Update on the ϵ'/ϵ measurement by the NA48 experiment at CERN

Patrizia Cenci
INFN Perugia

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The NA48 Collaboration:
Cagliari Cambridge CERN Dubna Edinburgh
Ferrara Firenze Mainz Orsay Perugia Pisa Saclay
Siegen Torino Vienna Warsaw

Plan of the presentation

- Physics motivation
- NA48 method
- Analysis of the 1998 data
- The world average
- Conclusions

Physics motivation

Strangeness eigenstates:

$$\mathrm{K}^0(\bar{\mathrm{s}}\mathrm{d}) \quad (S=+1)$$
$$\overline{\mathrm{K}^0}(\mathrm{s}\bar{\mathrm{d}}) \quad (S=-1)$$

CP eigenstates:

$$\mathrm{K}_1 = (\mathrm{K}^0 + \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=+1)$$
$$\mathrm{K}_2 = (\mathrm{K}^0 - \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=-1)$$
$$\pi^+\pi^-, \pi^0\pi^0 \quad (CP=+1)$$

Mass eigenstates:

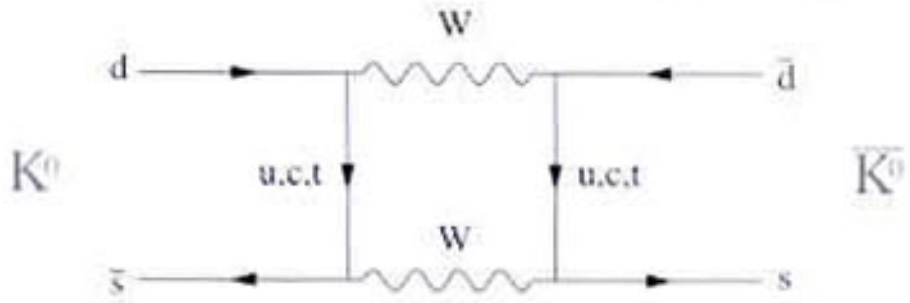
$$\mathrm{K_S} \simeq \mathrm{K}_1 + \varepsilon \mathrm{K}_2 \quad (c\tau_S = 2.67\,\mathrm{cm})$$
$$\mathrm{K_L} \simeq \mathrm{K}_2 + \varepsilon \mathrm{K}_1 \quad (c\tau_L = 15.5\,\mathrm{m})$$

$\mathrm{K_S}$		$\mathrm{K_L}$	
69 %	$\pi^+\pi^-$	21 %	$3\pi^0$
31 %	$\pi^0\pi^0$	13 %	$\pi^+\pi^-\pi^0$
		27 %	$\pi\mu\nu$
		39 %	$\pi e\nu$
		0.2 %	$\pi^+\pi^-$
		0.1 %	$\pi^0\pi^0$

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

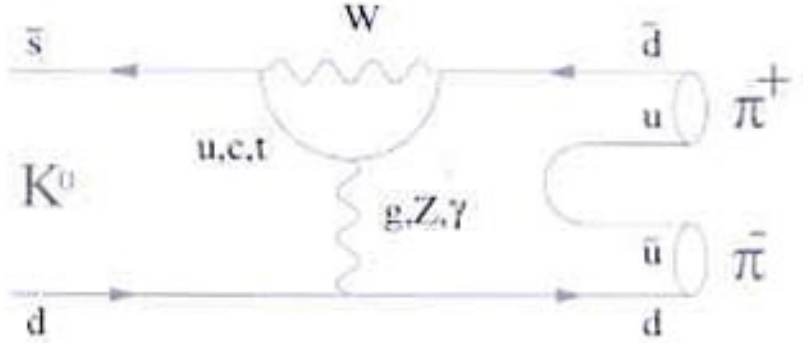
Physics motivation, contd.

$\varepsilon \Rightarrow$ Indirect CP violation via $K^0/\overline{K^0}$ mixing



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

$\varepsilon' \Rightarrow$ Direct CP violation:



$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \varepsilon - 2\,\varepsilon'$$

Double ratio technique

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

$\Rightarrow$ if at least K_S /K_L or $\pi^+\pi^-/\pi^0\pi^0$ are collected at the same time:

$$R = \frac{N_L^{00}}{N_S^{00}} \Big/ \frac{N_L^{+-}}{N_S^{+-}} \simeq 1 - 6\ \mathrm{Re}(\varepsilon'/\varepsilon)$$

$\Rightarrow$ it is a counting experiment

Available measurements of $\mathrm{Re}(\varepsilon'/\varepsilon)$:

NA31	$(23.0 \pm 6.5) \times 10^{-4}$	(1993)
E731	$(7.4 \pm 5.9) \times 10^{-4}$	(1993)
KTEV	$(28.0 \pm 4.1) \times 10^{-4}$	(1999)
NA48 97	$(18.5 \pm 7.3) \times 10^{-4}$	(1999)
NA48 98	new	(2000)

NA48 method

- Method: double ratio technique
- Aim: measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ at 2×10^{-4} accuracy
- High statistics: collect (limiting mode):

$$4 - 5 \times 10^6 \mathrm{K_L} \rightarrow \pi^0\pi^0$$

  - High intensity beam
  - Powerful Trigger and DAQ systems

- Minimize systematics effects:
  - the 4 modes are measured simultaneously
    $\Rightarrow$ cancellation of fluxes, inefficiencies, dead time, accidental activity
  - from the same fiducial volume
    $\Rightarrow$ accurate energy scale definition
  - applying lifetime weighting of $\mathrm{K_L}$ to have similar $\mathrm{K_L}$ and $\mathrm{K_S}$ longitudinal decay distributions
    $\Rightarrow$ small acceptance correction
  - with a high resolution magnetic spectrometer ($\pi^+\pi^-$ mode) and with a homogeneous Liquid Krypton calorimeter ($\pi^0\pi^0$ mode)
    $\Rightarrow$ small background levels
  - in bins of energy to eliminate slight differences in energy spectra

- Residual corrections applied to R due to:

$\Rightarrow$ K_S and K_L identification by proton tagging

$\Rightarrow$ trigger inefficiency

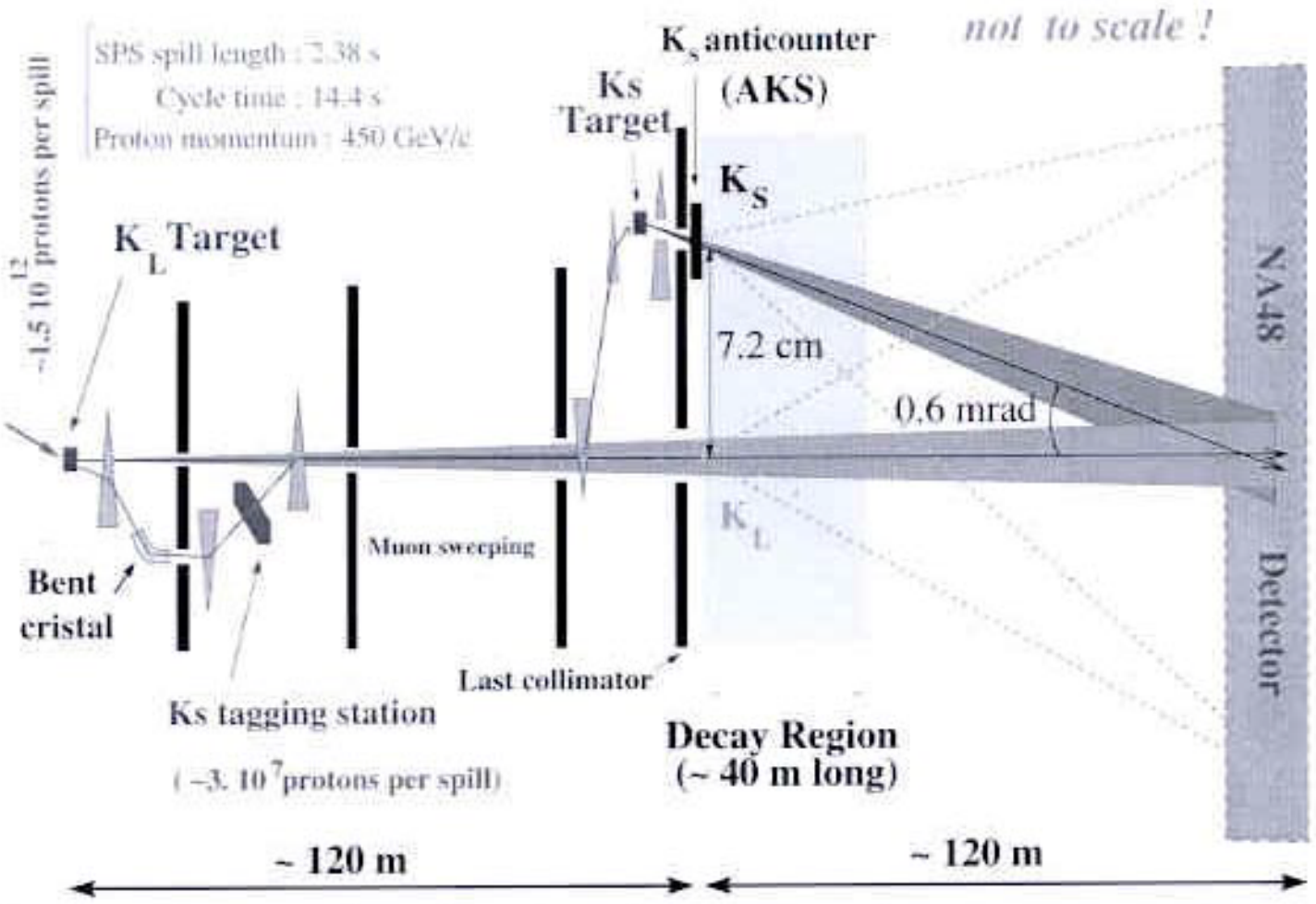
$\Rightarrow$ background subtraction

$\Rightarrow$ acceptance

$\Rightarrow$ energy scale

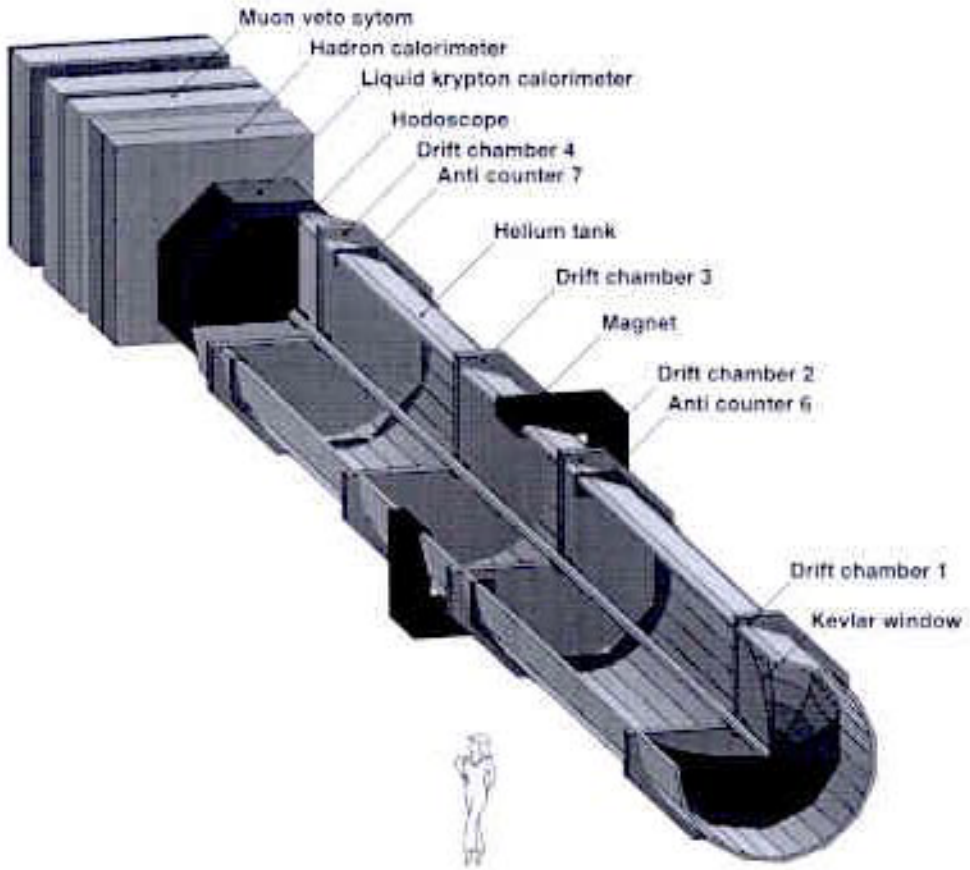
$\Rightarrow$ accidental activity

NA48: simultaneous K_L and K_S beams



- K_S are distinguished from K_L by tagging the protons upstream of the K_S target
- All the 4 decay modes are collected from the same decay region

NA48: detectors



- $K_{L,S} \to \pi^+\pi^-$
  - magnetic spectrometer
  - scintillators hodoscope (timing)
  - muon veto (background rejection)
- $K_{L,S} \to \pi^0\pi^0$
  - quasi-homogeneous Liquid Krypton electromagnetic calorimeter:
    - high granularity (13212 cells $2 \times 2\ cm^2$)
    - projective geometry

NA48: Data sample

- 1997: 89 days, 1×10^{12} ppp on K_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_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) $\to$ 30 % rate increase

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

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

  PRELIMINARY RESULT now

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

  Further improvements:

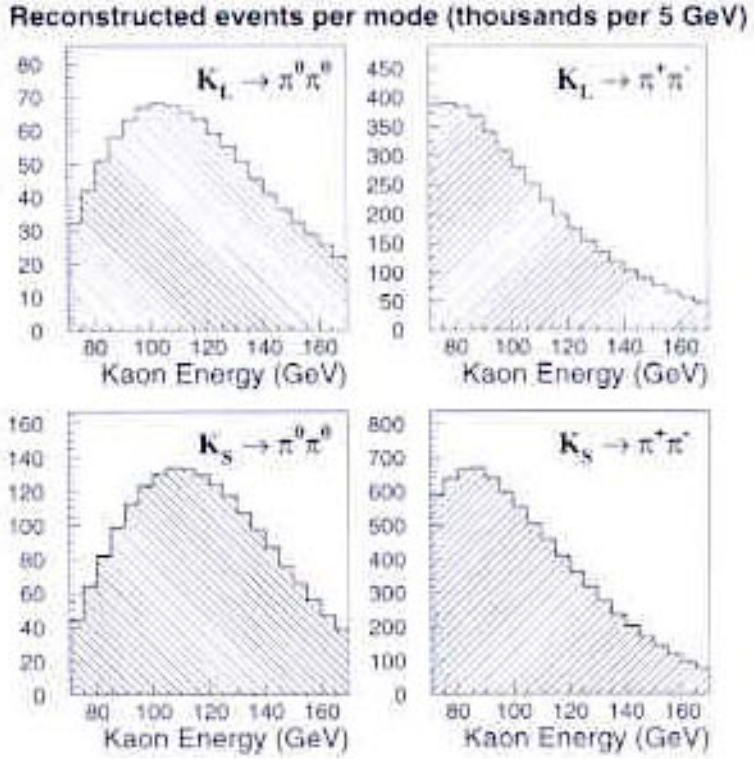
  - DCh read-out, dead time, DAQ efficiency, spill length

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

  ANALYSIS in progress...

NA48: Analysis strategy

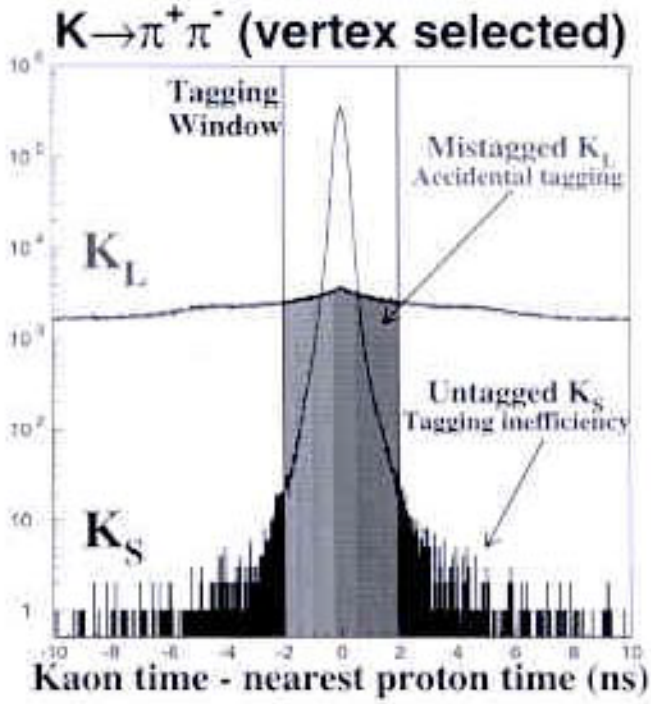
- $70 < E_{\rm K} < 170$ GeV
- Centre of Gravity $(R_{\rm cog}) < 10\,{\rm cm}$
- Decay region: $0 < t < 3.5\,\tau_{\rm S}$



- Charged dead time (<5 % from charged trigger and $\approx$ 25 % from DCH read out) is applied to neutrals.
- All corrections are applied in bins of energy to account for the slight difference in the spectra of $\rm K_S$ and $\rm K_L$

NA48: Tagging

K_L / K_S identification: TOF between a reconstructed Kaon decay and the tagger

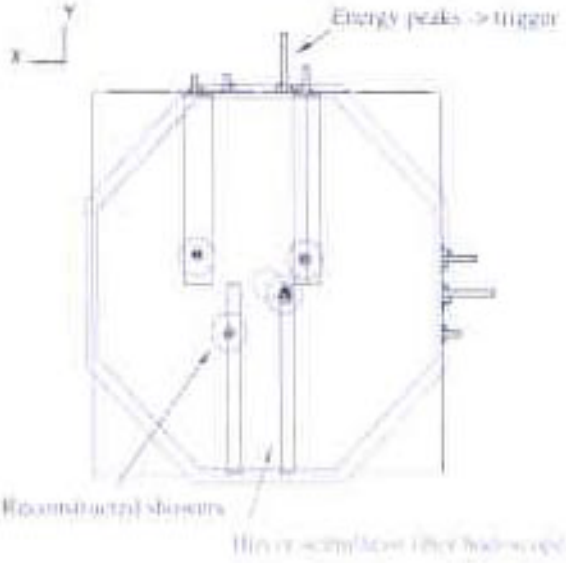


- Tagging inefficiency α_{SL}: $K_S \rightarrow K_L$
  the $\pi^+\pi^+/\pi^0\pi^0$ difference comes from tails in the detector (hodoscope/LKr) time distributions
- Accidental tagging α_{LS}: $K_L \rightarrow K_S$
  accidental protons in the ± 2 ns tagging window
- Vertex reconstruction is used for $K \rightarrow \pi^+\pi^-$:
  $\alpha_{LS}^{+-} = (11.05 \pm 0.01)\%$; $\alpha_{SL}^{+-} = (1.97 \pm 0.05) \times 10^{-4}$
- Indirect methods are used in $K \rightarrow \pi^0\pi^0$:
  $|\alpha_{SL}^{00} - \alpha_{SL}^{+-}| < 0.5 \times 10^{-4}$ $\quad \boxed{\Delta R < 3 \times 10^{-4}}$
  $\alpha_{LS}^{00} - \alpha_{LS}^{+-} = (0.5 \pm 4)\ 10^{-4}$ $\quad \boxed{\Delta R = (1 \pm 8) \times 10^{-4}}$

NA48: Triggers

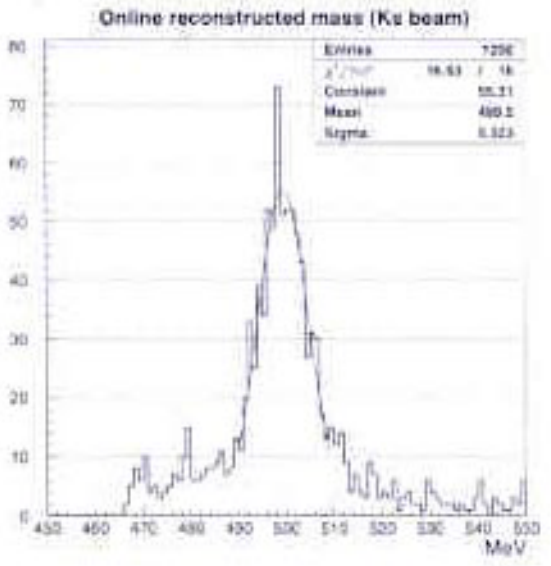
$\pi^0\pi^0$ trigger

- Fully pipelined system using LKr cell information to compute energy, centre of gravity and proper time
- Output rate ~ 2 kHz
- Negligible dead time
- Efficiency:
  99.93 ± 0.02 %



$\pi^+\pi^-$ trigger

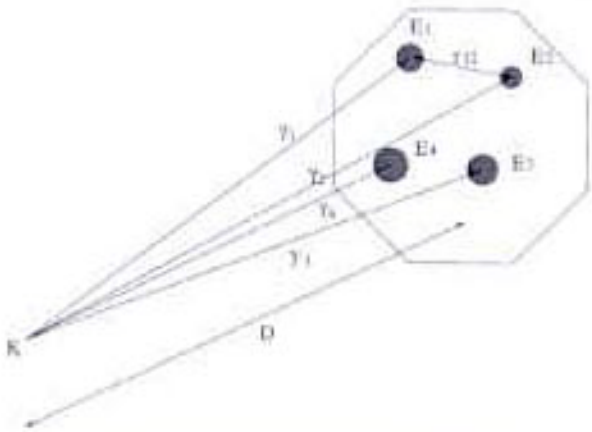
- Level 1: Efficiency
  - + Energy in calorimeters > 35 GeV 99.49 ± 0.03 %
  - + Two track topology in hodoscope 99.95 ± 0.01 %
  - + Two track multiplicity in chamber 1 > 99.99 %
- Level 2: online processing of vertices and $\pi\pi$ invariant mass.
  - Latency : $< 102\ \mu s$
  - Rejection ~ 45
    $\rightarrow$ 2 kHz output
  - Dead Time $< 5\%$
    monitored and
    applied to $\pi^0\pi^0$
  - Efficiency:
    $97.75 \pm 0.05\%$

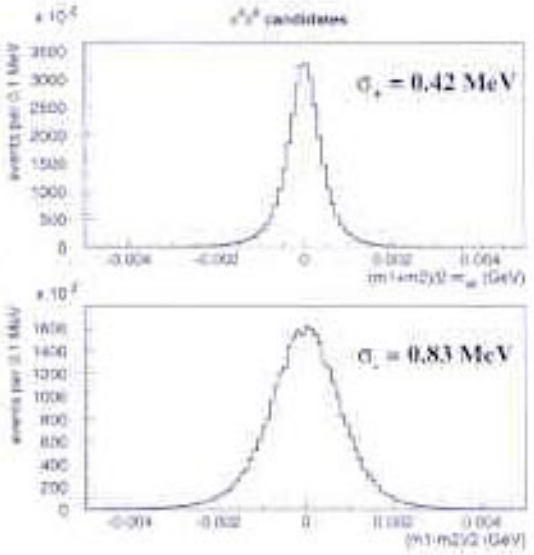


$$\Delta R = (-1 \pm 11) \times 10^{-4}$$

NA48: $K^0 \to \pi^0 \pi^0$ reconstruction

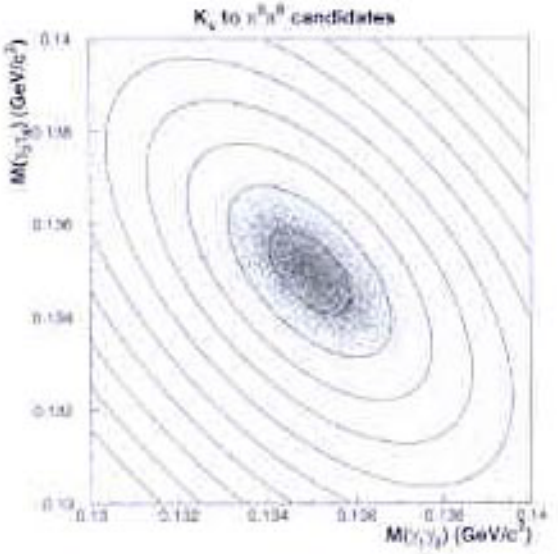
$$K^0 \to 2\,\pi^0 \to 4\gamma$$

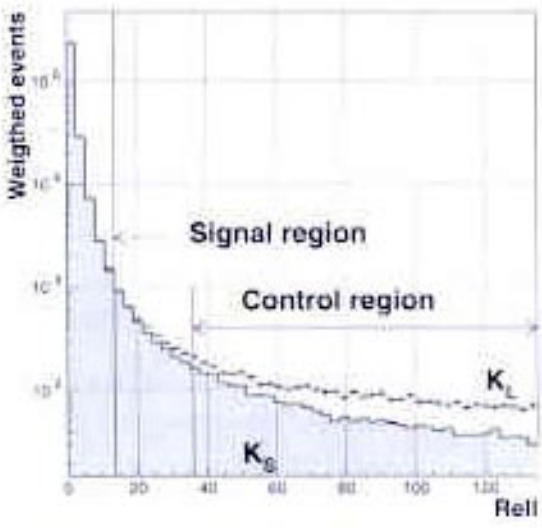




$$D = \frac{\sqrt{\sum E_i E_j \times (r_{ij})^2}}{M_K}$$

$$m_{ij} = \frac{\sqrt{E_i E_j} \cdot r_{ij}}{D}$$



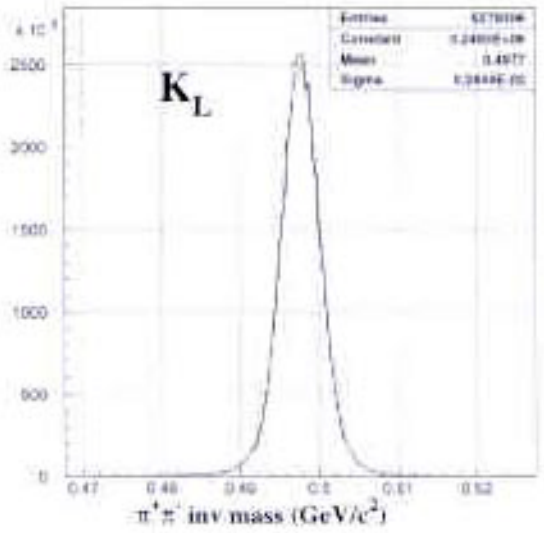


$3\,\pi^0$ background rejection:

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

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

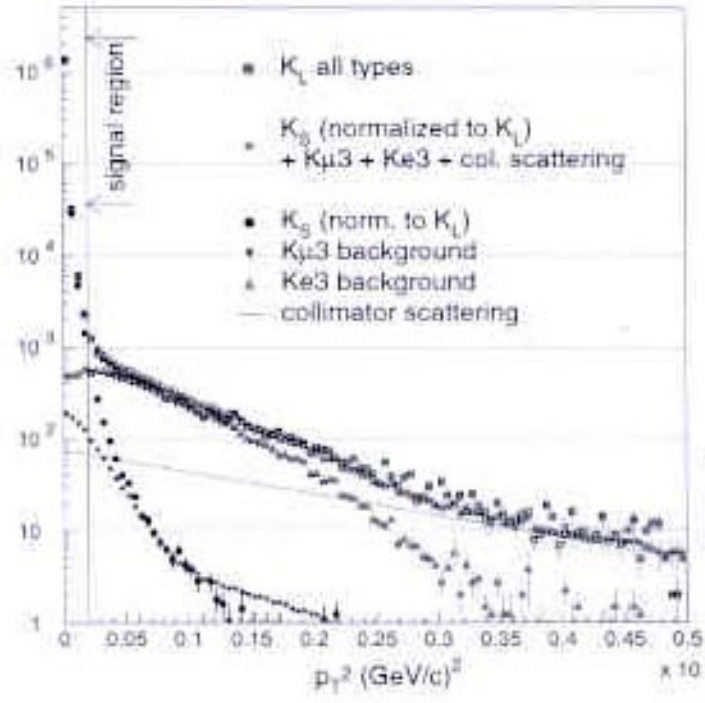
NA48: $K^0 \to \pi^+ \pi^-$ reconstruction



Kaon mass resolution
~ 2.5 MeV/c^2

$$\frac{\sigma(p)}{p} \simeq 0.5\% \oplus 0.009\, p\%$$

p in GeV/c



Background rejection:
No hits in the μ counters
$E/p < 0.8$

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

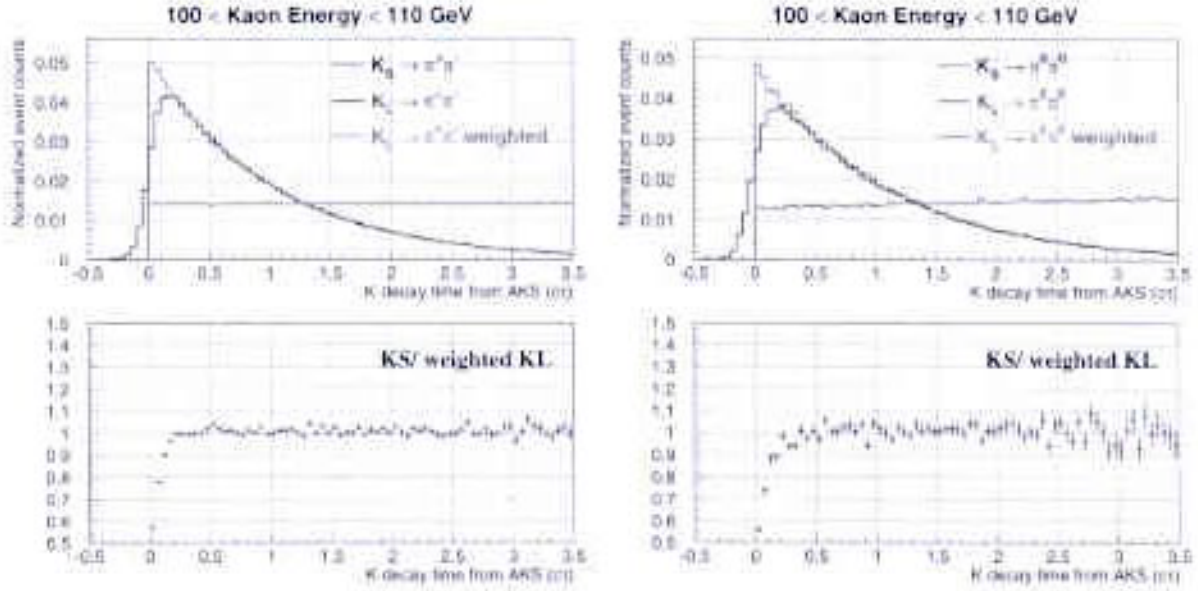
$\pi^+\pi^-$ energy: opening angle and tracks energy ratio

$E_K^2 = (C/\theta^2)\left\{m_K^2 - C\, m_\pi^2\right\}$

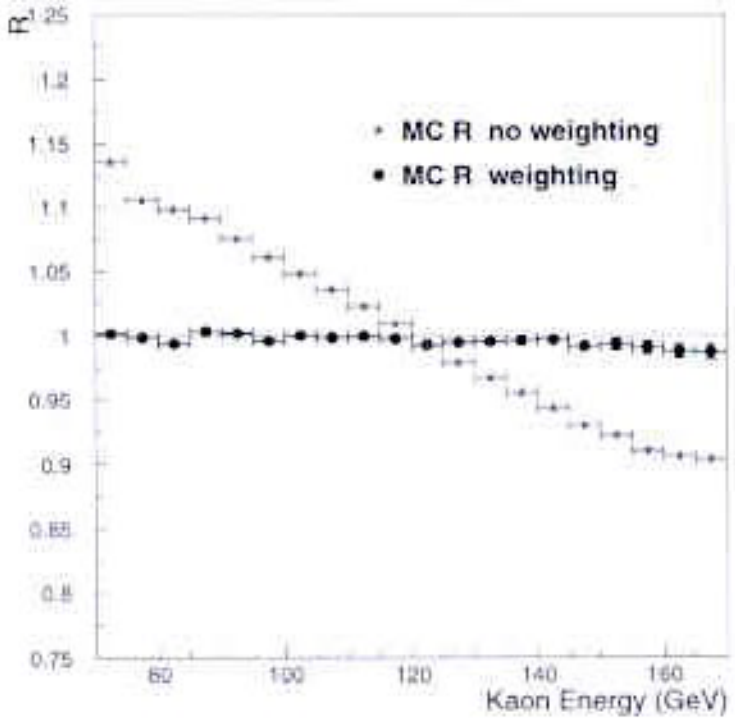
$C = 2 + E_{\pi 1}/E_{\pi 2} + E_{\pi 1}/E_{\pi 2}$

$\Rightarrow$ geometry of the drift chambers

NA48: K_L proper time weighting



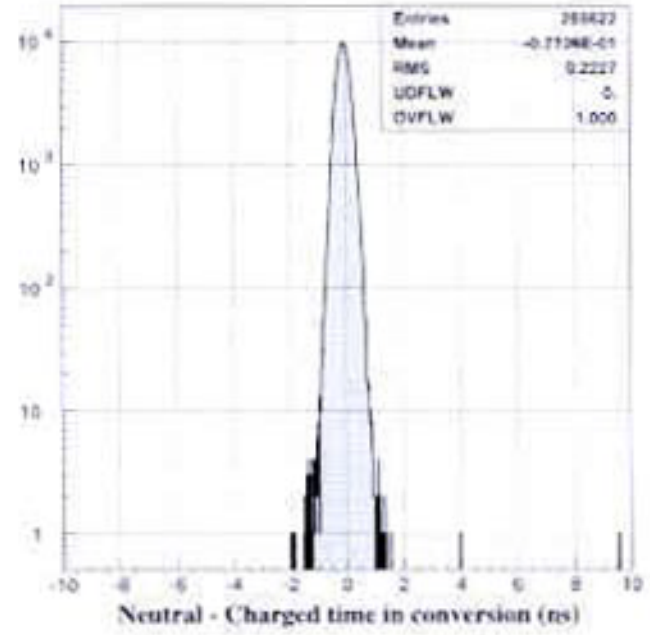
K_L are weighted with the K_S proper time



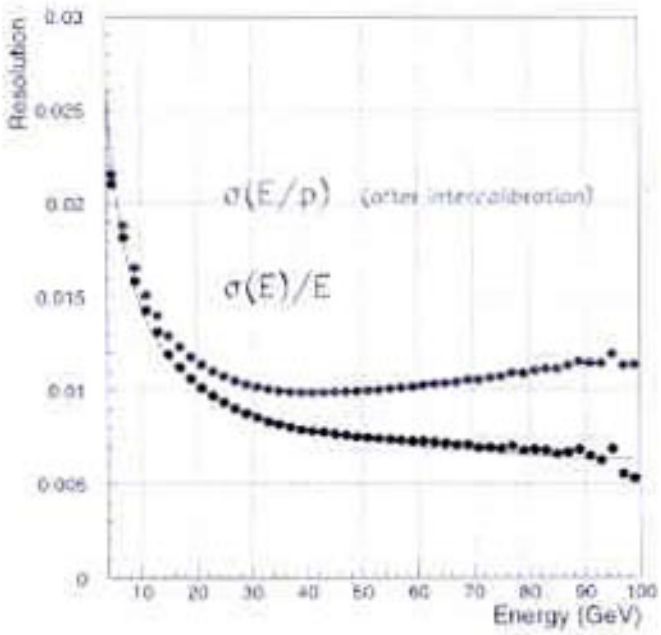
The increase of the statistical error due to weighting is 35%

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

NA48: $\pi^+\pi^-/\pi^0\pi^0$ time and energy resolution



Comparison of LKr and scintillators hodoscope times in K_L and K_S events ($3\pi^0$ and $2\pi^0$) containing a photon conversion



Comparison of LKr energy and magnetic spectrometer momentum for electrons in K_{e3} decays

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

NA48: energy scale

$$E_{\mathrm{M}} = (1+\alpha) \times E_{\mathrm{T}}$$

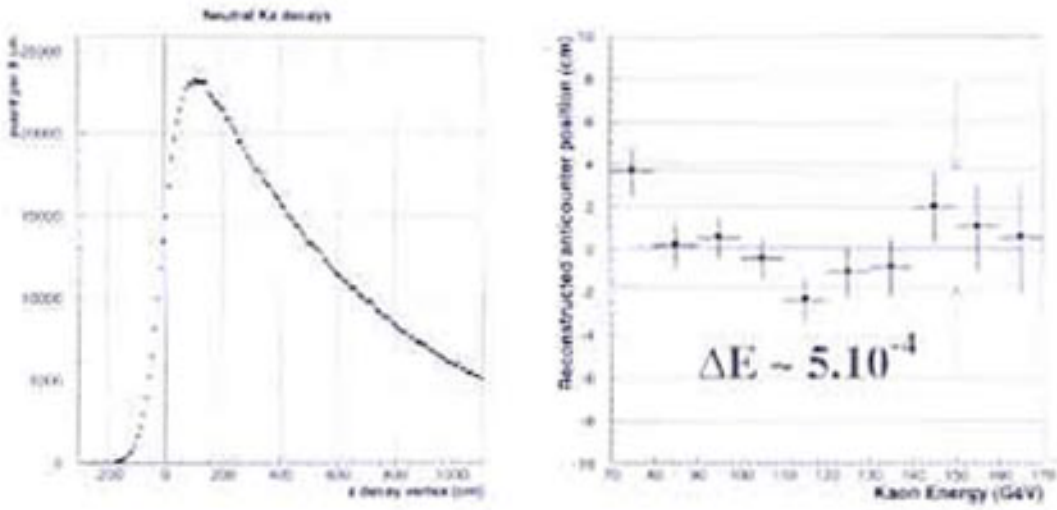
α = uncertainty on the $\pi^+\pi^-/\pi^0\pi^0$ energy scale

The beginning of the K_S decay region is defined by an anti-counter (AKS)

- The energy of the $\pi^0\pi^0$ is determined by the Lkr $\Rightarrow$ it relies on the calorimeter calibration

  To set the overall distance/energy scale, the position of the K_S anti-counter is used as a reference in $K_S \rightarrow \pi^0\pi^0$ events for the beginning of longitudinal vertex distribution

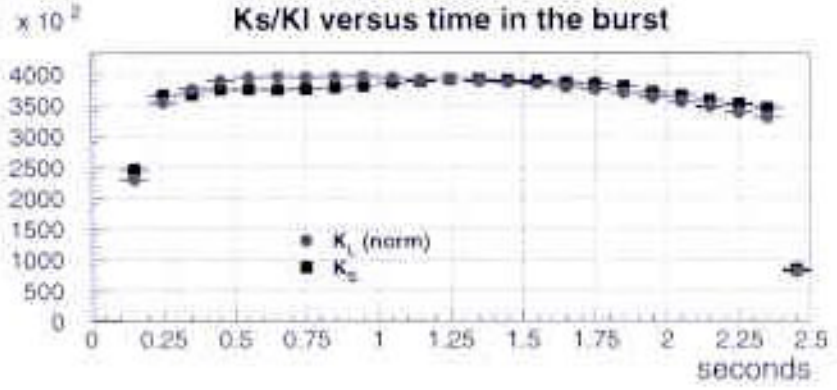
$$\boxed{\Delta R < 10 \times 10^{-4}}$$



- The energy for a $\pi^+\pi^-$ is determined from the geometry of the drift chambers

NA48: accidental activity

Accidental activity: asymmetric losses or gains in K_S and K_L → 4 modes collected simultaneously



- Geometric difference of the K_S and K_L beams: overlay events collected proportionally to the beam intensity to $\pi^+\pi^-$ and $\pi^0\pi^0$ events and evaluate the gain and losses induced by the analysis cuts:

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

- Effects related to the variation of the K_S/K_L ratio (R.M.S. of 10%) and effects not related to the K_L accidental activity:
  - difference in accidental activity seen by K_S and K_L events: < 1 %
  - asymmetric losses on $\pi^+\pi^-$ and $\pi^0\pi^0$ induced by the noise in the DCH read out: $< 2.5\%$
  - the noise in the detector does not change by more than a factor of two as a function of time

$$\boxed{\Delta R < 10 \times 10^{-4}}$$

NA48: 1998 Result

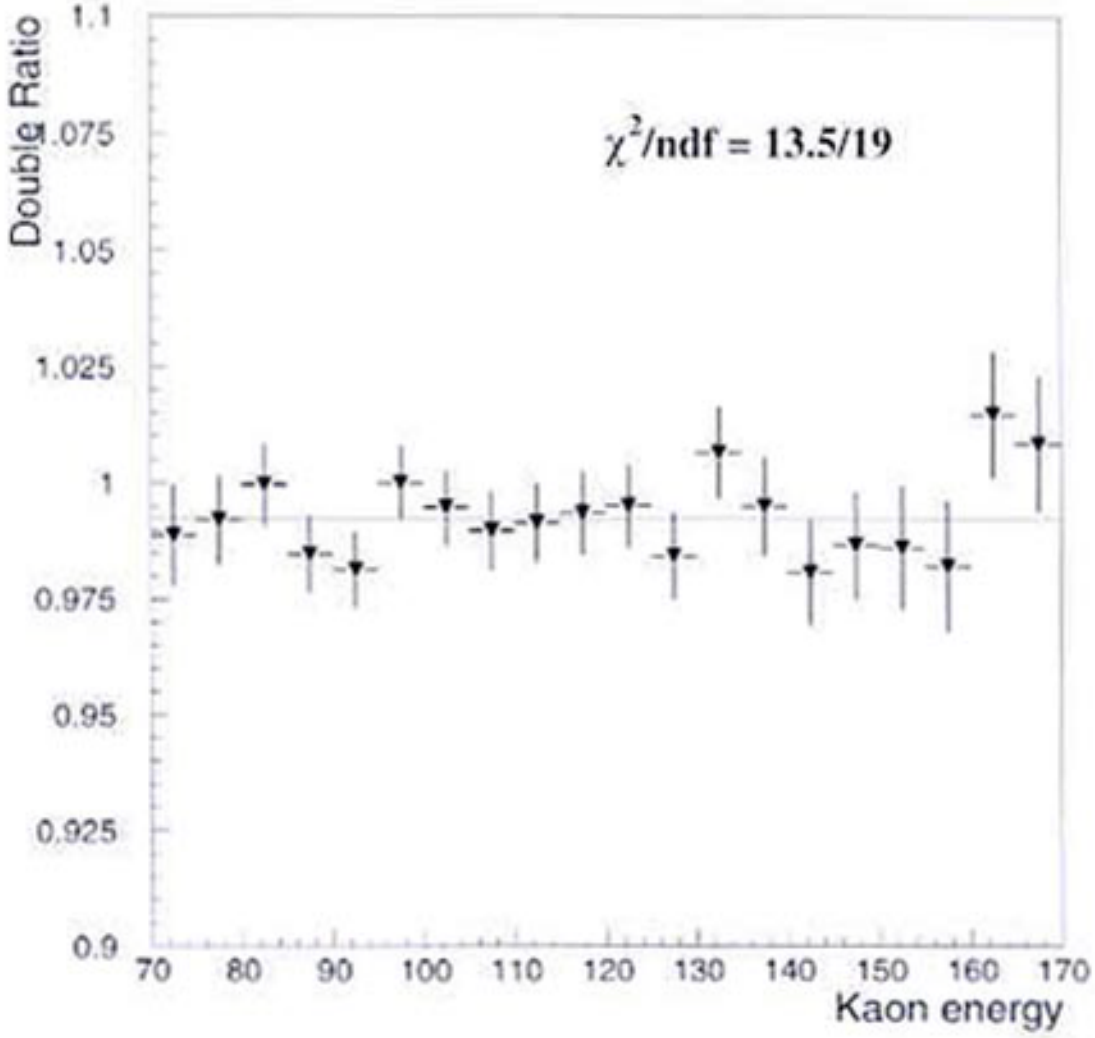
Statistics (millions) 1998			
$K_S \to \pi^+\pi^-$	7.46	$K_L \to \pi^+\pi^-$	4.87
$K_S \to \pi^0\pi^0$	1.80	$K_L \to \pi^0\pi^0$	1.14
Uncertainty on $R = 17.3 \times 10^{-4}$			

Corrections and systematic uncertainties on R (Units = 10^{-4})		
Source	1998 sample	
Charged trigger	−1	± 11
Mistagging probability	+1	± 8
Tagging efficiency	–	± 3
Neutral scale	–	± 10
Charged vertex	+2	± 2
Acceptance and AKS eff.	+31	± 9
Neutral BG	−7	± 2
Charged BG	+19	± 3
Beam scattering	−10	± 3
Accid. activity and in-time BG	+2	± 12
Total	+37	± 24

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

NA48: 1998 Result

PRELIMINARY RESULT ON 1998 DATA



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

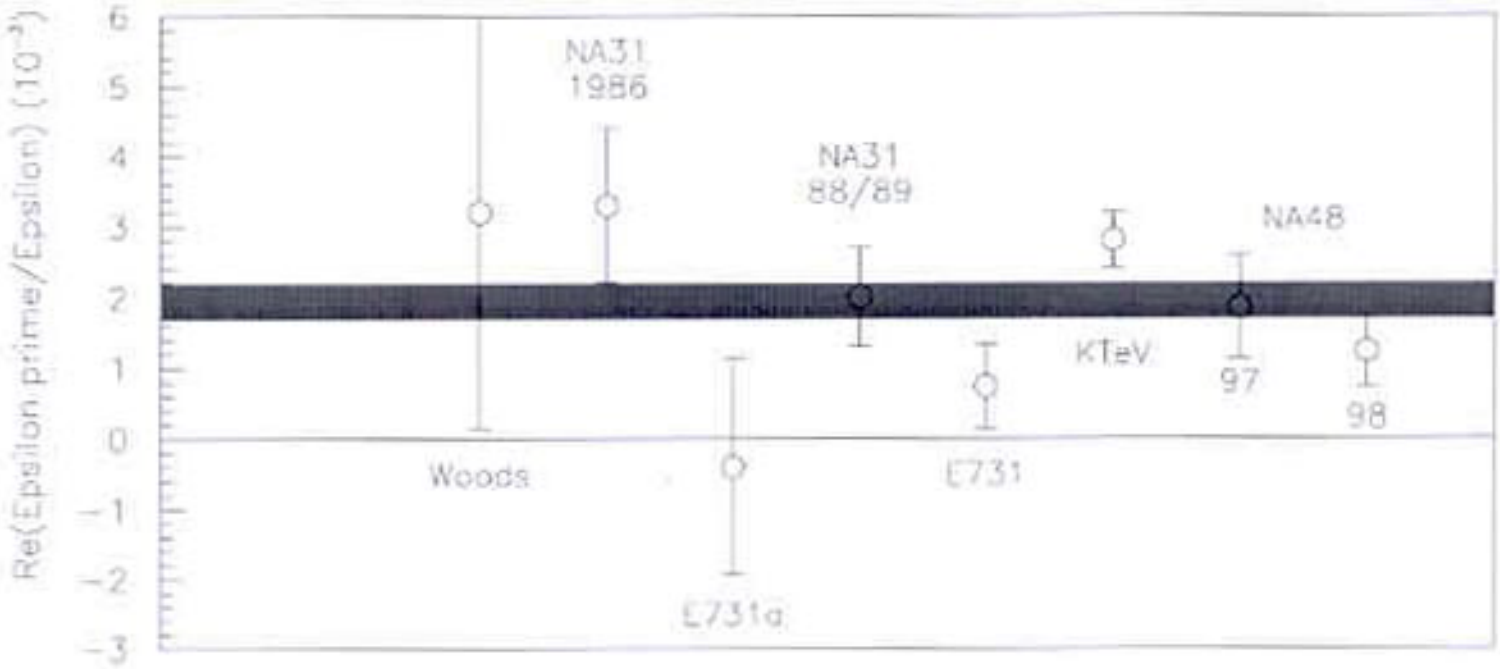
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 4.9) \times 10^{-4}$$

This result is preliminary. The systematic uncertainty is partly of statistical nature

Combined 1997 and preliminary 1998

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

New world average

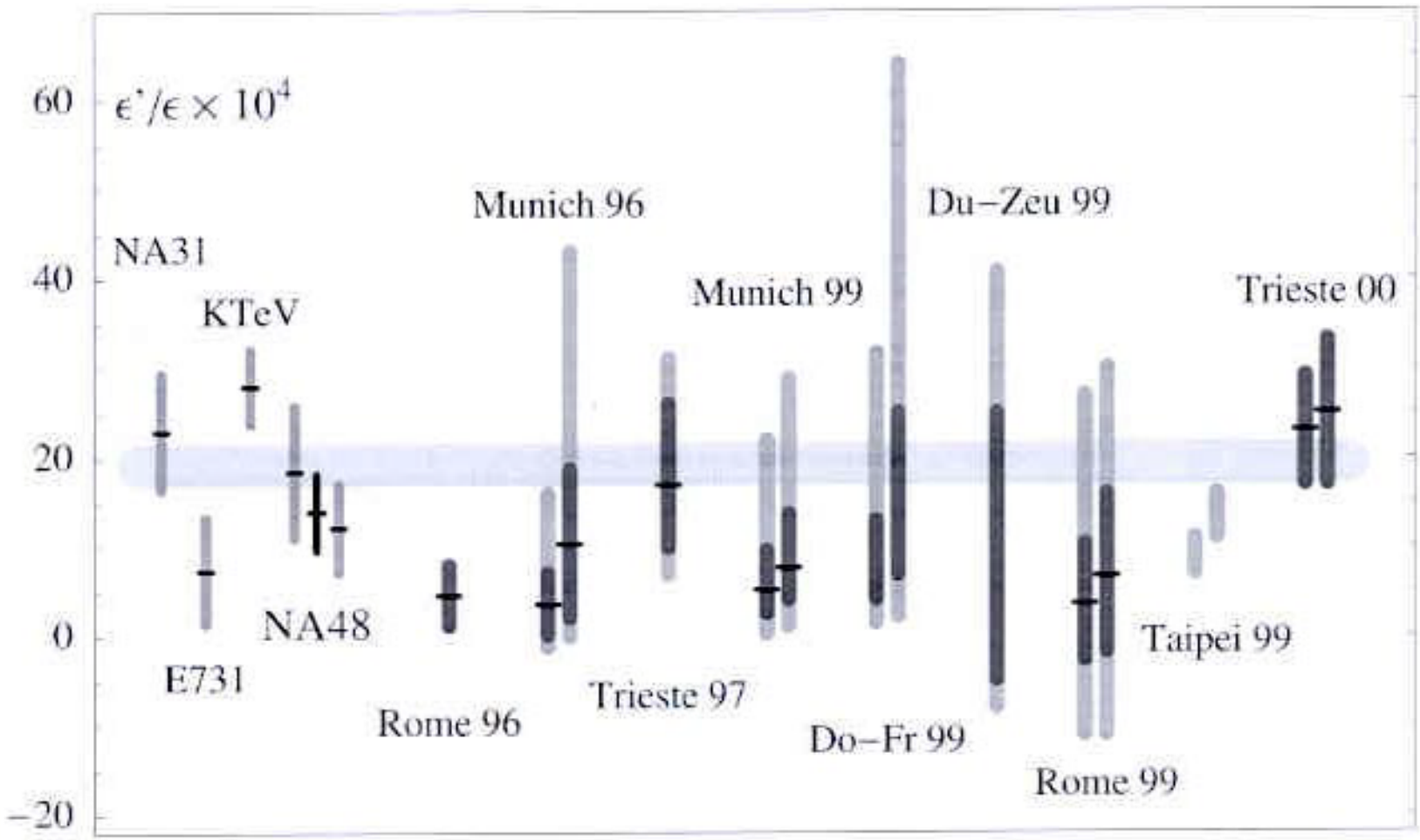


New world average:

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

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

Experiment vs. Theory



Experiments versus Theory

Conclusions

- NA48 has presented a new preliminary measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$ based on the 1998 data sample:

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

- Combining this result with the NA48 published data and taking into account the (small) correlated systematics, we obtain:

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

- The result confirms a non-zero, positive value for $\mathrm{Re}(\varepsilon'/\varepsilon)$

- Improvement on systematics expected
  - 1999 data analysis in progress
  - data taking in 2000 (neutral systematics) and 2001 (restored detector)

- New results are expected from KTEV (FNAL) and KLOE (DAΦNE)