Tests of Chiral Perturbation Theory in Kaon decays

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- $K_{S,L} \to \gamma\gamma$
- $K_{L,S} \to \pi^0\gamma\gamma$

$K_S \to \gamma\gamma$ and $K_L \to \pi^0\gamma\gamma$

Chiral Perturbation Theory (χPT):

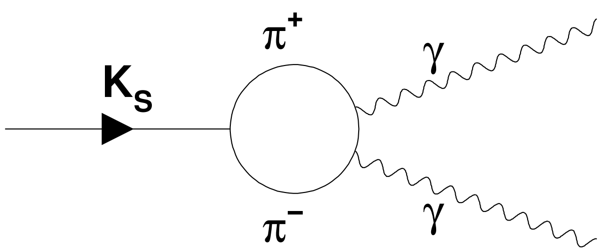
- Effective field theory at low energies (region of non-perturbative QCD).
- Expansion in particle momenta: $\mathcal{O}(p^2)$, $\mathcal{O}(p^4)$, $\mathcal{O}(p^6)$, . . .
- Higher orders $\to$ Loop diagrams of pseudo-scalar mesons.

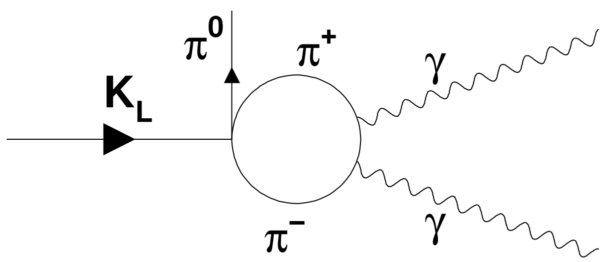
Decays $K_S \to \gamma\gamma$ and $K_L \to \pi^0\gamma\gamma$:

- Decays into neutral final states:

$$\Longrightarrow \mathcal{O}(p^2) = 0.$$

- $\mathcal{O}(p^4)$ unambiguously predicted by χPT loop diagrams (no counter terms).





$K_S \to \gamma\gamma$:

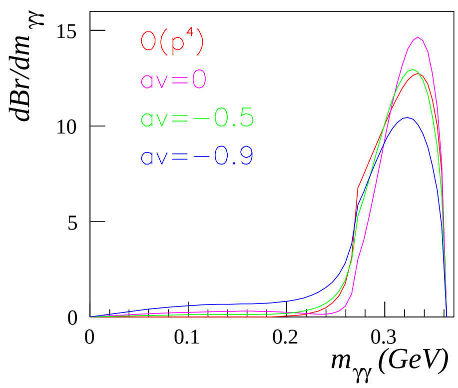
- $\mathcal{O}(p^4)$ prediction: $(2.1 \pm 0.1) \times 10^{-6}$
- Experiment (NA48, 2000): $(2.6 \pm 0.4) \times 10^{-6}$

  $\Longrightarrow$ Old measurements not yet conclusive about possible $\mathcal{O}(p^6)$ contributions.

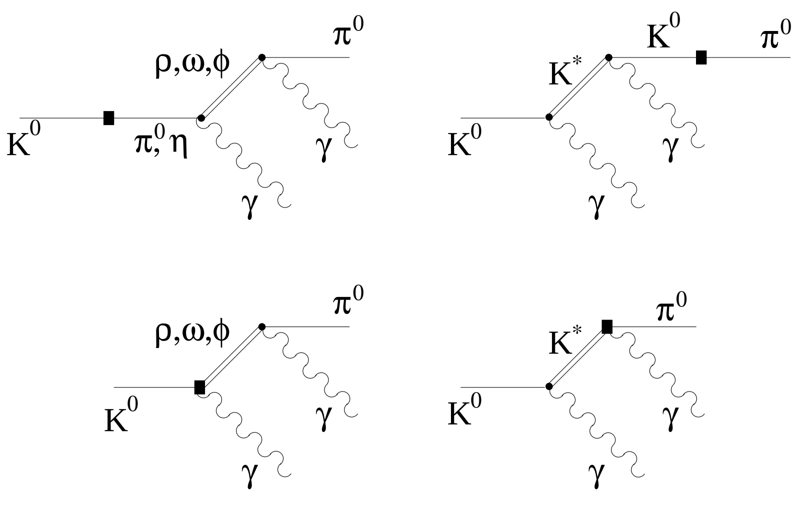
$K_L \to \pi^0\gamma\gamma$:

- $\mathcal{O}(p^4)$ already known to be not sufficient to explain large observed branching fraction.

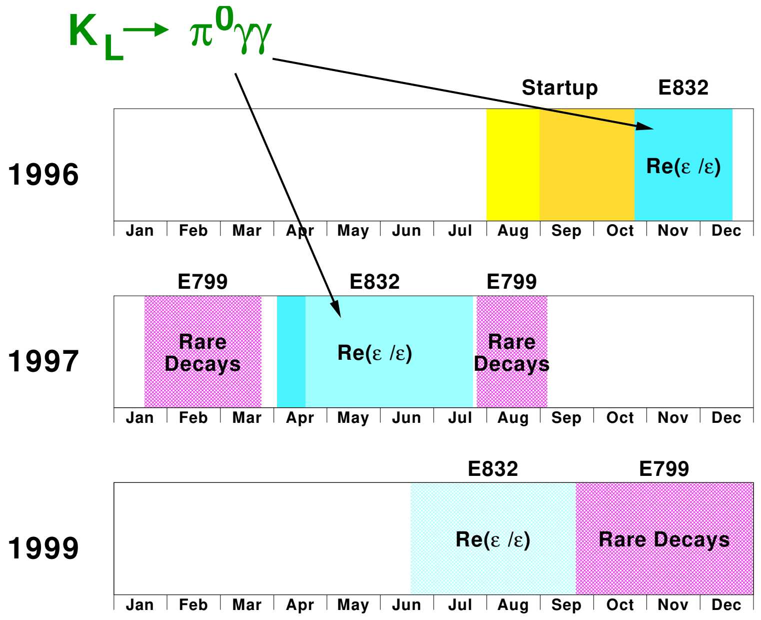
- Also:
  $\mathcal{O}(p^4)$ can not explain events with $m_{\gamma\gamma} < 2m_{\pi^0}$.



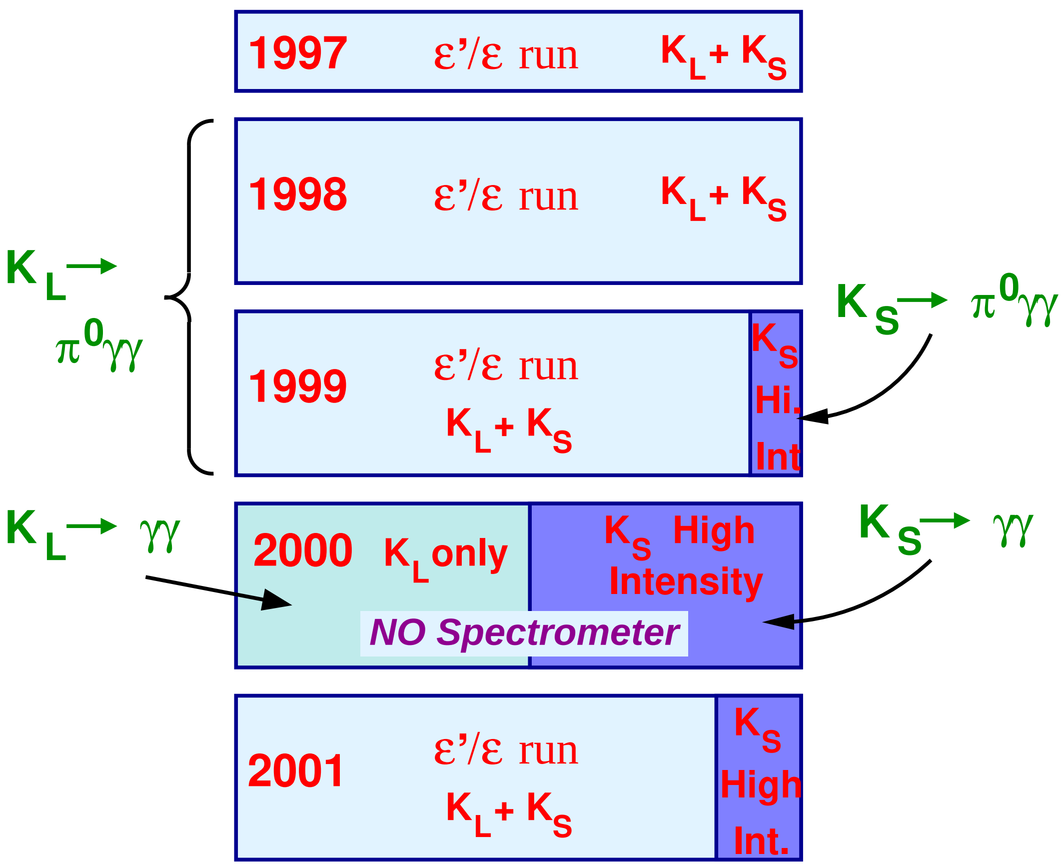
- Contributions to $\mathcal{O}(p^6)$ from vector meson exchange.



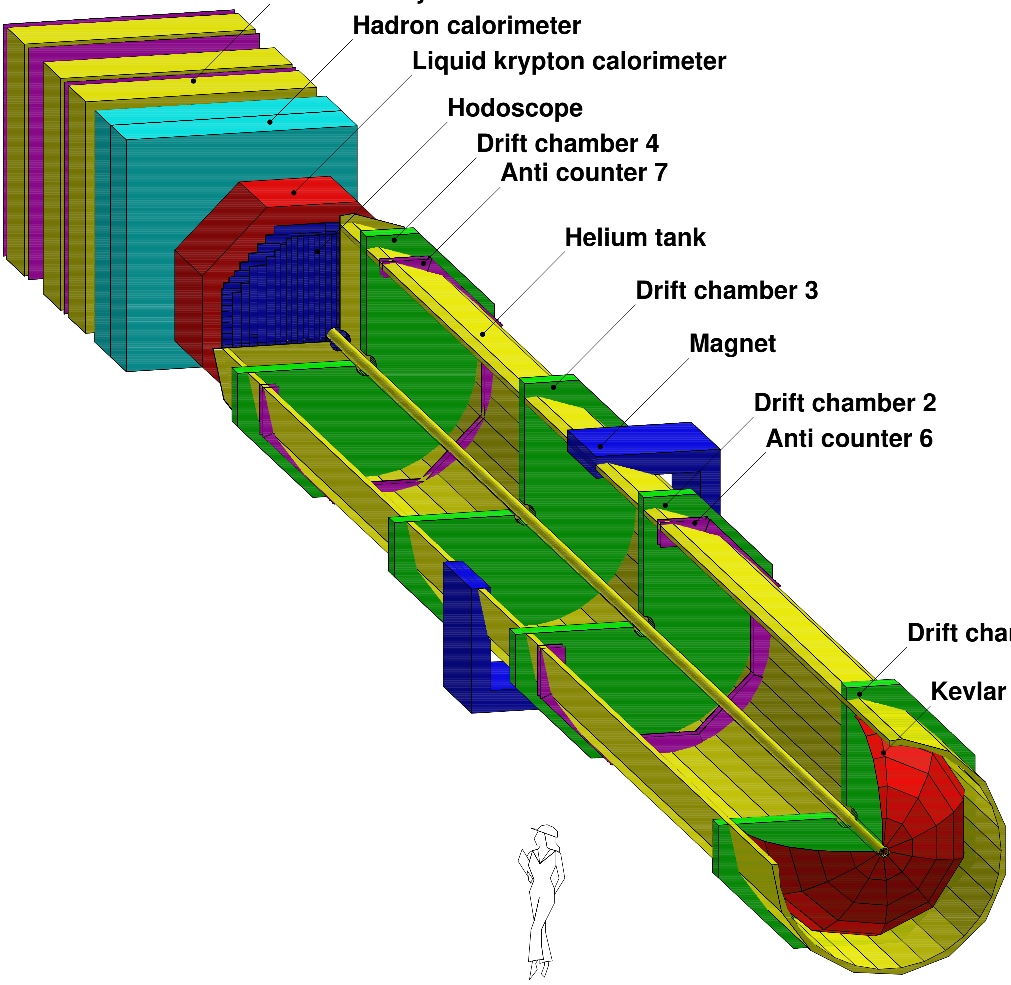
KTeV run periods



NA48 run periods



The NA48 Detector



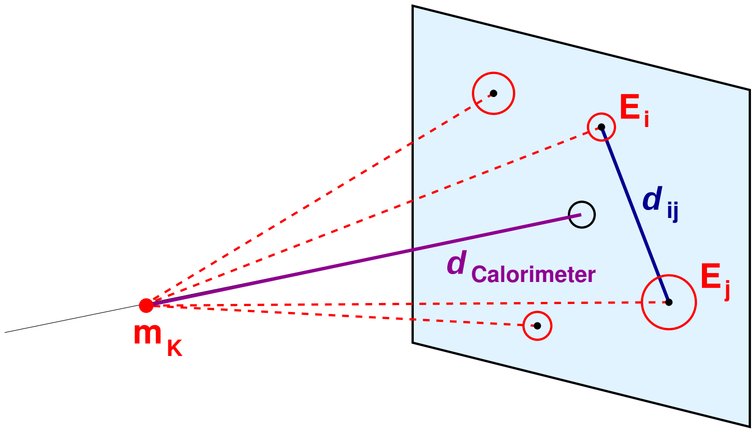
Liquid Krypton Calorimeter:

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

Energy resolution: $\sim 1\%$ for 25 GeV photons

Position resolution: ~ 1 mm for 25 GeV photons

Reconstruction of Neutral Decays



- No vertex information

- Assume kaon mass m_K and use relation between invariant mass and opening angle:

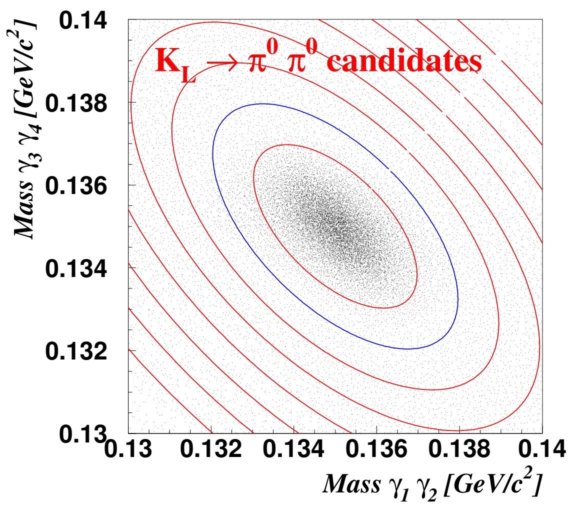
$$d_{\text{Calorimeter}} = \frac{1}{m_K}\sqrt{\sum_{i>j} E_i\, E_j\, d_{ij}^2}$$

- Lost Photons $\rightarrow$ Vertex shifted down-stream.

- In $K_S \rightarrow 2\,\pi^0$:

  Can now compute π^0 masses:

$$m_{\pi^0} = \frac{\sqrt{E_1\, E_2\, d_{12}^2}}{d_{\text{Calorimeter}}}$$



Measurement of $K_S \to \gamma\gamma$

Problem for high precision measurement of $K_S \to \gamma\gamma$:

Irreducible background from $K_L \to \gamma\gamma$
($\sim 60\%$ of all $\gamma\gamma$ in decay region).

$\Longrightarrow$ Accuracy limited by knowledge of $\mathrm{Br}(K_L \to \gamma\gamma)$ to more than $\pm 4\%$.

Better Method:

Normalize $K_L \to \gamma\gamma$ background to $K_L \to 3\pi^0$ events and separately measure $\Gamma(K_L \to \gamma\gamma)/\Gamma(K_L \to 3\pi^0)$ in pure K_L beam with similar experimental set-up.

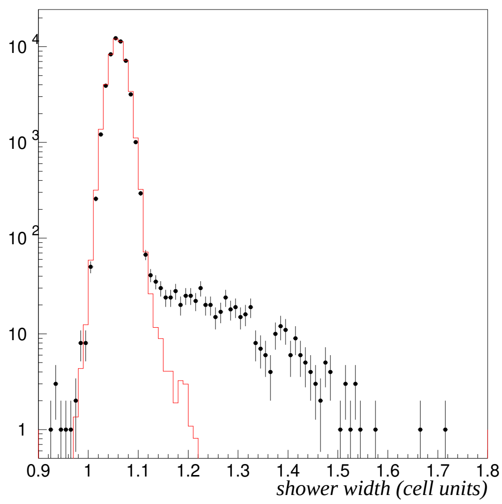
$\Longrightarrow$
- No dependence on $\mathrm{Br}(K_L \to \gamma\gamma)$.
- Same detector and decay volume
  $\Longrightarrow$ Many systematics cancel.

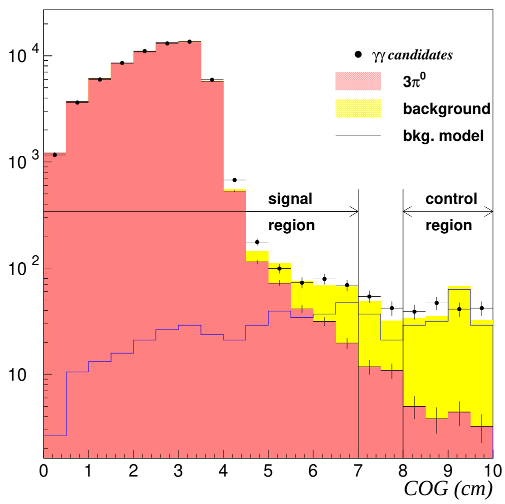
NA48 in 2000:

- No spectrometer.
- First half of run period: K_L target beam.
  $\Longrightarrow$ Measure $K_L \to \gamma\gamma$ and $K_L \to 3\pi^0$.
- Second half: K_S target beam.
  $\Longrightarrow$ Measure $K_{S,L} \to \gamma\gamma$, $K_L \to 3\pi^0$ and $K_L \to 2\pi^0$.

Measurement of $\frac{\Gamma(K_L \to \gamma\gamma)}{\Gamma(K_L \to 3\,\pi^0)}$

- 2000 K_L target run of NA48.
- 25% of statistics are sufficient.
- Use the same decay volume $(-1\text{ m} < z_{\text{vertex}} < 5\text{ m})$
  $\rightarrow$ Acceptance uncertainties mainly cancel.
- Negligible background from $K_L \to 2\,\pi^0$ and other K_L decays.
  (Magnet ON $\rightarrow$ Dalitz decays $K_L \to e^+e^-\gamma$ are swept out.)
- Only background from hadronic activity (e.g. Λ decays).





$\Longrightarrow$ Sideband subtraction:

Background to $K_L \to \gamma\gamma$: $\mathbf{(0.6 \pm 0.3)\%}$

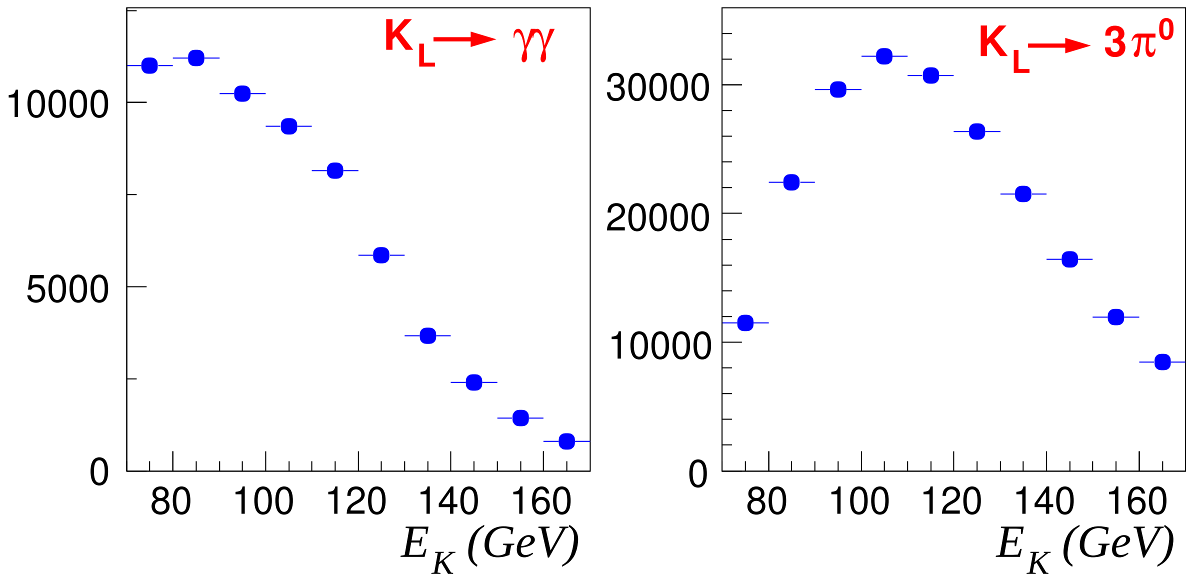
Measurement of $\frac{\Gamma(K_L \to \gamma\gamma)}{\Gamma(K_L \to 3\,\pi^0)}$

$\Longrightarrow$ Byproduct of $K_S \to \gamma\gamma$ measurement:

New measurement of $K_L \to \gamma\gamma$

Systematic uncertainties small:

- Backgrounds: $\pm 0.3\%$
- Acceptance: $\pm 0.6\%$
- Energy spectra:



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

(PDG value: $(2.77 \pm 0.08) \times 10^{-3}$)

$K_S \to \gamma\gamma$: Background from $K_S \to 2\,\pi^0$

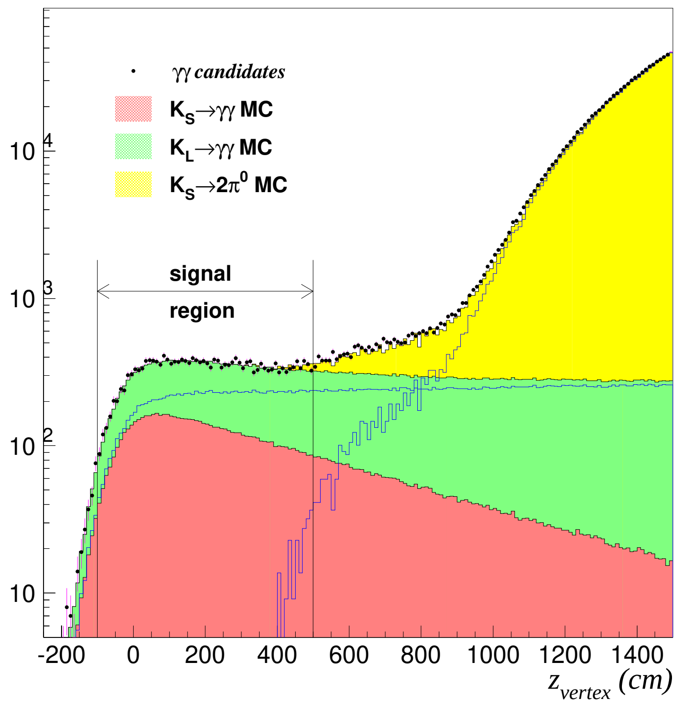
- $K_S \to 2\,\pi^0$ with two lost or overlapping photons might fake signal event.

- Missing energy shifts reconstructed decay vertex $z_{\rm vertex}$ down-stream.

  $\Longrightarrow$ Restrict decay volume to

  $$-1 \text{ m} < z_{\rm vertex} < 5 \text{ m}$$

  after final collimator.



- Determination from MC with absolute normalization to K_S flux.

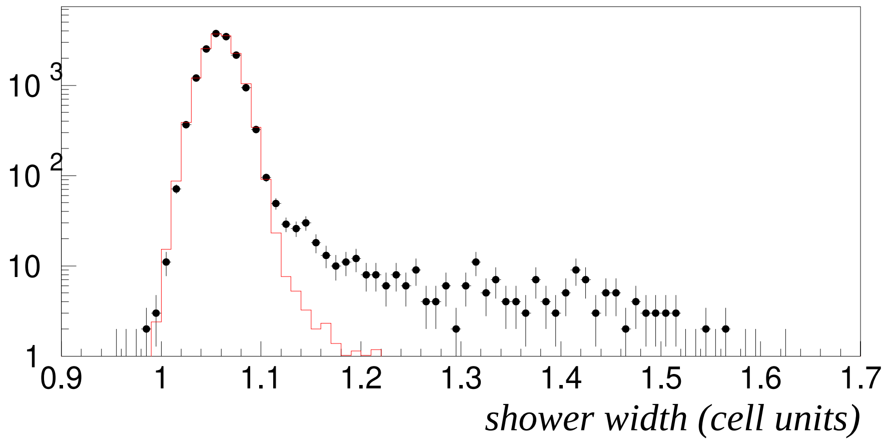
  $\Longrightarrow$ Background from $K_S \to 2\,\pi^0$:

  $$(\mathbf{0.8 \pm 0.2})\%$$

Hadronic and accidental background:

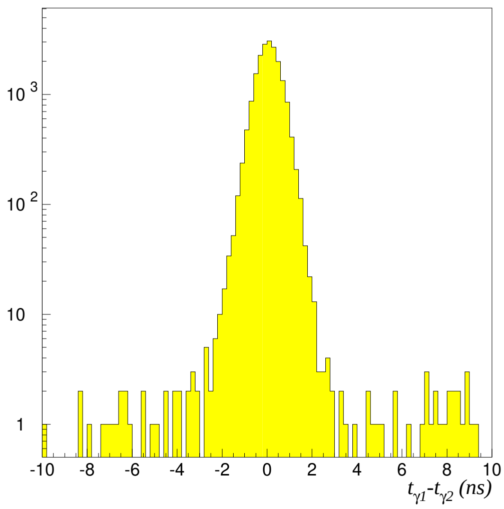
- Tails in shower width distribution

  $\Longrightarrow$ Hadron showers



- Tails in shower time difference

  $\Longrightarrow$ Accidental pairs



- Subtraction by extrapolating high-p_T events into signal region.

  $\Longrightarrow$ Hadronic and accidental background:

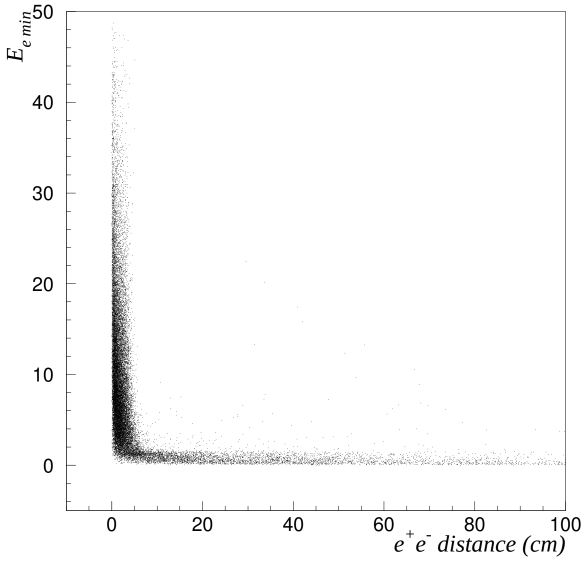
  $$(\mathbf{0.8 \pm 0.3})\%$$

Background from Dalitz decays:

- Spectrometer magnet OFF in high-Int-K_S run 2000

  $\Longrightarrow$ Background from Dalitz decays $K_{S,L}, \pi^0 \to e^+e^-\gamma$

- About 30% of e^+e^- pairs do not open up enough *or* have one $e^\pm$ with too little energy.



- No effect in K_L run (magnet was ON).

- Corrected with MC simulation.

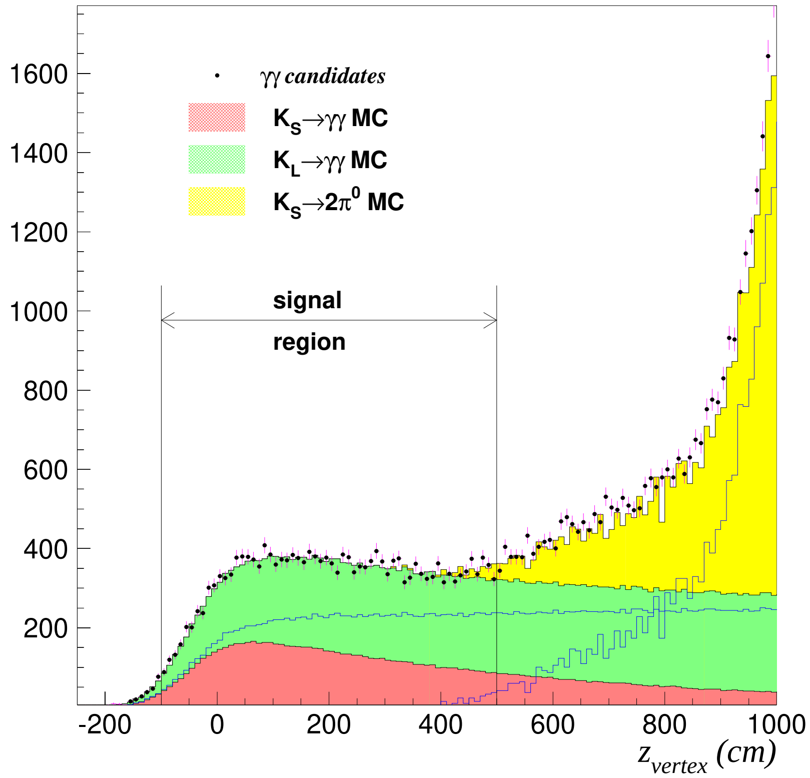
- Effect on $K_S \to 2\pi^0$ normalization twice as much as on $\gamma\gamma$ signal.

  $\Longrightarrow$ Dalitz decays raise $\mathrm{Br}(K_S \to \gamma\gamma)$:

$$\frac{\Delta(\mathrm{Br}(K_S \to \gamma\gamma))}{\mathrm{Br}(K_S \to \gamma\gamma)} = \mathbf{+(1.5 \pm 0.3)\%}$$

Measurement of $K_S \to \gamma\gamma$

- Roughly 20000 $K_{S,L} \to \gamma\gamma$ candidates in signal region.
- Total non-$\gamma\gamma$ background $\sim 2.5\%$.
- Normalization to $K_S \to 2\,\pi^0$.

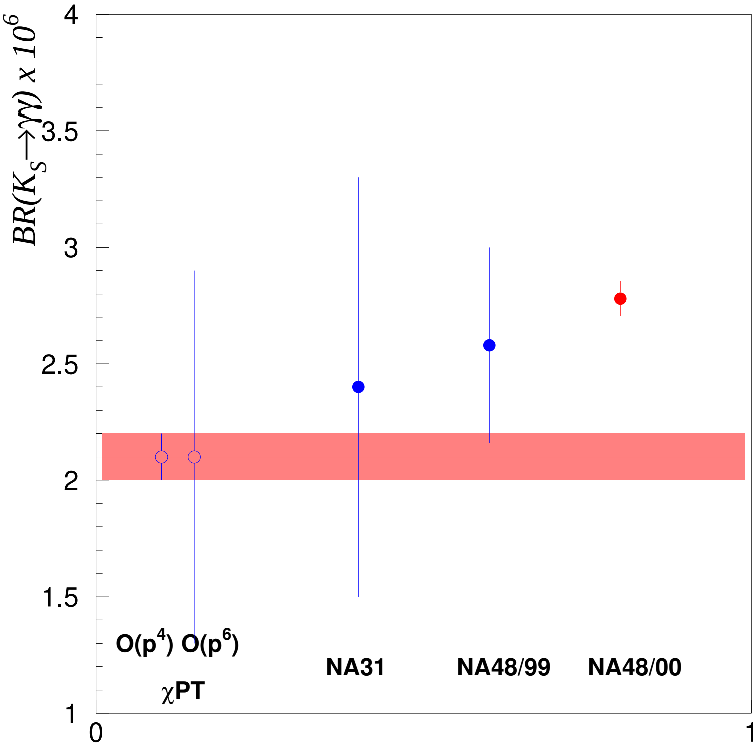


$$\mathrm{Br}(K_S \to \gamma\gamma) = (2.78 \pm 0.06_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}) \times 10^{-6}$$

Main systematic uncertainties:

$\mathrm{Br}(K_S \to 2\,\pi^0)$:	$\pm 0.9\%$
Hadronic/accidental background:	$\pm 0.7\%$
MC statistics:	$\pm 0.6\%$

Measurement of $K_S \to \gamma\gamma$



- Compatible with previous measurements. (But more than 5 times more precise.)
- $\sim 30\%$ larger than $\mathcal{O}(p^4)$ prediction

  $\Longrightarrow$ Indication of large $\mathcal{O}(p^6)$ contributions.

Measurement of $K_L \to \pi^0\gamma\gamma$

- Very similar signature as $K_L \to \pi^0\gamma\gamma$.
  $\Longrightarrow$ Can use data from ϵ'/ϵ data takings.

- NA48: Data from 1998 and 1999 ϵ'/ϵ runs.
  KTeV: Data from 1996 and 1997 ϵ'/ϵ runs.

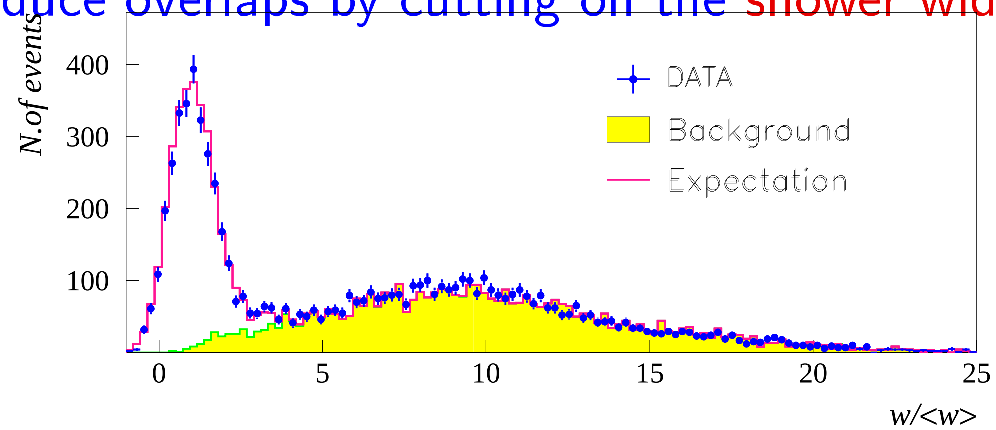
- Normalization to $K_L \to 2\,\pi^0$
  $\Longrightarrow$ Very similar trigger efficiencies and detector acceptances.

- Select events with 4 in-time photon showers. (Vetos from photon anti-counters and spectrometer activity).

- Have to fight strong backgrounds:
  - $K_L \to 3\,\pi^0$ with missing or overlapping showers.
  - Badly reconstructed $K_L \to 2\,\pi^0$.
  - Accidentally overlapping events (pile-up).

Background from $K_L \to 3\,\pi^0$:

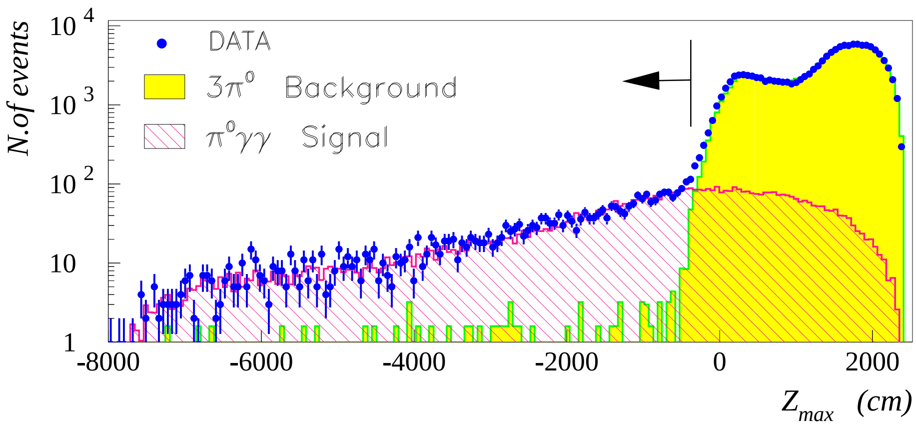
- Reduce overlaps by cutting on the shower width.



- $K_L \to 3\,\pi^0$ with lost or overlapping photons:

  Assume $K_L \to 3\,\pi^0$ with one lost photon

  $\Longrightarrow$ Construct variable $z_{\rm max}$ from possible $\gamma\gamma$ or $\gamma\gamma\gamma$ combinations as best estimate of $K_L \to 3\,\pi^0$ decay vertex.



$\Longrightarrow$ $K_L \to \pi^0\gamma\gamma$ signal in unphysical $z_{\rm max}$ region, separates well from $K_L \to 3\,\pi^0$ background. (But also 54% signal loss.)

$\Longrightarrow$ Remaining background from $K_L \to 3\,\pi^0$:

$$\mathbf{2.7 \pm 0.4\%}$$

Background from $K_L \to 2\,\pi^0$:

- No events with two $\gamma\gamma$ pairings compatible with π^0's.
- One pairing (1-2) within 3 MeV/c^2 of π^0 mass, Other pairing (3-4) outside $110 - 160$ MeV/c^2.

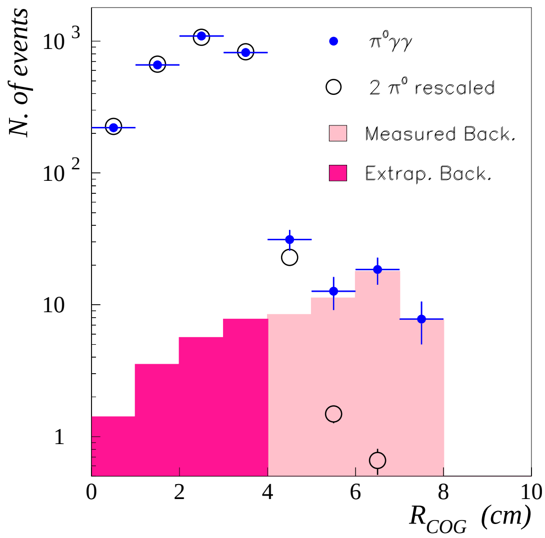
$\Longrightarrow$ Remaining background from $K_L \to \pi^0\gamma\gamma$:

$\mathbf{0.16 \pm 0.08\%}$

(Estimated from $K_S \to 2\,\pi^0$.)

Background from pile-up events:

- Pile-up = two decays occuring within 5 ns.
- Estimated by extrapolating high-p_T events into signal region.

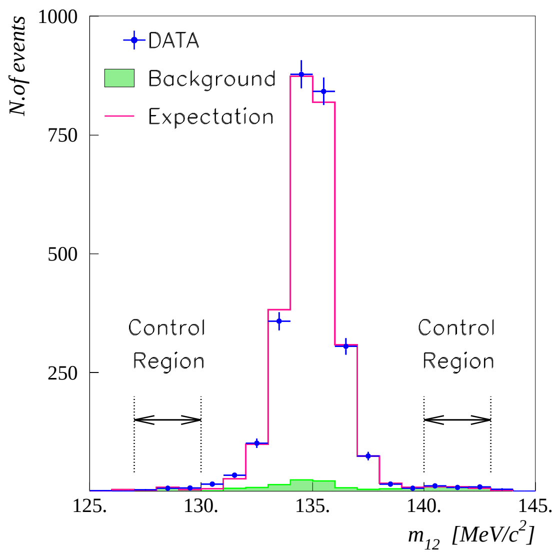


$\Longrightarrow$ Remaining background from Pile-up:

$\mathbf{0.3 \pm 0.2\%}$

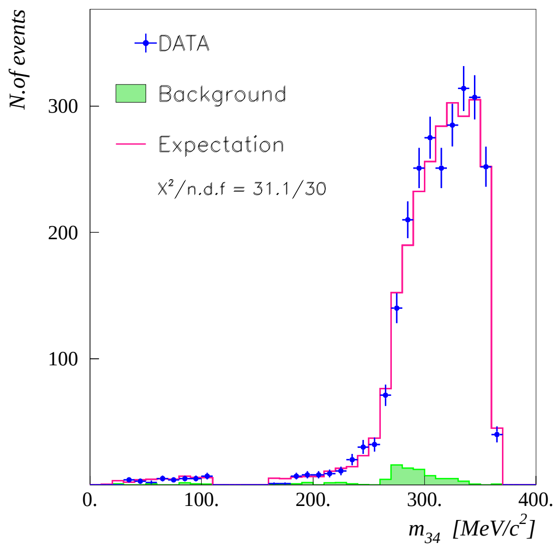
Measurement of a_V in $K_L \to \pi^0\gamma\gamma$

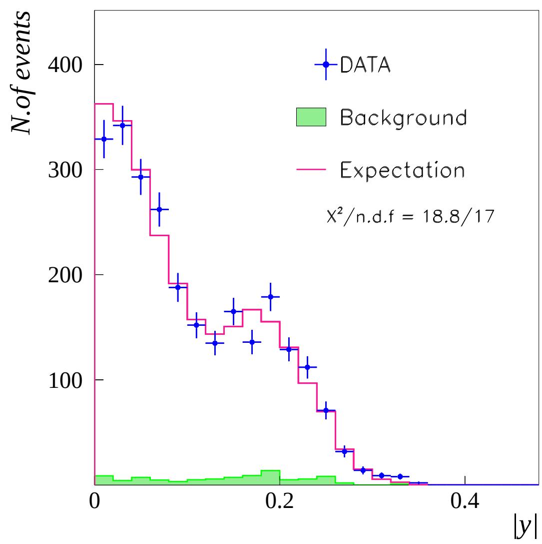
- **Invariant $\gamma_1\gamma_2$ mass:**



- 2558 total signal candidates.
- 345 ambiguous events $\Longrightarrow$ not used for a_V fit.
- Total background: 82 ± 12 events.

- **Invariant $\gamma_3\gamma_4$ mass and $y = |E_3 - E_4|/m_K$:**





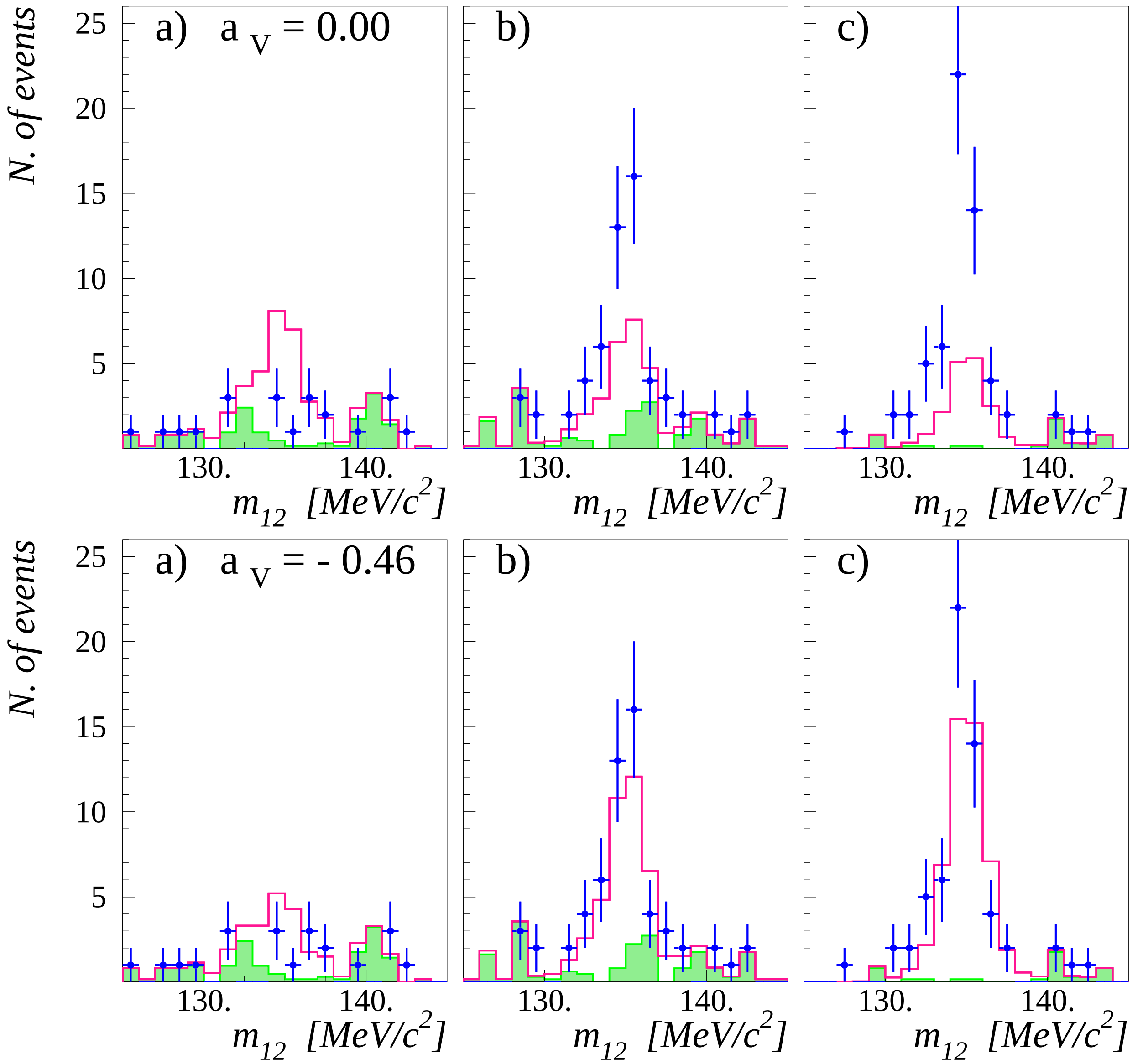
Simultaneous fit of m_{34} and y distribution:

$$\Longrightarrow \quad \boxed{a_V \;=\; -0.46 \pm 0.03_{\text{stat}} \pm 0.04_{\text{syst}}}$$

Measurement of a_V in $K_L \to \pi^0\gamma\gamma$

Low m_{34} mass region: Try to find π^0 signal:

m_{34} in 30 – 110 MeV	m_{34} in 160 – 240 MeV	m_{34} in 240 – 260 MeV

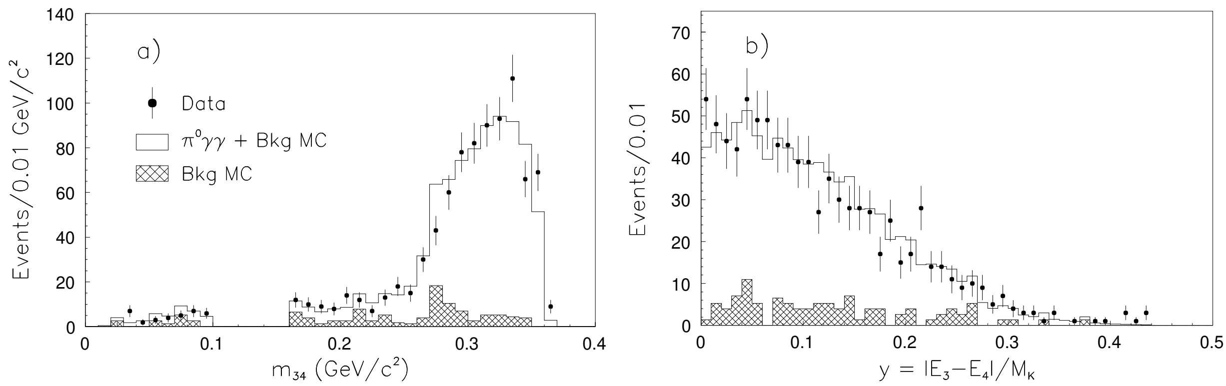


$\Longrightarrow$ **Clear evidence for $\mathcal{O}(p^6)$ contribution.**

Measurement of a_V in $K_L \to \pi^0\gamma\gamma$

KTeV (1999):

- Data from 1996 and 1997 $\mathrm{Re}(\epsilon'/\epsilon)$ data taking.
- **884 signal candidates** found.
- Estimated background: 111 ± 12 events.
  (Mainly from $K_L \to 3\,\pi^0$ events.)



- Simultaneous fit to m_{34} and y distribution:

$$a_V = -0.72 \pm 0.05_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}$$

$\Longrightarrow$ $2.8\,\sigma$ difference to NA48 result.
(KTeV sees more events in low m_{34} region.)

Measurement of $\mathrm{Br}(K_{\mathrm{L}} \to \pi^0\gamma\gamma)$

- Detector acceptance strongly depends on a_V.

  $\Longrightarrow$ $\sim \pm 2\%$ systematic uncertainty from error on a_V.

- Both experiments use their a_V for the acceptance.

- Systematic error from $K_{\mathrm{S}} \to 2\,\pi^0$ normalization: $\sim \pm 2\%$

- NA48:

  $$\boxed{\mathrm{Br}(K_{\mathrm{L}} \to \pi^0\gamma\gamma) = (1.36 \pm 0.03 \pm 0.04) \times 10^{-6}}$$

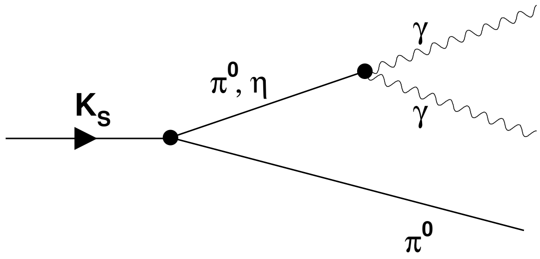
- KTeV:

  $$\boxed{\mathrm{Br}(K_{\mathrm{L}} \to \pi^0\gamma\gamma) = (1.68 \pm 0.07 \pm 0.08) \times 10^{-6}}$$

- Both measurements are consistent with the $\mathcal{O}(p^6)$ prediction of their respective a_V.

Search for $K_S \to \pi^0\gamma\gamma$

- $K_S \to \pi^0\gamma\gamma$ dominated by pion pole of $K_S \to 2\,\pi^0$.
  $\Longrightarrow$ Restriction to
  $$z = m^2_{\gamma\gamma}/m^2_K \geq 0.2.$$



- Theoretical prediction small:
  $$\mathrm{Br}(K_S \to \pi^0\gamma\gamma)|_{z\geq 0.2} = 3.8 \times 10^{-8}$$
  (Ecker, Pich, De Rafael, 1987)

- No experimental search so far.

NA48 analysis on two-day K_S high intensity run '99:

- About 3×10^8 K_S decays in the detector.

- Main experimental problem: Background suppression.
  $\Longrightarrow$ Veto all events with any non-γ activity.

- Remaining background mainly from $K_S \to 2\,\pi^0$.

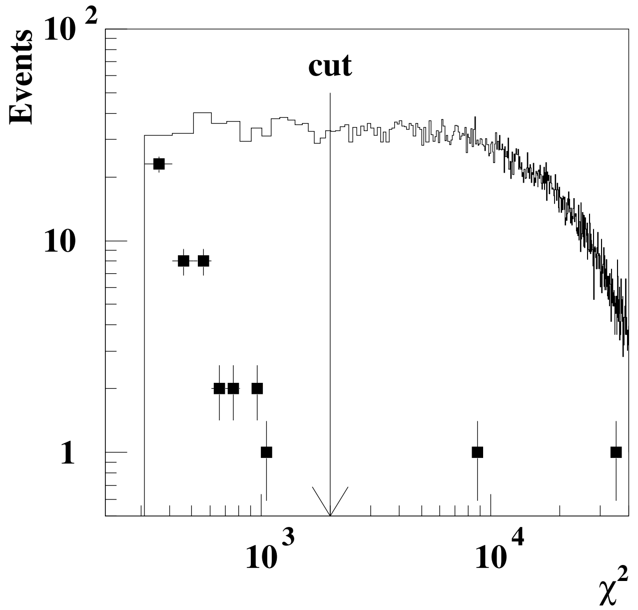
Search for $K_S \to \pi^0\gamma\gamma$

Background Sources:

- $K_S \to 2\,\pi^0$ with one lost + one accidental photon:
  From sideband extrapolation: 2.1 ± 0.1 events.
- $K_S \to 2\,\pi^0$ with mismeasured π^0 mass:
  MC simulation: 0.1 ± 0.1 events.
- $K_S \to \pi^0\pi^0_{\mathrm{Dalitz}}$, $K_L \to 3\,\pi^0$:
  MC simulation: < 0.1 event.
- $K_L \to \pi^0\gamma\gamma$: Irreducible, but small: 0.1 event.

$\Longrightarrow$ Expected background: 2.3 ± 0.2 **events.**

Found in data: **2 candidate events.**



$\Longrightarrow$ $\boxed{\mathrm{Br}(K_S \to \pi^0\gamma\gamma) < 4.4 \times 10^{-7} \text{ at } 90\% \text{ CL.}}$

Summary

$K_S \to \gamma\gamma$

New branching ratio measurement better than 3%:

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

$\Longrightarrow$ $\sim 30\%$ excess w.r.t. $\mathcal{O}(p^4)$ calculation.

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

Branching ratio and VMD contribution precisely measured, but discrepancy between experiments:

$\mathrm{Br}(K_L \to \pi^0\gamma\gamma)$:

$(1.36 \pm 0.03_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}) \times 10^{-6}$ (NA48)
$(1.68 \pm 0.07_{\mathrm{stat}} \pm 0.08_{\mathrm{syst}}) \times 10^{-6}$ (KTeV)

$a_V = -0.46 \pm 0.03_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$ (NA48)
$a_V = -0.72 \pm 0.05_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}}$ (KTeV)

$\Longrightarrow$ Significant $\mathcal{O}(p^6)$ contribution out of question.

$\Longrightarrow$ NA48 result indicates negligible CP-conserving contribution to the *direkt* CP-violating decay $K_L \to \pi^0 e^+ e^-$. (But KTeV does not.)

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

New measurement byproduct of $K_{\mathrm{S}} \to \gamma\gamma$:

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

$\Longrightarrow$ Accuracy improved by 4 times w.r.t to old PDG value.

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

Two candidates found, compatible with background expectation.
First limit on branching fraction set:

$$\mathrm{Br}(K_{\mathrm{S}} \to \pi^0\gamma\gamma) < 4.4 \times 10^{-7} \text{ at } 90\% \text{ CL.}$$

$\Longrightarrow$ Still one order of magnitude above theoretical expectation.