# Measurement of the branching ratio for the decay $K_S \to \pi^{\pm} e^{\mp} \bar{\nu}(\nu)$ with the KLOE detector


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**Abstract**

We present a preliminary measurement of the branching ratios for the two charge modes of the decay $K_S \to \pi e \nu$ performed using the KLOE detector. $K_S$-mesons are produced in the reaction $e^+e^- \to \phi \to K_S K_L$ at the DAΦNE collider. In a sample of $\sim 1.5 \times 10^8$ $K_S$-tagged events we find $22700 \pm 200$ semileptonic $K_S$ decays. Normalizing to the $K_S \to \pi^+\pi^-$ count in the same data sample, we obtain $\mathrm{BR}(K_S \to \pi^- e^+ \nu) = (3.54 \pm 0.05_{\mathrm{stat}} \pm 0.05_{\mathrm{syst}}) \times 10^{-4}$ and $\mathrm{BR}(K_S \to \pi^+ e^- \bar{\nu}) = (3.54 \pm 0.05_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}) \times 10^{-4}$. The total branching ratio is $\mathrm{BR}(K_S \to \pi e \nu) = (7.09 \pm 0.07_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}) \times 10^{-4}$. Each BR is inclusive of radiative photons in the final state. We measure for the first time the charge asymmetry $A_S = (-2 \pm 9_{\mathrm{stat}} \pm 6_{\mathrm{syst}}) \times 10^{-3}$.

## 1 Introduction

The measurement of the kaon semileptonic decay widths provides several tests of many fundamental aspects of the standard model, SM. The most precise test of unitarity of the CKM matrix comes from its first row. Defining $1 - \Delta \simeq |V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2$, we expect $\Delta = 0$ at $\mathcal{O}(10^{-5})$. Using $|V_{\mathrm{ud}}|$ as extracted from superallowed nuclear decays and the measured neutron lifetime [1], and $|V_{\mathrm{us}}|$ as extracted from the semileptonic decay width of the $K_L$, a precision test on $\Delta$ to better than 1% can be performed. We are able to test if $\Delta$ is zero with a comparable precision extracting $V_{\mathrm{us}}$ from the measurement of $K_S$ semileptonic decay width.

The knowledge of both the $K_L$ and the $K_S$ semileptonic decay branching ratios and lifetimes allows the validity of the $\Delta S = \Delta Q$ rule to be tested through the quantity

$$Re(x_+) = \frac{1}{2} \times \frac{\mathrm{BR}(K_S \to \pi e \nu)/\tau_S - \mathrm{BR}(K_L \to \pi e \nu)/\tau_L}{\mathrm{BR}(K_S \to \pi e \nu)/\tau_S + \mathrm{BR}(K_L \to \pi e \nu)/\tau_L} \tag{1}$$

In the Standard Model, $Re(x_+)$ is expected to be of the order of $G_F m_\pi^2 \sim 10^{-7}$, receiving contribution from second order weak transitions [2,3]. At present, the most precise test of the $\Delta S = \Delta Q$ rule comes from analysis of the time distribution of semileptonic strangeness-tagged kaon decays at CPLEAR [4]. The CPLEAR collaboration finds $Re(x_+)$ to be compatible with zero with an error of $6 \times 10^{-3}$.

Finally, discrete symmetries are tested through the measurement of the charge asymmetries for $K_L$ and $K_S$ decays, $A_{L,S}$, defined as

$$A_{L,S} = \frac{\Gamma\left(\mathrm{K_{L,S}} \to \pi^- \mathrm{e}^+ \nu\right) - \Gamma\left(\mathrm{K_{L,S}} \to \pi^+ \mathrm{e}^- \bar{\nu}\right)}{\Gamma\left(\mathrm{K_{L,S}} \to \pi^- \mathrm{e}^+ \nu\right) + \Gamma\left(\mathrm{K_{L,S}} \to \pi^+ \mathrm{e}^- \bar{\nu}\right)}$$

If $CPT$ invariance holds, each of the two charge asymmetries are expected to be equal to $2 \times Re(\epsilon) \simeq 3 \times 10^{-3}$, where $\epsilon$ is the parameter describing $CP$ violation in the $K^0 - \bar{K}^0$ mass matrix. A difference between $A_S$ and $A_L$ signals $CPT$ violation either in the mass matrix, or in the decay amplitudes. The value of $A_L$ is known at present with a precision of $10^{-4}$ [5,6], while $A_S$ has never yet been measured. At present, the most precise test of $CPT$ conservation in the mixing has been performed using interferometry technique at the CPLEAR experiment [7] and has a precision of $3 \times 10^{-4}$.

## 2 Measurement method

We measure the $K_S$ branching ratios using kaons from $\phi \to K_S K_L$ decays, collected with the KLOE experiment [8,9] operating at the DA$\Phi$NE $e^+e^-$ collider [10]. $\phi$-mesons are produced in small angle (25 mrad) collisions of equal energy electrons and positrons, giving the $\phi$ a small transverse momentum component in the horizontal plane, $p_\phi \sim 13\,\mathrm{MeV}/c$. $\phi$-mesons decay $\sim 34\%$ of the time into $K_L K_S$ pairs. $K_L$'s and $K_S$'s decay with mean paths $\lambda_\mathrm{L} \sim 340\,\mathrm{cm}$ and $\lambda_\mathrm{S} \sim 0.6\,\mathrm{cm}$, respectively.

The main advantage of studying kaons at a $\phi$–factory is that $K_L$'s and $K_S$'s are produced nearly back-to-back in the laboratory so that detection of a long-lived kaon tags the production of a $K_S$-meson and gives its direction and momentum. The contamination from $K_L K_L$ and $K_S K_S$ final states is negligible [11,12]. Since the branching ratio for $K_S \to \pi^+\pi^-$ is known with an accuracy of $\sim 0.2\%$ [13], the $K_S \to \pi e \nu$ branching ratio is evaluated by normalizing the number of signal events, separately for each charge state, to the number of $K_S \to \pi^+\pi^-$ events in the same data set. This allows cancellation of the uncertainties arising from the integrated luminosity, the $\phi$ production cross section, and the tagging efficiency. The measurement is based on an integrated luminosity of $410\,\mathrm{pb}^{-1}$ at the $\phi$ peak collected during two distinct data-taking periods in the years 2001 and 2002, corresponding to $\sim 1.2 \times 10^9$ $\phi$-mesons produced. Since the machine conditions were different during the two periods, we have measured the branching ratios separately for each data set. Our final results are based on the averages of these measurements.

## 3 Selection criteria

About half of the $K_L$-mesons reach the calorimeter, where most interact. A $K_L$ interaction is called a "$K_L$-*crash*" in the following. A $K_L$-crash is identified as a local energy deposit with energy above 100 MeV and a time of flight indicating low velocity: $\beta \sim 0.218$. The coordinates of the energy deposit determine the $K_L$'s direction to $\sim 20$ mrad and its momentum $\mathbf{p}_L$, which is weakly dependent on the $K_L$ direction because of the motion of the $\phi$-meson. A $K_L$-crash thus tags the production of a $K_S$ of momentum $\mathbf{p}_S = \mathbf{p}_\phi - \mathbf{p}_L$. $K_S$-mesons are tagged with an overall efficiency of $\sim 30\%$. Both $K_S \to \pi e \nu$ and $K_S \to \pi^+\pi^-$ decays are selected from this tagged sample. Event selection consists of fiducial cuts, particle identification by time of flight, and kinematic closure.

Identification of $K_S \to \pi^+\pi^-$ decays requires two tracks of opposite curvature. Tracks must extrapolate to the interaction point (IP) within few centimeters. The reconstructed momenta and polar angles must lie in the intervals $120\,\mathrm{MeV}/c < p < 300\,\mathrm{MeV}/c$ and $30° < \theta < 150°$. A cut in $(p_\perp, p_\parallel)$ selects non-spiralling tracks. The numbers of $K_S \to \pi^+\pi^-$ events found in each data set are shown in Tab. 1. Contamination due to $K_S$ decays other than $K_S \to \pi^+\pi^-$ is well below the per-mil level and is ignored.

Identification of $K_S \to \pi e \nu$ events also begins with the requirement of two tracks of opposite curvature. Tracks must extrapolate *and form a vertex* close to the IP. The invariant mass $M_{\pi\pi}$ of the pair, calculated assuming both tracks are pions, must be smaller than 490 MeV. This rejects $\sim 95\%$ of the $\pi^+\pi^-$ decays.

Electrons and pions are discriminated by time of flight (TOF). Tracks are therefore required to be associated with calorimeter energy clusters. For each track, we compute the difference $\delta_t(m) = t_{\mathrm{cl}} - L/c\beta(m)$ using the cluster time $t_{\mathrm{cl}}$ and the track length $L$. The velocity $\beta$ is computed from the track momentum for each mass hypothesis, $m = m_e$ and $m = m_\pi$. In order to avoid uncertainties due to the determination of $T_0$ (the time of the bunch crossing producing the event), we make cuts on the two-track difference

$$d\delta_{t,\mathrm{ab}} = \delta_t(m_a)_1 - \delta_t(m_b)_2,$$

where the mass hypothesis $m_{a(b)}$ is used for the track 1(2). This difference is zero for the correct mass assignments. An additional fraction of $K_S \to \pi^+\pi^-$ events is rejected by requiring $|d\delta_{t,\pi\pi}| > 1.7\,\mathrm{ns}$. The differences $d\delta_{t,\pi\mathrm{e}}$ and $d\delta_{t,\mathrm{e}\pi}$ are calculated for events surviving the previous cut. The scatter plot of the two variables is shown in Fig. 1 for Monte Carlo events. The cuts applied on these time differences for the selection of $K_S \to \pi e \nu$ events are illustrated in the figure: $|d\delta_{t,\pi\mathrm{e}}| < 1.4\,\mathrm{ns}$, $d\delta_{t,\mathrm{e}\pi} > 3.2\,\mathrm{ns}$; or $|d\delta_{t,\mathrm{e}\pi}| < 1.4\,\mathrm{ns}$, $d\delta_{t,\pi\mathrm{e}} > 3.2\,\mathrm{ns}$. After the TOF requirements, particle types and charges for signal events can

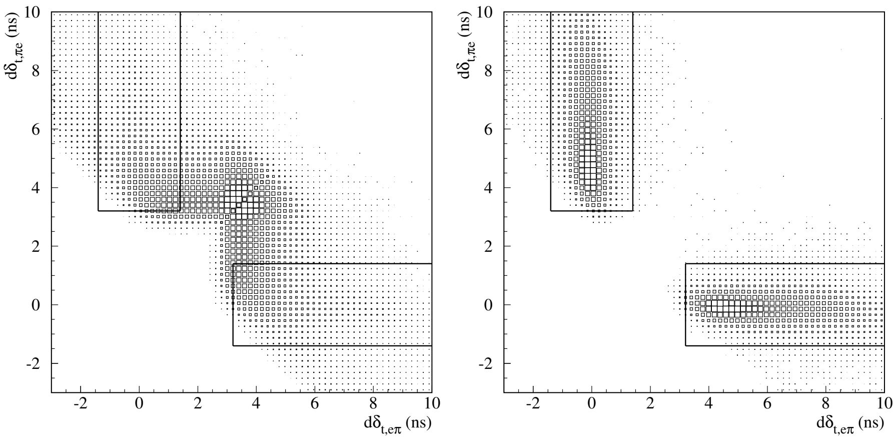


Fig. 1. Scatter plot of the time differences $d\delta_{t,\pi\mathrm{e}}$ vs $d\delta_{t,\mathrm{e}\pi}$ for $e\pi$ and $\pi e$ mass assignments for Monte Carlo events, from all $K_S$ decays (left) and from $K_S \to \pi e \nu$ decays (right).

be assigned very precisely: the probability of misidentifying a $\pi^+e^-\bar{\nu}$ ($\pi^-e^+\nu$) event as a $\pi^-e^+\nu$ ($\pi^+e^-\bar{\nu}$) is less than $10^{-4}$.

Finally, for events passing all of the above criteria, we compute the missing energy and momentum $E_{\mathrm{miss}}$, $p_{\mathrm{miss}}$. For $\pi^\pm e^\mp \bar{\nu}(\nu)$ decays, these variables are the neutrino energy and momentum, and satisfy $E_{\mathrm{miss}} = cp_{\mathrm{miss}}$. The distribution of $E_{\mathrm{miss}} - cp_{\mathrm{miss}}$ is shown in Fig. 2 after the time-of-flight cuts are imposed, for $\pi^+e^-\bar{\nu}$ (left panel) and for $\pi^-e^+\nu$ (right panel) candidate events. A clear peak at $E_{\mathrm{miss}} - cp_{\mathrm{miss}} = 0$ is evident and corresponds to a clean signal for $K_S \to \pi e \nu$. Events with $E_{\mathrm{miss}} - cp_{\mathrm{miss}} > 10\,\mathrm{MeV}$ are mostly due to $K_S \to \pi^+\pi^-$ decays in which a pion decays to a muon before reaching the tracking volume or in which one of the two pion tracks is badly reconstructed. The fit of the data to the sum of the signal and background spectra simulated using the Monte Carlo (MC) is also shown. The MC simulation of $K_S \to \pi e \nu$ decays includes an infrared-finite treatment of radiative corrections. The kinematics of the decay $K_S \to \pi e \nu$ has been sampled from a four-body differential decay width which includes a photon in the final state [14].

| Channel | Number of selected events | |
|---|---|---|
| | Year 2001 | Year 2002 |
| $K_S \to \pi^+\pi^-$ | 20 903 541 | 37 313 575 |
| $K_S \to \pi^+e^-\bar{\nu}$ | $4\,082 \pm 83$ | $7\,176 \pm 117$ |
| $K_S \to \pi^-e^+\nu$ | $4\,155 \pm 81$ | $7\,282 \pm 112$ |
| $K_S \to \pi e \nu$ | $8\,236 \pm 116$ | $14\,458 \pm 162$ |

Table 1
Number of selected $K_S \to \pi^+\pi^-$ and $K_S \to \pi e \nu$ decays for the 2001 and 2002 data sets.

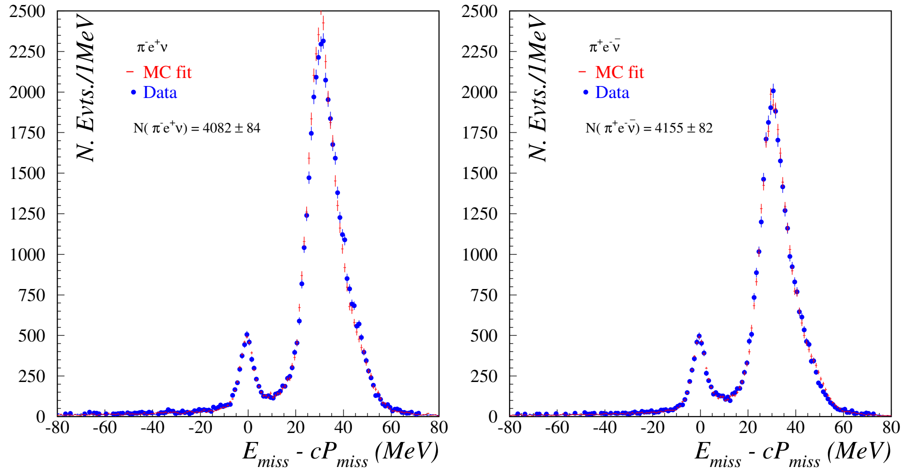


Fig. 2. $E_{\rm miss} - cp_{\rm miss}$ spectrum for $\pi^-e^+\nu$ (left panel) and for $\pi^+e^-\bar{\nu}$ (right panel) candidate events. Filled dots represent data from year-2001 data set; the crosses are the result of a fit varying the normalization of MC distributions for signal and background.

The free fit parameters are the signal and background normalizations. Three independent fits are performed: one for each charge state and one in which we do not distinguish by charge. The estimated numbers of signal events are shown in Tab. 1. The quoted errors includes the contributions from fluctuations in the signal statistics, from the background subtraction, and from the finite statistics of the MC spectra, which amount to $\sim 74\%$, $\sim 24$, and $\sim 59\%$, respectively.

## 4 Efficiency estimates

For both $K_S \to \pi^+\pi^-$ (normalization) and $K_S \to \pi e \nu$ (signal) events, contributions to the tagging and selection inefficiencies due to purely geometrical effects have been estimated using MC simulation, while data have been used to estimate the corrections for tracking and trigger inefficiencies. For $K_S \to \pi e \nu$

| $K_S$ decay mode | Selection efficiency | |
|---|---|---|
| | Year 2001 | Year 2002 |
| $\pi^+\pi^-(\gamma)$ | $0.6123 \pm 0.0006_{\text{stat}} \pm 0.0025_{\text{syst}}$ | $0.6273 \pm 0.0002_{\text{stat}} \pm 0.0025_{\text{syst}}$ |
| $\pi^-e^+\nu$ | $0.2277 \pm 0.0013_{\text{stat}} \pm 0.0017_{\text{syst}}$ | $0.2358 \pm 0.0010_{\text{stat}} \pm 0.0024_{\text{syst}}$ |
| $\pi^+e^-\bar{\nu}$ | $0.2324 \pm 0.0013_{\text{stat}} \pm 0.0012_{\text{syst}}$ | $0.2378 \pm 0.0012_{\text{stat}} \pm 0.0015_{\text{syst}}$ |
| $\pi e\nu$ | $0.2297 \pm 0.0009_{\text{stat}} \pm 0.0016_{\text{syst}}$ | $0.2361 \pm 0.0008_{\text{stat}} \pm 0.0018_{\text{syst}}$ |
| **$K_S$ decay mode** | **Ratio of tagging efficiencies** | |
| $\pi^-e^+\nu$ | $0.9924 \pm 0.0020_{\text{stat}} \pm 0.0020_{\text{syst}}$ | |
| $\pi^+e^-\bar{\nu}$ | $0.9912 \pm 0.0020_{\text{stat}} \pm 0.0020_{\text{syst}}$ | |
| $\pi e\nu$ | $0.9918 \pm 0.0015_{\text{stat}} \pm 0.0015_{\text{syst}}$ | |

Table 2
Efficiencies for $K_S \to \pi^+\pi^-$ and $K_S \to \pi e\nu$ decays, for the 2001 and 2002 data sets.

events, the corrections for vertex reconstruction and time-of-flight $\pi$-$e$ identification inefficiencies have also been evaluated using a data control sample of $K_L \to \pi e\nu$ prompt decays.

The methods used to estimate the selection efficiency are described in detail elsewhere [15–17]. For $K_S \to \pi e\nu$ decays, three efficiencies are estimated: one for each charge state and one for events in which we do not distinguish by charge. We summarize the results for the total efficiencies, given the tag requirement, in Tab. 2. The uncertainty in the trigger efficiency is the dominant contribution to systematic errors. The difference between efficiencies for the two semileptonic charge states arises from the different response of the calorimeter to $\pi^+$ and $\pi^-$, influencing both the trigger and the TOF efficiencies.

In principle, the $K_L$-crash identification efficiency cancels out in the ratio of the number of selected $K_S \to \pi e\nu$ and $K_S \to \pi^+\pi^-$ events. In practice, since the event $T_0$ is obtained from the $K_S$ and the $K_L$ is recognized by its time of flight, there is a small dependence of the $K_L$-crash identification efficiency on the $K_S$ decay mode. A correction for this effect is obtained by studying the accuracy of the $T_0$ determination in each case [15–17]. The ratio $R_{\text{tag}}$ of the tagging efficiencies for $K_S \to \pi e\nu$ and $K_S \to \pi^+\pi^-$ is found to differ from unity by $\sim$1% (see Tab. 2).

## 5 Preliminary results

The value for BR($K_S \to \pi e \nu$) is obtained by normalizing the number of signal events to the number of $K_S \to \pi^+\pi^-$ events in the same data set, correcting for the total selection efficiencies and the ratio $R_{\rm tag}$ of tagging efficiencies, and using the present experimental value for BR($K_S \to \pi^+\pi^-$) [13]:

$$\mathrm{BR}(K_S \to \pi e \nu) = \frac{N(\pi \mathrm{e} \nu)}{N(\pi\pi)} \times \frac{\varepsilon^{\pi\pi}_{\rm tot}}{\varepsilon^{\pi \mathrm{e} \nu}_{\rm tot}} \times R_{\rm tag} \times \mathrm{BR}(K_S \to \pi^+\pi^-).$$

Averaging the results obtained for each data set, we obtain the following branching ratios:

$$\begin{aligned}
\mathrm{BR}(K_S \to \pi^- e^+ \nu) &= (3.54 \pm 0.05_{\rm stat} \pm 0.05_{\rm syst}) \times 10^{-4}, \\
\mathrm{BR}(K_S \to \pi^+ e^- \bar{\nu}) &= (3.54 \pm 0.05_{\rm stat} \pm 0.04_{\rm syst}) \times 10^{-4}, \\
\mathrm{BR}(K_S \to \pi^\pm e^\mp \bar{\nu}(\nu)) &= (7.09 \pm 0.07_{\rm stat} \pm 0.08_{\rm syst}) \times 10^{-4}.
\end{aligned}$$

From the last result, we can extract the parameter $Re(x_+)$, Eq. 1, which is related to violations of the $\Delta S = \Delta Q$ rule for $CPT$-conserving transitions. Using the PDG-fit result of the $K_S$ lifetime, $\tau_S = (89.58 \pm 0.06)$ ps [13], which includes KTeV [18] and NA48 [19] recent measurements, we obtain the values shown in Tab. 3:

- **a** we use BR($K_L \to \pi e \nu$) $= (38.81 \pm 0.27)\%$ from PDG-fit and $\tau_L = (51.5 \pm 0.4)$ ns averaged by PDG; the result is $\sim 3\sigma$ away from zero;
- **b** we use BR($K_L \to \pi e \nu$) $= (40.67 \pm 0.11)\%$ from a recent measurement by KTeV collaboration [20] and $\tau_L$ averaged by PDG, getting a value compatible with zero;
- **c** we use BR($K_L \to \pi e \nu$) $= (39.85 \pm 0.35)\%$ and $\tau_L = 51.35 \pm 0.26$ ns from preliminary measurements by KLOE [21]; the result is $\sim 1.3\sigma$ from zero.

The most precise measurement of $Re(x_+)$ up to date, by the CPLEAR collaboration [4], is also shown in row **d**.

The charge asymmetry is also obtained as follows

$$A_S = \frac{N(\pi^- \mathrm{e}^+ \nu)/\varepsilon^+ - N(\pi^+ \mathrm{e}^- \bar{\nu})/\varepsilon^-}{N(\pi^- \mathrm{e}^+ \nu)/\varepsilon^+ + N(\pi^+ \mathrm{e}^- \bar{\nu})/\varepsilon^-},$$

$$A_S = (-2 \pm 9_{\rm stat} \pm 6_{\rm syst}) \times 10^{-3}$$

This result is compatible with that for $K_L$ semileptonic decays and with the expectation obtained assuming $CPT$ symmetry, $A_S = 2Re(\epsilon)$.

| | $\boldsymbol{Re(x_+)}$ |
|---|---|
| **a** | $(12.6 \pm 3.1_{\rm stat} \pm 2.9_{\rm syst}) \times 10^{-3}$ |
| **b** | $(0.9 \pm 2.9_{\rm stat} \pm 2.9_{\rm syst}) \times 10^{-3}$ |
| **c** | $(5.3 \pm 3.1_{\rm stat} \pm 2.9_{\rm syst}) \times 10^{-3}$ |
| **d** | $(-1.8 \pm 4.1_{\rm stat} \pm 4.5_{\rm syst}) \times 10^{-3}$ |

Table 3
Estimates of $Re(x_+)$. Rows labelled **a**, **b**, and **c** are obtained using the KLOE measurement of $\mathrm{BR}(K_S \to \pi e \nu)$. See text for details. The most precise measurement up to date, by the CPLEAR collaboration [4], is also shown in row **d**.

### *5.1 $V_{\rm us}$ determination*

The value of $V_{\rm us}$ can be extracted from the measurement of $\mathrm{BR}(K_S \to \pi e \nu)$ and from the $K_S$ lifetime, $\tau_S$:

$$V_{\rm us} \times f_+^{K^0\pi^-}(0) = \left[\frac{128\pi^3 \mathrm{BR}(K_S \to \pi e \nu)}{\tau_S G_\mu^2 M_K^5 S_{\rm ew} I_K^e(\lambda_+)}\right]^{1/2} \frac{1}{1+\delta_{\rm em}^{Ke}},$$

where $f_+^{K^0\pi^-}(0)$ is the vector form factor at zero momentum transfer and $I_K^e(\lambda_+)$ is the result of the phase space integration after factorizing out $f_+^{K^0\pi^-}(0)$. In the above expression, long-distance radiative corrections for both the form factor $f_+^{K^0\pi^-}$ and the phase space integral have been factorized out and are included in the parameter $\delta_{\rm em}^{Ke} = 0.55 \pm 0.10$ [22,23]. The short-distance electroweak corrections are included in the parameter $S_{\rm ew} = 1.0232$ [24].

The parameter $\lambda_+$ describes the dependence of the vector and scalar form factor on the momentum transferred, $t$. Two possible parametrizations are used in the literature: linear,

$$f_+(t) = f_+(0)\left[1 + \lambda_+ \frac{t}{m_{\pi_+^2}}\right],$$

and quadratic,

$$f_+(t) = f_+(0)\left[1 + \lambda'_+ \frac{t}{m_{\pi_+^2}} + \frac{\lambda''_+}{2}\frac{t^2}{m_{\pi^+}^4}\right].$$

Recently, ISTRA+ [25] and KTeV [26] experiments measured the dependence of $f_+^{K^0\pi^-}$ on $t$, using $K^+ \to \pi^0 e^+ \nu$ and $K_L \to \pi^\pm e^\mp \bar{\nu}(\nu), \pi^\pm \mu^\mp \bar{\nu}(\nu)$ decays, respectively. A visible non linear contribution was observed by both experiments. In the extraction of $V_{\rm us}$ we use the values obtained by KTeV experiment from a quadratic fit: $\lambda'_+ = 0.0206 \pm 0.0018$, $\lambda''_+ = 0.0032 \pm 0.0007$.

With this parametrization, the integration over the phase space yields $I_K^e = 0.1024 \pm 0.0007$.

We obtain:

$$f_+^{K^0\pi^-}(0) \times V_{\rm us} \; = 0.2171 \pm 0.0017$$

Using $V_{\rm ud} = 0.9740 \pm 0.0005$ from [1] and $f_+^{K^0\pi^-}(0) = 0.961 \pm 0.008$ from [27], also in agreement with a recent lattice calculation [28], the unitarity band is:

$$f_+^{K^0\pi^-}(0) \times V_{\rm us} \; = 0.2177 \pm 0.0028$$

in agreement with our preliminary result.

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