New results from NA48

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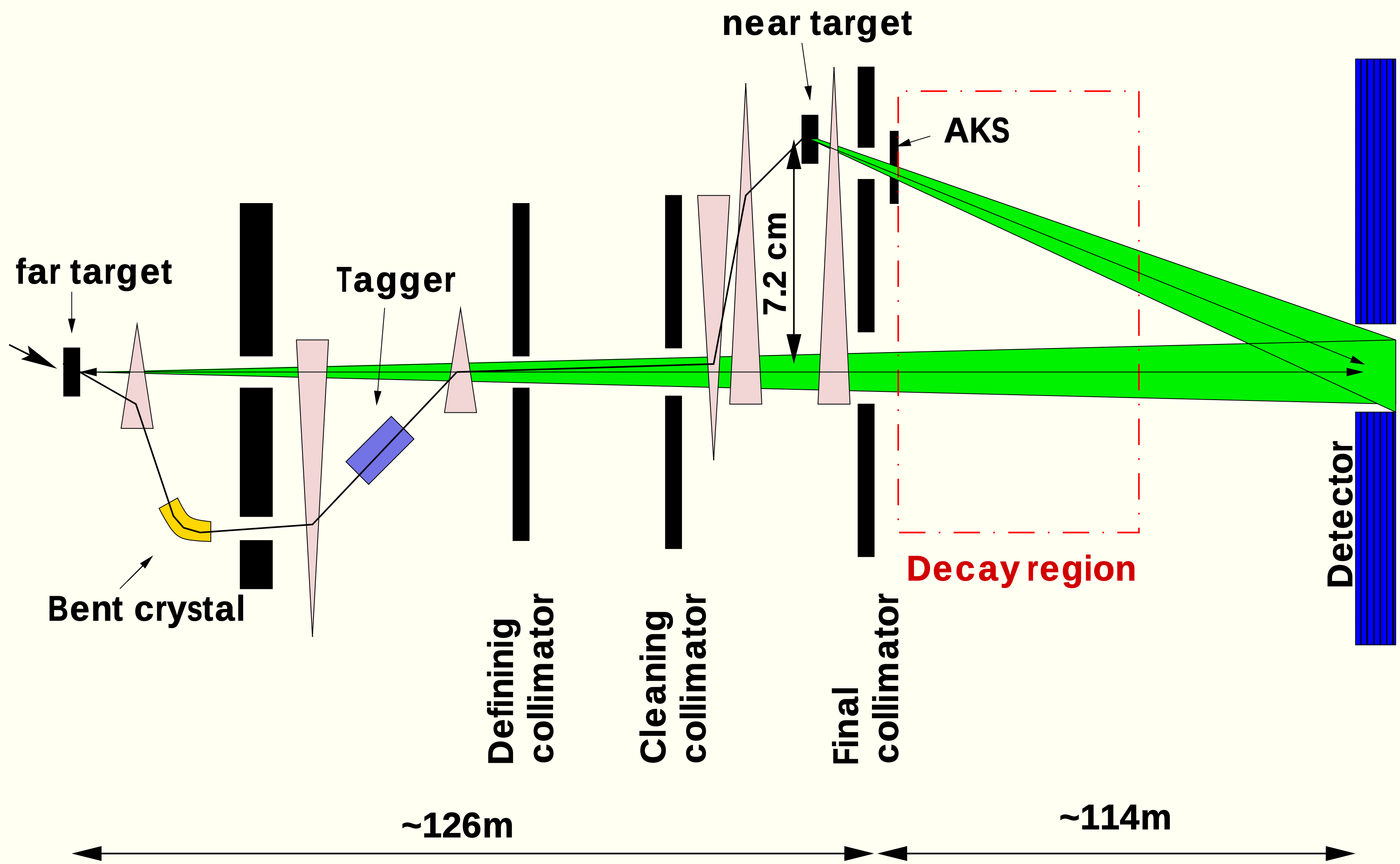
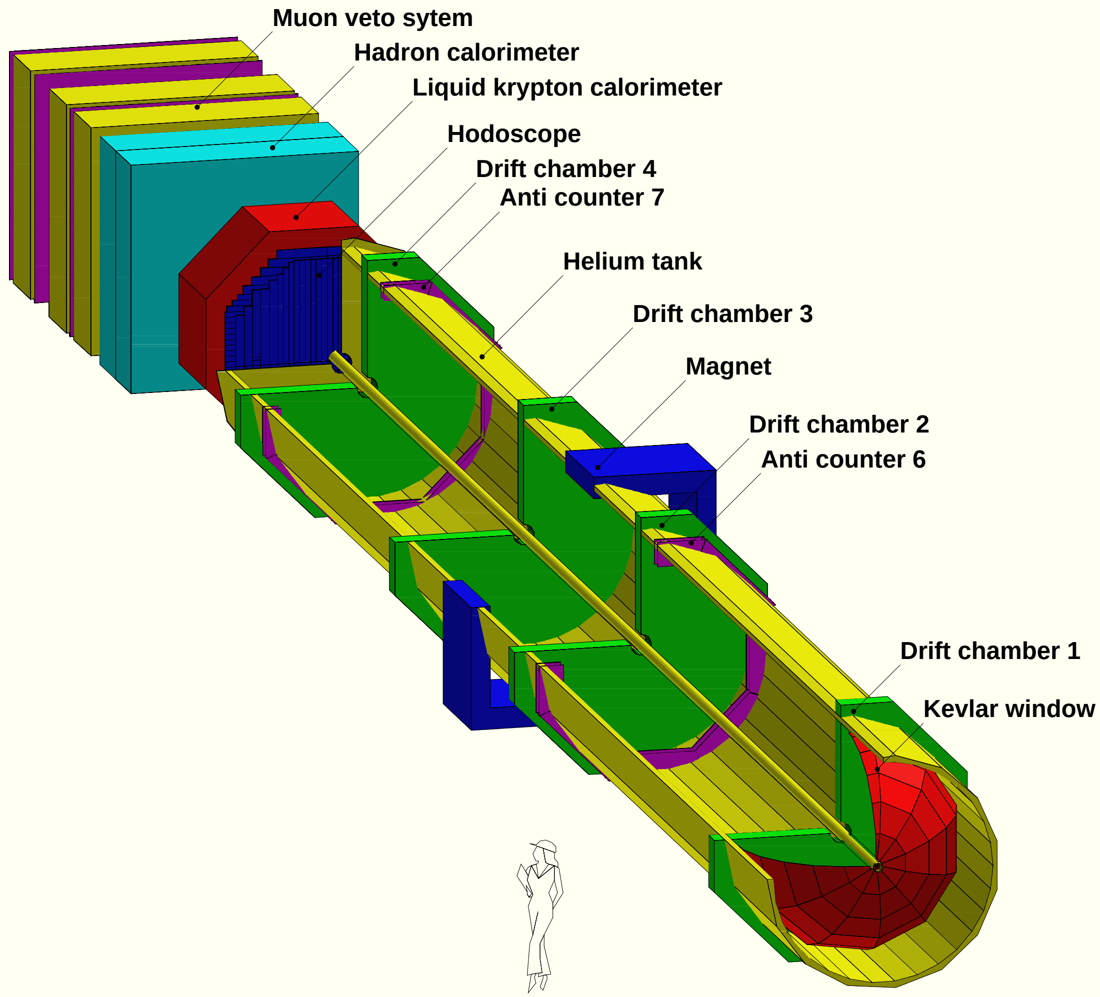
Outline

- Introduction
- By-products of $\mathfrak{Re}\frac{\varepsilon'}{\varepsilon}$ analysis:
  - $\mathrm{K_S}$ lifetime
  - η and K^0 masses
- Tests of Chiral Perturbation Theory:
  - Motivation for precise measurements of $\mathrm{K_L} \to \pi^0\gamma\gamma$ and $\mathrm{K_S} \to \gamma\gamma$
  - Measurement of $\mathrm{K_L} \to \pi^0\gamma\gamma$
  - Measurement of $\mathrm{K_S} \to \gamma\gamma$
- Summary

NA48 beam lines



NA48 detector



Liquid Krypton calorimeter

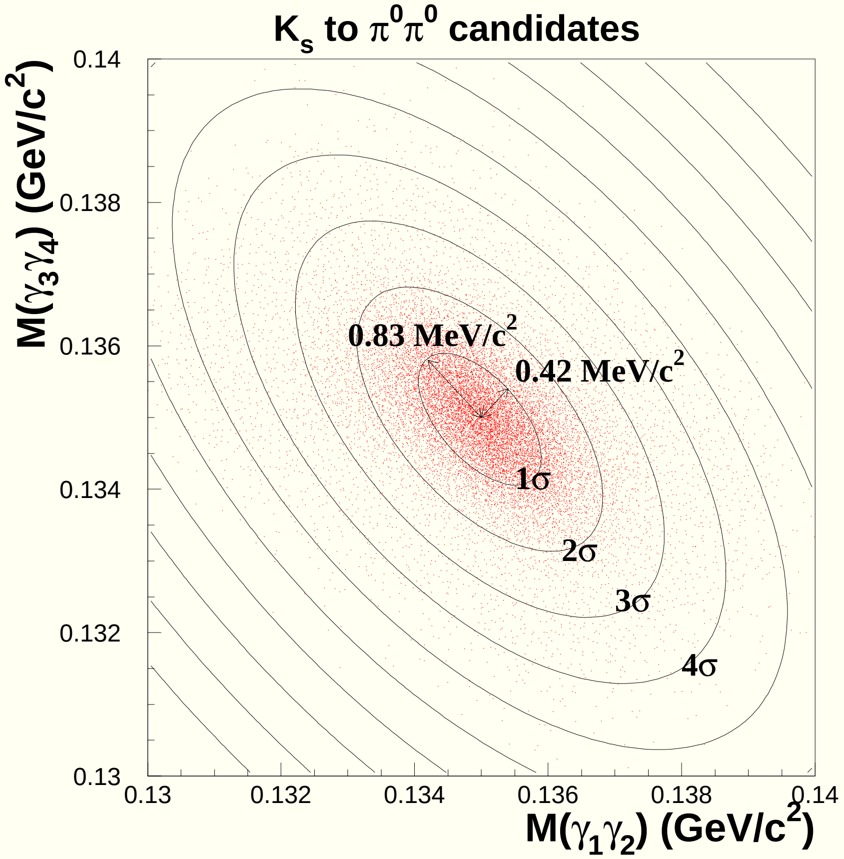
$m_{\gamma\gamma}$

LKr calorimeter resolutions:

energy $\lesssim$1% for >25 GeV photons

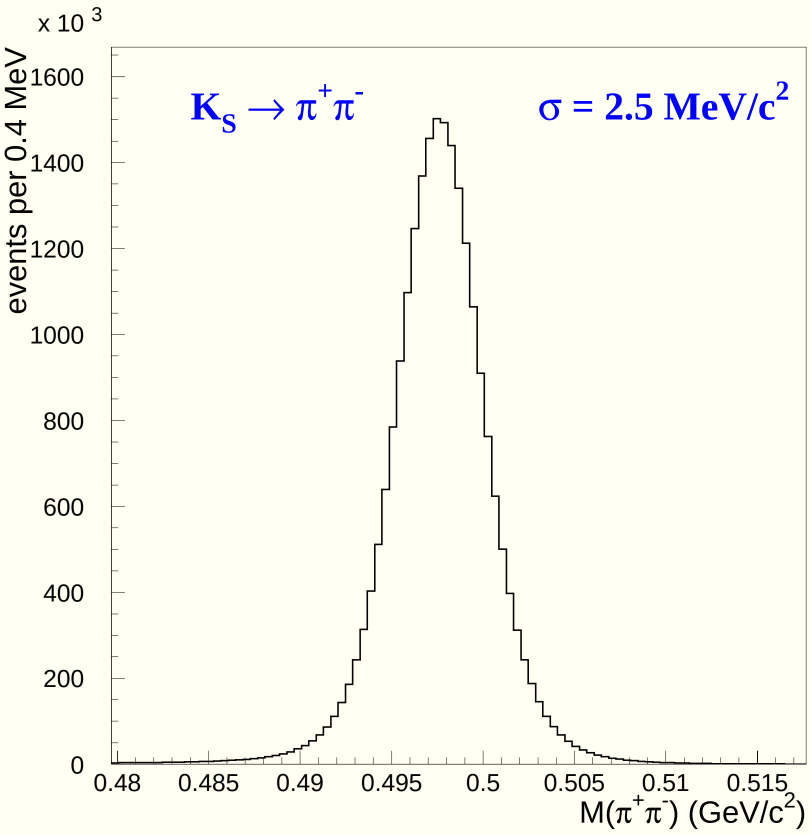
position $\lesssim$1 mm for >25 GeV photons

time $\sim$0.22 ns/$\pi^0\pi^0$



Spectrometer

$m_{\pi\pi}$



Spectrometer resolutions:

momentum $\sim$1% for 100 GeV pion

position $\sim$100 μm/plane

Hodoscope time res. $\sim$0.15 ns/$\pi^+\pi^-$

NA48 running overview

1997
$K_L + K_S$
ε'/ε run

1998
$K_L + K_S$
ε'/ε run
(K_S lifetime,
$K_L \to \pi^0\gamma\gamma$, ...)

1999
$K_L + K_S$
ε'/ε run
(K_S lifetime,
$K_L \to \pi^0\gamma\gamma$, ...)

2000

K_L
(K^0 mass,
$K_L \to \gamma\gamma$,
ε'/ε checks)

η
(η mass)

NA48/1-phase I
K_S high intensity
($K_S \to \gamma\gamma$, ...)

no spectrometer

2001
$K_L + K_S$
ε'/ε run

...

$\mathrm{K_S}$ lifetime measurement

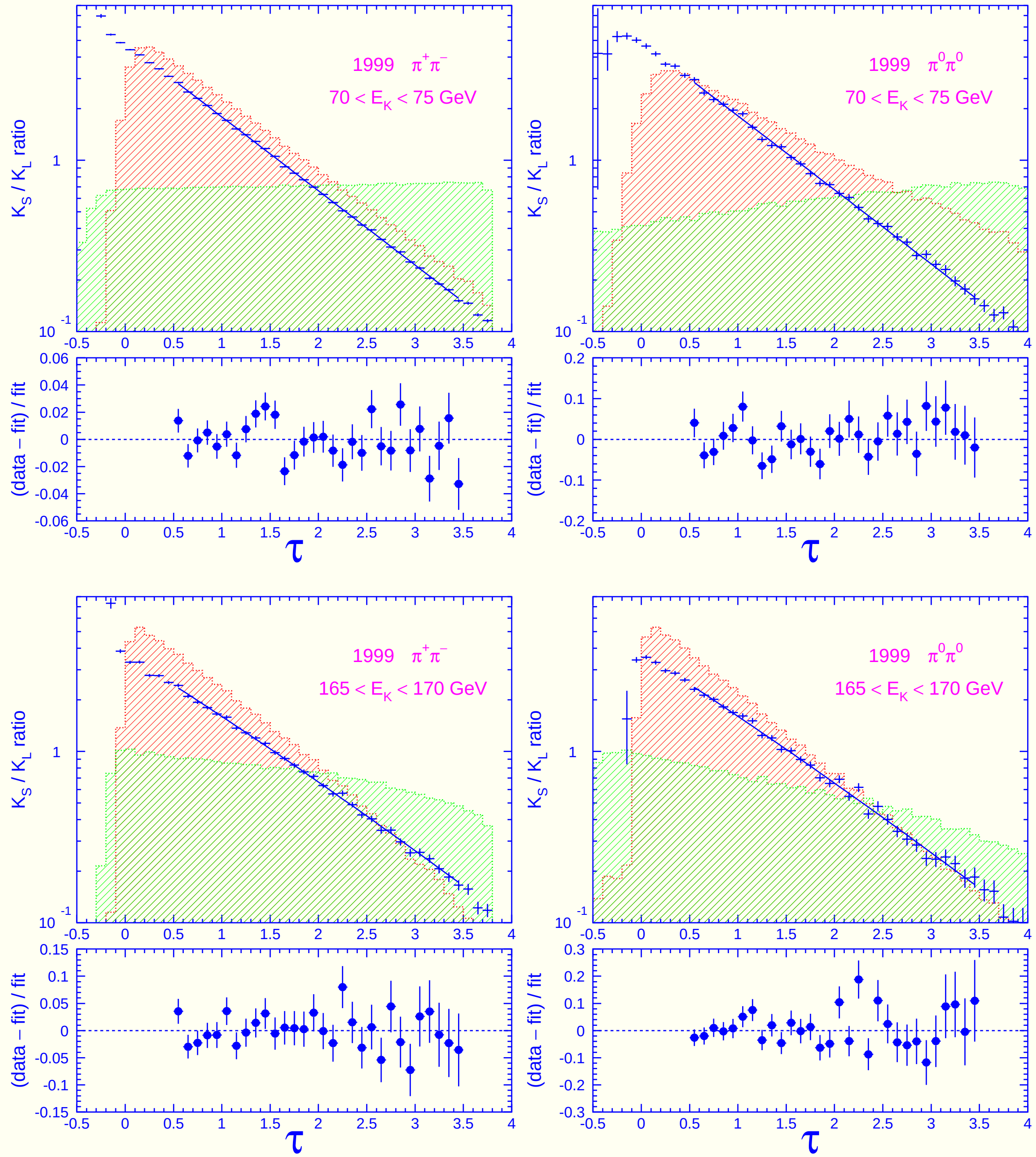
- Use the same samples as for $\mathfrak{Re}\frac{\varepsilon'}{\varepsilon}$ analysis from 1998 and 1999 runs.
- Decay region is defined in $0.5 < \tau/\tau_S < 3.5$.
  Cut at $0.5\tau_S$ avoids detector resolution effects.
- Analysis is done in 5 GeV energy bins and 0.1 τ_S lifetime bins.
- Both $\pi^+\pi^-$ and $\pi^0\pi^0$ are used. Lifetime is calculated separately and subsequently combined.

⟹ Statistics used:

Decay	$\mathrm{K_S} \to \pi^+\pi^-$	$\mathrm{K_L} \to \pi^+\pi^-$	$\mathrm{K_S} \to \pi^0\pi^0$	$\mathrm{K_L} \to \pi^0\pi^0$
Stat. in 10^6	13.2	12.2	3.1	2.8

K_S lifetime measurement

- The measurement relies as little as possible on MC: K_L samples are used to measure the acceptance.
- Only the residual acceptance differences between K_S and K_L due to beam geometry are corrected using MC.
- Background (at 10^{-3} level only in K_L samples) is subtracted using data.



K_S lifetime measurement

	$\pi^+\pi^-$		$\pi^0\pi^0$	
	$\tau_S/10^{-10}$s	χ^2/dof	$\tau_S/10^{-10}$s	χ^2/dof
1998	0.89578 ± 0.00109	$628.2/573$	0.89606 ± 0.00247	$551.0/573$
1999	0.89598 ± 0.00072	$601.2/573$	0.89635 ± 0.00167	$543.5/573$

Statistical uncertainties only

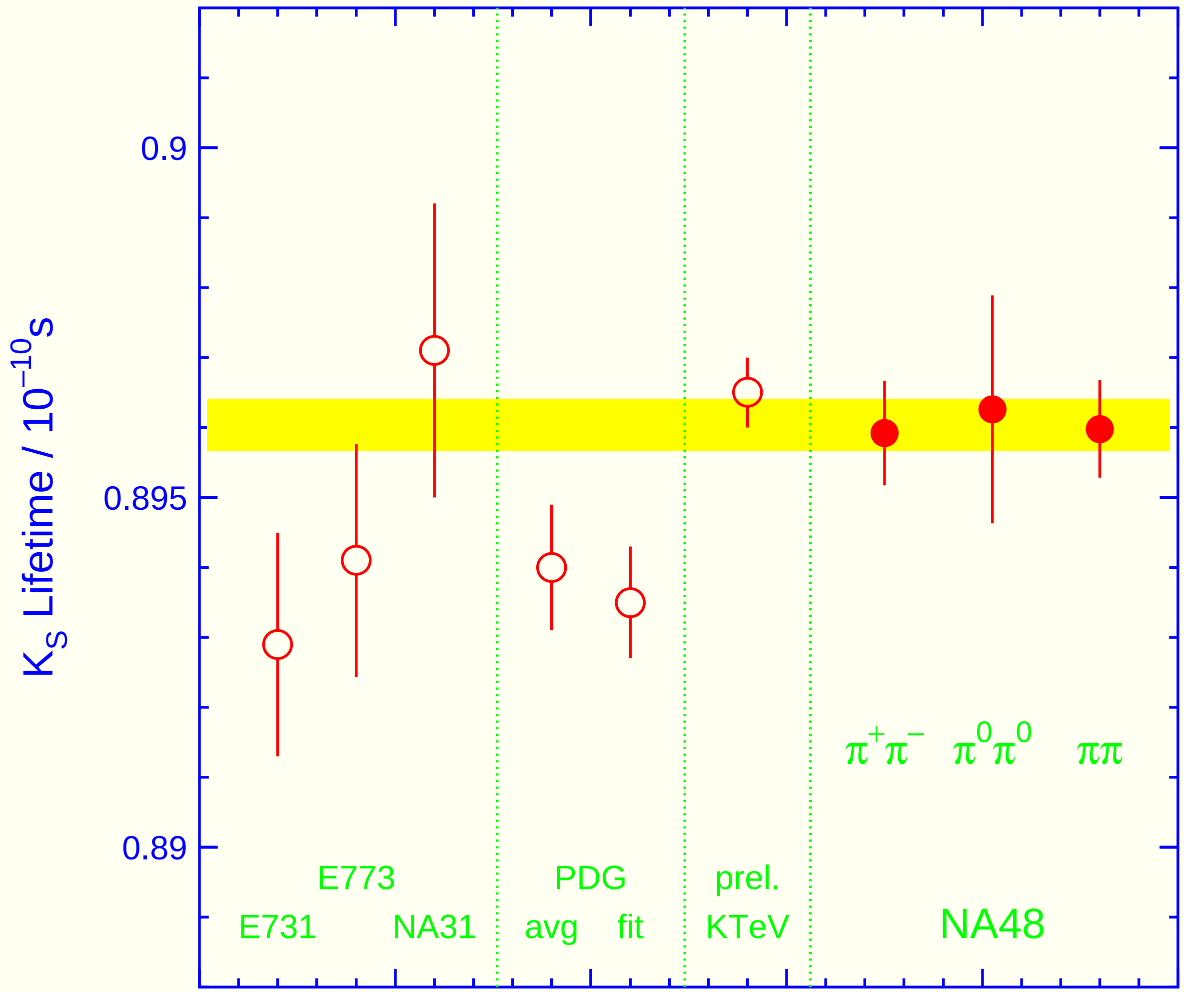
Combined result:

$$\tau_S = (0.89598 \pm 0.00048_{stat} \pm 0.00043_{syst} \pm 0.00027_{MCstat}) \times 10^{-10} \text{ s}$$

Systematics dominated by fit method and beam geometry uncertainties

Preprint: CERN-EP/2002-028 - hep-ex/0205008

K_S lifetime measurement



Our result differs 1.7 σ from current PDG average

New world average: $\tau_S = (0.89605 \pm 0.00038) \times 10^{-10}$ s $\chi^2/\mathrm{dof} = 6.3/4$

using also preliminary KTeV value

η and K^0 mass measurements

- Data taken during the 2000 run (no spectrometer).
- Using $\eta, \mathrm{K_L} \to 3\pi^0$ decays - background free.
- $\mathrm{K_L}$'s are produced in absence of $\mathrm{K_S}$ beam.
- η's are produced with π^- beam at two polyethylene targets 2cm thick. Used to calibrate the energy scale with $\eta \to \gamma\gamma$ decays.

π^0 mass constraint

$$d_{vertex} = \frac{1}{M_{\pi^0}} \sqrt{E_1 E_2} d_{12} \qquad M = \frac{1}{d_{\pi^0}} \sqrt{\Sigma_{ij,i<j} E_i E_j d_{ij}^2}$$

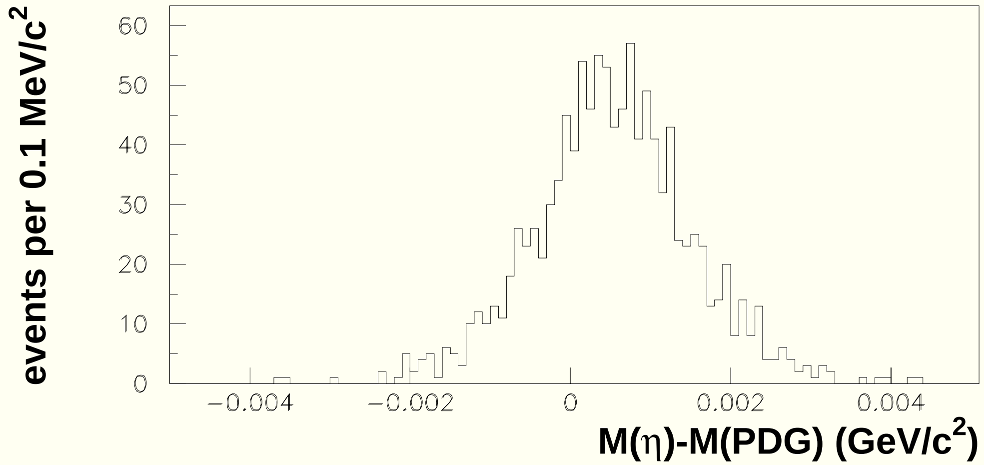
average from $3\pi^0$'s

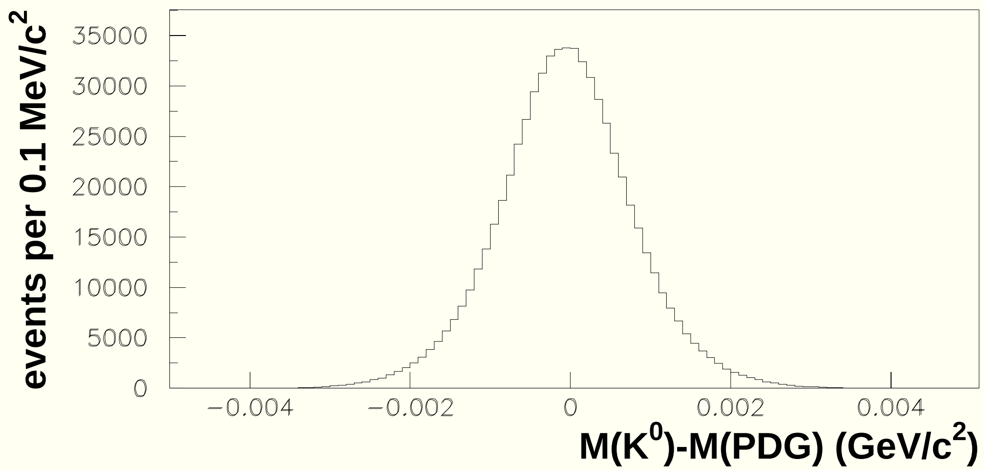
η and K^0 mass measurements

$$\Delta M \equiv M_{\mathrm{NA48}} - M_{PDG}$$

- M independent of the global energy scale
- main systematics from non-linearities in the energy measurement
- sensitivity to non-linearities reduced by using only symmetric π^0 decays:

$$0.7 < \frac{E_\gamma}{<E_\gamma>} < 1.3$$



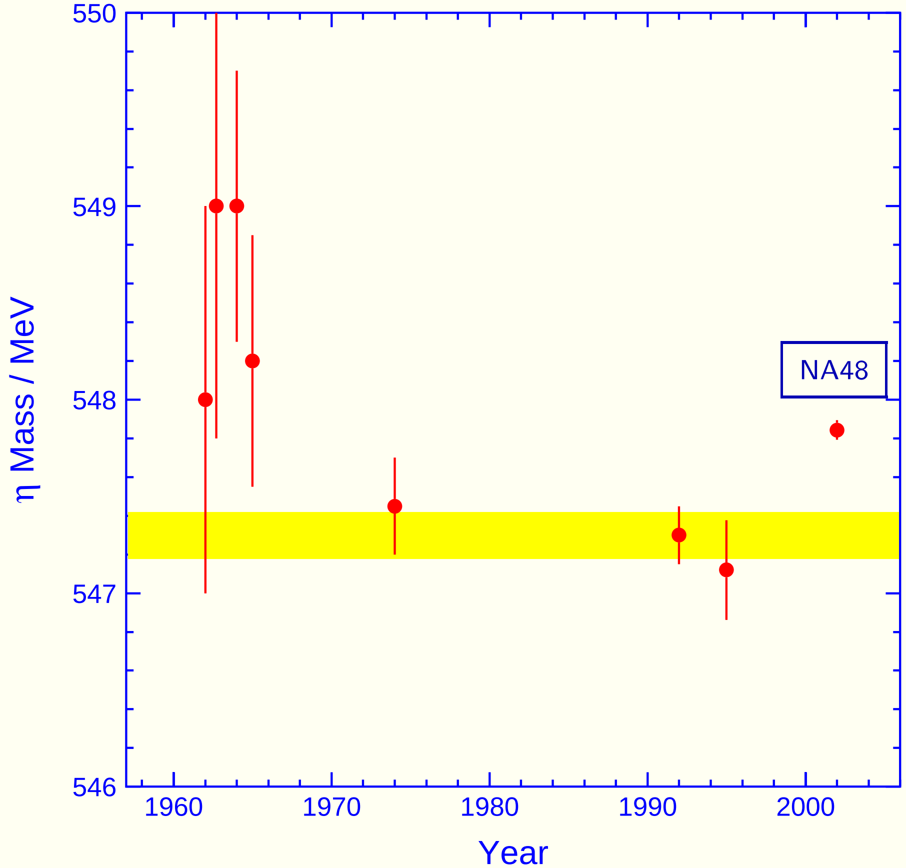


η and K^0 mass measurements

$$M_\eta = (547.843 \pm 0.030_{stat} \pm 0.041_{syst} \pm 0.005_{MCstat})\ \text{MeV/c}^2$$

$$M_{K^0} = (497.625 \pm 0.001_{stat} \pm 0.031_{syst} \pm 0.003_{MCstat})\ \text{MeV/c}^2$$

Preprint: CERN-EP/2002-025 - hep-ex/0204008



- Statistics:
  η: ~1.1k events
  K: ~650k events
- η mass differs from world average by 4.2 σ (0.1% of its value) the uncertainty is 2.4 times smaller
- K^0 mass agrees with the world average within 1.1 σ, and has similar uncertainty

Chiral Perturbation Theory

- χPT is an effective field theory of Standard Model at low energies where QCD is non-perturbative.

- Chiral symmetry spontaneously broken SU(3)$_L\times$SU(3)$_R \rightarrow$ SU(3)$_V$
  - → 8 pseudoscalar Goldstone bosons (π, η, K).

- Boson masses $\neq$0 → (soft) explicit breaking

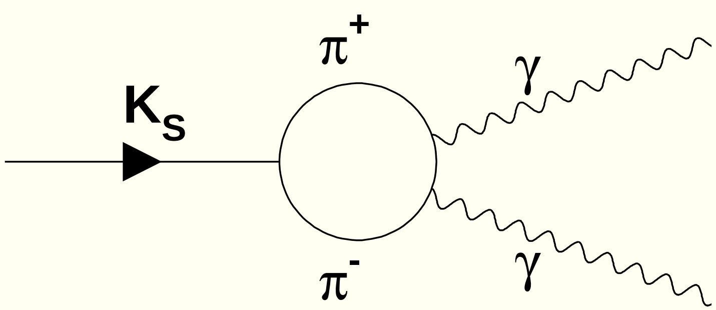
- → processes described in perturbative expansion of momenta and masses: $\frac{p^2}{(4\pi F_\pi)^2}$, $\frac{m^2}{(4\pi F_\pi)^2}$ where $(4\pi F_\pi) \sim$ 1.2 GeV

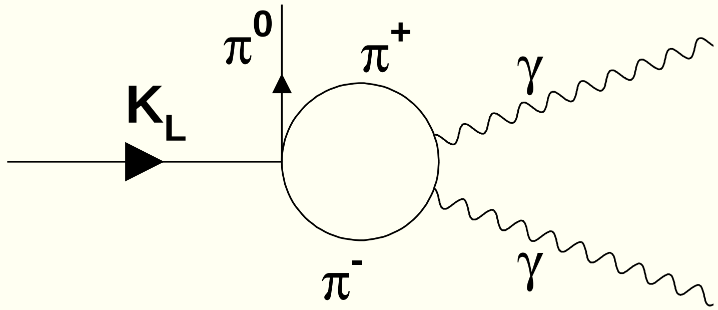
- Higher order boson loops are divergent, they are compensated by counter-terms with effective couplings determined from experiment

- Ideal to describe kaon decays ($m_K \approx$ 0.5 GeV)

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

- Many similarities in these two decays:
- In both cases $O(p^2) = 0$
- In both cases $O(p^4)$ is unambiguously predicted to better than 5% by χPT (no counter-terms) using similar elements:





2.1×10^{-6}
D'Ambrosio, Espriu
Goity

0.6×10^{-6}
Ecker, Pich, de Rafael
Capiello, D'Ambrosio

Motivation to measure $\mathrm{K_L} \to \pi^0\gamma\gamma$ and $\mathrm{K_S} \to \gamma\gamma$

at $O(p^6)$:

$\mathrm{K_L} \to \pi^0\gamma\gamma$

$\mathrm{K_S} \to \gamma\gamma$

"scalar" exchange — similar — "scalar" exchange

suppressed(?) by $\frac{m_K^2}{(4\pi F_\pi)^2} \approx 20\%$

addressed today first time!

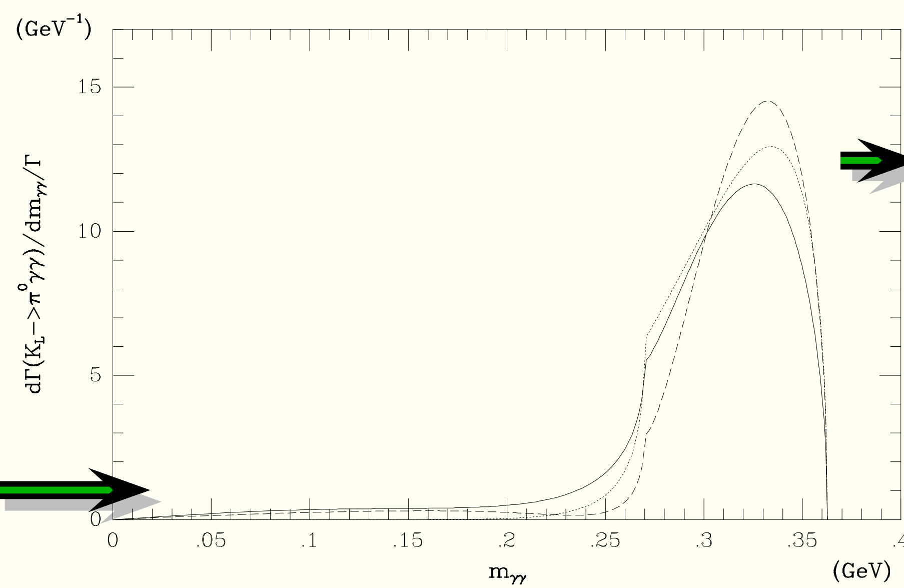
+

$O(p^4)$ correction to $A(\mathrm{K_L} \to \pi^0\pi^+\pi^-)$ $\approx 30\%\ O(p^4)_{\pi^0\gamma\gamma}$

+

vector-meson exchange (a_V)

a_V can be extracted e.g. from experimental $m_{\gamma\gamma}$ distribution knowing the non-vector-meson contributions to the $O(p^6)$



region $m_{\gamma\gamma} < 0.2\text{GeV}$ determines the CP-conserving part of $\mathrm{K_L} \to \pi^0 e^+ e^-$

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

- Data from 1998 and 1999 $\Re e \frac{\varepsilon'}{\varepsilon}$ runs
- Normalised to $K_L \to \pi^0\pi^0$ – most systematic effects cancel

- Background sources:
  - $K_L \to \pi^0\pi^0$ with badly reconstructed showers
  - $K_L \to 3\pi^0$ with missing or overlapping showers
  - pile-up events

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

➡ Background from $K_L \to \pi^0\pi^0$:

- events with two $\gamma\gamma$ pairings compatible with π^0 mass rejected
- one $\gamma\gamma$ pair must have invariant mass within 3 MeV/c^2 from π^0 mass
- the other pair must have invariant mass (m_{34}) outside the window 110 – 160 MeV/c^2
- transverse momentum of the lower-energy unpaired photon required larger than 40 MeV/c^2
- remaining background estimated from $K_S \to \pi^0\pi^0$ reconstruction tails:

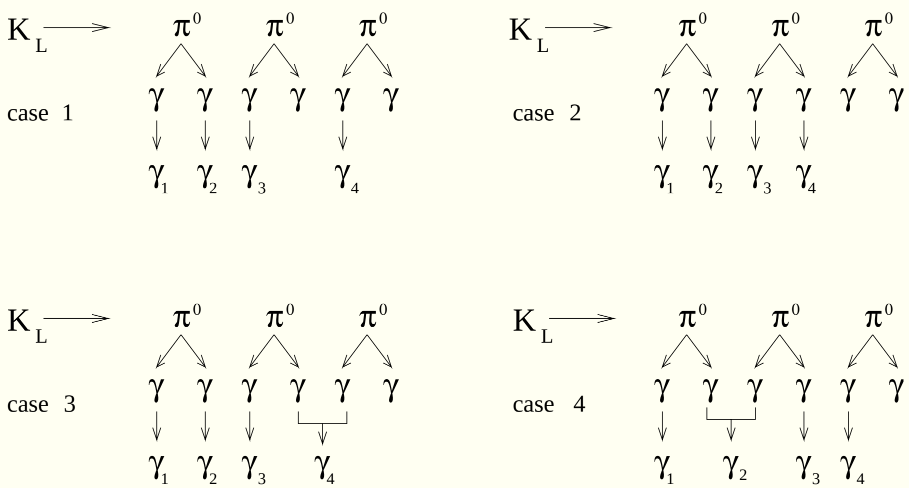
$$(0.16 \pm 0.08)\%$$

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

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

- rejected by requiring no hit in photon veto rings around the detector and by restricting the decay volume to 30 m behind the target
- overlaps partially rejected by restricting the allowed shower width
- further rejection by attempting to reconstruct correct decay vertex position assuming that all events come from background:

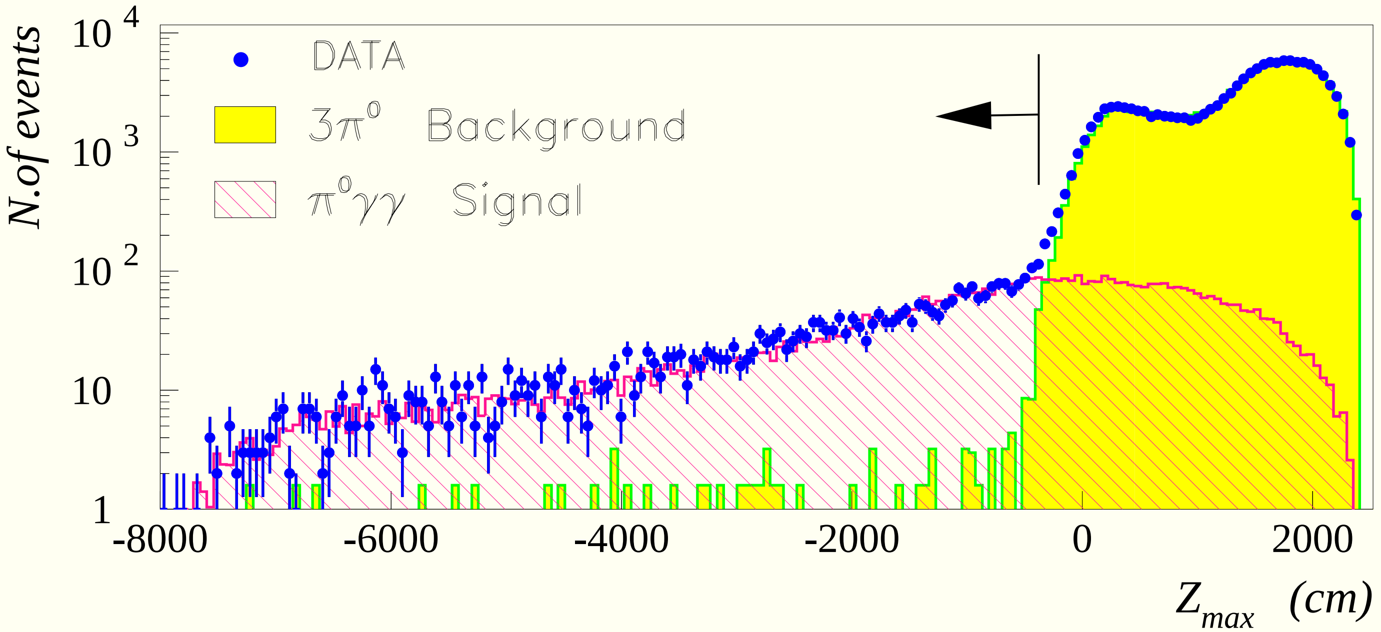
- in cases 1,2,3 at least one $\gamma\gamma$ pair gives correct vertex position ($z_{\gamma\gamma}$) assuming π^0 mass
- in case 4 at least one triplet gives correct vertex position ($z_{\gamma\gamma\gamma}$) assuming π^0 mass and one shower shared by 2 π^0's



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

A variable $z_{max} = max(z_{\gamma\gamma}, z_{\gamma\gamma\gamma})$ is constructed taking into account only those $z_{\gamma\gamma}, z_{\gamma\gamma\gamma}$ compatible with at least one photon loss wrt. the kaon mass constraint. ($z_{\gamma\gamma}, z_{\gamma\gamma\gamma} < z_K - 6$m).

For $\pi^0\gamma\gamma$ events z_{max} is unphysical (e.g. upstream from collimator) but separates well most of $3\pi^0$ background



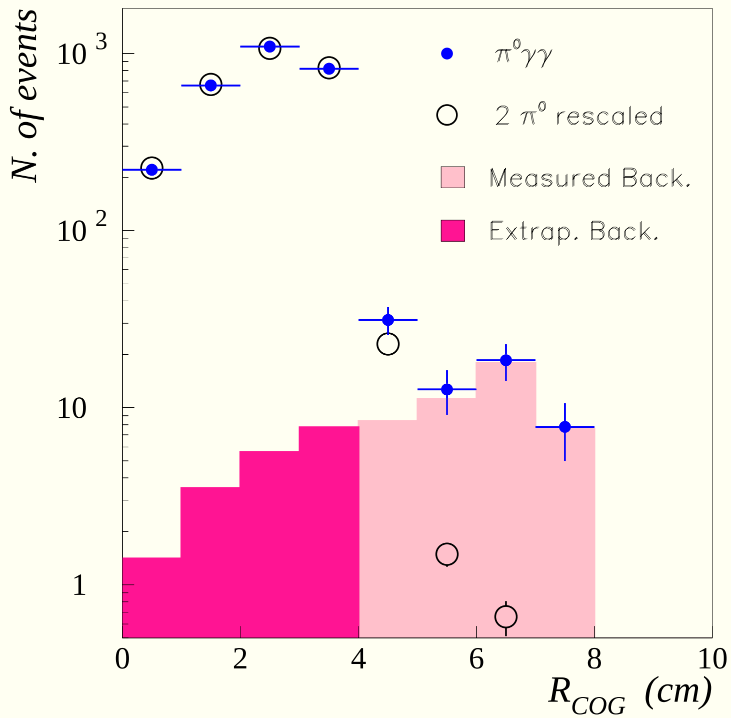
Remaining background estimated from MC normalised to flux:

$(2.74 \pm 0.42)\%$

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

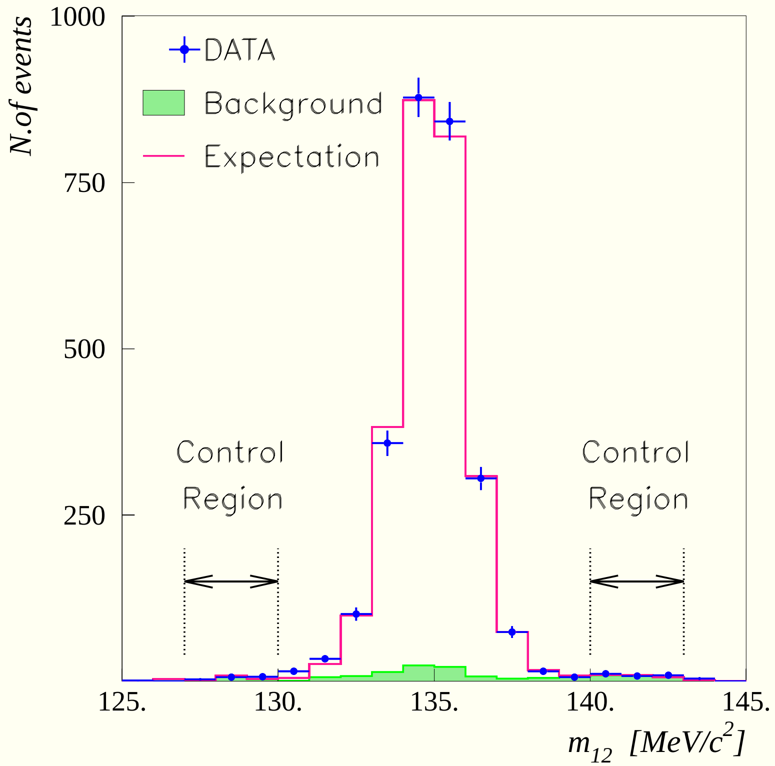
- Pile-up events from e.g. two decays occuring within 3ns:
- Subtracted from centre of energy (or centre of gravity - COG) distribution comparing the tail with the genuine beam profile obtained from good $\pi^0\pi^0$ events.
- Extrapolation done assuming random direction of the decay source:

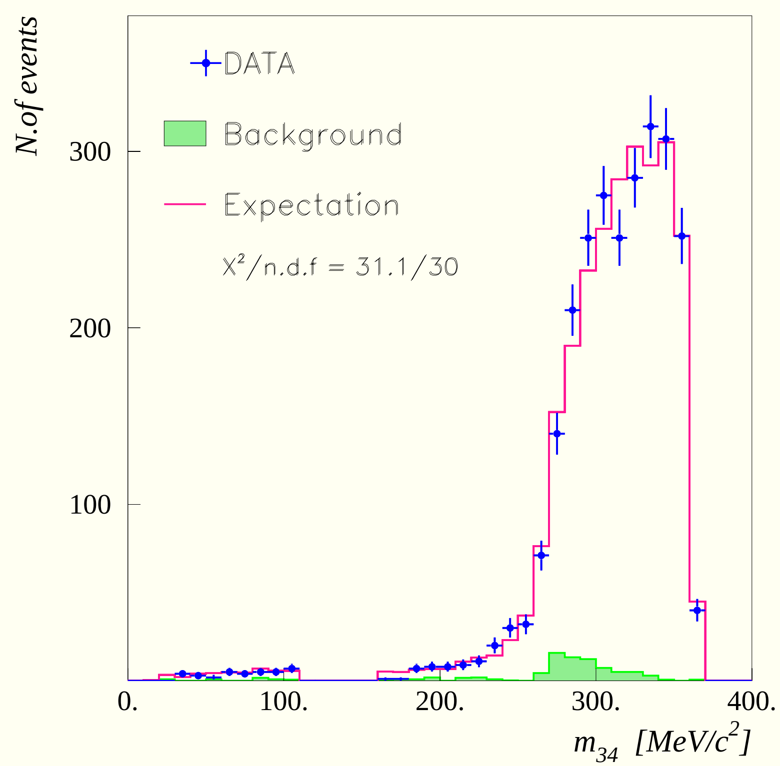
$$(0.32 \pm 0.21)\%$$



$K_L \rightarrow \pi^0\gamma\gamma$ measurement

Invariant mass distributions





$\mathrm{K_L} \rightarrow \pi^0\gamma\gamma$ measurement

- for the a_v fit, events with more than one $|m_{\gamma\gamma} - m_{\pi^0}| < 3\mathrm{MeV/c^2}$ solutions are dropped

$$a_v = -0.46 \pm 0.03_{stat} \pm 0.04_{syst}$$

- Using fitted value of a_v and ∼2.5k reconstructed $\mathrm{K_L} \rightarrow \pi^0\gamma\gamma$ events:

$$BR(\mathrm{K_L} \rightarrow \pi^0\gamma\gamma) = (1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \times 10^{-6}$$

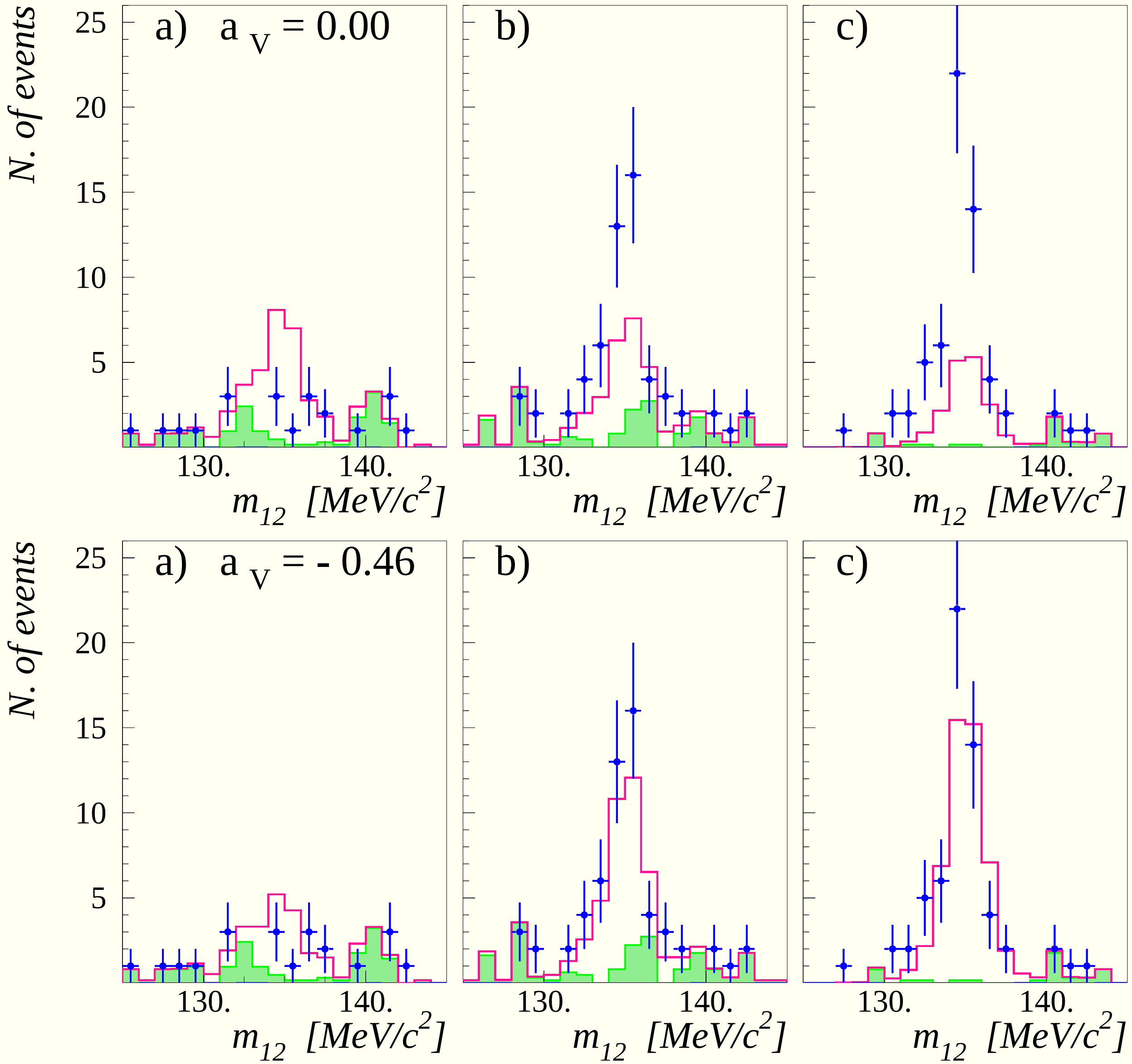
- Systematics in both cases dominated by acceptance evaluation and background subtraction
- Implies negligible CP-conserving amplitude in $\mathrm{K_L} \rightarrow \pi^0 e^+ e^-$

Preprint: CERN-EP/2002-030 - hep-ex/0205010

- KTeV results (PRL 83 (99) 917):

$$a_v = -0.72 \pm 0.05_{stat} \pm 0.06_{syst}$$
$$BR(\mathrm{K_L} \rightarrow \pi^0\gamma\gamma) = (1.68 \pm 0.07_{stat} \pm 0.08_{syst}) \times 10^{-6}$$

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



m_{34} [MeV/c^2]
a) 30 – 110
b) 160 – 240
c) 240 – 260

$K_S \to \gamma\gamma$ measurement

Use data from 2000 (no spectrometer) near-target run (high intensity K_S, NA48/1–Phase I)

normalise to $K_S \to \pi^0\pi^0$ decay rate

distance vertex–LKr: $d_{vertex} = \frac{d_{12}}{m_K}\sqrt{E_1 E_2}$

Must assume kaon mass to reconstruct the vertex position

Several sources of background:

- $K_S \to \pi^0\pi^0$ with only 2 showers in the LKr calorimeter.

  If 2 photons miss the acceptance $d_{true} - d_{rec} > 9m(\sim \frac{m_\pi^2}{m_K^2} d_{true})$
  shift is smaller if 1 miss/1 overlap

  decay region $-1m < z_{vertex} < 5m$ wrt. collimator exit.

- hadronic background from interactions of beam particles in the collimator

  require no in-time HAC cluster and cut on shower width

- accidental $\gamma\gamma$ pairs — require $\Delta t_{\gamma\gamma} < 5ns$

$\mathrm{K_S} \to \gamma\gamma$ measurement

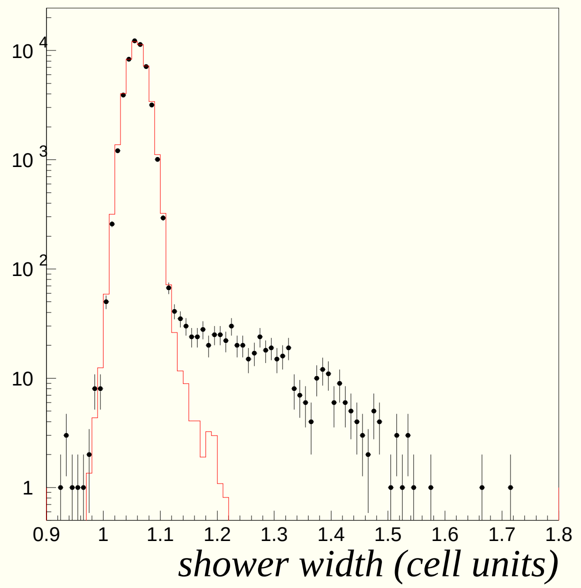
Other sources of background:

- $\boxed{\mathrm{K_L} \to \gamma\gamma}$ – irreducible $\frac{N(\mathrm{K_L}\to\gamma\gamma)}{N(\mathrm{K_S}\to\gamma\gamma)} \sim 1.5$ in the decay volume
  - use $\mathrm{K_L} \to 3\pi^0$ to estimate $\mathrm{K_L}$ flux
  - use far-target 2000 run to measure $\frac{\Gamma(\mathrm{K_L}\to\gamma\gamma)}{\Gamma(\mathrm{K_L}\to 3\pi^0)}$ (present PDG accuracy insufficient)

  need 5 data samples:
  near target: $\gamma\gamma$, $2\pi^0$, $3\pi^0$,
  far target: $\gamma\gamma$, $3\pi^0$.
- $\boxed{\text{Dalitz}}$ decays $K, \pi^0 \to ee\gamma$ – mainly due to collinear ee pairs.
  Subtracted using MC.

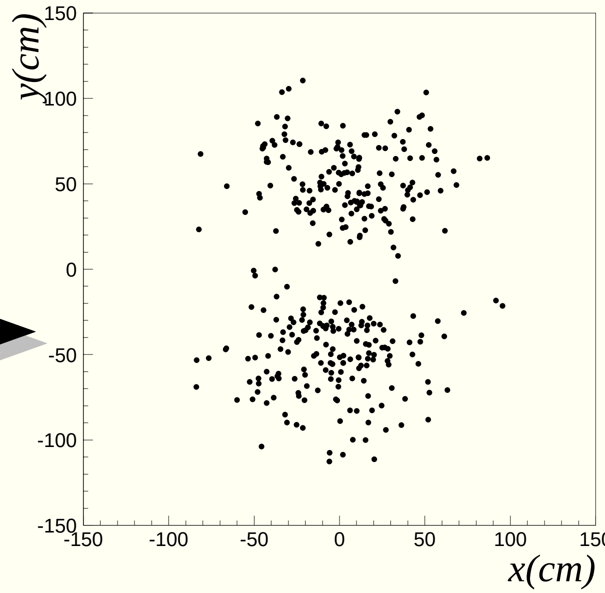
Measurement of $\frac{\Gamma(K_L \to \gamma\gamma)}{\Gamma(K_L \to 3\pi^0)}$

- Far-target run from 2000 – similar detector conditions as in near-target run – detector systematics cancels. 25% of statistics fully sufficient.
- Choose the same decay volume as for $K_S \to \gamma\gamma$ analysis – acceptance almost cancels.
- Far target $\gamma\gamma$ have their own background:



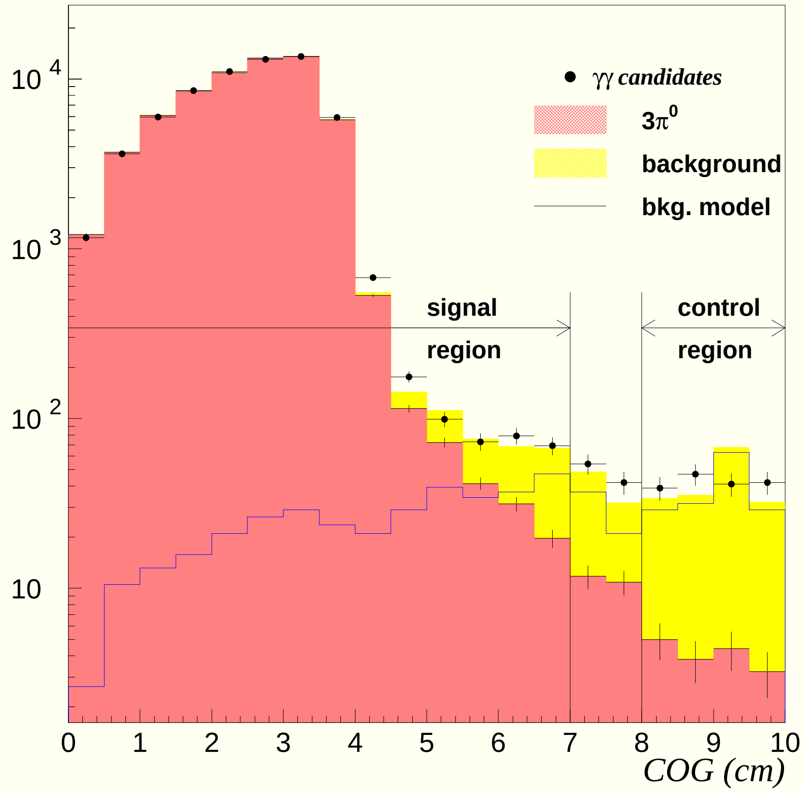
hadronic

charged



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

➡ Background subtracted using centre of energy (COG) distribution



➡ Shape from data:

- require HAC energy
- require hit in hodoscope

➡ Background: $(0.6 \pm 0.3)\%$

➡ Effect on BR$(K_S \to \gamma\gamma)$: $\Delta_{BR(K_S \to \gamma\gamma)} = (0.9 \pm 0.4)\%$

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

Measurement on its own:

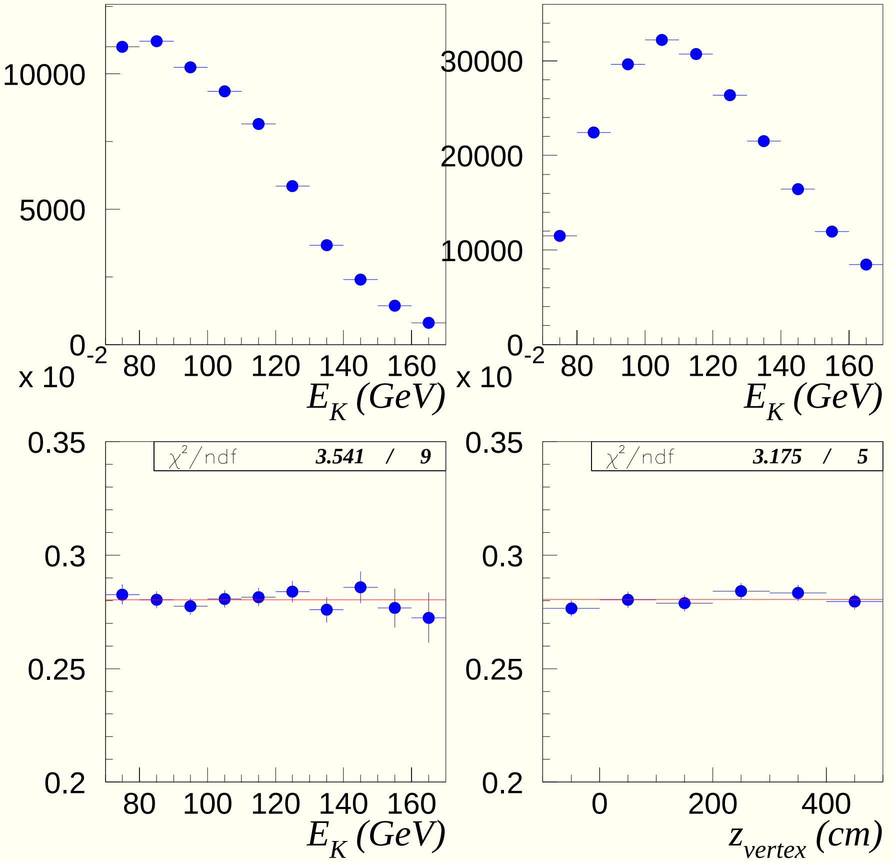
$$\frac{\Gamma(K_L \to \gamma\gamma)}{\Gamma(K_L \to 3\pi^0)} = (2.81 \pm 0.01_{stat} \pm 0.02_{syst}) \times 10^{-3}$$

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

Sytematics from acceptance determination and background

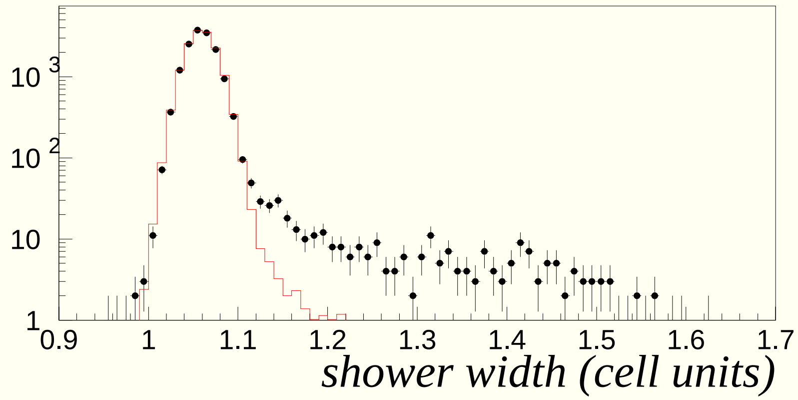
energy spectra

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

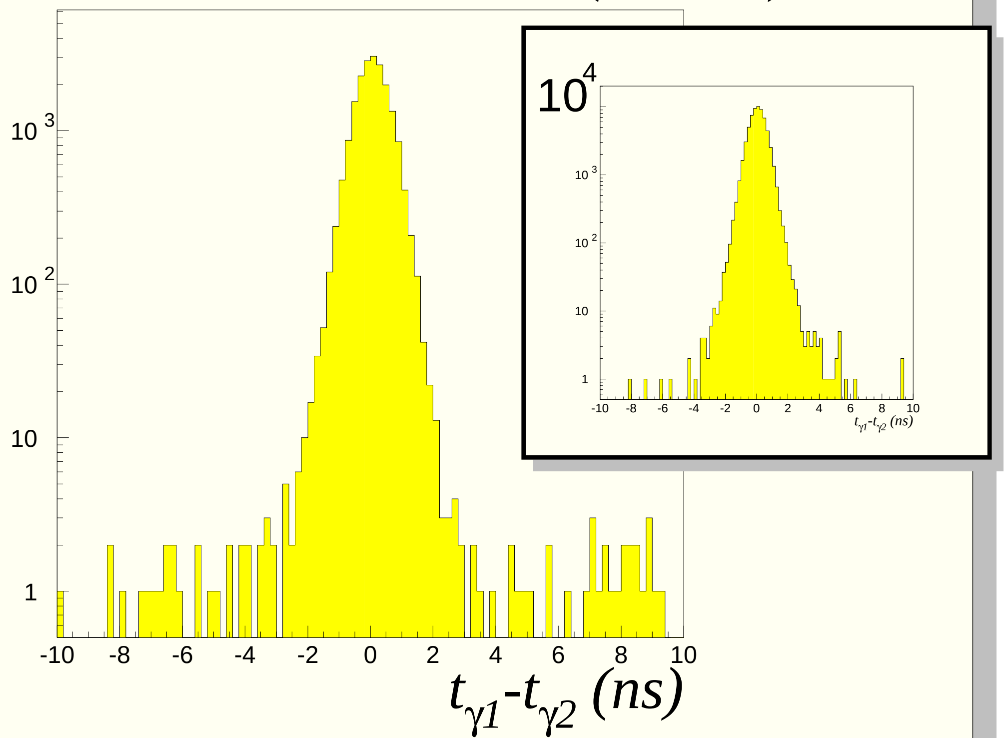


$K_S \to \gamma\gamma$ measurement

- hadronic background visible from shower width tails



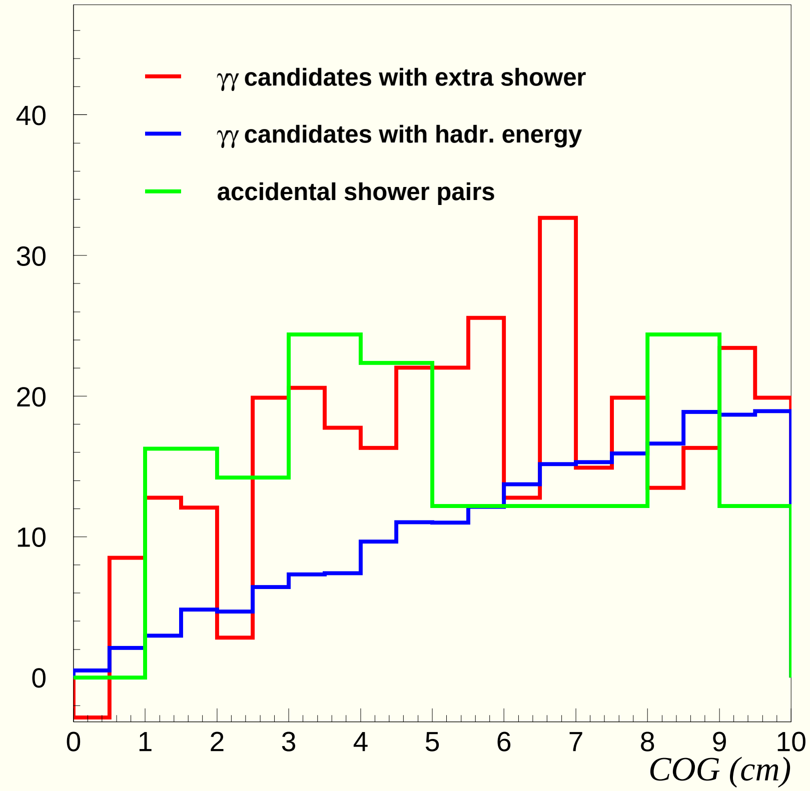
- accidental pairs visible in shower time difference (no such tails in far target run)



$K_S \to \gamma\gamma$ measurement

Background COG shapes modelled from data:

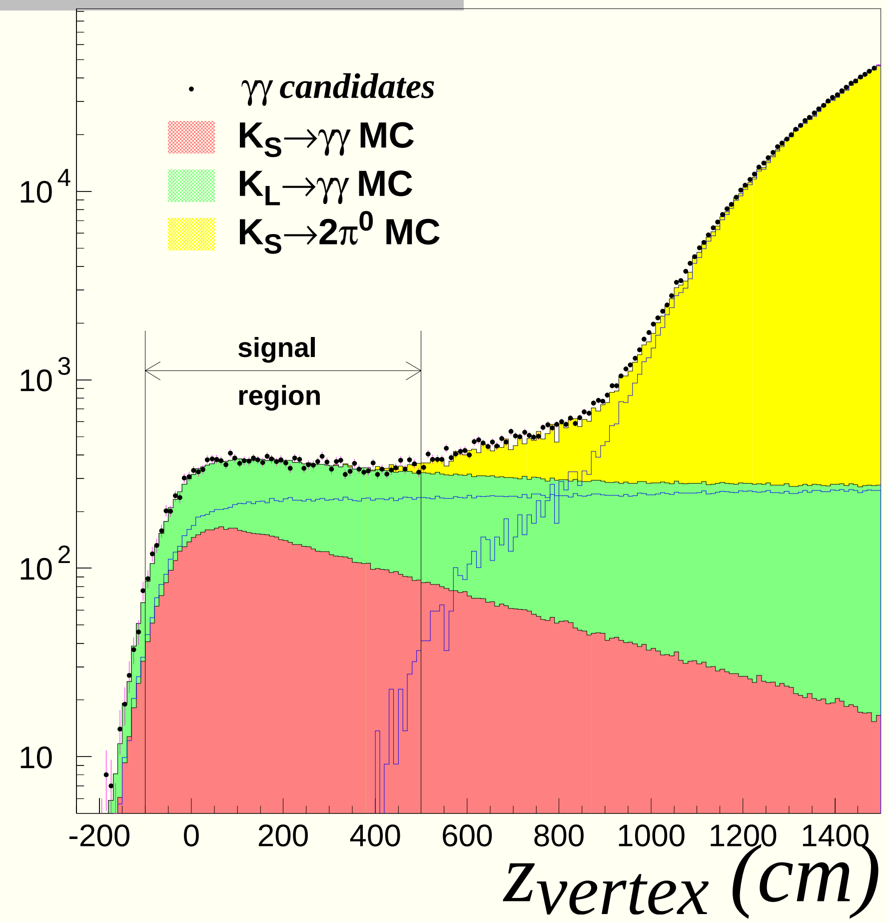
- Hadronic background:
  Model 1: events with HAC energy and no shower width restriction
  Model 2: all cuts applied but ask for extra cluster and $z_{vertex} < 4m$
- Accidental pairs:
  Model: use out-of-time shower pairs



Average extrapolation factor is used: $(0.8 \pm 0.3)\%$
Systematic uncertainty from the spread of models.

Effect on BR($K_S \to \gamma\gamma$): $\Delta_{BR(K_S \to \gamma\gamma)} = -(2.1 \pm 0.7)\%$

$K_S \to \gamma\gamma$ measurement



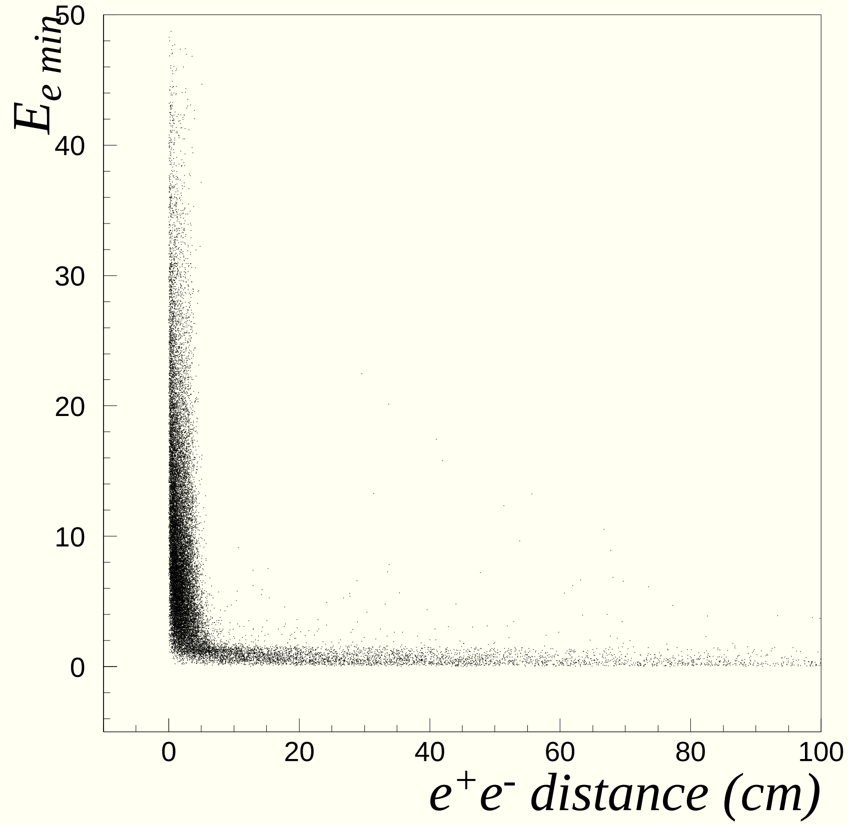
- Background from $\pi^0\pi^0$ subtracted using MC normalised to the flux obtained from fully reconstructed $\pi^0\pi^0$ events

- Background: $(0.8 \pm 0.2)\%$
  Systematic uncertainty from discrepancy between data and combined MC in the overlapping shower region $(5m < z_{vertex} < 9m)$

- Effect on BR($K_S \to \gamma\gamma$): $\Delta_{BR(K_S\to\gamma\gamma)} = -(2.1 \pm 0.4)\%$

$K_S \to \gamma\gamma$ measurement

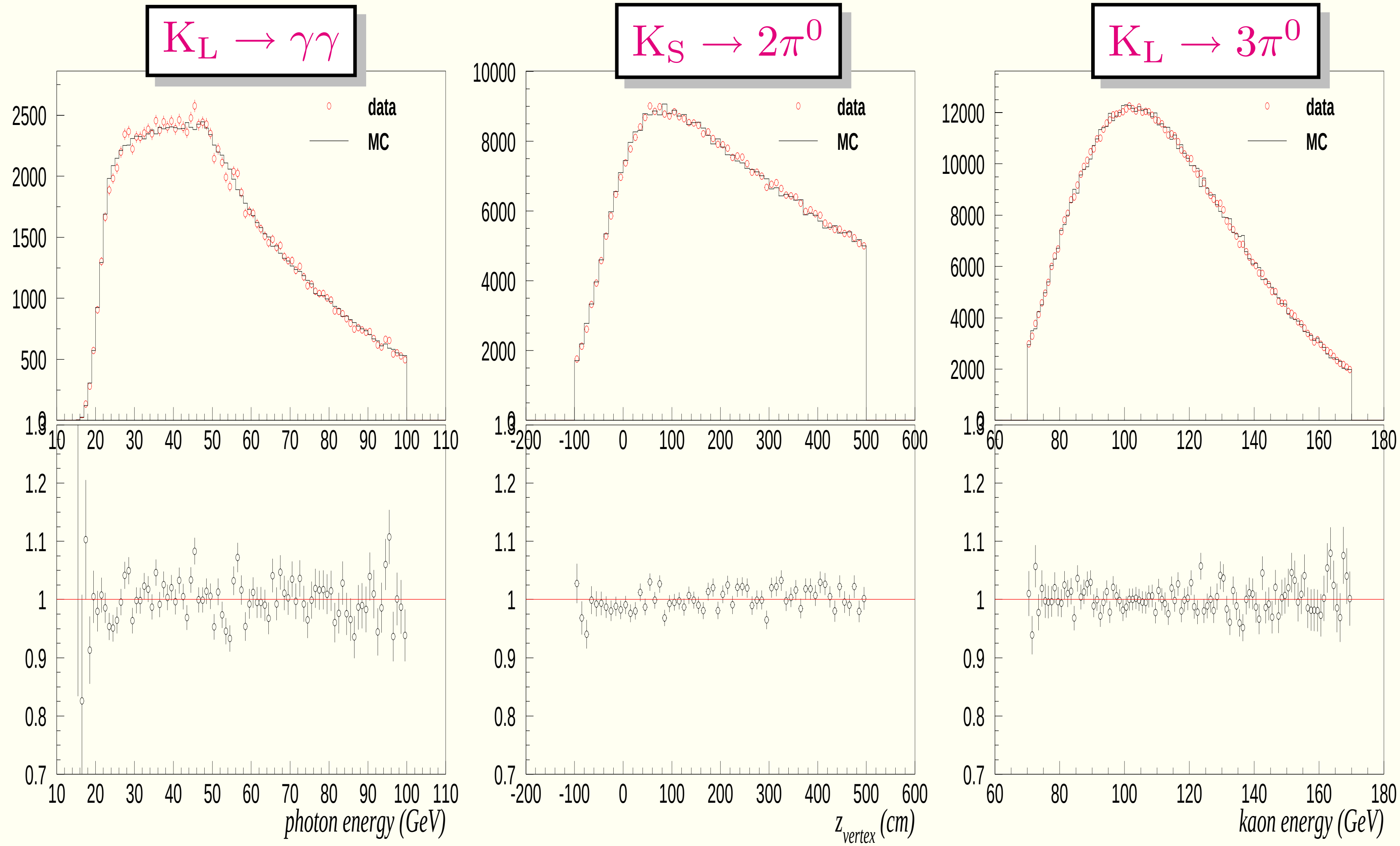
- All 3 decay modes have a Dalitz component $(K, \pi^0 \to ee\gamma)$
- $\sim$30% of ee pairs do not open up sufficiently to be resolved by the calorimeter
- This does not apply to far-target run because the spectrometer magnet was switched on



- Acceptances from MC
- Effect on BR($K_S \to \gamma\gamma$): $\Delta_{BR(K_S \to \gamma\gamma)} = (1.5 \pm 0.3)\%$
  Systematic uncertainty mainly due to uncertainty in the simulation of the shower overlaps

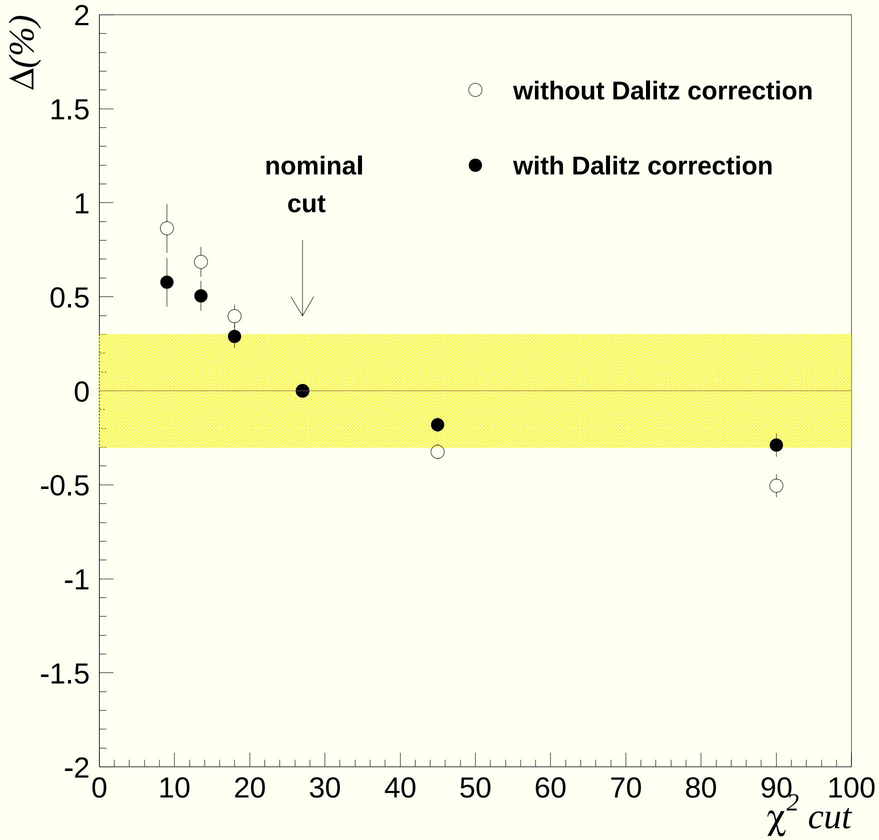
$K_S \to \gamma\gamma$ measurement

Data/MC comparisons



$K_S \to \gamma\gamma$ measurement

χ^2 cut (π^0 constraint aplied only to $2\pi^0$ and $3\pi^0$ samples) systematics



$K_S \to \gamma\gamma$ measurement

- Corrections and uncertainties

Hadronic background and accidentals	-2.1 $\pm$ 0.7 %
Background from $K_S \to \pi^0\pi^0$	-2.1 $\pm$ 0.4 %
Had. background in far target beam	0.9 $\pm$ 0.4 %
Dalitz decay correction	1.5 $\pm$ 0.3 %
χ^2 cut on π^0 mass in 2π^0 and 3π^0	$\pm$ 0.3 %
Trigger efficiency	$\pm$ 0.1 %
BR($K_S \to \pi^0\pi^0$)	$\pm$ 0.9 %
Total	-1.8 $\pm$ 1.4 %
Statistical uncertainty data	$\pm$ 2.0 %
Statistical uncertainty MC	$\pm$ 0.6 %

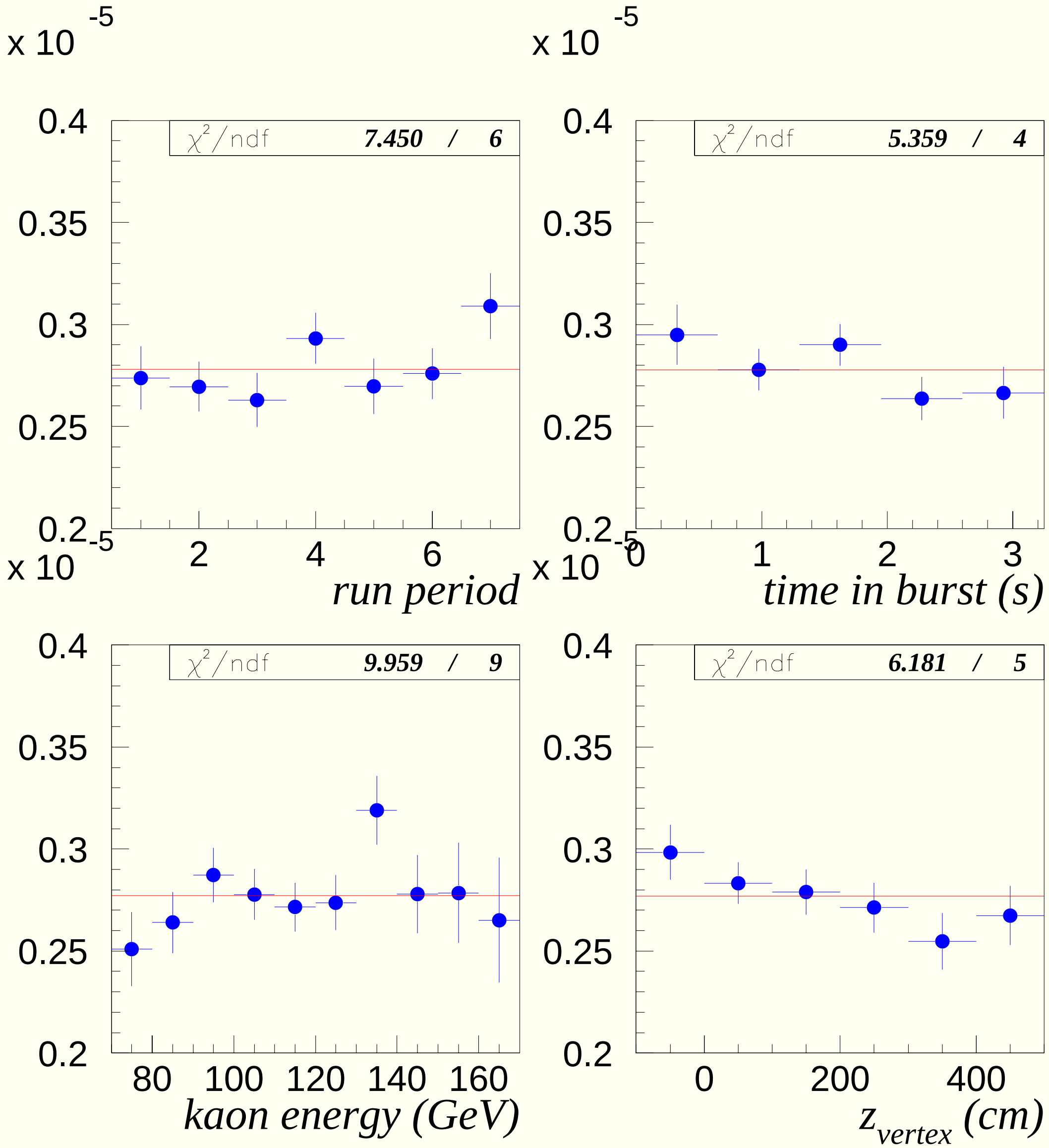
- Result

$$BR(K_S \to \gamma\gamma) = (2.78 \pm 0.06_{stat} \pm 0.02_{MCstat} \pm 0.04_{syst}) \times 10^{-6}$$

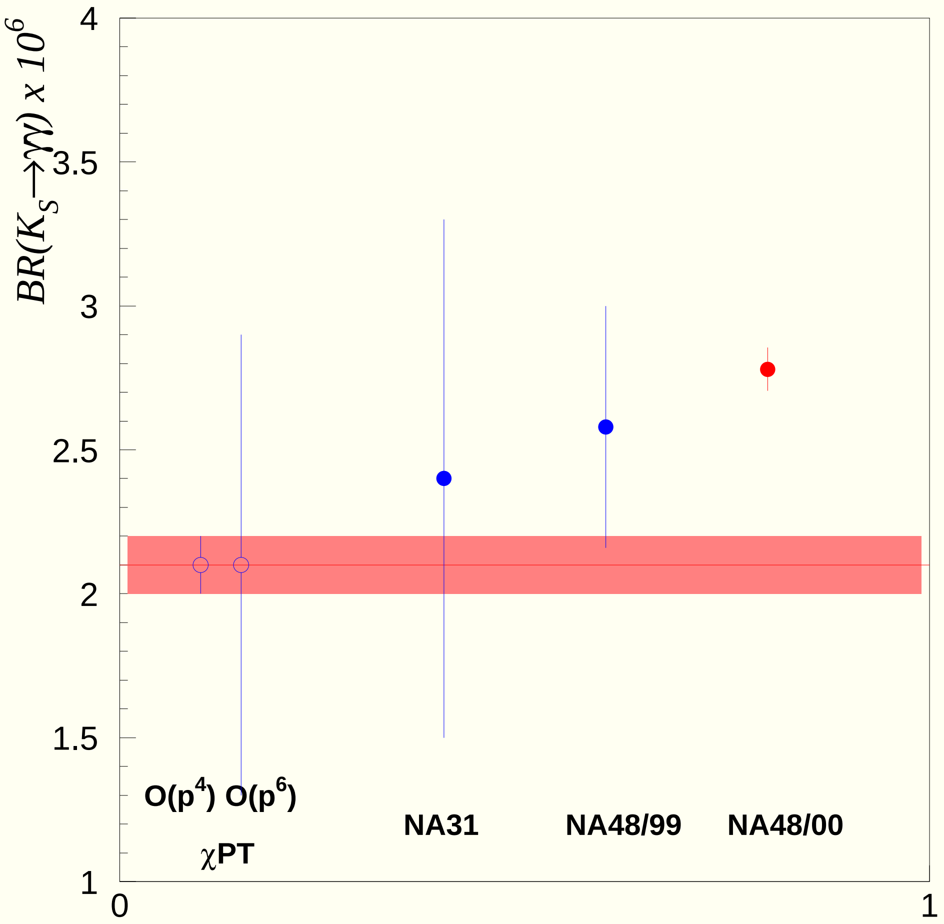
- Statistics: ~7.5k $K_S \to \gamma\gamma$ events.

$K_S \to \gamma\gamma$ measurement

Stability checks



$K_S \to \gamma\gamma$ measurement



- The new result differs by 30% from O(p^4) prediction of χPT
- Indication of a large O(p^6) contribution
- Compatible with previous measurements

Summary

- The $\mathrm{K_S}$ lifetime measurement differs by 1.7 σ from the current PDG value and has better precision.
- The η mass differs by 4.2 σ from current world average and has 2.4 times better accuracy.
- The K^0 mass agrees within 1.1 σ with the world average and has similar precision.

- The measurement of $\mathrm{K_L} \to \pi^0\gamma\gamma$ decay favours a value of vector-meson coupling of $a_V = -0.46$ and implies a negligible CP-conserving contribution to the direct CP-violating decay $\mathrm{K_L} \to \pi^0 e^+ e^-$.
- $\frac{\Gamma(\mathrm{K_L}\to\gamma\gamma)}{\Gamma(\mathrm{K_L}\to 3\pi^0)}$ has been measured with accuracy 4 times better than current PDG value.
- The new $BR(\mathrm{K_S} \to \gamma\gamma)$ has an accuracy better than 3% and indicates a 30% excess with respect to the $O(p^4)$ χPT prediction. This may influence the interpretation of $\mathrm{K_L} \to \pi^0\gamma\gamma$ measurement.