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

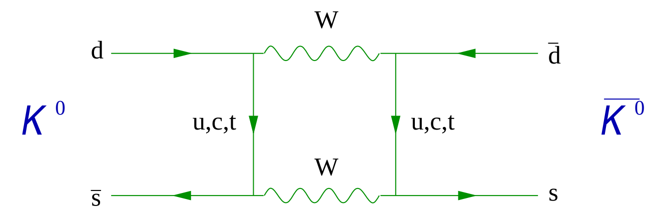
OUTLINE:

- ➜ 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

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

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



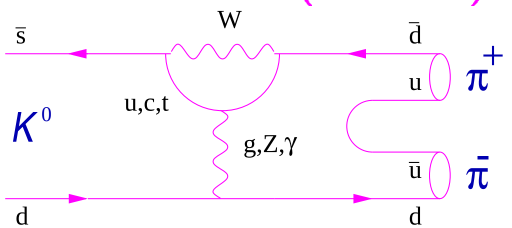
Indirect violation ($\Delta S = 2$)

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}

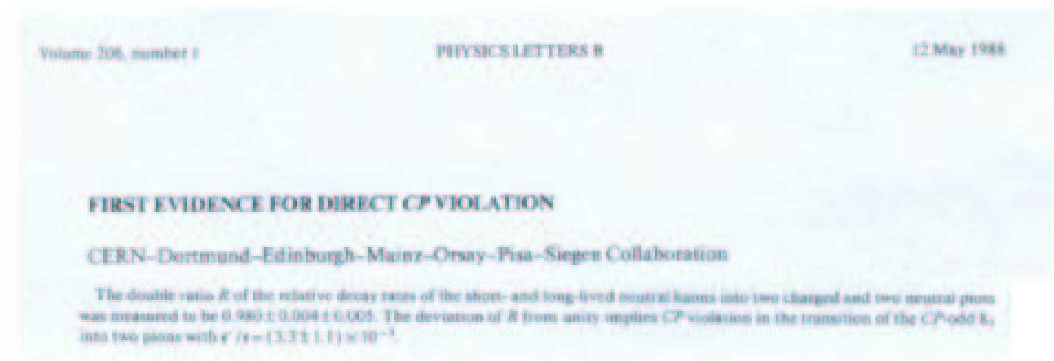
  Breakthrough from Lattice QCD computations?

- 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)

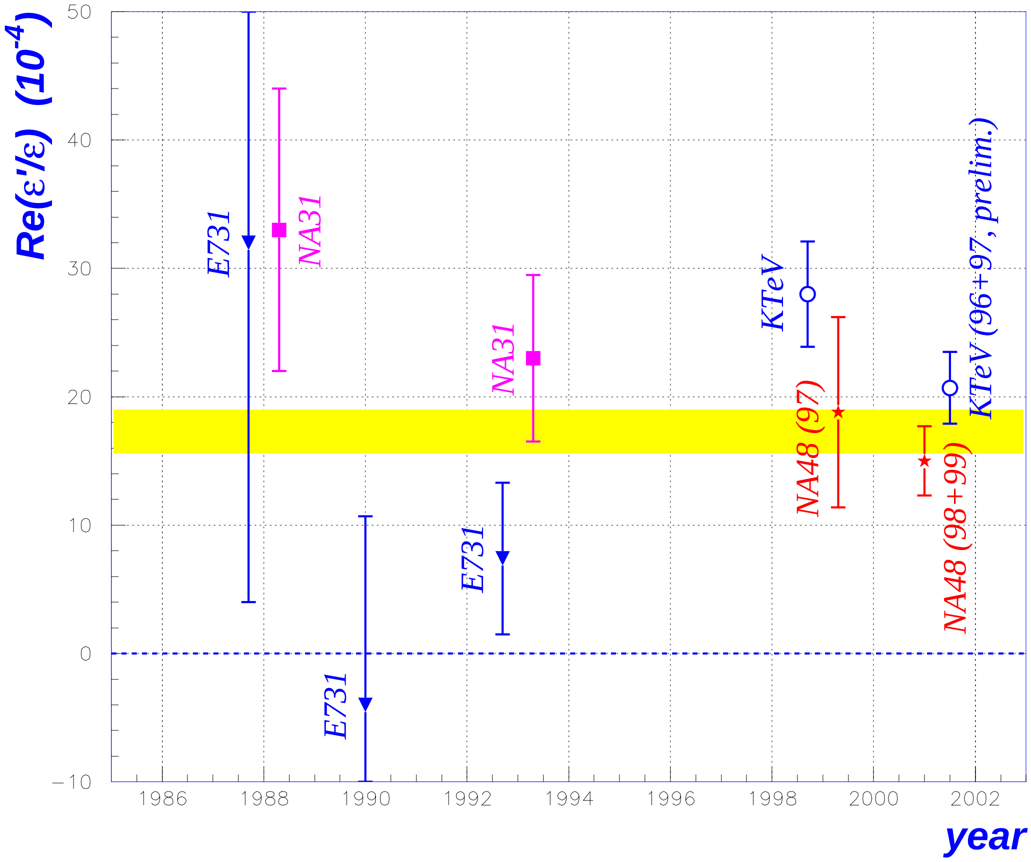


Volume 208, number 1 PHYSICS LETTERS B 12 May 1988

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 ± 0.004 ± 0.005. The deviation of *R* from unity implies *CP* violation in the transition of the *CP*-odd K_2 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:

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

$$\chi^2 = 5.6/3 \quad (13\% \text{ probability})$$

The NA48 Recipe

Minimize systematic errors on the double ratio

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

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:

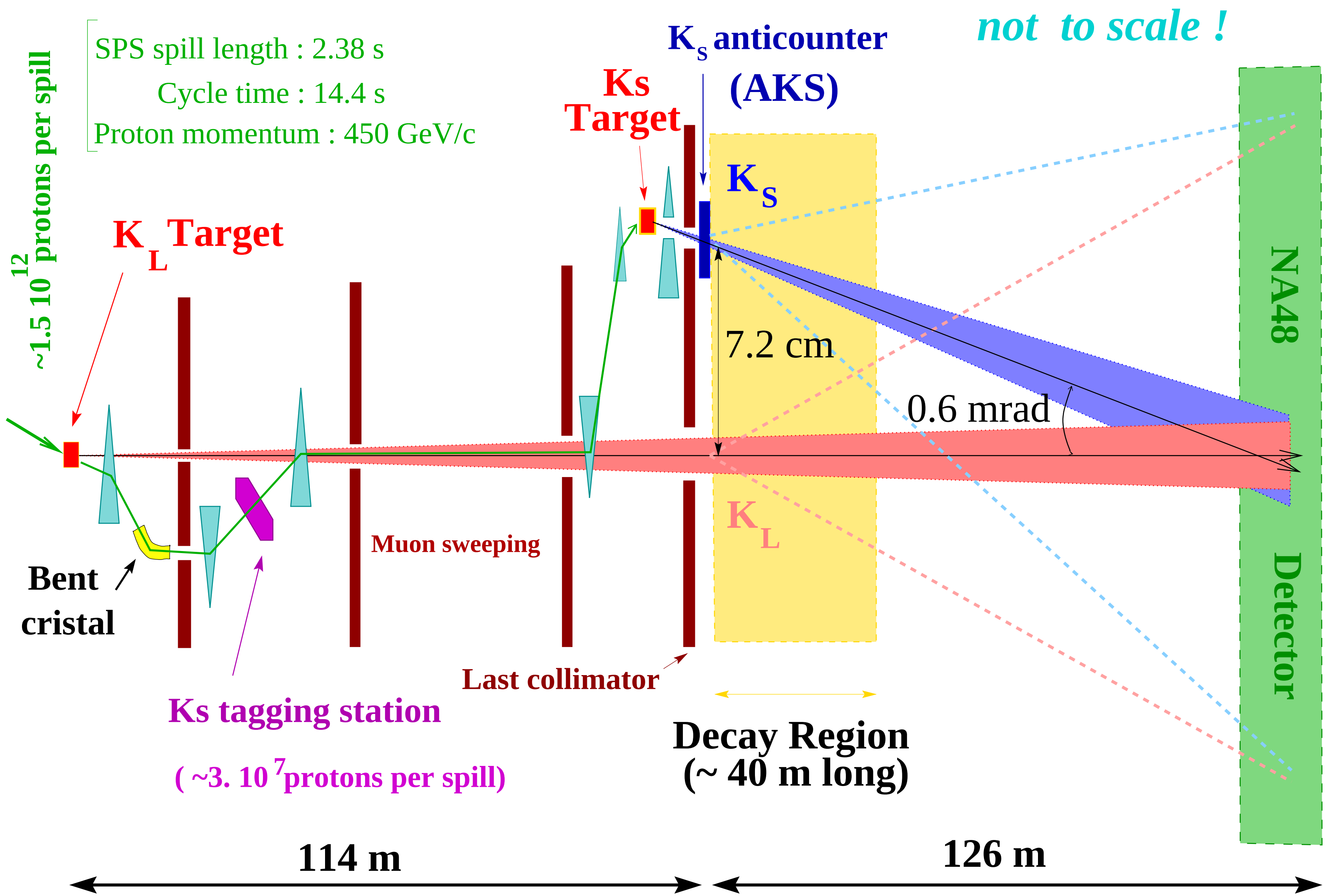
  energy spectra: analysis is performed in 20 energy bins between 70 and 170 GeV

  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



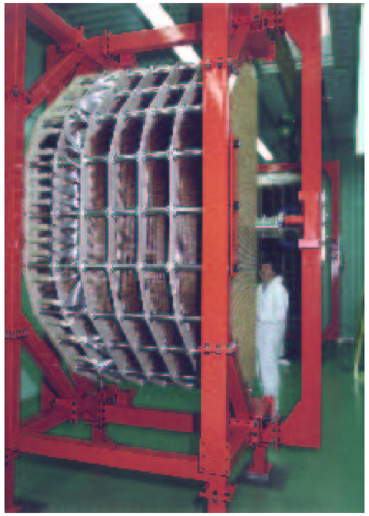
➜ The tagging station provides a measurement of proton time with < 200 ps resolution to distinguish K_S from K_L events

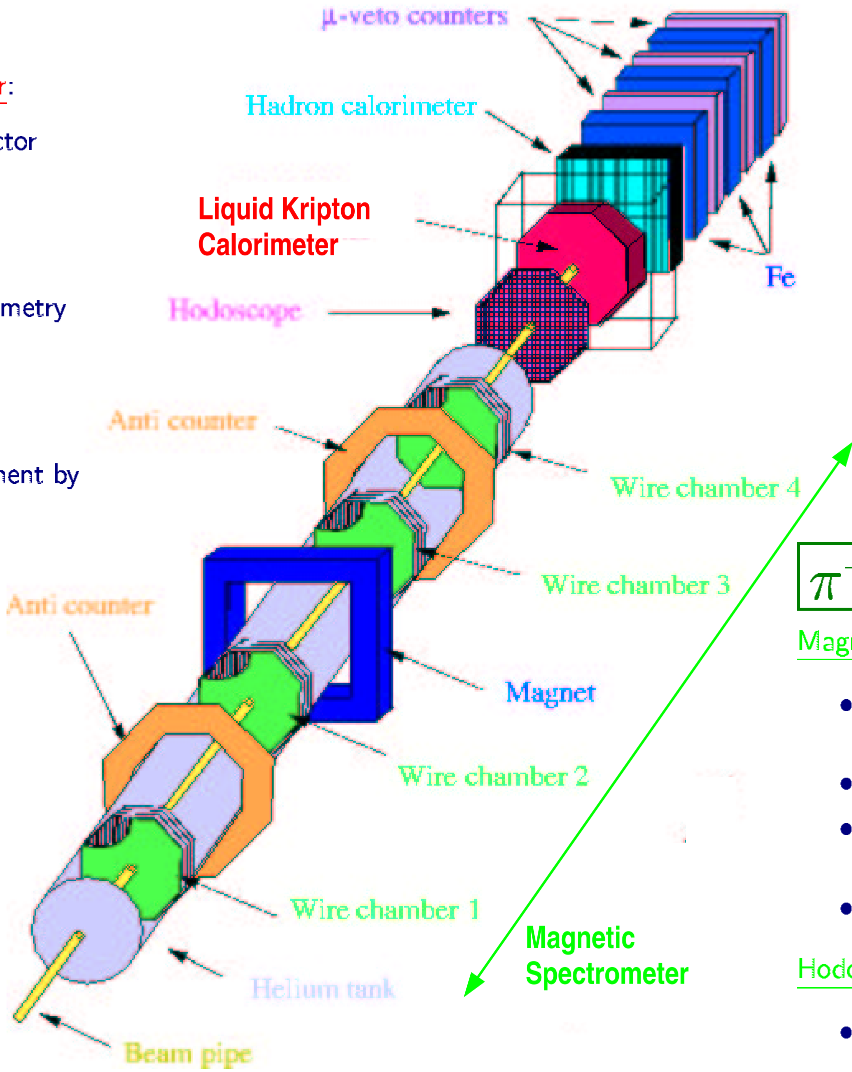
The Central Detector

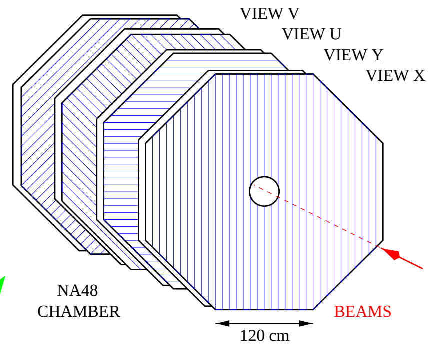
$\pi^0\pi^0$

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







$\pi^+\pi^-$

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

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

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

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

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

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

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

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

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

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

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

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

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

... New drift chambers rebuilt ...

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

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

The 1998+1999 Result

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

R before correction = 0.98739 ± 0.00101 (stat.)

Corrections and systematic errors on R

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

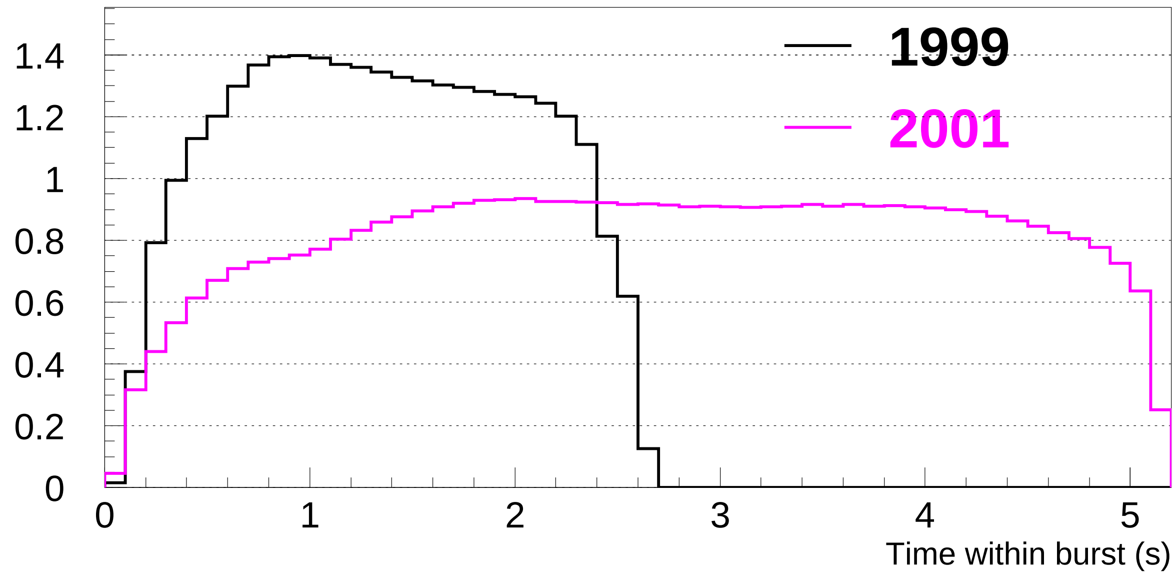
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (1\text{-R})/6 = (15.0 \pm 1.7\ (\mathrm{stat.}) \pm 2.1\ (\mathrm{syst.})) \times 10^{-4}$$

The 2001 Run

➜ Different Beam condition:

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

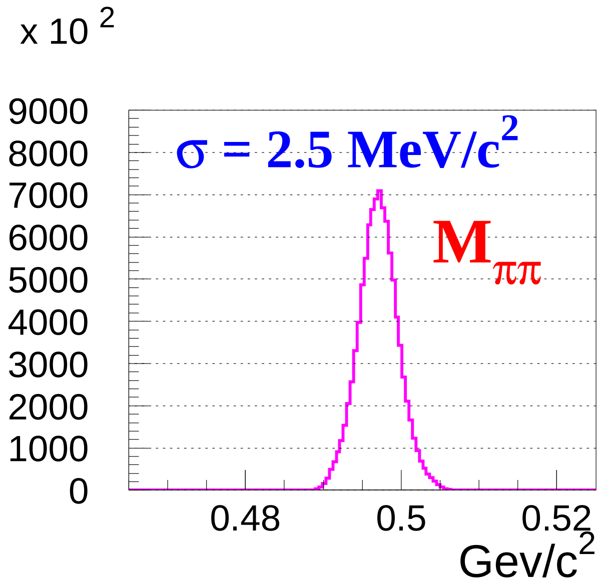
instantaneous intensity $\sim$ 30 % lower



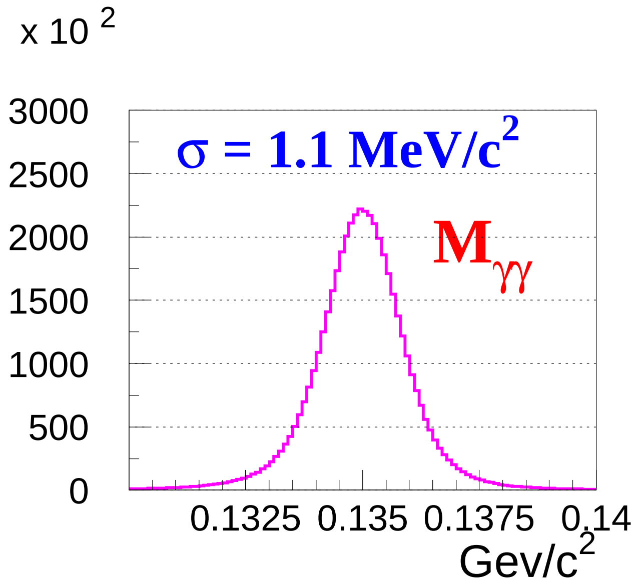
Good K_L Events / 100 ms

➜ New spectrometer's drift chambers

2001 data (preliminary)



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



$K_S \to \pi^0\pi^0$

Comparing 2001 with previous runs

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

➜ The statistical error on the final $\mathrm{Re}(\varepsilon'/\varepsilon)$ result will go from 1.7×10^{-4} to $<1.4\times10^{-4}$

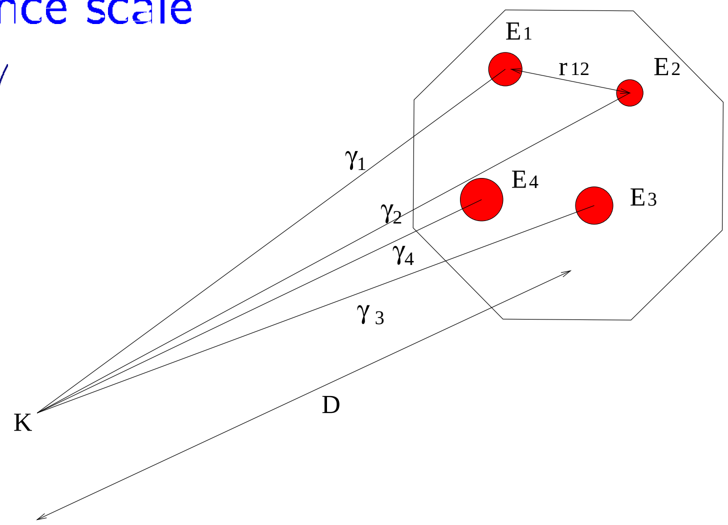
➜ The total error (stat.+syst.) for the 2001 result will be comparable with the published result
$\Longrightarrow$ the 2001 run will be a major cross-check of the measurement against intensity effects

Neutral Energy Scale

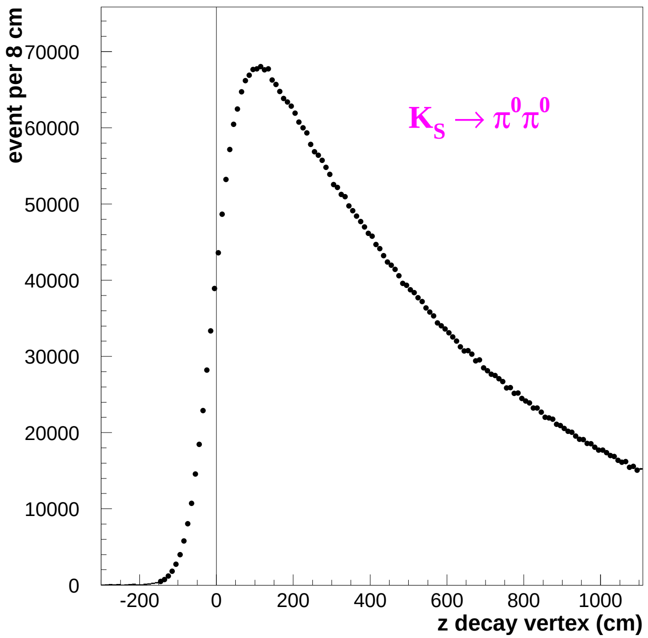
Global energy scale $\Longleftrightarrow$ longitudinal distance scale

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

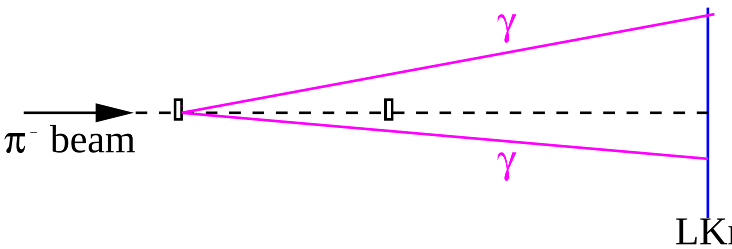
$$D = \sqrt{\sum E_i E_j \times (r_{ij})^2} \; / M_K$$



Energy scale is fixed by adjusting the
$K_S \to \pi^0\pi^0$ vertex distribution
to the know position of the
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:

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

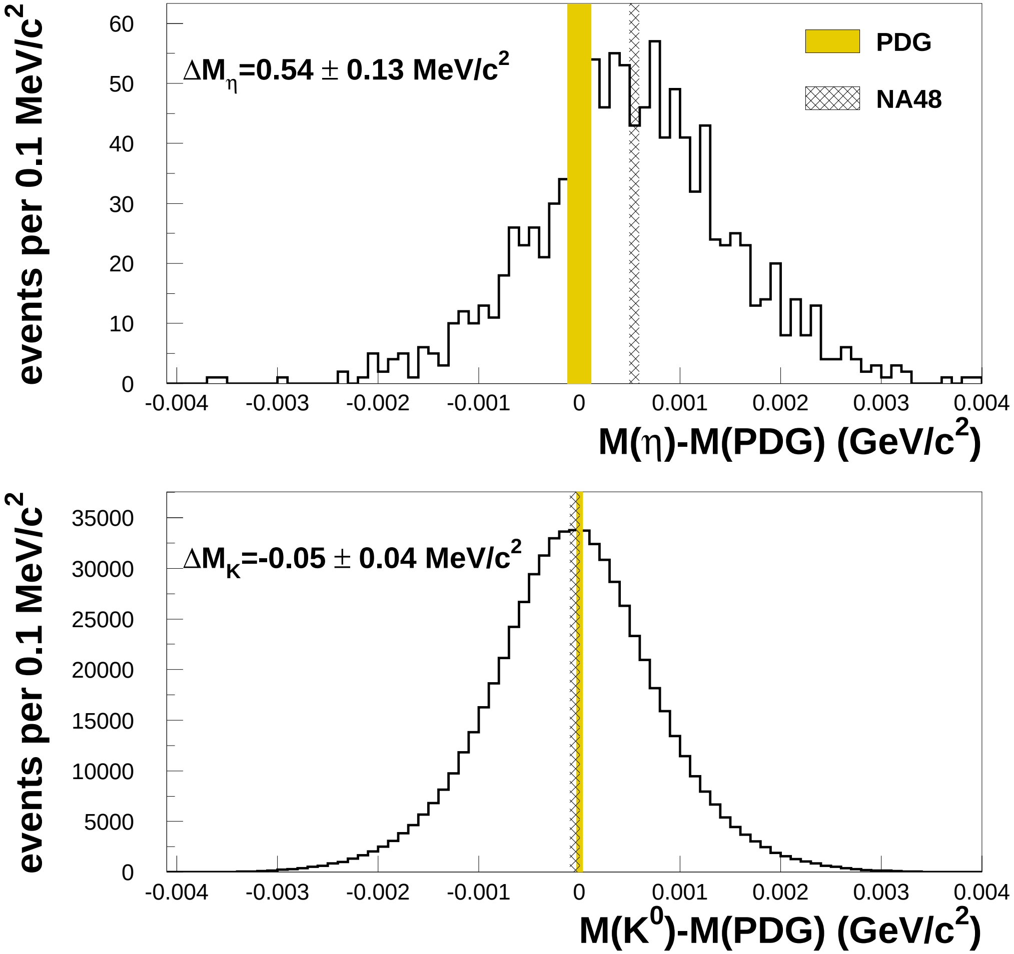
- non–uniformity: $\pm$ 23 KeV/c^2
  (minimized rejecting low–energy γs: $8 < E_\gamma < 37$ GeV)
- energy sharing: $\pm$ 33 KeV/c^2 for η
  $\pm$ 20 KeV/c^2 for K^0
- smaller effects from resolution bias (MC), position measurement, non–gaussian tails

Results for η and K^0 masses

Final samples:

$655 \times 10^3 \; K_L \to 3\pi^0$

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



PDG 2000 Values:

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

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

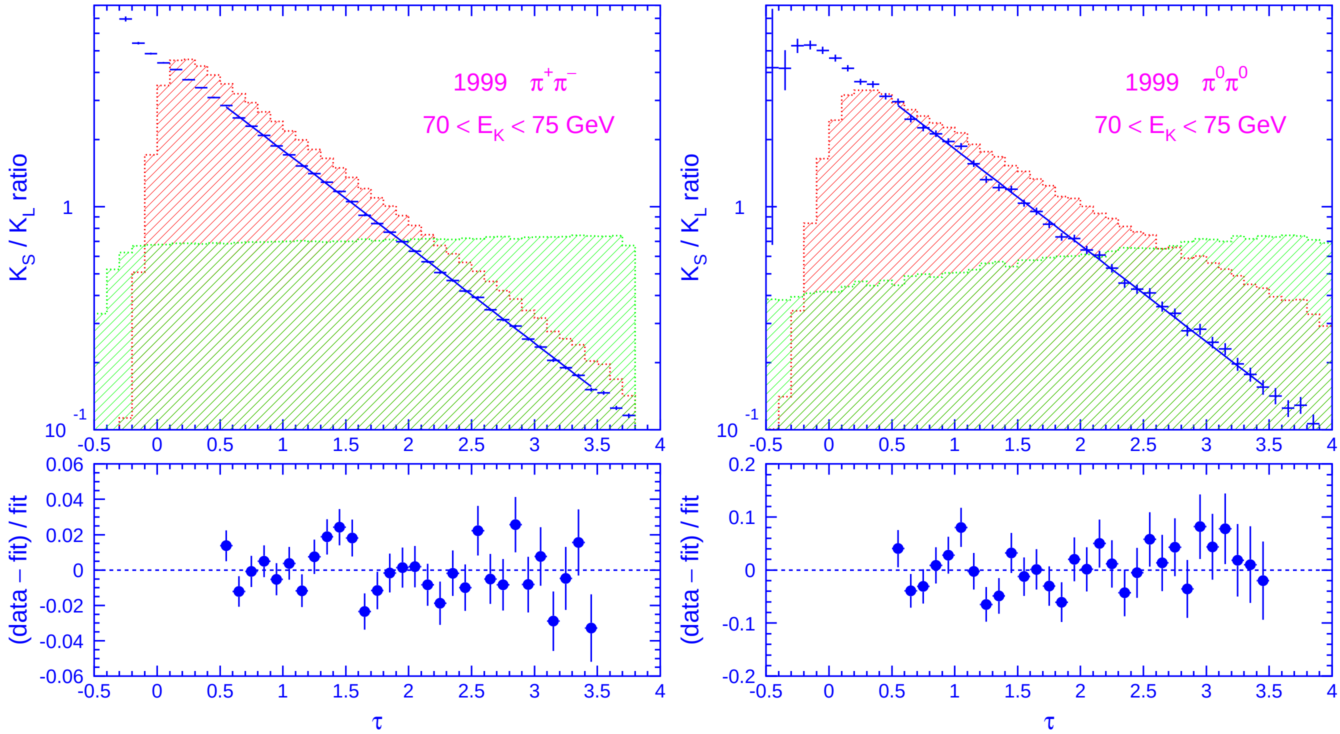
$$M_{K^0} = 497.625 \pm 0.001(stat) \pm 0.003(MC) \pm 0.031(syst) \text{ MeV/c}^2$$

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

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

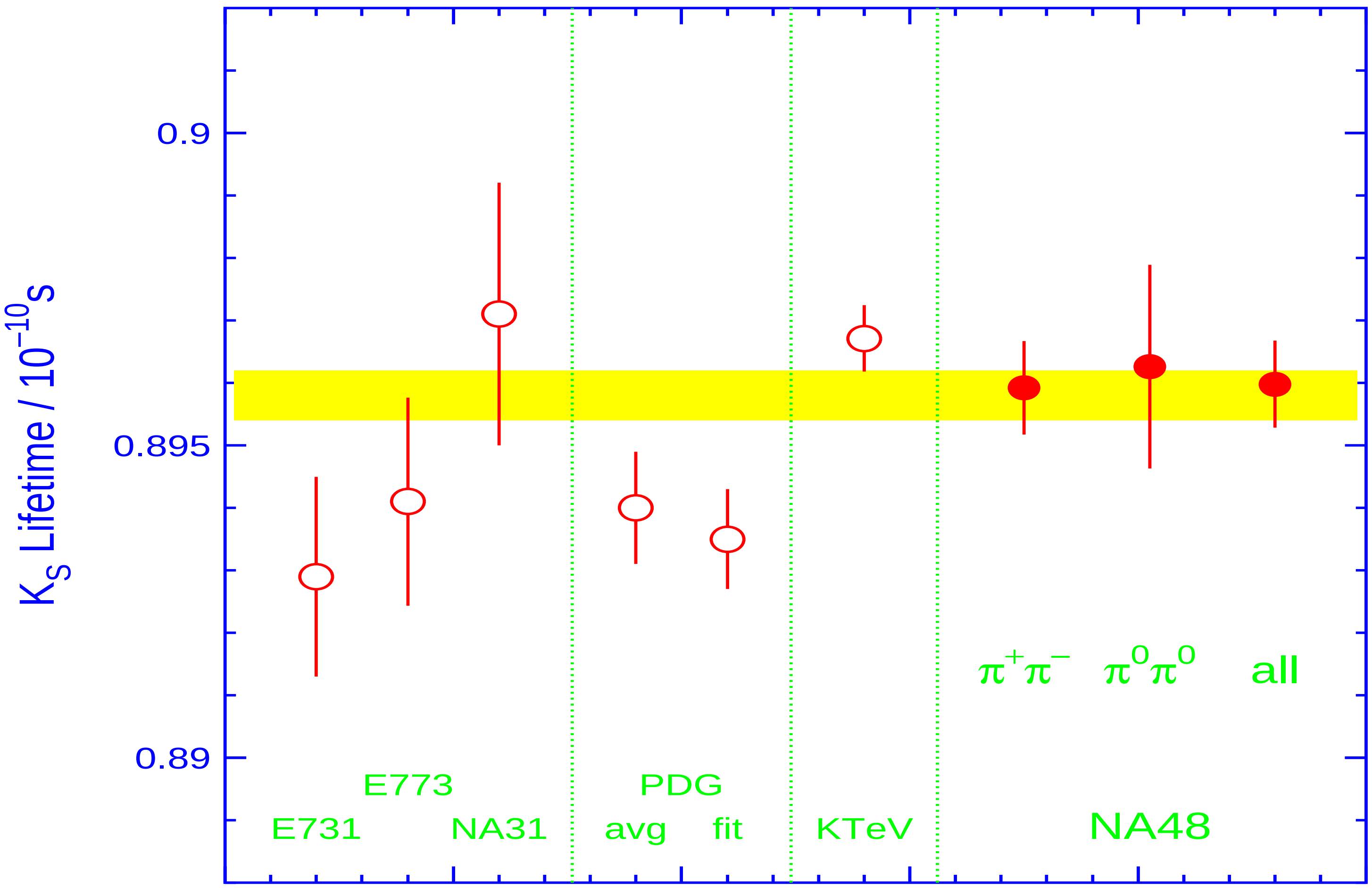
Measurement of K_S lifetime

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

Not only ε'/ε ...

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

Recent results:

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

$$BR = (3.1 \pm 0.1 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-7}$$
$$CPV\,Asymmetry = (13.9 \pm 2.7 \text{ (stat)} \pm 2.0 \text{ (syst)})\%$$

(preliminary)

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

$$BR = (4.3 \pm 0.2 \text{ (stat)} \pm 0.3 \text{ (syst)}) \times 10^{-5}$$
$$CPV\,Asymmetry = (-0.2 \pm 3.4 \text{ (stat)} \pm 1.4 \text{ (syst)})\%$$

(preliminary)

$K_S \to \gamma\gamma$

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

Phys. Lett. B493 (2000), 29

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

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

Phys.Lett. B514 (2001), 253–262

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

$$BR = (1.36 \pm 0.03 \text{ (stat)} \pm 0.03 \text{ (syst)} \pm 0.03 \text{ (norm)}) \times 10^{-6}$$
$$a_V = -0.46 \pm 0.03 \text{ (stat)} \pm 0.03 \text{ (syst)} \pm 0.02 \text{ (theo)}$$

(to be published)

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

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

(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 $K_L \to \pi^0\pi^0$ 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

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

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

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

- 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