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Measurement of $\Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0)$

The KLOE Collaboration*

Abstract

We have measured the ratio $R_S^\pi = \Gamma(K_S \to \pi^+\pi^-(\gamma))/\Gamma(K_S \to \pi^0\pi^0)$ with the KLOE detector at the DAΦNE e^+e^- collider. This measurement is fully inclusive with respect to the $\pi^+\pi^-\gamma$ £nal state. The sample of over 10^6 two-pion decays of tagged K_S mesons allows a statistical error as low as $\sim 0.1\%$ to be obtained. The accuracy is limited by systematic uncertainties, which are estimated primarily from data. We £nd $R_S^\pi = 2.236 \pm 0.003_{\rm stat} \pm 0.015_{\rm syst}$.

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* The KLOE Collaboration

A. Aloisio[b], F. Ambrosino[b], A. Antonelli[d], M. Antonelli[d], C. Bacci[e], R. Baldini-Ferroli[d], G. Bencivenni[d], S. Bertolucci[d], C. Bini[g], C. Bloise[d], V. Bocci[g], F. Bossi[d], P. Branchini[e], S. A. Bulychjov[c], G. Cabibbo[g], R. Caloi[g], P. Campana[d], G. Capon[d], G. Carboni[a], M. Casarsa[f], V. Casavola[h], G. Cataldi[h], F. Ceradini[e], F. Cervelli[i], F. Cevenini[b], G. Chiefari[b], P. Ciambrone[d], S. Conetti[o], E. De Lucia[g], G. De Robertis[j], P. De Simone[d], G. De Zorzi[g], S. Dell'Agnello[d], A. Denig[d], A. Di Domenico[g], C. Di Donato[b], S. Di Falco[m], A. Doria[b], M. Dreucci[d], O. Erriquez[j], A. Farilla[e], G. Felici[d], A. Ferrari[e], M. L. Ferrer[d], G. Finocchiaro[d], C. Forti[h], A. Franceschi[d], P. Franzini[g], C. Gatti[i], P. Gauzzi[g], S. Giovannella[d], E. Gorini[h], F. Grancagnolo[h], E. Graziani[e], S. W. Han[d,k], M. Incagli[i], L. Ingrosso[d], W. Kluge[m], C. Kuo[m], V. Kulikov[c], F. Lacava[g], G. Lanfranchi[d], J. Lee-Franzini[d,l], D. Leone[g], F. Lu[d,k], M. Martemianov[m], M. Matsyuk[d,c], W. Mei[d], L. Merola[b], R. Messi[a], S. Miscetti[d], M. Moulson[d], S. Müller[m], F. Murtas[d], M. Napolitano[b], A. Nedosekin[d,c], F. Nguyen[e], M. Palutan[a], L. Paoluzi[a], E. Pasqualucci[g], L. Passalacqua[d], A. Passeri[e], V. Patera[n,d], E. Petrolo[g], G. Pirozzi[b], L. Pontecorvo[g], M. Primavera[h], F. Ruggieri[j], P. Santangelo[d], E. Santovetti[a], G. Saracino[b], R. D. Schamberger[l], B. Sciascia[d], A. Sciubba[n,d], F. Scuri[f], I. S£ligoi[d], T. Spadaro[d], E. Spiriti[e], G. L. Tong[d,k], L. Tortora[e], E. Valente[g], P. Valente[d], B. Valeriani[m], G. Venanzoni[i], S. Veneziano[g], A. Ventura[h], Y. Xu[d,k], Y. Yu[d,k]

[a] *Dipartimento di Fisica dell'UniversitÁ "Tor Vergata" e Sezione INFN, Roma, Italy*
[b] *Dipartimento di Scienze Fisiche dell'UniversitÁ "Federico Secondo" e Sezione INFN, Napoli, Italy*
[c] *Permanent address: Institute for Theoretical and Experimental Physics, Moscow, Russia*
[d] *Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy*
[e] *Dipartimento di Fisica dell'UniversitÁ "Roma Tre" e Sezione INFN, Roma, Italy*
[f] *Dipartimento di Fisica dell'UniversitÁ e Sezione INFN, Trieste, Italy*
[g] *Dipartimento di Fisica dell'UniversitÁ "La Sapienza" e Sezione INFN, Roma, Italy*
[h] *Dipartimento di Fisica dell'UniversitÁ e Sezione INFN, Lecce, Italy*
[i] *Dipartimento di Fisica dell'UniversitÁ e Sezione INFN, Pisa, Italy*
[j] *Dipartimento di Fisica dell'UniversitÁ e Sezione INFN, Bari, Italy*
[k] *Permanent address: Institute for High Energy Physics, CAS, Beijing, China*
[l] *Physics Department, State University of New York at Stony Brook, NY, USA*
[m] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany*
[n] *Dipartimento di Energetica dell'UniversitÁ "La Sapienza", Roma, Italy*
[o] *Physics Department, University of Virginia, Charlottesville, VA, USA.*

1 Introduction

The most recent measurement of $R_S^\pi = \Gamma(K_S \to \pi^+\pi^-)/\Gamma(K_S \to \pi^0\pi^0)$ dates back to 1976. The authors quote an accuracy of 4.3% [1]. This and other results of similar accuracy determine the current world-average value of R_S^π, 2.197 ± 0.026, the fractional error on which is 1.2%. Moreover, the averaging of the existing results is somewhat questionable, since the various experiments have not clearly described their procedures for handling radiative $\pi^+\pi^-\gamma$ decays. It is currently of interest to improve the accuracy on R_S^π, with particular attention to an accurate determination of what part of the radiative spectrum is included in the quoted result [2]. The validity of the $\Delta I = 1/2$ rule, empirically established in K, Λ, Σ, and Ξ decays, has never been satisfactorily understood. This lack of understanding is closely connected with the dif£culty in relating $\Re(\epsilon'/\epsilon)$ to the CKM matrix elements [3]. The value of R_S^π also enters into the theoretical calculation for the ratio of branching ratios for the decays $K_L \to \mu^+\mu^-$ and $K_L \to \pi^+\pi^-$ [4].

We describe the £rst measurement of R_S^π to achieve an accuracy below 1%, which moreover fully includes $\pi^+\pi^-\gamma$ radiative decays. This should allow the extraction of the isospin $I=0$ and $I=2$ decay amplitudes.

The data were collected with the KLOE [5,6] detector at DAΦNE, the Frascati ϕ-factory [7]. DAΦNE is an e^+e^- collider which operates at a center of mass energy of $\sim$1020 MeV, the mass of the ϕ-meson. In the following, we use a coordinate system with the z axis along the nominal beam line, the x axis in the horizontal plane toward the machine center, the y axis vertical, and the origin at the center of the collision region. Equal-energy positron and electron beams collide at an angle of 25 mrad, producing ϕ-mesons nearly at rest: $p(\phi)_{y,z} = 0$ and $p(\phi)_x = 12.5\,\mathrm{MeV}/c$. ϕ-mesons decay $\sim$34% of the time into nearly collinear $K^0\bar{K}^0$ pairs. Because $J^{PC}(\phi) = 1^{--}$, these pairs are in an antisymmetric state, so that the £nal state is always K_SK_L. Two photon intermediate states can lead to K_SK_S and K_LK_L £nal states, but this contamination is negligible [8,9]. All of the above implies that the detection of a K_L guarantees the presence of a K_S of given momentum and direction. This fact can be exploited to identify K_S-mesons independent of their decay mode. We refer to this technique as K_S *tagging*.

2 Experimental setup

The KLOE detector consists of a large cylindrical drift chamber, DC, surrounded by a lead-scintillating £ber sampling calorimeter, EMC. A superconducting coil surrounding the calorimeter provides a 0.52 T magnetic £eld.

The drift chamber [10], 4 m in diameter and 3.3 m long, has 12 582 all-stereo tung-

sten sense wires and 37 746 aluminum £eld wires. The chamber shell is made of carbon £ber-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 and multiple scattering. The position resolutions are $\sigma_{xy} \approx 150\,\mu$m and $\sigma_z \approx 2\,\mathrm{mm}$. The momentum resolution is $\sigma(p_\perp)/p_\perp \approx 0.4\%$. Vertices are reconstructed with a spatial resolution of $\approx 3\,\mathrm{mm}$.

The calorimeter [11] is divided into a barrel and two endcaps containing a total of 88 modules, and covers 98% of the solid angle. The modules are read out at both ends by photomultipliers. The arrival times of particles and the three-dimensional positions of the energy deposits are determined from the signals at the two ends. The readout granularity is $\sim\ 4.4 \times 4.4\,\mathrm{cm}^2$; the 2440 "cells" are arranged in layers £ve-deep. Cells close in time and space are grouped into a "calorimeter cluster." For each cluster, the energy E_{CL} is the sum of the cell energies, and the time t_{CL} and position $\vec{r}_{\mathrm{CL}}$ are calculated as energy-weighted averages over the £red cells. The energy and time resolutions are $\sigma_E/E = 5.7\%/\sqrt{E(\,\mathrm{GeV})}$ and $\sigma_t = 54\,\mathrm{ps}/\sqrt{E(\,\mathrm{GeV})} \oplus 50\,\mathrm{ps}$, respectively.

While the trigger [12] uses calorimeter and chamber information, only the calorimeter trigger, which requires two local energy deposits above threshold (50 MeV on the barrel and 150 MeV on the endcaps), is used for the present measurement. Recognition and rejection of cosmic-ray events are also performed at the trigger level. Events with two energy deposits above a 30 MeV threshold in the outermost calorimeter plane are identi£ed as cosmic-ray events and rejected. The trigger has a large time spread with respect to the beam crossing time. However, it is synchronized with the machine RF divided by 4, $T_{\mathrm{sync}} = 10.8\,\mathrm{ns}$, with an accuracy of 50 ps. The time T_0 of the bunch crossing producing an event is determined after event reconstruction.

3 K_S tagging

The mean decay lengths of the K_S and K_L are $\lambda_S \sim 0.6\,\mathrm{cm}$ and $\lambda_L \sim 350\,\mathrm{cm}$. About 50% of K_L's therefore reach the calorimeter before decaying. The K_L interaction in the calorimeter (K_L-*crash*) is identi£ed by requiring a cluster of energy above 200 MeV, which is not associated with any track, and whose time corresponds to a velocity $\beta = r_{\mathrm{CL}}/ct_{\mathrm{CL}}$ compatible with that of the K_L, $\beta(K_L) \sim 0.214$. These K_L-crash events are used for K_S tagging. The tagging ef£ciency depends slightly on the K_S decay mode: the ratio R_{tag} of the tagging ef£ciencies for $K_S \to \pi^+\pi^-$ and $K_S \to \pi^0\pi^0$ is determined from data.

The interaction time T_0, which must be known for the measurement of the cluster times, is obtained from the £rst particle reaching the calorimeter (pions or photons for the

events of interest) assuming a velocity $\beta = 1$. In order to reduce the probability that T_0 is accidentally determined from a particle arising from machine background, we require the T_0 to be £xed by a cluster with energy $E_{\rm CL} > 50\,{\rm MeV}$ and distance to the beam line $\rho_{\rm CL} > 60\,{\rm cm}$. Charged pions from $K_S \to \pi^+\pi^-$ arrive at the EMC $\sim 3\,{\rm ns}$ later than γ's from π^0 decays. The computed time T_0 is therefore delayed by one RF period, $\sim 2.7\,{\rm ns}$. This results in a mismeasurement of the velocity for long-lived kaons accompanied by $K_S \to \pi^+\pi^-$ decays. The distribution of the observed K_L velocity transformed to the ϕ-rest frame, β^*, is shown in Fig. 1. The effect of the incorrect T_0 assignment for the case of $K_S \to \pi^+\pi^-$ is evident. Events are selected by requiring $0.195 \leq \beta^* \leq 0.2475$. This

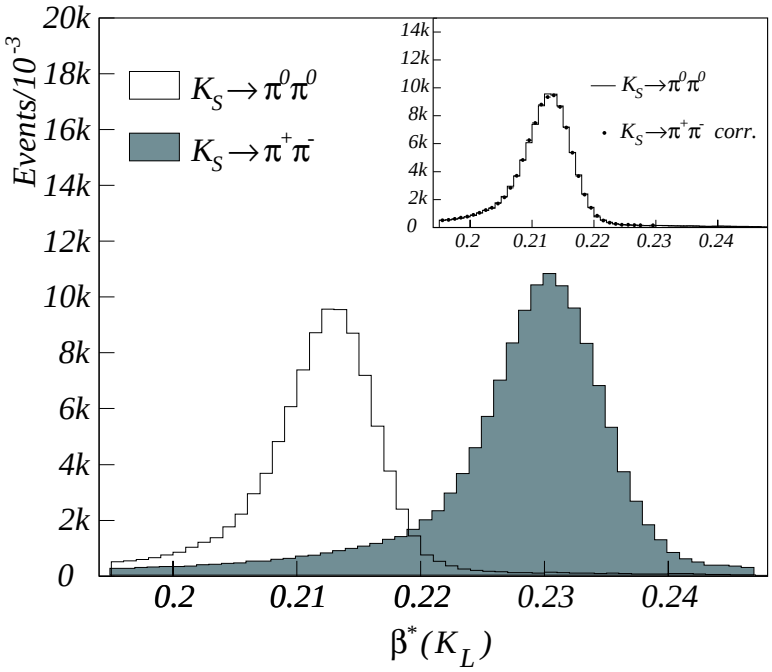

Figure 1: Distribution of the K_L velocity in the ϕ-rest frame, for $K_S \to \pi^0\pi^0$ (empty histogram) and $K_S \to \pi^+\pi^-$ (shaded histogram) events. In the inset, the distribution for T_0-corrected $K_S \to \pi^+\pi^-$ events (dots) is superimposed on that for $K_S \to \pi^0\pi^0$ events (line).

window in β^* encompasses both peaks and gives a tagging ef£ciency of $\sim 20\%$, which differs slightly for each of the two K_S decay modes. The ratio of tagging ef£ciencies $R_{\rm tag}$ is evaluated from a subsample of $K_S \to \pi^+\pi^-$ events in which both pion tracks are associated to a calorimeter cluster. In this case, the event T_0 can be correctly evaluated making use of the measured pion track lengths and velocities, resulting in the β^* spectrum shown in the inset of Fig. 1, which is very similar to that for $K_S \to \pi^0\pi^0$ events. This

corrected β^* distribution and that obtained from the standard T_0 estimate are normalized to the same number of K_L interactions. $R_{\rm tag}$ is computed from the ratio of the total number of events inside the β^* window in each of the two cases. The effects of residual differences between the β^* distributions for $K_S \to \pi^0\pi^0$ and T_0-corrected $K_S \to \pi^+\pi^-$ events are included in the determination of the systematic error.

Other sources of bias in the evaluation of $R_{\rm tag}$ have been taken into account as well. The probability that the event contains a cluster which determines T_0 is slightly different for $\pi^+\pi^-$ and $\pi^0\pi^0$ decays. These probabilities are estimated using K_S events tagged by $K_L \to \pi^+\pi^-\pi^0$ decays. For the identi£cation of such events, knowledge of T_0 is not necessary. These events are identi£ed by searching for two tracks forming a vertex in the drift chamber volume. The missing momentum of the π^0 is determined by kinematic closure at the K_L vertex. Photons from the π^0 are identi£ed using *the difference* between their times of ¤ight and by requiring that the $\gamma\gamma$ pair be back-to-back in the π^0 rest frame.

Accidental overlap of a $\pi^\pm$ track with the K_L cluster produces a loss of $K_S \to \pi^+\pi^-$ events. The magnitude of this effect has been estimated using K_L-crash events selected without requiring that the cluster not be associated with any track.

Finally, a small fraction of $\phi \to K_S K_L$ events is rejected by the cosmic-ray veto, since some K_L-crash interactions can deposit energy in the outermost EMC plane. $R_{\rm tag}$ is therefore corrected by the ratio of the ineff£ciencies induced by the cosmic-ray veto for $K_S \to \pi^+\pi^-$ and $K_S \to \pi^0\pi^0$ events. This ratio is obtained using a subsample of events for which the cosmic-ray veto was recorded but not enforced.

All of the above effects result in corrections to $R_{\rm tag}$, which are listed in Tab. 1. The largest uncertainty is due to the correction for the β^* cut.

4 Selection of $K_S \to \pi^+\pi^-$ events

$K_S \to \pi^+\pi^-(\gamma)$ events are selected by requiring the presence of two tracks of opposite charge that intersect a cylinder 4 cm in radius and 10 cm in length along the z-axis, centered at the interaction region (IR). Pion momenta and polar angles must satisfy the £ducial cuts $120 \le p \le 300\,{\rm MeV}/c$ and $30^\circ \le \theta \le 150^\circ$. Pions must also reach the EMC, as opposed to spiralling in the drift chamber. The requirement that both tracks reach the EMC results in an acceptance which depends on the energy of the photon in radiative decays. Fig. 2 shows the dependence of the ef£ciency $\epsilon_{\pi\pi\gamma}$ on the γ energy in the K_S rest frame E^*_γ, obtained by Monte Carlo (MC) simulation for $K_S \to \pi^+\pi^-\gamma$ events with $E^*_\gamma > 20\,$MeV and $K_S \to \pi^+\pi^-$ events without radiation ($E^*_\gamma = 0$). The ef£ciency for $0 < E^*_\gamma < 20\,{\rm MeV}$ is obtained by linear interpolation. The overall acceptance is obtained by folding the above ef£ciency with the photon spectrum from Ref. [2]. The result differs

from that computed assuming no radiation by $\sim 0.3\%$.

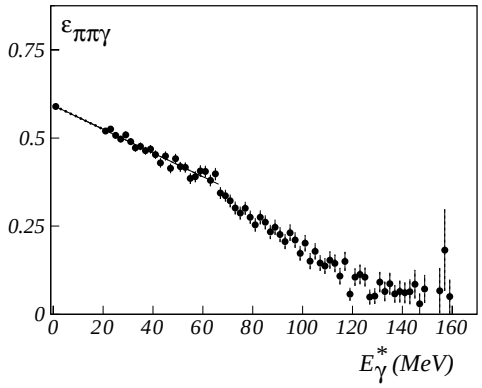

Figure 2: Ef£ciency for $K_S \to \pi^+\pi^-\gamma$ events vs radiated energy in the K_S rest frame E^*_γ, from Monte Carlo simulation.

The single-track reconstruction ef£ciency is obtained in bins of (p, θ) using $K_S \to \pi^+\pi^-$ events identi£ed by a single reconstructed pion track. This selection is applied to both data and MC. The ratio of data and MC reconstruction ef£ciencies is found to be constant (0.990 ± 0.001) for pions with momenta and polar angles the satisfy the £ducial cuts used in the analysis. The overall MC acceptance is therefore scaled accordingly and used to correct the data. Systematic errors due to possible misalignments of the DC are evaluated by studying the dependence of the acceptance on the angular cut applied and are found to be negligible. The acceptance is listed in Tab. 1.

The trigger ef£ciency is also obtained from data. K_L interactions always £re at least one trigger sector. About 40% of the time, however, the K_L-crash £res two nearby sectors, thus producing a valid trigger by itself. We use these events to £nd the probability that at least one K_S decay product complements the K_L-crash cluster to satisfy the trigger condition in the remaining 60% of the events. The trigger ef£ciency is given in Tab. 1.

5 Selection of $K_S \to \pi^0\pi^0$ events

$K_S \to \pi^0\pi^0$ events are identi£ed by the prompt photon clusters from π^0 decays. A prompt photon cluster must satisfy $|t_{\rm CL} - r_{\rm CL}/c| \leq 5\sigma_t$, where σ_t is the energy-dependent time resolution, and must not be associable to any track. Machine background is reduced by cuts on energy and polar angle; we require $E_{\rm CL} > 20\,{\rm MeV}$ and $\cos\theta < 0.9$. Three or more prompt photons are required to accept a $K_S \to \pi^0\pi^0$ event.

The photon-detection ef£ciency in bins of energy and polar angle has been obtained from data using a sample of $\phi \to \pi^+\pi^-\pi^0$ events. The acceptance for $K_S \to \pi^0\pi^0$ events

is obtained from MC simulation and is listed in Tab. 1. The simulation incorporates the experimentally determined photon-detection ef£ciencies; we rely on it essentially for the averaging over event geometries and kinematics. The 0.2% error on the $K_S \to \pi^0\pi^0$ selection ef£ciency is dominated by the uncertainty in the photon-detection ef£ciency below 50 MeV due to non-linearity in the energy response of the calorimeter and/or the photon reconstruction algorithm. The trigger ef£ciency, also listed in Tab. 1, is evaluated by the same method used for $K_S \to \pi^+\pi^-$ events.

Background in the sample of $K_S \to \pi^0\pi^0$ events is mainly due to $K_S \to \pi^+\pi^-$ events in which the track-to-cluster association failed, and in which there were residual split and accidental clusters. This contamination induces an error on the counting of events with three or more prompt clusters that is lower than 0.1%, as estimated directly from data.

Source	$R_{\rm tag}$
β^* window	0.986 ± 0.005
T_0 ef£ciency	0.990 ± 0.001
Track-cluster association	0.998 ± 0.002
Cosmic-ray veto	1.003 ± 0.002
Total	0.977 ± 0.005
	$\epsilon(\pi^+\pi^-)$
Event selection	0.5760 ± 0.0015
Trigger	0.989 ± 0.001
Total	0.5697 ± 0.0016
	$\epsilon(\pi^0\pi^0)$
Event selection	0.9005 ± 0.0018
Trigger	0.9986 ± 0.0004
Total	0.8992 ± 0.0018

Table 1: The analysis steps are listed, together with the associated ef£ciencies.

6 Result

The present measurement of R_S^π is based on an integrated luminosity of $17\,\mathrm{pb}^{-1}$ collected during the year 2000. The data set contains $N^{\pm} = 1\,060\,821$ selected $K_S \to \pi^+\pi^-$ events and $N^{00} = 766\,308$ selected $K_S \to \pi^0\pi^0$ events. The value for R_S^π is obtained by correcting the ratio of these numbers for the ratio of tagging and selection (including trigger)

ef£ciencies:

$$R_S^\pi = \frac{N^\pm}{N^{00}} \times \frac{1}{R_{\rm tag}} \times \frac{\epsilon_{\rm sele}^{00}}{\epsilon_{\rm sele}^{\pm}}$$

The result is

$$2.236 \pm 0.003_{\rm stat} \pm 0.015_{\rm syst}$$

The contributions to the estimated errors are listed in Tab. 2. Additional details are available in Ref. [13]. Our result is consistent with but slightly higher than the current world-average value $R_S^\pi = 2.197 \pm 0.026$ [14]. This might be expected, since our measurement was designed to include the entire radiative spectrum.

Source	Error, %
Event count	0.14
Tracking	0.26
Cluster counting	0.20
Trigger	0.10
Ratio of tag ef£ciencies	0.55
Cosmic-ray veto	0.21
Total error	0.70

Table 2: Contributions to the fractional error on R_S^π.

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