Direct CP violation and K_S /K_L rare decays from experiment NA48 at CERN

Augusto Ceccucci
CERN

January 11, 2001
Aspen Winter Workshop January 7-13, 2001

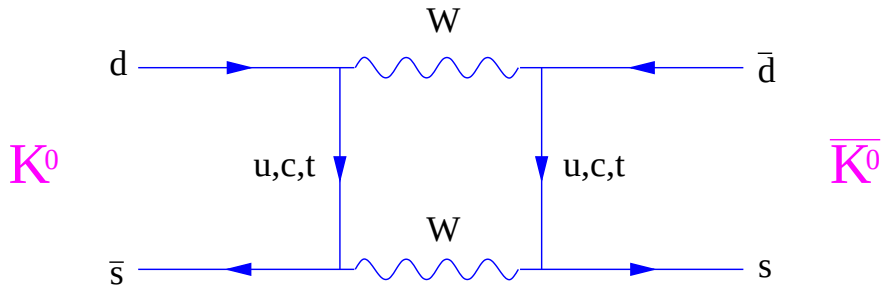
PARTICLE PHYSICS AT THE MILLENNIUM

On behalf of the NA48 Collaboration:
Cagliari Cambridge CERN Dubna Edinburgh Ferrara
Firenze Mainz Orsay Perugia Pisa Saclay Siegen Torino
Vienna Warsaw

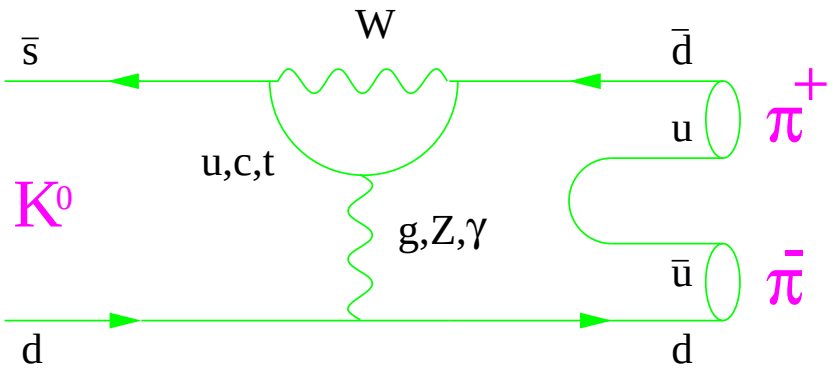
- Preliminary $\mathrm{Re}(\varepsilon'/\varepsilon)$ from 1998 sample
- Selected K_S /K_L rare decay results
- Prospects

Physics motivation

$\varepsilon \sim 2.28 \times 10^{-3} \Rightarrow$ Indirect CP violation via $K^0/\overline{K^0}$ mixing



$$K_L = K_2^{-1} + \varepsilon\, K_1^{+1} \qquad \underbrace{\pi^+\pi^-,\ \pi^0\pi^0}_{CP=+1}$$

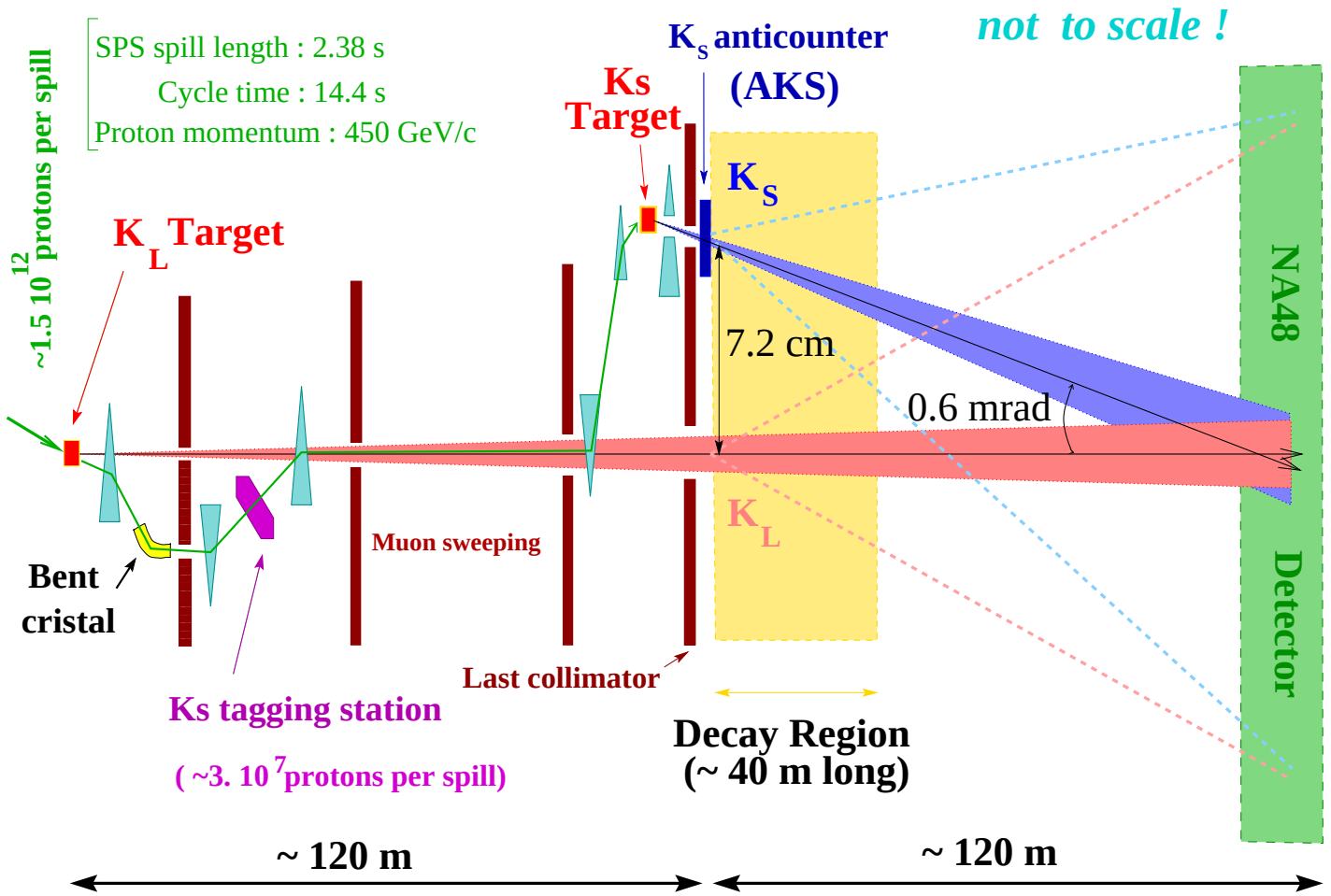


$$\varepsilon' = \frac{i}{\sqrt{2}} \mathfrak{Im} \frac{A_2}{A_0} \exp(i(\delta_2 - \delta_0))$$

$$\mathrm{Re}(\varepsilon'/\varepsilon) \simeq 1/6(1-R)$$

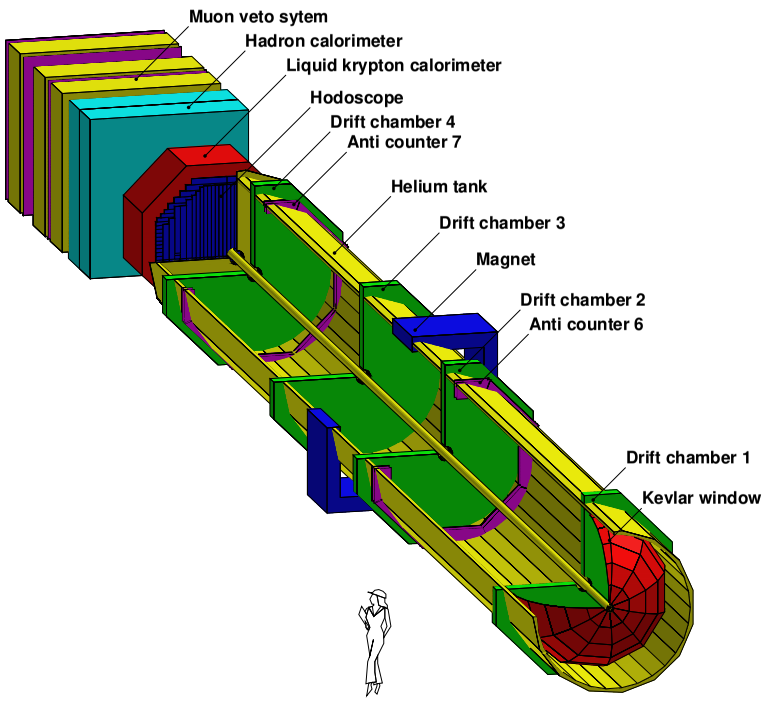
$$R = \frac{\Gamma(K_L \to 2\pi^0)}{\Gamma(K_S \to 2\pi^0)} \Big/ \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}$$

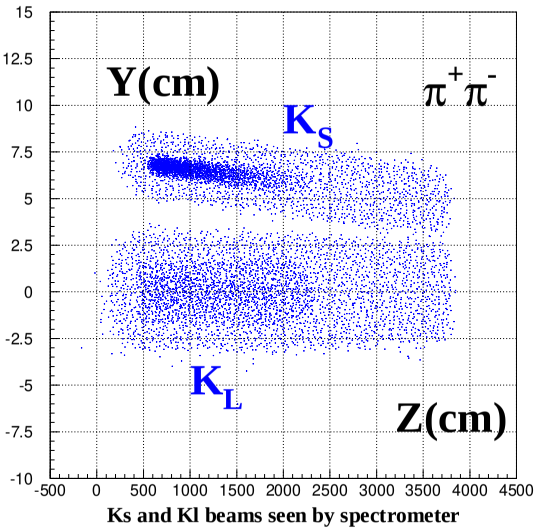
NA48 method: simultaneous K_L and K_S beams



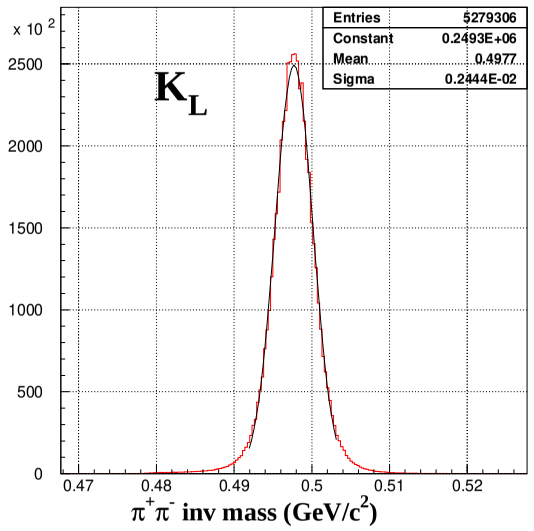
- K_S are distinguished from K_L by tagging the protons upstream of the K_S target
- NA48 detects all four modes from the same decay region

NA48 magnet spectrometer





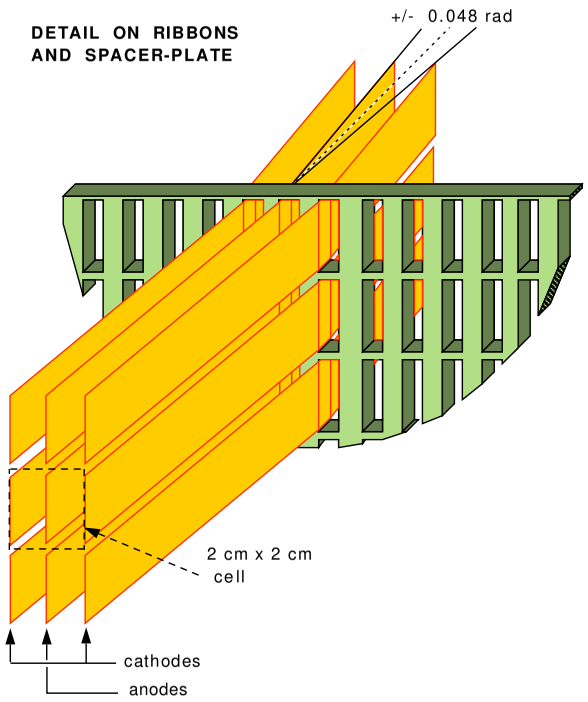
Vertex reconstruction
allows beam separation



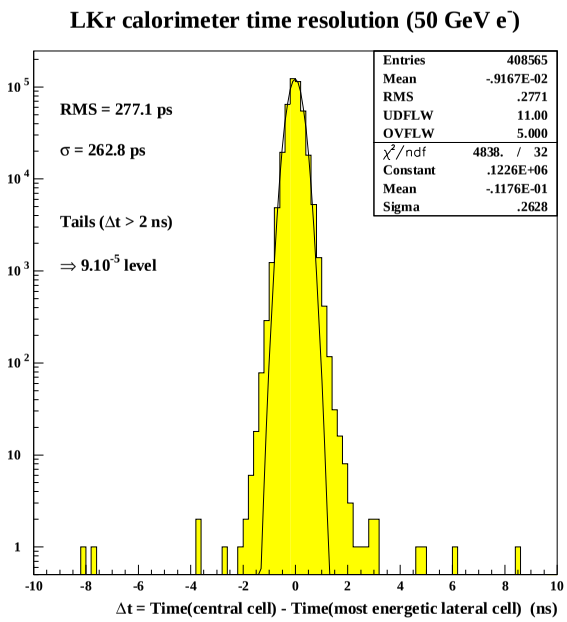
Kaon mass resolution
$\sim$2.5 MeV/c^2

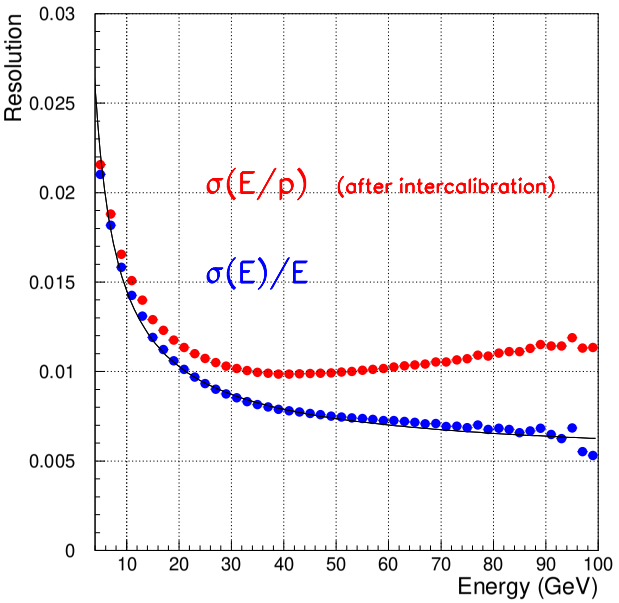
$$\sigma(p)/p \simeq 0.5\,\% \oplus 0.009\,p[\mathrm{GeV}/c]\,\%$$

NA48 Liquid Krypton calorimeter



- Made of $\approx 9m^3$ LKr
- Cu-Be electrodes
- bias HV: $+3$ KV/cm
- 2cm$\times$2cm$\times$127cm
- $\sim$13000 towers
- Electrodes: $\pm$ 48mrad zig-zag in each spacer
- Geometry controlled to $\approx$0.2mm/1m





$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{100MeV}{E} \oplus 0.5\%$$

Data sample

- 1997 : 89 days, 1×10^{12} ppp on $K_{\rm L}$ target

  $\Rightarrow$ 0.49 million of $K_L \to \pi^0\pi^0$

  PUBLISHED Phys. Lett. B 465 (1999)

  $\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$

- 1998 : 135 days, $\sim 1.4 \times 10^{12}$ ppp on $K_{\rm L}$ target

  Main improvements :

  - LKr High Voltage 1500 $\to$ 3000 V
  - Charged trigger efficiency 91.3 $\to$ 97.7 %
  - Carbon fibre pipe $\to$ less showers in the detectors
  - New data acquisition system (PC farm) + 30 % rate

  $\Rightarrow$ 1.14 million of $K_L \to \pi^0\pi^0$

  $\Rightarrow$ four-fold increase of $\pi^+\pi^-$

- 1999 : 128 days, $\sim 1.4 \times 10^{12}$ ppp on $K_{\rm L}$ target

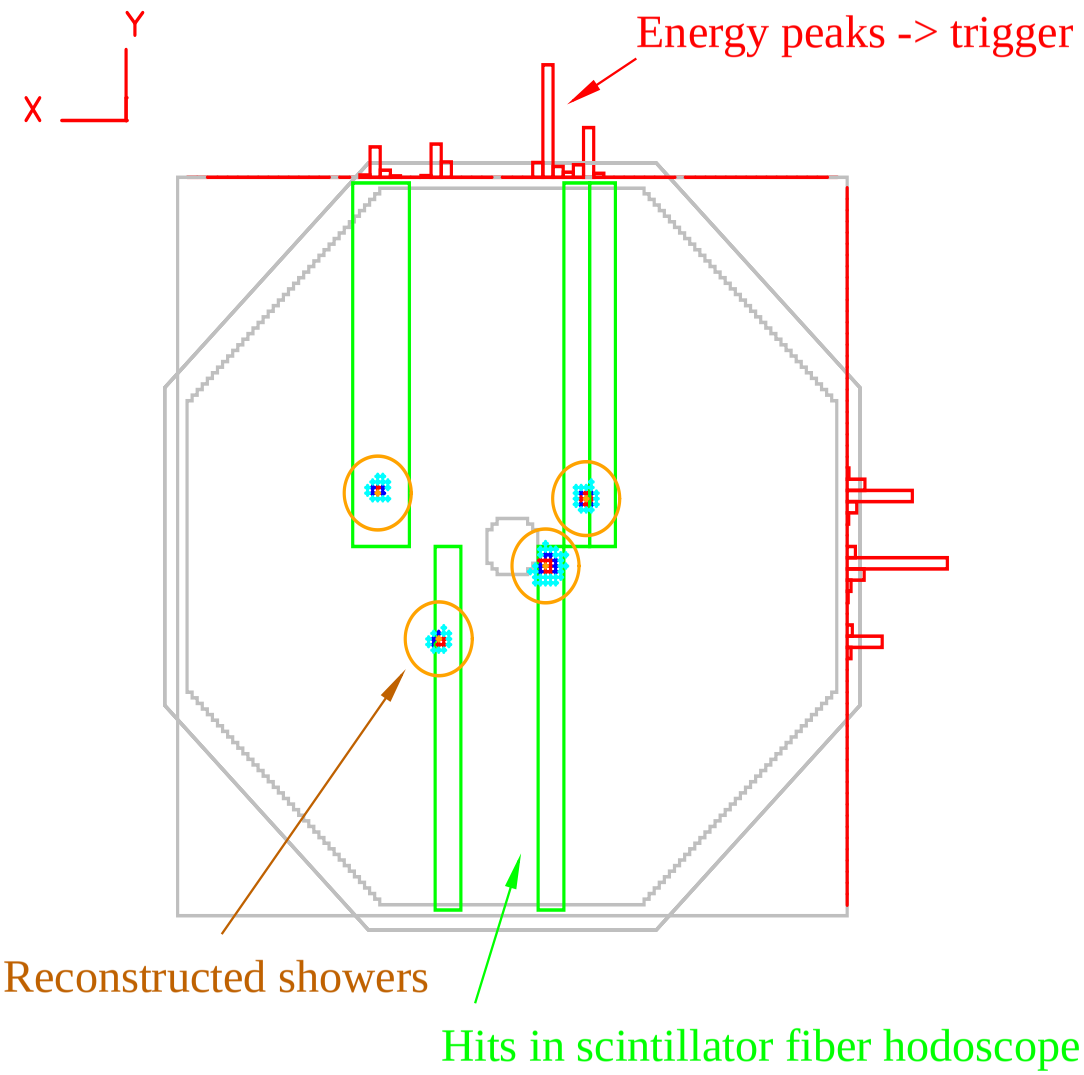
  Further improvements :

  - DCh read-out, dead time, DAQ efficiency, spill length

  $\Rightarrow$ Around 2 million of $K_L \to \pi^0\pi^0$

  ANALYSIS in progress...

Trigger $\pi^0\pi^0$



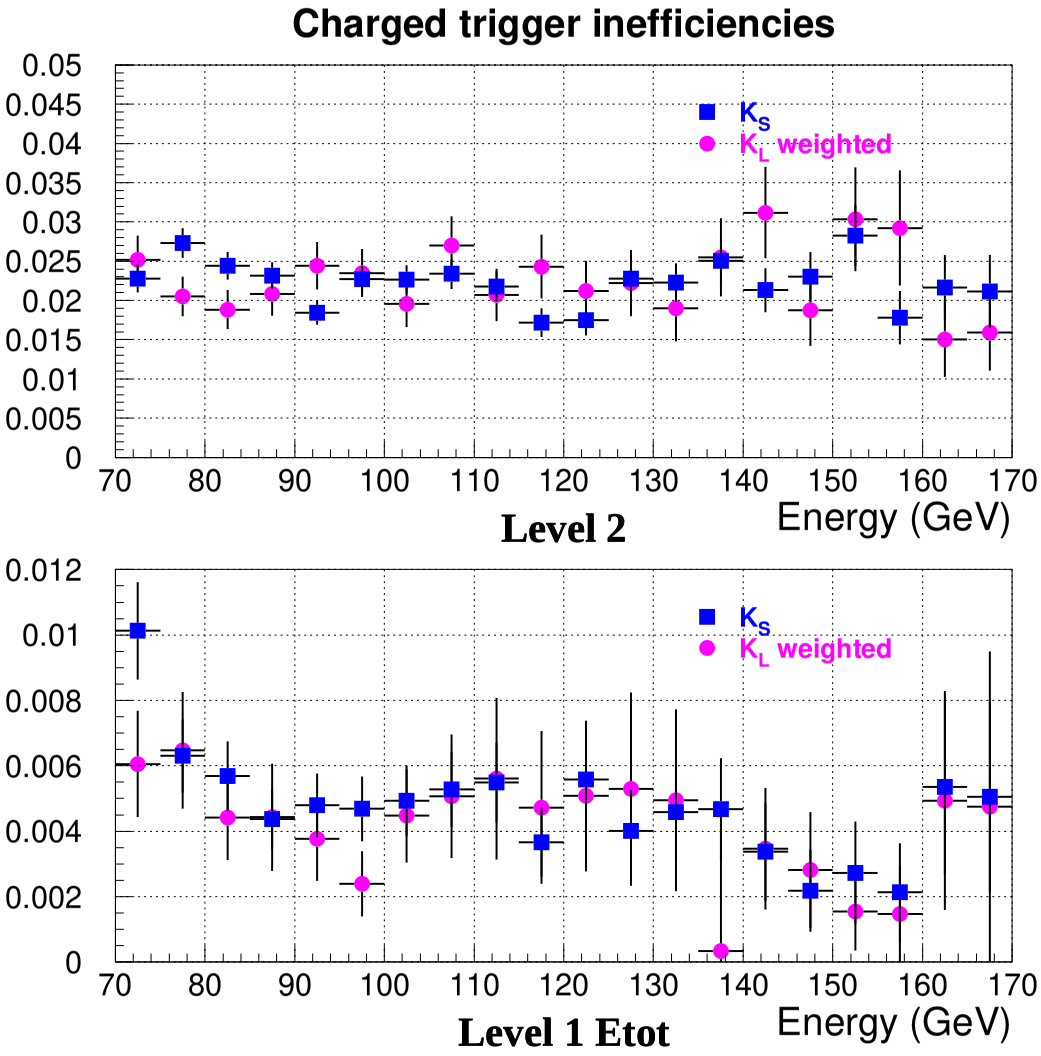
- $E_K > 50\text{GeV}$
- $C.O.G. < 15\text{cm}$
- $t < 4.5\ c\tau_S$
- < 6 peaks/projection

Efficiency: 99.93 $\pm$ 0.02 %

Control trigger provided by SCIFI hodoscope embedded in LKr

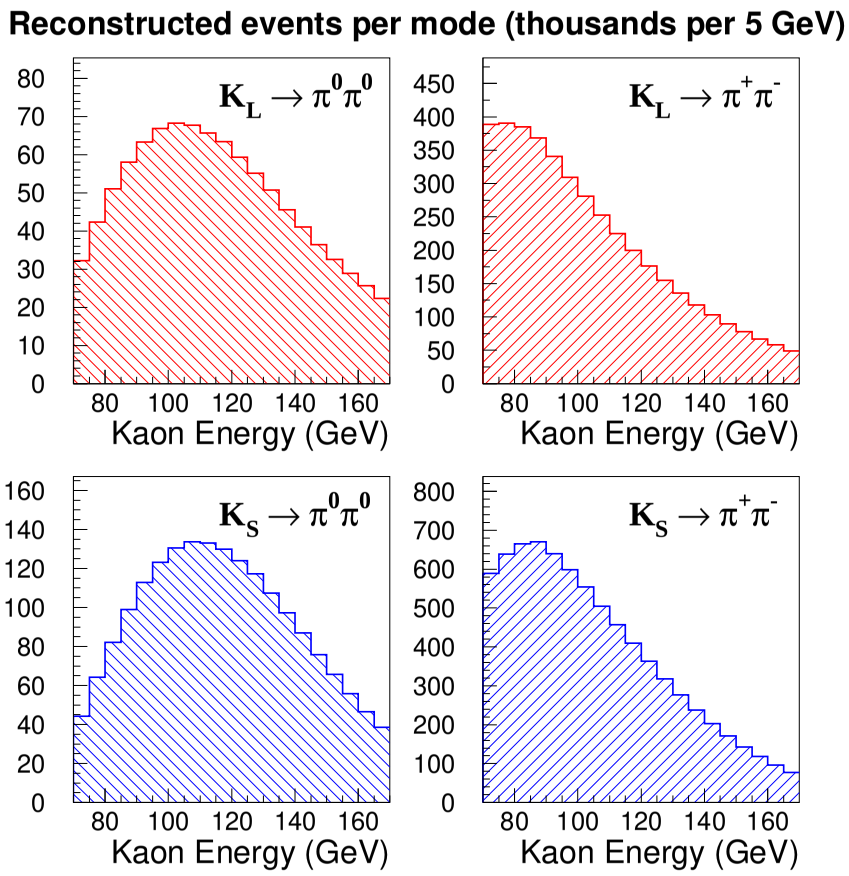
Trigger $\pi^+\pi^-$

- Level 1 :
  + Energy in calorimeters > 35 GeV
  + Two track topology in hodoscope
  + Two track multiplicity in chamber 1
- level 2 : on-line processing of vertices and $\pi\pi$ invariant mass



Analysis cuts

- $70 < E_{\rm K} < 170$ GeV
- Centre of Gravity $(R_{\rm cog}) < 10$ cm
- Decay region: $0 < t < 3.5\tau_{\rm S}$. For $K_{\rm S}$ the upstream cut (t >0) is done requiring no hits in the anti-counter placed on the $K_{\rm S}$ beam

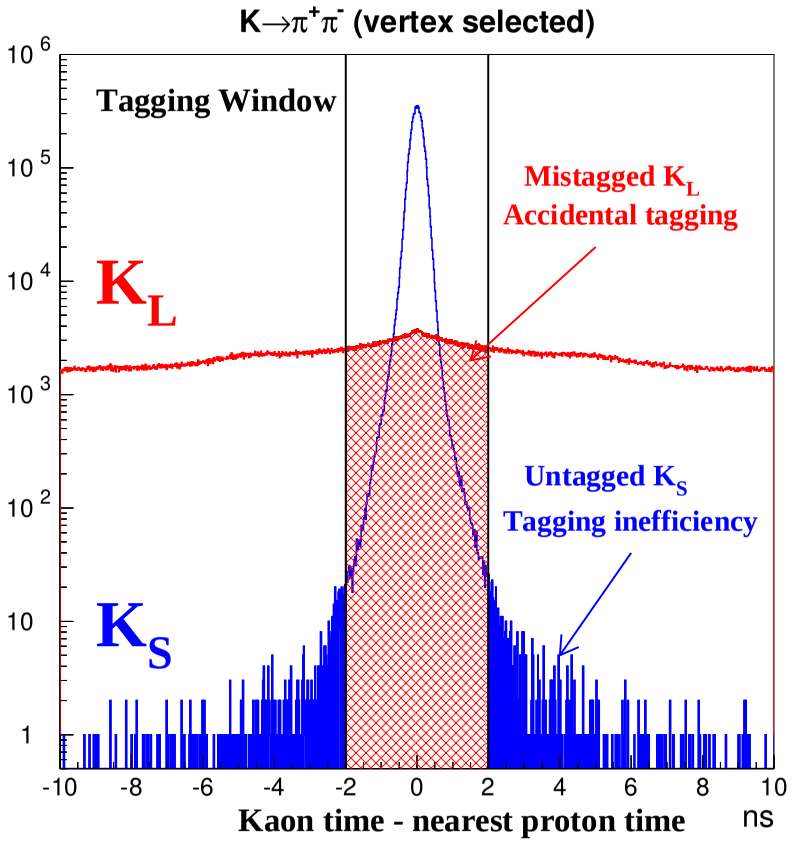


- Cut on dead time (<5 % from charged trigger and $\approx$ 25 % from DCH read out)
- All corrections are applied in bins of energy, to account for the slight difference in the spectra of $K_{\rm S}$ and $K_{\rm L}$

NA48 method: K_S tagger

T.O.F. between a reconstructed Kaon decay and the tagger:

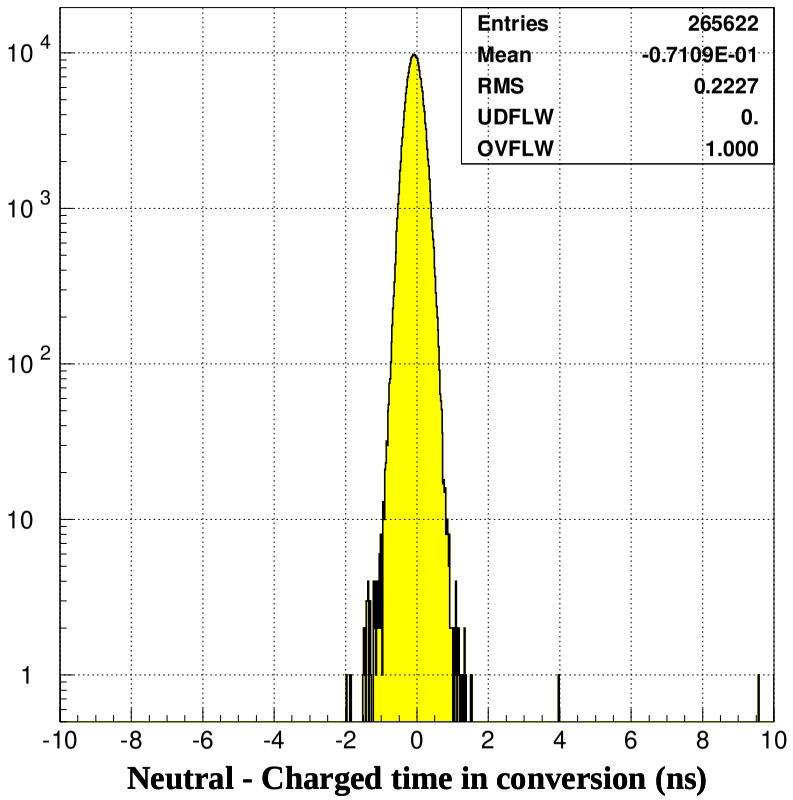
$$|t_K - t_{tagger}| < 2ns \Rightarrow K_S$$
$$|t_K - t_{tagger}| > 2ns \Rightarrow K_L$$



- tagging inefficiency: $K_S \Rightarrow K_L$
  The sensitivity comes from asymmetric tails in the detector time distributions:
  $$\Delta R \simeq 6 \times \Delta\alpha_{SL} = \pm 3 \times 10^{-4}$$
- mistagging probability: $K_L \Rightarrow K_S$
  $$\Delta R \simeq 2 \times \Delta\alpha_{LS} = (1 \pm 8) \times 10^{-4}$$

Tagging Inefficiency

- The *Tagger* contribution dominates the small inefficiency and is symmetric for $\pi^0\pi^0/\pi^+\pi^-$
- Comparison of hodoscope and LKr times in $K_{\rm L}$ and $K_{\rm S}$ events ($3\pi^0$ and $2\pi^0$) containing a conversion

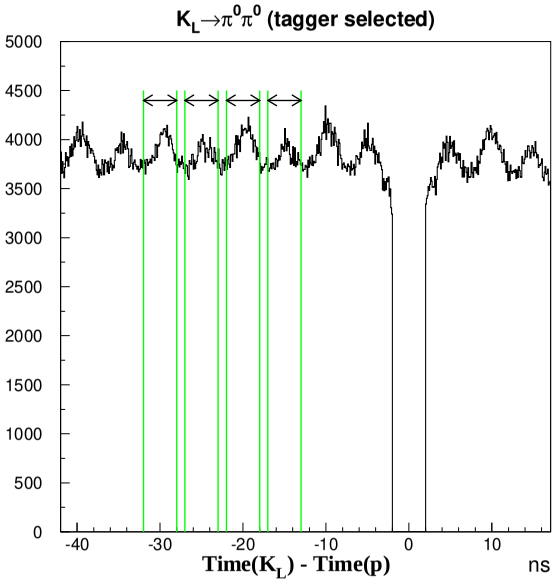


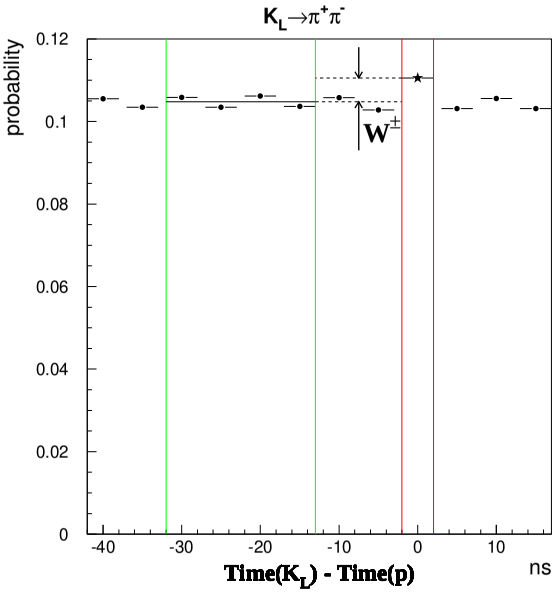
$$|\alpha_{SL}^{+-} - \alpha_{SL}^{00}| < 0.5 \times 10^{-4}$$

Mistagging probability

$$\Delta\alpha_{\rm LS} = \Delta\beta_{\rm tag} + \Delta {\rm W}$$

- $\Delta\beta_{\rm tag}$
  Untagged $\pi^0\pi^0$ and $\pi^+\pi^-$ are used to measure the mistagging probability in the side bands.
- $\Delta {\rm W}$
  Vertex selected $\pi^+\pi^-$ and $3\pi^0$ are used to measure the difference in mistagging between the side band and the tagging window. Currently the error is dominated by the statistics of reprocessed $3\pi^0$



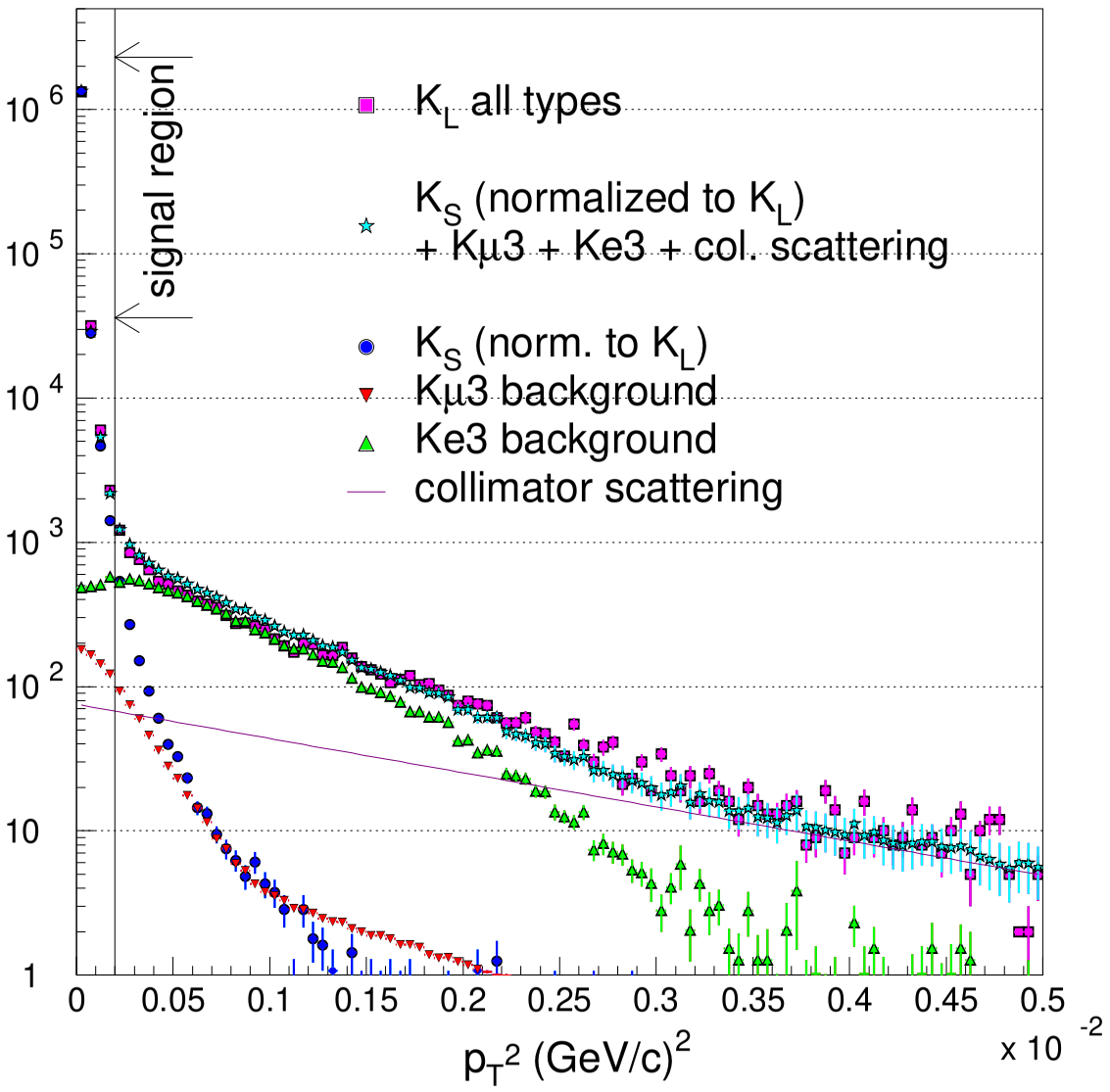


$$\Delta\beta_{\rm tag} = (5.3 \pm 1.6) \times 10^{-4}$$

$$\Delta {\rm W} = (-5.0 \pm 3.9) \times 10^{-4}$$

Background to $\pi^+\pi^-$

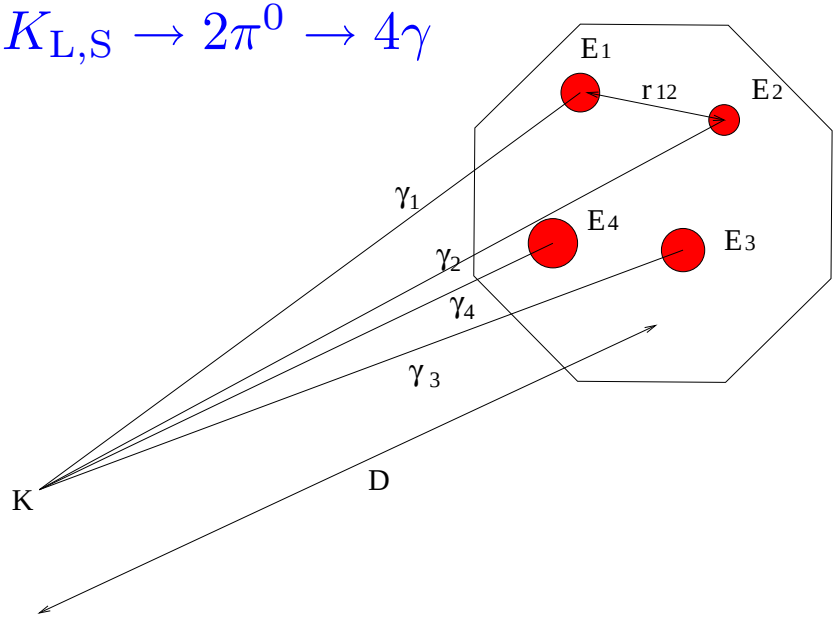
- $E/p < 0.8$
- No hits in the muon counters

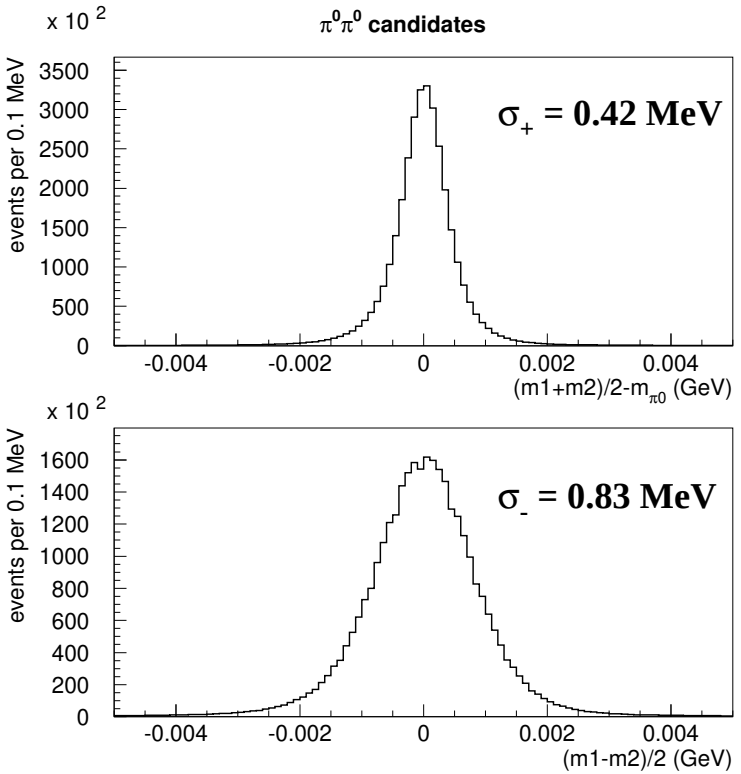


$$\Delta R = (+19 \pm 3) \times 10^{-4}$$

$K^0 \to \pi^0\pi^0$ identification

$K_{L,S} \to 2\pi^0 \to 4\gamma$



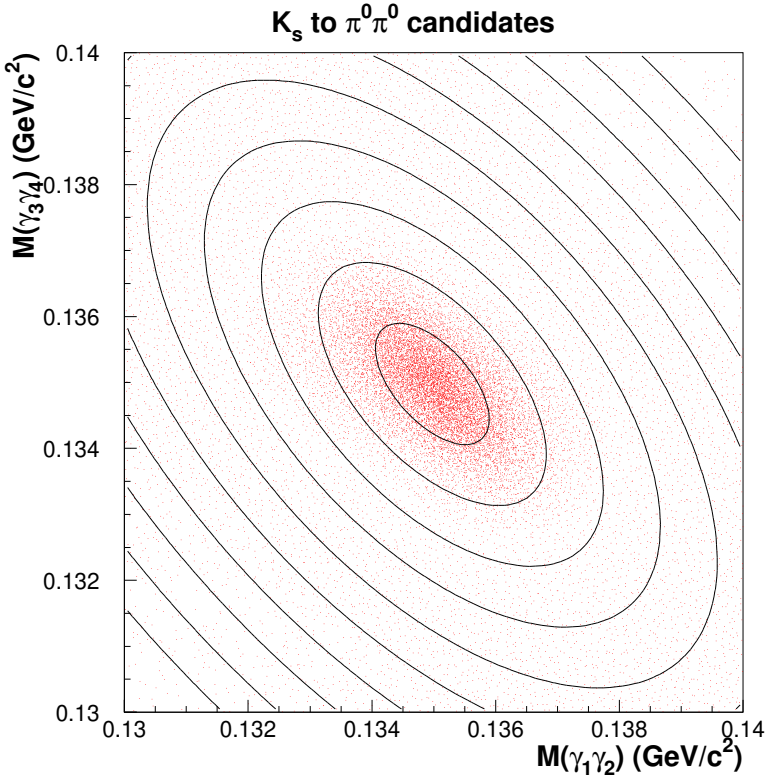


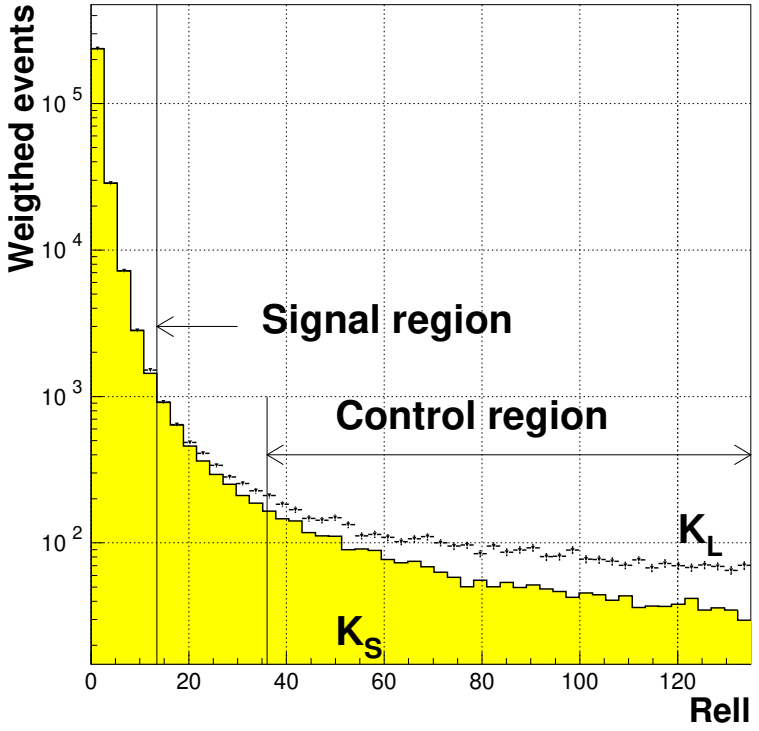
$$D = \sqrt{\sum E_i E_j \times (r_{ij})^2} \; / M_K$$

$$m_{ij} = \sqrt{E_i E_j} \; . \; r_{ij}/D$$

3 π^0 background

- $R_{ell} \equiv \left\{ \left(\frac{\frac{m_1+m_2}{2} - m_{\pi^0}}{\sigma_{\frac{m_1+m_2}{2}}} \right)^2 + \left(\frac{\frac{m_1-m_2}{2}}{\sigma_{\frac{m_1-m_2}{2}}} \right)^2 \right\}$ Signal: $R_{\rm ell} < 13.5$

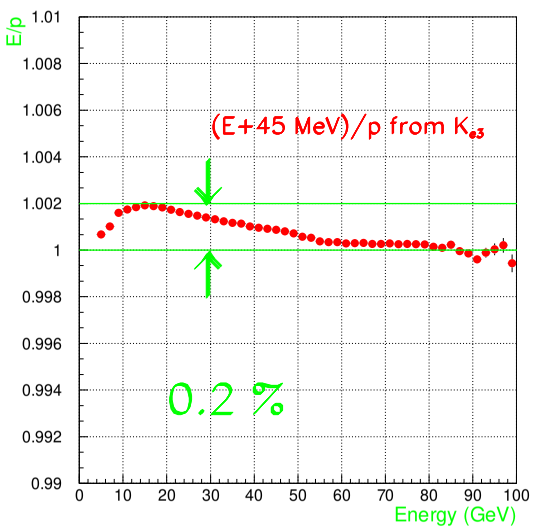


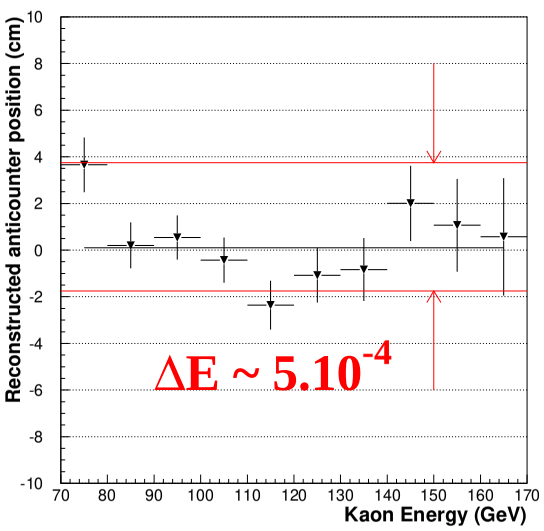


- Cut on in-time extra photons ($\pm$ 3ns)

$$\Delta \mathrm{R} = (-7 \pm 2) \times 10^{-4}$$

Neutral systematics



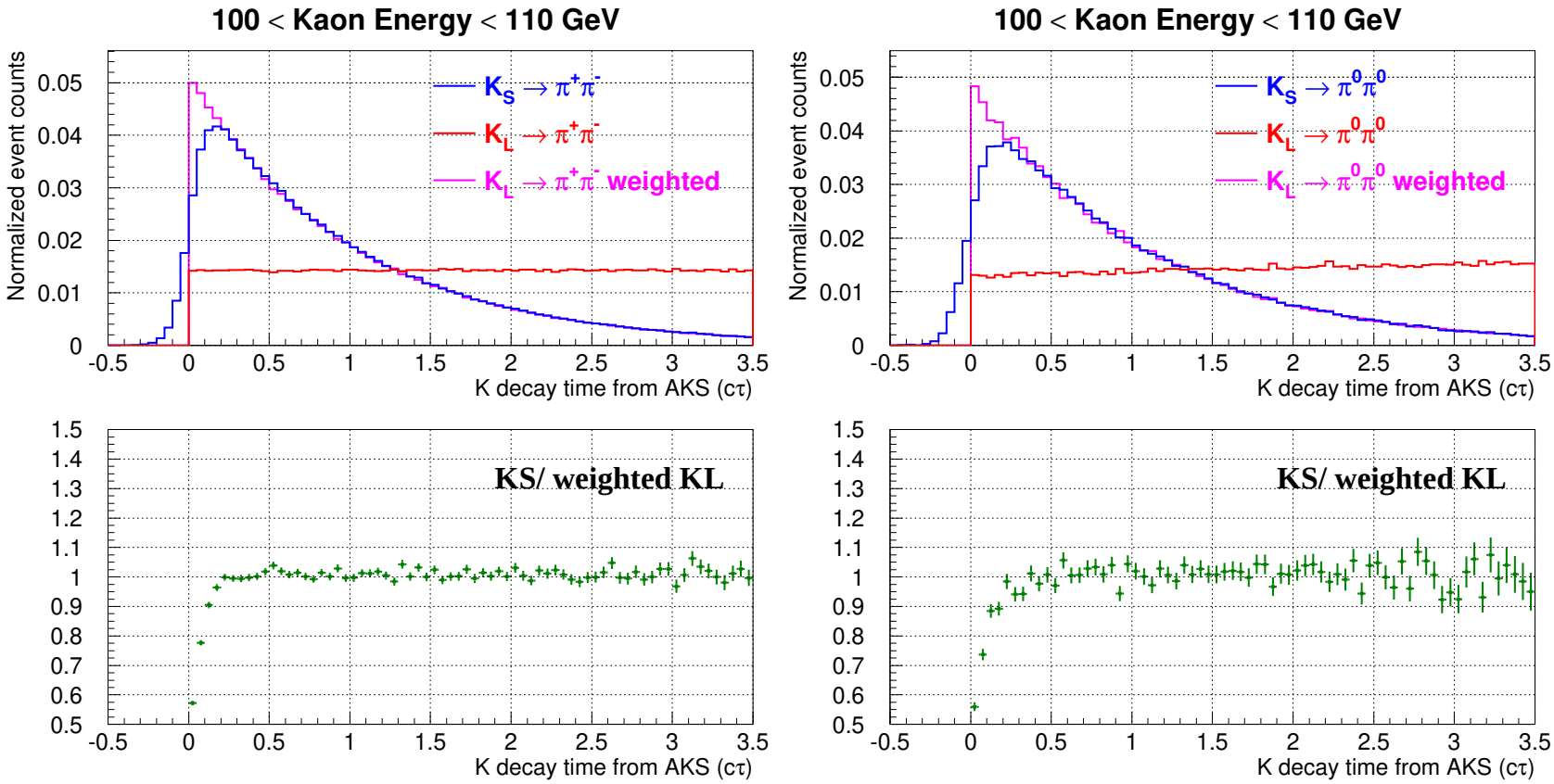


Source	ΔR (units 10^{-4})
Non linearity	$\pm$ 5
Non Gaussian tails in σ_E	$\pm$ 5
Transverse scale	$\pm$ 3
Intercalibration	$\pm$ 3
Distance/Energy scale	$\pm$ 3
Other sources	$\pm$ 4

We employ a π^- beam and two 3.5cm thick polyethylene targets, to produce $\eta, \pi^0 \to \gamma\gamma$ decays to cross check the distance scale. The m_η comes out 2σ off from PDG $\Rightarrow$ For now enlarge errors on non-linearity and energy scale

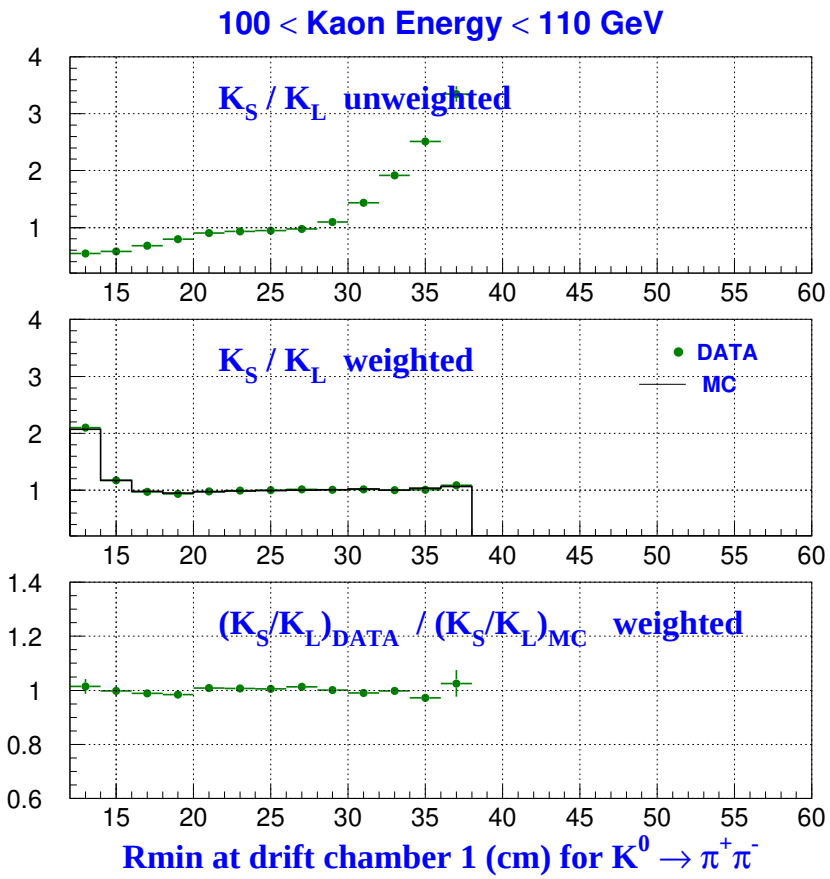
$$\Delta R = \pm 10 \times 10^{-4}$$

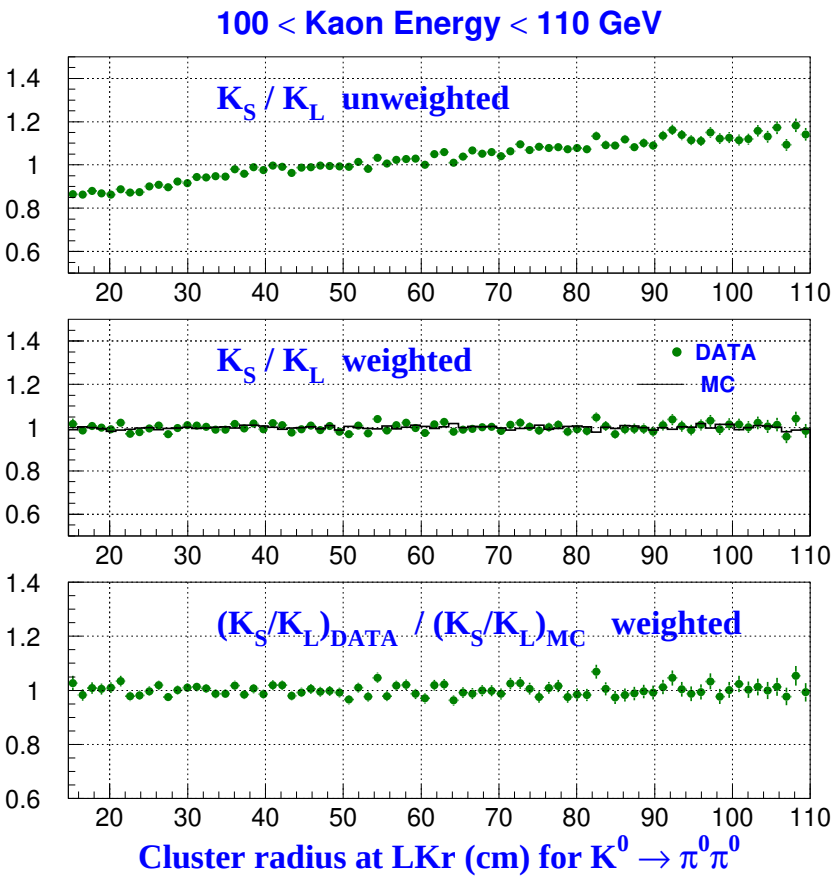
Weighting



- The $K_{\rm L}$ events are weighted according to the ratio of the proper time distribution of $K_{\rm S}$ and $K_{\rm L}$
- This reduces the acceptance correction to a few per mill

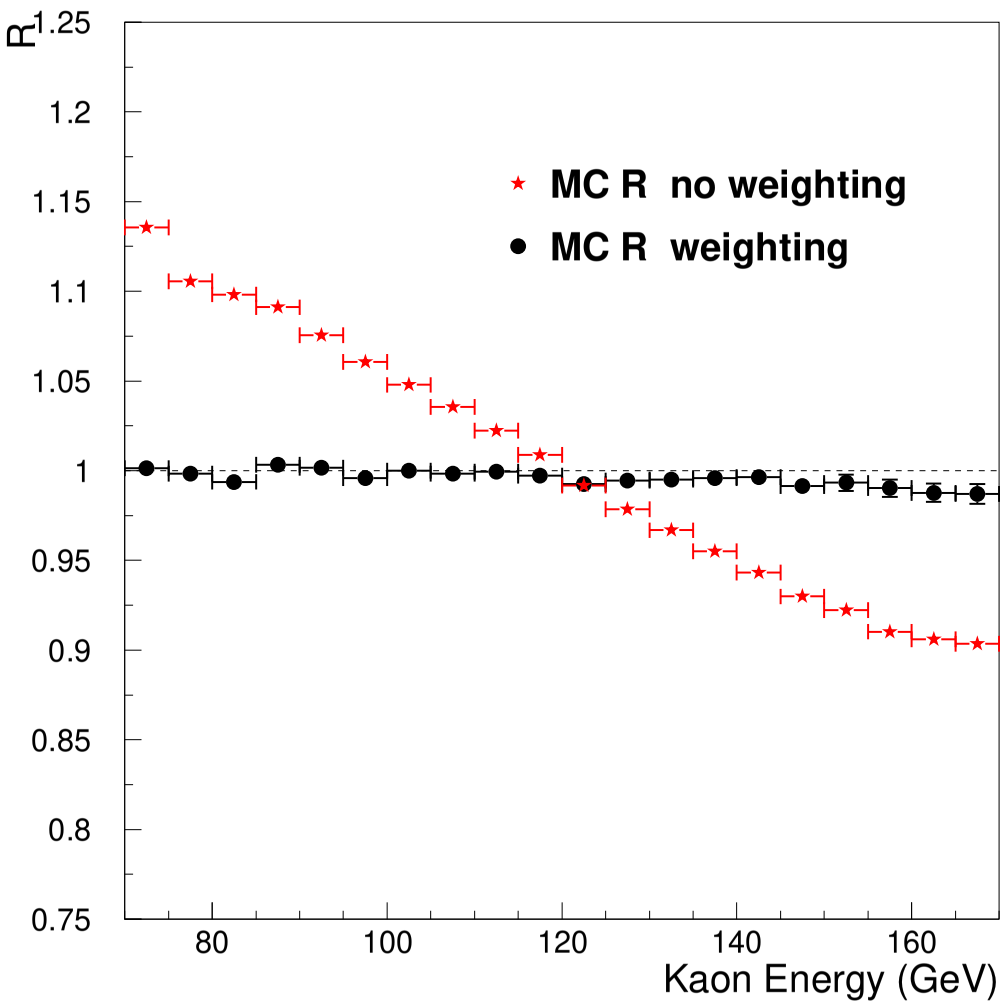
DATA/MC


100 < Kaon Energy < 110 GeV
K_S / K_L unweighted
K_S / K_L weighted
DATA
MC
$(K_S/K_L)_{DATA} / (K_S/K_L)_{MC}$ weighted
Rmin at drift chamber 1 (cm) for $K^0 \to \pi^+\pi^-$


100 < Kaon Energy < 110 GeV
K_S / K_L unweighted
K_S / K_L weighted
DATA
MC
$(K_S/K_L)_{DATA} / (K_S/K_L)_{MC}$ weighted
Cluster radius at LKr (cm) for $K^0 \to \pi^0\pi^0$

Acceptance

The increase of the statistical error due to weighting is 35%

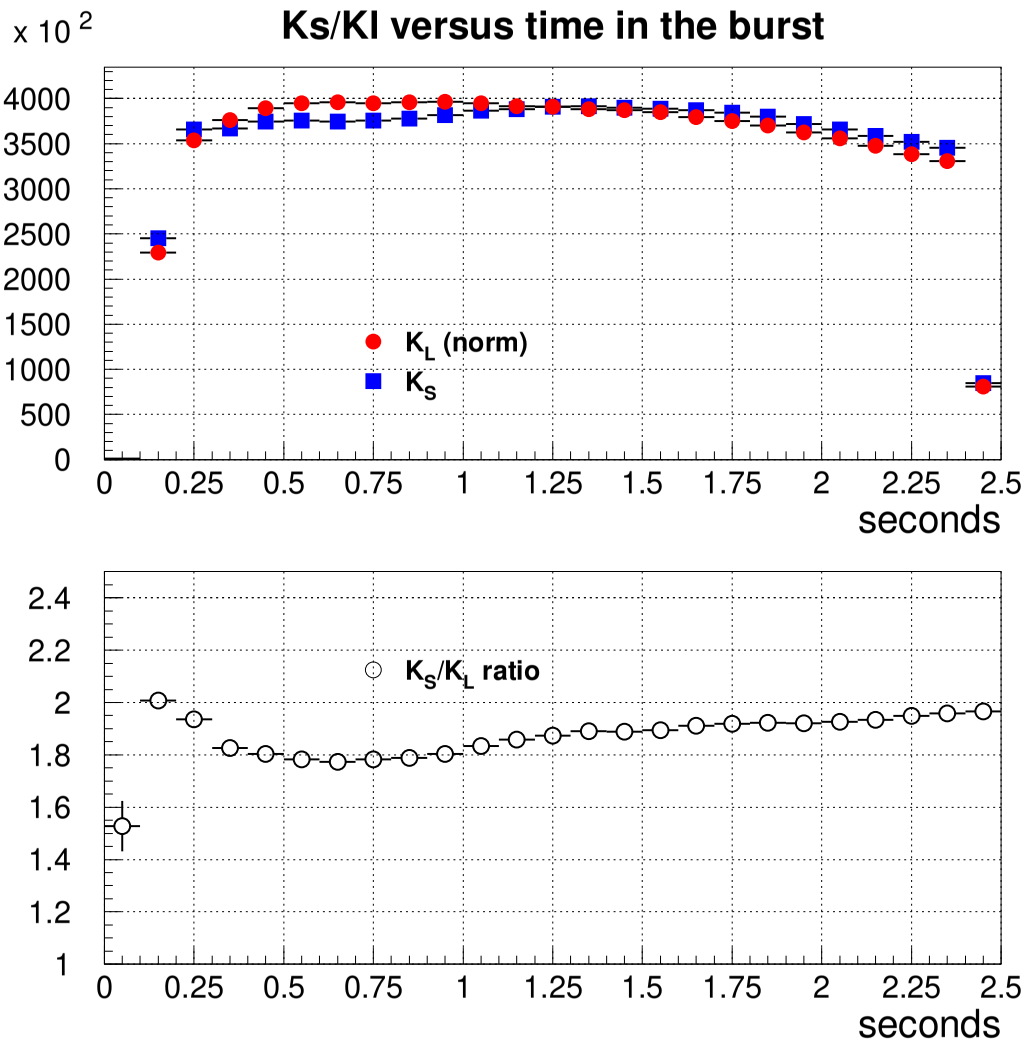


$$\Delta \mathrm{R} = (+31 \pm 6(stat) \pm 6(syst)) \times 10^{-4}$$

accidental activity

Geometric difference of the $K_{\rm S}$ and $K_{\rm L}$ beams:

$$\Delta {\rm R} = (2 \pm 6) \times 10^{-4}$$



Upper limit on the effects related to the variation of the $K_{\rm S}$ / $K_{\rm L}$ ratio (R.M.S. 10 %) and the effects which are not related to the $K_{\rm L}$ accidental activity:

$$\Delta {\rm R} = \pm 10 \times 10^{-4}$$

Statistics and systematics

Statistics (millions) 1998			
$K_S \to \pi^+\pi^-$	7.46	$K_L \to \pi^+\pi^-$	4.87
$K_S \to \pi^0\pi^0$	1.80	$K_L \to \pi^0\pi^0$	1.14

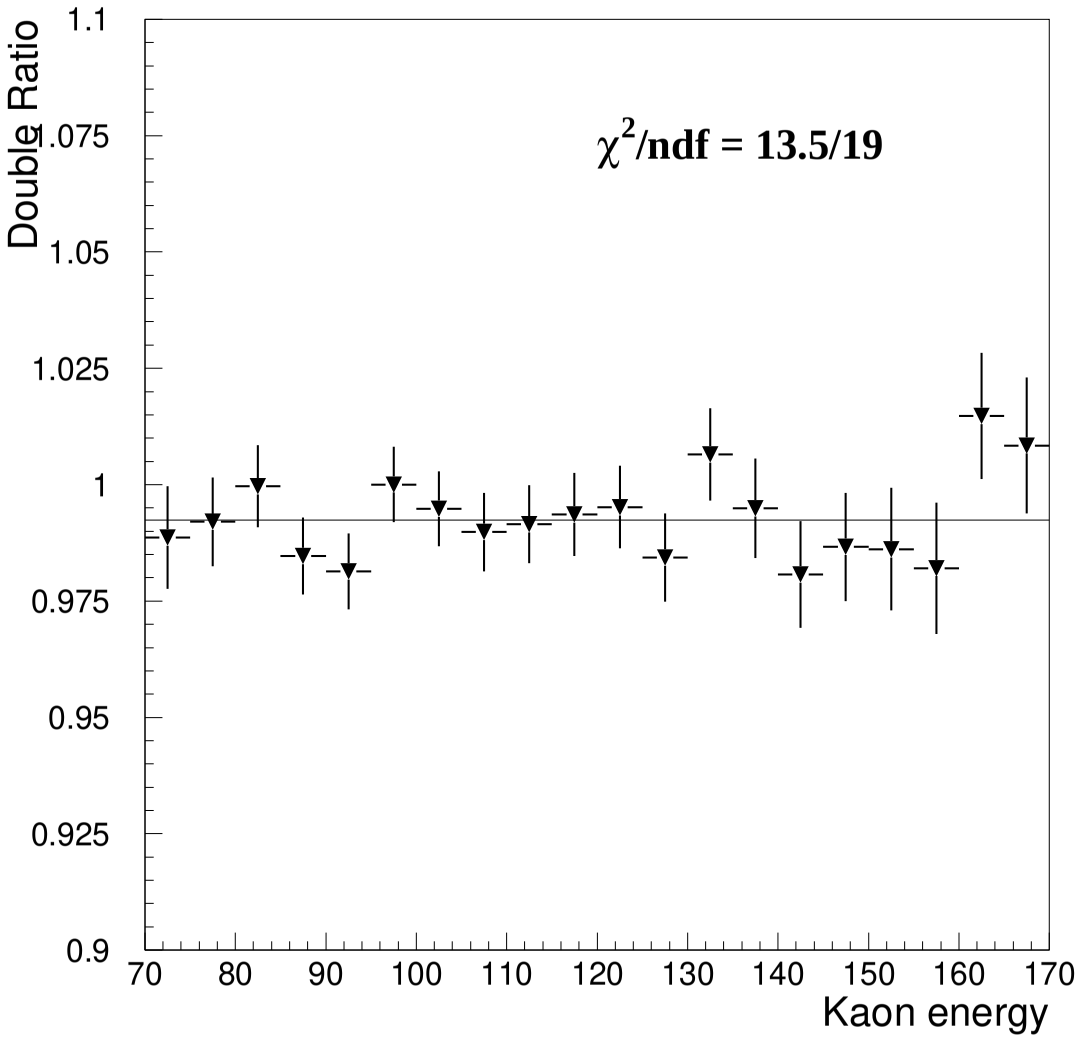
Subtracting the mistagging probability and averaging in energy bins, the weighted result is:

$$R_{RAW} = 0.98899 \pm 0.00173(stat)$$

Corrections and syst. errors on R (Units = 10^{-4})				
Source	1997 sample		1998 sample	
Charged trigger	+9	± 23	–1	± 11
Mistagging	+18	±9	+1	±8
Tagging efficiency	–	±6	–	± 3
Neutral scale	–	±12	–	±10
Charged vertex	–	±5	+2	±2
Acceptance	+29	±12	+31	±9
Neutral BG	–8	±2	–7	±2
Charged BG	+23	±4	+19	±3
Beam scattering	–12	±3	–10	±3
Accid. activity	–2	±14	+2	±12
Total	+57	±35	+37	±24

Result 1998

PRELIMINARY RESULT ON 1998 DATA



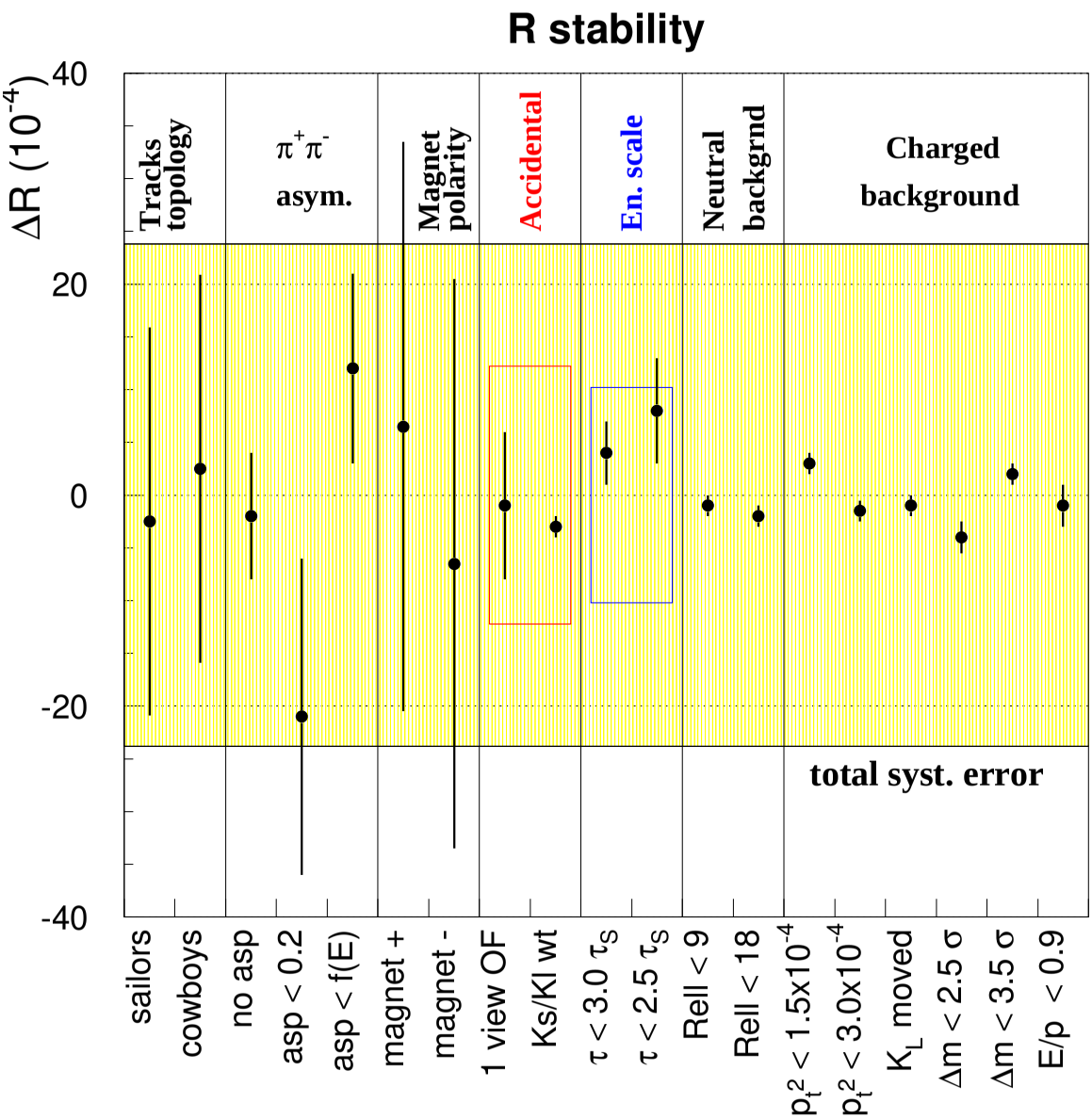
$$R = 0.99267 \pm 0.00173(stat.) \pm 0.00238(syst.)$$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 2.9\ (\mathrm{stat.}) \pm 4.0\ (\mathrm{syst.})) \times 10^{-4}$$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 4.9) \times 10^{-4}}$$

The systematic uncertainty is partly of statistical nature. It should be reduced in due time

Checks


R stability
ΔR (10^-4)
40
20
0
-20
-40
Tracks topology
π+π- asym.
Magnet polarity
Accidental
En. scale
Neutral backgrnd
Charged background
total syst. error
sailors
cowboys
no asp
asp < 0.2
asp < f(E)
magnet +
magnet -
1 view OF
Ks/Kl wt
τ < 3.0 τS
τ < 2.5 τS
Rell < 9
Rell < 18
pt2 < 1.5x10-4
pt2 < 3.0x10-4
KL moved
Δm < 2.5 σ
Δm < 3.5 σ
E/p < 0.9

Combined 1997 and 1998 result

Combined 1997 and preliminary 1998 NA48 result

1998

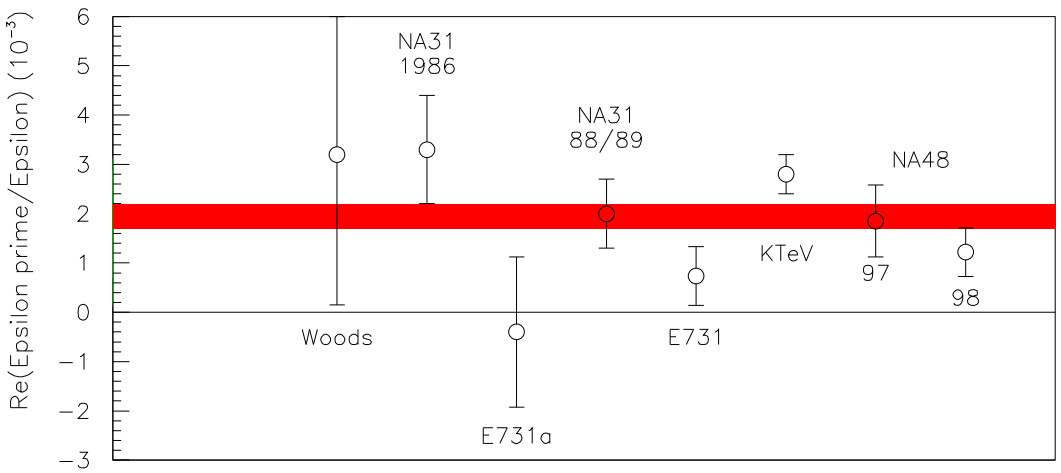
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 2.9(stat.) \pm 4.0(syst.)) \times 10^{-4}$$

1997

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5(stat.) \pm 5.8(syst.)) \times 10^{-4}$$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0 \pm 4.3) \times 10^{-4}}$$

(taking into account the small correlated systematics)



New world average:

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (19.3 \pm 2.4) \times 10^{-4}}$$

$$(\chi^2/ndf = 11.1/5)$$

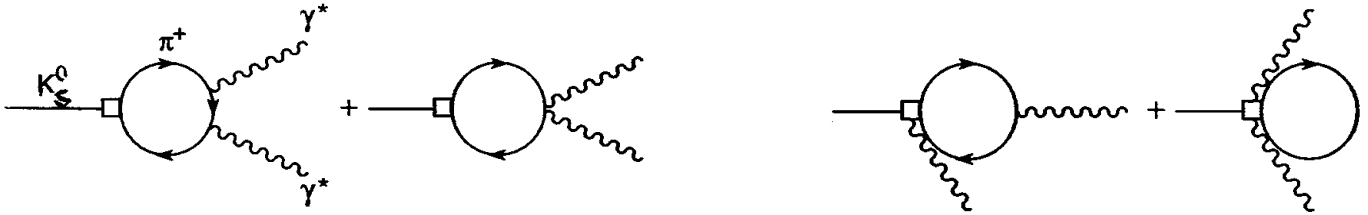
Rare decays in NA48

- 1997-1999 $\mathrm{Re}(\varepsilon'/\varepsilon)$ era:
  - K_{L} flux: $\sim 2 \times 10^7$/spill
  - K_{S} flux: $\sim 3 \times 10^2$/spill
  - Decays (70 -170 GeV/c range):
    $3.2 \times 10^{10} K_{\mathrm{L}}$ /year $\Rightarrow$ SES $\sim 3 \times 10^{-10}$
    $6.5 \times 10^{7} K_{\mathrm{S}}$ /year $\Rightarrow$ SES $\sim 1.5 \times 10^{-7}$
    (assuming 10% acceptance)
- 1999 High Intensity K_{S} run
  - No K_{L} beam
  - Proton beam intensity on K_{S} target increased by a factor of ~ 200
    $I_p \sim 6 \times 10^9 p$/spill
  - 2 day run $\Rightarrow$ 3-4 years of operation in $\mathrm{Re}(\varepsilon'/\varepsilon)$ mode
  - $\sim 2.3 \times 10^8 K_{\mathrm{S}}$ decays in 60-190 GeV/c range
  - SES $\sim 4 \times 10^{-8}$ for 10% acceptance
- 2000 High Intensity K_{S} run
  - No charged spectrometer
  - 400 GeV/c protons rather than 450 GeV/c
  - $\sim 10^{10} K_{\mathrm{S}}$ decays collected in 40 days
  - $\sim 10^6$ $3\pi^0/c\tau_{\mathrm{S}}$

$K_S \to \gamma\gamma$

Physics motivation

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



- Theory: $BR(K_S \to \gamma\gamma) \sim 2.1 \times 10^{-6}$ with small error
- NA31: $BR(K_S \to \gamma\gamma) = (2.4 \pm 0.9) \times 10^{-6}$

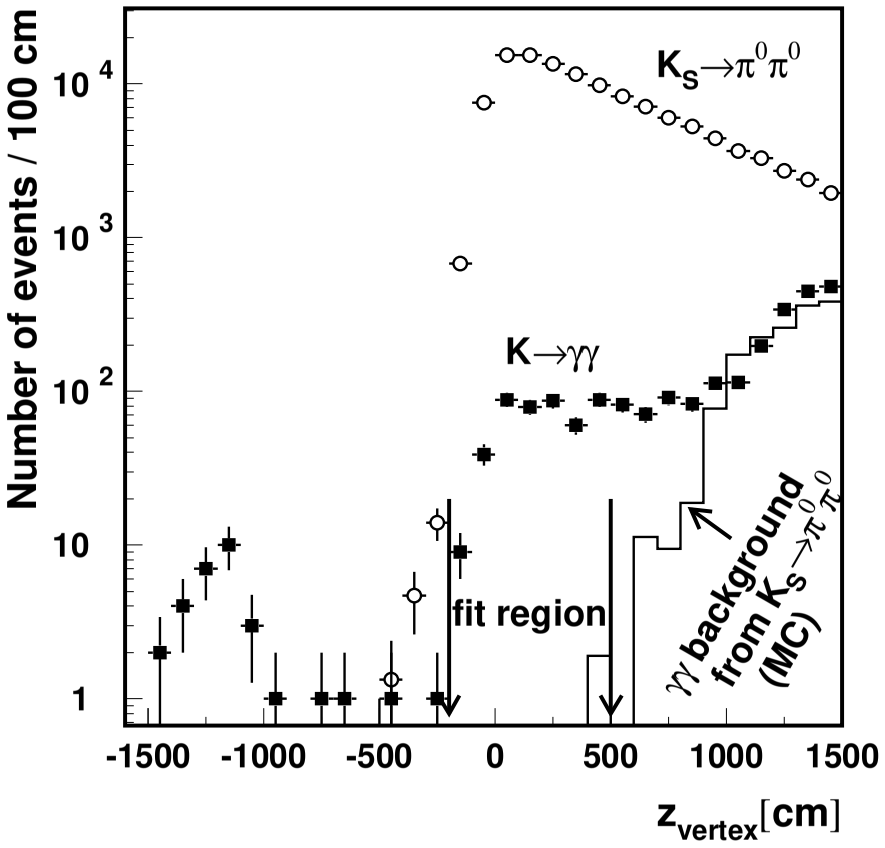
Experimental technique

- $\sim 6 \times 10^9$ ppp on a Be target placed 6 m upstream of the decay region
- The same number of K_S and K_L is produced at the target. The $K_L \to \gamma\gamma$ events must be subtracted

$K_S \to \gamma\gamma$

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

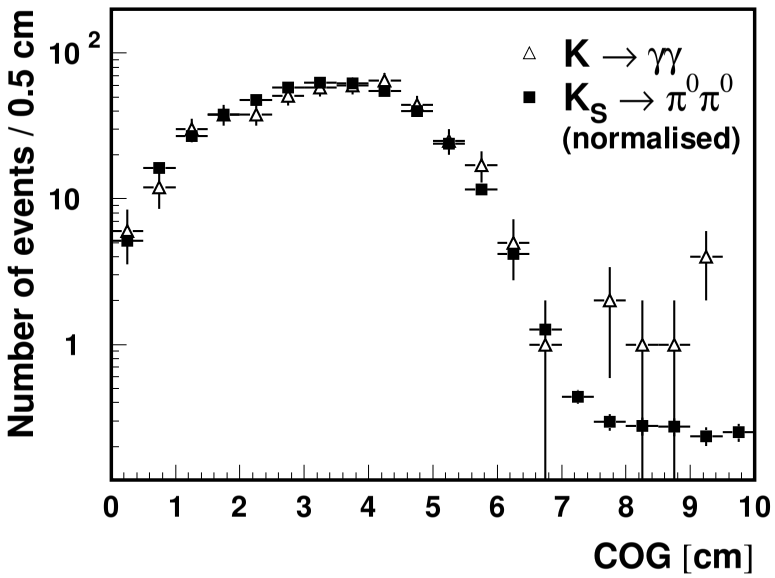


- 10^8 simulated $K_S \to 2\pi^0$
- The overlap of showers reduces the background free region to about 5 m

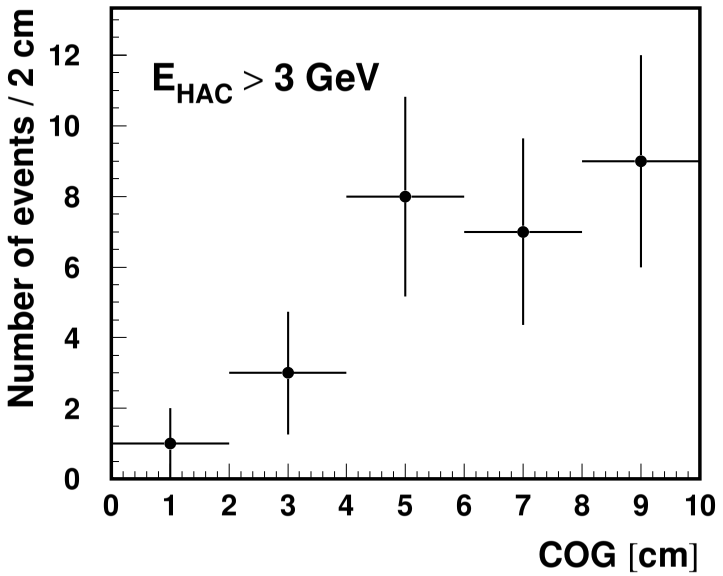
$K_S \to \gamma\gamma$

Hadronic background: 11 ± 8 events

There is an excess of $\gamma\gamma$ candidates for COG > 7 cm w.r.t. $K_S \to 2\pi^0$



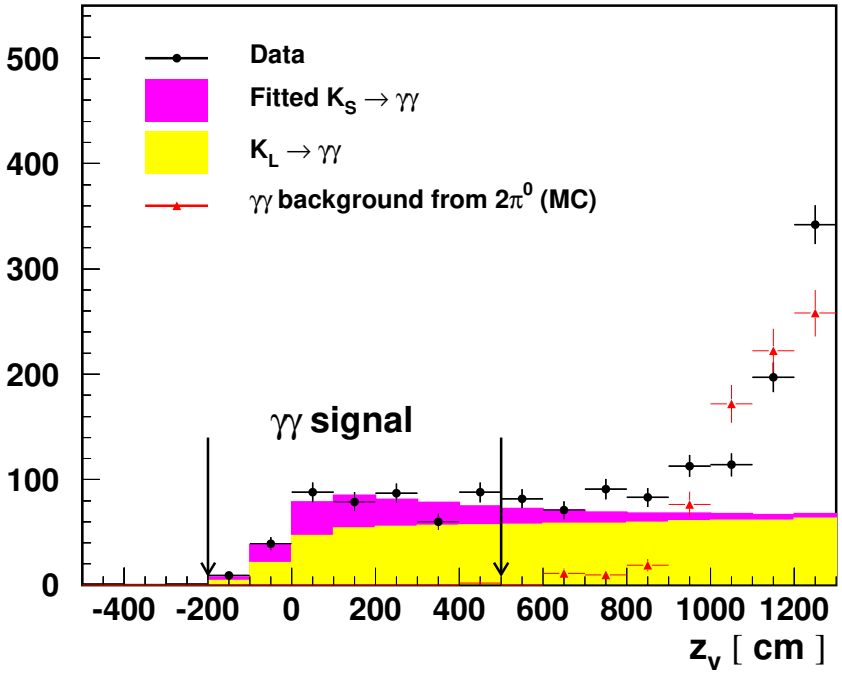
To compute the background in the signal region, an extrapolation is done using a sample for which $E_{\rm HAC} > 3$ GeV



$K_S \to \gamma\gamma$

Result

- 450 $K \to \gamma\gamma$
- 7.5×10^6 $2\pi^0$(Down-scale 100)
- A likelihood function (11 kaon energies and 7 longitudinal vertex positions) is maximised to extract $BR(K_S \to \gamma\gamma)$
- 50 % of the systematic error comes from the uncertainty of $BR(K_L \to \gamma\gamma)$



NA48 PL B493 29

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

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

Summary of the results

Decay mode	NA48 (Prel.)		PDG 2000	
	Evt.	BR	Evt.	BR
$K_L \to e^+e^-e^+e^-$	132	$(3.7 \pm 0.4)10^{-8}$	59	$(4.1 \pm 0.8)10^{-8}$
$K_L \to e^+e^-\mu^+\mu^-$	19		1	$(2.9^{+6.7}_{-2.4})10^{-9}$
$K_L \to e^+e^-\gamma\gamma$	492	$(6.3 \pm 0.5)10^{-7}$	98	$(6.9 \pm 1.0)10^{-7}$
$K_L \to \pi^0\gamma\gamma$	1397	$(1.5 \pm 0.2)10^{-6}$	947	$(1.7 \pm 0.1)10^{-6}$
$K_L \to \pi^+\pi^-e^+e^-$	1337	$(3.1 \pm 0.2)10^{-7}$	50	$(3.5 \pm 0.6)10^{-7}$
$K_S \to \pi^+\pi^-e^+e^-$	921	$(4.3 \pm 0.4)10^{-5}$	–	
$K_S \to \gamma\gamma$	149	$(2.6 \pm 0.4)10^{-6}$	35	$(2.4 \pm 0.9)10^{-6}$
$K_S \to \pi^0e^+e^-$	–	$< 1.6 \times 10^{-7}$	–	$< 1.1 \times 10^{-6}$
$\Xi^0 \to \Sigma^+e^-\bar{\nu}$	60		176	$(2.7 \pm 0.4)10^{-4}$
$\Xi^0 \to \Lambda\gamma$	497	$(1.9 \pm 0.2)10^{-3}$	147	$(1.2 \pm 0.3)10^{-3}$
$\Xi^0 \to \Sigma^0\gamma$	380	$(3.7 \pm 0.5)10^{-3}$	102	$(3.5 \pm 0.4)10^{-3}$

NA48/2

Direct CP violation in $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

$$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2$$

$$u = (s_3 - s_0)/m_\pi^2 \quad v = (s_1 - s_2)/m_\pi^2$$

$$s_0 = (s_1 + s_2 + s_3)/3$$

$$s_i = (P_K - P_i)^2 \quad (\mathrm{i} = 3 \text{ for the odd pion})$$

- Measure direct CP violation through the asymmetry:

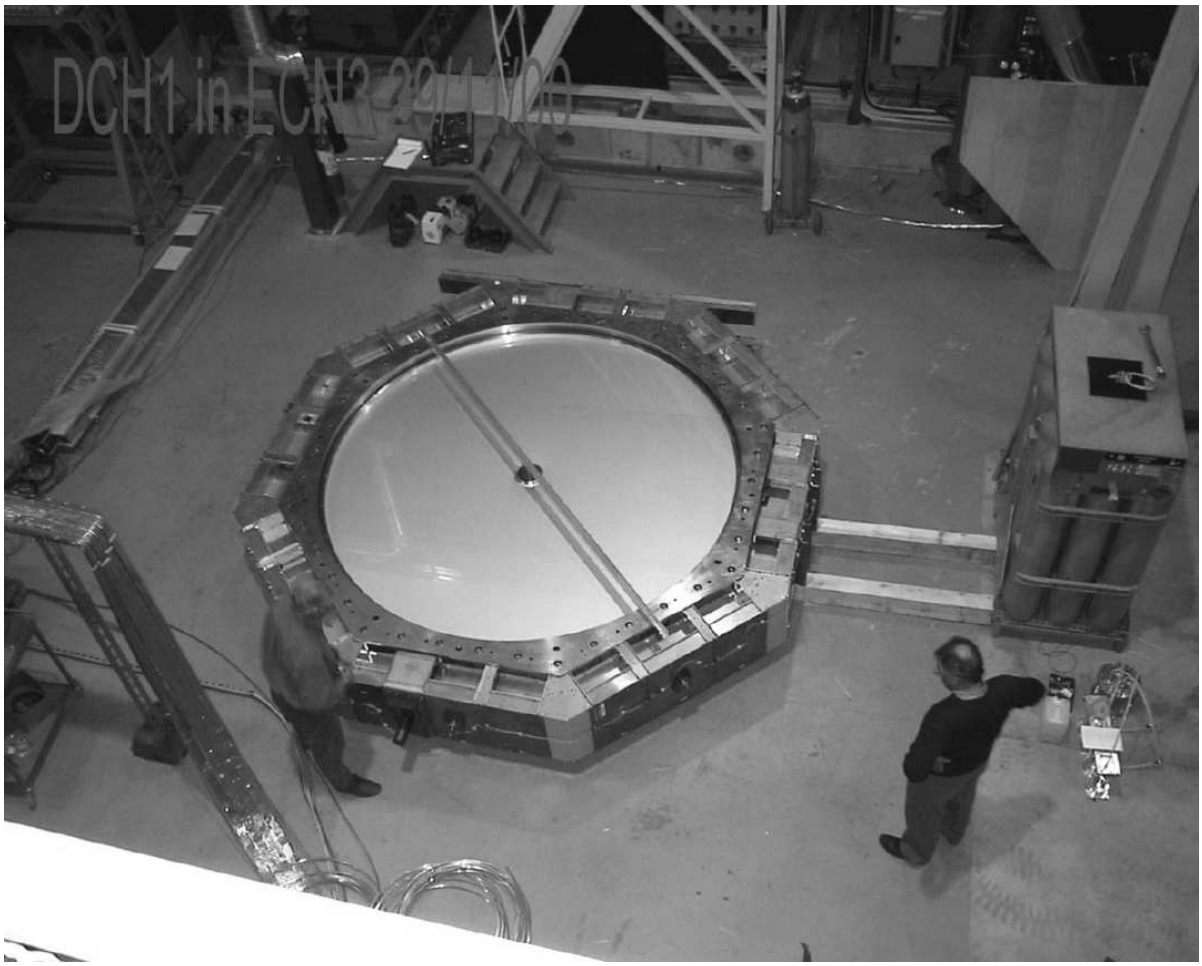
$$A_g = \frac{g^+ - g^-}{g^+ + g^-}$$

- Theoretical predictions are in the $10^{-6} - 10^{-4}$ range
- Experimental limit: $A_g = (-7 \pm 5) \times 10^{-3}$ Ford et al. (1970)
- With more than 2×10^9 $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays/year, NA48/2 can measure A_g with a precision of $< 2 \times 10^{-4}$

- CP can also be investigated in decays such as: $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ and $K^{\pm} \to \pi^{\pm}\pi^0\gamma$

Repair of the drift chambers

- The NA48 Drift Chambers were damaged by the beam pipe implosion in November 1999
- 2 out of 4 chambers already repaired
- 80% of the repair cost covered by insurance



Drift Chamber 4 is back in ECN3 after repair (29-11-2000)

Prospects

- During the year 2000 we collected $\sim 10^{10} K_{\rm S}$ decays into final states with π^0 and photons
- A new $\mathrm{Re}(\varepsilon'/\varepsilon)$ result based on 1998 + 1999 data should appear soon
- The repaired spectrometer will be used in 2001 to complete $\mathrm{Re}(\varepsilon'/\varepsilon)$
- A $K_{\rm S}$ rare decay search for the year 2002 has been approved by the CERN Research Board (CERN SPSC 2000-002). The program aims to, among other things:
  - Single Event Sensitivity of $\sim 3\ 10^{-10}$ for $K_{\rm S} \to \pi^0 \mathrm{e}^+ \mathrm{e}^-$
  - Study of $\Xi^0 \to \Sigma^+ e^- \bar{\nu}$ with approx. 25000 events
- Another phase with simultaneous K^+/K^- beams has also been approved. The aim is to reach a sensitivity of 10^{-4} on direct CP violation in $K^\pm \to 3\pi$ decays (CERN/SPSC 2000-003)