

## Measurement of the $\eta$ mass at KLOE.

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An integrated luminosity of  $410 \text{ pb}^{-1}$ , corresponding to  $\sim 17$  million of  $\eta$  events, has been analyzed to measure the  $\eta$  mass using the decay  $\eta \rightarrow \gamma\gamma$ . The measurement is insensitive to the calorimeter energy calibration and the systematic error on the measurement is dominated by the uniformity of the detector response. As a cross check of the method the  $\pi^0$  mass from the decay  $\phi \rightarrow \pi^0\gamma, \pi^0 \rightarrow \gamma\gamma$  has been measured and it is in agreement with the most accurate previous determinations.

The result obtained is  $m_\eta = 547.873 \pm 0.007_{stat.} \pm 0.031_{syst.} \text{ MeV}$ , that is today best measurement of the  $\eta$  mass.

### 1. Introduction

The KLOE experiment is performed at the Frascati  $\phi$  factory DAΦNE[1]. DAΦNE is a high luminosity  $e^+, e^-$  collider working at  $\sqrt{s} \sim 1020 \text{ MeV}$ , corresponding to the  $\phi$  meson mass. In the whole period of data taking (2001 – 2006) KLOE has collected an integrated luminosity of  $2.5 \text{ fb}^{-1}$ , corresponding to about 8 billions of  $\phi$  produced and 100 millions of  $\eta$  mesons through the electromagnetic decay  $\phi \rightarrow \eta\gamma$ .

The KLOE detector consists of a large cylindrical drift chamber [2], DC, surrounded by a lead/scintillating-fiber sampling calorimeter [3], EMC, both immersed in a solenoidal magnetic field of 0.52 T with the axis parallel to the beams,  $z$  in the following. The DC momentum resolution for charged particles is  $\delta p_\perp/p_\perp = 0.4\%$ . The calorimeter is divided into a barrel and two endcaps, and covers 98% of the total solid angle. Photon energies and arrival times are measured with resolutions  $\sigma_E/E = 0.057/\sqrt{E} \text{ (GeV)}$  and

$\sigma_t = 54 \text{ ps}/\sqrt{E \text{ (GeV)}} \oplus 50 \text{ ps}$ , respectively. Photon-shower centroid positions are measured with an accuracy of  $\sigma = 1 \text{ cm}/\sqrt{E \text{ (GeV)}}$  along the fibers, and 1 cm in the transverse direction. A photon is defined as a cluster of energy deposits in the calorimeter elements that is not associated to a charged particle. We require the distance between the cluster centroid and the nearest entry point of extrapolated tracks be greater than  $3 \times \sigma(z, \phi)$ , where  $\phi$  is the azimuthal angle.

The trigger [4] uses information from both the calorimeter and the drift chamber. The EMC trigger requires two local energy deposits above threshold ( $E > 50 \text{ MeV}$  in the barrel,  $E > 150 \text{ MeV}$  in the endcaps). The trigger has a large time spread with respect to the time distance between consecutive beam crossings. It is however synchronized with the machine radio frequency divided by four,  $T_{\text{sync}} = 10.85 \text{ ns}$ , with an accuracy of 50 ps. For the 2001-2002 data taking, the bunch crossing period was  $T = 5.43 \text{ ns}$ . The time ( $T_0$ ) of the bunch crossing producing an event is determined offline during event reconstruction.

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## 2. Measurement of the $\eta$ mass.

The value of the  $\eta$  mass has been recently measured with high precision by two collaborations NA48[5] ( $m_\eta = 547.843 \pm 0.030 \pm 0.041$  MeV/ $c^2$ ) and GEM[6] ( $m_\eta = 547.311 \pm 0.028 \pm 0.032$  MeV/ $c^2$ ) using different techniques and production reactions. The two measurements differ by more than eight standard deviations from each other. The GEM measurement is in agreement with the older ones[7] while the NA48 measurement is higher. For this reason it is interesting to provide a further measurement of comparable precision in order to clarify the experimental situation.

## 3. Measurement method.

We measure the mass studying the decay  $\phi \rightarrow \eta\gamma, \eta \rightarrow \gamma\gamma$ . A kinematic fit is performed imposing the 4 constraints given by the energy-momentum conservation. Since there are three photons and there are 4 constraints, the fit over-constrains the energies of the photons that are, practically, determined by the position of the clusters in the calorimeter. The inputs of the fit are the energy, the position and the time of the calorimeter clusters, the mean position of the  $e^+e^-$  interaction point, the total four-momentum of the colliding  $e^+e^-$  pair. Each of these variables is determined run by run using  $e^+e^- \rightarrow e^+e^-$  events (almost 90000 events for each run, allowing a very precise determination of the relevant parameters).

## 4. Selection.

The  $\phi \rightarrow \eta\gamma$  events are selected by requiring at least three energy deposits in the barrel with a polar angle  $\theta_\gamma : 50^\circ < \theta_\gamma < 130^\circ$ , not associated to a charged track. A kinematic fit imposing energy-momentum conservation and time of flight of photons equal to the velocity of light is done for all 3  $\gamma$ 's combination of N detected photons. The combination with the lowest  $\chi^2$  is chosen as a candidate event if  $\chi^2 < 35$ . The events surviving the cuts are shown in fig.1, where the Dalitz plot is shown. Three bands are clearly visible. The band at low  $m_{\gamma\gamma}^2$  is given by the  $\phi \rightarrow \pi^0\gamma, \pi^0 \rightarrow \gamma\gamma$ ,

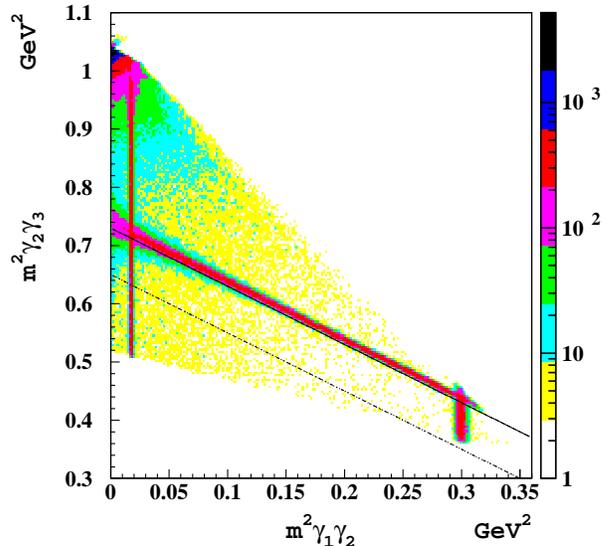


Figure 1. Dalitz plot distribution of the selected  $3\gamma$  events. The photons are sorted according their energies  $E_1 < E_2 < E_3$ .

while the other two bands are  $\phi \rightarrow \eta\gamma, \eta \rightarrow \gamma\gamma$  events.

With the cut shown in the Dalitz plot we select a pure sample of  $\eta, \pi^0 \rightarrow \gamma\gamma$  events. The resulting  $m_{\gamma\gamma}$  spectrum (fig.2) can be fitted well with a single gaussian of  $\sigma \sim 2.1$  MeV/ $c^2$ .

In order to determine the systematic error we have evaluated the uncertainties on all the quantities used in the kinematic fit and the effect on the fitted value.

A sample of  $e^+e^- \rightarrow \pi^+\pi^-\gamma$  events has been used to check the mean position of the interaction point, the energy response of the calorimeter and the alignment of the calorimeter with the Drift Chamber. The mean position of the interaction point, determined run by run using the  $e^+e^- \rightarrow e^+e^-$  events, has been compared with the reconstructed  $\pi^+\pi^-$  vertex. The difference between this two values has been computed run by run and the spread of the distribution is used for the systematic error on the determination of

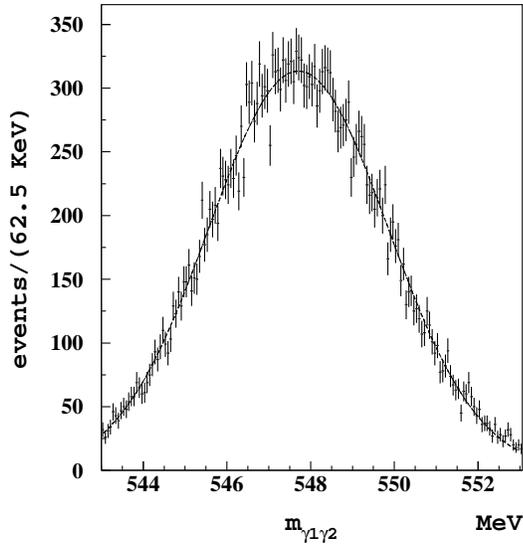


Figure 2. Invariant mass distribution of the  $\gamma_1\gamma_2$  pair. The fitted function is the continuous line.

the I.P mean position. Since the I.P position is determined with the tracks reconstructed in the Drift Chamber, small displacement between the DC and the calorimeter can affect position measurement of this point in the calorimeter reference frame. To check disalignment between the calorimeter and the Drift Chamber, the  $\pi^-$  and  $\pi^+$  tracks of the  $\pi^+, \pi^- \gamma$  events were extrapolated to the calorimeter and the closest approach point to the cluster centroid was determined. The difference in the position  $\vec{x}_{clu} - \vec{x}_{cst}$  were determined and the spread of these values are taken as systematic error on DC-Calo alignment. A small correction of 1.1 mm in the Calorimeter position along the  $y$  direction, the vertical, and 2 mm along the  $z$  direction (the direction of the beam axis) was applied.

The absolute energy scale of the calorimeter and the linearity of the energy response was checked using the  $e^+e^- \rightarrow e^+e^-\gamma$  events and the  $\pi^+\pi^-\gamma$  events. The energy of the  $\gamma$  can be determined using the two charged tracks in the Drift

Chamber and then compared to the reconstructed cluster energy. A linearity better than 2 % was found while the absolute scale was found to be calibrated at better than 1 %. These systematic uncertainties result in just 4 keV for the scale and 4 keV for the linearity on the value of the reconstructed mass. The measurement shows very small sensitivity to the calorimeter calibration because, as explained before, the kinematic fit over-constrains the photon energy with the cluster positions.

For this reason it is important to evaluate the systematic error due to the misalignment of single modules in the calorimeter. This has been done evaluating the value of the mass as a function of the position of the photons in the calorimeter. A spread of about 10-15 keV was found and assumed as systematic error.

Systematics due to the particular choice of the cut on the Dalitz plot shown in fig.1 was also determined to be 12 keV, while the cut on the  $\chi^2$  practically doesn't have any effect on the value of the  $\eta$  mass (0.7 keV).

The measured value of the mass is, instead, very sensitive to the energy in the center of mass of the  $\eta\gamma$  system. Due to initial state radiation emission (ISR) the available center of mass energy is a bit lower than the  $\sqrt{s}$  of the  $e^+e^-$  beams measured using  $e^+e^- \rightarrow e^+e^-$  events. A variation of 100 keV of the measured mass value is predicted by the MC simulation. Since this correction is relatively large we have checked the simulation of ISR emission in the MC in the following way:

- the correction to apply to the fitted value in order to obtain the real value of the mass has been determined as a function of  $\sqrt{s}$  and shown in fig.3;
- the whole data taking has been divided in ranges of  $\sqrt{s}$  using 8 points for the on peak data and two off-peak points at 1017 MeV and 1022 MeV;
- the value of the mass obtained for each value of  $\sqrt{s}$  has been corrected according the MC prediction;
- the residual spread of these points has been

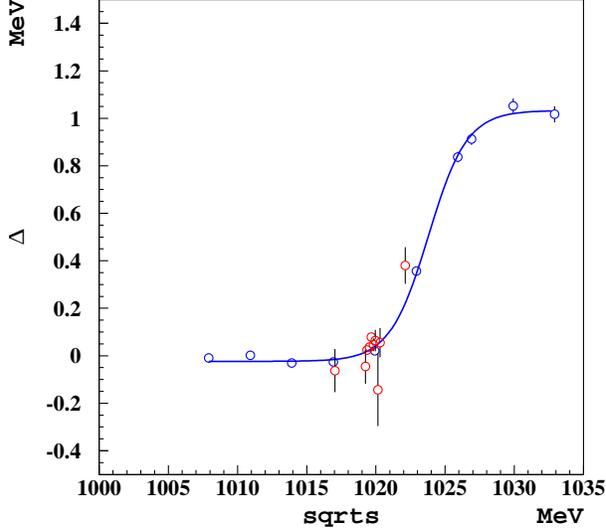


Figure 3. correction to the  $\eta$  mass evaluated by MC as a function of  $\sqrt{s}$ . Points without error bars: MC; continuous line: fitted curve to the MC points; points with error bars: DATA.

taken as systematic error (8 keV) (see fig. 4).

All these studies have been done also for the  $\pi^0$  mass using the  $\phi \rightarrow \pi^0\gamma$  events. The ratio of the two masses  $r = m_\eta/m_{\pi^0}$  has also been studied. All the contributions to the systematic error are summarized in table 1.

Finally stability versus run conditions are checked dividing the whole period of DATA taking 2001-2002 in 8 sub-periods and determining the value of  $m_{\pi^0}$ ,  $m_\eta$  and  $m_\eta/m_{\pi^0}$  as a function of the acquisition period. The results are shown in fig. 5.

The values shown in the figure have been fitted with a constant and the results of the fits are shown in tab. 2.

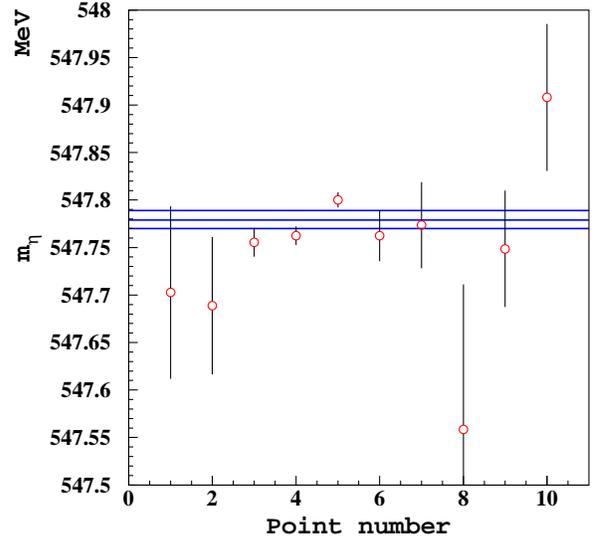


Figure 4.  $m_\eta$  as a function of  $\sqrt{s}$  after the ISR correction. The middle line is the mean value while the two line above and below are  $\pm 1\sigma$  systematic.

Fit results				
	Value	Error	$\chi^2/n.d.f$	C.L
$m_\eta$	547791 keV	7 keV	6.9/7	45%
$m_{\pi^0}$	134886 keV	12 keV	7.7/7	34%
$m_\eta/m_\pi$	4.0610	0.0004	8.9/7	26%

Table 2  
Fit results to the 8 data points.

systematic effect	$m_\eta$ (keV)	$m_{\pi^0}$ (keV)	$m_\eta/m_{\pi^0} \times 10^{-5}$
Calorimeter energy scale	4	1	5.6
Calorimeter not linearity	4	11	31
Vertex position	4	6	19
Angular uniformity $\phi$	15	12	37
Angular uniformity $\theta$	10	44	120
ISR effect	8	9	28
Dalitz plot cut slope	12	4	15
Dalitz plot cut constant	12	1.9	10
$\chi^2$ cut	0.7	4	13
<b>overall</b>	27	49	136

Table 1

Summary of all evaluated systematic effects. The Dalitz plot slope and constant refers to the change of slope or intercept of the stright line cut in fig. 1.

## 5. Computation of the final result.

We have two different ways to extract the value of the  $\eta$  mass. We can use the ratio  $m_\eta/m_{\pi^0}$  obtaining:

$$\frac{m_\eta}{m_{\pi^0}} = 4.0610 \pm 0.0004(\text{stat.}) \pm 0.0014(\text{syst.})$$

from which using the PDG2006 [7] value of the  $\pi^0$  mass ( $m_{\pi^0} = 134976.6 \pm 0.6$  keV) we obtain:  $m_\eta = 548140 \pm 50(\text{stat.}) \pm 190(\text{syst.})$  keV.

Alternatively we can use directly the value of  $m_\eta$  coming from the fit. For this purpose we need to calibrate the  $\sqrt{s}$  with high precision ( $m_\eta/m_{\pi^0}$  is in fact  $\sqrt{s}$  independent while the two values of  $m_\eta$  and  $m_{\pi^0}$  are fully correlated with the  $\sqrt{s}$  measurement). The absolute  $\sqrt{s}$  scale has been calibrated using the  $m_\phi$  value measured by CMD-2 [8]. To this purpose the cross section  $e^+e^- \rightarrow \phi \rightarrow K_S K_L$  has been measured as a function of the  $\sqrt{s}$  using the two off-peak points at  $\sqrt{s} = 1017$  MeV and  $\sqrt{s} = 1022$  MeV together with the on-peak data. The  $\phi$  resonance curve has been fitted using the CMD-2 parametrization that takes in account ISR and threshold effect in  $K_S K_L$  production. The central value of the  $\phi$  mass has been measured obtaining  $m_\phi = 1019.329 \pm 0.011$  MeV [9]. The difference respect to the CMD-2 value  $m_{\phi \text{ CMD-2}} = 1019.483 \pm 0.011_{\text{stat.}} \pm 0.025_{\text{syst.}}$  sets our absolute  $\sqrt{s}$  calibration.

This means that our measurements can be regarded as a measurement of the ratio

$m_\eta/m_{\phi \text{ CMD2}}$  and  $m_{\pi^0}/m_{\phi \text{ CMD2}}$ :

$$\begin{aligned} m_\eta/m_{\phi \text{ CMD2}} &= 0.537403 \pm 0.000007(\text{stat.}) \\ &\pm 0.000026(\text{syst.}) \pm 0.000006(m_\phi \text{ stat.}) \end{aligned}$$

and

$$\begin{aligned} m_{\pi^0}/m_{\phi \text{ CMD2}} &= 0.132328 \pm 0.000012(\text{stat.}) \\ &\pm 0.000048(\text{syst.}) \pm 0.000001(m_\phi \text{ stat.}) \end{aligned}$$

We can extract the  $\pi^0$  and  $\eta$  mass using the value of CMD-2  $m_\phi$  obtaining:

$$\begin{aligned} m_{\pi^0} &= 134.906 \pm 0.012(\text{stat.}) \pm 0.048(\text{syst.}) \text{ MeV} \\ m_\eta &= 547.873 \pm 0.007(\text{stat.}) \pm 0.031(\text{syst.}) \text{ MeV} \end{aligned}$$

where the statistical and sytematic error have been independently summed in quadrature.

The  $\pi^0$  mass is in agreement at  $1.4\sigma$  level with the PDG06 value, validating the whole procedure.

The value of the  $\eta$  mass obtained here has been compared with the previous measurements in fig. 6. This result confirms the measured value of the NA48 at  $0.6\sigma$ , with an error reduced by a factor 2 and is  $11\sigma$  away from the GEM result, it is also compatible, at  $1.4\sigma$  level, with less accurate CLEO result [10].

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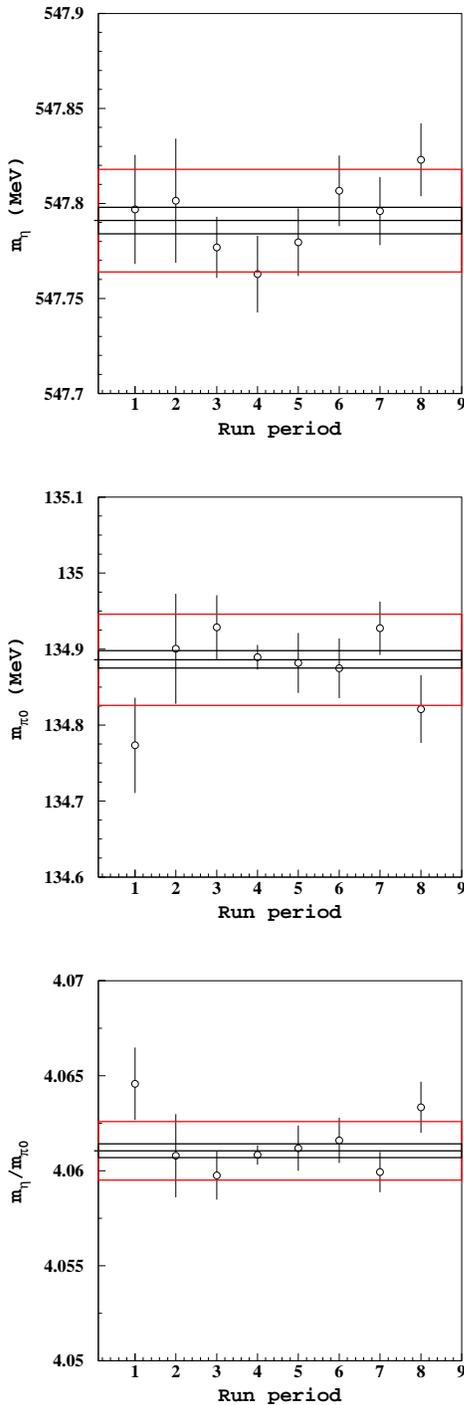


Figure 5. From top to bottom: values of the  $m_\eta$ ,  $m_{\pi^0}$  and  $r$  as a function of the data acquisition periods. The mean line is the fitted value to a constant plus a linear term with statistical errors.

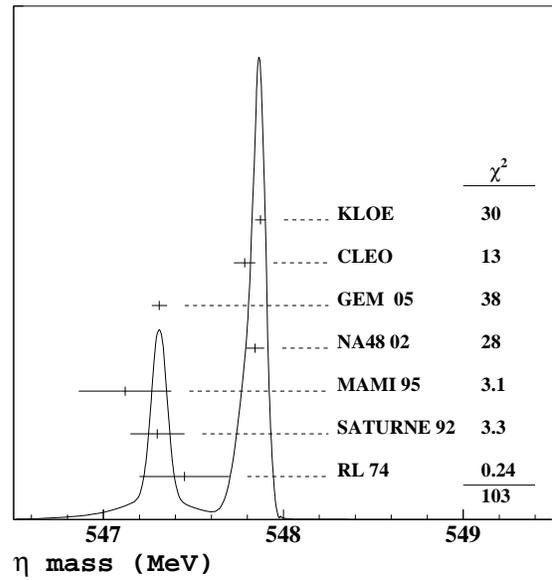


Figure 6.  $\eta$  mass measurements, see text for the references. The continuous line has been computed using the PDG procedure [7], pag. 14.

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