A new result on the direct CP violation in two pion decays of the neutral kaon

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June 20th, 2001

On behalf of the NA48 COLLABORATION

Cagliari, Cambridge, CERN, Dubna, Edinburgh,
Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa,
Saclay, Siegen, Torino, Warsaw, Wien

Outline

1. Direct CP violation in K^0 system and ϵ'/ϵ

2. NA48 method and setup

3. Data analysis
   - analysis overview
   - result

   Conclusion

1. Direct CP violation and ϵ'/ϵ

CP violation in 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)

$$K_S = K_1 + \epsilon\ K_2$$
$$K_L = K_2 + \epsilon\ K_1$$

indirect CP violation: $|\epsilon| = (2.28 \pm 0.02)\ 10^{-3}$

Is there also a component of *direct* CP violation in the decay process itself ?

$|A(K^0 \rightarrow F)| \neq |A(\overline{K^0} \rightarrow \overline{F})|$

Direct CP Violation

$\pi\pi$ from K^0 can have I=0 or 2 $\Rightarrow$ 2 amplitudes A_0 and A_2

Define ratio of CP violating/CP conserving amplitudes :

$$\begin{array}{ccccc} \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} & \equiv & \eta_{+-} & = & \epsilon + \epsilon' \\ \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} & \equiv & \eta_{00} & = & \epsilon - 2\epsilon' \end{array}$$

ϵ' : direct CP violation parameter

Typical theoretical predictions :
$\epsilon'/\epsilon \approx$ few 10^{-4} to $\approx 2.10^{-3}$

Experimental observable :

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

Current experimental situation of ϵ'/ϵ (May 2001)

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

NA31: $(23.0 \pm 6.5).10^{-4}$; E731: $(7.4 \pm 5.9).10^{-4}$

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

First published results two years ago :

- KTeV: $(28.0 \pm 4.1).10^{-4}$ (20% of 96-97 stat)
- NA48: $(18.5 \pm 7.3).10^{-4}$ (97 data)

Preliminary NA48 result on 98 data last year :

- NA48: $(14.0 \pm 4.3).10^{-4}$ (combined with 97)

Direct CP violation established

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

TODAY : NA48 result based on 98+99 data
($\approx$ 7 times the 97 published statistics)

2. NA48 method and setup

Double ratio measurement:

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

$\Leftrightarrow$ Count number of events

Need $> 3.10^6$ $\mathrm{K_L} \to \pi^0\pi^0$ for stat error on R $< 0.1\%$

Measure R $\Rightarrow$ exploit cancellation of possible systematics

Principles to minimise systematic effects :

- The 4 modes are taken simultaneously from the same decay region

$\Rightarrow$ Cancellation of fluxes, dead times, inefficiencies, accidental losses...

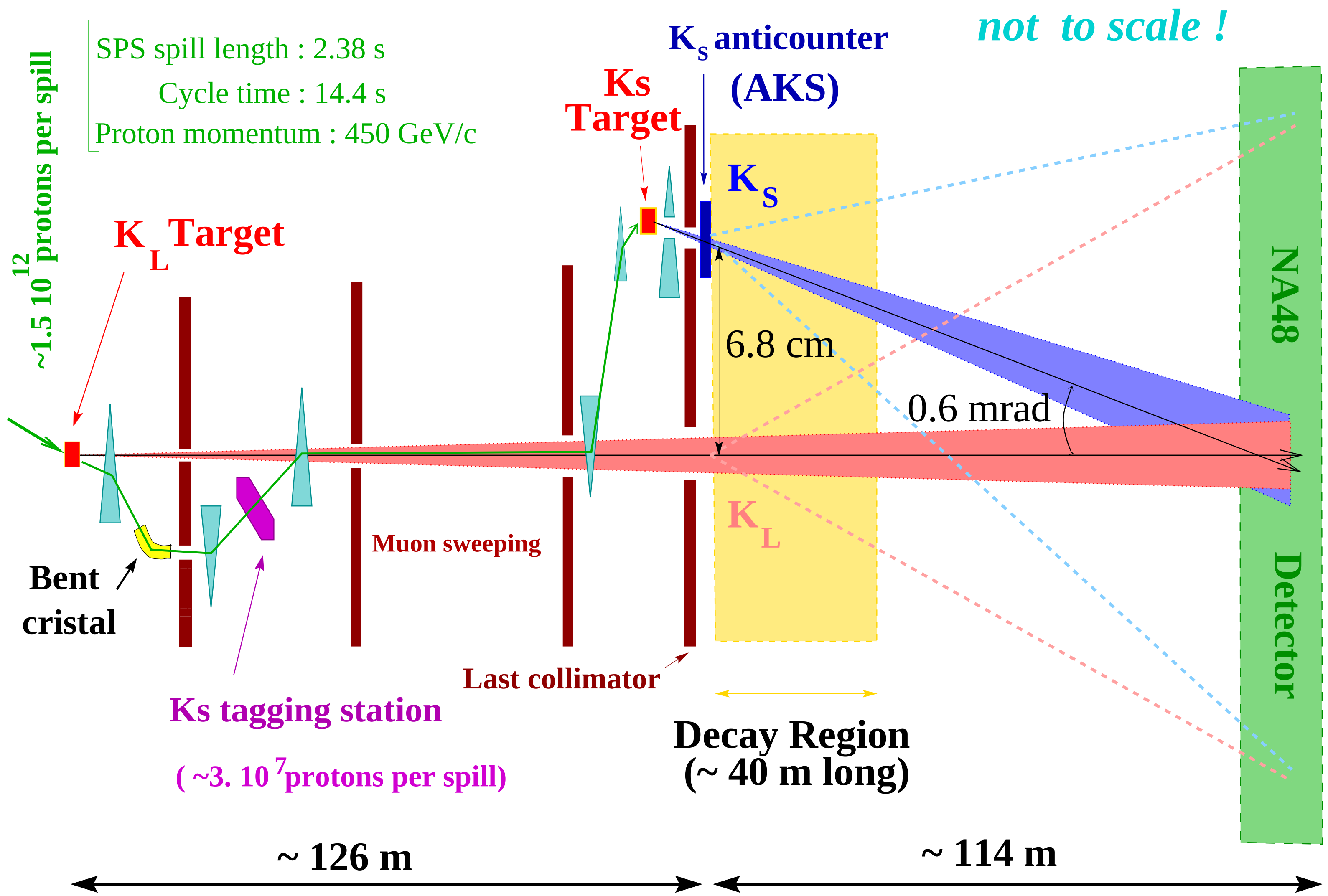
- Apply lifetime weighting to equalise distribution of $\mathrm{K_S}$ and $\mathrm{K_L}$ decay positions

$\Rightarrow$ Cancellation of detector acceptance effects

- Use quasihomogeneous Liquid Krypton calorimeter to detect $\pi^0\pi^0$ and magnetic spectrometer for $\pi^+\pi^-$

$\Rightarrow$ Minimise backgrounds

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.

Decay region and lifetime weighting

- $0 \le \tau \le 3.5$

  τ = proper time along the beam axis, in K_S lifetime units
  $\tau = (z_{vertex} - z_0) \frac{M_K}{E_K} \frac{1}{c\tau_{K_S}}$

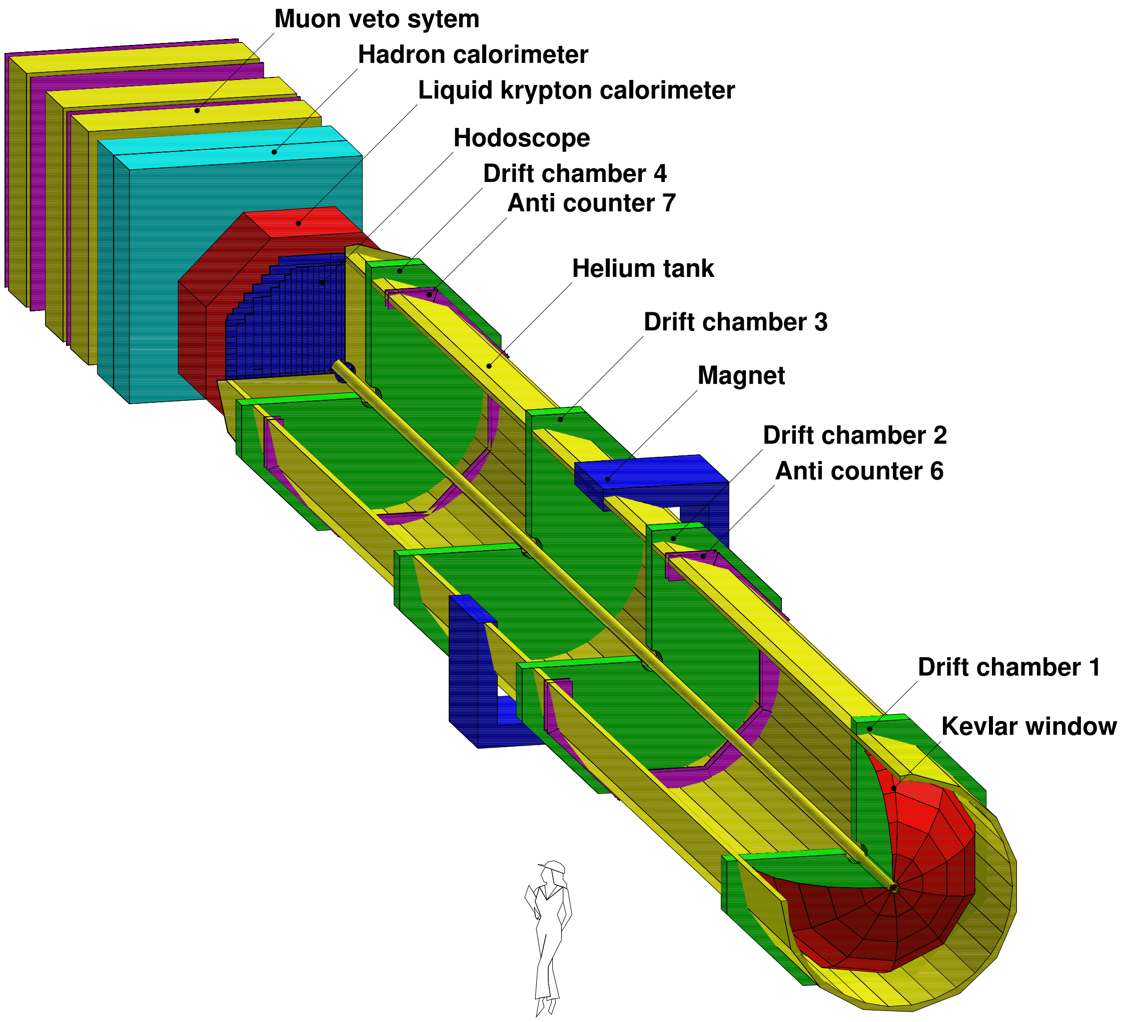
  For K_S beginning of decay region is defined by AKS anticounter
- $70 \le E_K \le 170$ GeV (K_L/K_S variations $< 20\%$)
- Weight K_L events with

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

$\Rightarrow$ Same decay vertex distribution for K_S and weighted K_L
Acceptance correction almost cancels

Price: Increase in statistical error

NA48 detector



- Magnetic spectrometer to detect $\pi^+\pi^-$ events
  + scintillator hodoscope for event time measurement
- Quasi homogeneous Liquid Krypton calorimeter to detect $\pi^0\pi^0$ events

Triggers

Rate of K_L decays ≈ 500 kHz

$\pi^0\pi^0$ trigger

- Based on LKr information summed into projections
- Cut on total energy, decay vertex and number of photons
- Fully pipelined, no dead time
- Output rate ≈ 2 kHz
- Efficiency $(99.920 \pm 0.009)\%$
  ΔR negligible

$\pi^+\pi^-$ trigger

1. Level 1 :
   - Scintillator hodoscope + Total energy + hits in drift chambers
   - Output rate ≈ 100 kHz
   - Dead time: 0.5%
   - Efficiency $(99.535 \pm 0.011)\%$
2. Level 2 :
   - Fast track reconstruction
   - Cut on decay vertex position + invariant mass
   - Output rate ≈ 2 kHz
   - Dead time: 1.1%
   - Efficiency $(98.353 \pm 0.022)\%$

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

3. Data Analysis

- Measure R in Kaon energy bins (5 GeV wide)
  $\Rightarrow$ insensitive to K_S-K_L difference in E spectrum

- Apply lifetime weighting to K_L

- Record dead time conditions
  $\approx$ 1.5% from $\pi^+\pi^-$ trigger
  $\approx$ 20% from drift chamber multiplicity limit
  and apply them offline to all events
  $\Rightarrow$ Minimise effect of K_S-K_L beam intensity difference

All corrections/uncertainties are given on R
Don't forget that to go to ϵ'/ϵ there is a factor 1/6 !

$\pi^+\pi^-$ selection

$K_S \rightarrow \pi^+\pi^-$: negligible background

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

Backgrounds : Ke3 (BR $\approx$ 39%), Kμ3 (BR $\approx$ 27%)

e and μ rejection

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

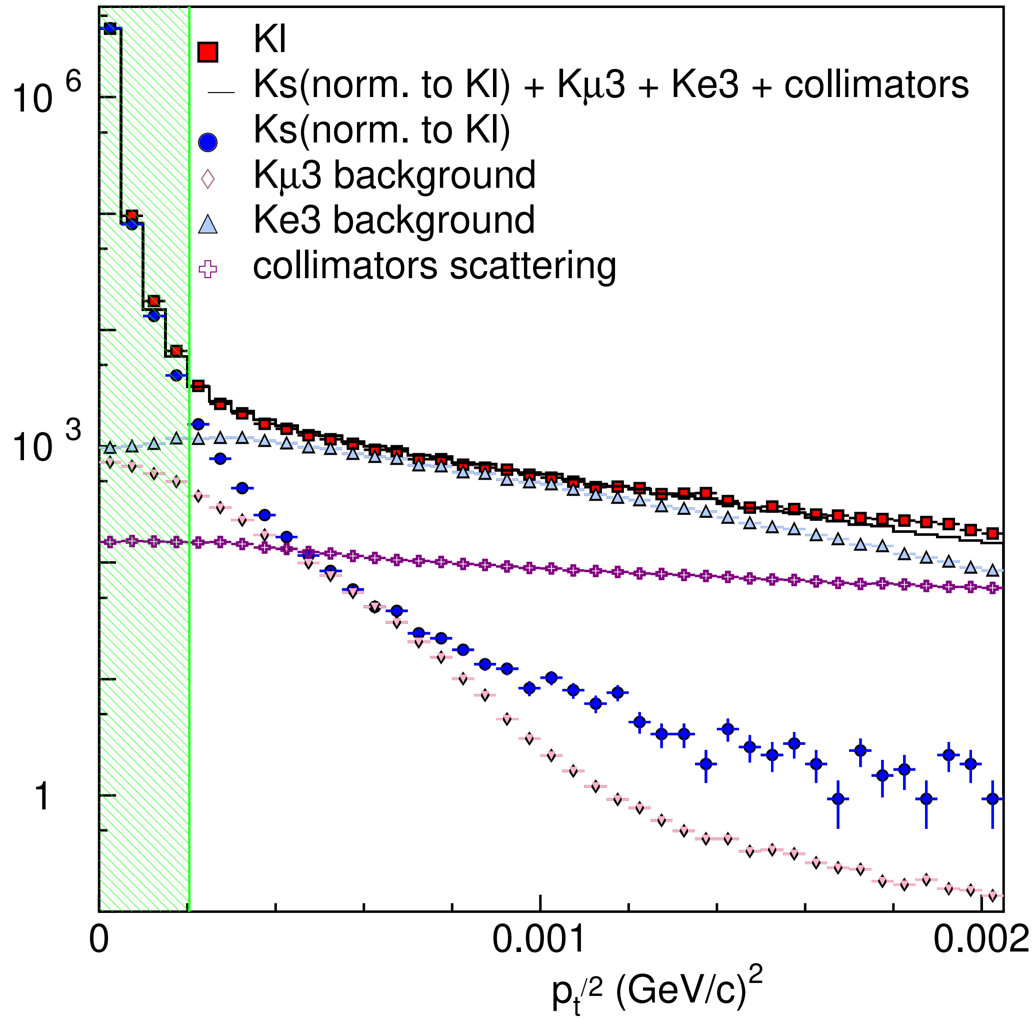
kinematical cuts

- $|M_{\pi\pi} - M_K| < 3 \times \sigma_M$, ($\sigma_M \approx 2.5$ MeV)
- $P_T'^2 < 200$ (MeV/c)^2
  $\propto$ transverse momentum of $\pi^+\pi^-$ / line connecting the target and K impact point
  ≈ 0 for two body decay, > 0 for Ke3, Kμ3
- $\frac{|p_1 - p_2|}{p_1 + p_2}$ <min(0.62,1.08-0.0052 $\times E_K$)

  ($\Leftrightarrow$ cut on $\cos(\theta^*)$)

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

Estimate residual background under K_L signal
using control regions in $M_{\pi\pi}$ and $P_T'^2$
and samples of identified Ke3 and Kμ3 data events.



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

(systematic error : changes in control regions, modelling of $P_T'^2$ shape)

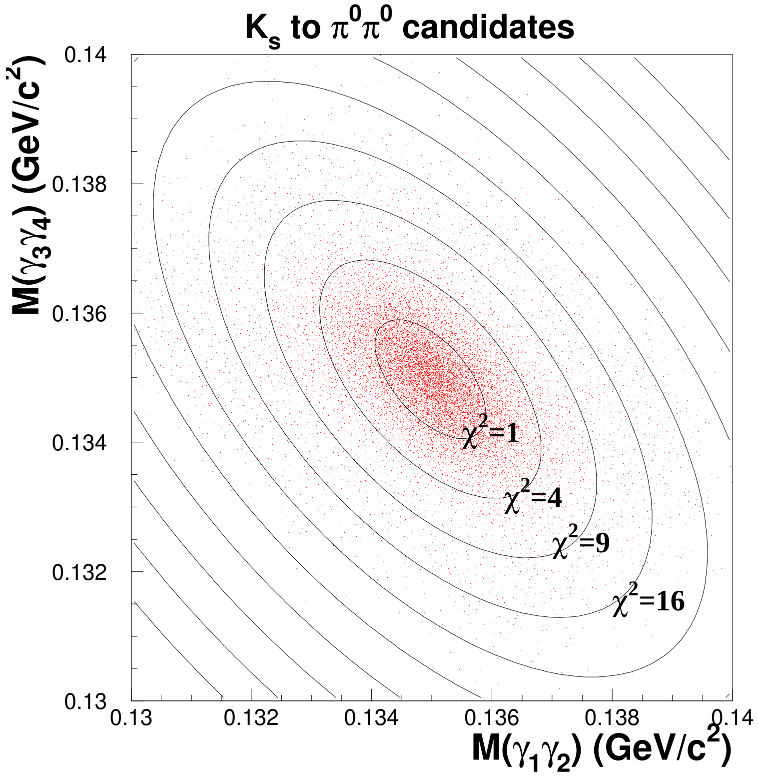
$\pi^0\pi^0$ selection

$K_S \rightarrow \pi^0\pi^0$: negligible background

$K_L \rightarrow \pi^0\pi^0$: BR $\approx$ 0.09%

Background: $K_L \rightarrow 3\pi^0$ (BR $\approx$ 21%)

- 4 γ in LKr
- γ angle not directly measured
- (E_i,x_i,y_i) + K mass hypothesis
  $\Rightarrow$ D=$z_{LKr} - z = \frac{1}{M_K}\sqrt{\Sigma_{ij} E_i E_j d_{ij}^2}$
- Pair photons to get best π^0 masses
  $m_{ij} = \frac{1}{D}\sqrt{E_i E_j} d_{ij}$
  (resolution $\approx$ 0.9 MeV)
- To reduce background:
  Cut on χ^2 from π^0 masses
  Veto events with 5th cluster

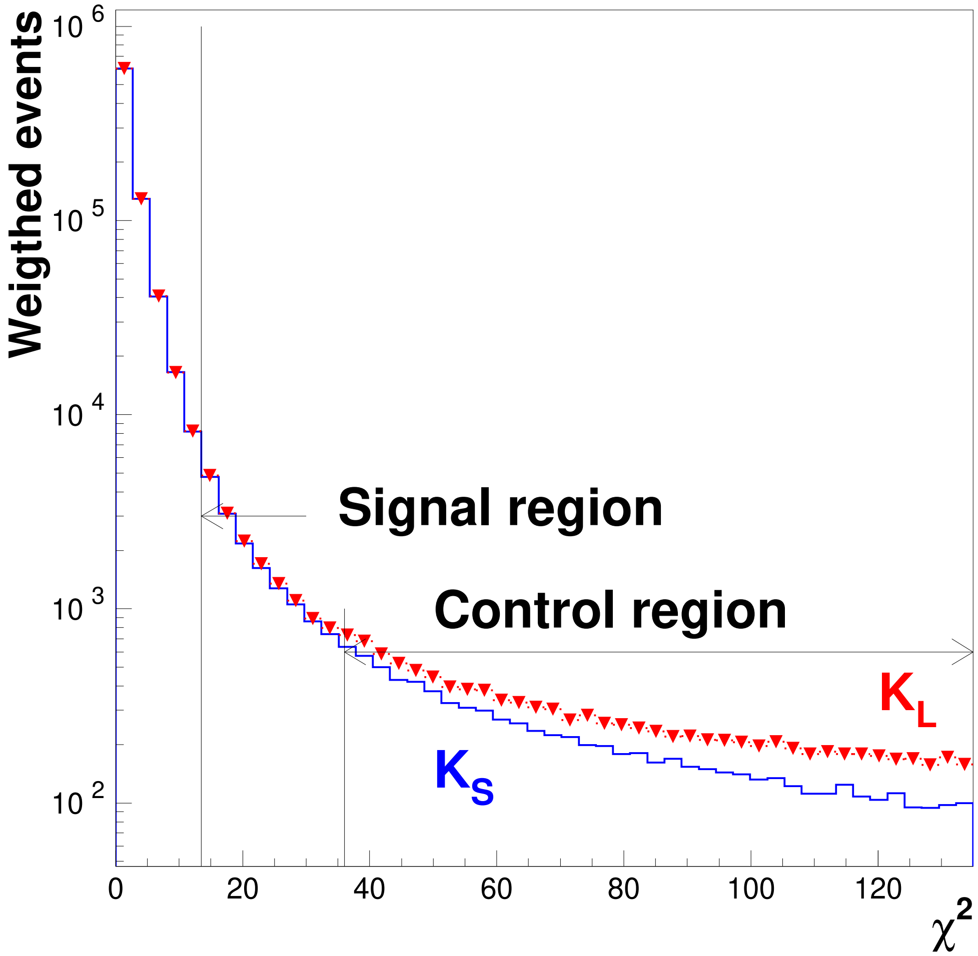


$\pi^0\pi^0$ background subtraction

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

($3\pi^0$ background is $\approx$ flat)

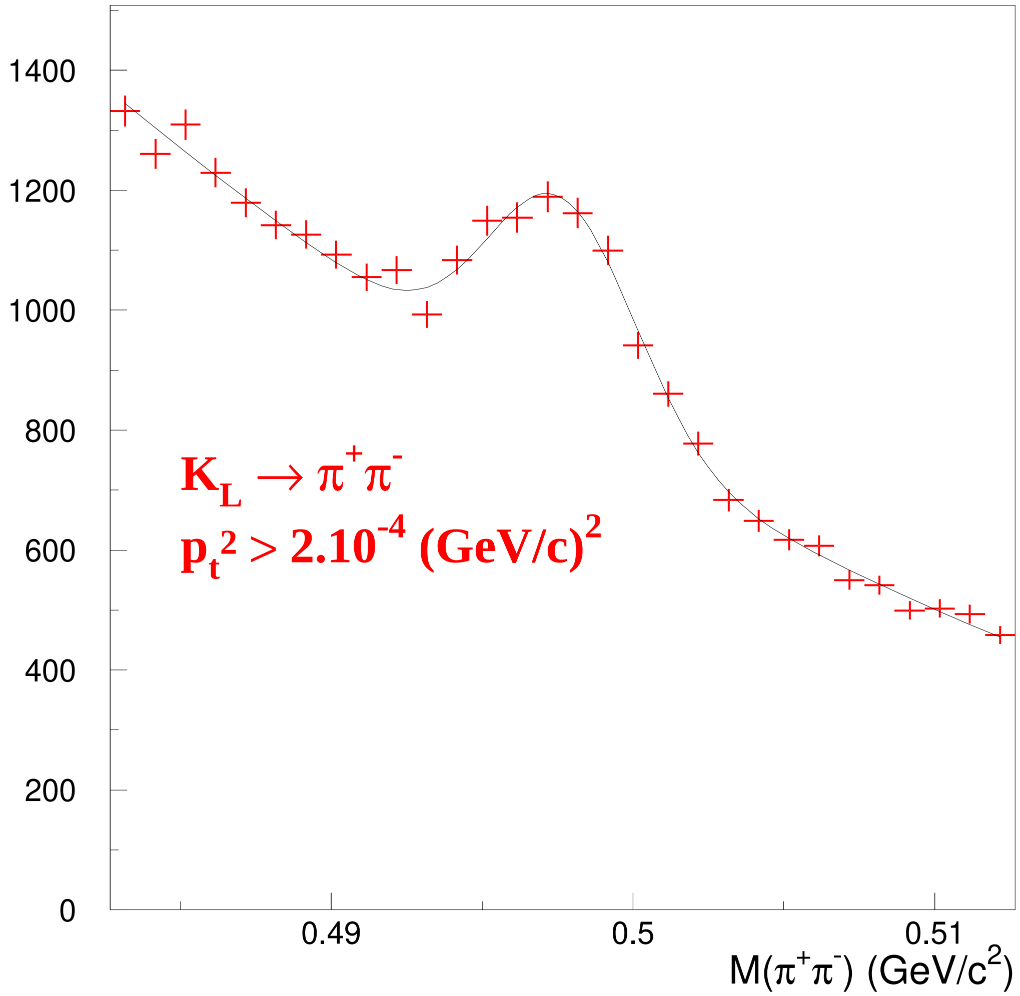
$\pi^0\pi^0$ contribution in control region from resolution tails is derived from K_S events.



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

syst.error: uncertainty in background extrapolation (from MC)

Measure collimator background in $K_L \to \pi^+\pi^-$
from events at $P_T'^2 > 200\ (\mathrm{MeV/c})^2$
with $M_{\pi\pi} = M_K$



Background from beam scattering produces K_S in final collimator. It is removed from $\pi^+\pi^-$ sample by $P_T'^2$ cut, but kept in $\pi^0\pi^0$ sample $\Rightarrow$

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

K_S-K_L identification

$$\Delta t(\text{Kaon-proton}) \begin{array}{ccc} \leq & 2\text{ns} & \Rightarrow & K_S \\ > & 2\text{ns} & \Rightarrow & K_L \end{array}$$

2 possible mistakes

Danger only if $\pi^+\pi^- \neq \pi^0\pi^0$

1. K_S mistagged as K_L: α_{SL}
   (tails in time measurement)

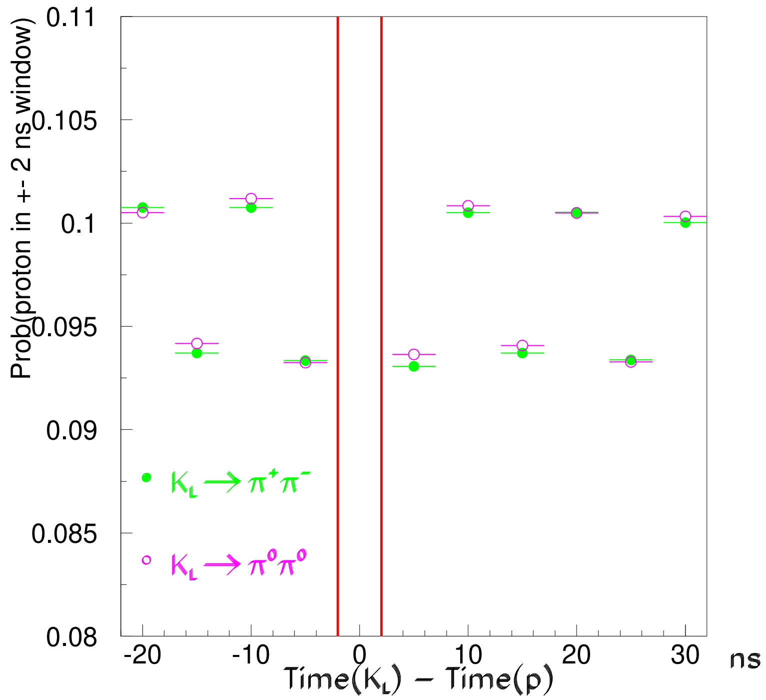
   $\Delta R \approx 6 \times \Delta\alpha_{SL}$
   Compare directly charged and neutral measurements using events with γ's and e^+e^-

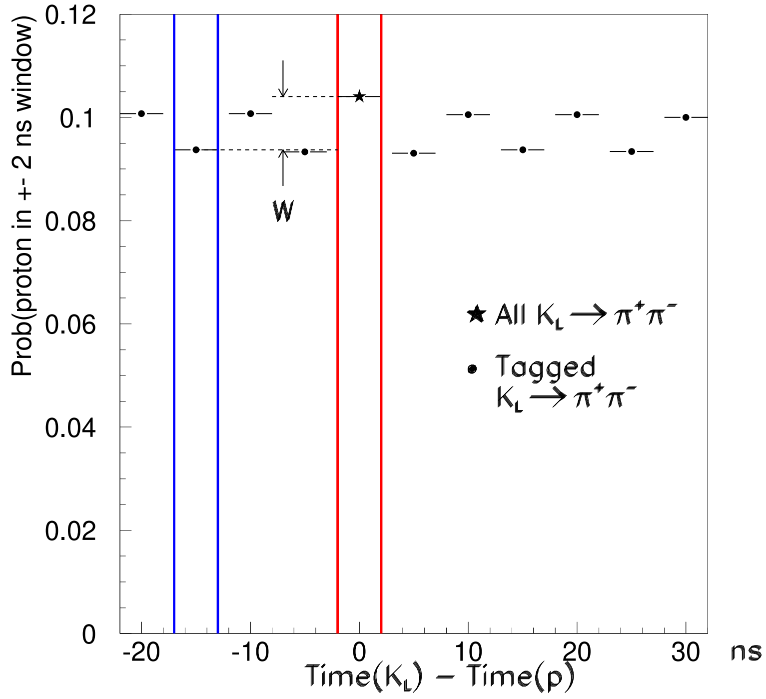
   $$\Delta\alpha_{SL} = (0 \pm 0.5) \times 10^{-4}$$

2. K_L mistagged as K_S: α_{LS}
   Accidental coincidence between K_L and a proton in tagger
   (rate $\approx$ 30 MHz)
   Accidental losses ($\propto$ beam intensity) are higher for $\pi^+\pi^-$ than for $\pi^0\pi^0$, so the beam intensity and accidental tagger activity is lower for the selected $\pi^+\pi^-$.

   $\Delta R \approx 2 \times \Delta\alpha_{LS}$

Estimate of $\Delta\alpha_{LS}$





Using sidebands of tagger selected K_L to $\pi^0\pi^0$ and $\pi^+\pi^-$:

$$\Delta = (3.0 \pm 1.0) \times 10^{-4}$$

Extrapolation to central window (W)

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

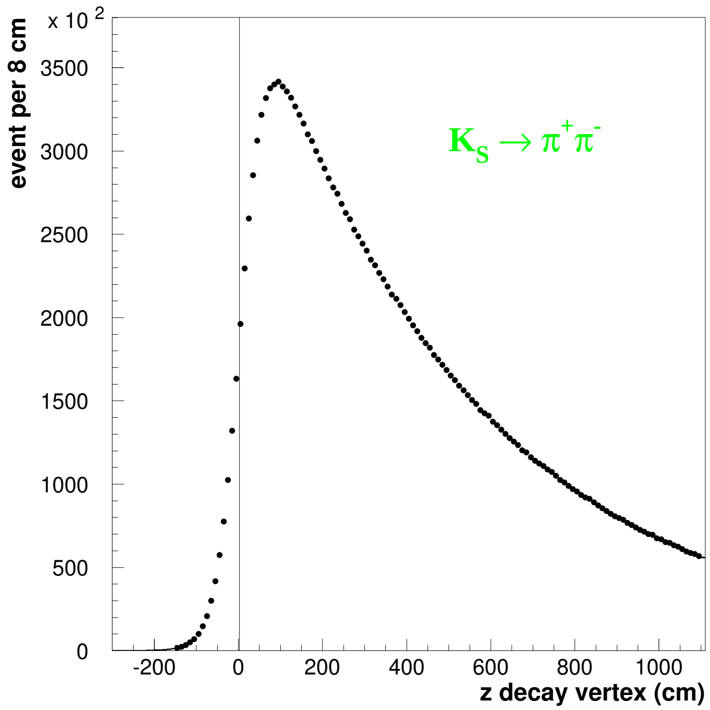
$\pi^0\pi^0$: use $3\pi^0$ events (only K_L)

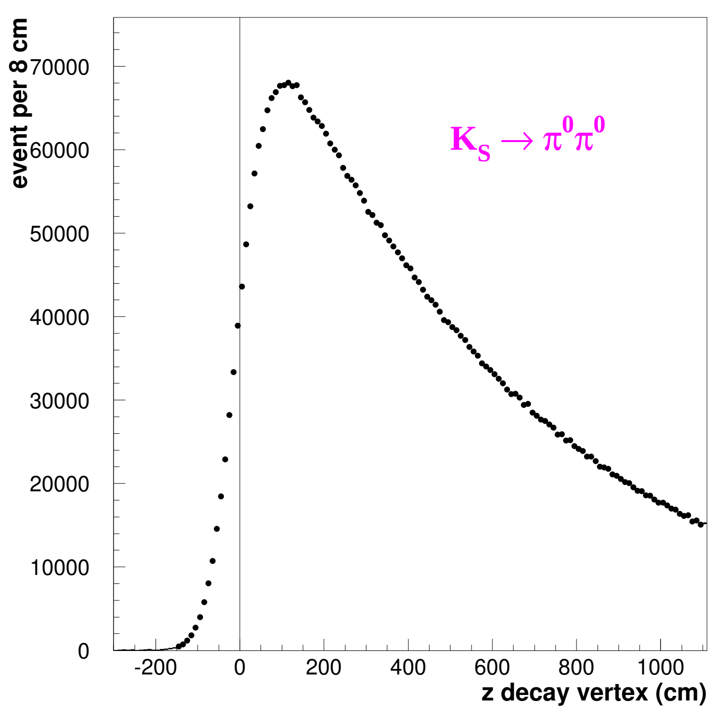
$$\Delta W = (1.3 \pm 1.1) \times 10^{-4}$$

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

(adding systematic error from choice of sideband windows: $\pm 1.0\times 10^{-4}$)

Reconstruction of AKS position





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

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

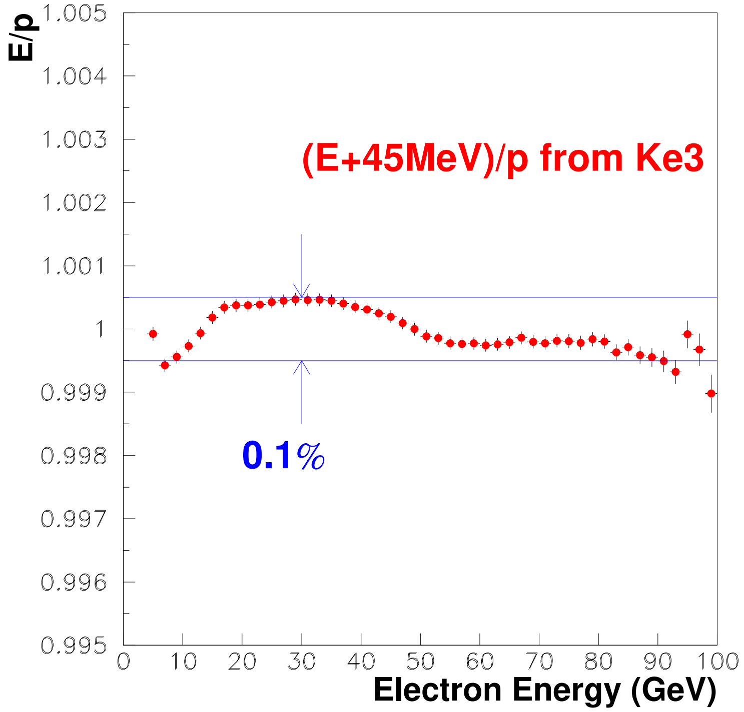
$\Rightarrow \Delta(R) = (2 \pm 2) \times 10^{-4}$

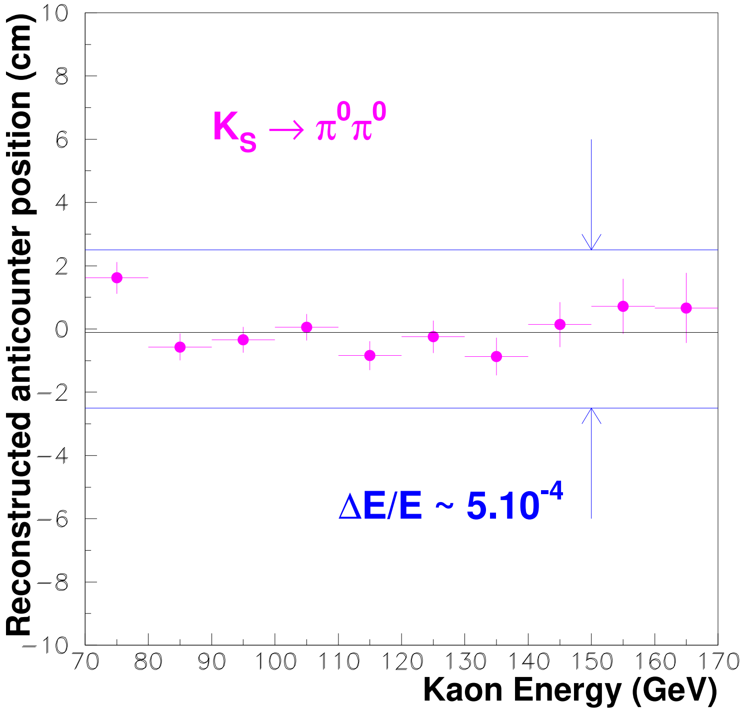
$\pi^0\pi^0$: Adjust energy scale to match nominal position

(1 factor independent of energy)

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

Non linearity checks

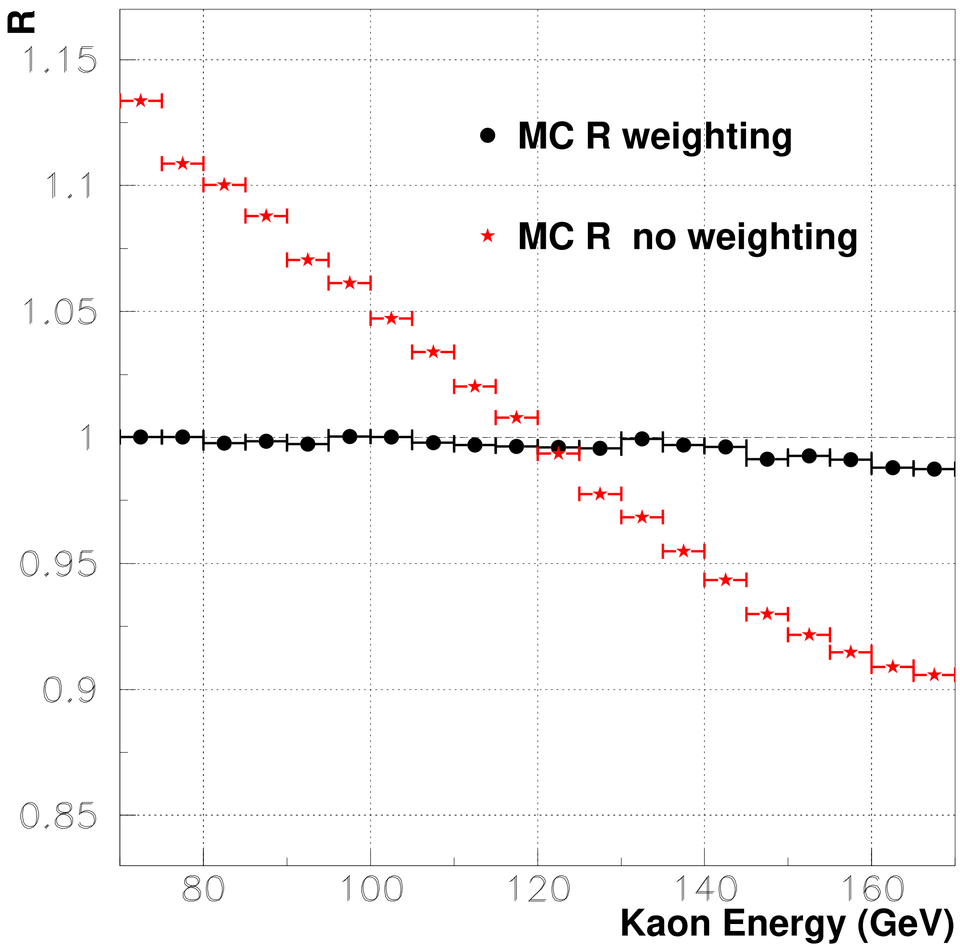




Electrons from Ke3 decays :
E/p constant within ≈ 0.1%
between a few GeV and 100 GeV

Overall Check :
Reconstructed AKS position
independent of K energy

Acceptance Correction



Acceptance correction : $+26.7\times10^{-4}$

Uncertainties :

MC stat error: $\pm4.1\times10^{-4}$

Systematic error: $\pm4.0\times10^{-4}$

beam positions and shapes: $\pm3.3\times10^{-4}$

Comparison fast MC/GEANT based spectrometer simulation: $\pm2.3\times10^{-4}$

Accidental activity

Accidental activity from beams (dominated by K_L beam) $\Rightarrow$ Event losses.

Due to the losses we see $(1 - A^{mode}_{beam}\, I_{beam})$ of good events, where I_{beam} is an average K_L beam intensity, seen by these events.

Residual effect
$\Delta R \approx I \times \delta(A^{\pi^+\pi^-} - A^{\pi^0\pi^0}) + \delta I \times (A^{\pi^+\pi^-} - A^{\pi^0\pi^0})$,
where δ means the difference between two beams.

- δI minimized by:
  - simultaneous beams $\Rightarrow$ K_L and K_S events see the same average activity, within 1% (checked directly in data);
  - applying dead time conditions to all modes.
- $\delta(A^{\pi^+\pi^-} - A^{\pi^0\pi^0})$ is small by design of the experiment. Lifetime weighting $\Rightarrow$ K_L and K_S events illuminate the same parts of the detector

Uncertainty on R :

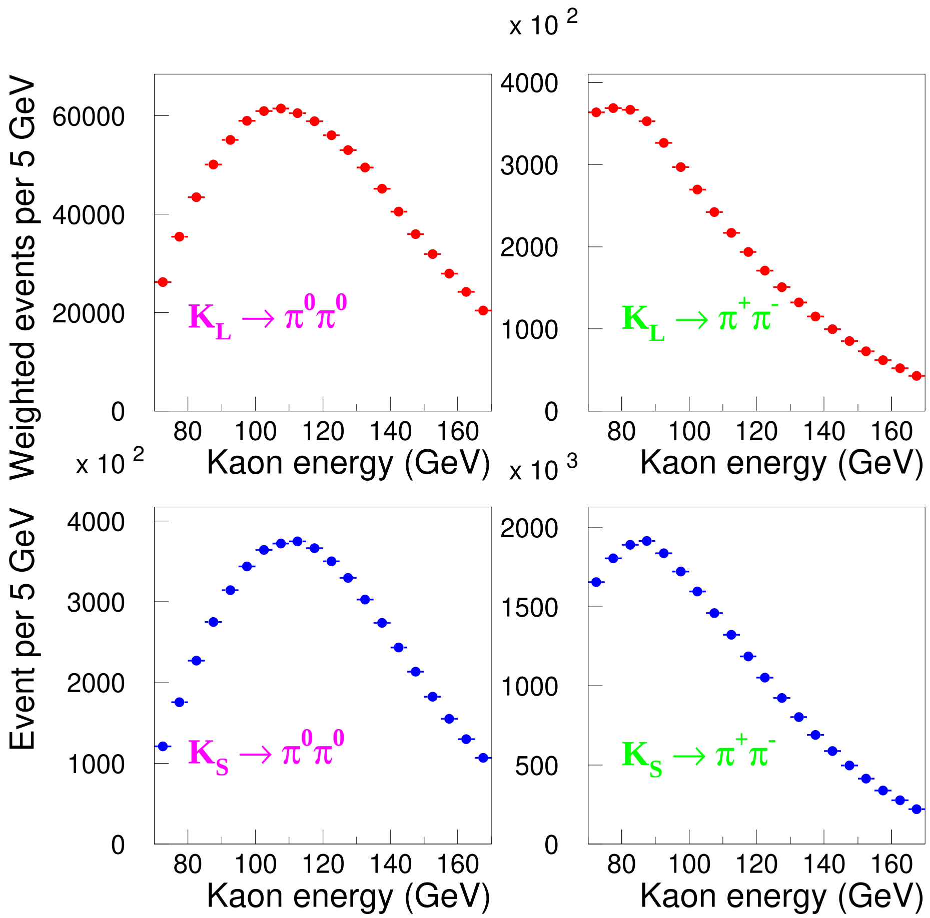
- Intensity difference $\Rightarrow$ $\Delta R = (0 \pm 3) \times 10^{-4}$
- Residual illumination difference $\Rightarrow$ $\Delta R = (0 \pm 3) \times 10^{-4}$

  (studied using random event overlays to $\pi\pi$ MC and data)

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	± 12.6

Some uncertainties are limited by data statistics
($\pi^+\pi^-$ trigger efficiency measurement, accidental tagging,...)



Event statistics:

(corrected for mistagging)

$K_L \to \pi^0\pi^0$: 3.29×10^6

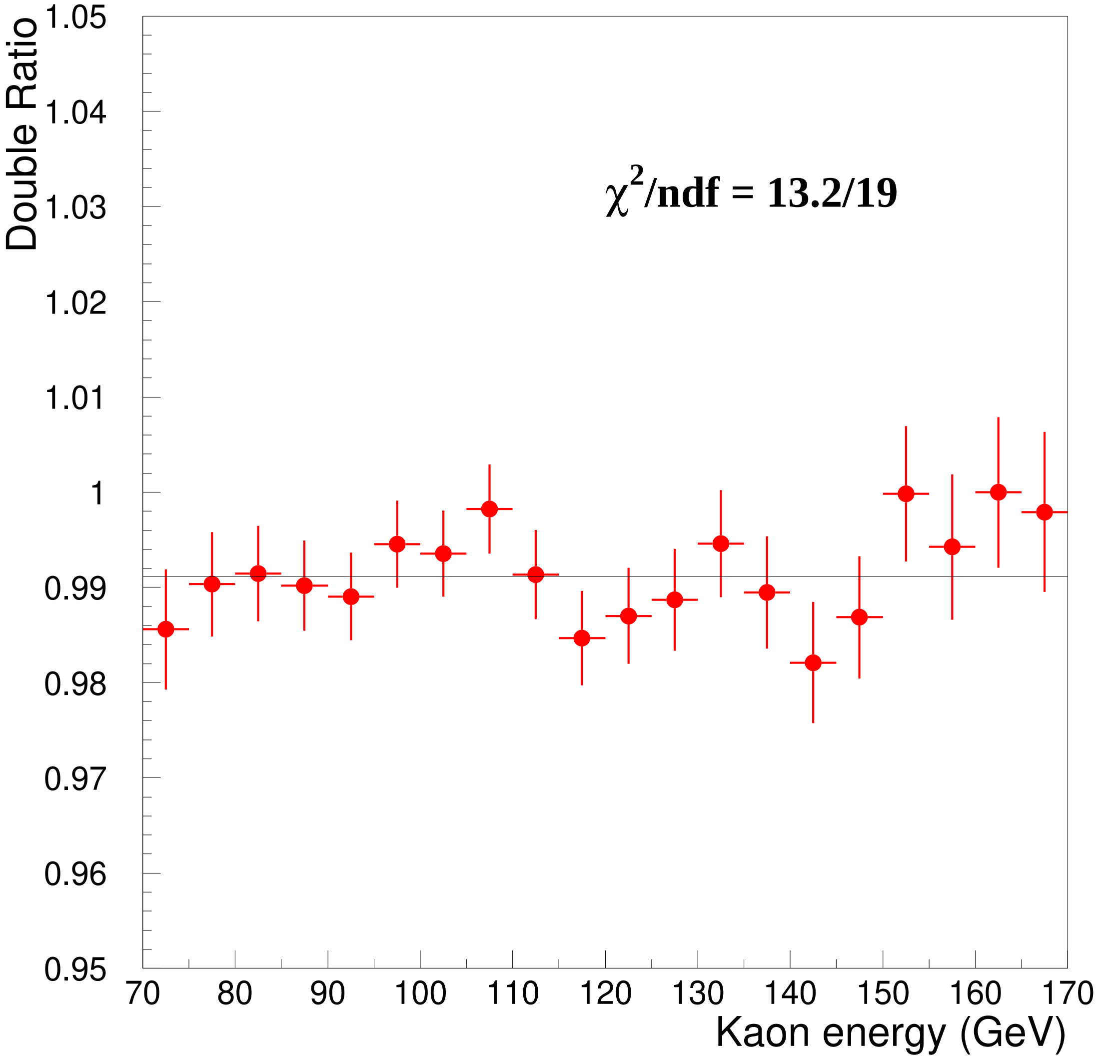
$K_S \to \pi^0\pi^0$: 5.21×10^6

$K_L \to \pi^+\pi^-$: 14.45×10^6

$K_S \to \pi^+\pi^-$: 22.22×10^6

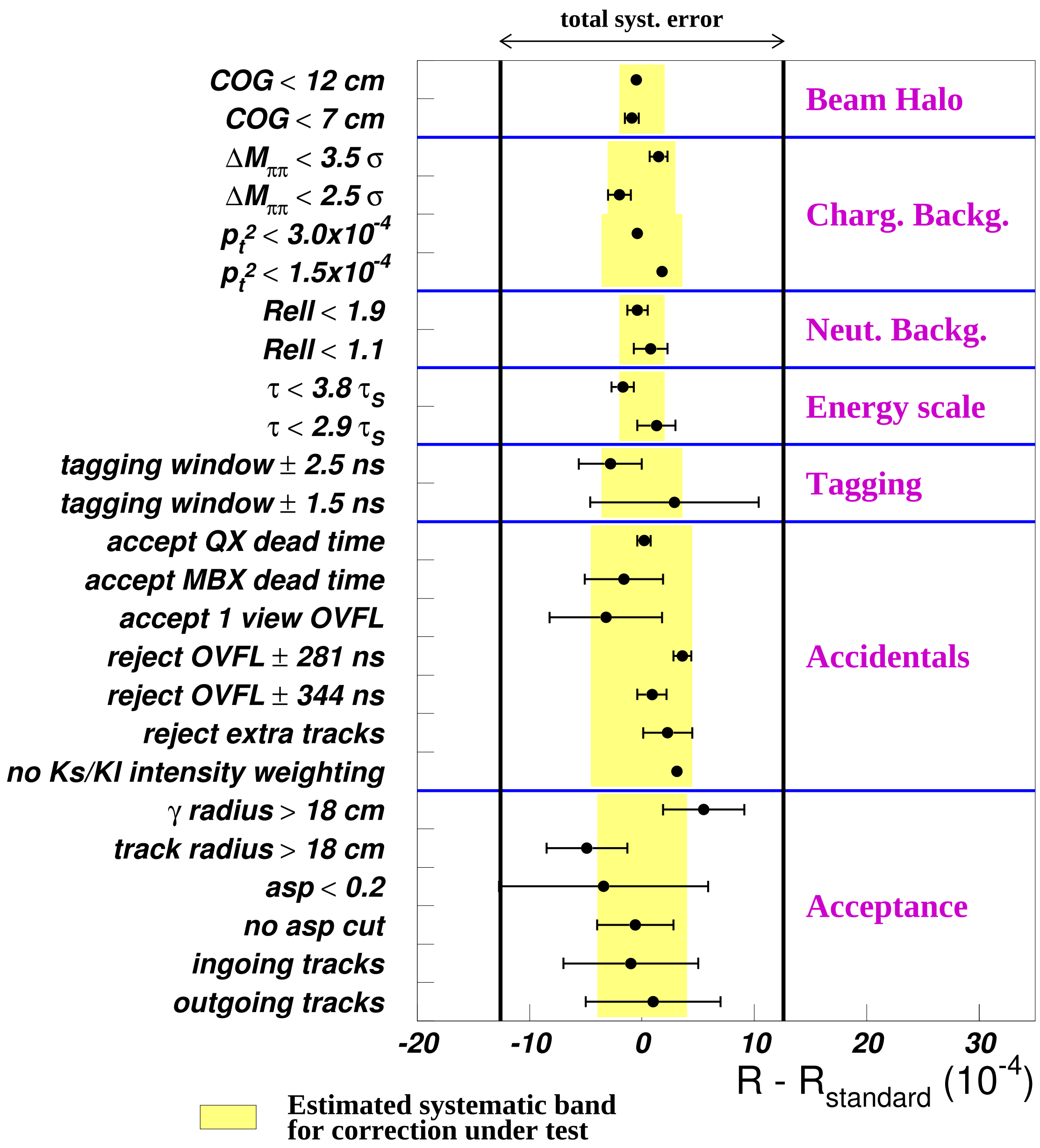
Result

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



Checks

R stability against cut variations



Conclusion

From 98+99 data:

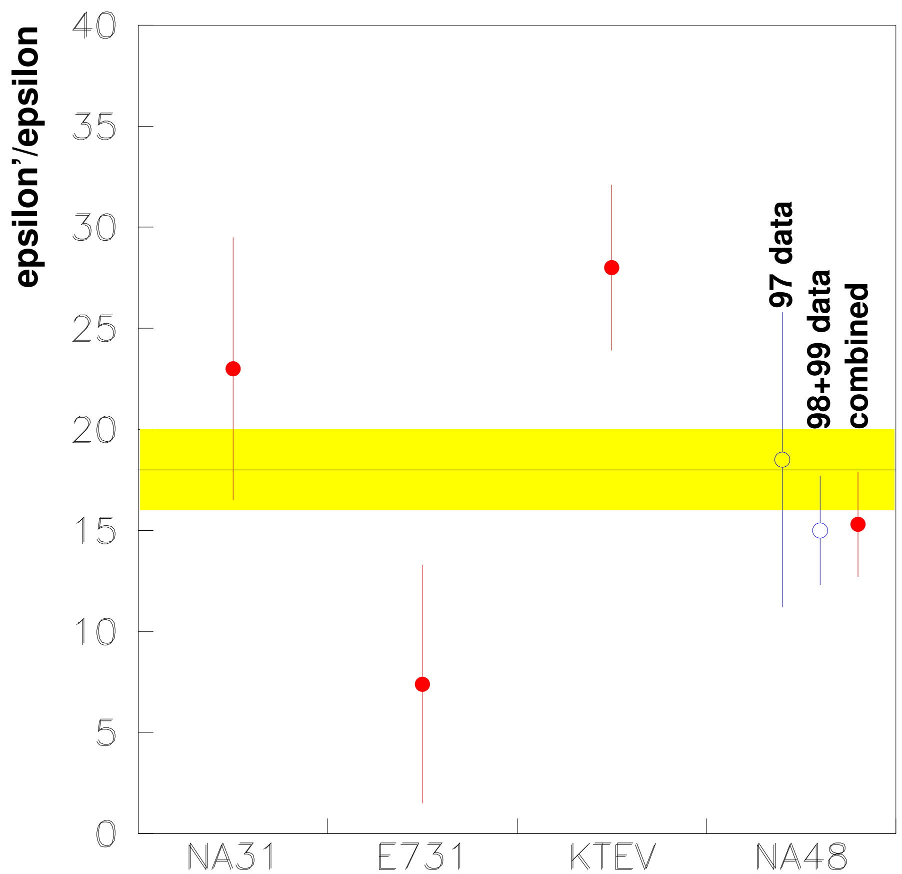
$$\epsilon'/\epsilon = (15.0 \pm 2.7) \times 10^{-4}$$

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

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

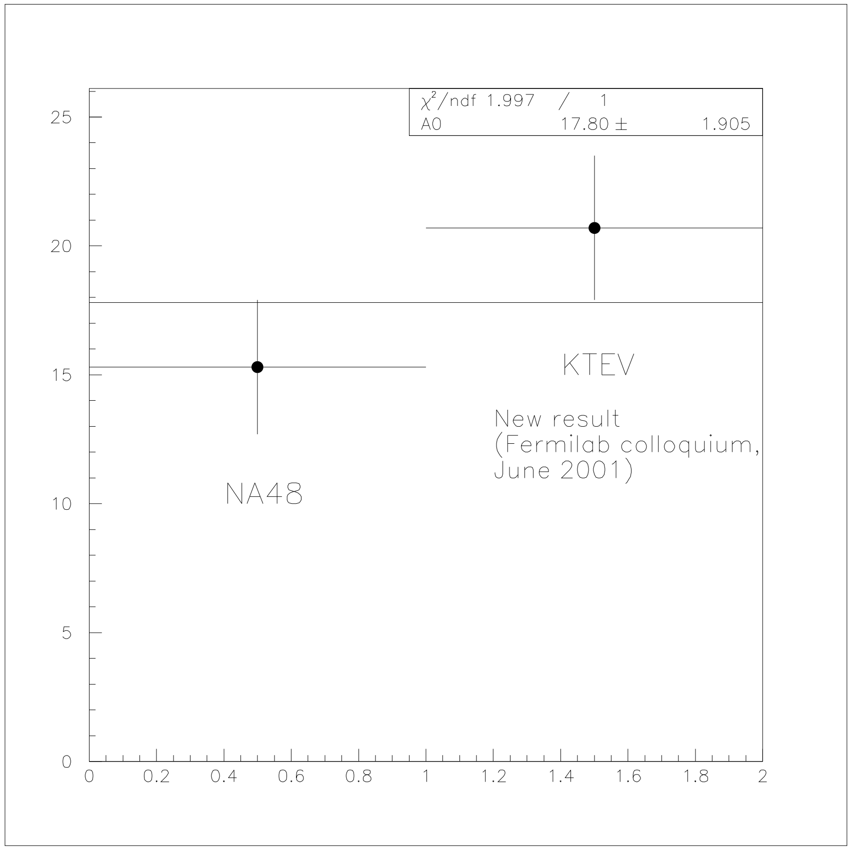
(5.9 σ away from 0)

Experimental results comparison (in May 2001)



Naive average : $\epsilon'/\epsilon = (18.0 \pm 2.0) \times 10^{-4}$ with $\chi^2/\mathrm{ndf} = 10.8/3$

New results comparison (in June 2001)



New KTeV result:

$Re(\frac{\epsilon\prime}{\epsilon}) = (20.7 \pm 1.5(sta) \pm 2.4(sys) \pm 0.5(MC))\ 10^{-4} = (20.7 \pm 2.8)\ 10^{-4}$