FIRST OBSERVATION OF $K_S \to \pi^0\mu^+\mu^-$ and $K_S \to \pi^0 e^+e^-$ AT NA48.

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Abstract

A search for the decays $K_S \to \pi^0\mu^+\mu^-$ and $K_S \to \pi^0 e^+e^-$ has been made by the NA48/1 Collaboration at the CERN SPS accelerator.

Six $K_S \to \pi^0\mu^+\mu^-$ events were found with a background of $0.22^{+0.18}_{-0.11}$.

Seven $K_S \to \pi^0 e^+e^-$ events were found with a background of $0.15^{+0.10}_{-0.04}$

The measured branching ratios are:

$Br(K_S \to \pi^0\mu^+\mu^-) = [2.9^{+1.5}_{-1.2}(stat) \pm 0.2(syst)] \times 10^{-9}$

$Br(K_S \to \pi^0 e^+e^-) = [5.8^{+2.9}_{-2.4}(stat) \pm 0.8(syst)] \times 10^{-9}$

Other recent results from NA48 are also presented.

1 Introduction

The NA48/1 Collaboration performed the first observation of the decays $K_S \to \pi^0\mu^+\mu^-$ and $K_S \to \pi^0 e^+e^-$, and a measurement of their branching ratios.

The main interest of these decays is that they measure the indirect CP violating component of the corresponding $K_L \to \pi^0 l^+l^-$, thereby allowing the direct CP violating component to be extracted. This allows to test the SM description of CP violation and the possible *new physics* contributions.

The measurement of the $K_S \to \pi^0 l^+l^-$ branching ratios and some of their kinematic distributions, namely the dilepton invariant mass, are also interesting because they increase our knowledge in the kaon sector. They provide input parameters and validity tests for phenomenological calculations.

The combined study of both channels $K \to \pi^0\mu^+\mu^-$ and $K \to \pi^0 e^+e^-$ is rich in information, due to their similarities and differences. For some observables, for instance the K_S branching ratios, the ratio of the two modes can be predicted in the so-called model independent way. For other observables, for example the K_L branching ratios, the two channels are sensitive to different contributions, and in the presence of *new physics* they will allow to distinguish among different models.

The NA48 Collaboration has also studied the $K^0 \to \pi^\pm e^\mp \nu_e \gamma$ and $K_L \to \pi^\pm \pi^0 e^\mp \nu_e$ decays.

2 Beam and Detector

The NA48 beam line and detector as well as the modifications performed for NA48/1, are described in detail in the references 1) and 2) respectively.

The NA48/1 experiment was performed at the CERN SPS accelerator during 2002 and used a 400 GeV proton beam impinging on a Be target to produce a high-intensity neutral beam. The spill length was 4.8 s out of a 16.8 s cycle time, with an average of 5×10^{10} protons per spill. On average there were 2×10^5 K_S decays per spill in the fiducial volume with a mean energy of 110GeV.

3 $K_S \to \pi^0 l^+l^-$ Analysis

The decays $K_S \to \pi^0\mu^+\mu^-$ and $K_S \to \pi^0 e^+e^-$ are very rare, their predicted branching ratios were of the order of $\sim 10^{-9} - 10^{-10}$. This translated, in the best case scenario, into the possibility of observing a handful of events in the data taken by NA48/1, which motivated the performance of a blind analysis to ensure that the event selection was kept unbiased. The signal region has been defined in the plane determined by the reconstructed kaon invariant mass

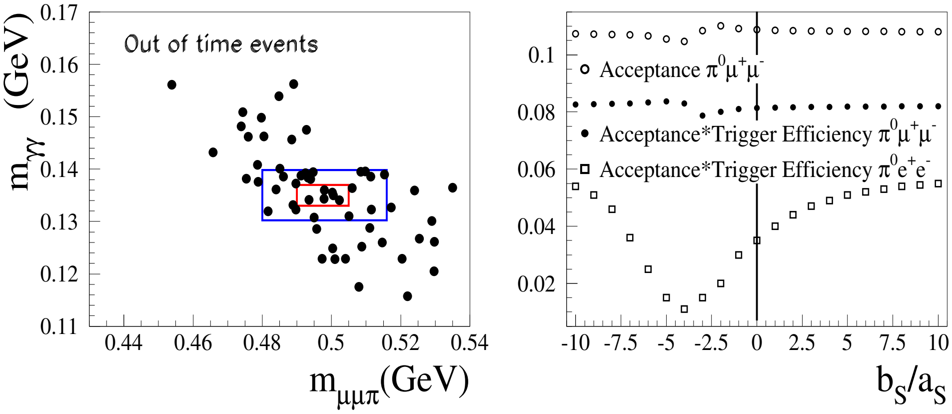

Figure 1: *a) Scatter plot of* $m_{\gamma\gamma}$ *vs* $m_{\mu\mu\pi^0}$ *for* $\mu^+\mu^-\pi^0$ *events in the out-of-time window. The* 2.5σ *and the* 6σ *signal and control regions are also shown. b) Acceptance dependence on the ratio of the form factor parameters* b_S/a_S*, for the* $K_S \to \pi^0\mu^+\mu^-$ *and* $K_S \to \pi^0e^+e^-$ *channels. .*

and the reconstructed π^0 invariant mass, it is $2.5\sigma \times 2.5\sigma$ wide. The signal region and a control region of 6σ were masked while the selection cuts and background were determined using data and MC, once they were fixed the control and signal regions were subsequently unmasked.

3.1 $K_S \to \pi^0\mu^+\mu^-$

A detailed explanation of the selection cuts can be found in ref. 3).

3.1.1 Background

The dominant source of background has been found to be the so-called *accidental background*. Accidental background was caused by the overlap of particles coming from two separate decays that happened to be in time and fake the signal, for example, an overlap between the decays $K_S \to \pi^+\pi^-$, where both pions decayed ($\pi \to \mu\nu$), and $K_S \to \pi^0\pi^0$, where two photons missed the detector.

The accidental background was determined from the data out-of-time sidebands, using the event selection with relaxed timing requirements (the in-time window was $3ns$ wide). The out-of-time window was $119ns$ wide, the corresponding event distribution in the m_K *vs* m_{π^0} plane is shown in fig. 1*a* . The accidental background has been estimated to be: $0.18^{+0.18}_{-0.11}$

Background originated from a single decay was studied and only two of the possible sources were found to be non-negligible, namely, $K_L \to \pi^+\pi^-\pi^0$ where both charged pions have decayed in flight and $K_L \to \mu^+\mu^-\gamma\gamma$. These two backgrounds were studied using data and MC. To achieve the required statistic precision the final background estimation was obtained using MC, that has been validated through careful comparison with data. Background due to $K_L \to \pi^+\pi^-\pi^0$ was estimated to be < 0.018 events at 90%CL. Background due to $K_{L,S} \to \mu^+\mu^-\gamma\gamma$ was estimated to be $0.04^{+0.04}_{-0.03}$ events.

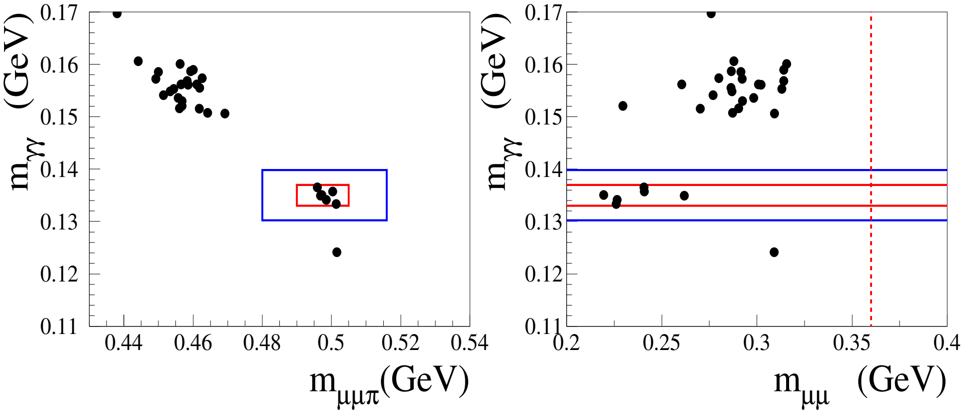

Figure 2: *Selected $K_S \to \pi^0\mu^+\mu^-$ events together with the events that pass all the selection cuts but the m_k and m_{π^0} reconstructed invariant mass cuts. 2.5σ signal region and 6σ control region are shown with solid line. a) $m_{\gamma\gamma}$ vs $m_{\mu\mu\pi^0}$ plane. b) $m_{\gamma\gamma}$ vs $m_{\mu\mu}$ plane.*

The total background in signal region was estimated to be $0.22^{+0.18}_{-0.11}$ events.

3.1.2 Result

As shown in fig. 2, six events were found in signal region, with a background estimate of $0.22^{+0.18}_{-0.11}$ events.

It was checked that there was no accumulation of events close to signal region when the main analysis cuts were relaxed. No events were found in signal region for the equivalent same sign ($\pi^0\mu^+\mu^+$ and $\pi^0\mu^-\mu^-$) selections.

Branching Ratio

The branching ratio was measured to be:

$$Br(K_S \to \pi^0\mu^+\mu^-) = (2.9^{+1.4}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9} \qquad (1)$$

The K_S flux has been determined using 132 million of $K_S \to \pi^+\pi^-$ from a minimum bias trigger. The K_S flux, in the same fiducial volume as used for the signal channel and without correcting for inefficiencies that were common to the signal, was found to be $(2.50 \pm 0.08) \times 10^{10}$.

The trigger efficiency was measured from a minimum bias data sample, selecting $K_L \to \pi^0\pi^+\pi^-$ decays where both pions have decayed into muons.

The dominant source of systematic error is the uncertainty in the form factor of the $K_S \to \pi^0\mu^+\mu^-$, which affects the geometrical acceptance correction. Usually the form factor is parametrized as $W(z) = a_S + b_S \cdot z$ where $z = m^2_{\mu\mu}/m^2_K$. On fig. 1 *b* we can see how the geometrical acceptance varies as a function of the ratio of the parameters b_S/a_S.

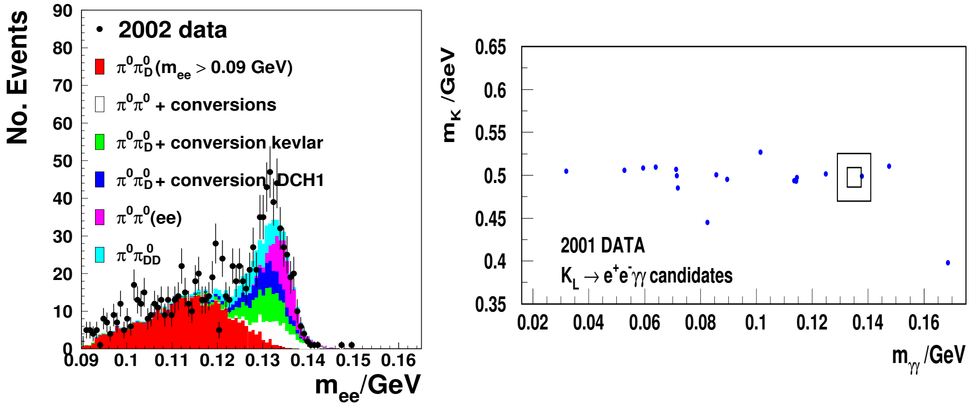

Figure 3: *a) Distribution of* m_{ee} *for events rejected by the* $m_{e^+e^-} < 0.165$ *cut after all the other selection cuts have been applied. Superimposed are shown the MC predictions from all important sources. b) Scatter plot of* $m_{ee\gamma\gamma}$ *vs* $m_{\gamma\gamma}$ *for events selected as* $K_L \to e^+e^-\gamma\gamma$ *in the 2001 data.*

3.2 $K_S \to \pi^0 e^+ e^-$

A detailed explanation of the event selection can be found in ref. $^{2)}$.

3.2.1 Background

The dominant background was coming from $K_S \to \pi^0\pi^0$ where one or more photons from the usual $\pi^0 \to \gamma\gamma$ decay converted or one or both of the π^0s undergoes Dalitz decay ($\pi^0_D \to e^+e^-\gamma$). This background was suppressed cutting on the reconstructed invariant mass of the particles combined in pairs: Events with $m_{e^+e^-} < 0.165$ GeV or with both $m_{e^+\gamma}$ and $m_{e^-\gamma}$ below 0.165 GeV were rejected. The events rejected by the $m_{e^+e^-} < 0.165$ GeV cut are shown in fig. 3 *a* together with MC simulation of the dominant backgrounds.

Three sources of background were found to be non-negligible:

- The $K_{L,S} \to e^+e^-\gamma\gamma$ background was measured using K_L data from the 2001 run, with a statistics $\sim$ 10 times the one expected in 2002 data. The distribution of $m_{ee\gamma\gamma}$ *vs* $m_{\gamma\gamma}$ is shown in fig. 3 *b*. Using a linear extrapolation from the low $m_{\gamma\gamma}$ region to signal region, the background from this channel was estimated to be $0.08^{+0.03}_{-0.02}$ events.

- The $K_S \to \pi^0_D\pi^0_D$ background was estimated to be less than 0.01 events, using a Monte Carlo sample 30 times greater than the data.

- The accidental background was determined relaxing the timing cuts for the signal and control regions. A further correction was applied to account for background shape in the $m_{\gamma\gamma}$ *vs* $m_{e^+e^-\gamma\gamma}$ plane as predicted by a simulation. The accidental background was estimated to be $0.07^{+0.07}_{-0.03}$ events in signal region.

The total background was estimated to be $0.15^{+0.10}_{-0.04}$ events.

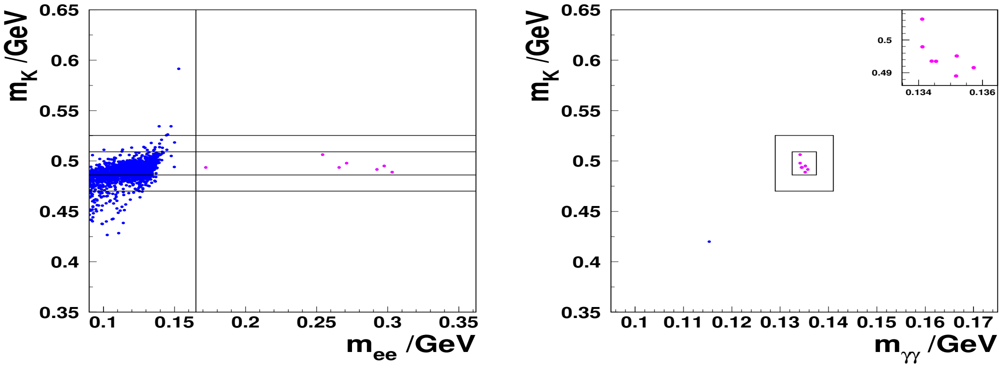

Figure 4: *Selected $K_S \rightarrow \pi^0 e^+ e^-$ events together with the events that pass all the selection cuts but the m_{ee}, m_k and m_{π^0} reconstructed invariant mass cuts. 2.5σ signal region and 6σ control region are shown with solid line. a) $m_{ee\gamma\gamma}$ vs m_{ee} plane. b) $m_{ee\gamma\gamma}$ vs $m_{\gamma\gamma}$ plane.*

3.2.2 Result

As shown in fig. 4, seven events were found in signal region, with a background estimate of $0.15^{+0.10}_{-0.04}$ events.

It was checked that there was no accumulation of events close to signal region when the main analysis cuts were relaxed. No events were found in signal region for the equivalent same sign ($\pi^0 e^+ e^+$ and $\pi^0 e^- e^-$) selections.

Branching Ratio

The trigger efficiency was measured to be 99.0% selecting $K_S \rightarrow \pi^0 \pi^0_D$ from a minimum bias data sample.

The K_S flux has been determined using $K_S \rightarrow \pi^0 \pi^0_D$ collected using the same trigger than for the signal. The total number of K_S decaying within the fiducial volume was $(3.51 \pm 0.17) \times 10^{10}$.

The acceptance depends on the form factor, as shown in fig. 1*b*. A geometrical acceptance was calculated for each event, according to its m_{ee}, using a unit form factor. The average acceptance was found to be 0.066 ± 0.004.

The branching ratio for $m_{ee} > 0.165$ GeV was measured to be:
$Br(K_S \rightarrow \pi^0 e^+ e^-)_{m_{ee}>0.165} = (3.0^{+1.5}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$

Using a vector matrix element with no form factor dependence, the measured branching ration was extrapolated to the full m_{ee} spectrum to obtain:

$$Br(K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.9}_{-2.3}(stat) \pm 0.8(syst)) \times 10^{-9} \qquad (2)$$

The systematic error is dominated by the uncertainty in the extrapolation due to the form factor dependence.

4 $K_S \rightarrow \pi^0 l^+ l^-$ Discussion

4.1 Test of Chiral Perturbation Theory

Chiral Perturbation Theory predicts the branching ratio for $K_S \rightarrow \pi^0 l^+ l^-$, using the usual parametrization of the form factor as a function of a_S and b_S we have (6):

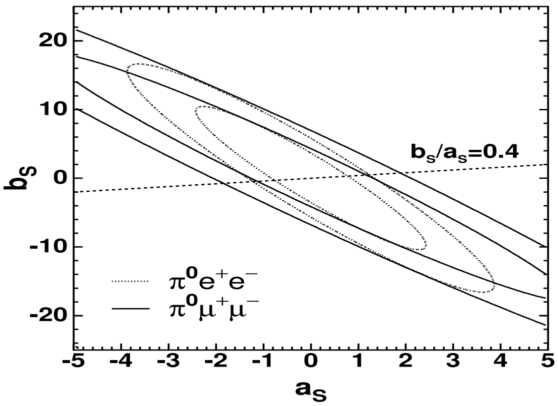

Figure 5: *Allowed regions of a_s and b_s determined from the observed number of $K_S \to \pi^0\mu^+\mu^-$ and $K_S \to \pi^0 e^+e^-$ events separately. The region between the inner and outer solid (dashed) elliptical contours is the allowed region for the $K_S \to \pi^0\mu^+\mu^-$ ($K_S \to \pi^0 e^+e^-$) at 68% CL.*

$$\begin{aligned} &Br(K_S \to \pi^0\mu^+\mu^-) = \\ &\quad \left[0.07 - 4.52a_S - 1.50b_S + 98.7a_S^2 + 57.7a_Sb_S + 8.95b_S^2\right] \times 10^{-11} \qquad (3) \\ &Br(K_S \to \pi^0e^+e^-) = \\ &\quad \left[0.01 - 0.76a_S - 0.21b_S + 46.5a_S^2 + 12.9a_Sb_S + 1.44b_S^2\right] \times 10^{-10} \qquad (4) \end{aligned}$$

Using the vector meson dominance (VMD) model, we can extract $|a_S|$ independently from each of the measured branching ratios, since:

$$Br(K_S \to \pi^0\mu^+\mu^-) \simeq 1.2 \times 10^{-9} a_S^2 \qquad (5)$$

$$Br(K_S \to \pi^0e^+e^-) \simeq 5.2 \times 10^{-9} a_S^2 \qquad (6)$$

So using the $K_S \to \pi^0\mu^+\mu^-$ branching ratio (eq. 1) as an input in eq. 5 we get: $|a_S| = 1.55^{+0.38}_{-0.32} \pm 0.05$. Analogously, for the $K_S \to \pi^0e^+e^-$, feeding eq. 2 into eq. 6 we get: $|a_S| = 1.06^{+0.26}_{-0.21} \pm 0.07$. Both measurements are compatible within 1σ.

The a_S and b_S parameters can be obtained from a combined analysis of $Br(K_S \to \pi^0\mu^+\mu^-)$ and $Br(K_S \to \pi^0e^+e^-)$ using eq.4 and eq.3. The 68% confidence level contours in the a_S, b_S plane derived separately from the measured decay rates of $Br(K_S \to \pi^0\mu^+\mu^-)$ (solid) and $Br(K_S \to \pi^0e^+e^-)$ (dashed) are shown in fig. 5. The VMD prediction $b_S/a_S = 0.4$ is also shown, it falls within both sets of contours.

The ratio of the branching ratios can be predicted by the theory more accurately than the branching ratios. The value measured by NA48 $Br(K_S \to \pi^0\mu^+\mu^-)/Br(K_S \to \pi^0e^+e^-) = 0.48^{+0.31}_{-0.32} \pm 0.08$ agrees within 1σ with the vector meson dominance (VMD) prediction of 0.23.

4.2 CPV Component of $K_L \to \pi^0l^+l^-$

The CP violating component of the decay $K_L \to \pi^0l^+l^-$ can be predicted as a function of the corresponding $K_S \to \pi^0l^+l^-$ branching ratio and $Im(\lambda_t)$ to within a sign ambiguity [8) 7)]:

$$Br(K_L \to \pi^0 l^+ l^-)_{\rm CPV} \times 10^{12} = C_{\rm IND} \pm C_{\rm INT} \left(\frac{Im(\lambda_t)}{10^{-4}}\right) + C_{\rm DIR} \left(\frac{Im(\lambda_t)}{10^{-4}}\right)^2 \tag{7}$$

where: $\lambda_t = V_{td}V^*_{ts}$, $C_{\rm DIR}$ is the direct CPV component, $C_{\rm IND}$ is the indirect CPV component, and it is proportional to the corresponding $Br(K_S \to \pi^0 l^+ l^-)$, and $C_{\rm INT}$ is the contribution due to the interference between the direct and indirect components, and it is proportional to $\sqrt{Br(K_S \to \pi^0 l^+ l^-)}$.

Using the measured branching ratios and $Im(\lambda_t) = (1.36 \pm 0.12) \times 10^{-4}$, we have:

$Br(K_L \to \pi^0 \mu^+ \mu^-)_{CPV} \approx (9_{\rm indirect} \pm 6_{\rm interference} + 1_{\rm direct}) \times 10^{-12}$

$Br(K_L \to \pi^0 e^+ e^-)_{CPV} \approx (17_{\rm indirect} \pm 9_{\rm interference} + 5_{\rm direct}) \times 10^{-12}$

The expected corresponding CPC components are of the order of 10^{-12} or below 8) 7).

5 Radiative $Ke3$ Branching Ratio

A measurement of the relative branching ratio of the decay $K^0 \to \pi^\pm e^\mp \nu\gamma$ ($Ke3\gamma$) with respect to $K^0 \to \pi^\pm e^\mp \nu$ ($Ke3$) decay has been performed by NA48 with 1999 data, the preliminary result is:

$$\frac{Br(K^0 e3\gamma, E^\star_\gamma > 30MeV, \theta^\star_{e\gamma} > 20^\circ)}{Br(K^0 e3)} = (0.960 \pm 0.007(stat)^{+0.012}_{-0.011})(syst)\% \tag{8}$$

More than 18000 $Ke3\gamma$ and $5 \cdot 10^6$ $Ke3$ decays were selected. This result is compatible with the theoretical predictions, as it is shown in fig. 6, and disagrees with the previous high statistic experimental measurement performed by the KTeV Collaboration 9). To determine this branching ratio NA48 has used a model independent method for improving the MC quality and acceptance calculations. It must be noticed that if the Fearing, Fischbach and Smith (FFS) 10) 11) estimations, used by KTeV, are used to calculate the acceptance, the corresponding result is compatible with KTeV measurement.

6 $K_L \to \pi^\pm \pi^0 e^\mp \nu_e$ Branching Ratio and Form Factors

The NA48 Collaboration has investigated the $K_L \to \pi^\pm \pi^0 e^\mp \nu_e$ ($Ke4$) decay. The branching ratio was determined from a sample of 5464 events with an estimated background of 62 events:

$$Br(K_L \to \pi^\pm \pi^0 e^\mp) = [5.21 \pm 0.07(stat) \pm 0.09(syst)] \times 10^{-5} \tag{9}$$

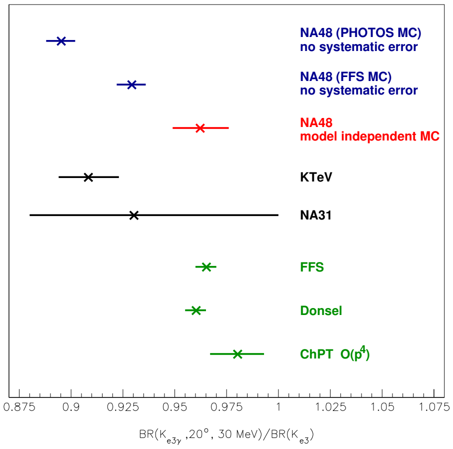

Figure 6: $Br(Ke3\gamma, 20°, 30MeV)/Br(Ke3)$ *NA48 result compared with previous experimental measurements (KTeV and NA31) and theoretical predictions.*

The form factors $\overline{f}_s, \overline{f}_p, \lambda_g$ and $\overline{h}$ were found to be in agreement with previous measurements but they have been determined with higher accuracy:

$$\begin{aligned}\overline{f}_s &= 0.052 \pm 0.006 \pm 0.002\\ \overline{f}_p &= -0.051 \pm 0.011 \pm 0.005\\ \lambda_g &= 0.087 \pm 0.019 \pm 0.006\\ \overline{h} &= -0.32 \pm 0.12 \pm 0.07\end{aligned}$$

The coupling parameter of the chiral Lagrangian $L_3 = (-4.1 \pm 0.2) \times 10^{-3}$ was evaluated from the data.

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