model-independent conclusions.

The results of the KLOE analysis of the $\pi^+\pi^-\gamma$ channel are shown in figs. 1 and 2. The signal due to the $f_0(980)$ is clearly seen in the $\pi^+\pi^-$ invariant-mass spectrum as a peak in the f_0 mass region (fig. 1) and in the profile of the forward-backward asymmetry (fig. 2) [11]. In the case of the $\pi^0\pi^0\gamma$ channel [12] the $f_0(980)$ signal can be observed as a population in the right corner of the Dalitz plot shown in fig. 3.

In the $\pi^+\pi^-\gamma$ channel the main background is provided by the initial-state radiation with the typical structure due to the ρ^0 peak and to the ρ^0-ω interference (the main structure in the spectrum of fig. 1(a)). In the case of the $\pi^0\pi^0\gamma$ channel the main background is provided by the reaction $e^+e^- \to \omega\pi^0$ with $\omega \to \pi^0\gamma$ (see fig. 3).

A good description of these data is provided by the kaon-loop model [10] but also by the model described in ref. [9]. In the first case the ϕ is assumed to couple to a kaon pair and these in turn, after the irradiation of the photon, annihilate producing the scalar meson. The amplitude is parametrised in terms of the f_0 mass and of the couplings $g_{f_0K^+K^-}$ and $g_{f_0\pi^+\pi^-}$. In the second case the ϕ is directly coupled to the scalar mesons through the emission of the photon. The main parameter is in this case the coupling $g_{\phi f_0\gamma}$.

The couplings of the f_0 to KK to $\pi\pi$ and to the ϕ-meson obtained by the fits are shown in table 2. An

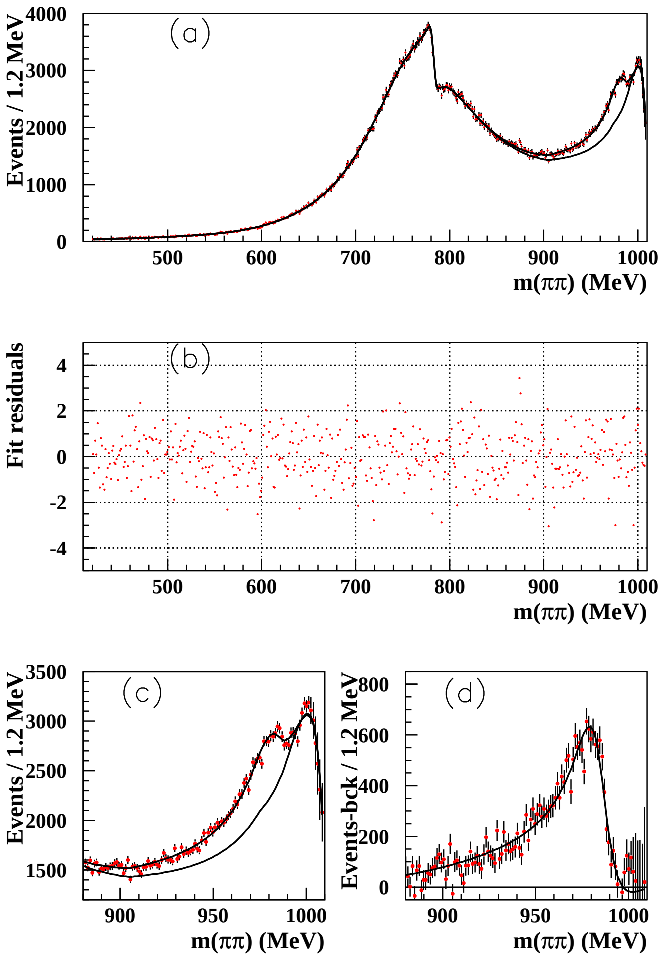

Fig. 1. Fit of the $\pi^+\pi^-$ invariant-mass spectrum for the $\pi^+\pi^-\gamma$ sample. (a) Experimental data compared to the fit function and to the background evaluated by the fit itself; (b) residuals of the fit; (c) expanded view of the fit in the $f_0(980)$ region and (d) experimental spectrum after background subtraction in the same mass region.

Table 2. Summary of the KLOE results on the most significant $f_0(980)$ parameters. The mass and the coupling to the ϕ are obtained using the fits done according to ref. [9] while the ratio R is obtained using the kaon-loop fit; the $B.R.$ is obtained by integrating the square of the resulting scalar amplitude.

Parameter	$\pi^+\pi^-\gamma$ [11]	$\pi^0\pi^0\gamma$ [12]
m_{f_0} (MeV)	973–981	981–987
$g_{\phi f_0\gamma}$ (GeV^{-1})	1.2–2.0	2.5–2.9
$R = g^2_{f_0K^+K^-}/g^2_{f_0\pi^+\pi^-}$	2.2–2.8	3.0–7.2
$B.R.(\times 10^{-4})$	2.1–2.4	1.0–1.2

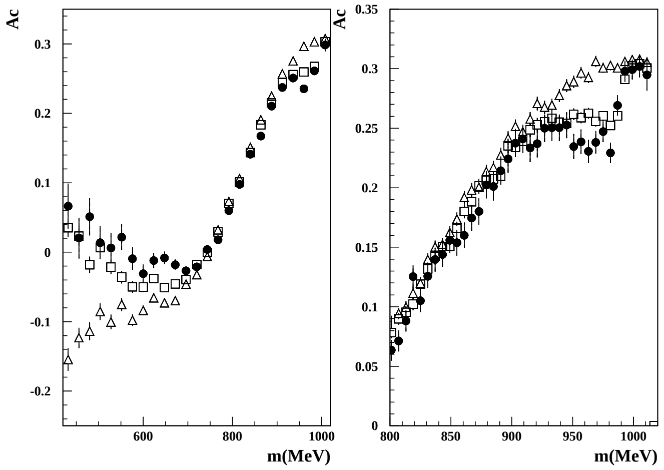

Fig. 2. The forward-backward asymmetry of $\pi^+\pi^-\gamma$ events. Data (full circles) are compared to the Monte Carlo expectations with no f_0 (open triangles), and with f_0 (open squares). The right plot shows the detail of the comparison in the f_0 region.

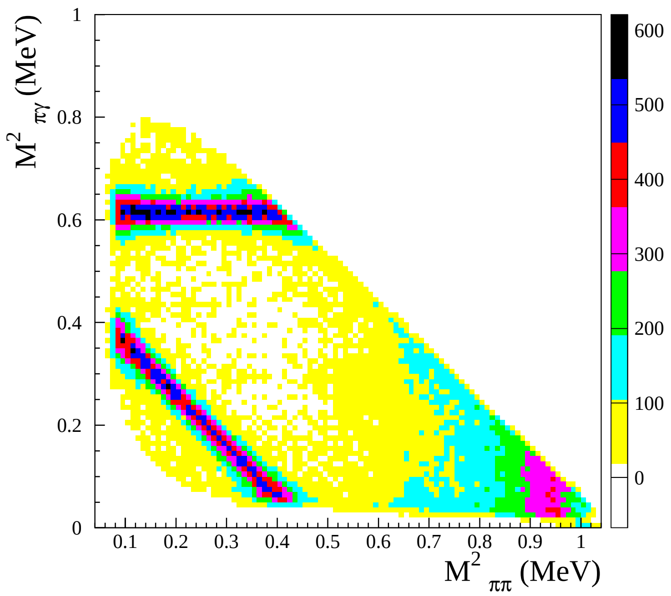

Fig. 3. Dalitz plot of the $\pi^0\pi^0\gamma$ sample. The two narrow bands are due to events $e^+e^- \to \omega\pi^0$ with $\omega \to \pi^0\gamma$, while the excess of the events in the right corner is due to the radiative decay $\phi \to f_0(980)\gamma$ with $f_0 \to \pi^0\pi^0$.

estimate of the branching ratio $B.R.(\phi \to f_0(980)\gamma \to \pi\pi\gamma)$ obtained by integrating the resulting scalar amplitudes, is also obtained and presented in table 2.

Looking at the results of the fit we make the following considerations:

- the mass of the $f_0(980)$ is in good agreement with the range reported by the Particle Data Group $m_{f_0} = 980 \pm 10\,\text{MeV}$ [13];
- the coupling to the ϕ is larger then $1\,\text{GeV}^{-1}$ in both cases; for comparison notice that the same couplings for the lowest-mass pseudoscalar mesons are all well below $1\,\text{GeV}^{-1}$ (between $\sim$ 0.1 for the π^0 and $\sim$ $0.7\,\text{GeV}^{-1}$ for the η and η');
- the ratio R is also larger than 1, showing that the f_0 has a larger coupling to kaons than to pions;
- the branching ratios of the two channels differ by a factor 2 as it should be based on isospin arguments.

For what concerns the σ the results are somehow contradictory. In fact the kaon-loop fit requires the presence of the σ in the case of the $\pi^0\pi^0\gamma$ analysis to account for the interference pattern with the $\omega\pi^0$ amplitude, but it does not require it in the $\pi^+\pi^-\gamma$ analysis. Moreover, the direct coupling fit describes the low-energy part of the amplitude as a polynomial background, so that even in this case the σ is not required. The conclusion is that it is not possible to obtain a model-independent indication on the σ.

Finally, the KLOE analysis of $\phi \to a_0\gamma$ [14] gives a lower branching ratio, $B.R.(\phi \to a_0\gamma \to \eta\pi^0\gamma) = (7.4 \pm 0.7) \times 10^{-5}$ and lower couplings to kaons, the ratio R between the coupling to kaons and to $\eta\pi^0$ being $R = g^2_{a_0K^+K^-}/g^2_{a_0\eta\pi^0} = 0.74 \pm 0.05$. A new analysis with a larger statistics is in progress and will be published soon.

3 Results on pseudoscalar mesons

Large samples of pseudoscalar mesons are also accessible at KLOE through the ϕ radiative decays (see table 1). In particular about 8×10^7 monochromatic η-mesons with $p = 360\,\text{MeV}/c$ and about 4×10^5 η'-mesons with $p = 60\,\text{MeV}/c$ are present in the full KLOE data sample.

A measurement of the η-η' mixing angle has already been published [15] based on the detection of the final state $\pi^+\pi^-3\gamma$ in the first $20\,\text{pb}^{-1}$ of data collected in the year 2000. Improved upper limits on the branching ratios of the forbidden decays $\eta \to \gamma\gamma\gamma$ [16] and $\eta \to \pi^+\pi^-$ [17] have been also obtained and the dynamic of the $\eta \to 3\pi$ decays has been studied by means of a Dalitz-plot analysis [18].

We present here two recent results: the first is an improved measurement of the η-η' mixing angle done using the $\pi^+\pi^-7\gamma$ and 7γ final states, the second is a new measurement of the η mass based on the 3γ final states $\phi \to \eta\gamma$ with $\eta \to \gamma\gamma$.

The pseudoscalar mixing angle in the flavour basis φ_P is obtained by the ratio

$$R = \frac{B.R.(\phi \to \eta'\gamma)}{B.R.(\phi \to \eta\gamma)} \tag{1}$$

according to ref. [19]. To get the $B.R.(\phi \to \eta'\gamma)$ we use the $\pi^+\pi^-7\gamma$ final states that are due either to the decay chain $\eta' \to \eta\pi^+\pi^-$ with $\eta \to 3\pi^0$ or to $\eta' \to \eta\pi^0\pi^0$ with $\eta \to \pi^+\pi^-\pi^0$. For the $B.R.(\phi \to \eta\gamma)$ we use the 7γ final states due to the decay chain $\eta \to 3\pi^0$. Out of a $427\,\text{pb}^{-1}$ data sample we select 3750 η' events and 1.7×10^6 η events. The estimated background is about 345 events (less than 10%) for the η' sample and is negligible for the η sample. The result for the ratio R is:

$$R = (4.79 \pm 0.09_{stat} \pm 0.20_{syst}) \times 10^{-3}, \tag{2}$$

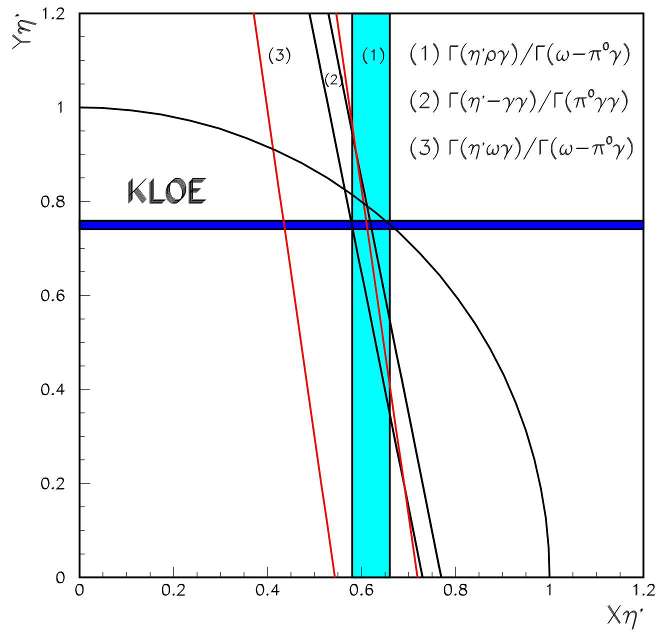

Fig. 4. Bounds in the $(Y_{\eta'}, X_{\eta'})$-plane coming from KLOE (horizontal band) and from the other experimental quantities indicated in the insert.

where the systematic uncertainty is dominated by the knowledge of the intermediate branching ratios of the η' that is not better than 3%. The mixing angle in the flavour basis is

$$\varphi_P = (41.4 \pm 0.3_{stat} \pm 0.7_{syst} \pm 0.6_{th})^\circ, \tag{3}$$

where we add a further theoretical uncertainty due to the knowledge of the parameters entering in the angle determination [19]. By applying the relation $\theta_P = \varphi_P - \mathrm{arctg}\sqrt{2}$ we get the mixing angle in the octet-singlet basis to be

$$\theta_P = (-13.3 \pm 0.3_{stat} \pm 0.7_{syst} \pm 0.6_{th})^\circ \tag{4}$$

in agreement with the recent BES results $\theta_P = (-15.9 \pm 1.2)^\circ$ [20] obtained using J/ψ radiative decays.

The KLOE result is used to check the amount of possible gluonium content in the η' wave function. We define the three coefficients $X_{\eta'}$, $Y_{\eta'}$ and $Z_{\eta'}$ as the coefficients of the quark and gluon component in the η' wave function:

$$|\eta'\rangle = X_{\eta'} \frac{1}{\sqrt{2}} |u\overline{u} + d\overline{d}\rangle + Y_{\eta'} |s\overline{s}\rangle + Z_{\eta'} |\mathrm{gluonium}\rangle. \tag{5}$$

In case of no gluonium content ($Z_{\eta'} = 0$) the mixing angle φ_P is simply related to $Y_{\eta'}$ through the

$$|Y_{\eta'}| = \cos\varphi_P \tag{6}$$

so that the KLOE result corresponds to a horizontal band in the $(Y_{\eta'}, X_{\eta'})$-plane shown in fig. 4 where other bands based on different measurements are included. A cross-check of the $Z_{\eta'} = 0$ hypothesis is obtained by checking that the bands meet in a region compatible with the

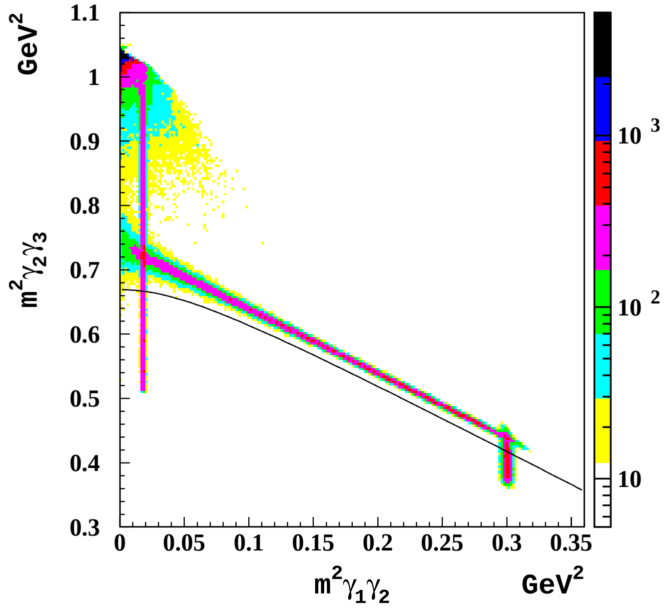

Fig. 5. Dalitz plot of 3γ events with the photons ordered in increasing energy. The solid line corresponds to the applied cut: only events below the line are considered. It can be seen that after the cut two populations survive at fixed values of $m^2_{\gamma_1\gamma_2}$: one gives the mass peak of the π^0, the other one gives the mass peak of the η.

$X^2_{\eta'} + Y^2_{\eta'} = 1$ curve. A preliminary result of this analysis gives $X^2_{\eta'} + Y^2_{\eta'} = 0.93 \pm 0.06$ that constrains the gluonium content of the η' to be below the few percent level.

The two most recent and most accurate measurements of the η mass are in bad disagreement with each other:

$$m_\eta = (547.843 \pm 0.030 \pm 0.041)\ \mathrm{MeV} \quad (\mathrm{NA48}), \tag{7}$$
$$m_\eta = (547.311 \pm 0.028 \pm 0.032)\ \mathrm{MeV} \quad (\mathrm{GEM}). \tag{8}$$

The NA48 experiment at CERN has looked at the decay $\eta \to \pi^0\pi^0\pi^0$ from a η sample of very high energy (in average 110 GeV) produced by protons hitting a beryllium target [21]. The GEM experiment has measured the missing-mass distribution of the reaction $p + d \to {}^3\mathrm{He} + \eta$ [22]. All the previous experiments quoted in ref. [13] have larger uncertainties but central values somehow more consistent with the GEM result.

KLOE performs the η mass measurement by exploiting the large samples of 3γ events mostly due to the decay chains: $\phi \to \eta\gamma$ with $\eta \to \gamma\gamma$ and $\phi \to \pi^0\gamma$ with $\pi^0 \to \gamma\gamma$. The kinematic fit of the 3γ events uses all the KLOE calorimeter information, in particular the very good timing and position resolutions, resulting in a very good resolution on the invariant masses of any photon pair. From the Dalitz plot shown in fig. 5 one can easily separate the events due to the η from those due to the π^0 and select a region of the plot from which to obtain two very narrow mass peaks, one for each meson. The preliminary results are

$$m_{\pi^0} = (134.990 \pm 0.006 \pm 0.030)\ \mathrm{MeV}, \tag{9}$$
$$m_\eta = (547.822 \pm 0.005 \pm 0.069)\ \mathrm{MeV}. \tag{10}$$

The statistical uncertainties are negligible, the systematic ones are mostly due to the knowledge of the effective center-of-mass energy and interaction region position. The value of the π^0 mass gives an absolute calibration of the method. In fact it is in agreement with the more precise value reported by the Particle Data Group $m_{\pi^0} = 134.9766 \pm 0.0006$ [13] within the systematic uncertainty.

The KLOE result on the η mass confirms the NA48 value and is in disagreement with the GEM value. At the moment there is no explanation for this inconsistency between different kinds of measurements of the same quantity.

4 Prospects for e^+e^- at Frascati

Here, the prospects of e^+e^- physics at Frascati are briefly discussed. More detailed information on accelerator developments and on experimental proposals can be found in ref. [23].

The e^+e^- program of the Frascati laboratory is well defined for the next 2 years. The FINUDA run is now in progress at DAFNE, aiming to collect an overall luminosity 5 times the one collected up to now. The main goal of the new FINUDA run is to confirm or disprove the evidence for a deeply bound hypernuclear state obtained in the first run [24]. After the FINUDA run there will be the run of the SIDDHARTA experiment [25] aiming to study the formation of exotic atoms with an improved version of the DEAR experiment.

The laboratory has not yet taken any decision concerning the program after these runs. However, the possibility to continue the e^+e^- program of DAFNE with two main improvements is strongly considered: an increase of luminosity at the ϕ peak up to $\sim 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and an increase of center-of-mass energy up to about $2.5\,\mathrm{GeV}$.

Based on this accelerator improvement scheme, 3 experimental proposals have been submitted, briefly described in the following:

- The KLOE2 proposal aims to continue the kaon and η/η' physics program at the ϕ peak, but also to take data at center-of-mass energies up to $2.5\,\mathrm{GeV}$ in order to perform a precision measurement of the multihadronic and $\gamma\gamma$ cross-sections.
- The AMADEUS proposal aims to refine the study of the deeply bound hypernuclear states using a large rate of monochromatic charged kaons at the ϕ peak and possibly exploiting a more general-purpose detector.
- The DANTE proposal wants to measure the time-like baryon form factors, in particular neutron and proton, by detecting the reactions $e^+e^- \to n\overline{n}$ and $e^+e^- \to p\overline{p}$ possibly measuring the polarisations of the nucleons in the final state.

A discussion of most of the physics items included in these proposals can be found in ref. [26]

References

1. M. Adinolfi *et al.*, Nucl. Instrum. Methods A **488**, 1 (2002).
2. M. Adinolfi *et al.*, Nucl. Instrum. Methods A **482**, 364 (2002).
3. KLOE Collaboration (A. Aloisio *et al.*), in *Le Rencontres de la Vallee d'Aoste - Results and Perspectives in Particle Physics, February 2005*, edited by M. Greco, Frascati Phys. Ser., Vol. **XXXIX**, p. 233.
4. KLOE Collaboration (A. Aloisio *et al.*), Phys. Lett. B **606**, 12 (2005).
5. R.L. Jaffe, Phys. Rev. D **15**, 15 (1977).
6. L. Maiani *et al.*, Phys. Rev. Lett. **93**, 212002 (2004).
7. J. Weinstein, N. Isgur, Phys. Rev. Lett. **48**, 10 (1982).
8. V. Baru *et al.*, Phys. Lett. B **586**, 53 (2004).
9. G. Isidori *et al.*, JHEP **0605**, 049 (2006).
10. N.N. Achasov, V.N. Ivanchenko, Nucl. Phys. B **315**, 465 (1989).
11. KLOE Collaboration (F. Ambrosino *et al.*), Phys. Lett. B **634**, 148 (2006).
12. KLOE Collaboration (F. Ambrosino *et al.*), Eur. Phys. J. C **49**, 473 (2007).
13. Particle Data Group (W.M. Yao *et al.*), J. Phys. G **33**, 1 (2006).
14. KLOE Collaboration (A. Aloisio *et al.*), Phys. Lett. B **536**, 209 (2002).
15. KLOE Collaboration (A. Aloisio *et al.*), Phys. Lett. B **541**, 45 (2002).
16. KLOE Collaboration (A. Aloisio *et al.*), Phys. Lett. B **591**, 49 (2004).
17. KLOE Collaboration (F. Ambrosino *et al.*), Phys. Lett. B **606**, 276 (2005).
18. KLOE Collaboration (F. Ambrosino *et al.*), in AIP Conf. Proc. **814**, 463 (2006).
19. A. Bramon *et al.*, Eur. Phys. J. C **7**, 24 (1999).
20. BES Collaboration (M. Ablikim *et al.*), Phys. Rev. D **73**, 052008 (2006).
21. NA48 Collaboration (A. Lai *et al.*), Phys. Lett. B **533**, 196 (2002).
22. GEM Collaboration (M. Abdel-Bary *et al.*), Phys. Lett. B **619**, 281 (2005).
23. See the web site: `http://www.lnf.infn.it/lnfadmin/direzione/roadmap`.
24. FINUDA Collaboration (M. Agnello *et al.*), Phys. Rev. Lett. **94**, 212303 (2005).
25. C. Curceanu, these proceedings.
26. F.Ambrosino *et al.*, submitted to Eur. Phys. J. C, hep-ex/0603056.