A measurement of direct CP violation in two pion decays of neutral kaons by NA48 at CERN

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Outline

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Physics motivation

Strangeness eigenstates:

$$K^0(\bar{s}d)$$
$$\overline{K^0}(s\bar{d})$$

CP eigenstates:

$$K_1 = (K^0 + \overline{K^0})/\sqrt{2} \quad (CP = +1)$$
$$K_2 = (K^0 - \overline{K^0})/\sqrt{2} \quad (CP = -1)$$

Mass eigenstates:

$$K_S \simeq K_1 + \varepsilon K_2$$
$$K_L \simeq K_2 + \varepsilon K_1$$
$$(\ \varepsilon = (2.28 \pm 0.02) \times 10^{-3}\ )$$

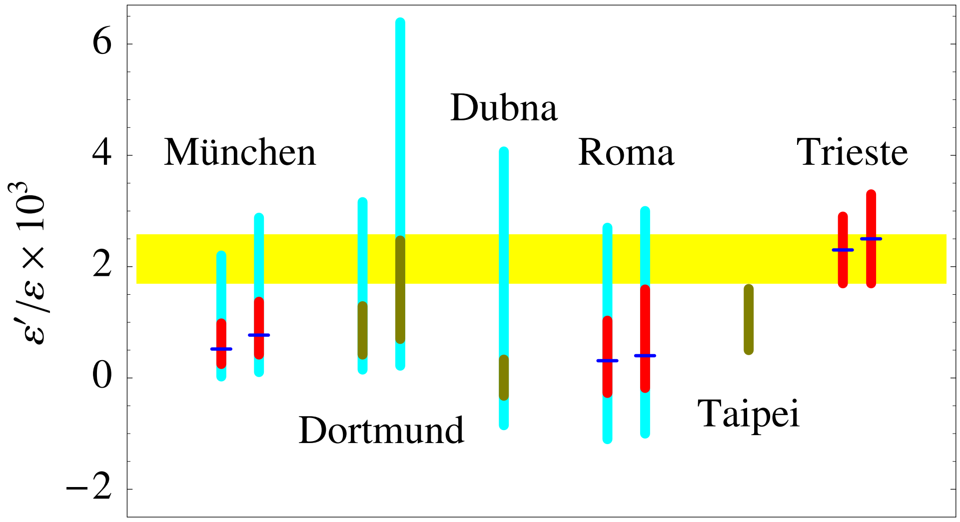
Two pion final states have $CP = +1$
CP violation in $K_L \to \pi\pi$ can occur either through:

- mixing indirect ε
- decay direct ε'

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

Current status of $\mathrm{Re}(\varepsilon'/\varepsilon)$

Typical theoretical predictions



Most recent measurements

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

NA48 Method

NA48 uses the double ratio technique:

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

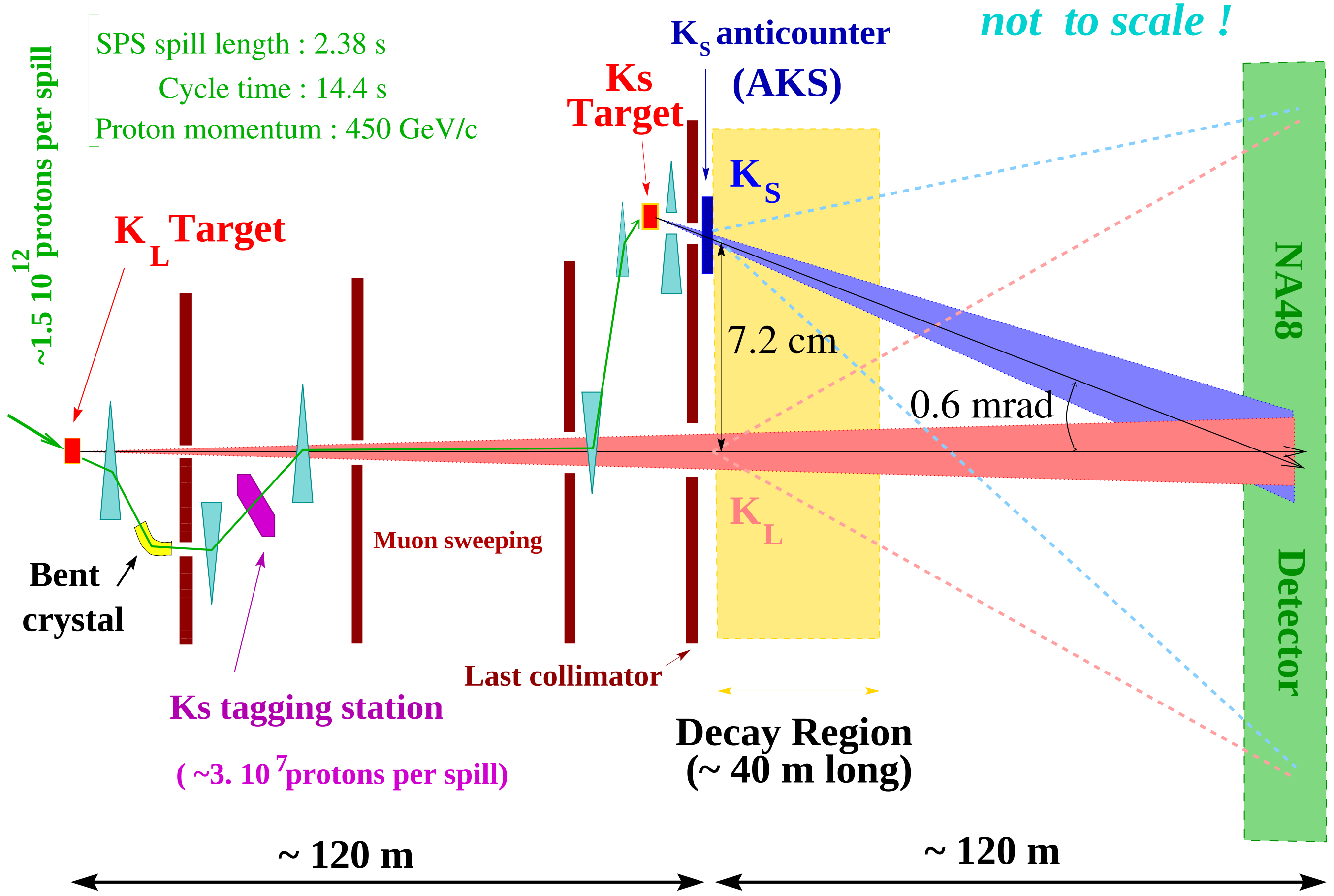
$$\mathrm{Re}(\varepsilon'/\varepsilon) \simeq \frac{1}{6}\left\{1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right\}$$

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

Systematic effects are reduced significantly by

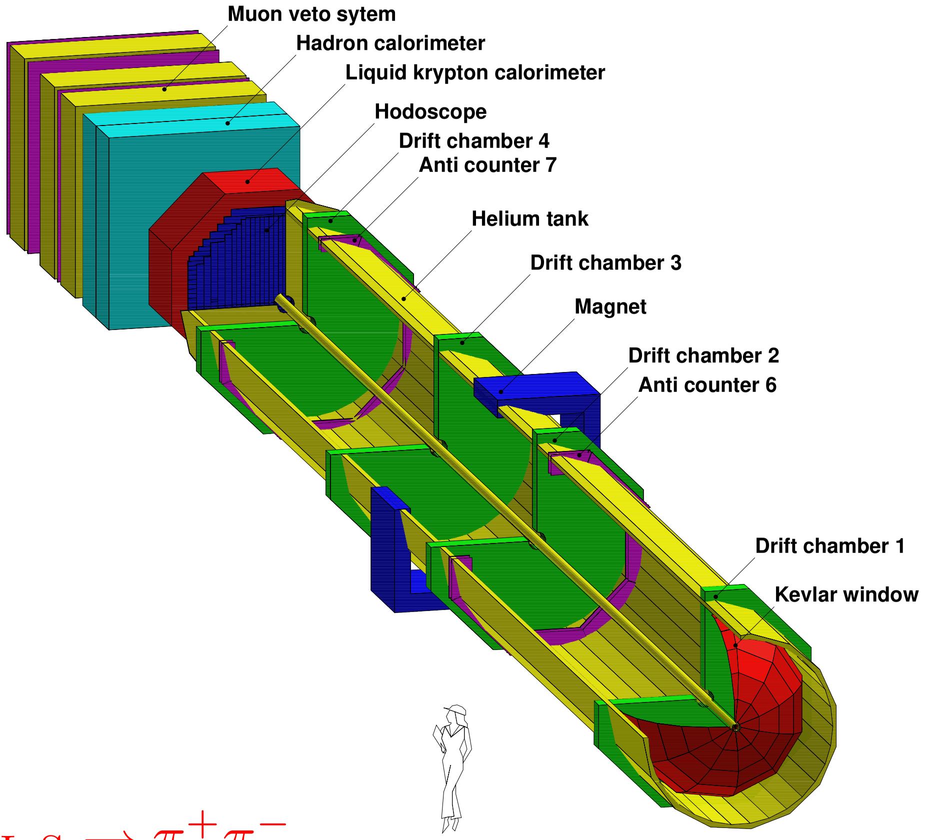
- using simultaneous and nearly collinear beams
- collecting data from all four modes at the same time
- weighting the $\mathrm{K_L}$ to the $\mathrm{K_S}$ lifetime distribution
- performing the analysis in bins of kaon energy

NA48 method: simultaneous K_L and K_S beams



K_S are distinguished from K_L by
tagging the protons which impinge on the K_S target

NA48 method: detectors



- $\mathrm{K_{L,S}} \rightarrow \pi^+\pi^-$
  - magnetic spectrometer ($\mathrm{P_T}^{kick} \sim 265$ MeV$/c$)

    $$\sigma(p)/p \simeq 0.5\ \% \oplus \frac{0.009\ p}{(\mathrm{GeV}/c)}\%$$
  - hodoscope
  - muon veto counters
- $\mathrm{K_{L,S}} \rightarrow \pi^0\pi^0$
  - quasi-homogeneous Liquid Krypton EMC :
    * high granularity (13212 2×2 cm^2 cells)
    * projective geometry

    $$\sigma(E)/E \simeq \frac{3.2\%}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{100\ \mathrm{MeV}}{E} \oplus 0.5\%$$

Triggers

$\pi^0\pi^0$ Trigger

A 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 : pretrigger — Efficiency
  - Two track topology (Q_x) — 99.95 ± 0.01 %
  - Two track multiplicity ($Dchm$) — > 99.99 %
  - Total energy (E_{tot}) — 99.49 ± 0.03 %
- Level 2 : on-line vertex reconstruction
  - Latency : $< 102\ \mu s$
  - Rejection $\sim 45 \rightarrow 2$ kHz output
  - Dead Time : $< 5\%$ monitored and applied to $\pi^0\pi^0$
  - Efficiency $\simeq 97.75 \pm 0.05\%$

Data sample

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

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

  PUBLISHED Phys. Lett. B 465 (1999)

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

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

  Main improvements :

  - LKR High Voltage 1500 $\rightarrow$ 3000 V
  - Charged trigger efficiency 91.3 $\rightarrow$ 97.7 %
  - Carbon fibre pipe $\rightarrow$ less showers in the detectors
  - New DAQ system (PC farm) + 30 % rate

  $\Rightarrow$ 1.14 million $K_L \rightarrow \pi^0\pi^0$

  PRELIMINARY result since February 2000

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

  Further improvements :

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

  $\Rightarrow$ Around 2 million $K_L \rightarrow \pi^0\pi^0$

  Analysis in progress

- 2000: 40 days without DCH

  Systematic studies: tagging, energy scale

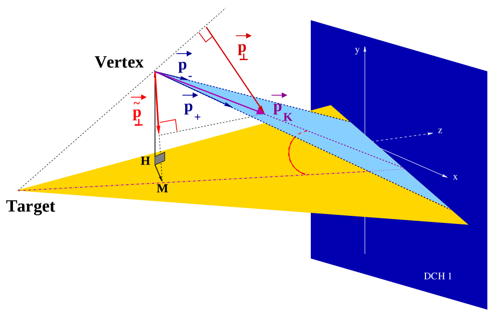
Event selection

All events

- Kaon energy : $70 < E_K/\mathrm{GeV} < 170$
- Centre of Gravity : $r_{cog} < 10$ cm
- Decay region : $0 < t < 3.5\,\tau_S$
  For K_S cut $(t > 0)$ by requiring $\overline{AKS}$
- No dead time

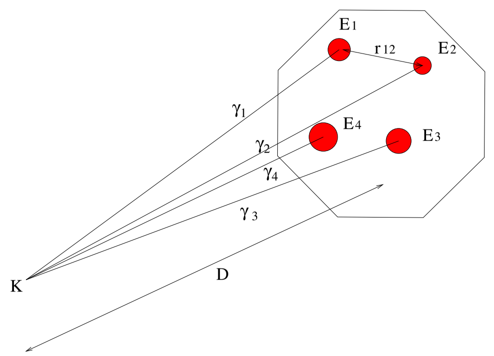
Charged events

- $K_{\mu 3}$: $\overline{MUV}$
- K_{e3} : $E/p < 0.8$
- $|m_{\pi\pi} - m_{K^0}| < 3\,\sigma$
- $p_t'^2 < 200\ (\mathrm{GeV}/c)^2$



$p_t'^2$ is the rescaled transverse momentum
$\Rightarrow$ same for K_S & K_L

Neutral events



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

$$m_{ij} = \sqrt{E_i E_j}\ .\ r_{ij}/D$$

- No extra clusters
- $R_{ell} < 13.5$

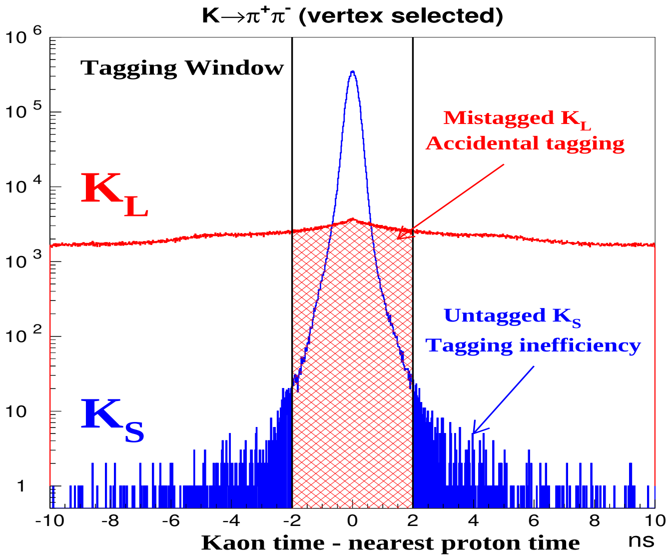
$$R_{ell} \equiv \left(\frac{m_1+m_2-2m_\pi}{2\sigma_+}\right)^2 + \left(\frac{m_1-m_2}{2\sigma_-}\right)^2$$

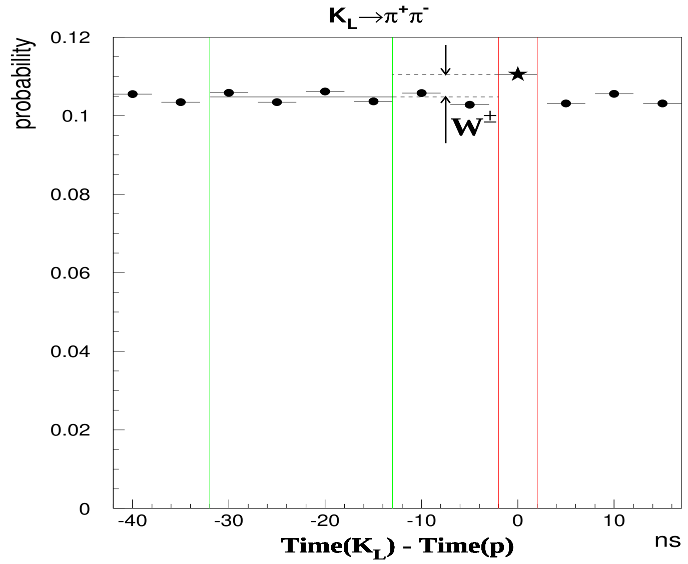
Tagging

Proton tagging allows us to distinguish K_S from K_L decays

T.O.F. between reconstructed Kaon decay and tagger:

$|t_K - t_{tagger}| \leq 2\text{ns} \Rightarrow K_S$ $\quad |t_K - t_{tagger}| > 2\text{ns} \Rightarrow K_L$





- In charged mode directly measure
  mistagging ($\alpha_{LS}^{+-} = (11.05 \pm 0.01)\%$) & inefficiency ($\alpha_{SL}^{+-} = (1.97 \pm 0.05) \times 10^{-4}$)
- In neutral mode:
  - mistagging : extrapolate from sidebands ($\alpha_{LS} = \beta + W$)
  - inefficiency : use Dalitz decays / conversions

Backgrounds

Charged Mode

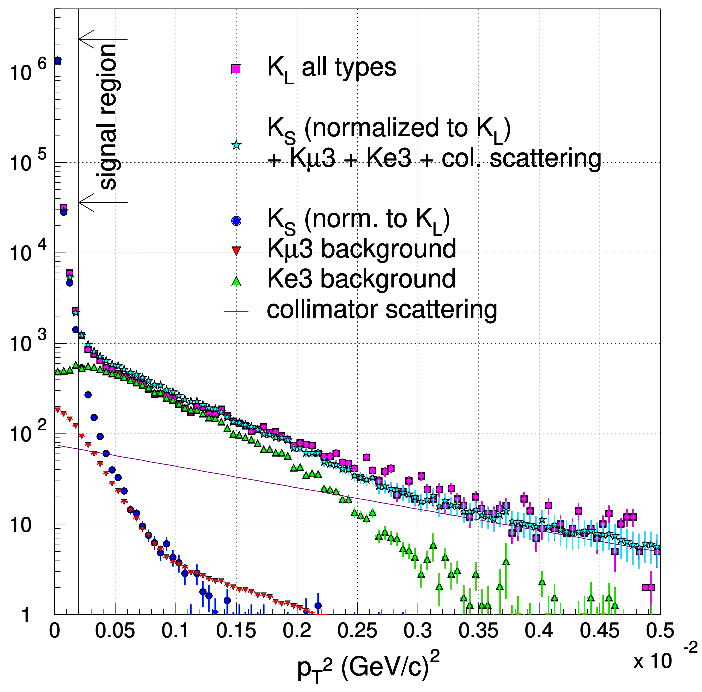
Contributions from:

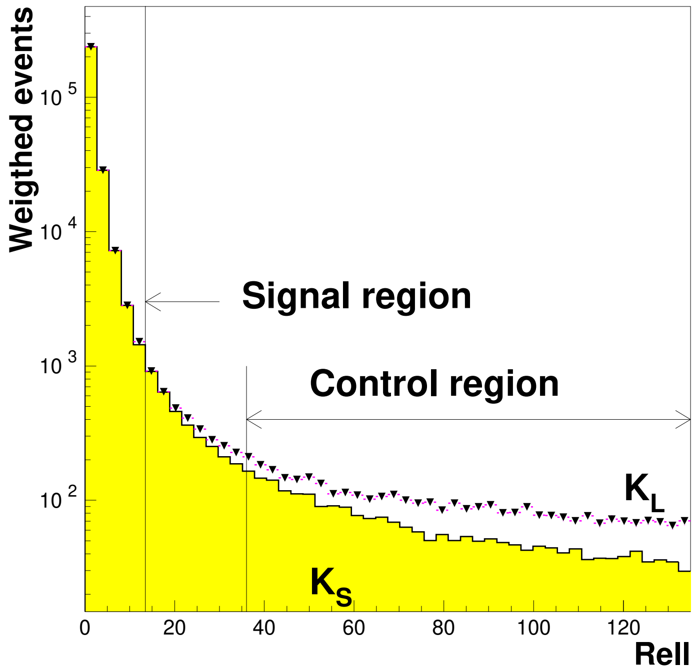
- K_{e3} $\bullet K_{\mu 3}$

Neutral Mode

Contribution from:

- $3\ \pi^0$



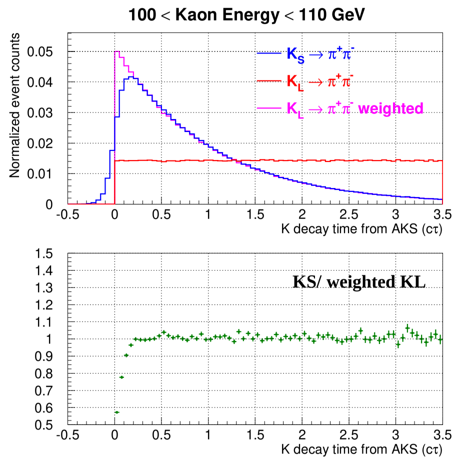


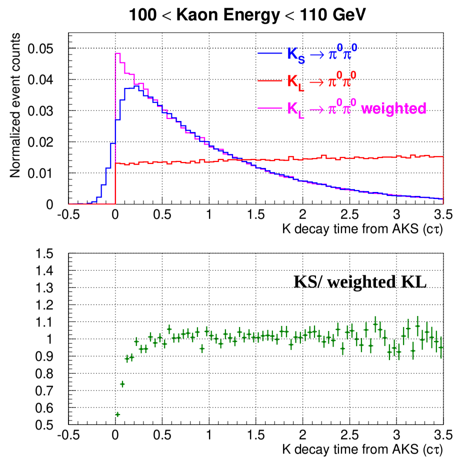
There is also some collimator scattering in the K_L beam

- rejected in charged mode through $p_t'^2$ cut
- corrected for in neutral mode

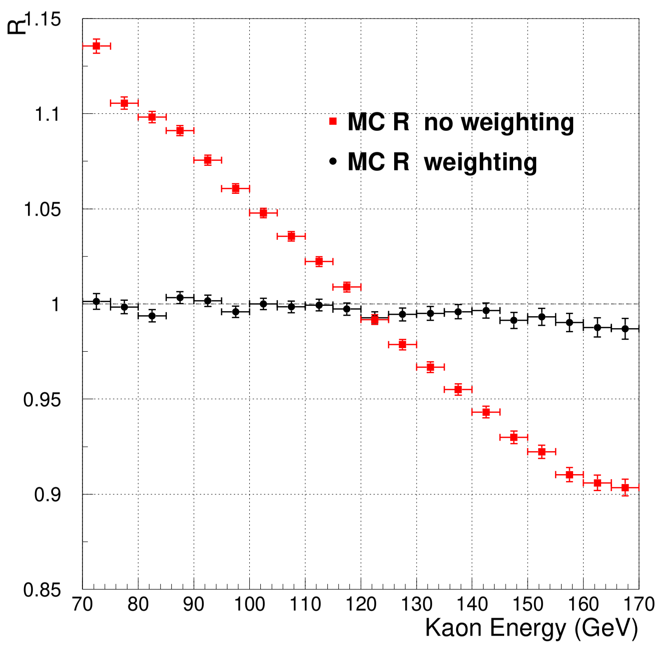
Weighting and Acceptance

The K_L events are weighted according to the ratio of the proper time distribution of K_S and K_L





This reduces the acceptance correction to $\mathcal{O}(10^{-3})$



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

Energy Scale & Accidentals

Neutral Energy Scale

Neutral reconstruction systematics

Source	ΔR (units 10^{-4})
Non linearity	$\pm$ 5
Non Gaussian tails in σ_E	$\pm$ 5
Transverse scale	$\pm$ 3
Intercalibration	$\pm$ 3
Distance/Energy scale	$\pm$ 3
Other sources	$\pm$ 4

Accidental Effects

- Geometrical K_S / K_L difference
  Effect on R measured with overlays
  $$\boxed{\Delta R = (2 \pm 6) \times 10^{-4}}$$
- Variation of K_S / K_L ratio
  Conservative estimate gives
  $$\boxed{\Delta R < 10 \times 10^{-4}}$$
- Noise effects
  Included in above
  To be estimated with overlaid MC in future

Systematic Errors

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

Subtracting the mistagging probability and averaging in energy bins, the weighted result is:

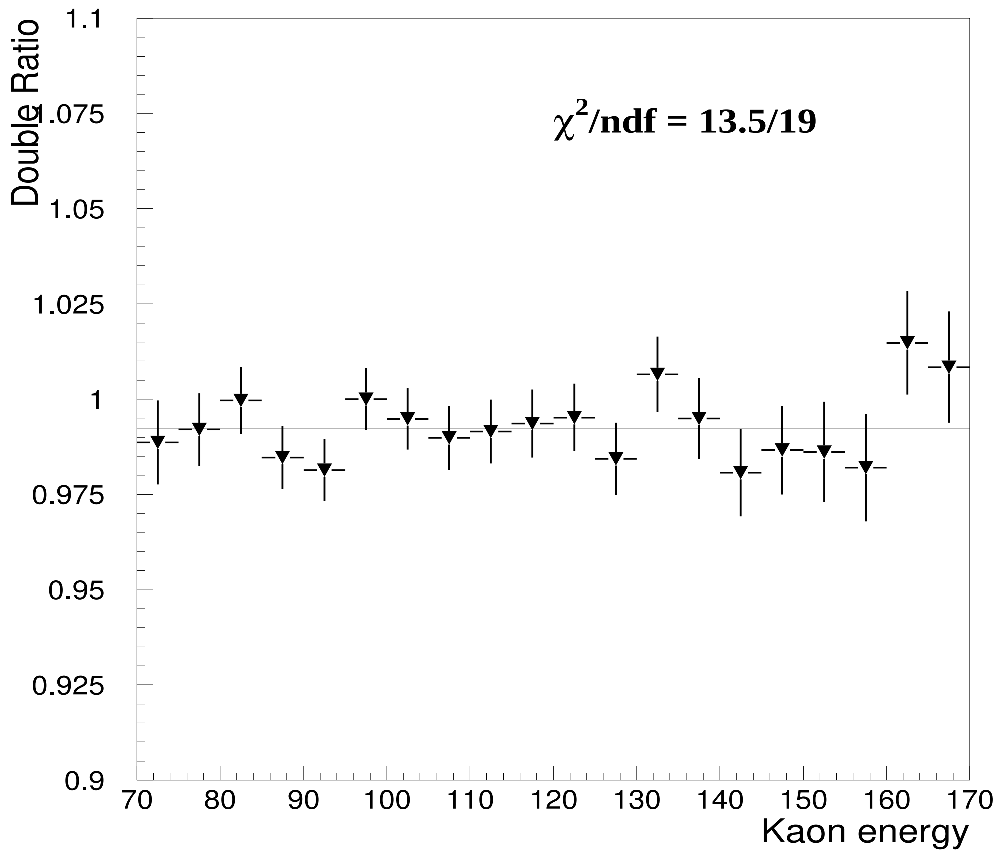
$$R_{RAW} = 0.98899 \pm 0.00173(stat)$$

Corrections and uncertainties on R (10^{-4})

Source	1998 sample		Limitation
Charged trigger	–1	± 11	(stat.)
Mistagging probability	+1	±8	(stat.)
Tagging efficiency	–	± 3	
Neutral scale	–	± 10	
Charged vertex	+2	± 2	
Acceptance and AKS	+31	± 9	
Neutral and BG	–7	± 2	
Charged BG	+19	± 3	
Beam scattering	–10	± 3	
Accid. activity	+2	± 12	
Total	+37	± 24	

Result

PRELIMINARY RESULT ON 1998 DATA



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

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

PRELIMINARY

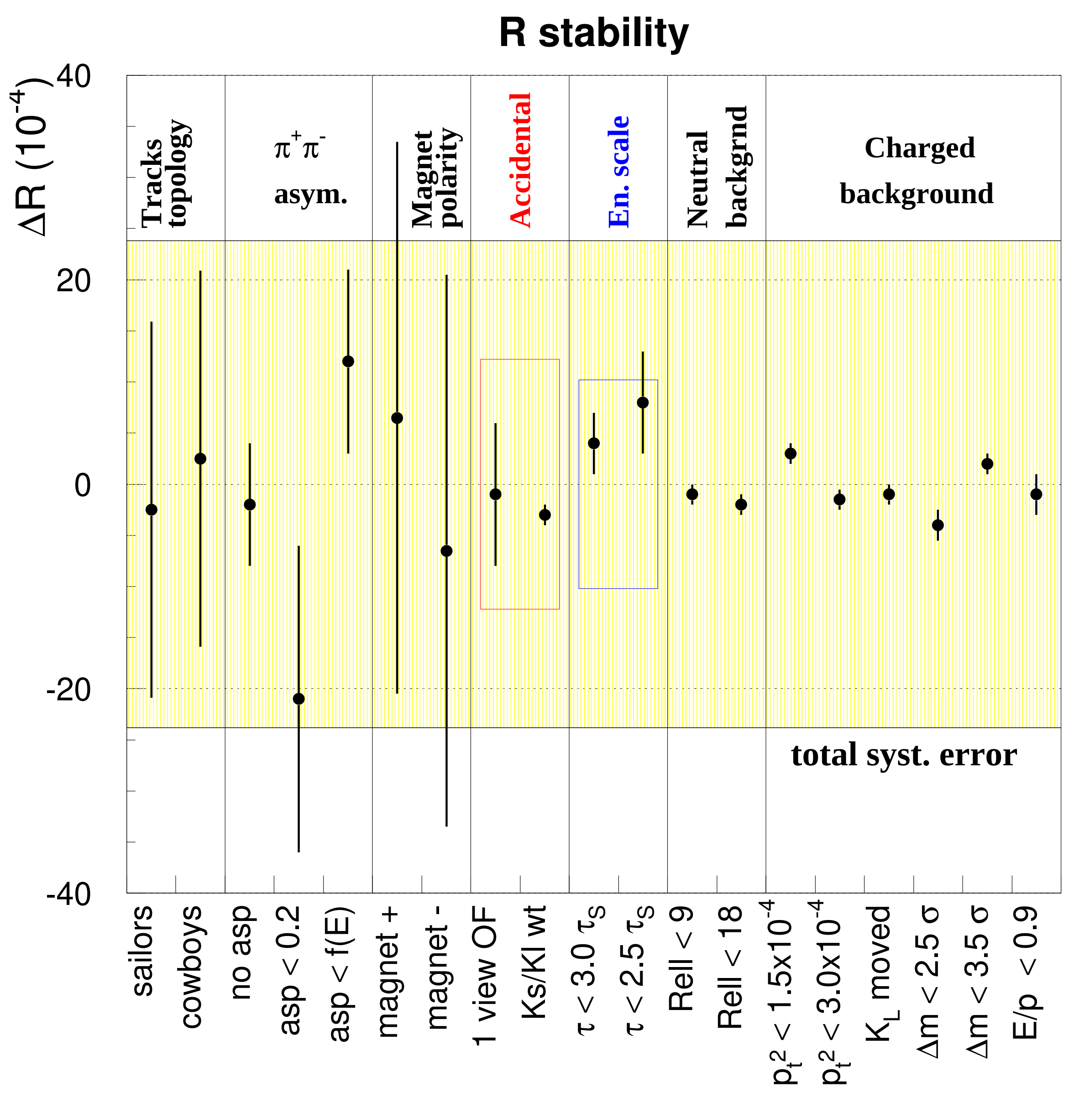
$$\boxed{\text{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 4.9) \times 10^{-4}}$$

(1997) $\text{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5(\text{stat.}) \pm 5.8(\text{syst.}) \times 10^{-4}$

Combined 1997 and 1998 result:

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

Checks



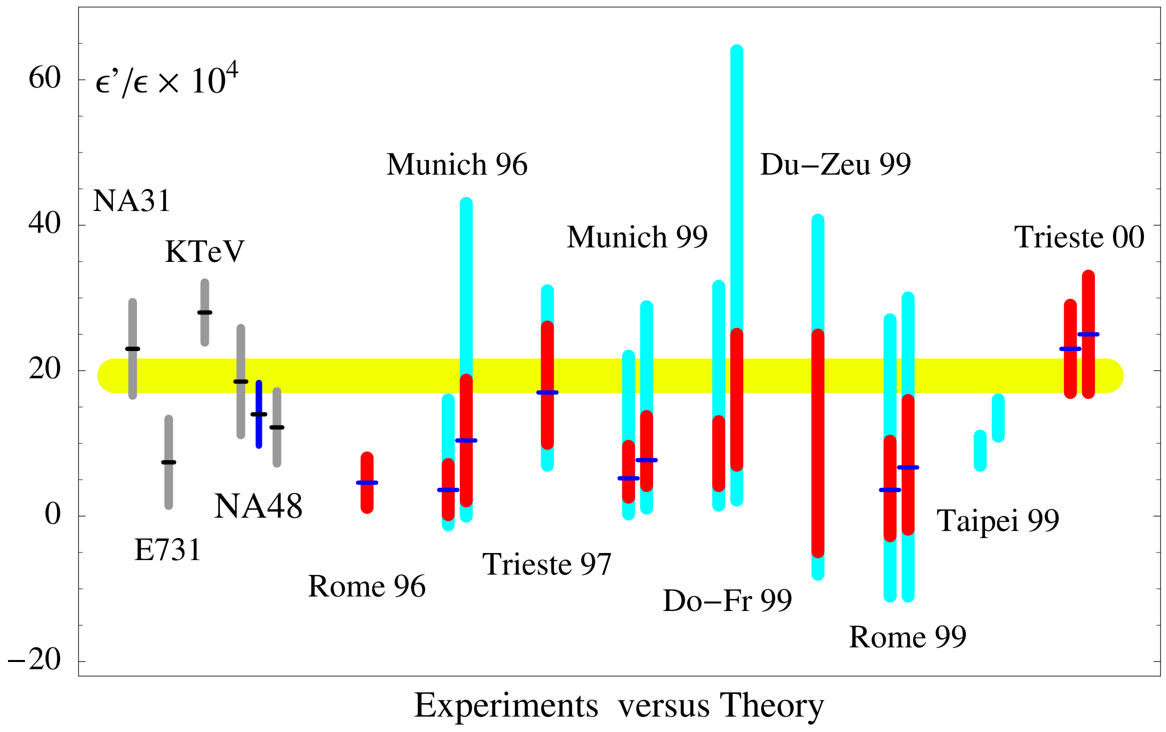
R stability
ΔR (10^-4)
40
20
0
-20
-40
Tracks topology
π+π- asym.
Magnet polarity
Accidental
En. scale
Neutral backgrnd
Charged background
total syst. error
sailors
cowboys
no asp
asp < 0.2
asp < f(E)
magnet +
magnet -
1 view OF
Ks/Kl wt
τ < 3.0 τS
τ < 2.5 τS
Rell < 9
Rell < 18
pt2 < 1.5x10-4
pt2 < 3.0x10-4
KL moved
Δm < 2.5 σ
Δm < 3.5 σ
E/p < 0.9

Conclusions and Perspectives

New world average:

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

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



- $\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$ is established
- NA48 will improve systematic error on 1998 result and analyse 1999 data
- More $\mathrm{Re}(\varepsilon'/\varepsilon)$ data will be collected in 2001 with repaired drift chambers
- Results are also anticipated from KTEV (FNAL) and KLOE (DAΦNE)