Measurement of Direct CP Violation by the NA48 experiment

Giuseppina Anzivino
University of Perugia

Seminar at LIP - Lisbon

Outline

- Discrete symmetries
- The neutral kaon system
- What we measure
- NA48 – the experiment
- Analysis and results
- KTeV
- Conclusions and perspectives

Symmetry - Conservation Laws

Invariance of equations describing a physical system under an operation

→ Conservation Law

Examples :

Rotation in space → Conservation of angular momentum

Gauge invariance of electromagnetic field → Conservation of electric charge

Discrete Symmetries

- **Parity P :**
  exchanges space coordinates (x,y,z) to (-x,-y,-z)

- **Charge Conjugation C :**
  exchanges a particle to its antiparticle (electron to positron, quark to its antiquark, etc.)

- **Time Reversal T :**
  exchanges t to -t

CPT Theorem

Under very general assumptions

↓

a CxPxT operation lets physics invariant

CPT conservation is verified experimentally

Particle-antiparticle properties:

Same mass and lifetime

Equal and opposite electric charge

What about C, P and T separately?

A brief history

- Beginning of sixties :
  - C and P conserved in strong and electromagnetic interactions
  - Weak interaction maximaly violate C and P
  - Their product CP was thought to be valid

This was in agreement with experiments

- In 1964 J. Christenson et al. discovered CP Violation effects in the decay of long lived kaons to pion pairs
- CP Violation implies T Violation (CPT Theorem)

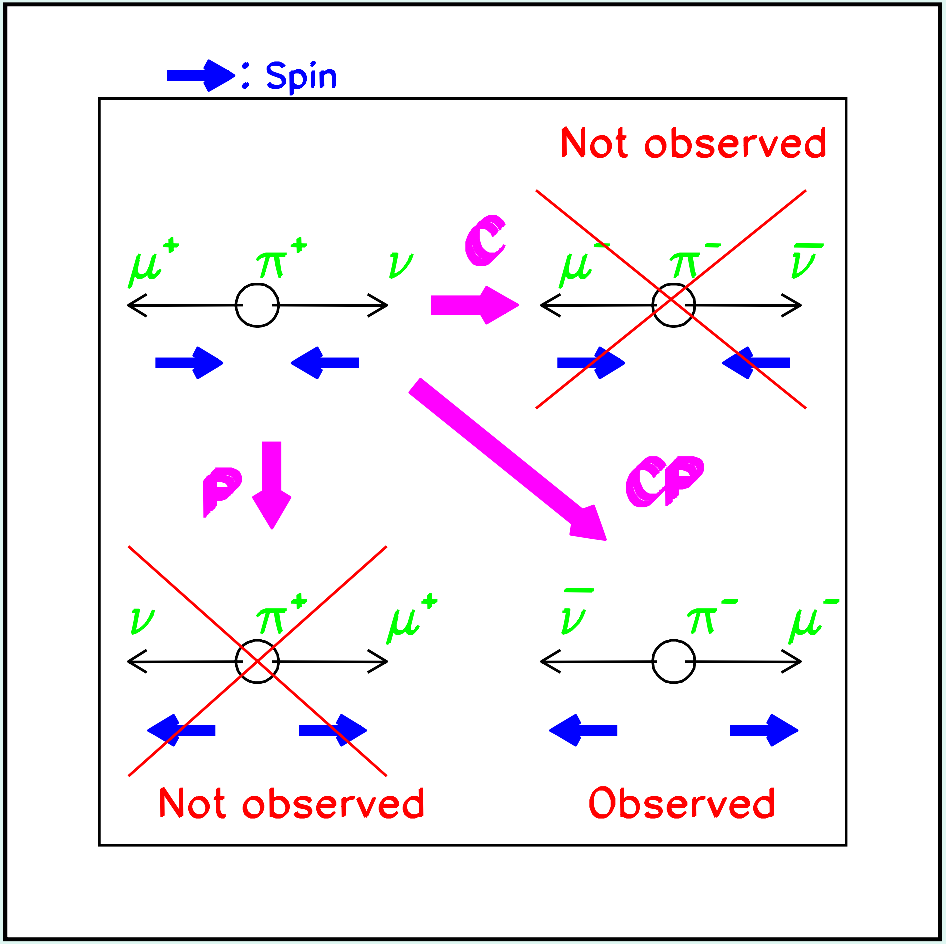
Pion decay

PION DECAY

Example of C and P

Non conservation

but CP conservation



The Neutral Kaon System

Neutral K are pseudoscalar mesons of S= ± 1

Strangeness eigenstates

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

CP eigenstates

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

Mass eigenstates

$$K_S \cong K_1 + \varepsilon K_2 \quad (c\tau = 2.67 \text{ cm})$$
$$K_L \cong K_2 + \varepsilon K_1 \quad (c\tau = 15.51 \text{ m})$$

Kaon decays

K_S Decays

69 %	$\pi^+\pi^-$
31%	$\pi^0\pi^0$

K_L Decays

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

CPV in the Kaon system

The mass eigenstates (K_S and K_L) are NOT pure CP eigenstates

The two decay modes in $\pi^+\pi^-$ and $\pi^0\pi^0$ have CP=+1

K_S (almost CP=+1) CAN decay to two pions
K_L (almost CP=-1) CANNOT decay to two pions

CP violation manifests in the observation of the

CP-forbidden $K_L \rightarrow \pi\pi$ decay

CP Violation

CP Violation has two components

Indirect CP Violation

due to CP eigenstates mixing inside K_S and K_L

parameter ε

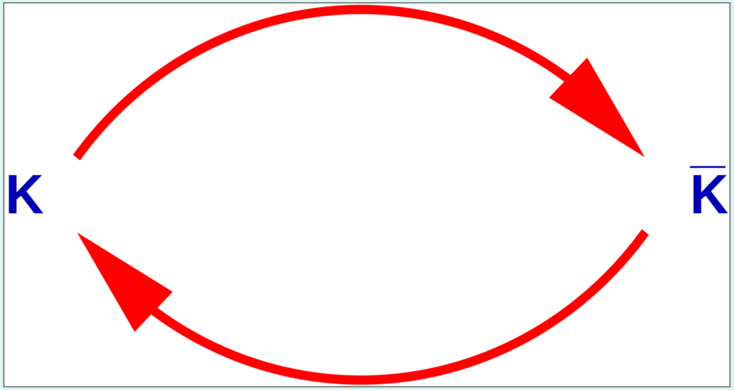
Direct CP Violation

in the decay process

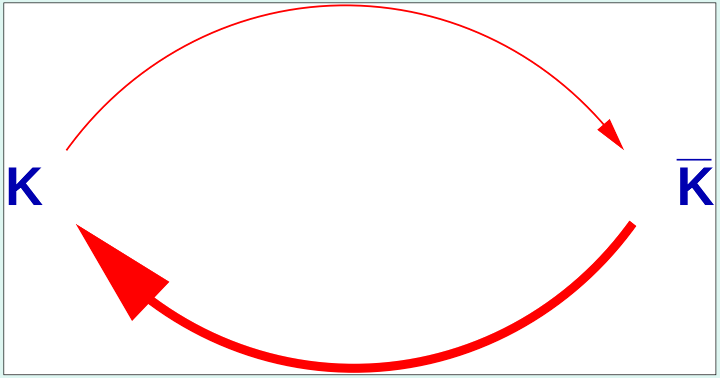
parameter ε'

Indirect CP Violation

Mixing of K^0 and $\overline{K}^0$ is independent of CP



Indirect CPV causes mixing to be asymmetric



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

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

Direct CP Violation

In the decay $K^0 \rightarrow \pi\pi$ the two pions can have isospin I=0,2

→ Two amplitudes A_0 and A_2

The phase difference of these two channels determines DIRECT CP VIOLATION

$$A(K_L \rightarrow \pi^+\pi^-) \,/\, A(K_S \rightarrow \pi^+\pi^-) = \eta_{+-} = \varepsilon + \varepsilon'$$

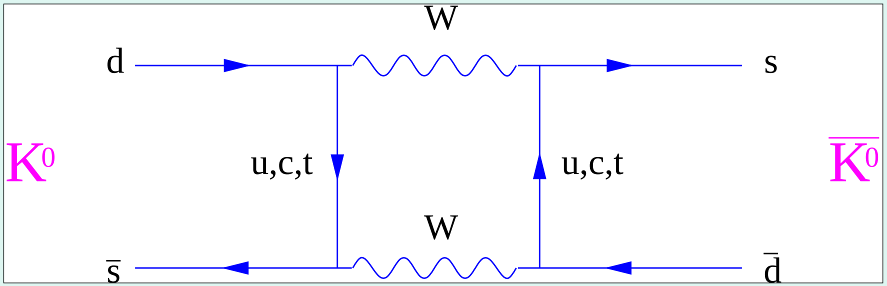
$$A(K_L \rightarrow \pi^0\pi^0) \,/\, A(K_S \rightarrow \pi^0\pi^0) = \eta_{00} = \varepsilon - 2\varepsilon'$$

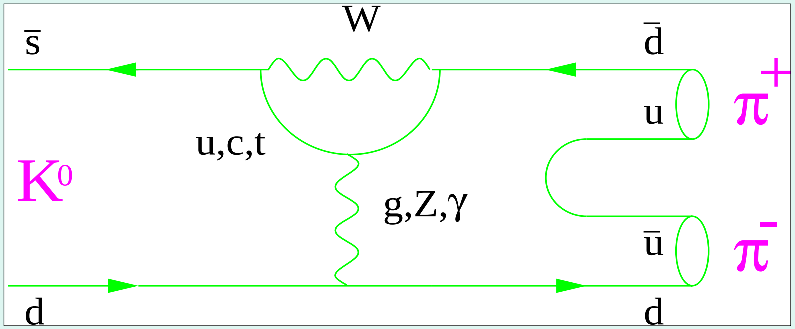
$$\varepsilon' = i\, e^{i(\delta_2-\delta_0)}\, \mathrm{Im}(A_2/A_0)\,/\sqrt{2}$$

Standard Model Predictions

CP Violation: naturally included in the Standard Model due to an irriducible complex phase in the quark mixing matrix in the case of three families

Indirect CPV	Direct CPV
Box diagram $\Delta S=2$	Penguin diagram $\Delta S=1$





What we measure

Direct CPV (ε') is small wrt Indirect CPV (ε)

Convenient to measure Re(ε'/ε)

It can be shown that the measurable quantity Re(ε'/ε) is connected to the ratio R of four observable decay rates:

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

Typical theretical predictions: Re(ε'/ε) in the range 5-30 x 10^{-4}

Experimental status of ε'/ε

- Previous generation experiments (results in early 90's):
  - NA31 (CERN) $(23.0 \pm 6.5) \times 10^{-4}$
  - E731 (Fermilab) $(7.4 \pm 5.9) \times 10^{-4}$

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

- First published results three years ago :
  - KTEV (Fermilab) $(28.0 \pm 4.1) \times 10^{-4}$ (part of 96-97 data)
  - NA48 (CERN) $(18.5 \pm 7.3) \times 10^{-4}$ (97 data)
  - Preliminary NA48 result on 98 data last year :

    $(14.0 \pm 4.3) \times 10^{-4}$ (combined with 97 data)

- Before May 2001

  world average $(19.2 \pm 2.5) \times 10^{-4}$ but $\chi^2/ndf = 10.4/3$

  Need final results from NA48 and KTEV to clarify the situation.

Data samples

GOAL:

measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ with an accuracy of 2×10^{-4}

Several millions of $K_L \rightarrow \pi^0\pi^0$ (the limiting decay mode)

A huge amount of data to control systematics

Raw Data taken:

D0, RUN I	~ 40 TB
ZEUS, RUN I	~ 30 TB
BaBar	~ 50 TB
NA48	~ 170 TB

~16K triggers/burst recorded

Only ~100 are good $\pi\pi$ modes, the rest is for systematics

Accumulated statistics

before 2000 → 3.8 millions

year 2001 → 1.4 millions

The NA48 method

The double ratio R is related to the decay widths

In the experiment we measure

$$R^{meas} = \frac{N_L^{00} \times N_S^{+-}}{N_S^{00} \times N_L^{+-}}$$

Basic principle is SYMMETRY between

K_L and K_S

$\pi^+\pi^-$ and $\pi^0\pi^0$

Take the four decay modes

- Simultaneously
- In the same decay region

Count the number of events

The double ratio

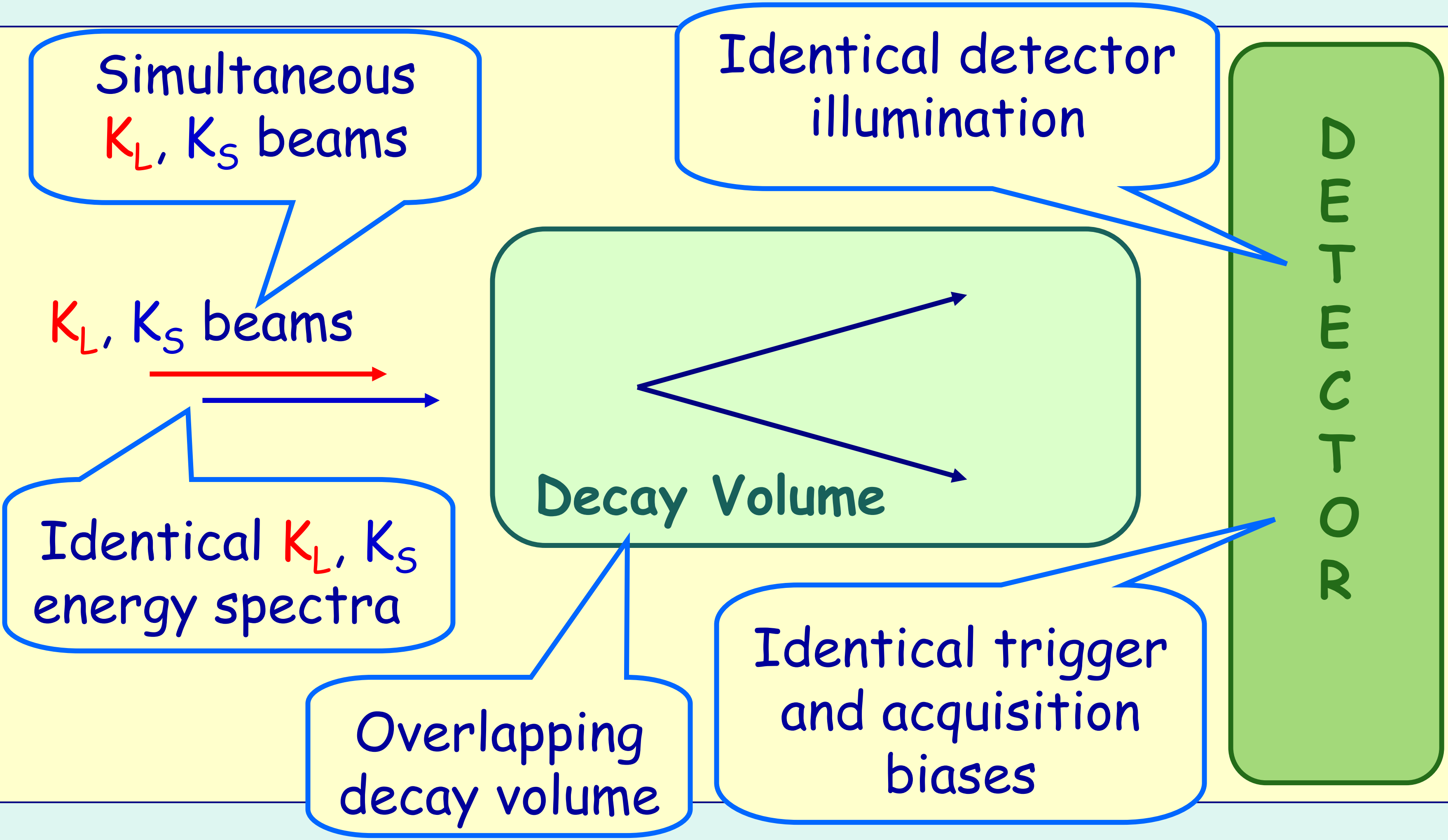
At first order:

- ★ Corrections on R^{meas} (common to either K_L and K_S or $\pi^+\pi^-$ and $\pi^0\pi^0$) cancel out in the double ratio.
- ★ Variation of fluxes, inefficiencies, dead time, accidental losses vanish (simultaneous data taking).
- ★ The amount of residual correction is minimized by weighting the K_L decay distribution to get similar acceptances for K_S and K_L

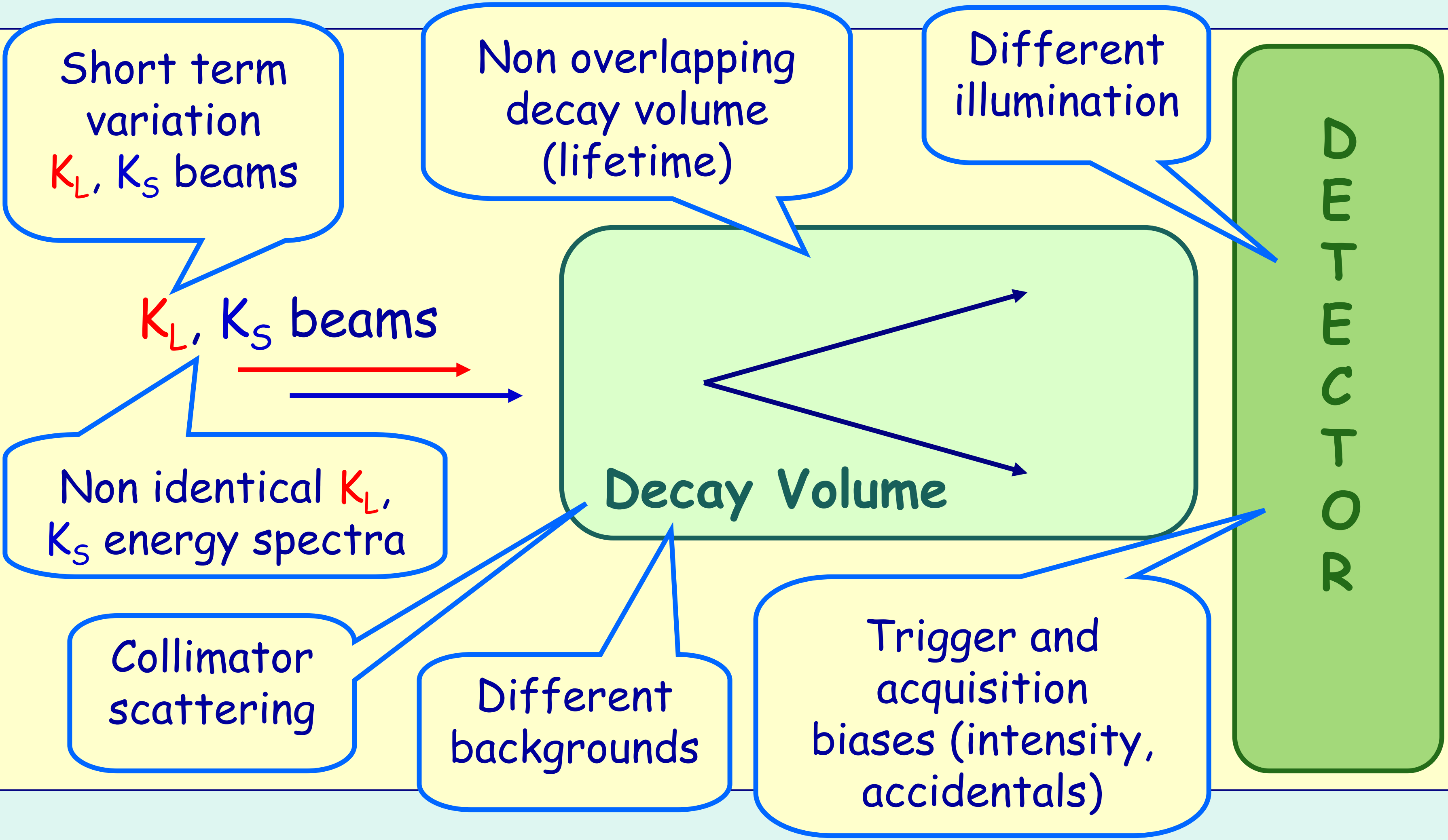
Only **second order effects** must be taken into account

→ need special care

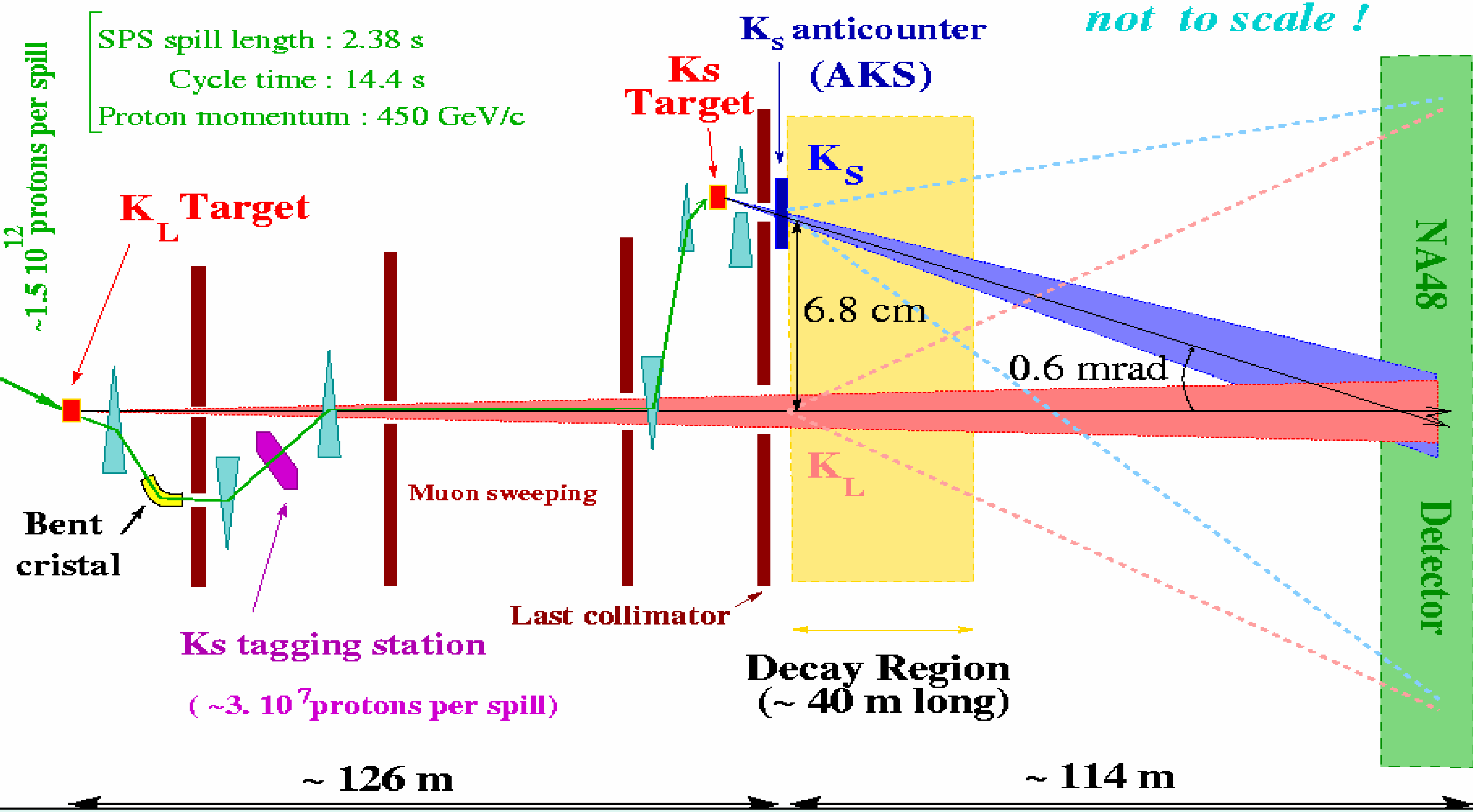
The ideal experiment…



...and the real case



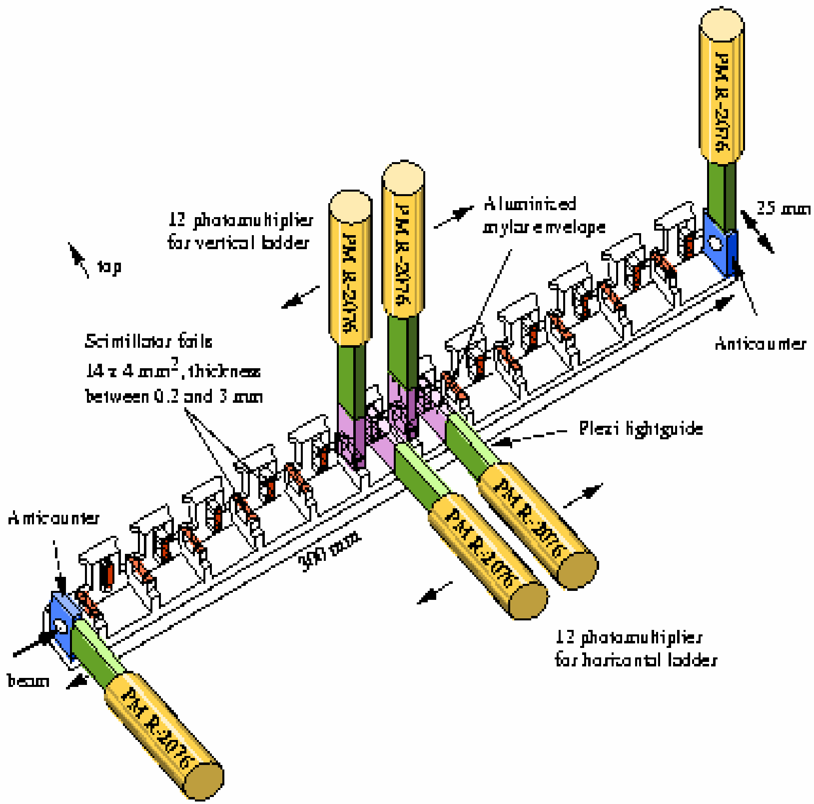
NA48 K_L and K_S beams



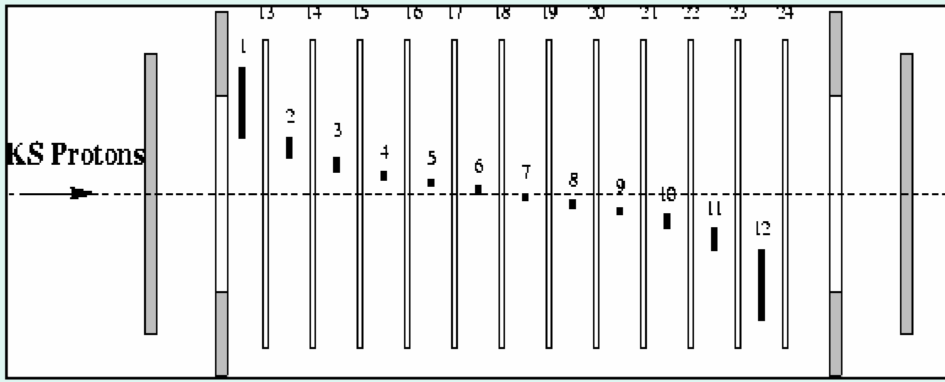
K_S and K_L beams are distinguished by proton tagging upstream of the K_S target

The Tagger

2x12 thin scintillator foils

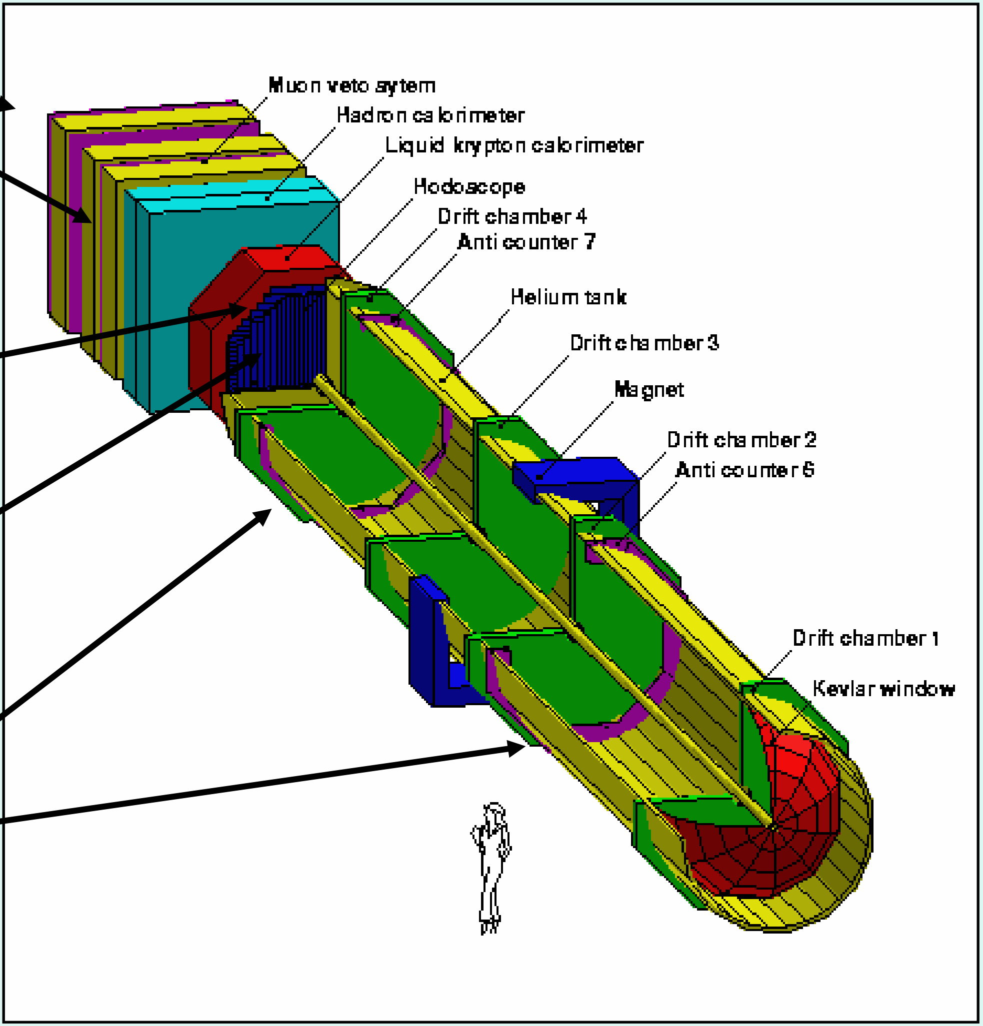


- ⇒ Proton rate ≈ 30MHz → split the intensity between foils, readout by 8 bits Flash ADC at 960 MHz
- ⇒ time resolution : 140 ps
- ⇒ double pulse separation : 4 ns

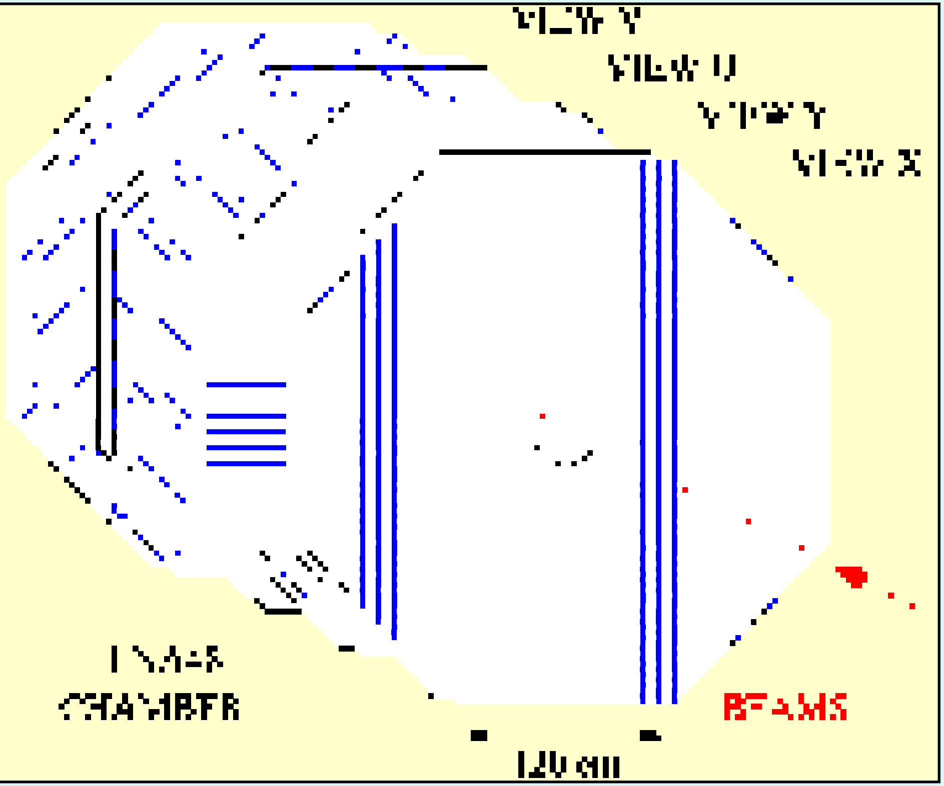


The NA48 Detector

- Muon veto and hadron calorimeter (background, trigger)
- Quasi homogeneous liquid krypton calorimeter to detect $\pi^0\pi^0$ events
- Scintillation hodoscope (trigger and timing $\pi^+\pi^-$)
- Magnetic spectrometer to detect $\pi^+\pi^-$ events



The Magnetic Spectrometer



2 + 2 drift chambers + magnet
→ 265 MeV/c kick

- ★ Good redudancy
- ★ 4 x 2 planes x 256 wires
- ★ Drift time < 100 ns
- ★ Space resolution ≈ 100 μm

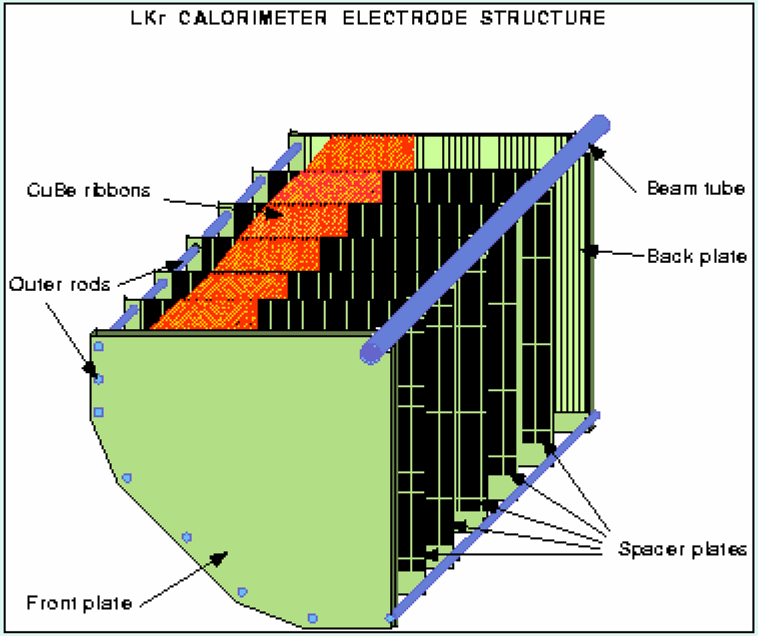
$$\sigma(p)/p = 0.5\% \oplus 0.009\ p[GeV/c]\%$$

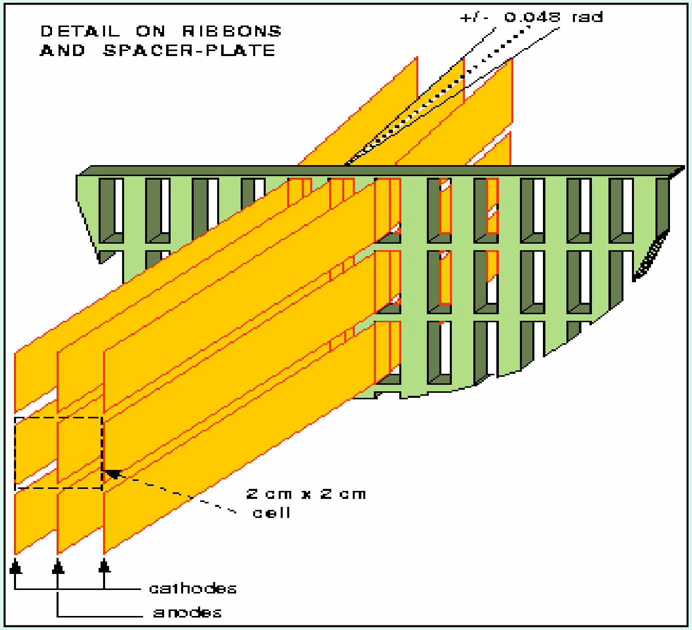
The LKr e.m. calorimeter

- Quasi-homogeneous detector
  10 m^3 liquid krypton (120 K)
  (X_0 = 4.7 cm, R_M = 6.1 cm)
- 13212 cells
- Granularity 2x2 cm^2
- Depth 1.25 m (27 X_0)

LKr geometry

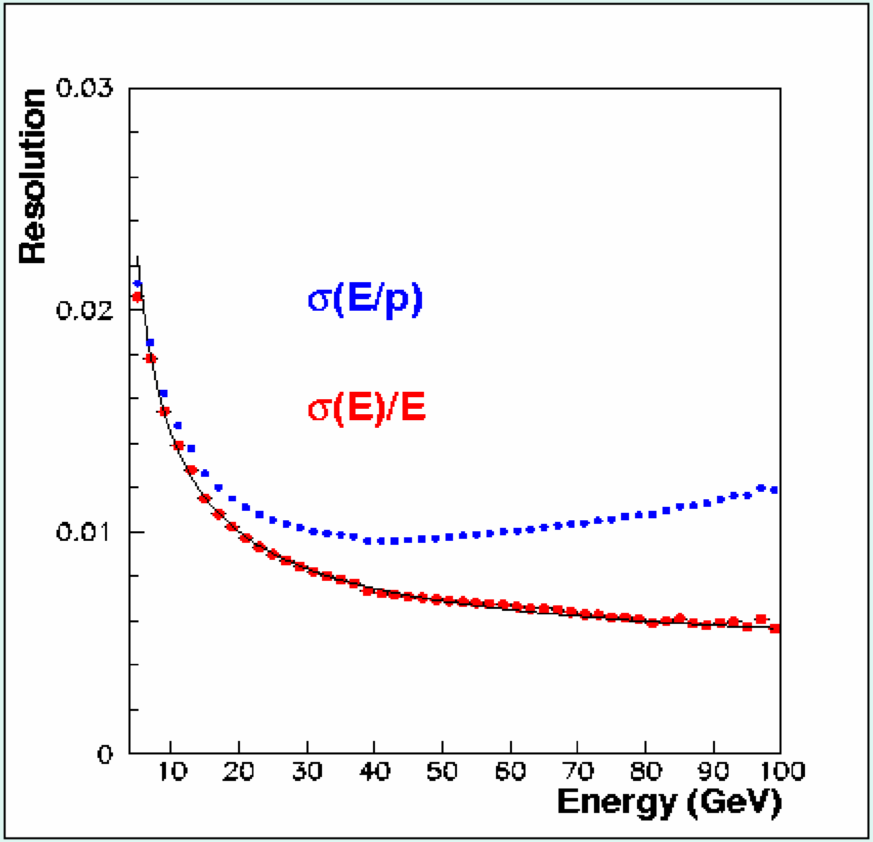
- Projective geometry pointing to decay region (~ 114 m upstream)
- Accordion geometry (± 48 mrad), Cu-Be-Co electrodes
- Initial current read-out





LKr resolution

- Use large sample of $K_L \to \pi e \nu$ to study LKr energy response.
- Compare p from spectrometer and E from calorimeter.



$$\sigma(E)/E \cong 3.2\% / \sqrt{E} \oplus 9\%/E \oplus 0.42\%$$

(E in GeV) (better than 1% for 25 GeV photons)

Trigger / 1

$\pi^+\pi^-$ trigger

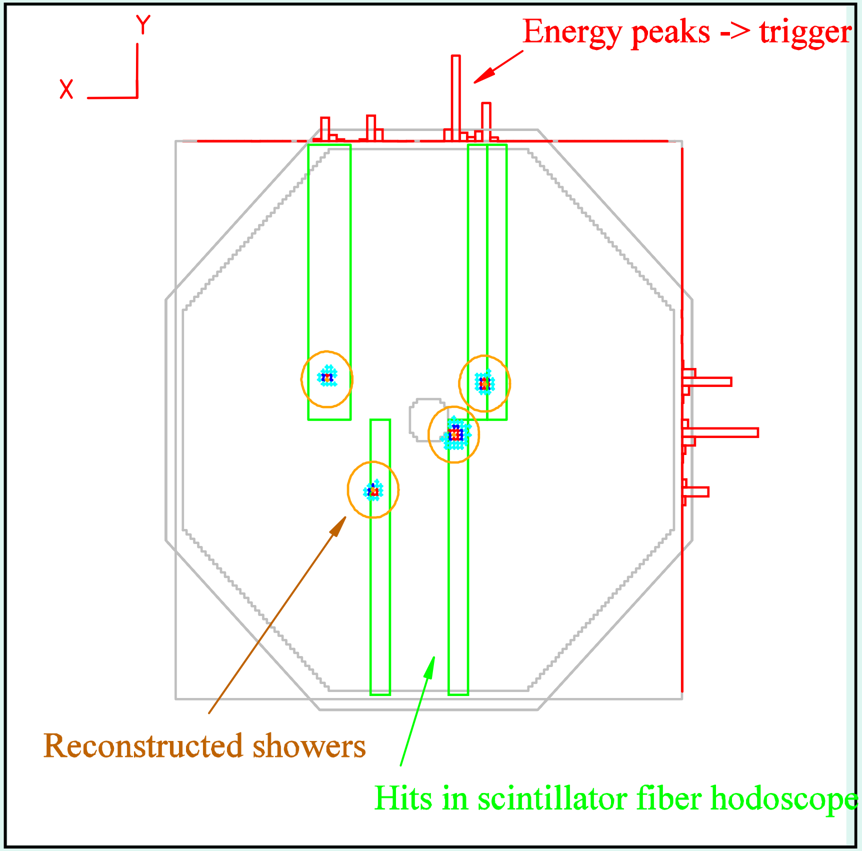
- **Level 1:**
  - Hodoscope + total energy + hits in drift chambers
  - Output rate 100 kHz, dead time 0.5 %
  - Efficiency $(99.535 \pm 0.011)\%$ (evaluated from trigger components)

- **Level 2:**
  - Fast track reconstruction (100 ms) from processors farm
  - Cut on vertex position and invariant mass
  - Output rate 2kHz, dead time 1.1%
  - Efficiency $(98.353 \pm 0.022)\%$ (from Level 1 triggers)

Trigger / 2

$\pi^0\pi^0$ trigger

- Based on LKr information summed into projections
- Cuts on total energy, decay vertex and number of photons
- Fully pipelined (3μs), no dead-time, 2 kHz
- Efficiency (99.920±0.009) % (from auxiliary trigger, NHOD)
- Negligible K_S to K_L (weighted) difference



Analysis

- Reconstruct and count $\pi^+\pi^-$ and $\pi^0\pi^0$ decays
- Disentangle K_S from K_L using tagging
- Subtract the remaining background
- Evaluate corrections and systematics
- Checks and stability of the result

!!!All given effects are on the double ratio!!!

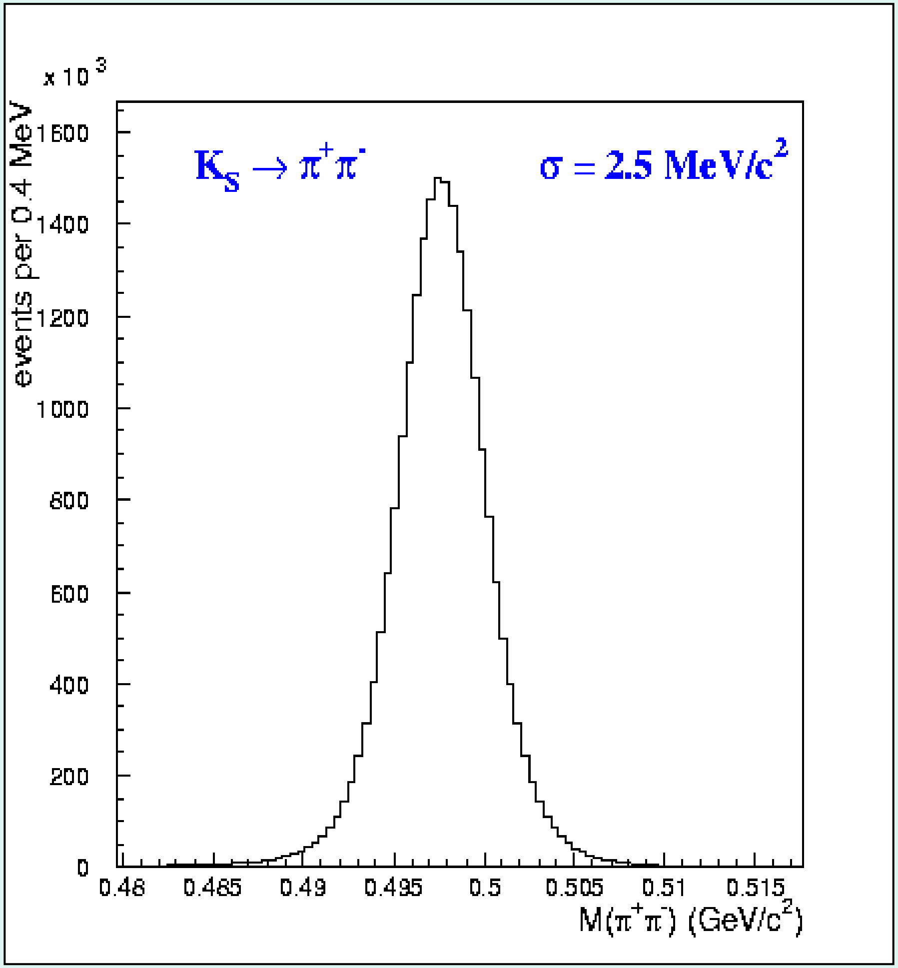
$$Re(\varepsilon'/\varepsilon) = (1-R)/6$$

$$\sigma(Re(\varepsilon'/\varepsilon)) = \sigma(R)/6$$

$\pi^+\pi^-$ sample

$K_S, K_L \rightarrow \pi^+\pi^-$

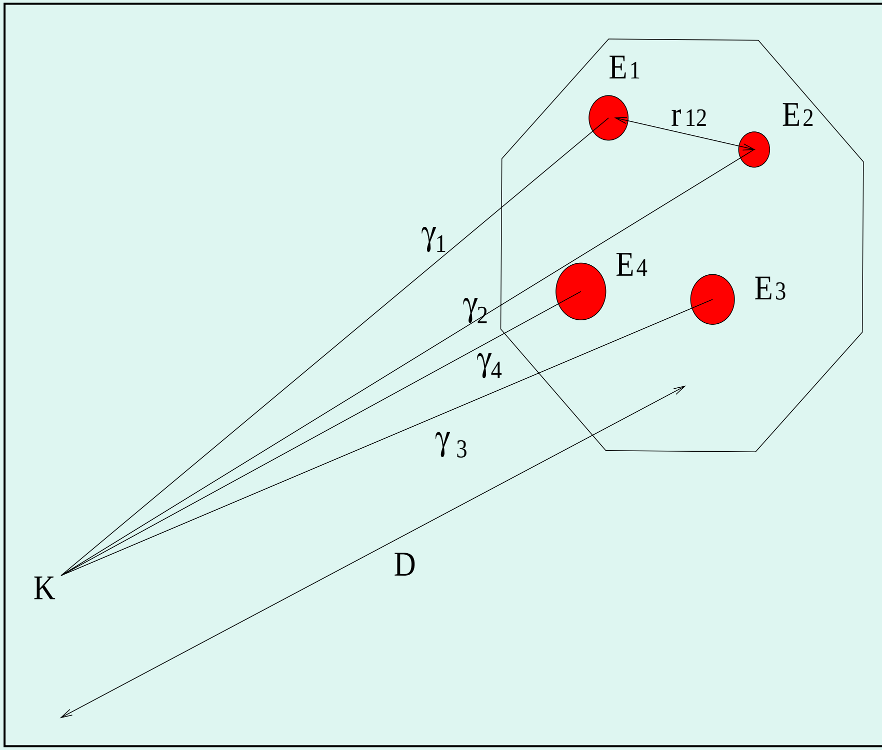
- Decay vertex and $M(\pi\pi)$ reconstructed by the spectrometer
- Decay time from the hodoscope (σ = 140 ps)



$\pi^0\pi^0$ sample

$K_S, K_L \rightarrow \pi^0\pi^0$

- E_i x_i and y_i of the four photons reconstructed in the LKr ➡ two $M(\gamma\gamma)$ and decay vertex
- Decay time from the LKr calorimeter (σ = 200 ps)



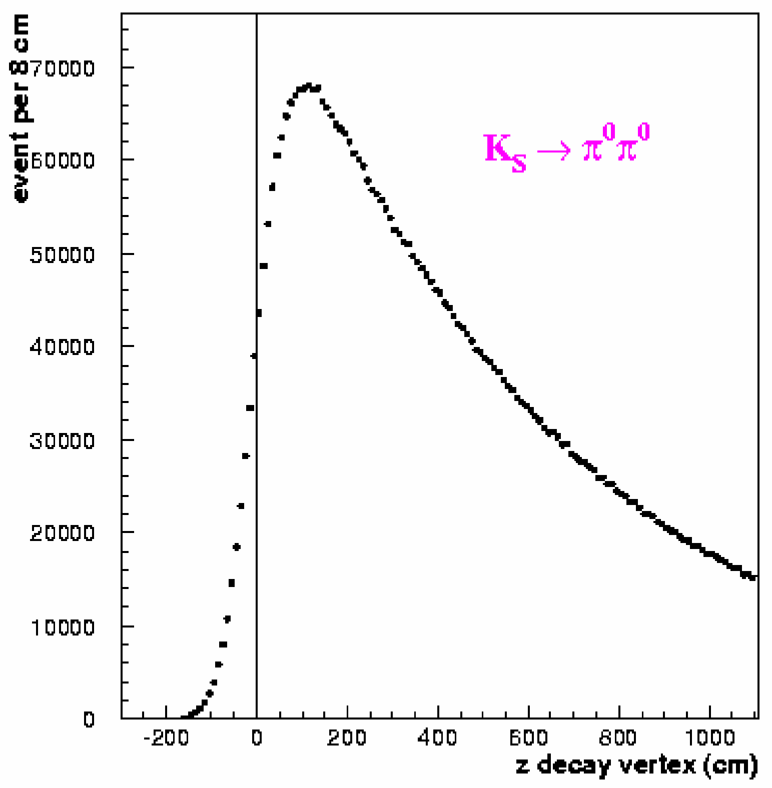
$$D = z_{LKr} - z_{decay} = \sqrt{\sum_{ij} E_i E_j r_{ij}^2} / M_K$$

Reconstruction

- In $\pi^+\pi^-$ case depends on chamber geometry
  - z position ≅ 1 mm
  - transverse scale ≅ 100 μm/m
- In $\pi^0\pi^0$ case depends on calorimeter geometry
  - transverse scale ≅ 100 μm/m

  and energy scale

Adjust energy scale to fit the known position of the AKS anticounter



1 cm of reconstruction error
⇒ 1×10^{-4} on energy scale and R

K_L-K_S identification

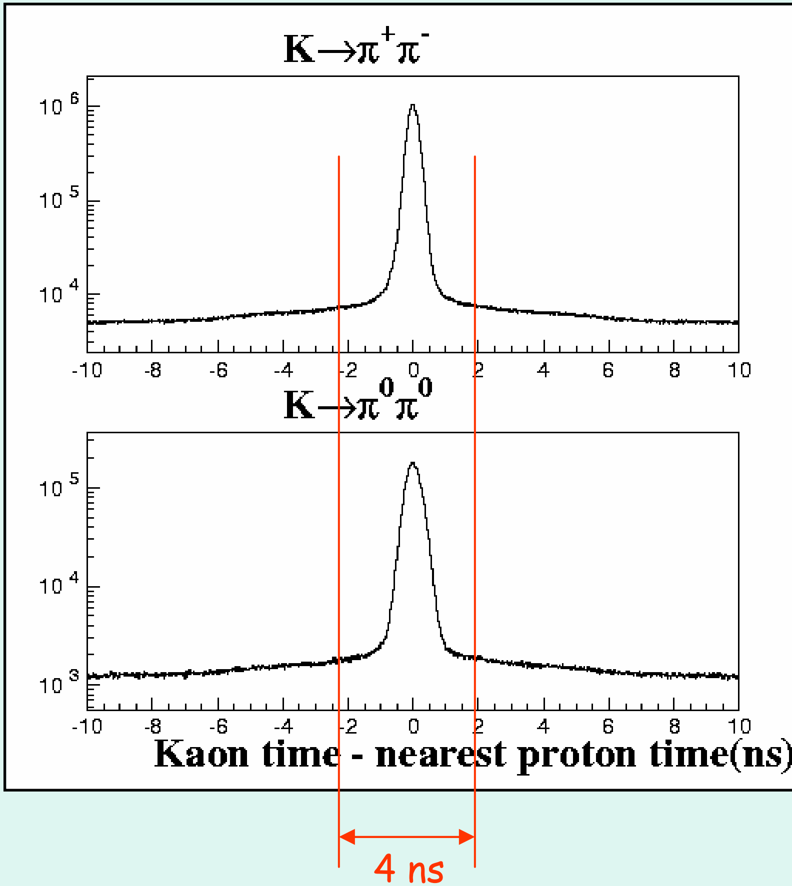
In both decay modes

K_S are tagged by comparing the event time to proton times as they pass through the tagging station

Δt (Kaon-proton)

≤ 2 ns $\Rightarrow$ K_S

> 2 ns $\Rightarrow$ K_L



Tagging errors

Two possible kind of mistakes

-K_S mistagged as K_L : probability α_{SL}

Due to inefficiency in time measurement by tagger counter or main detector (trigger hodoscope or calorimeter): α_{SL}^{+-} and α_{SL}^{00}

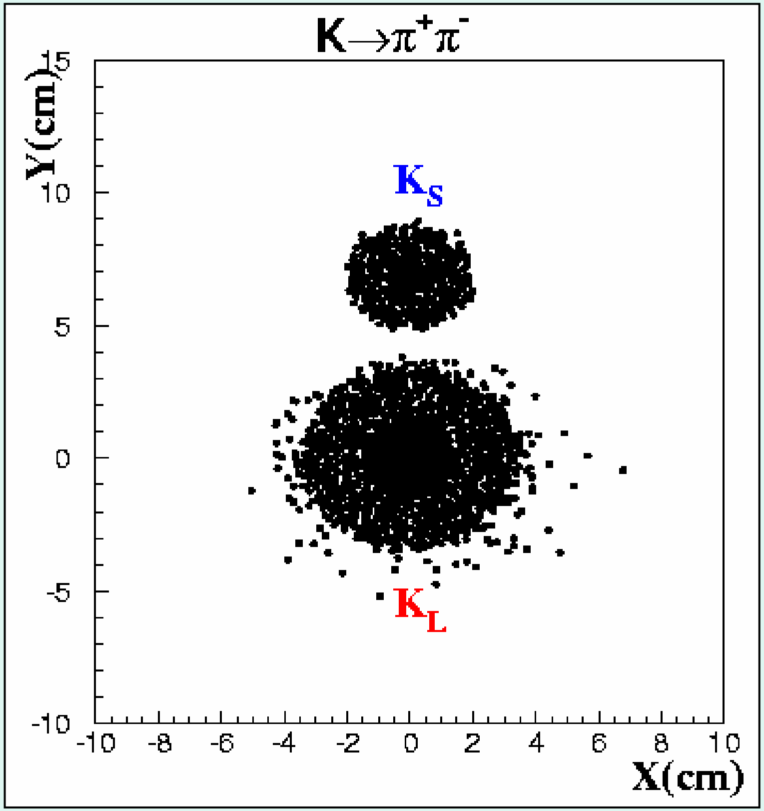
-K_L mistagged as K_S : probability α_{LS}

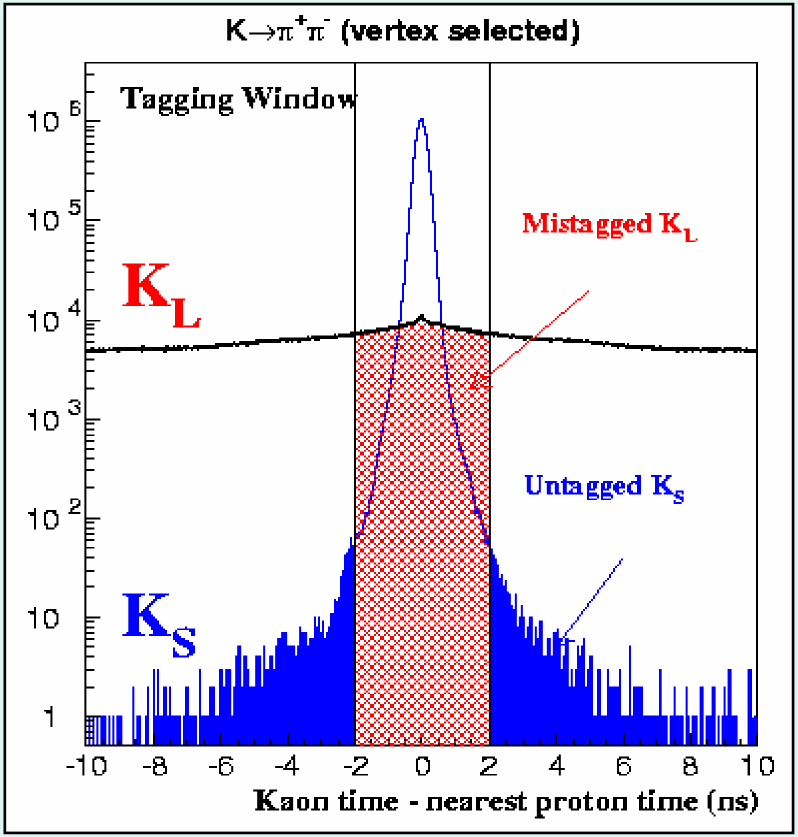
Due to accidental coincidence between K_L decay and a proton in the tagger - approximately symmetric between $\pi^+\pi^-$ and $\pi^0\pi^0$ because of simultaneous data taking: α_{LS}^{+-} and α_{LS}^{00}

α_{SL}^{+-} and α_{LS}^{+-} can be measured reconstructing the decay vertex with the tracking chambers

Double ratio → difference between neutral and charged modes

Tagging $\pi^+\pi^-$ events





Identify K_S, K_L with decay vertex position in transverse plane

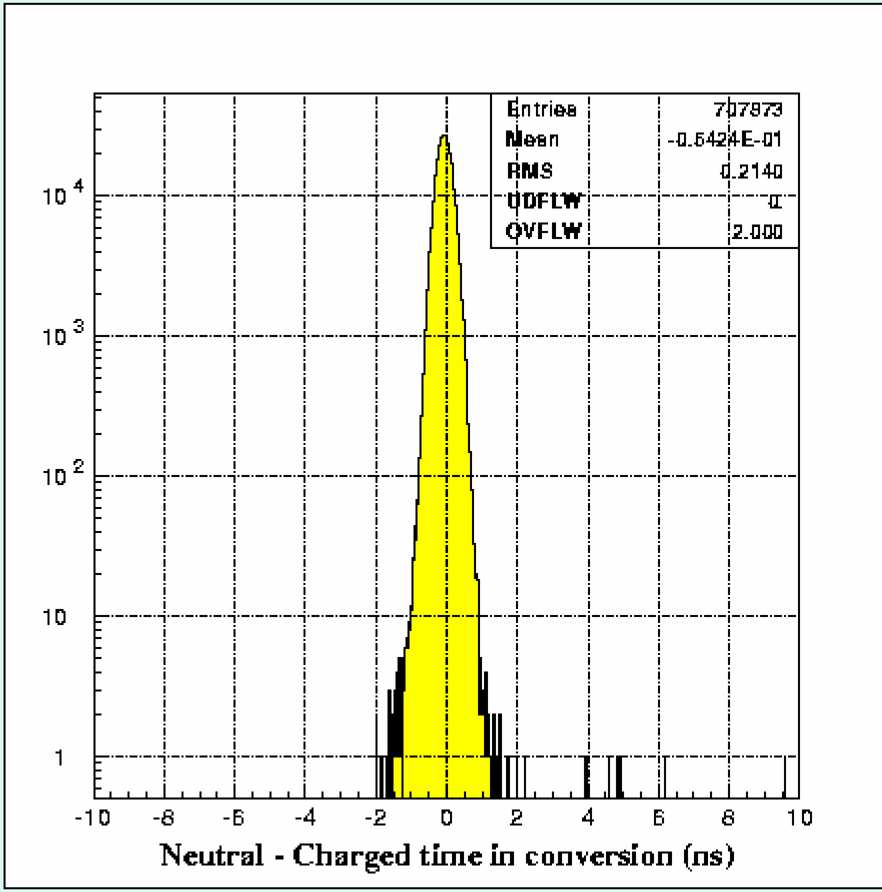
$\alpha_{SL} = (1.63 \pm 0.03)\ 10^{-4}$

$\alpha_{LS} = (10.649 \pm 0.008)\%$

Measuring $\Delta\alpha_{SL}$

- Compare the time measured by calorimeter and hodoscope in events where both are available: $2\pi^0$ and $3\pi^0$ decays
  - Dalitz decays of π^0
  - γ conversions in vacuum window

Tails < 0.5×10^{-4}

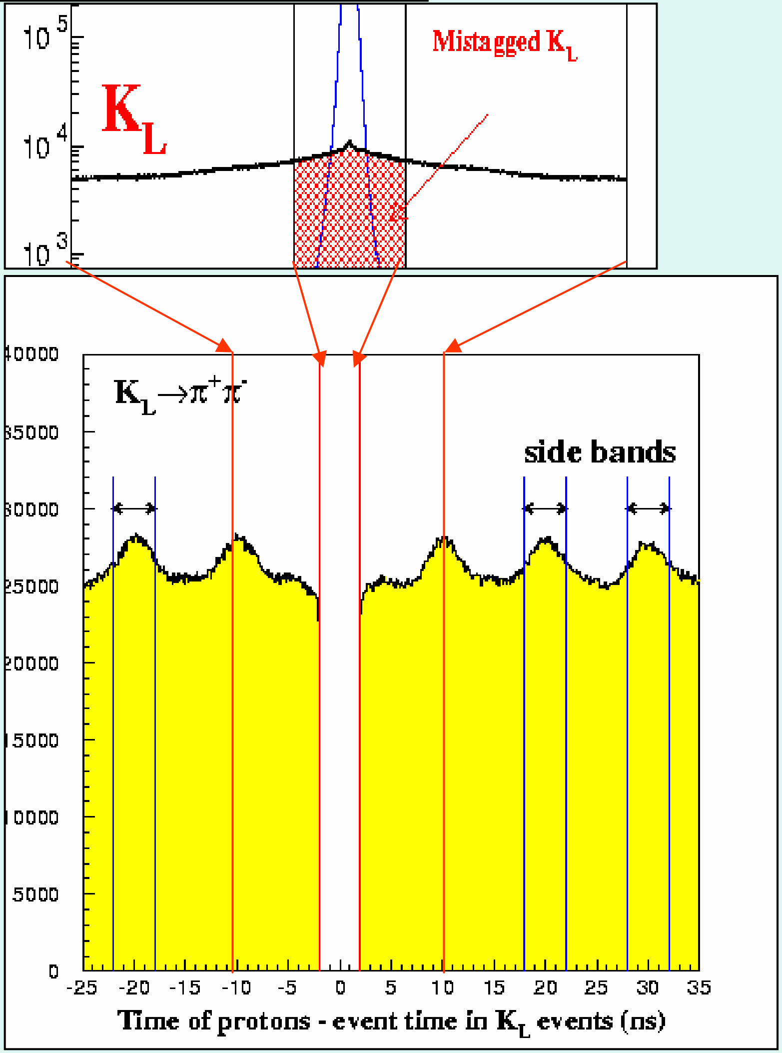


→ most of the tails in $\pi^+\pi^-$ tagging coincidence are due to the tagger

they are equal in $\pi^+\pi^-$ and $\pi^0\pi^0$

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

Measuring $\Delta\alpha_{LS}$



For events tagged as K_L (no proton in the central window)

→ measure $\Delta\alpha_{LS}$ using coincidence rate in tagging windows offset from the event time ("sidebands")

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

Charged background

- K_S – no background
- K_L – main background

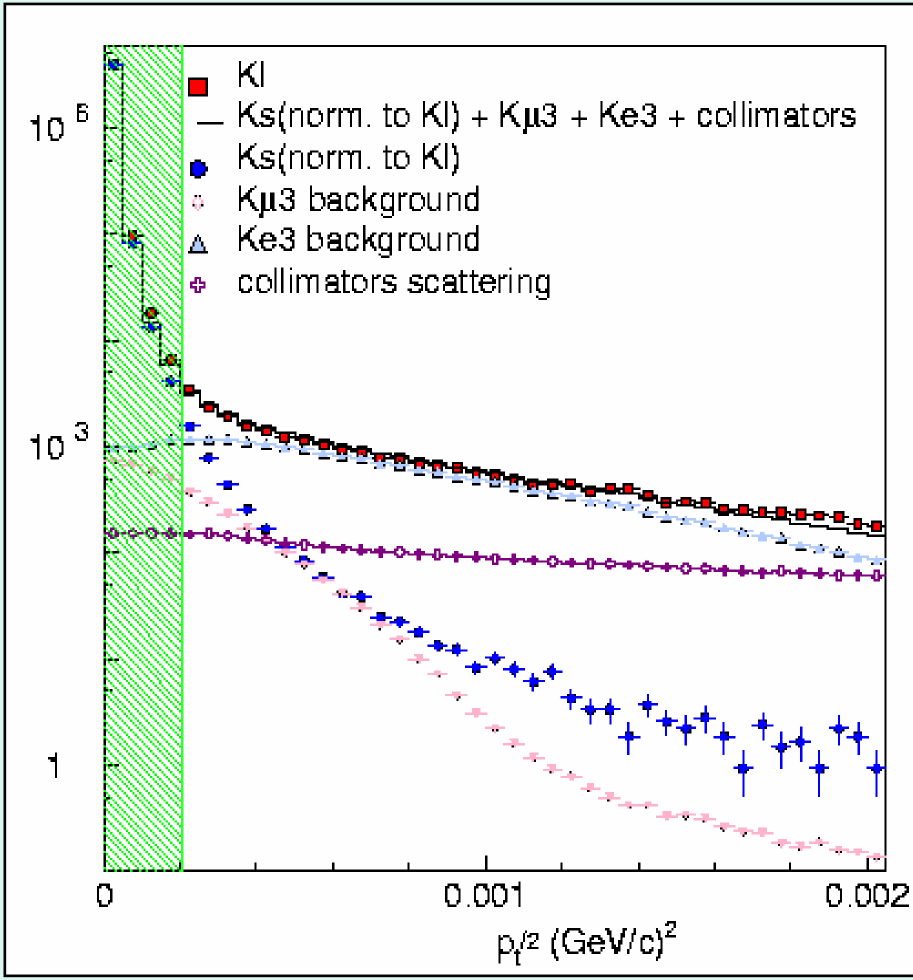
  $K_L \to \pi e \nu, \pi \mu \nu$

★ Rejected by:

- Requiring E/p < 0.8
- no hits in muon veto
- cutting in invariant mass and transverse momentum

★ Rest subtracted:

- using control regions in $m_{\pi\pi}$ - $p_t'^2$ distribution

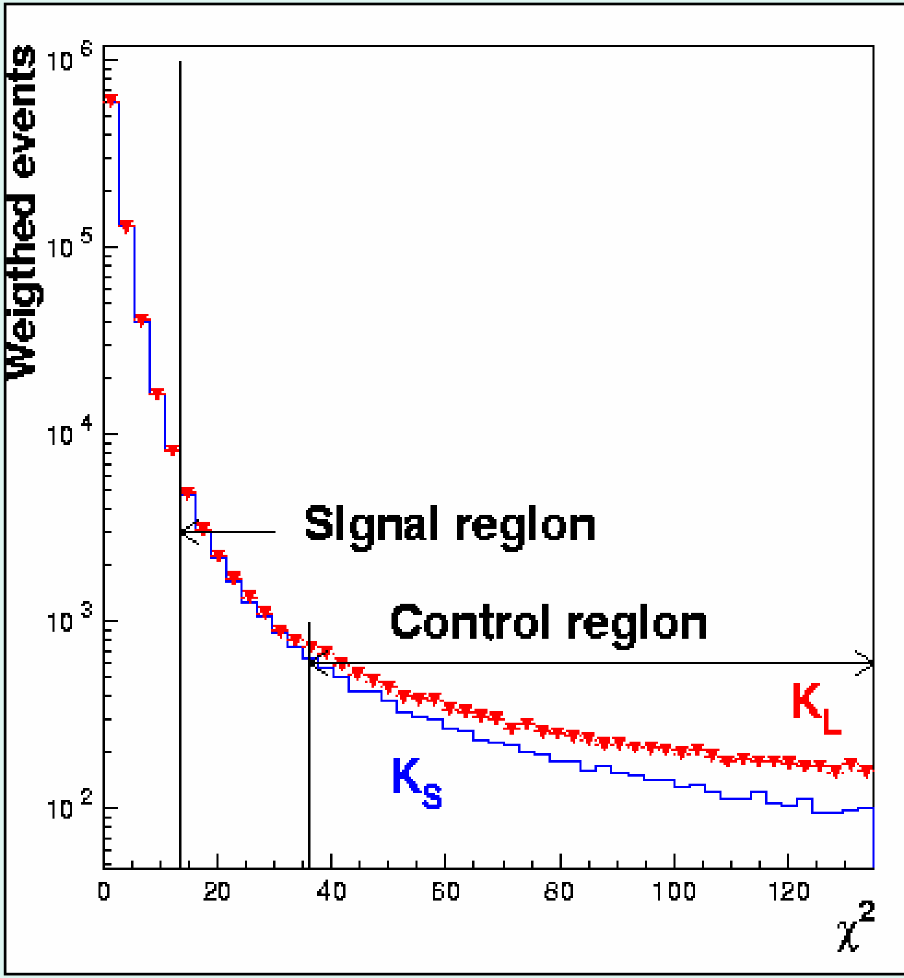


Neutral background

- K_S – no background
- K_L – main background
  $K_L \to 3\pi^0$

★ Rejected by:
- Requiring no extra showers in time (1.5 ns)
- χ^2 from the two π^0 masses < 13.5

★ Rest subtracted:
- Extrapolating from χ^2 control region



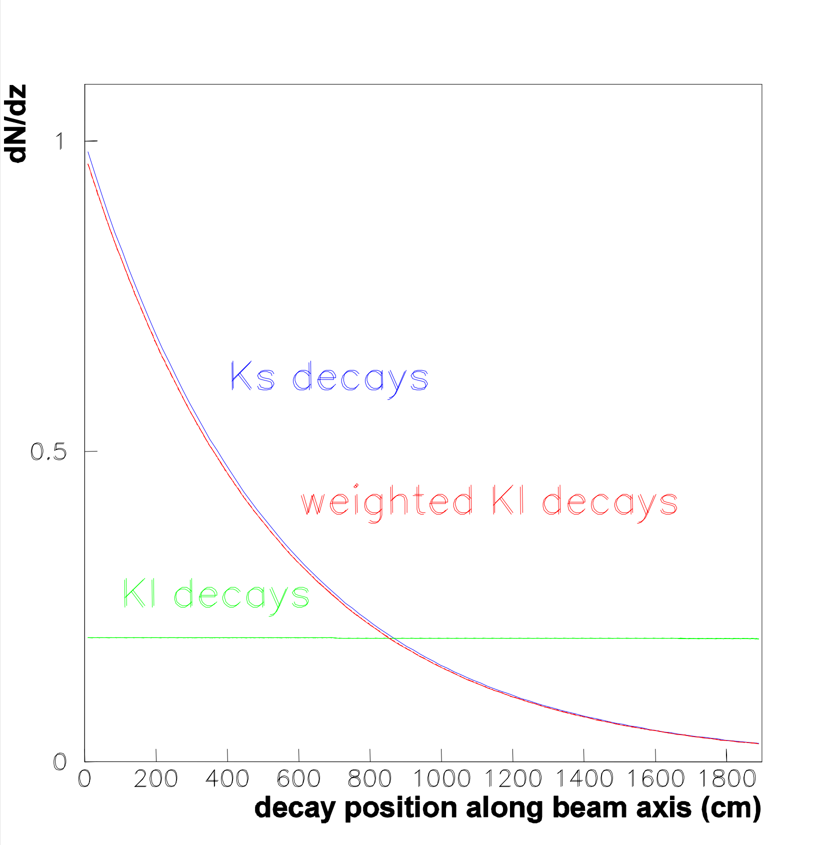
Lifetime weighting

At any given z:
acceptance $K_S \cong$ acceptance K_L
BUT ⟹ K_S and K_L have very different
decay lenghts $\tau_{KL} = 600 \times \tau_{KS}$

different acceptances for K_S and K_L
and large correction on R

SOLUTION: weight K_L events with
$$W = e^{-z/(\beta\gamma c)(1/\tau_S - 1/\tau_L)}$$

same decay vertex distribution
for K_S and weighted K_L



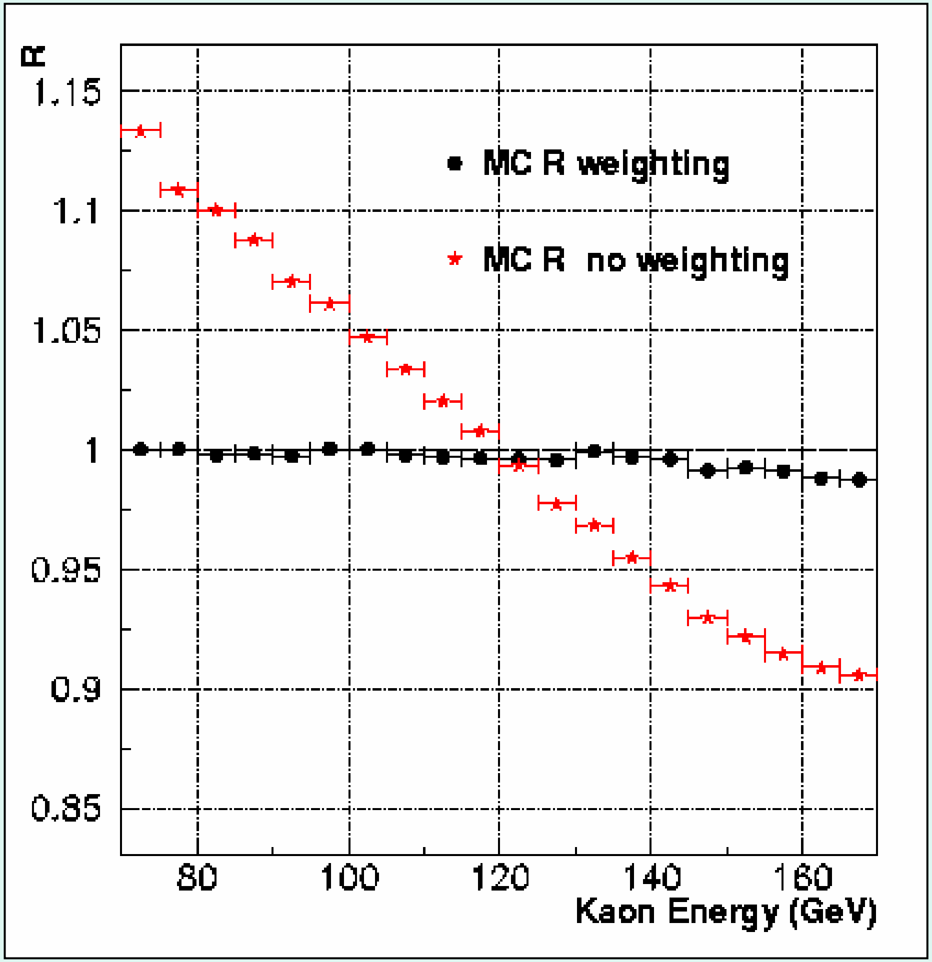
Acceptance correction cancels at the price of an increase of the statistical error (35 %)

Acceptance correction

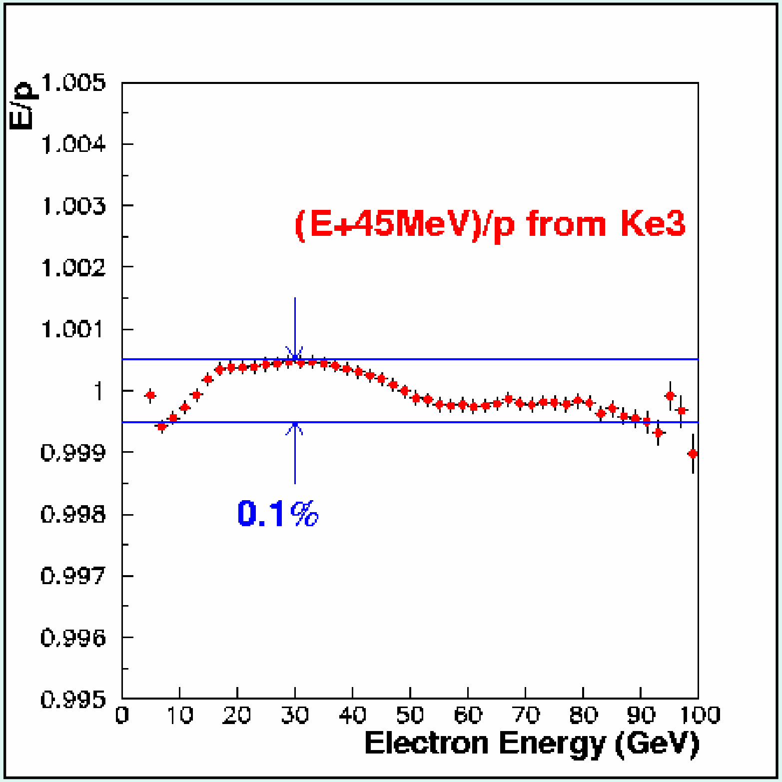
★ Small due to symmetric illumination
→ consequence of proper time weighting

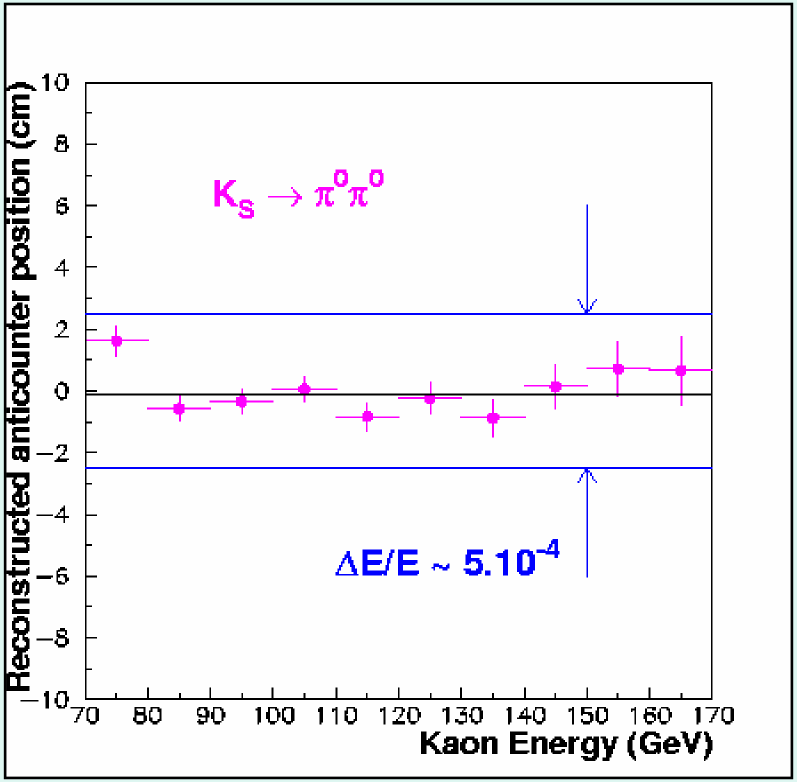
★ Small residual effects from 0.6 mrad angle between K_S and K_L beams

★ Correction estimated using Monte Carlo



Linearity checks





Electrons from Ke3 decays :

E/p constant within ≈ 0.1%

between a few GeV and 100 GeV

Overall check :

Reconstructed AKS position

independent of kaon energy

Systematic uncertainties

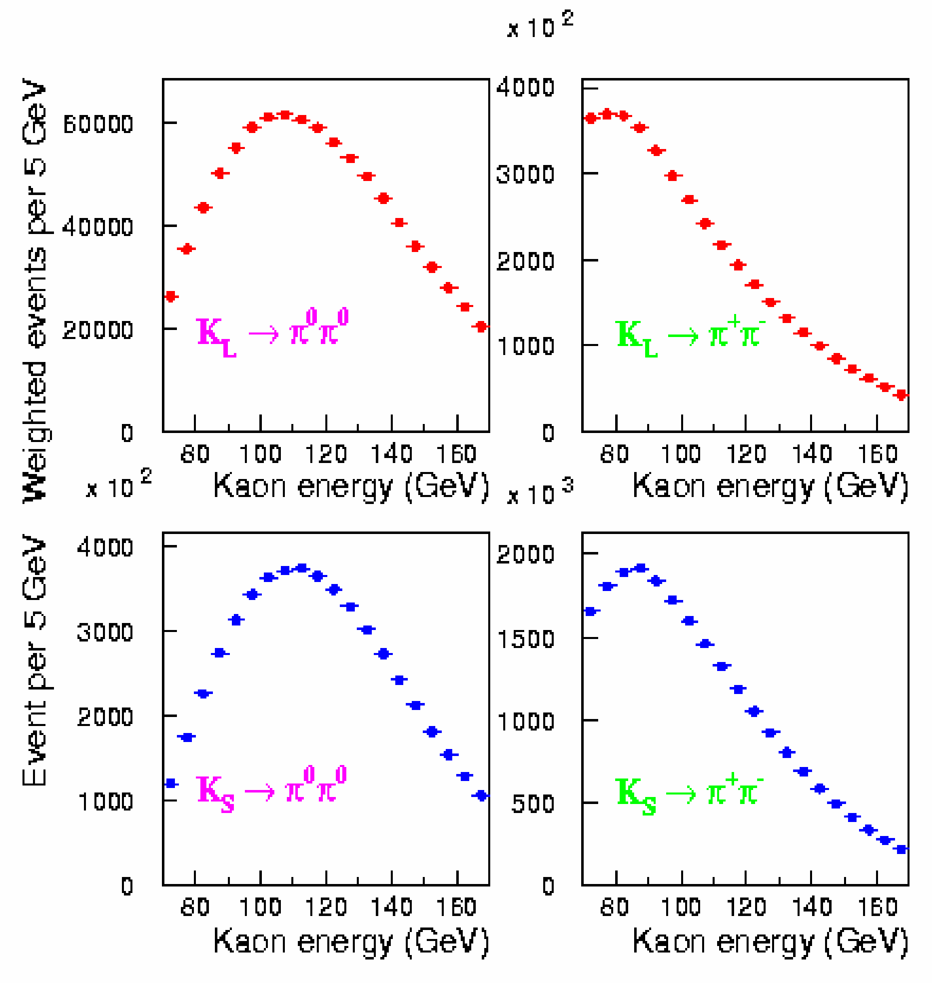
	$\Delta(R)$ (in 10^{-4} units)
background	1.4 $\pm$ 4.1
tagging errors	8.3 $\pm$ 4.5
geometrical/energy scale, linearity	2.0 $\pm$ 6.4
trigger/AKS efficiency	-2.5 $\pm$ 5.2
acceptance correction	26.7 $\pm$ 6.2
accidental losses	$\pm$ 4.4
Total	35.9 $\pm$ 12.6

Some uncertainties include a statistical component (trigger efficiency, tagging, acceptance …), contributing $\pm$ 8 to the total error above

Final Analysis

- Measure R in Kaon energy bins (5 GeV wide)
  $\Rightarrow$ insensitive to K_S–K_L difference in energy spectrum
- Apply lifetime weighting to K_L
- Record dead time conditions
  - 1.5% from $\pi^+\pi^-$ trigger
  - 21.5% from drift chamber multiplicity limit
  - apply them offline to $\pi^0\pi^0$ too
- Minimize effect of K_S–K_L beam intensity difference

Energy spectrum

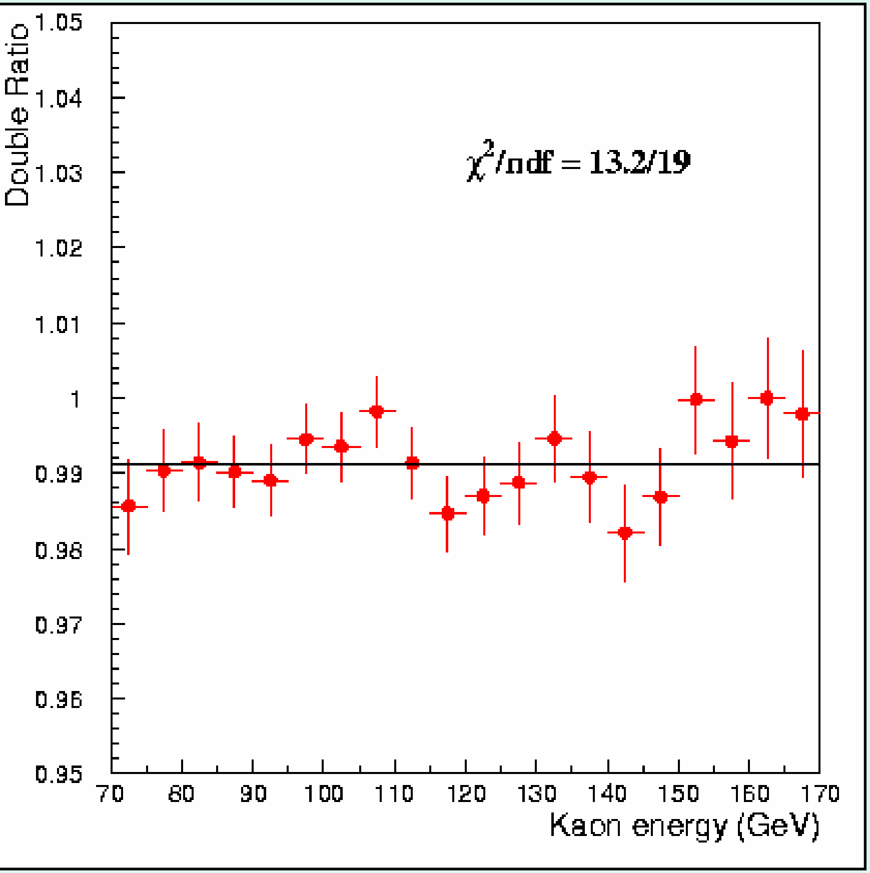


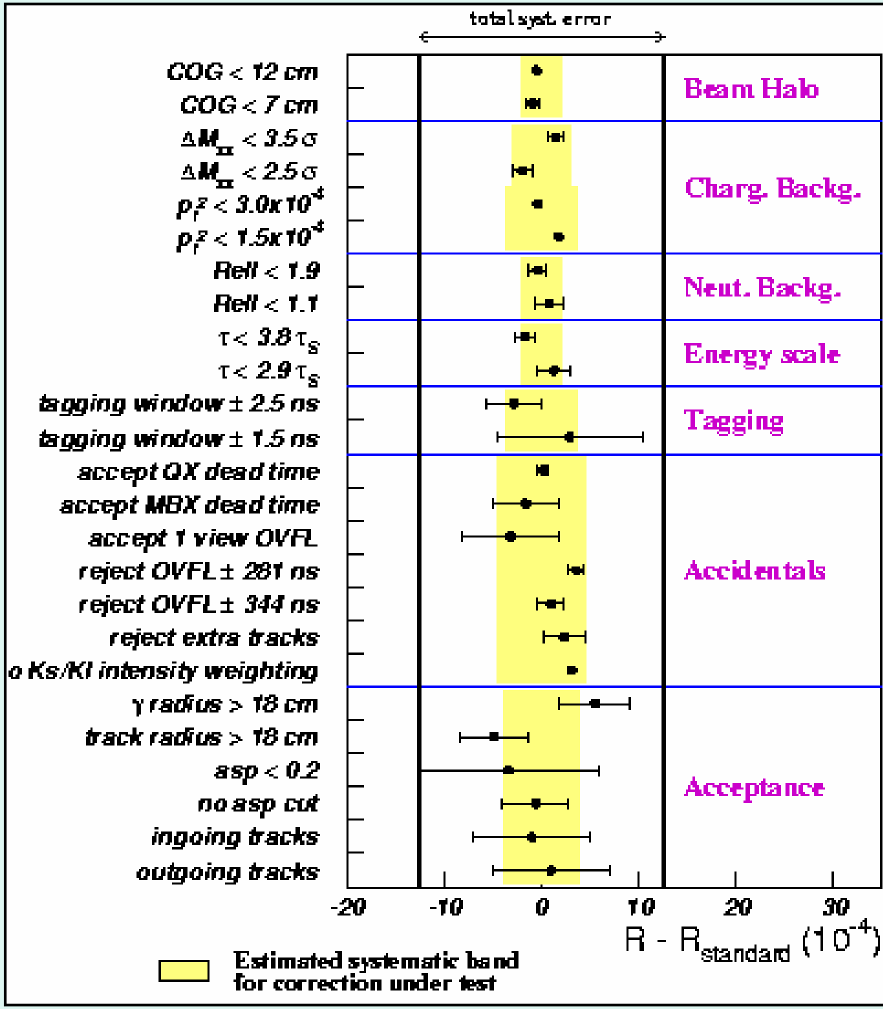
Event statistics :

- $K_L \to \pi^0\pi^0$: 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

Result and checks

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





The Result

From 98 and 99 data

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

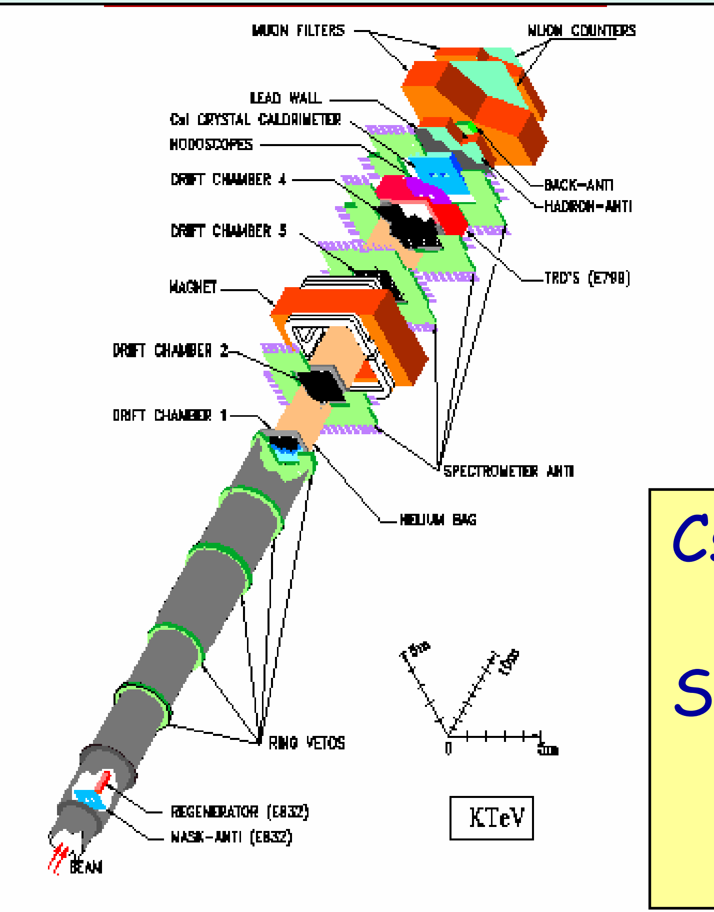
combined with
from 97 data

$$\mathrm{Re}\,(\varepsilon'/\varepsilon) = (18.5 \pm 7.3) \times 10^{-4}$$

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

Direct CP Violation established at 5.9 σ

KTeV @ Fermilab



Vacuum" beam $\rightarrow K_L$ beam

Regenerator" beam $\rightarrow K_L + \rho K_S$ beam

- Detector similar to NA48 but not identical
- Same method (double ratio) to measure R

CsI Calorimeter:

$\sigma(E)/E \cong 2.0\%/\sqrt{E} \oplus 0.45\%$

Spectrometer (p_T kick ~400 MeV/c):

$\sigma(p)/p \cong 0.17\% \oplus 0.007\ p[GeV/c]\%$

$\sigma_M(\pi^0\pi^0) \sim \sigma_M(\pi^+\pi^-) \sim 1.5$ MeV

KTeV - beams

Two parallel K_L beams. One of them goes through a movable (once per minute) "regenerator" creating a K_S component

What is the regenerator?

A series of plastic scintillator blocks ($2\lambda_I$)

Because of their different quark content K^0 and $\bar{K}^0$ have different nuclear cross-section and their initial mixture is modified when going through the matter

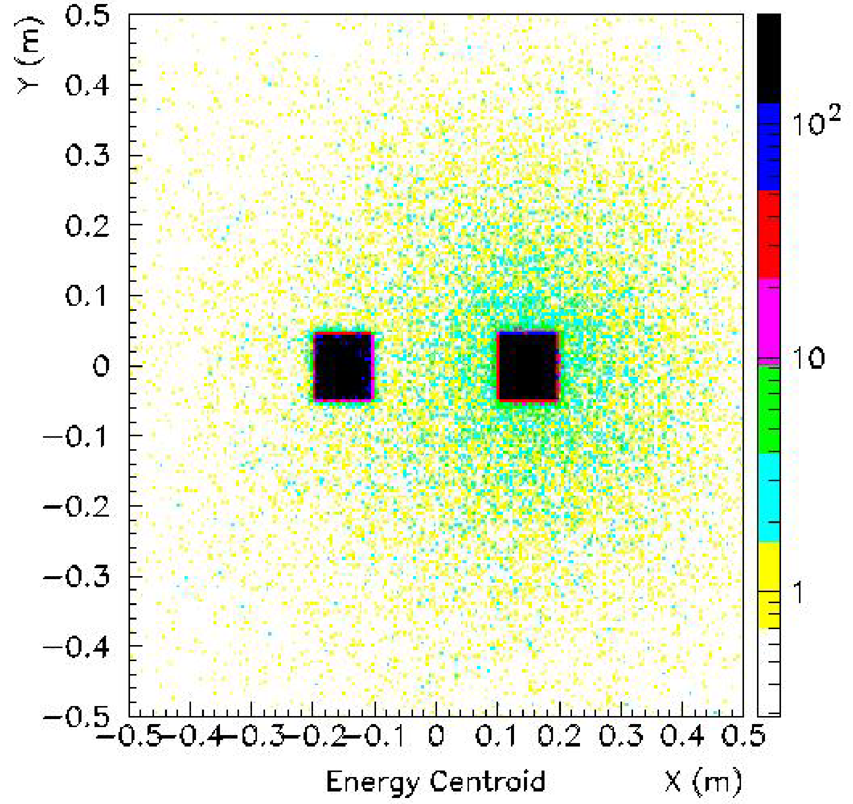
At the end of the block the initial pure K_L beam is regenerated to $K_L+\rho K_S$

KTeV - tagging K_S

- K_S are tagged using the position in the detector (vac & reg beams are parallel and 10cm apart)

$\pi^+\pi^-$ reconstructed x-y vertex position

$\pi^0\pi^0$ energy centroid in the CsI



KTeV - acceptance

➡ NA48 uses proper time weighting

➡ KTeV uses detailed MC predictions of the acceptance of each beam to correct data.

➡ The correction is large but mainly due to detector geometry

KTeV - results

June 2001

Anounced a revised result based on the 96 data

$$Re\,(\varepsilon'/\varepsilon) = (23.2 \pm 4.4) \times 10^{-4}$$

it was: $(28.0 \pm 4.1)\times 10^{-4}$

And a new result on part of 97 data

$$Re\,(\varepsilon'/\varepsilon) = (19.8 \pm 2.9) \times 10^{-4}$$

New average

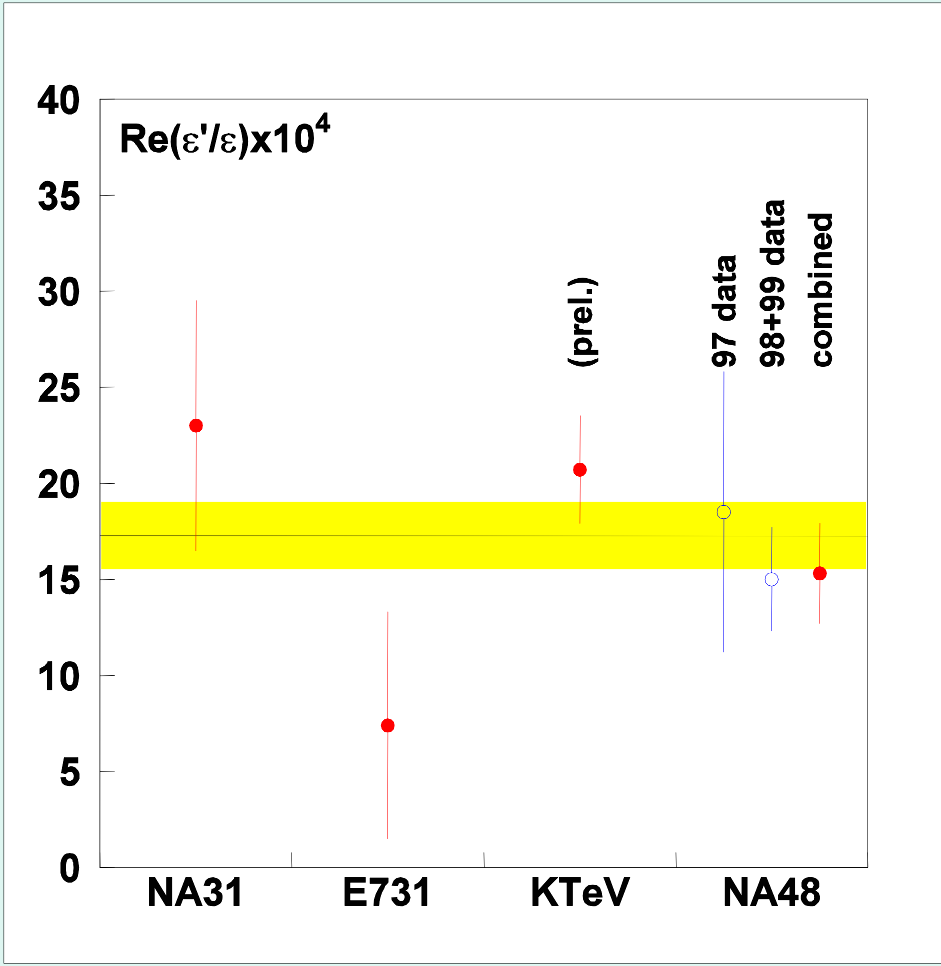
$$Re\,(\varepsilon'/\varepsilon) = (20.7 \pm 2.8) \times 10^{-4}$$

Experimental result comparison

New world average

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

With $\chi^2/ndf = 5.7/3$ (17% prob.)



Conclusions

After many years

Direct CP Violation has been established

- ➢good agreement between experiments
- ➢Hopefully KLOE will join

CP Violation larger than expected

BUT cannot explain Matter-Antimatter asymmetry observed in the Universe

...after 1999

- Year 2000
  - ★ No ε'/ε data (implosion of beam pipe)
- Year 2001
  - ★ New spectrometer
  - ★ Different beam conditions
    - ★ 97-99 2.4 s every 14.4 s (E_p = 450 GeV)
    - ★ 2001 5.2 s every 16.8 s (E_p = 400 GeV)
  - ★ Collected 1.4×10^6 K_L $\pi^0\pi^0$
  - ★ Complete statistics and verify result under different conditions

Rare decays

Summary of recent rare decay results

$K_S \to \gamma\gamma$	BR $(2.58 \pm 0.36_{stat} \pm 0.22_{sys}) \times 10^{-6}$
$K_S \to \pi^0 e^+ e^-$	BR < 1.4×10^{-7} at 90% CL
$K_S \to \pi^+\pi^- e^+ e^-$	BR $(4.3 \pm 0.2_{stat} \pm 0.3_{sys}) \times 10^{-5}$
	A $(-0.2 \pm 3.4_{stat} \pm 1.4_{sys})$ %
$K_L \to \pi^+\pi^- e^+ e^-$	BR $(3.1 \pm 0.1_{stat} \pm 0.2_{sys}) \times 10^{-7}$
	A $(13.9 \pm 2.7_{stat} \pm 2.0_{sys})$ %
$K_L \to \pi^0\gamma\gamma$	BR $(1.36 \pm 0.03_{stat} \pm 0.03_{sys}) \times 10^{-6}$

NA48 future

Two new programs have been approved by the CERN Research Board :

- A high sensitivity investigation of K_S and neutral hyperon decays using a modified beam (NA48/I, 2002)
- A precision measurement of charged kaon decay parameters with an extended NA48 setup (NA48/II, 2003)

NA48 / I

- High intensity K_S beam (factor 160)
- 80 days scheduled (-25% CERN budget)
- Physics interest
  - $K_S \to \pi^0 e^+ e^-$ (th. 5×10^{-9}, expected 7 events)

    Bound the indirect CPV component of $K_L \to \pi^0 e^+ e^-$
  - CPV in $K_S \to \pi^0\pi^0\pi^0$ (η^{000})
  - Non leptonics K_S decays (χPT)
  - Neutral hyperon decays

NA48 / II

- New K^+ and K^- simoultaneous beams
- New TRD for π/e separation
- Physics interest
  - ★ Direct CP Violation in $K^{\pm} \rightarrow 3\pi$ measured through the difference in K^+/K^- decay matrix elements (asymmetry)
  - ★ Charged Ke4 decays to test the hypotesis of strong qq condensate in QCD vacuum
  - ★ Measurement of rare charged kaon decays

Final conclusions

- ★ Direct CPV in the neutral kaon system established
- ★ Rare decay program → very interesting physics in the field of χPT and CP (kaons and hyperons)
- ★ Two new addenda approved (HI-K_S and $K^{\pm}$)

Kaon Physics still provides remarkable results