Results on Rare Kaon Decays from the NA48 Experiment

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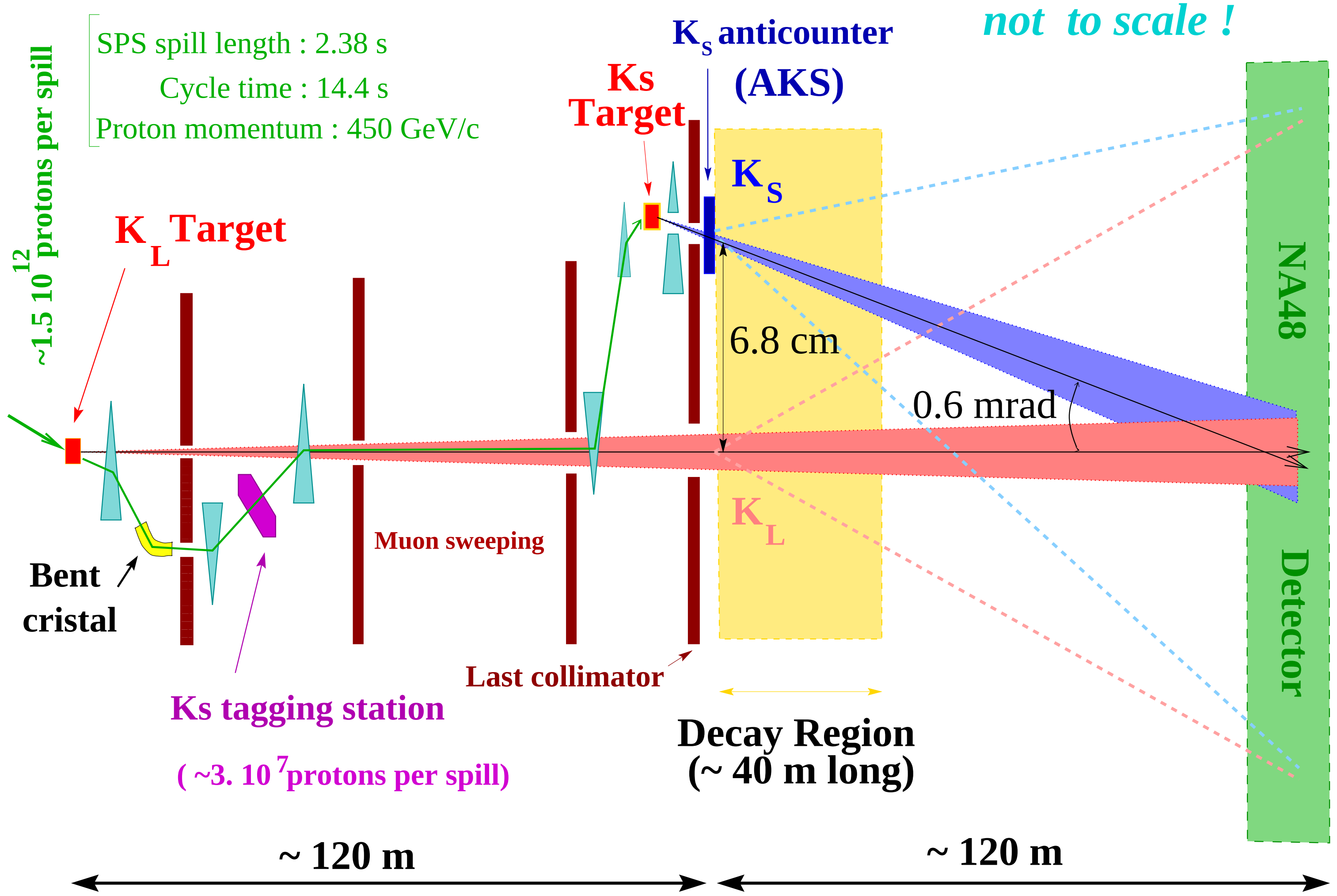
on behalf of the **NA48 COLLABORATION**:

Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warsaw, Wien

The NA48 Beams

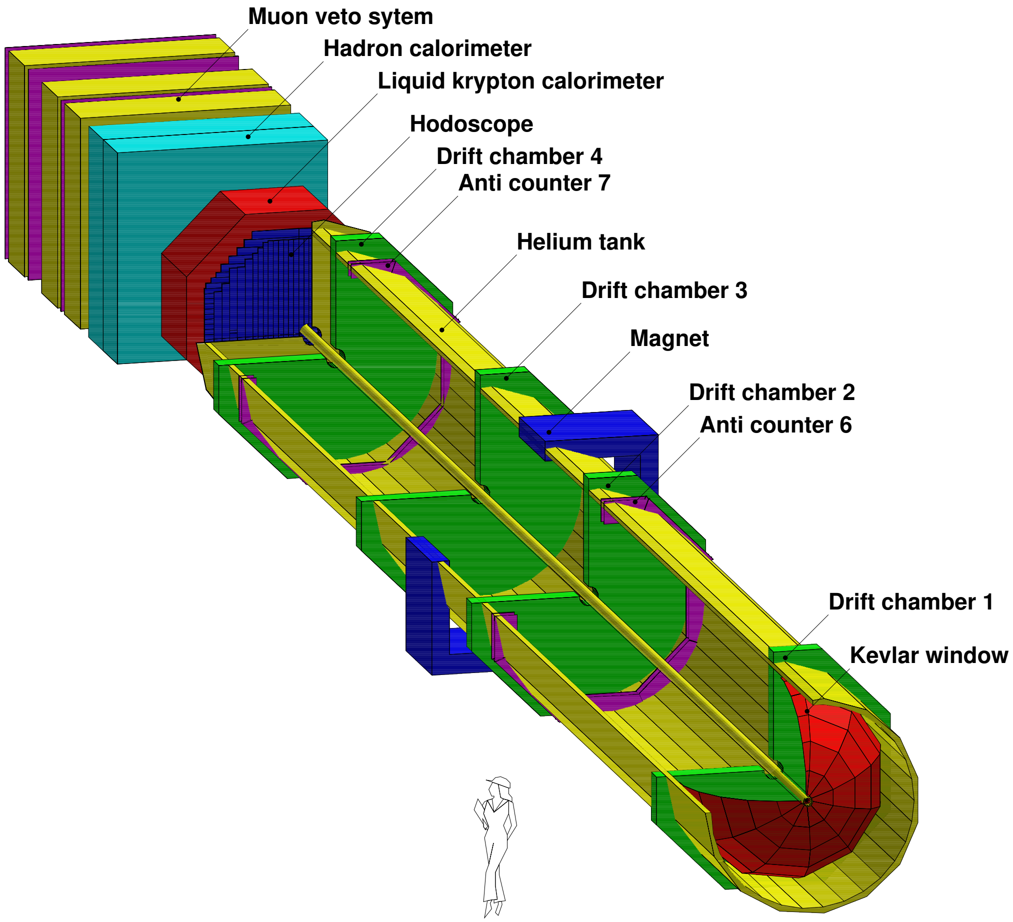


1997–1999 ε'/ε data taking: $\sim 3 \times 10^{10}$ $\mathrm{K_L}$ decays/year, $\sim 7 \times 10^{7}$ $\mathrm{K_S}$ decays/year

1999 KS High Intensity run: 2 days with no KL beam, KS beam intensity X200

$\Longrightarrow 2.3 \times 10^{8}$ $\mathrm{K_S}$ decays

The NA48 Detector



Magnetic Spectrometer:

4 chambers with 90 μm spacepoint resolution

magnet providing 265 MeV/c p_T kick

$$\frac{\sigma(P)}{P} \simeq 0.5\ \% \oplus 0.009\ P[\mathrm{GeV}/c]\ \%$$

plane efficiency > 99 %

LKr electromagnetic calorimeter:

quasi–homogeneous detector based on 9 m^3 LKr with 13212 readout cells

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{90\ MeV}{E} \oplus 0.42\%$$

(E in GeV)

$$\sigma_{\pi^0} \simeq 1MeV$$

$$\sigma_{X,Y} < 1.3\ \mathrm{mm}$$

Unexhaustive List of Decays under Study in NA48

Decay	B.R. (order)	Main motivations	today
$K_L \to \pi^+\pi^- e^+e^-$	10^{-7}	manifests indirect CPV	$\Longleftarrow$
$K_L \to \pi^0\gamma\gamma$	10^{-6}	tests χPT at $\mathcal{O}(p^6)$, constraints CP conserving part of $\Gamma(K_L \to \pi^0 e^+e^-)$	
$K_L \to e^+e^-e^+e^-$	10^{-8}	tests χPT for $K_L \to \gamma^*\gamma^*$ vertex	
$K_L \to \mu^+\mu^- e^+e^-$	10^{-9}	tests χPT for $K_L \to \gamma^*\gamma^*$ vertex	
$K_L \to e^+e^-\gamma\gamma$	10^{-6}		
$K_S \to \pi^+\pi^- e^+e^-$	10^{-5}	check of $K_L \to \pi^+\pi^- e^+e^-$ analysis first observation	$\Longleftarrow$
$K_S \to \pi^0 e^+e^-$	$< 10^{-7}$	constraints ind. CPV part of $\Gamma(K_L \to \pi^0 e^+e^-)$	$\Longleftarrow$
$K_S \to \gamma\gamma$	10^{-6}	clean χPT prediction	$\Longleftarrow$
$\Xi^0 \to \Lambda^0\gamma$	10^{-3}	tests SU(3) symmetries	
$\Xi^0 \to \Sigma^0\gamma$	10^{-3}		
$\Xi^0 \to \Sigma^+ e^-\bar{\nu}_e$	10^{-4}		
$\Xi^0 \to p\pi^-$	$< 10^{-6}$		

Very large samples to study parameters for common decays as $K_L \to \pi\ell\nu_\ell$

$K_L \to 3\pi^0$ $\Longleftarrow$

$K_L \to \pi^+\pi^-\pi^0$

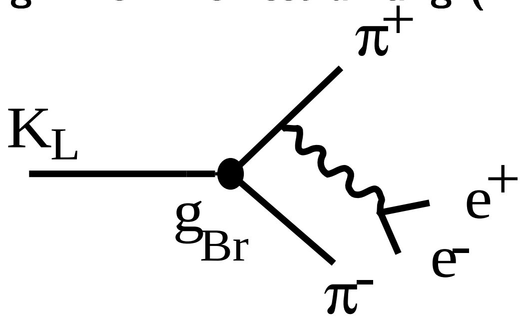
Outline

- $\mathrm{K_{L,S}} \to \pi^+\pi^-e^+e^-$
- $\mathrm{K_S} \to \pi^0 e^+e^-$
- $\mathrm{K_S} \to \gamma\gamma$
- $\mathrm{K_L} \to 3\pi^0$ Dalitz Plot
- NA48 Future Program for Rare Decays

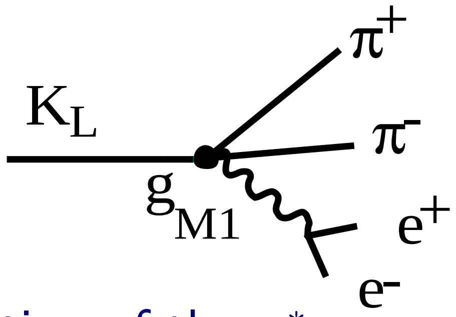
$K_{L,S} \to \pi^+\pi^-e^+e^-$: Motivations

K_L : two interfering contributions to the decay amplitude

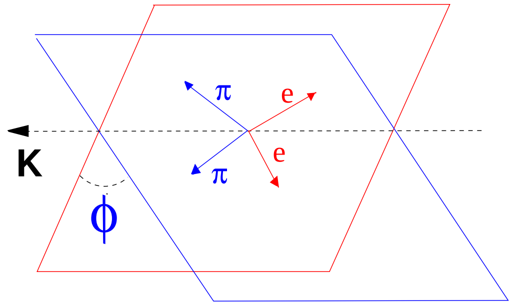
CP–violating Inner Bremsstrahlung (IB)



CP–conserving Direct Emission



produce a CP–violating circular polarization of the γ^*



$$A_\phi = \frac{N_{\cos\phi\sin\phi>0} - N_{\cos\phi\sin\phi<0}}{N_{\cos\phi\sin\phi>0} + N_{\cos\phi\sin\phi<0}}$$

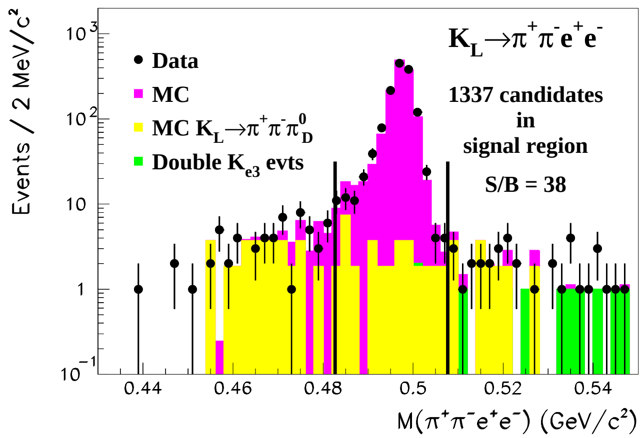
Theory (Heiliger and Sehgal 98): $A_\phi \sim 14\%$

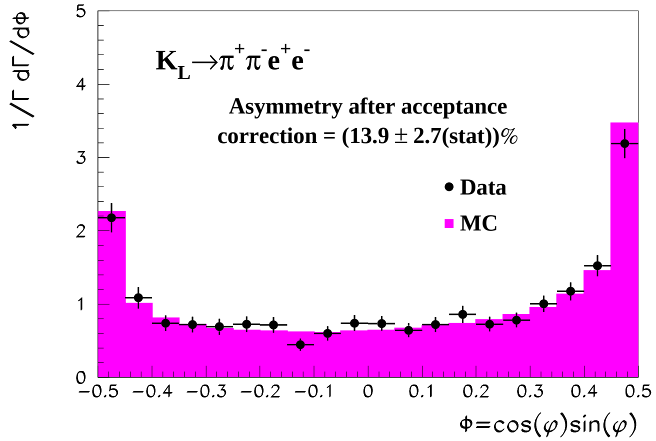
First Measurement (KTEV 99): $A_\phi = (13.6 \pm 2.5 \pm 1.2)\%$

K_S : dominated by IB $\Rightarrow$ no CP–violating asymmetry expected
First observation in NA48 (56 events from 1998 data, published in PL B496(2000),137), important to cross–check the K_L analysis

$K_{L,S} \to \pi^+\pi^-e^+e^-$: PRELIMINARY Results

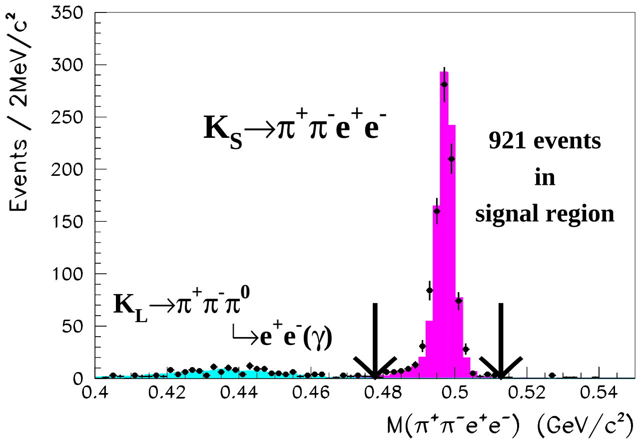
K_L (98+99 DATA)

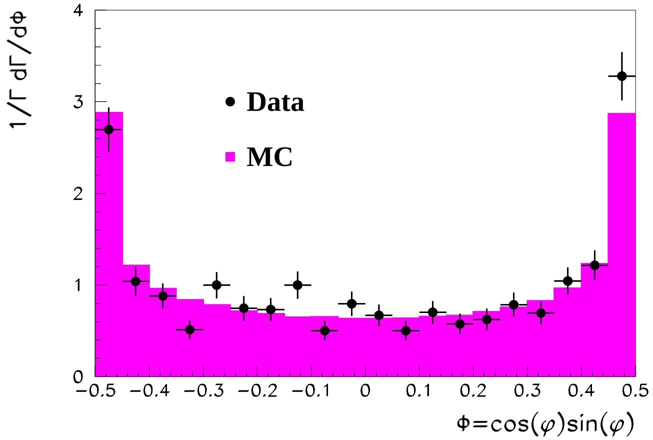




$$BR = (3.1 \pm 0.1 \pm 0.2) \times 10^{-7}$$
$$A_\phi^L = (13.9 \pm 2.7 \pm 2.0)\%$$

K_S (98+99+KSHI DATA)





$$BR = (4.3 \pm 0.2 \pm 0.3) \times 10^{-5}$$
$$A_\phi^S = (-0.2 \pm 3.4 \pm 1.4)\%$$

$K_S \to \pi^0 e^+ e^-$: Motivations

The main interest in this decay is the bound with the analogous K_L decay, which is expected to have a direct CP–violating component, but also a CP–conserving and an indirect CP–violating one.

SM prediction for the branching ratio is (D'Ambrosio et al. JHEP08(1998)004)

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

where a_S, expected to be $\mathcal{O}(1)$, is related to the indirect CP violating part of $K_L \to \pi^0 e^+ e^-$:

$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} = \left[15.3\ a_S^2 - 6.8 \frac{Im(V_{ts}^* V_{td})}{10^{-4}}\ a_S + 2.8 \left(\frac{Im(V_{ts}^* V_{td})}{10^{-4}} \right)^2 \right]$$

only one search was performed so far by NA31, giving

$$BR(K_S \to \pi^0 e^+ e^-) < 1.1 \times 10^{-6} \text{ at } 90\% \text{ C.L.}$$

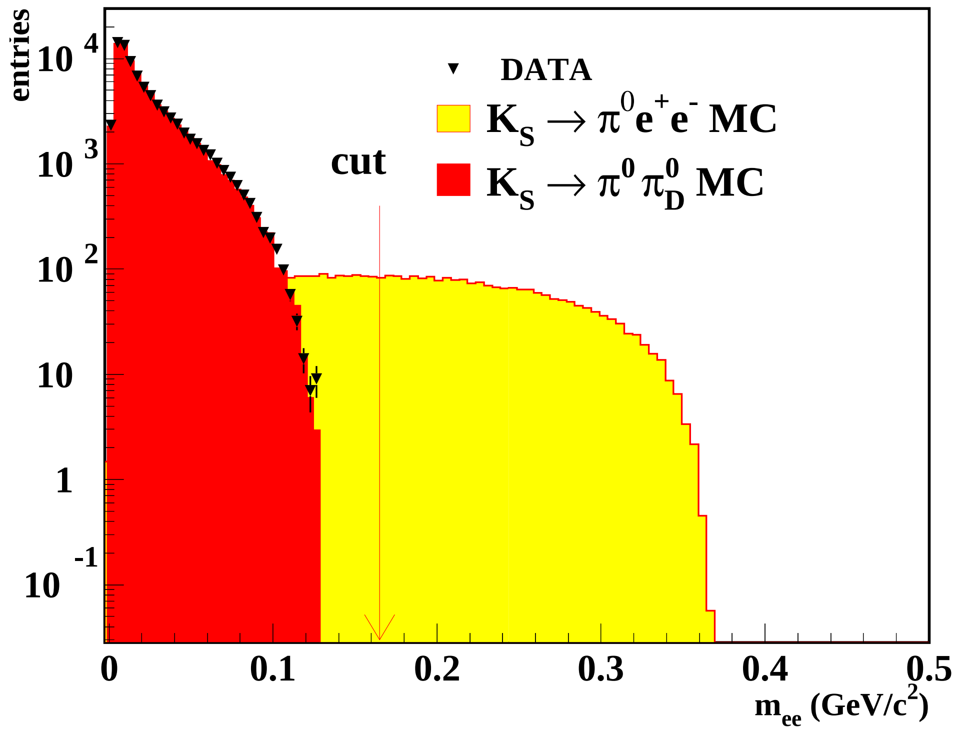
$\mathrm{K_S} \to \pi^0 e^+ e^-$: Data Analysis

Data taking:
- 1999 High Intensity KS data
- Dedicated trigger having 98.3 % efficiency (estimated from MC), also used for $\mathrm{K_S} \to \pi^0 \pi^0_{Dalitz}$ (normalization)

Event selection:
- quality cuts on total and single cluster energy, decay vertex position and center of gravity
- electrons identified through $0.9 < E/p < 1.1$
- rejection of hadrons ($\mathrm{E}_{HAC} < 6$ GeV), μ and accidental activity (no extra clusters)
- $|m_{\gamma\gamma} - M_{\pi^0}| < 2.5$ MeV
- $|m_{e^+e^-\gamma\gamma} - M_{K^0}| < 10$ MeV

Background rejection:
- $\mathrm{K_S} \to \pi^0_D \pi^0_D \to e^+ e^- \gamma e^+ e^- \gamma$ (two lost tracks)
  $|m_{e\gamma} - M_{\pi^0}| > 30$ MeV
- $\mathrm{K_S} \to \pi^0 \pi^0_D \to \gamma\gamma e^+ e^- \gamma$ (lost gamma)
  $m_{e^+e^-} > 165$ MeV (retains $\sim$ 50 % of signal)
- $K_{L,S} \to e^+ e^- \gamma\gamma$ and $\mathrm{K_S} \to \pi^0 \pi^0_{DD}$
  proved to be negligible through MC

$K_S \to \pi^0 e^+ e^-$: Results



Normalization events ($K_S \to \pi^0 \pi^0_D$): 79516

Acceptance: 7.4% (4.2 % for $K_S \to \pi^0 \pi^0_D$)

Background estimates: $K_S \to \pi^0 \pi^0_D < 0.3$ events
$K_S \to \pi^0_D \pi^0_D < 0.03$ events

No events found

$$\Rightarrow BR(K_S \to \pi^0 e^+ e^-)_{M_{ee}>165\mathrm{MeV}} < 8.3 \times 10^{-8}$$

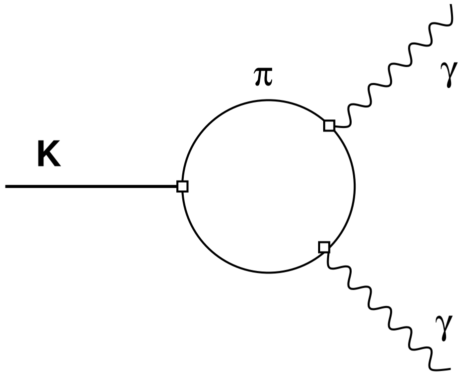
using χPT predictions for the matrix elements, the result for the full BR is extrapolated to be

$\boxed{BR(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}}$ at 90 % C.L.

systematic uncertainty is estimated to be 6 %, dominated by the theoretical error on the extrapolation

$\mathrm{K_S} \to \gamma\gamma$: Motivations and Data

Within the SM the amplitude is dominated by one–loop diagrams, allowing for a very clean prediction for the branching ratio from χPT (D'Ambrosio and Espriu 86):



Theory: $BR(\mathrm{K_S} \to \gamma\gamma) = (2.3 \pm 0.2) \times 10^{-6}$

Only 35 have been reported so far by NA31, which measured

PDG 2000 : $BR(\mathrm{K_S} \to \gamma\gamma) = (2.4 \pm 0.9) \times 10^{-6}$

Data taking:

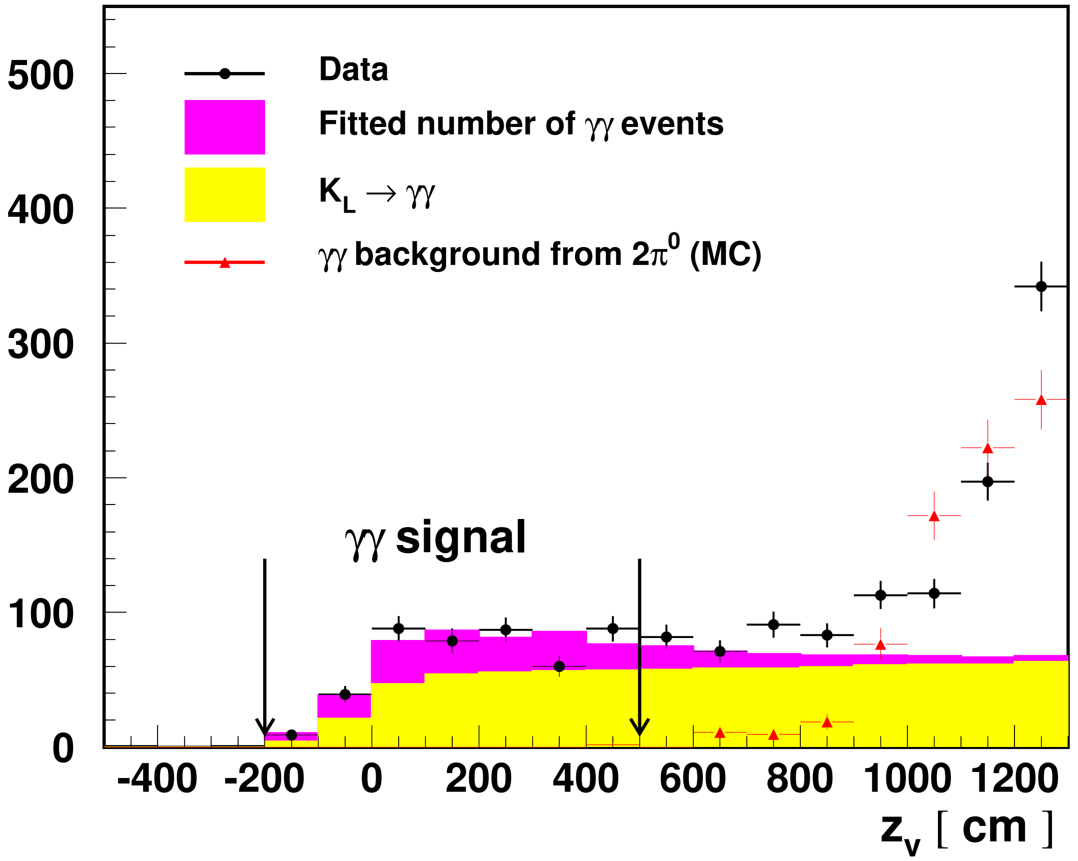
- ➜ 1999 High Intensity KS data
- ➜ Dedicated trigger having efficiency > 99 %

Event selection:

- ➜ beginning of decay region defined by an anti–counter (AKS)
- ➜ quality cuts on total and single cluster energy, cluster position and event center of gravity (COG)
- ➜ rejection of hadrons (E$_{HAC} < 3$ GeV) and accidental activity

$K_S \to \gamma\gamma$: Background evaluation

- $K_S \to \pi^0\pi^0$ with two lost γ
  in this case the reconstructed vertex position
  $z_V = z_{LKR} - \sqrt{\sum E_i E_j d_{ij}}/M_K$
  (d_{ij} transverse distance between 2 clusters)
  is overstimated by at least 9 m
  $\Rightarrow$ suppressed by $z_V < 5$ m
  MC estimation: 2 ± 2 events
- $\Lambda \to n\pi^0$ suppressed by $E_{HAC} < 3$ GeV
  and a cut on shower width in LKr
  estimation from high–COG tails: 11 ± 8 events
- $K_L \to \gamma\gamma$ (BR$\times 10^4$=$5.86 \pm .15$)
  KL flux equal to KS flux measured from $K_S \to \pi^0\pi^0$
  acceptance given by MC
  subtracted in each bin of z_V using maximum likelihood method: 294 events



$K_S \to \gamma\gamma$: **Result**

from maximum likelihood fit

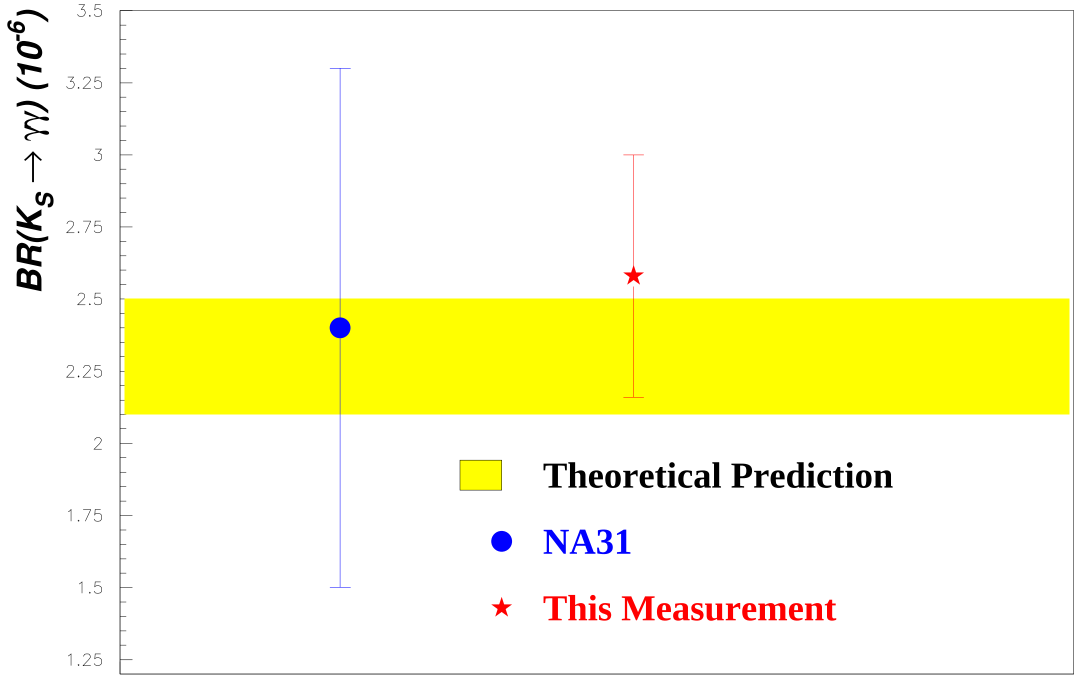
$$149 \pm 21 \ K_S \to \gamma\gamma \text{ events}$$

Normalization is $K_S \to \pi^0\pi^0$ (7.5×10^6 events)

Acceptances (from MC): 49 % for $K_S \to \gamma\gamma$
22 % for $K_S \to \pi^0\pi^0$

Systematics: 5 % background
5 % $BR(K_L \to \gamma\gamma)$
5 % trigger and selection cuts
2 % acceptance

$$\boxed{BR(K_S \to \gamma\gamma) = (2.58 \pm 0.36 \text{ (stat.)} \pm 0.22 \text{ (syst.)}) \times 10^{-6}}$$



corresponding to

$$R = \frac{\Gamma(K_S \to \gamma\gamma)}{\Gamma(K_L \to \gamma\gamma)} = 2.53 \pm 0.35 \text{ (stat.)} \pm 0.22 \text{ (syst.)}$$

$\mathrm{K_L} \to 3\pi^0$ Dalitz Plot: Motivations

The Dalitz plot distributions in the case of $\mathrm{K_L} \to 3\pi^0$ can be expressed as a function of a single parameter h:

$$|M_{000}(R^2,\theta)|^2 \propto 1 + hR^2$$

where $R^2 = (u^2 + v^2/3),\ \theta = arctan(v/\sqrt{3}u)$

$$u = \frac{s_3 - s_0}{m^2_{\pi^+}}, v = \frac{s_1 - s_2}{m^2_{\pi^+}}$$

$$s_i = (P_K - P_i)^2,\ s_0 = \frac{s_1 + s_2 + s_3}{3}$$

The h parameter can constrain the Dalitz plot parameters of others $K \to 3\pi$ decays.

χPT $\mathcal{O}(p^4)$ calculations predict (Kambor et al. PRL68(1992),1818)

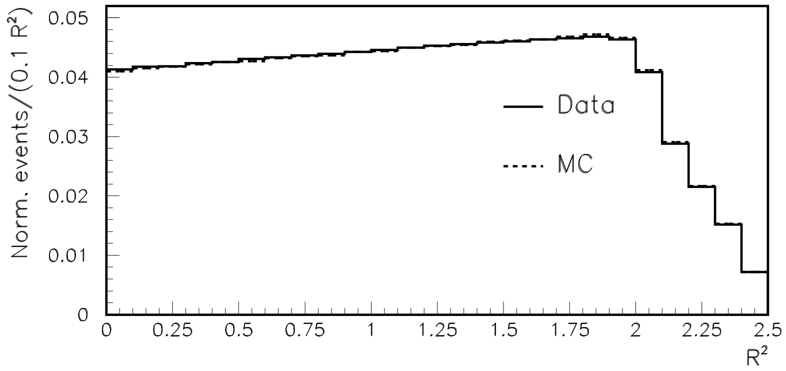
Theory: $h = (-12 \pm 4) \times 10^{-3}$

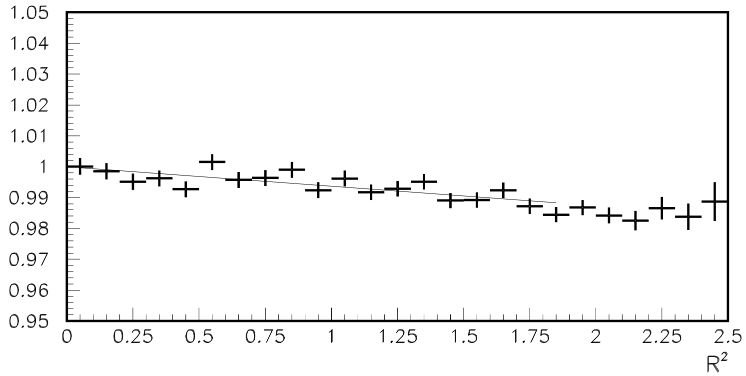
E731 collected 5×10^{-6} decays, measuring

PDG 2000 :
$h = (-3.3 \pm 1.1(\text{stat.}) \pm 0.7(\text{syst.})) \times 10^{-3}$

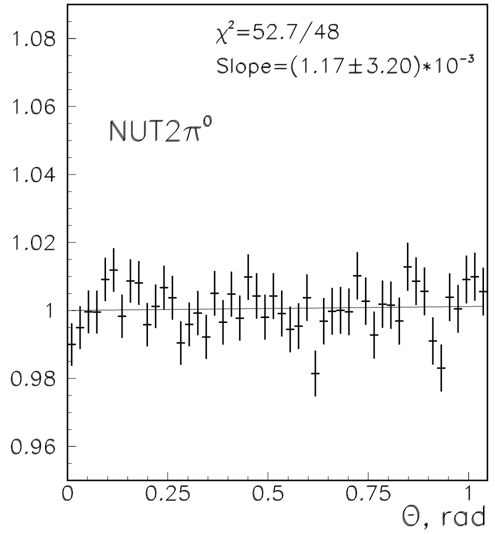
$K_L \to 3\pi^0$ Dalitz Plot: Results

The h parameter is obtained by fitting the DATA/MC ratio of R^2 distributions





As a check, the same ratio for the θ variable is verified to be flat



Main sources of systematics:

Lkr resolution	$.20 \times 10^{-3}$
Lkr non–linearity	$.17 \times 10^{-3}$
Lkr energy scale	$.17 \times 10^{-3}$
Trigger	$.10 \times 10^{-3}$

14.6×10^6 events
with negligible background

$$\boxed{h = (\ -6.1 \pm 0.9\ (\text{stat.}) \pm 0.5\ (\text{syst.})\ \ ) \times 10^{-3}}$$

in fair agreement with E731 (-3.3 ± 1.3) and theor. prediction (-12 ± 4)

NA48 Program for 2002

After the completion of the ε'/ε program, NA48 will search for very rare decays of $\mathrm{K_S}$ and neutral hyperons using a a slightly modified KS beam line:

- longer SPS duty cycle, proton energy optimized to 400 GeV
- KS intensity increased by $\sim$ 400
  $\Rightarrow$ expect 3×10^{10} $\mathrm{K_S}$ decays in 1 year
- minor upgrades of readout systems to stand 15 kHz instantaneous intensity

Physics goals:

- Measurement of $\Re(\eta_{000})$ (related to CPV in mixing) and $\Im(\eta_{000})$ (related to direct CPV) with accuracy 0.01
- Expect first observation of $\mathrm{K_S} \to \pi^0 e^+ e^-$ (SES$\sim 6 \times 10^{-10}$), as well as $\mathrm{K_S} \to \pi^0\gamma\gamma$, $\mathrm{K_S} \to \pi^0\pi^0\gamma\gamma$, $\mathrm{K_S} \to e^+e^-\gamma$, $\mathrm{K_S} \to \mu^+\mu^-\gamma$
- Precision measurements of Ξ^0 physics (mass, radiative decay modes, β decay $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$), allowing for checks of SU(3) symmetries and the Cabibbo model

Conclusions

NA48 is producing many interesting not–ϵ' results on kaon physics. Among the most recent ones:

- ➜ evidence for large CPV effects in $\mathrm{K_L} \to \pi^+\pi^-e^+e^-$
  first observation of $\mathrm{K_S} \to \pi^+\pi^-e^+e^-$ (PL B496(2000),137)
  (final results from 98+99 data to come)
- ➜ With 2 days of high–intensity KS data–taking
  - the sensitivity for the search of $\mathrm{K_S} \to \pi^0 e^+e^-$ has been improved by an order of magnitude:
    $BR(\mathrm{K_S} \to \pi^0 e^+e^-) < 1.4 \times 10^{-7}$ (to be published soon)
  - the largest sample of $\mathrm{K_S} \to \gamma\gamma$ decays was collected
    $BR(\mathrm{K_S} \to \gamma\gamma) = (2.58 \pm 0.36\ (\text{stat.}) \pm 0.22\ (\text{syst.})) \times 10^{-6}$
    (published in PL B493(2000),29)
- ➜ Very large sample of common kaon decays from the normal ε'/ε data–taking
  - precise measurement of the quadratic slope parameter in the $\mathrm{K_L} \to 3\pi^0$ Dalitz plot
    $h = (\ -6.1 \pm 0.9\ (\text{stat.}) \pm 0.5\ (\text{syst.})\ \ ) \times 10^{-3}$ (to be published soon)

Much better results on $\mathrm{K_S}$ and hyperon decays are expected from the dedicated run in 2002