New measurement of ε'/ε by NA48

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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

- Physics Motivation
- Measurement Principle
- Experimental Set-Up
- Data Analysis
- Result
- Conclusions

☞ The presented result (to be published) is based on data collected during the 1998 and 1999 runs.

The statistics is ~ 7 times larger than our published result based on 1997 data [Phys. Lett. B 465 (1999)]

The neutral kaon system

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 are not pure CP eigenstates**

$$\mathrm{K_S} \simeq \mathrm{K}_1 + \varepsilon \mathrm{K}_2 \quad (c\tau_{\mathrm{S}} = 2.67\ \mathrm{cm})$$
$$\mathrm{K_L} \simeq \mathrm{K}_2 + \varepsilon \mathrm{K}_1 \quad (c\tau_{\mathrm{L}} = 15.5\ \mathrm{m})$$

$\mathrm{K_S}$		$\mathrm{K_L}$	
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 %	$\pi^0\pi^0$

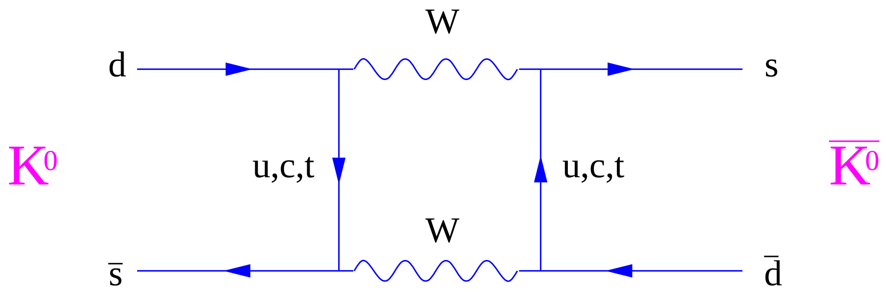
$$\boxed{|\varepsilon| = (2.28 \pm 0.02)\ 10^{-3}}$$

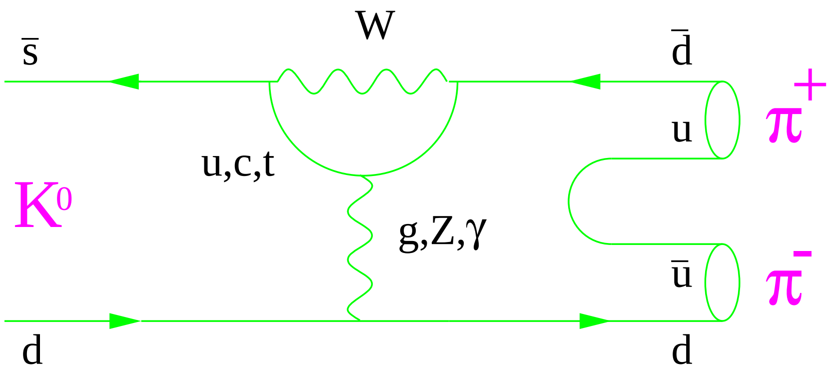
indirect CP violation

CP Violation in the Standard Model

Indirect violation
through mixing in $K^0/\overline{K^0}$ states

Box diagram : $\Delta S = 2 \to \varepsilon$





Direct violation through decay

Penguin diagram : $\Delta S = 1 \to \varepsilon'$

- Need interference of two decay amplitudes $|A(K^0 \to f\bar{f})| \neq |A(\overline{K^0} \to f\bar{f})|$
- Two pion state from K^0 can have I=0 or 2 $\Rightarrow$ 2 amplitudes A_0 and A_2

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

Typical theoretical predictions ➔ Re(ε'/ε) in the range $5 - 30 \times 10^{-4}$

Experimental status

Previous generation of experiments (results in early 90's)

NA31	$(23.0 \pm 6.5) \times 10^{-4}$	$(3.5\,\sigma)$
E731	$(7.4 \pm 5.9) \times 10^{-4}$	$(1.2\,\sigma)$

$\varepsilon'/\varepsilon \neq 0$? $\Rightarrow$ New generation of experiments

First published results two years ago

KTEV	$(28.0 \pm 4.1) \times 10^{-4}$	$(6.8\,\sigma)$
NA48	$(18.5 \pm 7.3) \times 10^{-4}$	$(2.5\,\sigma)$

Preliminary NA48 result on 98 data last year (combined with 97)

NA48	$(14.0 \pm 4.3) \times 10^{-4}$	$(3.3\,\sigma)$

Before May 2001

- World average:
  $(19.2 \pm 2.5) \times 10^{-4}$ BUT $\chi^2/\mathrm{ndf} = 10.4/3$
- Need final results from NA48 and KTeV

Measurement principle

Measure the double ratio R that is related to the decay widths and to $\mathrm{Re}(\varepsilon'/\varepsilon)$:

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

by counting the number of events.

Statistics: Need millions of $\mathrm{K_L} \to \pi^0\pi^0$ for statistical error on $\mathrm{R} < 0.1\%$

➔ use high intensity $\mathrm{K_L}$ beam with fast detectors and powerful trigger, DAQ and computing farm.

Systematics: Need symmetry between $\mathrm{K_L}$ and $\mathrm{K_S}$ or $\pi^+\pi^-$ and $\pi^0\pi^0$

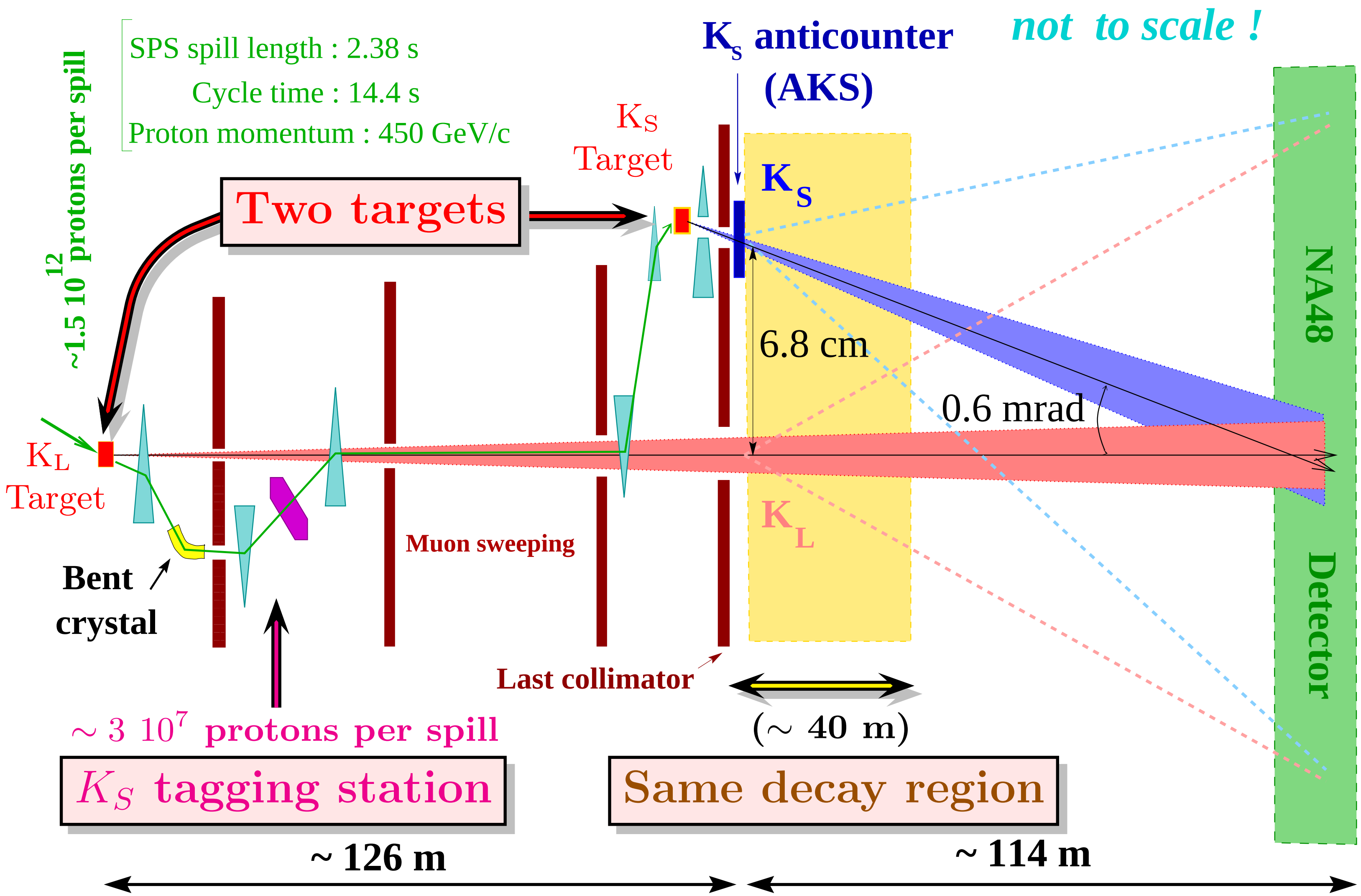
➔ systematic biases will cancel in the ratio:

- take the four decay modes simultaneously in the same decay region
  ➔ cancellation of fluxes, dead times, inefficiencies, accidental losses
- apply lifetime weighting to equalize distributions of $\mathrm{K_L}$ and $\mathrm{K_S}$ decay positions
  ➔ cancellation of detector acceptance effects

➔ **small correction on R**

➔ **smaller systematic uncertainty**

NA48 simultaneous and collinear K_S and K_L beams



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

Lifetime weighting

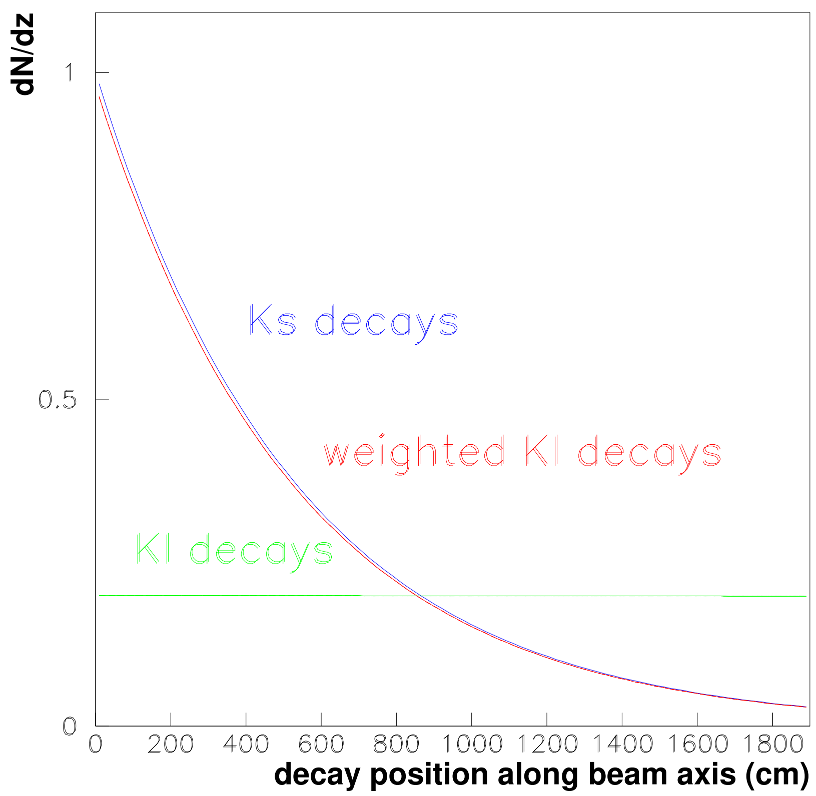
For a given z: acceptance $\mathrm{K_S} = \mathrm{K_L}$
BUT very different decay lengths: $\tau_{\mathrm{K_L}} \approx 600 \times \tau_{\mathrm{K_S}}$
$\Rightarrow$ Different total acceptance for $\mathrm{K_S}$ and $\mathrm{K_L}$
$\Rightarrow$ Large correction on R

➡ Weight $\mathrm{K_L}$ events with:

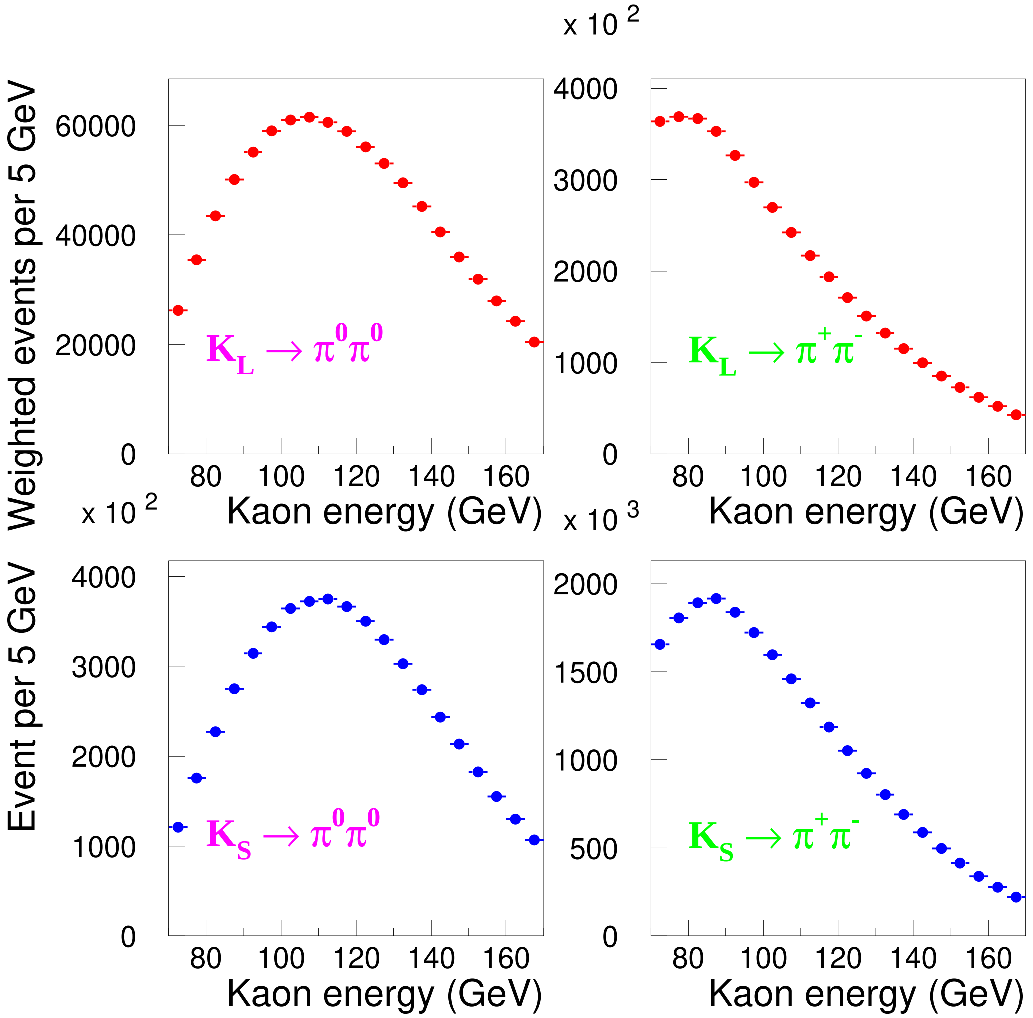
$$W = \frac{\pi\pi \text{ decay rate in } \mathrm{K_S} \text{ beam}}{\pi\pi \text{ decay rate in } \mathrm{K_L} \text{ beam}} \approx e^{-z/(\beta\gamma c)(1/\tau_{KS} - 1/\tau_{KL})}$$

➡ Same decay vertex distribution for $\mathrm{K_S}$ and weighted $\mathrm{K_L}$ (same geometrical acceptance, no effect from detector inefficient regions)

➡ Acceptance correction cancels
Price: increase in statistical error ($\approx$ 35 %)

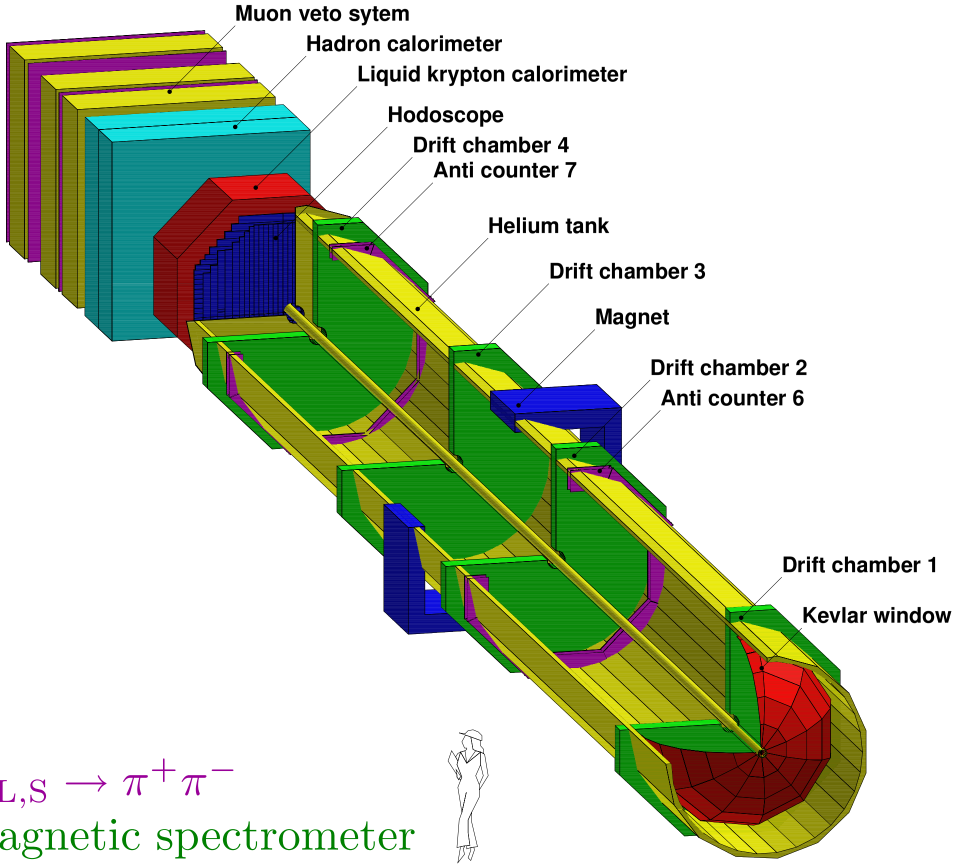


Kaon energy spectra



- The targeting angles are tuned to deliver similar decay spectra in the chosen decay volume and in the energy interval 70 to 170 GeV
- Residual differences in the K_S and K_L energy spectra are reduced by performing the analysis in twenty 5 GeV bins

The NA48 detector



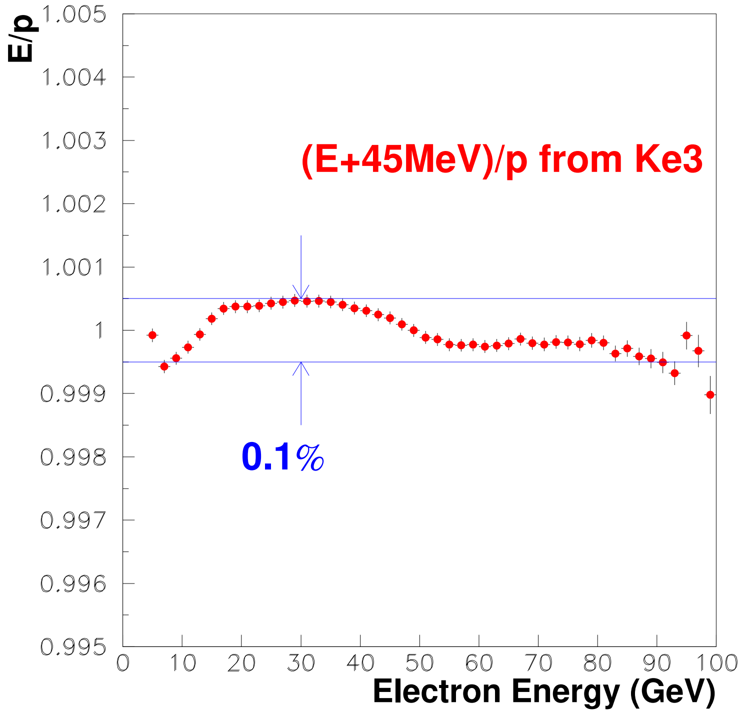
- $K_{\rm L,S} \to \pi^+\pi^-$
  Magnetic spectrometer
  2×2 drift chambers + magnet $\to$ 265 MeV/c p_t kick
  $$\boxed{\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\, P[\mathrm{GeV}/c]\,\%}$$
  ($\sim$ 1 % for 100 GeV/c track momentum)

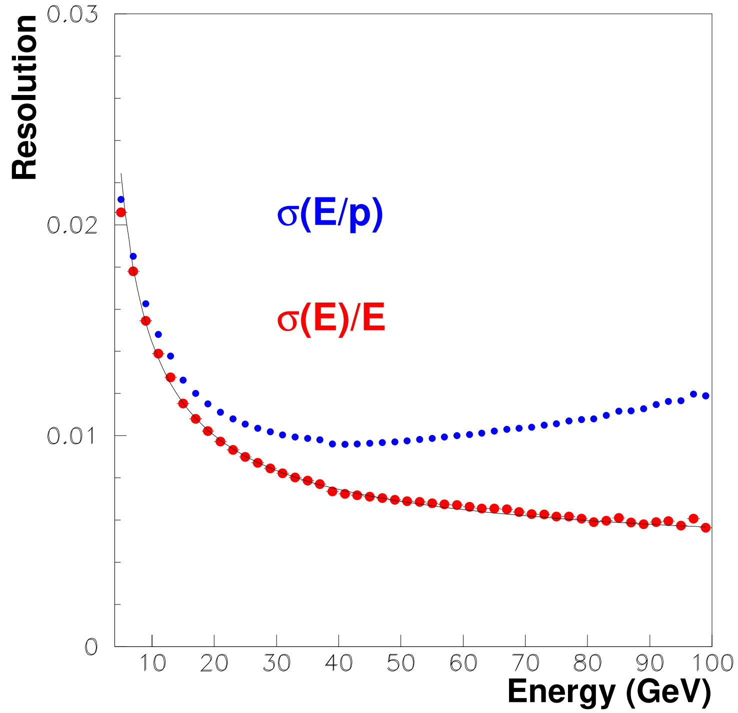
- $K_{\rm L,S} \to \pi^0\pi^0$
  Liquid Krypton e.m. calorimeter
  Granularity 13212 cells 2×2 cm^2
  Depth 1.25 m = $\sim 27\ X_0$ (X_0= 4.7 cm)
  Projective geometry $\to$ 114 m upstream decay region
  $$\boxed{\sigma(E)/E \simeq 3.2\%/\sqrt{E} \oplus 0.09/E \oplus 0.42\%}$$ E in GeV

- Dead time conditions:
  $\approx$ 1.5% from $\pi^+\pi^-$ trigger
  $\approx$ 20% from DCH multiplicity limit
  $\Rightarrow$ applied offline to all events

LKr energy resolution

- Using electrons from $K_L \rightarrow \pi e \nu$ as a probe





Compare p from spectrometer
and E from calorimeter
$E/p = 1$ for perfect detectors

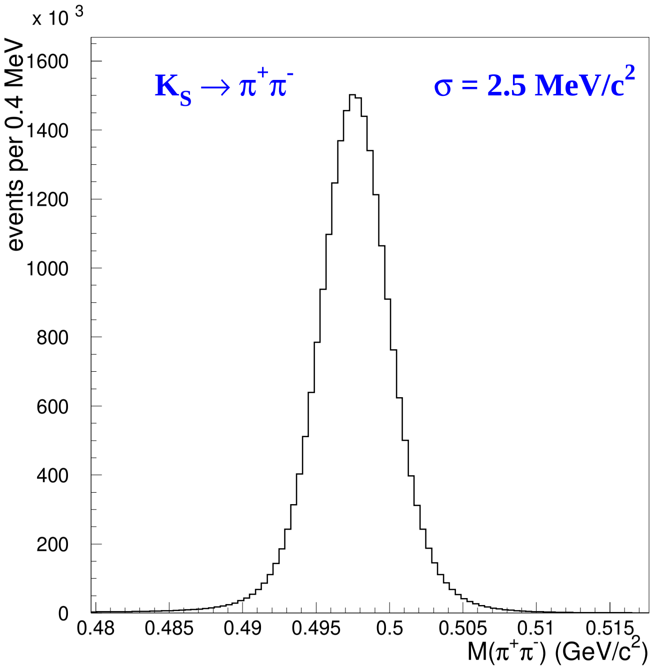
E/p resolution
Drift chamber deconvoluted

$$\boxed{\sigma(E)/E \simeq 3.2\%/\sqrt{E} \oplus 0.09/E \oplus 0.42\%} \text{ (E in GeV)}$$

(better than 1 % for 25 GeV photons)

$\pi^+\pi^-$ Selection

Decay vertex and $M_{\pi\pi}$ reconstucted by the spectrometer
Decay time from hodoscope ($\sigma \approx 140$ ps)



Background rejection

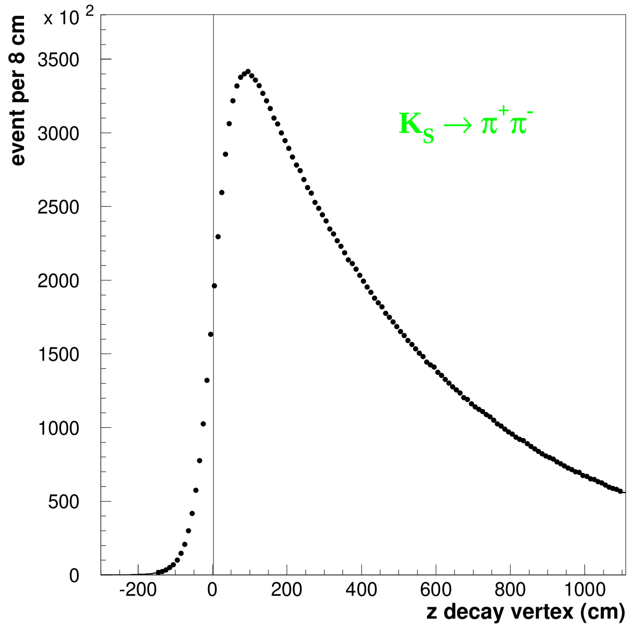
$\pi\mu\nu$: no hit in μ veto

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

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

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

$\pi^+\pi^-$ energy: opening angle and the track energy ratio
$\Rightarrow$ defined by the geometry of the drift chambers

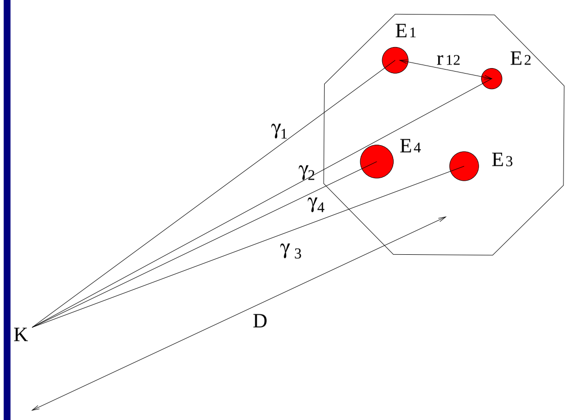


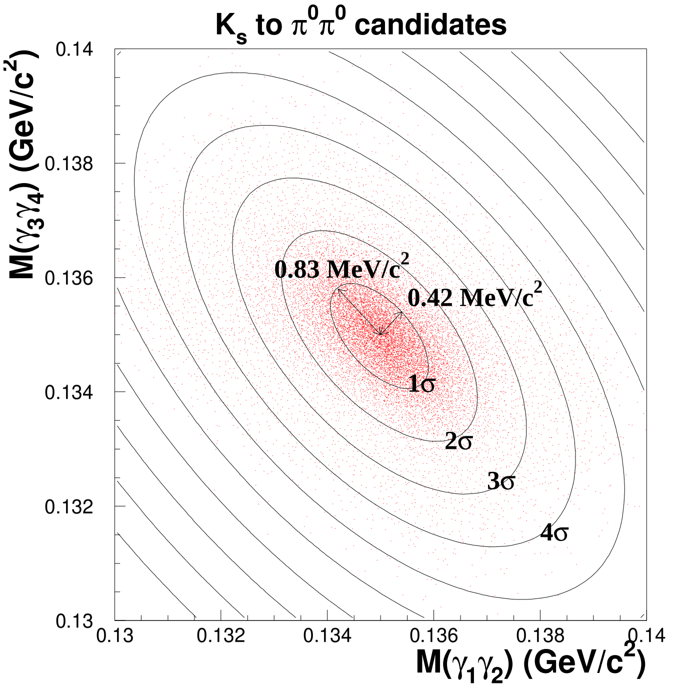
Reconstruction of AKS position:

Check of geometry
$\Downarrow$
$\Delta z = 2$ cm

$\pi^0\pi^0$ Selection

$K^0 \to 2\pi^0 \to 4\gamma \Rightarrow$ Measure (E,x,y) of 4 γ in calorimeter
Decay time from LKr calorimeter ($\sigma \approx 200$ ps)

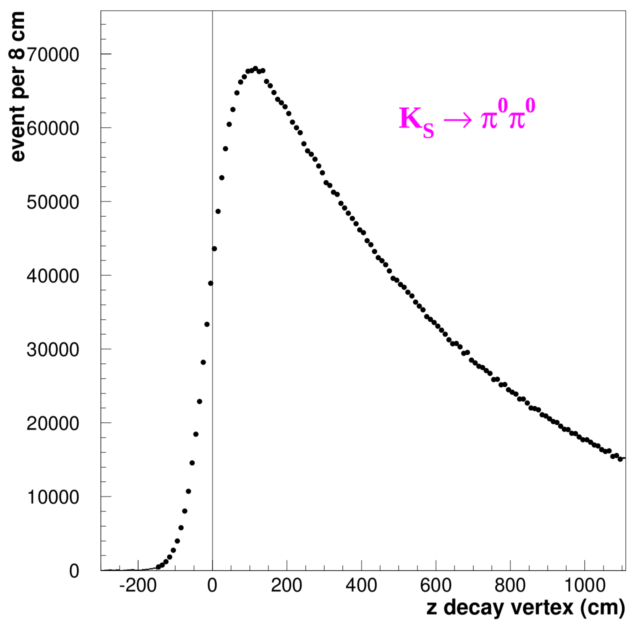




$$D = \frac{\sqrt{\sum E_i E_j \times (r_{ij})^2}}{M_K}$$

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

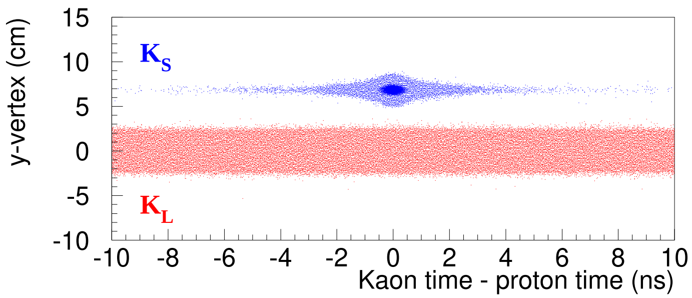
- ☞ Cut on χ^2 from π^0 masses
- ☞ 3 π^0 rejection: veto events with 5th cluster in-time

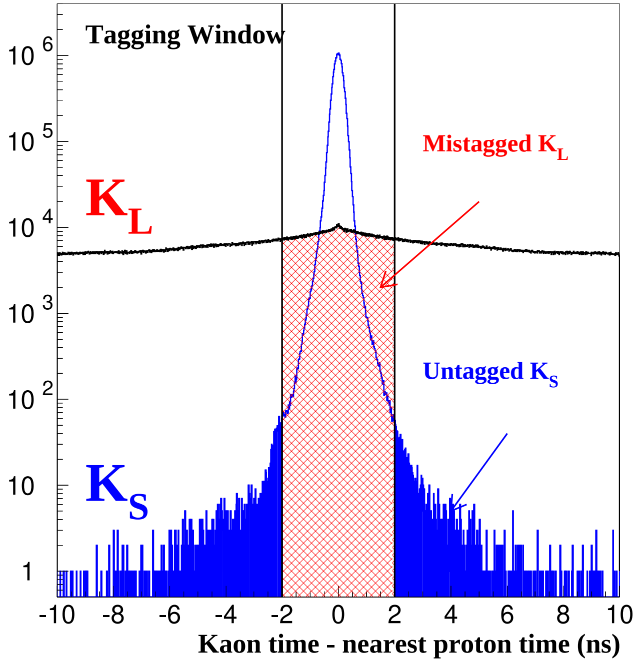


Reconstruction of AKS position:

Match nominal position
$\Downarrow$
adjust energy scale

Tagging : K_L - K_S identification





- In both decay modes
  K_S tagged by comparing the event time to proton times as they pass through tagging station

$$\Delta t(\text{Kaon-Proton}) \quad \begin{array}{l} \leq 2 \text{ ns} \Rightarrow K_S \\ > 2 \text{ ns} \Rightarrow K_L \end{array}$$

- In charged modes only
  identification can also be done by vertex reconstruction

➔ Two possible misidentifications:

- K_S identified as K_L
  Tagging inefficiency: α_{SL}
  tails in time measurement
- K_L identified as K_S
  Accidental tagging: α_{LS}
  proton rate in the tagging station

Effect on R if difference between neutral and charged modes

Source of systematics

Corrections to the first order result

- **Charged background**
- **Neutral background**
- **Beam scattering background**
- **Tagging (Neutral-Charged difference)**
- **Triggers inefficiencies**
- **AKS veto inefficiency**
- **Energy scale uncertainty**
- **Acceptance**
- **Accidental activity induced losses**

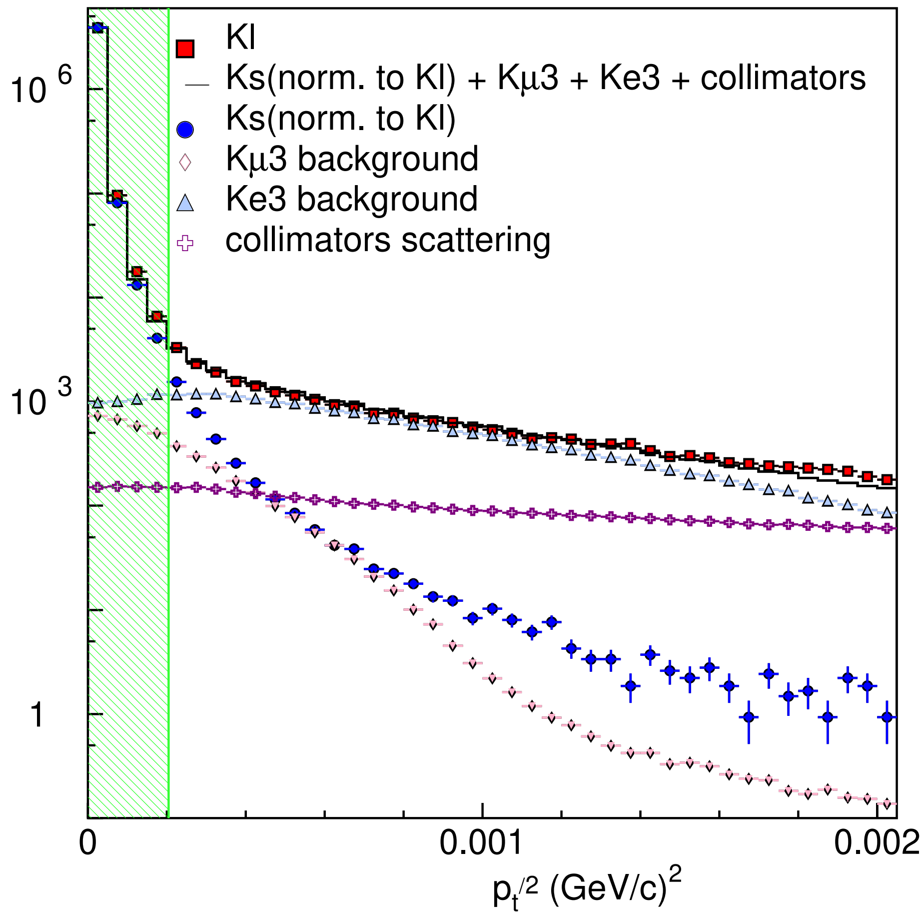
Background in $\pi^+\pi^-$

➡ $\mathrm{K_S}$ - no background

➡ $\mathrm{K_L}$ - background source: $\boxed{\mathrm{K_L} \to \pi e \nu, \pi \mu \nu}$

The residual $\mathrm{K_L}$ background is estimated and subtracted

- using control region in the $m_{\pi\pi} - {p_T}'^2$ distribution of $\mathrm{K_L} \to \pi^+\pi^-$
- using samples of identified $Ke3$ and $K\mu3$ decays in two control regions



$$\boxed{\Delta R = (16.9 \pm 3.0) \times 10^{-4}}$$

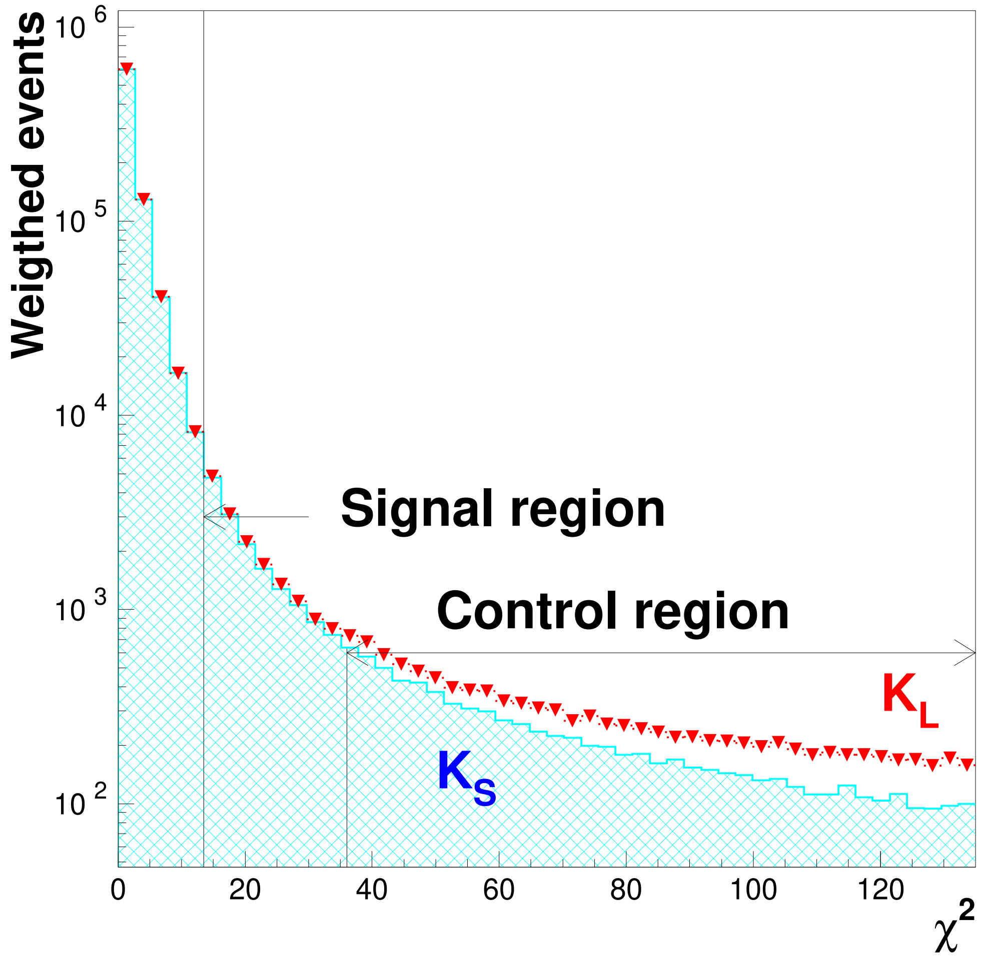
(Systematic error: variation of control regions, modelling of ${p_T}'^2$ shape)

Background in $\pi^0\pi^0$

- ➔ K_S - no background
- ➔ K_L - background source: $\boxed{K_L \rightarrow 3\pi^0}$

The residual K_L background is estimated and subtracted

- extrapolating from χ^2 control region ($3\pi^0$ background is almost flat)
- using K_S events to evaluate resolution tails



$$\boxed{\Delta R = (-5.9 \pm 2.0) \times 10^{-4}}$$

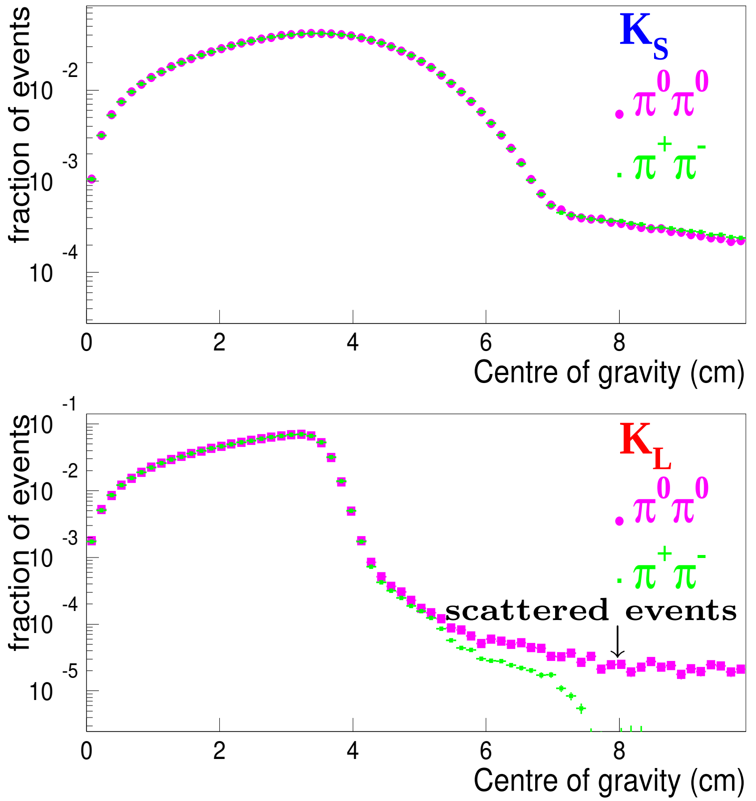
(Systematic error: uncertainty in background extrapolation from MC)

Collimator scattering background

- K_S - beam scattering removed by centre of gravity (COG) cut symmetric for $\pi^+\pi^-$ and $\pi^0\pi^0$
  $\Rightarrow$ No effect on R
- K_L - in $\pi^+\pi^-$ beam scattering removed by $p_T'^2$ cut $\Rightarrow$ must be subtracted in $\pi^0\pi^0$
  $\Rightarrow$ Correction on R

The Collimator background is:

- estimated from $m_{\pi\pi}$ distribution of $\pi^+\pi^-$ decays at high $p_T'^2$
- cross-checked from tails of COG in $\pi^0\pi^0$ (taking into account background and scattering at defining collimator)



$$\boxed{\Delta R = (-9.6 \pm 2.0) \times 10^{-4}}$$

K_L - K_S misidentification

Double ratio method ⇒ difference between neutral and charged mode

$$\Delta\alpha_{SL} = \alpha^{00}_{SL} - \alpha^{+-}_{SL}$$

$$\alpha^{+-}_{SL} = (1.63 \pm 0.03) \times 10^{-4}$$

- measured from $K_S \to \pi^+\pi^-$ decays identified by vertex
- dominated by tagger inefficiency $\pi^+\pi^-$ and $\pi^0\pi^0$ **symmetric**

$\Delta\alpha_{SL}$ from difference in tails between $\pi^+\pi^-$ and $\pi^0\pi^0$ event time

➡ compare charged time (from e^+e^-) with neutral time (from $\gamma' s$) in $2\pi^0$ and $3\pi^0$ events with conversions

$$\Delta\alpha_{SL} = 0 \pm 0.5 \times 10^{-4}$$

$$\boxed{\Delta R = (0 \pm 3.0) \times 10^{-4}}$$

$$\Delta\alpha_{LS} = \alpha^{00}_{LS} - \alpha^{+-}_{LS}$$

$$\alpha^{+-}_{LS} = (10.649 \pm 0.008)\%$$

- measured from $K_L \to \pi^+\pi^-$ decays identified by vertex
- dominated by **accidental** coincidences of protons on the tagger

$\Delta\alpha_{LS}$ from coincidence rate in lateral windows for tagged K_L events

➡ extrapolate under the coincidence window using

$\pi^+\pi^-$ for vertex selected K_L

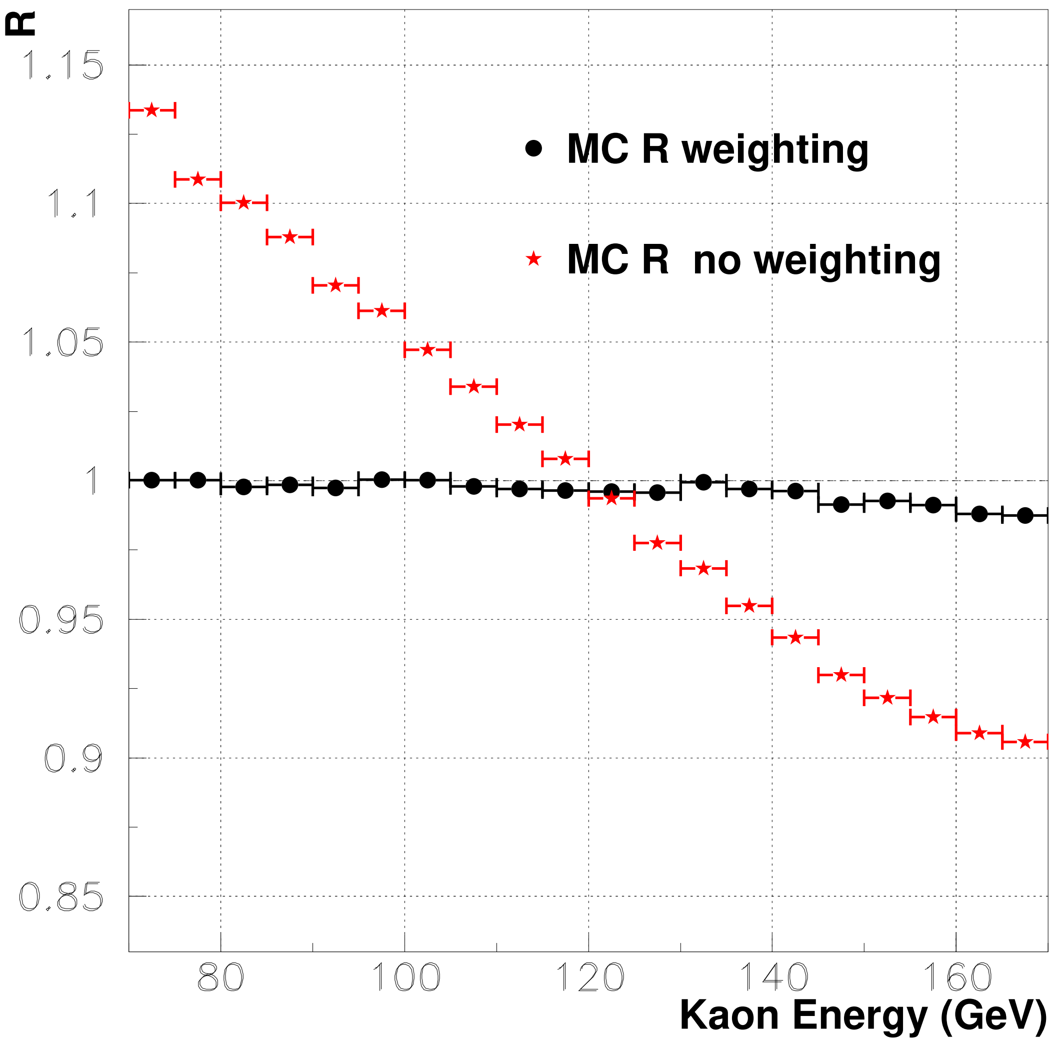
$\pi^0\pi^0$ from $3\pi^0$ (only K_L)

$$\Delta\alpha_{LS} = 4.3 \pm 1.8 \times 10^{-4}$$

$$\boxed{\Delta R = (8.3 \pm 3.4) \times 10^{-4}}$$

Acceptance Correction

- K_L are weighted with K_S proper time
  - ➔ symmetric illumination
  - ➔ small acceptance correction
- Small residual effect from 0.6 mrad angle between K_S and K_L beams
  - ➔ correction estimated using Monte Carlo



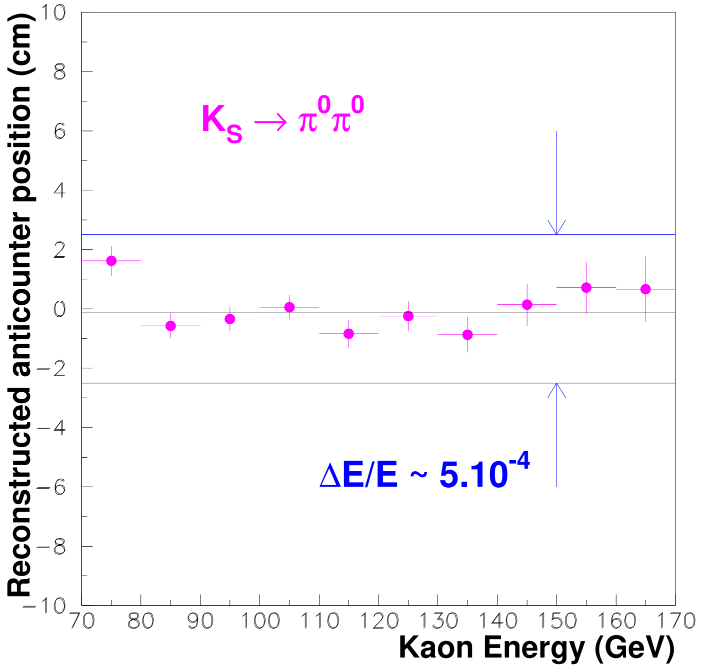
$$\Delta R = (26.7 \pm 4.1_{MCstat} \pm 4.0_{syst}) \times 10^{-4}$$

Energy scale

$\pi^0\pi^0$

- Energy scale $\Leftrightarrow$ Distance scale adjusted by measurement of AKS position
- uncertainties from: (energy scale, transverse size, non-linearities, non-uniformities, non-Gaussian tails etc.)
- checks from special samples: electrons, η, π^0, $3\pi^0$, MC

$$\boxed{\Delta R = 0 \pm 5.8 \times 10^{-4}}$$



Reconstructed AKS position independent of Kaon energy

$\pi^+\pi^-$

- depends on geometry of drift chambers before the magnet (straight track extrapolation to vertex)
- checked by AKS position measurement

$$\boxed{\Delta R = (2.0 \pm 2.8) \times 10^{-4}}$$

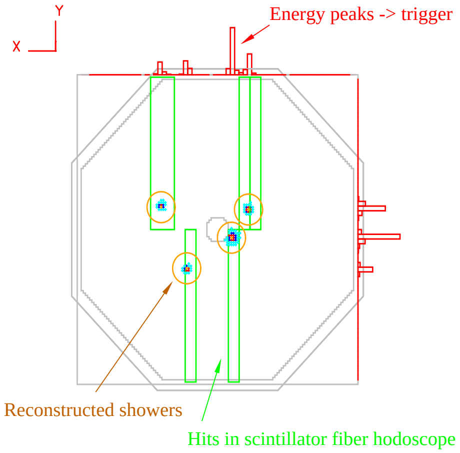
Trigger efficiency

$\pi^0\pi^0$

- Fully pipelined system using LKr cell information to compute energy, centre of gravity, proper lifetime and number of showers
- Output rate $\sim$ 2 kHz
- No dead time

$\Rightarrow$ Efficiency : $(99.920 \pm 0.009)\%$

$\boxed{\Delta R \textbf{ negligible}}$



$\pi^+\pi^-$

- Level 1:
  - Energy in calorimeters
  - Two track topology in hodoscope
  - Two track multiplicity in drift chamber 1

$\Rightarrow$ Efficiency: $(99.535 \pm 0.011)\%$

- Level 2
  on-line processing of vertex position and $\pi^+\pi^-$ invariant mass from spectrometer hits
  - Output rate $\sim$ 2 kHz
  - Dead Time: 1.1% monitored and applied to $\pi^0\pi^0$

$\Rightarrow$ Efficiency: $(98.353 \pm 0.022)\%$

$$\boxed{\Delta R = (-3.6 \pm 5.2) \times 10^{-4}}$$

Accidental activity

Accidental activity from beam $\Rightarrow$ Event losses

Simultaneity and intensity correlation of the beams

$\Downarrow$

Cancel at first order in R

Residual effect:

$$\boxed{\Delta R \approx \Delta(\pi^0\pi^0 - \pi^+\pi^-) \times \Delta(\mathrm{K_L} - \mathrm{K_S})}$$

- $\Delta(\pi^0\pi^0 - \pi^+\pi^-) = (1.4 \pm 0.7)\%$ difference between neutral and charged losses
  - measured by overlaying random triggers on signal candidates
  - minimized by applying dead-time conditions to all modes
- $\Delta(\mathrm{K_L} - \mathrm{K_S}) \lesssim 1\%$
  difference in accidental activity seen by $\mathrm{K_L}$ and $\mathrm{K_S}$
  small by design of experiment:
  - Simultaneous beams $\Rightarrow$ $\mathrm{K_L}$ and $\mathrm{K_S}$ events see the same activity (checked directly in data)
  - Lifetime weighting $\Rightarrow$ $\mathrm{K_L}$ and $\mathrm{K_S}$ events illuminate the same parts of the detector

$$\boxed{\Delta R = (\pm 3_{Intensity} \pm 3_{Illumination} \pm 1_{In-time}) \times 10^{-4}}$$

Corrections and Systematics

Summary of corrections and systematic errors

	$\Delta(R)$ (in 10^{-4} units)	
$\pi^+\pi^-$ background	16.9	± 3.0
$\pi^0\pi^0$ background	-5.9	± 2.0
Beam scattering background	-9.6	± 2.0
Tagging inefficiency		± 3.0
Accidental tagging	8.3	± 3.4 (part. stat)
$\pi^+\pi^-$ scale	2.0	± 2.8
$\pi^0\pi^0$ scale		± 5.8
AKS inefficiency	1.1	± 0.4
Acceptance correction	26.7	± 4.1 (MC stat)
		± 4.0 (syst)
$\pi^+\pi^-$ trigger	-3.6	± 5.2 (stat)
Accidental event losses		± 4.4 (part. stat)
Total	35.9	$\pm$ 12.6

➔ Some uncertainties are limited by statistics of control samples or MC

Final result

➔ From 98 and 99 data samples:

$K_L \to \pi^0\pi^0$	3.29×10^6	$K_S \to \pi^0\pi^0$	5.21×10^6
$K_L \to \pi^+\pi^-$	14.45×10^6	$K_S \to \pi^+\pi^-$	22.22×10^6

$$R = 0.99098 \pm 0.00101_{stat} \pm 0.00126_{syst}$$

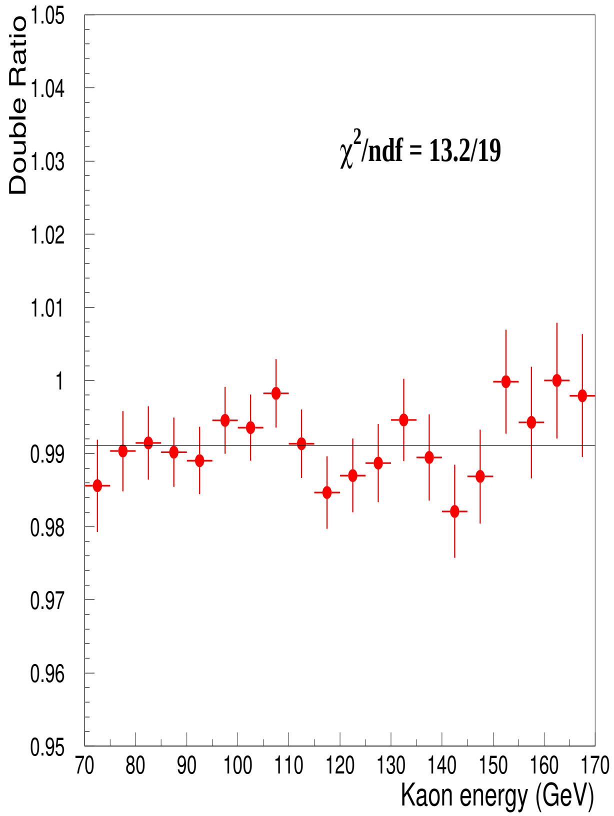
$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) \ = (15.0 \pm 2.7) \times 10^{-4}}$$

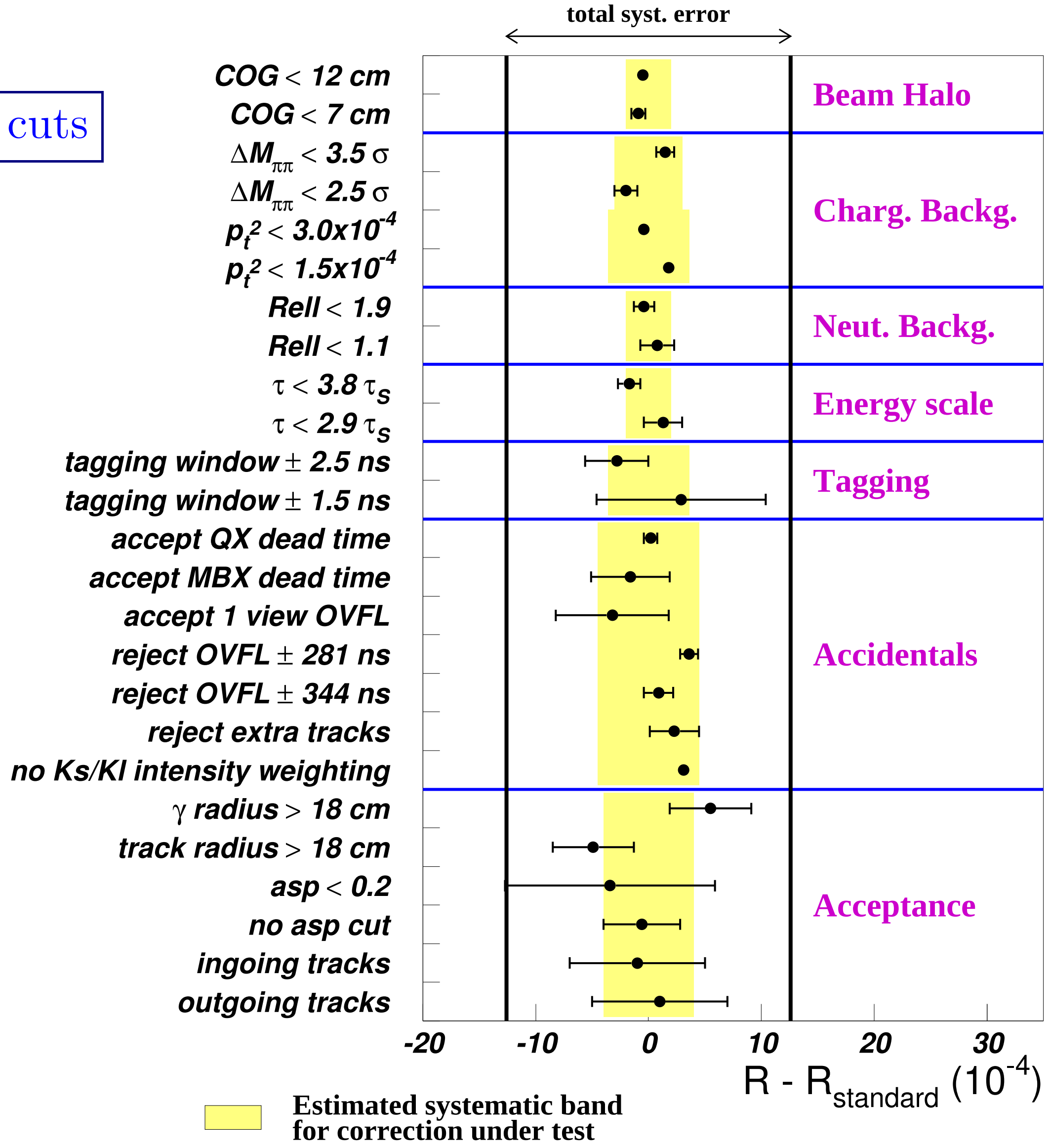
➔ Combined with $\mathrm{Re}(\varepsilon'/\varepsilon) \ = (18.5 \pm 7.3) \times 10^{-4}$ from 97 data:

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) \ = (15.3 \pm 2.6) \times 10^{-4}}$$

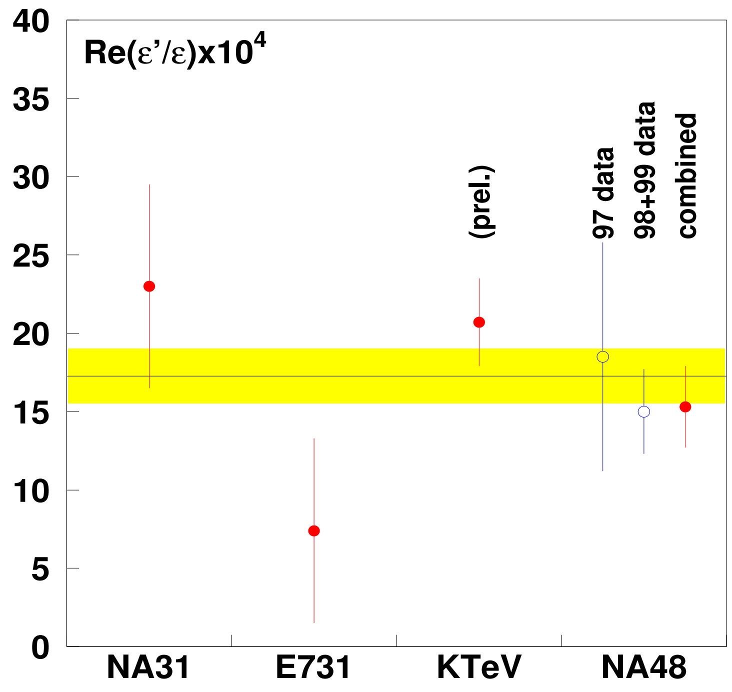
Checks

Stability with kaon energy and cuts





World average



- May 2001
  Na48 final result on 98+99 statistics

$$\mathrm{Re}(\varepsilon'/\varepsilon) \;= (15.3 \pm 2.6) \times 10^{-4}$$

- June 2001
  KTeV has announced a new result: reanalysis of the published result (based on 96 statistics) + 97 data

$$\mathrm{Re}(\varepsilon'/\varepsilon) \;= (20.7 \pm 2.8) \times 10^{-4}$$

➔ **New world average**

$$\mathrm{Re}(\varepsilon'/\varepsilon) \;= (17.2 \pm 1.8) \times 10^{-4}$$

with $\chi^2/\mathrm{ndf} = 5.5/3$ (14 % probability)

Direct CP violation definitely established

Conclusions and prospects

➡ After 3 years of data taking NA48 measures direct CP violation 5.9 σ from zero

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) \;= (15.3 \pm 2.6) \times 10^{-4}}$$

➡ Run 2001: complete statistics and verify result under different conditions

- new spectrometer
- different beam conditions (better duty cycle)

  97-99 2.4 s every 14.4 s (E_p energy = 450 GeV)

  2001 5.2 s every 16.8 s (E_p energy = 400 GeV)
- Expected $\approx 1.5 \times 10^6$ $K_L \rightarrow \pi^0\pi^0$