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# Study of the properties of the light scalar mesons with the KLOE experiment

D. Capriotti on behalf of the KLOE Collaboration(*)

*Dipartimento di Fisica, Università Roma Tre and INFN, Sezione Roma Tre - Rome, Italy*

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**Summary.** — Some experiments have shown evidence for the $\sigma(600)$ meson as a $\pi^+\pi^-$ resonance. Here we recall the contribution of the KLOE experiment to the study of the light scalar mesons $0^+$ and present a search for the $\sigma$ meson production in the reaction $e^+e^- \to e^+e^-\pi^0\pi^0$ based on a data sample of $11\,\mathrm{pb}^{-1}$ integrated luminosity at $\sqrt{s} = 1\,\mathrm{GeV}$.

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## 1. – Introduction

The particles that interact through the strong interaction can be described as bound states of two or three quarks (mesons and baryons). Bound states with different composition are not excluded by the quark model. Light scalar mesons $0^+$ are not easily described as a $q\bar{q}$ state with zero orbital angular momentum and may be interpreted as a four-quark system, either a $[q\bar{q}][q\bar{q}]$ molecule [1] or a $[qq][\bar{q}\bar{q}]$ diquark-antidiquark system [2].

The $\sigma(600)$ is supposed to be the lightest isospin singlet of the $0^+$ scalar nonet. Evidence for the $\sigma$ meson as a bound state $\pi^+\pi^-$ was shown by the E791 [3], CLEO [4] and BES [5] experiments, the values of mass and width cover a large interval as shown

(*) F. Ambrosino, A. Antonelli, M. Antonelli, F. Archilli, P. Beltrame, G. Bencivenni, S. Bertolucci, C. Bini, C. Bloise, S. Bocchetta, F. Bossi, P. Branchini, P. Campana, G. Capon, T. Capussela, F. Ceradini, P. Ciambrone, F. Crucianelli, E. De Lucia, A. De Santis, P. De Simone, G. De Zorzi, A. Denig, A. Di Domenico, C. Di Donato, B. Di Micco, M. Dreucci, G. Felici, M. L. Ferrer, S. Fiore, P. Franzini, C. Gatti, P. Gauzzi, S. Giovannella, E. Graziani, W. Kluge, V. Kulikov, G. Lanfranchi, J. Lee-Franzini, D. Leone, M. Martini, P. Massarotti, S. Meola, S. Miscetti, M. Moulson, S. Muller, F. Murtas, M. Napolitano, F. Nguyen, M. Palutan, E. Pasqualucci, A. Passeri, V. Patera, F. Perfetto, P. Santangelo, B. Sciascia, A. Sciubba, A. Sibidanov, T. Spadaro, M. Testa, L. Tortora, P. Valente, G. Venanzoni, R.Versaci.

 

TABLE I. – *Parameters of the $\sigma$ meson.*

| | Mass (MeV) | Width (MeV) | Pole (MeV) |
|---|---|---|---|
| E791 [3] | $478 \pm 24 \pm 17$ | $324 \pm 41 \pm 21$ | |
| CLEO [4] | $513 \pm 32$ | $335 \pm 67$ | |
| BES [5] | | | $(541 \pm 39) - i(252 \pm 42)$ |

in table I and its nature is still debated. There is no direct evidence for the $\sigma \to \pi^0\pi^0$ decay; an interpretation of the $\pi^0\pi^0$ mass distribution in terms of the $\sigma$ contribution is given in ref. [6].

The KLOE experiment, operating at the $e^+e^-$ Frascati $\phi$-factory DA$\Phi$NE, has studied the properties of the isospin singlet $f_0$ and the isospin triplet $a_0$ produced in $\phi$ radiative decays. In particular, the $\pi\pi$ mass spectrum in $\phi \to \pi^0\pi^0\gamma$ events is well described by the interference of two contributions $f_0 \to \pi^0\pi^0$ and $\sigma \to \pi^0\pi^0$ [7], showing indirect evidence for a $\sigma$ to $\pi^0\pi^0$ coupling. The $\sigma$ meson can be produced in $\gamma\gamma$ interactions and its $\pi^0\pi^0$ decay observed in the reaction

$$e^+e^- \to e^+e^-\sigma \to e^+e^-\pi^0\pi^0 \tag{1}$$

as suggested in ref. [8].

## 2. – The experiment

The KLOE detector consists of a large-volume cylindrical drift chamber [9] (3.3 m length and 2 m radius) surrounded by a sampling calorimeter [10] made of lead and scintillating fibers. Both are surrounded by a superconducting coil producing a solenoidal field $B = 0.52\,\mathrm{T}$. Charged particle momenta are reconstructed with a resolution $\sigma_{p_T}/p_T = 0.4\%$. Energy clusters are reconstructed from calorimeter cells close in space and in time with energy, time and position resolution of $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$, $\sigma_t = 57\,\mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 100\,\mathrm{ps}$ and $\sigma_r = 1\,\mathrm{cm}/\sqrt{E(\mathrm{GeV})}$. Photons are defined as neutral prompt clusters if they are not associated to tracks within a space distance of 30 cm and if they satisfy $|t - R/c| < 5\sigma_t$, with $t$ the time of the cluster and $R$ its distance from the interaction point. The trigger [11] for this analysis requires at least two clusters of energy greater than 50 MeV for $45° < \theta < 135°$ and 150 MeV in the forward (backward) region.

The KLOE experiment has run most of the time at the energy of the $\phi$ meson, $\sqrt{s} = 1.02\,\mathrm{GeV}$. A small set of data was collected off-peak, at $\sqrt{s} = 1.00\,\mathrm{GeV}$, for studies in the continuum. At this energy, the background of $\phi$ decays is highly reduced making the study of reaction (1) possible.

## 3. – Monte Carlo simulation of signal and background

The kinematics of reaction (1) is such that $e^+$ and $e^-$ are emitted at small polar angles and their detection is not required. The signature we search for is $\pi^0\pi^0 \to 4\gamma$ with a small value of the total transverse momentum.

To evaluate the acceptance for $\sigma$ production we use the model of ref. [2] with the $\sigma$ described by a Breit-Wigner with mass and width according to the values measured by

E791 [3] and CLEO [4]. The $\sigma$ decay is then fully simulated in the detector with the KLOE Monte Carlo (MC) program *GEANFI* [12].

For the analysis we have to take into account several background processes. In fact, even if data are collected at $\sqrt{s} = 1\,\mathrm{GeV}$, $\omega\pi^0$ production in the continuum and $\phi$ decays with at least four photons in the final state can have a rate comparable to the expected signal:

- $e^+e^- \to \phi \to \eta\gamma \to 3\pi^0\gamma$. The cross-section is evaluated $\sim 0.35\,\mathrm{nb}$, extrapolating the measurements of the SND experiment [13]. This process can cause a background if some photons escape the detector.

- $e^+e^- \to \phi \to K_S K_L$. The cross-section is evaluated $\sim 2\,\mathrm{nb}$, extrapolating the measurements of SND [14]. This process can cause a background if the $K_L$ escapes detection and the $K_S$ decays into $\pi^0\pi^0$.

- $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$. The cross-section is measured at $\sqrt{s} = 1\,\mathrm{GeV}$ by KLOE: the result is $\sigma = (0.550 \pm 0.005)\,\mathrm{nb}$ [15].

- $e^+e^- \to \phi \to \pi^0\gamma$. The cross-section is evaluated $\sim 0.45\,\mathrm{nb}$, extrapolating the measurement of SND [16].

- $e^+e^- \to \phi \to f_0\gamma \to \pi^0\pi^0\gamma$. The cross-section is evaluated $\sim 0.15\,\mathrm{nb}$ extrapolating the measurements of SND [17] for $e^+e^- \to \pi^0\pi^0\gamma$ and subtracting the contribution of $e^+e^- \to \omega\pi^0$.

- $e^+e^- \to \gamma\gamma$. The cross-section is evaluated $\sim 400\,\mathrm{nb}$. There can be more than two clusters in the final state caused by the splitting of the most energetic clusters. The probability of splitting of one cluster is small, but it is compensated by the large cross-section of $e^+e^- \to \gamma\gamma$.

## 4. – Event selection

The amount of data collected at $\sqrt{s} = 1\,\mathrm{GeV}$ is $220\,\mathrm{pb}^{-1}$ of integrated luminosity. A $1:20$ sample of downscaled events is processed without any data filter. The analysis is performed on this data sample of $11\,\mathrm{pb}^{-1}$ integrated luminosity. The event preselection requires at least four prompt neutral clusters, with a minimum energy of $10\,\mathrm{MeV}$. It may happen that a cluster is reconstructed as two (or more) clusters; a recover-splitting procedure allows the merging of the clusters if their distance in space is less than $50\,\mathrm{cm}$. This threshold is evaluated studying a subsample of $e^+e^- \to \gamma\gamma$ events where only two photons are produced in the final state. These events are selected requiring two neutral clusters with energies greater then $400\,\mathrm{MeV}$. Figure 1 shows the time difference as a function of the spatial distance of any cluster respect to the most energetic cluster for $e^+e^- \to \gamma\gamma$ events.

After applying the recover-splitting procedure, we select events with 4 or 5 prompt neutral clusters with a minimum energy of 10 MeV and with polar angle $20^\circ < \theta < 160^\circ$. The candidate $\pi^0\pi^0$ pairs are selected using the variable

$$\chi^2_{\pi^0\pi^0} = \frac{(m_{\pi^0} - m_{\gamma_i\gamma_j})^2}{\sigma^2_{\gamma_i\gamma_j}} + \frac{(m_{\pi^0} - m_{\gamma_k\gamma_l})^2}{\sigma^2_{\gamma_k\gamma_l}} \tag{2}$$

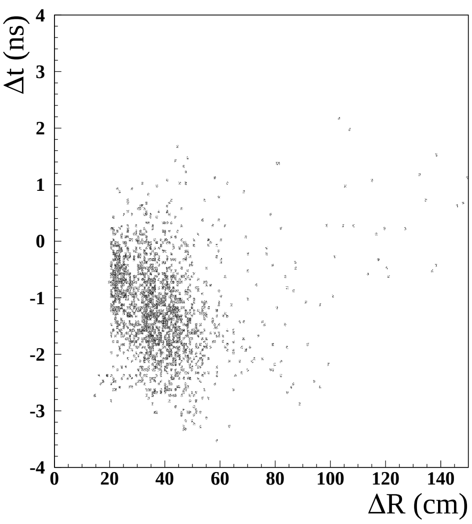


Fig. 1. – Spatial and time difference respect to the most energetic cluster in $e^+e^- \to \gamma\gamma$ events.

computed for all combinations; here $m_{\gamma_i\gamma_j}$ is the invariant mass of photon pairs and $\sigma_{\gamma_i\gamma_j}$ depends on the resolution of the calorimeter.

Events are then selected with the following requirements:

- $\chi^2_{\pi^0\pi^0} < 4$; fig. 2 shows the distribution of $m_{\gamma_i\gamma_j} \times m_{\gamma_k\gamma_l}$ for the combination with the minimum $\chi^2_{\pi^0\pi^0}$ before and after applying the cut;
- no tracks reconstructed in the drift chamber;

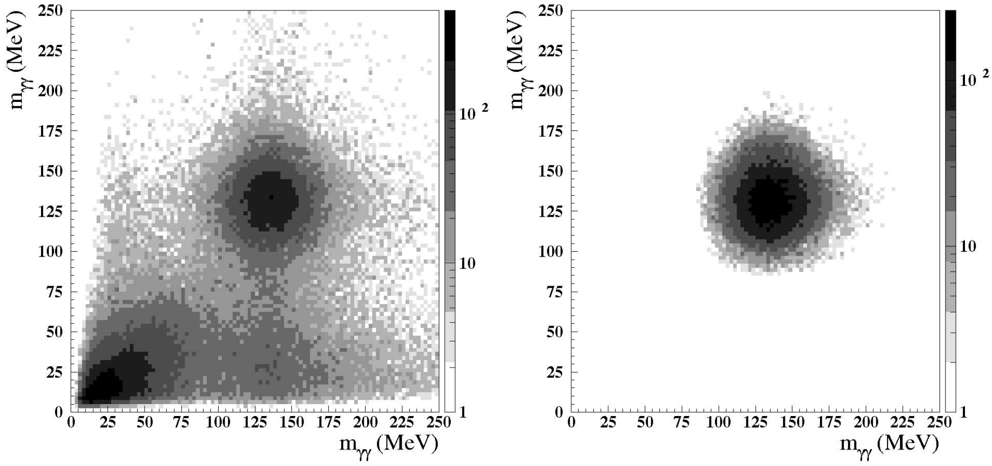


Fig. 2. – Distribution of the two-photon invariant mass $m_{\gamma_i\gamma_j} \times m_{\gamma_k\gamma_l}$ for the combination with the minimum $\chi^2_{\pi^0\pi^0}$, before (left) and after (right) applying the cut $\chi^2_{\pi^0\pi^0} < 4$.

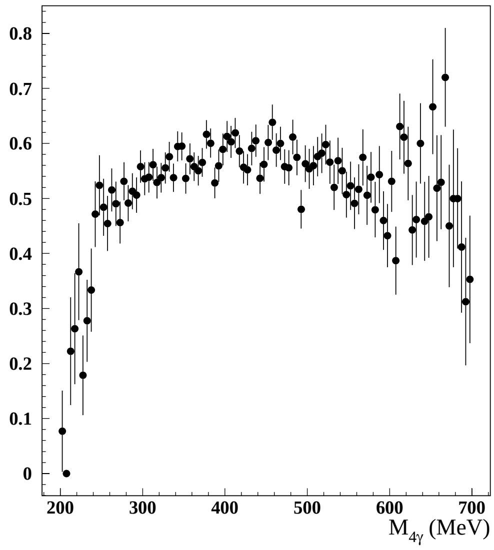


Fig. 3. – Efficiency of the signal evaluated with MC as a function of the 4-photon invariant mass $m_{4\gamma}$.

– $R = \sum_{i=1}^{4} E_i/E_{\text{calo}} > 0.75$, where the sum runs over the 4 clusters that minimize the $\chi^2_{\pi^0\pi^0}$ and $E_{\text{calo}}$ is the total energy measured in the calorimeter;

– the total transverse momentum $|\vec{p}_T| < 100\,\text{MeV}/c$, where $\vec{p}_T$ is calculated from the 4 clusters that minimize $\chi^2_{\pi^0\pi^0}$;

– $E_3 + E_4 > 50\,\text{MeV}$, where $E_3$ and $E_4$ refer to the least energetic clusters (of the 4 clusters that minimize $\chi^2_{\pi^0\pi^0}$);

– $E_1 < 450\,\text{MeV}$ and $E_2 < 400\,\text{MeV}$ for the two most energetic clusters, to reject $e^+e^- \to \gamma\gamma$ events.

The efficiency for each cut has been evaluated with the MC and it was checked that the efficiencies are rather constant as a function of the 4-photons invariant mass $m_{4\gamma}$ for $m_{4\gamma} > 250\,\text{MeV}$. The efficiency for selecting the events of reaction (1) with the above cuts is shown in fig. 3 as a function of $m_{4\gamma}$. The efficiency for the signal and the background processes listed above are given in table II; these values include the efficiency of the trigger and the off-line filter [12] used to reject cosmic-ray and machine background events.

## 5. – Results

The distribution of the four-photon invariant mass is used to search for the signal. Figure 4 shows the four-photon invariant mass spectrum for data, MC signal and MC background.

A fit procedure is used to normalize the background distributions to the data. The input to the fit are the MC distributions while their normalization factors are free parameters that can fluctuate in a fixed range. The range is defined by the error of

TABLE II. – *Total efficiency of signal and background processes evaluated with MC.*

| Reaction | Total efficiency | Error (%) |
|---|---|---|
| $e^+e^- \to e^+e^-\sigma \to e^+e^-\pi^0\pi^0$ | 0.289 | 0.7 |
| $e^+e^- \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ | 0.011 | 1.8 |
| $e^+e^- \to K_S K_L$ | 0.009 | 0.4 |
| $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ | 0.051 | 0.4 |
| $e^+e^- \to \gamma\gamma$ | $9.7\ 10^{-6}$ | 4.1 |
| $e^+e^- \to \pi^0\gamma$ | 0.0007 | 14.3 |
| $e^+e^- \to f_0\gamma, a_0\gamma, \eta'\gamma$ | 0.084 | 3.6 |

the extrapolation of the background cross-section to $\sqrt{s} = 1\,\text{GeV}$. Figure 5 shows the invariant-mass spectrum after the fit without including a contribution of the $\sigma$ meson.

The excess of event $n \approx 220$ at low invariant mass can be associated to the production of the $\sigma$ meson. With the present statistics, the result is far from bringing clear evidence for the production of the $\sigma$ meson via reaction (1). The possible background processes have been extensively studied by KLOE at the $\phi$ mass and extrapolated to $\sqrt{s} = 1\,\text{GeV}$, and can hardly explain the small excess of events where the contribution of the $\sigma$ meson is expected. The preliminary results of this analysis are encouraging and motivate the

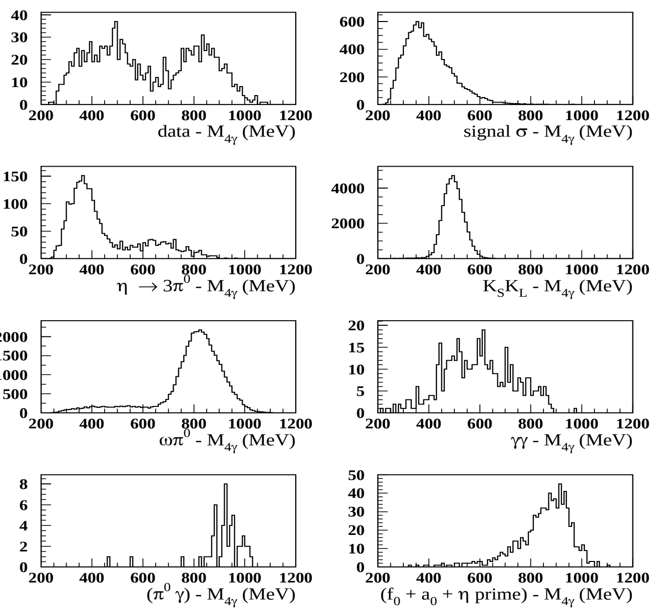


Fig. 4. – Four-photon invariant-mass spectrum after all cuts for data (top left), MC signal (top right) and MC background (second, third and fourth row). The mass and width parameters for the signal are taken from [3].

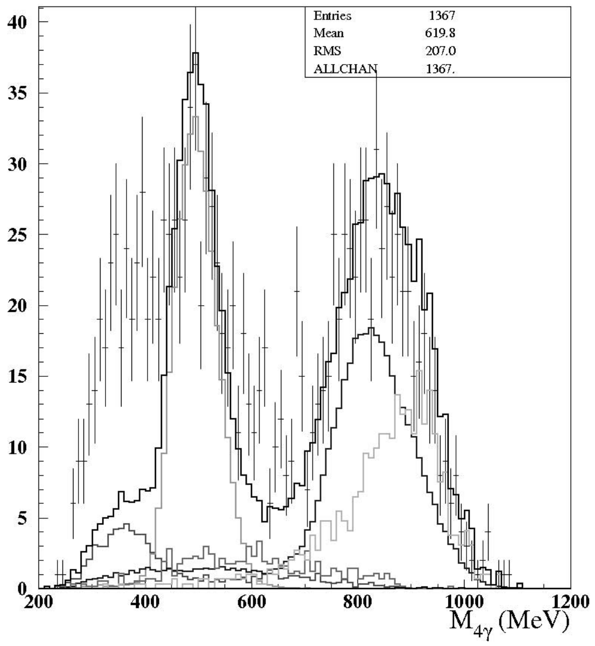


Fig. 5. – Four-photon invariant-mass spectrum of data and MC background, weighted after the fit procedure. The sum of the MC distributions of the background processes is superimposed to data.

extension of the analysis to the whole data sample collected by the KLOE experiment at $\sqrt{s} = 1\,\text{GeV}$. In fact the number of events in the $m_{4\gamma}$ distribution and the shape of the signal depend upon the value of the mass, width and $\gamma\gamma$-$\sigma$ coupling. The latter has been evaluated by various authors [18]. A substantial gain in statistic can bring more information on the $\sigma \to \pi^0\pi^0$ decay.

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