NA48: Results on rare decays and Future Prospects

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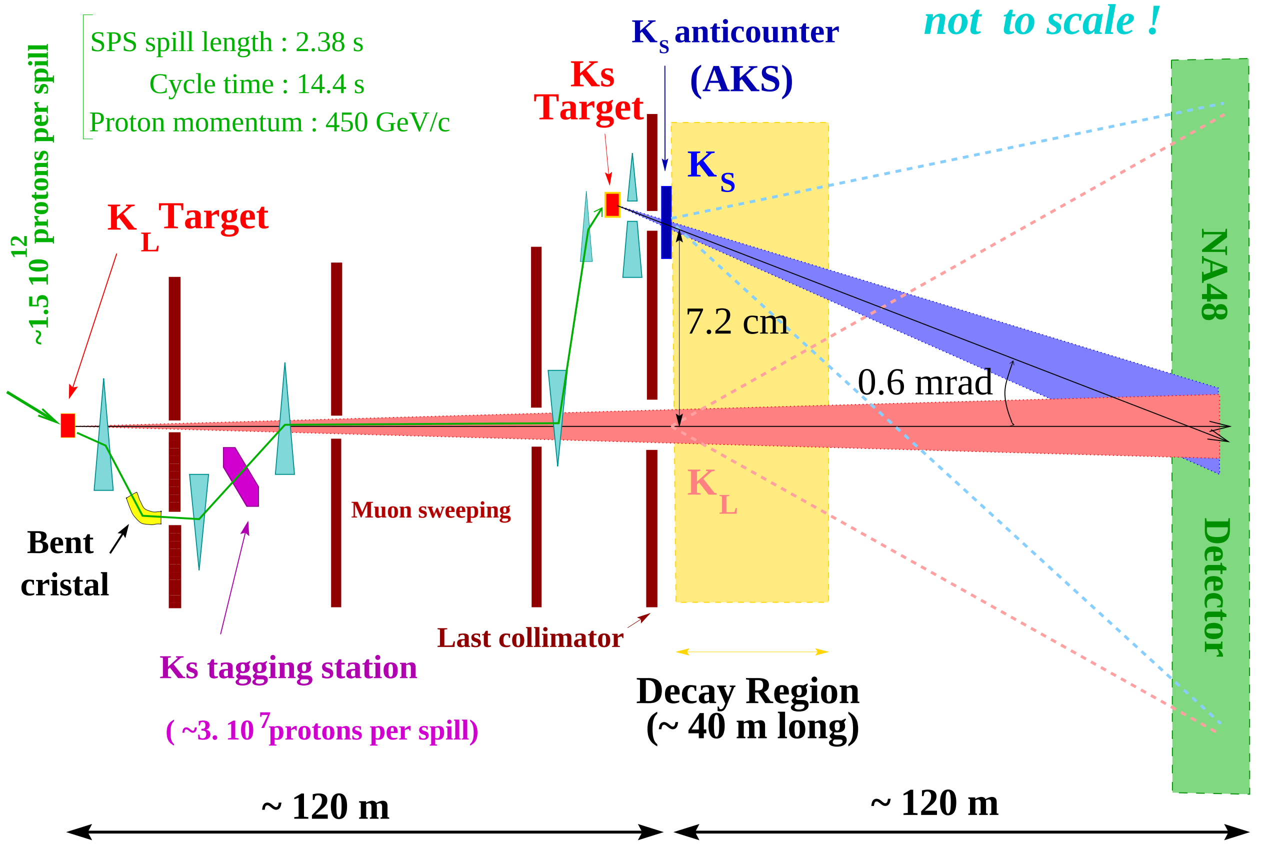
On behalf of the NA48 Collaboration

- Introduction
- CP violation asymmetry in K_L decays
  - $K_{\mathrm{L}} \rightarrow \pi^+ \pi^- e^+ e^-$
  - $K_{\mathrm{S}} \rightarrow \pi^+ \pi^- e^+ e^-$
- $K \rightarrow \pi l^+ l^-$ decays
  - $K_{\mathrm{S}} \rightarrow \pi^0 e^+ e^-$
- Tests of Chiral Perturbation Theory (χPT)
  - $K_{\mathrm{L}} \rightarrow \pi^0 \gamma\gamma$
  - $K_{\mathrm{S}} \rightarrow \gamma\gamma$
- Perspectives: NA48/1

NA48 simultaneous K_S and K_L beams

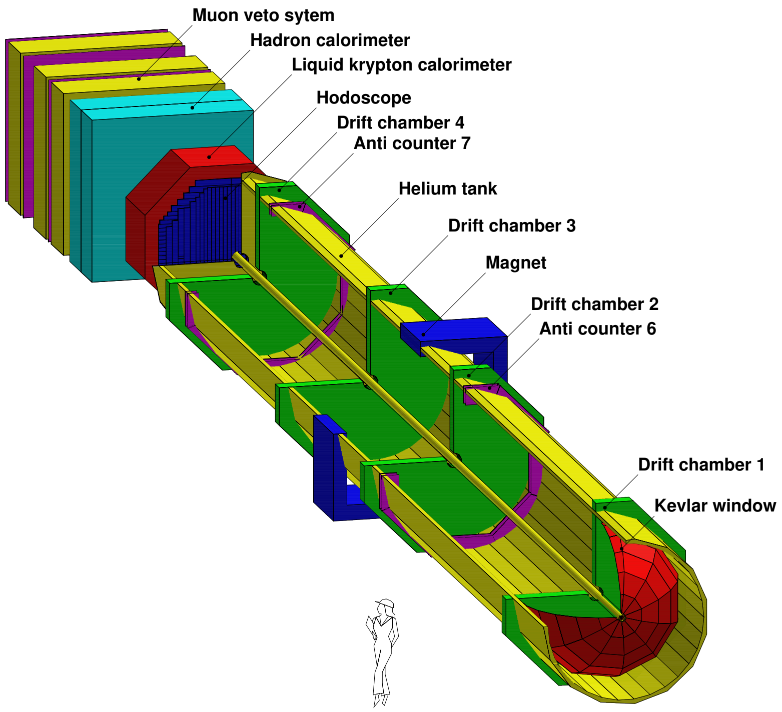
Year	$P_p - dC$ (GeV/c)-(%)	ppp	K_L flux	K_S flux
97-99 ϵ'/ϵ: K_S tagged	450-17	$1.2 \cdot 10^{12}$	$3.2 \cdot 10^{10}$	$6.5 \cdot 10^{7}$
99 HIKS: K_L target removed	450-17	$6.0 \cdot 10^{9}$	-	$2.3 \cdot 10^{8}$
00 HIKS: K_L target removed	400-22	$1.0 \cdot 10^{10}$	-	$1.0 \cdot 10^{10}$



Summary of NA48 BR results

Decay mode	NA48 (prel.)		Most Precise Publication	
	Evt.	BR	Evt.	BR
$K_L \rightarrow e^+e^-\gamma$			6864	$(1.06 \pm 0.05)10^{-5}$ (NA48)
$K_L \rightarrow e^+e^-e^+e^-$	132	$(3.7 \pm 0.4)10^{-8}$	441	$(3.7 \pm 0.3)10^{-8}$ (KTeV)
$K_L \rightarrow e^+e^-\mu^+\mu^-$	19		1	$(2.9^{+6.7}_{-2.4})10^{-9}$ (E799I)
$K_L \rightarrow e^+e^-\gamma\gamma$	492	$(6.3 \pm 0.5)10^{-7}$	1543	$(5.84 \pm 0.35)10^{-7}$ (KTeV)
$K_L \rightarrow \pi^0\gamma\gamma$	1397	$(1.5 \pm 0.2)10^{-6}$	947	$(1.5 \pm 0.1)10^{-6}$ (KTeV)
$K_L \rightarrow \pi^+ \pi^- e^+ e^-$	1337	$(3.1 \pm 0.2)10^{-7}$	46	$(3.2 \pm 0.7)10^{-7}$ (KTeV)
$K_S \rightarrow \pi^+ \pi^- e^+ e^-$	921	$(4.3 \pm 0.4)10^{-5}$	56	$(4.5 \pm 0.8)10^{-5}$ (NA48)
$K_S \rightarrow \gamma\gamma$			149	$(2.6 \pm 0.4)10^{-6}$ (NA48)
$K_S \rightarrow \pi^0e^+e^-$	–	$< 1.4 \times 10^{-7}$	–	$< 1.1 \times 10^{-6}$ (NA31)

CERN-NA48 Detectors



LKr electro-magnetic calorimeter:

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

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.42\%$$

$\sigma_{\pi^0} \approx 1$ MeV, $\sigma_t = 222$ ps,
$\sigma_{X,Y} < 1.3$ mm

Magnetic Spectrometer:

4 chambers with 90 μm spacepoint resolution. $\epsilon_{plane} > 99\%$

$P_{\mathrm{T}}{}^{kick} \sim 265$ MeV/c

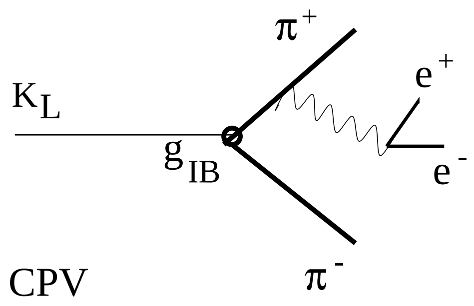
$\sigma_{X,Y}{}^{vtx} \simeq 2\ mm$

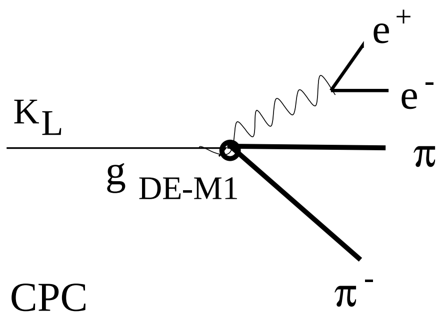
$\sigma_{m_K} \sim 2.5$ MeV/c^2

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

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

Main Contribution to $K_{\rm L} \to \pi^+ \pi^- e^+ e^-$:



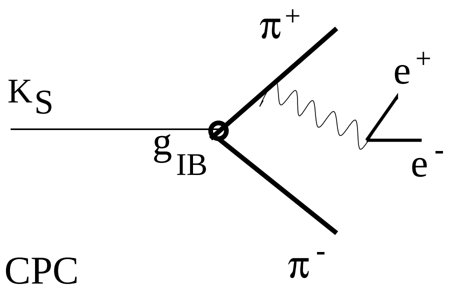


Interference between the dominant M1 (CP=–1) and the IB (CP=+1) diagrams

$\Rightarrow$ large CP-violating asymmetry in ϕ

angle between the normals to the $\pi^+\pi^-$ and e^+e^- planes in the Kaon c.m. system:
Theory (P.Heiliger and L.M.Sehgal): $|A(\phi)| \approx 14\%$

$K_{\rm S} \to \pi^+ \pi^- e^+ e^-$ dominated by IB process



$BR(K_{\rm L} \to \pi^+ \pi^- e^+ e^-)_{IB} \simeq BR(K_{\rm S} \to \pi^+ \pi^- e^+ e^-) \times |\epsilon_L|^2 \frac{\tau_L}{\tau_S}$

$\Rightarrow$ no CP-violating asymmetry is expected.

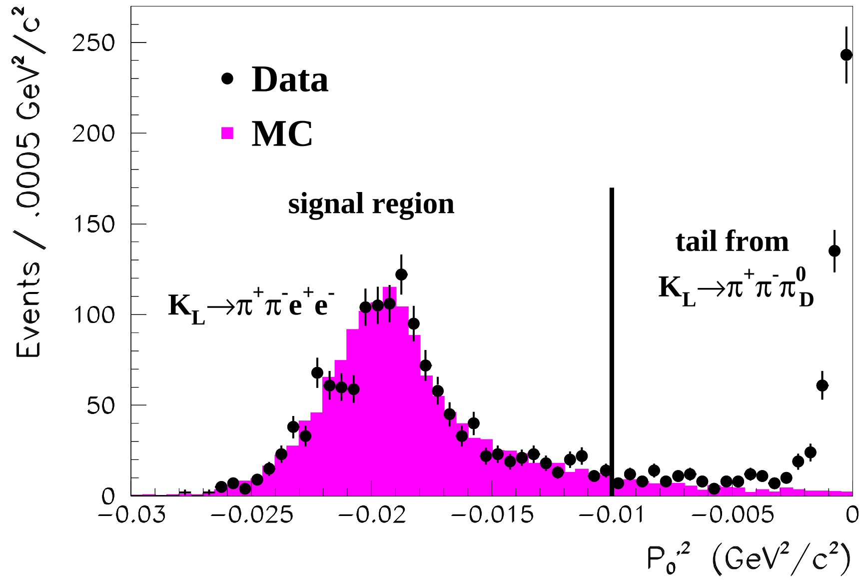
- First observation in NA48: 56 events from 98 data (PL B496(2000),137))
- cross-check the asymmetry effect for the $K_{\rm L}$.

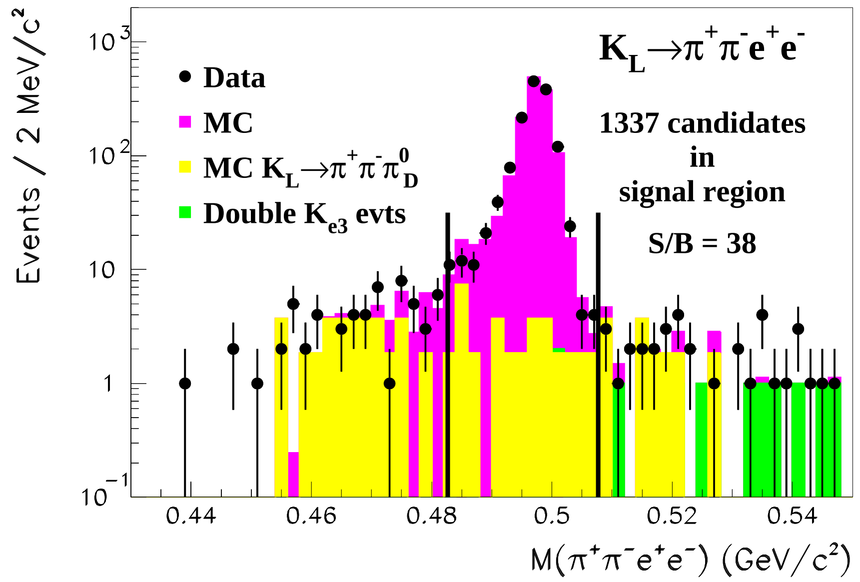
$K_L \rightarrow \pi^+ \pi^- e^+ e^-$

(1998+1999 data)

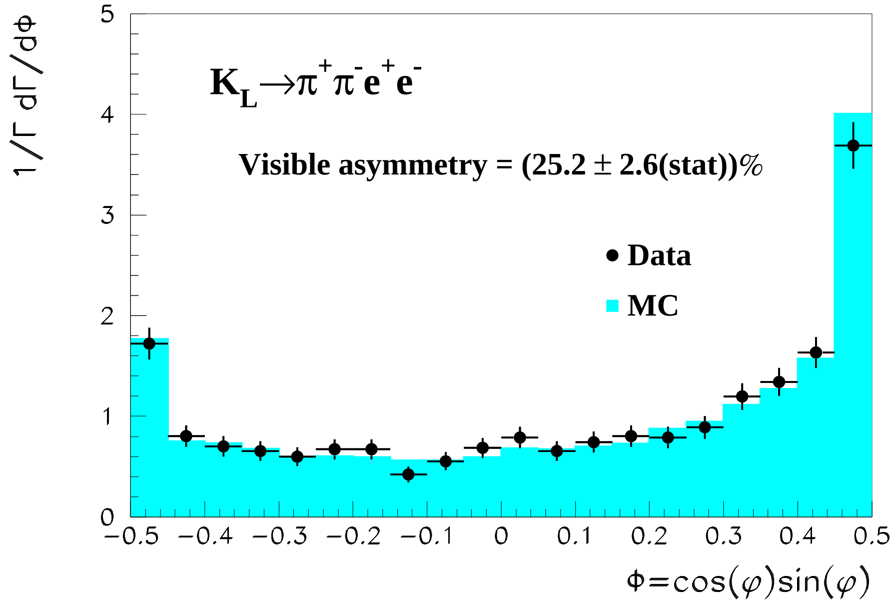
- Large background ($> \times 10^3$) from $K_L \rightarrow \pi^+\pi^-\pi^0_D$ decays is suppressed using the $P_0'^2$ variable
- normalisation: $K_L \rightarrow \pi^+\pi^-\pi^0_D$

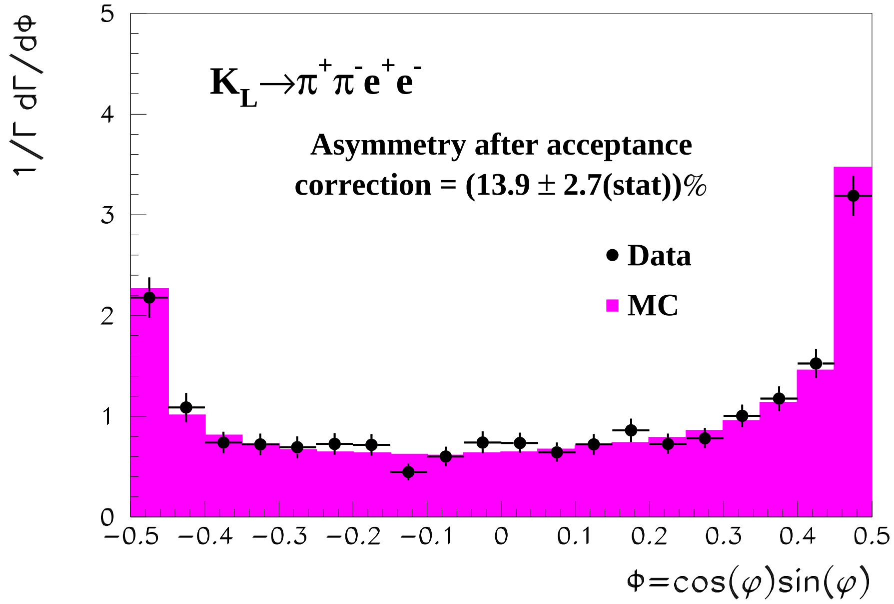
482.7$< M_{\pi\pi ee} <$ 507.7 MeV/c^2 and $P_\perp^2 < 5 \cdot 10^{-4}$ GeV/c^2





$K_L \rightarrow \pi^+ \pi^- e^+ e^-$





Preliminary result in agreement with the theory

$A^{\mathrm{L}}_{\pi\pi ee} = 13.9 \pm 2.7_{sta} \pm 2.0_{sys}\%$

(KTeV PRL 84 408,2000: $A^{\mathrm{L}}_{\pi\pi ee} = 3.6 \pm 2.5_{sta} \pm 1.2_{sys}\ \%$)

$K_S \rightarrow \pi^+ \pi^- e^+ e^-$

- Rely on very good vertex resolution for K_S / K_L separation
- $K_L \rightarrow \pi^+\pi^-\pi^0_D$ decays produced at the K_S target used as normalisation

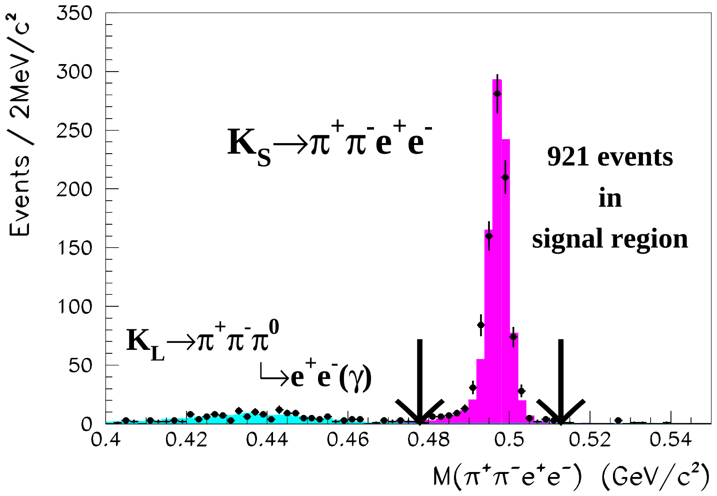
1998: First observation: 56 events, (PL B496 137)

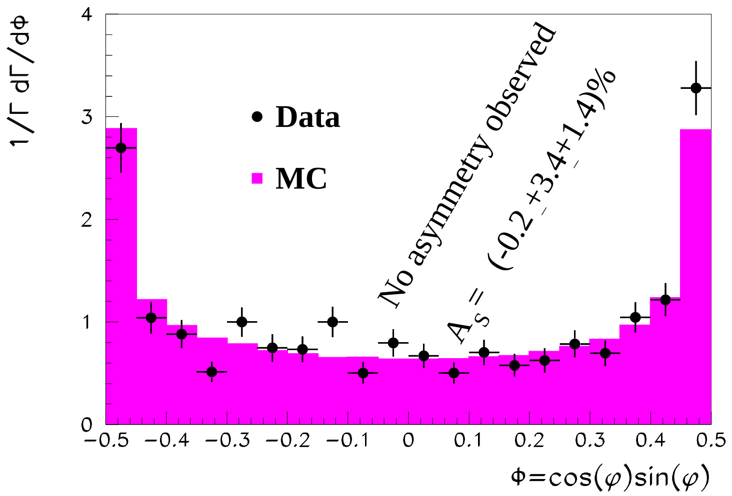
$$BR = (4.5 \pm 0.7_{stat} \pm 0.4_{syst}) \times 10^{-5}$$

1998+1999+2 days HIK_S Preliminary:

$$BR = (4.3 \pm 0.2_{stat} \pm 0.3_{syst}) \times 10^{-5}$$

$$BR(K_L \rightarrow \pi^+ \pi^- e^+ e^-)_{IB} = (1.3 \pm 0.1) \times 10^{-7}$$





$K_S \to \pi^0 l^+ l^-$

$K_S \to \pi^0 l^+ l^-$ bounds the indirect CP violation component of the $K_L \to \pi^0 l^+ l^-$ decay

- In the SM: $\mathrm{BR}(K_L \to \pi^0 e^+ e^-)_{\mathrm{CPVdir}} \sim 6.7 \times 10^{-11} \mathrm{A}^4 \eta^2$ where η is the CP violating phase in the CKM matrix
- The current upper limits:
  $BR(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$ KTEV,PRL 84, 5279 (2000)
  $BR(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$ KTEV,PRL 86, 397 (2001)
  could be improved of ≈ 2 by KTEV and -for $l = \mu$- more significantly by KAMI

$\mathrm{BR}(K_L \to \pi^0 l^+ l^-)_{\mathrm{CPVind}} = |\epsilon|^2 \frac{\tau_L}{\tau_S} \times BR(K_S \to \pi^0 l^+ l^-) \sim 1/330 \times BR(K_S \to \pi^0 l^+ l^-)$

Theoretical expectation:

$$\mathrm{BR}(K_S \to \pi^0 e^+ e^-) \approx {a_S}^2 \times 10^{-9} \text{ with } a_S \approx O(1)\text{[a]}$$

$$\Rightarrow \text{cannot be reliably predicted}$$

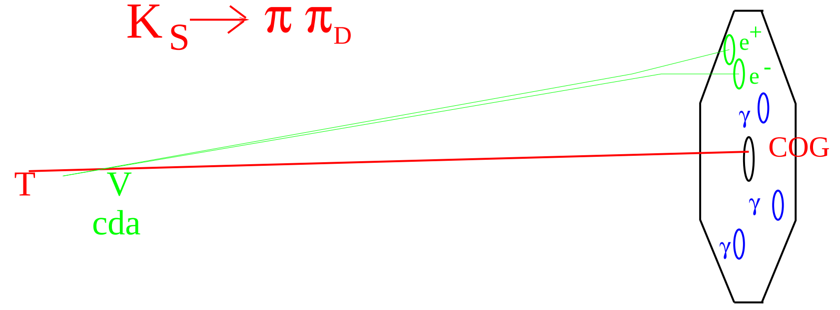
So far only one search: NA31: $BR(K_S \to \pi^0 e^+ e^-) < 1.1 \times 10^{-6}$

[a] G. Isidori, KAON-99 Conference, June 1999, hep-ph/9908399.

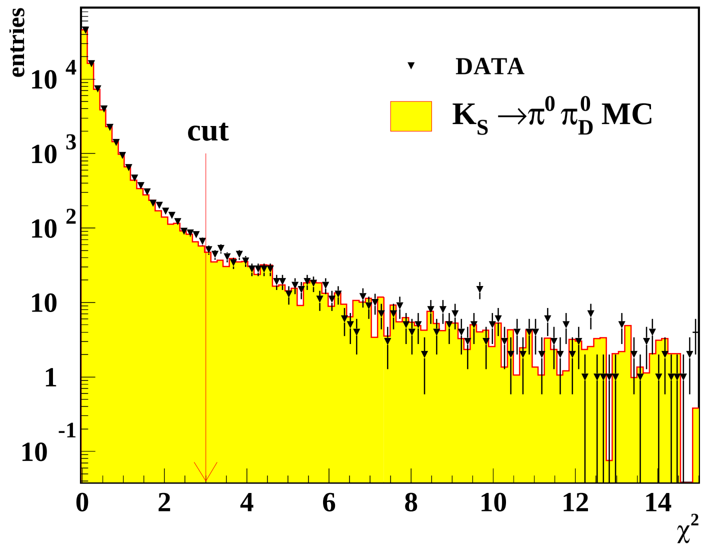
$K_S \rightarrow \pi^0 e^+ e^-$

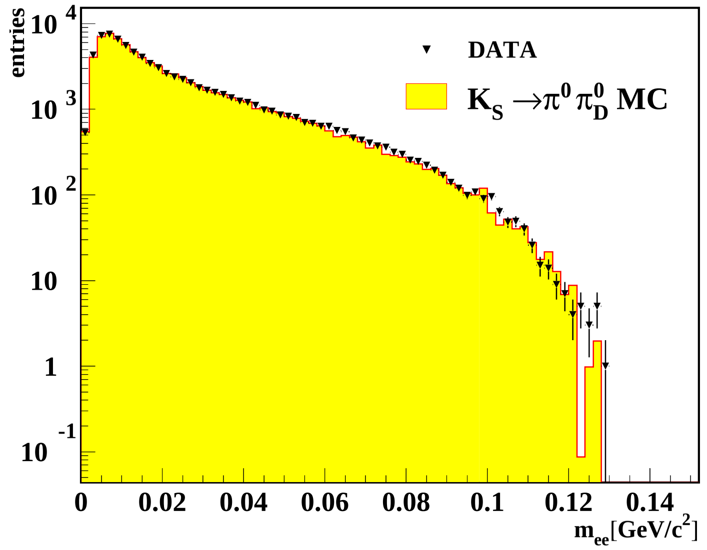
Normalisation: $\sim 8 \times 10^4$ $K_S \rightarrow \pi^0 \pi^0_D$

Efficiency: $\sim 4.2\%$



$$\chi^2 = \left[\frac{(m_{\gamma\gamma} + m_{ee\gamma})/2 - m_{\pi^0}}{\sigma_+}\right]^2 + \left[\frac{(m_{\gamma\gamma} - m_{ee\gamma})/2}{\sigma_-}\right]^2$$





$K_S \rightarrow \pi^0 e^+ e^-$

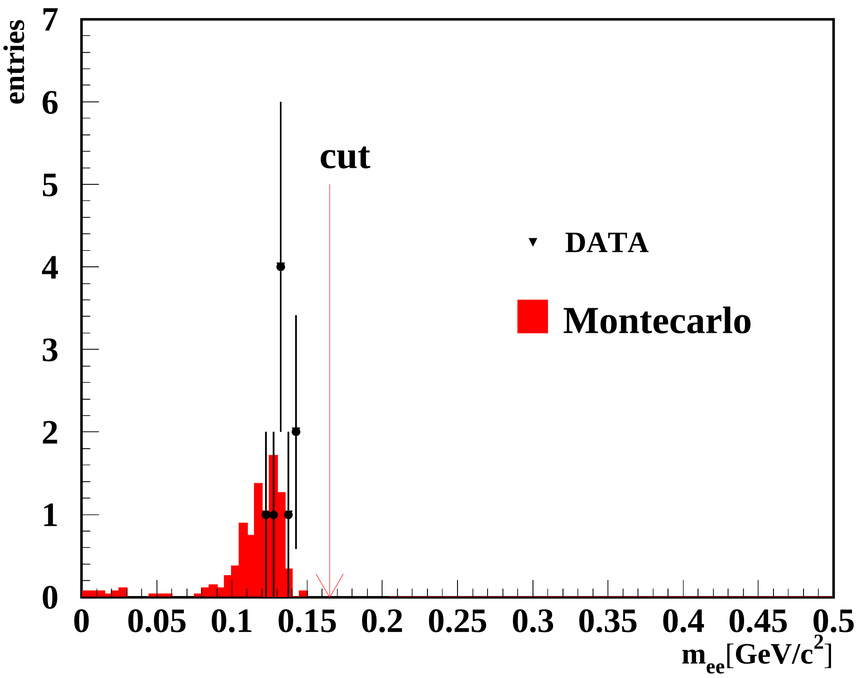
Background from $K_S \rightarrow \pi^0 \pi^0_D$

- One lost photon from the π^0 Dalitz decay
- Generated 6×10^7 $K_S \rightarrow \pi^0 \pi^0_D \rightarrow \pi^0 e^+ e^- \gamma$
- $m_{ee} > 0.165$ GeV/c^2

$\Rightarrow$ < 0.07 background events expected

Other backgrounds

- $K_{S,L} \rightarrow e^+ e^- \gamma\gamma \Rightarrow$ negligible
- $K_S \rightarrow \pi^0 \pi^0_{DD}$ with lost $e^+ e^-$ $\Rightarrow$ negligible



No events in the signal region

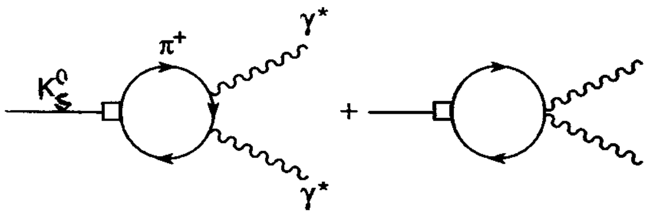
Assuming from χPT: $f_V(z) \sim 1 + z/r_V^2$, r_V^2=2.5

$\boxed{BR(K_S \rightarrow \pi^0 e^+ e^-) < 1.4 \times 10^{-7} \text{ 90 \% CL}}$

$K_S \to \gamma\gamma$

Physics motivation

- This decay is interesting because it is calculable in χPT with no counter-terms and it is sensitive to loops



- Theory: $BR(K_S \to \gamma\gamma) = (2.3 \pm 0.2) \times 10^{-6}$
- NA31: $BR(K_S \to \gamma\gamma) = (2.4 \pm 0.9) \times 10^{-6}$

Experimental technique

- 1999 High intensity KS data with dedicated trigger ($\epsilon_{trigger} > 99\%$)
- The same number of K_S and K_L is produced at the target. The $K_L \to \gamma\gamma$ events must be subtracted.
- The flux is measured using $K_S \to 2\pi^0$ and $K_L \to 3\pi^0$ decays.

$K_S \to \gamma\gamma$

Event Selection

- $3\ \text{GeV} \leq E_\gamma \leq 100\ \text{GeV}$
- $60\ \text{GeV} \leq E_K \leq 170\ \text{GeV}$
- $COG = \sqrt{COG_x^2 + COG_y^2} < 7\ \text{cm}$
- No extra photon ($E > 1.5$ GeV) within 3ns from the event
- No hits in the Drift Chambers and in the AKL
- Energy in the hadronic calorimeter $<$ 3 GeV

Normalisation

- $7.5 \times 10^6\ 2\pi^0$ (Down-scale 100)
- acceptance $\simeq 22\%$ (49% for $K_S \to \gamma\gamma$)

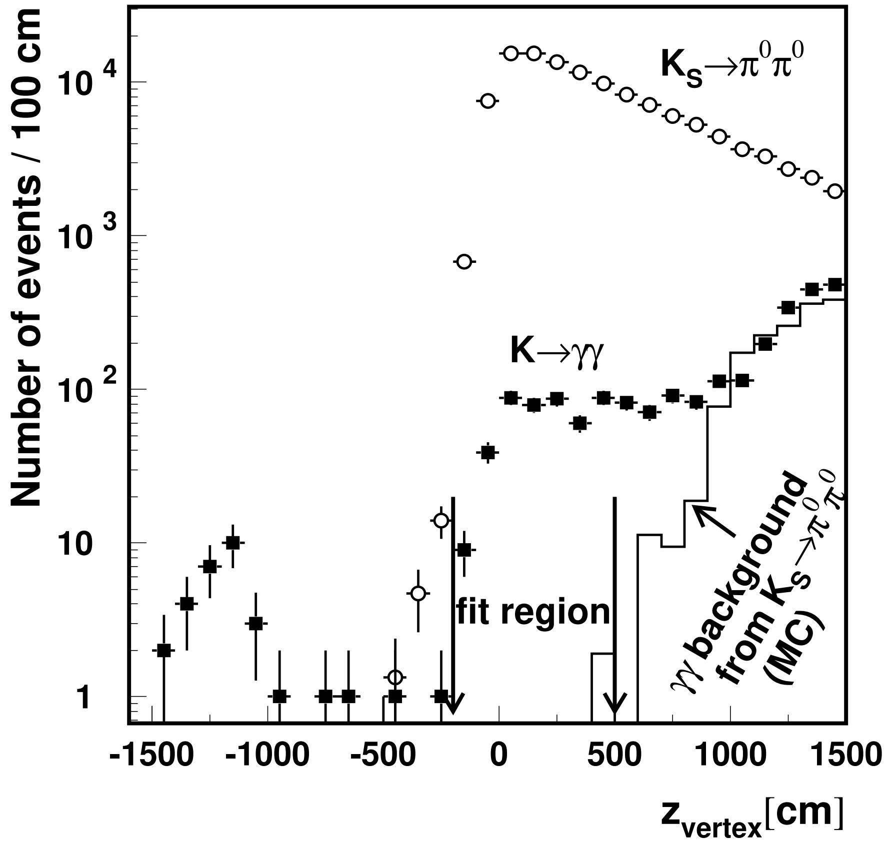
Background evaluation

- $\Lambda \to n\pi^0$ background estimated from high COG tails and suppressed by E_{HAC} <3 GeV and a cut on shower width: 11 ± 8 events.
- $K_L \to \gamma\gamma$ $(BR \times 10^4 = 5.86 \pm .15)$
  A likelihood function (11 Kaon energies and 7 longitudinal vertex positions) is maximised to extract $N(K_S \to \gamma\gamma)$ and consequently $BR(K_S \to \gamma\gamma)$

$K_S \to \gamma\gamma$

Background from $K_S \to 2\pi^0$: 2 ± 2 events

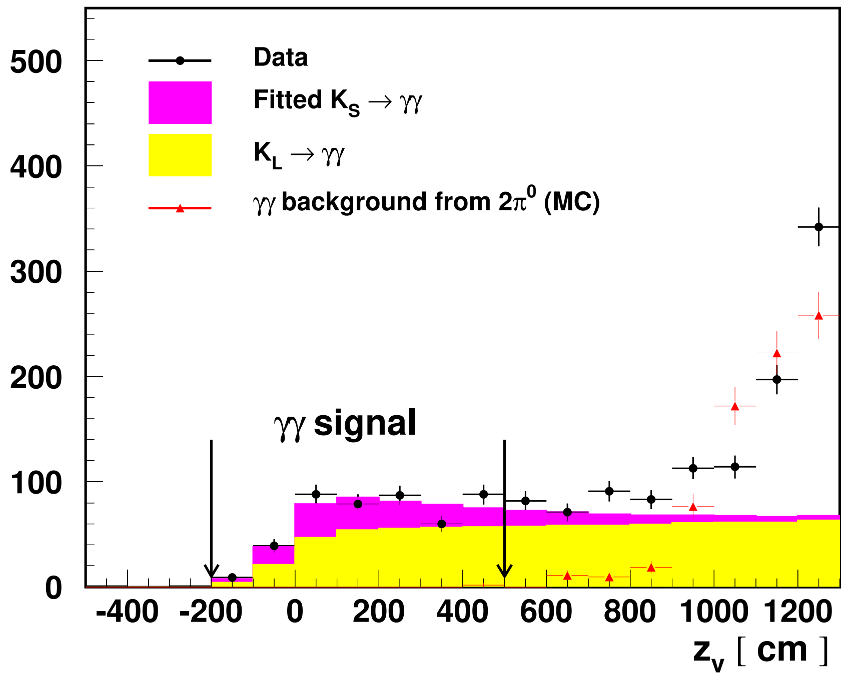
The maximum $m_{\gamma\gamma}$ from a $K_S \to \pi^0\,\pi^0$ decay is $458\ \mathrm{MeV/c^2}$ $\Rightarrow$ the reconstructed vertex for $\pi^0\pi^0$ decay with two lost photons is shifted downstream by at least 9 m



- 10^8 simulated $K_S \to 2\pi^0$
- The overlap of showers reduces the background free region to about 5 m

$K_S \to \gamma\gamma$

- 450 $K \to \gamma\gamma$ events
- $149 \pm 21 K \to \gamma\gamma$ candidates
- The systematic error comes from the uncertainty on:
  - 5% background evaluate
  - 5% $BR(K_L \to \gamma\gamma)$ knowledge
  - 5% trigger and selection cuts
  - 2% acceptance
- NA48 pub PL B493(2000) 29



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

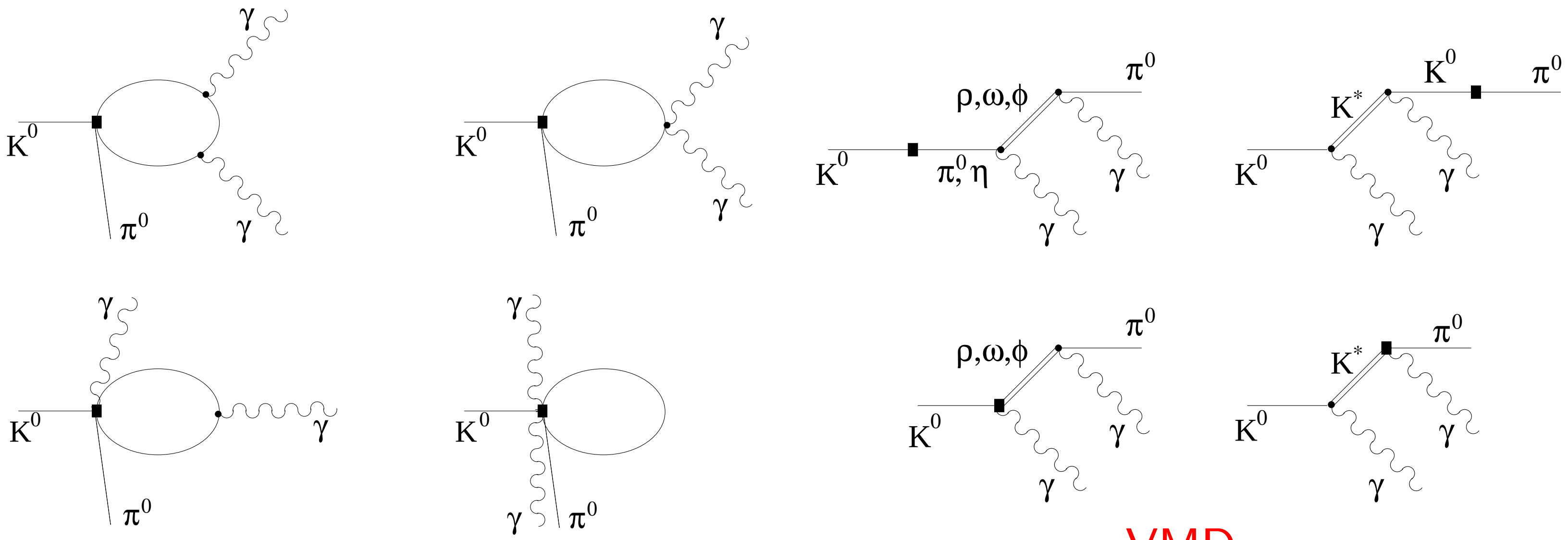
$$R = \frac{\Gamma(K_S \to \gamma\gamma)}{\Gamma(K_L \to \gamma\gamma)} = 2.53 \pm 0.35(stat) \pm 0.22(syst)$$

2000 run: 40 days of run in HIKS mode $\Rightarrow$ increase statistics by $\simeq \times 50$

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

Physics Motivation

- The decay rate is finite at one loop χ PT, but at $O(p^4)$ only 1/3 of the measured rate is predicted.
- $O(p^6)$ calculations including vector mesons exchange can reproduce the rate and predicts a tail at low $m_{\gamma\gamma}$ The VMD contribution is parameterised by a_V, which has to be experimentally determined.

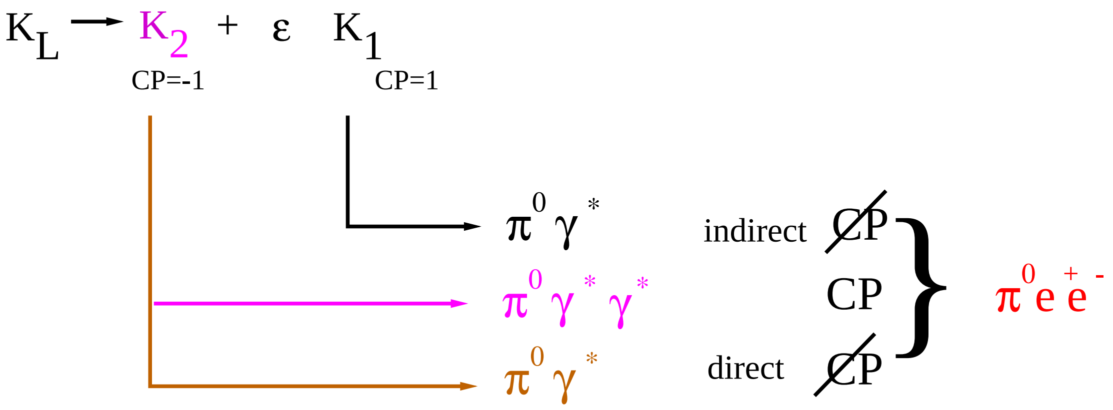


$O(p^4)$ VMD

- KTEV: $BR(K_L \to \pi^0\gamma\gamma) = (1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$
  $a_V = -0.72 \pm 0.05 \pm 0.06$ (PRL 83, 917 (1999))

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

- The a_V contribution leads to a CP conserving component to $K_L \to \pi^0 e^+ e^-$, e.g.:
  $BR(K_L \to \pi^0 e^+ e^-)_{CPC} = 1.24 \times 10^{-12}$ for $a_V = -0.7$[a]



The CP conserving contribution J=0 state is elicity-suppressed

The VMD mechanism could enhance the state J=2 for the two photons

$\Rightarrow$ sizeable CP conserving contribution for $K_L \to \pi^0 e^+ e^-$.

[a] G. D'Ambrosio, J. Portolés, NP B492 417

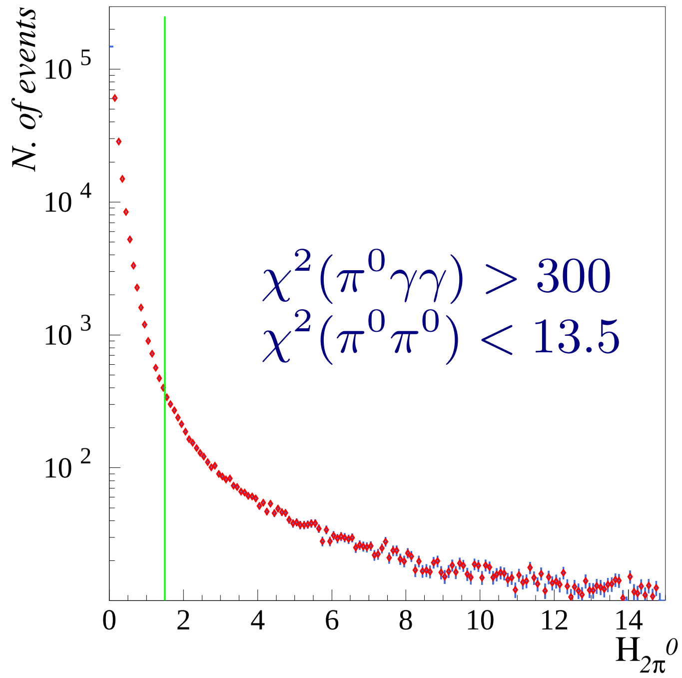
$K_{\mathrm{L}} \to \pi^0\gamma\gamma$

Rare process without a clear signature but a very high background

- Normalisation channel: $K_{\mathrm{L}} \to \pi^0\pi^0$
  In the ratio $K_{\mathrm{L}} \to \pi^0\gamma\gamma$ over $K_{\mathrm{L}} \to \pi^0\pi^0$ most of the systematic uncertainties cancel.
- Trigger Selection
  same as for $\mathrm{Re}(\varepsilon'/\varepsilon)$ neutral $\pi^0\pi^0$ decays):
  $E_{\mathrm{LKr}} > 50$ GeV, $COG < 15$ cm, t $< 5.5\ c\tau_{\mathrm{S}}$,
  $<$ 6 peaks in each LKr projection.
  $\Rightarrow \quad \epsilon_{trig} > 99.9\%$
- Event Selection Event quality
  - Select K_{L} from the tagger (i.e. use 2 ns coincidence window)
  - Four clusters in time and within the LKr acceptance
  - $E_\gamma > 3$ GeV
  - $70 < E_K < 170$ GeV
- Background sources
  - $K_{\mathrm{S}} \to \pi^0\pi^0$ residual background evaluated from the tagged $K_{\mathrm{S}} \to \pi^0\pi^0$
  - $K_{\mathrm{L}} \to \pi^0\pi^0\pi^0$ residual background evaluated from a MC sample of 3×10^9 $K_{\mathrm{L}} \to \pi^0\pi^0\pi^0$
  - pile-up events evaluated from the tails of the R_{COG} distribution and from the events with cluster out-of-time.

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

- Background rejection: $2\pi^0$ events.
  $K_L \to \pi^0\pi^0$ decays mis-reconstructed and/or γ conversion in the spectrometer could spoil one of the π^0 mass.
- It concentrates in the most interesting region of low $m_{3,4}$ value where the signal is lower
  - from $3 \times \gamma\gamma$ combinations we compute a χ^2



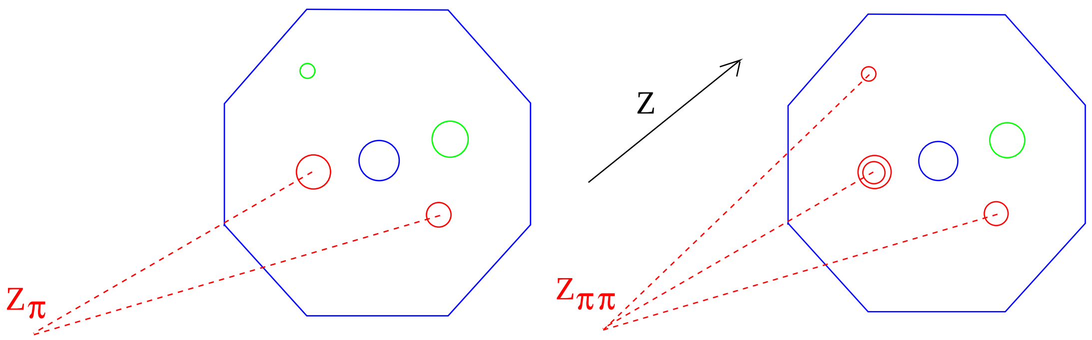
  - $|m_{1,2} - m_{\pi^0}| < 3$ MeV and $m_{3,4}$ not in the $[110 - 160]$ Mev/c^2 range.
  - DCH in veto (conversions and Dalitz decays)
  - $P_{T,4} > 40$ MeV/c with $P_{T,4}$ transverse momentum of the lowest energy γ of the unpaired photons

$\Rightarrow$ Residual background negligible, evaluated from data, using tagged $K_S \to \pi\pi$

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

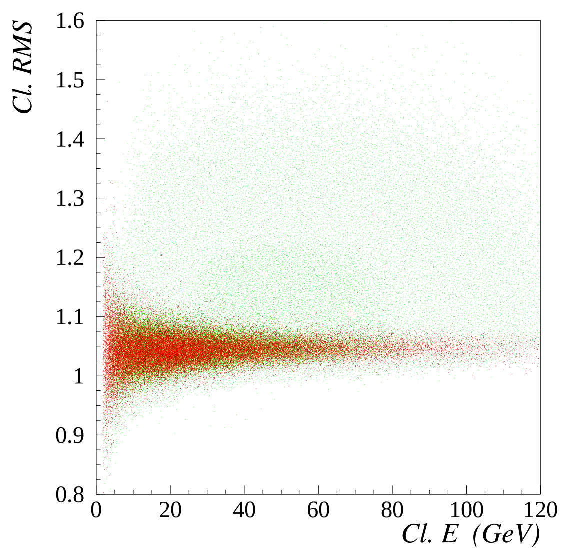
Background source: $K_L \to 3\pi^0$ decays.

- *Missing photons:*
  - Apply Rthe AKL veto
  - missing energy: decay region: $z_K < 3000$ cm and $R_{COG} < 4$ cm
- *Missing and overlapping photons:*
  - Reject events if 2 (3) clusters reconstruct 1 (2) π^0 more than 6 m upstream of the K decay vertex which is wrong in case of a $3\pi^0$ event.
    $\Rightarrow$ cut 99% of the $3\pi^0$ background (but also 49% of the signal).



- *Overlapping photons:*

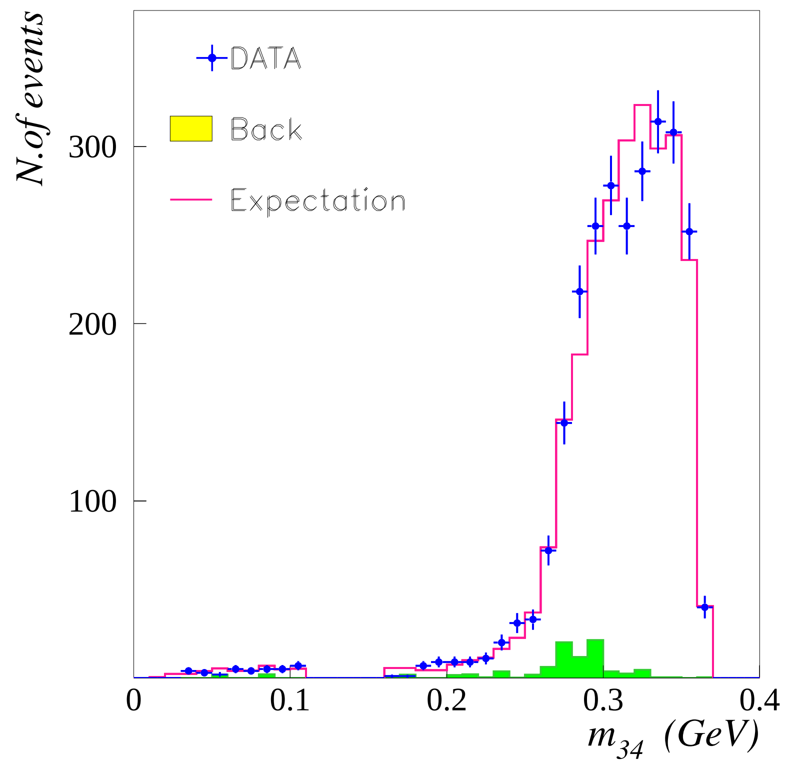
Energy dependent cut on the cluster width against two overlaps of photons

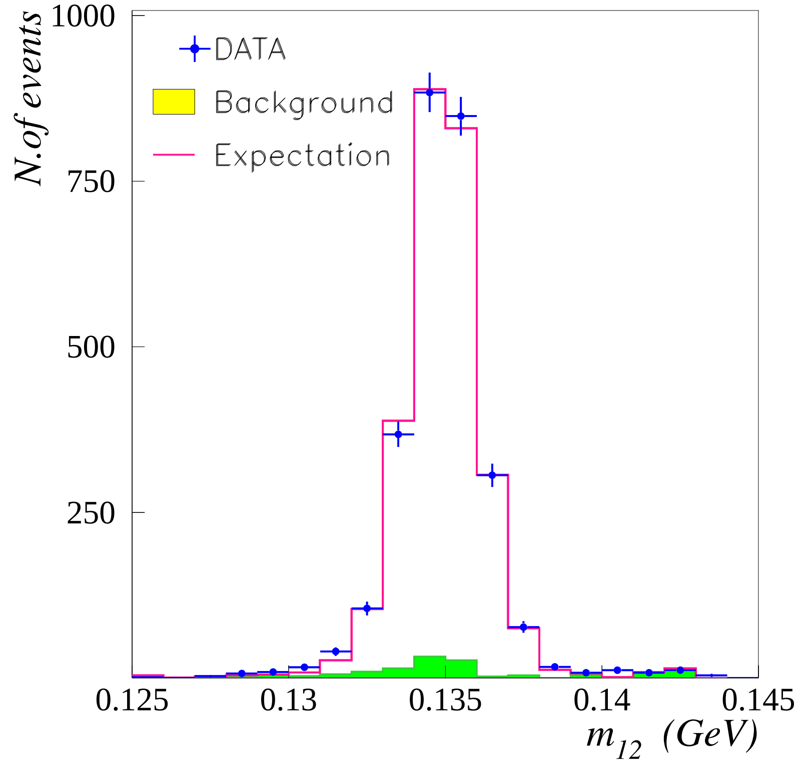


$K_\mathrm{L} \to \pi^0\gamma\gamma$

1998 + 1999 data

$\approx$ 2500 candidates in the signal region $132 < m_{1,2} < 138$ MeV/c2





$m_{\gamma\gamma}$ for the two non-π^0 photons $\qquad$ $m_{\gamma\gamma}$ for the π^0 candidate

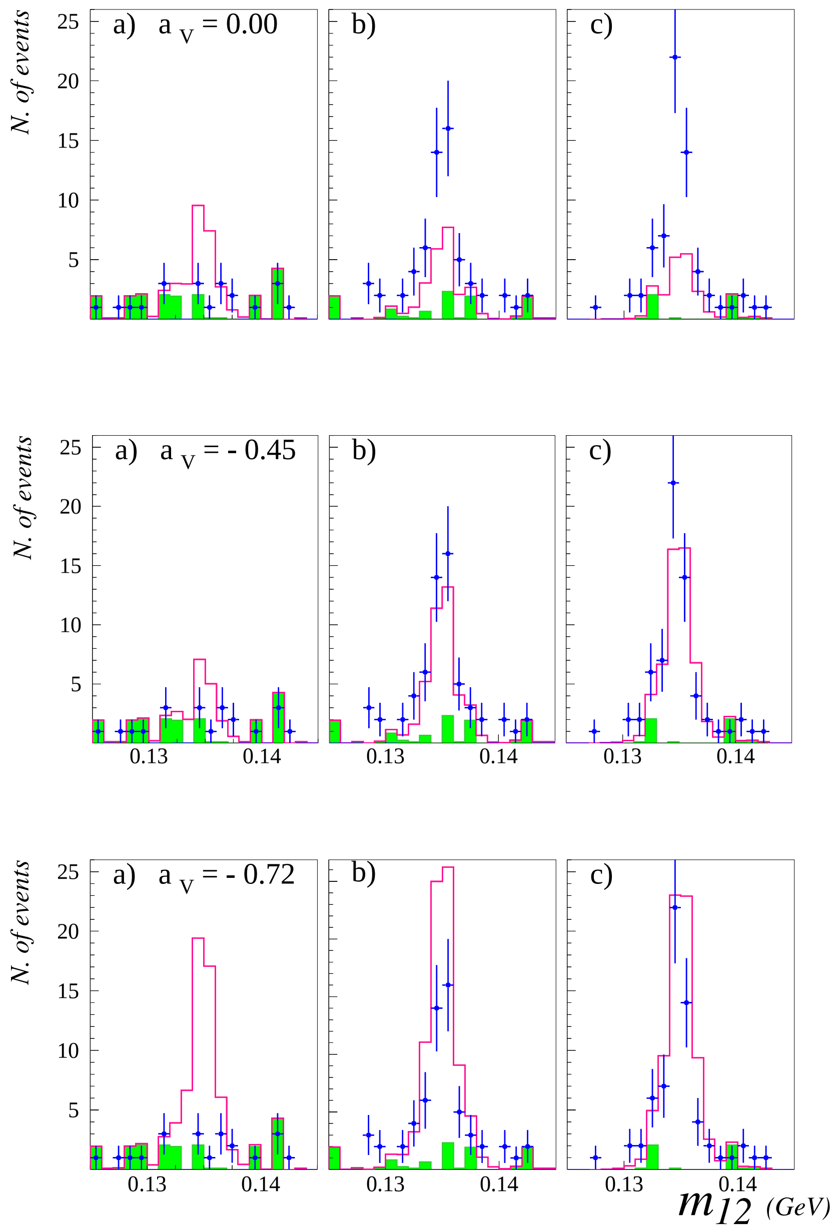
Final result is being prepared. The expected error on the measurement of the BR is $\approx 5\%$

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

Most of the events in the low $m_{3,4}$ mass region are characterised by the wrong combination of γ.
$\Rightarrow$ we exclude the ambiguous events ($\approx 50\%$ of the events in the tail are affected) to extract a_v.

Our sensitivity:

a) $m_{34} \in [30 \div 110]$ b) $m_{34} \in [160 \div 240]$ c) $m_{34} \in [240 \div 260]$



NA48/1

- A program for K_{S} rare decay and neutral hyperon search in the year 2002 has been approved by the CERN Research Board (CERN SPSC 2000-002).

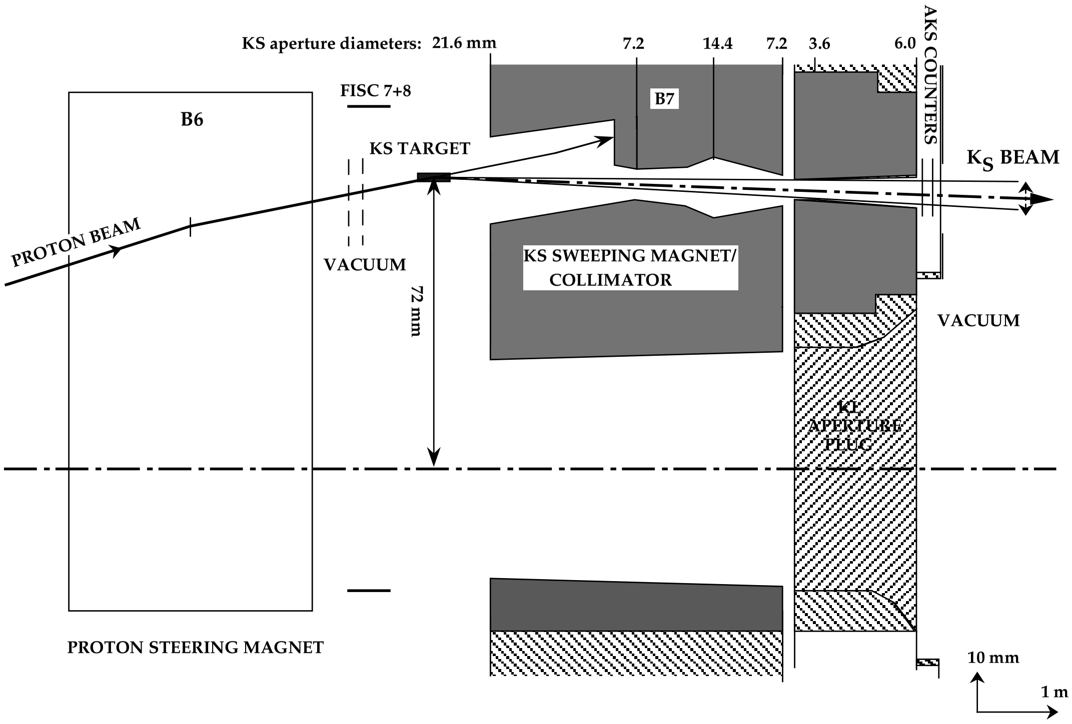
- the magnet spectrometer is being restored

- a new drift chamber readout and an optimised collimator should significantly improve the proposed sensitivity.

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

NA48/1

Detail of the K_S target station



SPS momentum (GeV/c)	400 GeV/c
Duty Cycle	5.2 sec/16.8 sec
Protons per pulse on target	1×10^{10}
Production angle	-2.5 mrad
Total kaon flux/pulse	$\sim 1.5\times10^{5}$
K-decays (40-240 GeV)/pulse	1.1×10^{5}
K-decays (40-240 GeV)/year ($\frac{1}{2} \times 120$ days)	3.0×10^{10}

With respect to NA48:

- Additional sweeping magnet
- Removable lead converter
- No K_S veto counter

NA48/1

K_S Physics program

Decay	Theory	Events in NA48/1
Non-Leptonic decays (χPT)		
$K_S \rightarrow \gamma\gamma$	2.1×10^{-6}	24000
$K_S \rightarrow \pi^0\gamma\gamma$	3.8×10^{-8}	114
$K_S \rightarrow \pi^0\pi^0\gamma\gamma$	5.6×10^{-9}	7
Dalitz decays ($\gamma\gamma^*$)		
$K_S \rightarrow \gamma e^+e^-$	3.4×10^{-8}	304
$K_S \rightarrow \gamma\mu^+\mu^-$	8×10^{-10}	12
$K \rightarrow \pi l^+l^-$		
$K_S \rightarrow \pi^0 e^+e^-$	5×10^{-9}	7
$K_S \rightarrow \pi^0\mu^+\mu^-$	1×10^{-9}	3
$K_S \rightarrow \pi^+\pi^-\gamma(\gamma^*)$		
$K_S \rightarrow \pi^+\pi^-\gamma$	1.8×10^{-3}	5.3×10^6
$K_S \rightarrow \pi^+\pi^-e^+e^-$	3.6×10^{-5}	5.4×10^4
$K \rightarrow 3\pi$		
$K \rightarrow \pi^+\pi^-\pi^0$		$2.6 \times 10^6/\tau_S$
$K \rightarrow \pi^0\pi^0\pi^0$		$1.5 \times 10^6/\tau_S$

Conclusions

- The NA48 rare decays program is providing interesting physics results in the field of the χPT and of the CP violation in the neutral Kaon sector
  - the CP violation asymmetry in $K_{\mathrm{L}} \rightarrow \pi^+ \pi^- e^+ e^-$ has been measured
  - the result of $K_{\mathrm{L}} \rightarrow \pi^0\gamma\gamma$ is in preparation

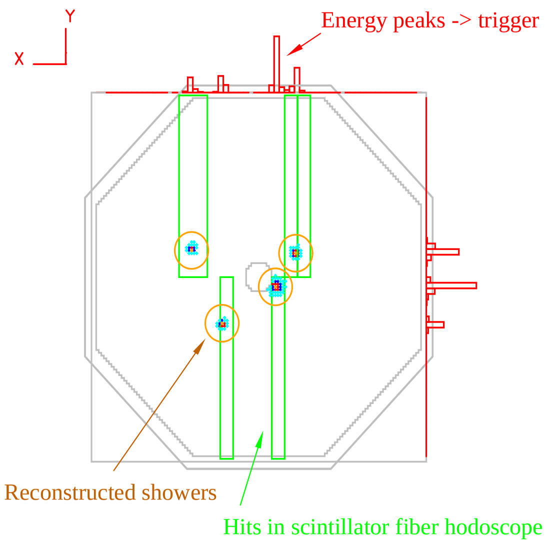
- With 2 days of High-Intensity KS data-taking:
  - we improved by a factor ≈ 10 the limit of $K_{\mathrm{S}} \rightarrow \pi^0 e^+ e^-$
  - we have the best measurement of $BR(K_{\mathrm{S}} \rightarrow \gamma\gamma)$ and $BR(K_{\mathrm{S}} \rightarrow \pi^+ \pi^- e^+ e^-)$

- we look forward for the 2002 HIKS data taking

Triggers

Neutral trigger

- 40 MHz fully pipelined system based on LKr information from 64 vertical and 64 horizontal projections to compute number of peaks, energy, centre of gravity and lifetime.
- Output rate $\approx$ 2 KHz with negligible dead time.
- Used for:
  $\gamma\gamma, e^+e^-\gamma, e^+e^-\gamma\gamma, \pi^0\gamma\gamma, \pi^0 e^+e^-, \pi^0\pi^0\pi^0 \ldots$



Charged trigger

- **Level I** Total Energy, DCH1 track multiplicity and Charged Hodoscope.
- **Level II** ϵ'/ϵ trigger used as 2 tracks or $\geq$3 tracks vertex finder.
- Used for:
  $\mu\mu\gamma, K_{e4}, e^+e^-e^+e^-, e^+e^-\mu^+\mu^-, \pi^+\pi^- e^+ e^- \ldots$