Latest results on ε'/ε from NA48

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HQ2K, Rio de Janeiro

October 9-12, 2000

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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

Outline

1) Physics motivation

2) NA48 Method and Detector

3) Analysis of the 1998 Data

4) Result and the World Average

5) Conclusions

The neutral kaon system

Strangeness eigenstates:

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

CP eigenstates:

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

Weak interactions allow $\Delta S = 1$ or 2 transitions.
If CP were a good symmetry, the physical states would be K_1 and K_2
K_1 can decay to two pions (CP=+1)
K_2 cannot decay to two pions

- **1964** : **CP violation discovery**

⇒Mass eigenstates are not pure CP eigenstates :

$$K_S \simeq K_1 + \varepsilon K_2 \quad (c\tau_S = 2.67\ \text{cm})$$
$$K_L \simeq K_2 + \varepsilon K_1 \quad (c\tau_L = 15.5\ \text{m})$$

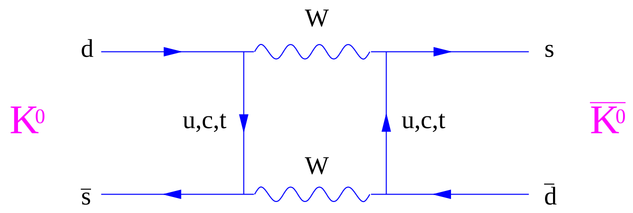
K_S		K_L	
69 %	$\pi^+\pi^-$	21 %	$3\pi^0$
31 %	$\pi^0\pi^0$	13 %	$\pi^+\pi^-\pi^0$
		27 %	$\pi\mu\nu$
		39 %	$\pi e\nu$
		0.2 %	$\pi^+\pi^-$
		0.1 %	$\pi^0\pi^0$

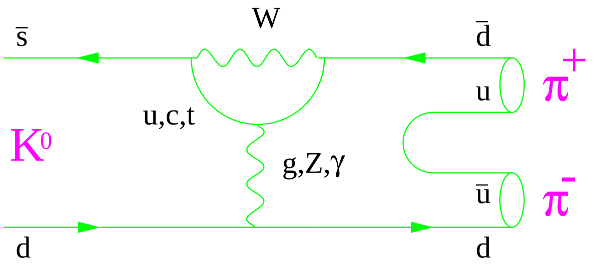
$$\boxed{|\varepsilon| = (2.28 \pm 0.02)\ 10^{-3}}$$

indirect CP violation

CP Violation

Indirect violation
through mixing
$K^0/\overline{K^0}$ oscillations
$\Rightarrow \varepsilon$ parameter





Direct violation
through decay
penguin diagrams
$\Rightarrow \varepsilon'$ parameter

Direct CP Violation :

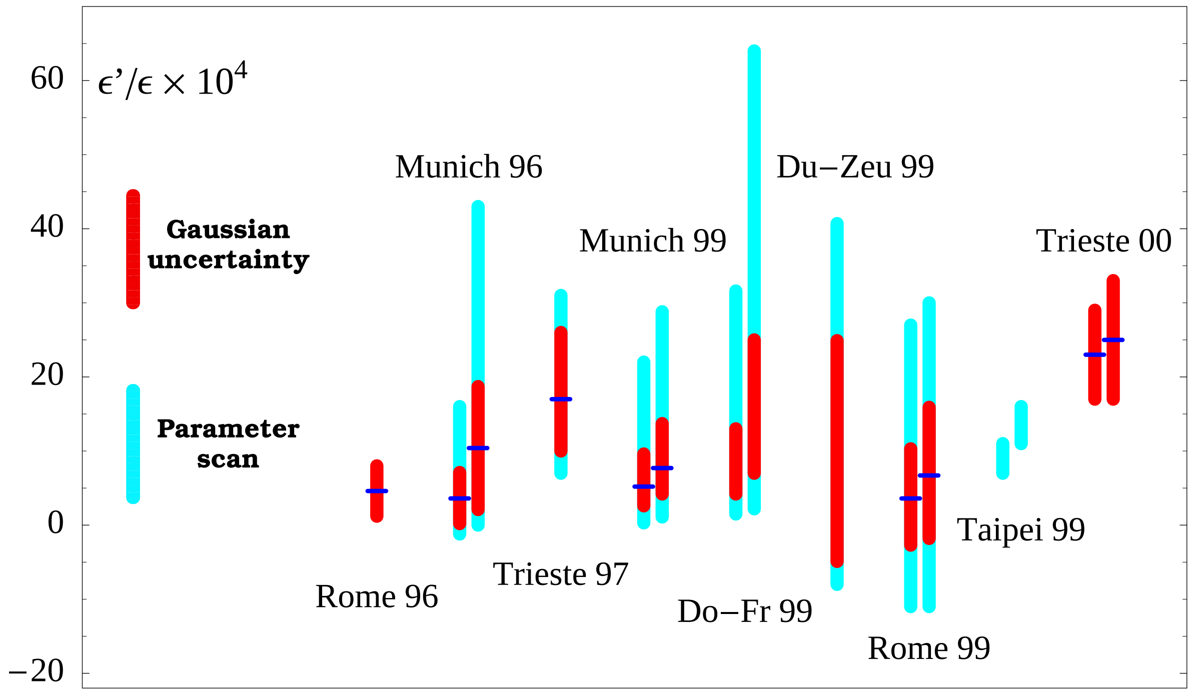
$$|A(K^0 \to f\bar{f})| \neq |A(\overline{K^0} \to f\bar{f})|$$

- Need interference of two decay amplitudes
- Two pion state from K^0 can have I=0 or 2
  $\Rightarrow$ 2 amplitudes A_0 and A_2

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

Predictions and measurements on $\mathrm{Re}(\varepsilon'/\varepsilon)$

Theoretical predictions



Previous Measurements

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \begin{array}{lll} \text{NA31} & (23.0 \pm 6.5) \times 10^{-4} & (3.5\,\sigma) \\ \text{E731} & (7.4 \pm 5.9) \times 10^{-4} & (1.2\,\sigma) \\ & & \\ \text{KTEV} & (28.0 \pm 4.1) \times 10^{-4} & (6.8\,\sigma) \\ \text{NA48} & (18.5 \pm 7.3) \times 10^{-4} & (2.5\,\sigma) \end{array}$$

Double ratio technique

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

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

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

Experimental uncertainties cancel at first order in the ratio if $\mathrm{K_S}/\mathrm{K_L}$ and $\pi^+\pi^-/\pi^0\pi^0$ are collected at the same time and in the same fiducial volume
$\Rightarrow$ Count number of events

More care is needed for acceptance corrections.

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

Direct CP Violation $\Leftrightarrow$ $\mathrm{R} \neq 1$

The NA48 method

- Goal : measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ (final precision $\approx 2 \times 10^{-4}$)
- Mean : measure the double ratio of the four modes

✔ To achieve the required statistical precision:

☞ Collect $> 10^6$ $K_L \rightarrow \pi^0\pi^0$ (rarest mode)

✔ To minimize systematic effects related to detector instabilities and (or) beam intensity:

☞ NA48 uses two simultaneous and almost collinear K_S and K_L beams

☞ The 4 decay modes are collected concurrently in the same decay region (lifetime $< 3.5 \times \tau_S$)

⇒ **Cancellation of flux, dead times, inefficiencies, accidental losses...**

☞ Apply lifetime weighting to equalize distribution of K_S and K_L decay positions

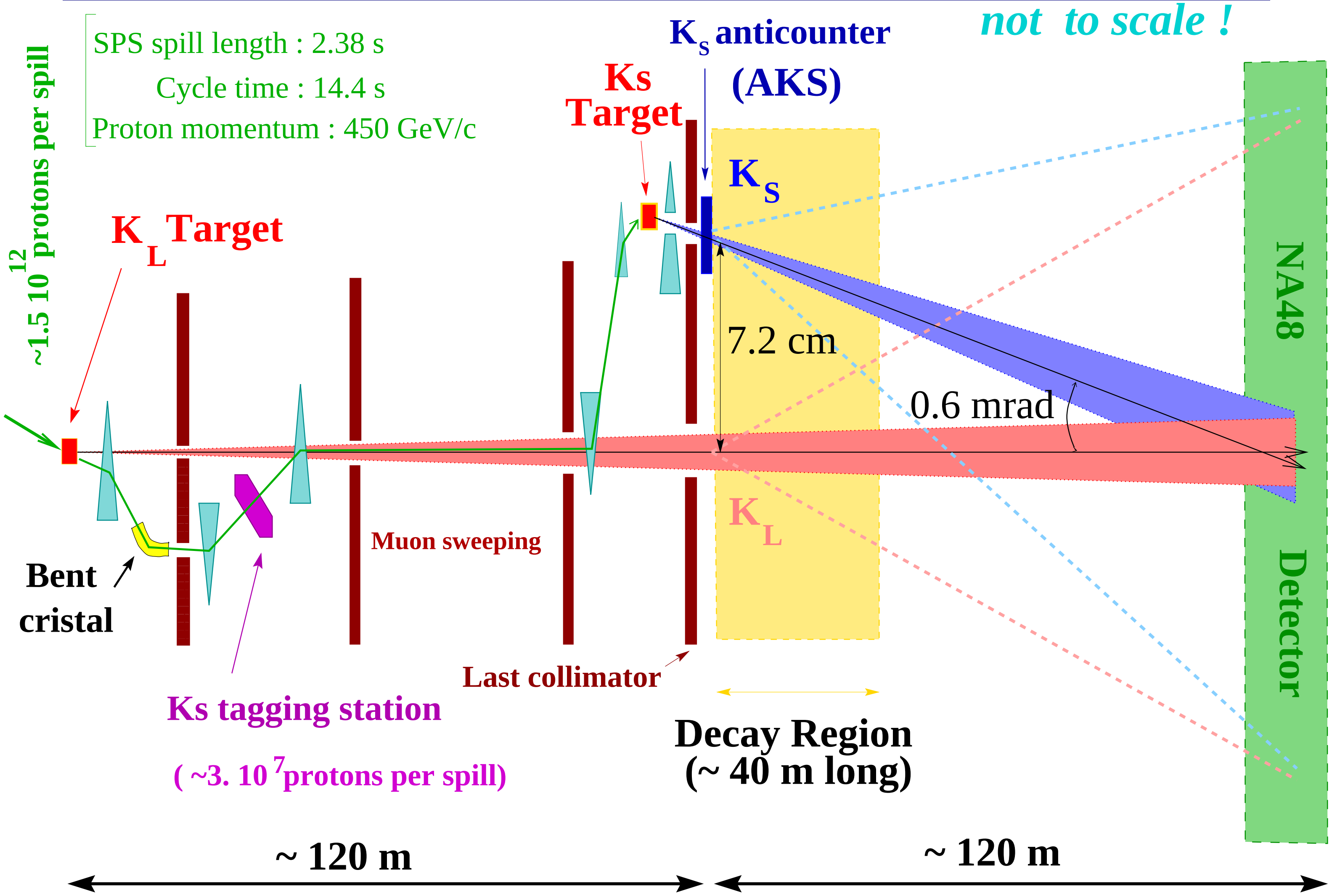
⇒ **Cancellation of detector acceptance effects**

☞ Use quasi-homogeneous Liquid Krypton calorimeter to detect $\pi^0\pi^0$ and magnetic spectrometer for $\pi^+\pi^-$

⇒ **Minimize backgrounds**

☞ Analysis in bins of energy to get rid of slight differences of K_S and K_L energy spectra (20 bins 70–170 GeV)

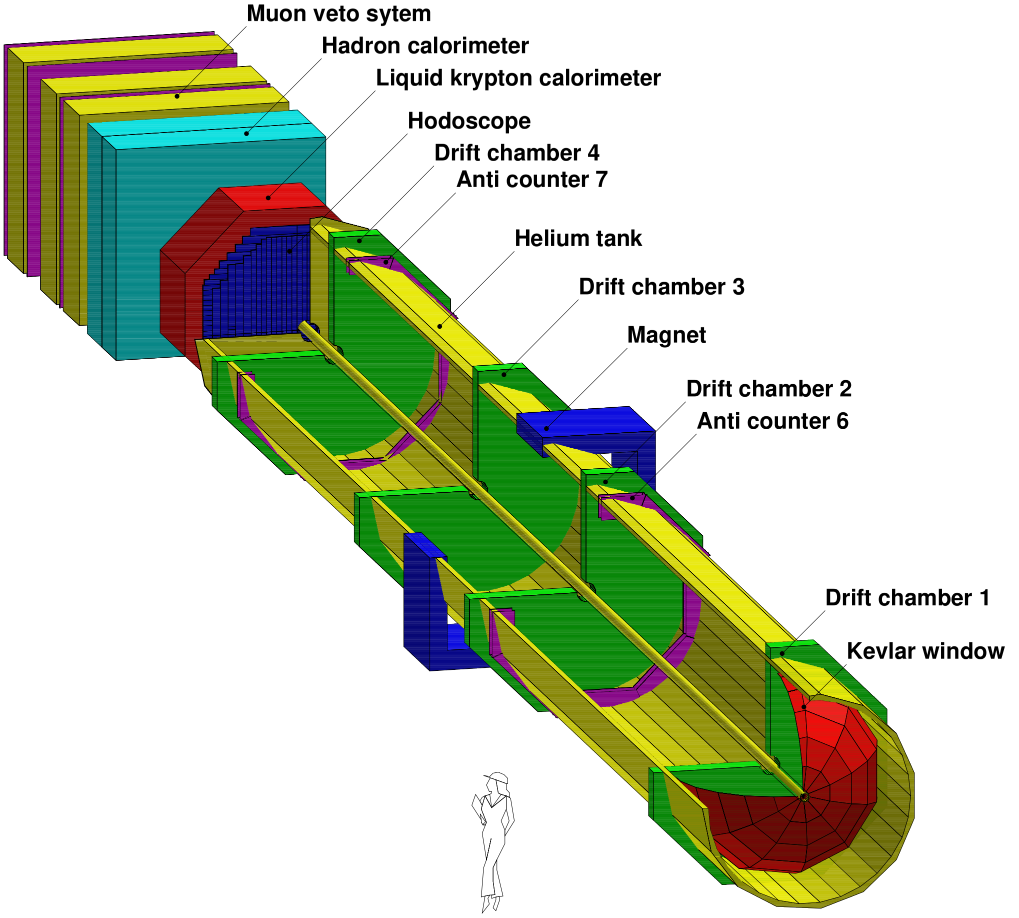
NA48 simultaneous and collinear K_S and K_L beams



Two simultaneous and almost collinear neutral beams converge towards the NA48 calorimeters with an angle of 0.6 mrad.

K_S and K_L beams are distinguished by proton tagging upstream of the K_S target.

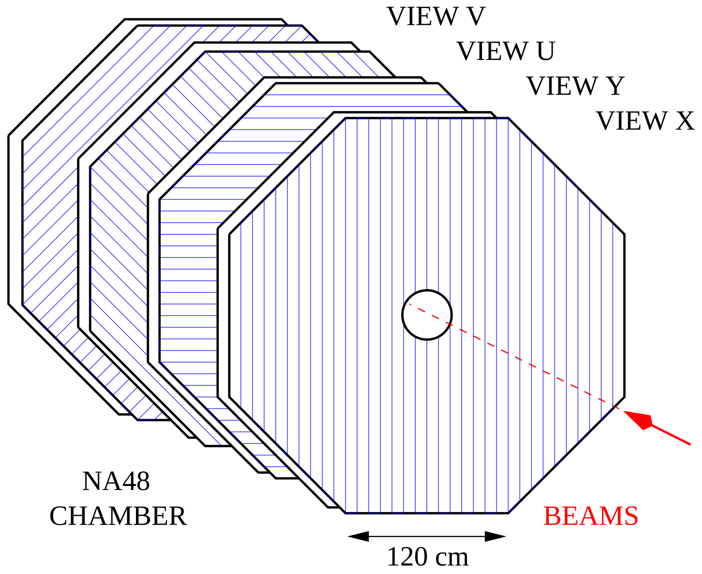
The NA48 detector



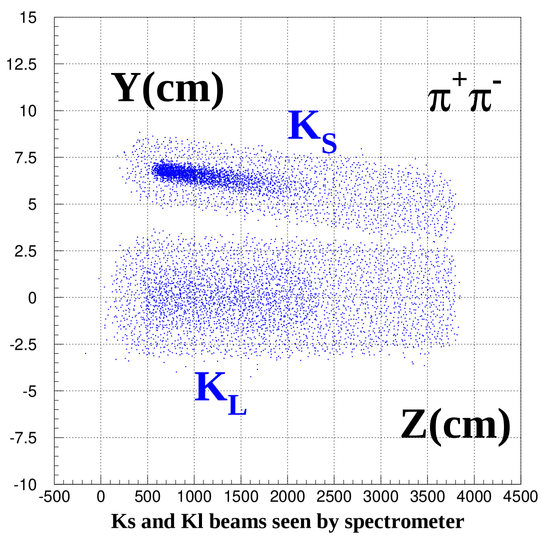
- $K_{\mathrm{L,S}} \to \pi^+\pi^-$
  - Magnetic spectrometer ($\sigma_{X,Y} \sim 90\ \mu$m)
  - $\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\ P[\mathrm{GeV}/c]\ \%$
  - Hodoscope for timing measurements ($\sigma(t) \sim 200\ ps$)
  - Muon veto to reject $\pi\mu\nu$ background.
- $K_{\mathrm{L,S}} \to \pi^0\pi^0$
  - Liquid Krypton e.m. calorimeter high granularity (13212 $2 \times 2\,cm^2$ cells), projective geometry
  - $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus (100\,MeV)/E \oplus 0.5\%$
  - $\sigma(t) \simeq 250\,ps$
  - $\sigma_{X,Y} = 1\,mm$

The magnetic spectrometer

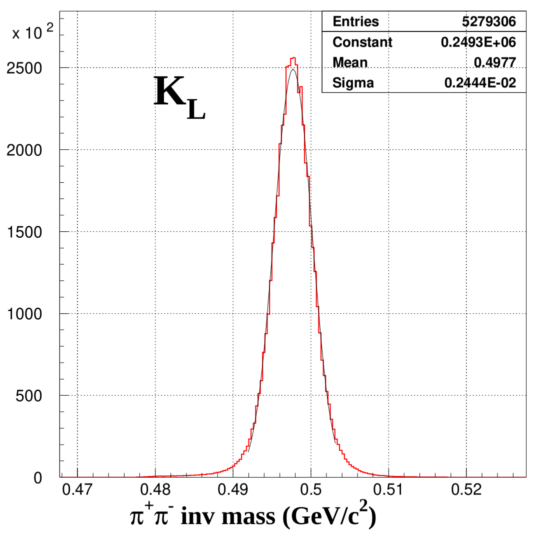
- 2×2 drift chambers + magnet $\rightarrow$ 265 MeV$/c$ p_t kick.



- Each chamber has 4×2 planes $\times$ 256 wires
- Absolute wire position better than 100 $\mu m/m$
- $\frac{1}{2}$ argon / $\frac{1}{2}$ ethane



Vertex reconstruction allows beam separation



Kaon mass resolution ~ 2.5 MeV$/c^2$

$$\boxed{\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\,P[\text{GeV}/c]\,\%}$$

(~ 1 % for 100 GeV$/c$ track momentum)

LKr electromagnetic calorimeter

- Quasi-homogeneous detector

  $10\ m^3$ liquid krypton (120 K)

  ($X_0 = 4.7\ cm$, $R_M = 6.1\ cm$)

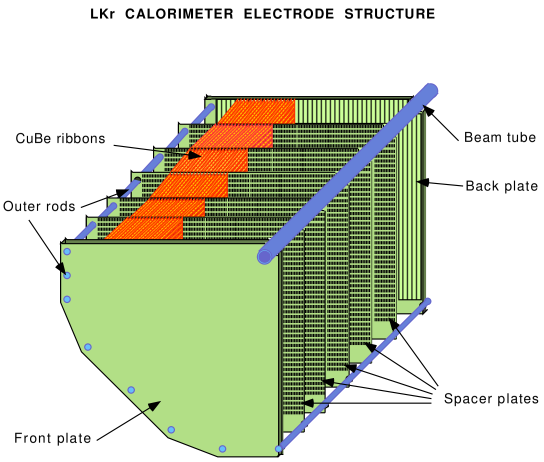
- 13212 cells

  – Granularity $2 \times 2\ cm^2$

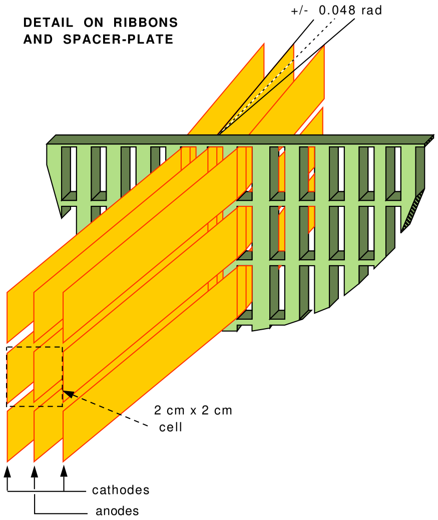
  – Depth $1.25\ m$ ($\sim 27\ X_0$)

- Projective geometry pointing to decay region ($\sim$ 114 m upstream)

- Accordion geometry ($\pm 48\ mrad$) to diminish anode effects.



A quarter of calorimeter

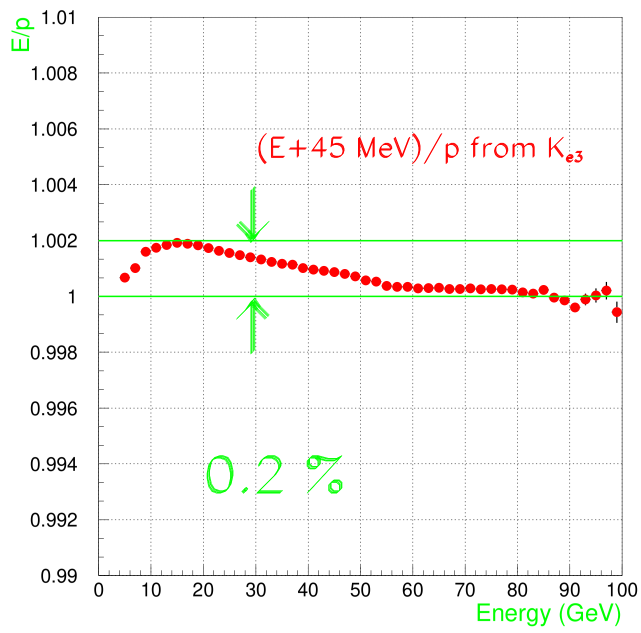


Ribbons and a spacer

- Initial current read-out technique.

Calorimeter performance

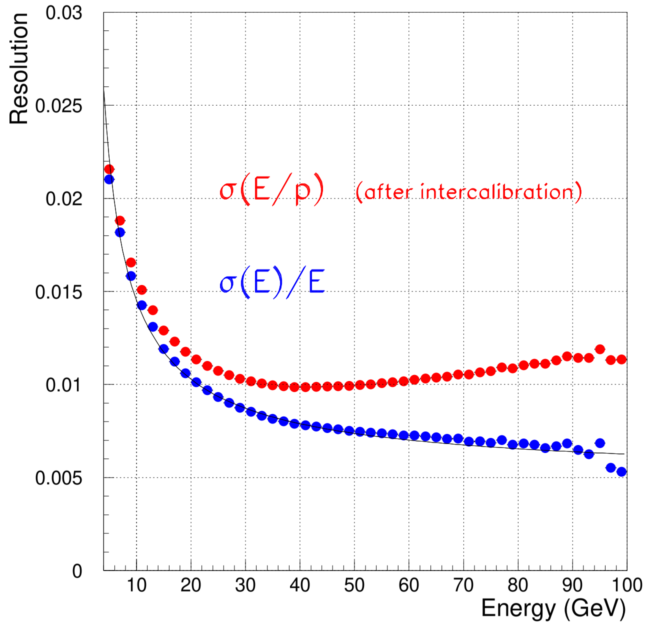
Using electrons from $\pi e \nu$ decay as a probe



Linearity

$$\frac{Energy(LKR)}{Momentum(DCH)}$$

$\Rightarrow$ Non-Linearity
$< 0.2\%$
(from 5 to 100 GeV)



Resolution

E/P resolution

drift chamber
deconvoluted

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

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 %
- Control trigger provided by SCIFI hodoscope embedded in LKr

No correction on R

☞ $\pi^+\pi^-$ trigger

Level 1 :	Efficiency
+ Energy in calorimeters	99.49 ± 0.03 %
+ Two track topology	99.95 ± 0.01 %
+ Two track multiplicity	> 99.99 %

- Level2 : on-line processing of vertices and $\pi\pi$ invariant mass
  - Latency : $< 102\ \mu s$
  - Rejection $\sim 45 \rightarrow 2$ kHz output
  - Dead Time : $< 5\%$ (applied also to $\pi^0\pi^0$)
  - Efficiency: 97.75 ± 0.05 %

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

NA48 Data Samples

- <u>1997</u> : 42 days at 1×10^{12} ppp on $\mathrm{K_L}$ target

  $\Rightarrow$ **0.49 millions of** $K_L \to \pi^0\pi^0$

  PUBLISHED Phys. Lett. B 465 (1999)

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

- <u>1998</u> : 105 days $\sim 1.4 \times 10^{12}$ ppp on $\mathrm{K_L}$ target

  Main improvements :

  – LKr High Voltage 1500 $\to$ 3000 V
  – Charged trigger efficiency 91.3 $\to$ 97.7 %
  – Lighter (carbon fiber) beam pipe $\to$ less activity in the detector
  – New data acquisition system (PC farm) + 30% increased rate

  $\Rightarrow$ **1.14 millions of** $K_L \to \pi^0\pi^0$

  PRELIMINARY RESULT since February 2000

- <u>1999</u> : 124 days $\sim 1.4 \times 10^{12}$ ppp on $\mathrm{K_L}$ target

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

- <u>2000</u> : 40 days for systematic checks on $2\pi^0$: $\mathrm{K_S}$ tagging, energy scale (no spectrometer available)

  ANALYSIS IN PROGRESS...

Analysis path

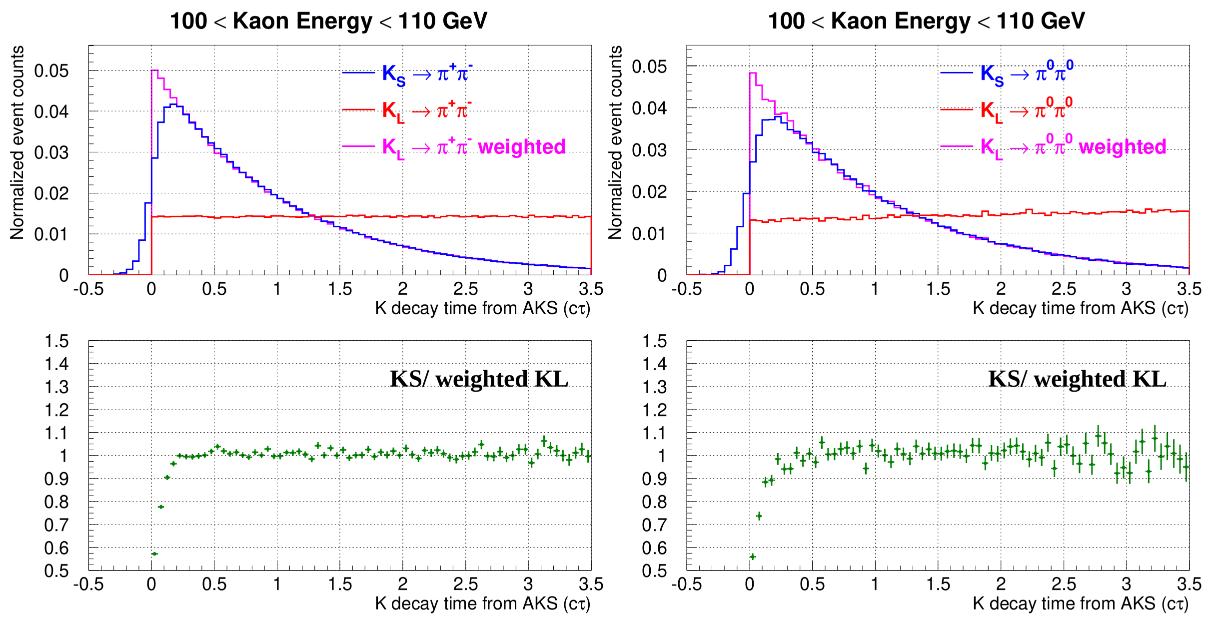
NA48 is a counting experiment:

$$R = \frac{N(\mathrm{K_L} \to \pi^0\pi^0)N(\mathrm{K_S} \to \pi^+\pi^-)}{N(\mathrm{K_S} \to \pi^0\pi^0)N(\mathrm{K_L} \to \pi^+\pi^-)}$$

- Identify $\pi^+\pi^-$ and $\pi^0\pi^0$ events
  and subtract small residual backgrounds
  - $\mathrm{K_S}$: No background
  - $\mathrm{K_L}$: Background from CP conserving $\pi\mu\nu$, $\pi e\nu$ and $\pi^0\pi^0\pi^0$ decays
- Identify $\mathrm{K_L}$ and $\mathrm{K_S}$ events with the tagger
  check misidentification probabilities
- Define same fiducial region to count $\pi^+\pi^-$ and $\pi^0\pi^0$
  (energy scale definition and non linearities)
- Weight $\mathrm{K_L}$ events and correct for small residual acceptance difference
- Check other systematic effects : trigger efficiencies, event loss related to beam intensity, ...

Weighting principle

- ✥ Weighting ⇒ make similar K_S K_L lifetime distributions
- ✥ Without weighting, due to the spectra difference, the energy dependance of acceptance correction would be large (up to 13%)
- At E(K) ≈ 100 GeV, $\beta\gamma c\tau_{KS} \approx 540$ cm
- Weight K_L events with W $= e^{-z/(\beta\gamma c)(1/\tau_{KS}-1/\tau_{KL})}$

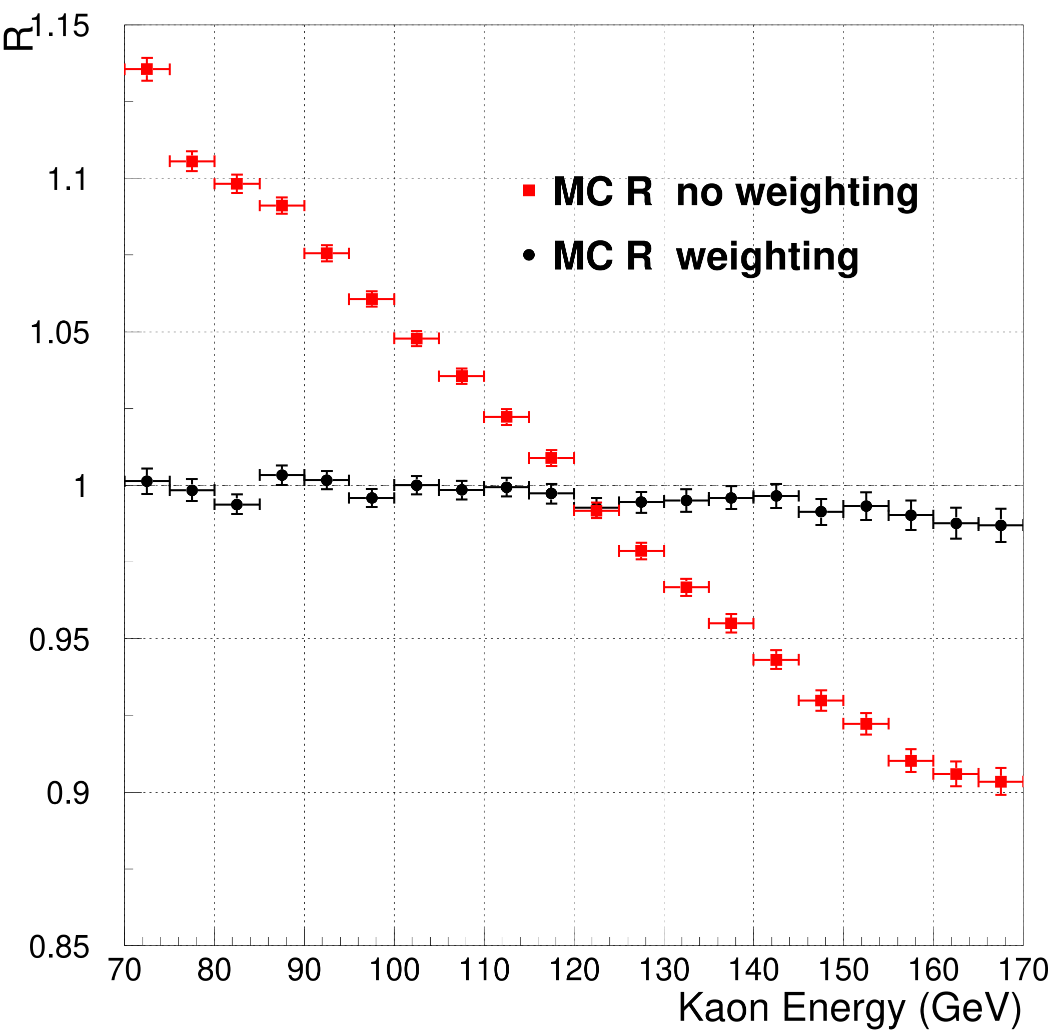


- ⇒ Weighted $K_L = K_S$ for the detector
- ⇒ Same geometrical acceptance, no effect from detector inefficient regions
- ⇒ Reduce systematic effects
- Price : Increase of the statistical error (by 35%)

Acceptance Correction

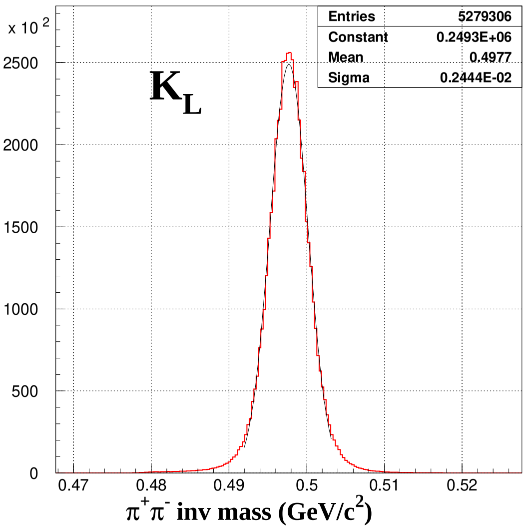
- K_L are weighted with the K_S proper time

Weighting Kl events minimizes the acceptance correction. A Monte-Carlo is used to evaluate the small residual effects.



$$\boxed{\Delta R = 31 \pm 6 \text{ (MC stat.) } \pm 6 \text{ (syst.) } \times 10^{-4}}$$

$\pi^+\pi^-$ Selection



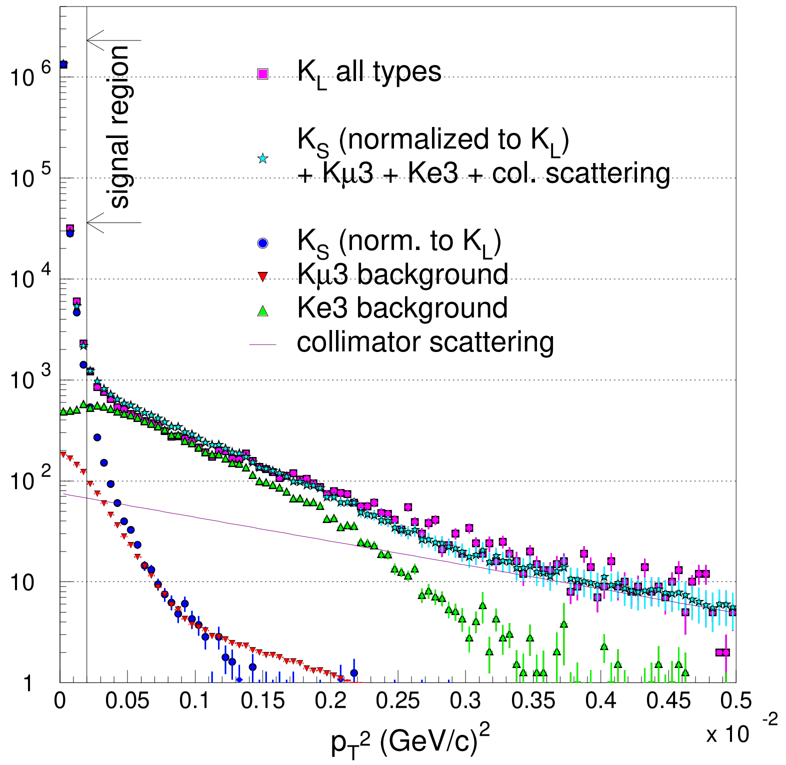
Background rejection

$\pi\mu\nu$: no hit in μ veto

$\pi e\nu$: $E/p < 0.8$

$|m_{\pi\pi} - m_{K^0}| < 3\sigma$
($\sigma \approx 2.5$ MeV/c^2)

$p_T'^2 < 200\ (MeV/c)^2$

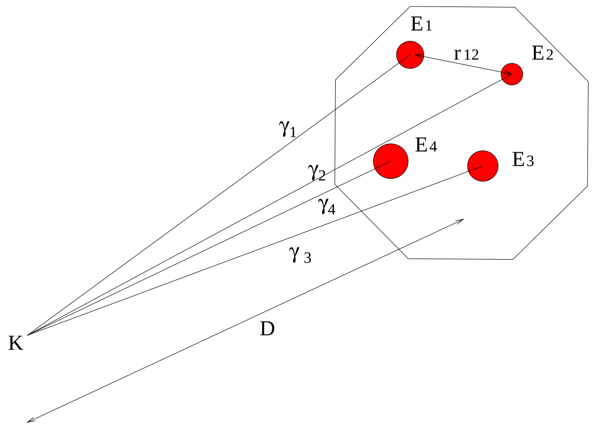


Fit K_L distribution as $\pi^+\pi^- + \pi\mu\nu + \pi e\nu$ in a wide $(m_{\pi\pi}, p_T'^2)$ control region

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

$\pi^0\pi^0$ Selection

Measure (E,x,y) of 4 γ in calorimeter



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

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

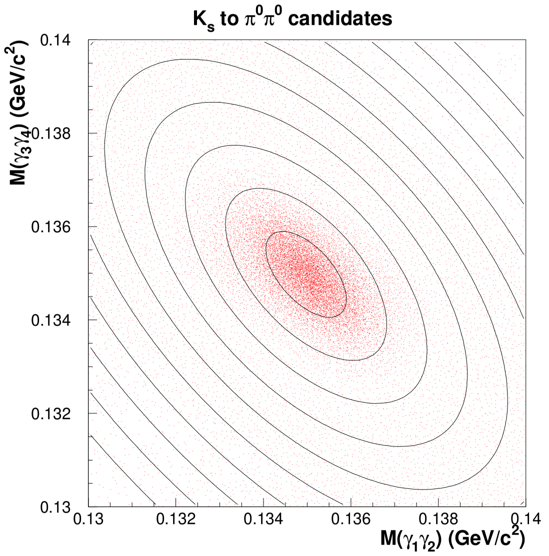
☞ Define pseudo χ^2 to separate signal and background :

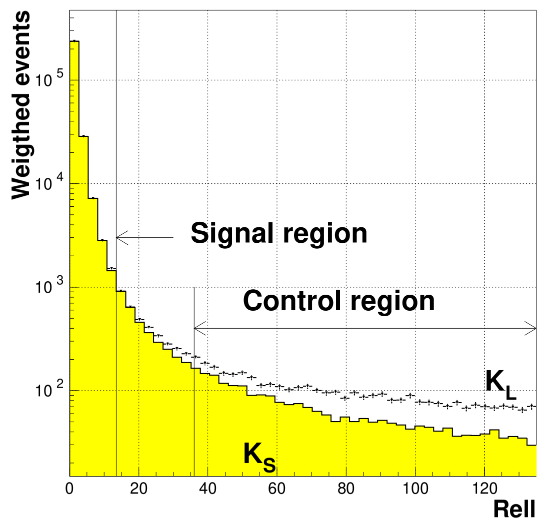
$$R_{ell} = \left[\frac{(m_1+m_2)/2 - m_{\pi^0}}{\sigma_+}\right]^2 + \left[\frac{(m_1-m_2)/2}{\sigma_-}\right]^2$$

Signal region : $R_{ell} < 13.5$

☞ $3\ \pi^0$ background rejection:

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





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

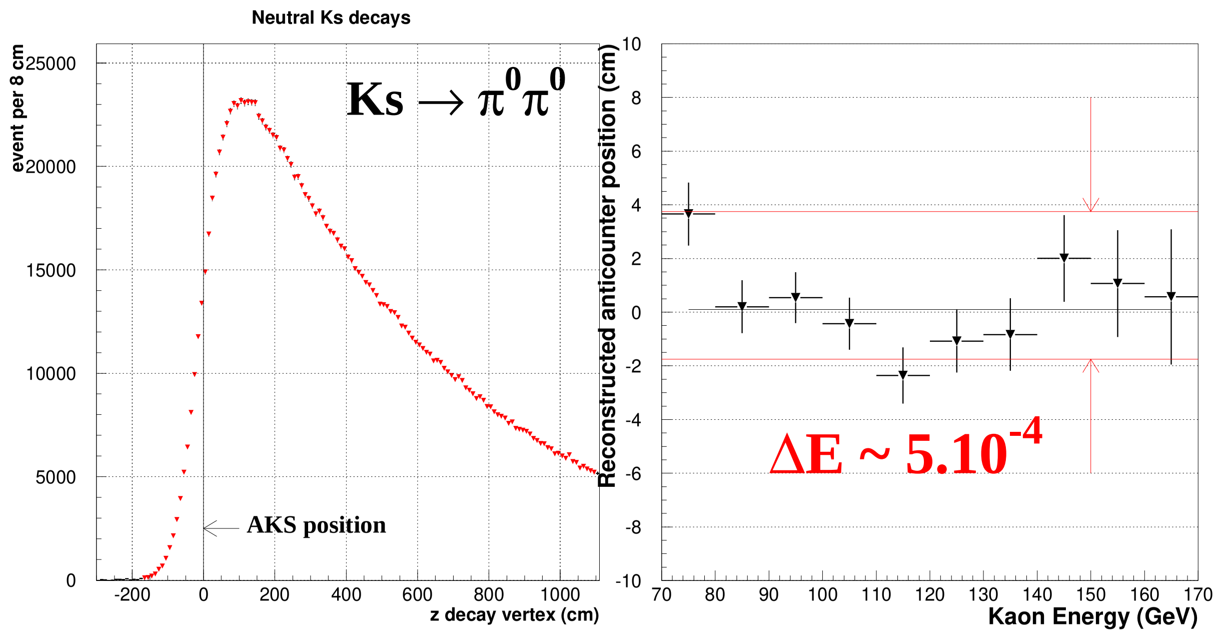
$\pi^0\pi^0$ / $\pi^+\pi^-$ energy scale

Energy scale $\Leftrightarrow$ Distance scale

$E \to (1+\alpha) \times E \Rightarrow \Delta z \to (1+\alpha) \times \Delta z$

- In the neutral mode : $D = \sqrt{\sum E_i E_j \times (r_{ij})^2} \, / M_K$

  $\Rightarrow$ Need good knowledge of Energy scale to define fiducial region.
- The beginning of the K_S decay region is defined by an anti-counter (AKS):
  Known AKS position $\to$ adjust Energy scale



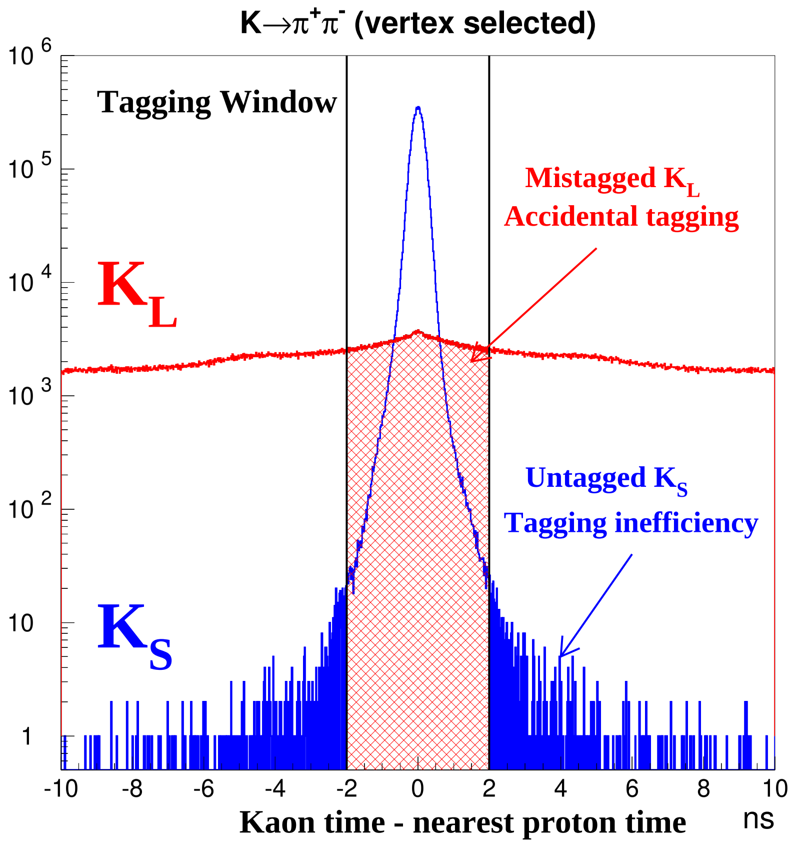
$$\boxed{\Delta R < \pm 10 \times 10^{-4}}$$

- In the charged mode the energy is determined by the opening angle and the ratio of the energy of the two tracks $\Rightarrow$ defined by the geometry of the drift chambers

$$\boxed{\Delta R < \pm 2 \times 10^{-4}}$$

Tagging : K_L / K_S identification

In the charged modes only, identification can also be done by vertex reconstruction.



- Tagging inefficiency: K_S taken as K_L

$$\alpha^{+-}_{SL} = (1.97 \pm 0.05) \times 10^{-4}$$

- Accidental tagging: K_L taken as K_S

$$\alpha^{+-}_{LS} = (11.05 \pm 0.01)\%$$

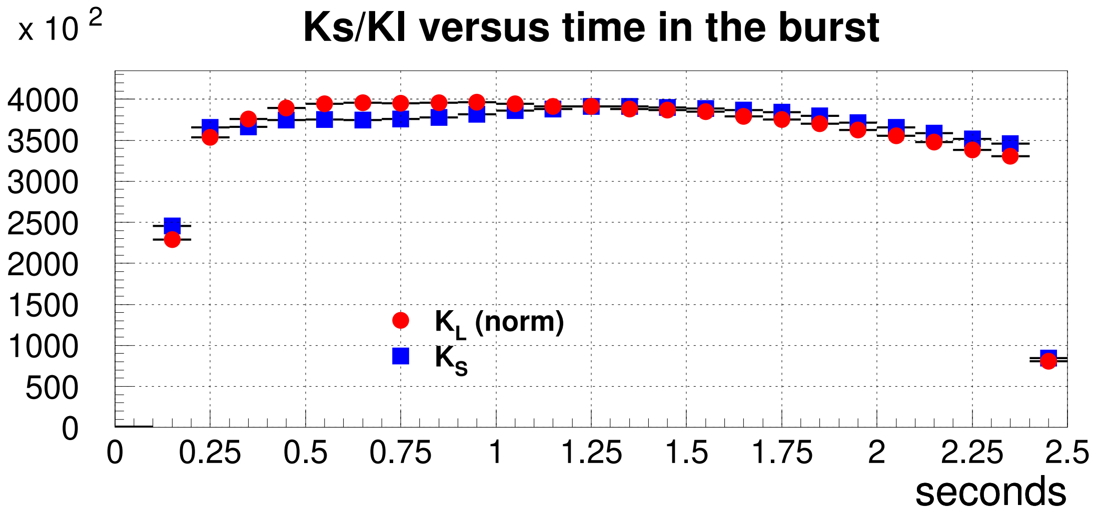
Effect on R if difference between neutral and charged modes

$|\alpha^{00}_{SL} - \alpha^{+-}_{SL}| < 0.5 \times 10^{-4}$ $\boxed{\Delta R < 3 \times 10^{-4}}$

$\alpha^{00}_{LS} - \alpha^{+-}_{LS} = (0.3 \pm 4.2) \times 10^{-4}$ $\boxed{\Delta R = (0.6 \pm 8.5) \times 10^{-4}}$

Accidental activity

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



Accidental activity can induce asymmetric losses or gains of selected events between K_S and K_L

☞ Geometrical difference of the beams :

- overlay events collected proportionally to the beam intensity (random triggers) to $\pi^+\pi^-$ and $\pi^0\pi^0$ events.
- The gains and losses induced by the analysis cuts lead to :

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

☞ Variations in KL/KS ratio (constant - R.M.S. 10%) :

- the difference in accidental activity seen by K_S and K_L events is ≈ 1 %
- The asymmetric losses on $\pi^+\pi^-$ and $\pi^0\pi^0$ induced by the noise in the DCH read out are $< 2.5\%$

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

Result from 1998 data

Mode	Statistics (millions)
$K_S \to \pi^+\pi^-$	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

(after correcting for accidental tagging)

Statistical uncertainty on R :

(taking weighting into account)

$$\boxed{17.3 \times 10^{-4}}$$

Corrections and systematics

Corrections and uncertainties on R (Unit = 10^{-4})		
Source	1998 sample	
Charged trigger	–1.4	$\pm$ 11.5
Accidental tagging	+0.6	$\pm$ 8.5
Tagging efficiency	–	$\pm$ 3.0
Neutral E-scale	–	$\pm$ 10.2
Charged vertex	+2.0	$\pm$ 2.0
Acceptance	+31.1	$\pm$ 8.7
Neutral BG	–6.6	$\pm$ 2.0
Charged BG	+19.0	$\pm$ 3.0
Beam scattering	–9.9	$\pm$ 3.0
Accid. activity	+2.0	$\pm$ 12.2
Total	+36.8	$\pm$ 23.8

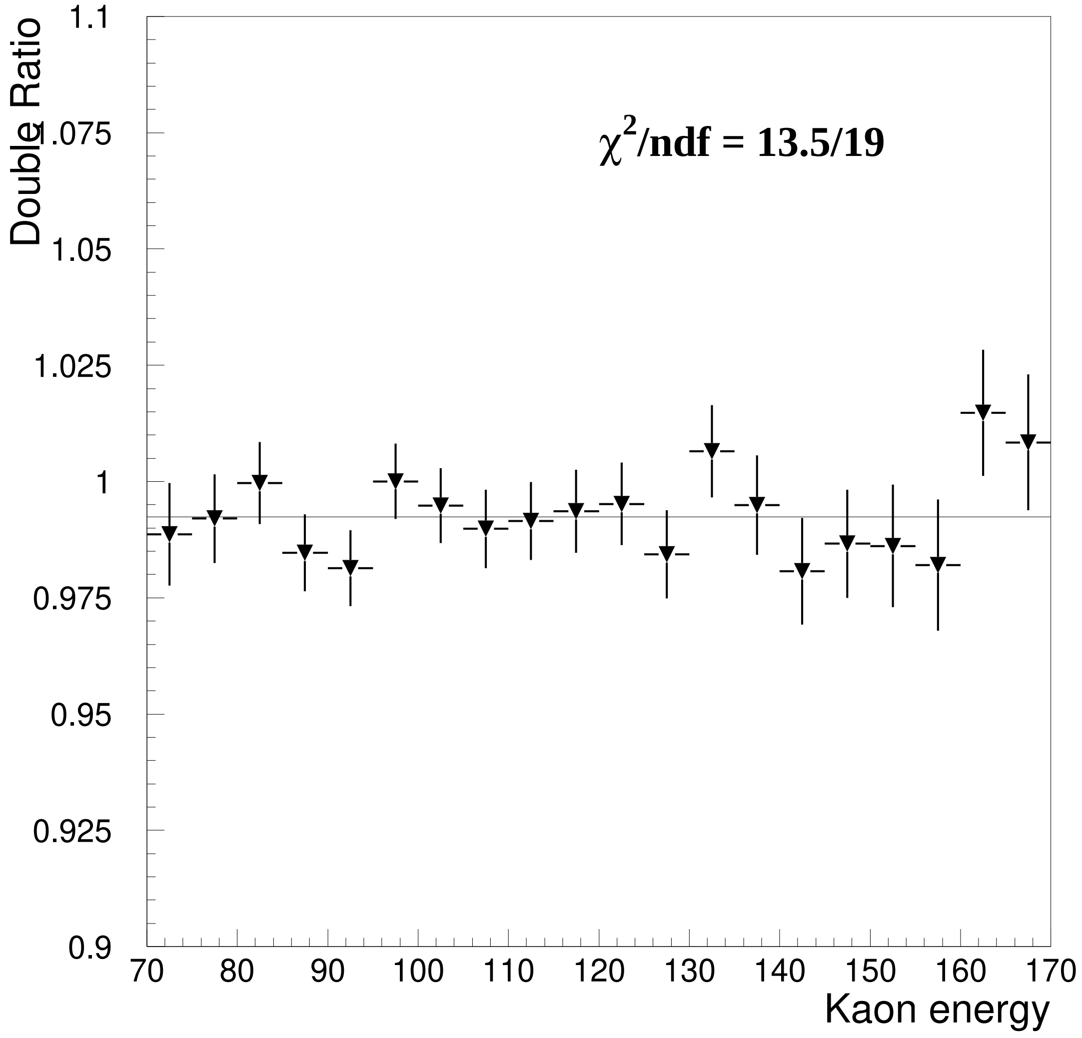
Errors in green = limited by data statistic
Errors in violet = work in progress to improve for final result

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

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \frac{1}{6} \times (1 - R)$$

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

PRELIMINARY RESULT ON 1998 DATA



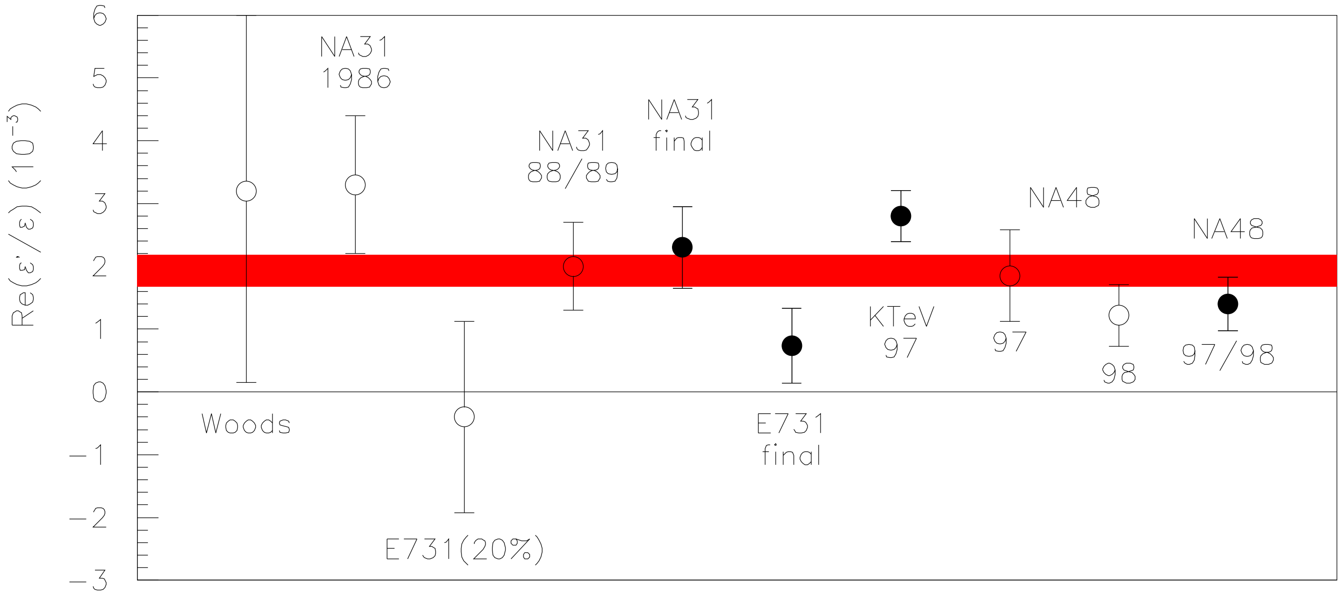
$\Downarrow$

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

Combining with published 97 result :

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

World average



New world average:

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.5) \times 10^{-4}}$$

$(\chi^2/ndf = 10.4/3)$

$\Rightarrow$ $\epsilon'/\epsilon \neq 0$ well established but exact value debatable

Prospects

- Finalize systematic errors for 98 and analyze 99 data:

  ($\approx 2{\times}10^6$ $K_L \to \pi^0\pi^0$, twice as much as 98 data)

  ☞ Expected accuracy : ≈ 2.5 to 3×10^{-4} on $\mathrm{Re}(\varepsilon'/\varepsilon)$

- End of 99: implosion of beam tube $\longrightarrow$ drift chambers damaged.

  ☞ Run 2000 : perform systematic checks with neutral events

  – measure the difference in mistagging probability for $\pi^0\pi^0$

  – improve distance/momentum scale and nonleariry of the LKr using $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$

- Drift chambers repair underway $\longrightarrow$ run in 2001 for $\mathrm{Re}(\varepsilon'/\varepsilon)$

Conclusions

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

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

- Combining this result with the NA48 published data (1997) and taking into account the (small) correlated systematics, we obtain:

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

- $\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$ established

- Current world average is :

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.5) \times 10^{-4}}$$

  but with a poor χ^2

- More results to come and hopefully to clarify experimental situation