Latest Results on Kaon Physics from the NA48 experiment

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on behalf of the **NA48 COLLABORATION**:

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

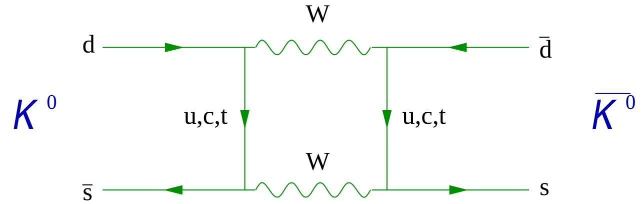
OUTLINE:

- ➜ The NA48 measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$
- ➜ A preview of 2001 data
- ➜ Neutral energy scale, K^0 and η masses
- ➜ $\mathrm{K_S}$ lifetime
- ➜ A look at the future

CP Violation in the Neutral Kaon System

	CP conserved	CP violated
Mass eigenstates:	$K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0}) \quad (CP = +1)$	$K_S = (K_1 + \varepsilon K_2) / \sqrt{1 + \lvert\varepsilon\rvert^2}$
	$K_2 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0}) \quad (CP = -1)$	$K_L = (K_2 + \varepsilon K_1) / \sqrt{1 + \lvert\varepsilon\rvert^2}$

➜ 1964: K_L can decay into $\pi^+\pi^-$ $(CP = +1)$ with $2 \cdot 10^{-3}$ B.R.



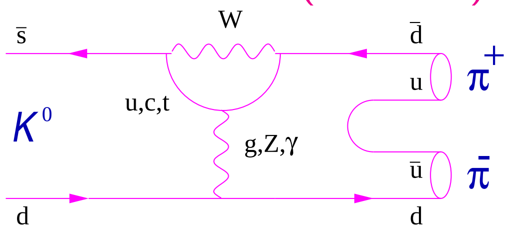
Indirect violation $(\Delta S = 2)$

Experimentally

$|\varepsilon| = (2.28 \pm 0.02) \cdot 10^{-3}$

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

Direct violation $(\Delta S = 1)$



$$\langle I, 0|T|K^0\rangle = A_I e^{i\delta_I}$$
$$\langle I, 0|T|\bar{K}^0\rangle = A_I^* e^{i\delta_I}$$

$$\varepsilon' \equiv \frac{i}{\sqrt{2}} Im\left(\frac{A_2}{A_0}\right) e^{i(\delta_2 - \delta_0)} \qquad (Im(A_0) \equiv 0)$$

Direct CP Violation

➜ within the Standard Model ε' can be computed as a function of the CKM matrix elements ...

$$\frac{\varepsilon'}{\varepsilon} = \frac{|V_{ub}||V_{cb}|\sin\delta}{0.074}\left(\frac{110\ \mathrm{MeV}}{M_S(M_C)}\right)^2\left[0.75\ B_6 - 0.4\ B_8\left(\frac{M_T}{165\ \mathrm{GeV}}\right)^{2.5}\right]\frac{\Lambda_{\overline{MS}}}{340\ \mathrm{MeV}}$$

("pedagogical" formula by A.Buras)

➜ but errors are dominated by long distance contributions to the penguin diagram terms B_6 and B_8
Typical theoretical predictions:

ε'/ε in the range 0 to 30×10^{-4}

Breakthrough from Lattice QCD computations?

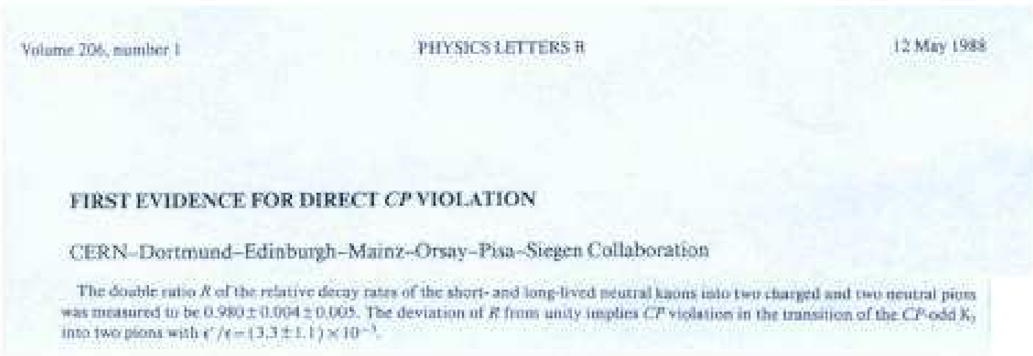
➜ A precision measurement of ε'/ε can test SM predictions against other possibilities, as the Superweak Model ($\varepsilon' = 0$) or SUSY contributions

➜ So far all experiments used the Double Ratio method:

$$\mathrm{R} = \frac{\Gamma(K_L^0 \to \pi^0\pi^0)}{\Gamma(K_L^0 \to \pi^+\pi^-)}\frac{\Gamma(K_S^0 \to \pi^+\pi^-)}{\Gamma(K_S^0 \to \pi^0\pi^0)} \simeq 1 - 6 \times \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

A long history ...

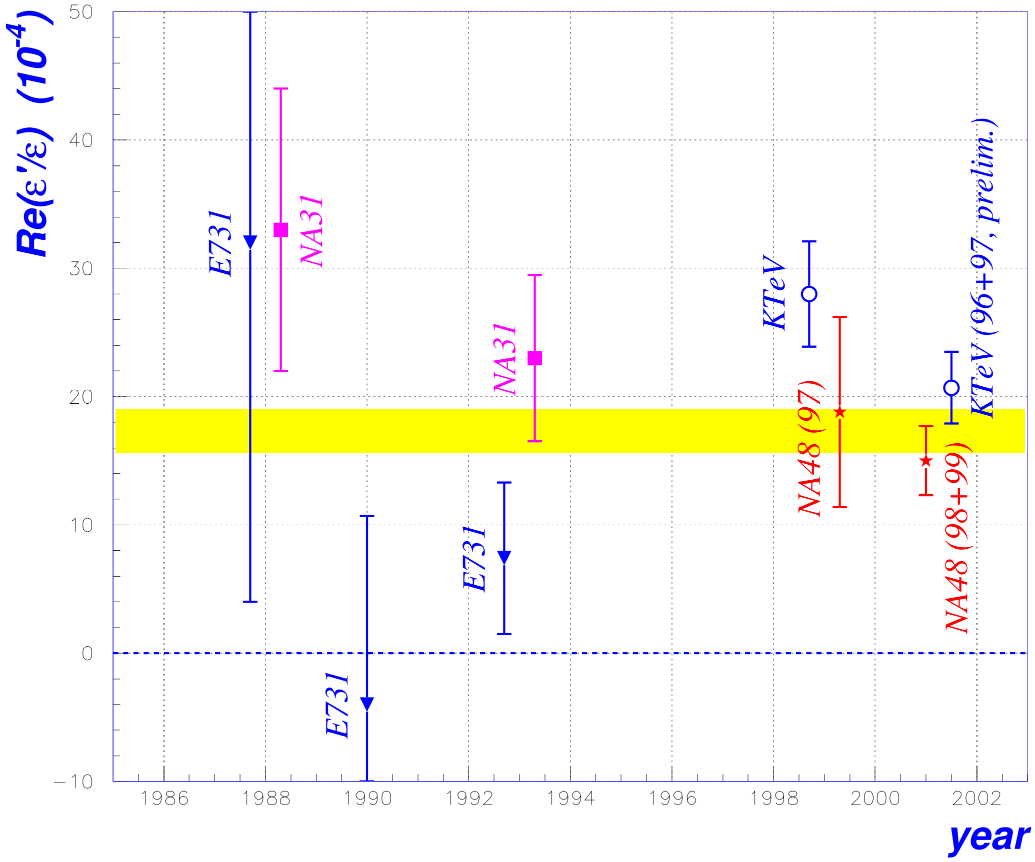
The first claim for direct CPV (1988)


Volume 206, number 1 PHYSICS LETTERS B 12 May 1988

FIRST EVIDENCE FOR DIRECT *CP* VIOLATION

CERN–Dortmund–Edinburgh–Mainz–Orsay–Pisa–Siegen Collaboration

The double ratio *R* of the relative decay rates of the short- and long-lived neutral kaons into two charged and two neutral pions was measured to be $0.980 \pm 0.004 \pm 0.005$. The deviation of *R* from unity implies *CP* violation in the transition of the *CP*-odd K_L into two pions with $\varepsilon'/\varepsilon = (3.3 \pm 1.1) \times 10^{-3}$.



Latest results for $\mathrm{Re}(\varepsilon'/\varepsilon)$ (2001):

NA48 97+98+99	$(15.3 \pm 2.6) \times 10^{-4}$
KTEV 96+97 (prelim.)	$(20.7 \pm 2.8) \times 10^{-4}$

new World average:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (17.3 \pm 1.7) \times 10^{-4}$$

$\chi^2 = 5.6/3$ (13% probability)

The NA48 Recipe

Minimize systematic errors on the double ratio

$$\mathrm{R} = \frac{\Gamma(K_L^0 \to \pi^0\pi^0)}{\Gamma(K_L^0 \to \pi^+\pi^-)} \frac{\Gamma(K_S^0 \to \pi^+\pi^-)}{\Gamma(K_S^0 \to \pi^0\pi^0)} \simeq 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$$

through

- simultaneous acquisition of the 4 decay modes
- in the same fiducial region
- from two high–intensity quasi–collinear beams
- $\mathrm{K_S}$ and $\mathrm{K_L}$ are identified by tagging in time the $\mathrm{K_S}$ beam protons
- the effects of remaining $\mathrm{K_S}$ / $\mathrm{K_L}$ differences are minimized offline:

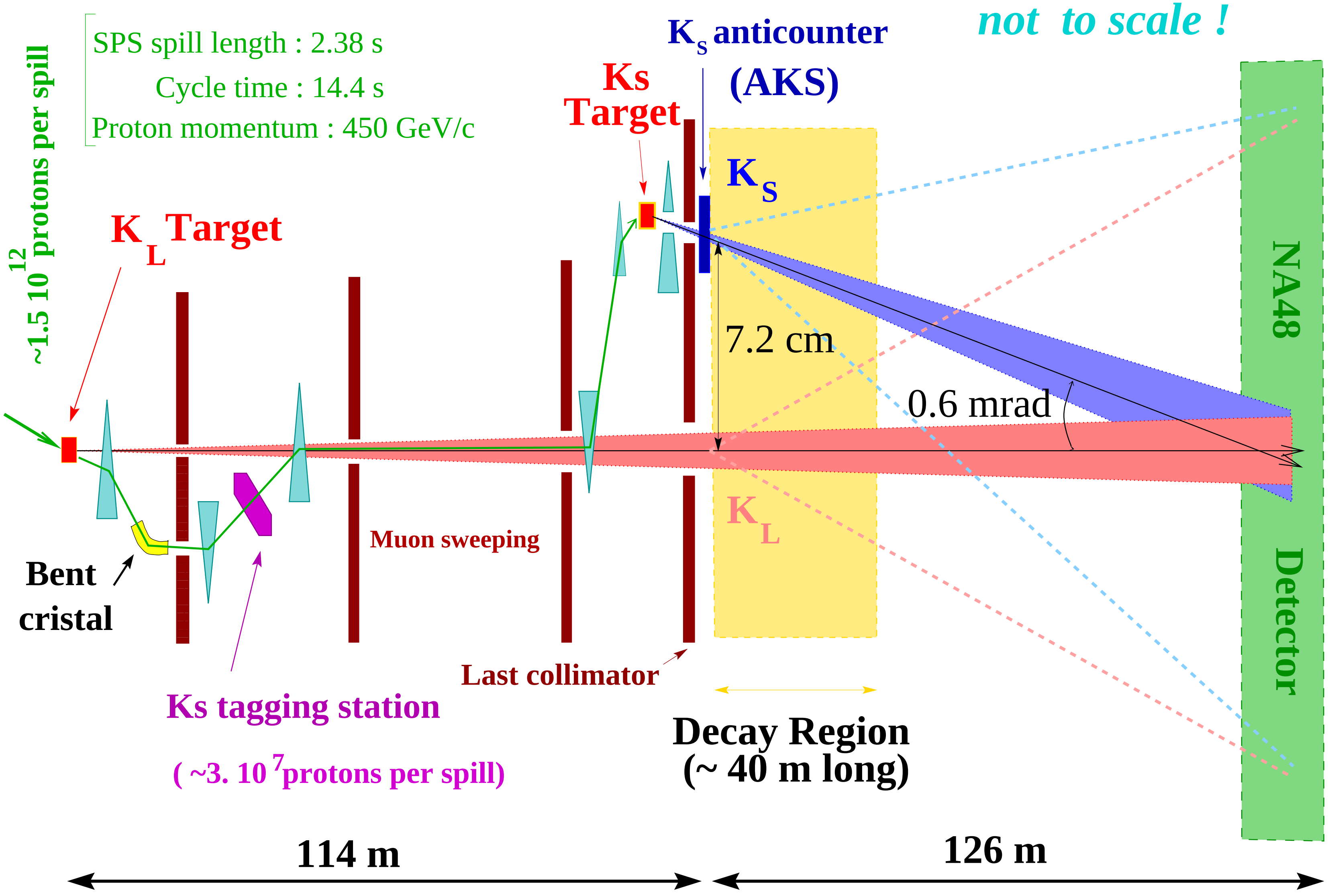
  energy spectra: analysis is performed in 20 energy bins between 70 and 170 GeV

  lifetime: $\mathrm{K_L}$ events are weighted according to the theoretical $\mathrm{K_S}$ to $\mathrm{K_L}$ ratio of proper time distributions:

$$w(t) \sim e^{-t\left(\frac{1}{\tau_S} - \frac{1}{\tau_L}\right)}$$

- apply small (< 0.3 % by first principles) corrections for remaining biases (backgrounds, mistagging, intensity effects . . .)

The NA48 Beams



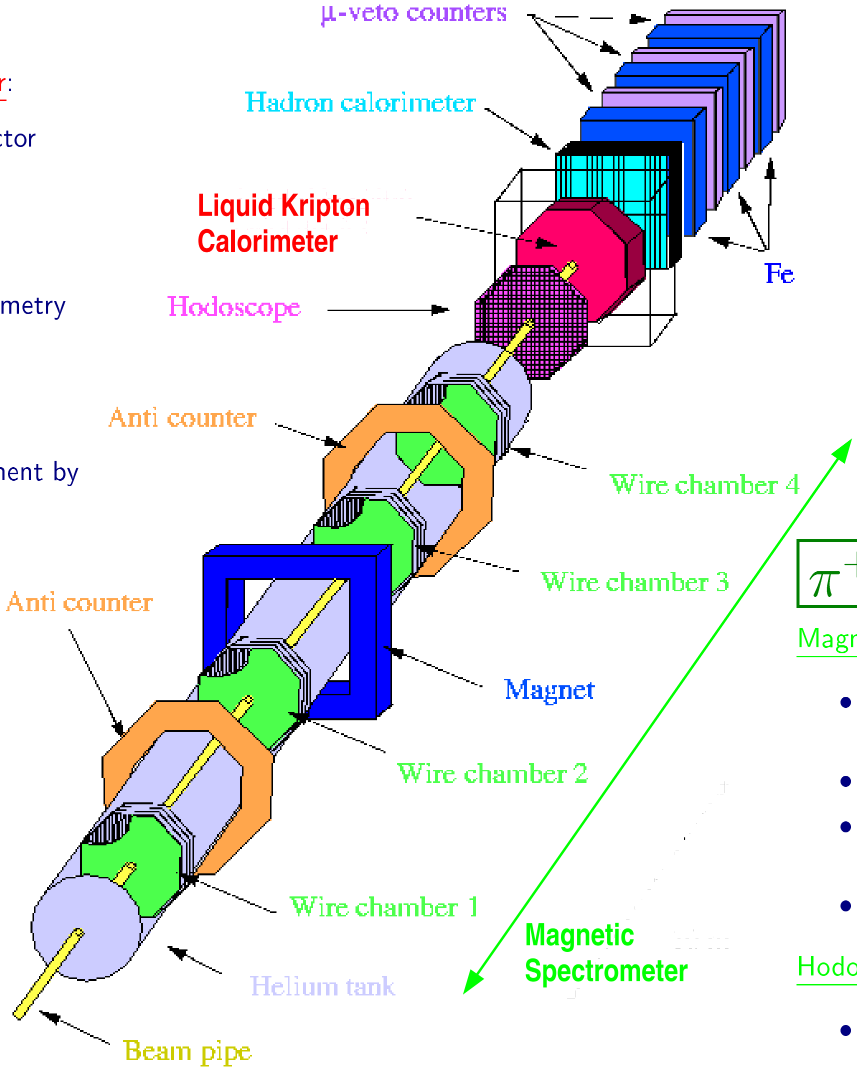
➜ The tagging station provides a measurement of proton time with < 200 ps resolution to distinguish K_S from K_L events

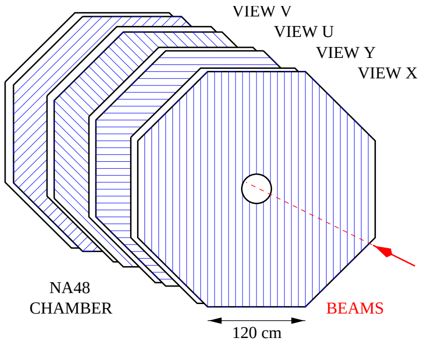
The Central Detector

$\boxed{\pi^0\pi^0}$

LKr electromagnetic calorimeter:

- quasi–homogeneous detector based on 9 m^3 LKr
- Cu–Be electrodes
- 13212 $2 \times 2 \times 127$ cm^3
- $\pm$ 48 mrad accordion geometry
- projective geometry
- geometry machined with 0.2 mm/m accuracy
- redundant time measurement by scintillating fiber neutral hodoscope





$\boxed{\pi^+\pi^-}$

Magnetic Spectrometer:

- 4 chambers with 4 views each, 2 staggered planes per view
- 90 μm spacepoint resolution
- wire position known better than 100 μm/m
- magnet providing 265 MeV/c p_T kick

Hodoscope:

- 2 planes of scintillators for precise measurement of event time

Data Samples

$\boxed{1997}$ 89 days @ 1×10^{12} ppp on $\mathrm{K_L}$ target

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

First Result Phys.Lett. B465 (1999) 335–348

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

... detector improvements to allow for higher rates ...

$\boxed{1998}$ 135 days @ 1.4×10^{12} ppp on $\mathrm{K_L}$ target

1.04 million of $K_L \to \pi^0\pi^0$

$\boxed{1999}$ 128 days @ 1.4×10^{12} ppp on $\mathrm{K_L}$ target

2.24 million of $K_L \to \pi^0\pi^0$

New Result Eur.Phys.J. C22 (2001) 231–254

Nov '99: the implosion of the carbon fiber beam pipe damaged all four drift chambers

$\boxed{2000}$ only neutral events for cross–checks and rare $\mathrm{K_S}$ decays

... New drift chambers rebuilt ...

$\boxed{2001}$ 90 days @ 2.4×10^{12} ppp (modified beam)

$>$1.4 million of $K_L \to \pi^0\pi^0$

The 1998+1999 Result

Event Statistics (millions) 1998+1999							
$K_L \rightarrow \pi^0\pi^0$	3.29	$K_S \rightarrow \pi^0\pi^0$	5.21	$K_L \rightarrow \pi^+\pi^-$	14.45	$K_S \rightarrow \pi^+\pi^-$	22.22

R before correction $= 0.98739 \pm 0.00101$ (stat.)

Corrections and systematic errors on R

$\pi^0\pi^0$ reconstruction	–	$\pm$ 0.00058	
Acceptance	+0.00267	$\pm$ 0.00057	
$\pi^+\pi^-$ trigger inefficiency	–0.00036	$\pm$ 0.00052	$\leftarrow$ rate effects
Accidental activity	–	$\pm$ 0.00044	$\leftarrow$ rate effects
Accidental tagging	+0.00083	$\pm$ 0.00034	$\leftarrow$ rate effects
Tagging inefficiency	–	$\pm$ 0.00030	$\leftarrow$ rate effects
Background to $\pi^+\pi^-$	+0.00169	$\pm$ 0.00030	
$\pi^+\pi^-$ reconstruction	+0.00020	$\pm$ 0.00028	
Beam scattering	–0.00096	$\pm$ 0.00020	
Background to $\pi^0\pi^0$	–0.00059	$\pm$ 0.00020	
Long term K_S /KL variations	–	$\pm$ 0.00006	
Total Systematic	+0.00359	$\pm$ 0.000126	

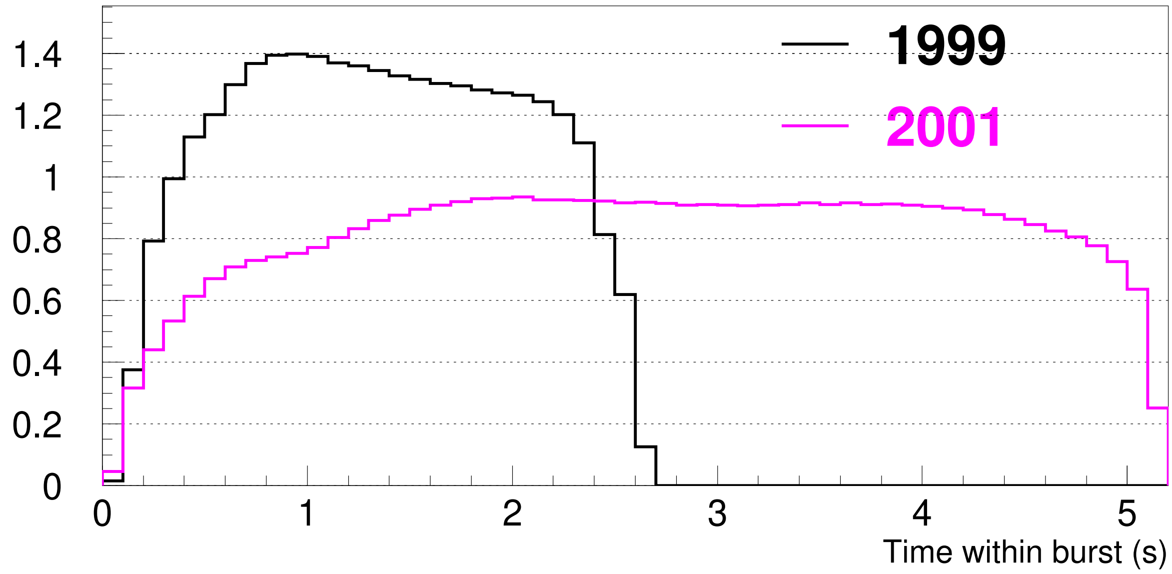
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1\text{-R})/6 = (15.0 \pm 1.7\ (\mathrm{stat.}) \pm 2.1\ (\mathrm{syst.})) \times 10^{-4}$$

The 2001 Run

- Different Beam condition:

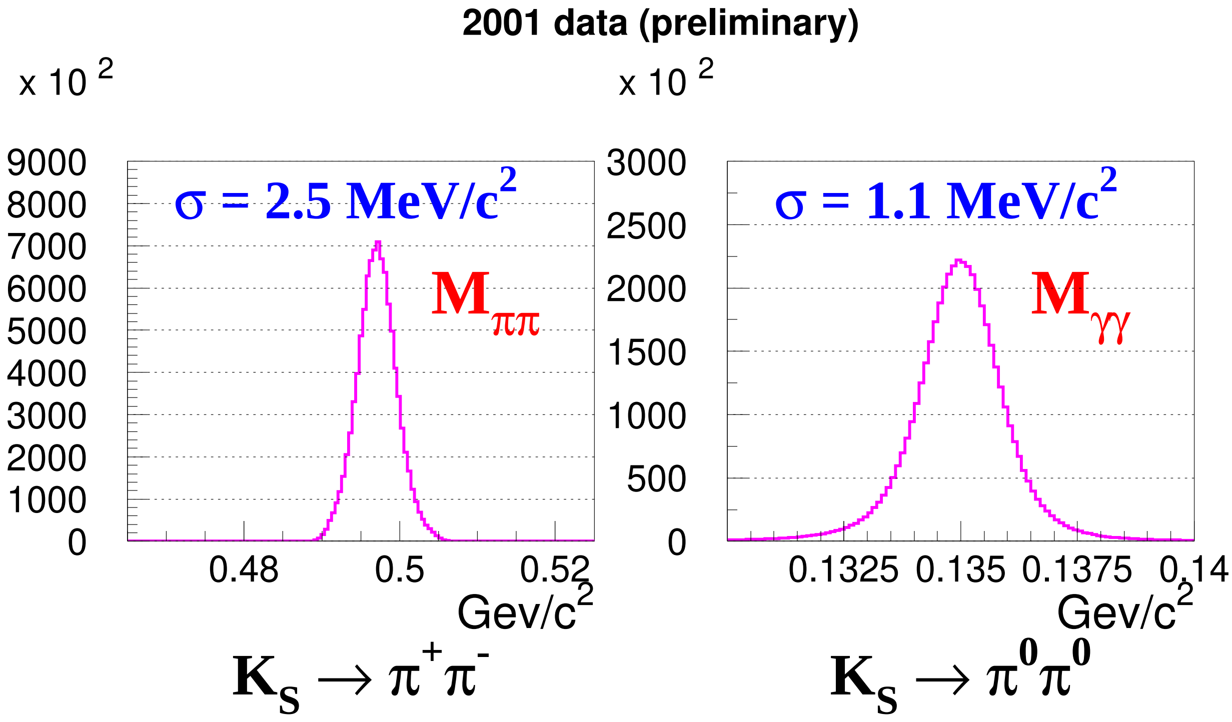
proton energy	450 GeV	$\rightarrow$	400 GeV
duty cycle	2.4/14.4 s	$\rightarrow$	5.2/16.8 s

instantaneous intensity $\sim$ 30 % lower



Good K_L Events / 100 ms

- New spectrometer's drift chambers



Comparing 2001 with previous runs

	1998+1999	2001
$\#K_L \rightarrow \pi^0\pi^0$	3.29×10^6	$>1.4\times10^6$
statistical error on R	10.1×10^{-4}	$\sim14\ \times10^{-4}$
DCH overflow rate	21.5 %	$\sim$ 12 %
Mistagging prob. α_{LS}	10.6 %	$\sim$ 8 %
L2 charged trigger efficiency	98.3 %	99.2 %
stat. error on R from eff. measurement	4.7×10^{-4}	3.0×10^{-4}

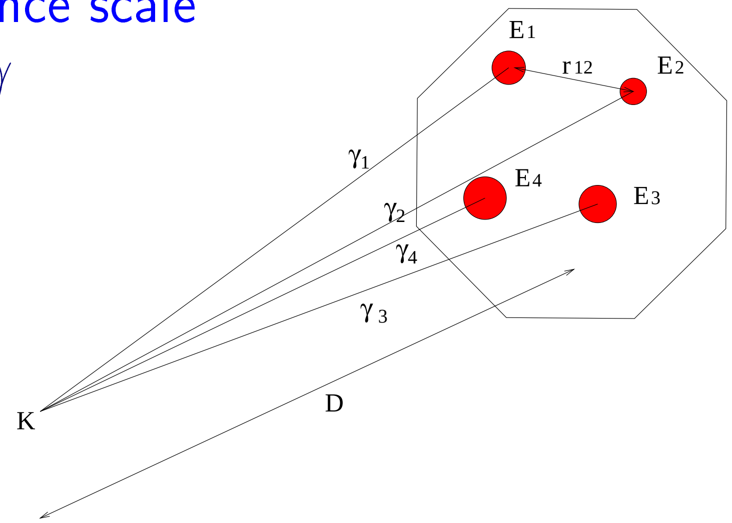
- ➜ The statistical error on the final $\mathrm{Re}(\varepsilon'/\varepsilon)$ result will go from 1.7×10^{-4} to $<1.4\times10^{-4}$
- ➜ The total error (stat.+syst.) for the 2001 result will be comparable with the published result
  $\Longrightarrow$ the 2001 run will be a major cross-check of the measurement against intensity effects

Neutral Energy Scale

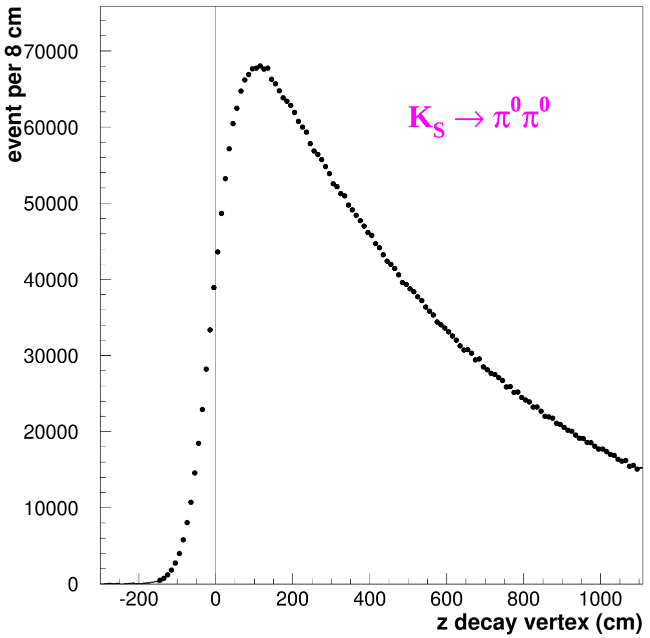
Global energy scale $\Longleftrightarrow$ longitudinal distance scale

Imposing the K^0 mass to $K \to \pi^0\pi^0 \to 4\gamma$

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

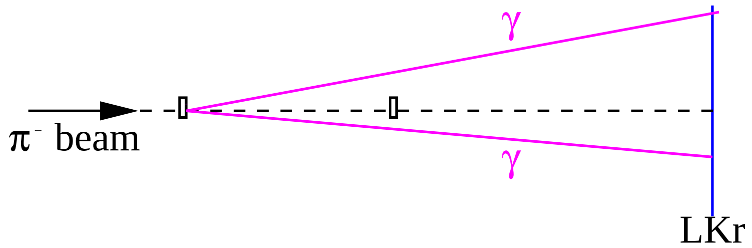


Energy scale is fixed by adjusting the $\mathrm{K_S} \to \pi^0\pi^0$ vertex distribution to the know position of the $\mathrm{K_S}$ anticounter (AKS)



and checked through special η **runs**

π^- beam on two thin targets



compare reconstructed vertex for $\pi^0, \eta \to \gamma\gamma$ (obtained imposing the known values of η and π^0 masses) with the known target positions

uncertainty on energy scale $\pm 3 \times 10^{-4}$

($\pm 2 \times 10^{-4}$ on R)

Measurement of the η and K^0 Masses

- PDG 2000 uncertainties:

π^0	4×10^{-6}
K^0	6×10^{-5}
η	2×10^{-4}

- Use data from 2000 run with $\mathrm{K_L}$ and η beams
- Use $3\pi^0$ decays, reconstruct vertex using π^0 mass

  No background

  Result independent from energy scale

  Large statistics:

  128×10^6 $\mathrm{K_L} \to 3\pi^0$ candidates

  264×10^3 $\eta \to 3\pi^0$ candidates

- Systematics errors:
  - non–linearity: potentially dangerous, can be suppressed with a tight cut on photon energy asymmetry:

$$0.7 < \frac{E_\gamma}{E_{tot}/6} < 1.3$$

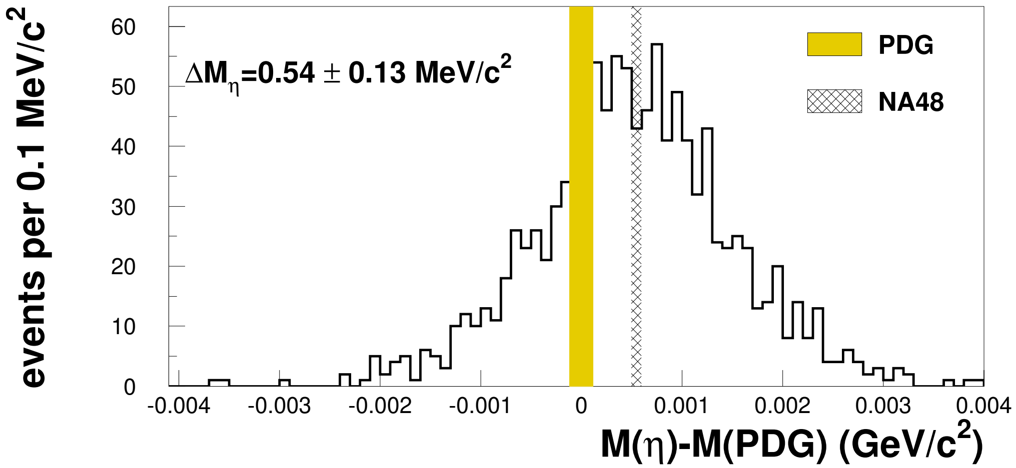
  - non–uniformity: $\pm$ 23 KeV/c^2
    (minimized rejecting low–energy γs: $8 < E_\gamma < 37$ GeV)
  - energy sharing: $\pm$ 33 KeV/c^2 for η
    $\pm$ 20 KeV/c^2 for K^0
  - smaller effects from resolution bias (MC), position measurement, non–gaussian tails

Results for η and K^0 masses

Final samples:

$655 \times 10^3 \ \mathrm{K_L} \to 3\pi^0$

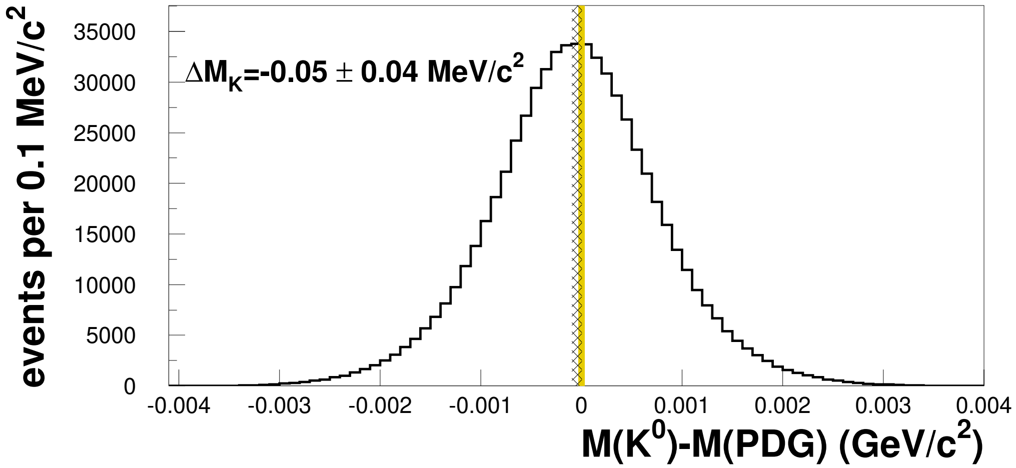
$1134 \ \ \eta \to 3\pi^0$



PDG 2000 Values:

$M_{\mathrm{K}^0} = 497.672 \pm 0.031$ MeV/c^2

$M_\eta = 547.30 \pm 0.12$ MeV/c^2



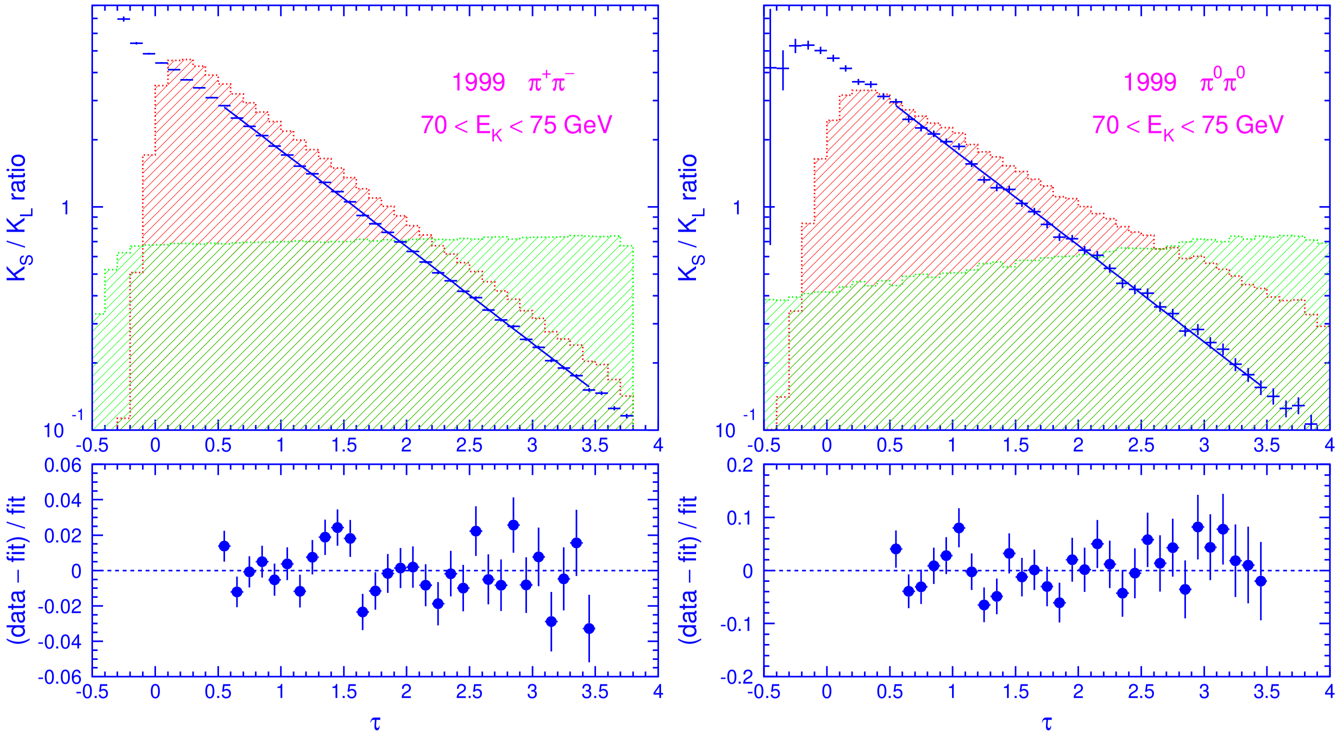
$$M_{\mathrm{K}^0} = 497.625 \pm 0.001(stat) \pm 0.003(MC) \pm 0.031(syst) \ \mathrm{MeV/c^2}$$

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

Using this M_η value instead of the PDG one improves the energy scale check!

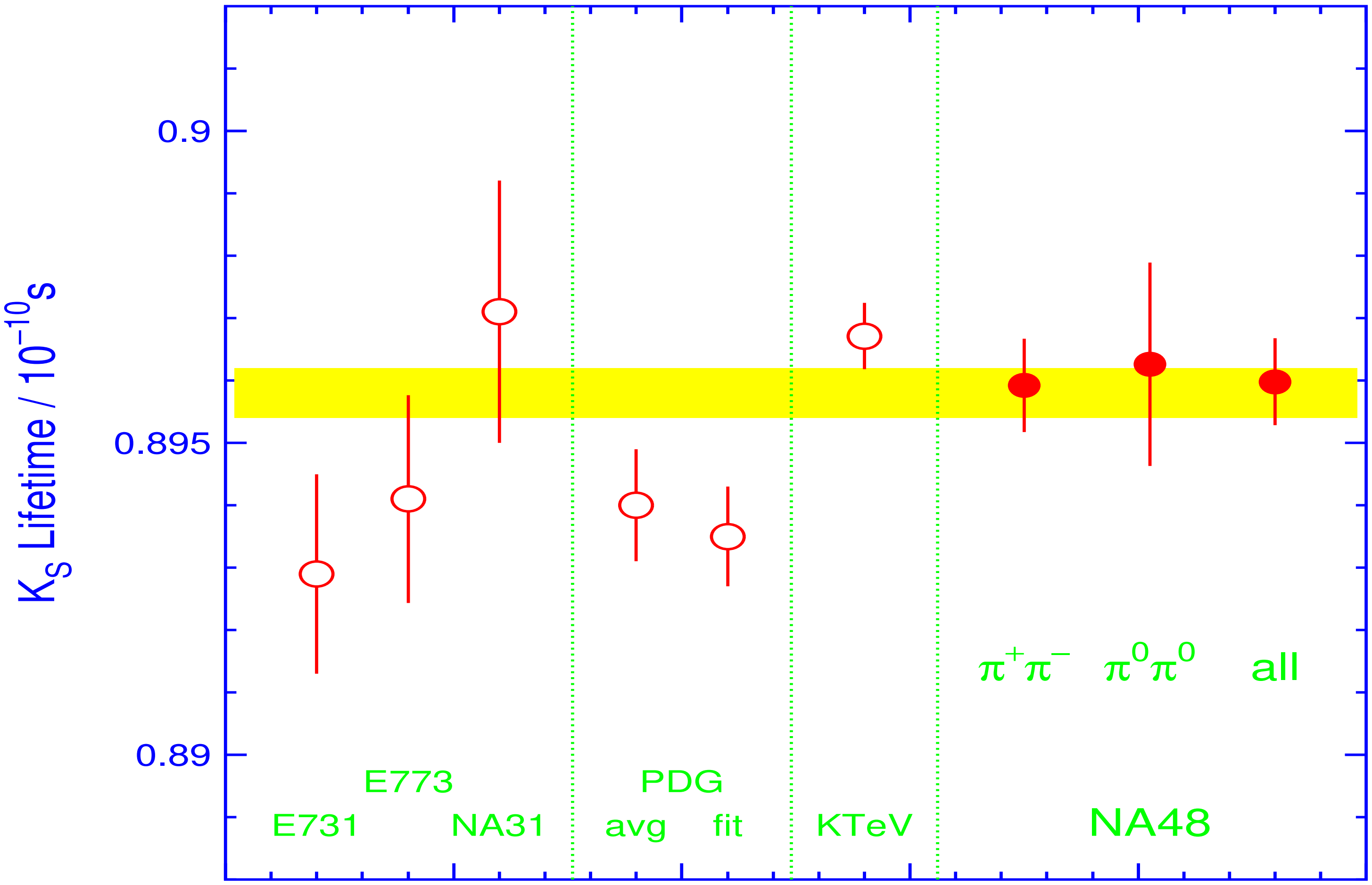
Measurement of K_S lifetime

- Method: fit $K_S\,/K_L$ ratio of lifetime distributions (acceptance cancel to the first order) in 20 energy bins between 70 and 170 GeV
- use 1998+1999 ε' data samples
- can be done independently for $\pi^+\pi^-$ and $\pi^0\pi^0$ events



- Many sources of small ($\lesssim 3 \times 10^{-4}$) systematic errors have been considered:
  - residual acceptance correction
  - distance and energy scales
  - fit method
  - background subtraction
  - Neutral reconstruction (for $\pi^0\pi^0$)
  - mistagging (for $\pi^0\pi^0$)
  - errors on external physical parameters (from PDG)

Result for $\mathrm{K_S}$ lifetime



$$\tau_S = (0.89592 \pm 0.00052\ \text{(stat)} \pm 0.00054\ \text{(syst)}) \times 10^{-10}\ \text{s} \qquad (\pi^+\pi^-)$$

$$\tau_S = (0.89626 \pm 0.00129\ \text{(stat)} \pm 0.00100\ \text{(syst)}) \times 10^{-10}\ \text{s} \qquad (\pi^0\pi^0)$$

Combined result: $\boxed{\tau_S = (0.89598 \pm 0.00048\ \text{(stat)} \pm 0.00051\ \text{(syst)}) \times 10^{-10}}$

Not only ε'/ε ...

NA48 is producing many other physics results on $\mathrm{K_L}$, $\mathrm{K_S}$ **and hyperon rare decays** to study indirect CPV and low energy hadron dynamics (tests of χPT)

Recent results:

$\boxed{\mathrm{K_L} \to \pi^+\pi^-e^+e^-}$

$$BR = (3.1 \pm 0.1\ (\text{stat}) \pm 0.2\ (\text{syst})) \times 10^{-7}$$

$$CPV\,Asymmetry = (13.9 \pm 2.7\ (\text{stat}) \pm 2.0\ (\text{syst}))\%$$

(preliminary)

$\boxed{\mathrm{K_S} \to \pi^+\pi^-e^+e^-}$

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

$$CPV\,Asymmetry = (-0.2 \pm 3.4\ (\text{stat}) \pm 1.4\ (\text{syst}))\%$$

(preliminary)

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

$$BR = (2.6 \pm 0.4\ (\text{stat}) \pm 0.2\ (\text{syst})) \times 10^{-6}$$

Phys. Lett. B493 (2000), 29

$\boxed{\mathrm{K_S} \to \pi^0 e^+e^-}$

$$BR < 1.4 \times 10^{-7}\ \ (90\ \%\ \text{conf. level})$$

Phys.Lett. B514 (2001), 253–262

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

$$BR = (1.36 \pm 0.03\ (\text{stat}) \pm 0.03\ (\text{syst}) \pm 0.03\ (\text{norm})) \times 10^{-6}$$

$$a_V = -0.46 \pm 0.03\ (\text{stat}) \pm 0.03\ (\text{syst}) \pm 0.02\ (\text{theo})$$

(to be published)

$\boxed{\mathrm{K_S} \to \pi^0\gamma\gamma}$

$$BR(z > 0.2) < 4.4 \times 10^{-7}$$

(to be published)

A look at the (next) future

The ε' program is finished, but not NA48

2002 **NA48/1** High–Intensity $\mathrm{K_S}$ run:
$2 \times 10^{10} ppp$ (ε' intensity $\times$ 600)

➜ minor modifications of the beam line

➜ new DCH read–out (no more overflows)

Physics goal: reach unprecedented sensitivity for

- $\mathrm{K_S} \to \pi^0 e^+ e^-$ (3×10^{-10})
- other rare $\mathrm{K_S}$ decays
- CPV in $\mathrm{K_S} \to 3\pi$

2003 **NA48/2** Simultaneous K^+/K^- beam

➜ new beam line for an unseparated K^+/K^- beam

➜ new detectors: beam spectrometer (KABES) and TRD

Physics goal: search for direct CPV in $K^\pm \to 3\pi$ decays (measure A_g with 10^{-4} accuracy), look for QCD vacuum condensate in K_{e4} decays

Conclusions

- The ε' program was ended with the successful 2001 run: more than 1.4×10^6 $\mathrm{K_L} \to \pi^0\pi^0$ collected with different beam conditions
- The 2001 data will allow to improve the statistical accuracy and perform a major systematic check of the present $\mathrm{Re}(\varepsilon'/\varepsilon)$ result

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}}$$

- New precision measurements as a byproduct of ε'/ε analysis:

$$M_{\mathrm{K}^0} = 497.625 \pm 0.031 \text{ MeV/c}^2$$
$$M_\eta = 547.843 \pm 0.051 \text{ MeV/c}^2$$
$$\tau_{\mathrm{K_S}} = (0.8960 \pm 0.0007) \times 10^{-10}\ s$$

- Many new interesting results on Kaon Physics are coming out from the collected data ...
- ... and many more quantitative tests of CPV in the Standard Model (complementary to B physics) and of low–energy hadron dynamics to come from the next years