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A new measurement of the branching ratio of $K_S \rightarrow \gamma\gamma$

A. Lai, D. Marras

Dipartimento di Fisica dell'Università e Sezione INFN di Cagliari, I-09100 Cagliari, Italy

A. Bevan, R.S. Dosanjh, T.J. Gershon, B. Hay[1], G.E. Kalmus, C. Lazzeroni, D.J. Munday, E. Olaiya, M.A. Parker, T.O. White, S.A. Wotton

Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, UK[2]

G. Barr, G. Bocquet, A. Ceccucci, T. Cuhadar-Dönszelmann, D. Cundy[*], G. D'Agostini, N. Doble, V. Falaleev, L. Gatignon, A. Gonidec, B. Gorini, G. Govi, P. Grafström, W. Kubischta, A. Lacourt, M. Lenti[3], I. Mikulec[4], A. Norton, S. Palestini, B. Panzer-Steindel, G. Tatishvili[5], H. Taureg, M. Velasco, H. Wahl

CERN, CH-1211 Genève 23, Switzerland

C. Cheshkov, A. Gaponenko, P. Hristov, V. Kekelidze, D. Madigojine, N. Molokanova, Yu. Potrebenikov, A. Tkatchev, A. Zinchenko

Joint Institute for Nuclear Research, Dubna, Russian Federation

I. Knowles, V. Martin, R. Sacco, A. Walker

Department of Physics and Astronomy, University of Edinburgh, JCMB King's Buildings, Mayfield Road, Edinburgh, EH9 3JZ, UK

M. Contalbrigo, P. Dalpiaz, J. Duclos, P.L. Frabetti, A. Gianoli, M. Martini, F. Petrucci, M. Savrié

Dipartimento di Fisica dell'Università e Sezione INFN di Ferrara, I-44100 Ferrara, Italy

A. Bizzeti[6], M. Calvetti, G. Collazuol, G. Graziani, E. Iacopini, F. Martelli[7], M. Veltri[7]

Dipartimento di Fisica dell'Università e Sezione INFN di Firenze, I-50125 Firenze, Italy

H.G. Becker, M. Eppard, H. Fox, K. Holtz, A. Kalter, K. Kleinknecht, U. Koch, L. Köpke, P. Lopes da Silva, P. Marouelli, I. Pellmann, A. Peters, B. Renk, S.A. Schmidt, V. Schönharting, Y. Schué, R. Wanke, A. Winhart, M. Wittgen

Institut für Physik, Universität Mainz, D-55099 Mainz, Germany[8]

J.C. Chollet, L. Fayard, L. Iconomidou-Fayard, J. Ocariz, G. Unal, I. Wingerter-Seez

Laboratoire de l'Accélératur Linéaire, IN2P3-CNRS, Université de Paris-Sud, 91406 Orsay, France[9]

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G. Anzivino, P. Cenci, E. Imbergamo, P. Lubrano, A. Mestvirishvili, A. Nappi, M. Pepe, M. Piccini

Dipartimento di Fisica dell'Università e Sezione INFN di Perugia, I-06100 Perugia, Italy

L. Bertanza, R. Carosi, R. Casali, C. Cerri, M. Cirilli, F. Costantini, R. Fantechi, S. Giudici, I. Mannelli, G. Pierazzini, M. Sozzi

Dipartimento di Fisica, Scuola Normale Superiore e Sezione INFN di Pisa, I-56100 Pisa, Italy

J.B. Cheze, J. Cogan, M. De Beer, P. Debu, A. Formica, R. Granier de Cassagnac, E. Mazzucato, B. Peyaud, R. Turlay, B. Vallage

DSM/DAPNIA — CEA Saclay, F-91191 Gif-sur-Yvette, France

M. Holder, A. Maier, M. Ziolkowski

Fachbereich Physik, Universität Siegen, D-57068 Siegen, Germany [10]

R. Arcidiacono, C. Biino, N. Cartiglia, R. Guida, F. Marchetto, E. Menichetti, N. Pastrone

Dipartimento di Fisica Sperimentale dell'Università e Sezione dell'INFN di Torino, I-10125 Torino, Italy

J. Nassalski, E. Rondio, M. Szleper, W. Wislicki, S. Wronka

Soltan Institute for Nuclear Studies, Laboratory for High Energy Physics, PL-00-681 Warsaw, Poland [11]

H. Dibon, G. Fischer, M. Jeitler, M. Markytan, G. Neuhofer, M. Pernicka, A. Taurok, L. Widhalm

Österreichische Akademie der Wissenschaften, Institut für Hochenergiephysik, A-1050 Wien, Austria [12]

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[*] Corresponding author.
E-mail address: don.cundy@cern.ch (D. Cundy).

[1] Present address: EP Division, CERN, 1211 Genève 23, Switzerland.

[2] Funded by the U.K. Particle Physics and Astronomy Research Council.

[3] On leave from Sezione INFN di Firenze, I-50125 Firenze, Italy.

[4] On leave from Österreichische Akademie der Wissenschaften, Institut für Hochenergiephysik, A-1050 Wien, Austria.

[5] On leave from Joint Institute for Nuclear Research, Dubna, 141980, Russian Federation.

[6] Dipartimento di Fisica dell'Università di Modena e Reggio Emilia, I-41100 Modena, Italy.

[7] Instituto di Fisica dell'Università di Urbino, I-61029 Urbino, Italy.

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Abstract

The decay rate of $K_S \to \gamma\gamma$ has been measured with the NA48 detector at the CERN SPS. A total of 149 $K_S \to \gamma\gamma$ events have been observed. The branching ratio is determined to be $(2.58 \pm 0.36(\text{stat}) \pm 0.22(\text{sys})) \times 10^{-6}$.

1. Introduction

The study of the decays $K_{S,L} \to \gamma\gamma$ and $K_{S,L} \to \pi^0\gamma\gamma$ is important for understanding the low energy hadron dynamics of Chiral Perturbation Theory (χPT), since they are sensitive to higher order loop effects [1]. At present only the K_L modes of these decays have been measured precisely. NA31 has measured a branching ratio of $K_S \to \gamma\gamma$ to be $(2.4 \pm 0.9) \times 10^{-6}$ [2], and $K_S \to \pi^0\gamma\gamma$ has not yet been observed. The decay $K_S \to \gamma\gamma$ is especially interesting because χPT predicts unambiguously that the branching ratio is 2.25×10^{-6}, with an error of less than 10% [3]. Hence a precision measurement of this mode is an important test of χPT. We report here an analysis of a data set collected with the NA48 detector taken in a short test run in 1999 using only a high intensity K_S beam.

2. Experimental set-up and data taking

The NA48 experiment is designed to measure direct CP violation in neutral kaon decays [4]. The K_S beam was produced on a 2 mm diameter, 400 mm long beryllium target by 450 GeV protons at a production angle of 4.2 mrad in the vertical plane. In this special high intensity K_S mode, the primary proton beam is attenuated and collimated to the desired intensity, far upstream of the K_S target. The target is followed by a sweeping magnet packed with tungsten-alloy inserts in which the protons not interacting in the target are absorbed, and by a 0.36 cm diameter collimator. The 1.5 m long collimator is followed successively by an anti counter (AKS), an 89 m long evacuated decay volume and by a helium filled tank which contains the drift chambers. The distance between the centre of the target and the end of the collimator is 6 m. Seven ring-shaped anti counters (AKL), surround the decay region and the helium tank in order to veto events in which photons miss the calorimeter.

In normal running the AKS is formed by a set of three scintillation counters preceded by an aligned 3 mm thick iridium crystal and is used to veto decays occurring upstream of its position. However, for this special K_S run, the iridium crystal was removed in order to reduce the hit rates in the detectors. The present analysis is based on the data recorded during a 2-day run in 1999 with a proton intensity of about $\sim 6 \times 10^9$ protons hitting the target during the 2.4 s long SPS spill. This is a factor of ~ 200 higher than the usual K_S beam, accompanying a K_L beam for the CP violation experiment [4]. The detector elements used for the present analysis are the following:

- A magnetic spectrometer is used to measure tracks of charged particles. It includes four drift chambers two upstream and two downstream of a dipole magnet whose magnetic field, directed vertically, produces a 265 MeV$/c$ transverse momentum kick. Each drift chamber is composed of four double planes with staggered wires to resolve left-right ambiguities. The wire orientations in the four views are horizontal, vertical and at ±45° with respect to the horizontal/vertical plane (only horizontal and vertical wires are read out in chamber 3). The average efficiency per plane is 99.5%.
- A liquid krypton calorimeter (LKr) [5] is used to measure energy position and timing of the electromagnetic showers initiated by photons (γ). About 20 t of liquid krypton at 121 K are used as an ionization detector. The high density of krypton with its small Molière radius (6.1 cm) provides a good separation of electromagnetic showers. The calorimeter has a structure of $\sim$13000 square towers of 2×2 cm^2 cross section and 127 cm length (27 radiation length) each. The cells are formed by copper–beryllium ribbons, 1.8 cm wide and 40 μm thick, stretched longitudinally. The ionization signal from each of the cells is integrated, ampli-

fied, shaped, and digitized by 10-bit FADCs at 40 MHz sampling frequency. The energy resolution is

$$\sigma(E)/E \simeq 0.100/E \oplus 0.032/\sqrt{E} \oplus 0.005, \qquad (1)$$

where E is in GeV. The read-out system was calibrated by a charge pulse injected every burst during data taking. The final calibration of the energy scale is fixed by the fit of the AKS position using the $K_S \rightarrow \pi^0\pi^0$ decays, collected during ϵ' running just preceding this, special high intensity K_S run. The position and time resolutions for a single photon are better than 1.3 mm and 300 ps, respectively, for energies greater than 20 GeV.

- A sampling hadron calorimeter composed of 48 steel plates, each 24 mm thick, interleaved with scintillator planes is designed to measure hadronic showers with a readout in horizontal and vertical projection.

A more complete description of the apparatus can be found elsewhere [6].

The trigger decision for $\gamma\gamma$ decays is based on quantities which are derived from the orthogonal projections of the energy deposit in the electromagnetic liquid krypton calorimeter [7]. The trigger required that the total deposited energy E_{tot} is larger than 50 GeV, the centre of gravity of the event, COG^{trig}, computed from the first moments of energy $M_{1,x}$ and $M_{1,y}$ of the projections,

$$\text{COG}^{\text{trig}} = \frac{\sqrt{M_{1,x}^2 + M_{1,y}^2}}{E_{\text{tot}}}, \qquad (2)$$

is smaller than 15 cm and that the longitudinal vertex position of the decay, $z_{\text{vertex}}^{\text{trig}}$, computed from second moments $M_{2,x}$ and $M_{2,y}$,

$$z_{\text{vertex}}^{\text{trig}} = z_{\text{LKr}} - \frac{\sqrt{E_{\text{tot}}(M_{2,x} + M_{2,y}) - (M_{1,x}^2 + M_{1,y}^2)}}{m_K}, \qquad (3)$$

is less than 15 m away from the collimator. In Eq. (3), z_{LKr} is the z coordinate of the LKr calorimeter with respect to the end of the collimator and m_K is the kaon mass. To improve the rejection power of the trigger an additional condition requiring not more than two energy peaks in both projections was introduced during the run. This condition decreased the trigger rate such that no down-scaling was needed and most of the data presented here were taken under this condition. The time window for energy peak counting was 20 ns. The main source of trigger inefficiency was therefore accidental showers. From the rate of accidental showers the limit on the trigger inefficiency is $< 1\%$.

A similar trigger as for $\gamma\gamma$ was set up for $3\pi^0$ decays, used in further analysis to independently determine the K_L component in the K_S beam. The only difference was the number of energy peaks requirement which was set to accept only more than four peaks in at least one of the two projections. In order to measure the efficiency of this trigger a minimum bias sample was triggered by a scintillating fibre hodoscope placed in the liquid krypton calorimeter. The rate of this control trigger was down-scaled by a factor of 100. This control trigger was also used to collect $2\pi^0$ decays, for normalisation of K_S and K_L flux. The efficiency of the hodoscope trigger for $2\pi^0$ decays was measured by using a reference sample triggered by the $\gamma\gamma$ trigger in the period in which the number of peaks cut was not yet applied.

3. Event selection

The energies and the position of the electromagnetic showers initiated by the photons are measured in the liquid krypton calorimeter and they are used to calculate the kaon energy and decay vertex. To select the $K \rightarrow \gamma\gamma$ candidates all events with $\geqslant 2$ energy clusters are considered. From these clusters, pairs of clusters are selected which are in time within 5 ns and have no other cluster with energy > 1.5 GeV closer in time than 3 ns with respect to the event time. The event time is computed from the times of the two most energetic cells of the selected clusters taking into account the energy dependent time resolution. In addition, the $\gamma\gamma$ pair must pass the following cuts:

- The energy of each cluster must be greater than 3 GeV and less than 100 GeV.
- The transverse distance between two clusters is required to be greater than 10 cm.
- The total energy of the selected cluster pair is required to be less than 170 GeV and to be greater than 60 GeV.

- The centre of gravity,

$$\mathrm{COG} = \frac{\sqrt{(\sum_i E_i x_i)^2 + (\sum_i E_i y_i)^2}}{\sum_i E_i}, \tag{4}$$

is required to be less than 7 cm, where E_i, x_i, y_i are the ith cluster energy, x and y coordinates in the LKr calorimeter, respectively.

- The energy deposited in the hadron calorimeter must not exceed 3 GeV in a time window of ±15 ns around the event time.
- Events with some activity in the AKS counter in a time window of ±3 ns are rejected.
- Events associated with an in time hit within ±20 ns in the drift chambers are rejected.
- Events with some activity in the AKL counters in a time window of ±3 ns are rejected.

In order to determine the K_S and K_L fluxes in the beam the decay $K_S \to \pi^0\pi^0$ has been used. Similar conditions as for $\gamma\gamma$ cluster pairs are applied to groups of 4 in time clusters. In addition a χ^2 cut of 27 ($\sim 5\sigma$) is applied to the invariant masses, m_1 and m_2 of the two $\gamma\gamma$ pairs having the smallest χ^2. For this, a χ^2 variable is defined as follows:

$$\chi^2 = \left[\frac{(m_1 + m_2)/2 - m_{\pi^0}}{\sigma_+}\right]^2 + \left[\frac{(m_1 - m_2)/2}{\sigma_-}\right]^2, \tag{5}$$

where $\sigma_\pm$ are the resolutions of $(m_1 \pm m_2)/2$ measured from the data and parametrised as a function of the lowest photon energy.

The decay vertex, z_{vertex}, of kaons decaying into photons or π^0's is calculated from

$$z_{\mathrm{vertex}} = z_{\mathrm{LKr}} - \frac{\sqrt{\sum_{i,j,i>j} E_i E_j [(x_i - x_j)^2 + (y_i - y_j)^2]}}{m_K}, \tag{6}$$

where $E_{i(j)}$, $x_{i(j)}$, $y_{i(j)}$ are the ith (jth) cluster energy, x and y coordinates in the LKr, respectively. The study of $K_S \to \gamma\gamma$ can only be carried out in a very restricted decay region. This is due to the large background which comes from $K_S \to \pi^0\pi^0$ decays. Kinematically, the maximum $\gamma\gamma$ mass from a $K_S \to \pi^0\pi^0$ decay is 458 MeV which would lead to an apparent vertex shift of 9 m. However because of overlapping showers, Monte Carlo calculations show that a decay region of 5 m downstream of the K_S collimator is almost background free. In order to remove events with overlapping showers an energy dependent shower width cut is applied to the $\gamma\gamma$ events. This cut, which is calibrated from showers in $K_S \to \pi^0\pi^0$ decay, discards $< 0.5\%$ of good $K \to \gamma\gamma$ events.

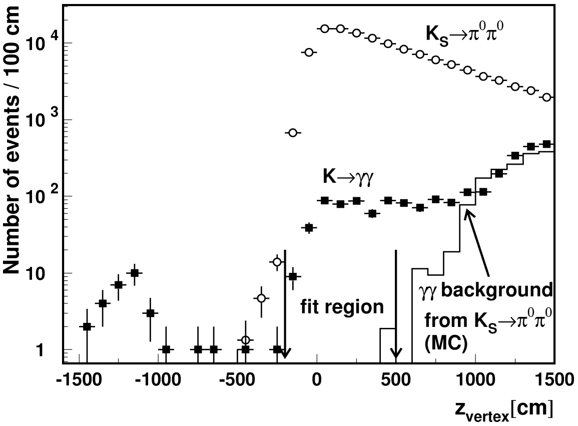

Fig. 1. The z_{vertex} distribution for data and MC. The open circles represent $K_S \to \pi^0\pi^0$ events while closed squares show $K \to \gamma\gamma$. The solid line shows the $\gamma\gamma$ background from MC simulated $K_S \to \pi^0\pi^0$ decays. The peak at $z = -1250$ cm is due to η mesons produced in the AKS.

After the cuts 450 $K \to \gamma\gamma$ events remain, along with 7.5×10^6 $K_S \to \pi^0\pi^0$ events. The vertex distribution of these events is shown in Fig. 1.

4. Determination of $K_S \to \gamma\gamma$ branching ratio

The number of $K \to \gamma\gamma$ events observed is made up of three components: (a) $K_S \to \gamma\gamma$ decays, (b) $K_L \to \gamma\gamma$ decays and (c) background.

As the $K_L \to \gamma\gamma$ branching ratio [8] is $(5.92 \pm 0.15) \times 10^{-4}$, it is only necessary to know the K_L flux in order to estimate this contribution. The K_L and K_S fluxes at the production target are equal. The K_S flux at the target has been determined using the observed $K_S \to \pi^0\pi^0$ events.

The number of K_S decays in the 5 m decay region at a given energy E is given by

$$N_{K_S}(E) = \frac{N_{2\pi^0}(E)}{\alpha_{2\pi^0}(E)\epsilon_{2\pi^0}(E)\mathrm{BR}(K_S \to \pi^0\pi^0)}, \tag{7}$$

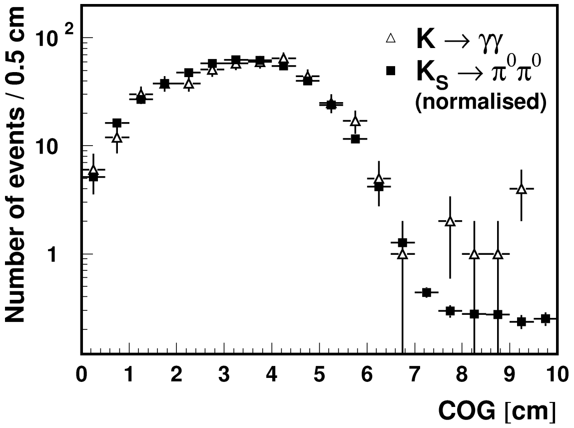

Fig. 2. The COG distribution for $K \to \gamma\gamma$ (open triangle) and $K_S \to \pi^0\pi^0$ (closed squares) events. The COG distribution of $K_S \to \pi^0\pi^0$ is normalised to that of $K \to \gamma\gamma$.

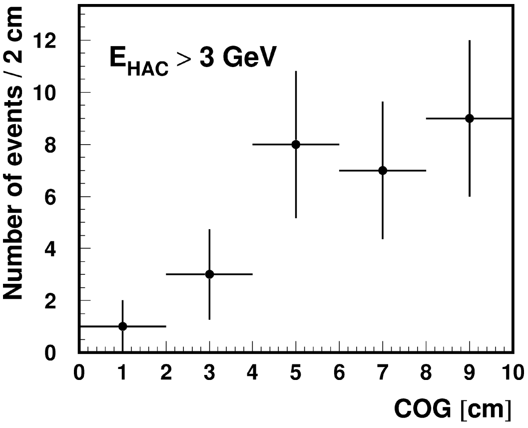

Fig. 3. The COG distribution of $\gamma\gamma$ events which deposit more than 3 GeV energy in the hadron calorimeter (HAC).

where $\alpha_{2\pi^0}$ is the $2\pi^0$ acceptance, $\epsilon_{2\pi^0}$ the trigger efficiency and $\mathrm{BR}(K_S \to \pi^0\pi^0) = (31.39 \pm 0.28)\%$ the $K_S \to \pi^0\pi^0$ branching ratio. $N_{2\pi^0}(E)$ is the number of $K_S \to \pi^0\pi^0$ decays observed in the fiducial region. The detector acceptances have been calculated using a Monte Carlo simulation, and have been corrected for Dalitz decays and photon conversions. The acceptances for $K_S \to \pi^0\pi^0$, $K_S \to \gamma\gamma$, and $K_L \to \gamma\gamma$ have mean values in the fiducial region of $(21.56 \pm 0.06)\%$, $(48.97 \pm 0.11)\%$, and $(43.52 \pm 0.17)\%$, respectively. The trigger efficiency for $K_S \to \pi^0\pi^0$ was determined to be $(96.0 \pm 1.2)\%$ and for $K_L \to \gamma\gamma$ to be $> 99\%$.

Using the K_S lifetime, the number of decays $N(E)$ in the fiducial region is then extrapolated back to the production target to determine the K_S and hence the K_L flux. The total number of K_S and K_L, with kaon energy $60 < E_K < 170$ GeV, produced at the target is found to be $(6.4 \pm 0.2) \times 10^8$. As a cross check this flux was calculated using a sample of ~ 14000 $K_L \to \pi^0\pi^0\pi^0$ decays and found to be $(6.1 \pm 0.4) \times 10^8$. In this case the error is dominated by the acceptance uncertainty.

The remaining background comes from two sources. The first is from $K_S \to \pi^0\pi^0$ decays with two undetected photons. This background has been estimated using a full detector simulation based on GEANT. On the basis of 10^8 simulated $K_S \to \pi^0\pi^0$ decays it is estimated that 2 ± 2 background events come from this source.

Evidence for a small remaining background of neutral hadronic origin is demonstrated by comparing the COG distributions of $K \to \gamma\gamma$ and $K_S \to \pi^0\pi^0$ as shown in Fig. 2.

The excess of $\gamma\gamma$ events with COG > 7 cm over that expected is 6 ± 3. In order to estimate this background, the COG distribution of $\gamma\gamma$ events in which energy deposit in the hadron calorimeter (HAC) is greater than 3 GeV (Fig. 3) is used to extrapolate this background to the signal region with COG < 7 cm. The background is estimated to be 11 ± 8 events.

A binned maximum likelihood method is used to measure the $K_S \to \gamma\gamma$ branching ratio by comparing the data to the expected rates in 11 kaon energy (60 GeV to 170 GeV) and 7 longitudinal vertex position (−2 m to 5 m) bins. The expected rates are derived from the computed flux, acceptances and background, leaving the branching ratio as a free parameter. The result of the fit is shown in Fig. 4. The obtained branching ratio,

$$\mathrm{BR}(K_S \to \gamma\gamma)$$
$$= \bigl(2.58 \pm 0.36(\mathrm{stat}) \pm 0.22(\mathrm{sys})\bigr) \times 10^{-6},$$

which is in good agreement with the theoretical prediction, corresponds to 149 ± 21 $K_S \to \gamma\gamma$ events.

The main contribution to the systematic error are:the uncertainty of branching ratio $\mathrm{BR}(K_L \to \gamma\gamma)$ (5%), the selection cuts (4%), background (5%), acceptance (2%), and the trigger efficiency (2%).

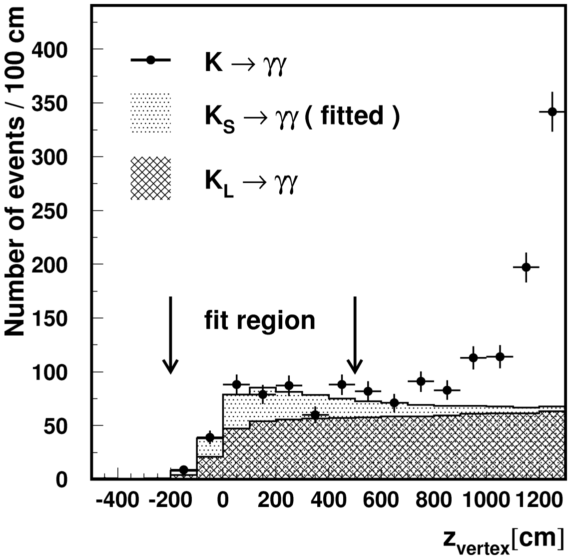

Fig. 4. The z_{vertex} distribution obtained from maximum likelihood method for fitted $K_S \to \gamma\gamma$ events (dotted area) and $K_L \to \gamma\gamma$ component (hatched area). The dots show the data and the arrows show the fitted region.

From this new measurement the ratio of the relative decay widths of $K_S \to \gamma\gamma$ to $K_L \to \gamma\gamma$ is determined to be

$$R = \frac{\Gamma(K_S \to \gamma\gamma)}{\Gamma(K_L \to \gamma\gamma)} = 2.53 \pm 0.35(\text{stat}) \pm 0.22(\text{sys}).$$

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