Final measurement of ε'/ε by NA48

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- **Direct CP violation in neutral kaon decays**
- **History of the ε'/ε measurement by NA48**
- **Analysis of the 2001 data sample**
- **Final result and conclusions**

CP violation in neutral kaon decays

- CP violation in mixing (« indirect »)

$$K_L = K_2 + \varepsilon K_1 \qquad K_S = K_1 + \varepsilon K_2$$

(K_1,K_2 = CP eigenstates) $|\varepsilon| = (2.28 \pm 0.02) 10^{-3}$

- CP violation in $\pi\,\pi$ decay

$$A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-) = \varepsilon + \varepsilon'$$

$$A(K_L \to \pi^0\pi^0)/A(K_S \to \pi^0\pi^0) = \varepsilon - \mathbf{2}\,\varepsilon'$$

ε' = « direct » CP violation (interference between I=0 and I=2 amplitudes)

Standard Model: both ε and ε'

Quantitative predictions difficult: $\varepsilon'/\varepsilon \approx (-10 \text{ to } +30)\ 10^{-4}$

The double ratio R

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

- need to measure small deviation of R from 1
- reduce to event counting if at least 2 modes taken simultaneously

NA48 method:

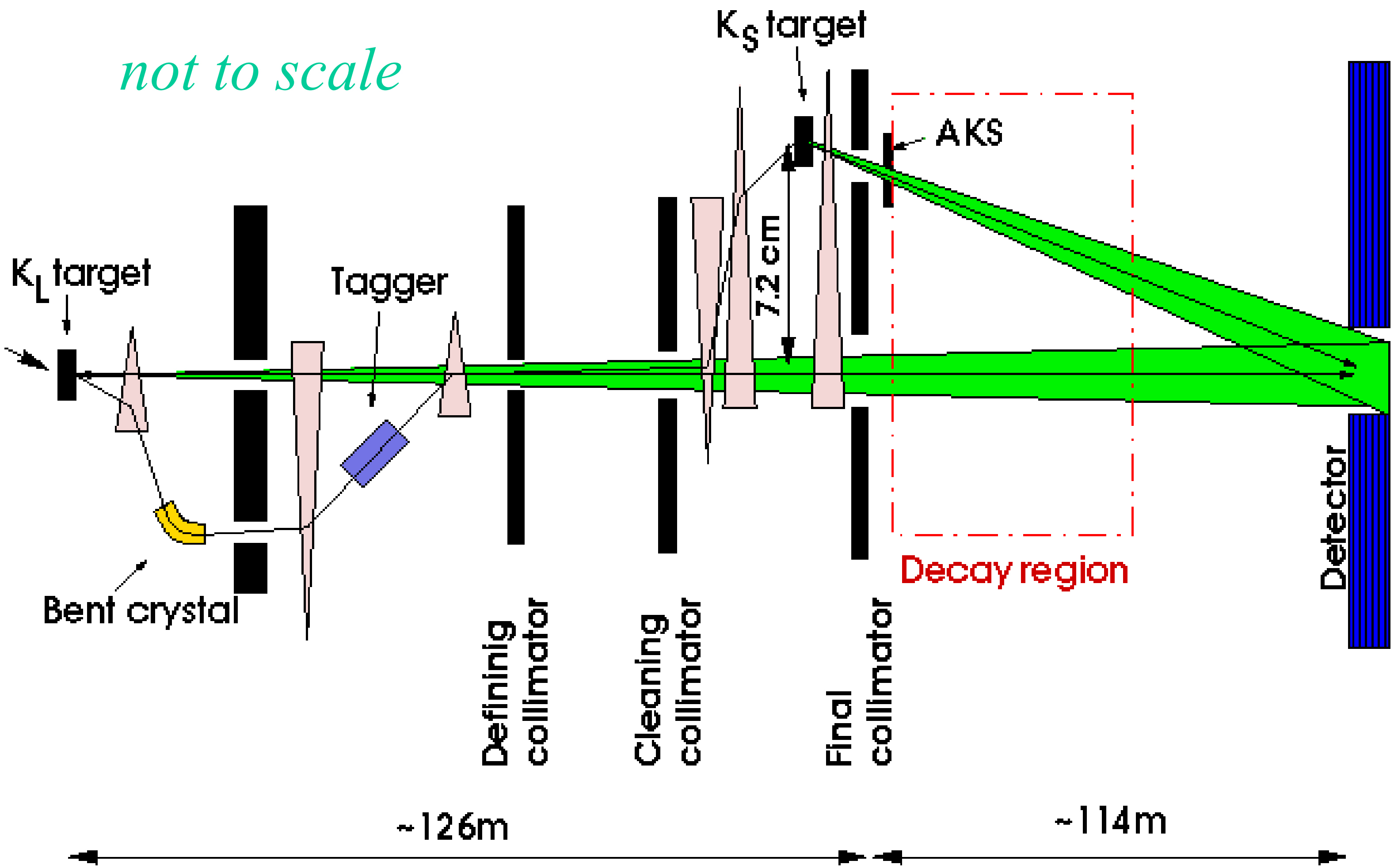
- take the 4 modes
  - o **simultaneously** (⇒cancellation of dead time, inefficiencies, …)
  - o **from same decay region**

    K_L events are **weighted** to have same decay distribution as K_S

    (⇒minimise detector acceptance correction)
- **high resolution detectors** ⇒minimise residual backgrounds
- K_S/K_L identification by **« tagging »** the proton creating the K_S

The Simultaneous K_S and K_L beams

not to scale



The NA48 detector

$\pi^0\pi^0$ detection ($\rightarrow 4\ \gamma$)

LKr calorimeter

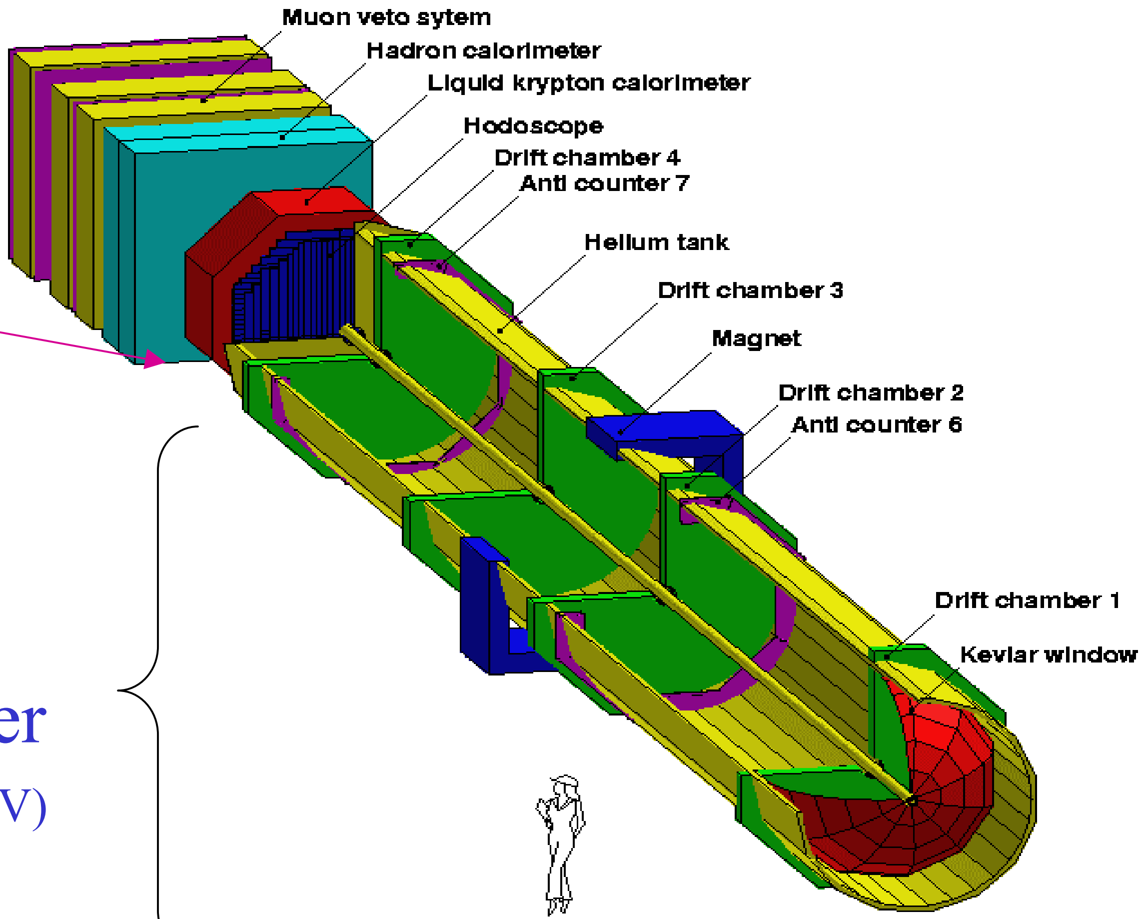
$\sigma(E)/E=0.032/\sqrt{E}\oplus 0.09/E\oplus 0.0042$

$< 1\%$ for E=25 GeV

$\pi^+\pi^-$ detection

magnetic spectrometer

$\sigma(p)/p = 0.5\%\oplus 0.9\%*(p/100\ \text{GeV})$



History of the ε'/ε measurement by NA48

Year:	1997	1998	1999	2000	2001
$N(K_L \to 2\pi^0)$	**0.5** M	**1** M	**2** M	-	**1.5** M

improvements in LKr, triggers, DAQ,efficiency (1997–1999)

2000:
Beam tube implosion

Cross-checks with neutrals (+rare Ks decays)

2001:
Drift chambers rebuilt

Lower beam intensity

$\varepsilon'/\varepsilon = (15.3 \pm 2.6)\ 10^{-4}$
(published in 2001)

Result today !

Summary of uncertainties on R for 98-99 data

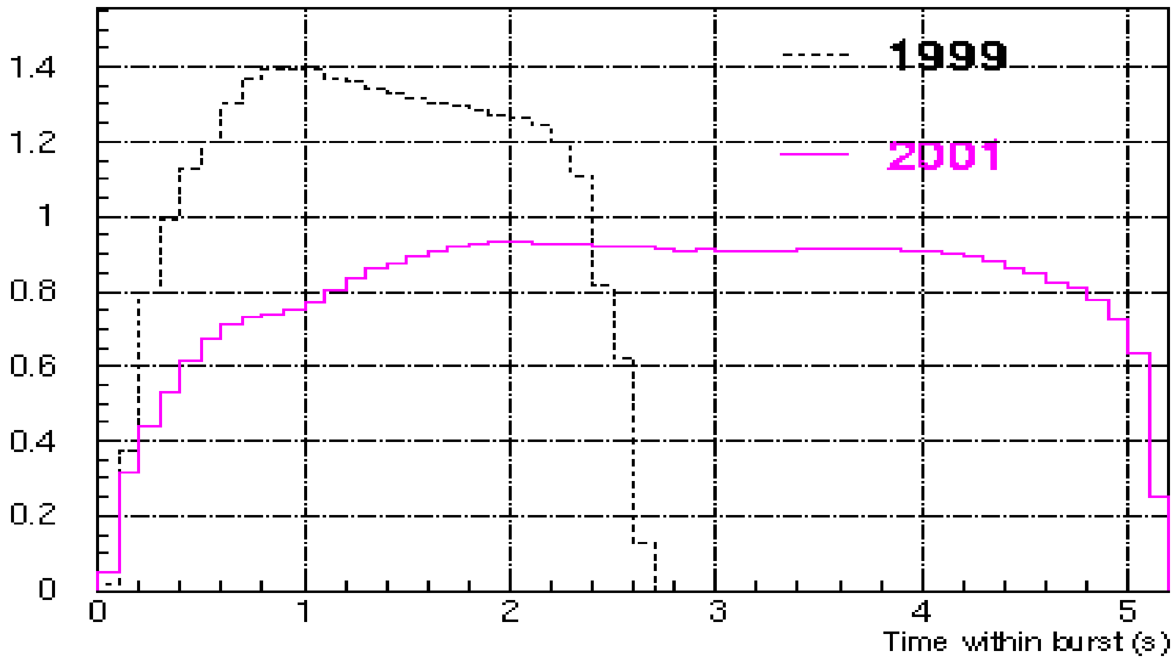
$\pi^+\pi^-$ trigger	± 5.2
K_L accidental tagging as K_S	± 3.4
K_S tagging inefficiency	± 3.0
Accidental activity	± 4.2
K_S in time activity	± 1.0
$\pi^0\pi^0$ reconstruction	± 5.8
$\pi^+\pi^-$ reconstruction	± 2.8
$\pi^0\pi^0$ background	± 2.0
$\pi^+\pi^-$ background	± 3.0
beam scattering bkg	± 2.0
Acceptance (stat)	± 4.1
(syst)	± 4.0
AKS inefficiency	± 0.4

related to beam intensity effects

smaller uncertainties for 2001 data

Example:
$\pi^+\pi^-$ trigger efficiency increased from **97.78%** to **98.70%**

smaller uncertainty in efficiency measurement



Good K_L Events / 100 ms

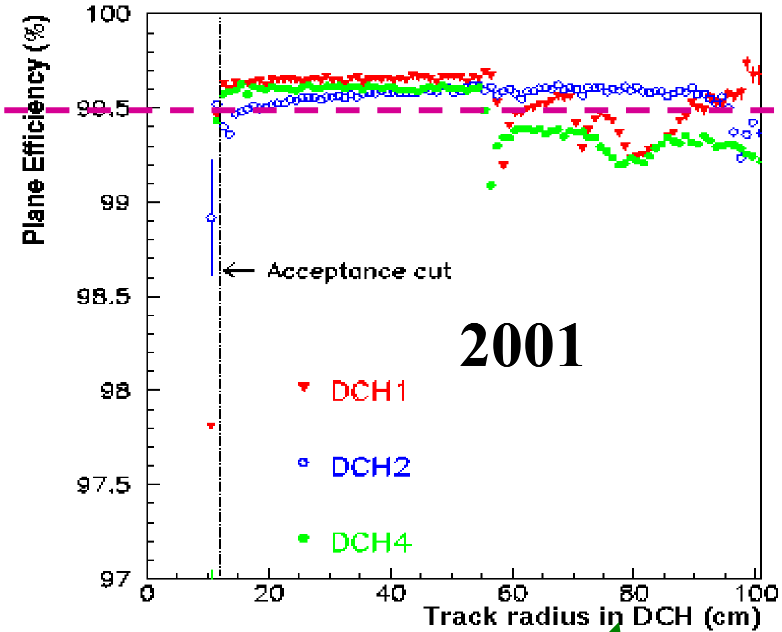
1998-1999 spill=2.4s every 14.4s

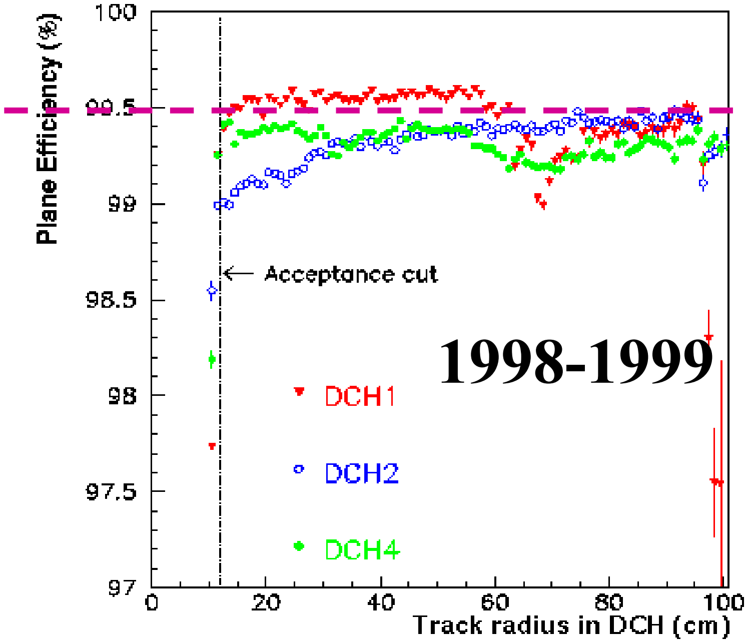
2001 spill=5.2s every 16.8s => 80 % higher duty cycle

Instantaneous beam intensity reduced by ≈30%

Dead time in drift chamber readout: 20% → 11%

(this dead time condition is recorded and applied in the analysis to all events)

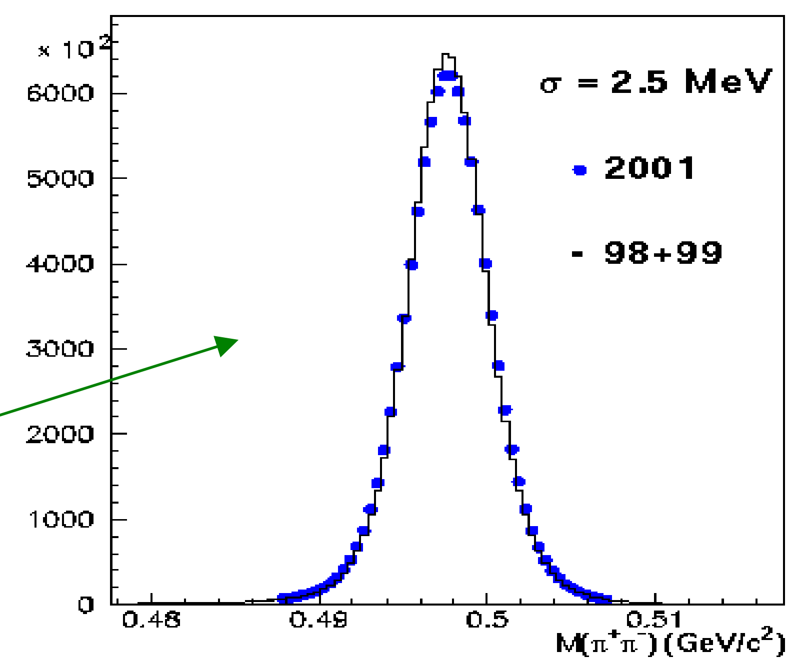




slightly better efficiency

Performances of rebuilt DCH

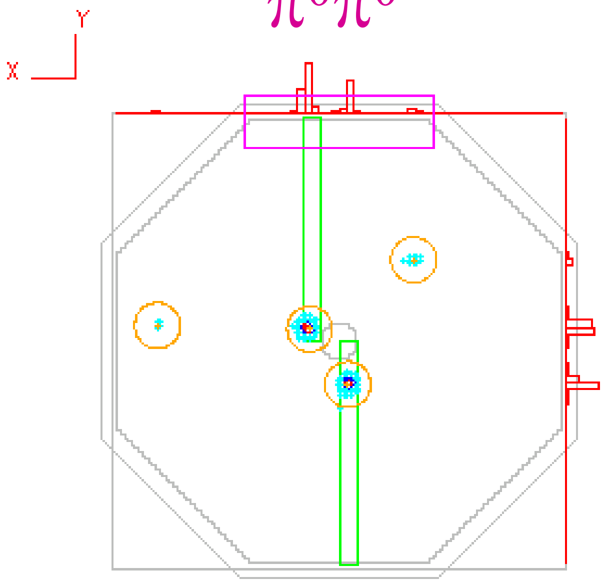
similar $\pi^+\pi^-$ mass resolution



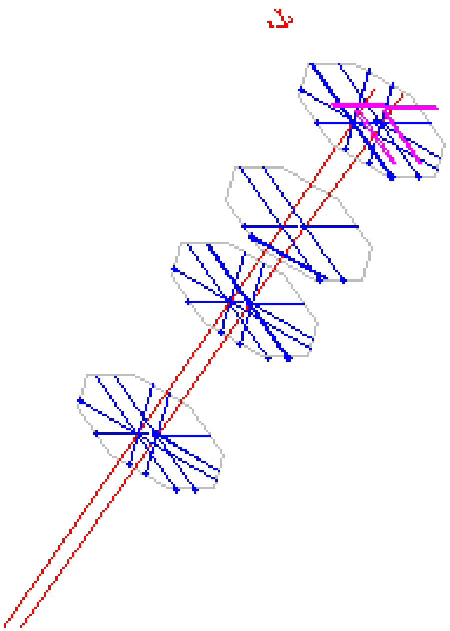
Analysis of the 2001 data sample

(some selected topics…)

$\pi^0\pi^0$



$\pi^+\pi^-$



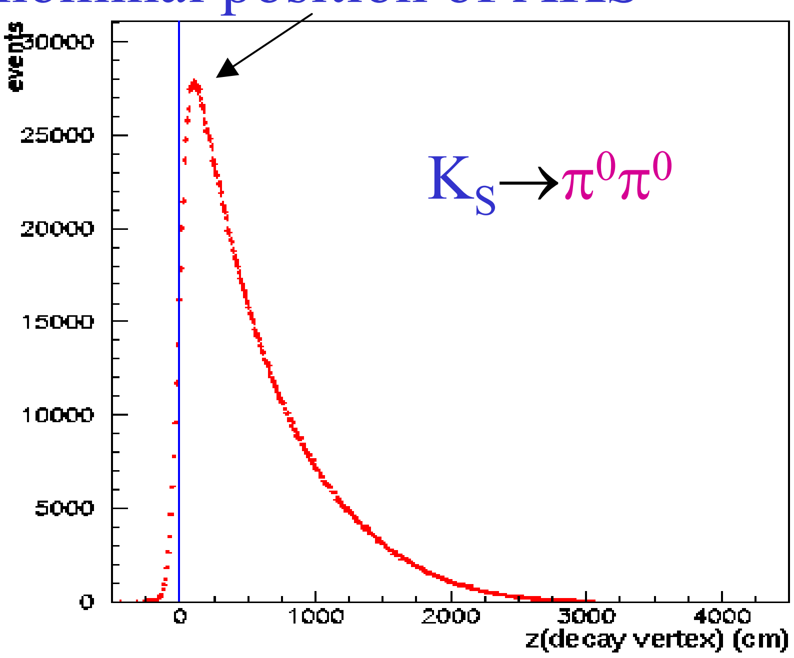
$\pi^0\pi^0$ reconstruction

D(vertex-LKr) = $1/M(K)\sqrt{\sum E_i E_j d_{ij}}$
(from K mass constraint)

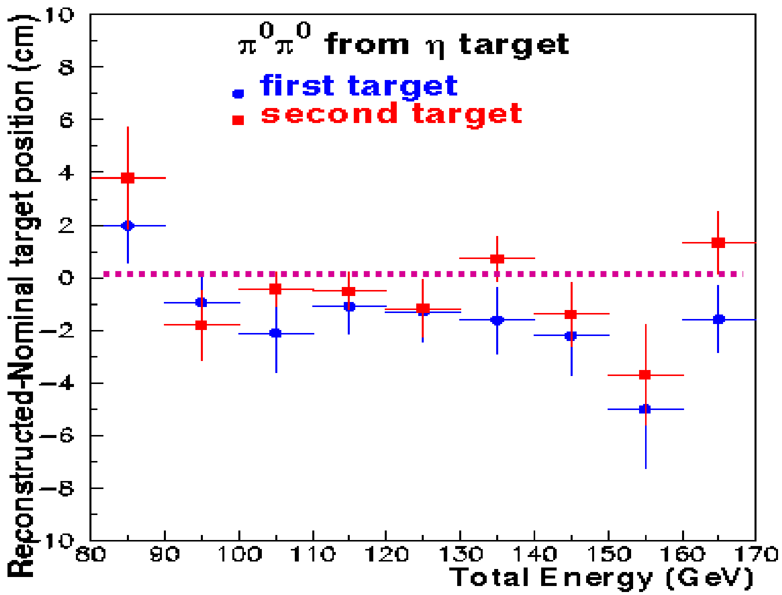
Decay region definition ⇔ Energy scale

1 cm on decay vertex ⇔ 10^{-4} on E-scale

Adjust E-scale to reproduce nominal position of AKS



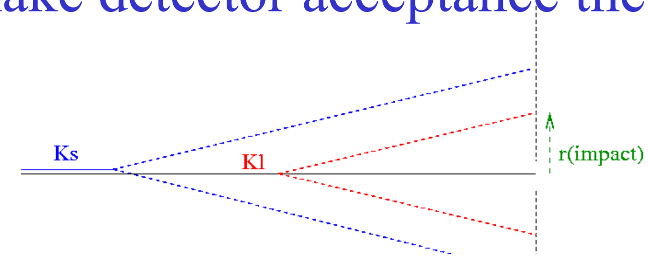
Cross-check: use $\pi^0\pi^0$ hadronic production from π^- beam striking two thin targets during special runs

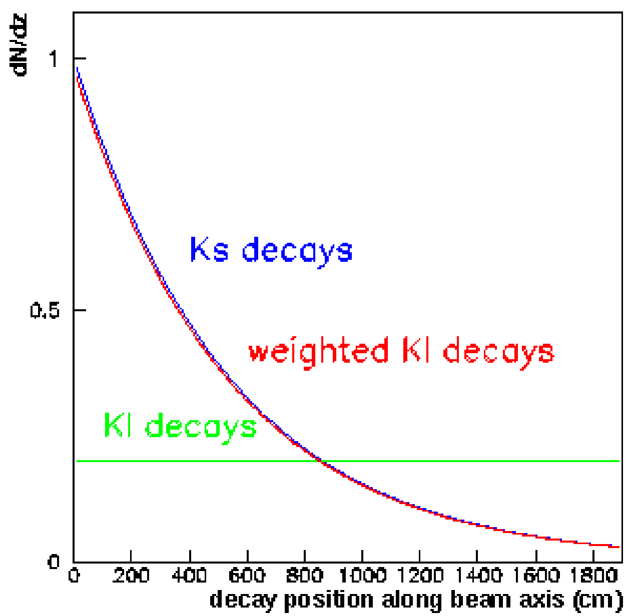


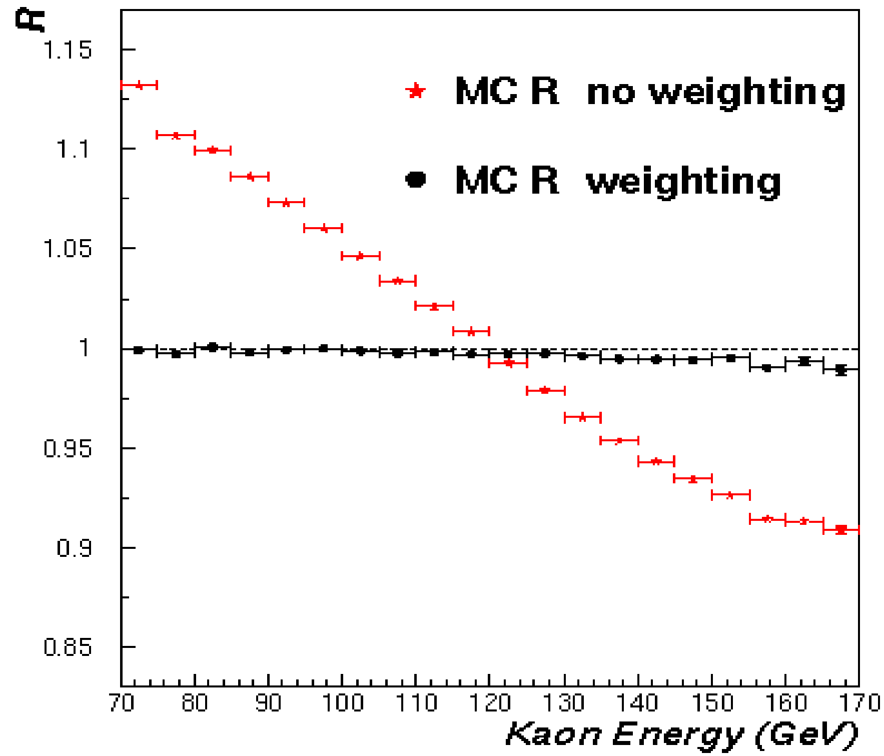
Total uncertainty (E-scale+non linearities+…) = **± 5.3 10^{-4} on R**

Acceptance

Weight K_L events to equalize decay vertex distribution and make detector acceptance the same







Residual correction (beam geometry)

$\Delta(R) = (21.9 \pm 3.5 \pm 4.0)\ 10^{-4}$

Does not rely on detailed detector simulation

K_S-K_L identification

From vertex-identified $\pi^+\pi^-$:

α_{SL}=(1.12±0.03)10^{-4} (K_S tagging inefficiency)

α_{LS}=(8.115±0.010)% (K_L accidental tagging)

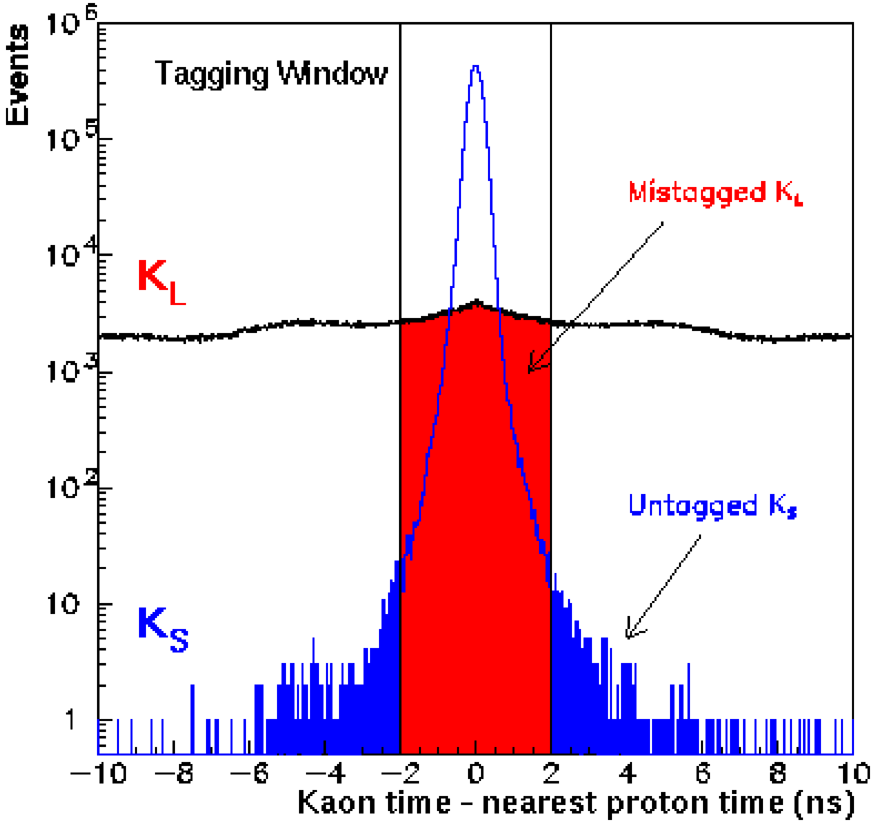
R sensitive to $\pi^+\pi^-$ $\pi^0\pi^0$ differences

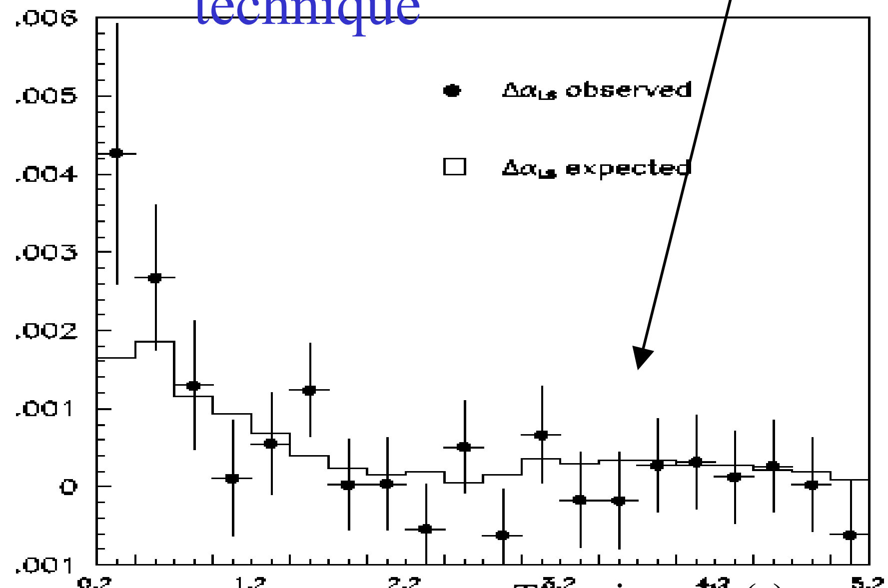
$\Delta\alpha_{SL}$ =(0±0.5)10^{-4} ⇒ **ΔR = (0±3)10^{-4}**

$\Delta\alpha_{LS}$ =(3.4±1.4)10^{-4} ⇒**ΔR =(6.9±2.8)10^{-4}**

Higher losses related to beam intensity in $\pi^+\pi^-$

Can be predicted using overlay technique





Accidental effects

Accidental effect≡event losses induced by (K_L) beam activity

Miminised by simultaneous data collection in 4 modes

$$\Delta R = \Delta(\pi^0\pi^0 - \pi^+\pi^-) * \Delta(K_L\text{-}K_S)$$

- $\Delta(\pi^0\pi^0\text{-}\pi^+\pi^-)$ minimised by applying to all events the recorded dead time conditions

  main tool: overlay $\pi\pi$ events with random events ($\propto$ beam intensity)

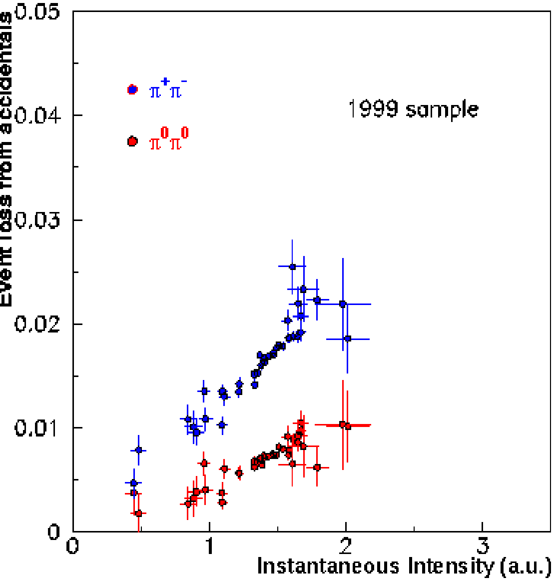
- $\Delta(K_L\text{-}K_S)$ small by design of the experiment:
  - **simultaneous beam**

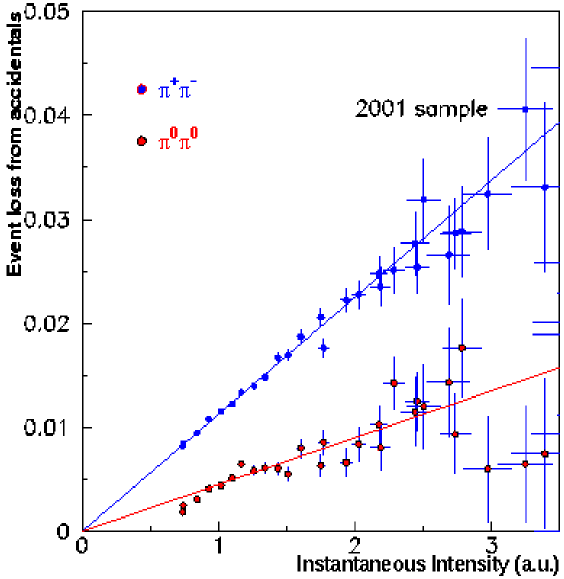
    K_S and K_L decays see the ***same beam intensity***

    deviation = « intensity difference effect »
  - **lifetime weighting**

    K_S and K_L decays illuminate the ***same part of the detector***

    residual effect = « illumination difference effect »



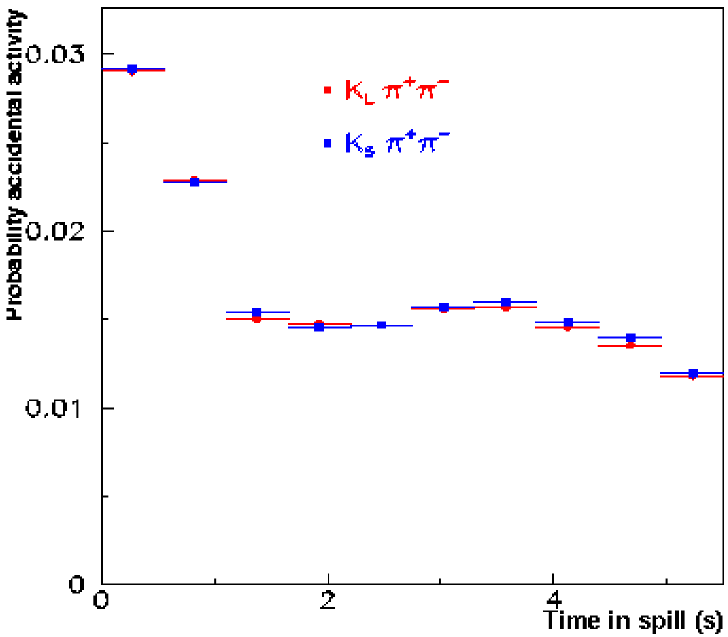


Event losses (from overlay):

$\Delta(\pi^+\pi^- - \pi^0\pi^0) = (1.0 \pm 0.5)\%$

for 2001 data

Better check of linearity of losses in 2001 (better beam monitors)



Measure accidental activity ($\propto K_L$ beam intensity) in K_S and K_L events

$\Rightarrow \Delta I/I = (0 \pm 1)\%$

Uncertainties from accidental effects:

- Intensity difference effect:
  from estimates of $\Delta(\pi^+\pi^- - \pi^0\pi^0)$ and $\Delta I/I$

$$\Delta R = \pm\ 1.1\ 10^{-4}$$

(was $\pm 3\ 10^{-4}$ for 98-99 data)

- Illumination difference effect:
  overlaying « random » events to K_S and K_L decays

$$\Delta R = \pm\ 3.0\ 10^{-4}$$

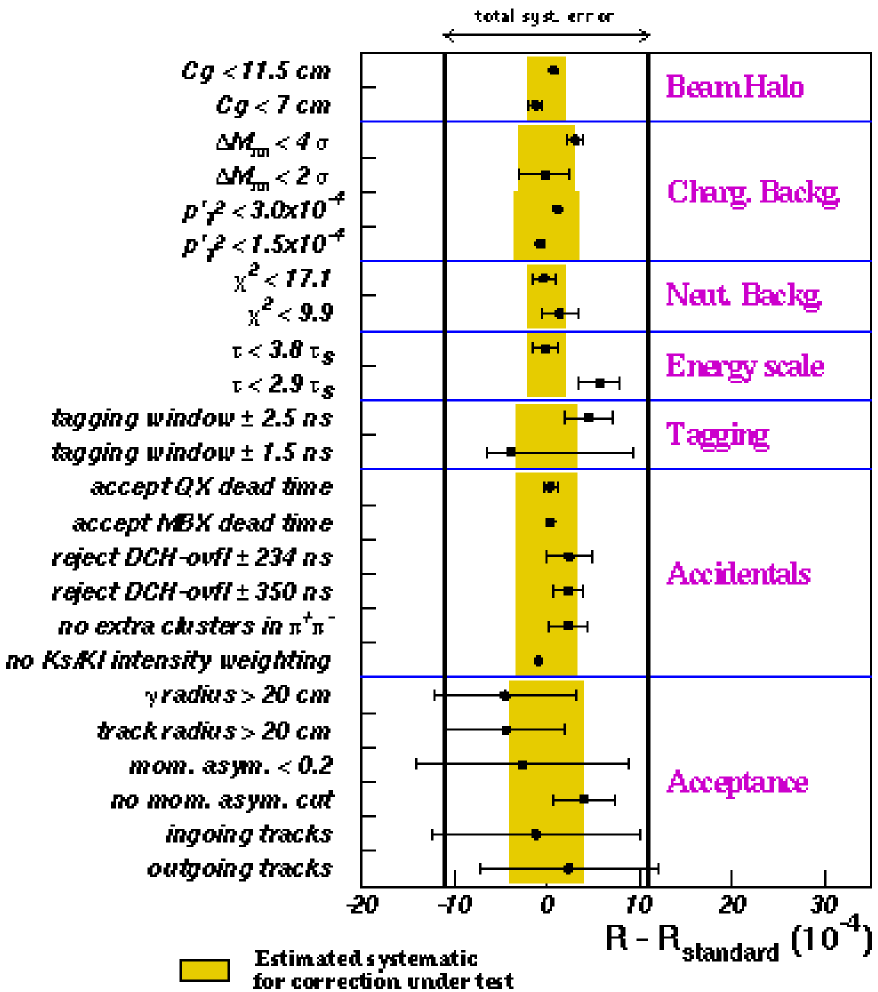
(limited by statistical uncertainty of overlay sample)

Summary of corrections and uncertainties on R for 2001 data

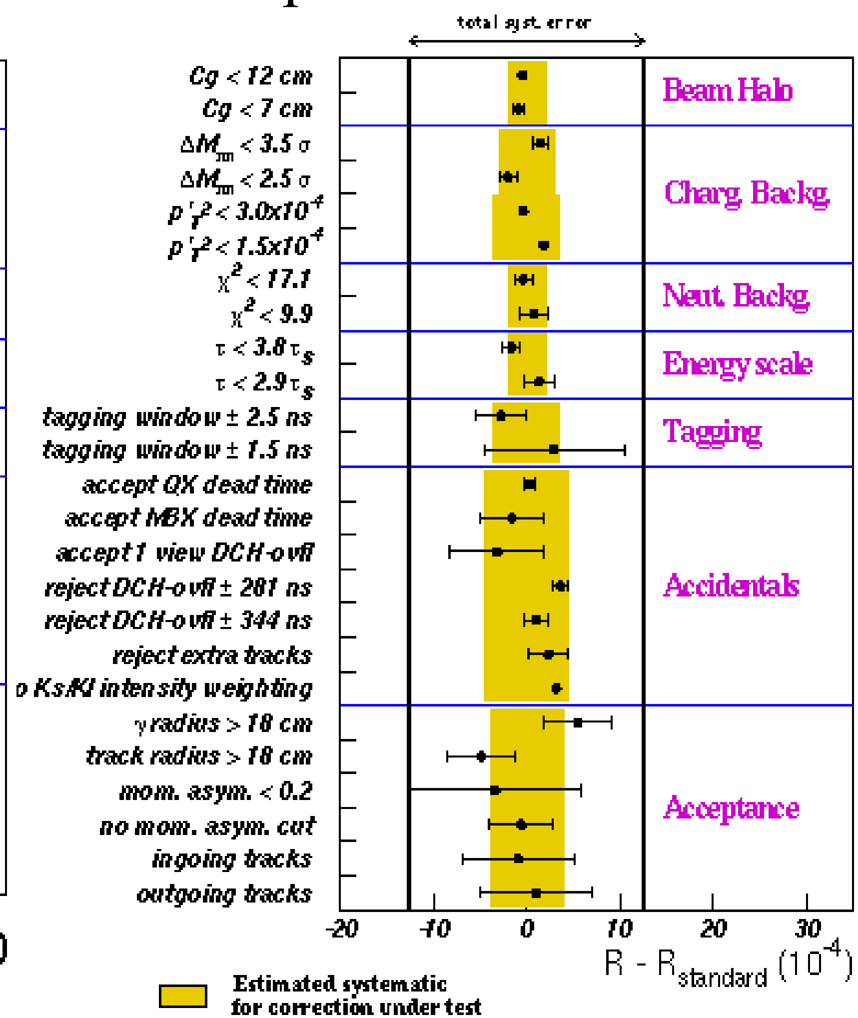
	in 10^{-4}	units
$\pi^+\pi^-$ trigger inefficiency	+5.2	± 3.6 (stat)
$\pi^0\pi^0$ reconstruction		± 5.3
$\pi^+\pi^-$ reconstruction		± 2.8
$\pi^0\pi^0$ background	- 5.6	± 2.0
$\pi^+\pi^-$ background	+14.2	± 3.0
Beam scattering background	- 8.8	± 2.0
K_S tagging inefficiency		± 3.0
K_L accidental tagging as K_S	+ 6.9	± 2.8 (stat)
Accidental activity intensity difference		± 1.1
illumination difference		± 3.0 (stat)
K_S in time activity		± 1.0
Acceptance correction	+21.9	± 3.5 (stat)
		± 4.0
AKS inefficiency	+ 1.2	± 0.3
Total	**+35.0**	**±11.0**

Cross-checks of the stability of the result

2001 data

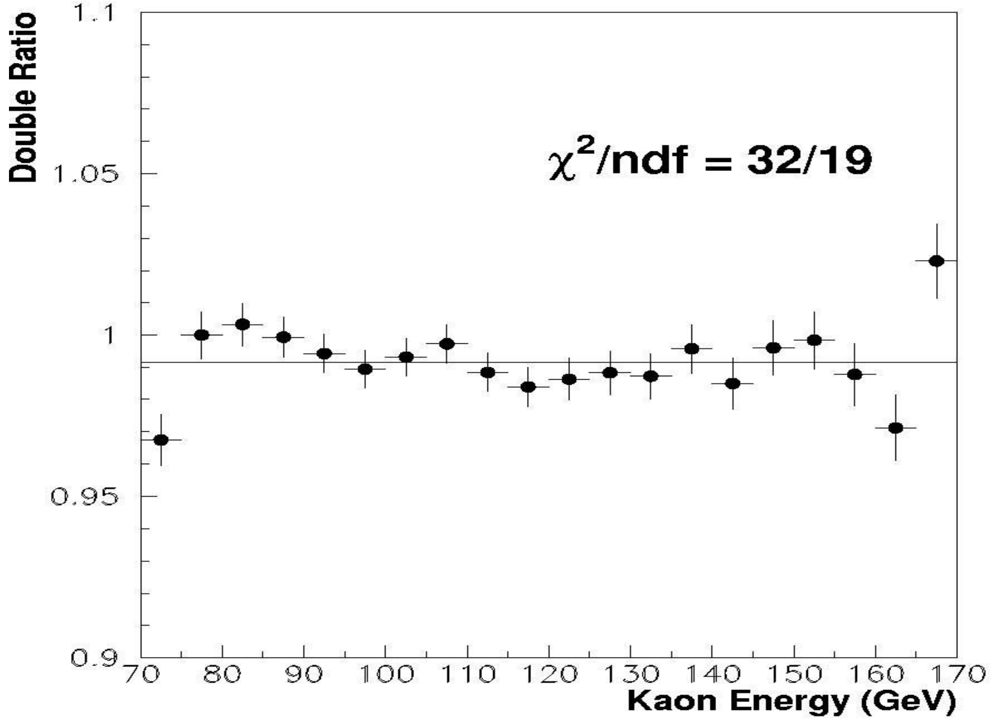


published 98-99 data



The double ratio result (2001 data)

The analysis is performed in Kaon energy bins to be insensitive to K_S-K_L differences in energy spectra



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

Final result

From 2001 data:

$\varepsilon'/\varepsilon = (13.7 \pm 2.5 \pm 1.8) 10^{-4}$

$\mathbf{= (13.7 \pm 3.1)\ 10^{-4}}$

in very good agreement with 97-98-99 published result

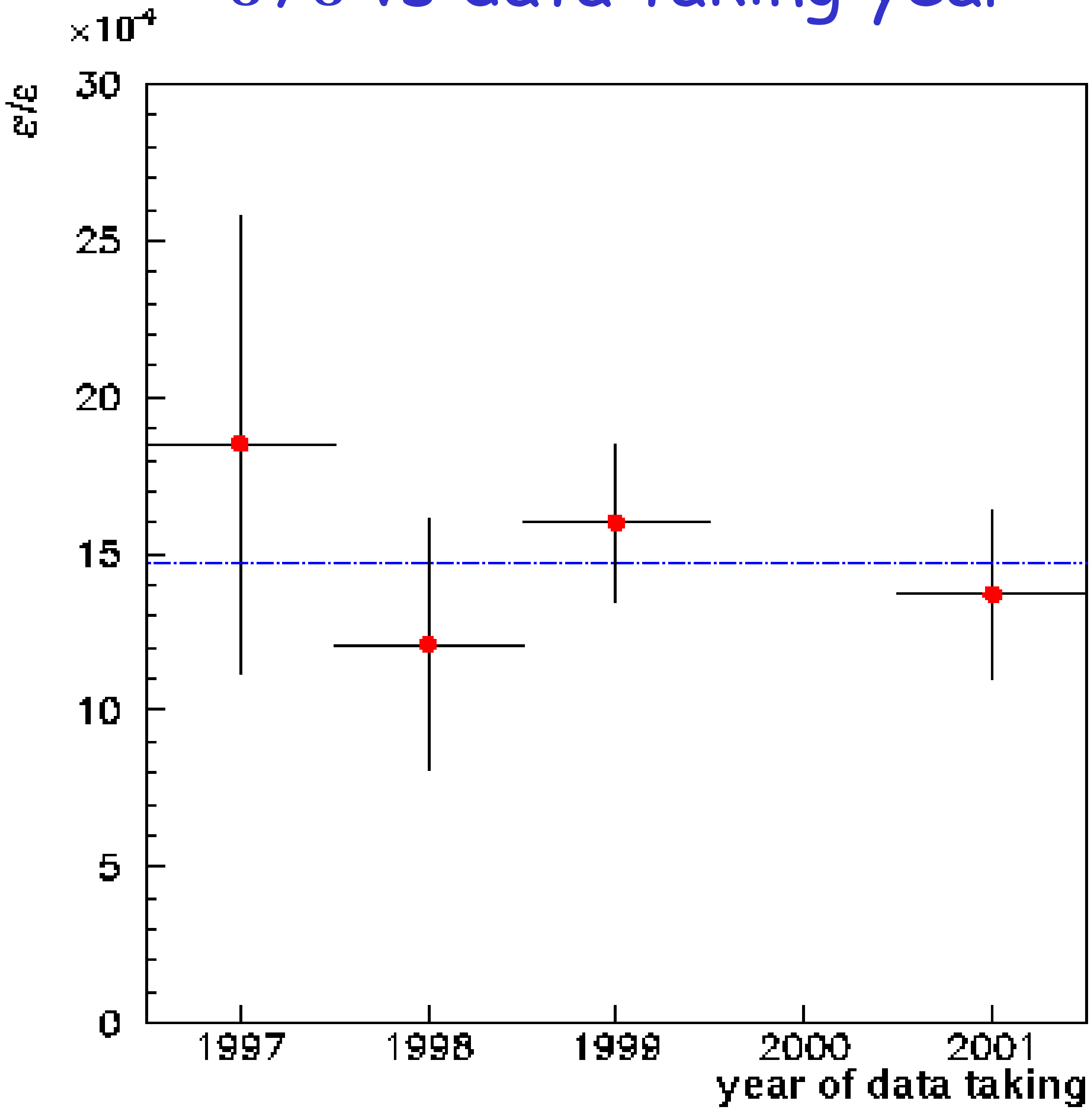
$\varepsilon'/\varepsilon = (15.3 \pm 2.6) 10^{-4}$

Final combined result from NA48:

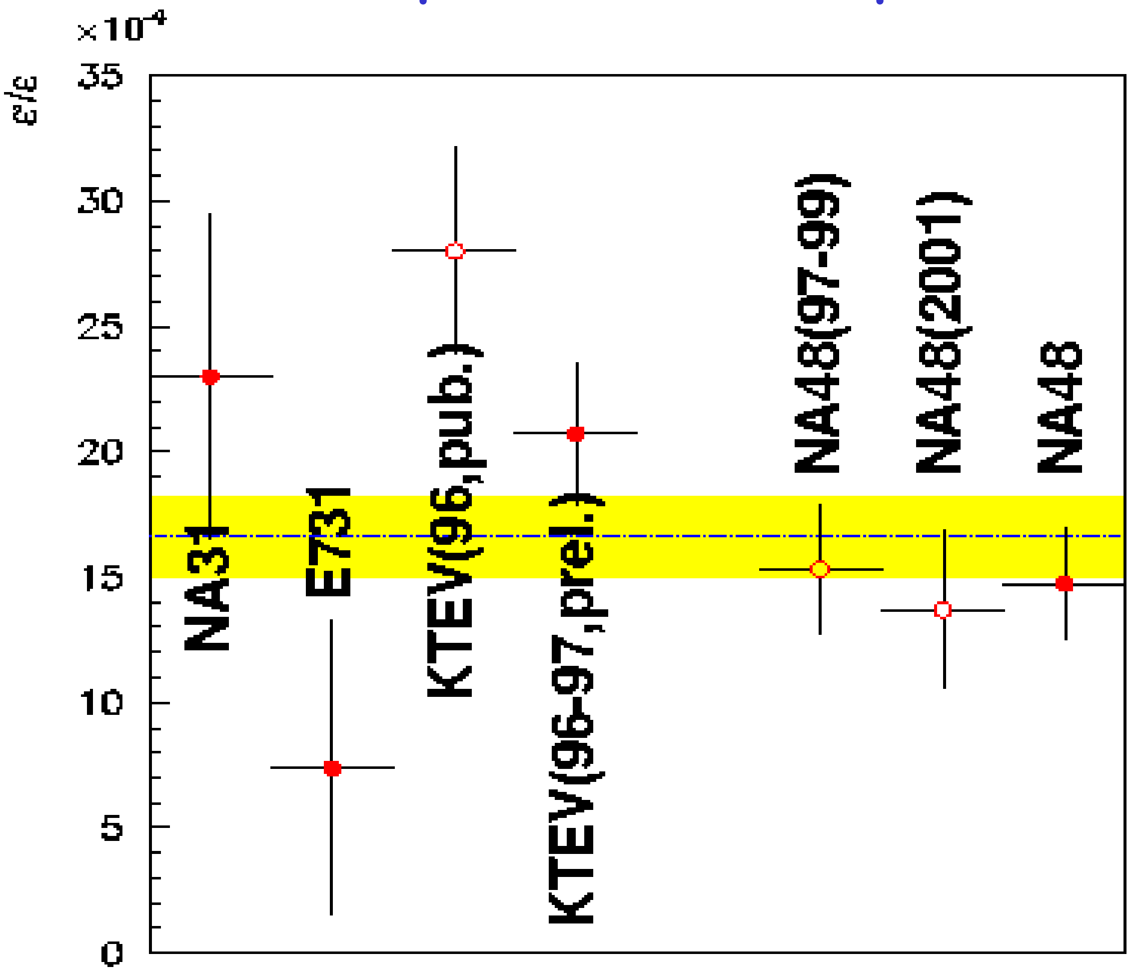
$\mathbf{\varepsilon'/\varepsilon = (14.7 \pm 2.2) 10^{-4}}$

(correlated systematic uncertainty is $\mathbf{\pm 1.4\ 10^{-4}}$)

ε'/ε vs data taking year



Comparison of experimental results



NA31: $(23.0 \pm 6.5)10^{-4}$

E731: $(7.4 \pm 5.9)10^{-4}$

KTeV: $(20.7 \pm 2.8)10^{-4}$
(preliminary)

NA48: $(14.7 \pm 2.2)10^{-4}$

World average **$\varepsilon'/\varepsilon = (16.6 \pm 1.6)10^{-4}$** $\chi^2=6.2/3$ (prob=10%)

Conclusions

NA48 measurement of ε'/ε is completed:

$$\varepsilon'/\varepsilon = (14.7 \pm 2.2)\ 10^{-4}$$

proposed accuracy is reached

papers: - V.Fanti et al, Phys. Lett. B465, 335(1999) 97 data result
- A.Lai et al, Eur. Phys. Jour.C83,22(2001) 98-99 data
- coming out soon on 2001 data

KTeV still to analyse 1999 data (≈same stat as 96-97 data)
Kloe with different method (need luminosity)

The ball is now on the theory side …