Rare Kaon Decays

New Results from NA48

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on behalf of the

NA48 Collaboration

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

Rencontres de Physique de la Vallée d'Aoste

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Overview

New NA48 results on rare K_L and K_S decays:

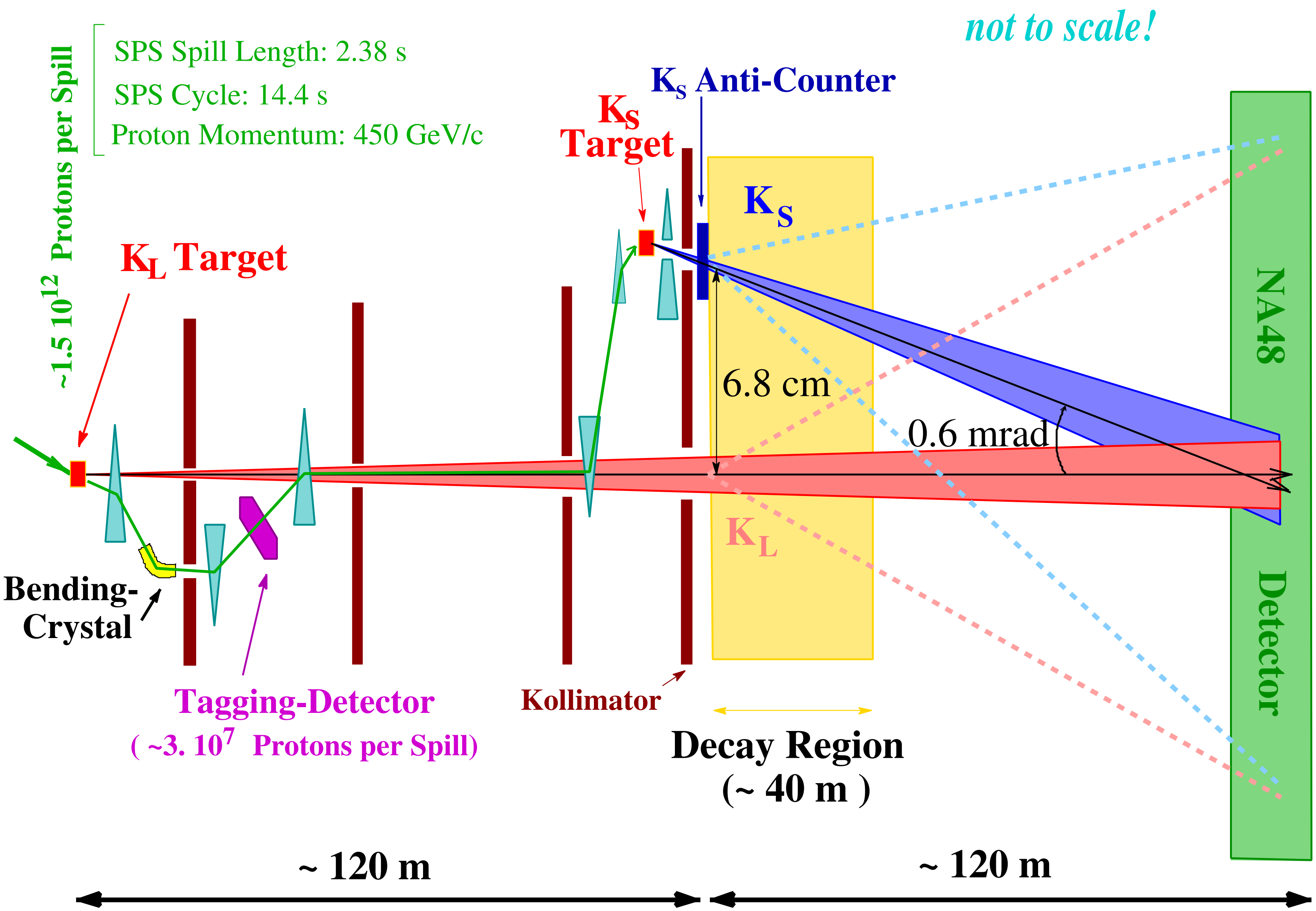
K_L decays

- $K_L \to 3\pi^0$ Dalitz plot slope
- $K_L \to 4$ leptons
- $K_L \to \pi^+\pi^-e^+e^-$

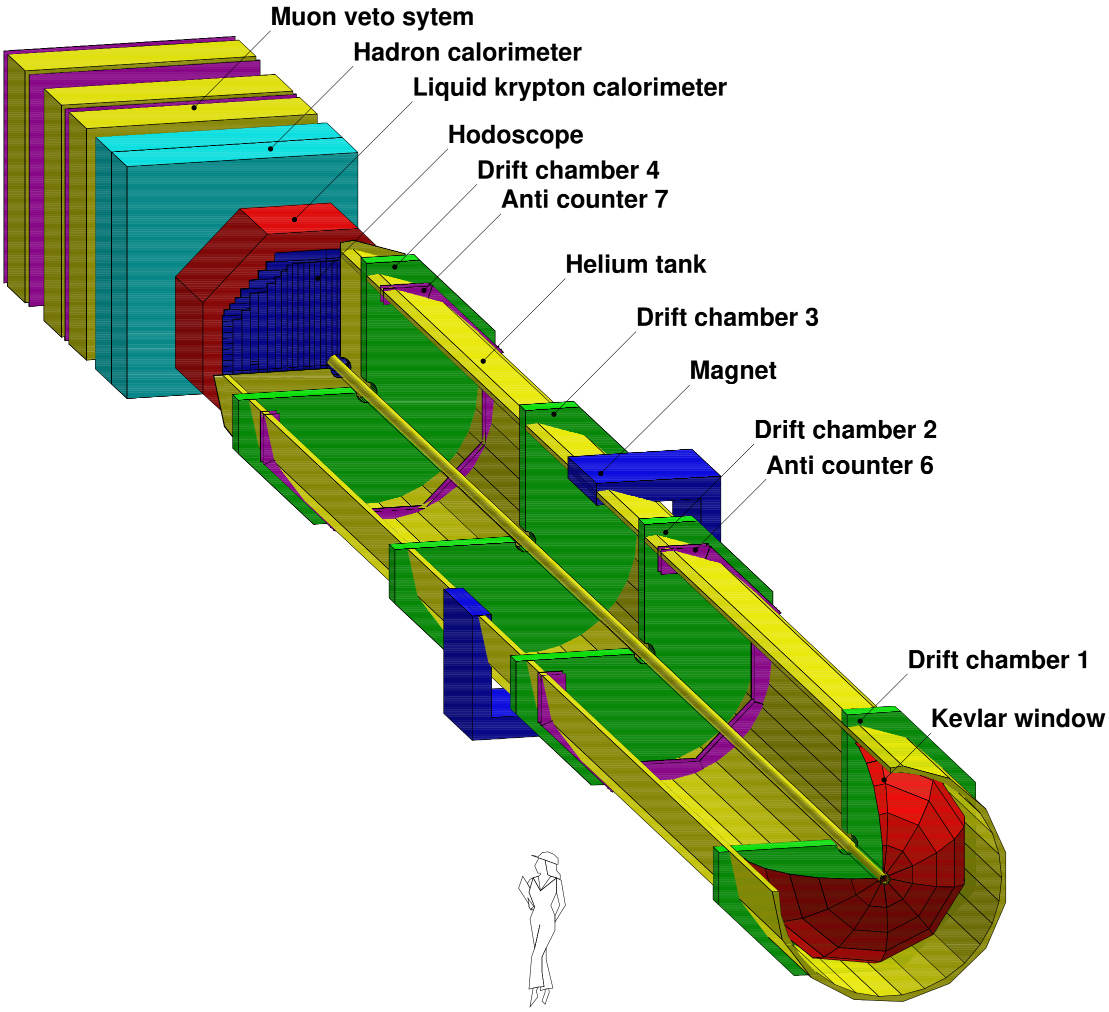
K_S decays

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

The NA48 Kaon Beams



The NA48 Detector



Magnetic Spectrometer:

$$\Delta p/p \simeq 0.5\% \oplus 0.009\% \times p\,[\mathrm{GeV/c}]$$

Liquid Krypton Calorimeter:

$$\Delta E/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 100\ \mathrm{MeV}/E \oplus 0.5\%$$

$K_L \to 3\pi^0$ Dalitz Plot Slope

$K \to 3\pi$ in general:

Expansion in Dalitz plot variables:

$$|M(u,v)|^2 \;\propto\; 1 \,+\, g\,u \,+\, h\,v \,+\, j\,u^2 \,+\, k\,v^2 \,+\, \cdots$$

with $u = (s_3 - s_0)/m_{\pi^+}^2, \;\; v = (s_1 - s_2)/m_{\pi^+}^2$

and $s_0 = \frac{1}{3}(s_1 + s_2 + s_3), \;\; s_{1,2,3} = (p_K - p_{\pi_{1,2,3}})^2.$

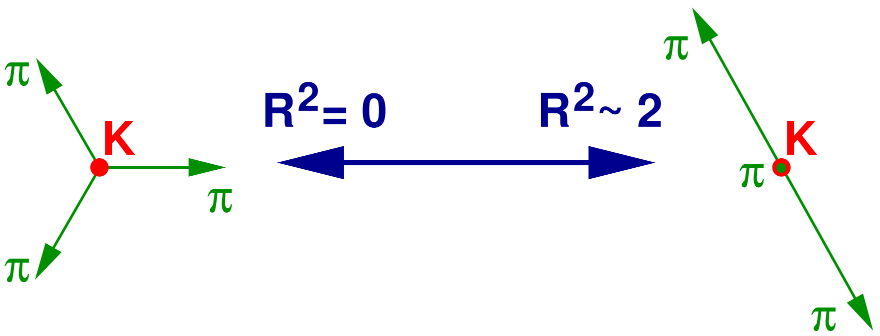
For $K_L \to 3\pi^0$:

Identical final state particles $\to$ **Simplification:**

$$|M_{K_L \to 3\pi^0}(R^2,\theta)|^2 \;\propto\; 1 \,+\, h \times R^2$$

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

$\Longrightarrow$ Only quadratic slope h left!



$K_L \to 3\pi^0$ **Dalitz plot: Motivation**

Measurement of h allows investigation of the $\Delta I = \frac{1}{2}$ rule violation (together with information from $K^\pm$ decays).

Theoretical predictions unclear:

J.Kambor *et al.* (PRL 68, 1818 (1992))

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

G.D'Ambrosio *et al.* (Phys. Rev. D50, 5767 (1994))

$$h \simeq +1.4 \times 10^{-3}$$

L.Maiani, N.Paver (2. DAΦNE Phys. Handbook, '95)

$$h = (-1.2 \pm 3.6) \times 10^{-3}$$

Previous measurement:

Only one measurement so far (E731, 1992):

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

based on 5×10^6 $K_L \to 3\pi^0$ decays (and 6.8×10^6 simulated).

Data samples

1998 NA48 Data:

Data taken during ϵ'/ϵ running.
Three different triggers to maximize statistics:

- Neutral trigger for $3\pi^0$ events (NUT3pi0)
  No requirements on peaks in the LKR, down-scaled
  $\longrightarrow 12.4 \times 10^6$ events
- Neutral trigger for $2\pi^0$ events (NUT2pi0)
  Requirements on LKR peaks to prefer $K^0 \to 2\pi^0$
  $\longrightarrow 1.5 \times 10^6$ events
- Neutral hodoscope trigger (NHodo)
  NHod coincidences inside the LKR, down-scaled
  $\longrightarrow 0.8 \times 10^6$ events

Monte Carlo Simulation:

In total (all three trigger conditions):
11.8×10^6 fully reconstructed events
(from 8×10^8 generated)

$K_L \to 3\pi^0$ Event Selection:

- Six well defined clusters in the LKR calorimeter. (Energy within linear range, minimum distances from LKR edges and dead cells, all clusters within ± 5 ns.)
- Minimum cluster distance < 10 cm.
  $\longrightarrow$ No overlapping clusters.
- No additional clusters within ± 3 ns.
  $\longrightarrow$ No overlapping events.
- Cluster center-of-gravity in the LKR < 10 cm
  $\longrightarrow$ Event coming from K_L target.

$\Longrightarrow$ Very clean events, no backgrounds left.

For each event, the π^0 combinations are picked, which give the minimal χ^2 for coming from a $K_L \to 3\pi^0$ decay.

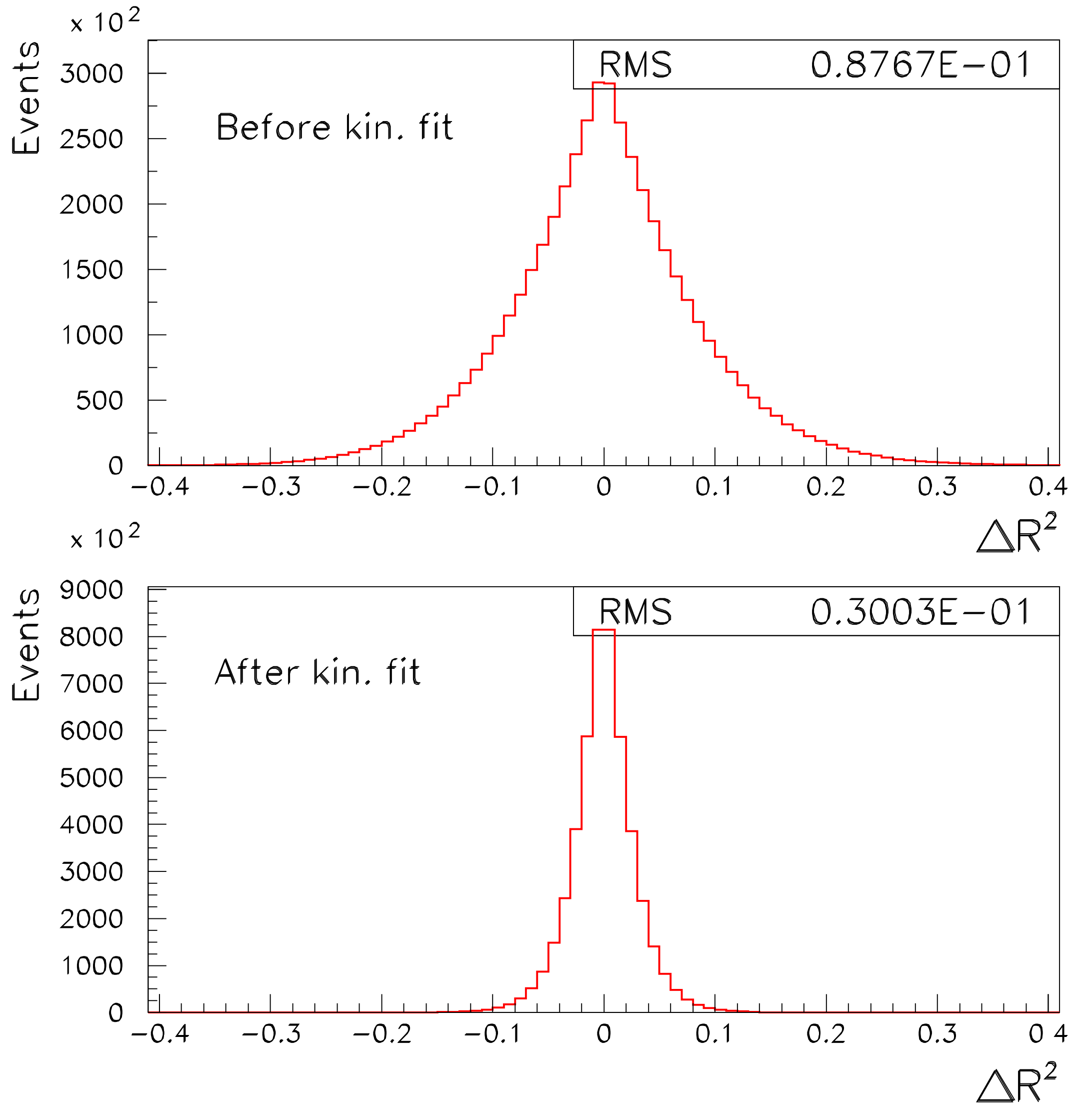
Kinematic fit

Perform kinematic fit to improve resolution ($\rightarrow \pi^0$ masses constrained).

$$E_i^{\text{Cluster}}, x_i^{\text{Cluster}}, y_i^{\text{Cluster}} \text{ (18 measurements)}$$

$$\Downarrow$$

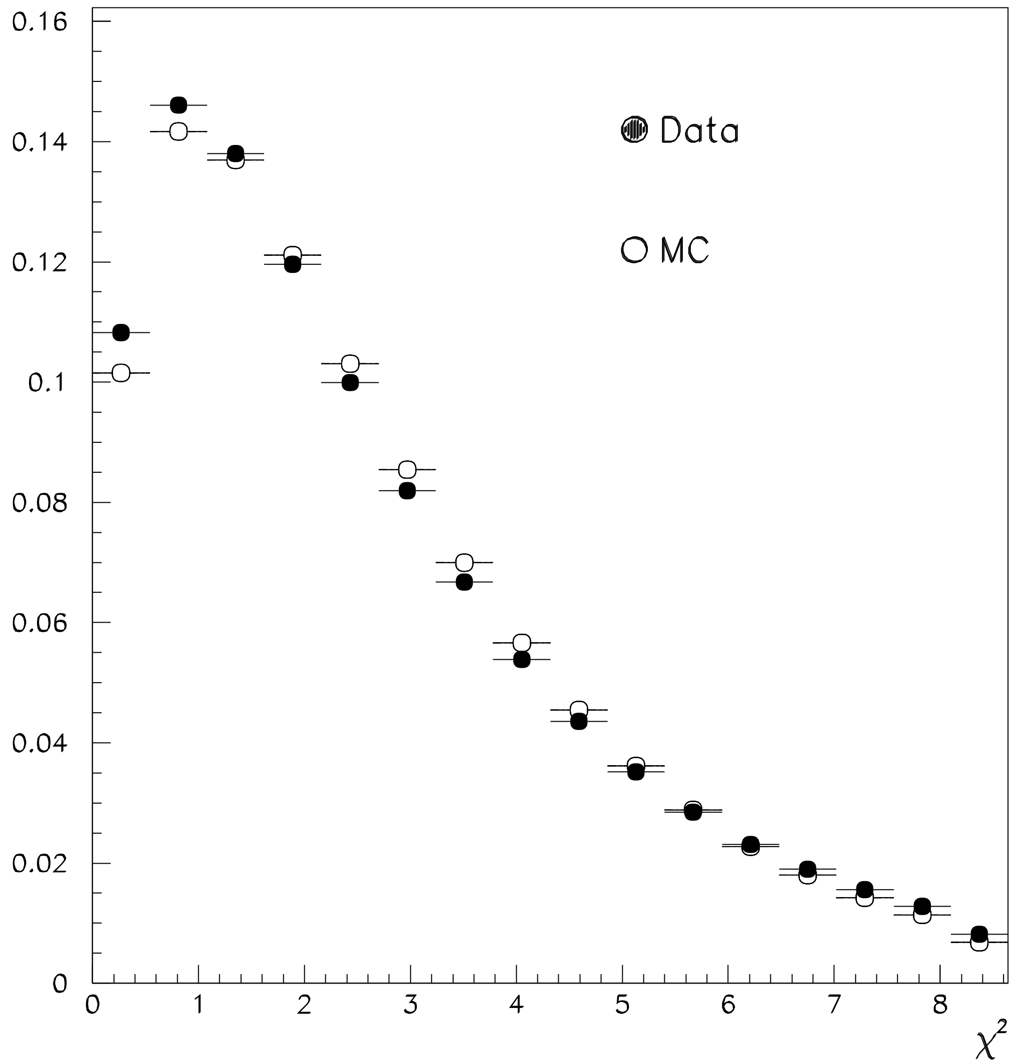
R^2, θ, 3 Euler angles, K energy, decay vertex, π^0 decay angles (15 parameters)



$\Longrightarrow$ Factor ≈ 3 improvement in R^2, θ resolution.

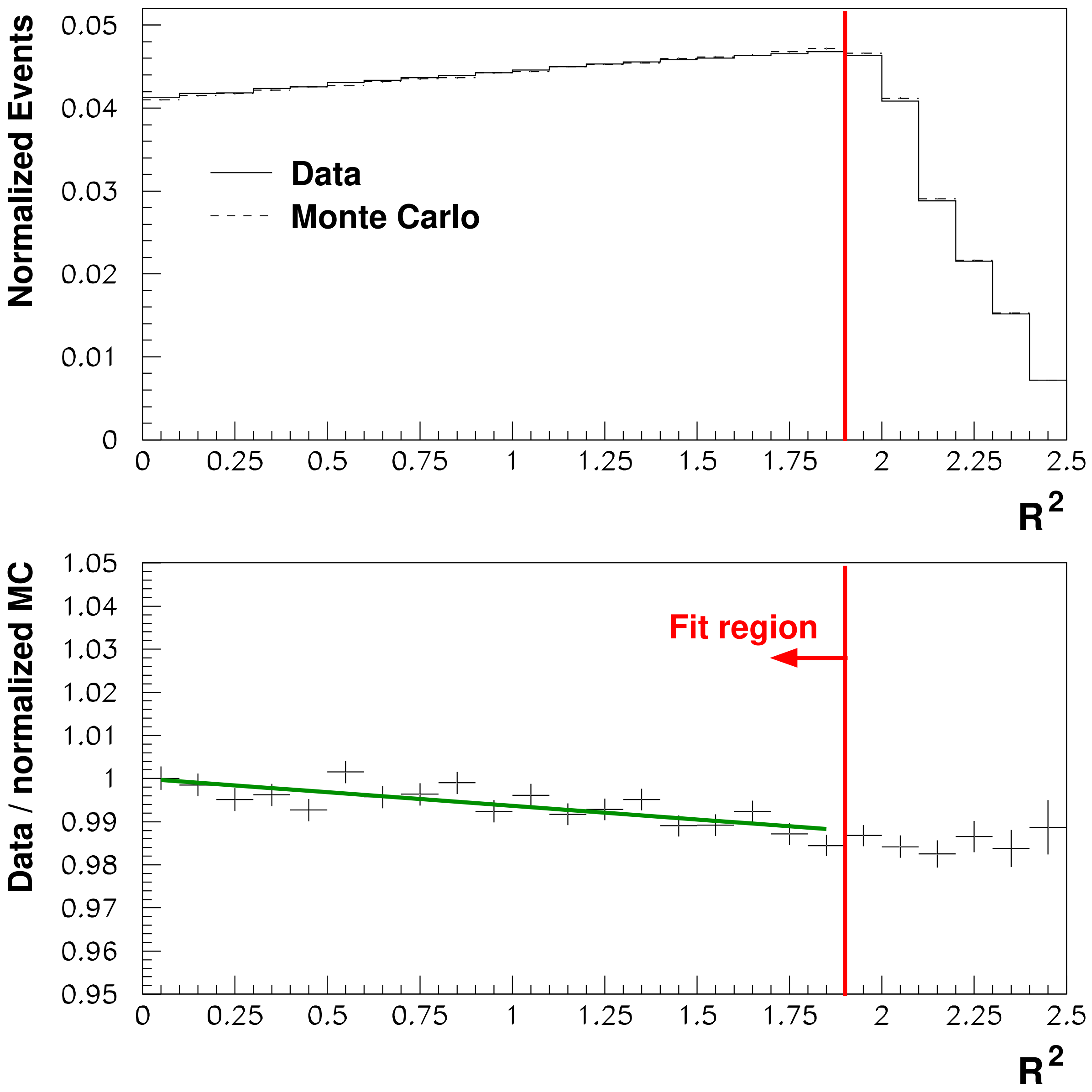
To assure goodness of the kinematic fit:

$$\chi^2_{\text{Kinematic Fit}} < 8.5 \text{ required.}$$



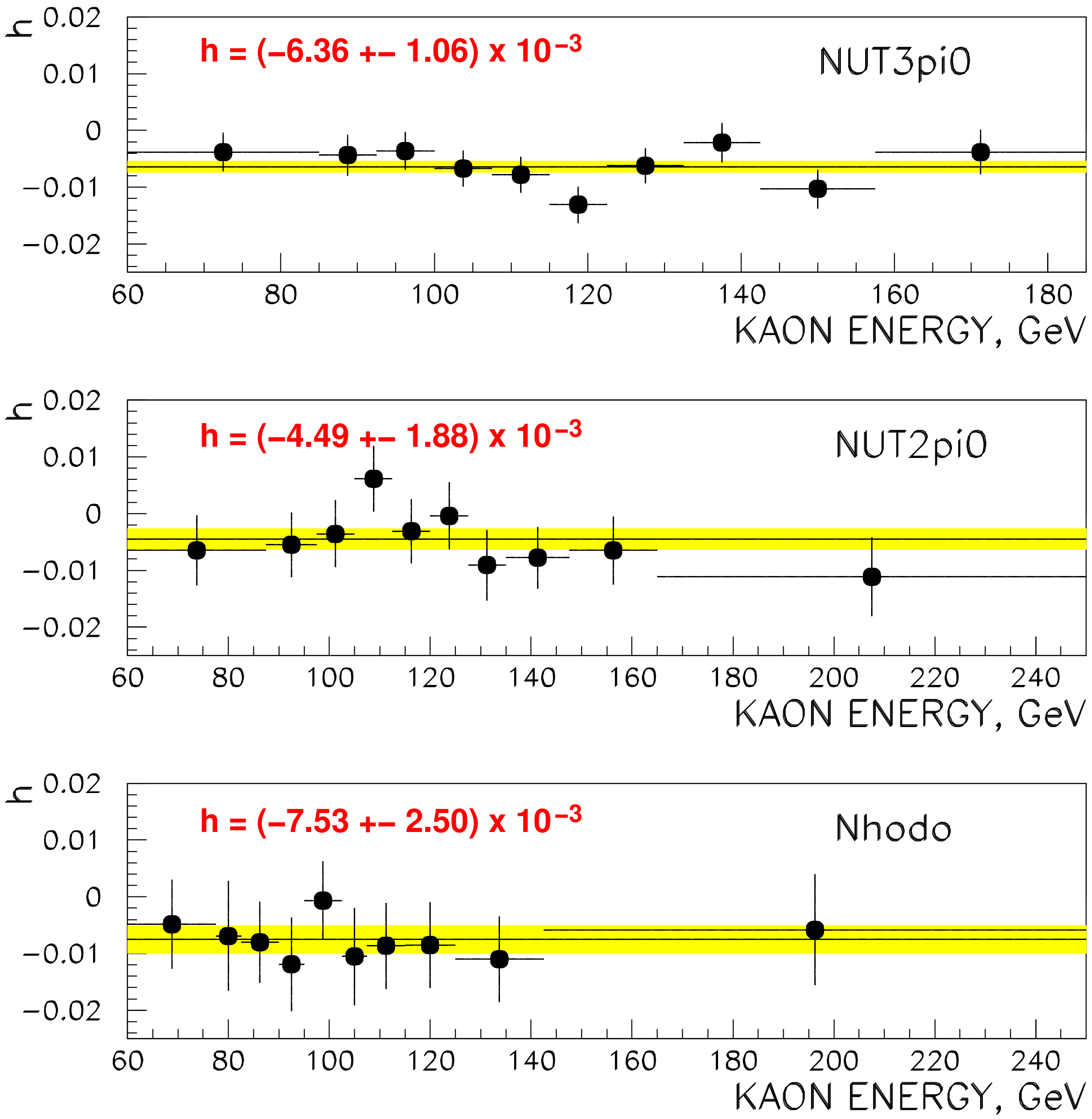
Fit of the slope h

Divide data by normalized MC ($h = 0$) and fit slope in the region $0 < R^2 < 1.9$
(to avoid resolution effects at the edge).



Fit Result

Fit of the slope h is performed in energy bins and separately for the three samples.



$$\Longrightarrow \boxed{h = (-6.1 \pm 0.9_{\text{stat}}) \times 10^{-3}}$$

Systematics Checks:

Taking advantage of near-perfect understanding of the LKR calorimeter due to ϵ'/ϵ measurement.

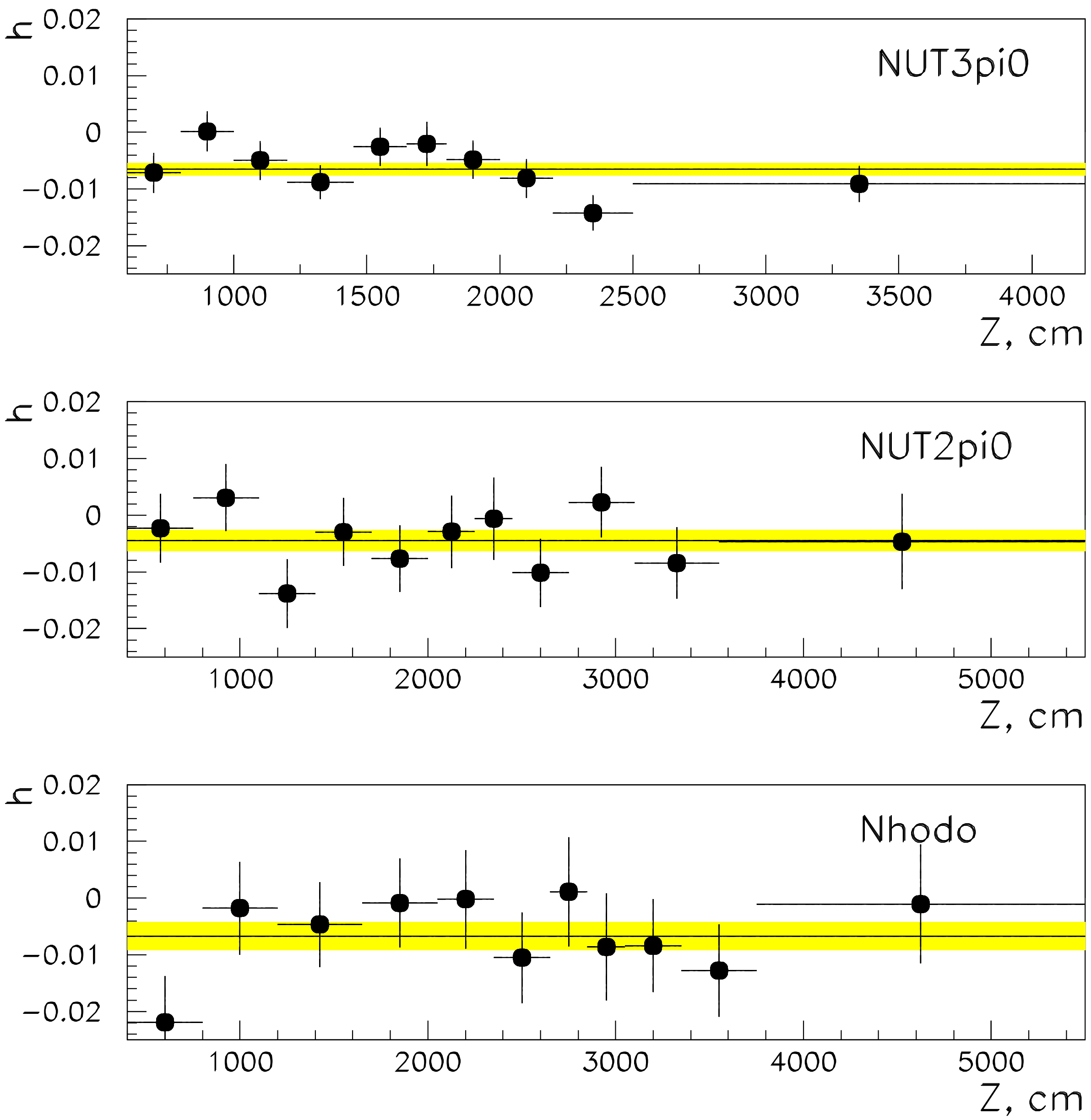
- Cluster energy resolution in the MC
  $\longrightarrow \Delta h = \pm\, 0.20 \times 10^{-3}$
- LKR calorimeter (energy scale (known to $< 0.1\%$)
  $\longrightarrow \Delta h = \pm\, 0.17 \times 10^{-3}$
- Non-linearities in the LKR calorimeter
  $\longrightarrow \Delta h = \pm\, 0.17 \times 10^{-3}$
- Non-gaussian tails in the energy resolution
  $\longrightarrow$ negligible
- LKR inefficiencies not modelled by the MC
  $\longrightarrow \Delta h = \pm\, 0.06 \times 10^{-3}$
- Trigger efficiency
  $\longrightarrow \Delta h = \pm\, 0.10 \times 10^{-3}$
- Variations when splitting in bins of z vertex, lifetime, center-of-gravity, cluster positions, etc.
  $\longrightarrow \Delta h = \pm\, 0.38 \times 10^{-3}$

$$\Longrightarrow \boxed{\Delta h_{\text{syst}} = \pm\, 0.5 \times 10^{-3}}$$

Fits in bins of the reconstructed decay vertex:

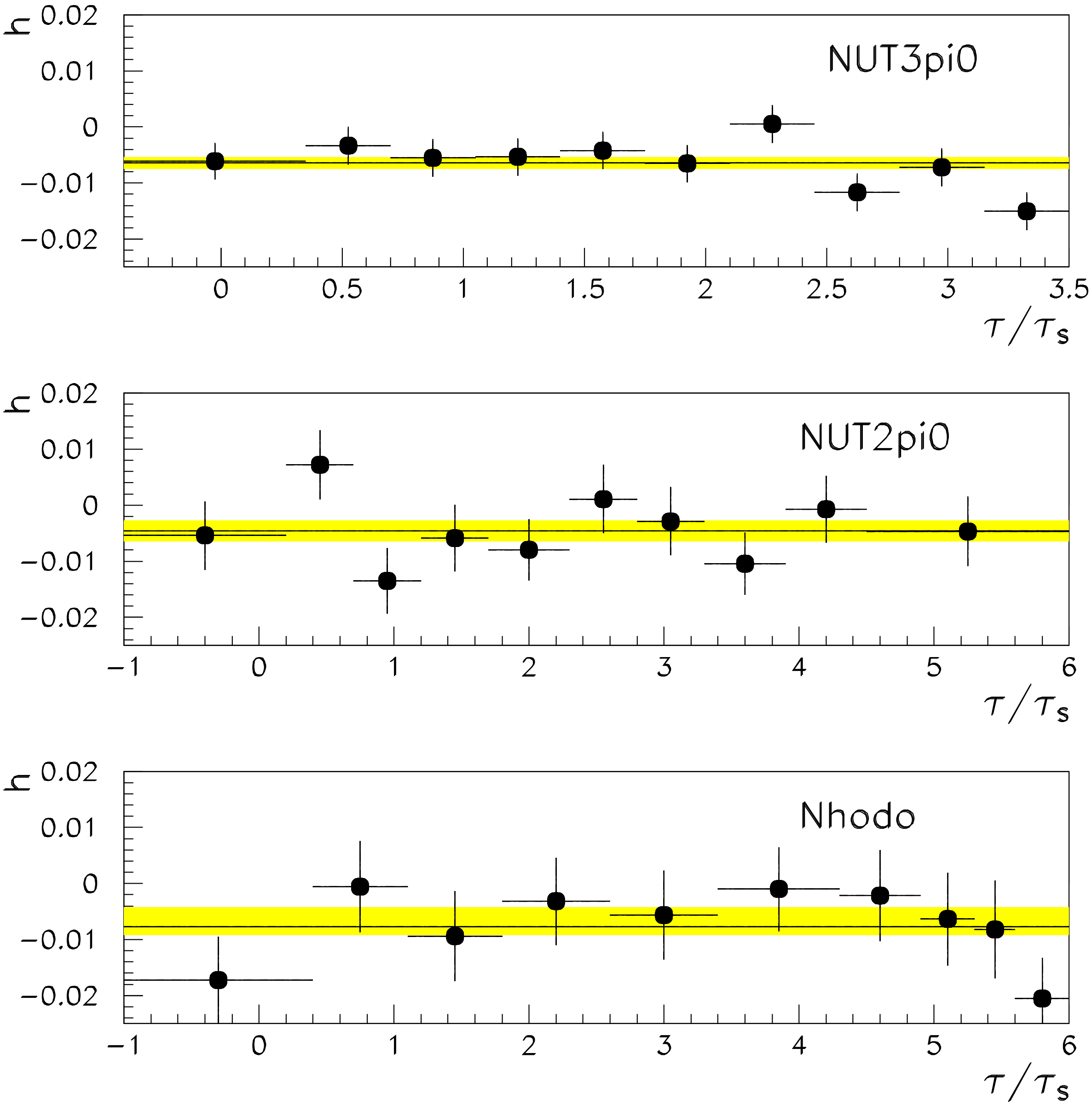
The decay vertex z_{vertex} is reconstructed using the nominal K^0 mass:

$$z_{\mathrm{vertex}} = z_{\mathrm{LKR}} - \frac{1}{m_{K^0}} \sqrt{\sum_{i,j;i>j} E_i E_j (\vec{r}_i - \vec{r}_j)^2}$$



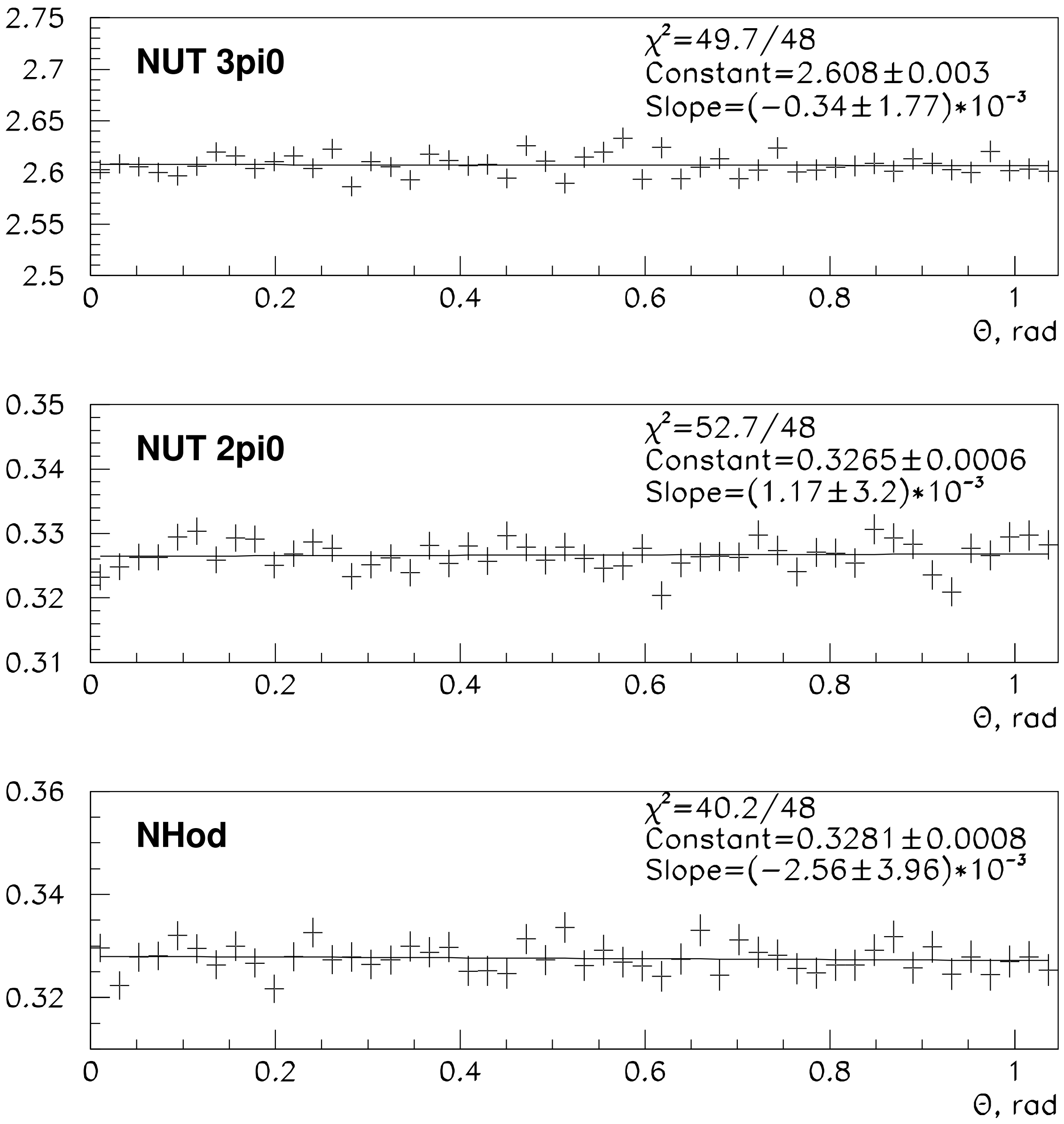
Fits in bins of the reconstructed lifetime:

K_L lifetime is measured from the final collimator using the total energy and the reconstructed decay vertex.



Additional Cross-check:

Try to fit slope to θ distribution (should be flat):



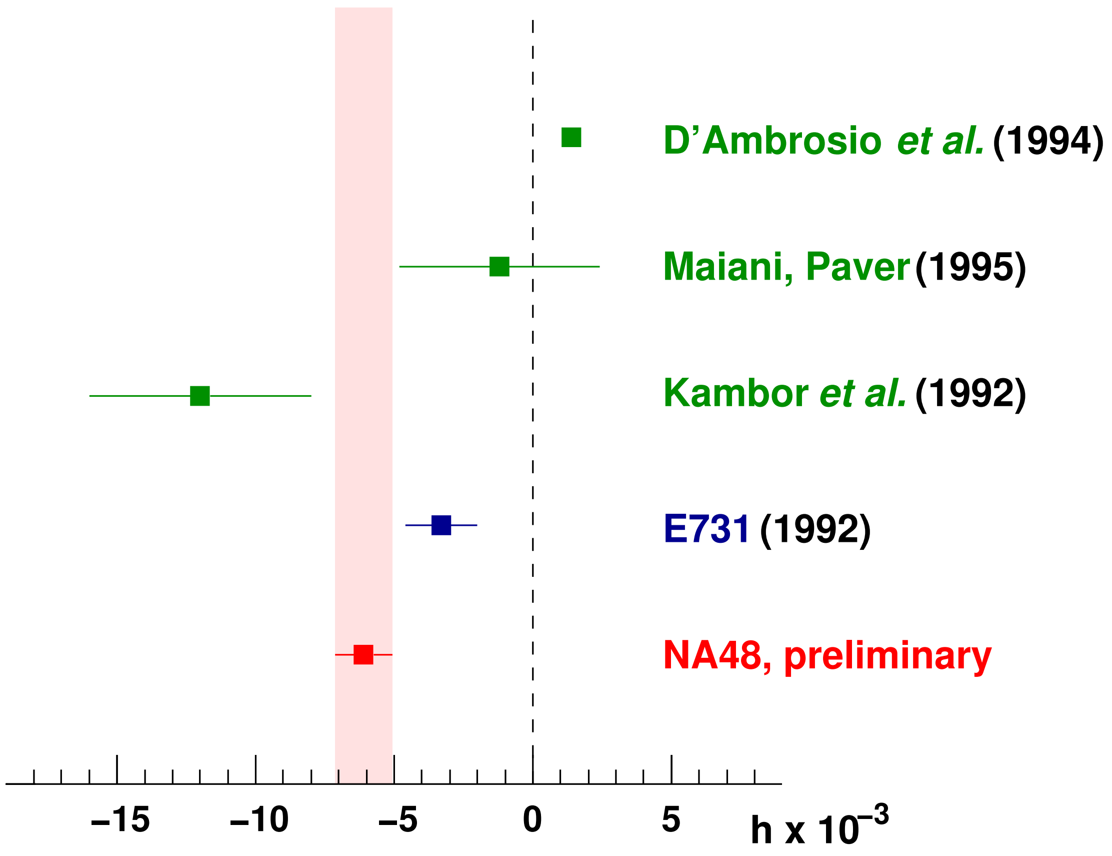
$\Longrightarrow$ Fitted θ slope consistent with zero in all three samples.

Conclusion on the $K_{\mathrm{L}} \to 3\pi^0$ Dalitz plot slope

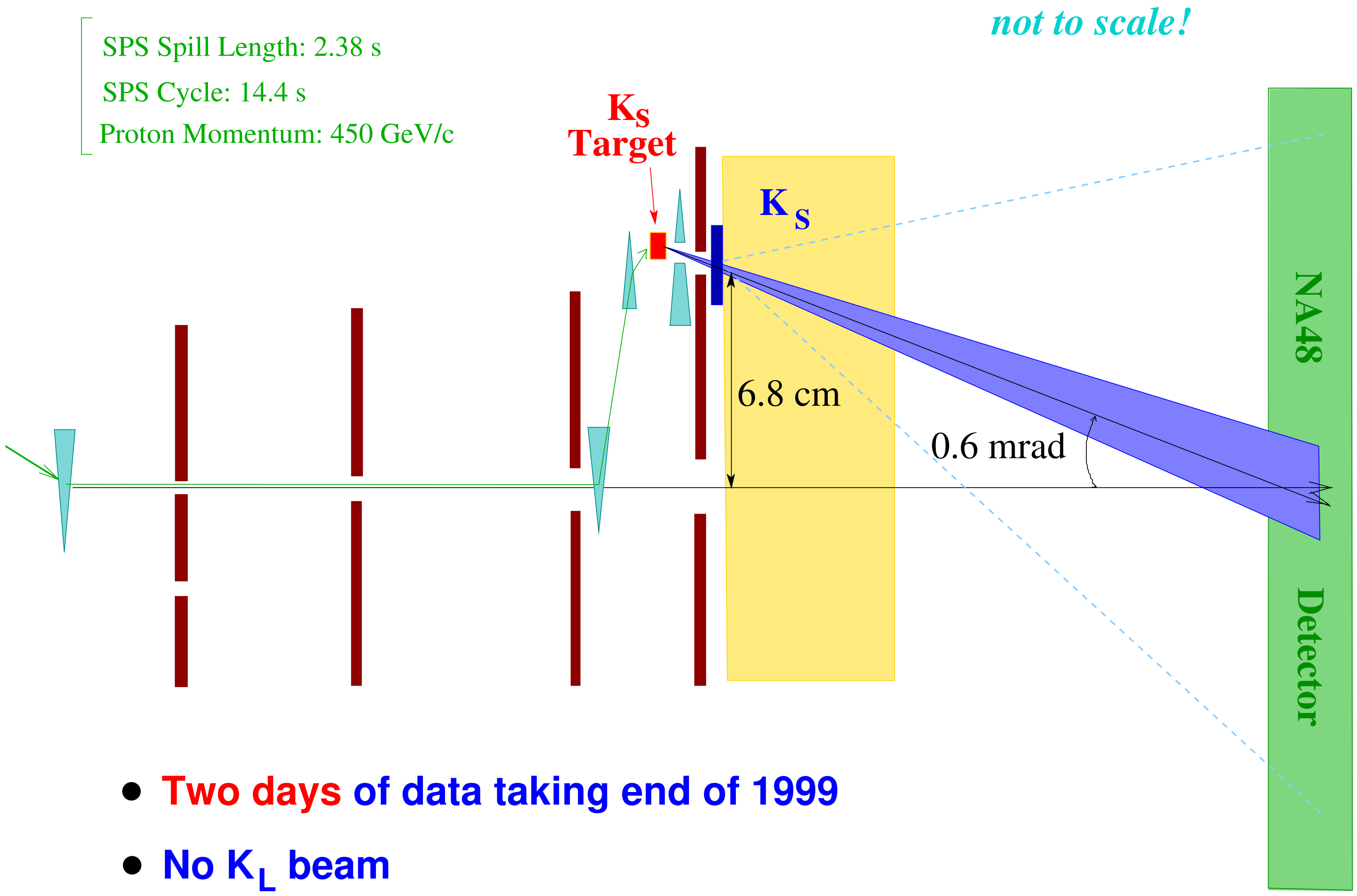
We measure for the quadratic slope parameter h of the $K_{\mathrm{L}} \to 3\pi^0$ Dalitz plot:

Preliminary

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



K_S and Hyperon Running in 1999



- Two days of data taking end of 1999
- No K_L beam
- 7×10^9 protons per spill on K_S target (200 times ε'/ε intensity)

Search for $K_S \to \pi^0 e^+ e^-$

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

Three amplitudes: Direct CP violation, indirect CP violation, CP conserving.

It is expected, that the decay is dominated by direct CP violation, $\mathrm{Br}(K_L \to \pi^0 e^+ e^-) \sim \mathcal{O}(10^{-12})$.

$\Longrightarrow$ Inaccessible for NA48.

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

This decay is directly connected to the amplitude of indirect CP violation in $K_L \to \pi^0 e^+ e^-$.

$\Longrightarrow$ Measurement of $\mathrm{Br}(K_S \to \pi^0 e^+ e^-)$ important for future measurements of $K_L \to \pi^0 e^+ e^-$.

Theoretical expectation:

$$\mathrm{Br}(K_S \to \pi^0 e^+ e^-) \sim \text{ few} \times 10^{-9}.$$

Previous best limit (NA31,1993):

$$\mathrm{Br}(K_S \to \pi^0 e^+ e^-) < 1.1 \times 10^{-6}$$

$K_S \to \pi^0 e^+ e^-$ Event Selection:

- Two oppositely charged tracks.
  Distance in first drift chamber > 2 cm.

  $\longrightarrow$ No photon conversions.

- Four well defined clusters in the LKR calorimeter.
  Clusters associated with tracks: $E/p > 0.9$.

  $\longrightarrow$ Pion rejection.

- Cluster center-of-gravity in the LKR < 10 cm

  $\longrightarrow$ Avoiding missing energy.

- π^0 selection:

  $$|m(\gamma\gamma) - m_{\pi^0}| < 2.5 \text{ MeV/c}^2 \quad (\hat{=}\, 2.5\,\sigma)$$

- K_S selection:

  $$|m(\gamma\gamma e^+ e^-) - m_{K^0}| < 10 \text{ MeV/c}^2 \quad (\hat{=}\, 3\,\sigma)$$

- No coincidence with veto-counter in the K_S beam.

- No energy in the hadron calorimeter.

$\Longrightarrow$ 10 events left after general event selection criteria.

But not yet thought about backgrounds. . .

Background: $K_S \to \pi^0_{\rm Dalitz}\,\pi^0_{\rm Dalitz}$

Double Dalitz decay (with $\pi^0_{\rm Dalitz} \to e^+e^-\gamma$):

$\mathrm{Br}(K_S \to \pi^0_{\rm Dalitz}\,\pi^0_{\rm Dalitz}) = 4.5 \times 10^{-5}$

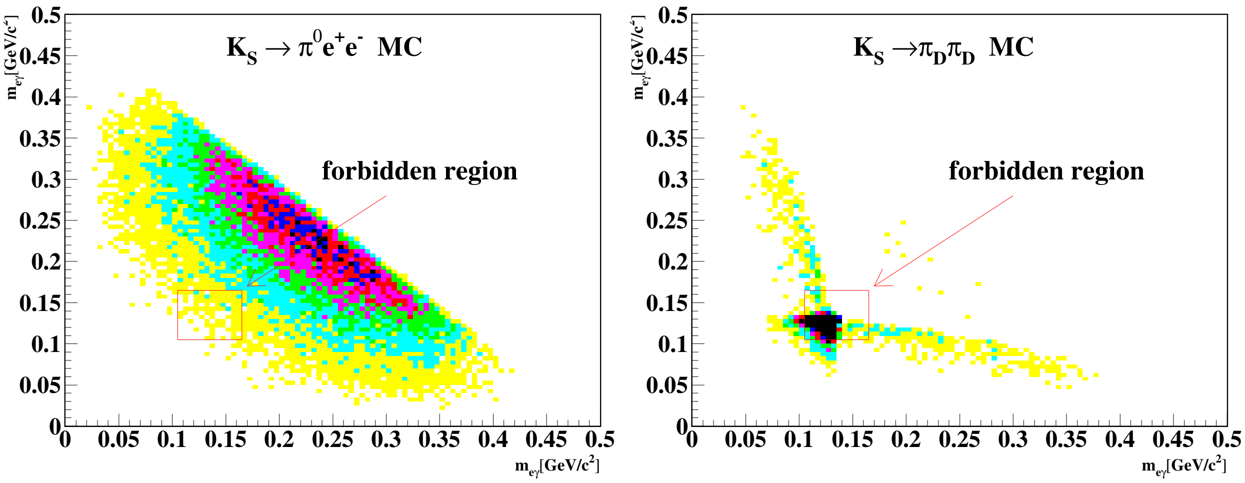
$\longrightarrow$ Expect ≈ 14000 decays in total.

Potentially severe when two soft electrons from different pions are lost.

Rejection:

Require for all possible $e^{\pm}\,\gamma_{1,2}$ combinations:

$$|m(e\gamma) - m_{\pi^0}| > 30\ \text{MeV/c}^2$$

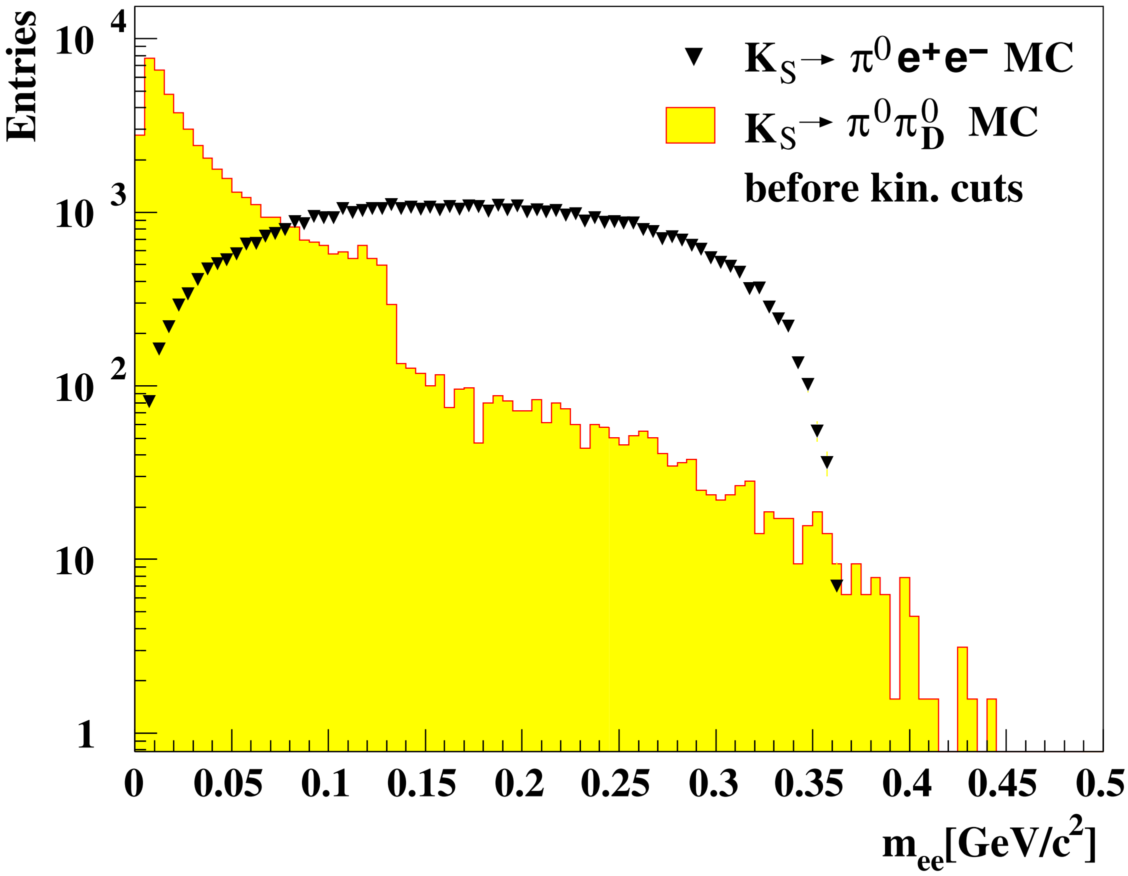


$\Longrightarrow$

- Only 4.5% signal efficiency loss.
- $< 0.01\ K_S \to \pi^0_{\rm Dalitz}\,\pi^0_{\rm Dalitz}$ remaining background events expected.

Background: $K_S \to \pi^0\,\pi^0_{\mathrm{Dalitz}}$

For low $m(e^+e^-)$ serious background comes from $K_S \to \pi^0\,\pi^0_{\mathrm{Dalitz}}$, with $\pi^0_{\mathrm{Dalitz}} \to e^+e^-\gamma$, and one soft photon lost.



For $m(e^+e^-) \approx m_{\pi^0}$ this background cannot be suppressed requiring a good K_S invariant mass.

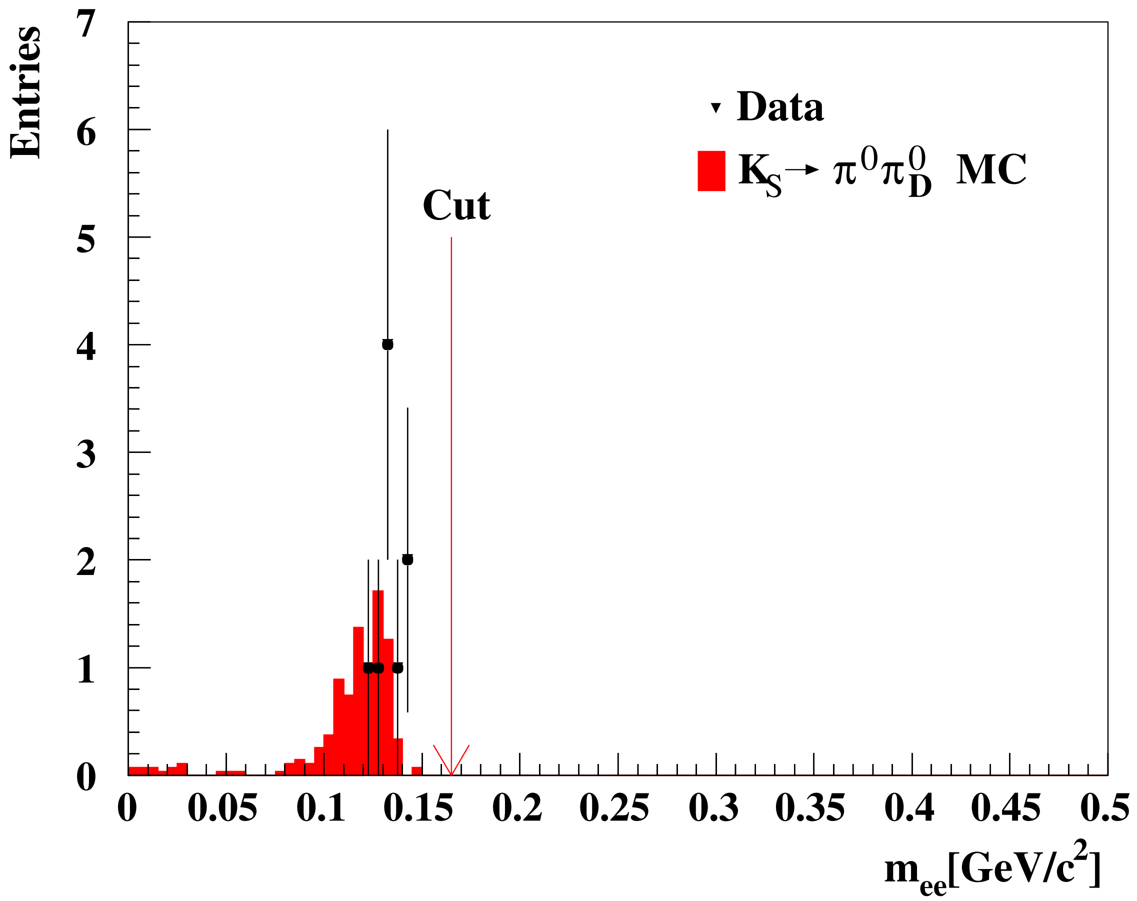
To take into account smearing by the detector resolution and multiple scattering, we require:

$$m(e^+e^-) > 165\ \mathrm{MeV/c^2}.$$

$\Longrightarrow$ < 0.07 remaining $K_S \to \pi^0\,\pi^0_{\mathrm{Dalitz}}$ events expected.

After all cuts (except on $m(e^+e^-)$) 9 signal candidates remain.

All candidates are below $m(e^+e^-) = 165$ MeV/c^2 and compatible with the $K_S \to \pi^0\,\pi^0_{\rm Dalitz}$ background expectation of ≈ 12 events.



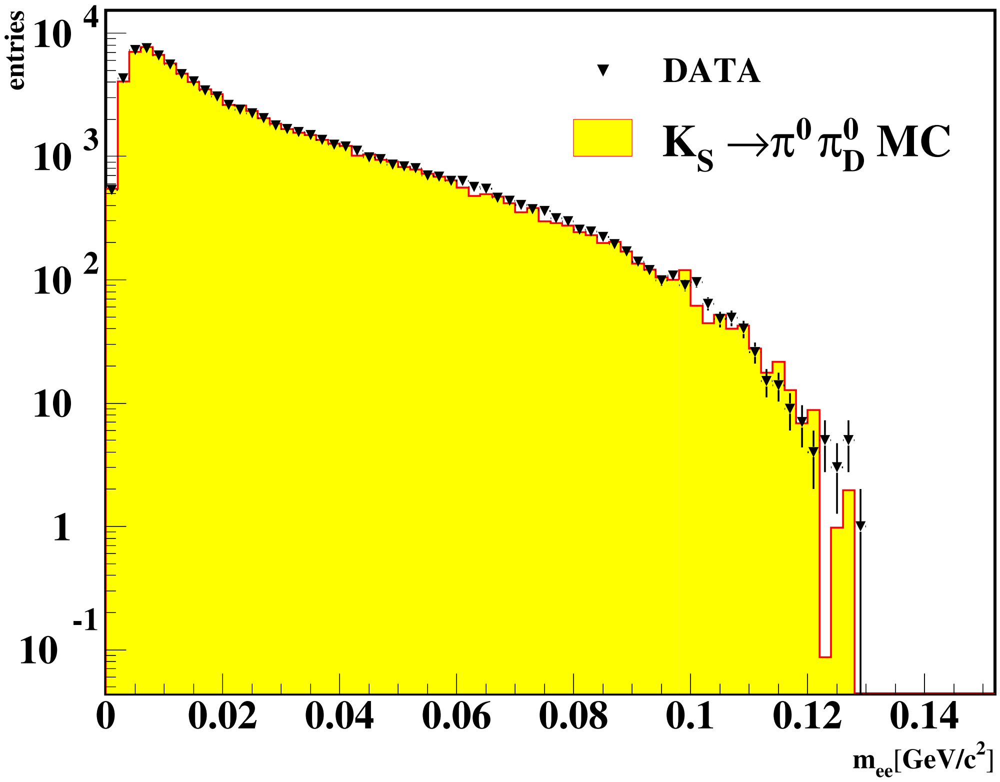
Requiring $m(e^+e^-) > 165$ MeV/c^2:

$\Longrightarrow$ $\boxed{\text{No signal event found.}}$

Normalization: $K_S \to \pi^0 \pi^0_{\text{Dalitz}}$

- Almost the same topology.
- $\text{Br}(K_S \to \pi^0\, \pi^0_{\text{Dalitz}}) \approx 3.5 \times 10^{-3}$

Very similar event selection (5 clusters, $m_{ee\gamma} \approx m_{\pi^0}$).
Photon conversions from $K_S \to \pi^0\, \pi^0$ are suppressed by minimum track distance and K_S anti-counter vetos
$\longrightarrow \sim 1\%$ remaining background



$\Longrightarrow \quad \approx 80000\ K_S \to \pi^0\, \pi^0_{\text{Dalitz}}$ candidates found.

Detector acceptance: $\epsilon_{\text{geom}} = \ 4.2\%$
Trigger efficiency: $\epsilon_{\text{trig}} = 99.7\%$

$\Longrightarrow$ Total integrated K_S meson flux $\approx 3 \times 10^8$.

Upper limit on $K_S \to \pi^0 e^+ e^-$

$K_S \to \pi^0 e^+ e^-$ detector acceptance:

Using matrix element from χPT (D'Ambrosio *et al.*, JHEP 08(1998)004) and varying the form factor
$\longrightarrow \epsilon_{\rm geom} = (7.5 \pm 0.4)\%$

$K_S \to \pi^0 e^+ e^-$ trigger efficiency:

$\epsilon_{\rm trig} = 98.3\%$

$\Longrightarrow$ $\boxed{\mathrm{Br}(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7} \text{ at } 90\% \text{ CL.}}$

Better by one order of magnitude than previous best limit, still one order of magnitude above theoretical expectation.

Using this result, a limit on the indirect CP violating amplitude of $K_L \to \pi^0 e^+ e^-$ can be derived to

$$\mathrm{Br}(K_S \to \pi^0 e^+ e^-)_{\text{indirect CPV}} < 4.1 \times 10^{-10} + \text{interference terms}$$

consistent with the recent limit of

$$\mathrm{Br}(K_S \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10} \text{ (KTeV, 2001)}$$

Measurement of $K_S \to \gamma\gamma$

- $K_{S,L} \to \gamma\gamma$ sensitive to higher loop effects in Chiral Perturbation Theory.
- $\mathrm{Br}(K_L \to \gamma\gamma)$ measured with $\sim 2.5\%$ accuracy.

$\mathrm{Br}(K_S \to \gamma\gamma)$:

Precise theoretical prediction by χPT: $(2.3 \pm 0.2) \times 10^{-6}$

Measurement (NA31, 1995): $(2.6 \pm 0.9) \times 10^{-6}$

Experimental problem:

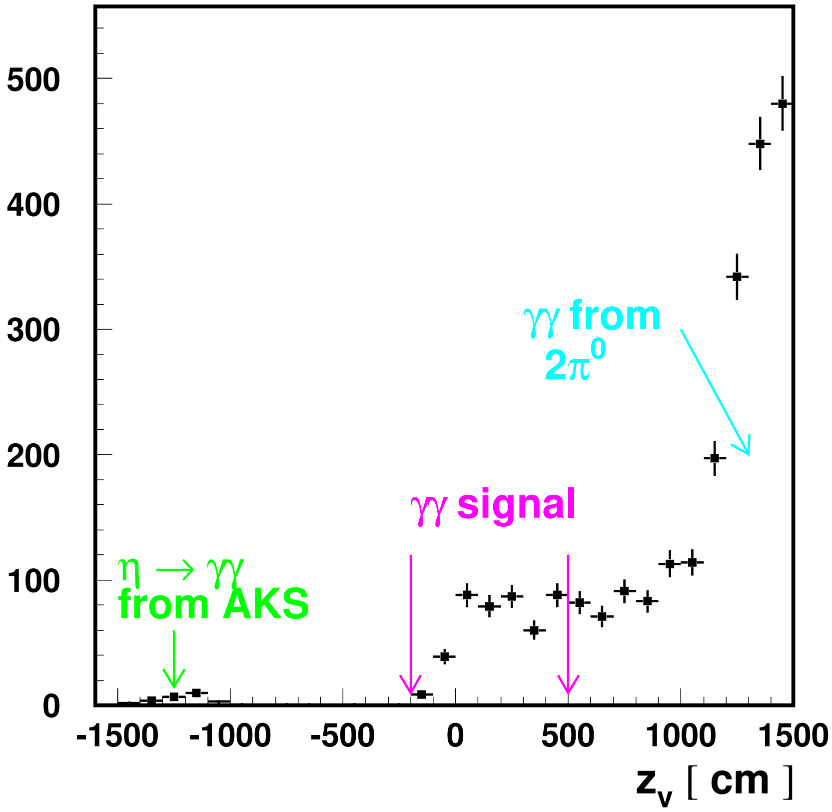
$K_S \to \gamma\gamma$ can be faked by $K_S \to \pi^0\pi^0$ with two missing photons.

Missing energy shifts reconstructed decay vertex down-stream by > 7 m.

$\Longrightarrow$ Restrict decay vertex to $0 \text{ m} < z_{\text{vertex}} < 5 \text{ m}$ after defining collimator.

$K_S \to \gamma\gamma$ Event Selection

- Require exactly 2 clusters in the LKR calorimeter.
- Kaon energy within 60 GeV – 170 GeV.
- LKR center-of-gravity < 7 cm.
- Vetos: Hadronic energy, drift chamber hits, AKS/AKL veto counter hits



Backgrounds:

- $K_S \to \pi^0\,\pi^0 \longrightarrow$ Only at large $z_{\rm vertex}$.
- $K_L \to \gamma\gamma \longrightarrow$ Same signature, is subtracted $(\mathrm{Br}(K_L \to \gamma\gamma) = 5.9 \times 10^{-4})$
- $\Lambda \to n\,\pi^0 \longrightarrow$ center-of-gravity side-band subtraction.

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

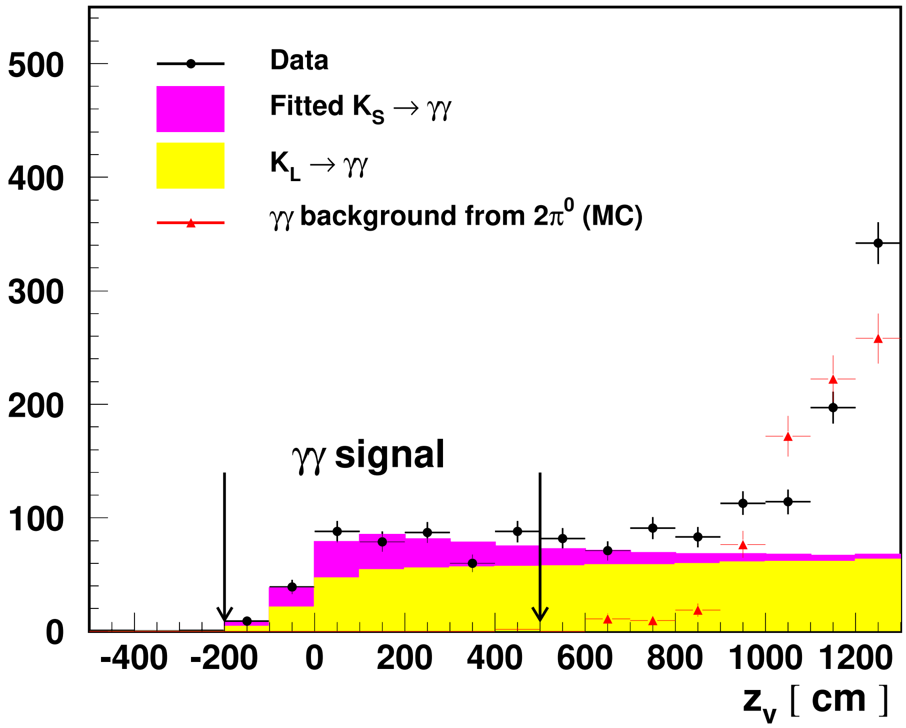
After all cuts remain in the signal region:

$450\ K \to \gamma\gamma$ candidates.

Subtract: $2 \pm 2\ K_S \to \pi^0\pi^0$
$11 \pm 8\ \Lambda \to n\,\pi^0$

Maximum likelihood fit to the signal region and subtracting $K_L \to \gamma\gamma$ contribution:

$149 \pm 21\ K_S \to \gamma\gamma$ candidates.



Normalization: $7.5 \times 10^6\ K_S \to \pi^0\pi^0$ decays.

$$\boxed{\mathrm{Br}(K_S \to \gamma\gamma) = (2.6\ \pm\ 0.4_{\mathrm{stat}}\ \pm\ 0.2_{\mathrm{syst}}) \times 10^{-6}}$$

Outlook

2000:

No drift chambers
$\Longrightarrow$ Running for Neutral Decays only.

Both K_L and K_S decays.

No material (vacuum) between collimator and calorimeter $\longrightarrow$ No photon conversions.

- $K_S \to \gamma\gamma$

  $\approx 30\times$ 1999 data

- $K_S \to 3\pi^0$

  Expect statistical error on η_{000} of ± 0.02

- $K_L \to 3\pi^0$ Dalitz plot slope

  No down-scaling & clean environment
  $\longrightarrow$ More statistics and less systematics.

2001:

New drift chambers
$\Longrightarrow$ NA48 finishes the $\mathrm{Re}(\epsilon'/\epsilon)$ measurement.

Hoping for 50% – 100% more data for rare K_L decays.

2002:

One full year of high-intensity K_S and hyperon data taking.

We expect to collect at least $50\times$ the statistics of the 1999 data, and much more in some channels due to trigger improvements.

- Observation of $\mathrm{Br}(K_S \to \pi^0 e^+ e^-)$.
- Even more $K_S \to \gamma\gamma$ and $K_S \to 3\pi^0$
- Neutral Hyperon Decays
  Expecting to collect ~ 30000 Ξ^0 beta decays
  $\Longrightarrow$ Precision measurements of Ξ^0 form factors and the Cabibbo angle possible.

2003/2004:

$K^\pm$ program. Main goals:

- Measurement of CP violation in $K^\pm \to \pi^\pm \pi^\pm \pi^\mp$.
- $K^\pm \to \pi^\pm \pi^\mp e^\pm \nu$ form factor measurement.

Summary

The NA48 experiment has the following new results on rare decays of neutral kaons:

$K_{\rm L} \to 3\pi^0$ Dalitz plot slope

From 14.7 million $K_{\rm L} \to 3\pi^0$ decays we preliminarily measure the quadratic slope parameter $h = (-6.1 \pm 0.9_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-3}$

$K_{\rm S} \to \pi^0 e^+ e^-$

In an integrated flux of 3×10^8 $K_{\rm S}$ mesons we find no signal candidate and derive an upper limit of $\mathrm{Br}(K_{\rm S} \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$ at 90% CL.

$K_{\rm S} \to \gamma\gamma$

From 497 $K^0 \to \gamma\gamma$ candidates, we measure $\mathrm{Br}(K_{\rm S} \to \pi^0 e^+ e^-) = (2.6 \pm 0.4_{\rm stat} \pm 0.2_{\rm syst}) \times 10^{-6}$

Future program:

Stay tuned!