Rare Decays from NA48

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The NA48 collaboration has measured different rare decays using data obtained in normal K_L and K_S beam conditions for the ε'/ε measurement as well as a special run with a high intensity K_S beam. Recent results on rare decays as well as the future project to measure very rare K_S decays are presented.

1 The NA48 Experiment

The fixed target experiment NA48 at CERN is primarily designed to measure direct CP violating effects in neutral kaon decays into two pions using simultaneous K_S and K_L beams. Both beams were produced during 2.4 s proton spills every 14.4 s. The primary 450 GeV/c proton beam, with a nominal flux of 1.5×10^{12} particles per pulse, impinges on a Beryllium target at a downward angle of 2.4 mrad to produce the K_L beam. Part of the non-interacting primary protons are deflected towards a bent Silicium crystal. A small fraction of these protons are channeled by the crystal and are lead onto a second Beryllium target with an intensity of $\sim 3 \times 10^7$ protons per pulse and a downward angle of 4.2 mrad. The K_S target is positioned 7.2 cm above the K_L beam axis 120 m downstream of the K_L target. The two beams cross at the position of the electromagnetic calorimeter with a convergence angle of 0.6 mrad.

In the year 1999, for essentially two days the K_L beam was suppressed and the intensity of the K_S beam increased by a factor of ~ 200 (high intensity K_S run) as a test for the future plans to measure very rare K_S decays.

The most important components of the NA48 detector are the electromagnetic liquid Krypton calorimeter and the spectrometer.

The calorimeter is a quasi-homogeneous detector with an active volume of $\sim 7\,\mathrm{m}^3$ of liquid Krypton. The readout is done by ~ 13000 longitudinal projective $2\times 2\,\mathrm{cm}^2$ cells pointing towards the center of the decay region. The calorimeter has a length of $27\,X_0$ and fully contains electromagnetic showers with energies up to 100 GeV. It has the following energy resolution, with E in GeV:

$$\frac{\sigma(E)}{E} = \frac{(3.2 \pm 0.2)\%}{\sqrt{E}} \oplus \frac{(9 \pm 1)\%}{E} \oplus (0.42 \pm 0.05)\% \,.$$

The first term is dominated by the fluctuations of the shower fraction outside the cluster radius used in the reconstruction. The second term is given by the total noise in the cluster. The last term has contributions from cell-to-cell calibration, the residual gap width variations, the response variation with impact distance from the electrodes and the pulse reconstruction accuracy.

The spectrometer consists of two drift chambers in front of and two after a magnet. They have an octagonal shape and cover an area of $4.5\,\mathrm{m}^2$. Using special electron runs, the following momentum resolution was obtained, with p in GeV/c:

$$\frac{\sigma(p)}{p} = 0.48\% \oplus 0.009 \times p\% \,.$$

A detailed description of the detector can be found elsewhere [1].

2 Decays related to CP-violation

2.1 The decay $K_L \to \pi^+\pi^-e^+e^-$

The investigation of the decay $K_L \to \pi^+\pi^-e^+e^-$ offers a good opportunity to study CP-violation in the neutral kaon system. The amplitude of this decay is dominated by two processes: the CP-conserving direct emission associated with a magnetic dipole transition (M1), and the CP-violating decay with inner bremsstrahlung (Fig. 1).

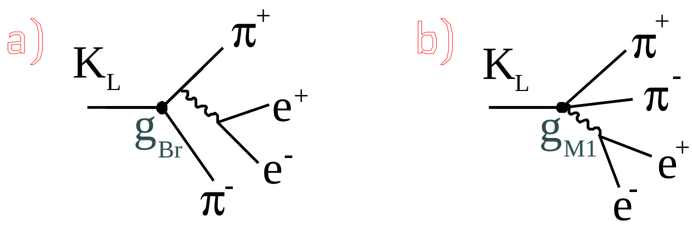

Fig. 1. Contributions for the decay $K_L \to \pi^+\pi^-e^+e^-$:
a) CP-violating bremsstrahlung.
b) CP-conserving direct photon emission.

The interference between the CP-even and the CP-odd amplitudes produces a CP-violating circular polarisation of the virtual photon which gives rise to a large asymmetry in the distribution of the angle Φ between the normals to the $\pi^+\pi^-$ and the e^+e^- planes in the kaon center-of-mass system [2, 3]:

$$\frac{d\Gamma}{d\Phi} = \Gamma_1 \cos^2\Phi + \Gamma_2 \sin^2\Phi + \Gamma_3 \sin\Phi\cos\Phi \ .$$

A non-zero value of Γ_3 leads to an unambiguous signature of CP violation which can be observed in the differential decay rate $\frac{d\Gamma}{d\Phi}$.

During the 1998 and 1999 run periods, more than 1300 $K_L \to \pi^+\pi^-e^+e^-$ candidates were recorded using a four track trigger. Using the values $\tilde{g}_{M1} = 1.35^{+0.20}_{-0.17}$ and $a_1/a_2 = (-0.720 \pm 0.029)\,\mathrm{GeV}^2/c^2$, measured by the KTEV experiment [4], the following branching ratio was obtained (preliminary):

$$\mathrm{BR}(K_L \to \pi^+\pi^-e^+e^-) = (3.1 \pm 0.1_{stat} \pm 0.2_{sys}) \times 10^{-7} \ .$$

The asymmetry $\mathcal{A}_L$ in the $\sin\Phi\cos\Phi$ distribution of the events after acceptance correction is found to be (preliminary):

$$\mathcal{A}_L = (13.9 \pm 2.7_{stat} \pm 2.0_{sys})\% \ .$$

This value agrees with the theoretical predictions [2, 3] as well as with the previously published value by the KTEV collaboration [4].

2.2 The decay $K_S \to \pi^+\pi^-e^+e^-$

The decay $K_S \to \pi^+\pi^-e^+e^-$ is dominated by the inner bremsstrahlung, which is CP-conserving for the K_S decay. Therefore, no significant asymmetry in the Φ distribution is expected.

This decay was first observed by the NA48 experiment based on a very clean sample of 56 events taken in the 1998 run period (Fig. 3).

The following branching ratio is obtained [5]:

$$\mathrm{BR}(K_S \to \pi^+\pi^-e^+e^-) = (4.5 \pm 0.7_{stat} \pm 0.4_{sys}) \times 10^{-5} \ .$$

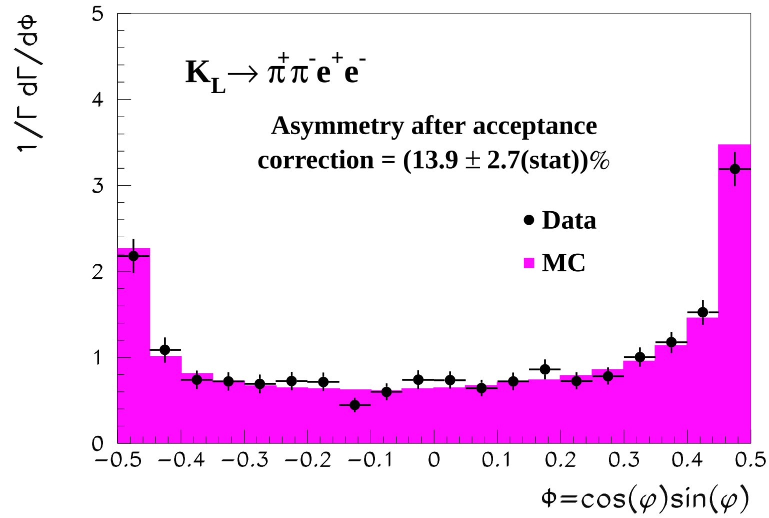

Fig. 2. Asymmetry in the $\sin\Phi\cos\Phi$ distribution after acceptance correction.

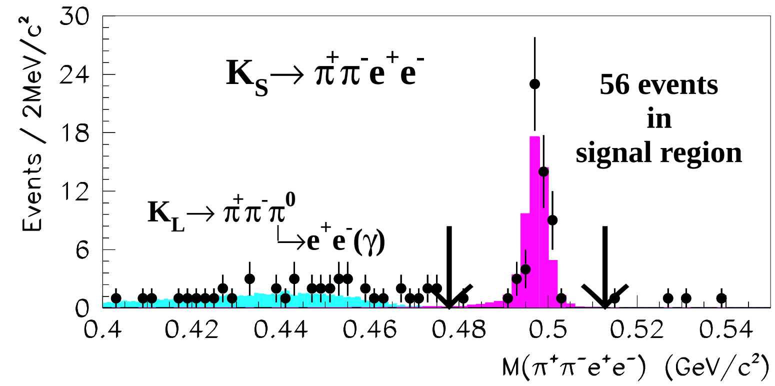

Fig. 3. Invariant $\pi^+\pi^-e^+e^-$ mass distribution for $K_S \to \pi^+\pi^-e^+e^-$ candidates from 1998 data. The signal region is indicated by the arrows.

Combining the 1998 and 1999 data with the special high intensity K_S run data, the branching ratio is obtained based on more than 700 candidates (preliminary):

$$\mathrm{BR}(K_S \to \pi^+\pi^-e^+e^-) = (4.3 \pm 0.2_{stat} \pm 0.3_{sys}) \times 10^{-5} \,.$$

The observed asymmetry $\mathcal{A}_S$ is consistent with 0 (preliminary):

$$\mathcal{A}_S = (-0.2 \pm 3.4_{stat} \pm 1.4_{sys})\% \,.$$

2.3 The decay $K_L \to \pi^0 e^+e^-$

The decay $K_L \to \pi^0 e^+e^-$ is of considerable interest because it yields another possibility to measure direct CP-violation [6, 7, 8, 9]. It's amplitude consists of three parts, which are expected to be of the same order of magnitude (Fig. 4).

1. The direct CP-violating amplitude is predicted to be of the order of some 10^{-12}.

2. The indirect CP-violating amplitude can be estimated from the decay $K_S \to \pi^0 e^+ e^-$, which will be discussed in the next section.

3. The CP-conserving amplitude of the decay $K_L \to \pi^0 e^+ e^-$ via $K_L \to \pi^0 \gamma^* \gamma^*$ can be determined by analysis of the decay $K_L \to \pi^0 \gamma\gamma$, which is described later in this chapter. Additionally, the latter decay is a very good test of chiral perturbation theory.

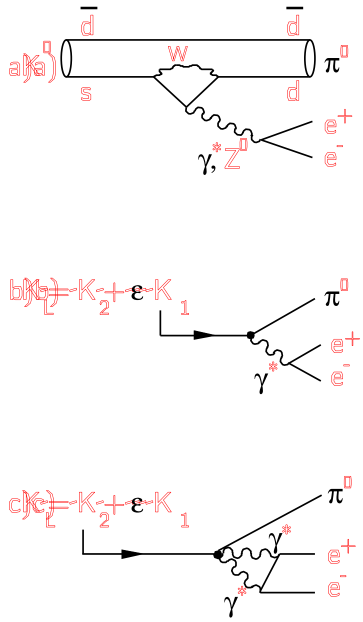

Fig. 4. Feynman diagrams for the decay $K_L \to \pi^0 e^+ e^-$; **(a)** direct CP-violating, **(b)** indirect CP-violating **(c)** and CP-conserving.

Unfortunately, NA48 will not be able to measure the decay $K_L \to \pi^0 e^+ e^-$. Besides its very small branching ratio, the very large background is difficult to suppress, mainly due to the decay $K_L \to e^+ e^- \gamma\gamma$.

This decay has exactly the same signature in the detector as $K_L \to \pi^0 e^+ e^-$, two photons and two electrons, while the invariant mass of the two photons covers the whole kinematically allowed range, including the pion mass. The decay $K_L \to e^+ e^- \gamma\gamma$ has larger branching ratio than $K_L \to \pi^0 e^+ e^-$, and is measured by NA48 (preliminary):

$$\mathrm{BR}(K_L \to e^+ e^- \gamma\gamma) = (6.32 \pm 0.31_{stat} \pm 0.20_{sys} \pm 0.29_{norm}) \times 10^{-7} \,.$$

This measurement is in agreement with the recent KTEV measurement [10].

2.3.1 The decay $K_S \to \pi^0 e^+ e^-$

The decay $K_S \to \pi^0 e^+ e^-$ can be used to estimate the strength of the indirect CP-violating amplitude in the decay $K_L \to \pi^0 e^+ e^-$. In this decay, the direct and indirect CP-violating amplitudes interfere, and their contribution to the branching ratio can be written as [11]:

$$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPV}} \simeq (15.3 a_S^2 - 6.8 a_S \frac{Im(\lambda_t)}{10^{-4}} + 2.8 \frac{Im(\lambda_t)}{10^{-4}}^2) \times 10^{-12} \,,$$

where $\lambda_t = v_{ts}^* v_{td}$ is the relevant combination of CKM matrix elements and describes the strength of the indirect CP violating component in this decay. The parameter a_S is related to the branching ratio of the decay $K_S \to \pi^0 e^+ e^-$ via:

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) = 5.2 \times 10^{-9} a_S^2 \, .$$

According to dimensional analysis in chiral perturbation theory, $a_S \sim \mathcal{O}(1)$.

The NA48 analysis is based on the data recorded during the high intensity K_S run taken in 1999. After all cuts, no signal event was found (Fig. 5), leading to an upper limit of 2.44 expected events.

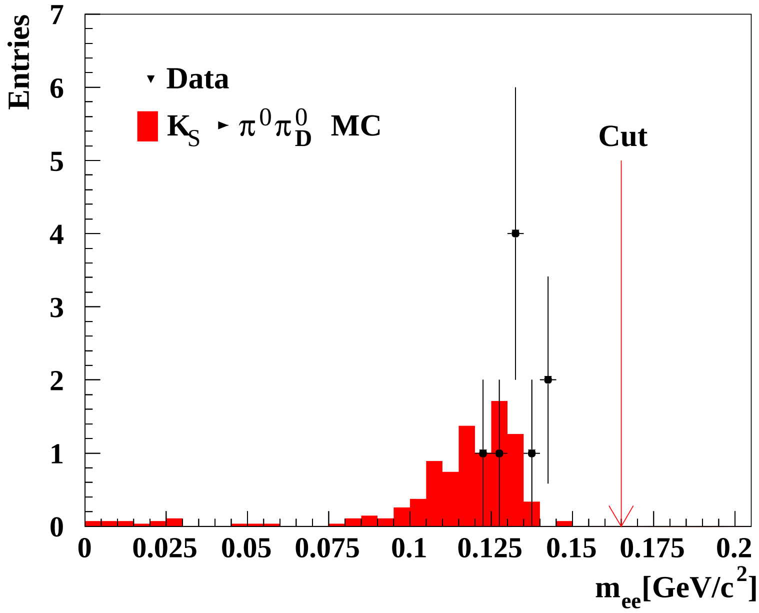

Fig. 5. The invariant e^+e^- mass distribution before the last cut. The background is located in the low mass region and removed by the shown cut.

Using the decay $K_S \to \pi^0 \pi^0_D$ with more than 77000 candidates as normalization channel, a nominal K_S flux of 2.8×10^8 was calculated, which leads to the following upper limit [12]:

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7} \quad (90\,\%\; CL) \, .$$

This improves the previous NA31 measurement [13] by a factor of 10. An upper limit for the indirect CP violating part of the branching ratio can be determined:

$$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\text{indirect CPV}} < 4.1 \times 10^{-10} \, .$$

2.3.2 The decay $K_L \to \pi^0 \gamma\gamma$

The decay $K_L \to \pi^0 \gamma\gamma$ is not only interesting because of the possibility to estimate the CP-conserving amplitude of the decay $K_L \to \pi^0 e^+ e^-$ but also because it is a very good test of chiral perturbation theory up to the order $\mathcal{O}(p^6)$. The first order ($\mathcal{O}(p^2)$) is 0 because all external particles are neutral. The second order ($\mathcal{O}(p^4)$) can be fully calculated by chiral perturbation theory [14], but the expected branching ratio is a factor of two lower than the measured value [15, 16, 17]. Therefore, in the next order calculation, contributions of vector meson exchange have been included [18, 19, 20, 21]. The strength of the vector meson dominance can be described by the effective vector coupling parameter a_V. The spectra of the Lorentz invariant variables and the branching ratio are dependent on this parameter a_V (Fig. 6).

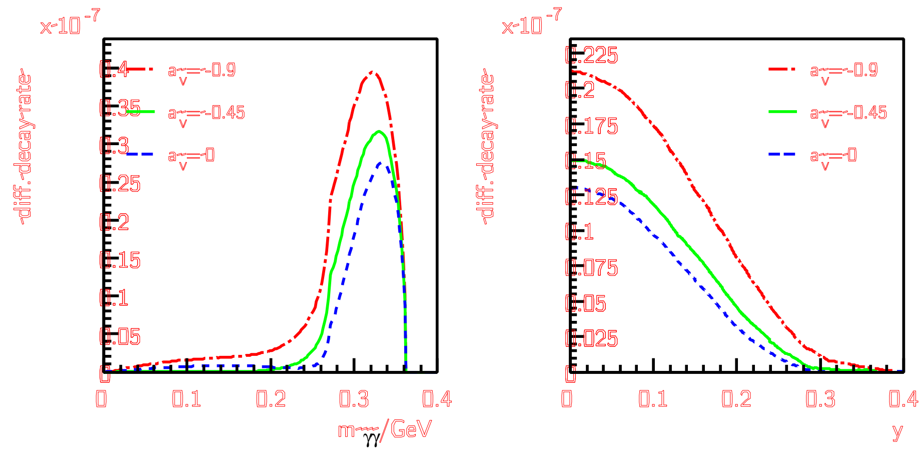

Fig. 6. The Lorentz invariant variables (invariant diphoton mass $m_{\gamma\gamma}$ and difference of the energies of the initial photons in the kaon center of mass frame y) are plotted in dependence on the effective vector coupling parameter a_V.

This decay was analysed using the NA48 data of the 1998 and 1999 run periods. The main difficulty in the analysis of this decay is the large background due to the decays $K_L \to 3\pi^0$ and $K_L \to \pi^0\pi^0$, which have a much higher branching ratio than the investigated decay. About 2500 candidates were found in the signal region.

The best fitting effective vector coupling parameter was found by fitting the both Lorentz invariant distributions at the same time using a two-dimensional maximum likelihood fit:

$$a_V = -0.46 \pm 0.03_{stat} \pm 0.03_{sys} \pm 0.02_{theo} \,.$$

For this value of a_V, both distributions are well described (Fig. 7). The parameter a_V has a deviation from the previous KTEV [17] measurement of 3σ.

Using the acceptance for this a_V value, the following branching ratio is found:

$$\mathrm{BR}(K_L \to \pi^0\gamma\gamma) = (1.36 \pm 0.03_{stat} \pm 0.03_{sys} \pm 0.03_{norm}) \times 10^{-6} \,.$$

This is the most precise measurement. The KTEV experiment has measured a higher value with 3σ deviation from this measurement.

From the knowledge of the branching ratio in the low $m_{\gamma\gamma}$ mass region it should be possible to calculate a model independent upper limit for the CP-conserving contribution to the decay amplitude of $K_L \to \pi^0 e^+ e^-$. In the lower mass region an upper limit can be quoted:

$$\mathrm{BR}(K_L \to \pi^0\gamma\gamma)^{30\,\mathrm{MeV}/c^2 < m_{\gamma\gamma} < 110\,\mathrm{MeV}/c^2}_{y<0.2} < 6 \times 10^{-9} \quad (90\,\%\; CL) \,.$$

3 Further interesting decays

3.1 The decay $K_S \to \gamma\gamma$

The decay $K_S \to \gamma\gamma$ offers like the previously discussed decay $K_L \to \pi^0\gamma\gamma$ a good opportunity to test chiral perturbation theory up to higher loops. The branching ratio of the decay $K_S \to \gamma\gamma$ can be unambiguously predicted to be 2.25×10^{-6} with an error of less than $10\,\%$ [22, 23, 24].

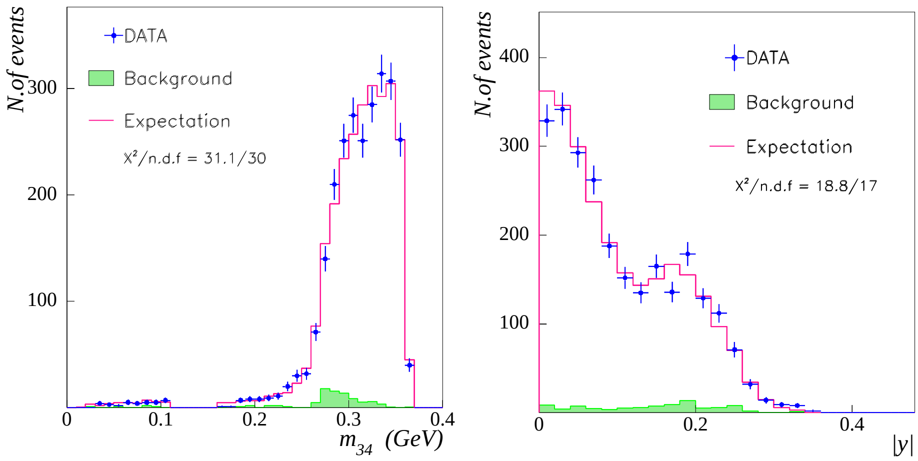

Fig. 7. Data, background, and theoretical expectation for the best fitting effective vector coupling parameter a_V are shown for the Lorentz invariant variables.

The analysis is based on the data taken during the high intensity K_S run in 1999. The $K_S \to \gamma\gamma$ candidates are mainly diluted with $K_L \to \gamma\gamma$, as the K_L and K_S fluxes at the production target are equal. With the known $K_L \to \gamma\gamma$ branching ratio of $(5.92 \pm 0.15) \times 10^{-4}$ and the total flux it is possible to estimate this contribution. The number of $K_S \to \gamma\gamma$ events is calculated using a maximum likelihood fit of the vertex distribution in direction of the beam (Fig. 8), which differs for K_L and K_S decays due to the different kaon life times. A total number of 149 ± 21 $K_S \to \gamma\gamma$ events is estimated.

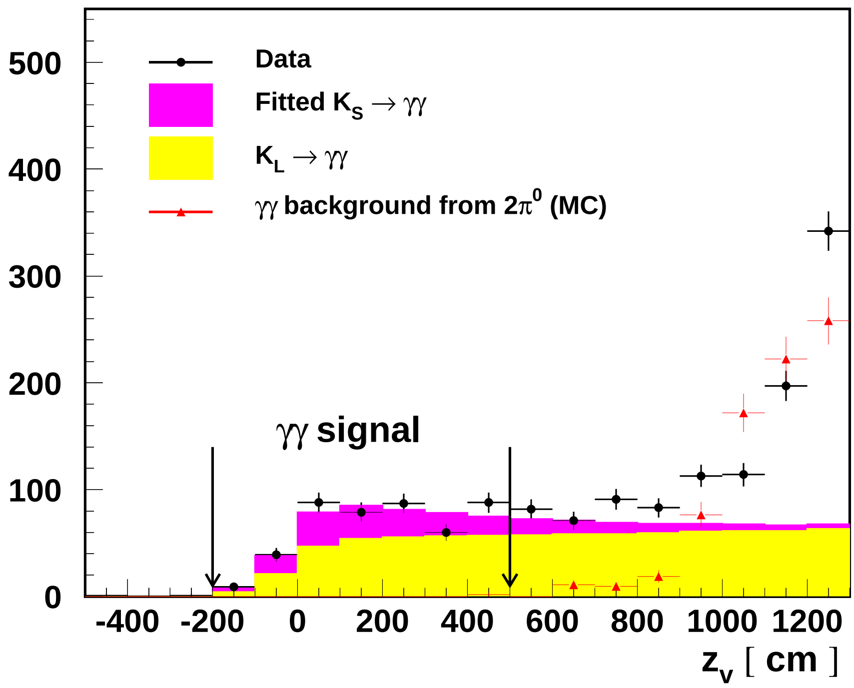

Fig. 8. Data and MC distribution for the z vertex.

The remaining background has two sources: The decay $K_S \to \pi^0\pi^0$ with two lost photons can fake a signal, but this is shifted to a higher vertex region due to the wrong reconstructed vertex. Using 10^8 generated $K_S \to \pi^0\pi^0$ MC events, a background of 2 ± 2 events is estimated. The second background, due to neutral hadronic events, is estimated to be 11 ± 8 events.

From this, the following branching ratio is derived [25]:

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

This result is in good agreement with the theoretical prediction and with the previous measurement of NA31 [26].

3.2 The $K_L \to 3\pi^0$ Dalitz Plot

The decay $K_L \to 3\pi^0$ is not a rare decay, but nevertheless the analysis of its Dalitz plot yields some very interesting results. Generally, the Dalitz plot distributions of $K \to \pi\pi\pi$ decays can be expanded in powers of the Dalitz plot variables u and v [27]:

$$|\mathcal{M}(u,v)|^2 \propto 1 + gu + jv + hu^2 + kv^2 ;$$

$$u = \frac{s_3 - s_0}{m_{\pi^+}^2} , \quad v = \frac{s_1 - s_2}{m_{\pi^+}^2} ;$$

$$s_0 = \frac{s_1 + s_2 + s_3}{3} , \quad s_i = (p_K - p_i)^2 , \quad i = 1, 2, 3 ,$$

with the four-momenta of the decaying kaon p_K and the i-th pion p_i ($i = 3$ for the odd charge pion). For the special case of the decay $K_L \to 3\pi^0$ this expression is reduced to [28]:

$$|\mathcal{M}_{000}(R^2, \Theta)|^2 \propto 1 + hR^2 ;$$

$$R^2 = u^2 + v^2/3 , \quad \theta = \arctan\left(v/\sqrt{3}u\right) ;$$

A positive value of the quadratic slope parameter h would mean that asymmetric states are favoured while for a negative value symmetric states are prefered. Furthermore, combining the parameter h with the linear and quadratic slope parameters in the $K^\pm \to \pi^\pm\pi^\mp\pi^\pm$ decays gives a possibility to probe the validity of the $\Delta I = 1/2$ rule. The quadratic slope parameter h has been estimated in the framework of chiral perturbation theory leading to different results, e.g.$(-12 \pm 4) \times 10^{-3}$ [29] and $+1.4 \times 10^{-3}$ [30].

The analysis is based on 14.7×10^6 fully reconstructed $K_L \to 3\pi^0$ decays and 11.8×10^6 MC events. To estimate the quadratic slope parameter h, the R^2 distribution is corrected for the acceptance using a Monte Carlo with $h = 0$. The following value is measured [31]:

$$h = (-6.1 \pm 0.9_{stat} \pm 0.5_{sys}) \times 10^{-3} .$$

This result is in agreement with the last result of the E731 experiment [32] and the most precise measurement.

4 Future of NA48

In the year 2002 NA48 will use a modified K_S beam line in order to investigate not only K_S decays, but also to analyze neutral hyperon decays with a much higher intensity. The SPS duty cycle will be changed to 16.8 s with a longer spill duration of 5.2 s. With a primary proton flux of 1×10^{10} per pulse a rate of about 3×10^{10} K_S decays per year.

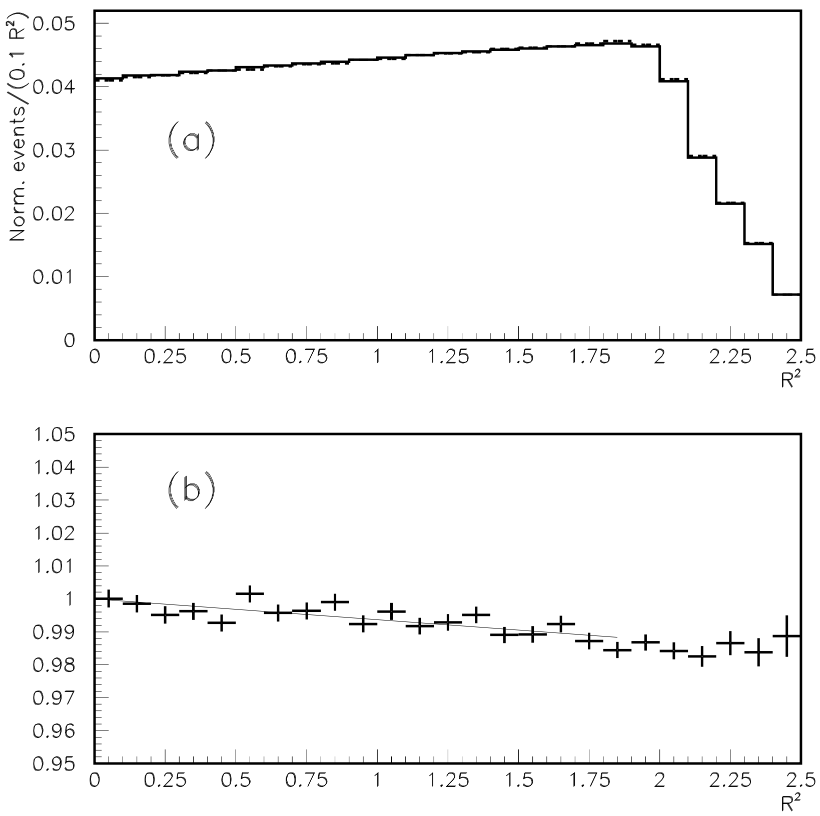

Fig. 9. Distribution of the variable R^2 **(a)** shows the distribution of R^2 for data (dots) and MC (line), while **(b)** shows the ratio of data/MC (crosses) with the fit (line).

Table 1. Rare K_S decay modes

Decay	Theory	No. of exp. events in NA48
$K_S \to \gamma\gamma$	2.1×10^{-6}	24 000
$K_S \to \pi^0\gamma\gamma$	3.8×10^{-8}	114
$K_S \to \pi^0\pi^0\gamma\gamma$	5.6×10^{-9}	7
$K_S \to e^+e^-\gamma$	3.4×10^{-8}	304
$K_S \to \mu^+\mu^-\gamma$	8×10^{-10}	12
$K_S \to \pi^0 e^+e^-$	5×10^{-9}	7
$K_S \to \pi^0\mu^+\mu^-$	1×10^{-9}	3
$K_S \to \pi^+\pi^-\gamma$	1.8×10^{-3}	5.3×10^6
$K_S \to \pi^+\pi^-e^+e^-$	3.6×10^{-5}	54 000
$K_S \to \pi^+\pi^-\pi^0$	5.6×10^{-9}	$2.6 \times 10^6/\tau_S$
$K_S \to 3\pi^0$	2.5×10^{-9}	$1.5 \times 10^6/\tau_S$

One of the main goals of this run is the search for the decay $K_S \to \pi^0 e^+e^-$, for which the expected signal rate is 7 events per year. There are a lot of other interesting decays, which can be investigated. Table 1 shows a list of the decays to be measured with theoretical branching ratios and expected number of events.

In further future, NA48 plans to establish a $K^\pm$ program, which is discussed in this workshop by V. Kekelidze.

Conclusion

Rare decays are a powerful instrument to test theory in different physics fields, ranging from CP violation to chiral perturbation theory. NA48 has measured many different rare decays and has shown its capability to investigate rare K_S decays with high sensitivity in the near future.

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