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# Measurement of the branching ratio of the $K_L \to \pi^+\pi^-$ decay with the KLOE detector

KLOE Collaboration

F. Ambrosino [e], A. Antonelli [b], M. Antonelli [b,*,1], C. Bacci [i], P. Beltrame [c], G. Bencivenni [b], S. Bertolucci [b], C. Bini [g], C. Bloise [b], V. Bocci [g], F. Bossi [b], D. Bowring [a], P. Branchini [i], R. Caloi [g], P. Campana [b], G. Capon [b], T. Capussela [e], F. Ceradini [i], S. Chi [b], G. Chiefari [e], P. Ciambrone [b], S. Conetti [a], E. De Lucia [b], A. De Santis [g], P. De Simone [b], G. De Zorzi [g], S. Dell'Agnello [b], A. Denig [c], A. Di Domenico [g], C. Di Donato [e], S. Di Falco [k], B. Di Micco [i], A. Doria [e], M. Dreucci [b], G. Felici [b], A. Ferrari [b], M.L. Ferrer [b], G. Finocchiaro [b], S. Fiore [g], C. Forti [b], P. Franzini [g], C. Gatti [b], P. Gauzzi [g], S. Giovannella [b], E. Gorini [d], E. Graziani [i], M. Incagli [k], W. Kluge [c], V. Kulikov [n], F. Lacava [g], G. Lanfranchi [b], J. Lee-Franzini [b,l], D. Leone [c], M. Martini [b], P. Massarotti [e], W. Mei [b], S. Meola [e], S. Miscetti [b], M. Moulson [b], S. Müller [c,b], F. Murtas [b], M. Napolitano [e], F. Nguyen [i], M. Palutan [b], E. Pasqualucci [g], A. Passeri [i], V. Patera [b,f], F. Perfetto [e], L. Pontecorvo [g], M. Primavera [d], P. Santangelo [b], E. Santovetti [h], G. Saracino [e], B. Sciascia [b], A. Sciubba [b,f], F. Scuri [k], I. Sfiligoi [b], A. Sibidanov [b,j], T. Spadaro [b], M. Testa [g,**], L. Tortora [i], P. Valente [b], B. Valeriani [c], G. Venanzoni [b], S. Veneziano [g], A. Ventura [d], R. Versaci [b], G. Xu [b,m]

[a] *Physics Department, University of Virginia, Charlottesville, VA, USA*
[b] *Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy*
[c] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany*
[d] *Dipartimento di Fisica dell'Università e Sezione INFN, Lecce, Italy*
[e] *Dipartimento di Scienze Fisiche dell'Università "Federico II" e Sezione INFN, Napoli, Italy*
[f] *Dipartimento di Energetica dell'Università "La Sapienza", Roma, Italy*
[g] *Dipartimento di Fisica dell'Università "La Sapienza" e Sezione INFN, 2, Piazzale Aldo Moro, 00185 Roma, Italy*
[h] *Dipartimento di Fisica dell'Università "Tor Vergata" e Sezione INFN, Roma, Italy*
[i] *Dipartimento di Fisica dell'Università "Roma Tre" e Sezione INFN, Roma, Italy*
[j] *Budker Institute of Nuclear Physics, Novosibirsk, Russia* [2]
[k] *Dipartimento di Fisica dell'Università e Sezione INFN, Pisa, Italy*
[l] *Physics Department, State University of New York at Stony Brook, NY, USA*
[m] *Institute of High Energy Physics, CAS, Beijing, China* [2]
[n] *Institute for Theoretical and Experimental Physics, Moscow, Russia* [2]

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* Corresponding author. Tel. +39 06 94032728.
** Corresponding author. Tel. +39 06 49914614.
*E-mail addresses:* mario.antonelli@lnf.infn.it (M. Antonelli), marianna.testa@roma1.infn.it (M. Testa).
[1] Mailing address: INFN–LNF, Casella postale 13, 00044 Frascati, Roma, Italy.
[2] Permanent address.


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**Abstract**

We present a measurement of the branching ratio of the CP violating decay $K_L \to \pi^+\pi^-$ performed by the KLOE experiment at the $\phi$ factory DAΦNE. We use 328 $\text{pb}^{-1}$ of data collected in 2001 and 2002, corresponding to $\sim 150$ million tagged $K_L$ mesons. We find $\text{BR}(K_L \to \pi^+\pi^-) = (1.963 \pm 0.012_{\text{stat.}} \pm 0.017_{\text{syst.}}) \times 10^{-3}$. This branching ratio measurement is fully inclusive of final-state radiation. Using the above result, we determine the modulus of the amplitude ratio $|\eta_{+-}|$ to be $(2.219 \pm 0.013) \times 10^{-3}$ and $|\epsilon|$ to be $(2.216 \pm 0.013) \times 10^{-3}$.


CP violation was discovered in 1964 through the observation of the decay $K_L \to \pi^+\pi^-$ [1]. The value of $\text{BR}(K_L \to \pi^+\pi^-)$ is known today with high accuracy from the results of many experiments, but a recent measurement by KTeV [2] is in disagreement with the value reported by the PDG [3]. In the Standard Model, CP violation is naturally accommodated by a phase in the quark mixing matrix [4,5]. $\text{BR}(K_L \to \pi^+\pi^-)$, together with the well-known values of $\text{BR}(K_S \to \pi^+\pi^-)$, $\tau_{K_S}$, and $\tau_{K_L}$, determines the modulus of the amplitude ratio $|\eta_{+-}| = \sqrt{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}$, which is related to the CP violation parameters $\epsilon$ and $\epsilon'$ by $\eta_{+-} = \epsilon + \epsilon' \simeq \epsilon$. The value of $|\epsilon|$ can thus be obtained and compared with the Standard Model calculation. In this Letter, we present a measurement of the branching ratio of the decay $K_L \to \pi^+\pi^-$ performed by the KLOE experiment at the $\phi$ factory DAΦNE.

The KLOE detector consists of a large, cylindrical drift chamber (DC), surrounded by a lead/scintillating-fiber electromagnetic calorimeter (EMC). A superconducting coil around the calorimeter provides a 0.52 T field. The drift chamber [6] is 4 m in diameter and 3.3 m long. The momentum resolution is $\sigma_{p_\perp}/p_\perp \approx 0.4\%$. Two-track vertices are reconstructed with a spatial resolution of $\sim 3$ mm. The calorimeter [7] is divided into a barrel and two endcaps. It covers 98% of the solid angle. Cells close in time and space are grouped into calorimeter clusters. The energy and time resolutions for photons of energy $E$ are $\sigma_E/E = 5.7\%/\sqrt{E\ (\text{GeV})}$ and $\sigma_t = 57\ \text{ps}/\sqrt{E\ (\text{GeV})} \oplus 100$ ps, respectively. For this analysis, events triggered [8] only by calorimeter signals are used. Two energy deposits above threshold ($E > 50$ MeV for the barrel and $E > 150$ MeV for the endcaps) are required.

For the present measurement, we use a subset of the data collected by KLOE during the years 2001 and 2002 that satisfies basic quality criteria [9]. The data used corresponds to an integrated luminosity of $\sim 328\ \text{pb}^{-1}$. Each run used in the analysis is simulated with the KLOE Monte Carlo program, GEANFI [10], using values of relevant machine parameters such as $\sqrt{s}$ and $\mathbf{p}_\phi$ as determined from data. Because of the small beam-crossing angle, $\phi$ mesons are produced at DAΦNE with a momentum of about of 12 MeV/$c$, toward the ring's center. Machine background obtained from data is superimposed on Monte Carlo events on a run-by-run basis. The number of events simulated for each run in the data set is equivalent to that expected on the basis of the run luminosity. For this analysis, we use a Monte Carlo sample consisting of $\phi \to K_S K_L$ events in which the $K_S$ and $K_L$ decay in accordance with their natural branching ratios. The effects of initial- and final-state radiation are included in the simulation. The treatment of final-state radiation in $K_S$ and $K_L$ decays follows the method discussed in Ref. [11]. In particular, the $K_L \to \pi^+\pi^-(\gamma)$ event generator includes the amplitudes for inner bremsstrahlung and direct emission. Good runs, and the corresponding Monte Carlo events, are organized into 14 periods. The branching ratio analysis is performed independently for each of these periods. The average over the 14 periods gives the final result.

At a $\phi$ factory, neutral kaons are produced through $\phi \to K_S K_L$ decays. A pure sample of $K_L$'s can be selected by identification of $K_S \to \pi^+\pi^-$ decays (tagging). The tagging efficiency depends slightly on the fate of the $K_L$: it is different for events in which the $K_L$ decays to each channel, interacts in the calorimeter, or escapes the detector. KLOE has already used the tag method to measure the dominant $K_L$ branching ratios and the $K_L$ lifetime [12]. The tagging criteria described in Ref. [12] where chosen to minimize the difference in the tagging efficiency among the various decay modes. In the present analysis, in order to increase the statistics, we employ a tagging algorithm with an efficiency of about a factor of seven larger than that used in Ref. [12].

A precise measurement of $\text{BR}(K_L \to \pi^+\pi^-)$ is obtained here by measuring the ratio $R = \text{BR}(K_L \to \pi^+\pi^-)/\text{BR}(K_L \to \pi^\pm\mu^\mp\nu)$ since the values of the tagging efficiency for $K_L \to \pi^+\pi^-$ and $K_L \to \pi\mu\nu$ are similar. The value of $\text{BR}(K_L \to \pi^+\pi^-)$ is finally obtained using the value of $\text{BR}(K_L \to \pi^\pm\mu^\mp\nu)$ from Ref. [12].

For $K_L$ tagging, we select $K_S \to \pi^+\pi^-$ decays by requiring two tracks of opposite curvature from a vertex in a cylindrical fiducial volume with $r_{xy} < 10$ cm and $|z| < 20$ cm, centered on the collision region as determined for each run using Bhabha events. We also require that the two tracks give $|m(\pi^+\pi^-) - m_{K^0}| < 5\ \text{MeV}/c^2$ and that $||\mathbf{p}_+ + \mathbf{p}_-| - p_{K_S}| < 10\ \text{MeV}/c$, with $p_{K_S}$ calculated from the kinematics of the $\phi \to K_S K_L$ decay. The $K_L$ momentum, $p_{K_L}$, is obtained from the $K_S$ direction and $\mathbf{p}_\phi$. The $K_L$ line of flight (*tagging line*) is then constructed from the $K_L$ momentum, $\mathbf{p}_{K_L} = \mathbf{p}_\phi - \mathbf{p}_{K_S}$, and the position of the production vertex, $\mathbf{x}_\phi$.

The overall value of the tagging efficiency is about 66%, and that of the ratio of the tagging efficiencies for events in which $K_L \to \pi^+\pi^-$ and $K_L \to \pi\mu\nu$, averaged over all periods, is $1.012 \pm 0.001$ as obtained from Monte Carlo.

To reconstruct the $K_L$ decay vertex, all relevant tracks in the chamber, after removal of those from the $K_S$ decay and their descendants, are extrapolated to their points of closest approach to the tagging line. For each track candidate, we evaluate the point of closest approach to the tagging line, $\mathbf{x}_\text{c}$, and the distance of closest approach, $d_\text{c}$. The momentum $\mathbf{p}_\text{c}$ of the track at

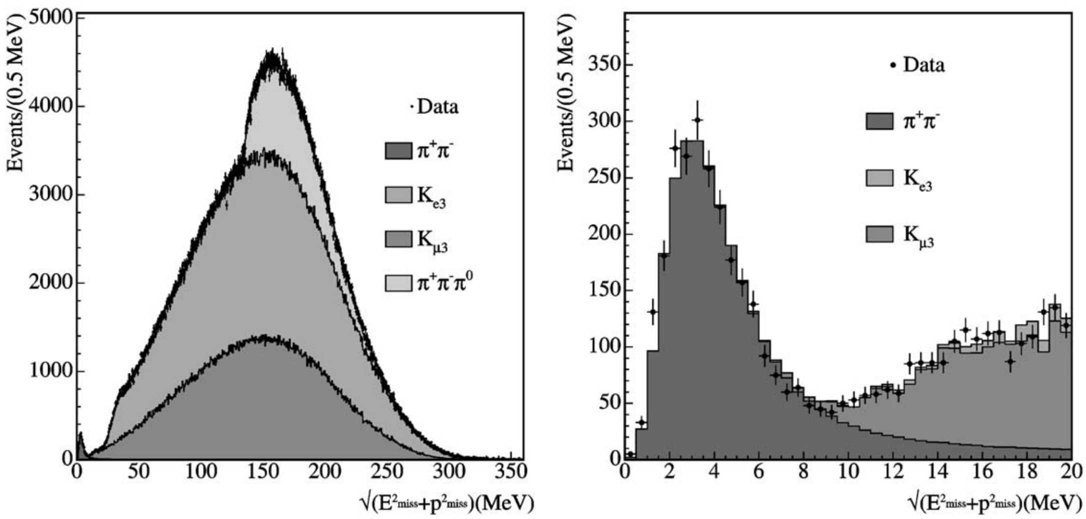


Fig. 1. Distribution of $\sqrt{E_{\text{miss}}^2 + |\mathbf{p}_{\text{miss}}|^2}$ for a single run period, with fit to Monte Carlo distributions for different decay channels: full fit range (left panel); signal region (right panel).

$\mathbf{x}_c$ and the extrapolation length, $l_c$, are also computed. Tracks satisfying $d_c < ar_{xy} + b$, with $a = 0.03$ and $b = 3$ cm, and $-20$ cm $< l_c < 25$ cm are accepted as $K_L$ decay products, $r_{xy}$ being the distance of $\mathbf{x}_c$ from the origin in the transverse plane. For each sign of charge we consider as associated to the $K_L$ decay the track with the smallest value of $d_c$. We attempt to find a vertex using these two tracks. Candidate $K_L$ vertices must be within the fiducial volume defined by $30 < r_{xy} < 150$ cm and $|z| < 120$ cm.

The tracking efficiency has been evaluated by Monte Carlo with corrections obtained from data control samples[9]. The corrections range between 0.99 and 1.03 depending on the $K_L$-decay channel and on the run period. We determine the conditional tracking efficiency as the ratio of the number of events in which there are two $K_L$-decay tracks of opposite sign and the number of events in which there is a single $K_L$-decay track. We use the same method for both data and Monte Carlo, and correct the efficiency obtained from the simulation with the data-Monte Carlo ratio of the conditional tracking efficiencies from control samples. The corrections are evaluated as functions of the track momentum using $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi e\nu$ control samples. To select $K_L \to \pi^+\pi^-\pi^0$ events, we require at least one $K_L$ decay track and two photons from $\pi^0$ decay. To reject background, we apply cuts on the two-photon invariant mass and on the photon times of flight. The momenta of decay tracks are calculated with a resolution of about 10 MeV/$c$ using the two photons from the $\pi^0$ decay and the momentum of the other track. In order to obtain the corrections for higher momentum tracks (above $\sim 150$ MeV/$c$), $K_L \to \pi e\nu$ decays are used. To select $K_L \to \pi e\nu$ decays, we identify electrons by time of flight with a purity of about 95%. The background is mostly due to $K_{\mu3}$ decays. The momentum of the second $K_L$ track is evaluated from the missing energy with a resolution of about 30 MeV/$c$. The average value of the tracking efficiency is about 61% for $\pi^+\pi^-$ decays and 51% for $\pi^\pm\mu^\mp\nu$ decays with fractional variations on the order of 7% as a function of time due to changes in the level of machine background. Once two tracks have been found, the vertex efficiency is about 97%. We find values for data and Monte Carlo to be in agreement within 0.1%.

Table 1
Analysis summary: number of signal and normalization events obtained from the fits, and the average values of the efficiency ratios

| | |
|---|---|
| Number of $\pi^+\pi^-$ events | $45267 \pm 255$ |
| Number of $\pi\mu\nu$ events | $5243723 \pm 2805$ |
| $\epsilon_{\text{tagging}}(\pi^+\pi^-)/\epsilon_{\text{tagging}}(\pi\mu\nu)$ | $1.0119 \pm 0.0008$ |
| $\epsilon_{\text{tracking}}(\pi^+\pi^-)/\epsilon_{\text{tracking}}(\pi\mu\nu)$ | $1.1726 \pm 0.0011$ |

The number of $K_L \to \pi^\pm\mu^\mp\nu(\gamma)$ events is obtained by fitting the distribution of $\Delta_{\pi\mu} = |\mathbf{p}_{\text{miss}}| - E_{\text{miss}}$ with a linear combination of Monte Carlo distributions as in Ref. [12]. $\Delta_{\pi\mu}$ is obtained from the smaller absolute value of the two possible values of $|\mathbf{p}_{\text{miss}}| - E_{\text{miss}}$, where $\mathbf{p}_{\text{miss}}$ and $E_{\text{miss}}$ are the missing momentum and missing energy at the $K_L$ vertex, evaluated by assuming the two tracks to be a $\pi\mu$ or $\mu\pi$ pair.

The best variable for selecting $K_L \to \pi^+\pi^-(\gamma)$ decays is $\sqrt{E_{\text{miss}}^2 + |\mathbf{p}_{\text{miss}}|^2}$ where $E_{\text{miss}}$ in this case is the missing energy in the hypothesis of the $K_L \to \pi^+\pi^-$ decay. The result of the fit to the $\sqrt{E_{\text{miss}}^2 + |\mathbf{p}_{\text{miss}}|^2}$ distribution with a linear combination of Monte Carlo distributions is shown in Fig. 1, left for a single run period. The signal region is shown expanded in Fig. 1, right. The sum over the 14 periods of the numbers of signal and normalization events obtained from the fits, and the average values over the 14 periods for the efficiency ratios are given in Table 1. Distributions of the $\pi^+$–$\pi^-$ invariant mass and of the pion momentum in the $K_L$ rest frame, $p^*$, for events selected requiring $\sqrt{E_{\text{miss}}^2 + |\mathbf{p}_{\text{miss}}|^2} < 20$ MeV are shown in Fig. 2 for data and Monte Carlo for different decay channels.

The systematic errors due to the limited knowledge of the corrections, data-Monte Carlo discrepancies, and instabilities in the signal counting have been studied as described in the following.

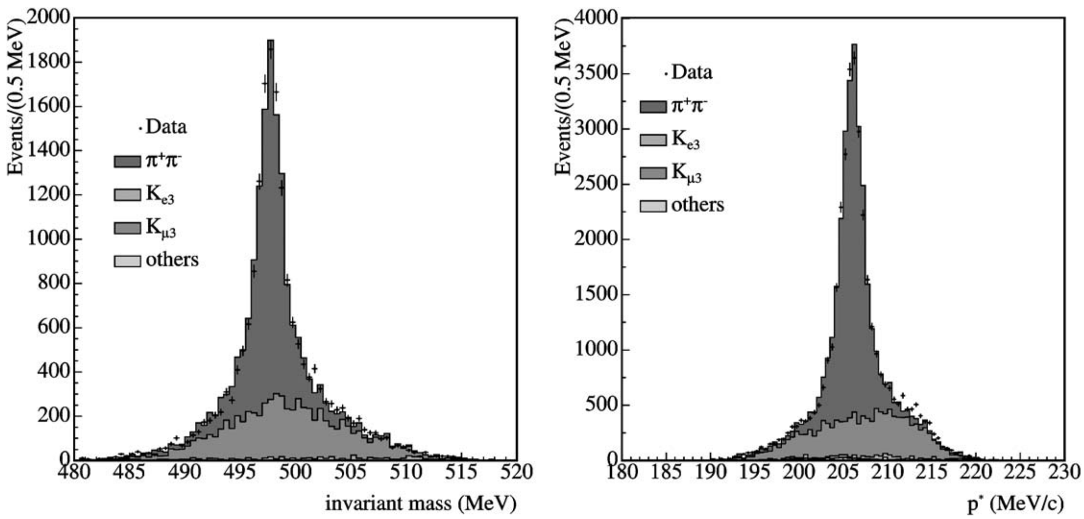


Fig. 2. Distributions of $\pi^+$–$\pi^-$ invariant mass (left panel) and pion momentum in the $K_L$ rest frame, $p^*$, (right panel) for two run periods, for data and Monte Carlo for different decay channels.

The systematic error on the determination of the ratio of the tagging efficiencies is evaluated from the stability of the results obtained with different tagging criteria. Since the variations in the tagging efficiency are mostly due to the dependence of the calorimeter trigger on the $K_L$ decay channel, the analysis has been repeated with the additional requirement that the event trigger be due to the $K_S$ decay products alone (*self-triggering* event). Another contribution to the systematic uncertainty on the tagging efficiency is due to the dependence of the reconstruction efficiency of the pions from $K_S \to \pi^+\pi^-$ on the presence of other tracks in the drift chamber. This effect is reduced for events in which the pion directions are almost orthogonal to the $K_S$ line of flight. The analysis has been repeated with the requirement that the difference between the $K_S$ pion momenta be less than 60 MeV. The largest fractional difference in the results obtained using different tagging criteria is $32 \times 10^{-4}$. This value is taken as the systematic uncertainty on the tagging efficiency.

The uncertainty on the tracking efficiency is dominated by the control sample statistics and by the variation of the results observed by using different criteria to identify tracks from $K_L$ decays. The systematic error due to the possible bias introduced in the selection of the control sample has been studied by varying the values of the cuts made on $d_c$ and $l_c$ when associating tracks to $K_L$ vertices. These changes result in a variation of the tracking efficiency by about ±20%. The corresponding fractional change in $R$ is $37 \times 10^{-4}$. This value is taken as the systematic uncertainty on the tracking efficiency.

The systematic error due to the reliability of the Monte Carlo distributions in the variables $|\mathbf{p}_{\text{miss}}| - E_{\text{miss}}$ and $\sqrt{E^2_{\text{miss}} + |\mathbf{p}_{\text{miss}}|^2}$ has been evaluated by studying the sensitivity of $R$ to the momentum resolution. The fits to the $\sqrt{E^2_{\text{miss}} + |\mathbf{p}_{\text{miss}}|^2}$ and the $|\mathbf{p}_{\text{miss}}| - E_{\text{miss}}$ distributions have been repeated using Monte Carlo samples in which the momentum resolution has been varied according to the uncertainty determined using high purity control samples of the dominant $K_L$ decays. A fractional systematic uncertainty of $55 \times 10^{-4}$ is obtained.

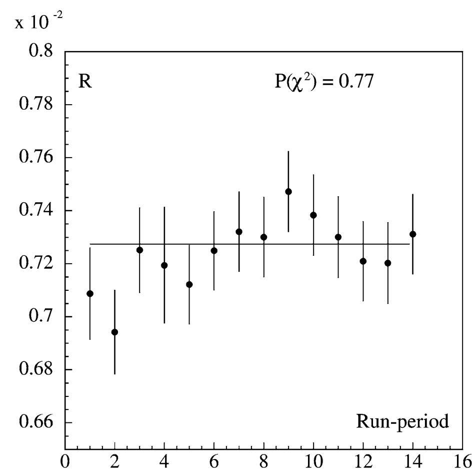


Fig. 3. Values of $R$ for 14 run-periods. The result of a fit to a constant value is also shown.

The final value for $\text{BR}(K_L \to \pi^+\pi^-)$ has been calculated as the average over the 14 periods of data taking. Good stability of the results is observed after application of the period-dependent tracking efficiency corrections. The $\chi^2$ value of the fit corresponds to a confidence level of 77%; see Fig. 3. Including systematic uncertainties, we obtain:

$$\frac{\text{BR}(K_L \to \pi^+\pi^-)}{\text{BR}(K_L \to \pi\mu\nu)} = (0.7275 \pm 0.0042_{\text{stat}} \pm 0.0054_{\text{syst}}) \times 10^{-2},$$

where the statistical error includes the contribution from Monte Carlo statistics and the statistical uncertainty on the tracking efficiency correction. Using the KLOE result $\text{BR}(K_L \to \pi\mu\nu) = 0.2698 \pm 0.0015$ [12] we find:

$$\text{BR}(K_L \to \pi^+\pi^-) = (1.963 \pm 0.012_{\text{stat.}} \pm 0.017_{\text{syst.}}) \times 10^{-3}.$$

This result is fully inclusive with respect to final-state radiation including both the inner bremsstrahlung and the (CP-conserving) direct emission components. The result is in good agreement with the measurement from KTeV [2],[3] $(1.975 \pm 0.012) \times 10^{-3}$, and in strong disagreement with the value reported by the PDG, $(2.090 \pm 0.025) \times 10^{-3}$ [3].

The error on the measurement of $\text{BR}(K_L \to \pi\mu\nu)$ of Ref. [12] is correlated with the errors on $\text{BR}(K_L \to \pi e\nu)$, $\text{BR}(K_L \to \pi^0\pi^0\pi^0)$, $\text{BR}(K_L \to \pi^+\pi^-\pi^0)$, and the $K_L$ lifetime. This is because, in the treatment of Ref. [12], the branching ratios and the lifetime are determined from lifetime-dependent absolute branching ratio measurements using the constraint $\sum \text{BR} = 1 - 0.0036$, where 0.0036 represents the small contribution due to the sum of the branching ratios for $K_L \to \pi^+\pi^-$, $K_L \to \pi^0\pi^0$, and $K_L \to \gamma\gamma$ listed in the PDG compilation [3]. As a consequence, the error on the value for $\text{BR}(K_L \to \pi^+\pi^-)$ reported here is correlated with the errors on the branching ratio and $K_L$ lifetime values reported in Ref. [12]. Additional sources of correlation arise from common systematic uncertainties in the branching ratio measurements. The complete correlation matrix is:

$$\begin{pmatrix} 1 & -0.25 & -0.56 & -0.07 & -0.12 & 0.25 \\ & 1 & -0.43 & -0.20 & 0.51 & 0.33 \\ & & 1 & -0.39 & -0.24 & -0.21 \\ & & & 1 & -0.09 & -0.39 \\ & & & & 1 & 0.11 \\ & & & & & 1 \end{pmatrix},$$

where the columns and the rows refer, in order, to the BR's for decays to $\pi^\pm e^\mp\nu$, $\pi^\pm\mu^\mp\nu$, $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$, and $\tau_{K_L}$. Because $\text{BR}(K_L \to \pi^+\pi^-)$ is small, the KLOE values for the dominant BR's are essentially unchanged when the new KLOE value for $\text{BR}(K_L \to \pi^+\pi^-)$ is used in constraining the sum of the $K_L$ BR's to unity.

The measurement of $\text{BR}(K_L \to \pi^+\pi^-)$ can be used to determine $|\eta_{+-}|$ and $|\epsilon|$, correcting for the small contribution of $\epsilon'$. Using the measurements of $\text{BR}(K_S \to \pi^+\pi^-)$ and $\tau_{K_L}$ from KLOE [12,13] and the value of $\tau_{K_S}$ from the PDG [3], and subtracting the contribution of the CP-conserving direct-photon emission process $K_L \to \pi^+\pi^-\gamma$ [14] from the inclusive measurement of $\text{BR}(K_L \to \pi^+\pi^-)$, we obtain $|\eta_{+-}| = (2.219 \pm 0.013) \times 10^{-3}$. Finally, using the world average measurement of $\text{Re}(\epsilon'/\epsilon) = (1.67 \pm 0.26) \times 10^{-3}$ and assuming $\arg\epsilon' = \arg\epsilon$, we obtain $|\epsilon| = (2.216 \pm 0.013) \times 10^{-3}$. This result is in disagreement with the value $|\epsilon| = (2.284 \pm 0.014) \times 10^{-3}$ reported in the PDG compilation [3]. The value of $|\epsilon|$ be can predicted from the measurement of other observables and compared with measurements. For this purpose, we use the prediction $|\epsilon| = (2.875 \pm 0.455) \times 10^{-3}$ obtained by the UTfit Collaboration [15,16], where to test the mechanism of the CP violation in the Standard Model, the value of $|\epsilon|$ has been computed from measurements of the CP-conserving observables $\Delta M(B_d)$, $\Delta M(B_s)$, $V_{ub}$, and $V_{cb}$. The probability density function of the prediction of $|\epsilon|$ is shown in Fig. 4. No significant deviation from the Standard Model prediction is observed. Notice that, due to the large uncertainties on the computation of the hadronic matrix element corresponding to the $K$–$\bar{K}$ mixing, the theoretical error is much larger than the experimental error.

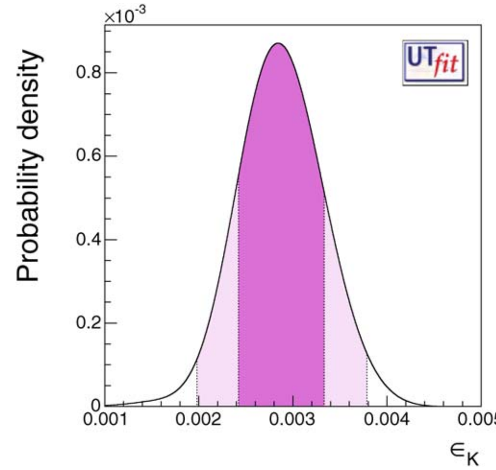


Fig. 4. Standard Model prediction of $|\epsilon|$ from measurements of $|V_{ub}|/|V_{cb}|$, and $\Delta M(B_d)$ and from the limit on $\Delta M(B_s)$ from Ref. [15].

In summary, a new, precise measurement of the $K_L \to \pi^+\pi^-$ branching ratio has been performed. The result:

$$\text{BR}(K_L \to \pi^+\pi^-) = (1.963 \pm 0.012_{\text{stat.}} \pm 0.017_{\text{syst.}}) \times 10^{-3}$$

is in good agreement with that recently obtained by KTeV [2], and in disagreement with the value reported by the PDG[3]. The impact of this measurement on the determination of the apex of the unitarity triangle has been studied and compared with determinations from measurements of other observables.

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[3] The contribution of direct emission is claimed to be negligible in the KTeV result.

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