Review of Chiral Perturbation Theory experimental results in kaon decays

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Chiral Perturbation Theory, as a low-energy effective field theory of strong interactions, is a very useful tool to study the interactions of kaons. Both in the semileptonic sector and in the non-leptonic one, several results have been achieved by NA48, KTeV, KLOE and ISTRA+. Recent results from both neutral and charged kaons are reviewed.

1. Chiral Perturbation Theory

Chiral Perturbation Theory [1] is the effective quantum field theory for hadronic interactions below the breaking scale of the chiral symmetry ($\approx$ 1 GeV). At these energies, the spectrum of the theory is simple and it consists only of the octet of light pseudoscalar mesons π, K and η. χPT is now a mature technique able to provide high precision predictions for the mesonic sector, for instance in K decays.

2. Active kaon decay experiments

Several experiments around the world are studying kaon decays, being able to do accurate measurements to be compared with χPT predictions. Each of them has its own peculiar characteristics which provide complementary measurements. NA48 at CERN combines the use of high energy neutral and charged kaon beams with precision measurement of photon energies. KLOE in Frascati is complementing high energy measurement with low-energy, tagged kaon decays. KTeV at FNAL has collected the greatest sample of K_L decays in the world for rare decay studies. ISTRA+ in Protvino uses intermediate energy negative kaon beams to study rare decays.

3. Radiative decays

3.1. $K_L \to \gamma\gamma$

In this decay $O(p^4)$ contributions vanishes and $O(p^6)$ ones mediated by pseudoscalar mesons depend on the value of singlet-octet mixing [2]. NA48 has performed a measurement of the branching ratio of $K_L \to \gamma\gamma$ normalized to $K_L \to 3\pi^0$ using K_L data collected in 2000. KLOE has made the same measurement with a sample of $\approx 1.6 \cdot 10^8 K_L$ tagged by $K_S \to \pi^+\pi^-$.

The results from NA48 [3] and KLOE [4] are respectively:

$$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.81 \pm 0.01_{st} \pm 0.02_{sy})\cdot 10^{-3}$$

$$\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0) = (2.79 \pm 0.02_{st} \pm 0.02_{sy})\cdot 10^{-3}$$

The corresponding decay width agrees with $O(p^4)$ predictions, provided that the mixing angle is close to the value, measured by KLOE, of $-12.9^{+1.9}_{-1.6}$ degrees.

3.2. $K_S \to \gamma\gamma$

$K_S \to \gamma\gamma$ is interesting because it is calculable in $O(p^4)$ χPT with no counterterms and it is sensitive to loops [5][6][7]. The theoretical prediction for the BR is $(2.1 \pm 0.2)\cdot 10^{-6}$. Previous measurements by NA31 [8] and NA48 [9] gave respectively

$$BR(K_S \to \gamma\gamma) = (2.4 \pm 0.9)\cdot 10^{-6}$$
$$BR(K_S \to \gamma\gamma) = (2.58 \pm 0.36_{st} \pm 0.22_{sy})\cdot 10^{-6}.$$

A better measurement has been performed by NA48 using data from the 2000 run. The normalisation channel is $K_S \to \pi^0\pi^0$.

The subtraction of the irreducible background from $K_L \to \gamma\gamma$, which amounts to 1.5 times the

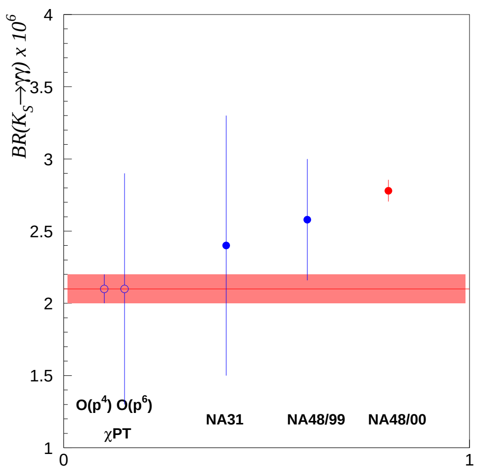

Figure 1. $K_S \to \gamma\gamma$: *Theoretical predictions and measured values*

K_S channel, is done using the NA48 measurement of the $K_L \to \gamma\gamma$ branching ratio quoted above.

With a total number of 19916 $K_{S,L} \to \gamma\gamma$ events, the result is [3]

$$BR(K_S \to \gamma\gamma) = (2.78 \pm 0.06_{st} \pm 0.03_{sy} \pm 0.02_{ext}) \cdot 10^{-6}$$

This result is compatible with previous measurements (Fig. 1), but it shows a 30% difference wrt to $O(p^4)$ χPT predictions, indicating a possible large $O(p^6)$ contribution.

3.3. $K_S \to \pi^0\gamma\gamma$

The study of $K_S \to \pi^0\gamma\gamma$, as in other radiative non-leptonic kaon decays, is useful to check χPT predictions for the low energy hadron dynamics. In the decay $K_S \to \pi^0\gamma\gamma$ the photon pair is produced by a pseudo-scalar meson. A measurement of the branching ratio can give information on possible extra non-pole contributions [10]. The prediction for the branching ratio is limited to the kinematical region $z = m^2_{\gamma\gamma}/m^2_K > 0.2$ and it is $3.8 \cdot 10^{-8}$ [11]. Additional information from the z spectrum can determine, if sufficient statistics is available, the momentum dependence of the weak vertex.

Using data from the 1999 K_S run, NA48 has published [12] the upper limit

$$BR(K_S \to \pi^0\gamma\gamma)_{z>0.2} < 3.3 \cdot 10^{-7}$$

at 90% confidence level.

Data has been collected by NA48 in the 2000 run using the same trigger for $K_S \to \pi^0\pi^0$ and $K_S \to \pi^0\gamma\gamma$, so that many systematic uncertanties cancel out.

After the selection the final sample consists of 31 events, with a background estimation is 13.7±3.2 events, half of which due to pile-up accidentals. 17.3±6.4 signal events are obtained after background subtraction, which is the first observation of this decay. Using a normalization sample of about $285 \cdot 10^3$ events, one gets

$$\Gamma(K_S \to \pi^0\gamma\gamma)_{z>0.2}/\Gamma(K_S \to \pi^0\pi^0) = (1.57 \pm 0.51_{st} \pm 0.29_{sy}) \cdot 10^{-7}$$

Using $BR(K_S \to \pi^0\pi^0)$ from PDG one obtains [13]

$$BR(K_S \to \pi^0\gamma\gamma)_{z>0.2} = (4.9 \pm 1.6_{st} \pm 0.9_{sy}) \cdot 10^{-8} = (4.9 \pm 1.8) \cdot 10^{-8}$$

in agreement with [11].

The z distribution of the events after background subtraction has been compared with z distributions of simulated events using two different decay generators, one with χPT matrix element and the other with pure phase space (Fig. 2). The experimental data agree with both calculations and none of the two predictions can be preferred.

3.4. $K_L \to \pi^0\gamma\gamma$

$K_L \to \pi^0\gamma\gamma$ decay is important because the decay rate prediction from $O(p^4)$ χPT is finite, but 2-3 times smaller than the measured one [11]. Going to $O(p^6)$ and including vector meson exchange, the measured rate is reproduced and a tail at low $m_{\gamma\gamma}$ is predicted [14]. The vector meson dominance contribution is parametrized by a_v [5][15], to be measured, and the low $m_{\gamma\gamma}$ tail determines the CPC amplitude to the decay $K_L \to \pi^0 e^+ e^-$ [16]. Predictions from χPT are $BR(K_L \to \pi^0\gamma\gamma) = 1.5 \cdot 10^{-6}$ and a_v = -0.7.

Data from 1998 and 1999 NA48 runs were selected using the same trigger as the normalization

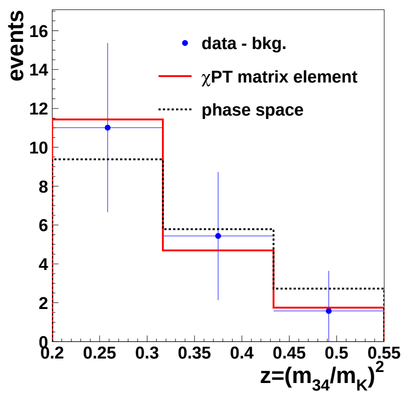

Figure 2. $K_S \to \pi^0\gamma\gamma$: *$z_q$ distribution for data and two theoretical models*

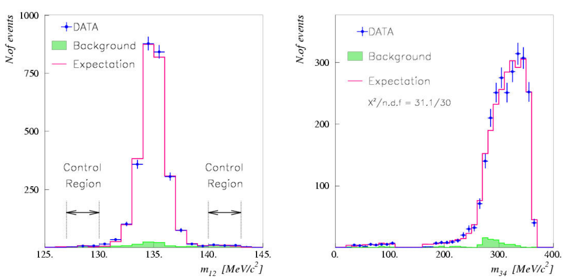

Figure 3. $K_L \to \pi^0\gamma\gamma$: *Events in the signal region and $m_{\gamma\gamma}$ distribution*

channel $K_L \to \pi^0\pi^0$ to cancel out many systematic uncertainties.

≈ 2500 events were found in the signal region 132 MeV < M_{π^0} < 138 MeV [17]. Fig. 3 shows the distribution of events in the signal region and of the invariant mass of the two photons. Fitting the $M_{\gamma\gamma}$ distribution, one obtains

$$a_v = -0.46 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.02_{th}$$

Using the fitted a_v value, the branching ratio is

$$BR(K_L \to \pi^0\gamma\gamma) = (1.36 \pm 0.03_{st} \pm 0.03_{sy} \pm 0.03_{norm}) \cdot 10^{-6}.$$

and the CP conserving part of the $K_L \to \pi^0 e^+e^-$ decay is

$$BR(K_L \to \pi^0 e^+e^-)_{CPC} = (4.7 \pm 2.2) \cdot 10^{-13}$$

KTev has obtained with a partial data sample [18]

$$BR(K_L \to \pi^0\gamma\gamma) = (1.68 \pm 0.10) cdot 10^{-6} \text{ and } a_v = -0.72 \pm 0.08.$$

They plan to complete the analysis with the full data sample.

3.5. $K_L \to \pi^+\pi^-\pi^0\gamma$ **and** $K_L \to \pi^+\pi^-\pi^0 e^+e^-$

Up to now there were no published results on these decays. $K_L \to \pi^+\pi^-\pi^0\gamma$ is expected to be dominated by inner bremsstrahlung [19] with a $BR(E_\gamma > 10 \text{ MeV}) = (1.65 \pm 0.03) \cdot 10^{-4}$. Direct emission is estimated to be very small [20]. Instead, no theoretical predictions for $K_L \to \pi^+\pi^-\pi^0 e^+e^-$ are available. KTeV have observed for the first time these decays from the analysis of 40% of their large K_L sample.

For $K_L \to \pi^+\pi^-\pi^0\gamma$ they have obtained 2853 candidates, normalized to $K_L \to \pi^+\pi^-\pi^0$. The final branching ratio is $BR(E_\gamma > 10 \text{ MeV}) = (1.70 \pm 0.03_{st} \pm 0.04_{st} \pm 0.03_{norm}) \cdot 10^{-4}$.

For $K_L \to \pi^+\pi^-\pi^0 e^+e^-$, 132 candidates, normalized to $K_L \to \pi^+\pi^-\pi^0{}_D$, with an estimated background of 1.2 ± 0.9 events, give a branching ratio of $BR(E_{ee} > 20 \text{ MeV}) = (1.60 \pm 0.18_{st}) \cdot 10^{-7}$.

The KTeV Collaboration plans to measure Direct Emission and Charge radius in the near future with their full dataset.

3.6. $\eta \to \pi^0\gamma\gamma$

The decay $\eta \to \pi^0\gamma\gamma$ has been extensively studied by theorists and many predictions within χPT has been published [21]. All span in the interval 0.11 eV < Γ < 0.92 eV, which translates in a value for the branching ratio between 8.5 and 71 in units of 10^{-5}.

KLOE has measured this branching ratio using 68 ± 23 signal events, normalized to $\eta \to \pi^0\pi^0\pi^0$.

The measured branching ratio [22] is $BR(\eta \to \pi^0\gamma\gamma) = (8.4 \pm 2.7_{st} \pm 1.4_{sy}) \cdot 10^{-5}$, which is in agreement with $O(p^6)$ calculations with VMD resonance saturation and also with Belkov NJL.

3.7. $K^\pm \to \pi^\pm\gamma\gamma$

The decay $K^\pm \to \pi^\pm\gamma\gamma$ has no tree $O(p^2)$ contribution; the leading contribution is at order $O(p^4)$ with an undetermined constant ĉ of order 1 [23](Fig. 4). $O(p^6)$ corrections to the branching ratio are expected to be around 30-40 %. Differ-

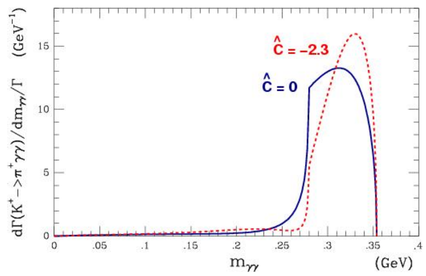

Figure 4. $K^{\pm} \to \pi^{\pm}\gamma\gamma$: *theoretical predictions for two different values of* $\hat{c}$

ent models give a branching ratio of about $7 \cdot 10^{-7}$. The E787 experiment at BNL observed this decay for the first time [24], with 5.1 ± 3.3 events in the range 100 MeV/c $< P_\pi <$ 180 MeV/c and a branching ratio of $(6.0 \pm 1.5_{st} \pm 0.7_{sy}) \cdot 10^{-7}$. NA48 is performing an analysis of this decay with data collected in 2003 and in 2004. A first sample from 2003 consists of about 2000 events with very small backgrounds. There will be at least as many events in 2004 data.

3.8. $K^+ \to \pi^+ e^+ e^-$

The form factor in the amplitude for this decay contains two parameters a_i, b_i to parametrize respectively contributions at $O(p^4)$ and $O(p^6)$ [25]. Data from E865 at BNL [26] (≈ 10000 events with 1.2% background) have been used to fit a_i, b_i finding $a_+ = -0.587 \pm 0.010, b_+ = -0.655 \pm 0.044$ and a branching ratio of $(2.94 \pm 0.05_{st} \pm 0.13_{sy} \pm 0.05_{model}) \cdot 10^{-7}$. All these results are consistent with χPT predictions. NA48 is doing an analysis of this decay: the sample from 2003 data contains about 4000 events, which will at least double with the addition of 2004 data. The background is less than 1%.

4. Radiative semileptonic decays

K_L and $K^{\pm}$ radiative semileptonic decays give information on the kaon structure. The ratio $R = \frac{\Gamma(K_{e3\gamma}, E^*_\gamma > 30 MeV, \theta^*_{e\gamma} > 20^0)}{\Gamma(K_{e3})}$ is predicted to be between 0.95% and 0.99%. Two different theoretical approaches are used: current algebra [27] and χPT [28]. Both basically agree and the latter is continuosly improving accuracy: the latest estimate is (0.96 ± 0.01). A recent measurement from KTeV [29] gives $R = (0.908 \pm 0.008^{+0.013}_{-0.012})\%$, in disagreement with the predictions. NA48 has analyzed the decay $K_L \to \pi^{\pm} e^{\mp} \nu\gamma$ finding 18977 candidates and 6 million $K_L \to \pi^{\pm} e^{\mp} \nu$ normalization events. The background is less than 1%. The result [30], in full agreement with the predictions, is $R = (0.964 \pm 0.008^{+0.011}_{-0.009})\%$. An analysis is in progress by NA48 on the $K^{\pm}$ radiative semileptonic decays. On this subject, it should be noted that radiative K^- semileptonic decays are studied also at ISTRA+, as it has been presented in this Conference [31].

5. K_{e4}

The K_{e4} decays ($K_L \to \pi^{\pm}\pi^0 e^{\mp}\nu_e$, $K^{\pm} \to \pi^{\pm}\pi^- e^{\mp}\nu_e$, $K^{\pm} \to \pi^0\pi^0 e^{\pm}\nu_e$) are known to be a good test of ChPT predictions for long-distance meson interactions. They are used to determine the $\pi\pi$ partial wave expansion parameters, like threshold parameters, slopes and scattering lengths, which can be further related to the quark condensate [32]. The complete set of the parameters has been computed at order $O(p^4)$ and the form factors at $O(p^6)$ [33] NA48 has studied all the three decays. The report of the results for the $K^{\pm}$ decays have been presented in this Conference [34]. For the K_L decay, NA48 has got 5500 events with $\approx 1\%$ of background, obtaining the best measurement of the branching ratio up to now [35] (Fig. 5):

$$BR(K_L \to \pi^{\pm}\pi^0 e^{\mp}\nu_e) = (5.21 \pm 0.07_{st} \pm 0.09_{sy}) \cdot 10^{-5}$$

together with the values of the form factors

$$\bar{f}_s = 0.052 \pm 0.006_{st} \pm 0.002_{sy}$$

$$\bar{f}_p = -0.051 \pm 0.011_{st} \pm 0.005_{sy}$$

$$\lambda_g = 0.087 \pm 0.019_{st} \pm 0.006_{sy}$$

$$\bar{h} = -0.32 \pm 0.12_{st} \pm 0.07_{sy}$$

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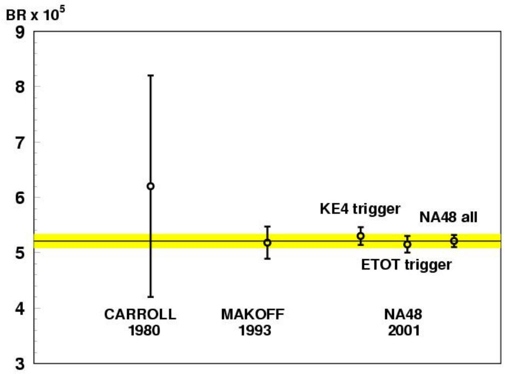

Figure 5. $K_L \to \pi^{\pm}\pi^0 e^{\mp}\nu_e$: *Theoretical predictions and measured values*

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