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Precise Measurement of the η and K^0 Masses

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Abstract

New measurements of the η and K^0 masses have been performed using decays into $3\pi^0$ with the NA48 detector at the CERN SPS. Using symmetric decays to reduce systematic effects, the results $M(\eta) = 547.843 \pm 0.051$ MeV/c^2 and $M(K^0) = 497.625 \pm 0.031$ MeV/c^2 were obtained.

1. Introduction

Precise values of the η and K^0 masses are often used as input for measurements, machine energy tuning or detector calibration. One such example is the measurement of the CP violation parameter ϵ'/ϵ performed by NA48 [1]. The current world average relative uncertainty [2] on the K^0 mass, $\pm 6 \times 10^{-5}$, is dominated by a measurement at a ϕ factory using $\pi^+\pi^-$ decays [3]. The η mass is less well known, the current uncertainty being $\pm 2 \times 10^{-4}$. So far the most precise estimates come from near-threshold measurements of the production cross sections for the reactions $dp \to \eta\,^3He$ [4] and $\gamma p \to \eta p$ [5]. In this paper, we present a new measurement of the η and K^0 masses using decays into $3\pi^0(\to 6\gamma)$, with the NA48 experiment at CERN SPS. The second section describes the method used for reconstruction, the experimental set-up and details of the electromagnetic calorimeter performances are described in the third section. Results and cross-checks are presented in the fourth section.

2. Method

NA48 collects K$_L$ and K$_S$ decays to charge or neutral pion pairs in order to measure the parameter

$$Re(\epsilon'/\epsilon) = \frac{1}{6} \times \left(\frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} : \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} - 1 \right)$$

with a precision at the level of a few 10^{-4}. The NA48 experimental set-up makes use of two quasi-collinear neutral beams (K$_L$ and K$_S$), a drift chamber to detect charged pions and an electromagnetic calorimeter [6], based on Krypton as active medium, to detect photons originating from π^0 decays. The desired accuracy is achieved if the response of the calorimeter is calibrated at the level of 10^{-4} in terms of absolute energy scale and non-linearities.

The large sample of K$_{e3}$ decays collected allows the performance of the calorimeter to be studied in detail by comparing the electron momentum (p), measured by the magnetic spectrometer, and the energy (E) measured by the calorimeter. The K$_{e3}$ method offers the advantage of collecting simultaneously calibration and ϵ'/ϵ data, but it implicitly assumes a 'perfect' spectrometer. An alternative method has been developed to get an auto-calibration of the calorimeter: special runs have been taken regularly where the K$_S$ beam is switched off and the K$_L$ beam replaced by a negatively charged particle beam impinging on two thin polyethylene targets (3.5 cm thick) placed at known positions near the beginning and towards the end of the fiducial kaon decay region. The negative beam consists mostly of π^- with a broad momentum spectrum of average energy ≈ 100 GeV, and a flux of $\approx 1.3 \times 10^6$ particles per pulse. A fraction of K^- is also present in the beam. The π^-/K^- mixture ($\pi^- : K^- = 10:1$) on the targets provides, through the charge exchange mechanism, short lifetime π^0 and η mesons decaying within the targets, and K^0 mesons as well. The π^0 and η meson decays into photon pairs are used to fix the calorimeter energy scale. In the limit of small opening angle, the distance d between the decay position and the calorimeter can be computed as

$$d = \frac{r_{12}}{M_{\pi^0,\eta}} \sqrt{E_1 E_2}$$

where $M_{\pi^0,\eta}$ is the π^0 or η mass, E_1, E_2 the energies of the two decay photons from a π^0 or an η and r_{12} is the distance between the two photons in the plane orthogonal to the beam axis at the calorimeter. Figure 1 shows the set-up used during the special runs and the reconstructed decay vertex distribution for the 2γ samples.

The sample $\eta \to 3\pi^0 \to 6\gamma$ allows a measurement of the η mass independent on the energy scale. Let i, j be the photon index running from 1 to 6 and a, b the index of the two photons originating from an intermediate pion; for each pion we have the following relation:

$$\left(\frac{M_\eta}{M_{\pi^0}}\right)^2 = \frac{\sum_{i,j<i} E_i E_j r_{ij}^2}{E_a E_b r_{ab}^2}.$$

From the above relation one can take the π^0 mass from the PDG[1] and compute the η mass for each intermediate pion and then take the average of the three values obtained. The advantages of using this method are the following:

- The $3\pi^0$ decay mode is virtually background free.
- Thanks to the π^0 mass constraint, the resolution on M_η is better than 1 MeV/c^2.
- The measured quantity is the η to π^0 mass ratio, in which the absolute energy scale cancels out. For the same reason, the absolute transverse size scale also cancels.
- The measurement is only sensitive to residual non-linearities in the energy or position measurements. In the limit in which 6 photons have the same energy

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[1] $M_{\pi^0} = 0.1349766 \pm 0.0000006$ GeV/c^2.

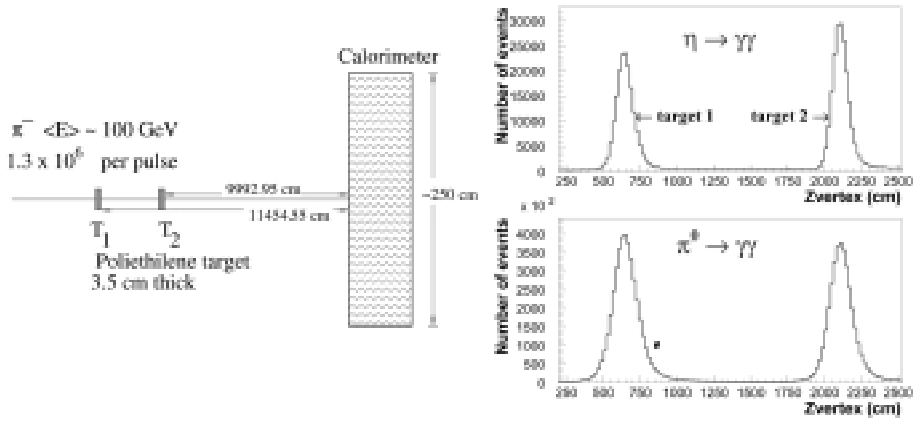

Fig. 1. Sketch of the special run set-up (left) and reconstructed decay vertex distributions.

(symmetric decay), the sensitivity to energy non-linearities also cancels.

- The same method can be applied to the $K^0 \rightarrow 2\pi^0$ or $K^0 \rightarrow 3\pi^0$ sample collected in ordinary ϵ'/ϵ or during special data taking runs, so that many systematic cross-checks can be performed to validate the measurement.

3. Trigger, data set and calorimeter performances

The trigger on multiphoton final states [7] is based on analogue sums of signals from 2×8 cells of the calorimeter in both horizontal and vertical orientations. Those signals, digitised and summed in x and y projections, are the inputs of the neutral trigger system. During the special runs, the $\eta \rightarrow 3\pi^0$ and $\pi^0, \eta \rightarrow 2\gamma$ samples are selected on-line by a cut on the total energy: events with energy above 90 GeV are taken without downscaling, the 15–40 GeV and 40–90 GeV windows are downscaled by suitable factors depending on the beam intensity. The $K_L \rightarrow 3\pi^0$ sample is taken during the ϵ'/ϵ run and is triggered by requiring the total energy to be more than 50 GeV and the radial position of the center of gravity to be less than 15 cm from the beam axis.

During the ϵ'/ϵ runs in 1998 and 1999, large statistics of K_{e3} decays were collected for studying the calorimeter performances. In the year 2000, the detector operated with vacuum in place of the spectrometer. During this period, data with only the K_L beam were taken, as well as data with the negatively charged beam. These data are used for the mass measurements presented here. More than 150×10^6 K_{e3} decays have been used to estimate the energy resolution by comparing the electron energy measured by the calorimeter and its momentum measured by the spectrometer, the resolution on the ratio E/p being $\approx 1\%$, unfolding the spectrometer resolution we obtain in the range 5–100 GeV:

$$\frac{\sigma(E)}{E} = \frac{(0.032 \pm 0.002)}{\sqrt{E}} \oplus \frac{(0.090 \pm 0.010)}{E} \oplus (0.0042 \pm 0.0005)$$

where E is the energy in GeV. The large amount of K_{e3} events has been used also to improve the cell-to-cell intercalibration. Residual non-uniformities have been corrected with the large statistics sample $\pi^0 \rightarrow 2\gamma$ taken during special runs by deriving suitable position dependent calibration factors, in order to keep the π^0 mass uniform over the full active surface of the detector. These procedures ended up with a uniformity at the level of 0.4%. The energy response is linear within about 0.1% in the 5–100 GeV range. Residual nonlinearities in the energy response can be parametrized as:

$$\frac{\Delta(E)}{E} = \frac{\alpha}{E} + \beta E + \gamma r \qquad (1)$$

where E is the photon energy and r the impact radius over the calorimeter. From the $\pi^0 \rightarrow 2\gamma$ data, α can be constrained to be ± 10 MeV, β can be bound to be within $\pm 2 \times 10^{-5}$ GeV^{-1} and γ within $\pm 10^{-5}\,\mathrm{cm}^{-1}$.

4. Results and cross-checks

The η and K_L decays into $3\pi^0$ are reconstructed by requiring 6 clusters in the calorimeter and selecting the best 6 photon pairings to the $3\pi^0$ mesons by minimizing a χ^2 like variable. To remove any residual background (like events with a π^0 Dalitz decay), a loose χ^2 cut is applied. This method selects the correct π^0 pairing in the 99.75% of the events. Therefore the residual bias on the mass result due to wrong pairing is completely negligible. The procedure selects 128×10^6 $K_L \rightarrow 3\pi^0$ candidates and 264×10^3 $\eta \rightarrow 3\pi^0$ in the data from the year 2000. In order to minimize the effects due to residual energy non-linearity, photons with comparable energy are selected by using the following cut:

$$0.7 < \frac{E_\gamma}{\frac{1}{6}E_{\mathrm{tot}}} < 1.3$$

where E_γ is the energy of the photon and E_{tot} is the sum of the six photon energies. This cut leaves a "symmetric" sample of 655×10^3 K_L and 1134 η and restricts the single photon energy to the range 8–37 GeV.

The distributions of the differences of the reconstructed η and K_L masses from the PDG values are shown in Fig. 2.

A shift of ≈ 500 keV, with respect to the PDG value, is evident in the η mass distribution. For K_L, on the contrary, we find a small difference of ≈ 30 keV. The main systematics for the symmetric decays are summarized in Table I.

- The uncertainties related to residual non-linearities have been estimated by changing the photon energy according to the parametrisation given in Eq. (1) and varying the parameters α and β within the bounds determined from the $\pi^0 \rightarrow 2\gamma$ data. If the symmetric cut on the photon energies is relaxed, the sensitivity increases at the level of ± 50 keV.

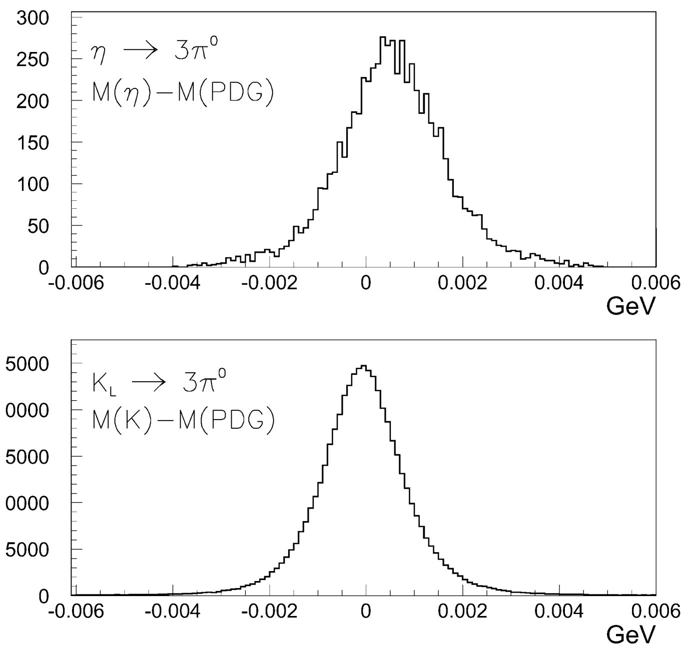

Fig. 2. Reconstructed masses from $3\pi^0$ decays of the η sample (top) and the K_L sample (bottom).

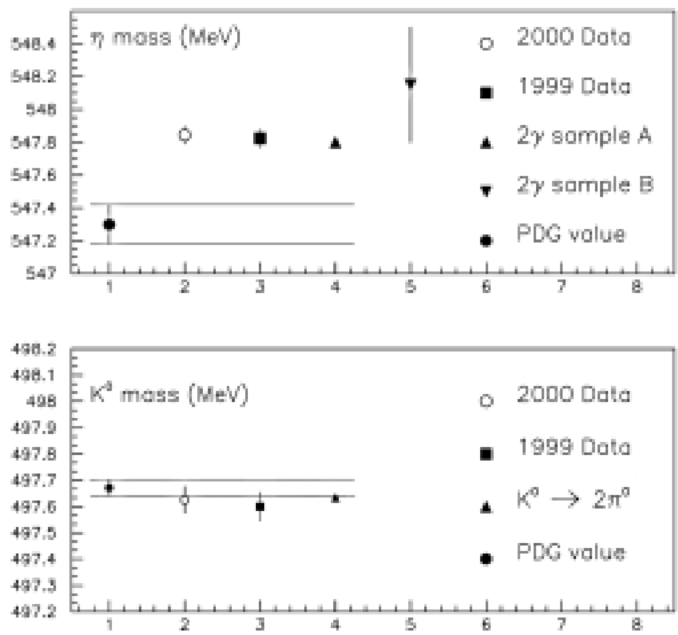

Fig. 3. Cross-checks on the η mass measurement (top) and on the K_L mass measurement (bottom).

Table I. *Summary of the main systematic uncertainties.*

Systematics-Symmetric decays (keV)		
Source	$\eta \to 3\pi^0$	$K_L \to 3\pi^0$
Non-linearities	± 2	± 2
Uniformity	± 23	± 23
Reconstruction	7 ± 5	4 ± 3
Non-Gaussian tail	± 2	± 2
Other	± 34	± 20

- The effect of non-uniformity in the calorimeter response has been estimated by switching off the $x - y$ dependent corrections to the energy derived from the K_{e3} and $\pi^0 \to 2\gamma$ data. The difference between the masses computed with or without those corrections is taken as 1-σ uncertainty.
- The uncertainty due to the reconstruction procedure has been estimated by simulation comparing the Monte-Carlo input mass with the reconstructed one.
- Non-Gaussian tails in the calorimeter response have been parametrised and the effect on the mass has been estimated from the simulation.
- Other error sources come from a bad measurement of the photon energy due to showers partially overlapping in the calorimeter, and uncertainties in the photon impact positions which can be studied with the K_{e3} sample. All these effects are corrected by a suitable set of corrections on the measured photon energy and the difference on the mass computed with or without those corrections is assumed as 1-σ uncertainty.

Combining the various contributions in quadrature, the total systematic error amounts to $\pm 41\,\mathrm{keV/c^2}$ for the η mass and $\pm 31\,\mathrm{keV/c^2}$ for the K^0 mass. Correcting the data for the small observed Monte-Carlo shift, the following values are thus obtained:

$$M_\eta = 547.843 \pm 0.030_{\mathrm{stat}} \pm 0.041_{\mathrm{syst}}\,\mathrm{MeV/c^2},$$

$$M_{K_L} = 497.625 \pm 0.001_{\mathrm{stat}} \pm 0.031_{\mathrm{syst}}\,\mathrm{MeV/c^2}.$$

Many cross checks of this measurement have been made. The stability of the reconstructed masses as a function of several variables has been investigated and found to be within the quoted systematic errors. The same value of the mass is found for η originating from either target. The value of the K_L mass has been found in agreement with a similar measurement performed with the $K^0 \to 2\pi^0$ sample available in special runs. The $\pi^0, \eta \to 2\gamma$ samples have been used to compute the ratio of the η mass to the π^0 mass. The selection has been done such as to have either (sample A) the same energy for η and π^0, but a different separation between the photons (by a factor 4 which is the mass ratio), or (sample B) the same distance between the two photons but then the energies differing by a factor 4. These two samples allow to disentangle effects due to shower overlap and non-linearities. All these cross-checks, including also the result of the same analysis based on the 1999 data, are compared with the main $3\pi^0$ analysis in Fig. 3.

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