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Precise measurement of the neutral kaon mass in $\phi \to K_S K_L$, $K_S \to \pi^+\pi^-$

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Abstract

The fact that the mass difference $M_\phi - 2M_K$ is very small (~26 MeV) allows us to make a very precise determination of the neutral kaon mass, once the overall mass scale has been fixed using the precisely known value of the ϕ mass. From the analysis of the 500 nb^{-1} of data collected during an energy scan around the ϕ peak, we obtain $M_K = 497.583 \pm 0.005$ (stat) $\pm\, 0.020$ (syst) MeV.

1 Introduction

The neutral kaon mass can be measured in KLOE using the process $\phi \to K_S K_L$, $K_S \to \pi^+\pi^-$, if the ϕ mass is used for calibration of the center-of-mass energy scale. Because of the small mass difference $\Delta M = M_\phi - 2M_K \sim 26$ MeV, it is particularly convenient to begin by expressing the center-of-mass energy, W, in terms of the kaon quantities: $W \sim E_{K_S} + E_{K_L} \sim 2E_K$ and $M_K^2 = W^2/4 - P_K^2$, therefore $\delta W/\delta M_K \sim 2$. The fractional uncertainties on M_K, $\delta M_K/M_K$, due to a fractional error on P_K, $\delta P_K/P_K$, is about $\beta^2 \sim \Delta M/M_K \sim 0.05$ times $\delta P_K/P_K$, allowing a high precision kaon mass measurement.

The center-of-mass energy W has been measured from the distribution of the e^+e^- invariant mass in Bhabha events. The calibration of W has been performed by comparing the ϕ mass obtained from a line-shape fit to the $e^+e^- \to \phi \to K_S K_L$ cross section with the value of the ϕ mass measured by CMD-2 [1] at VEPP-2M, where the energy is determined from resonant depolarization.

Initial state radiation (ISR), where one or both initial colliding particles radiate a photon before interacting, affects the available center-of-mass energy and therefore the final state invariant mass. ISR, which is mostly collinear to the beam, is in general not detected. In $\phi \to K_S K_L$ events, the center-of-mass energy is reduced by an amount $f_K(W)$ from the nominal value, W, to W_{KK}. The function $f_K(W)$ has been calculated by Monte Carlo simulation.

The measurement of the neutral kaon mass presented in this letter has been performed with the data collected by the KLOE detector at DAΦNE at center-of-mass energies ranging from 1015 to 1025 MeV, corresponding to an integrated luminosity of 500 nb^{-1}. Measurements of the neutral kaon mass have also been performed at VEPP-2M by CMD [2] and recently by NA48 [3] using symmetric $K_L \to \pi^0\pi^0\pi^0$ decays.

2 The KLOE detector

A thorough description of the KLOE detector can be found in Ref. [4,5]. Only a brief overview is given here. The KLOE detector consists of a large, cylindrical drift chamber surrounded by a lead-scintillating fiber sampling calorimeter. A superconducting coil outside the calorimeter provides a 0.52 T field. The drift chamber [6], 4 m in diameter and 3.3 m long, has 12 582 all-stereo sense wires and 37 746 aluminium field wires. The chamber shell is made of carbon fiber-epoxy composite and the gas used is a 90% helium, 10% isobutane mixture. These features maximize transparency to photons and reduce $K_L \to K_S$ regeneration. The position resolutions are $\sigma_{xy} \sim 150\,\mu$m and $\sigma_z \sim 2$mm. The momentum resolution is $\sigma(p_\perp)/p_\perp \le 0.4\%$. Vertices are reconstructed with a spatial resolution of $\sim$3mm.

The calorimeter [7], which is divided into a barrel and two endcaps, covers 98% of the solid angle. The energy resolution is $\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$ and the timing resolution is $\sigma_t = 54\mathrm{ps}/\sqrt{\mathrm{E(GeV)}} \oplus 50\mathrm{ps}$.

3 Analysis

The center-of-mass energy, W, has been measured for each run by fitting the e^+e^- invariant-mass distribution for Bhabha events to a Monte Carlo based function. Bhabha events were generated by using BABAYAGA [8], which accounts for both the final and the initial state radiation. An example of this fit is shown in figure 1.

In a typical run, 50 nb^{-1} of integrated luminosity are collected, and W is measured with a statistical precision of about 3 keV. To check the linearity of the W measurement, the stability of momentum calibration has been studied.

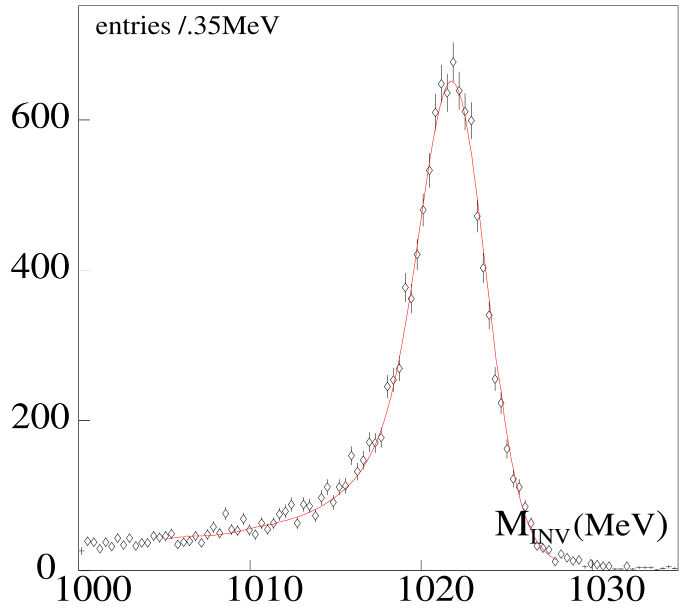

Fig. 1. Fit to reconstructed e^+e^- invariant-mass distribution for Bhabha events, for a run with W=1021.7 MeV

The two-pion invariant mass in $K_S \to \pi^+\pi^-$ decay is found to be stable to within 10 keV in the analyzed runs.

The center-of-mass energy scale has been calibrated by obtaining the ϕ mass from a fit to cross section measurements for the process $e^+e^- \to\phi \to K_S K_L$. The cross section is measured at different values of W around M_ϕ by counting the number of $K_S \to \pi^+\pi^-$ events, correcting for selection efficiency and background, and normalizing to the integrated luminosity. $K_S \to \pi^+\pi^-$ events are selected by requiring two tracks with opposite charge that form a vertex within a cylinder of 5 cm radius and 10 cm length centered on the interaction point. The invariant mass computed from the two pion tracks is required to be within 20 MeV/c^2 of the nominal neutral kaon mass. The luminosity is measured by using very-large-angle Bhabha events ($\theta \geq 55°$)

The measured cross section is fitted to a function [1] that depends on the ϕ parameters, takes into account the effects due to ISR, and includes the interference with the $\rho(770)$ and the $\omega(782)$ mesons. The ϕ mass, total width, and peak cross section are the only free parameters of the fit, the $\rho(770)$ and the $\omega(782)$ parameters being fixed. The results of the fit to the data are shown in Fig. 2. The fitted ϕ mass is $M_\phi = 1019.329 \pm 0.011$ MeV, to be compared with $M_\phi = 1019.483 \pm 0.011 \pm 0.025$ MeV, measured by CMD-2 at VEPP-2M [1] where the center-of-mass energy is measured with the resonant depolarization method. The ratio of these two values is used to fix the overall energy scale. The correction factor $M_\phi^{CMD}/M_\phi^{KLOE}$ is 1.00015, corresponding to a shift in the value of W of ~150 keV.

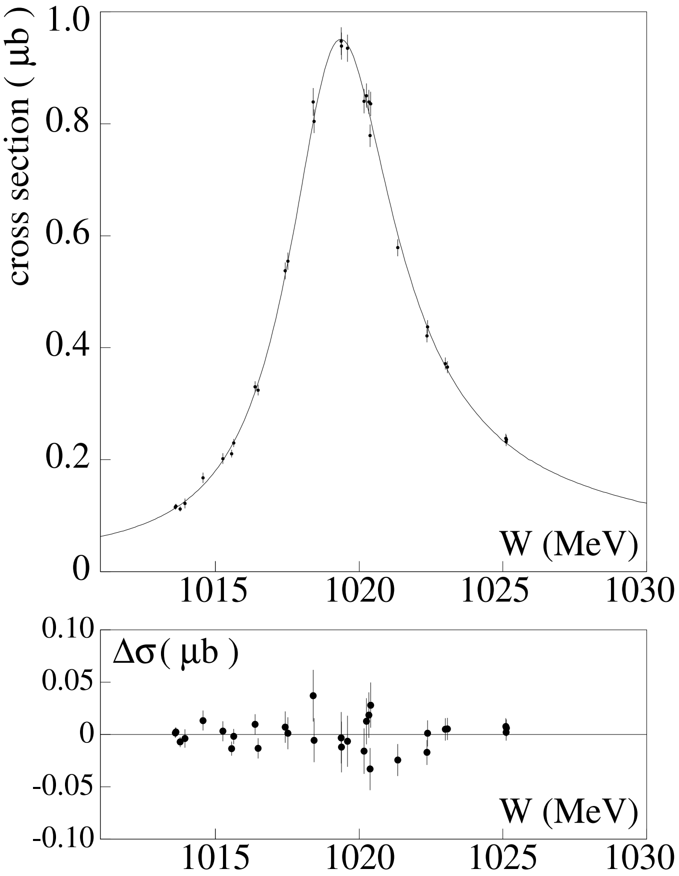

Fig. 2. Cross section for $e^+e^- \to \phi \to K_SK_L$ as a function of the center-of-mass energy. The solid line represents the fit to the data.

The peak value W_{KK}, measured from a gaussian fit to the K_SK_L invariant mass distribution, depends mainly on the value of the neutral kaon mass.

For each event, infact, the K_SK_L invariant mass is given by: $W_{KK} = (2M_K^2 + 2E_{K_S}E_{K_L} - 2\vec{P}_{K_S} \cdot \vec{P}_{K_L})^{1/2}$, where $\vec{P}_{K_S}$ is the K_S momentum obtained using pion tracks. $\vec{P}_{K_L} = \vec{P}_\phi - \vec{P}_{K_S}$ is determined using the average ϕ momentum value, $\vec{P}_\phi$, as measured in Bhabha events collected in the same runs. Typically we have $\vec{P}_\phi = (-12.5, 0., 0.)$ MeV/c.

Using the above relation for W_{KK} we can found a linear behavior between W_{KK} and M_K with a calibration factor of about 2.

Corrections due to ISR have to be taken into account in deriving the center-of-mass energy, W, from W_{KK}. The correction function $f_K(W)$, defined as above, has been evaluated using a full detector simulation where the radiation from both beams has been implemented, and W_{KK} is reconstructed as in the data. The expression of the radiator function has been taken from Ref. [9], including $\mathcal{O}(\alpha^2)$ corrections. The correction function is very small below the resonance, about 1.00004, corresponding to about 40 keV. It increases up to

1.0001 when W is above the resonance. In this region radiative return begins to be important. Figure 3 shows the $K_S K_L$ invariant mass distribution at a center-of-mass energy of 1025 MeV both for the data and the Monte Carlo.

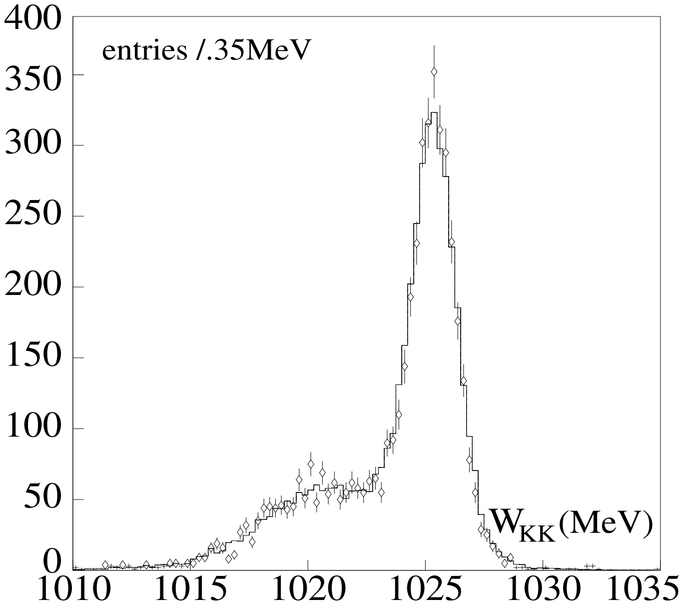

Fig. 3. W_{KK} distribution at $W \sim 1025$ MeV, for the data (dots with errors) and the Monte Carlo (solid histogram)

The radiative return events are concentrated at values around the ϕ mass causing a strong distortion of the $K_S K_L$ invariant mass distribution. Therfore, affecting the determination of W_{KK} for center-of-mass energies just above the ϕ peak.

The neutral kaon mass is obtained from the relation: $W = f_K(W) \cdot W_{KK}(M_K)$. The single event mass resolution is about 430 keV, as shown in Fig. 4. Contributions to the mass resolution are: experimental resolution about 370 keV, beam energy spread about 220 keV, as measured by KLOE (in agreement with machine theory), and ISR about 100 keV.

4 Result and systematic uncertainties

Mass values determined in each run are shown in figure 5 as a function of the center-of-mass energy. Only the statistical errors are shown. The result is seen to be stable as a function of the center of mass energy except just above the ϕ peak. This effect is related to the difficulty in fitting the $K_S K_L$ invariant mass distribution for center-of-mass energies just above the resonance where the presence of the radiative return to the ϕ causes a strong distortion to the $K_S K_L$ invariant mass distribution.

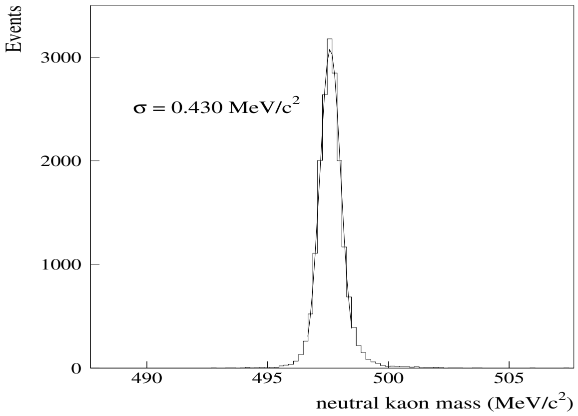

Fig. 4. Neutral kaon mass resolution.

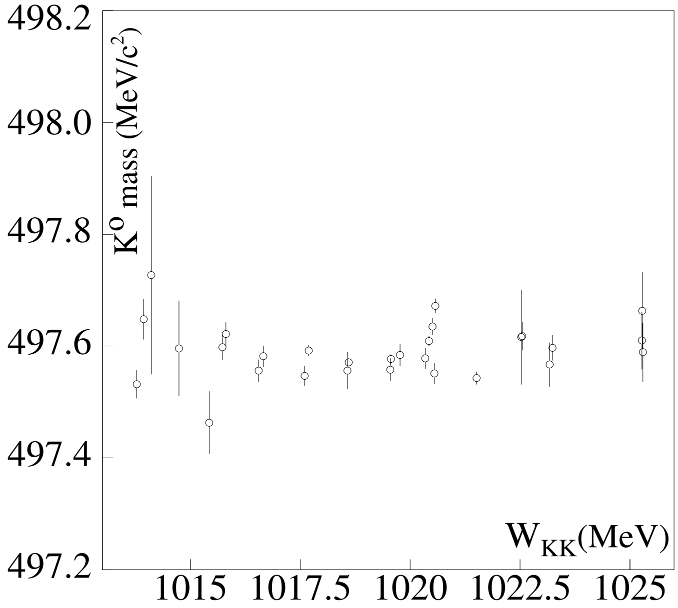

Fig. 5. Measured kaon mass run by run vs W

We therefore average only the measurements performed at $W < 1020$ MeV obtaining $M_K = 497.583 \pm 0.004$ MeV. The distribution of the values used in the calculation of this average is symmetric with a normalized RMS close to unity.

The systematic error due to the momentum calibration has been evaluated by changing the momentum scale in computing the pion momenta. A momentum miscalibration, $\delta P/P$, translate into 0.06 $\delta W_{KK}/W_{KK}$ in agreement with the qualitative calculation made in the introduction. The momentum scale is obtained by using several processes, covering a wide momentum range [50-500]MeV/c, ($K_L \to \pi^+\pi^-\pi^0$, $K_L \to \pi\ell\nu$, $\phi \to \pi^+\pi^-\pi^0$). A fractional accuracy of 2×10^{-4} is obtained traslating in a systematic error on M_K of 6 keV.

To asses the uncertainty due to the missing higher order terms in the radiator function, the correction factor $f_K(W)$ has been evaluated by excluding the constant terms in the $\mathcal{O}(\alpha^2)$. The relative change in the radiator amounts to 1.3 10^{-5} corresponding to a variation of 7 keV on the neutral kaon mass. A drastic change in this correction, i.e. putting $f_K(W) = 1$, increases the neutral kaon mass value of 20 keV. As additional prove we compare the average of the measurements with data collected at $W < 1020$ MeV with the one at $W > 1021$ MeV, where the value of $f_K(W)$ is more than a factor two larger. The difference between the two mass values is consistence with zero and yields $M_K(W < 1020) - M_K(W > 1021) = 9 \pm 10$ keV. Further checks have been made by using the radiator function given in Ref. [10]: no significant differences have been observed.

Other sources of systematics are due to the uncertainties on the W calibration, i.e., the statistic and systematic error on M_ϕ^{CMD-2} and on M_ϕ obtained from our fit. The total contribution from these sources amounts to a mass uncertainty of 15 keV, the largest effect. Systematic uncertainties are treated as uncorrelated.

The neutral kaon mass is found to be: $M_K = 497.583 \pm 0.005$ stat ± 0.020 syst MeV. The error has the same size as the one obtained by CMD[2] and by a recent NA48 analysis [3]. The three results are shown in figure 6.

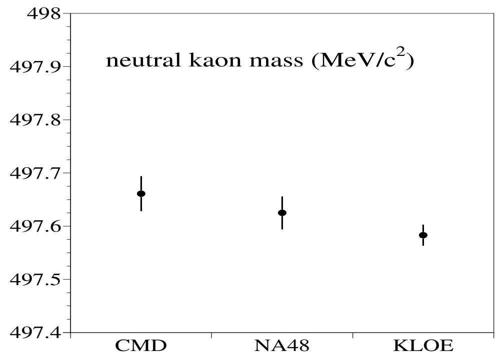

Fig. 6. Recent precise neutral kaon mass measurements

Conclusion

A measurement of the neutral kaon mass has been performed using the ϕ scan data collected in 2001. The center-of-mass energy has been calibrated from the line shape fit with the CMD-2 measurement of the ϕ mass. The value of the neutral kaon mass obtained with this method is:

$$M_K = 497.583 \pm 0.005 \text{ stat} \pm 0.020 \text{ syst} \quad \text{MeV}.$$

The error is dominated by the systematic uncertainties on the center-of-mass energy scale and on the correction applied to account for initial state radiation effects.

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