New ϵ'/ϵ results

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Plan of the presentation :

- Physics motivation
- The NA48 experimental technique
- Analysis of the 1998 data
- Result and the world average
- Conclusions

I. What is ϵ'/ϵ ?

Mixing of CP eigenstates in the Neutral Kaon System :

- CP allowed decays:

$$K_{CP=-1} \rightarrow 3\pi$$
$$K_{CP=+1} \rightarrow 2\pi$$

- Physical Particles:

$$K_S \simeq K_{CP=+1} + \epsilon \; K_{CP=-1} \quad (c\tau_S = 2.67 \text{ cm})$$
$$K_L \simeq K_{CP=-1} + \epsilon \; K_{CP=+1} \quad (c\tau_L = 15.5 \text{ m})$$

(1964: $K_L \rightarrow 2\pi$)

Indirect CP Violation in states mixing: $|\epsilon| \simeq (2.27 \pm .02)\ 10^{-3}$

Direct CP Violation in decay amplitudes:

$$\mathbf{A}(K_L \rightarrow 2\pi) =$$
$$= \epsilon \; \mathbf{A}(K_{CP=+1} \rightarrow 2\pi) + \mathbf{A}(K_{CP=-1} \rightarrow 2\pi)$$

Direct CP Violation is related to the interference between decay amplitudes to final states with different Isospin, and can be measured comparing the decays to $\pi^0\pi^0$ and $\pi^+\pi^-$:

$$\mathbf{A}(K_L \rightarrow \pi^0\pi^0) \simeq \mathbf{A}(K_S \rightarrow \pi^0\pi^0) \times (\epsilon - 2\,\epsilon')$$

$$\mathbf{A}(K_L \rightarrow \pi^+\pi^-) \simeq \mathbf{A}(K_S \rightarrow \pi^+\pi^-) \times (\epsilon + \epsilon')$$

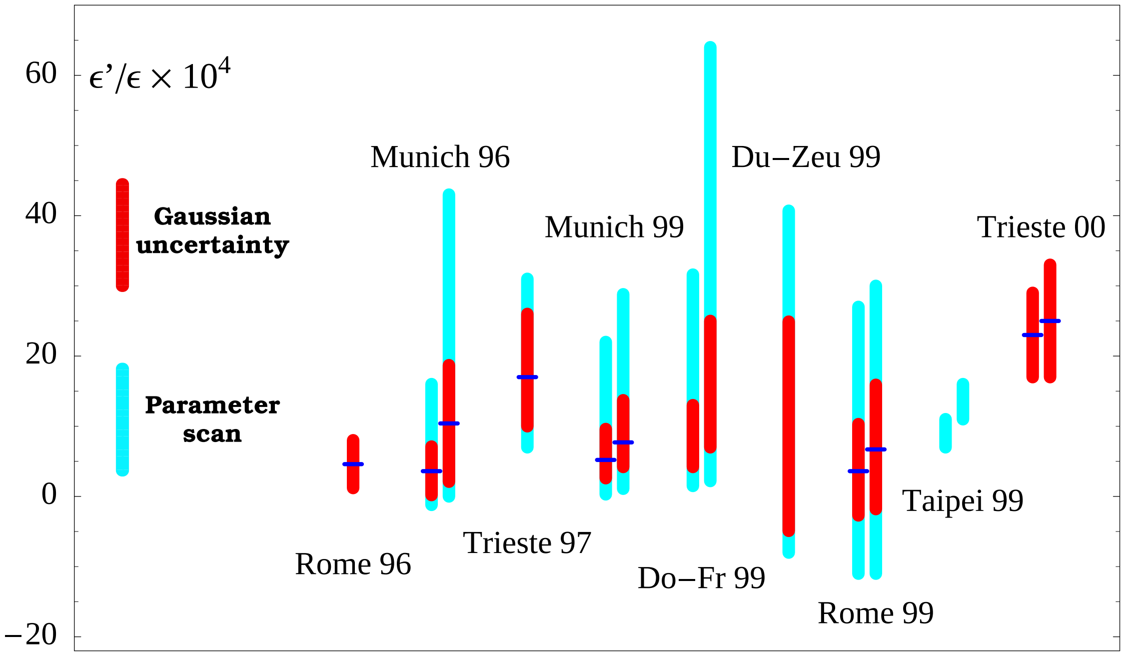
Measure the Double Ratio R :

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

Direct CP Violation $\Leftrightarrow$ $R \neq 1$

I. Predictions and measurements on $\mathrm{Re}(\epsilon'/\epsilon)$

- Standard Model Predictions:



The new experiments aim to measure the Direct CP Violation parameter $\mathrm{Re}(\epsilon'/\epsilon)$ with an accuracy of $\simeq 2 \times 10^{-4}$.

- Latest published measurements:

$\mathbf{Re}(\epsilon'/\epsilon) =$	$\mathbf{(\ 7.4 \pm 5.9) \times 10^{-4}}$	E731	1993
	$\mathbf{(23.0 \pm 6.5) \times 10^{-4}}$	NA31	1993
	$\mathbf{(28.0 \pm 4.1) \times 10^{-4}}$	KTEV	1999
	$\mathbf{(18.5 \pm 7.3) \times 10^{-4}}$	NA48	1999
	new	NA48	2000

II. The NA48 experimental technique

Goal : measure $\mathrm{Re}(\epsilon'/\epsilon)$ with final precision $\sim 2 \times 10^{-4}$

$\Leftrightarrow$ Collect $> 10^6 \ \ \mathrm{K}_L \rightarrow \pi^0\pi^0$ (rarest mode)

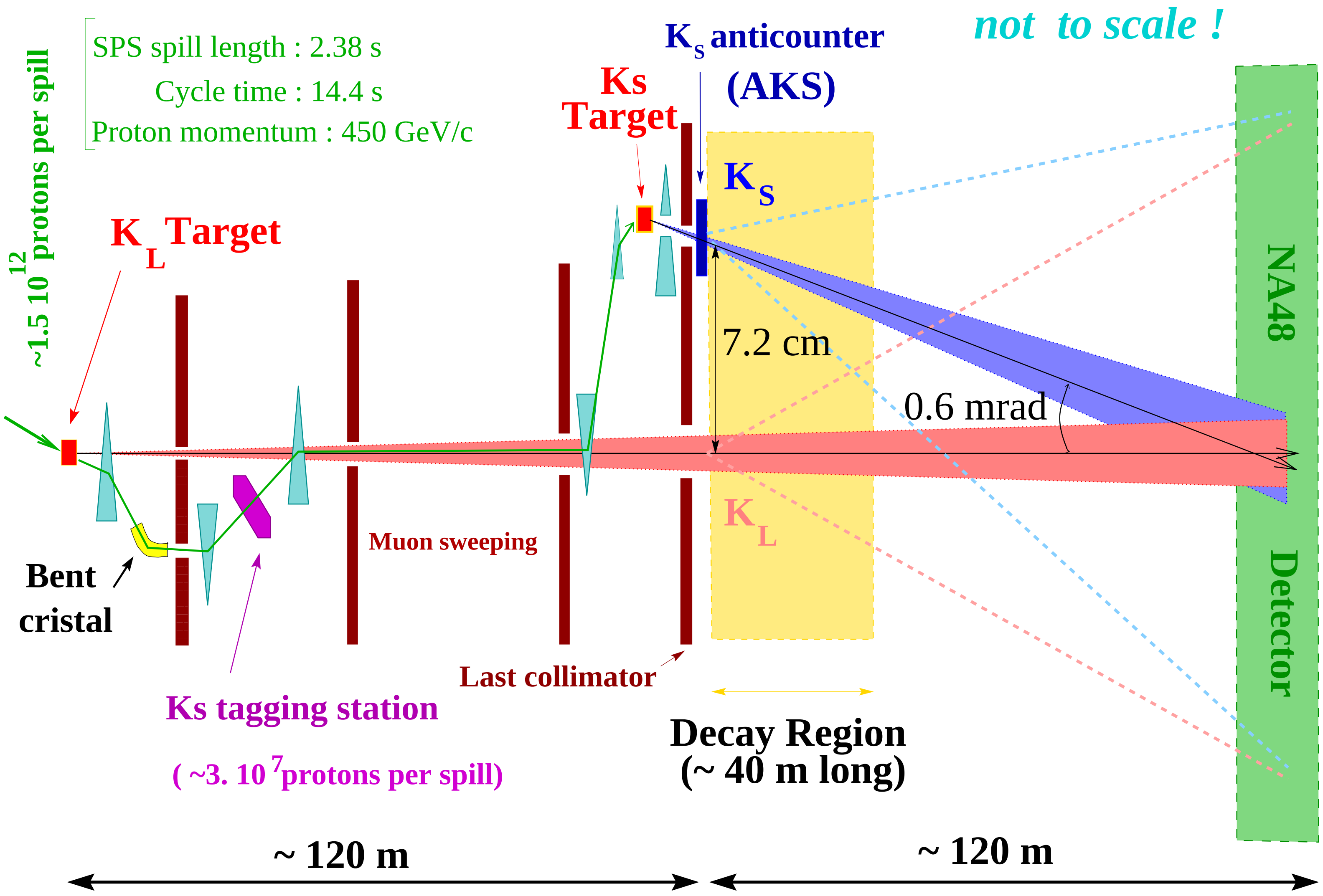
Experimental features :

- Use of almost collinear K_L and K_S beams
- All four decay modes are detected concurrently in the same decay region to obtain cancellation of fluxes, inefficiencies, dead time, accidental losses
- K_S decays are identified by tagging protons upstream of the K_S production target
- Use of detectors with high resolution, linearity and stability to reduce background and systematic uncertainties

Data analysis :

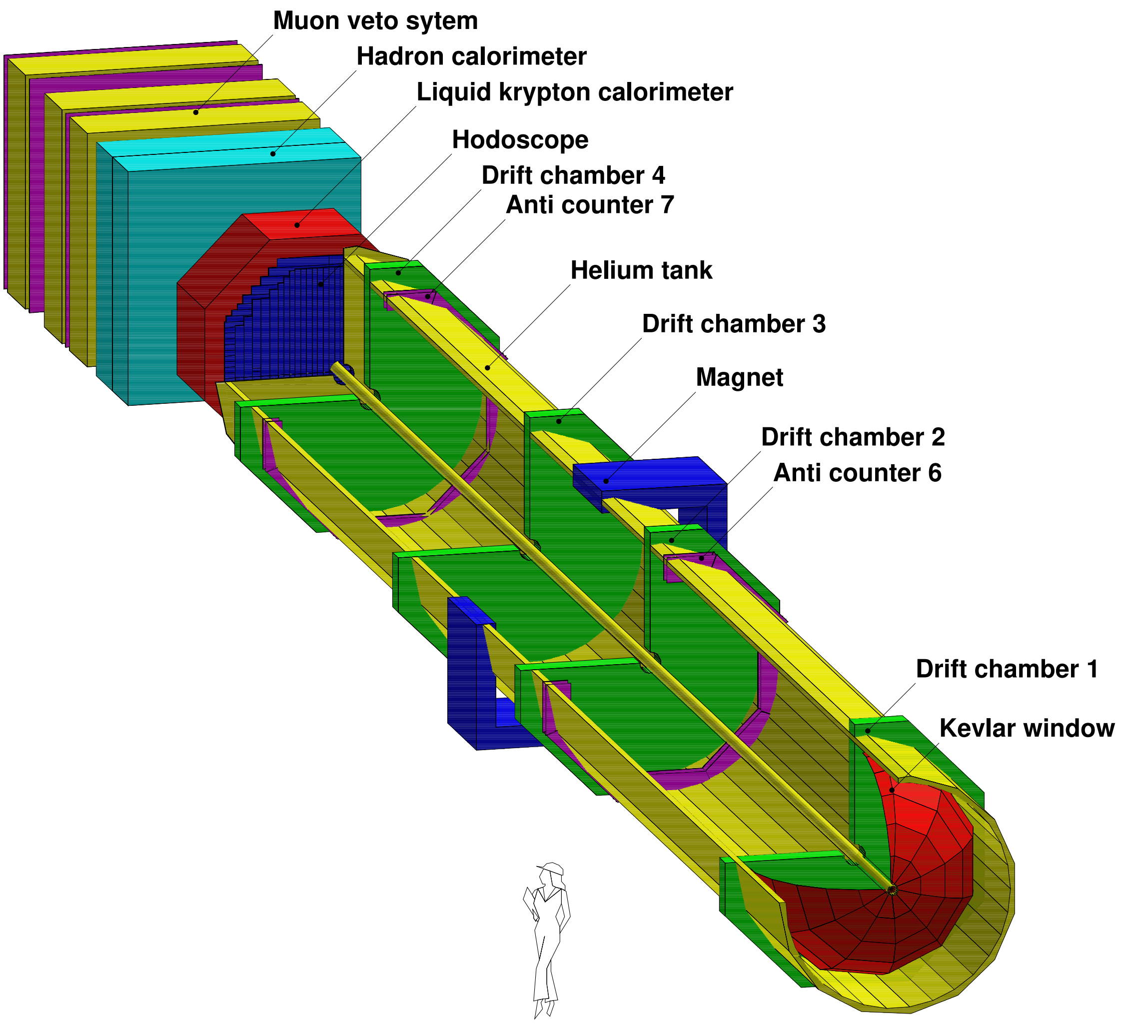
- Select K^0 decays in the $70 \ < E_K < \ 170 \ GeV$ and $c\tau < \ 3.5 \ c\tau_S$ region and analyze data in energy bins to make measurements insensitive to slight differences between K_S and K_L energy spectra
- Apply lifetime weighting to K_L events in order to make similar z-vertex distributions for K_L and K_S ($\lambda_S \simeq 6 \ m, \ \ \lambda_L \simeq 3 \ Km$ at $E_K = 110 \ GeV$) and consequently to reduce acceptance corrections

II. NA48 simultaneous and collinear K_S and K_L beams



- K_S are distinguished from K_L by tagging the protons upstream of the K_S target
- NA48 detects all four modes from the same decay region

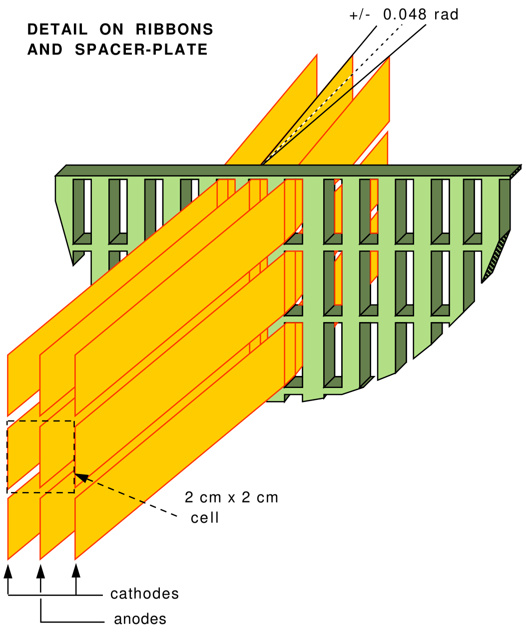
NA48 detector



- $K_{\mathrm{L,S}} \rightarrow \pi^+\pi^-$
  - Magnetic spectrometer ($p_t^{kick} \sim 265 MeV/c$)
  - Hodoscope for timing measurements ($\sigma_t \sim 200\ ps$)
  - Muon veto to reject $\pi\mu\nu$ background.
- $K_{\mathrm{L,S}} \rightarrow \pi^0\pi^0$
  - High resolution Liquid Krypton electromagnetic calorimeter

($\sigma_t \sim 250\ ps$)

II. LKr electromagnetic calorimeter

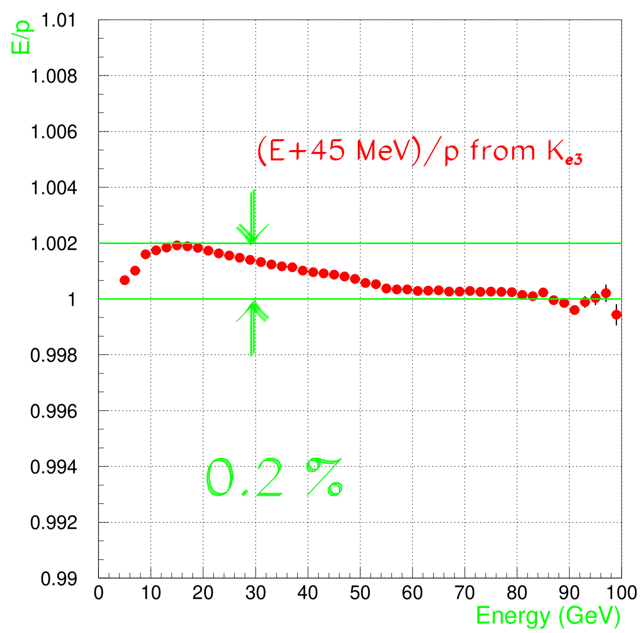


Ribbons and a spacer

- Quasi-homogeneous detector, $10\ m^3$ liquid krypton (120 K) ($X_0 = 4.7\ cm$, $R_M = 4.7\ cm$), $40\ \mu m$ thick Cu-Be electrodes along beam direction
- 13212 cells , granularity $2 \times 2\ cm^2$, depth $1.25\ m$ ($\sim 27\ X_0$)
- Projective geometry pointing to decay region (~ 114 m upstream)
- Accordion geometry (± 48 mrad) to reduce anode effects.
- Geometry machined with 0.2 mm/m accuracy
- Initial current read-out technique.
- Dynamical range: 3.5 MeV $\rightarrow$ 50 GeV
- $\sim 1\%$ electronic channel calibration improved with calibration run and K_e3 events
- Calibration stability $\sim 0.1\%$
- Resolutions: $\sigma_{x,y} < 1.3$ mm, $\sigma_t < 300$ ps, $\sigma_{m_{\pi^0}}$ =1.1 MeV

II. Calorimeter performances

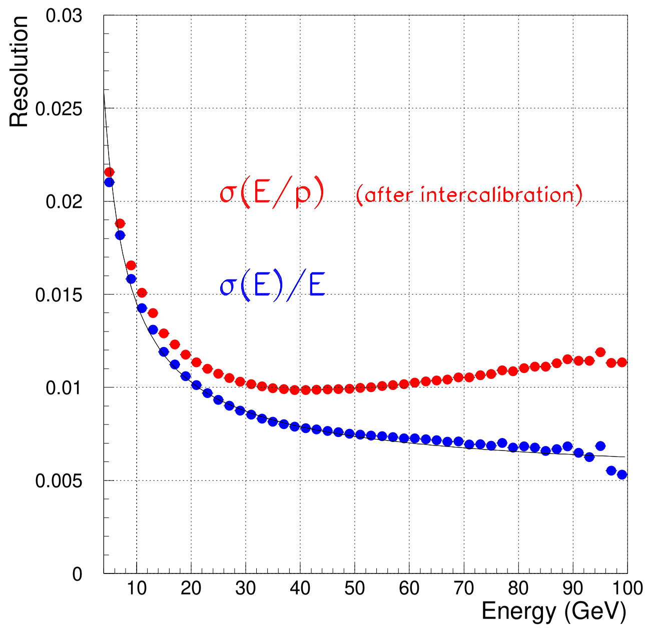
Using electrons from $\pi e \nu$ decay as a probe



- Linearity

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

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



- Resolutions

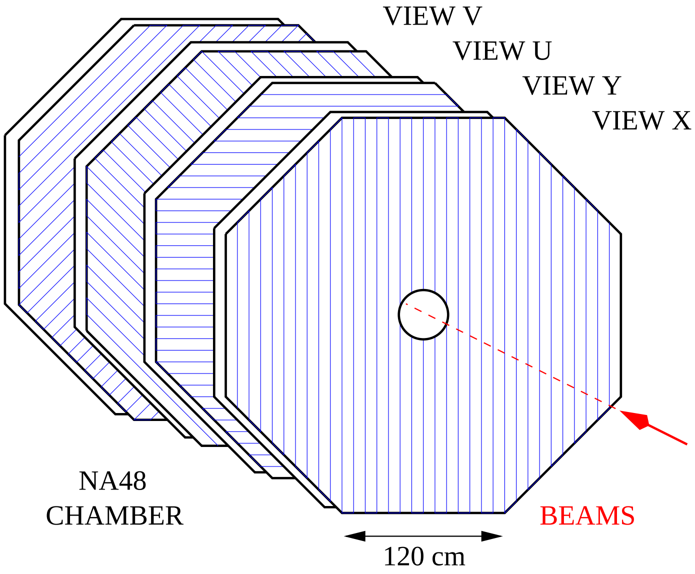
E/P resolution

drift chamber
resolution
deconvoluted

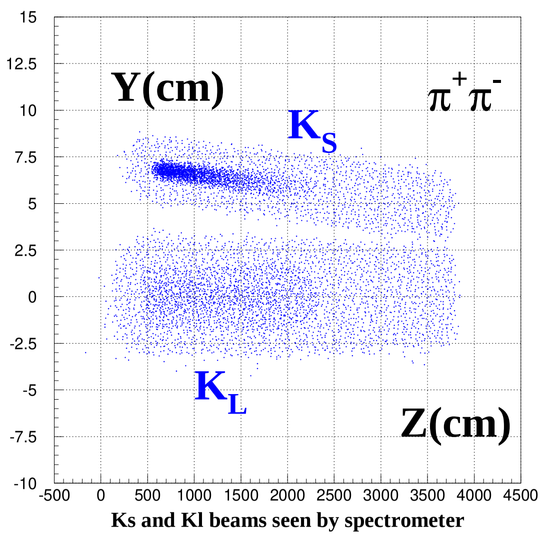
$$\boxed{\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{100\ MeV}{E} \oplus 0.5\%}$$

II. The magnetic spectrometer

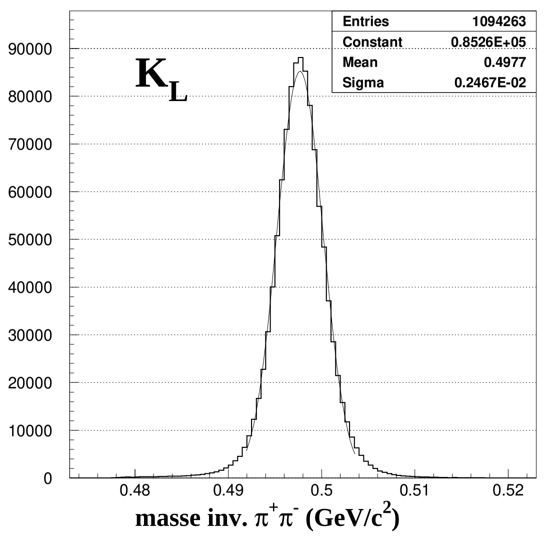
❖ $2+2$ drift chambers + magnet → 265 MeV/c p_t kick



- Each chamber has 4×2 planes $\times$ 256 wires
- Absolute wire position better than 100 $\mu m/m$
- High rate capability (± 5 mm drift distance)



Vertex reconstruction allows beam separation



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

$\epsilon_{plane} > 99\%$ $\quad \sigma_{X,Y} \simeq 90\ \mu m$ $\quad \sigma^{vtx}_{X,Y} \simeq 2\ mm$

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

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

III. NA48 data samples

- 1997: 42 days, 1×10^{12} ppp on $\mathrm{K_L}$ target

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

  PUBLISHED Phys. Lett. B 465 (1999)

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

- 1998: 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 %
  - Carbon fiber pipe $\to$ less showers in the detectors
  - New data acquisition system (PC farm) + 30 % rate

  $\Rightarrow$ 1.14 million of $K_L \to \pi^0\pi^0$
  $\Rightarrow$ four-fold increase of $\pi^+\pi^-$

  PRELIMINARY RESULT in this presentation

- 1999: 124 days, $\sim 1.4 \times 10^{12}$ ppp on $\mathrm{K_L}$ 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...

III. $\pi^+\pi^-$ Reconstruction and Selection

$\pi^+\pi^-$ energy computed from opening angle and tracks energy ratio $\rightarrow$ depends only on the geometry of the drift chambers

$\mathrm{K_S}$: No background (Λ events rejected by kinematical cuts)
$\mathrm{K_L}$: Background from CP conserving $\pi\mu\nu$ and $\pi e\nu$ decays

Background rejection

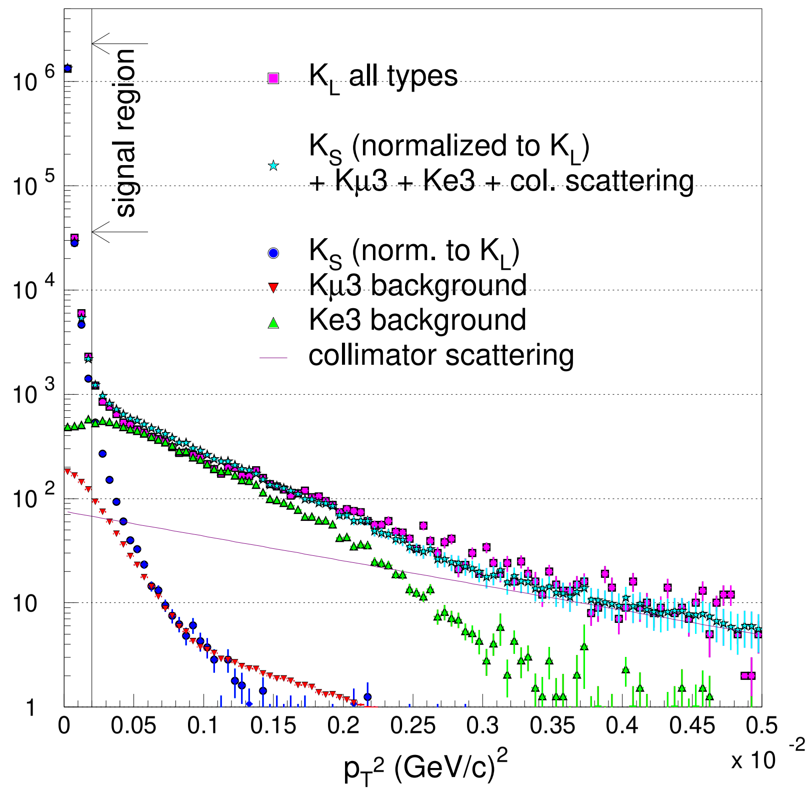
$\pi\mu\nu$: no hit in μ veto
$\pi e\nu$: $\frac{E_{LKr}}{P_{DCh}} < 0.8$

$\pi\pi$ mass within 3σ
($\sigma \approx 2.5$ MeV/c^2)

$p_t^2 < 200\ (MeV/c)^2$

Background subtraction

Fit K_L distribution as
$\pi^+\pi^- + \pi\mu\nu + \pi e\nu$
(in a wide $m_{\pi\pi} \times p_t$ control region)

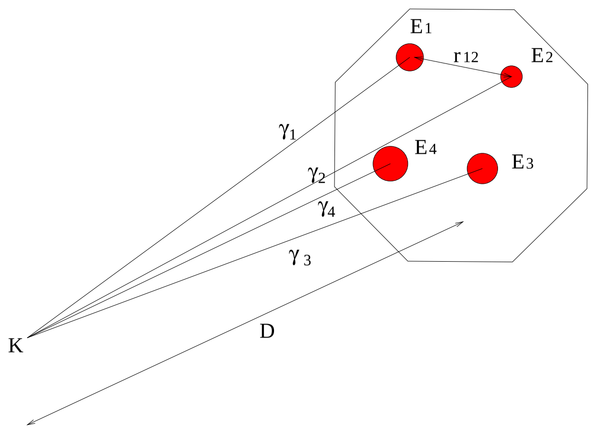


Overall background $\boxed{\Delta R = (19 \pm 3) \times 10^{-4}}$

III. $\pi^0\pi^0$ Reconstruction and Selection

K_S: No background
K_L: Background from CP conserving $\pi^0\pi^0\pi^0$ decays

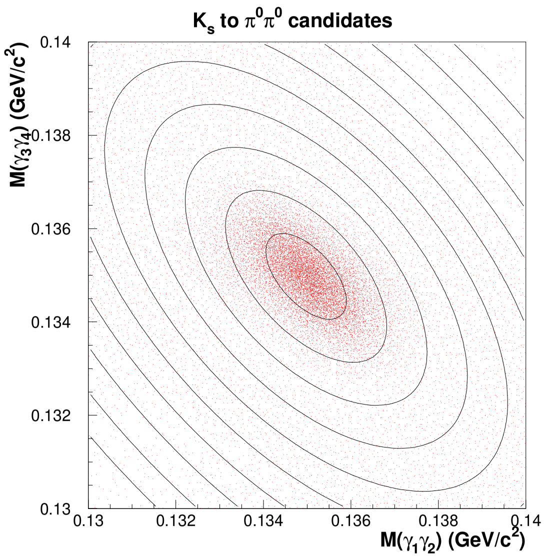
$K^0 \to 2\,\pi^0 \to 4\gamma$

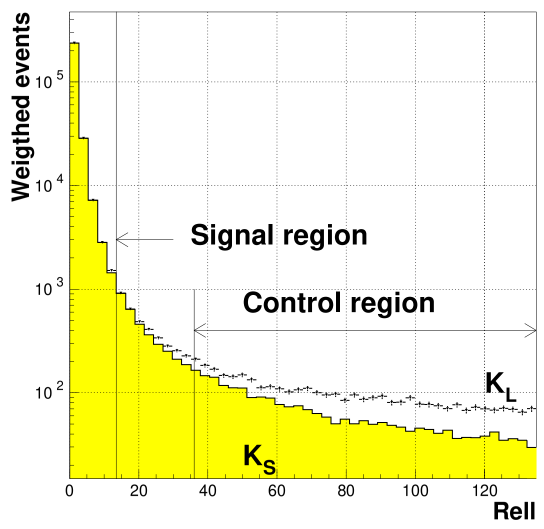


$$D = \frac{\sqrt{\sum_i \sum_{j>i} E_i E_j \times r_{ij}^2}}{M_K}$$

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

- Select best masses:
  $$R_{ell} = \left[\frac{(m_1+m_2)/2 - m_{\pi^0}}{\sigma_+}\right]^2 + \left[\frac{(m_1-m_2)/2}{\sigma_-}\right]^2$$
- 3 π^0 background rejection:
  Cut on in-time extra photons ($\pm$ 3ns)





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

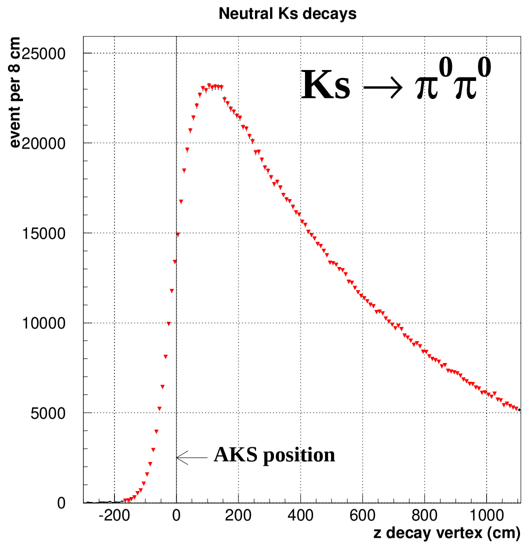
III. Beginning of decay region and energy scale

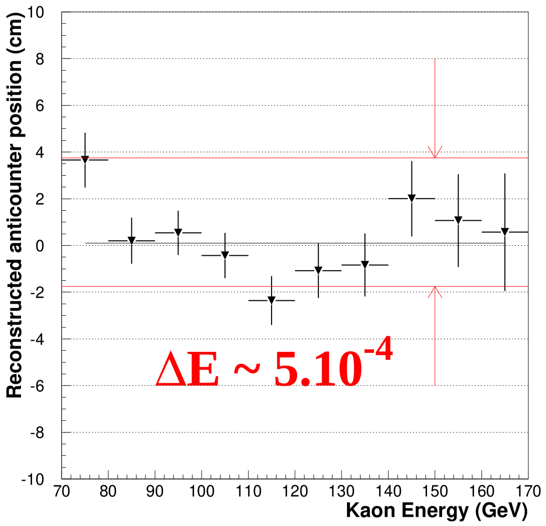
The KS Anticounter (iridium crystal converter and scintillators) located on the K_S beam line, at the collimator exit defines the beginning of the decay region for charged and neutral K_S decays.

A shift in energy in the calorimeter: $E_{meas.} = (1+\alpha)\ E_{true}$ translates to an apparent decay vertex displacement: $\Delta z \to (1+\alpha)\ \Delta z$

By fitting the raising edge of the reconstructed z decays distribution (KS Anticounter position) we can obtain:

- an absolute calibration for the energy scale of the calorimeter
- an alignment check on the tracking chambers

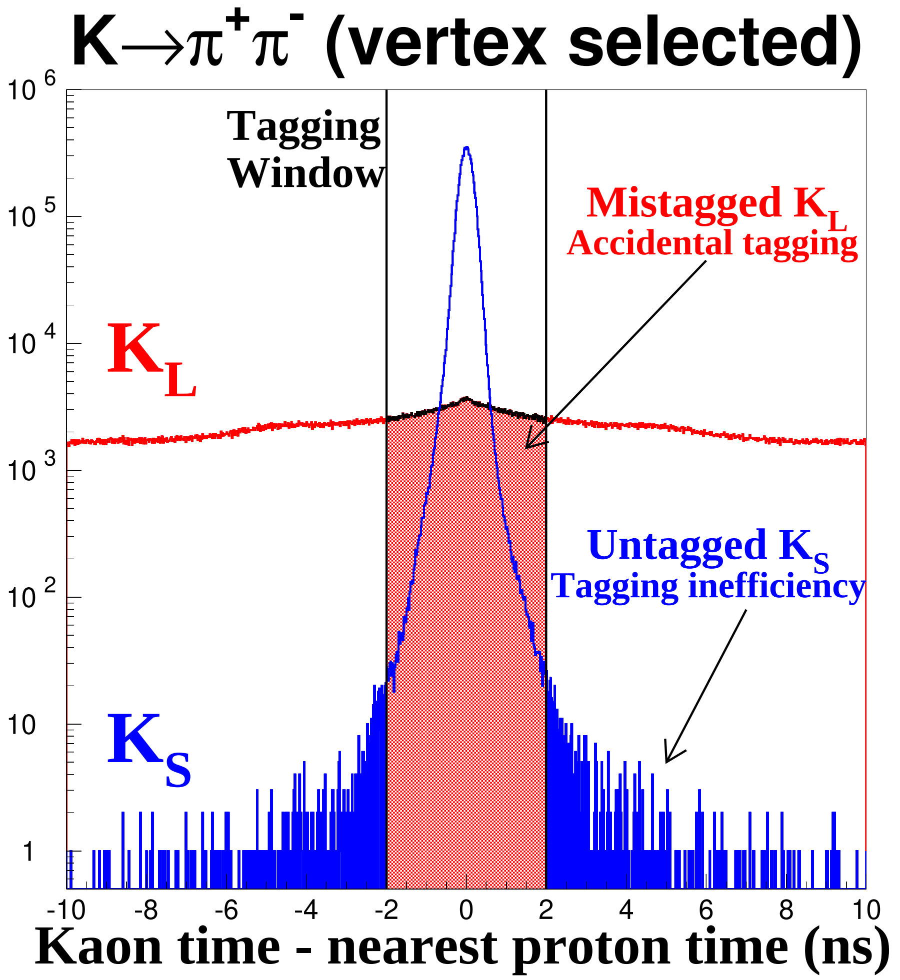




Non-linearity $(5.\ 10^{-4}) \oplus$ energy scale $(3.\ 10^{-4}) \oplus$ transverse scale $(3.\ 10^{-4}) \oplus$ non-gaussian tails $(5.\ 10^{-4}) \oplus \ldots$

$\Rightarrow$ $\boxed{\text{Uncertainty } \Delta R\ <\ 10. \times 10^{-4}}$

III. $\mathrm{K_L}$ vs. $\mathrm{K_S}$ Identification: Tagging Effects



- Tagging inefficiency

  $\mathrm{P(K_S \to K_L)} : \alpha^{+-}_{\mathrm{SL}} = (1.97 \pm 0.05)10^{-4}$

- Accidental tagging

  $\mathrm{P(K_L \to K_S)} : \alpha^{+-}_{\mathrm{LS}} = (11.05 \pm 0.01)\%$

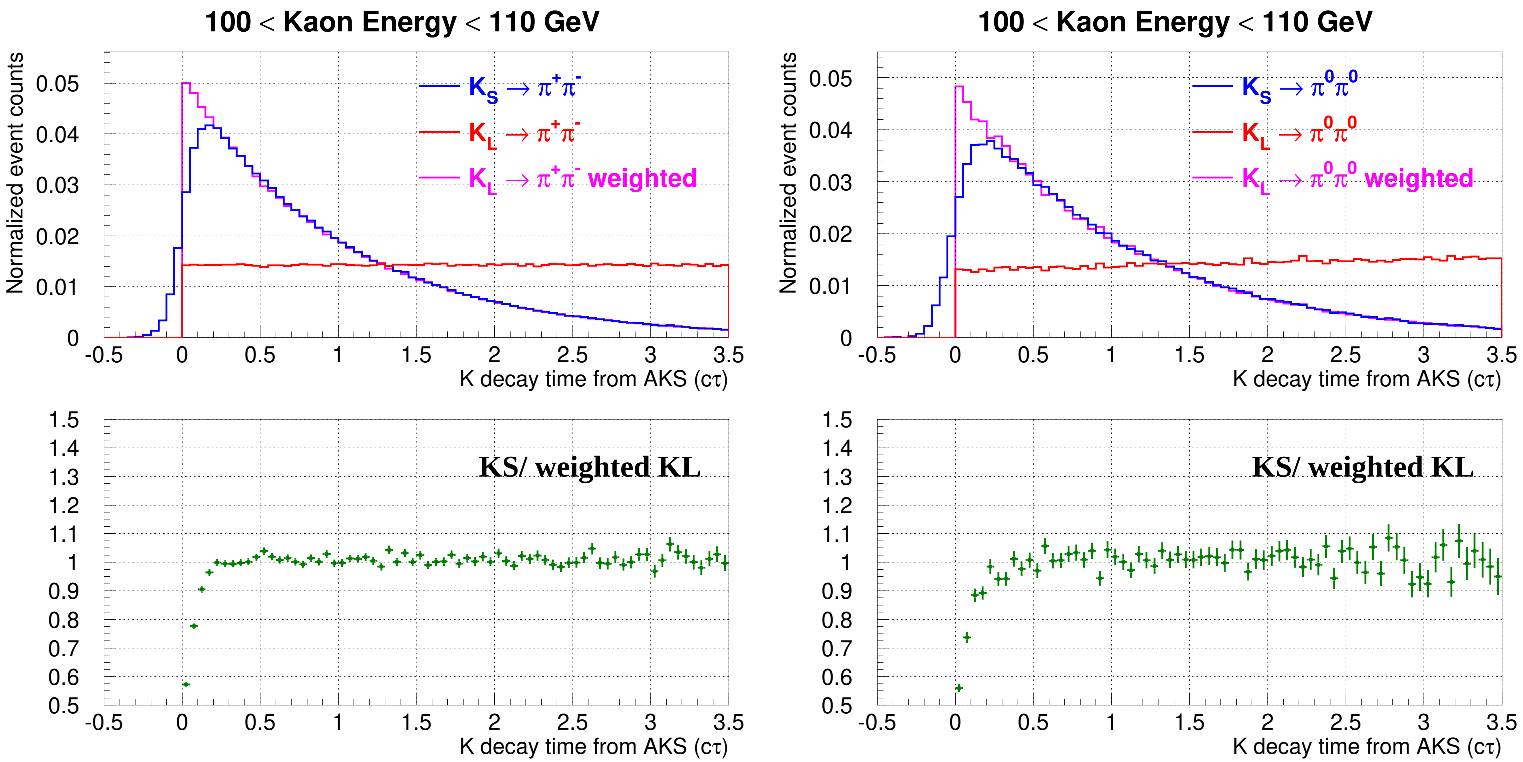
In $\mathrm{K} \to \pi^0\pi^0$ indirect methods are used.

Effect on R if difference between neutral and charged modes.

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

$$\alpha^{00}_{LS} - \alpha^{+-}_{LS} = (0.5 \pm 4) \times 10^{-4} \quad \boxed{\Delta\mathrm{R} = (1 \pm 8) \times 10^{-4}}$$

III. $\mathrm{K_L}$ Proper Time Weighting



$\mathrm{K_L}$ are weighted with the $\mathrm{K_S}$ proper time

- Weight K_L events with W $= e^{-z/(\beta\gamma c)(1/\tau_{KS}-1/\tau_{KL})}$

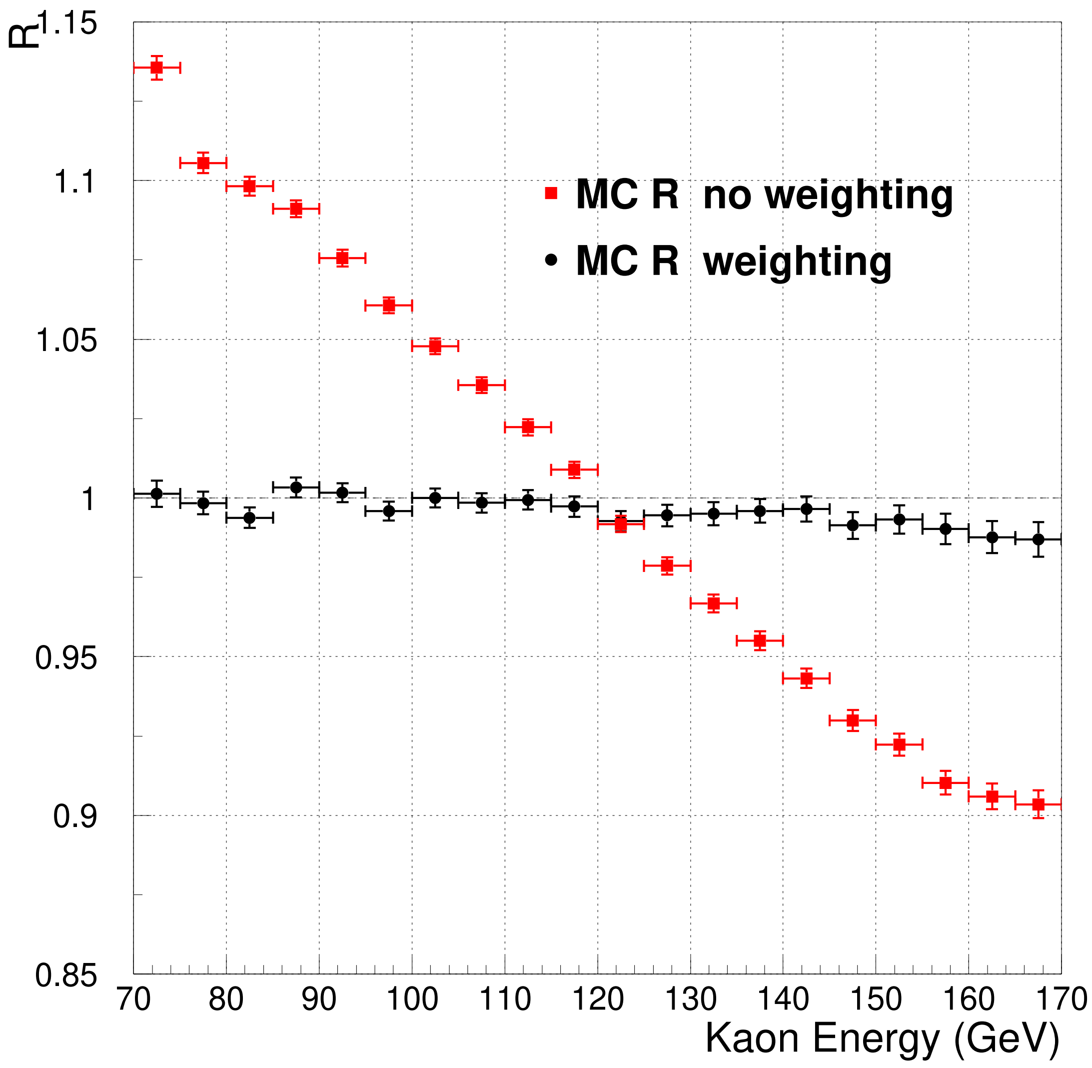
$\Rightarrow$ Weigthed $K_L = K_S$ for the detector

$\Rightarrow$ Same geometrical acceptance, no effect from detector inefficient regions

$\Rightarrow$ Reduce systematic effects

- Price : Increase of the statistical error

III. K_L Proper Time Weighting



Weighting K_L events minimize the acceptance correction.

A Monte Carlo is used to evaluate the small residual effects.

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

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

IV. Event counts in 98 data

Statistics

Mode	Events (10^6)
$K_S \to \pi^+\pi^-$	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)

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

IV. Correction and systematic uncertainties

Corrections and uncertainties on R (Unit = 10^{-4})		
Source	1998 sample	
Charged trigger	$-\ 1$	$\pm\ 11$
Accidental tagging	$+\ 1$	$\pm\ 8$
Tagging efficiency	–	$\pm\ 3$
Neutral energy scale/linearity	–	$\pm\ 10$
Charged vertex	$+\ 2$	$\pm\ 2$
Acceptance and reconstruction	$+31$	$\pm\ 9$
Neutral BG	$-\ 7$	$\pm\ 2$
Charged BG	$+19$	$\pm\ 3$
Beam scattering	$-\ 10$	$\pm\ 3$
Accidental activity	$+\ 2$	$\pm\ 12$
Total	$+37$	$\pm\ 24$

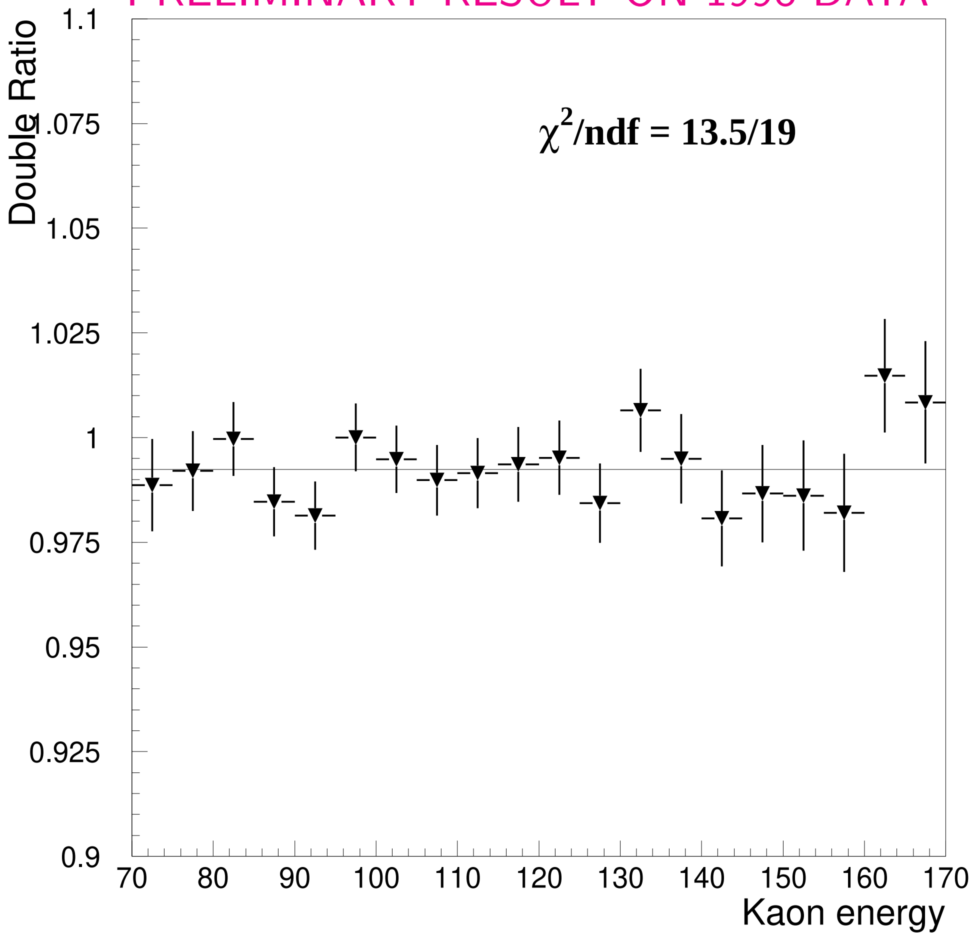
$$\mathrm{Re}(\epsilon'/\epsilon) = \frac{1}{6} \times (1 - R)$$

Errors in green = limited by data statistic

Errors in blue = work in progress to improve for final result

IV. ϵ'/ϵ result

PRELIMINARY RESULT ON 1998 DATA



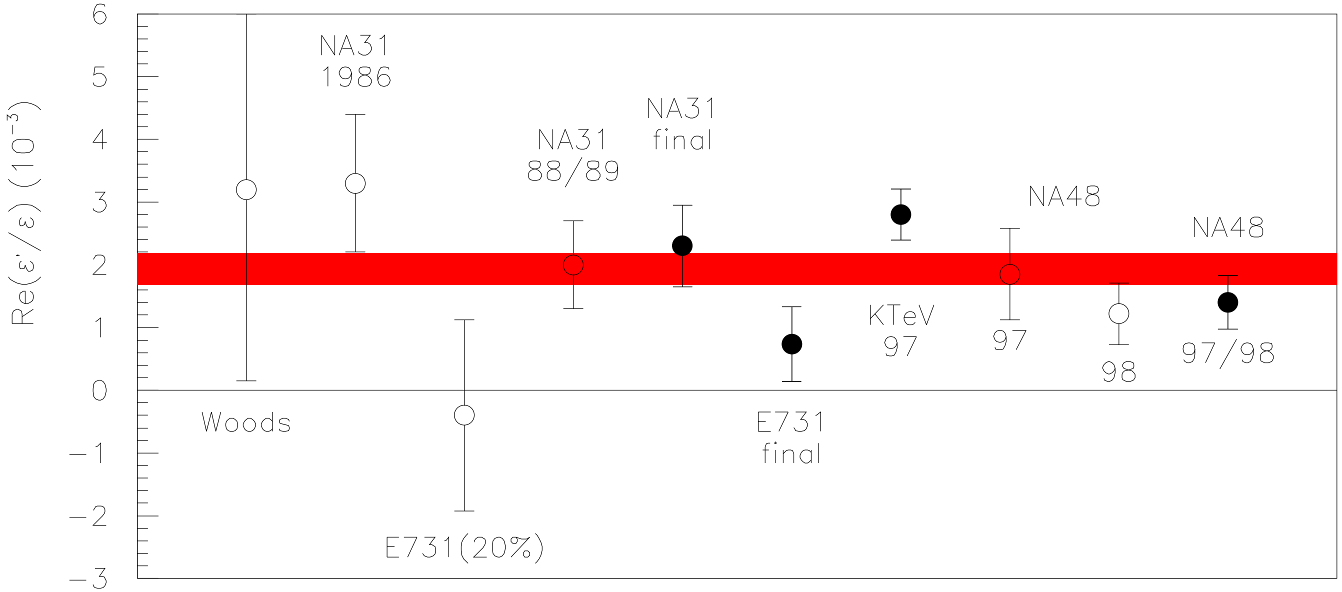
$$\Rightarrow \mathrm{Re}(\epsilon'/\epsilon) = (12.2 \pm 2.9(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})) \times 10^{-4}$$

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

Combined published 1997 and preliminary 1998

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

IV. New world average



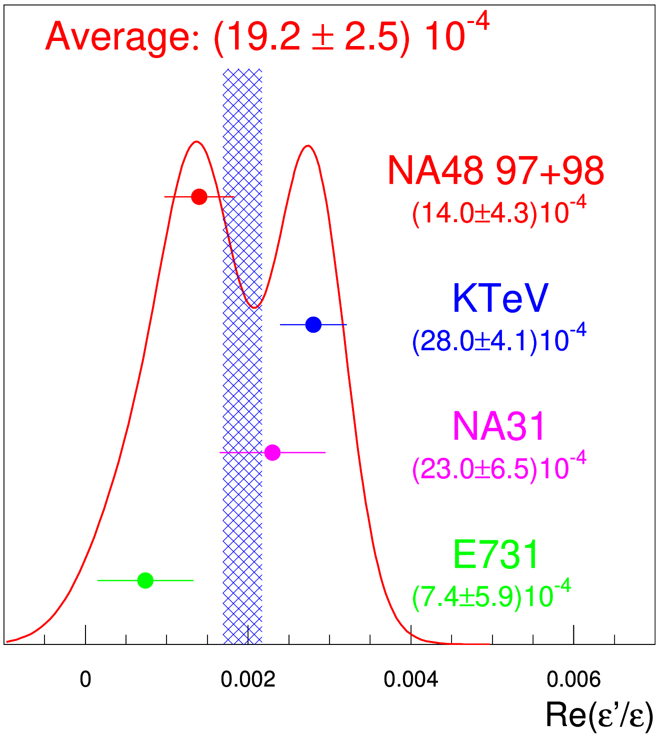
New world average: $\boxed{\mathrm{Re}(\epsilon'/\epsilon) = (19.2 \pm 2.5) \times 10^{-4}}$

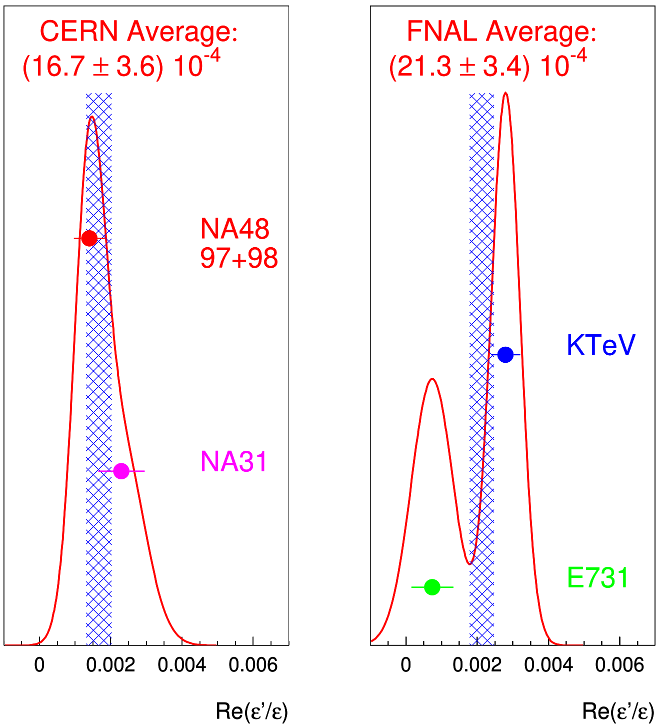
(but $\chi^2/ndf = 10.4/3$)

$\Rightarrow$

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

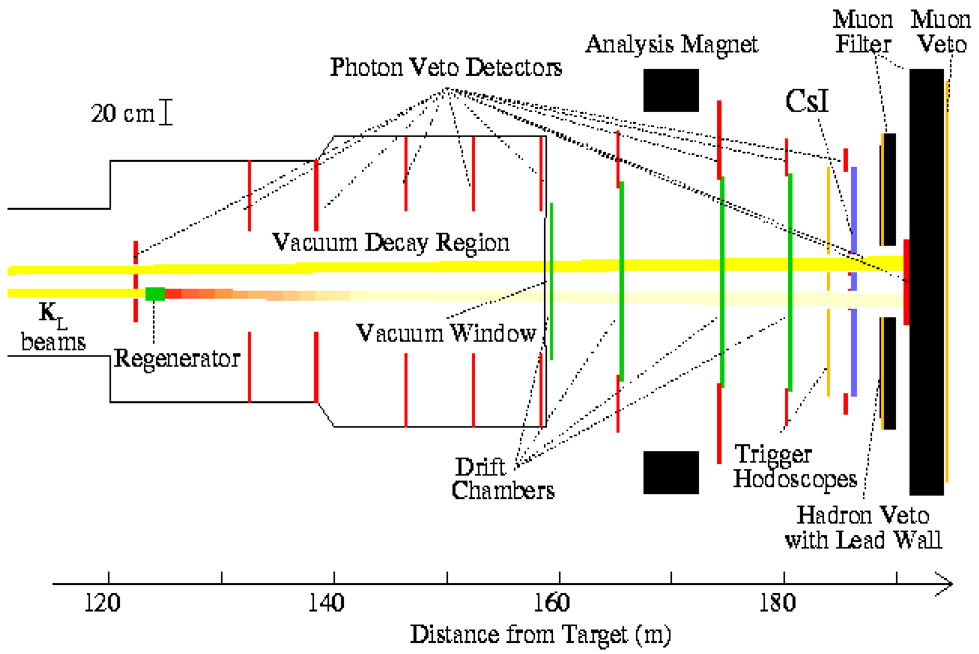
IV. New world average





KTEV

KTeV Detector, E832 Configuration



PUBLISHED Phys. Rev. Lett. 83 (1999)

$$\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 3.0(stat.) \pm 2.8(syst.)) \times 10^{-4}$$

$$\boxed{\mathrm{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}}$$

KTEV-NA48 comparison

	NA48	KTEV
$\mathrm{K_S}$ production	2nd target	regenerator
$\mathrm{K_S}$ identification	Time (proton t.o.f.)	Space (C.O.G.)
Simult. $\mathrm{K_S}$ & $\mathrm{K_L}$	Yes	Yes
Simult. $\pi^+\pi^-$& $\pi^0\pi^0$	Yes	Yes(not yet)
$\mathrm{K_S}$ $\mathrm{K_L}$ beams distance	7.2 cm $\rightarrow$ 0	30 cm
Acceptance (correction)	ctau weight (small)	MC*** (large)
Calorimeter	Liquid Krypton	CsI crystals
Magnetic Spectrometer	Yes	Yes
Evacuated decay region	Yes	Yes
$\mathrm{K_S}$ decay region begin.	Sharp (Veto)	Sharp (Veto)
Data taking years	1997-98	1996($\pi^0\pi^0$)-97($\pi^+\pi^-$)
Selected kaon energy	70-170 GeV	40-160 GeV
K_{l3} BG in $\mathrm{K_L} \rightarrow \pi^+\pi^-$	0.19%	0.07%
$3\pi^0$ BG in $\mathrm{K_L} \rightarrow \pi^0\pi^0$	0.07%	0.27%
Scatt.BG in $\mathrm{K_{L(S)}} \rightarrow \pi^+\pi^-$	-	0.014% (0.086%)
Scatt.BG in $\mathrm{K_{L(S)}} \rightarrow \pi^0\pi^0$	0.10%	0.46% (1.21%)
$\mathrm{K_S}$ /$\mathrm{K_L}$ ratio	const. $\pm 10\%$	const.

IV. Prospects

NA48 :

- Finalize systematic errors for 98 and analyze 99 data ($\sim 2{\times}10^6$ $\mathrm{K_L}$ to $\pi^0\pi^0$, twice as much as 98 data)
  Expected accuracy $\simeq$ 2.5 to 3 $\times$ 10^{-4} on ϵ'/ϵ
- The implosion of the carbon fiber beam pipe occurred last november has damaged all four drift chambers.
  Drift chambers repair is underway and the ϵ' program will be completed next year.
  During the 2000 run we have been studing systematic effects in neutral events (mistagging probability in $\pi^0\pi^0$ events and energy scale/linearity of the LKr calorimeter using dedicated runs with a negative pion beam to produce large amount of $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$).

KTeV : new result on full 97 sample expected soon (99 sample similar size as 97 sample)

KLOE : very different method

IV. Conclusions

- New NA48 preliminary result :

  $\mathrm{Re}(\epsilon'/\epsilon) = (14.0 \pm 4.3) \times 10^{-4}$
  based on 1997 and 1998 data samples,
  the result confirm a non-zero, positive value for $Re(\epsilon'/\epsilon)$

- Improvements on systematics expected.
  1999 data analysis in progress

- Current world average is :

  $\mathrm{Re}(\epsilon'/\epsilon) = (19.2 \pm 2.5) \times 10^{-4}$
  but with a poor χ^2

- More results to come (KTEV, NA48, KLOE) and hopefully to clarify experimental situation