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TESTS OF CHIRAL PERTURBATION THEORY IN RARE KAON DECAYS

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ABSTRACT

The neutral Kaon decays $K_{\rm S} \to \gamma\gamma$ and $K_{\rm L} \to \pi^0\gamma\gamma$ are very sensitive to higher order loop effects of Chiral Perturbation Theory (ChPT). New measurements of the NA48 experiment show that ChPT contributions of $\mathcal{O}(p^6)$ cannot be neglected in these modes. In addition a new measurement of the related decay $K_{\rm L} \to \gamma\gamma$ and an upper limit of the rate of $K_{\rm S} \to \pi^0\gamma\gamma$ are presented.

1 Introduction

Chiral Perturbation Theory (ChPT) has been proven as an extremely successful effective theory for low energy hadron dynamics. Nevertheless, the knowledge of higher order effects is rather scarse at present. The decays $K_{\rm S} \to \gamma\gamma$ and $K_{\rm L} \to \pi^0\gamma\gamma$ are well suited for investigation of higher order contributions. In

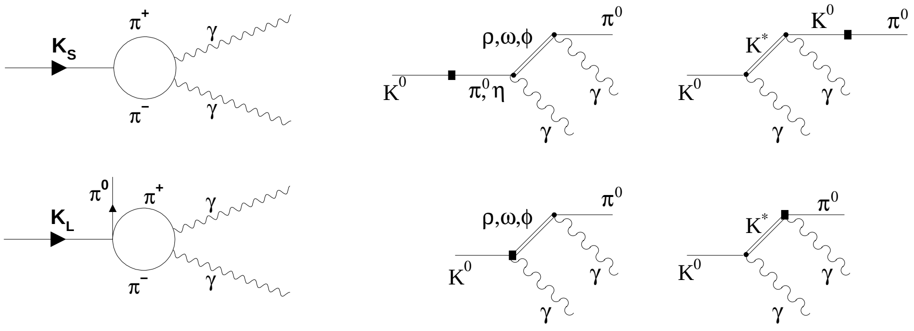

Figure 1: *Left:Examples of* $\mathcal{O}(p^4)$ *loop diagrams for* $K_{\rm S} \to \gamma\gamma$ *and* $K_{\rm L} \to \pi^0\gamma\gamma$. *Right: Vector meson exchange diagrams for* $K_{\rm L} \to \pi^0\gamma\gamma$.

both cases the lowest order $\mathcal{O}(p^2)$ vanishes 1) and the next order $\mathcal{O}(p^4)$ can precisely been calculated, since no counter-terms exist 2, 3) (Fig. 1 (left)).

The $\mathcal{O}(p^4)$ prediction of the $K_{\rm S} \to \gamma\gamma$ branching ratio is $\mathrm{Br}(K_{\rm S} \to \gamma\gamma) = 2.1 \times 10^{-6}$ to an accuracy of about 5% 2). Calculations of the next order $\mathcal{O}(p^6)$ do not exist up to now. The measured value of $\mathrm{Br}(K_{\rm S} \to \gamma\gamma) = (2.6 \pm 0.5) \times 10^{-6}$ 4) is in agreement with this prediction, however, the experimental errors were still too large to allow an accurate comparison.

For $K_{\rm L} \to \pi^0\gamma\gamma$ it is known that $\mathcal{O}(p^4)$ alone underestimates the observed branching fraction by about a factor of three 3, 5, 6). At $\mathcal{O}(p^6)$ the rate can be reproduced by adding a vector meson exchange contribution 7) (Fig. 1 (right)) via the coupling constant a_V 8). However, the parameter a_V has to be measured experimentally. Additional interest in measuring $K_{\rm L} \to \pi^0\gamma\gamma$ arises, since it can constrain the CP conserving amplitude of the direct CP violating decay $K_{\rm L} \to \pi^0 e^+ e^-$. The VMD mechanism could enhance the size of this amplitude, depending on the value of a_V 9).

2 Experimental Method

With KTeV and NA48 mainly two experiments have investigated neutral kaon decays into neutral final states in the recent years. Both experiments were built to perform precise measurements on the parameter ϵ'/ϵ of direct CP violation. Both are fixed target experiments with the neutral kaon beams being produced by high-energetic proton beams.

2.1 The NA48 Experiment

The NA48 experiment, located at the SPS accelerator at CERN, has been taking data for the $\mathrm{Re}(\epsilon'/\epsilon)$ measurement in the years $1997-1999$ and 2001. In addition to the regular ϵ'/ϵ data taking, several runs with a high intensity K_{S} beam have been taken, where the K_{S} intensity has been increased by more than a factor of 200 with respect to the ϵ'/ϵ runs. In the year 2000, the spectrometer has not been available. In this year half of the data taking took place under ϵ'/ϵ conditions while the second half of the run period was performed with a high intensity K_{S} beam.

2.2 The KTeV Experiment

The KTeV experiment is located at the TeVatron at Fermilab. It has been taking data in the years 1996, 1997, and 1999 with runs dedicated to determine $\mathrm{Re}(\epsilon'/\epsilon)$ and runs for measuring rare K_{L} and hyperon decays. The data from the last year of data taking are mostly still being analyzed.

2.3 Reconstruction of Neutral Decays

For detecting the photons in the final states of the decays discussed here, NA48 and KTeV use a quasi-homogeneous liquid krypton and, respectively, a CsI crystal electromagnetic calorimeter. By assuming a kaon decay, the z position (along the beam pipe) of the decay vertex can be calculated to

$$z_{\mathrm{vertex}} = z_{\mathrm{calorimeter}} - \frac{1}{m_K}\sqrt{\sum_{i>j} E_i E_j d_{ij}^2}\,,$$

with the shower energies $E_{i,j}$, distances d_{ij}, and the nominal kaon mass m_K. If photons are lost, the missing energy shifts the vertex position down-stream towards the calorimeter. If the decay contains one or more intermediate π^0, background can be suppressed by requiring the π^0 decay vertex to be consistent with the kaon decay vertex.

3 $K_{\mathrm{S,L}} \to \gamma\gamma$

For a decay rate measurement of $K_{\mathrm{S}} \to \gamma\gamma$ in a fixed-target experiment an irreducible background of $K_{\mathrm{L}} \to \gamma\gamma$ events has to be subtracted. Therefore, a precise determination of $K_{\mathrm{L}} \to \gamma\gamma$ is necessary while the current world average

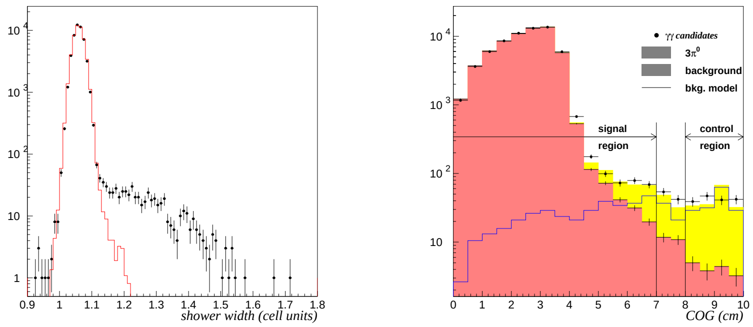

Figure 2: *Shower width (left) and center-of-gravity distribution (right) of the NA48* $K_\mathrm{L} \to \gamma\gamma$ *candidates compared with* $K_\mathrm{L} \to 3\pi^0$ *events.*

on Br($K_\mathrm{L} \to \gamma\gamma$) has a relative error of about 3% 10). For this reason the NA48 experiment has used a different method for subtracting $K_\mathrm{L} \to \gamma\gamma$ events: In using the K_L target run in 2000 with a very similar experimental set-up the relative rate $\Gamma(K_\mathrm{L} \to \gamma\gamma)/\Gamma(K_\mathrm{L} \to 3\pi^0)$ is measured. By also measuring the $K_\mathrm{L} \to 3\pi^0$ rate in the high intensity K_S run 2000, the number of background $K_\mathrm{L} \to \gamma\gamma$ events can then be accurately subtracted.

3.1 $K_\mathrm{L} \to \gamma\gamma$

The NA48 K_L target run of the year 2000 has provided very clean conditions to measure $K_\mathrm{L} \to \gamma\gamma$ decays. Backgrounds from $K_\mathrm{L} \to 2\pi^0$ or other K_L decays are completely negligible, in particular $K_\mathrm{L} \to e^+e^-\gamma$ Dalitz decays are swept out by the spectrometer magnet. The only remaining background source is hadronic activity, e.g. from Λ decay products, which in rare cases might enter the decay volume via the K_L beam line. To estimate this background the sidebands in the shower width and center-of-gravity distributions are evaluated (Fig. 2). By using both methods, the hadronic background is determined to $(0.6 \pm 0.3)\%$, where the error reflects the difference of the two estimations.

The normalization channel $K_\mathrm{L} \to 3\pi^0$, which needs three good $\pi^0 \to \gamma\gamma$ combinations to be selected, is virtually background-free. Both, signal and normalization channel have trigger efficiencies larger than 99%. For the analyis only 25% of the K_L target run data were used which already provides sufficient statistics. Evaluating the event numbers in the vertex region -1 m $< z < 5$ m (measured from the K_S collimator) and taking the acceptance ratio from Monte Carlo simulation, NA48 finds

$$\frac{\Gamma(K_\mathrm{L} \to \gamma\gamma)}{\Gamma(K_\mathrm{L} \to 3\pi^0)} = (2.81 \pm 0.01_\mathrm{stat} \pm 0.02_\mathrm{syst}) \times 10^{-3}$$

The systematic error is dominated by uncertainties in the $\gamma\gamma/3\pi^0$ acceptance ratio. This result improves the current world average by about a factor of four.

3.2 $K_\mathrm{S} \to \gamma\gamma$

In addition to the irreducible $K_\mathrm{L} \to \gamma\gamma$ decays more background sources have to be taken into account when selecting $K_\mathrm{S} \to \gamma\gamma$ candidates:

$K_\mathrm{S} \to 2\pi^0$ with lost and/or overlapping photons may fake a good $\gamma\gamma$ event. Since in these cases energy is lost, the neutral vertex is shifted downstream. Background from $K_\mathrm{S} \to 2\pi^0$ can therefore be efficiently rejected by restricting the allowed vertex range to be within -1 and 5 m behind the final collimator. Doing so, the remaining background from $K_\mathrm{S} \to 2\pi^0$ is estimated to $(0.8 \pm 0.2)\%$, where the uncertainty is arising from the shower overlap probabilities being different in the simulation as in the data.

Further background sources are hadronic events (originating e.g. from scattering at the collimator) or from accidentally overlapping events. Both are determined by a sideband subtraction in the center-of-gravity distribution of the LKr calorimeter (Fig. 3). From this, the total background from hadronic and accidental activity is estimated to $(0.8 \pm 0.3)\%$.

Finally, Dalitz decays $\pi^0 \to e^+e^-\gamma$ and $K^0 \to e^+e^-\gamma$ have to be taken into account. In the high intensity K_S running in 2000, the NA48 experiment had no magnetic field in the detector. Therefore, many Dalitz e^+e^- pairs did not separate and were overlapping in the calorimeter. From Monte Carlo Simulation, the probability of a Dalitz decay misidentified as $\gamma\gamma$ pair was estimated to about 30%. With Dalitz decay probabilities assumed to be equal for $K^0 \to \gamma\gamma$ and $\pi^0 \to \gamma\gamma$, the effect is twice as big for the $K_\mathrm{S} \to 2\pi^0$ normalization than in the $K^0 \to \gamma\gamma$ events and results in a relative correction to the $K_\mathrm{S} \to \gamma\gamma$ branching ratio of $(+1.5 \pm 0.3)\%$.

The decay vertex distribution of the NA48 $\gamma\gamma$ candidates is shown in Fig. 4 together with the estimated contributions of $K_\mathrm{S} \to \gamma\gamma$, $K_\mathrm{L} \to \gamma\gamma$ and $K_\mathrm{S} \to 2\pi^0$ background. The $K_\mathrm{S} \to 2\pi^0$ background contribution has been normalized

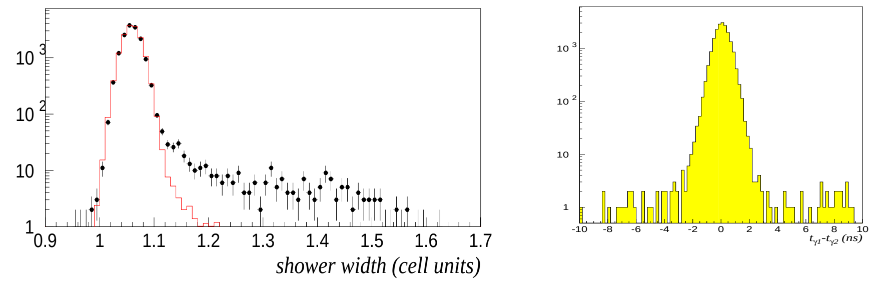

Figure 3: *Distributions of the normalized shower width (left) and the cluster time difference (right) of the NA48* $K_{\mathrm{S}} \to \gamma\gamma$ *candidates compared with* $K_{\mathrm{L}} \to 2\pi^0$ *events.*

to the absolute K_{S} flux. In the fiducial region between -1 and 5 m about 20000 $\gamma\gamma$ candidates were found. Subtracting all background contributions and normalizing to fully reconstructed $K_{\mathrm{S}} \to 2\pi^0$ events, the branching fraction was determined to

$$\mathrm{Br}(K_{\mathrm{S}} \to \gamma\gamma) \;=\; (2.78 \pm 0.06_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}) \times 10^{-6}.$$

The systematic uncertainty is dominated by the branching fraction of the $K_{\mathrm{S}} \to 2\pi^0$ normalization ($\pm 0.9\%$), the estimation of the hadronic and accidental background ($\pm 0.7\%$) and the Monte Carlo statistics ($\pm 0.6\%$).

This new result significantly improves the previous measurements and is in clear discrepancy with the $\mathcal{O}(p^4)$ based theoretical predictions.

4 $K_{\mathrm{L}} \to \pi^0\gamma\gamma$

With four photons in the final state the decay $K_{\mathrm{L}} \to \pi^0\gamma\gamma$ has almost the same signature as the CP-violating decay $K_{\mathrm{L}} \to 2\pi^0$, which is one of the signal decays for the $\mathrm{Re}(\epsilon'/\epsilon)$ measurement of the KTeV and NA48 experiments. Therefore the decay $K_{\mathrm{L}} \to \pi^0\gamma\gamma$ can be taken in parallel with regular ϵ'/ϵ data taking. Moreover, both signal and normalization ($K_{\mathrm{L}} \to 2\pi^0$) have practically identical trigger efficiencies. However, the analysis of $K_{\mathrm{L}} \to \pi^0\gamma\gamma$ events has to fight strong backgrounds, in particular $K_{\mathrm{L}} \to 3\pi^0$ events with lost and/or overlapping photons, badly reconstructed $K_{\mathrm{L}} \to 2\pi^0$ events, and accidentally overlapping events.

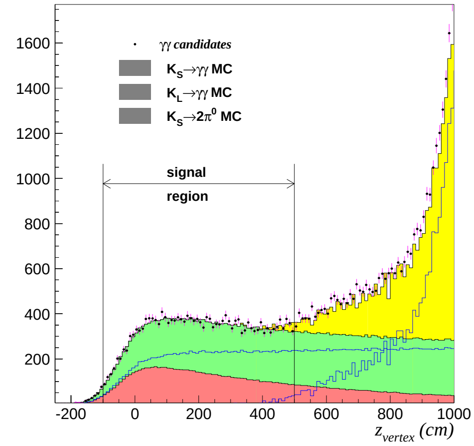

Figure 4: *z vertex distribution of $\gamma\gamma$ candidates.*

The NA48 analysis [11)], which is described more detailed in the following, is based on the NA48 data of the years 1998 and 1999. The suppression of background from $K_{\mathrm{L}} \to 3\pi^0$ with overlapping or lost photons is done by cutting on the shower width in the calorimeter. As shown in Fig. 5 (left), overlapping photons produce on average a much wider shower and can clearly be separated from the signal. To suppress the $K_{\mathrm{L}} \to 3\pi^0$ background even further, a variable $z_{\max}$ is constructed as estimate of the real kaon vertex under the assumption of a misidentified $K_{\mathrm{L}} \to 3\pi^0$ event. For real background events this variable should be in the physical region down-stream of the collimator (Fig. 5 (right)). By rejecting events with $z_{\max} > -5$ m, the $K_{\mathrm{L}} \to 3\pi^0$ background is reduced to $(2.7 \pm 0.4)\%$. However, the signal acceptance is also reduced by 54%.

A second source of background are misidentified $K_{\mathrm{L}} \to 2\pi^0$ events. They are rejected by requiring the invariant mass $m(\gamma_3\gamma_4)$ of the photons not coming from the π^0 to be outside a window of ± 25 MeV/c^2 around the nominal π^0 mass. By using $K_{\mathrm{S}} \to 2\pi^0$ events from both ϵ'/ϵ and high intensity K_{S} runs, the remaining background from $K_{\mathrm{L}} \to 2\pi^0$ is estimated to $(0.2 \pm 0.1)\%$.

Finally, good $\pi^0\gamma\gamma$ candidates may be mimicked by accidentally overlapping events. This background is estimated by extrapolating events with high transverse momentum into the signal region to $(0.3 \pm 0.2)\%$.

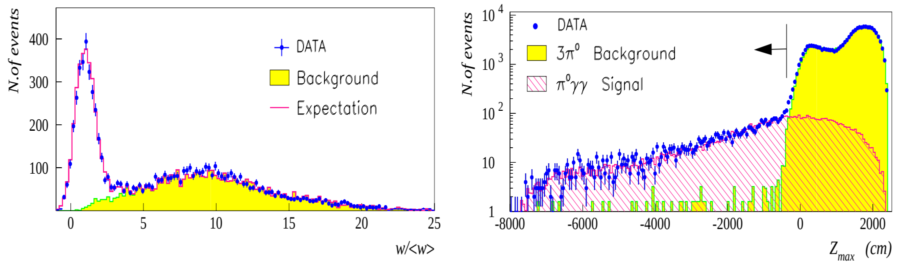

Figure 5: *Distributions of shower width (left) and* $z_{\max}$ *(right) of the selected* $K_{\rm L} \to \pi^0\gamma\gamma$ *candidates of the NA48 experiment. Shown are the data (crosses), the* $K_{\rm L} \to 3\pi^0$ *background expectation from Monte Carlo simulation (shaded), and the total expectation (histogram).*

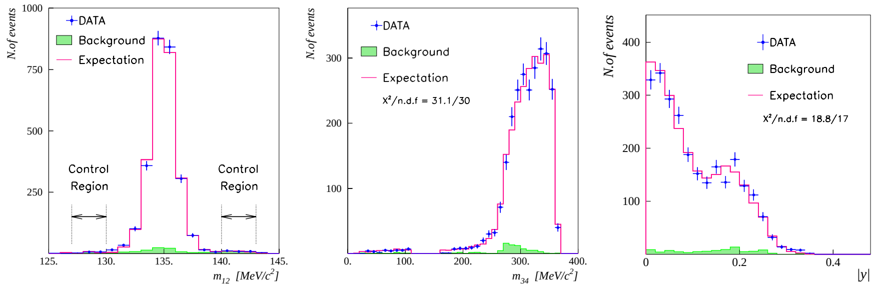

Figure 6: *Distributions of* $m(\gamma_1\gamma_2)$ *(left),* $m(\gamma_3\gamma_4)$ *(center) and* $y = |E_3 - E_4|/m_K$ *(right) of the selected NA48* $K_{\rm L} \to \pi^0\gamma\gamma$ *candidates.*

The invariant mass $m(\gamma_1\gamma_2)$ of the two photons originating from the π^0 is shown in Fig. 6 (left). NA48 finds 2558 $K_{\rm L} \to \pi^0\gamma\gamma$ candidates with an estimated background of 82 ± 12 events, which are used for the branching ratio measurement. For the fit of the VMD parameter a_V, 345 ambigous events which allow two possible $\pi^0 \to \gamma\gamma$ assignments are excluded. The parameter a_V is fitted using the distributions of both kinematic decay variables $m(\gamma_3\gamma_4)$ and $y = |E_3 - E_4|/m_K$ (Fig. 6). The result of the fit is

$$a_V \;=\; -0.46 \pm 0.03_{\rm stat} \pm 0.04_{\rm syst} \qquad\qquad ({\rm NA48, 2002}),$$

with the systematic error being dominated by uncertainties of the acceptance evaluation (±0.03) and the parametrization of the $K_{\rm L} \to 3\pi^0$ vertex [12] (±0.02).

For low $m(\gamma_3\gamma_4)$ the distributions of the π^0 signal $m(\gamma_1\gamma_2)$ are shown

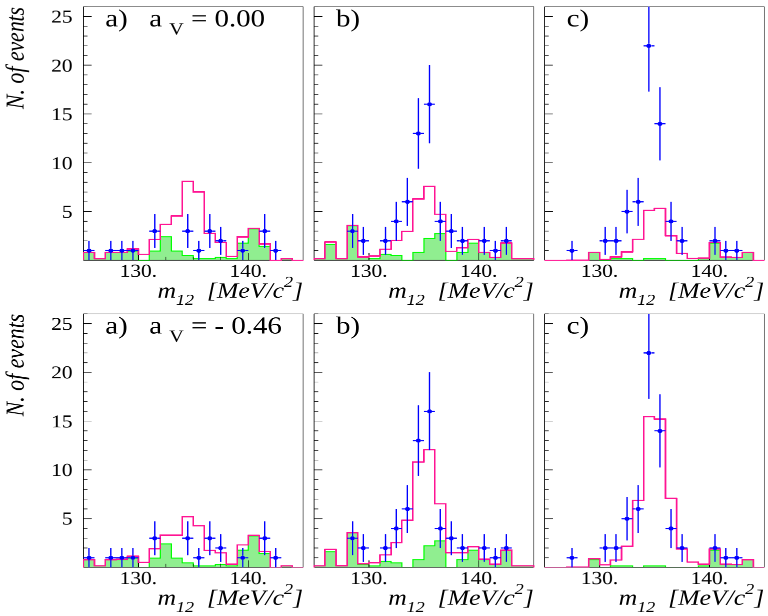

Figure 7: *NA48 data (crosses) and expected background (shaded) for a)* $30\ MeV/c^2 < m(\gamma_3\gamma_4) < 110\ MeV/c^2$, *b)* $160\ MeV/c^2 < m(\gamma_3\gamma_4) < 240\ MeV/c^2$, *and c)* $220\ MeV/c^2 < m(\gamma_3\gamma_4) < 260\ MeV/c^2$ *together with the expectation of* $a_V = 0.0$ *(top) and* $a_V = 0.46$ *(bottom).*

in Fig. 7. There is no significant signal of $K_\mathrm{L} \to \pi^0\gamma\gamma$ events for $m(\gamma_1\gamma_2) < 110\ \mathrm{MeV}/c^2$, as expected for $a_V \approx -0.46$ due to cancellation effects. Nevertheless, in the region $160 < m(\gamma_3\gamma_4) < 240\ \mathrm{MeV}/c^2$ a clear signal shows up, which is evidence for a sizeable $\mathcal{O}(p^6)$ contribution to the $K_\mathrm{L} \to \pi^0\gamma\gamma$ amplitude.

However, an analysis of the KTeV experiment using the data of the years 1996 and 1997, comes to a different result [6]. Performing a similar analysis as described above, KTeV finds 884 signal candidates with estimated 111 ± 12 background events. Fitting both the $m(\gamma_3\gamma_4)$ and y distributions (Fig. 8) the measured value of a_V is

$$a_V \ = \ -0.72 \pm 0.05_\mathrm{stat} \pm 0.06_\mathrm{syst} \qquad\qquad (\mathrm{KTeV}, 1999),$$

also measuring a large $\mathcal{O}(p^6)$ contribution, but about 2.8 standard deviations different from the NA48 result. The systematics are dominated by the knowledge of the $3\pi^0$ background. While NA48 has finished the analysis on

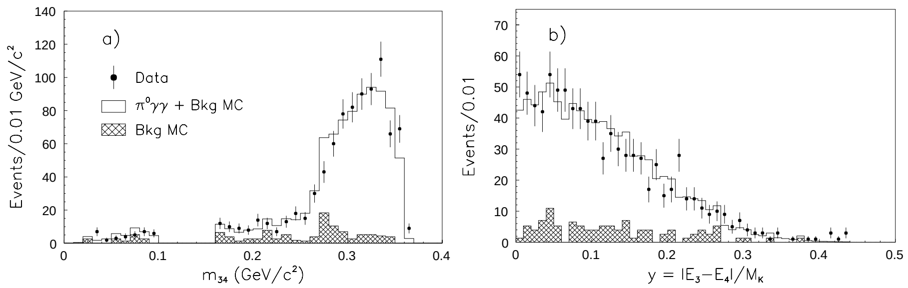

Figure 8: *Distributions of* $m(\gamma_3\gamma_4)$ *(left) and* $y = |E_3 - E_4|/m_K$ *(right) of the selected* $K_\mathrm{L} \to \pi^0\gamma\gamma$ *candidates of the KTeV experiment.*

$K_\mathrm{L} \to \pi^0\gamma\gamma$, the KTeV collaboration plans to additionally analyze the data from the 1999 data taking period, which might help to understand the different results of the two experiments.

The two experiments also arrive at different measurements of the $K_\mathrm{L} \to \pi^0\gamma\gamma$ branching fraction, which can partially be explained by the strong dependence of the detector acceptances on $m(\gamma_3\gamma_4)$:

$$\text{NA48 (2002)}: \quad \mathrm{Br}(K_\mathrm{L} \to \pi^0\gamma\gamma) \;=\; (1.36 \pm 0.03_\mathrm{stat} \pm 0.04_\mathrm{syst}) \times 10^{-6}$$

$$\text{KTeV (1999)}: \quad \mathrm{Br}(K_\mathrm{L} \to \pi^0\gamma\gamma) \;=\; (1.68 \pm 0.07_\mathrm{stat} \pm 0.08_\mathrm{syst}) \times 10^{-6}$$

The NA48 a_V measurement indicates a negligible CP-conserving amplitude of the (yet to be observed) direct CP-violating decay $K_\mathrm{L} \to \pi^0 e^+ e^-$ 9). However, this does not hold for the a_V value measured by KTeV.

5 $K_\mathrm{S} \to \pi^0\gamma\gamma$

The decay $K_\mathrm{S} \to \pi^0\gamma\gamma$ is dominated by the pion pole in $K_\mathrm{S} \to 2\pi^0$.To be able to distinguish this decay from the dominating $K_\mathrm{S} \to 2\pi^0$, a minimum two-gamma invariant mass of $z = m(\gamma_3\gamma_4)^2/m_K^2 > 0.2$ is required. One theoretical investigation based on ChPT exists 3), predicting the shape of the $m(\gamma_3\gamma_4)$ distribution together with a branching fraction of $\mathrm{Br}(K_\mathrm{S} \to \pi^0\gamma\gamma)|_{z\geq 0.2} = 3.8 \times 10^{-8}$. No experimental observation or limit has been published so far.

Using the data of a two-day high intensity K_S run in 1999, the NA48 experiment has performed a search for the decay $K_\mathrm{S} \to \pi^0\gamma\gamma$. In this run about 3×10^8 K_S decays took place in the fiducial detector volume.

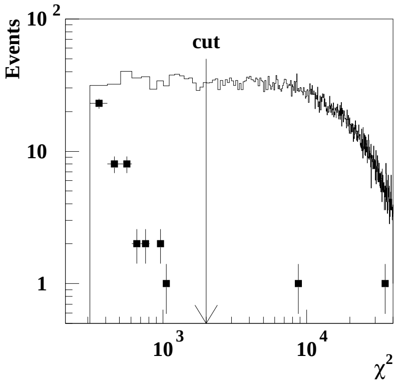

Figure 9: *Right:* $\chi^2_{2\pi^0}$ *distribution of* $K_S \to \pi^0\gamma\gamma$ *candidates under* $K_S \to 2\pi^0$ *hypothesis (crosses). The histogram shows the expected signal distribution.*

Because of the smallness of the expected branching fraction, the main experimental problem is the background suppression. Any non-γ activity in the photon anti-counters, drift chambers, and hadron calorimeter is vetoed. To suppress $K_S \to 2\pi^0$ events, the $\chi^2_{2\pi^0}$ of the event for being a $K_S \to 2\pi^0$ decay is required to be larger than 2000. In this way, only 0.1 ± 0.1 mismeasured $K_S \to 2\pi^0$ events are expected, as determined from Monte Carlo simulation. The main background then comes from $K_S \to 2\pi^0$ decays with one lost and one accidentally in-time photon. This background is estimated by simulated and randomly triggered events to 2.1 ± 0.1 events. The irreducible background coming from $K_L \to \pi^0\gamma\gamma$ decays accounts for another 0.1 expected background event.

The $\chi^2_{2\pi^0}$ distribution of the remaining events is shown in Fig. 9. Only two events above $\chi^2_{2\pi^0} = 2000$ survive the selection, compatible with the background expectation of 2.3 ± 0.2 events. Using $K_S \to 2\pi^0$ decays for normalization, the limit on the branching fraction set by NA48 is

$$\mathrm{Br}(K_S \to \pi^0\gamma\gamma)|_{z\geq 0.2} \;<\; 4.4 \times 10^{-7} \quad \text{at 90\% CL.}$$

This is the first limit set on the decay width of $K_S \to \pi^0\gamma\gamma$. However, it is still about one order of magnitude above the theoretical expectation.

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