La misura della Violazione Diretta di CP con l' Esperimento CERN/NA48

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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 eigen-states (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, $\to \pi\pi\pi, \pi l \nu$ ...)

Indirect CP Violation : $|\varepsilon| = (2.28 \pm 0.02) 10^{-3}$

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

Which requires: interference of two decay amplitudes (with different weak and strong phases)

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 $K^0 \to \pi\pi$

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

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

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

ε' : direct CP violation parameter

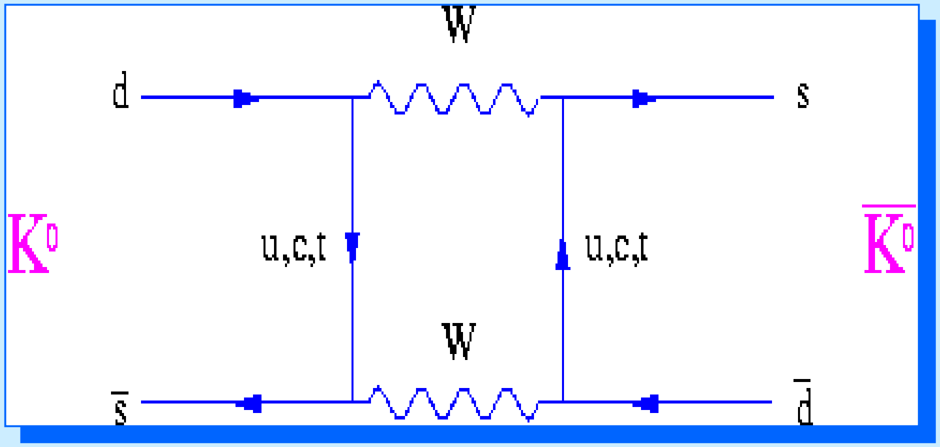
$$\varepsilon' = i\, e^{i(\delta_2-\delta_0)} (\mathrm{Re}A_2/\mathrm{Re}A_0)\,(\mathrm{Im}A_2/\mathrm{Re}A_2 - \mathrm{Im}A_0/\mathrm{Re}A_0)/\sqrt{2}$$

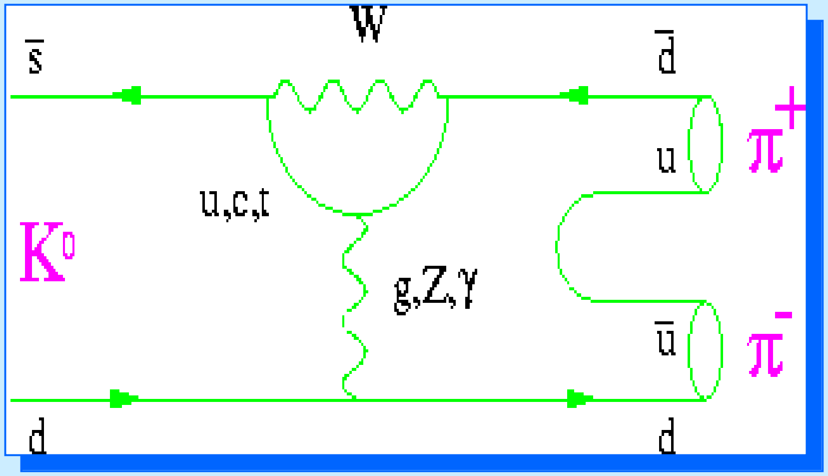
Experimental observable :

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

Standard Model predictions

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





Direct violation through decay
penguin diagram ε' 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) $(7.4 \pm 5.9) \times 10^{-4}$

  $(\varepsilon' / \varepsilon) \neq 0$? 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** $\chi^2/ndf = 10.4/3$

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

NA48 method and setup

Measure the double ratio:

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

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

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

$c\tau_S$	=	**2.67 cm**
$c\tau_L$	=	**15.5 m**

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

NA48 method and setup

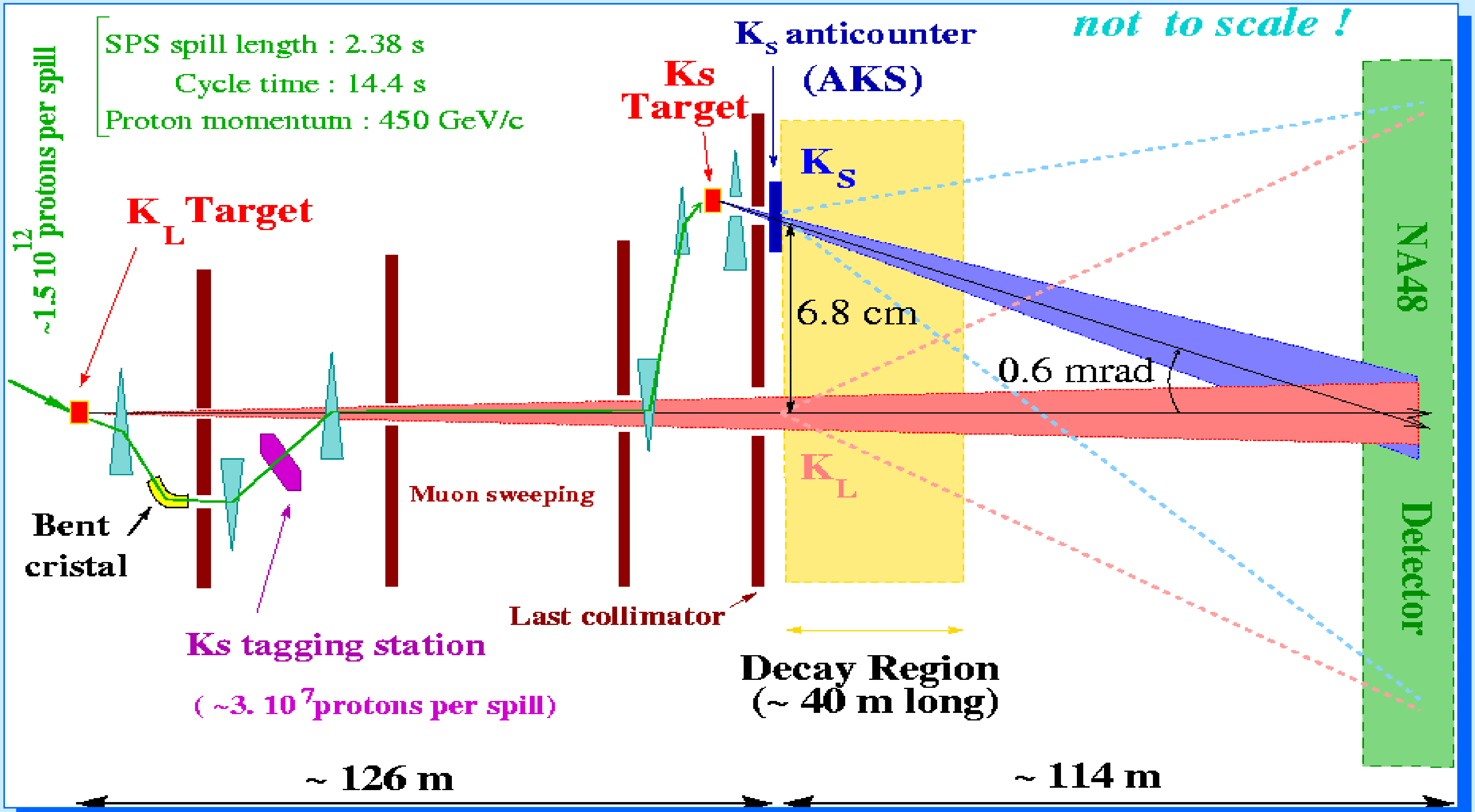
Strategy to minimize systematic effects:

- 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

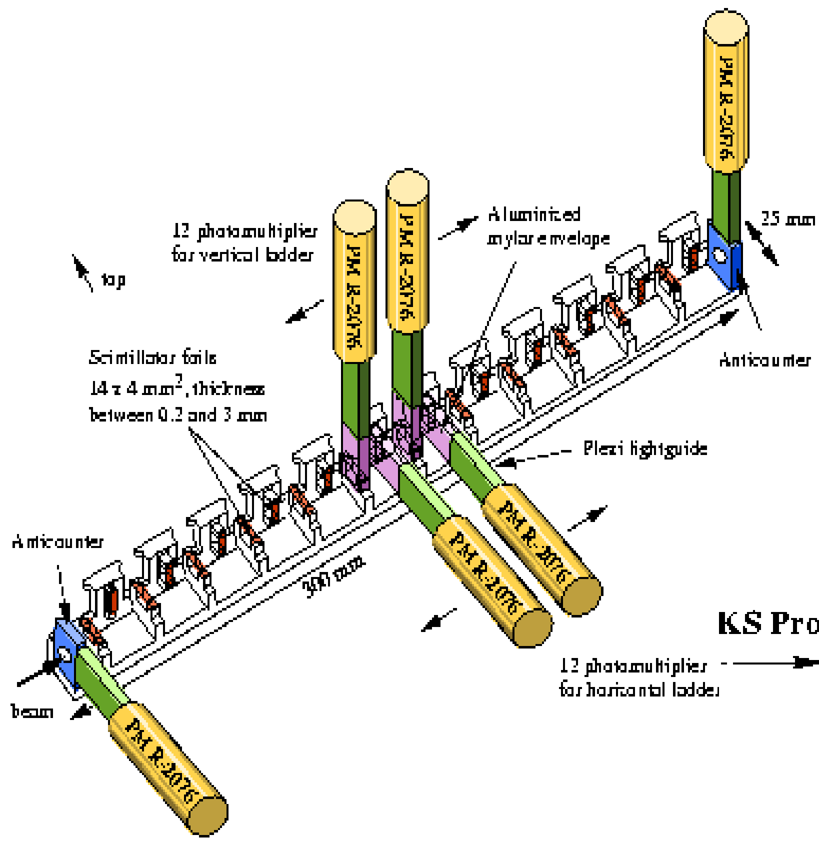
NA48 simultaneous and collinear K_L and K_S beams



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

The Tagger

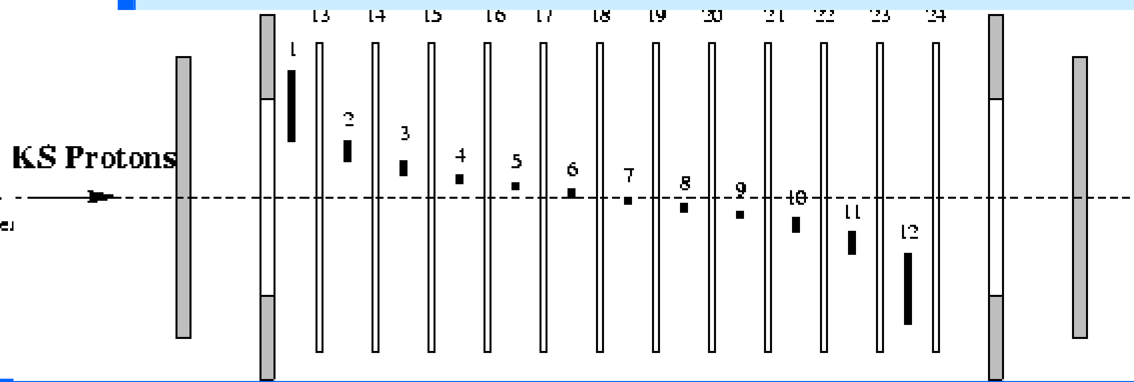
2x12 thin scintillator foils



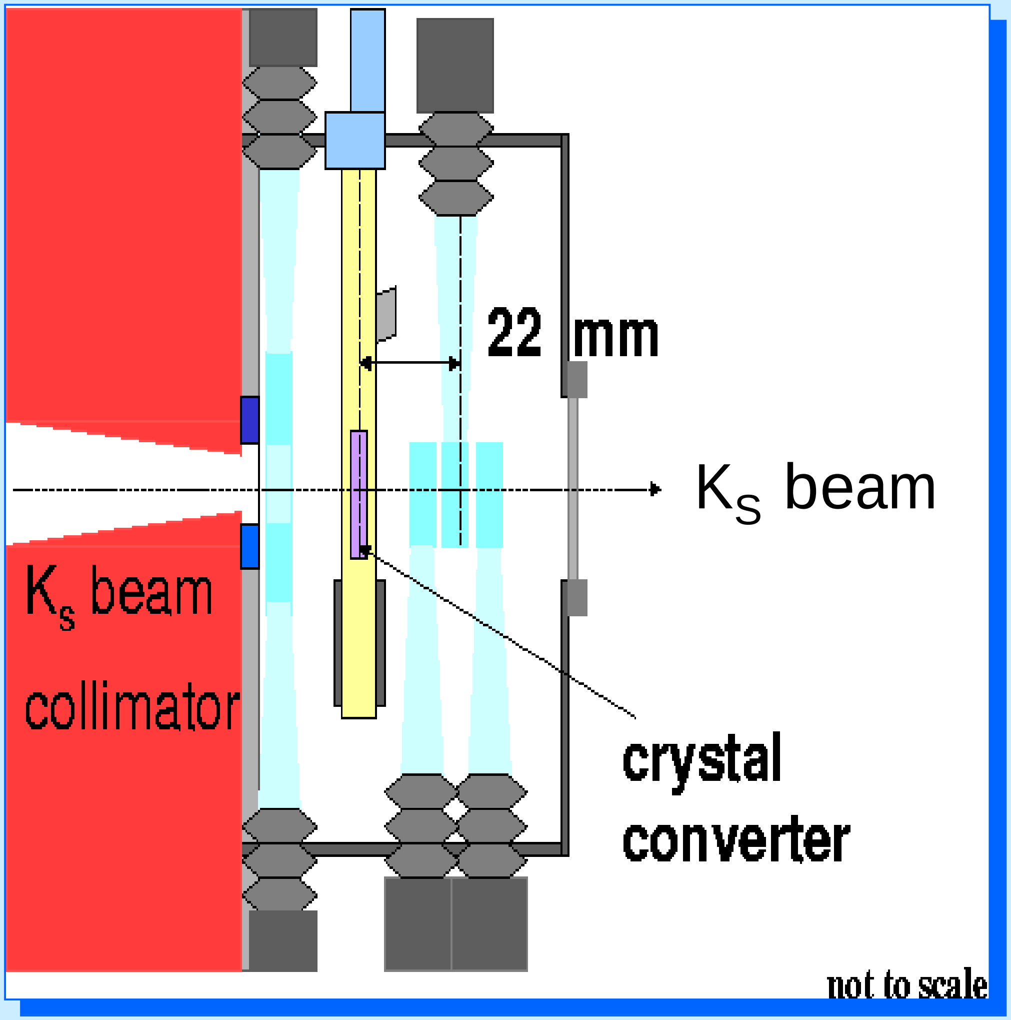
- Proton rate ≈ 30MHz → split the intensity between foils, readout by Flash ADC 8 bits at 960 MHz

  time resolution : 140 ps

  double pulse separation : 4 ns



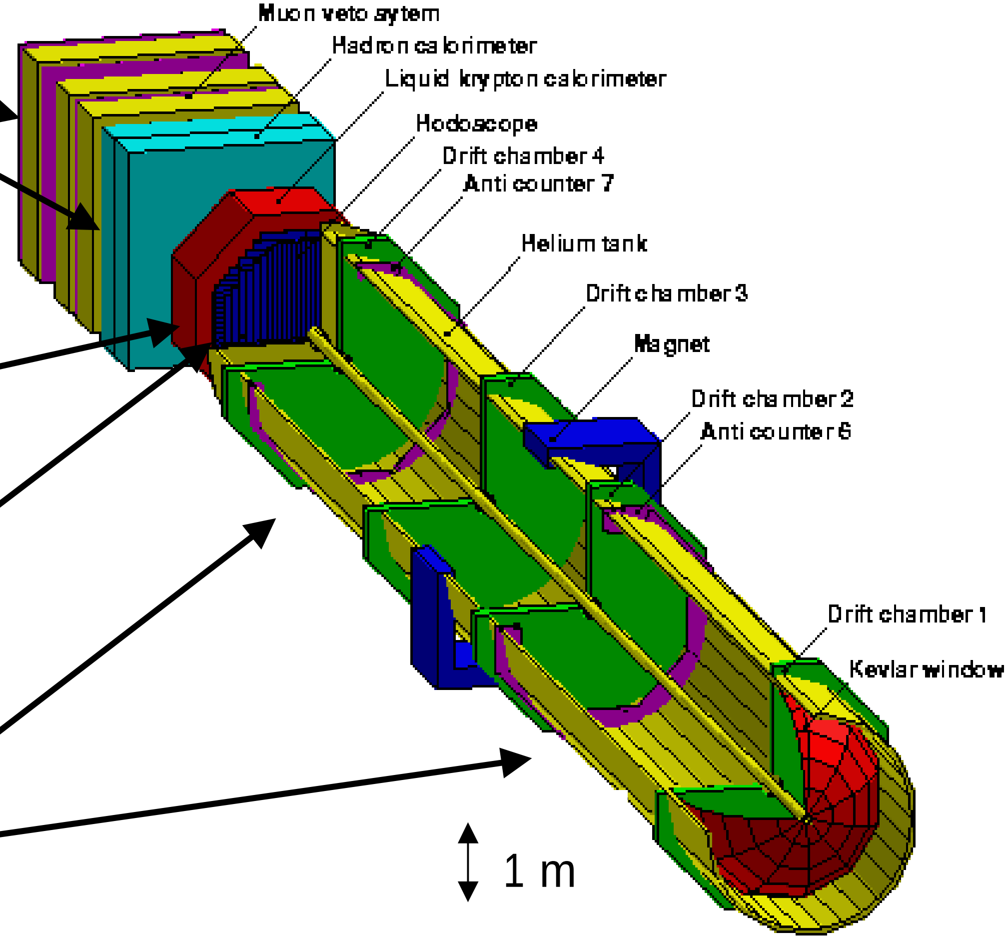
The AKS counter



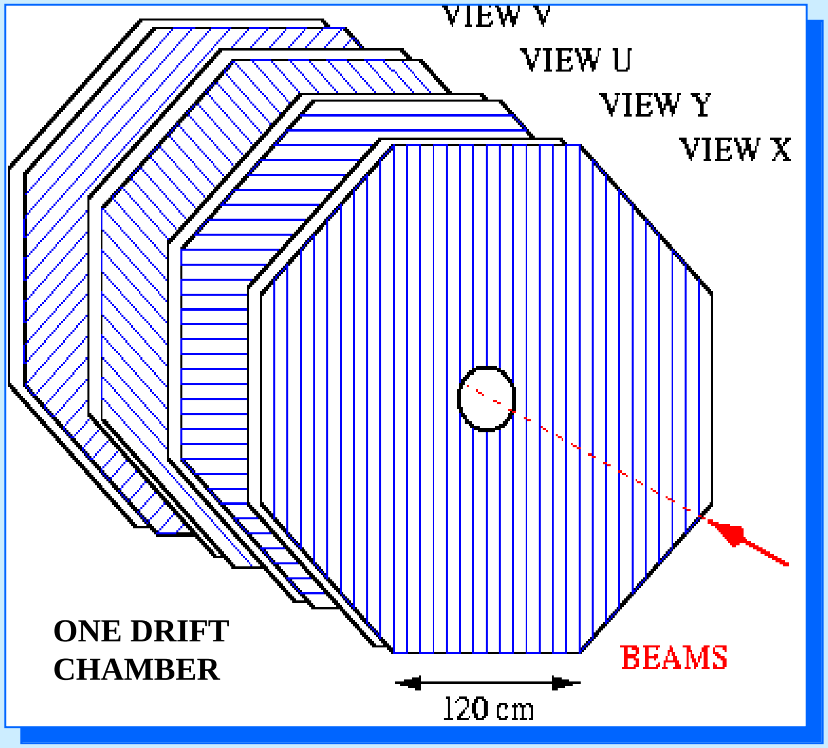
- Defines beginning of decay region for $\pi^+\pi^-$ and $\pi^0\pi^0$ K_S decays
- Plastic scintillation counters following a
- Photon converter :
  - iridium crystal 3mm thick , (22 $\pm$ 5) mm upstream of counter
    1.79 X_0 instead of
    0.98 X_0 for amorphous iridium

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



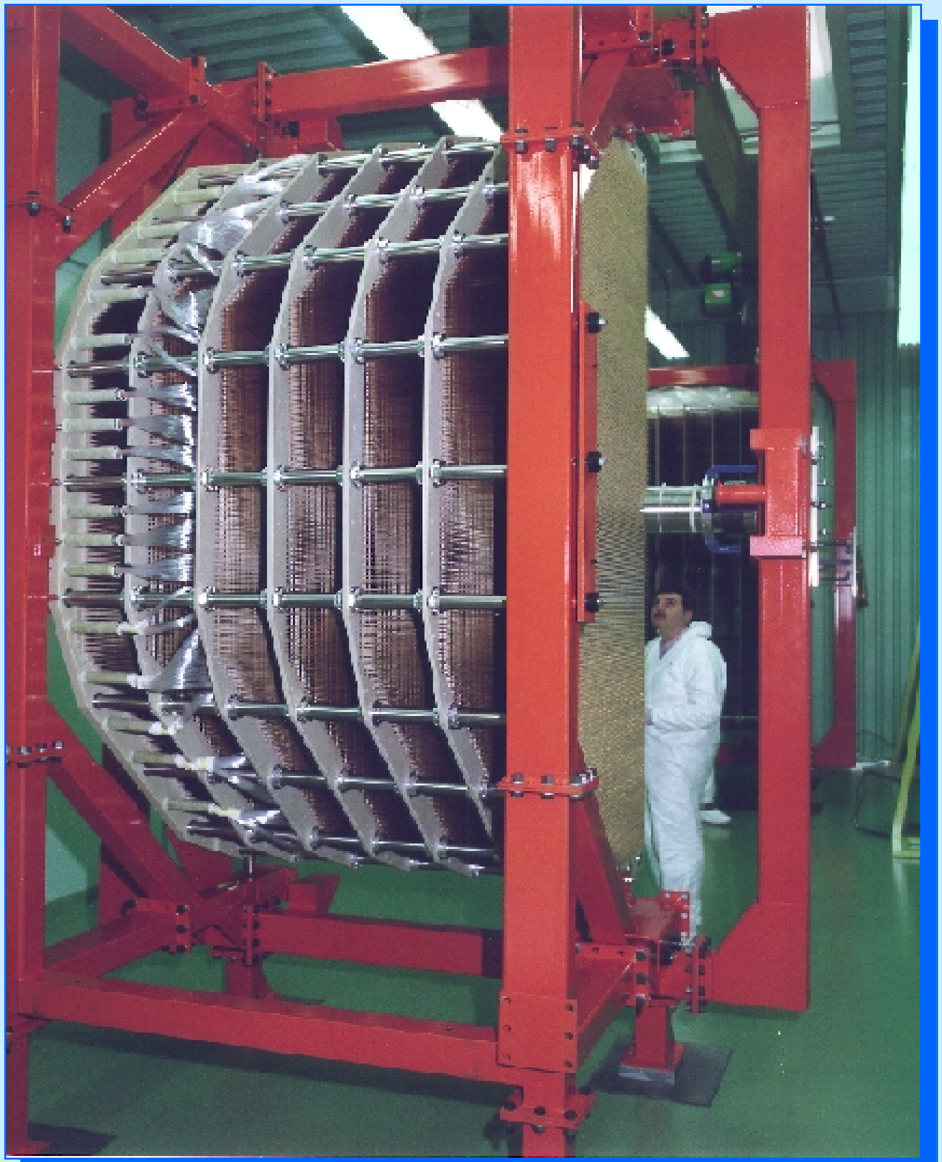
- 4 drift chambers
- Space point resolution $\approx$100 μm ;

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

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

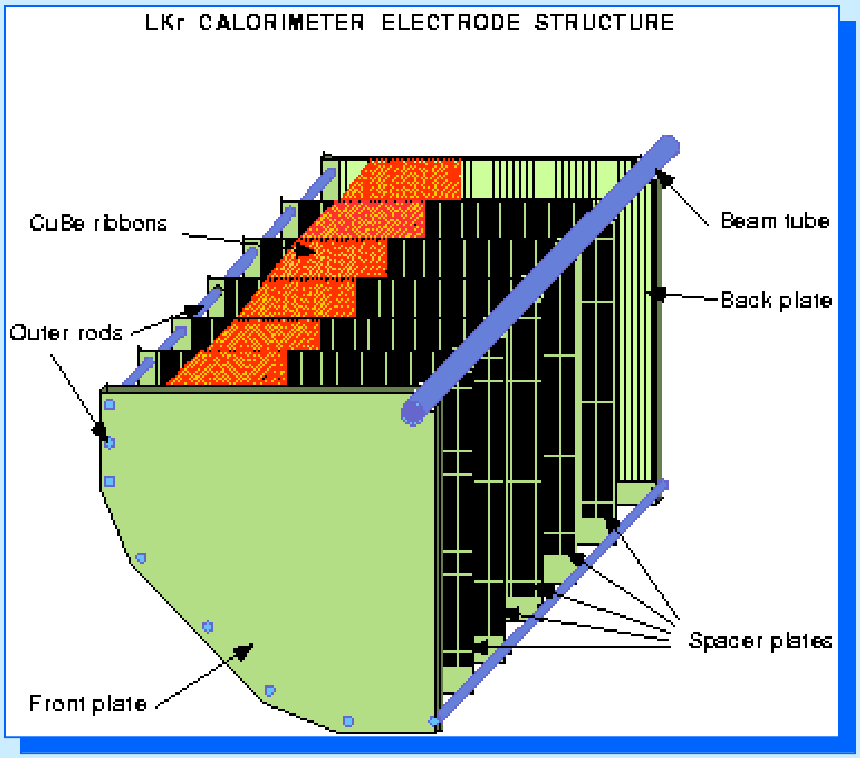
LKr electromagnetic calorimeter

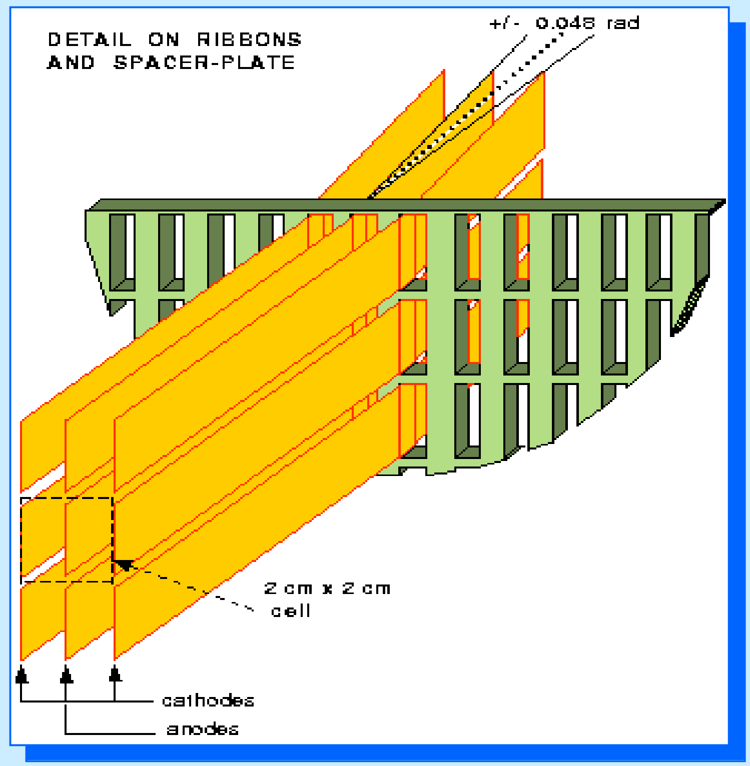
- Quasi-homogeneous detector
  - 10 m^3 liquid krypton (120 K);
  - (X_0 = 4.7 cm, R_M = 6.1 cm)
- 13,212 cells
  - granularity 2×2 cm^2
  - Depth 1.25 m (27 X_0)



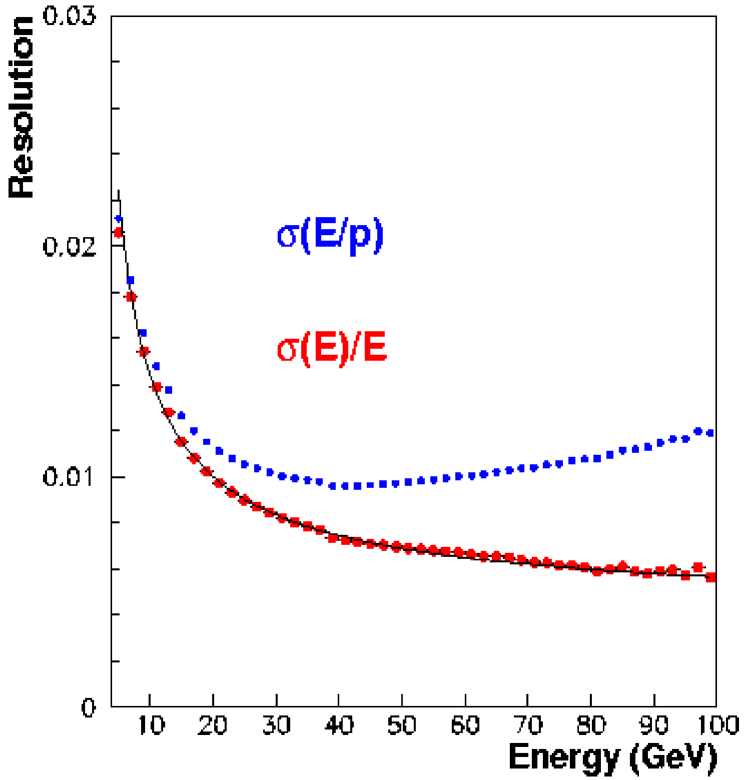
LKr electromagnetic calorimeter

- 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 ± 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 ± 0.022)% (from Level 1 triggers)

$\pi^+\pi^-$ selection

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

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

Backgrounds : Ke3(BR=39%), Kμ3 (BR=27%)

e and μ rejection

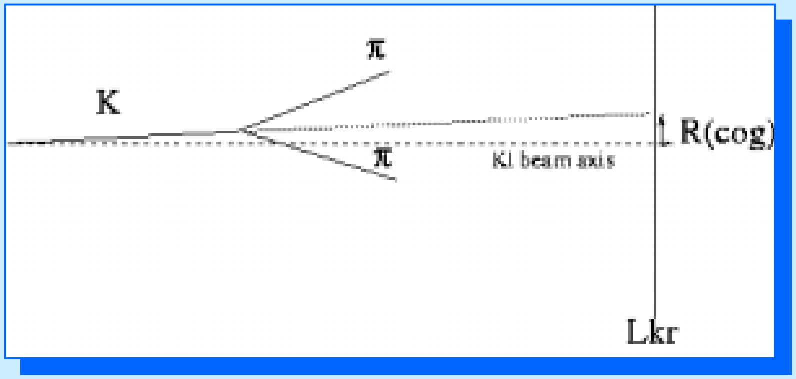
- E(LKr)/p < 0.8
- no hits in μ detector

Kinematical cuts

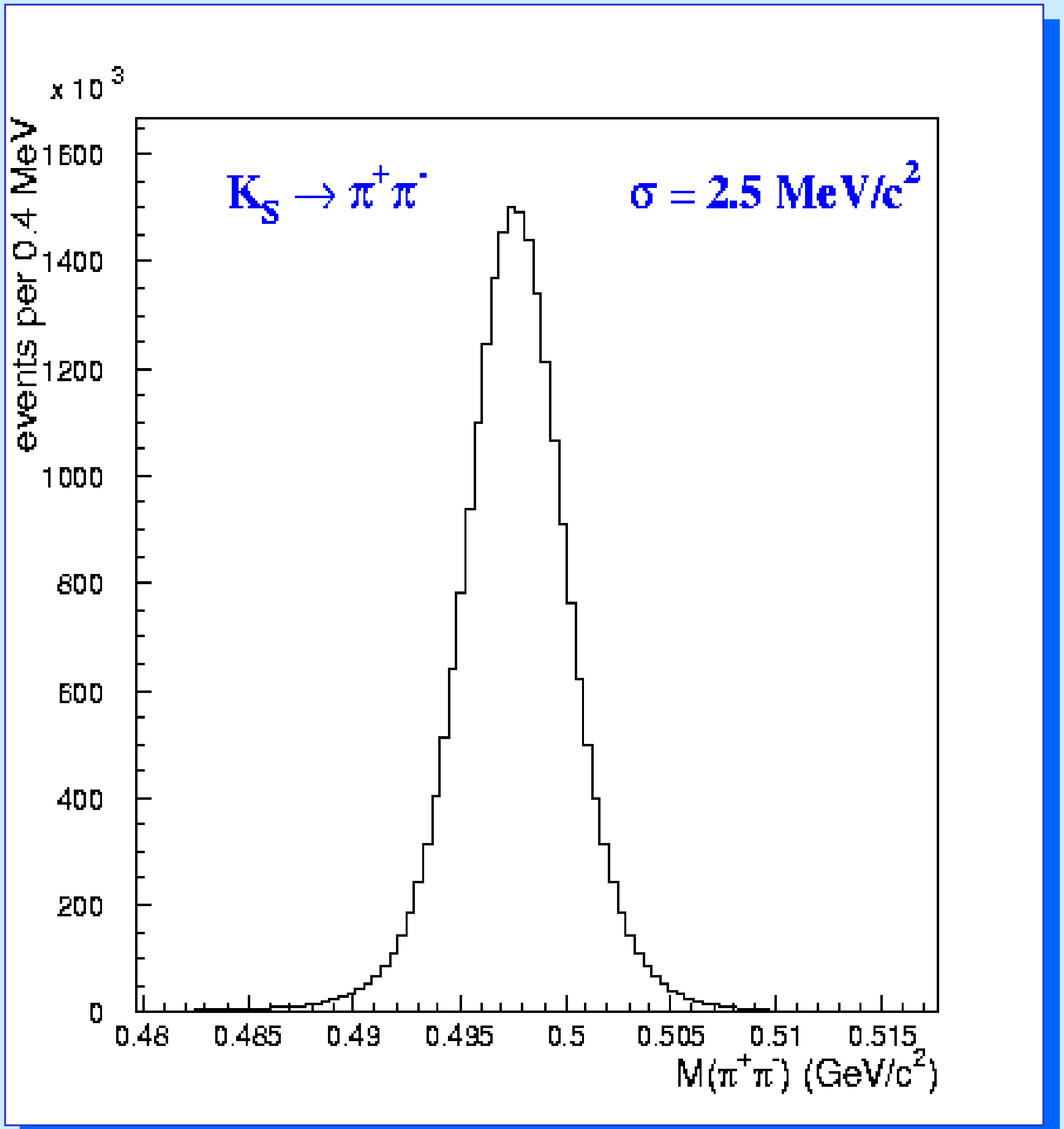
- $|M_{\pi\pi} - M_K| < 3 \cdot \sigma_M$, ($\sigma_M \approx 2.5$ MeV)
- $P_\perp'^2 < 200\ (\text{MeV}/c)^2$
  transverse momentum of $\pi^+\pi^-$ to the line between target and Kaon projection to spectrometer
  ≈ 0 for two body decay,
  > 0 for Ke3, Kμ3
- $|p_1 - p_2| / p_1 + p_2 <$ min (0.62,1.08-0.0052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

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

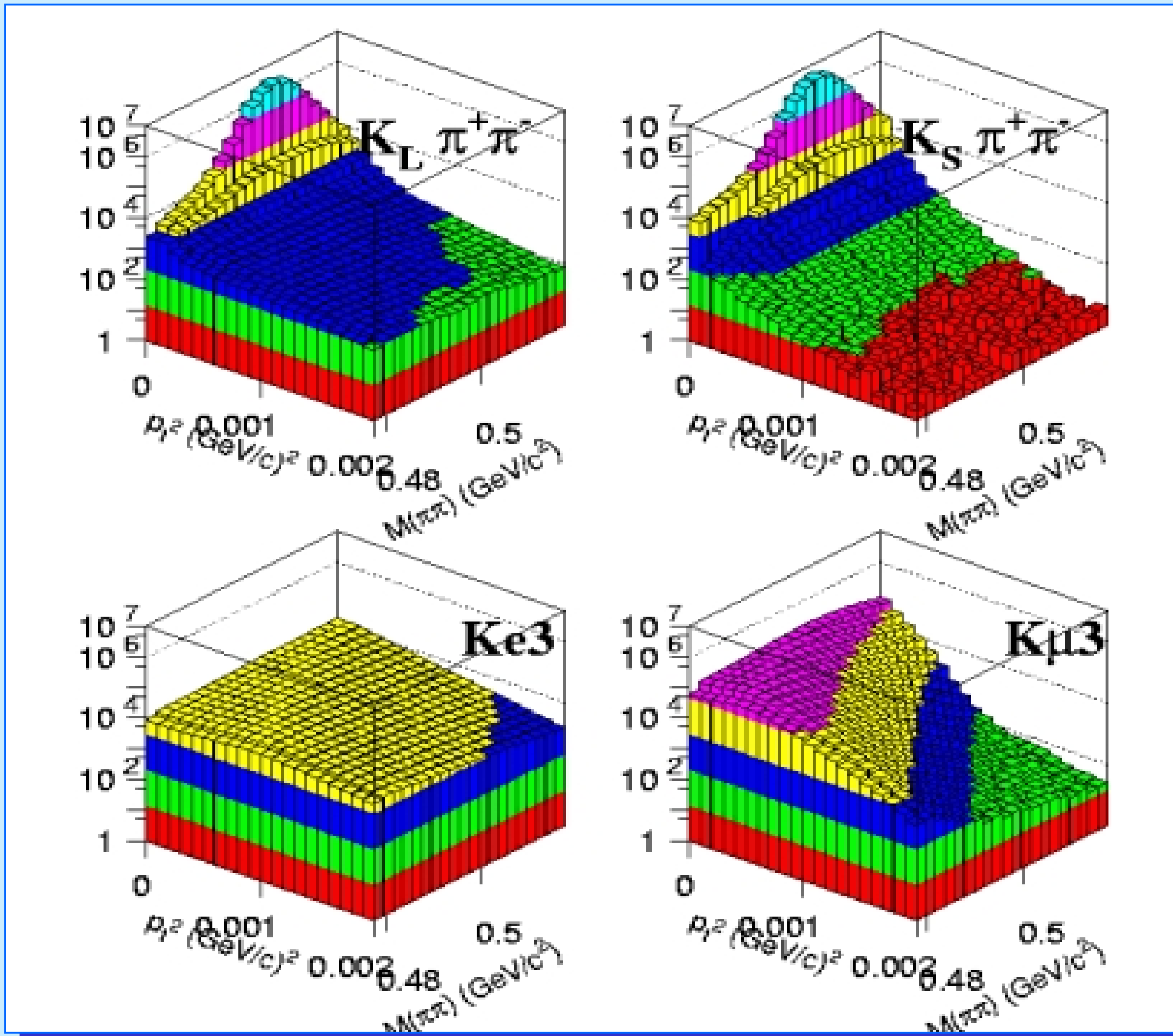
Kaon impact point extrapolated to the calorimeter COMMON WITH $\pi^o\pi^o$



$\pi^+\pi^-$ 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

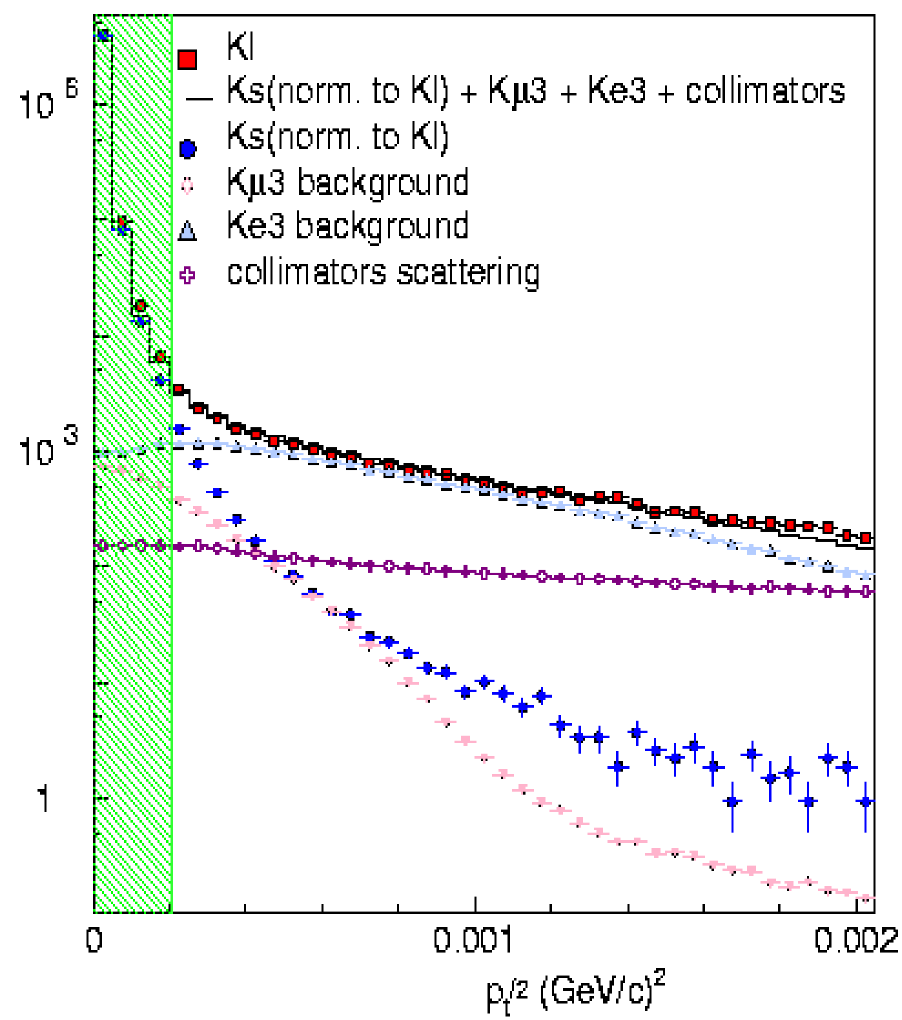
In the signal region ($M_{\pi\pi}$ and $P_\perp'^2$ cuts), the background is due to Ke3, Kμ3

and a smaller fraction of collimator scattered Kaons (partially asymmetric in $\pi^+\pi^-$ and $\pi^0\pi^0$)

Background = $(16.9 \pm 3.0)\ 10^{-4}$

(systematic error :

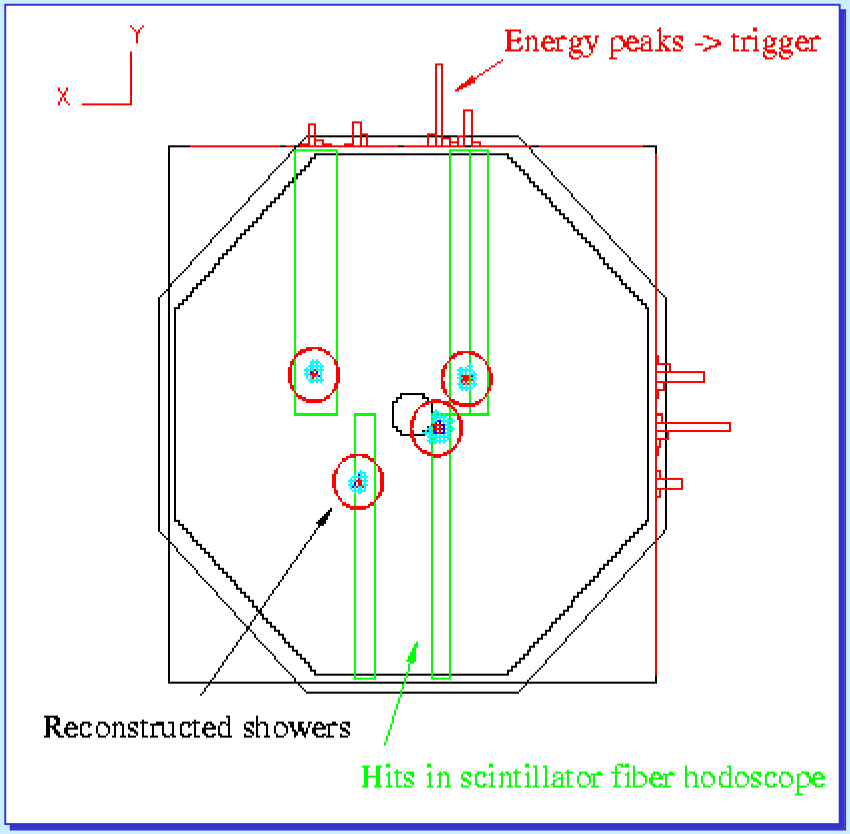
- changes in control regions,
- modeling of $P_\perp'^2$ shape)



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

$$D = z_{LKr} - z_{decay}$$

$$= 1/M_K \sqrt{\quad_{ij} E_i E_j d_{ij}^2}$$

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

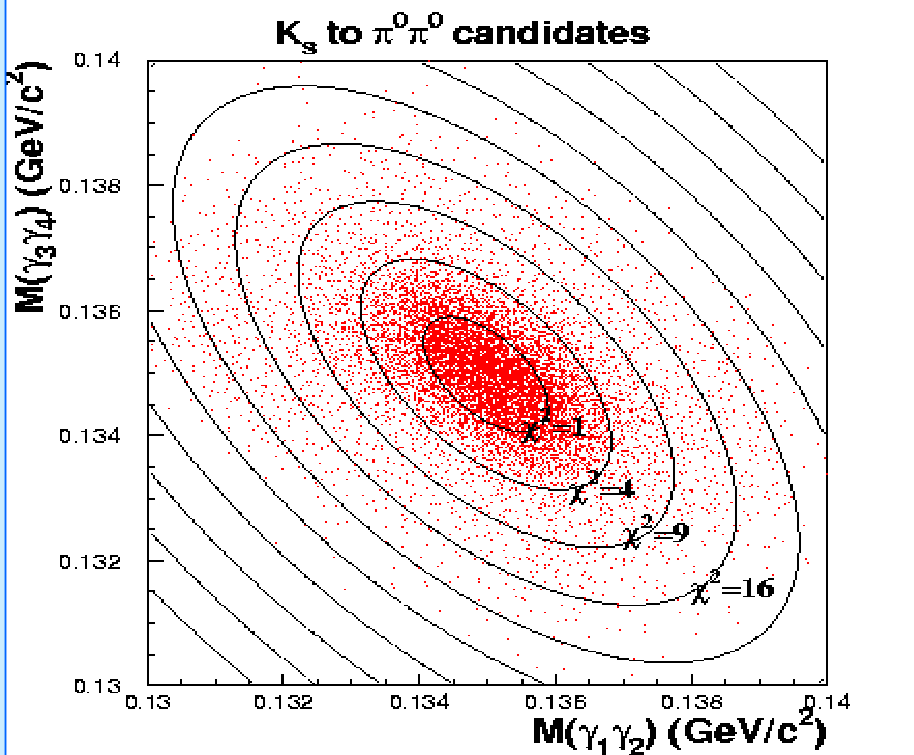
$K_L \to \pi^0\pi^0$: BR ≈ 0.09%

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.

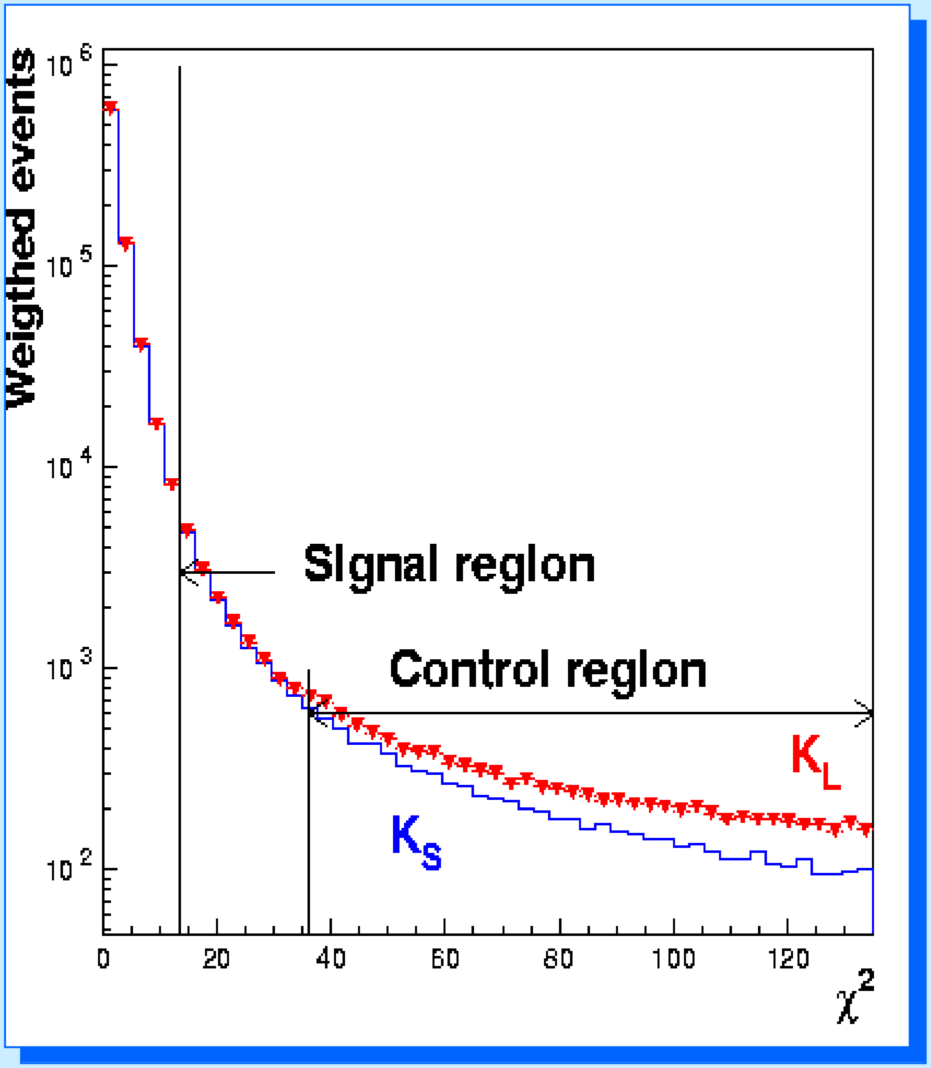
($3\pi^0$ background is ≈ flat)

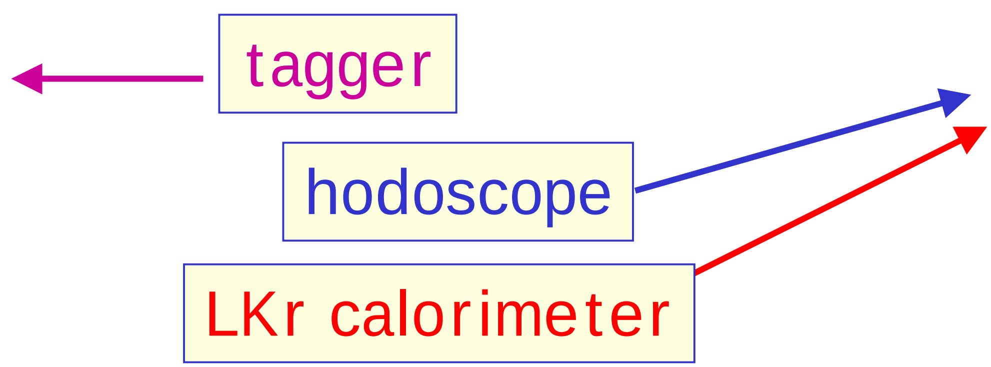
$\pi^0\pi^0$ contribution in control region from resolution tails is derived from K_S events.

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

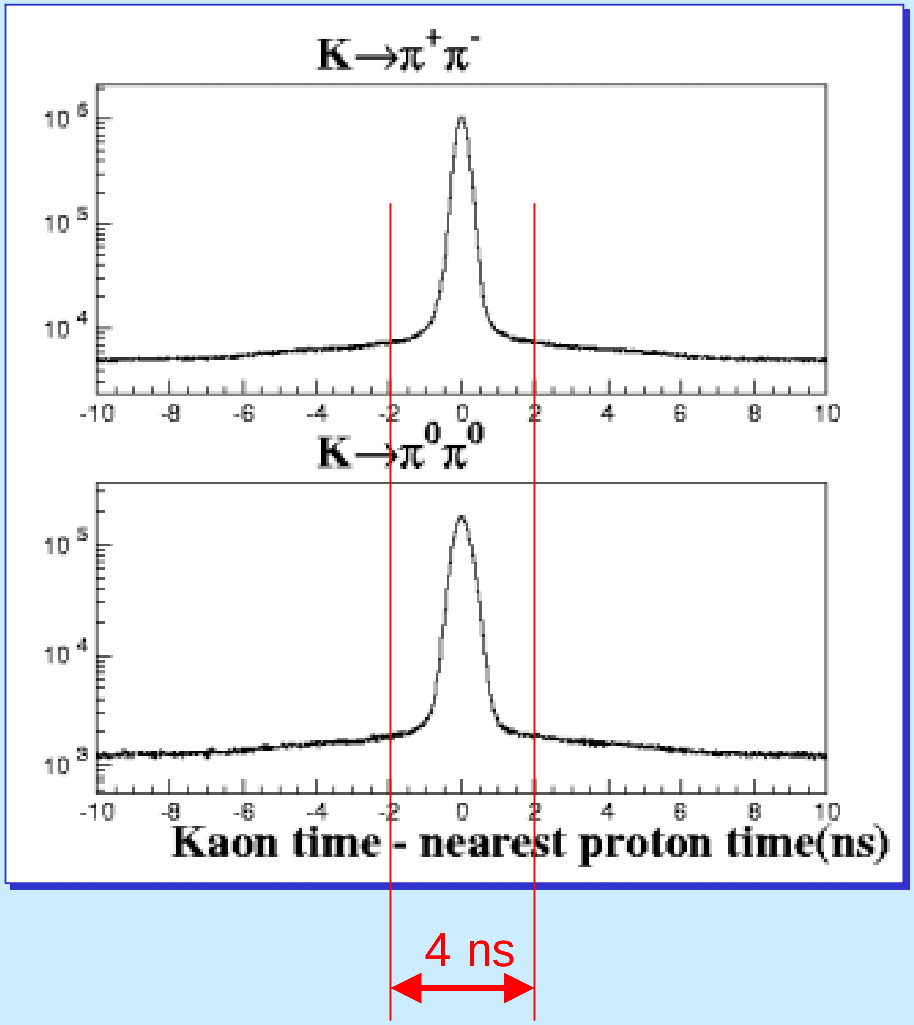
(systematic error : uncertainty in background extrapolation)

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

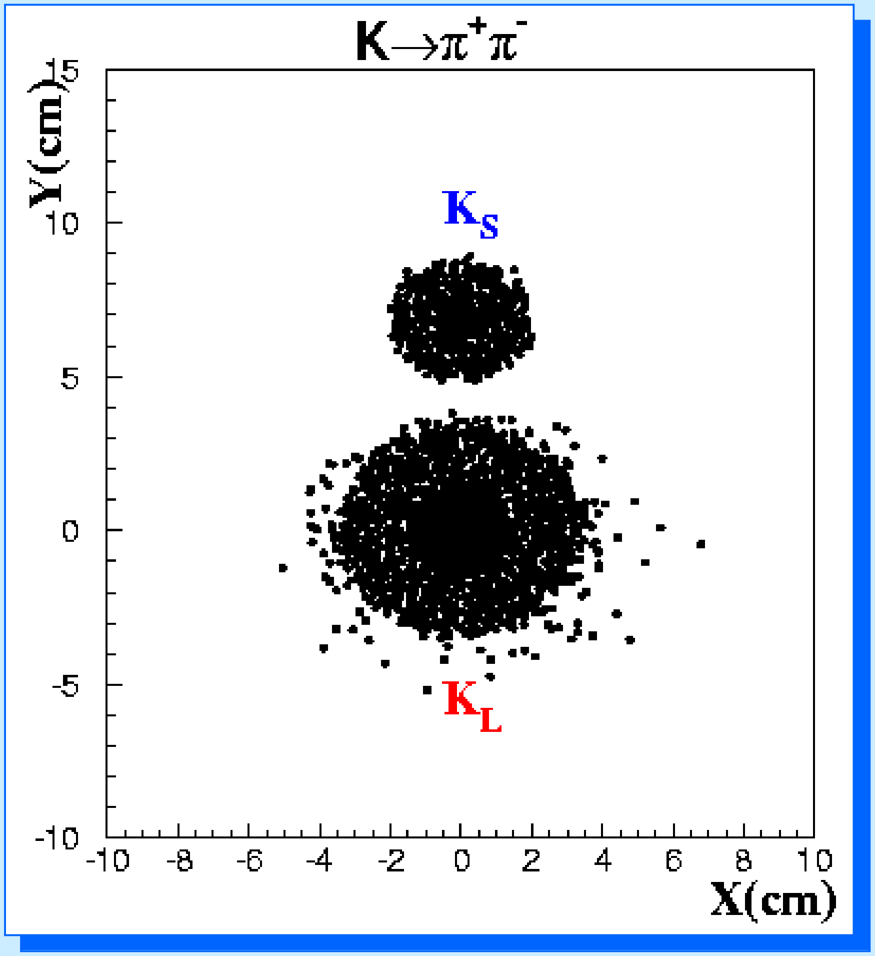
Two possible kinds of mistake :

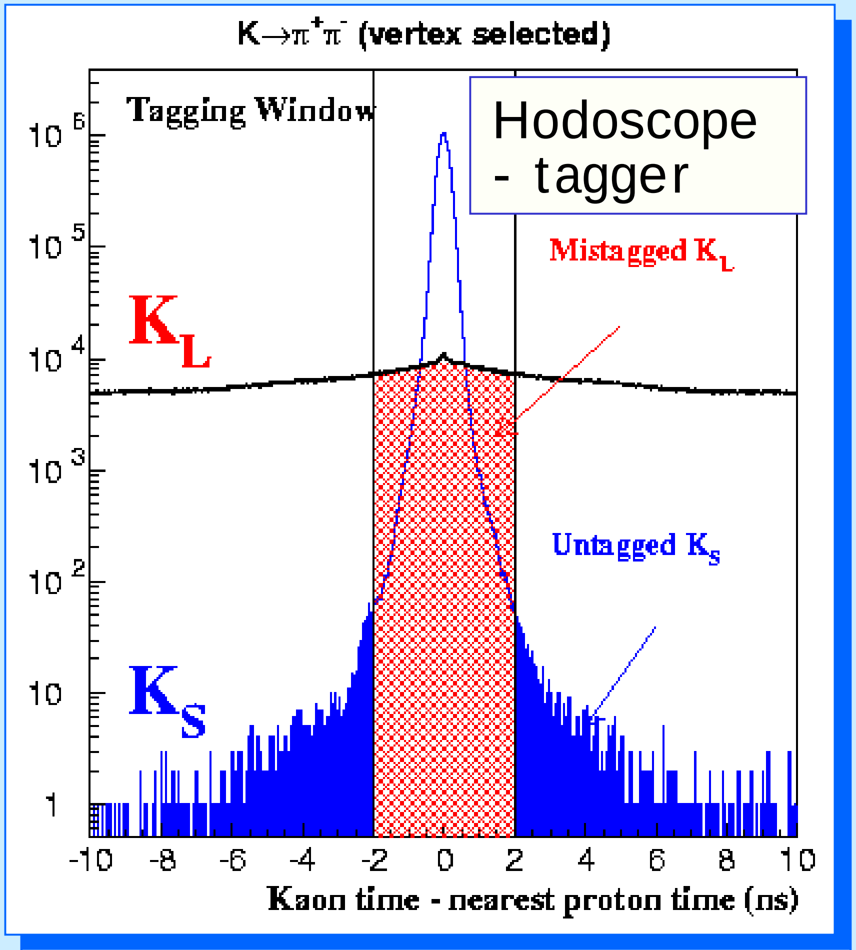
– K_S mistagged as K_L : probability α_{SL}
[inefficiency in time measurement by tagger counter or main detector (=trigger hodoscope or calorimeter): α_{SL}^{+-} and α_{SL}^{oo}]

– 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}^{oo} - 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:

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

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

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

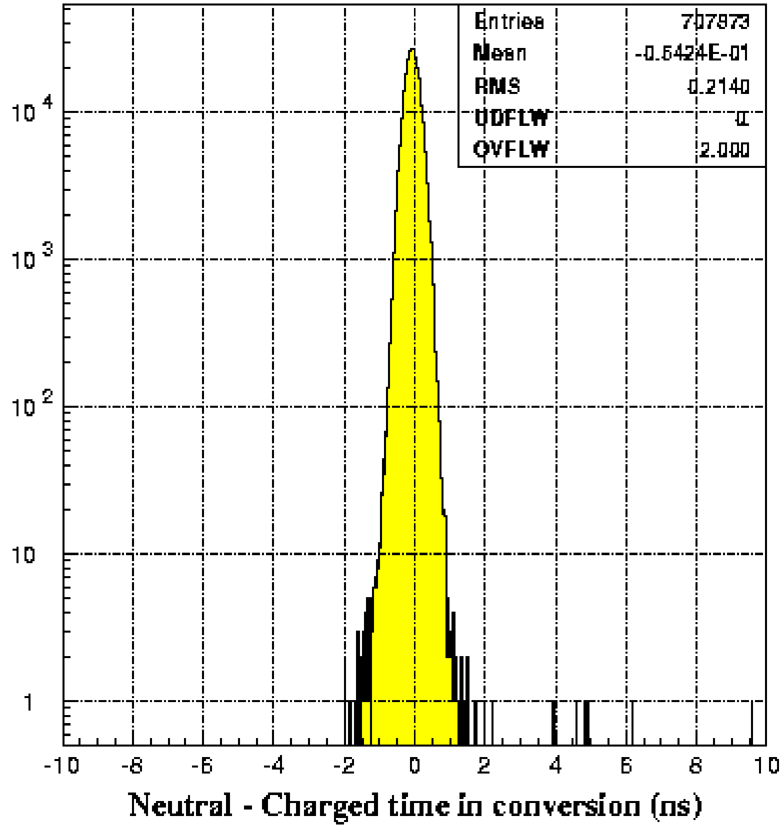
Measuring $\Delta\,\alpha_{SL}$

- 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



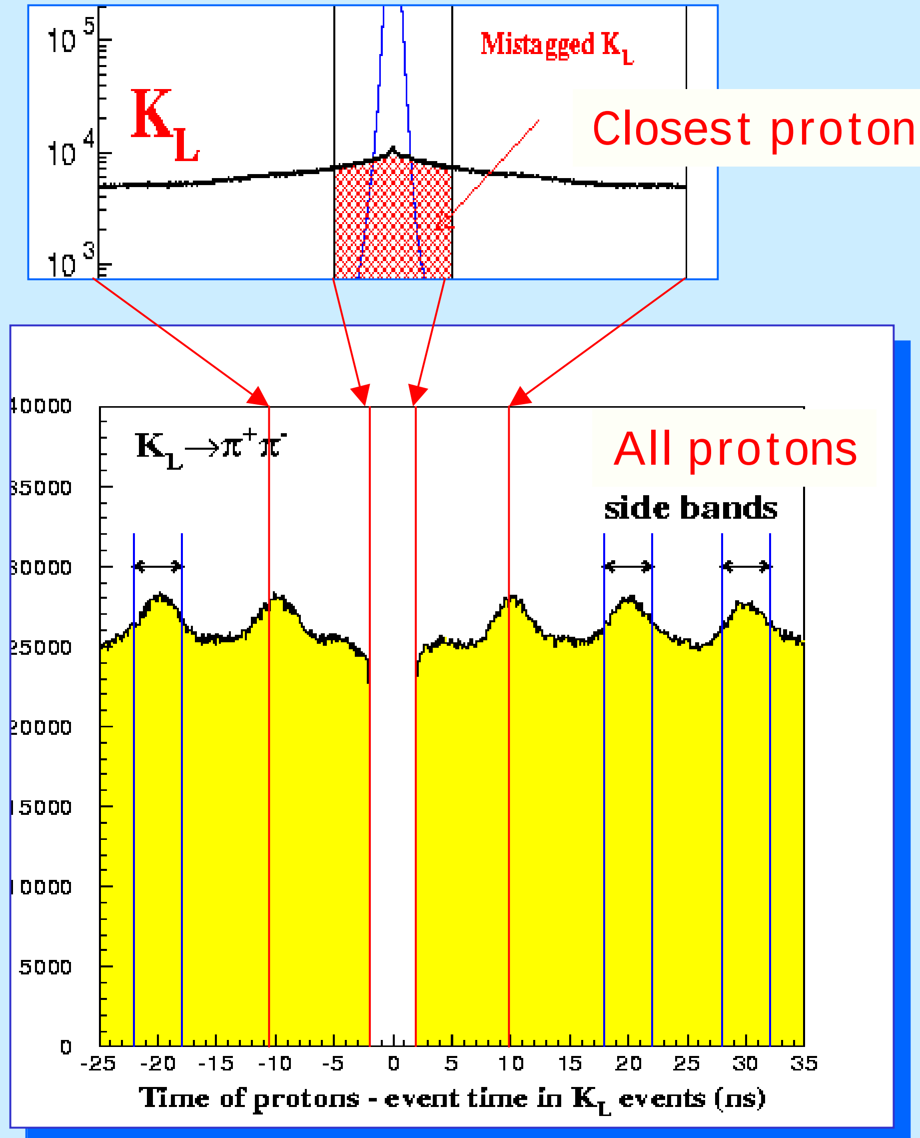
$$\Delta\alpha_{SL} = (0. \pm 0.5)\ 10^{-4}$$

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

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

	Δ(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:

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

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

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

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)

$\pi^0\pi^0$

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

= (Energy scale)

× (Transverse size scale)

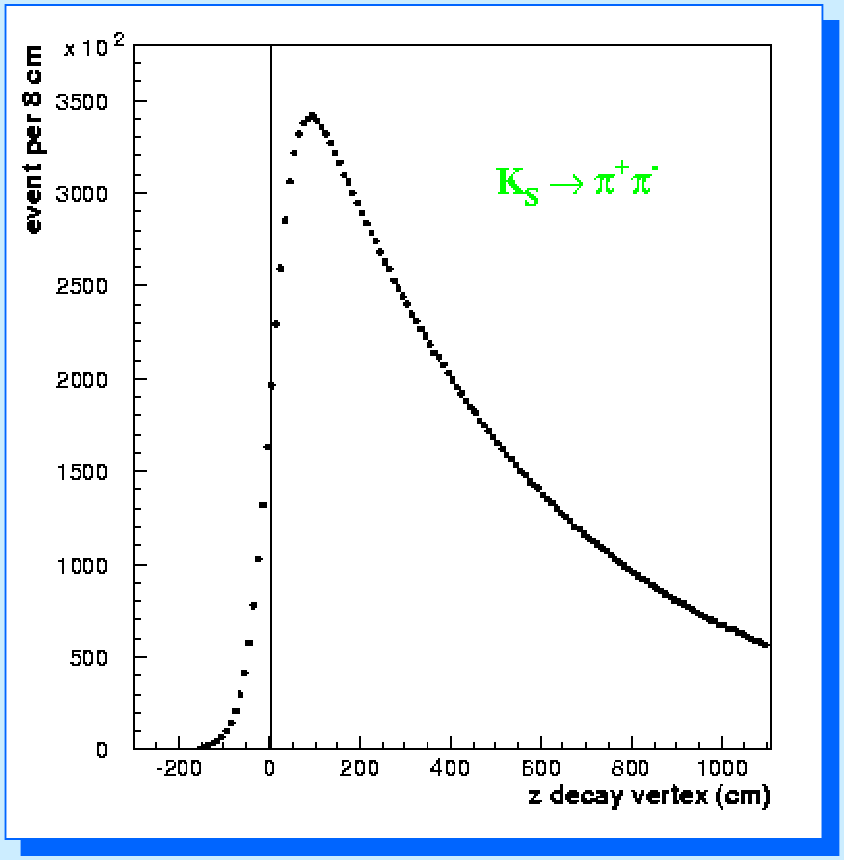
Energy scale

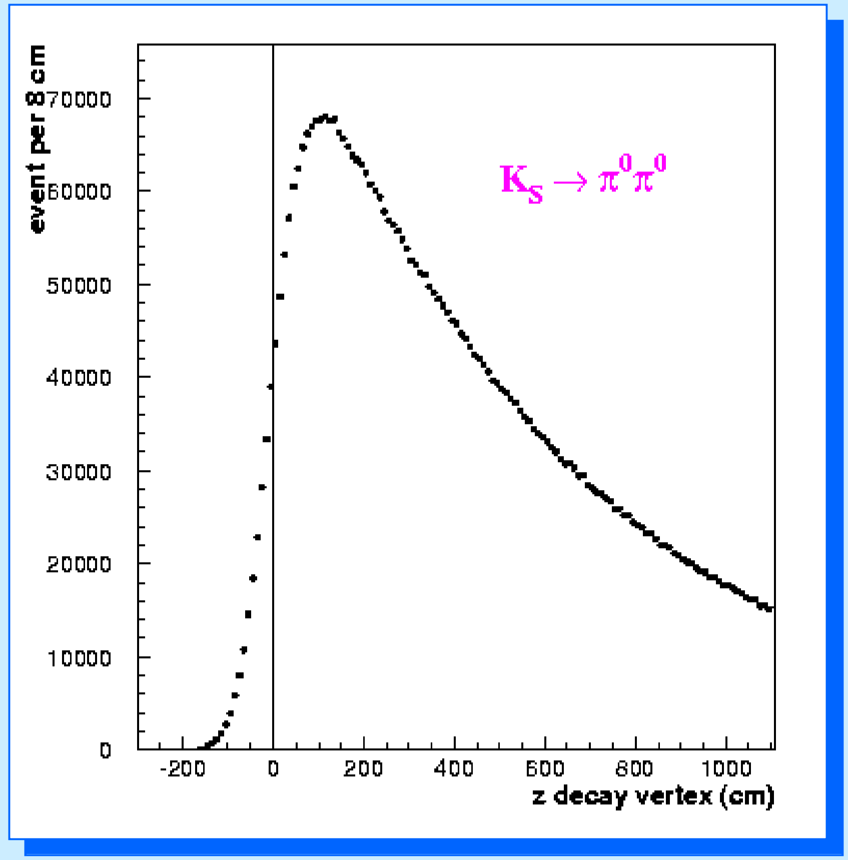
•adjust energy scale to fit the known position of the AKS anticounter

1 cm of reconstruction error

1×10^{-4} on energy scale

Reconstruction of AKS position





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

$\Delta(z) = 2$ cm

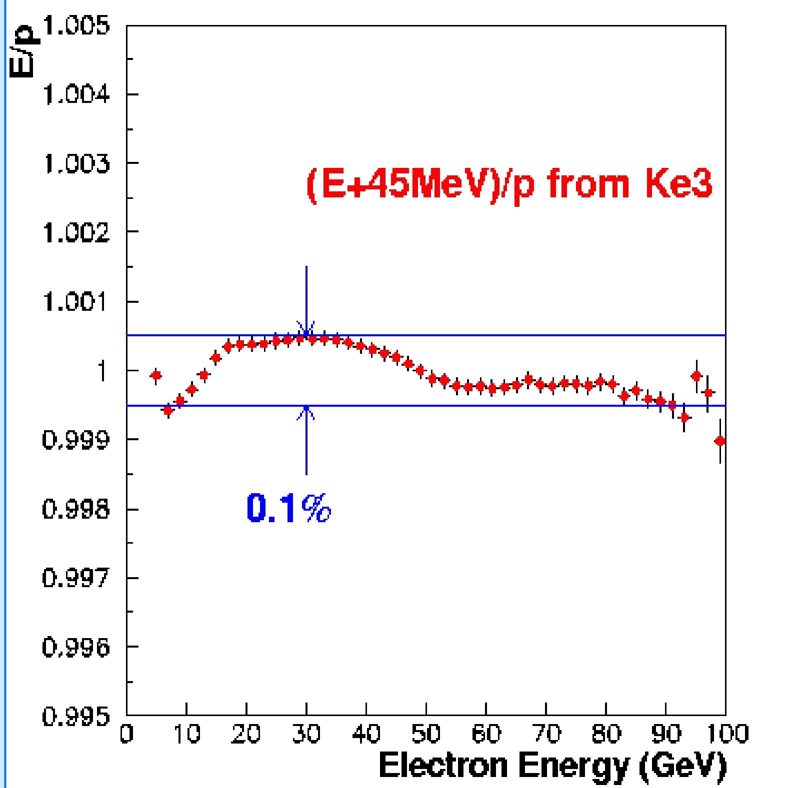
$\Delta(R) = (2 \pm 2)\ 10^{-4}$

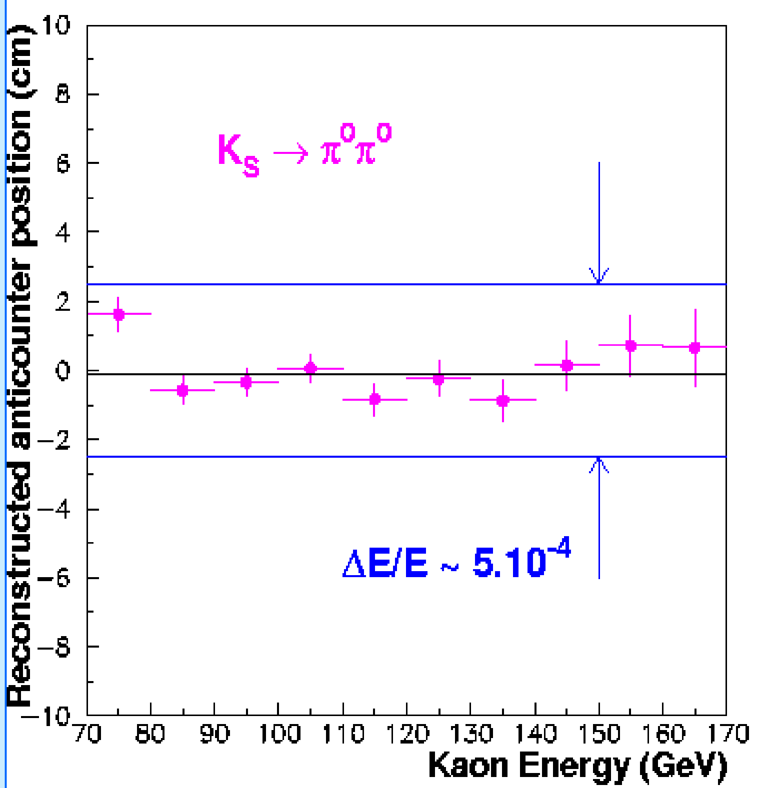
$\pi^0\pi^0$: Adjust energy scale to match nominal position

(one factor, independent of energy)

Stability with time better than $\pm 5{\times}10^{-4}$

Non linearity checks





Electrons from Ke3 decays :

E/p constant within ≈ 0.1%

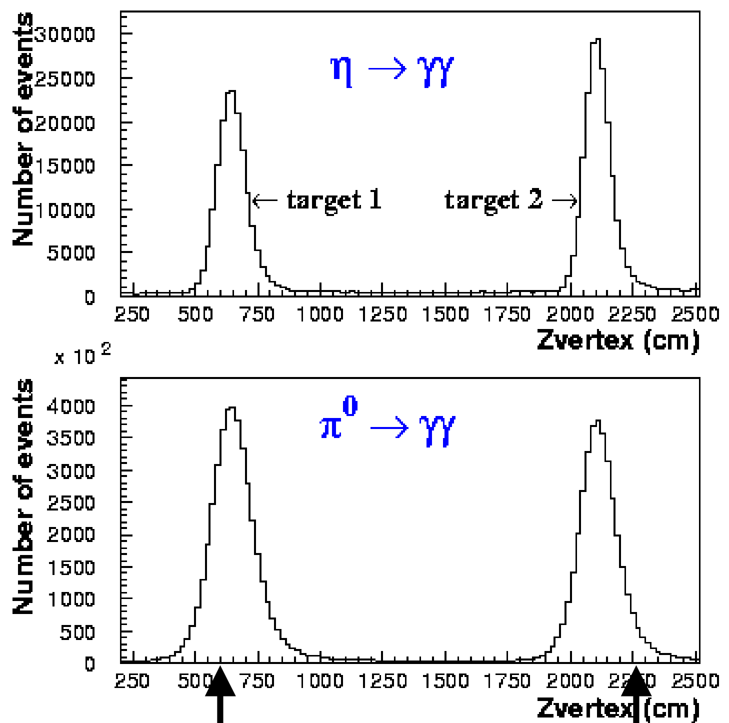
between a few GeV and 100 GeV

Overall check :

Reconstructed AKS position

independent of kaon energy

Energy scale check



- **special run** with π^- beam directed to two thin targets inserted in decay tube
- produce π^0 and η with known decay position
- use $\gamma\gamma$ decays to reconstruct vertex (assuming π^0 or η masses)

$$D = 1/M \sqrt{E_1 E_2}\, d_{12}$$

AKS position

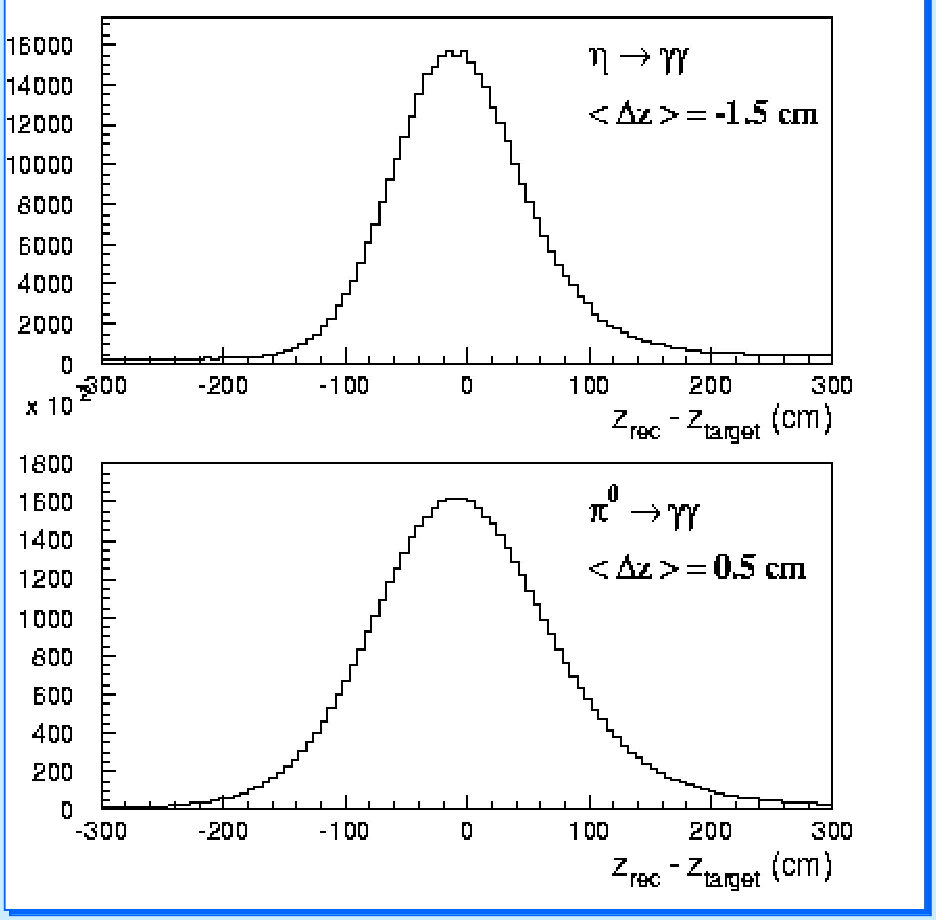
Average $\tau=3\tau_S$ position

Do we find the known target position?

If yes, energy scale is OK

Can also check non linearity and uniformity of energy response

η target position check

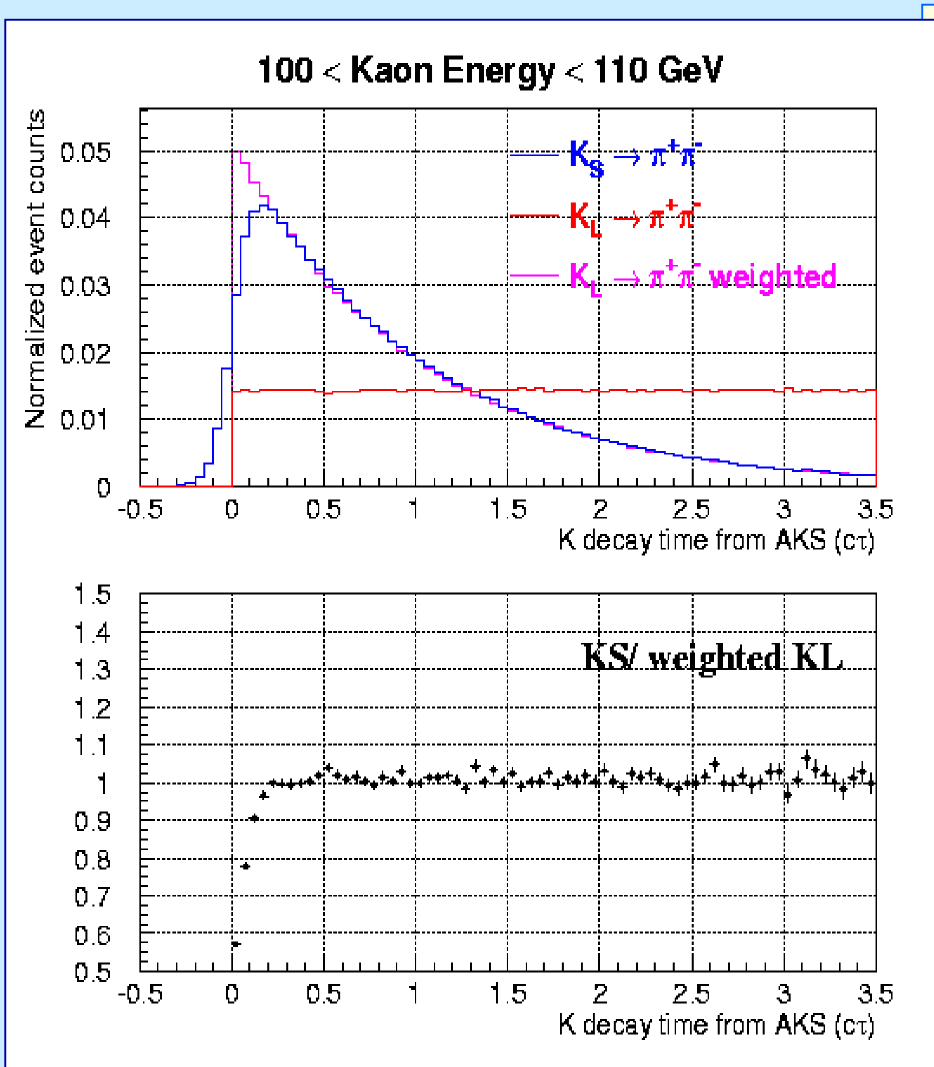


OK to $\cong 2 \times 10^{-4}$

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



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

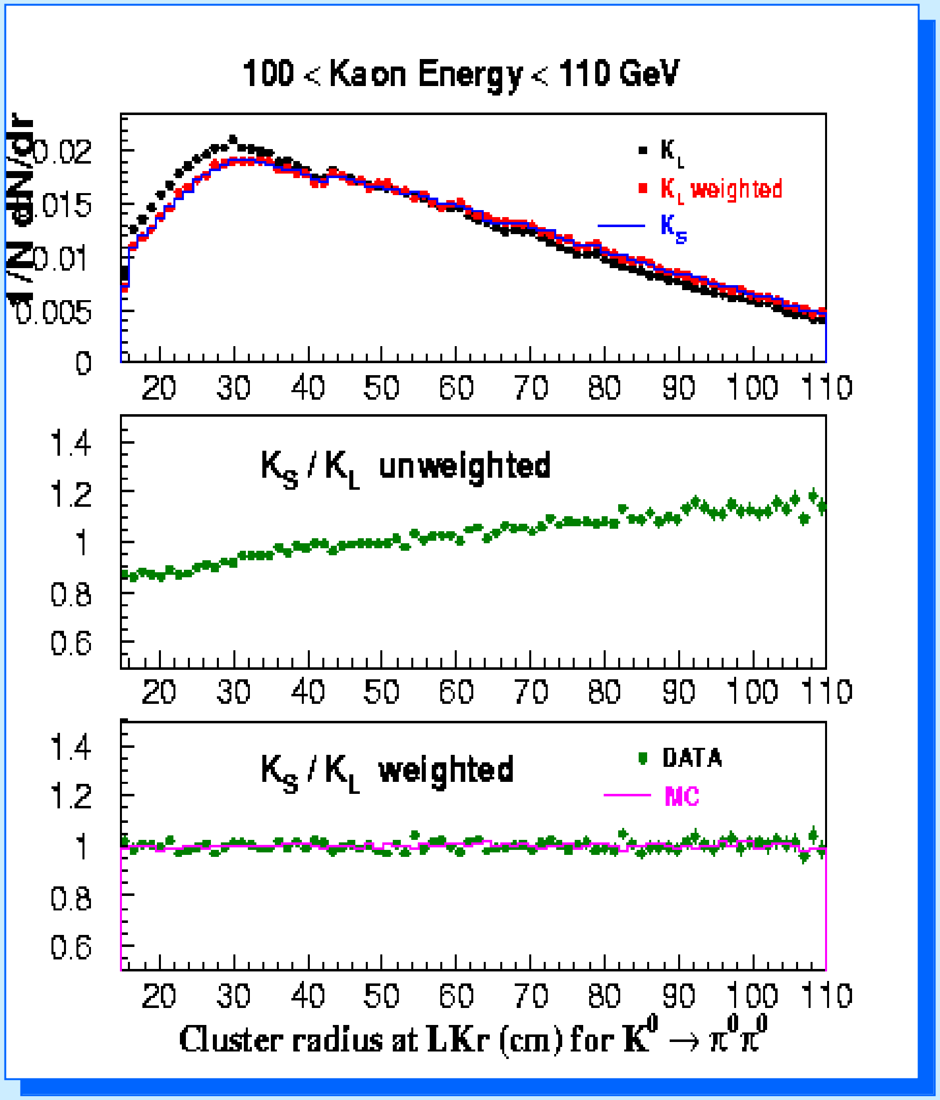
$$W = e^{-z/(\beta\gamma c)\,(1/\tau_S - 1/\tau_L)}$$

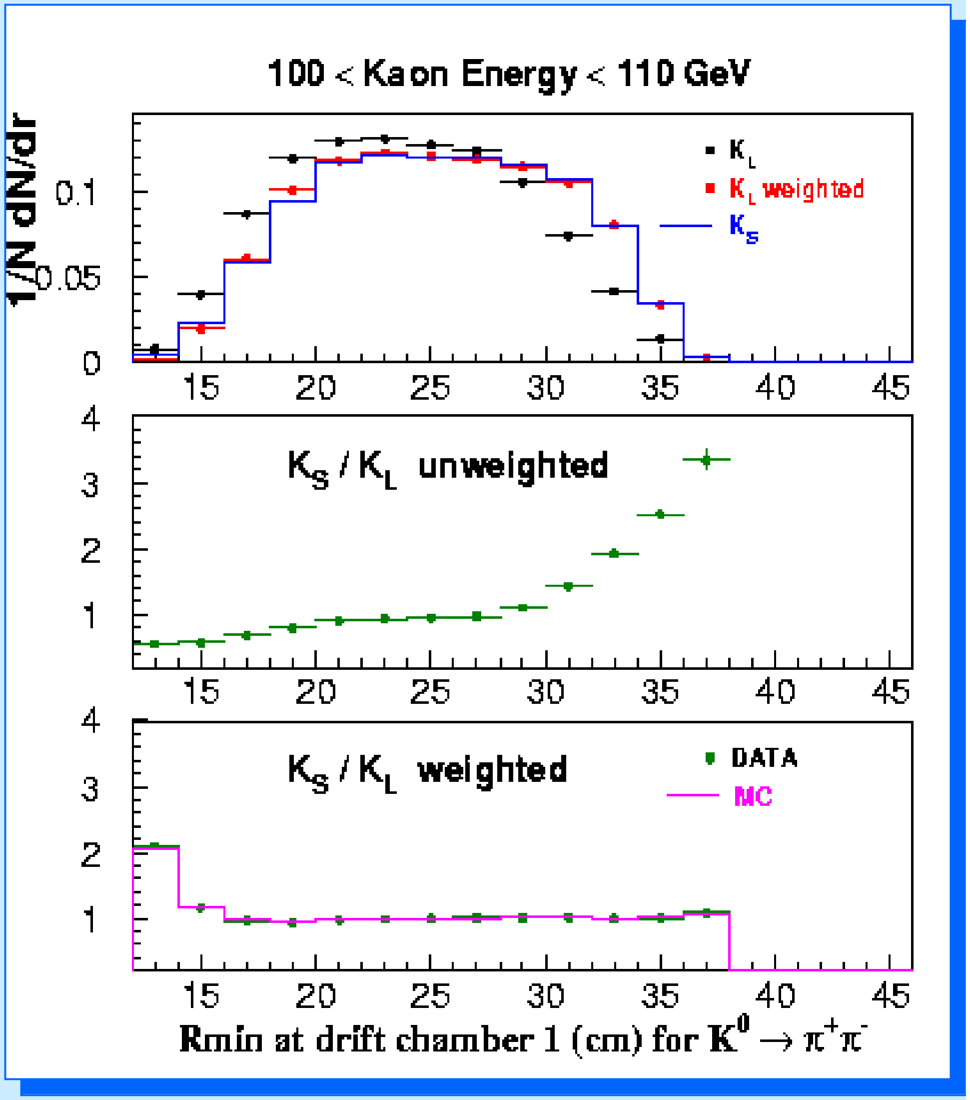
same decay vertex distribution for K_S and weighted K_L

same illumination of detector by decay products

Acceptance correction cancels at the price of an increase of the statistical error

Detector illumination





Acceptance Correction

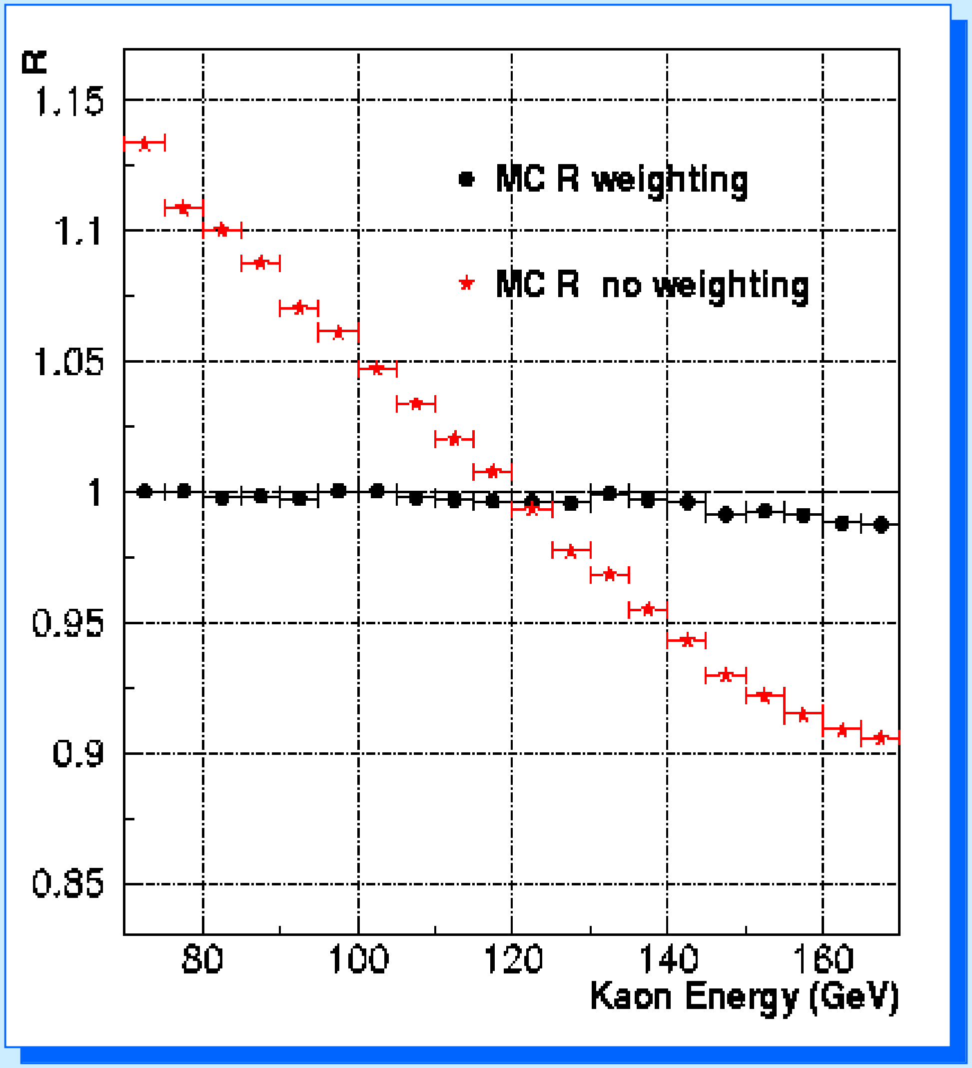
- **Acceptance correction :**

  $+26.7 \times 10^{-4}$

- Uncertainties on R :
  - MC stat error : $\pm 4.1 \times 10^{-4}$
  - Systematic error :

    $\pm 4.0 \times 10^{-4}$ due to:

    - beam positions and shapes: $\pm 3.3 \times 10^{-4}$
    - Comparison of fast MC with GEANT based spectrometer simulation: $\pm 2.3 \times 10^{-4}$



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

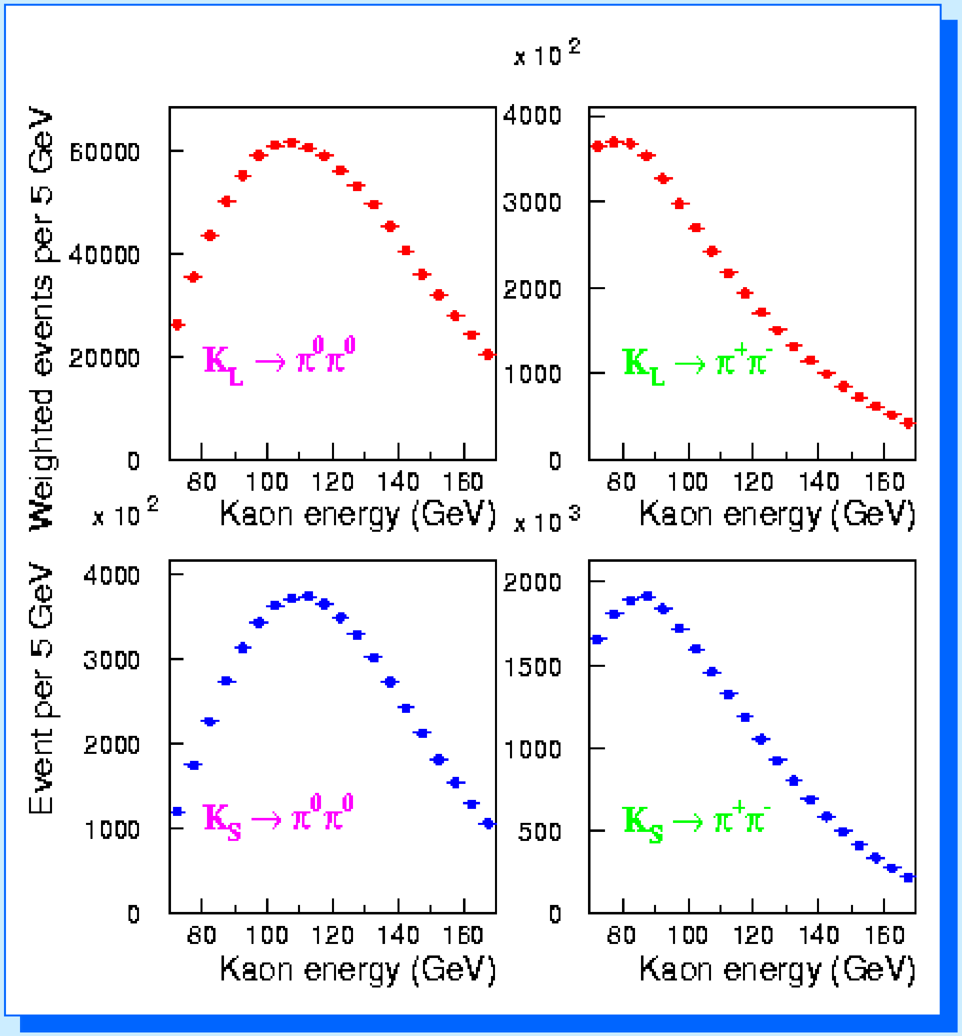
Correction to R : $\Delta R = (0 \pm 4.4) \times 10^{-4}$

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 ± 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)

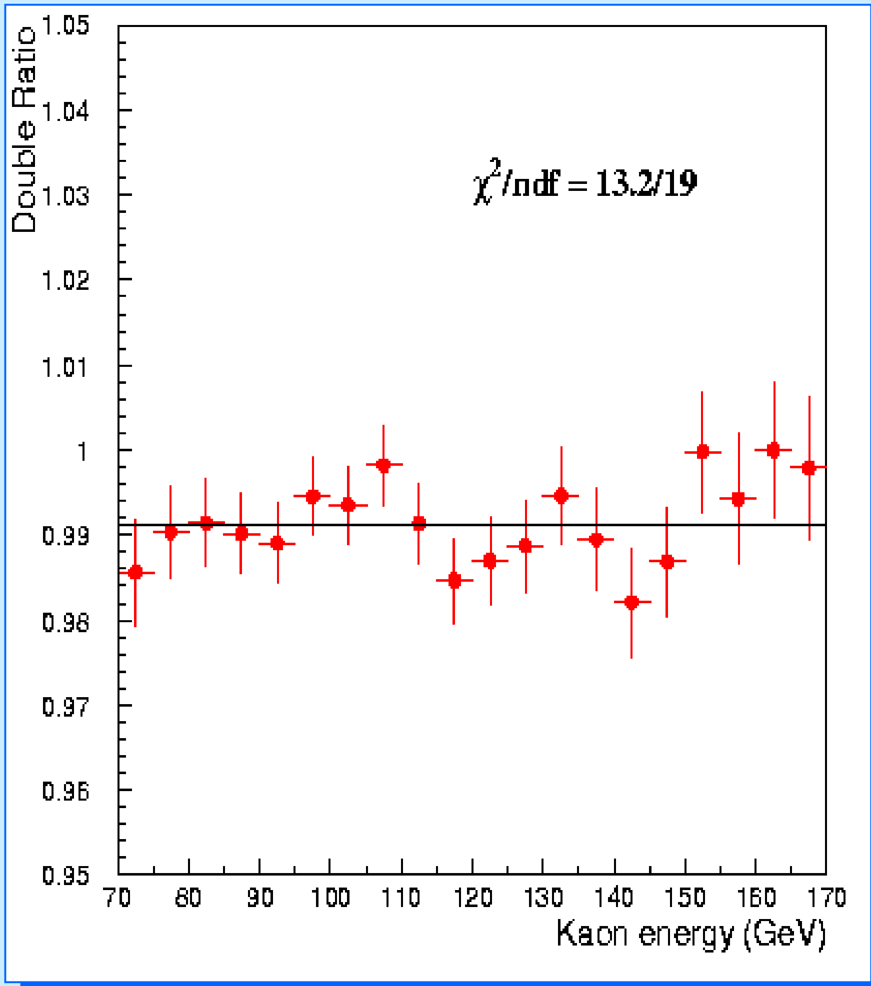
  insensitive to K_S–K_L difference in energy spectrum

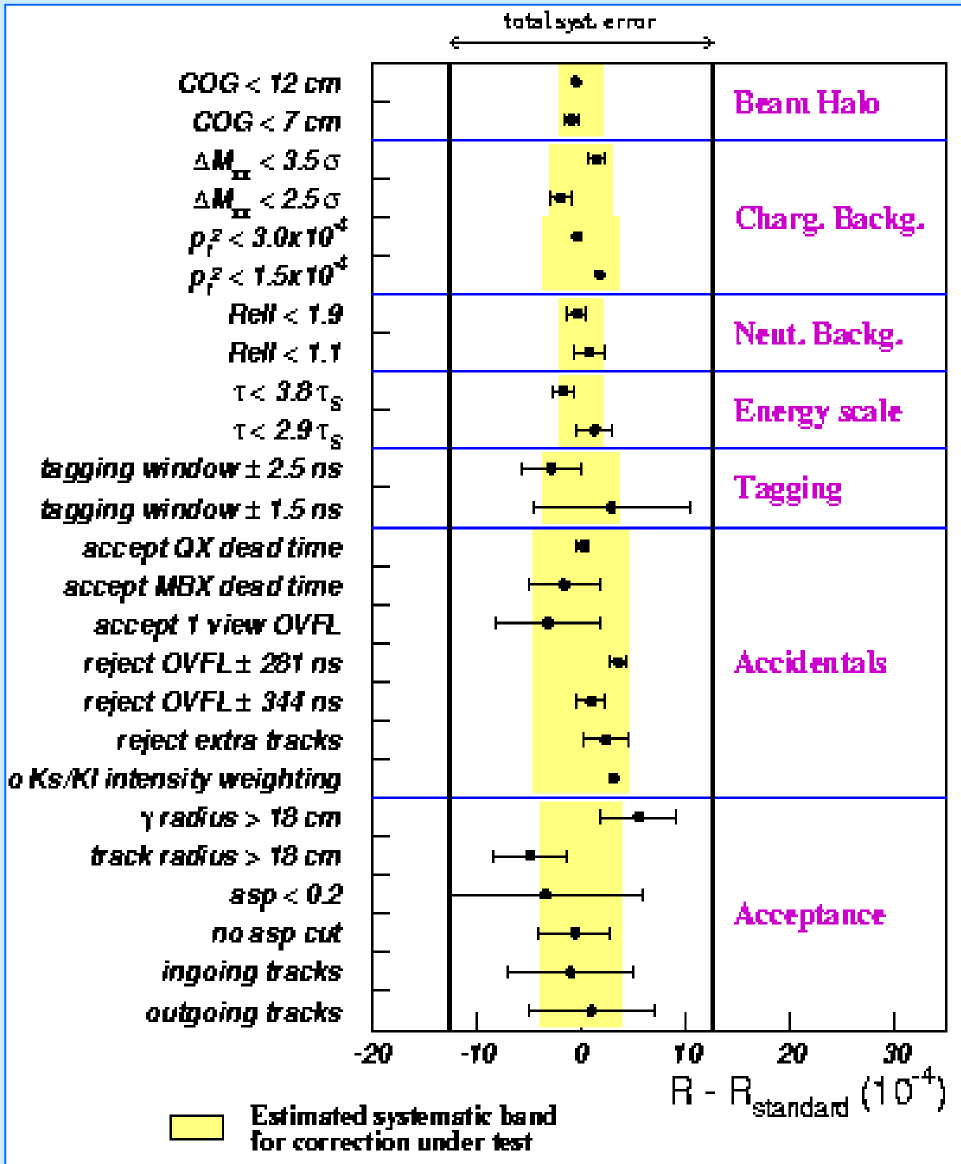
- Apply lifetime weighting to K_L
- Record dead time conditions
  - 1.5% from $\pi^+\pi^-$ trigger
  - 21.5% from drift chamber multiplicity limit

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 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 established at 5.9 σ, and :

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

New results from Fermilab

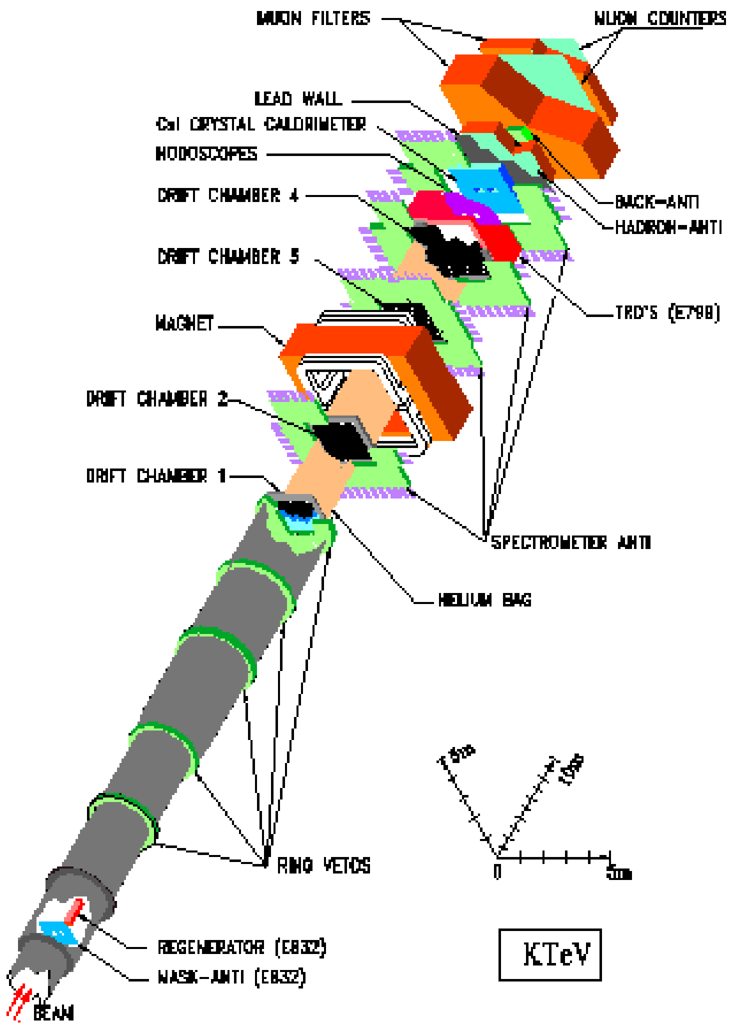
The KTeV collaboration has just presented new results:

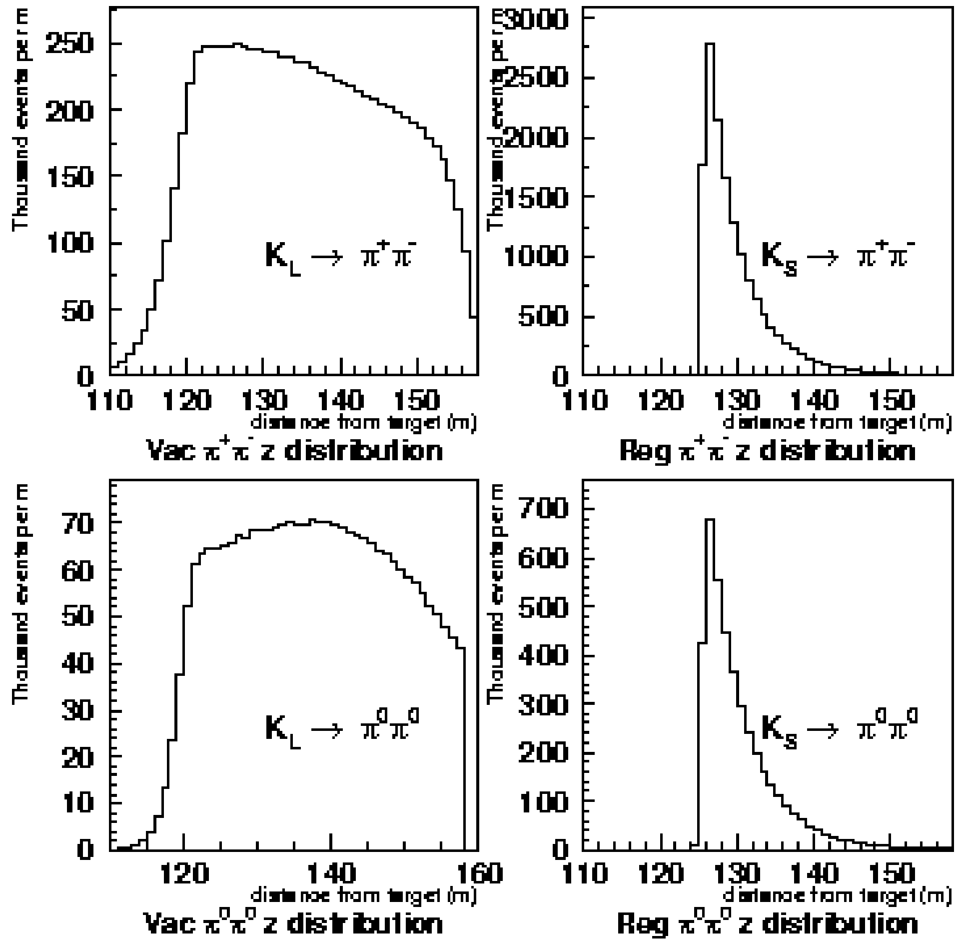
1. Re-analysis of 96-97 partial sample, published in 1999, now with revised result

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





"Vacuum" beam $\rightarrow K_L$ beam

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

KTeV new results

1. Revised result: $\varepsilon'/\varepsilon = (23.2 \pm 4.4)\times 10^{-4}$
   it was: $(28.0 \pm 4.1)\times 10^{-4}$
   (-1.7 due to *mistake;* remaining: *better corrections*)

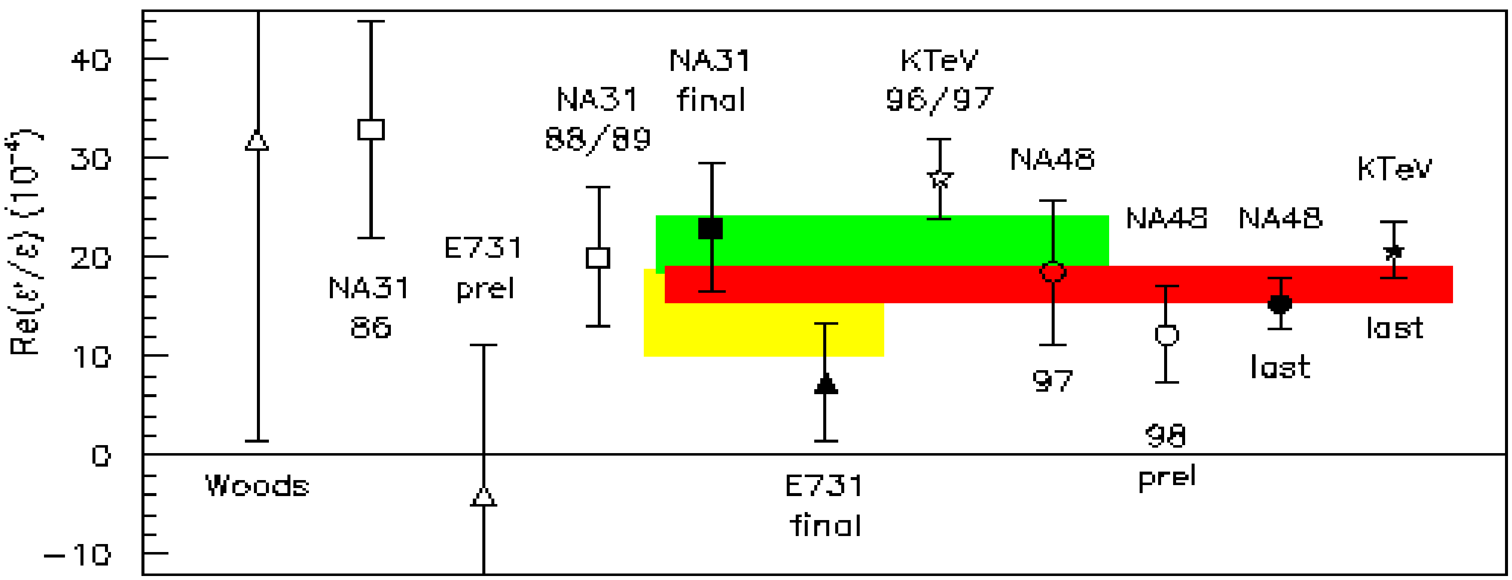
2. New sample : $\varepsilon'/\varepsilon = (19.8 \pm 2.9)\times 10^{-4}$

3. KTeV new average: $\varepsilon'/\varepsilon = (20.7 \pm 2.8)\times 10^{-4}$, or namely:

$$(20.7 \pm 1.5_{(stat)} \pm 2.4_{(syst)} \pm 0.5_{(MC\ stat)})\times 10^{-4}$$

The main systematic errors include energy scale/linearity, neutral background, and acceptance.
[*The acceptance correction to R is about:* $(\approx 480 \pm 7)\times 10^{-4}$, *vs. NA48's:* $(27 \pm 6)\times 10^{-4}$]

Experimental results comparison



Total average : $\varepsilon' / \varepsilon = (17.3 \pm 1.8) \, 10^{-4}$

with χ^2/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 $\chi^2/ndf = 5.7/3$)

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

Plans for 2001 and the future

- Re-commission the 4 drift chambers
- Take ε'/ε data with different K_S, K_L intensities to study the effects of the accidental events etc…
- Proton beam energy 400 GeV
- Increase duty cycle to 5.2 s /19.2 s

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
- A precision measurement of charged kaon decay parameters with an extended NA48 setup

NA48 / I

SPS momentum 400 GeV/c

Duty Cycle 5.2 sec/16.8 sec

ppp on target 1×10^{10}

production angle -2.5 mrad

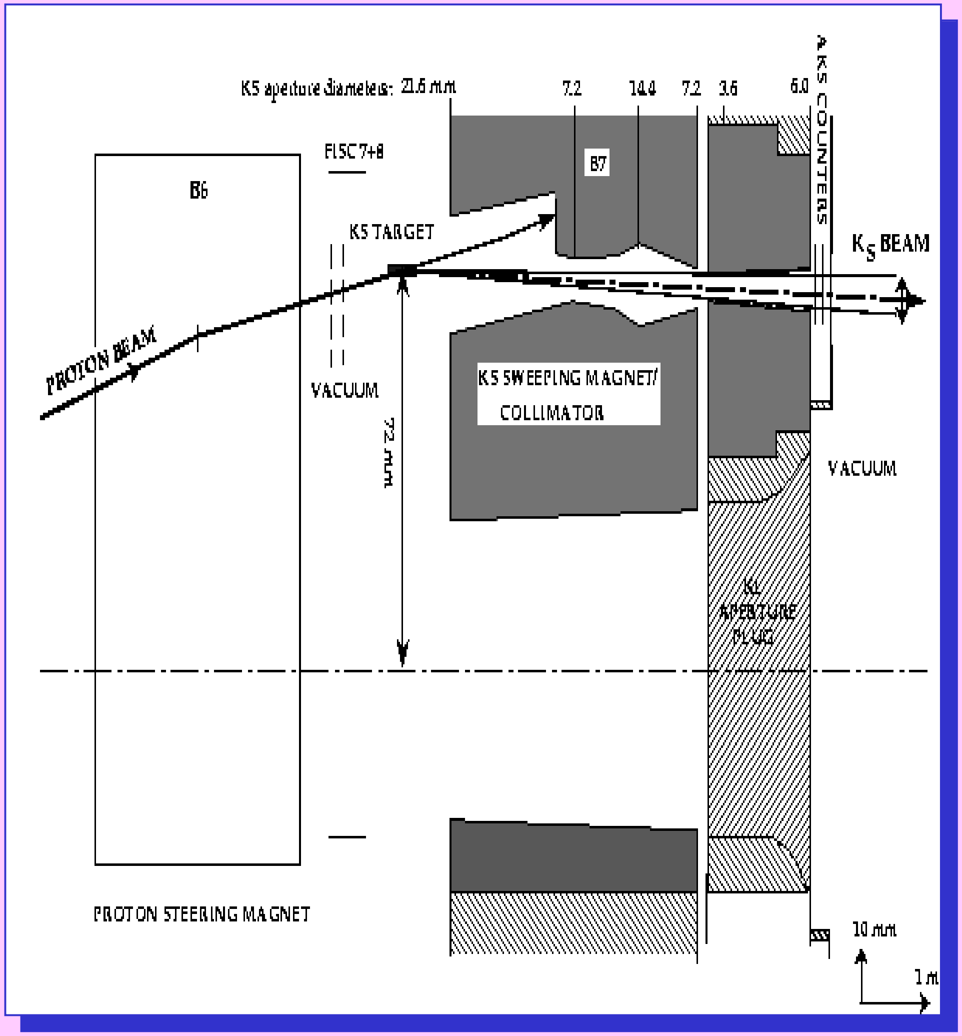
Total kaon flux/pulse 1.5×10^{5}

K decays/pulse 1.1×10^{5}

K decays/year 3.0×10^{10}

With respect to NA48:

- additional sweeping magnet
- removable lead converter
- no K_S veto counter
- beam intensity increased by a factor 160



NA48 / I physics case : $K_S \rightarrow \pi^0 e^+ e^-$

The interest in $K_S \rightarrow \pi^0 e^+ e^-$ (theory 5×10^{-9} ; expected 7 events) is to bound the indirect CP violation in the $K_L \rightarrow \pi^0 e^+ e^-$ decay.

$K_L \rightarrow \pi^0 e^+ e^-$ is a place to look for direct CP violation within and beyond the standard model. The current upper limit $BR(K_L \rightarrow \pi^0 e^+ e^-) < 5.64\ 10^{-10}$ could be improved in the next few years by KAMI.

The direct and indirect CP violating components interfere and the indirect contributions is linked to the parameter a_s

Since the a_s parameter cannot be predicted to any degree of confidence, a high sensitivity search for $K_S \rightarrow \pi^0 e^+ e^-$ is needed.

NA48 / I physics case : Non-leptonic K_S decays

The non-leptonic K_S decays are important for understanding the low energy hadron dynamics of Chiral Perturbation Theory since they are sensitive to higher order loop effects.

Decay mode	BR (exp)	BR (th)	Evts/year
$K_S \to \gamma\gamma$	$(2.4 \pm 0.9) \times 10^{-6}$	2.1×10^{-6}	24000
$K_S \to \pi^0\gamma\gamma$		3.8×10^{-8}	114
$K_S \to \pi^0\pi^0\gamma\gamma$		5.6×10^{-9}	7
$K_S \to \pi^0\pi^0\gamma$		1.7×10^{-11}	

NA48 / II

- Study with high statistics specific properties of the decay of charged kaons: direct CP violation induces an asymmetry in the Dalitz plot density of the decays

$$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-} \quad \text{and} \quad K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$$

- use new charged kaon beams
- upgrade NA48 detector with a TRD (for Ke4) and a small beam spectrometer

NA48 / II

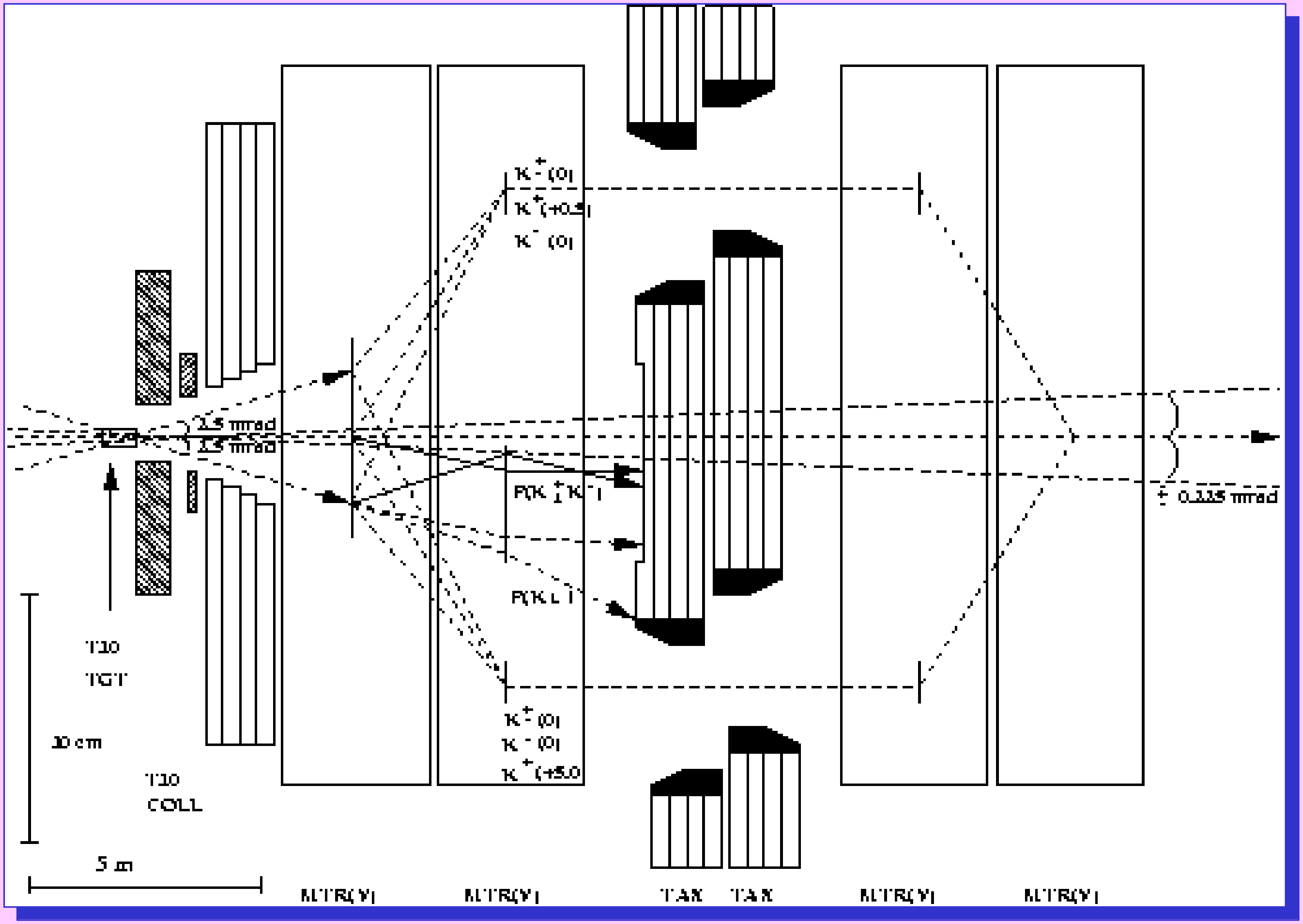
Systematics that can create an asymmetry:

- different spectra of K^+ and K^-
- local inefficiency in drift chambers
- differences between magnetic field in the two polarities
- relative offset of the two beams
- relative asymmetry in the profile of the two beams

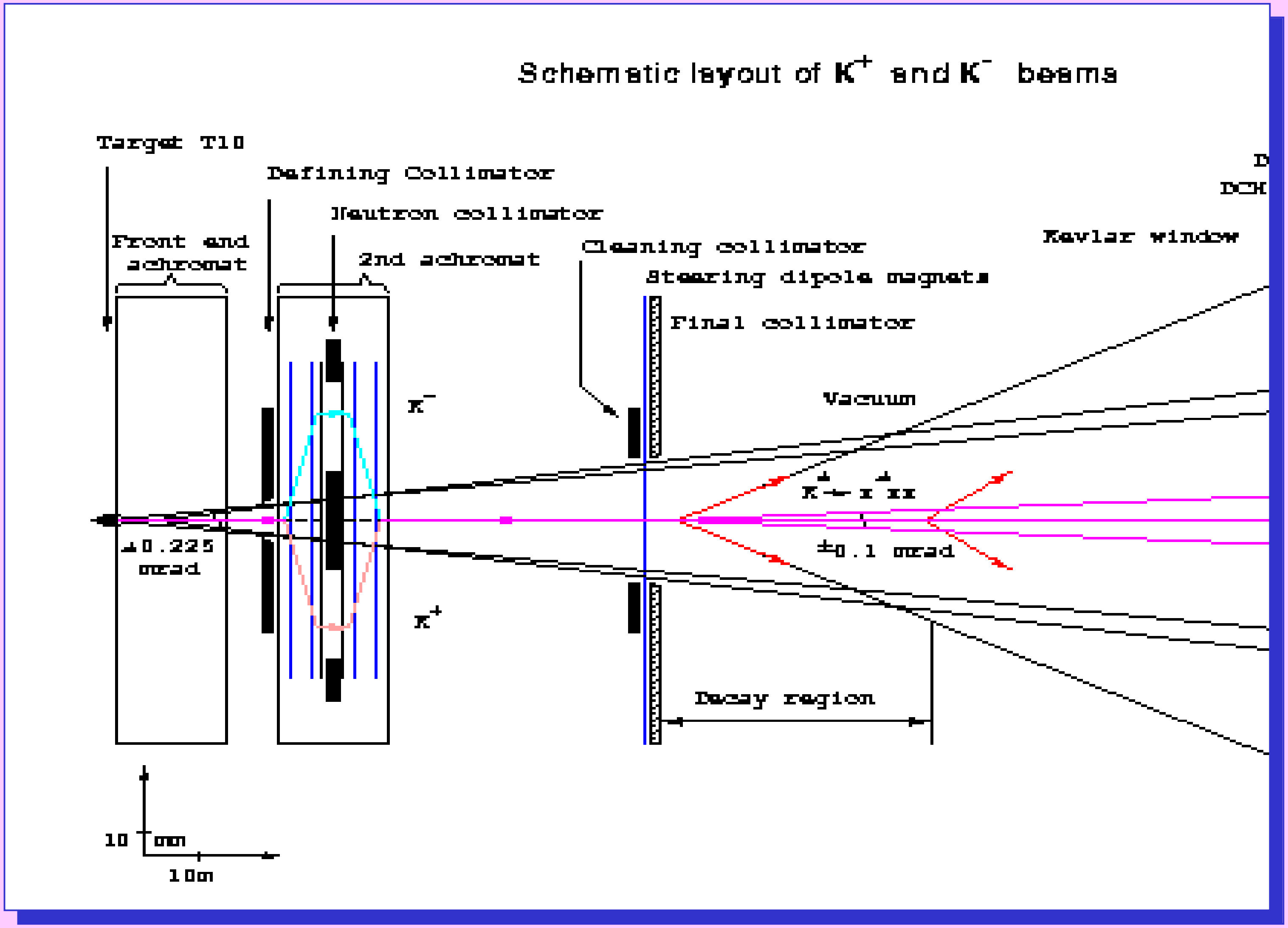
Can be kept at a level of less than 10^{-4} if :

- use simultaneous K^+ and K^- beams
- alternate the sign of the spectrometer field
- bin in p_K
- do offline circular acceptance cuts centered on the center of gravity of the two beams

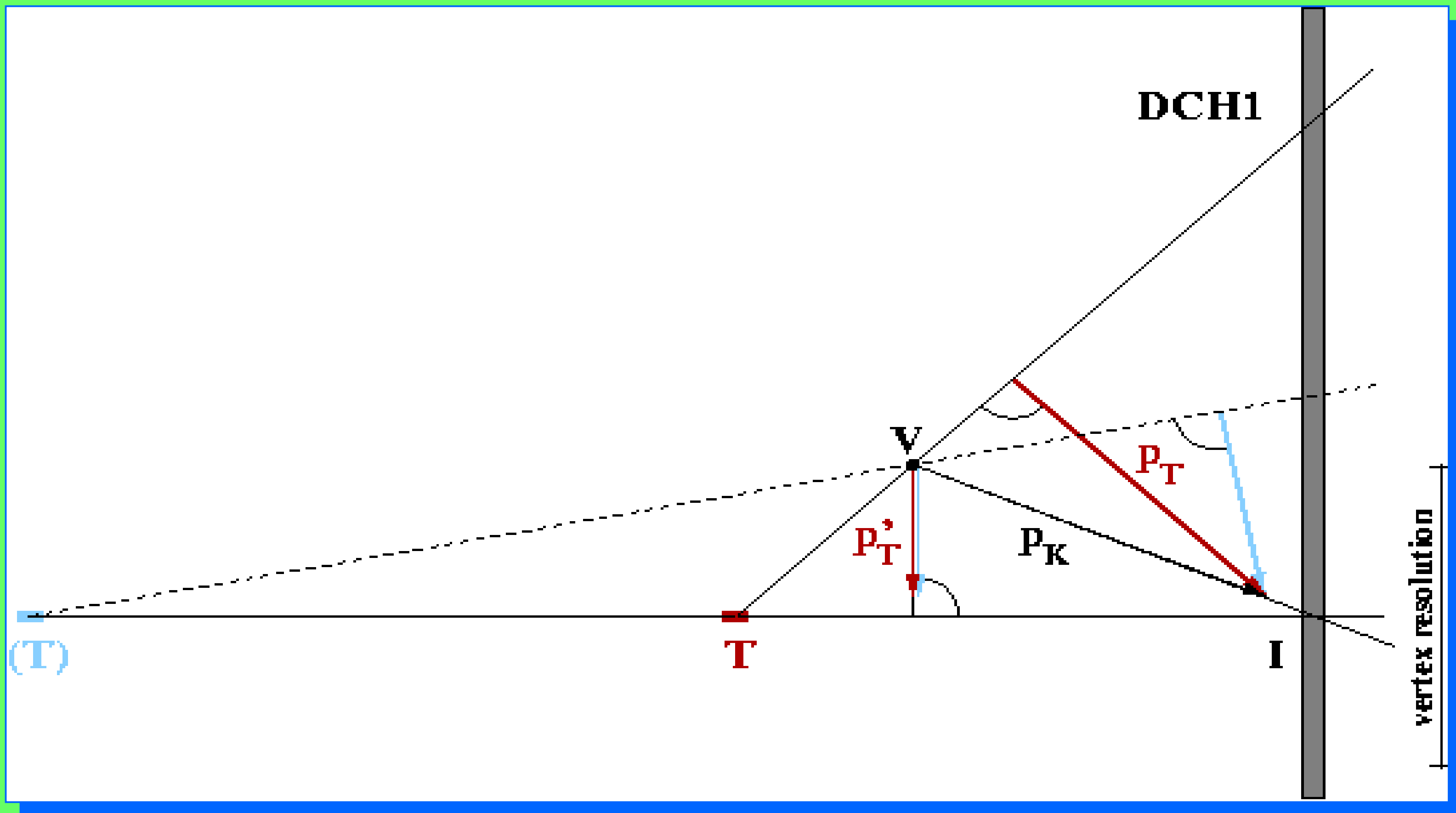
NA48 / II - simultaneous beams



NA48 / II - simultaneous beams

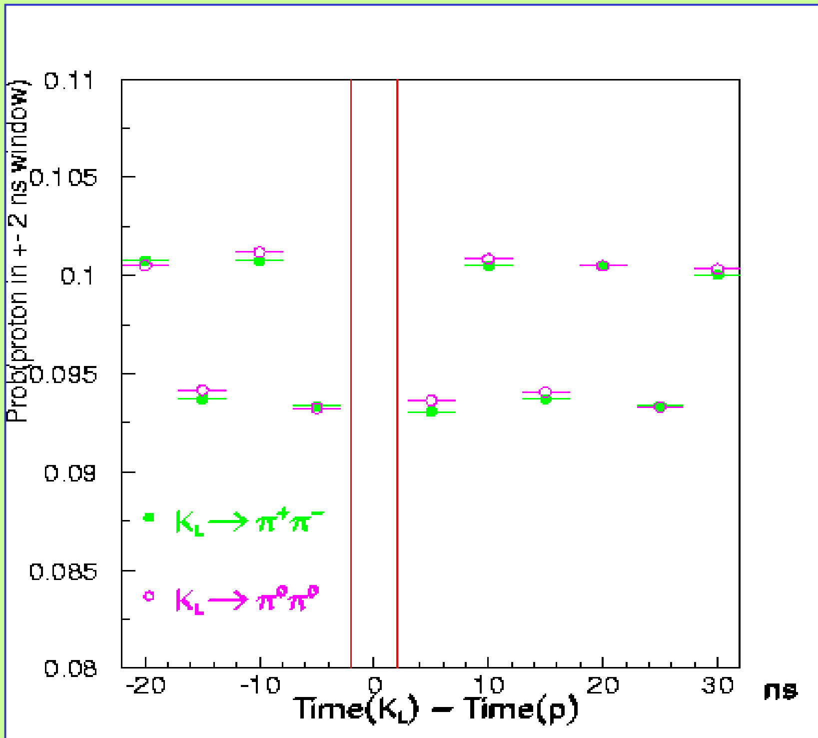


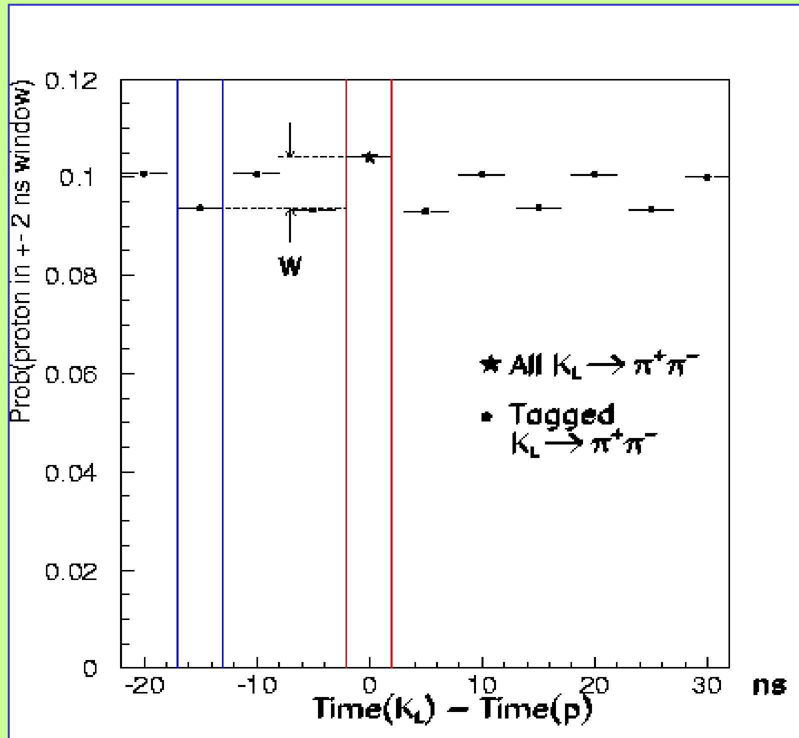
$P_{\perp}'^2$ definition



- Target distance is ~120 m $P_{\perp}'^2$ very different for K_S and K_L
- $P_{\perp}'^2$: same resolution for K_S and K_L (dominated by vertex res.)

Estimate of $\Delta\ \alpha_{LS}$





Using sidebands of tagger (S)

selected K_L to $\pi^+\pi^-$ and $\pi^0\pi^0$:

$\Delta_S = (3.3 \pm 1.0_{stat}) \ 10^{-4}$

Extrapolation to central window (W)

$\pi^+\pi^-$: use vertex selected K_L

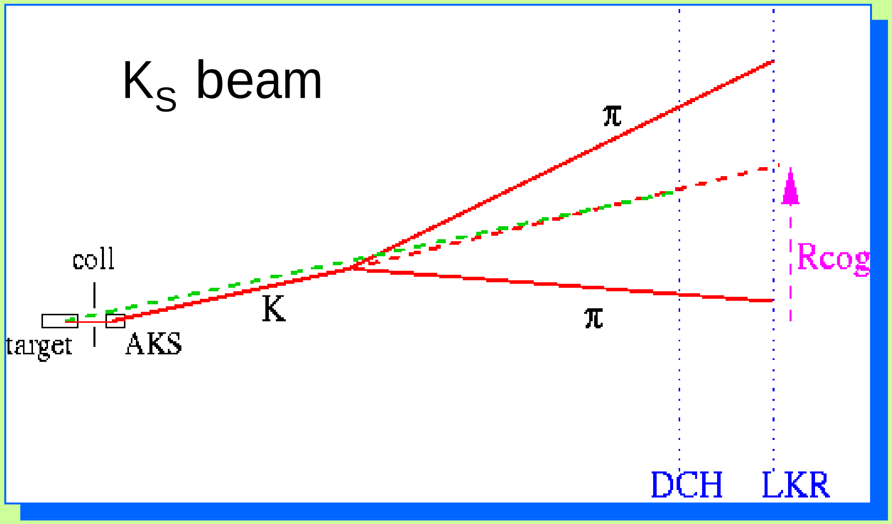
$\pi^0\pi^0$: use $3\pi^0$ events (only K_L)

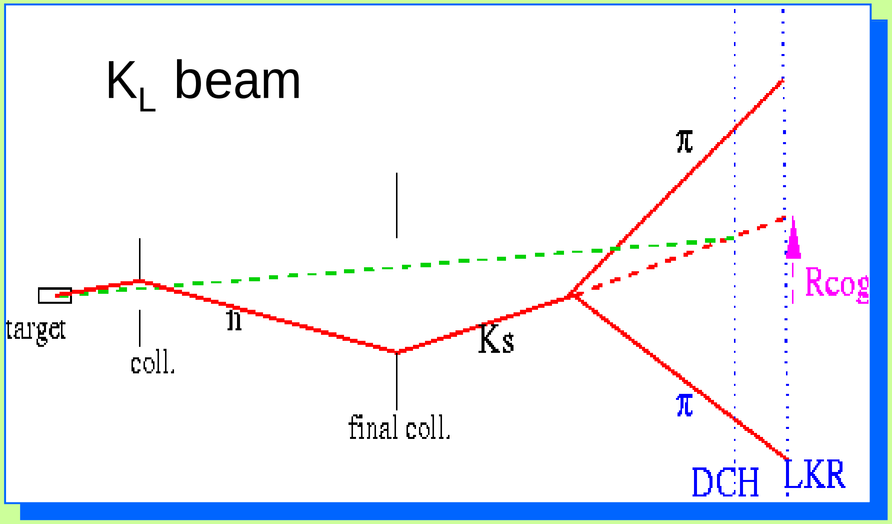
$\Delta_W = (1.3 \pm 1.0_{stat}) \ 10^{-4}$

$\Delta\ \alpha_{LS} = (4.6 \pm 1.7) \ 10^{-4}$

(adding systematic error from choice of sideband windows)

Beam scattering backgrounds



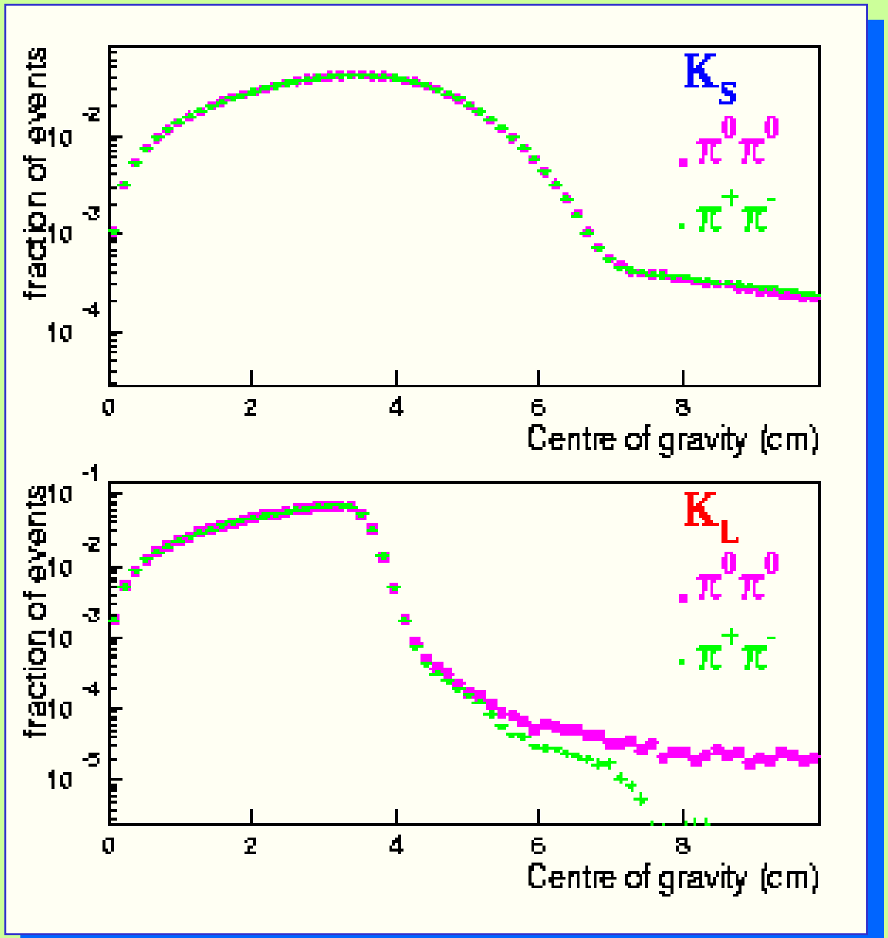


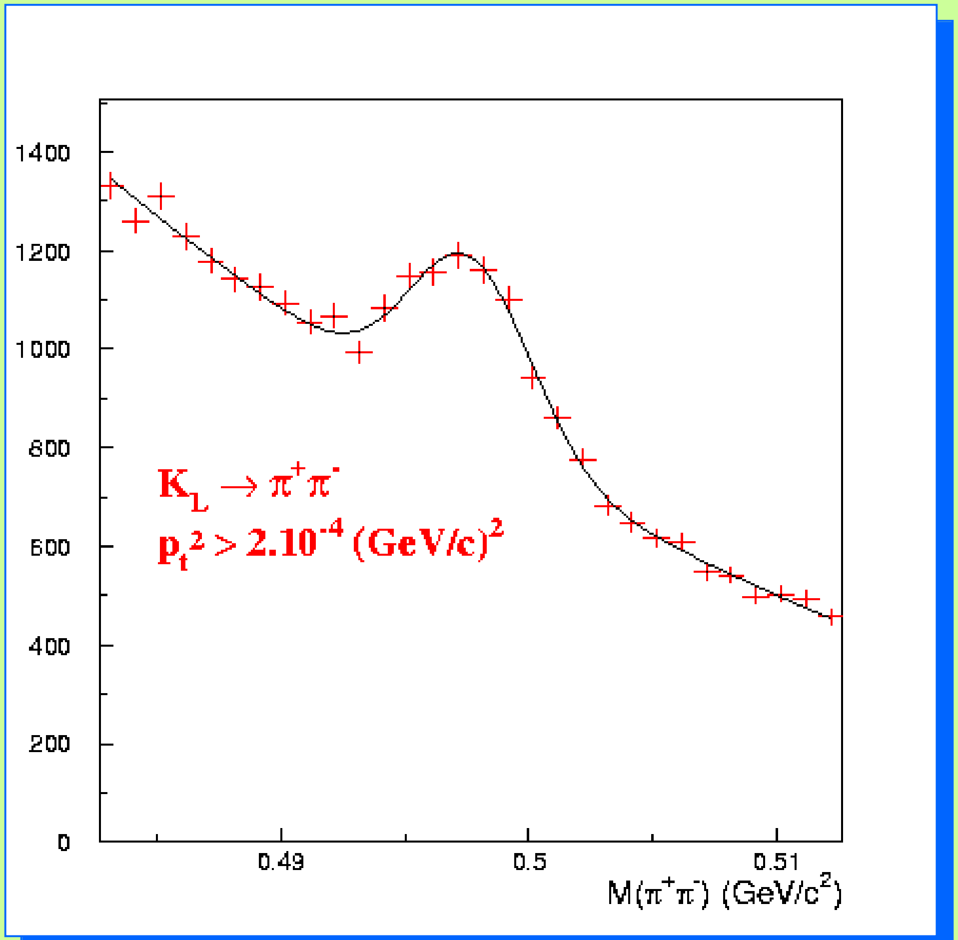
K_S Scattering removed by R_{COG} cut
- symmetric $\pi^+\pi^-$ and $\pi^0\pi^0$
- no effect on R

Background from K_L beam scattering produces K_S in final collimator
Removed from $\pi^+\pi^-$ sample by $P_\perp'^2$ cut
Kept in $\pi^0\pi^0$ sample
- correction

Beam scattering backgrounds

Measure collimator background in $\pi^+\pi^-$ mode from events at $P_\perp'^2 > 200\ (MeV/c)^2$ with $M_{\pi\pi} \cong M_K$ (cross-checked by other observations)





Background in $\pi^0\pi^0$ = $(9.6 \pm 2.0)\ 10^{-4}$

Summary on background effects on R

Mode	$\Delta(R)$ (in 10^{-4} units)
$K_L \rightarrow \pi^+\pi^-$	
Ke3 and Kμ3 background	16.9 ± 3.0
$K_L \rightarrow \pi^0\pi^0$	
$3\pi^0$ background	-5.9 ± 2.0
Collimator scattering	-9.6 ± 2.0
Total	1.4 ± 4.1

Understanding the effects of tagging errors

Because of the four tagging errors, the measured samples differs from the correct ones by:

- $K_L^{oo}{}_{(meas)} = K_L^{oo}(1-\alpha_{LS}^{oo}) + K_S^{oo}\alpha_{SL}^{oo}$
- $K_L^{+-}{}_{(meas)} = K_L^{+-}(1-\alpha_{LS}^{+-}) + K_S^{+-}\alpha_{SL}^{+-}$
- $K_S^{oo}{}_{(meas)} = K_S^{oo}(1-\alpha_{SL}^{oo}) + K_L^{oo}\alpha_{LS}^{oo}$
- $K_S^{+-}{}_{(meas)} = K_S^{+-}(1-\alpha_{SL}^{+-}) + K_L^{+-}\alpha_{LS}^{+-}$

Change to the notation:

$$\alpha_{AB}^{+-} = \alpha_{AB}\,, \quad \alpha_{AB}^{oo} = \alpha_{AB} + \Delta\alpha_{AB}$$

And compare:

$$R_{(meas)} = (K_L^{oo}{}_{(meas)} / K_L^{+-}{}_{(meas)}) / (K_S^{oo}{}_{(meas)} / K_S^{+-}{}_{(meas)})$$

to the correct R

Understanding the effects of tagging errors

Use $\rho = K_L^{+-} / K_S^{+-}$ and consider effects separately:

1. effect of α_{LS}: $(R_m-1) = (R-1) \,/\, (1+R\,\rho\,\alpha_{LS})$
2. α_{SL}: $(R_m-1) = (R-1) \,/\, (1+\alpha_{SL}/\rho)$

α_{LS} and α_{SL} reduce the deviation of R from 1:

a soft bias :

they do not mimic direct CP violation

(besides, they can be measured very well …)

3. $\Delta\alpha_{LS}$: $R_m \cong R - \Delta\alpha_{LS}\, R\,(1+\rho)/[(1-\alpha_{LS})(1+\rho\,R\,\alpha_{LS})]$
4. $\Delta\alpha_{SL}$: $R_m \cong R + \Delta\alpha_{SL}\, R\,(1+\rho)/[(\rho+\alpha_{SL})(1-\alpha_{SL})]$

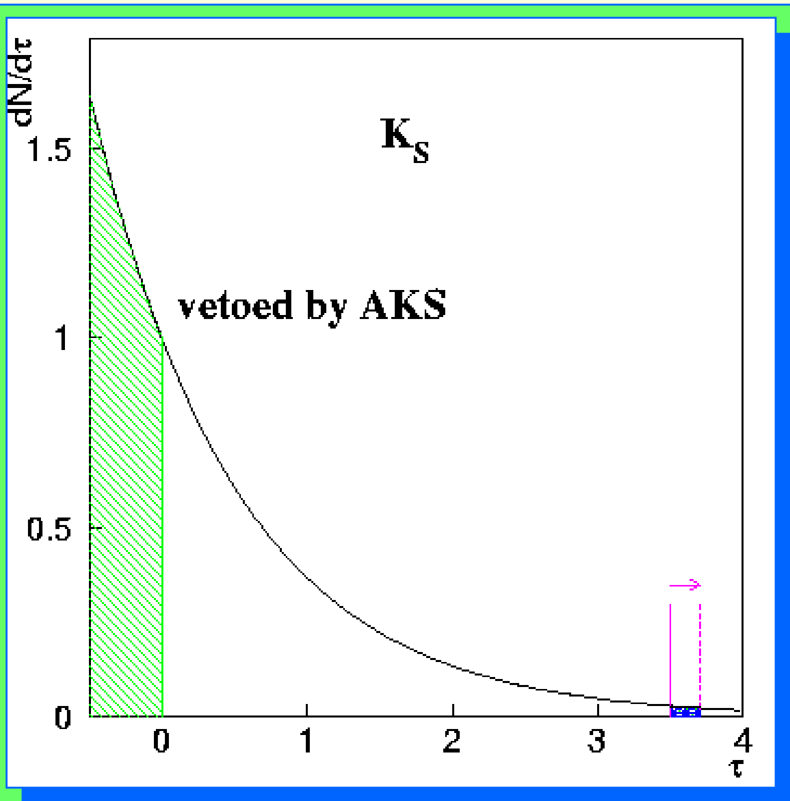
$\Rightarrow$ **$\Delta\alpha_{LS}$ and $\Delta\alpha_{SL}$ can produce a *hard bias***

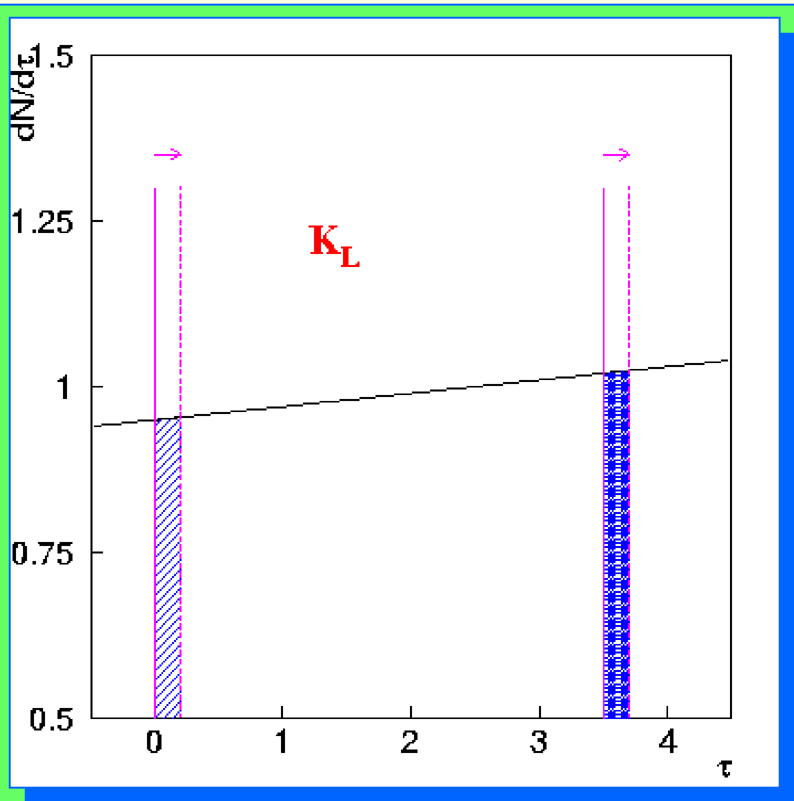
Full analysis, including decay distribution and weighting: conclusions remain valid

Correction to R : $\Delta R \approx 2\times\Delta\alpha_{LS} + 6\times\Delta\alpha_{SL}$

Effect of error in energy scale - $\pi^0\pi^0$ case

$E \rightarrow E\,(1+\alpha)$ and $D \rightarrow D\,(1+\alpha) \Rightarrow t \rightarrow t + 15\,\alpha$ (at $E = 100$ GeV)





Sensitivity limited thanks to use of AKS to define beginning of K_S decay region

Typically $\Delta R \approx \alpha$

Energy scale correct to few 10^{-4}

Also sensitive to Non-Linearities ($\Leftrightarrow \alpha = \alpha(E_K)$)