A new result on direct CP violation 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

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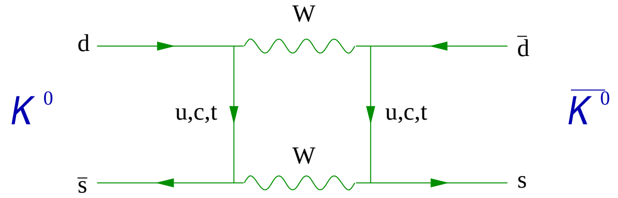
OUTLINE:

- ➜ Physics motivation
- ➜ The NA48 way: beams and detector
- ➜ Preliminary $\mathrm{Re}(\varepsilon'/\varepsilon)$ result from the 1998 data
- ➜ Checks
- ➜ Prospects

CP Violation in the Neutral Kaon System

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

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



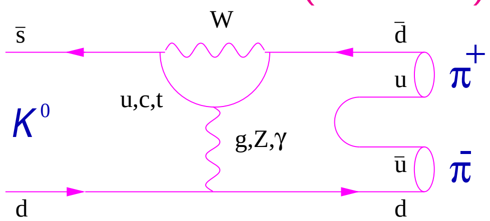
Indirect violation $(\Delta S = 2)$

Experimentally

$|\epsilon| = (2.28 \pm 0.02) \cdot 10^{-3}$

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

Direct violation $(\Delta S = 1)$



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

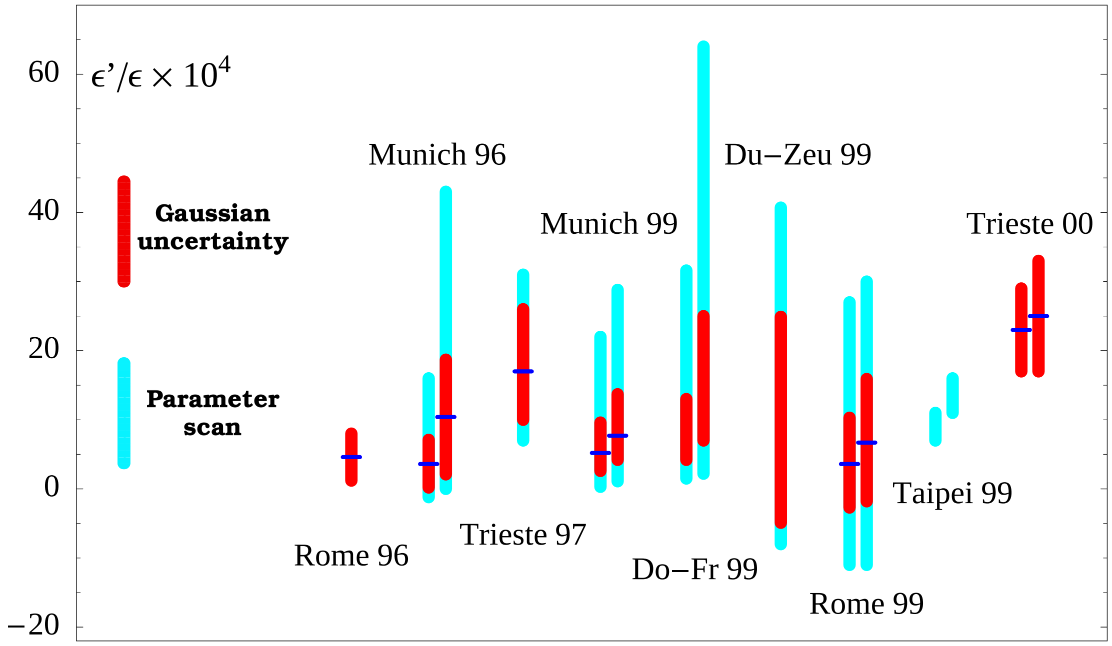
$$\langle I,0|T|\bar{K}^0\rangle = A_I^* e^{i\delta_I}$$

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

$\mathrm{Re}(\varepsilon'/\varepsilon)$: Predictions and Measurements

➜ Standard Model Predictions

Computations typically point to values between 0 and 20×10^{-4}



Alternatives:

- Superweak model : ϵ'=0
- SUSY and other physics beyond SM could contribute

➜ Measurements: double ratio method

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

$\mathrm{Re}(\varepsilon'/\varepsilon)$ =

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

The NA48 Experiment

AIM

Measurement of the double ratio

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

with $2 \cdot 10^{-4}$ final accuracy on $\mathrm{Re}(\varepsilon'/\varepsilon)$

METHOD

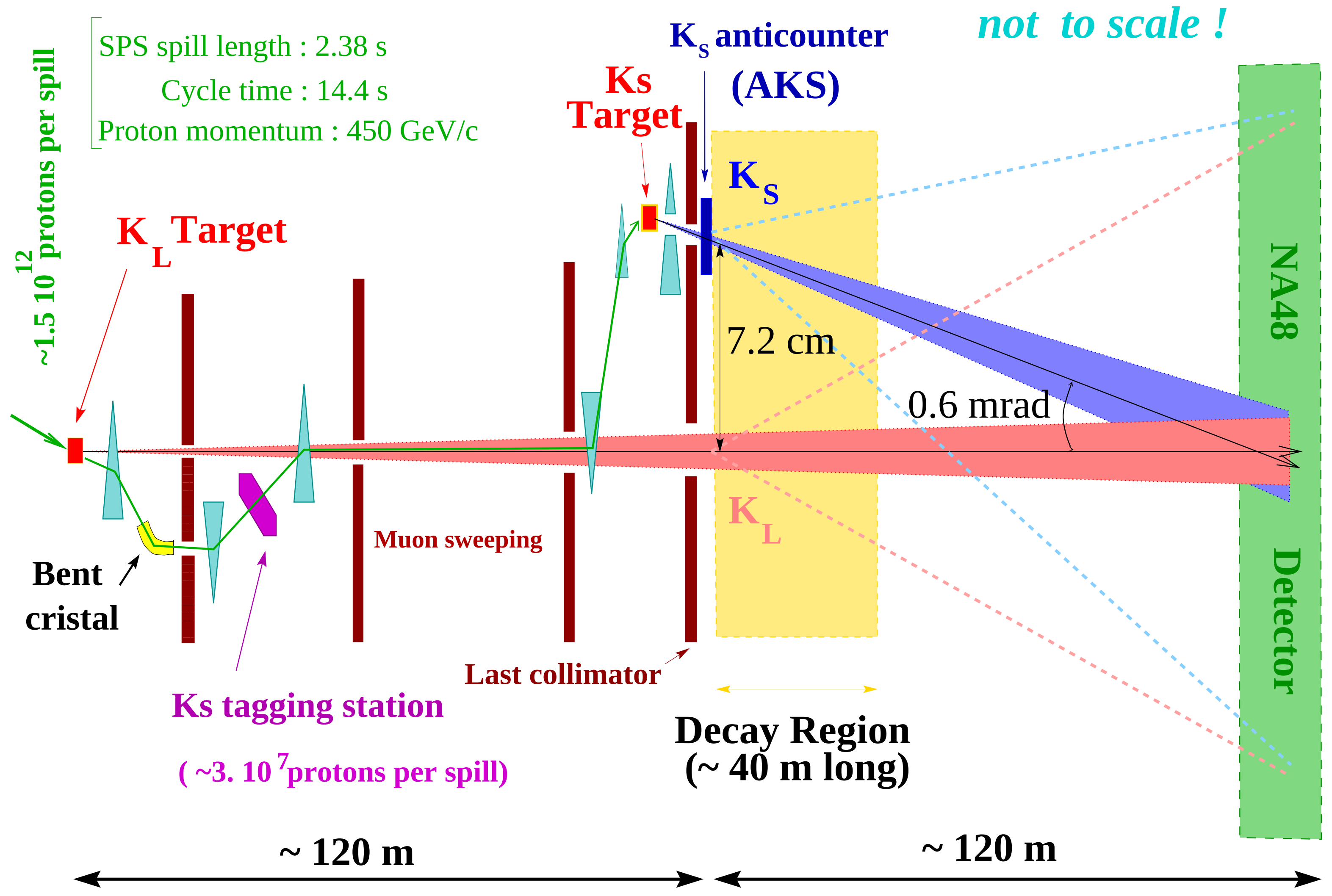
- simultaneous acquisition of the 4 decay modes
- in the same fiducial region
- from two high–intensity quasi–collinear beams
- $\mathrm{K_S}$ and $\mathrm{K_L}$ are identified by tagging in time the $\mathrm{K_S}$ beam protons
- the effects of remaining $\mathrm{K_S}$ / $\mathrm{K_L}$ differences are 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:

$$w(t) \sim e^{-t\left(\frac{1}{\tau_S} - \frac{1}{\tau_L}\right)}$$

The NA48 Beams



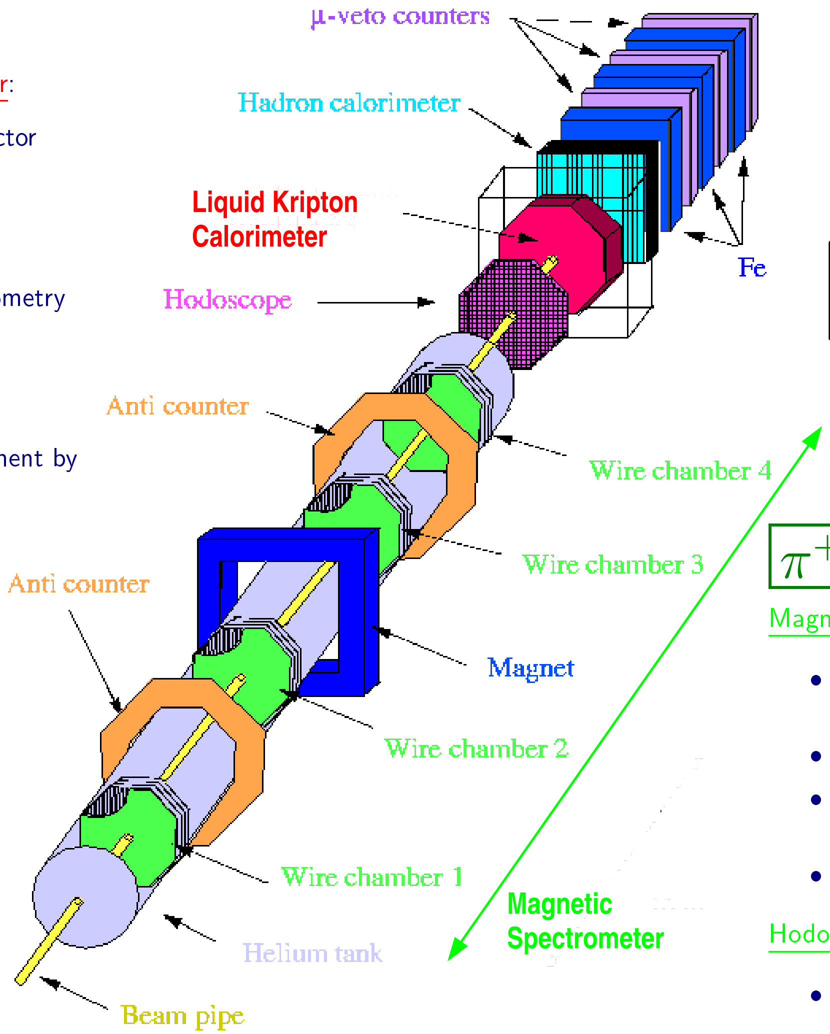
- The tagging station provides a measurement of proton time with $<$ 200 ps resolution
- The beginning of the fiducial region is defined by an anti–counter (AKS) on the K_S beam line

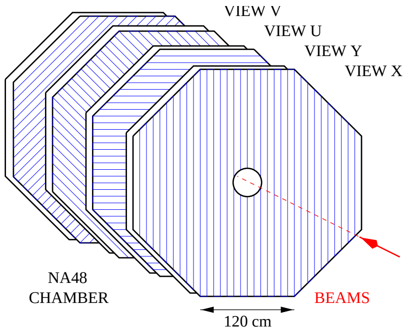
The Central Detector

$\pi^0\pi^0$

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:

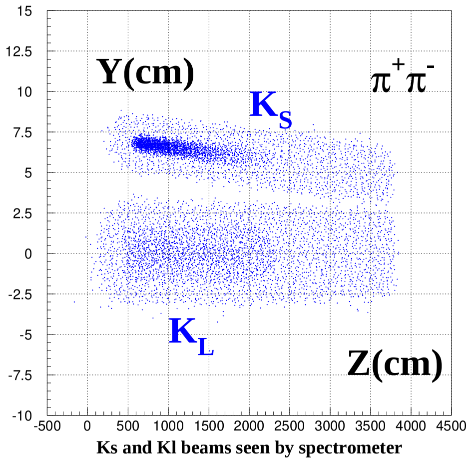
- 4 chambers with 4 views each, 2 staggered planes per view
- 90 μm spacepoint resolution
- wire position known better than 100 μm/m
- magnet providing 265 MeV/c p_T kick

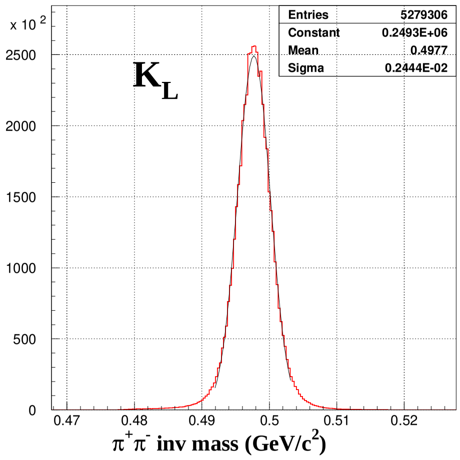
Hodoscope:

- 2 planes of scintillators for precise measurement of event time

Detector Performances

➜ Magnetic spectrometer





$\sim$ 2 mm resolution on vertex transverse position (allows beam separation)

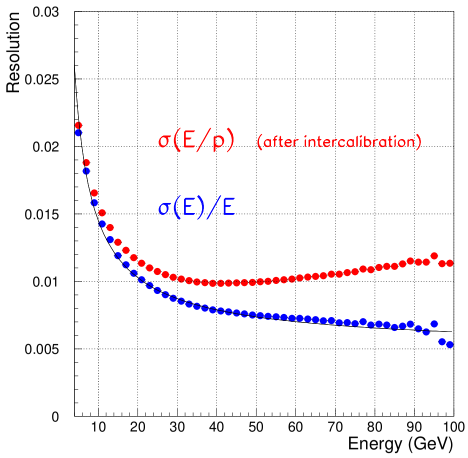
Kaon mass resolution $\sim$ 2.5 MeV/c^2

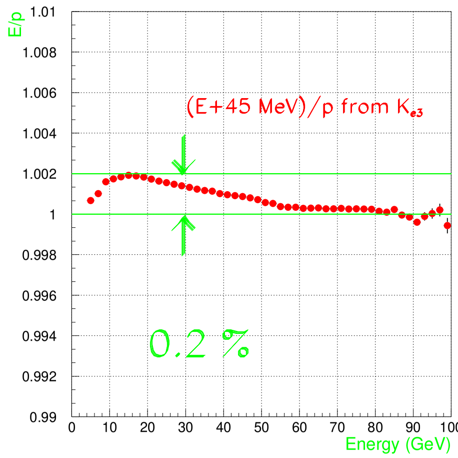
Momentum: $\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\,P[\mathrm{GeV}/c]\,\%$

➜ Charged Hodoscope

$<$ 200 ps time resolution for $\pi^+\pi^-$ event time

➜ LKr calorimeter





Energy resolution:
$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{100\ MeV}{E} \oplus 0.5\%$$
(E in GeV)

Non–Linearity $<$0.2% (from 5 to 100 GeV)

Time resolution for $\pi^0\pi^0$ event time: $<$ 250 ps

Data Samples

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

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

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

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

Main improvements :

- Improved charged trigger (efficiency 91.3 → 97.7 %) and DAQ ⟹ + 30 % rate, no downscaling for charged
- LKr High Voltage 1500 → 3000 V (new capacitors)
- Lighter beam pipe → less showers in the detector

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

PRELIMINARY RESULT in this presentation

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

Further improvements in DCh read-out, DAQ, spill length

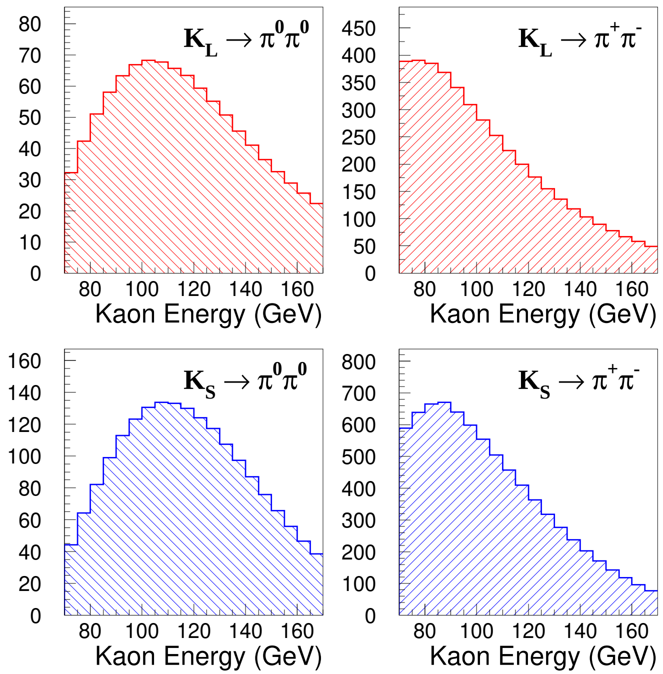
Around 2 millions of $K_L \to \pi^0\pi^0$

Analysis in progress...

Analysis Strategy

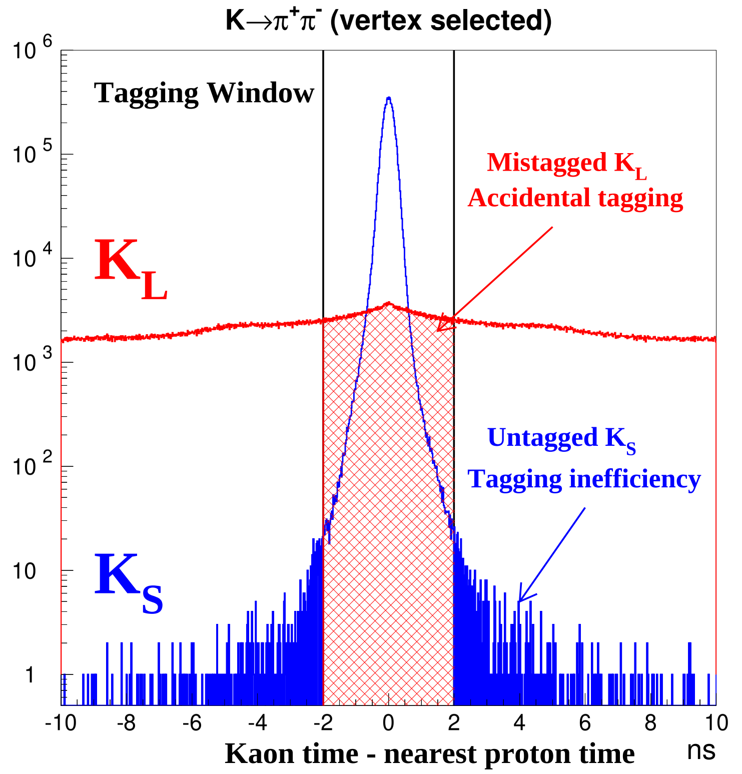
- General cuts:
  - 70 < Kaon Energy < 170 GeV
  - center of gravity at LKr within 10 cm from center
  - decay proper time within 3.5 K_S lifetimes from AKS. K_L events are weighted according to the lifetime ratio. The upstream cut is done for K_S events using the AKS signal.
  - events taken with some dead time condition ($<$ 5 % from charged trigger and $\sim$ 25 % from overflow in DCh readout) are rejected for both charged and neutral modes
- K_S and K_L are identified using the tagger and event counts in each energy bin are then corrected for mistagging (as measured for charged events using vertex).
- R is computed in each bin using an unbiased estimator

Reconstructed events per mode (thousands per 5 GeV)



- A set of small corrections are applied to the double ratio in each energy bin to account for:
  - charged / neutral difference of mistagging probabilities
  - background
  - residual K_S / K_L acceptance difference
  - trigger inefficiencies
  - energy scale and non–linearity
  - accidental activity

Tagging



- The mistagging probabilities can be precisely measured for charged events:

  Inefficiency ($K_S \to K_L$) $\quad \alpha_{SL}^{+-} = (1.97 \pm 0.05) \cdot 10^{-4}$

  Accidental tagging ($K_L \to K_S$) $\quad \alpha_{LS}^{+-} = (11.05 \pm 0.01)\%$

- $\alpha_{SL}^{+-} - \alpha_{SL}^{00}$ is measured through
  - K$_S$ only runs
  - $K_S \to \pi^0 e^+ e^- \gamma$ events
  - comparison of charged and neutral time for neutral events with conversions

$\boxed{|\alpha_{SL}^{00} - \alpha_{SL}^{+-}| < 0.5 \times 10^{-4}}$ $\Longrightarrow$ R correction $< 3 \cdot 10^{-4}$

- $\alpha_{LS}^{+-} - \alpha_{LS}^{00}$ is measured by
  - comparing rate of out–of–time protons for charged and neutral events
  - checking the difference between in–time and out–of–time windows using $K_L \to \pi^+\pi^-$ (vertex–identified) and $K_L \to 3\pi^0$

$\boxed{\alpha_{LS}^{00} - \alpha_{LS}^{+-} = (0.3 \pm 4.2) \times 10^{-4}}$

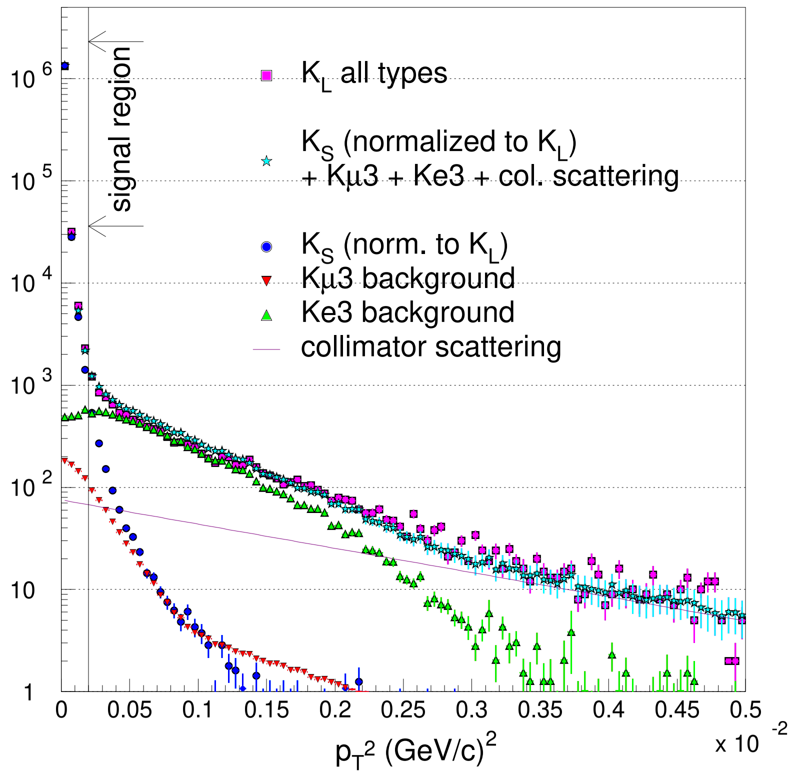
$\Longrightarrow$ R correction $= (0.6 \pm 8.4) \times 10^{-4}$

Background to $K \to \pi^+\pi^-$

➜ Dominated by $K_L \to \pi e \nu$ and $K_L \to \pi \mu \nu$

Rejected using:

- muon veto counters
- $E_{LKr}/P_{DCh} < 0.8$
- invariant mass $m_{\pi\pi} = M_{K^0} \pm 3\sigma$
- total transverse momentum $p_T^2 < 200$ (MeV/c)^2



➜ Estimated by fitting the $\mathrm{K_L}$ distribution as $\pi^+\pi^- + \mathrm{K}_{e3} + \mathrm{K}_{\mu 3}$ in a control region in the plane $(m_{\pi\pi}, p_T^2)$

$\Longrightarrow$ Total Background = $\boxed{(19 \pm 3) \cdot 10^{-4}}$

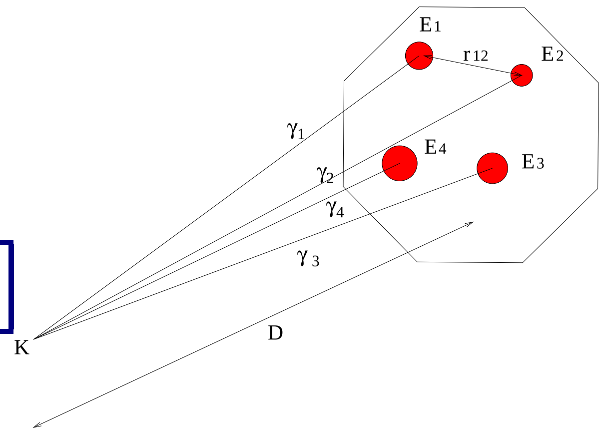
➜ A small $K \to \pi\pi$ signal is observed at high p_T for the $\mathrm{K_L}$, coming from scattering + $\mathrm{K_S}$ regeneration in the collimators.

Different cuts for charged and neutral modes

$\Longrightarrow$ R correction $= (-9.9 \pm 3.3) \cdot 10^{-4}$

Background to $K \to \pi^0\pi^0$

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

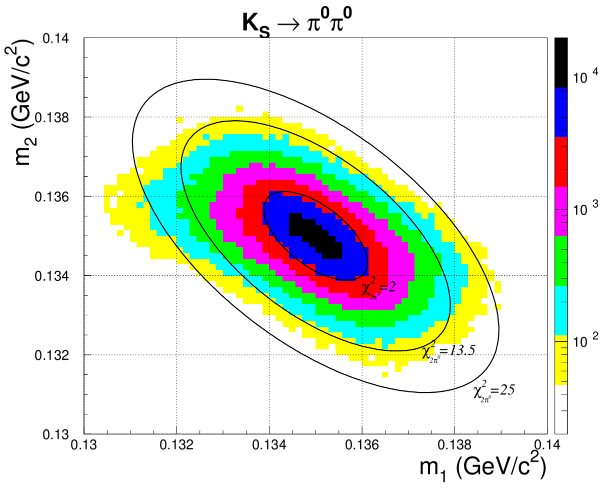


Imposing K^0 mass :

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

➜ Measure "best" π^0 masses $\quad m_{ij} = \sqrt{E_i E_j}\ .\ r_{ij}/D$

$$\chi^2 \equiv \left[\frac{(m_1+m_2)/2 - m_{\pi^0}}{\sigma_+}\right]^2 + \left[\frac{(m_1-m_2)/2}{\sigma_-}\right]^2$$

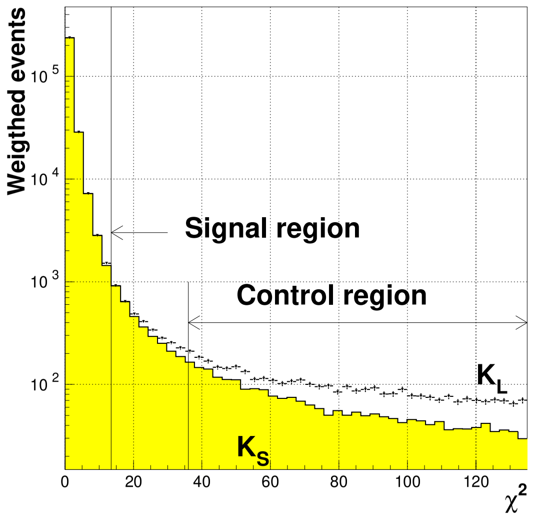


$\sigma_+ \sim$ 0.45 MeV

$\sigma_- \sim$ 0.85 MeV

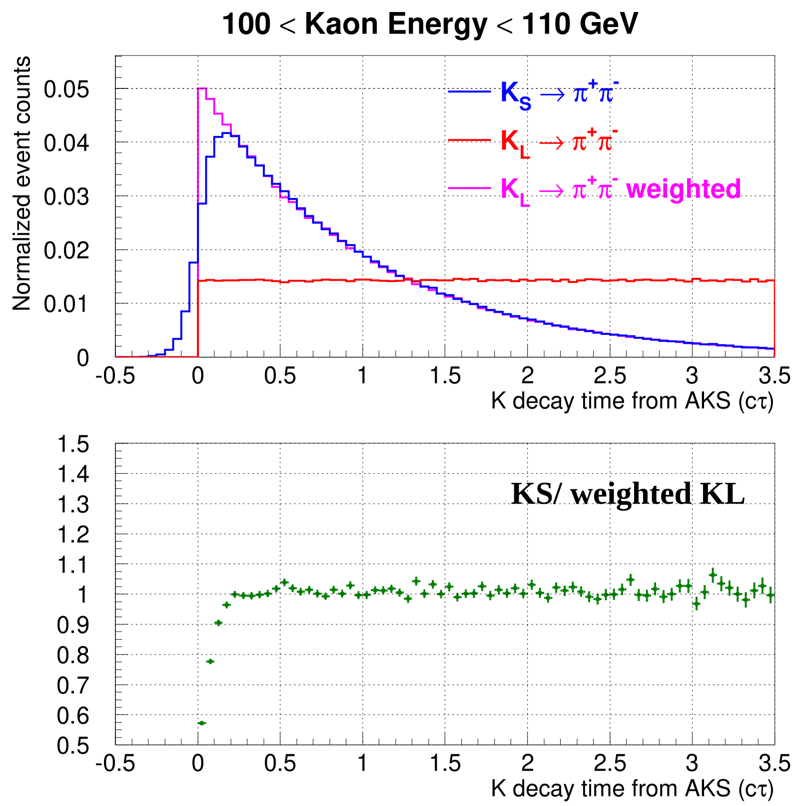
Total background (estimated in χ^2 control region)

$= (6.6 \pm 2.0) \cdot 10^{-4}$

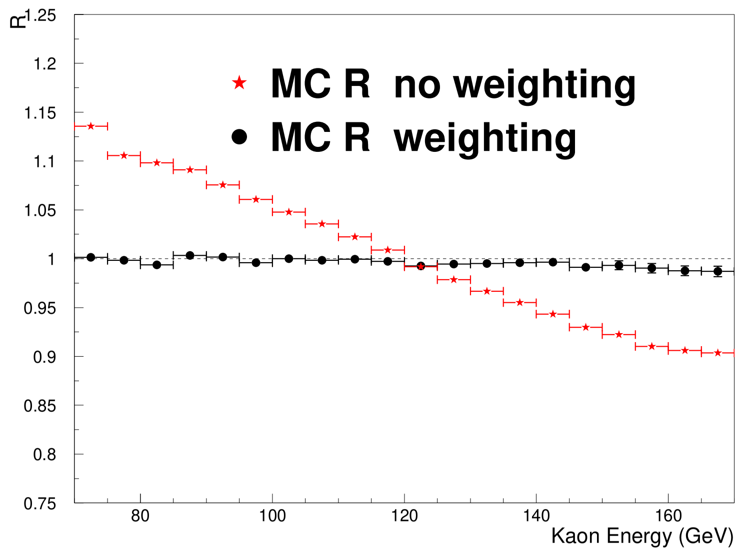


K_L weighting and Acceptance

K_L events are weighted according to the K_S / K_L ratio of proper time distributions



- ➜ The acceptance correction is reduced to a few per mill
- ➜ The price to pay is a 35 % increase of the statistical error



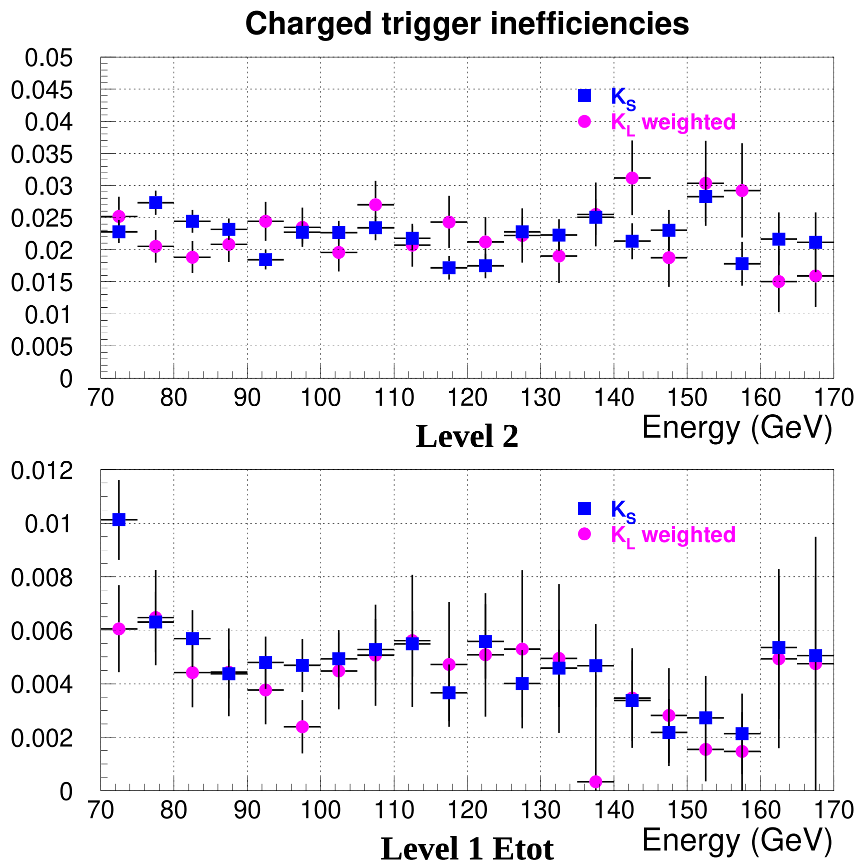
$$\text{R correction} = (+31 \pm 6(stat) \pm 6(syst)) \times 10^{-4}$$

Trigger Efficiencies

➜ Charged Trigger

		Efficiency
Level 1:	Total energy signal + 2 track topology in hodoscope	99.44 ± 0.03 %
Level 2:	on–line reconstruction of vertex and $\pi\pi$ invariant mass	97.75 ± 0.05 %

K_S / K_L symmetry checked through control triggers



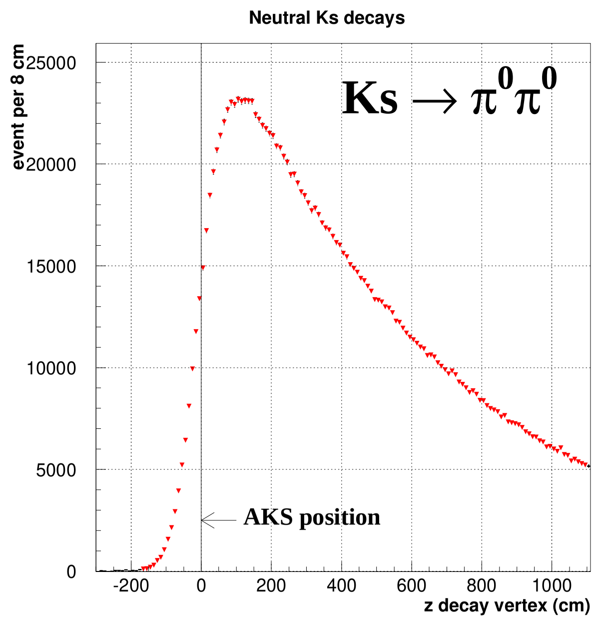
$$\boxed{\mathrm{R\ correction} = (-1 \pm 11) \times 10^{-4}}$$

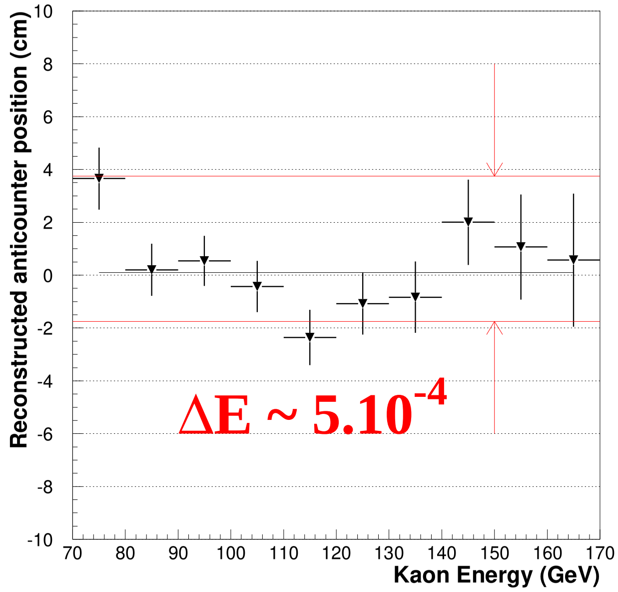
➜ Neutral Trigger

on–line reconstruction of number of peaks, kaon energy and vertex position

Efficiency $= 99.93 \pm 0.02$ % $\Longrightarrow$ no bias on R

Systematics from Neutral Reconstruction





The global energy scale ($\to$ distance scale) for neutral events is fixed by fitting the reconstructed Z distribution with the AKS position.
The uncertainty is $5 \cdot 10^{-4}$

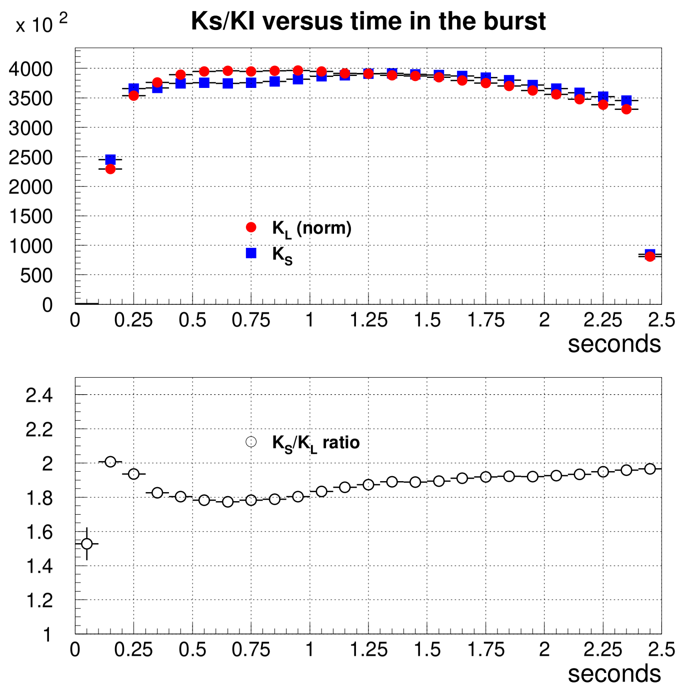
$\Longrightarrow \Delta R = \pm 3 \cdot 10^{-4}$

➜ Other sources of error from neutral reconstruction are non–linearity ($\pm 5 \cdot 10^{-4}$), non–gaussian tails in σ_E ($\pm 5 \cdot 10^{-4}$), transverse scale ($\pm 3 \cdot 10^{-4}$), accuracy of intercalibration ($\pm 3 \cdot 10^{-4}$)

$\Longrightarrow$ $\boxed{\text{total uncertainty on R} = \pm 10 \cdot 10^{-4}}$

Accidental Activity

➜ The simultaneity and intensity correlation of the two beams minimizes the effect of accidentals



➜ The geometrical difference of the effect for the two beams is estimated by overlaying random–triggered events to good events. The resulting losses and gains lead to

$$\text{R correction} = (2 \pm 6) \cdot 10^{-4}$$

➜ The residual $\mathrm{K_S}$ / $\mathrm{K_L}$ difference in intensity can produce a bias if losses are not symmetric for charged and neutrals. We measure that

- accidental out–of–time activity is identical for $\mathrm{K_S}$ and $\mathrm{K_L}$ within 1 %
- asymmetric losses on $\pi^+\pi^-$ and $\pi^0\pi^0$ are $< 2.5\%$

$\Longrightarrow$ we presently quote a conservative limit

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

➜ Further studies in progress will hopefully reduce this error.

The Result from 1998 data

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

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

Corrections and systematic uncertainties on R (Units = 10^{-4})		
Accidental tagging ($\pi^0\pi^0/\pi^+\pi^-$ asymmetry)	+1	$\pm$ 8
Tagging inefficiency ($\pi^0\pi^0/\pi^+\pi^-$ asymmetry)	–	$\pm$ 3
Background to $\pi^+\pi^-$	+19	$\pm$ 3
Beam scattering and regeneration	–10	$\pm$ 3
Background to $\pi^0\pi^0$	–7	$\pm$ 2
Acceptance and K_S anti-counter	+31	$\pm$ 9
Charged trigger inefficiency	–1	$\pm$ 11
Neutral reconstruction	–	$\pm$ 10
Charged reconstruction	+2	$\pm$ 2
Accidental activity and in–time background	+2	$\pm$ 12
Total	+37	$\pm$ 24

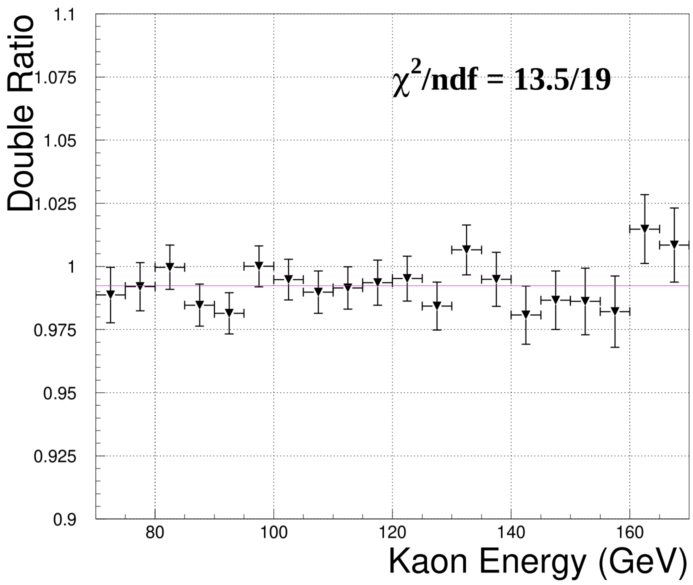
(errors in green are mostly of statistical nature)

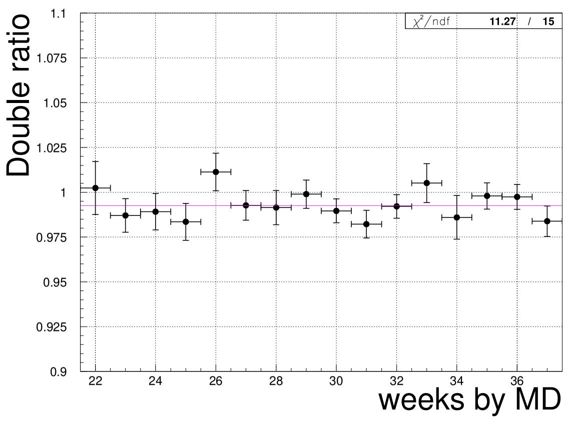
PRELIMINARY RESULT OF 1998 DATA:

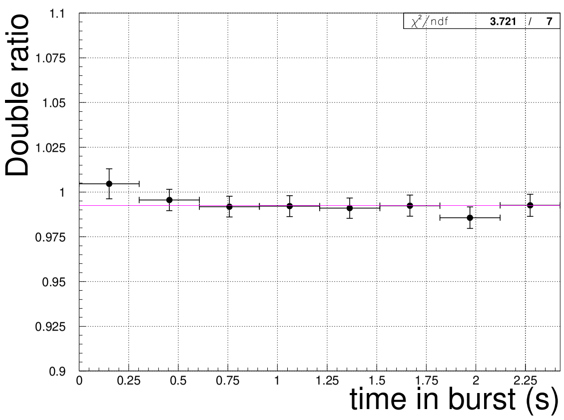
$$Re\left(\frac{\epsilon'}{\epsilon}\right) = \frac{1-R}{6} = (12.2 \pm 2.9 \text{ (stat.)} \pm 4.0 \text{ (syst.)}) \times 10^{-4}$$

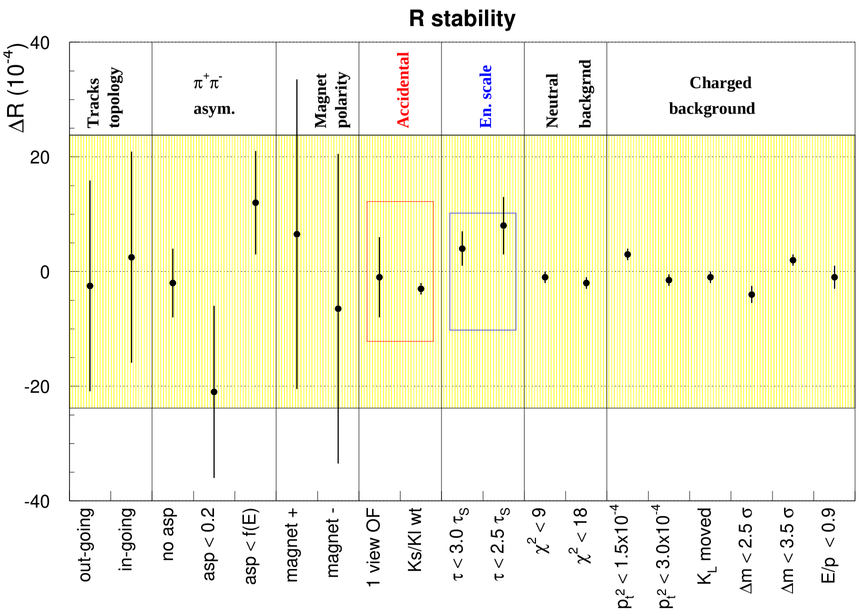
$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 4.9) \times 10^{-4}}$$

Stability Checks









Prospects

- ➜ Analysis of 1998 data is continuing and some systematic uncertainties will be probably reduced

- ➜ Data taken in 1999 are being analyzed

- ☹ The implosion of the carbon fiber beam pipe occurred last November has damaged all four drift chambers

- ☺ NA48 has already been granted for the chamber repair

- ➜ The ϵ' program will be completed in year 2001. During the 2000 and 2001 runs we will perform dedicated runs to study systematic effects.

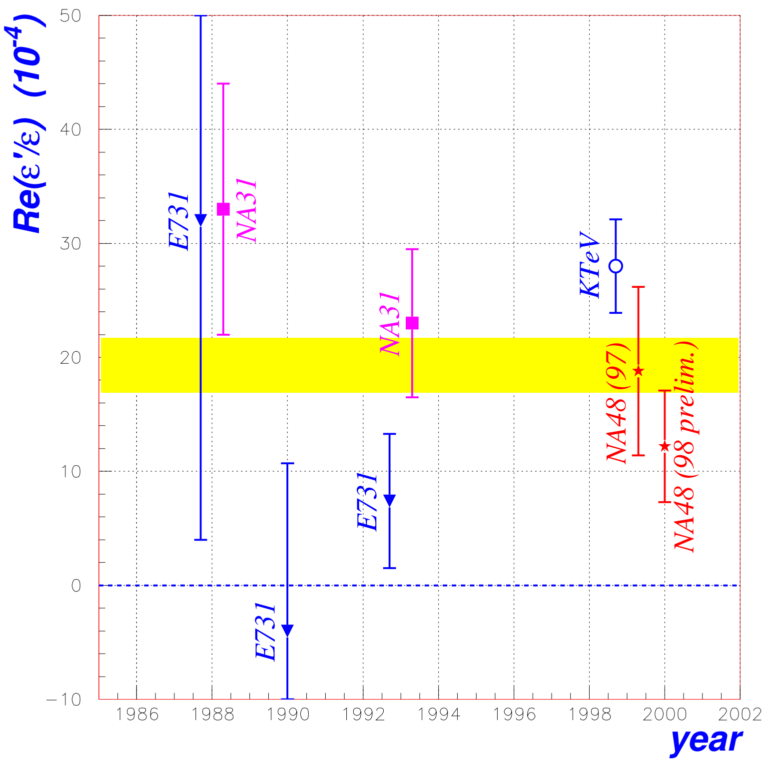
Conclusions

- NA48 has presented a new preliminary result on direct CP violation in the neutral kaon system based on the 1998 data sample:

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

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

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



- the world average value for $\mathrm{Re}(\varepsilon'/\varepsilon)$ becomes

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

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

- looking forward for final results from NA48 and KTEV, and new results from KLOE.