The Final Result on Direct CP Violation from the NA48 Experiment

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on behalf of the NA48 collaboration

International Symposium on Multiparticle Dynamics
Alushta, Ukraine
September 11, 2002

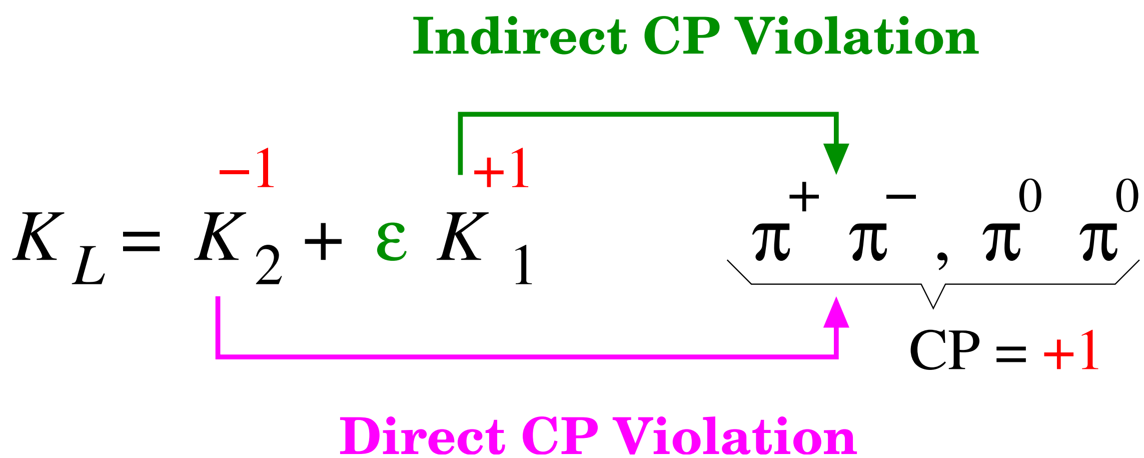
Outline

- ✎ **Short history of direct CP violation in the Neutral Kaon System**
- ✎ **The peculiar NA48 method**
- ✎ **The 2001 data and the FINAL result**
- ✎ **Not only ε'/ε . . .**

CP Violation in the Neutral Kaon System

CP conserved $\Longrightarrow$ $\boxed{K_L = K_2 \equiv \frac{1}{\sqrt{2}}(K^0 - \overline{K^0})}$ (CP=-1) $\Longrightarrow$ $\boxed{K_L \not\Rightarrow \pi\pi}$

1964 : K_L decay to $\pi^+\pi^-$ observed with B.R. $= 2 \cdot 10^{-3}$



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

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

Superweak Model by Wolfenstein : CP violation due to a new force in $\Delta S = 2$ transitions $\Longrightarrow$ $\varepsilon' = 0$

1973 : Kobayashi and Maskawa show that CP violation can be accomodated in the Standard Model by increasing the number of quark generations.

Direct CP Violation in the Standard Model

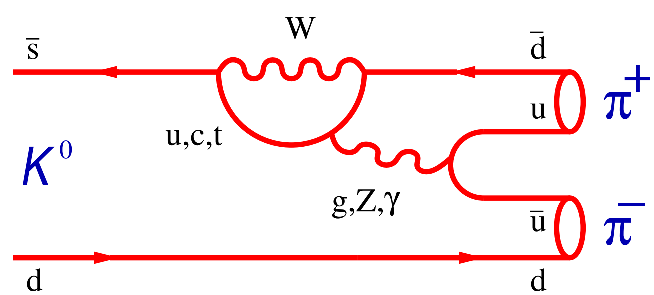
- within the Standard Model ε' can be computed as a function of the CKM matrix elements...

$$\frac{\varepsilon'}{\varepsilon} = \frac{Im(\lambda_t)}{0.074}\left(\frac{110\ MeV}{m_s(2GeV)}\right)^2\left[0.75\ B_6 - 0.4\ B_8\left(\frac{m_t}{165\ GeV}\right)^{2.5}\right]\frac{\Lambda_{\overline{MS}}}{340\ MeV}$$

("pedagogical" formula by A.Buras)

- but errors are dominated by long distance contributions to the penguin diagram terms B_6 and B_8

Current theoretical predictions:
ε'/ε in the range -10 to 30×10^{-4}



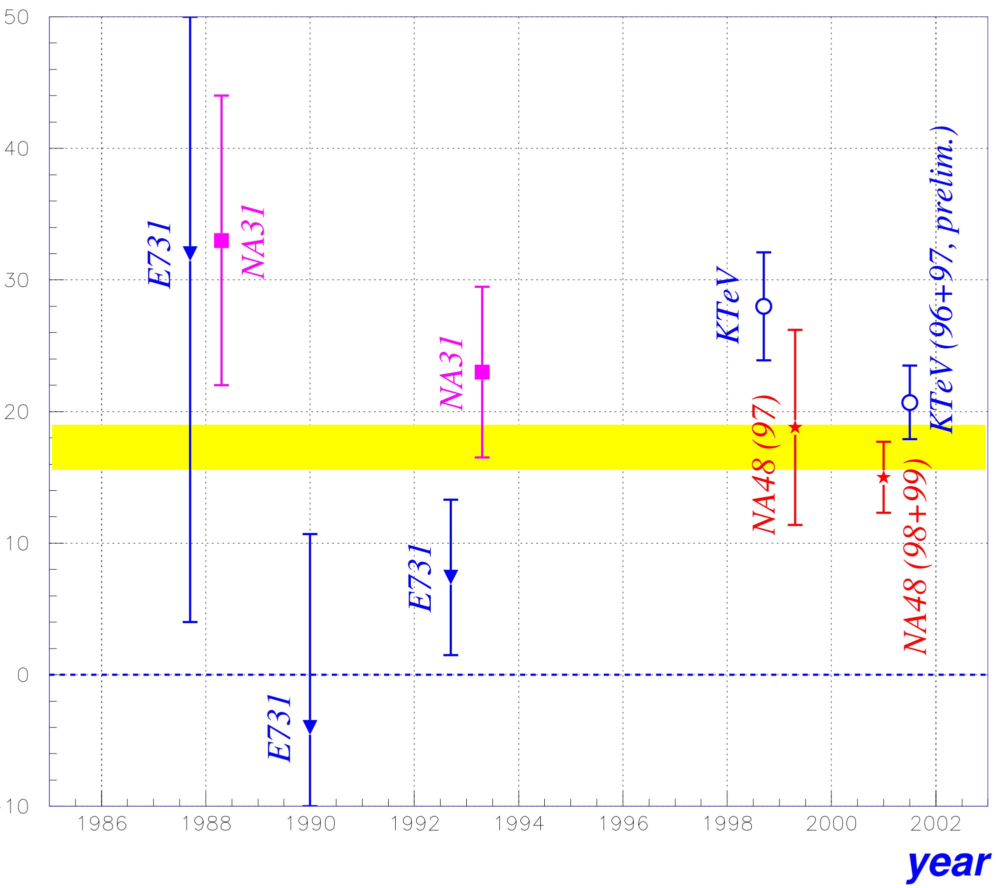
Breakthrough from Lattice QCD computations?

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

Measurements of ε'/ε

So far all experiments used the Double Ratio method:

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



Evolution of World Average:

Year	Average (10^{-4})	χ^2/ndf	χ^2 prob.
1993	14.4 ± 4.4	3.2/1	7%
1999	19.2 ± 2.5	10.4/3	2%
2001	17.3 ± 1.7	5.6/3	13%

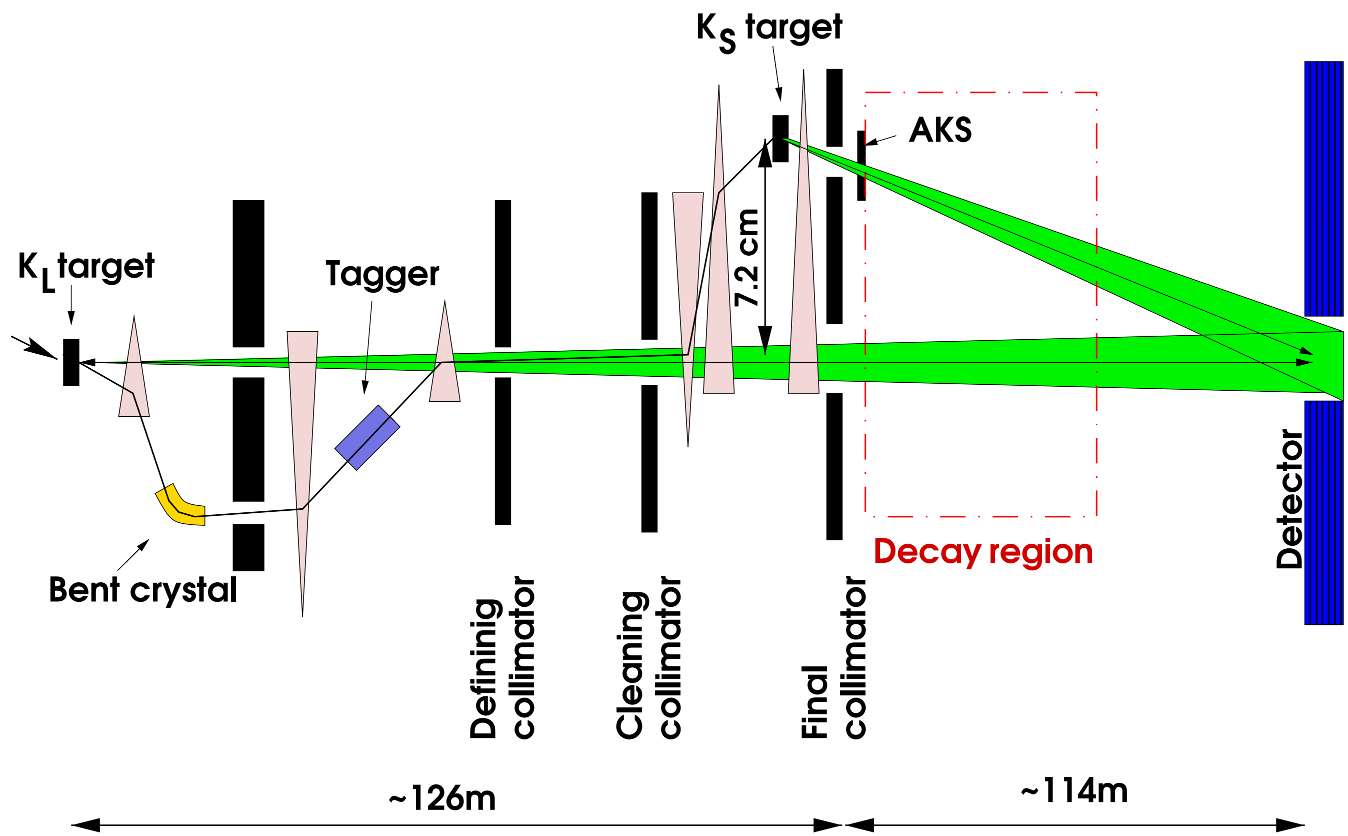
The NA48 Recipe

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

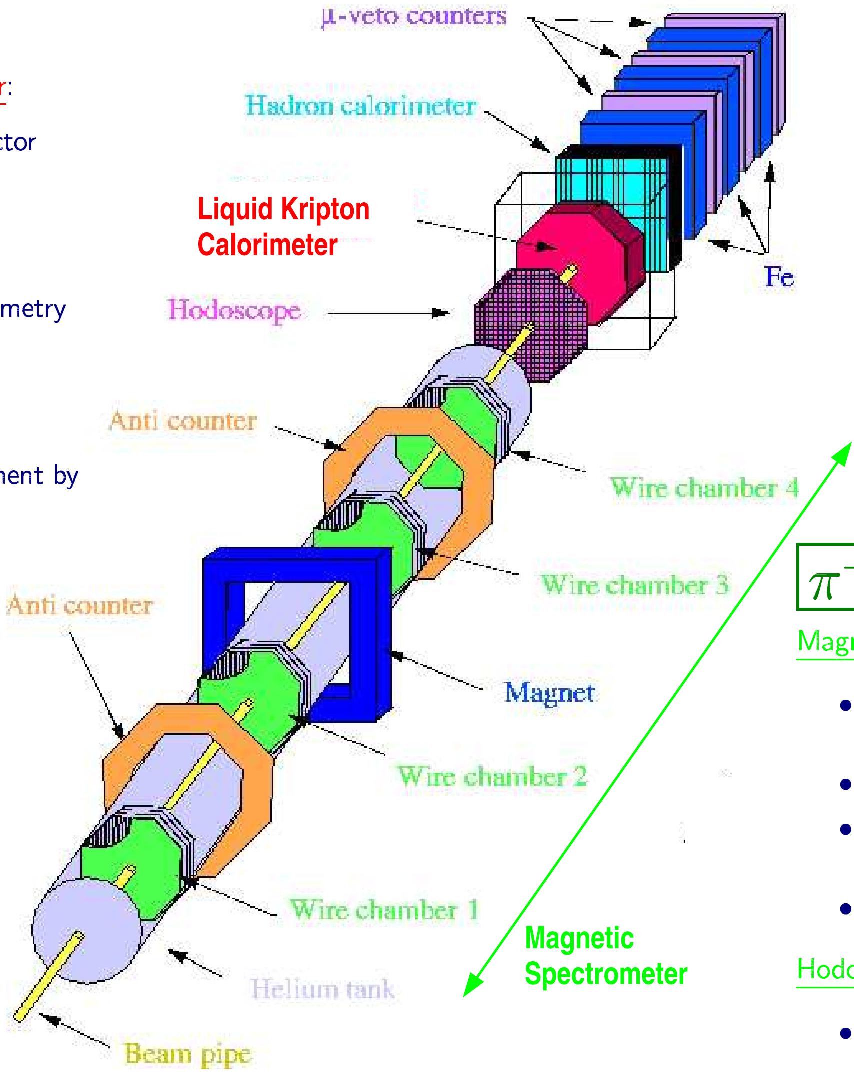


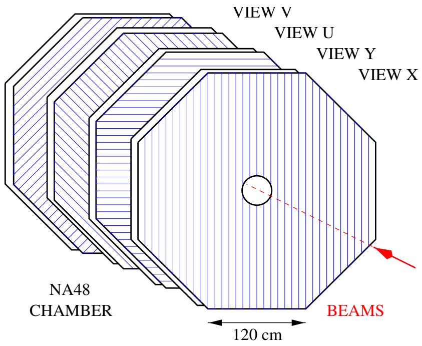
The Central Detector

$\pi^0\pi^0$

LKr electromagnetic calorimeter:

- quasi–homogeneous detector based on 9 m^3 LKr
- Cu–Be electrodes
- 13212 2 × 2 × 127 cm^3
- ± 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

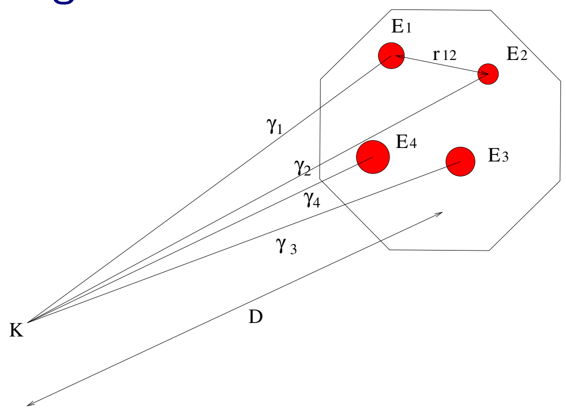
Hodoscope:

- 2 planes of scintillators for precise measurement of event time

Event Reconstruction

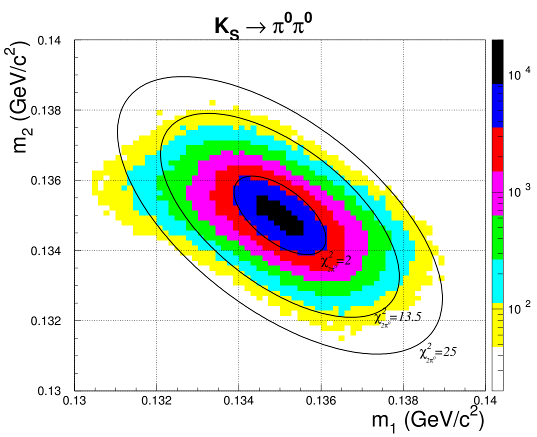
$\pi^0\pi^0$

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



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

- Longitudinal vertex resolution: ~ 55 cm
- π^0 mass resolution:

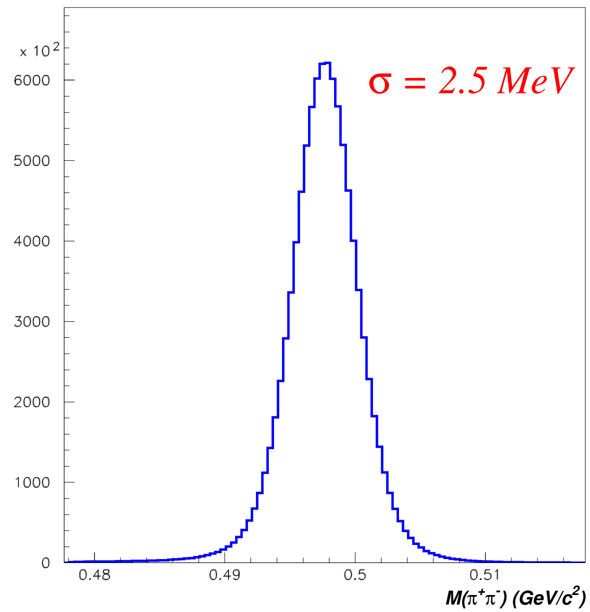


$\sigma_+ \sim 0.42$ MeV

$\sigma_- \sim 0.83$ MeV

$\pi^+\pi^-$

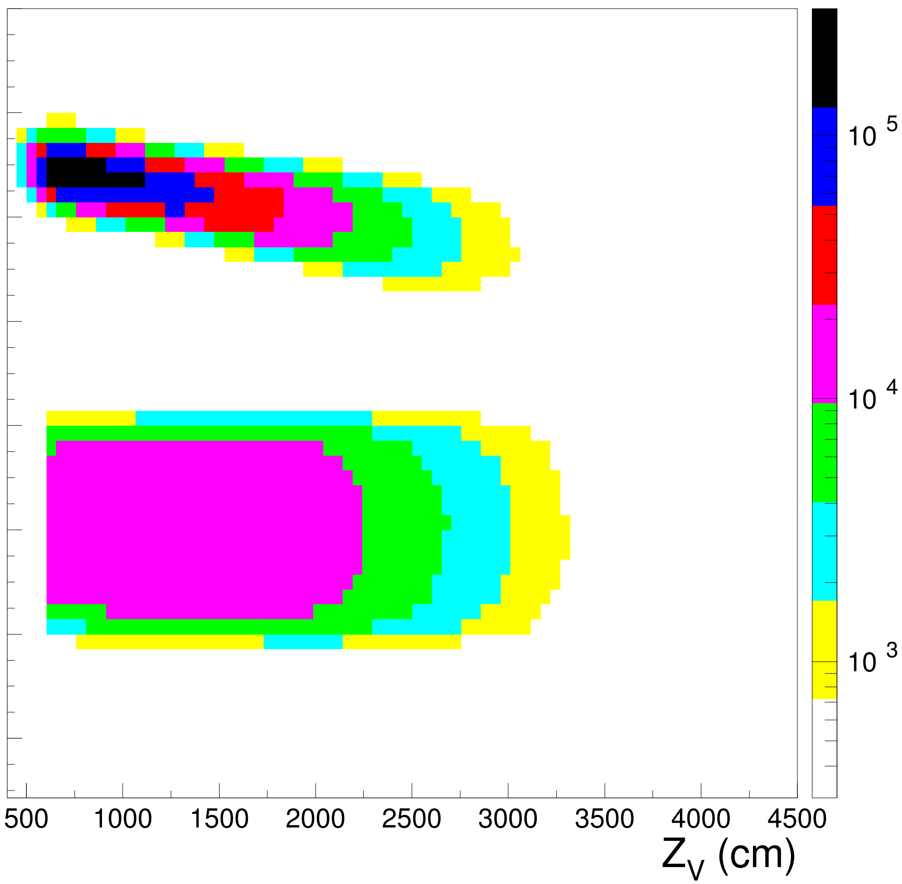
- Momentum resolution:
  $\sigma(P)/P = 0.45\,\% \oplus 0.009\; P[\mathrm{GeV}/c]\,\%$
- Vertex resolution:
  longitudinal ~ 50 cm
  transverse ~ 2 mm
- $\pi^+\pi^-$ invariant mass resolution:



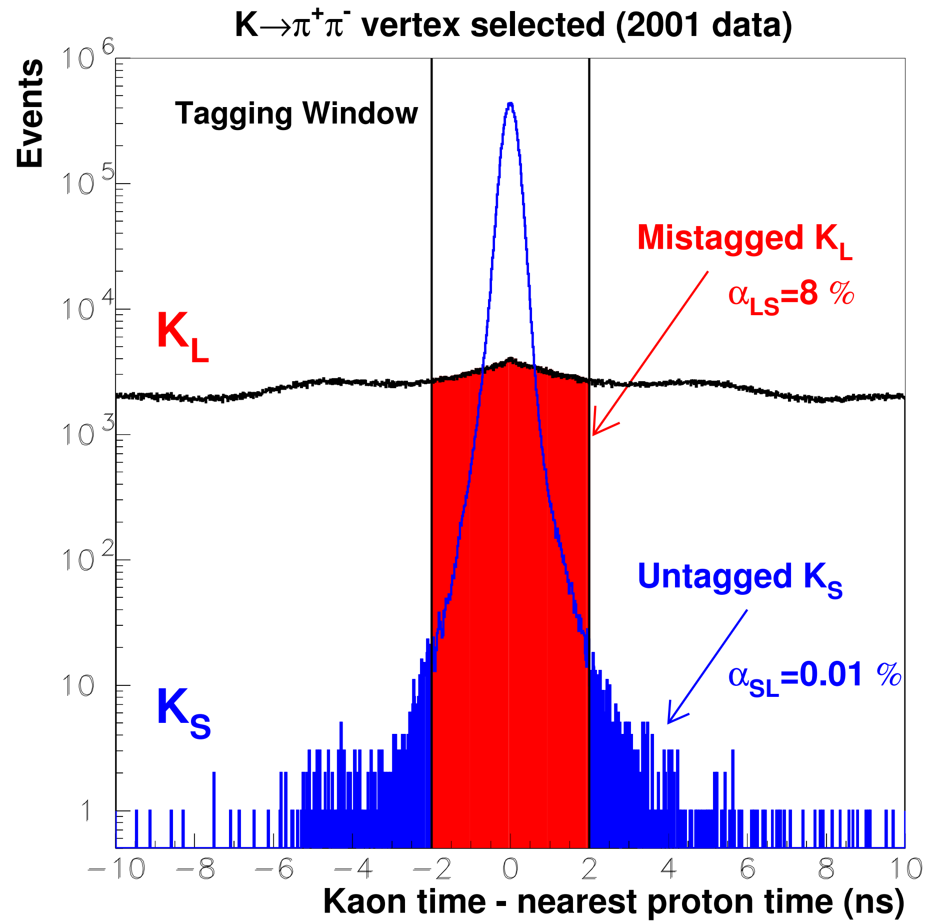
Backgrounds ($3\pi^0, K_{e3}, K_{\mu3}$ decays from $\mathrm{K_L}$) reduced to < 0.2 % !!

Telling K_S *from* K_L

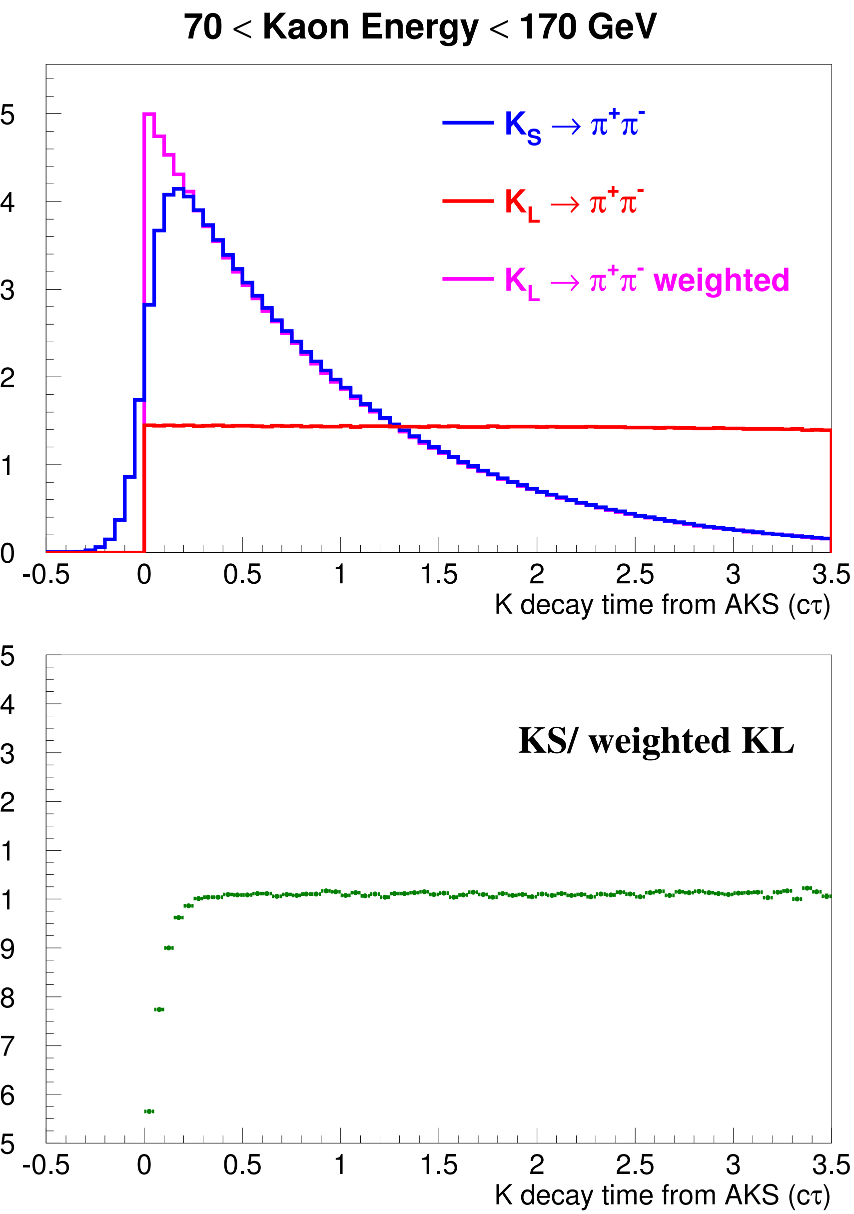
Vertex Identification for $\pi^+\pi^-$

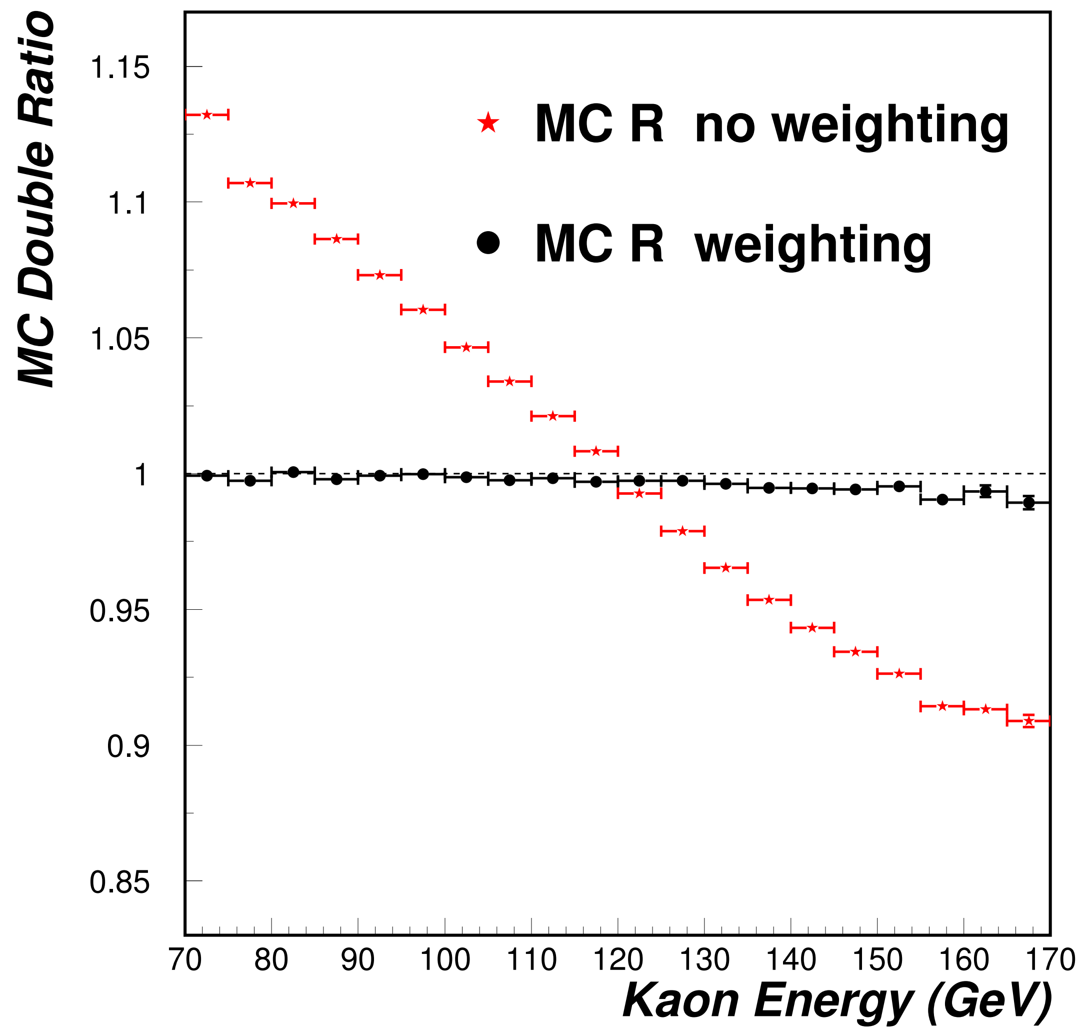


Tagger Identification



K_L Weighting and Acceptance Correction





Residual acceptance difference
after weighting is $< 3 \times 10^{-3}$

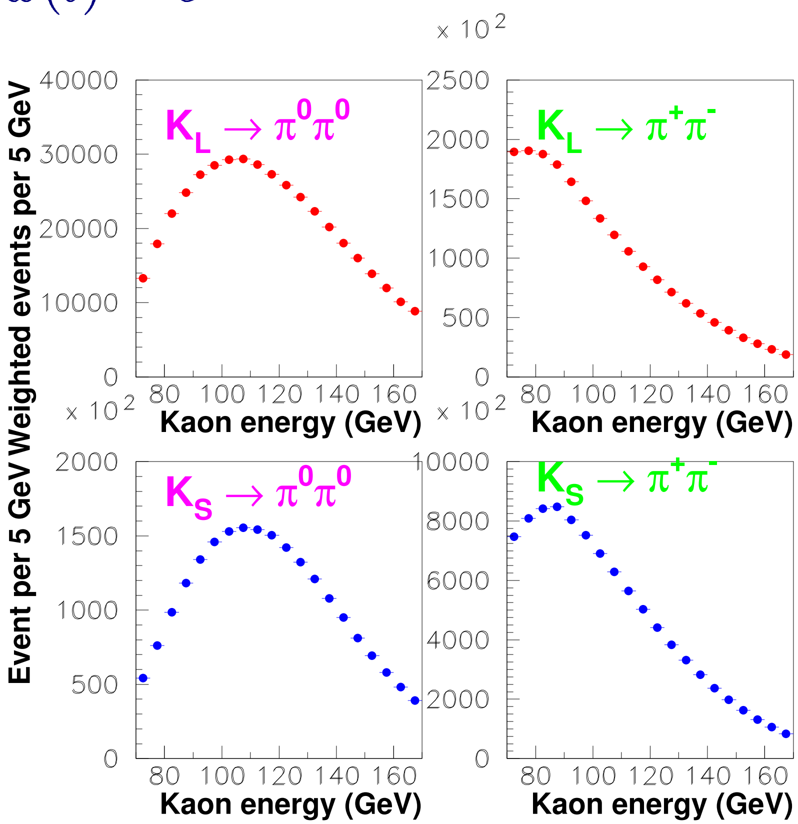
Analysis Strategy

- ➜ identify K_S and K_L by tagging in time the K_S beam protons (correct event counts for mistagging using vertex identification for $\pi^+\pi^-$)
- ➜ the main K_S / K_L differences are minimized offline:

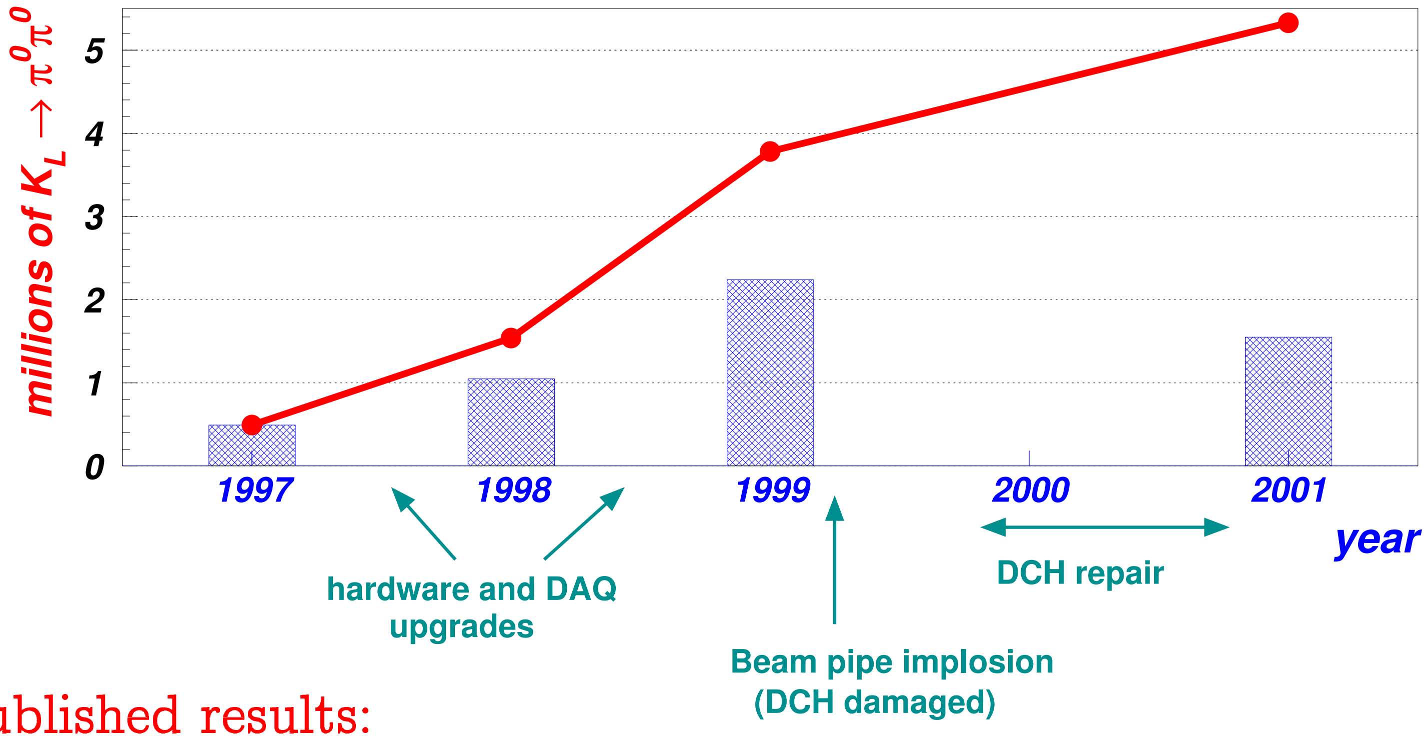
  energy spectra: perform analysis in 20 energy bins from 70 to 170 GeV

  lifetime: weight K_L events according to the theoretical K_S to K_L ratio of proper time distributions: $w(t) \sim e^{-t\left(\frac{1}{\tau_S}-\frac{1}{\tau_L}\right)}$

- ➜ compute the double ratio in each energy bin
- ➜ apply small ($<$ 0.3 % by first principles) corrections for remaining biases (backgrounds, mistagging, reconstruction and intensity effects...)



Data Samples for ε'/ε



➜ Published results:

1997 data: $Re(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$ (Phys.Lett.B465(1999),335)

1998/1999 data: $Re(\varepsilon'/\varepsilon) = (15.0 \pm 1.7 \pm 2.1) \times 10^{-4}$ (Eur.Phys.J.C22(2001),231)

➜ All four chambers damaged after beam pipe implosion in nov. 1999

➜ 2000 run only for neutral events (cross–checks and rare K_S decays)

➜ Chambers rebuilt in time for the 2001 data–taking

FINAL RESULT (INCLUDING 2001) TODAY

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	

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

The 2001 Run

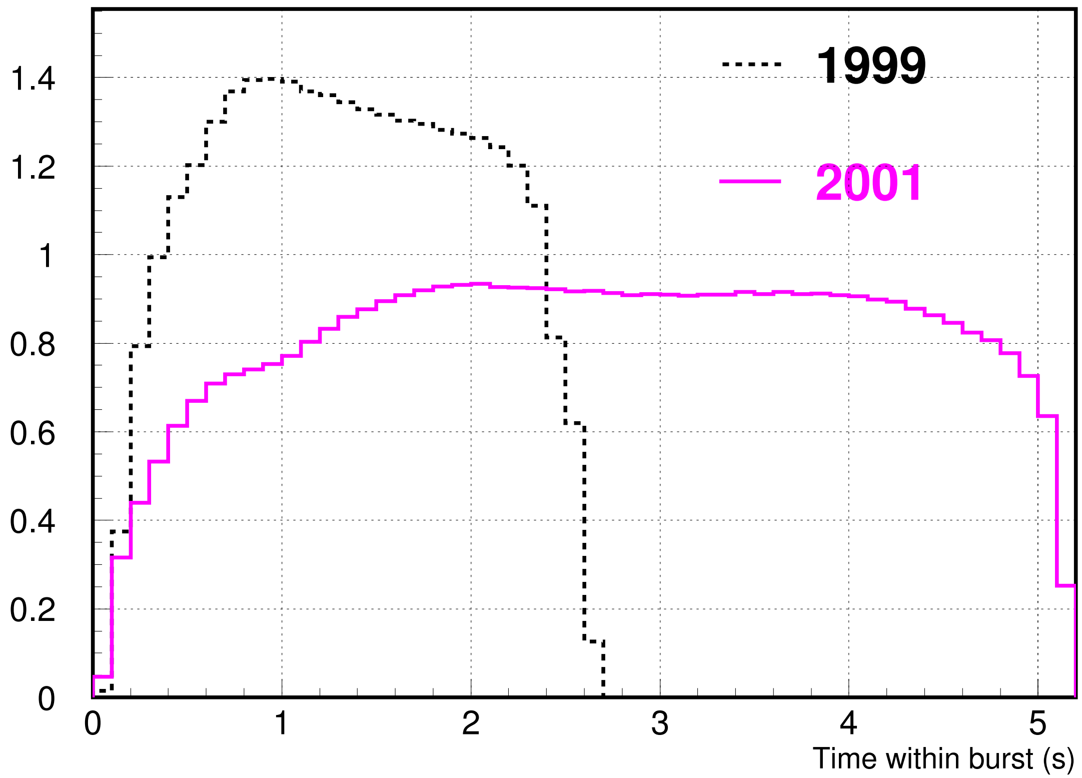
➜ Different Beam conditions:

duty cycle 2.4/14.4 s → 5.2/16.8 s

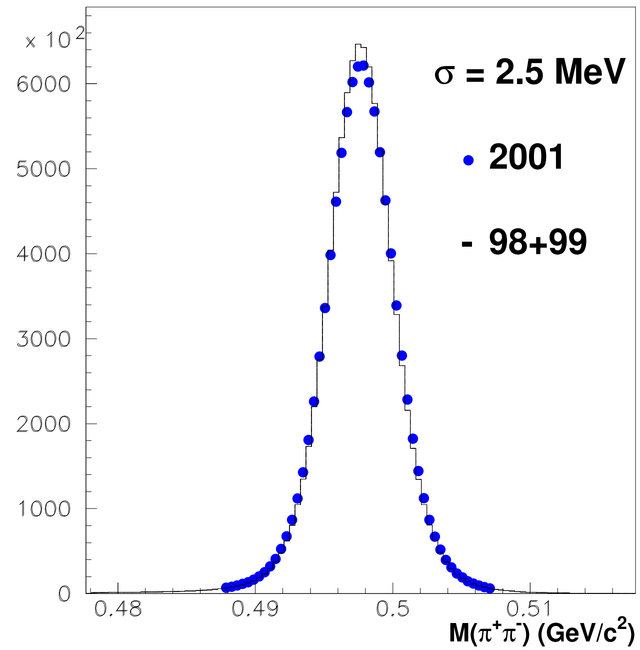
proton energy 450 GeV → 400 GeV

instantaneous intensity ∼ 30 % lower

➜ New spectrometer's drift chambers

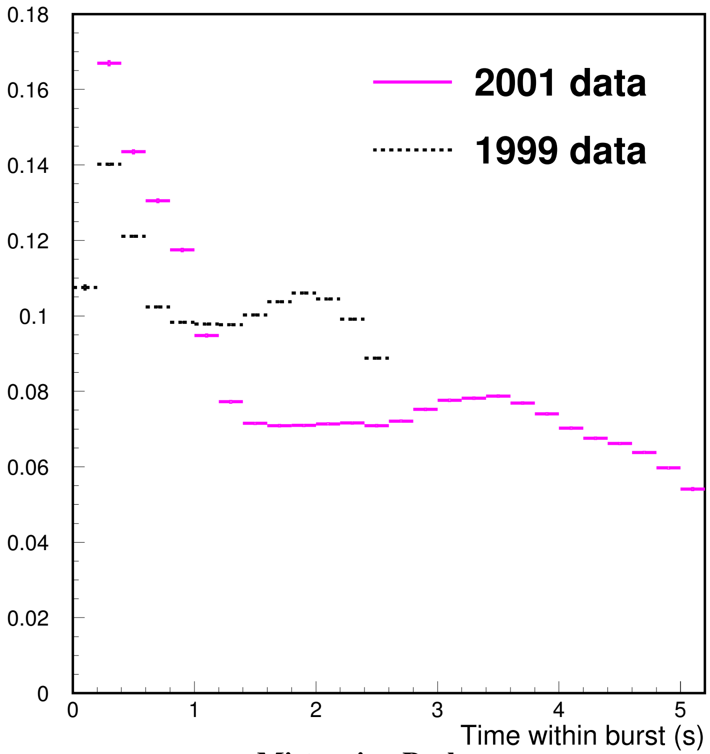


Good K_L Events / 100 ms



Comparing 2001 with 1998/1999

	1998+1999	**2001**
$\#K_L \to \pi^0\pi^0$	3.29×10^6	1.54×10^6
statistical error on R	10.1×10^{-4}	14.7×10^{-4}
DCH overflow rate	21.5 %	11.7 %
Mistagging prob. α_{LS}	10.6 %	8.1 %
L2 charged trigger efficiency	98.3 %	99.2 %



Mistagging Prob. α_{LS}

- ➜ lower average intensity
- ➜ but wider intensity range...
- ➜ better monitors of instantaneous rate

$\Longrightarrow$ lower systematic uncertainty related to rate effects

The Result

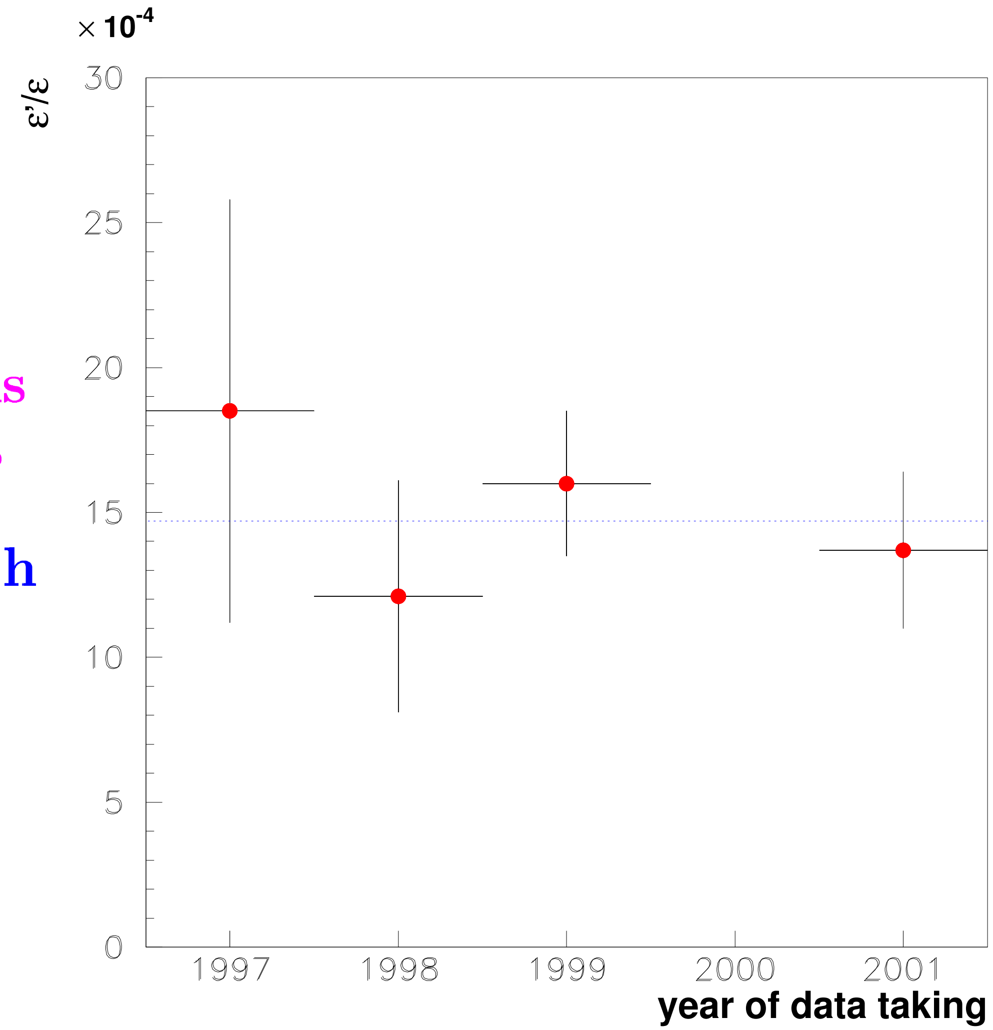
Corrections and uncertainties on R (Units = 10^{-4})
errors are pure stat or pure syst

Source	2001	2001 stat	2001 syst	1998/1999	1998/1999 stat	1998/1999 syst
statistical error		± 14.7			± 10.1	
$\pi^0\pi^0$ reconstruction			± 5.3			± 5.8
Acceptance	21.9	± 3.5	± 4.0	26.7	± 4.1	± 4.0
$\pi^+\pi^-$ trigger inefficiency	5.2	± ✌ 3.6		-3.6	± ☞ 5.2	
Accidentals: intensity diff.			± ✌ 1.1			± ☞ 3.0
illumination diff.		± 3.0			± 3.0	
K_S in–time activity			± 1.0			± 1.0
Accidental tagging	6.9	± ✌ 2.8		8.3	± ☞ 3.4	
Tagging inefficiency			± 3.0			± 3.0
$\pi^+\pi^-$ background	14.2		± 3.0	16.9		± 3.0
$\pi^+\pi^-$ reconstruction			± 2.8			± 2.8
beam scattering	-8.8		± 2.0	-9.6		± 2.0
$\pi^0\pi^0$ background	-5.6		± 2.0	-5.9		± 2.0
AKS inefficiency	1.2		± 0.3	1.1		± 0.4
Total systematic	+35.0	± 6.5	± 9.0	+35.9	± 8.1	± 9.6

$$R = 0.99181 \pm 0.00147_{stat} \pm 0.00110_{syst}$$

ε'/ε *vs Year*

2001 RESULT: $Re(\varepsilon'/\varepsilon) = (13.7 \pm 3.1) \times 10^{-4}$



different beam conditions and new drift chambers

very good agreement with previous years

The Final Result

combining the 2001 result with the 97+98+99 one

$$\left[(15.3 \pm 2.6) \times 10^{-4}\right]$$

we get the final result

$$\boxed{\mathrm{R}e(\varepsilon'/\varepsilon) \;=\; (14.7 \;\pm\; 2.2) \;\times\; 10^{-4}}$$

➜ 5 years of data–taking

➜ 5.3×10^6 $K_L \to \pi^0\pi^0$ collected

➜ proposal goal successfully reached

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)

Notably:

$K_S \to \gamma\gamma$ $\quad BR = (2.78 \pm 0.06\,(\text{stat}) \pm 0.02\,(\text{MC stat}) \pm 0.04\,(\text{syst})) \times 10^{-6}$

(preliminary)

$K_L \to \pi^0\gamma\gamma$ $\quad BR = (1.36 \pm 0.03\,(\text{stat}) \pm 0.03\,(\text{syst}) \pm 0.03\,(\text{norm})) \times 10^{-6}$

$a_V = -0.46 \pm 0.03\,(\text{stat}) \pm 0.04\,(\text{syst})$

Phys.Lett.B536 (2002), 229–240

$K_S \to \pi^0\gamma\gamma$ $\quad BR(m^2_{\gamma\gamma}/m^2_K > 0.2) < 4.4 \times 10^{-7}$ (90 % conf. level)

(preliminary)

$K_S \to \pi^0 e^+ e^-$ $\quad BR < 1.4 \times 10^{-7}$ (90 % conf. level)

Phys.Lett. B514 (2001), 253–262

$K_L \to \pi^+\pi^- e^+ e^-$ $\quad BR = (3.1 \pm 0.1\,(\text{stat}) \pm 0.2\,(\text{syst})) \times 10^{-7}$

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

(preliminary)

$K_S \to \pi^+\pi^- e^+ e^-$ $\quad BR = (4.3 \pm 0.2\,(\text{stat}) \pm 0.3\,(\text{syst})) \times 10^{-5}$ *first observation!*

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

(preliminary)

NA48 program extension

The ε' program is finished, but not NA48

NA48/1 *PRESENTLY RUNNING!*

High–Intensity K_S run : $2 \times 10^{10} ppp$ (ε' intensity $\times$ 600)

- ➜ minor modifications of the beam line
- ➜ new DCH read–out (higher rate capability)

Physics goal: reach unprecedented sensitivity for

- $K_S \to \pi^0 e^+ e^-$ ($\sim 2 \times 10^{-10}$)
- other rare K_S and hyperon decays
- CPV in $K_S \to 3\pi$

NA48/2 *STARTING IN 2003*

Simultaneous K^+/K^- beam

- ➜ new beam line for an unseparated K^+/K^- beam
- ➜ new beam spectrometer (KABES)

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

after the succesfull 2001 run, NA48 presented the final result on $\mathrm{Re}(\varepsilon'/\varepsilon)$:

$$\boxed{\mathrm{R}e(\varepsilon'/\varepsilon) \;=\; (14.7 \;\pm\; 2.2) \;\times\; 10^{-4}}$$

NA48 establishes direct CP violation by more than 6 σ!!

Results of similar accuracy expected from KTEV (FNAL) final sample and possibly from KLOE (at DAPHNE ϕ factory)

THEORY is expected to improve its predictive power for $\mathrm{Re}(\varepsilon'/\varepsilon)$ in the Standard Model, mainly through Lattice QCD calculations.
Example of recent results (systematic errors not finalized...):

CP–PACS group (*hep–lat/0108013*): $\mathrm{R}e(\varepsilon'/\varepsilon) = (-8 \;\div\; 0) \times 10^{-4}$
RBC group (*hep–lat/0110075*): $\mathrm{R}e(\varepsilon'/\varepsilon) = (-9 \;\div\; -1) \times 10^{-4}$

too early to claim for new physics...

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 in the next futures