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The measurement of Direct CP Violation with the experiment CERN/NA48

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The NA48 collaboration: Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Vienna, Warsaw

Outline

- Direct CP violation in K^0 system and ε'/ε .
- How to measure ε'/ε ?
  NA48 method and setup
- Data analysis:
  - analysis overview
  - highlights of some key features
- Result (May 2001)
- New result from KTeV (June 2001)

CP Violation in $K^o \to \pi\pi$

CP Violation in the neutral kaon system is dominated by states mixing . Mass eigenstates (K_S and K_L) are not pure CP eigenstates (K_1 and K_2) :

$K_S = K_1 + \varepsilon K_2$ (K_1 : CP= +1, $\to \pi\pi$ dominantly)

$K_L = K_2 + \varepsilon K_1$ (K_2 : CP= -1, $\to \pi\pi\pi, \pi\ell\nu$ ...)

Indirect CP Violation, or $|\varepsilon| = (2.28 \pm 0.02)\ 10^{-3}$, is the main cause of $K_L \to \pi\pi$ decays

Is there also a component of Direct CP Violation in the decay process itself? That is, are there decays: $K_2 \to \pi\pi$?

This would imply: $|A(K^0 \to \pi\pi)|^2 \neq |A(\overline{K}^0 \to \pi\pi)|^2$

This requires the combination of two amplitudes, with **different phases in the weak couplings**, and different final state phases due to strong interaction between the decay products.

In the decay probability, the interference term would generate Direct CP Violation (because the weak phases change sign between CP conjugate states)

Direct CP Violation

$\pi\pi$ from K^0 can have two Isospin (I = 0 or 2) amplitudes: A_0 , A_2

⇒ Direct CP Violation possible, in principle, in $K^0 \rightarrow \pi\pi$

⇒ Since $\pi^0\pi^0$ and $\pi^+\pi^-$ select different I amplitudes, we identify DCP violation comparing the decay modes:

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

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

(the numerical factors +1 and –2 come from Clebsch-Gordan coefficients between $\pi\pi$ and Isospin eigenstates)

(Instead indirect CP violation - ε - does not distinguish the two final states, because it occurs equally in K_L and K_S via the amplitude $K_1 \rightarrow \pi\pi$)

ε' : **direct CP violation parameter**, could be written as:

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

(it vanishes if A_2 is zero or if it has the same phase of A_0)

Measured quantity

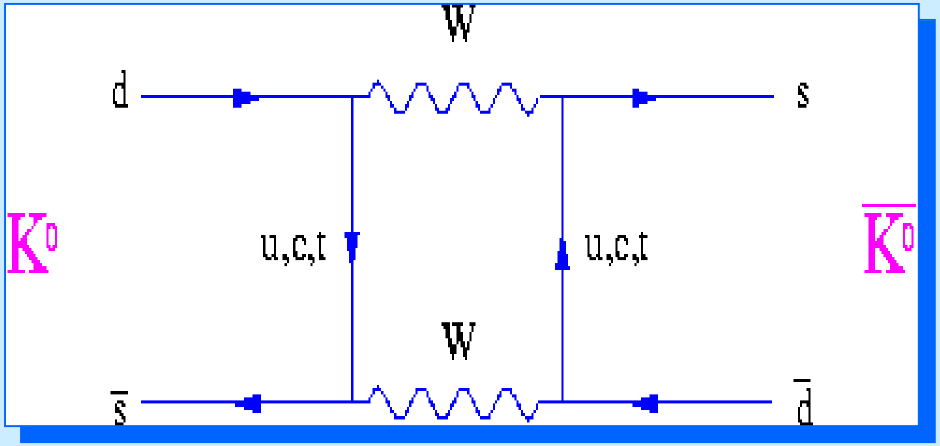
Experimental observable :

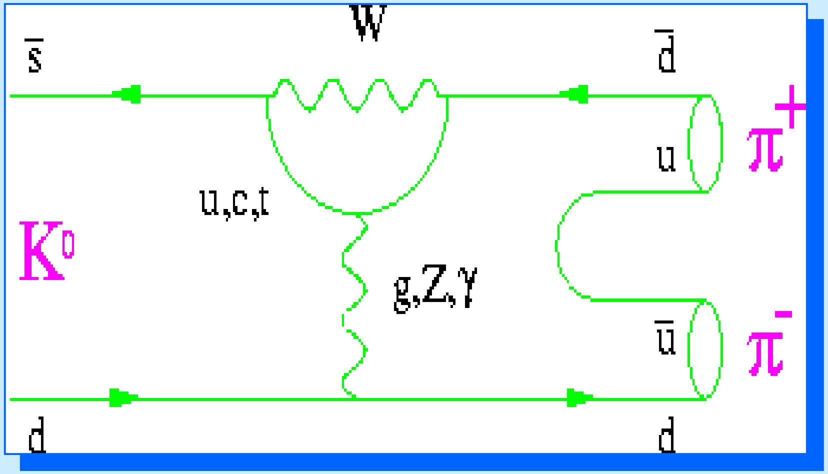
$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)\,\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)\,\Gamma(K_L \to \pi^+\pi^-)} = 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$$

This is to first order in $|\varepsilon'/\varepsilon|$, which is a correct approximation, since $|A_2| \ll |A_0|$,
in agreement with the $\Delta I = 1/2$ rule of weak decays

Standard Model predictions

Indirect violation through K^0- $\bar{K}^0$ coupling $\Rightarrow \varepsilon$ parameter





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

Typical theoretical predictions : $\varepsilon' / \varepsilon \approx$ few 10^{-4} to $\approx 2.\ 10^{-3}$

Improvements from forthcoming lattice QCD computations (?)

Current experimental situation of $\varepsilon' / \varepsilon$

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

$(\varepsilon' / \varepsilon) \neq 0$? Not clear ⇒ New generation of experiments

- First published results two 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)

⇒ **Direct CP violation seems established**

with 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 to clarify the situation.

NA48 method and setup

Measure the double ratio:

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

by counting the number of decays in two beams of K_L and K_S

Need $> 3.\,10^6$ $K_L \rightarrow \pi^0\pi^0$ for stat. error on $R < 0.1\%$ and look for cancellation of systematic effects related to differences in acceptance, efficiency, backgrounds:

(lifetimes are very different, KL decays are *rare* and are affected by background)

$c\tau_S$ = **2.67 cm**

$c\tau_L$ = **15.5 m**

$K_S \rightarrow \pi^+\pi^-$:	**69%**	$K_L \rightarrow \pi^+\pi^-$:	**0.2%**
$K_S \rightarrow \pi^0\pi^0$:	**31%**	$K_L \rightarrow \pi^0\pi^0$:	**0.1%**

NA48 method and setup

Strategy to minimize systematic effects:

- the 4 modes are collected concurrently

⇒ cancellation of fluxes, dead times, inefficiencies, accidental rates

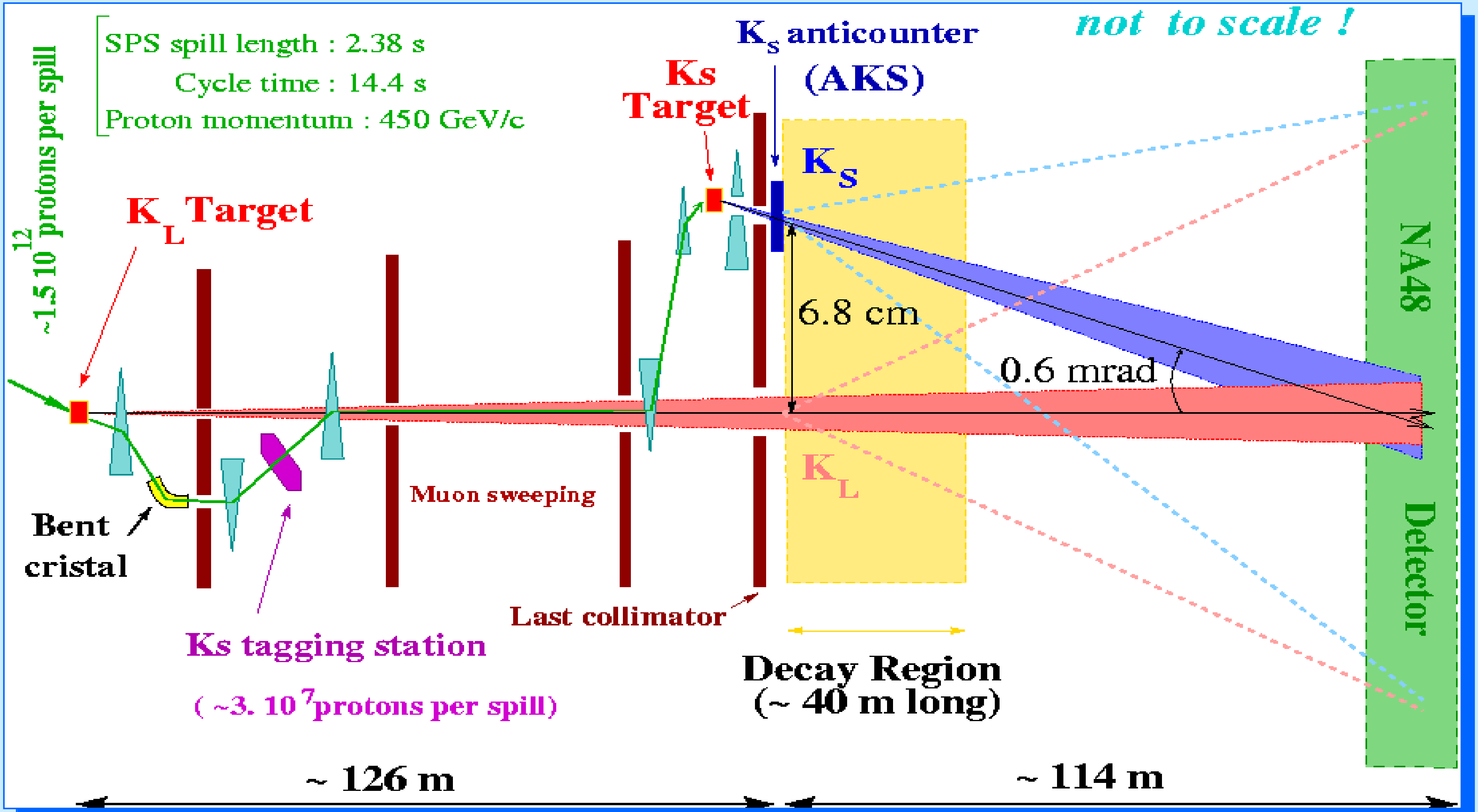
- use same decay regions for all modes, apply lifetime weighting to equalize distribution of K_S and K_L decay positions

⇒ cancellation of detector acceptance effects

- use quasi-homogeneous liquid Krypton calorimeter to detect $\pi^0\pi^0$ and magnetic spectrometer for $\pi^+\pi^-$

⇒ optimize resolution, uniformity, linearity and stability

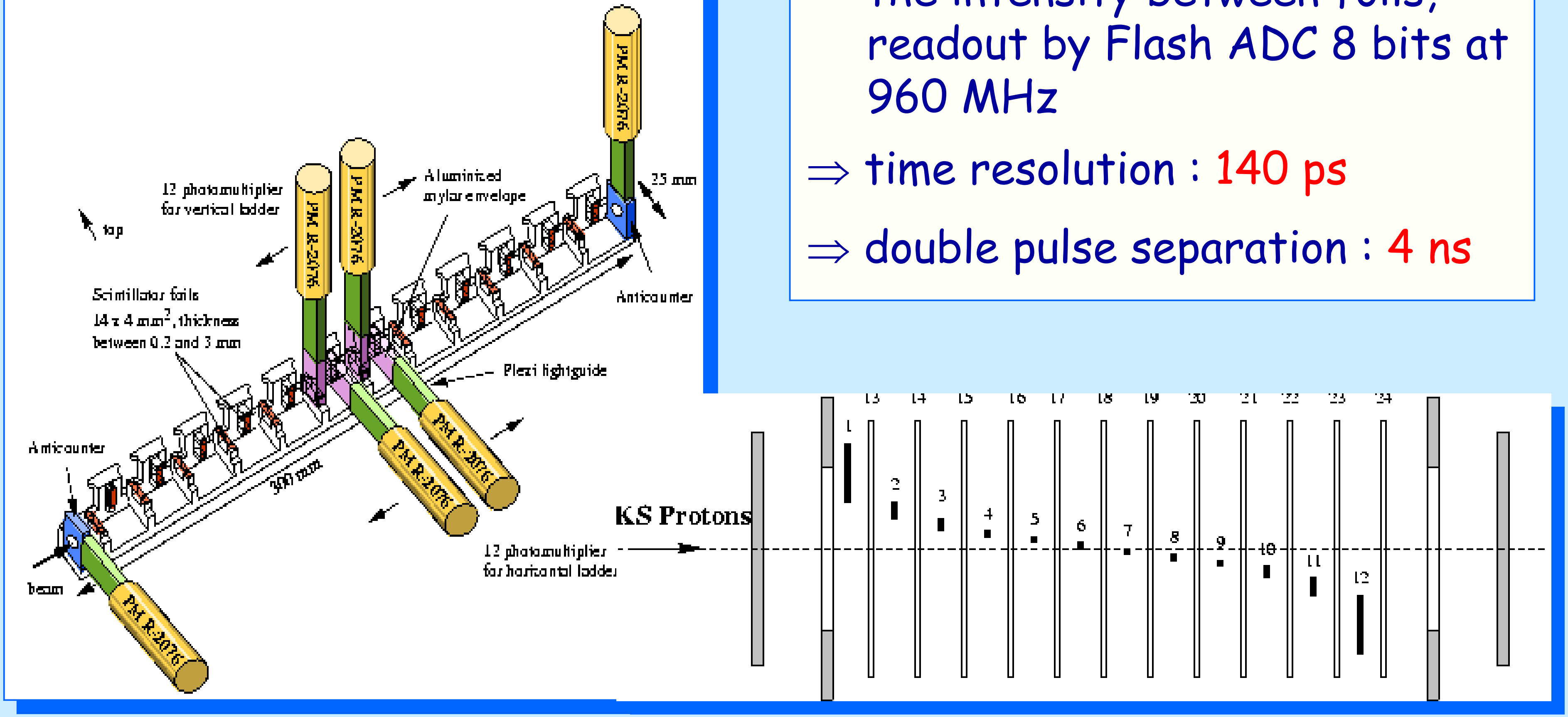
NA48 simultaneous and collinear K_L and K_S beams



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

The Tagger

2x12 thin scintillator foils

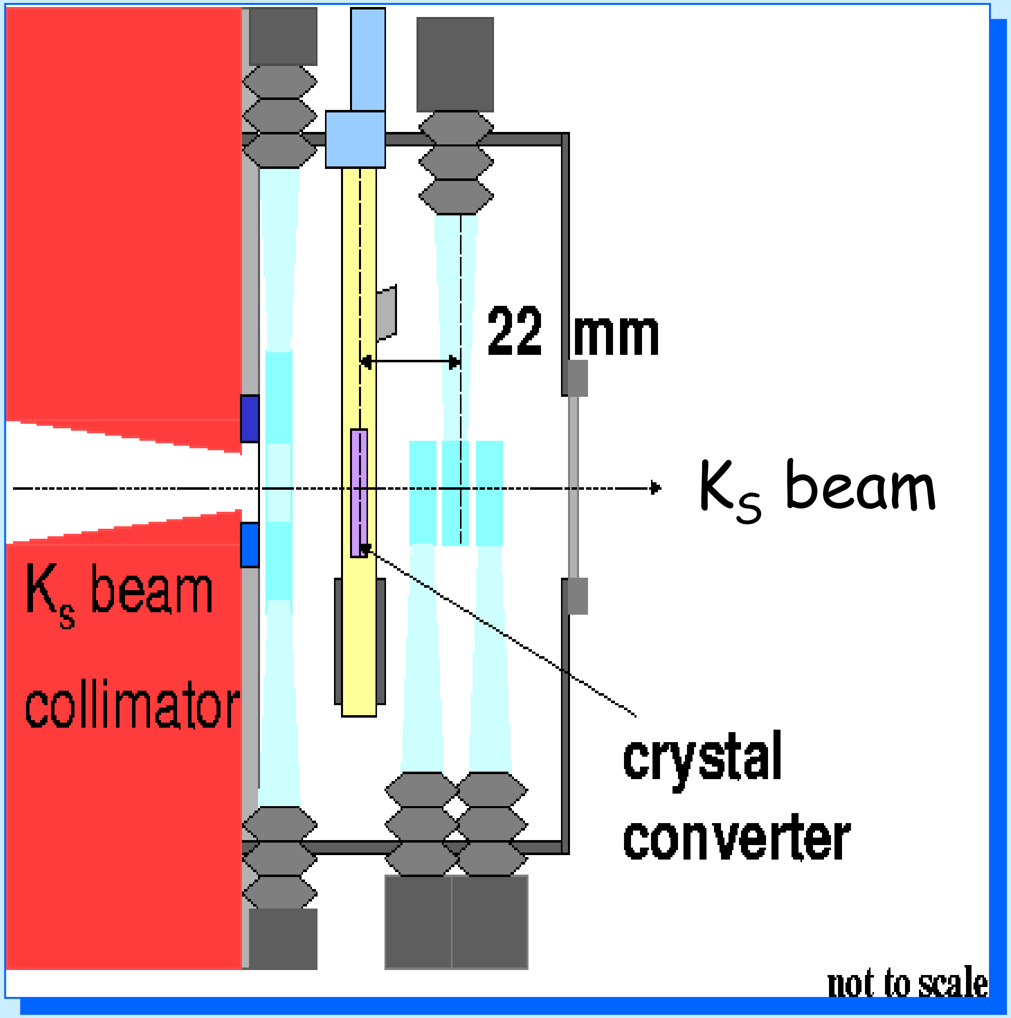


- Proton rate ≈ 30MHz → split the intensity between foils, readout by Flash ADC 8 bits at 960 MHz

⇒ time resolution : 140 ps

⇒ double pulse separation : 4 ns

The AKS counter

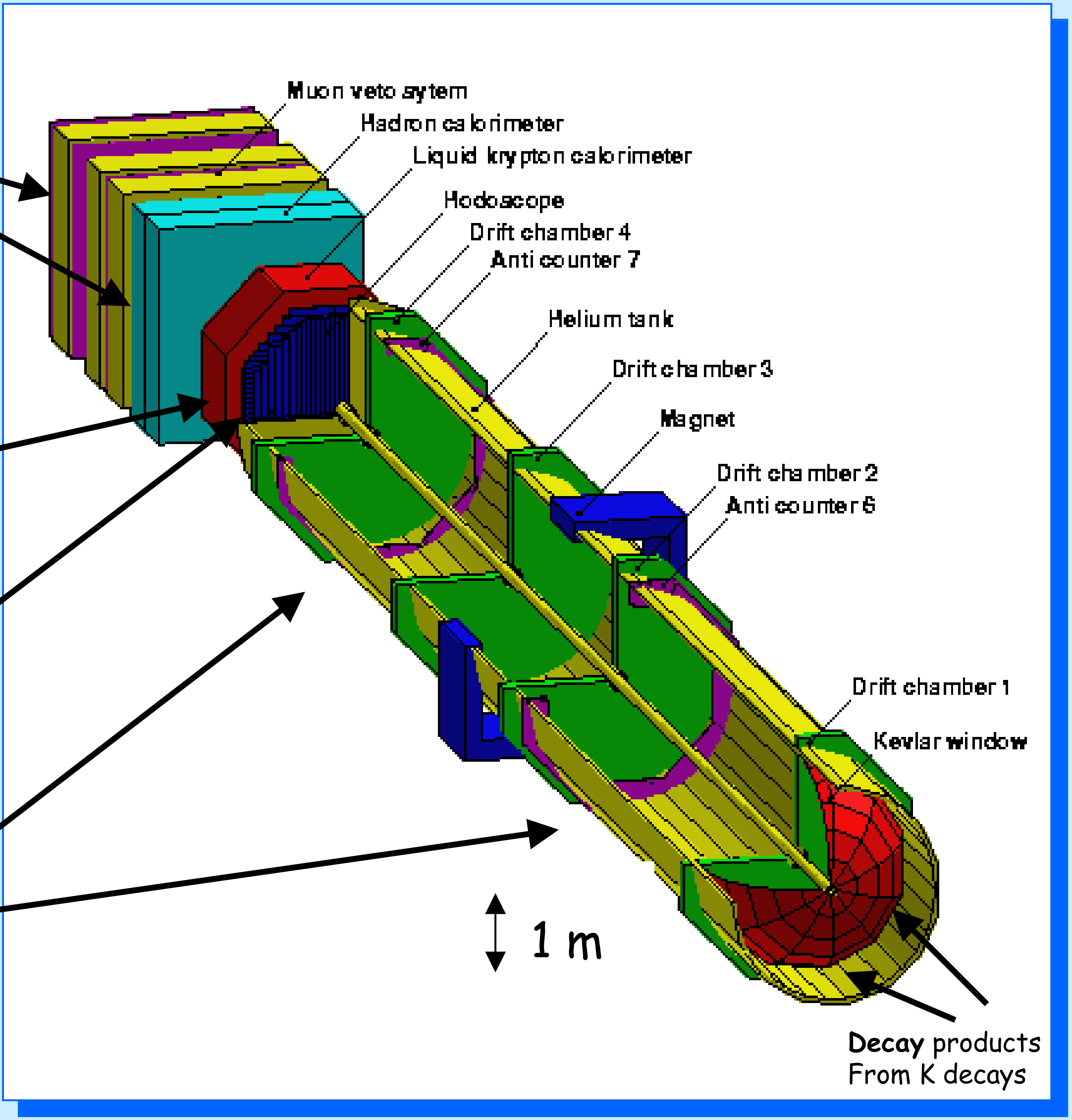


- Defines beginning of decay region for $\pi^+\pi^-$ and $\pi^0\pi^0$ K_S decays
- Plastic scintillation counters following a
- Photon converter :
  - iridium crystal 3mm thick , (22 ± 5) mm upstream of counter

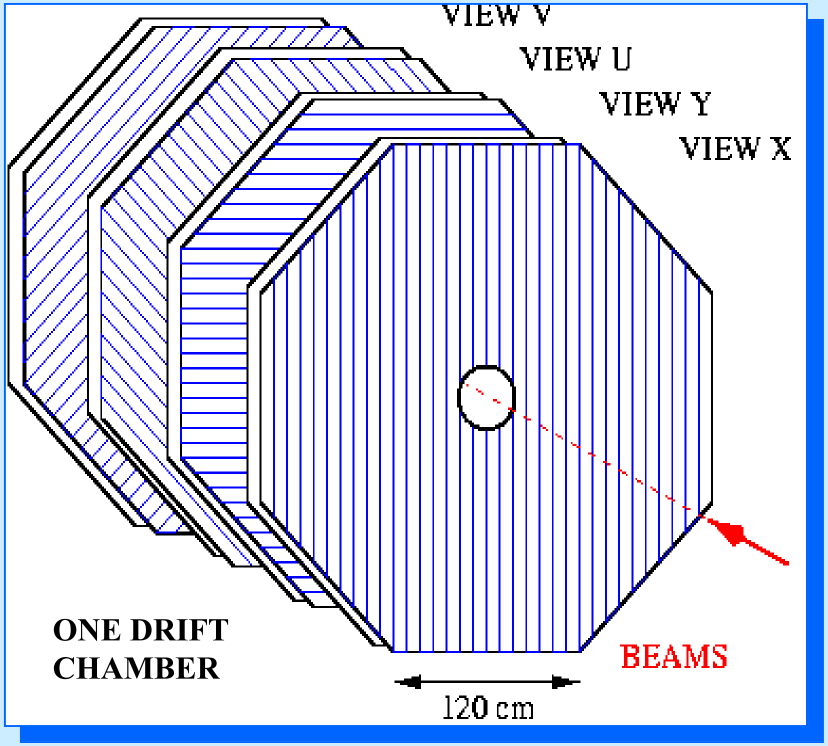
  $\Rightarrow$ 1.79 X_0 instead of 0.98 X_0 for amorphous iridium

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



Magnetic spectrometer



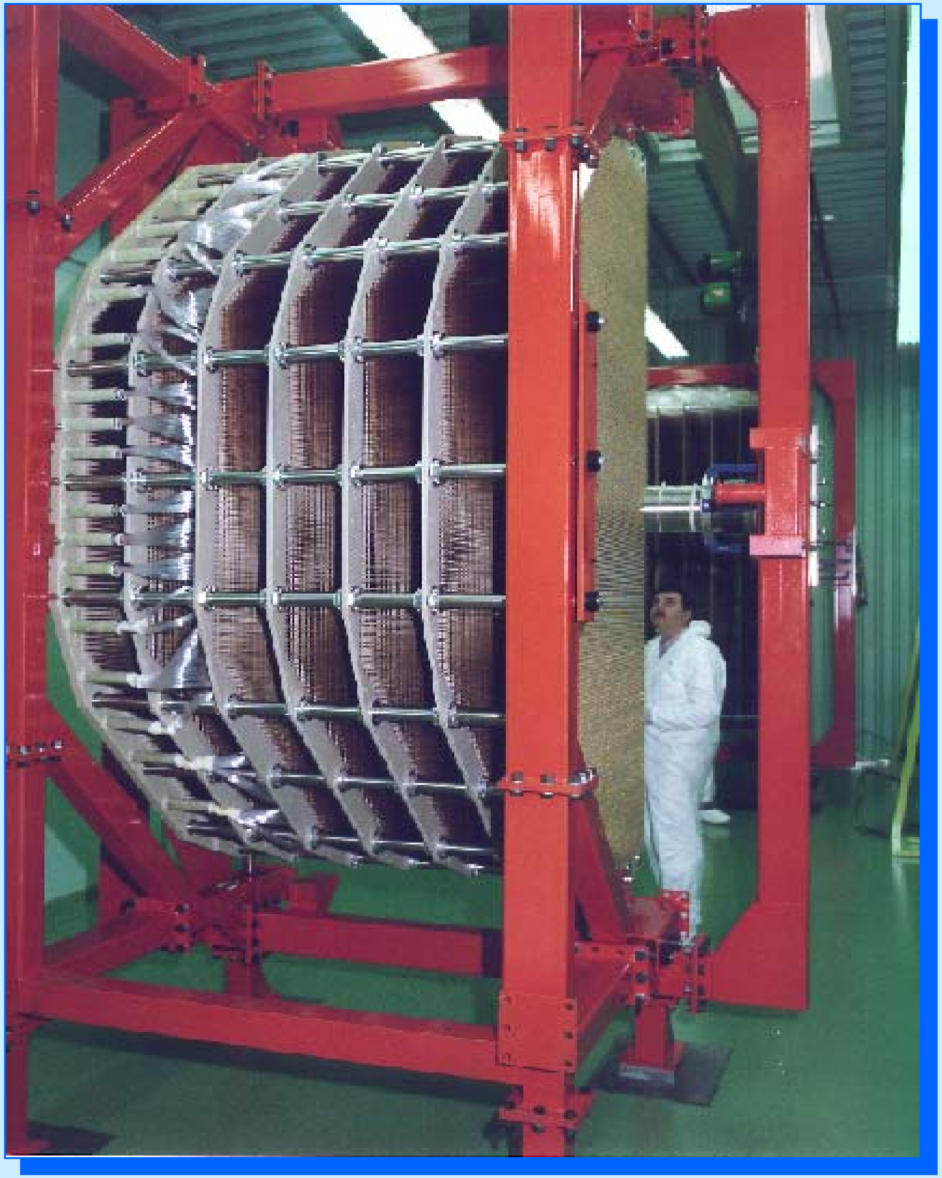
- 4 drift chambers
- Space point resolution ≈100 μm ;

$\sigma(P)/P \cong 0.5\,\% \oplus 0.009\ P[GeV/c]\%$

(≅ 1% for 100 GeV/c track momentum)

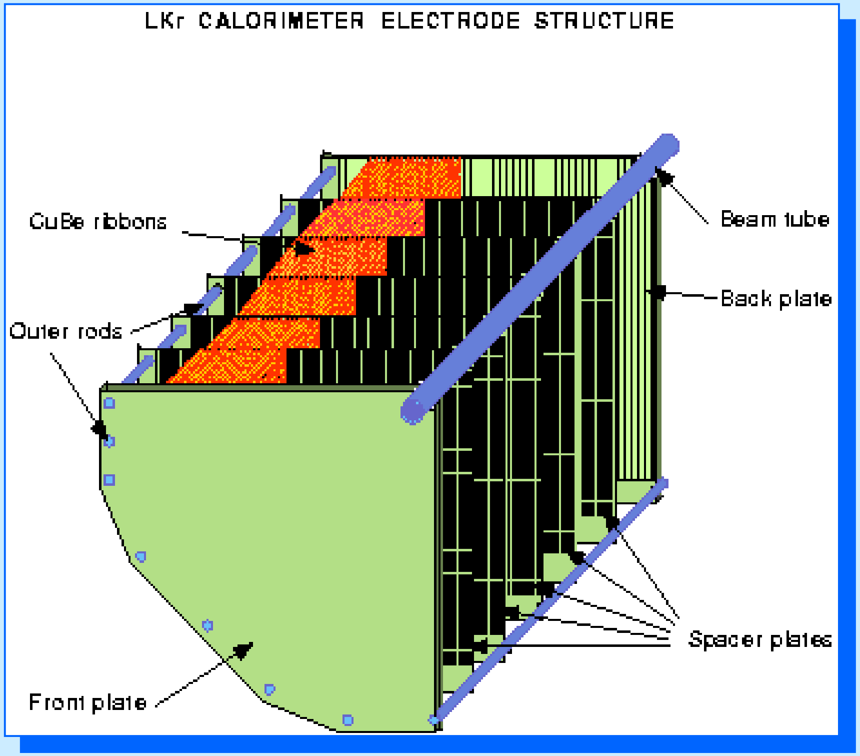
LKr electromagnetic calorimeter

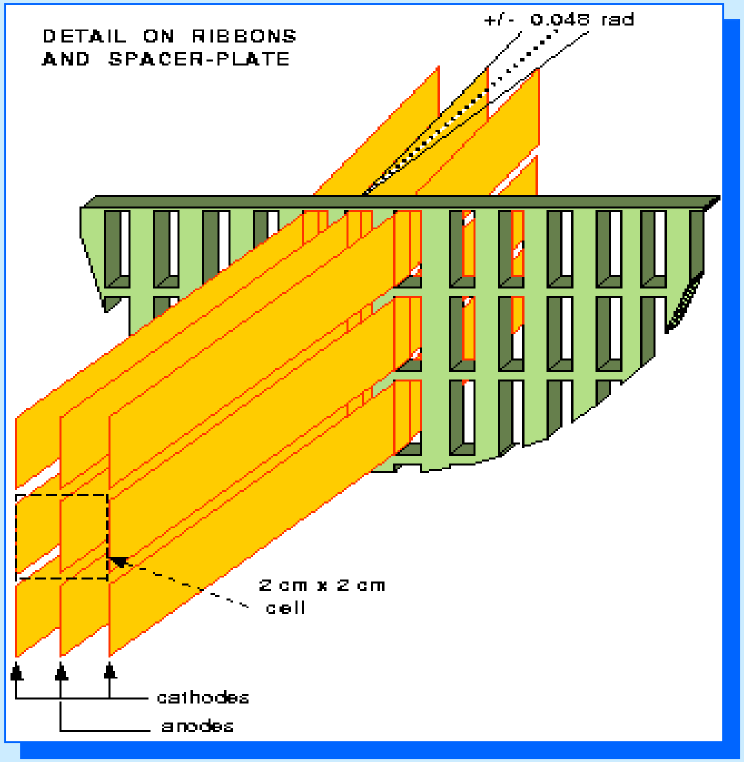
- Quasi-homogeneous detector
  - 10 m^3 liquid krypton (120 K);
  - (X_0 = 4.7 cm, R_M = 6.1 cm)
- 13,212 cells
  - granularity 2×2 cm^2
  - Depth 1.25 m (27 X_0)



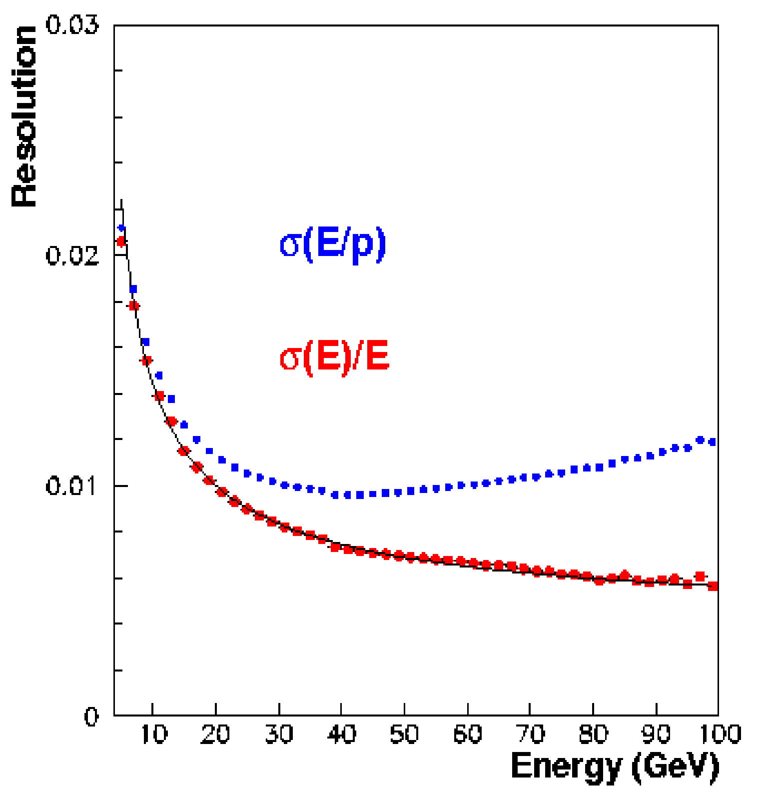
LKr electromagnetic calorimeter

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





LKr energy resolution



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

$$\sigma(E)/E \cong 3.2\,\% / \sqrt{E} \oplus 0.09\,/E \oplus 0.42\%$$

(E in GeV)

(better than 1% for 25 GeV photons)

Trigger, reconstruction and analysis

Beware:

All the corrections and uncertainties are quoted as applied to R:

When referred to $(\varepsilon'/\varepsilon)$, they need to be multiplied by -1/6

Trigger

$\pi^+\pi^-$ 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 comparison of trigger components)
- Level 2:
  - Fast track reconstruction (100μs) 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)

$\pi^+\pi^-$ selection

$K_S \rightarrow \pi^+\pi^-$: no background

$K_L \rightarrow \pi^+\pi^-$: $BR = 0.2\%$

Backgrounds : Ke3(BR=39%),

Kμ3 (BR=27%)

e and μ rejection

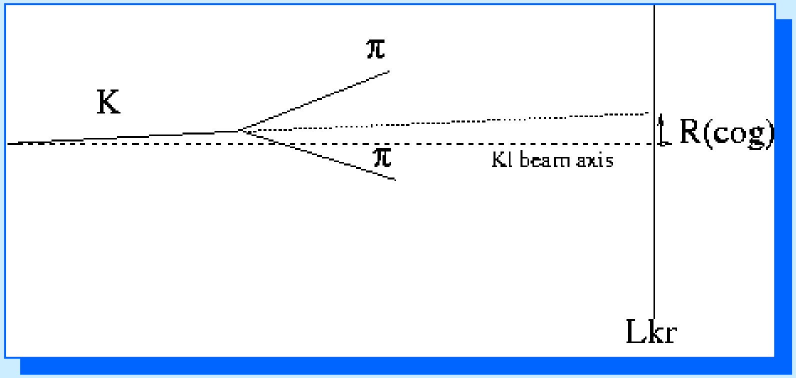
- $E(LKr)/p < 0.8$
- no hits in μ detector

Kinematical cuts

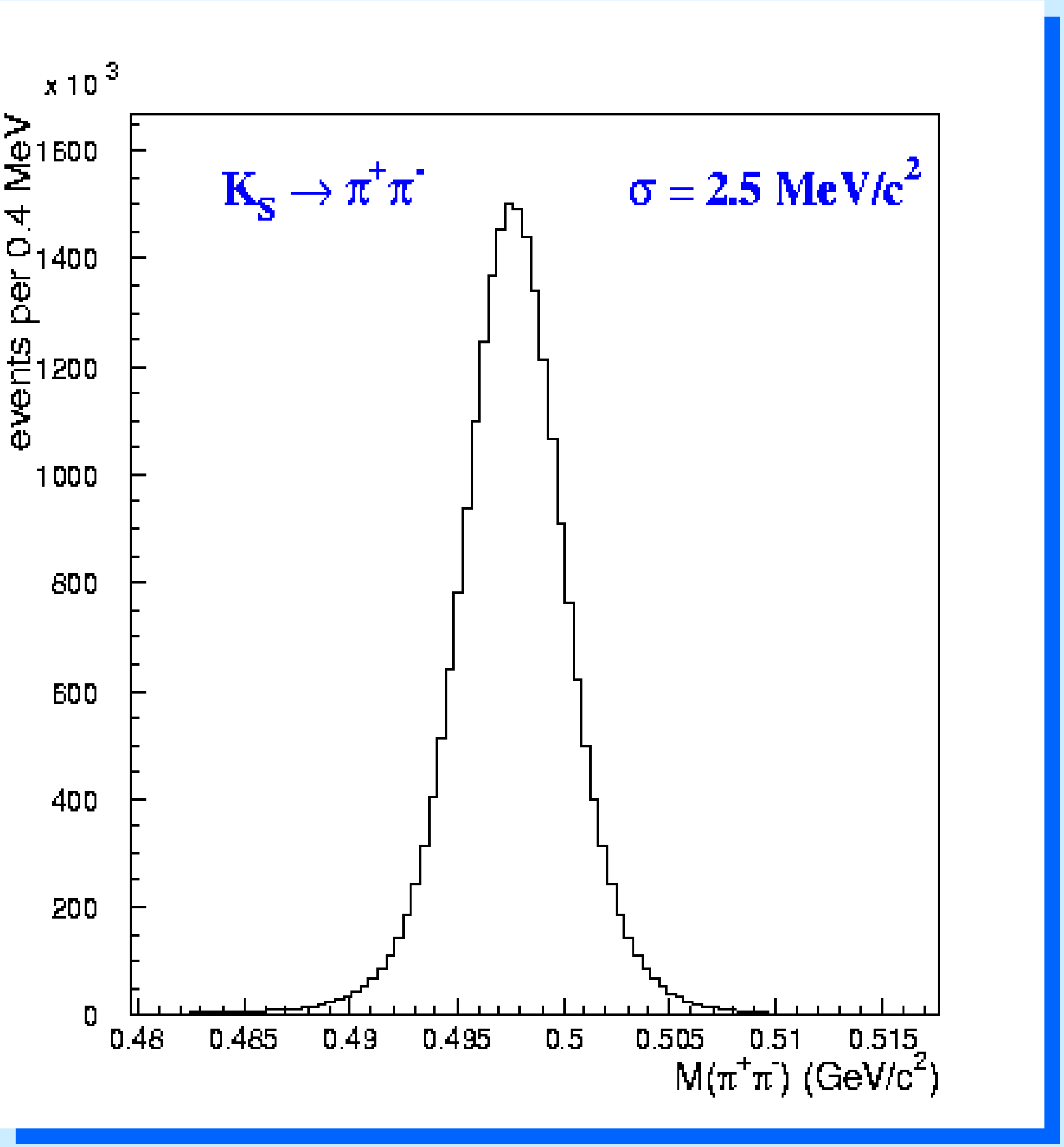
- $|M_{\pi\pi} - M_K| < 3 \cdot \sigma_M$, ($\sigma_M \approx 2.5$ MeV)
- $P_\perp'^2 < 200\ (\mathrm{MeV}/c)^2$
  transverse momentum of $\pi^+\pi^-$ to the line between target and Kaon projection to spectrometer
  ≈ 0 for two body decay,
  > 0 for Ke3, Kμ3
- $|p_1-p_2| / p_1+p_2 <$ min (0.62,1.08-0.0052 E_K) [$\Leftrightarrow$ cut on $\cos(\Theta^*)$, reduces acceptance difference between K_L and K_S]

- Center of gravity $R_{COG} \leq 10$ cm

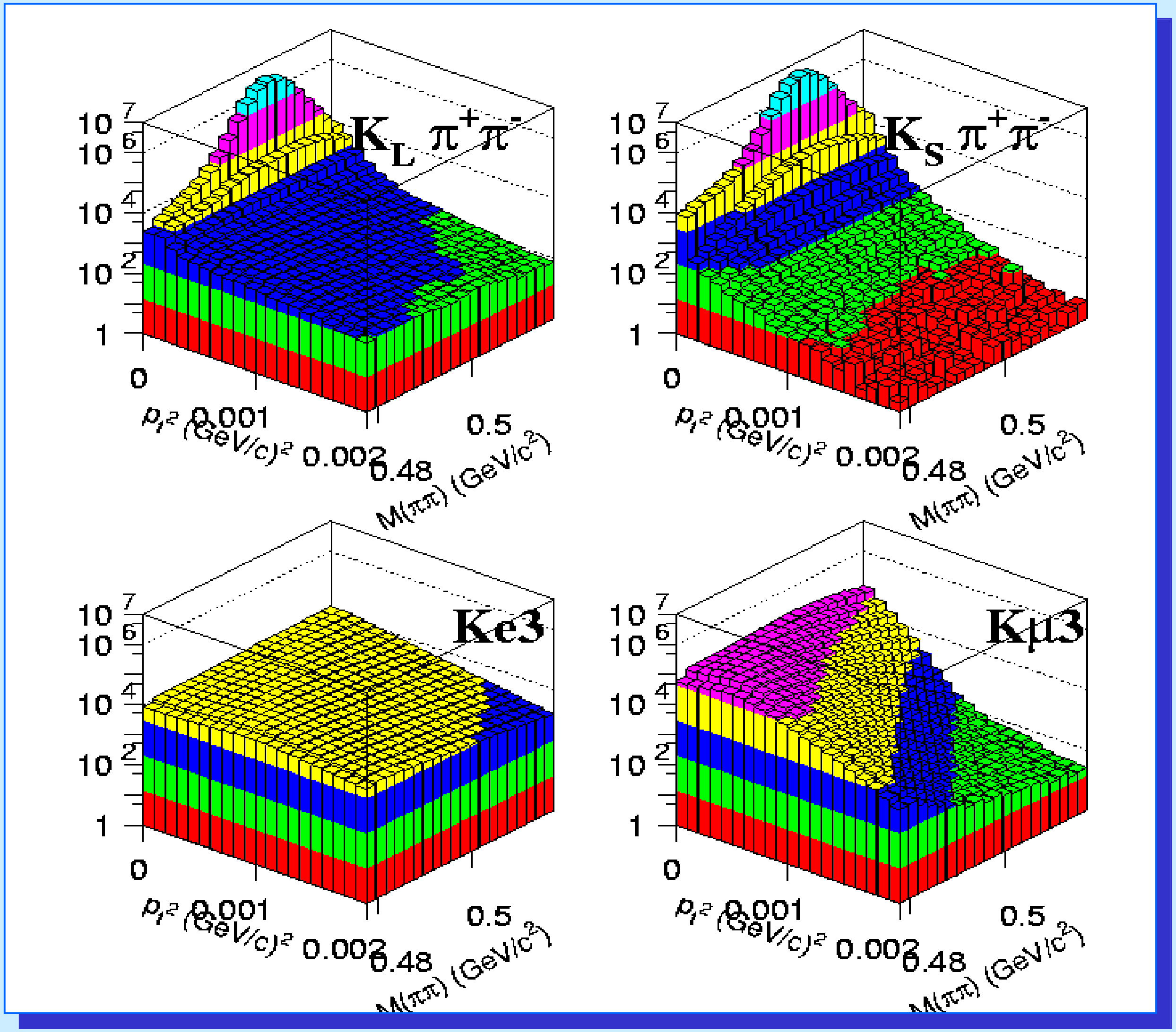
Kaon impact point extrapolated to the calorimeter COMMON WITH $\pi^o\pi^o$



$\pi^+\pi^-$ mass resolution



Signal and background in M_{+-} - $P_\perp'^2$ plane



- Study background with inverted cuts,
- and fit it in K_L sample,
- together with signal shape from K_S sample

$\pi^+\pi^-$ background subtraction

In the signal region ($M_{\pi\pi}$ and $P_\perp'^2$ cuts), the background is due to Ke3, Kμ3

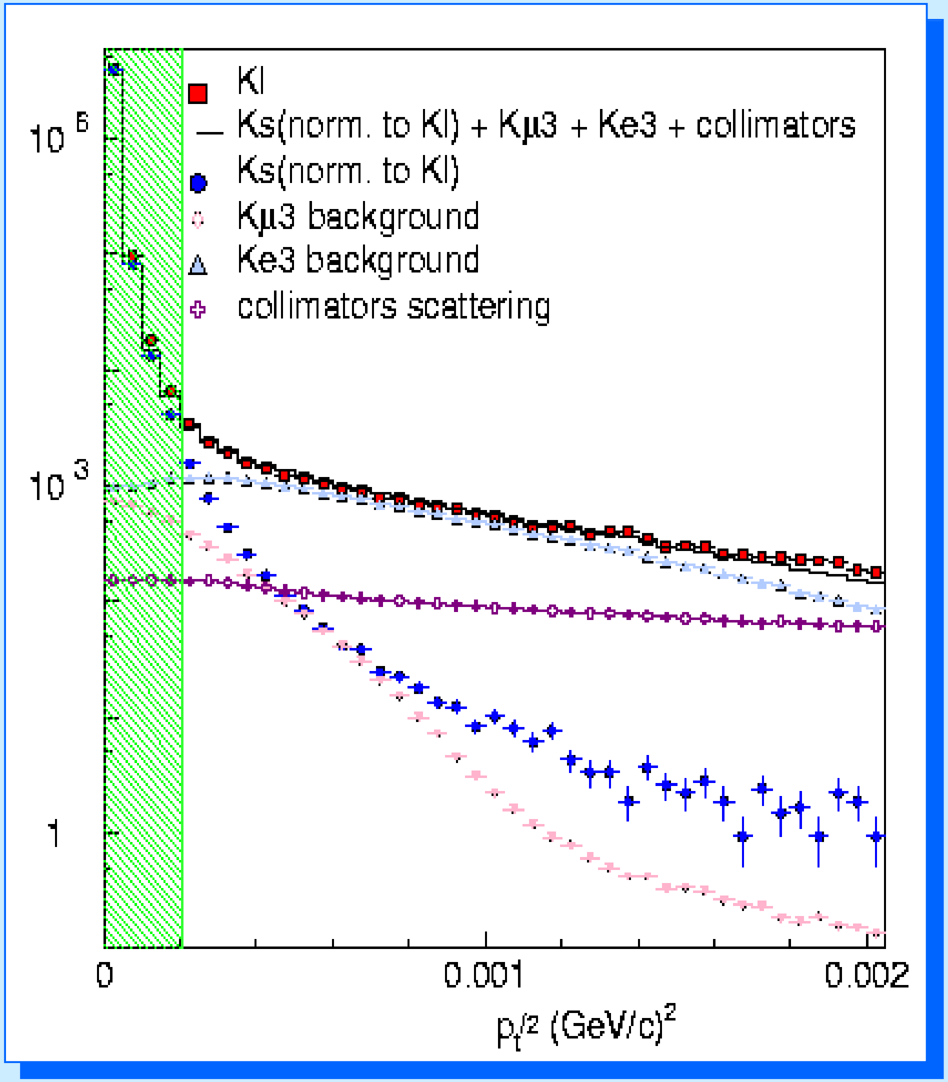
and a smaller fraction of collimator scattered Kaons

(partially asymmetric in $\pi^+\pi^-$ and $\pi^o\pi^o$)

Background = (16.9 ± 3.0) 10^{-4}

(systematic error :

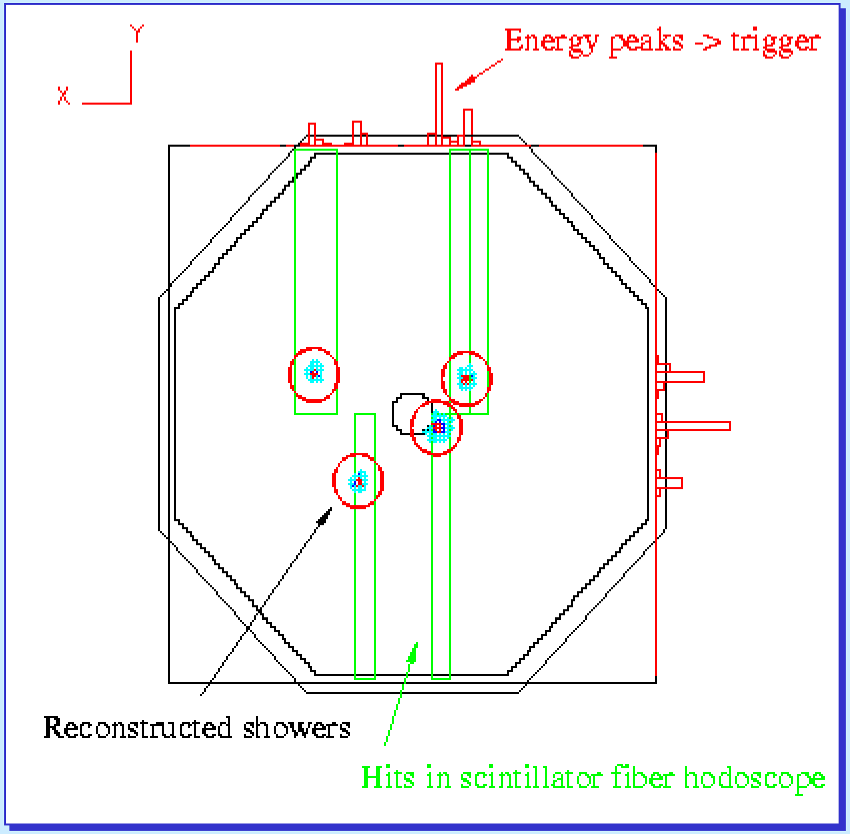
- changes in control regions,
- modeling of $P_\perp'^2$ shape)



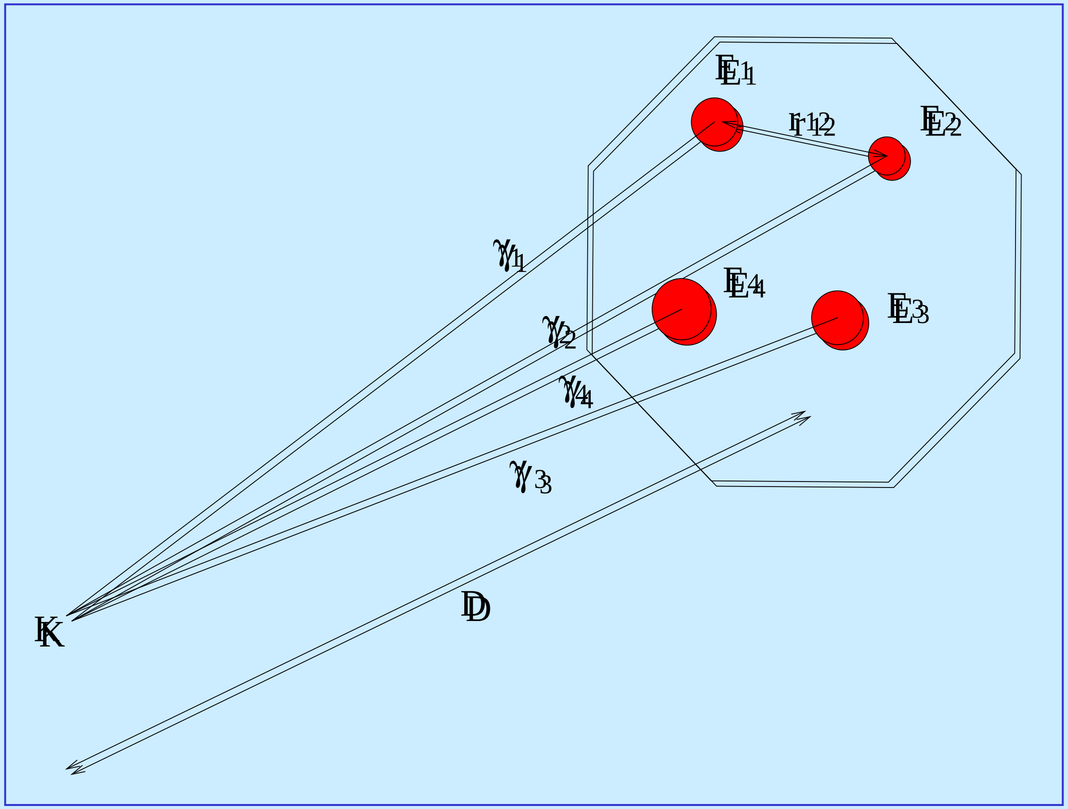
Trigger

$\pi^0\pi^0$ trigger

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



Neutral reconstruction



$$D = z_{LKr} - z_{decay}$$
$$= 1/M_K \sqrt{\sum_{ij} E_i E_j d_{ij}^2}$$

The neutral reconstruction is based on

- showers energies and positions,
- the Z decay vertex follows assuming M_K as total invariant mass

$\pi^0\pi^0\pi^0$ background subtraction

$K_S \to \pi^0\pi^0$: no background

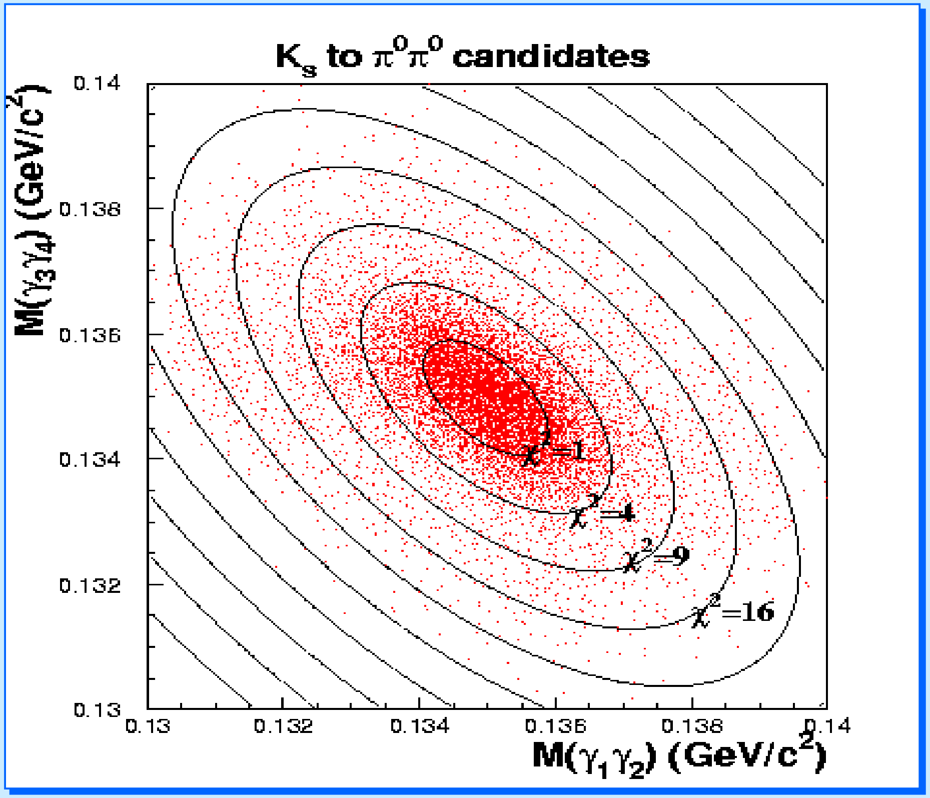
$K_L \to \pi^0\pi^0$: BR ≈ 0.09%

Background : $K_L \to 3\ \pi^0$ (BR≈21%)

TO REDUCE THE BACKGROUND:

- after assuming M_K invariant mass for the 4 showers
- at a corresponding decay vertex Z_{decay}
- the showers can be further paired, at the same Z_{decay}, reproducing twice the π^0 mass

⇒study a χ^2 distribution (2 d.o.f., mass resolution ≈ 0.9 MeV)



To reduce the background further:

veto events with additional in-time clusters

$\pi^0\pi^0\pi^0$ background subtraction

Estimate residual background under K_L signal using control region in χ^2.

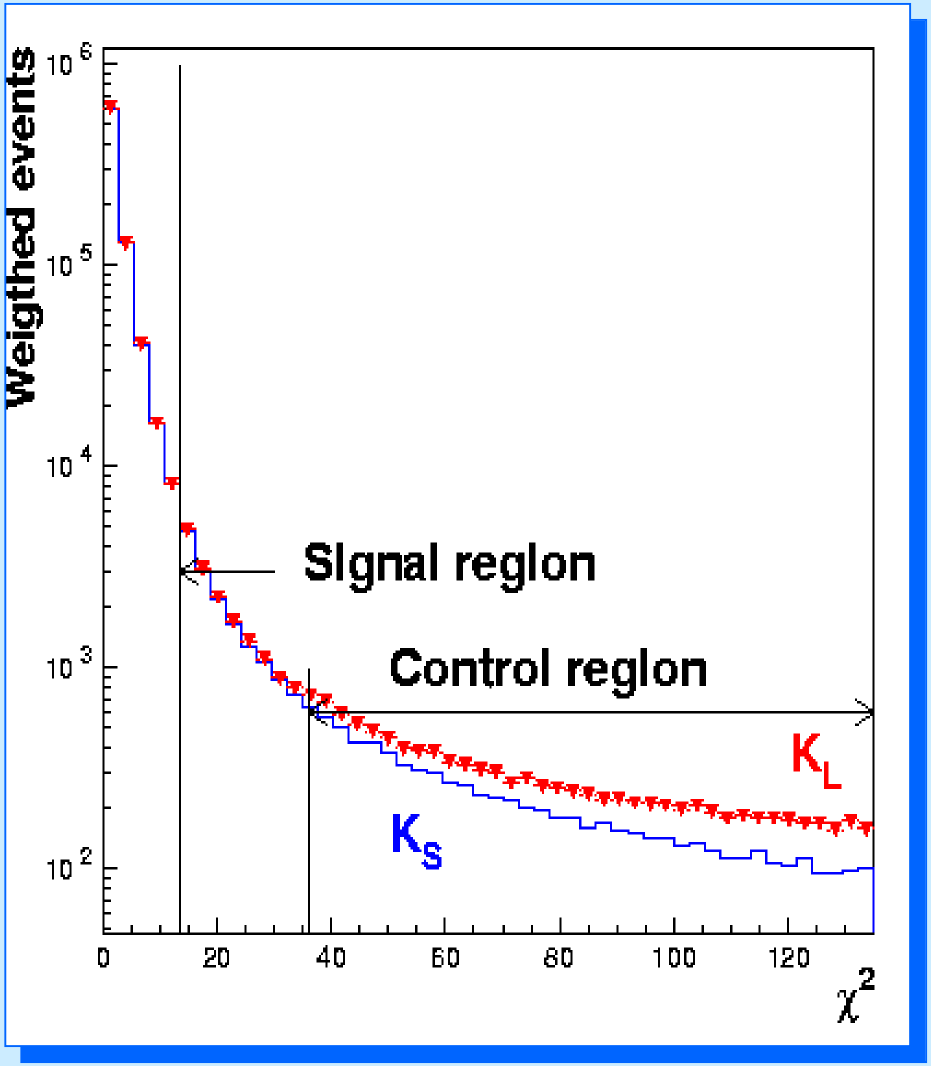
($3\pi^0$ background is ≈ flat)

$\pi^0\pi^0$ contribution in control region from resolution tails is derived from K_S events.

Background = $(5.9 \pm 2.0)\ 10^{-4}$

(systematic error : uncertainty in background extrapolation)

Additional $\pi^0\pi^0$ background due to collimator scattering: $(9.6 \pm 2.0)\ 10^{-4}$

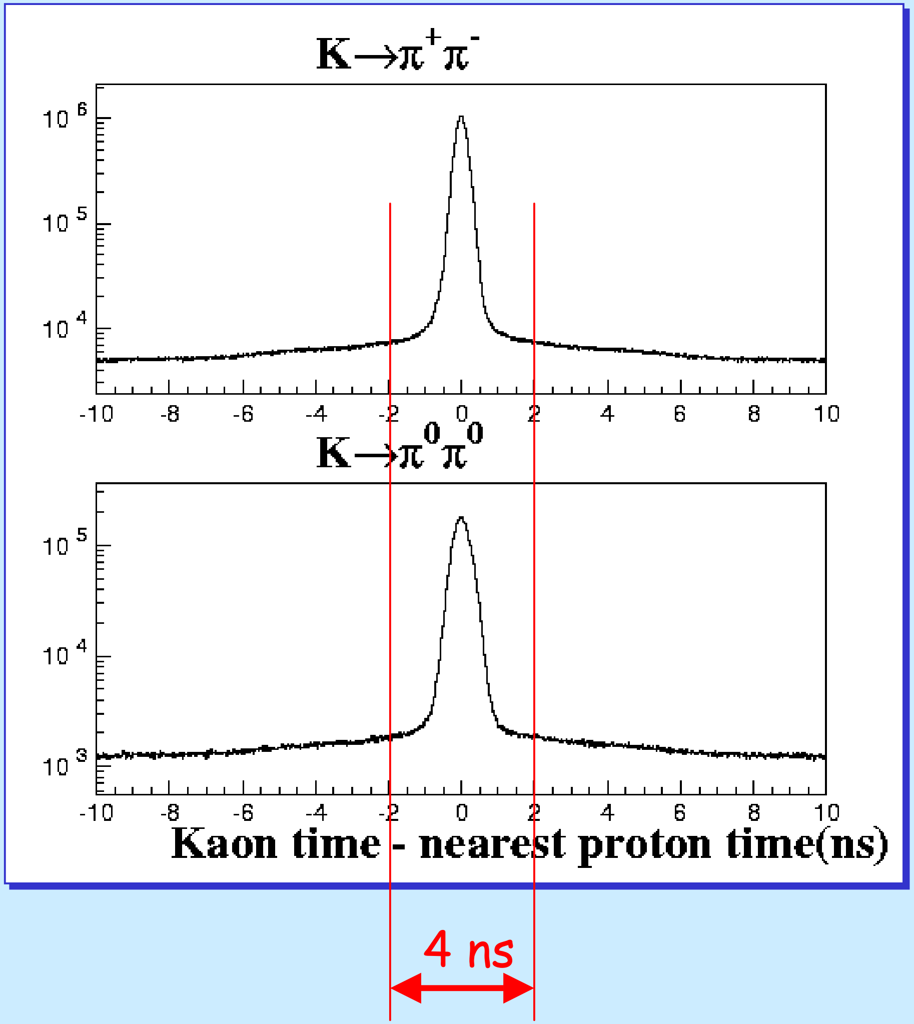


tagger

hodoscope

LKr calorimeter

Tagging coincidence



Δt (Kaon-proton)

≤ 2 ns $\Rightarrow$ K_S

> 2 ns $\Rightarrow$ K_L

Tagging errors

Two possible kinds of mistake :

-K_S mistagged as K_L : probability α_{SL}

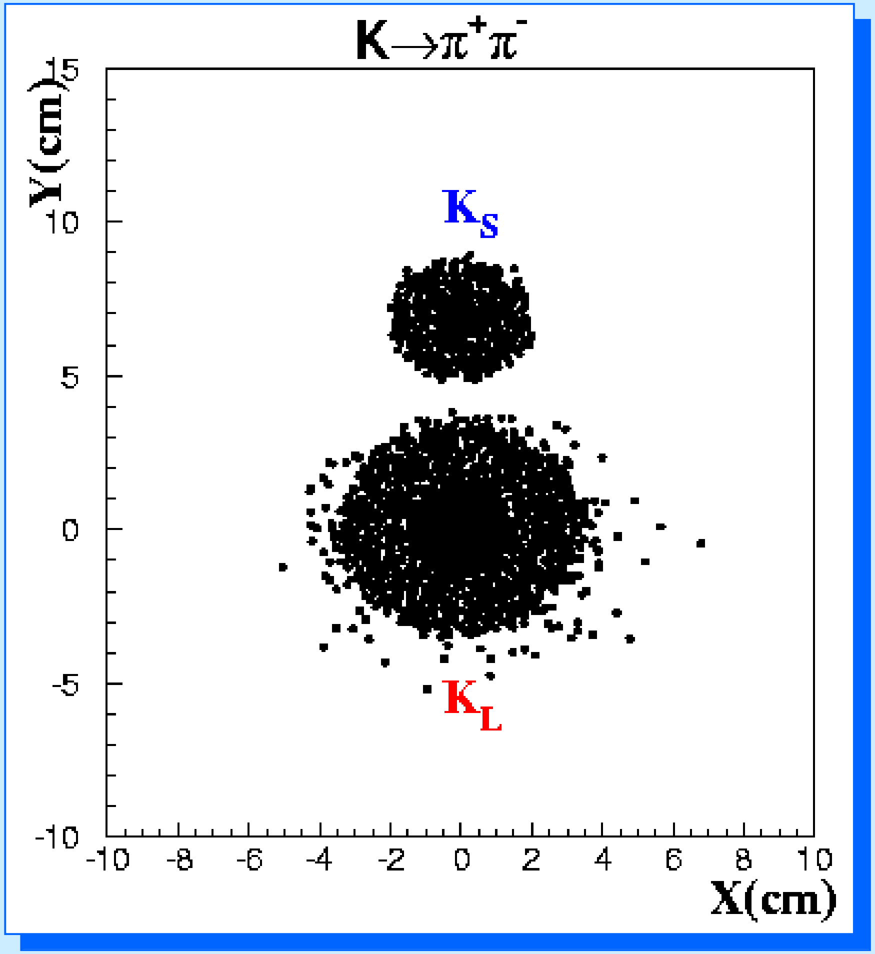
[inefficiency in time measurement by tagger counter or main detector (=trigger hodoscope or calorimeter): α_{SL}^{+-} and α_{SL}^{00}]

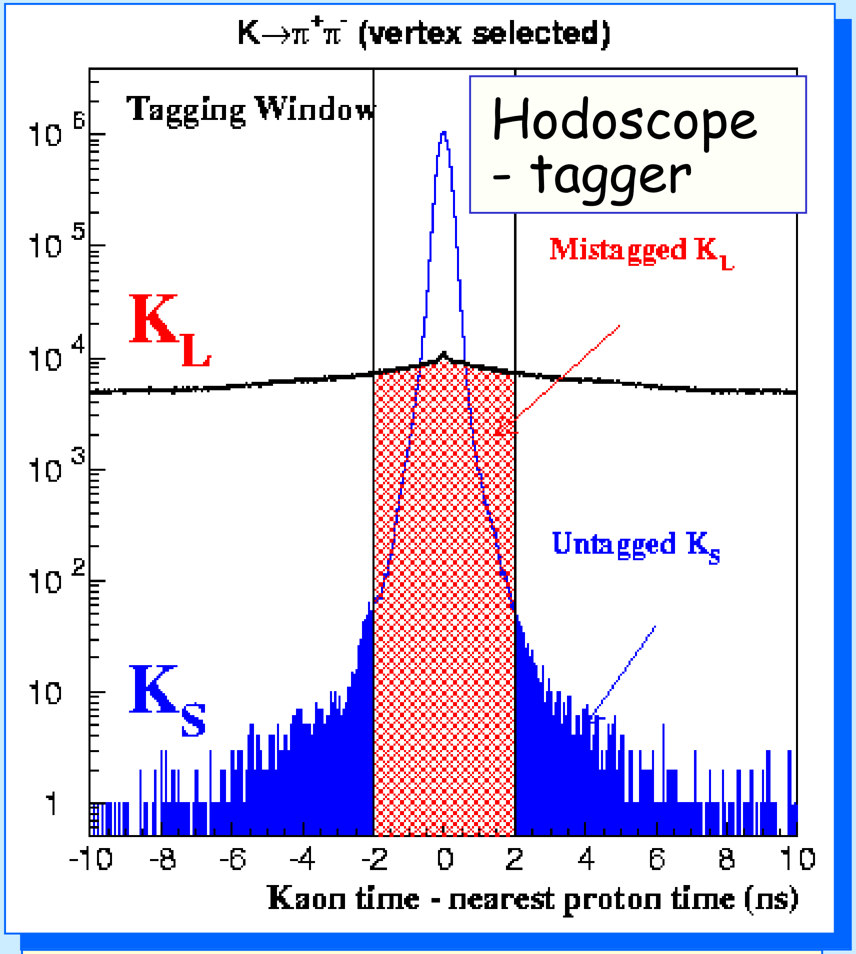
-K_L mistagged as K_S : probability α_{LS}

[accidental coincidence between K_L decay and a proton in the tagger (rate 30 MHz) - α_{LS}^{+-} and α_{LS}^{00} - approximately symmetric between $\pi^+\pi^-$ and $\pi^0\pi^0$ because of simultaneous data taking]

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

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





Identify K_S, K_L with decay vertex position in transverse plane

$$\alpha_{SL}^{+-} = (1.63 \pm 0.03)\ 10^{-4}$$
$$\alpha_{LS}^{+-} = (10.649 \pm 0.008)\%$$

Tagging errors

- The measurement of R is mostly affected by the asymmetries in tagging errors:

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

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

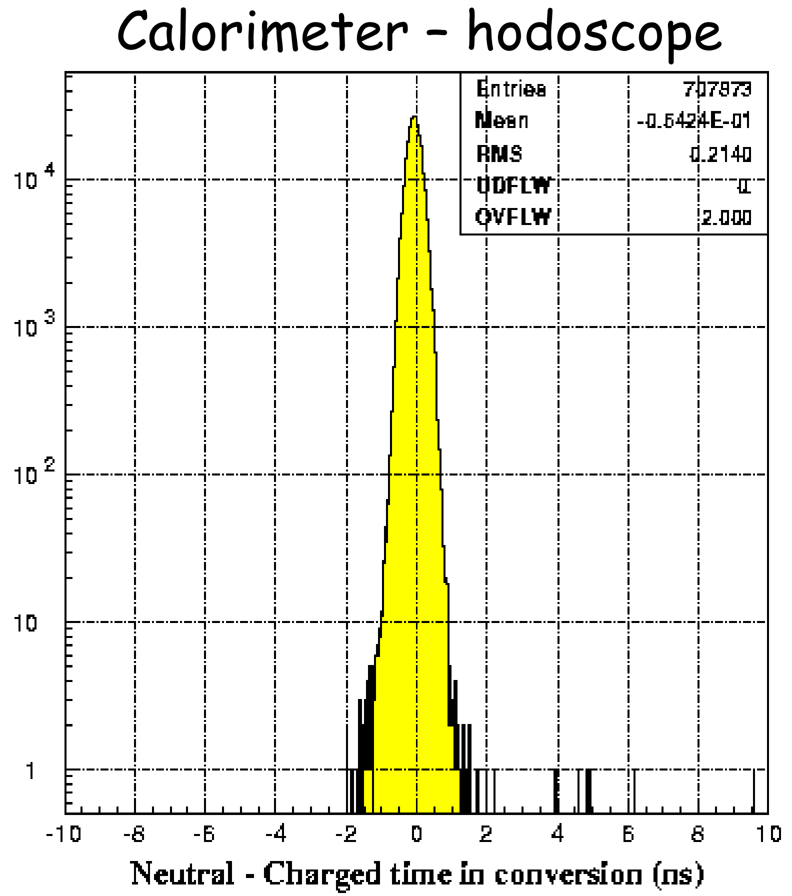
- Correction to R : $\Delta R \cong 2 \times \Delta\alpha_{LS} - 6 \times \Delta\alpha_{SL}$

Measuring $\Delta\,\alpha_{SL}$

- Compare the time provided by calorimeter and hodoscope in events where both are available:
  1. Dalitz decays of π^0
  2. γ conversions in vacuum window
     - **Tails < 0.5×10^{-4}**

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

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


Calorimeter – hodoscope

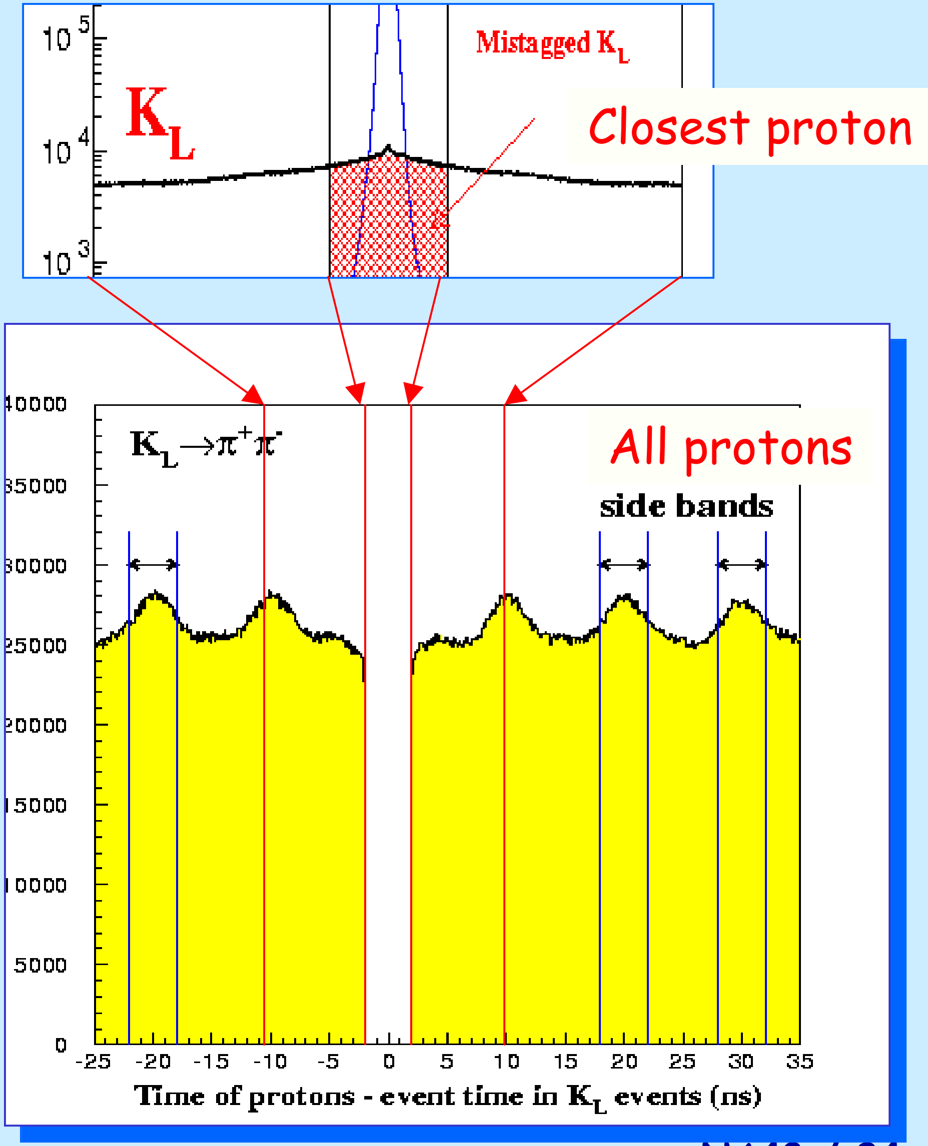
$\Rightarrow \Delta\alpha_{SL} = (0. \pm 0.5)\ 10^{-4}$

Measuring Δ α_{LS}

- α_{LS} comes from accidental coincidences

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

This is done for events tagged as K_L (no proton in central window), and allows $\pi^+\pi^-$ / $\pi^0\pi^0$ comparison



Summary on tagging

- Data corrected for tagging mistakes
- Error on **R** ⇔ $\pi^+\pi^- - \pi^0\pi^0$ difference

	$\Delta(R)$ (in 10^{-4} units)
K_S tagging inefficiency	
$\alpha_{SL}^{+-} = 1.6 \times 10^{-4}$	
$\Delta\alpha_{SL} = (0. \pm 0.5)\ 10^{-4}$	0. ± 3.
K_L accidental mistagging	
$\alpha_{LS}^{+-} = (10.649 \pm 0.008)\ \%$	
$\Delta\alpha_{LS} = (4.6 \pm 1.7)\ 10^{-4}$	8.3 ± 3.4
Total	8.3 ± 4.5

Fiducial volume definition

The event samples are selected applying cuts on the reconstructed kaon energy and the decay vertex position:

$70 \leq E_K \leq 170$ GeV,

$0 < \tau < 3.5$ (proper decay time:

$\tau = 1/c\tau_{KS}\,(z_{vertex}-z_0)\,M_K / E_K$)

The control of the boundaries of the fiducial volume is of major relevance, good control of:

- vertex computation,
- scale and linearity of the energycomputation.

Energy and decay vertex computations

$\pi^+\pi^-$

- z_{vertex} from track segments upstream of magnet

⇒ Computation based on spectrometer geometry

Detector geometry

- Z positions known to ≅ 1 mm
- Transverse size scale known

to:

  - spectrometer ≅ 100 μm/m
  - LKr ≅ 300 μm/m (after cool down)

$\pi^0\pi^0$

- $D(\text{LKr-vertex}) = 1/M_K \sqrt{(\Sigma_{ij} E_i E_j d_{ij}^2)}$

$$= (\text{Energy scale}) \times (\text{Transverse size scale})$$

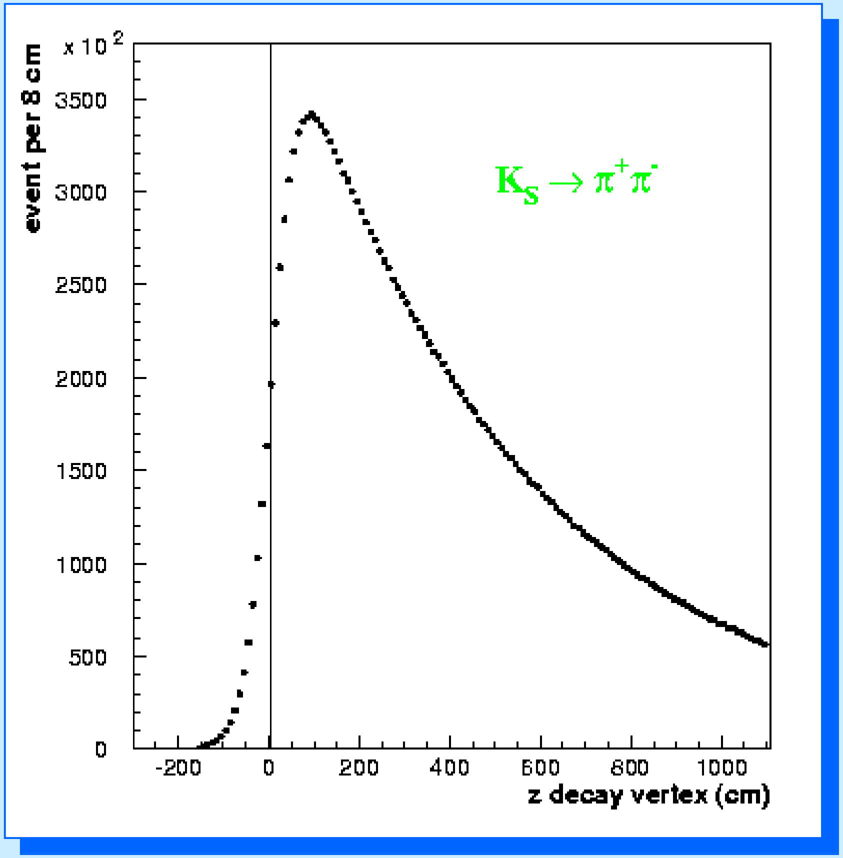
Energy scale

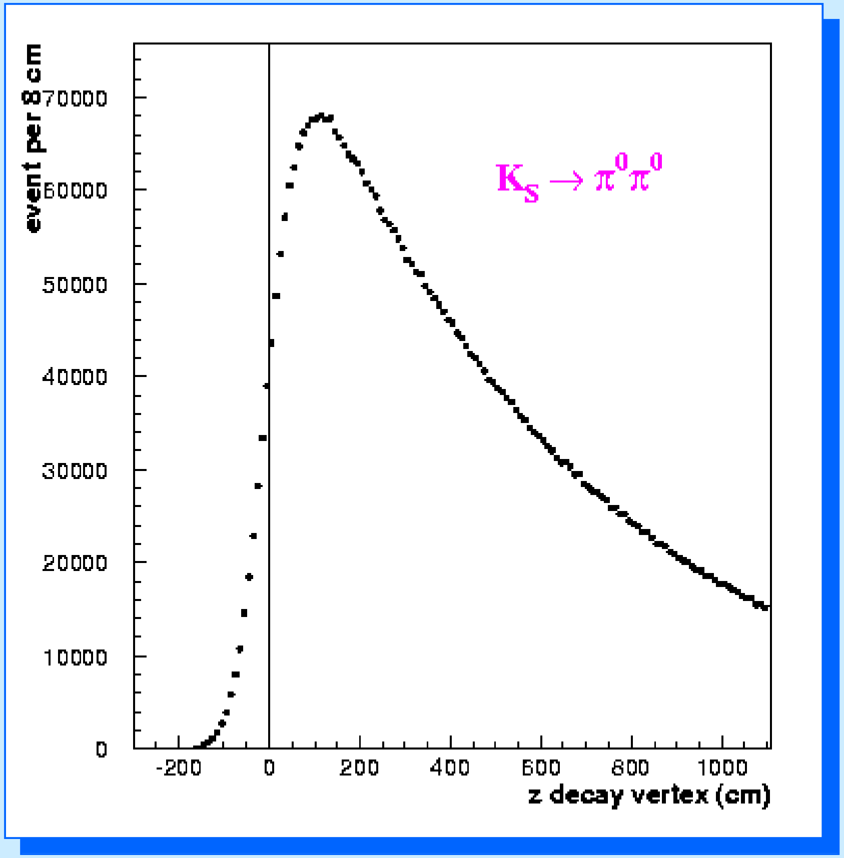
- adjust energy scale to fit the known position of the AKS anticounter

1 cm of reconstruction error

⇒ 1×10^{-4} on energy scale

Reconstruction of AKS position





$\pi^+\pi^-$: Check of geometry and reconstruction

$\Rightarrow \Delta(z) = 2$ cm

$\Rightarrow \Delta(R) = (2 \pm 2)\,10^{-4}$

$\pi^0\pi^0$: Adjust energy scale to match nominal position

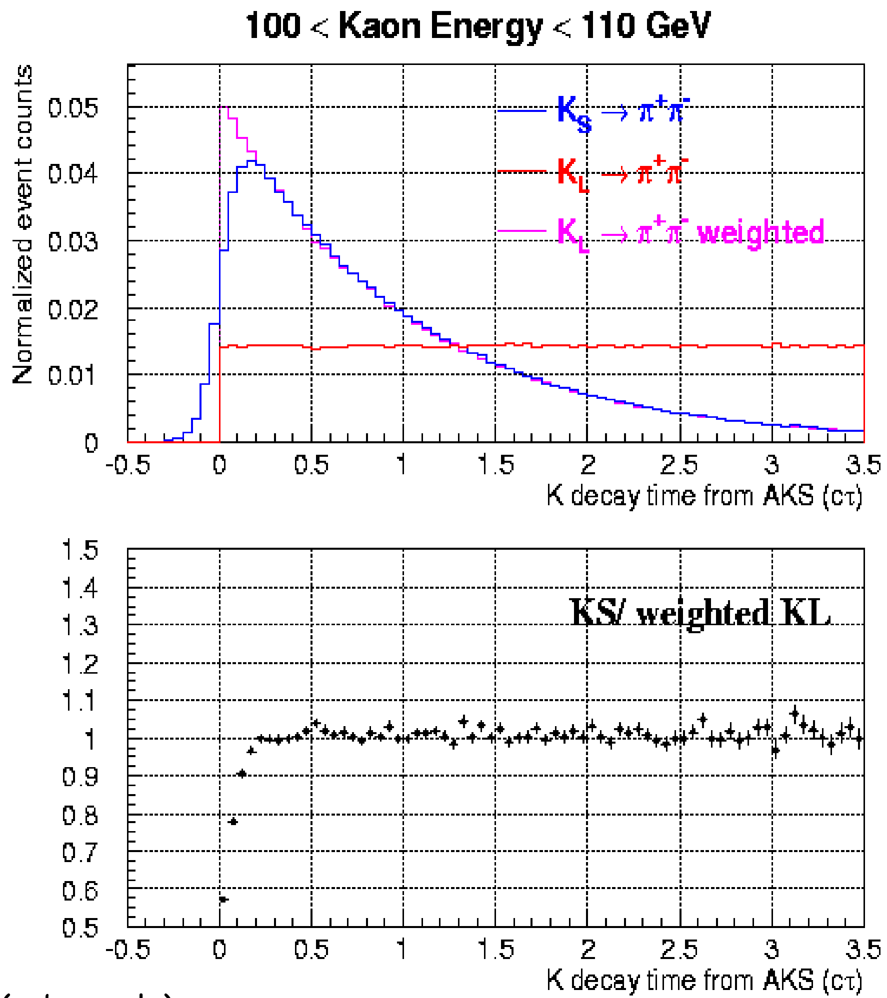
(one factor, independent of energy)

Stability with time better than $\pm 5\times10^{-4}$

Summary on Decay Region Definition

	$\Delta(R)$ (in 10^{-4} units)
$\pi^+\pi^-$	
AKS position	± 2.0
Non gaussian response	± 2.0
Total	± 2.8
$\pi^0\pi^0$	
Energy scale	± 2.0
Non linearities	± 3.8
Transverse size	± 2.5
Non uniformities	± 1.5
Non gaussian response	± 1.2
Others (energy sharing …)	± 2.3
Total	± 5.8

Lifetime Weighting



(subsample)

At any given z:

acceptance $K_S \cong$ acceptance K_L .

But K_S and K_L have very different decay lengths

$$\tau_{KL} \approx 600 \times \tau_{KS}$$

⇒ different integrated acceptance for K_S and K_L and large correction on R

solution: weight K_L events with

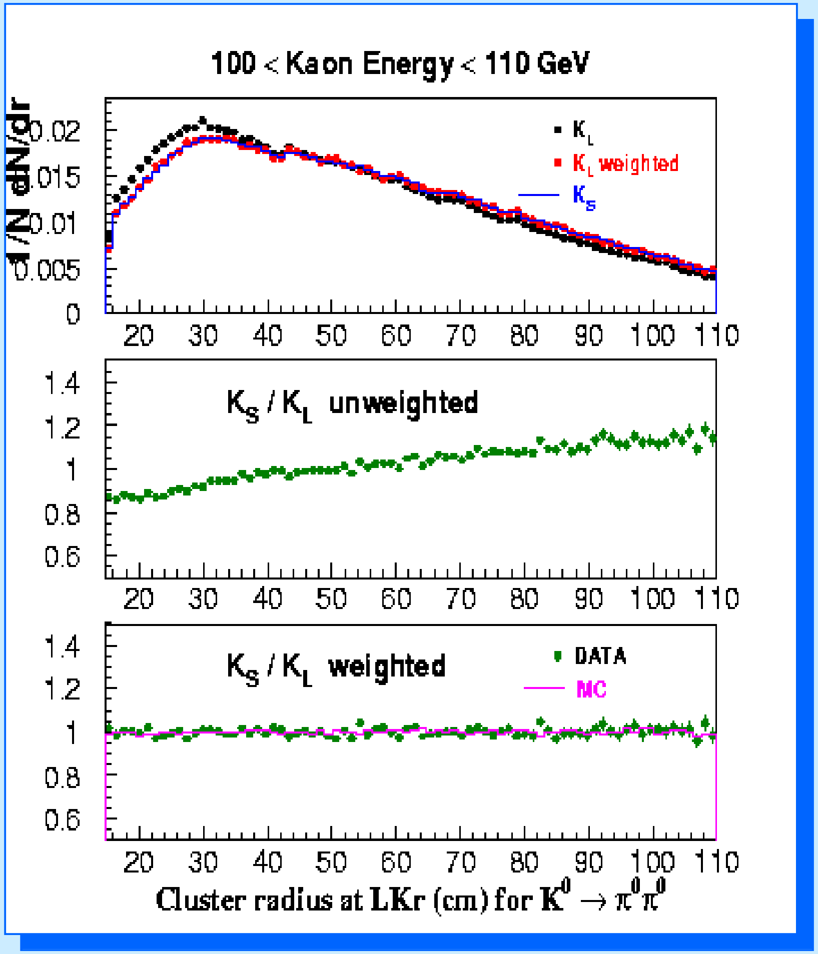
$$W = e^{-z/(\beta\gamma c)(1/\tau_S - 1/\tau_L)}$$

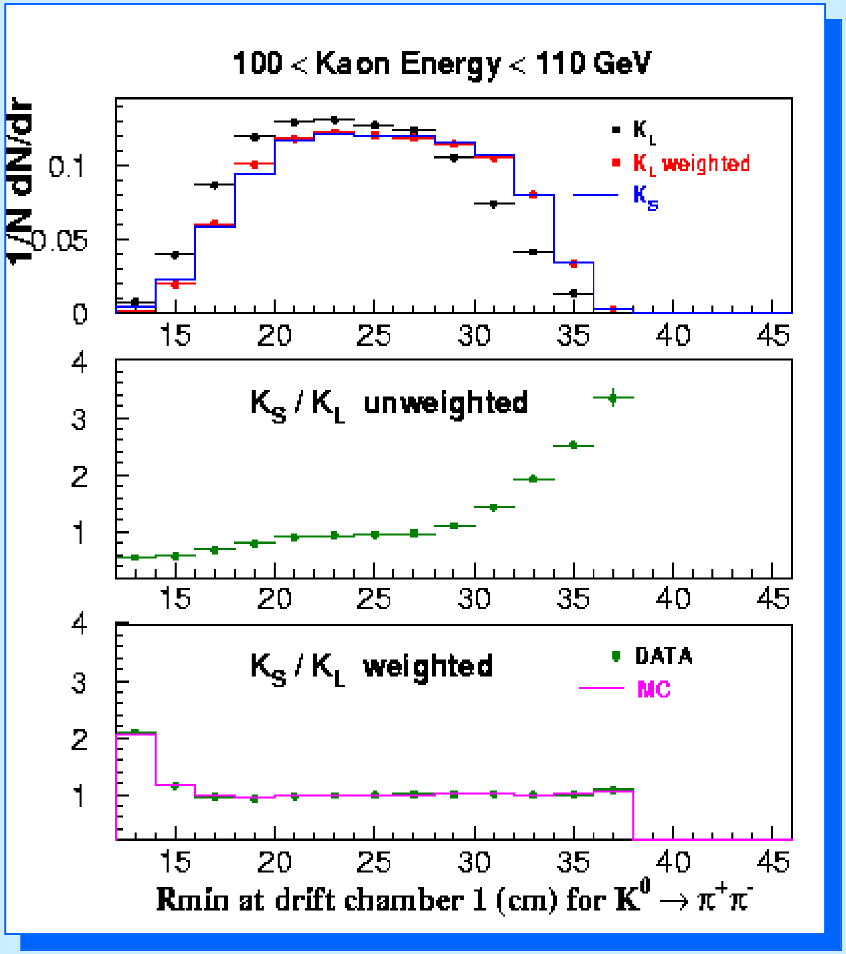
⇒ same decay vertex distribution for K_S and weighted K_L

⇒ same illumination of detector by decay products

Acceptance correction cancels at the price of an increase of the statistical error by factor ≅1.4

Detector illumination





After weighting, the illuminations are equal for K_L and K_S
(apart from limited effect in charged decays due to beam angles)

Acceptance Correction

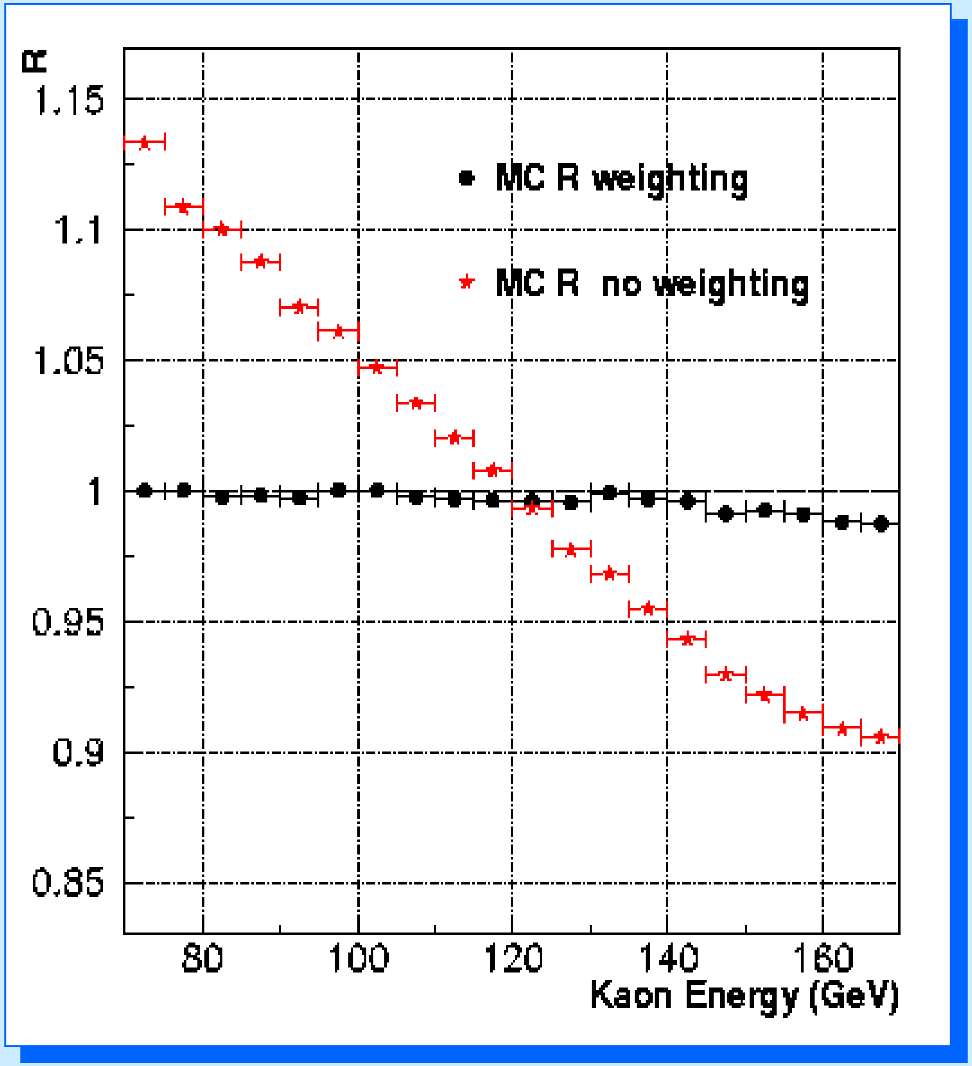
- **Acceptance correction :**

  +26.7 × 10^{-4}

- Uncertainties on R :
  - MC stat error : ± 4.1×10^{-4}
  - Systematic error :

    ± 4.0×10^{-4} due to:

    - beam positions and shapes: ± 3.3×10^{-4}
    - Comparison of fast MC with GEANT based spectrometer simulation: ± 2.3×10^{-4}



Accidental Activity

Event losses cancel accurately in R because of simultaneous data taking in four modes

Residual effect: $\Delta R \approx \Delta(\pi^0\pi^0 - \pi^+\pi^-) \times \Delta(K_L - K_S)$

$\Delta(\pi^0\pi^0 - \pi^+\pi^-)$ minimized by applying dead time conditions to all modes (accidental losses $\cong$ 1 – 2 %, studied with random events overlaid with data and Monte Carlo)

$\Delta(K_L - K_S)$ small because K_L and K_S events see the same accidental activity, within 1% (checked directly with data), and because lifetime weighting produces equal detector illumination for K_L and K_S events

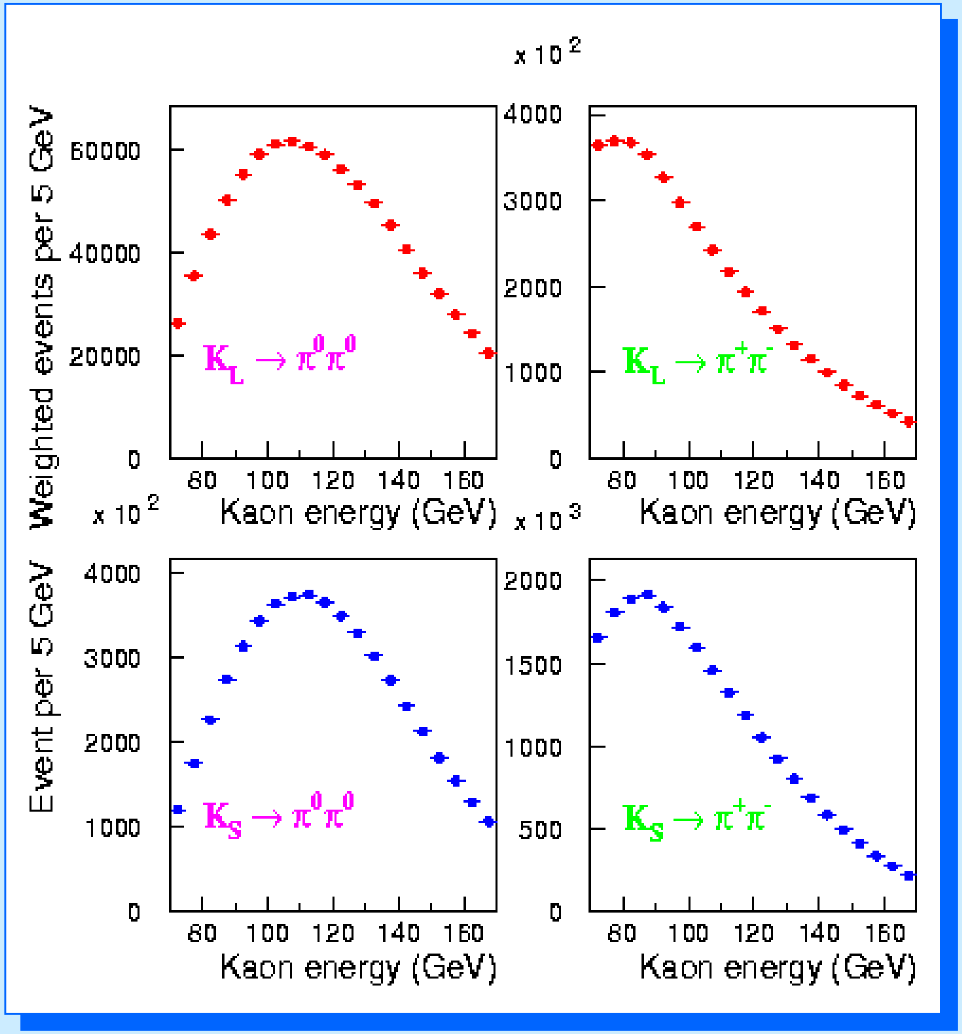
Correction to R : $\Delta R = (0 \pm 4.4) \times 10^{-4}$

Summary of corrections and systematic errors

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

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

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

Data Analysis

- Measure R in Kaon energy bins (5 GeV wide)

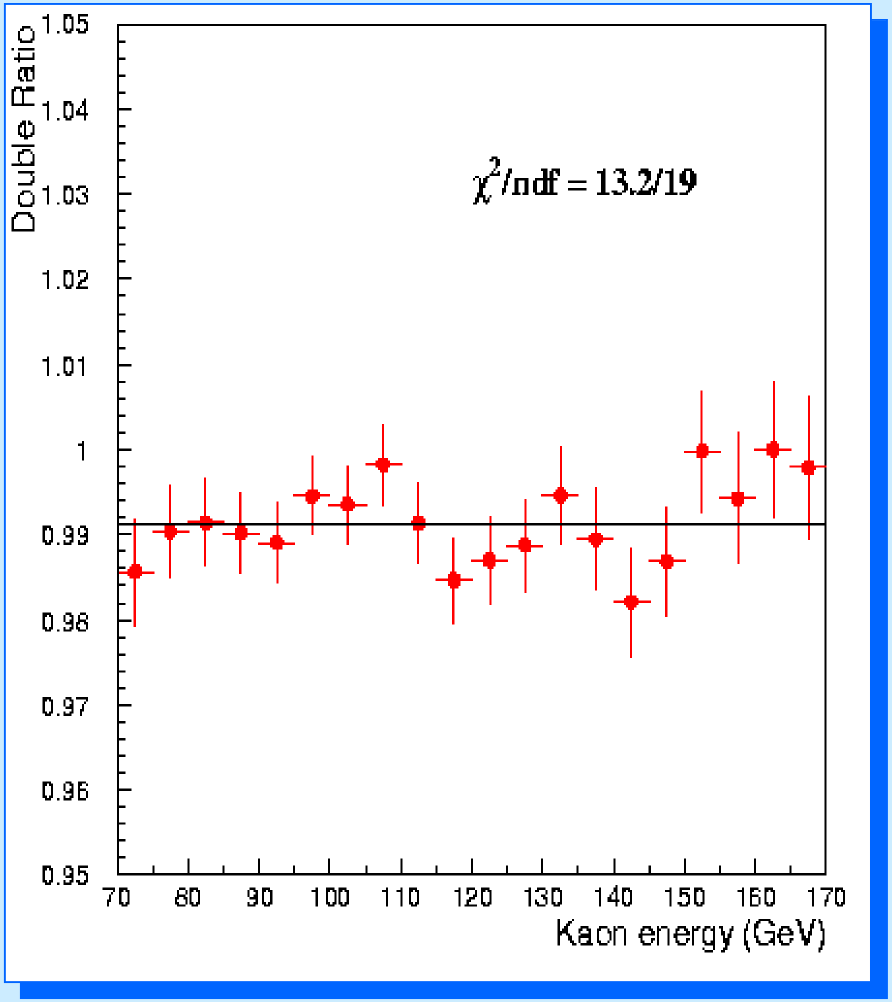
  ⇒ insensitive to K_S–K_L difference in energy spectrum

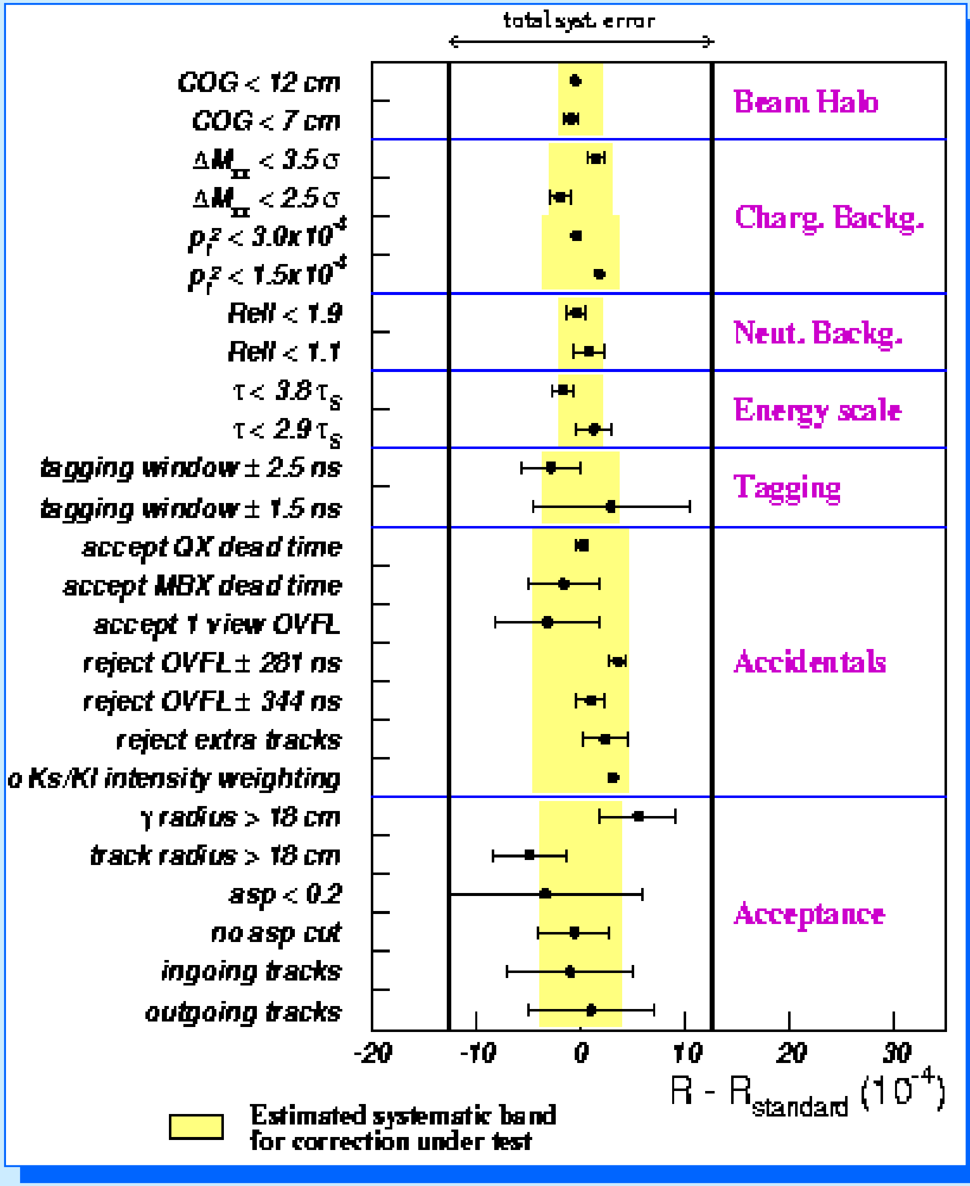
- Apply lifetime weighting to K_L
- Record dead time conditions
  - 1.5% from $\pi^+\pi^-$ trigger
  - 21.5% from drift chamber multiplicity limit

and apply them offline to $\pi^o\pi^o$ too ⇒ Minimize effect of K_S–K_L beam intensity difference

Result and systematic checks

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





Result

From (1-R)/6, we determine from 98 and 99 data :

$$\varepsilon' / \varepsilon = (15.1 \pm 2.7)\ 10^{-4}$$

Combining with 97 result $(18.5 \pm 7.3)\ 10^{-4}$:

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

Direct CPV is established at 5.9 σ, and, with some algebra, we could say:

$$\frac{\Gamma(K^0 \to \pi^+\pi^-) - \Gamma(\overline{K^0} \to \pi^+\pi^-)}{\Gamma(K^0 \to \pi^+\pi^-) + \Gamma(\overline{K^0} \to \pi^+\pi^-)} = (5.0 \pm 0.9) \times 10^{-6}$$

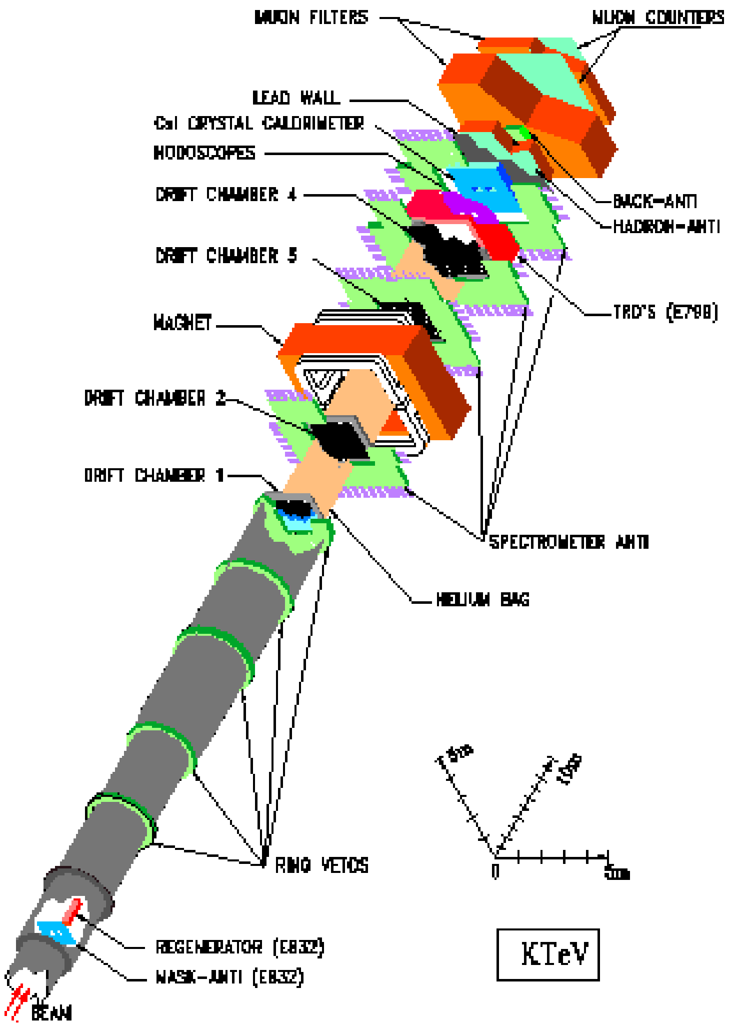
New results from Fermilab

The KTeV collaboration has just presented new results:

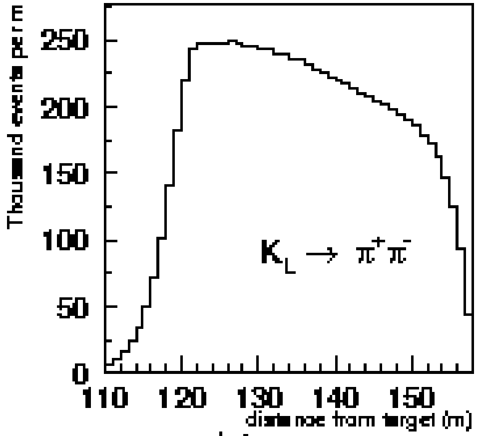
1. Re-analysis of 96-97 partial sample, published in 1999, now with revised result

2. Result of the analysis of the remaining 1997 sample

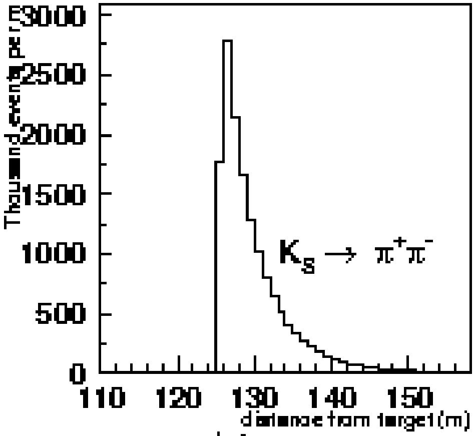
KTeV technique



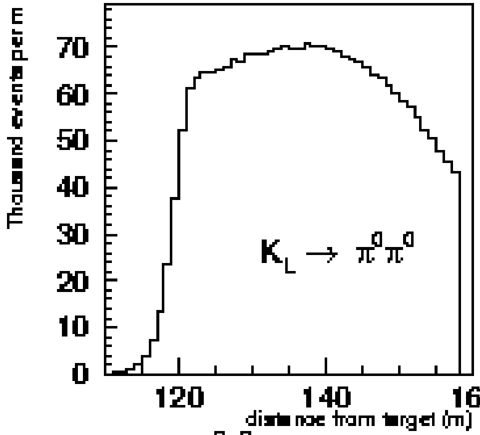
Decay identification by vertex ($\pi^+\pi^-$)
and CoG in calorimeter ($\pi^0\pi^0$)
Similar P but different Z spectra for L/S



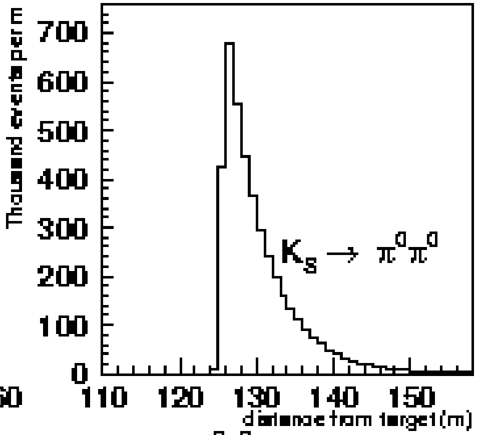
Vac $\pi^+\pi^-$ z distribution



Reg $\pi^+\pi^-$ z distribution



Vac $\pi^0\pi^0$ z distribution



Reg $\pi^0\pi^0$ z distribution

"Vacuum" beam $\to K_L$ beam

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

KTeV new results

1. Revised result: $\varepsilon'/\varepsilon = (23.2 \pm 4.4)\times10^{-4}$
   it was: $(28.0 \pm 4.1)\times10^{-4}$
   (-1.7 due to *mistake;* remaining: *better corrections*)

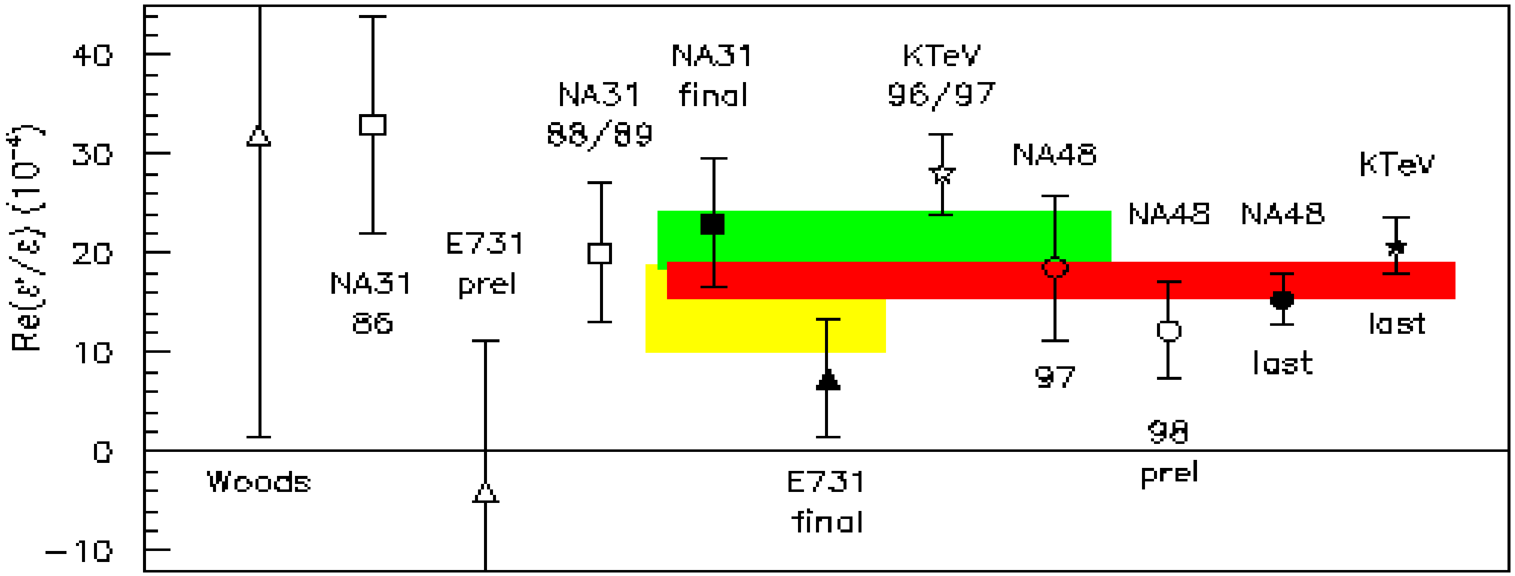
2. New sample : $\varepsilon'/\varepsilon = (19.8 \pm 2.9)\times10^{-4}$

3. KTeV new average: $\varepsilon'/\varepsilon = (20.7 \pm 2.8)\times10^{-4}$, or namely:

$$(20.7 \pm 1.5_{(stat)} \pm 2.4_{(syst)} \pm 0.5_{(MC\ stat)})\times10^{-4}$$

The main systematic errors include energy scale/linearity, neutral background, and acceptance.
[*The acceptance correction to R is about:* $(\approx480\pm7)\times10^{-4}$, *vs. NA48's:* $(27\pm6)\times10^{-4}$]

Experimental results comparison



Total average : ε' / ε = (17.3 ± 1.8) 10^{-4}

with $\chi^2/\mathrm{ndf} = 5.7/3$

Conclusions

- The average of the 4 last experiments (NA31, E731, KTeV and NA48) is:

$$\varepsilon'/\varepsilon = (17.3 \pm 1.8) \times 10^{-4}$$

(weighted average, with $\chi^2/\text{ndf} = 5.7/3$)

- This is a very significant improvement in resolution and consistency of results over 2 and 8 years ago

- Direct CP violation is established, and the experimental precision is challenging the computational accuracy of the Standard Model