New measurement of $Re(\varepsilon'/\varepsilon)$ by the NA48 experiment at CERN

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on behalf of the *NA48* collaboration

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

Outline

- ☞ $\mathcal{CP}$ **violation in the** K^0 **system**
- ☞ **Double ratio method in** *NA48*
- ☞ **Experimental setup**
- ☞ **Data analysis and** $Re(\varepsilon'/\varepsilon)$ **measurement**
- ☞ **Conclusion and perspectives**

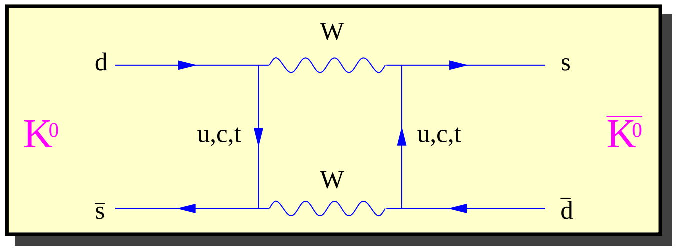
➡ The presented result is based on data collected in 1998 and 1999 runs
- Eur. Phys. J. C 22,231-254 (2001)

➡ The statistics is almost 7 times larger than the previous published result based on 1997 data
- Phys. Lett. B 465 (1999)

$\mathcal{CP}$ violation in the K^0 system

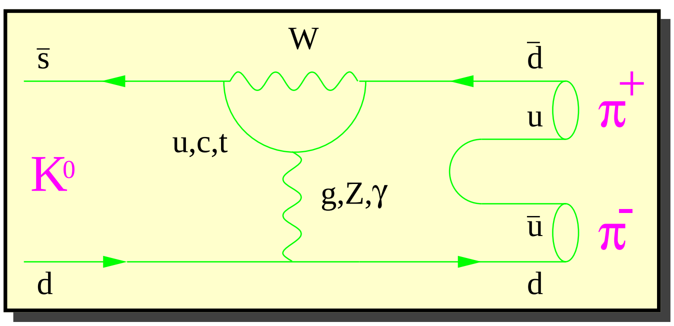
✦ in 1964 $\mathcal{CP}$ violation discovery : $K_L \to \pi^+\pi^-$

Indirect $\mathcal{CP}$ violation
through mixing $K^0/\overline{K^0}$
Box diagrams ($\Delta S = 2$)
$\Rightarrow \varepsilon = (2.28 \pm 0.02) \times 10^{-3}$



Mass eigenstates K_S and $K_L \neq \mathcal{CP}$ eigenstates K_1^0 and K_2^0

$$K_L = K_2{}^{-1} + \varepsilon K_1{}^{+1} \qquad \underbrace{\pi^+\pi^-, \pi^0\pi^0}_{\mathcal{CP} = +1}$$



Direct $\mathcal{CP}$ violation
through decay
Penguin diagrams ($\Delta S = 1$)
$\Rightarrow \varepsilon'$ parameter

Define the ratio of $\mathcal{CP}$ violating / $\mathcal{CP}$ conserving amplitudes :

$$\eta^{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon'$$

$$\eta^{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \simeq \varepsilon - 2\,\varepsilon'$$

The measurable quantity $Re(\varepsilon'/\varepsilon)$ is connected to the ratio of observable decay rates :

$$R \equiv \left|\frac{\eta^{00}}{\eta^{+-}}\right|^2 = 1 - 6 \times Re(\varepsilon'/\varepsilon)$$

Double ratio method in *NA48*

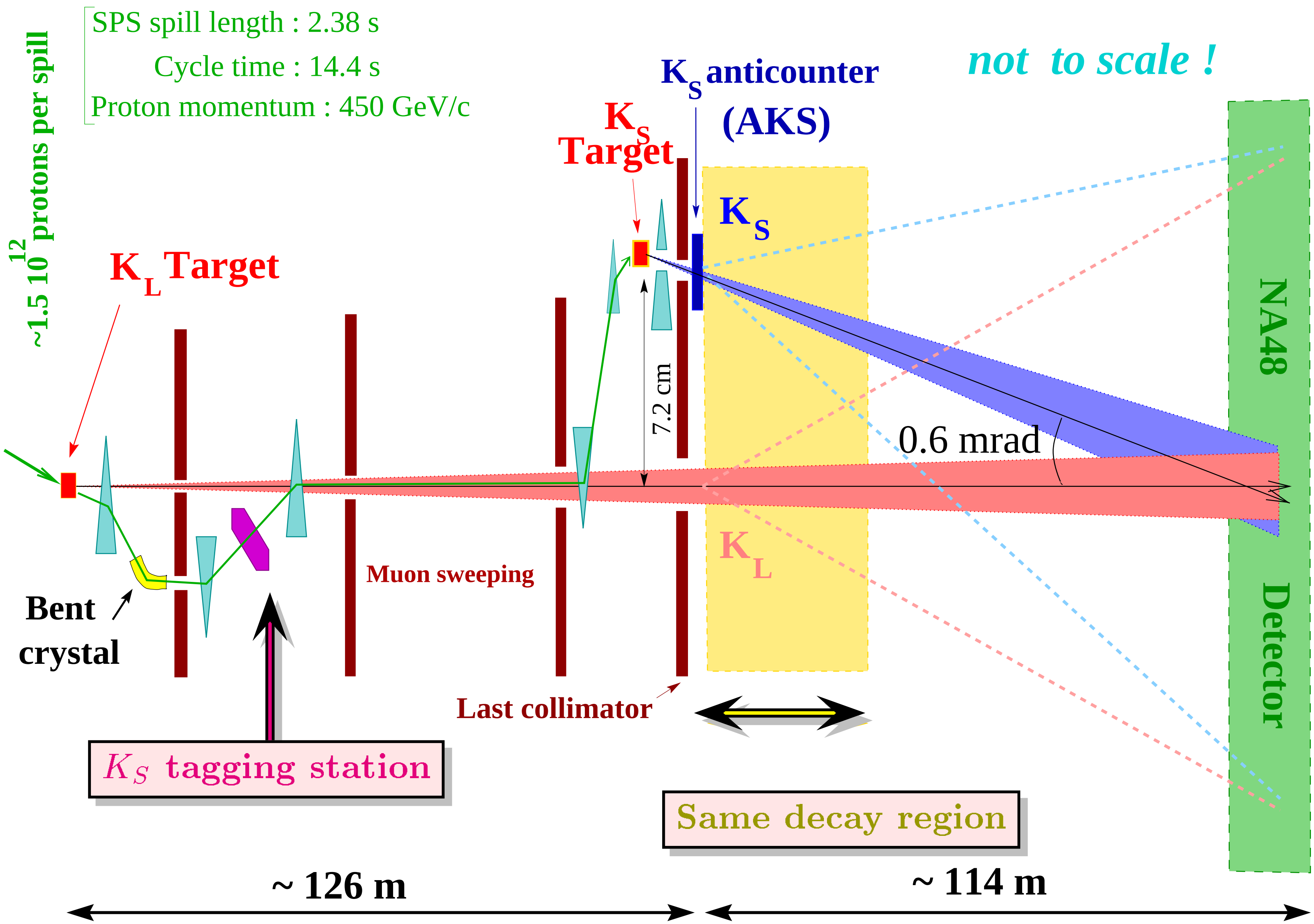
$$R^{meas} = \frac{N(\mathrm{K_L} \to \pi^0\pi^0)N(\mathrm{K_S} \to \pi^+\pi^-)}{N(\mathrm{K_S} \to \pi^0\pi^0)N(\mathrm{K_L} \to \pi^+\pi^-)} \simeq 1 - 6Re(\varepsilon'/\varepsilon)$$

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

➡ Systematics: systematic biases in the event counting are made symmetric between $\pi^0\pi^0$ and $\pi^+\pi^-$, or K_L and K_S

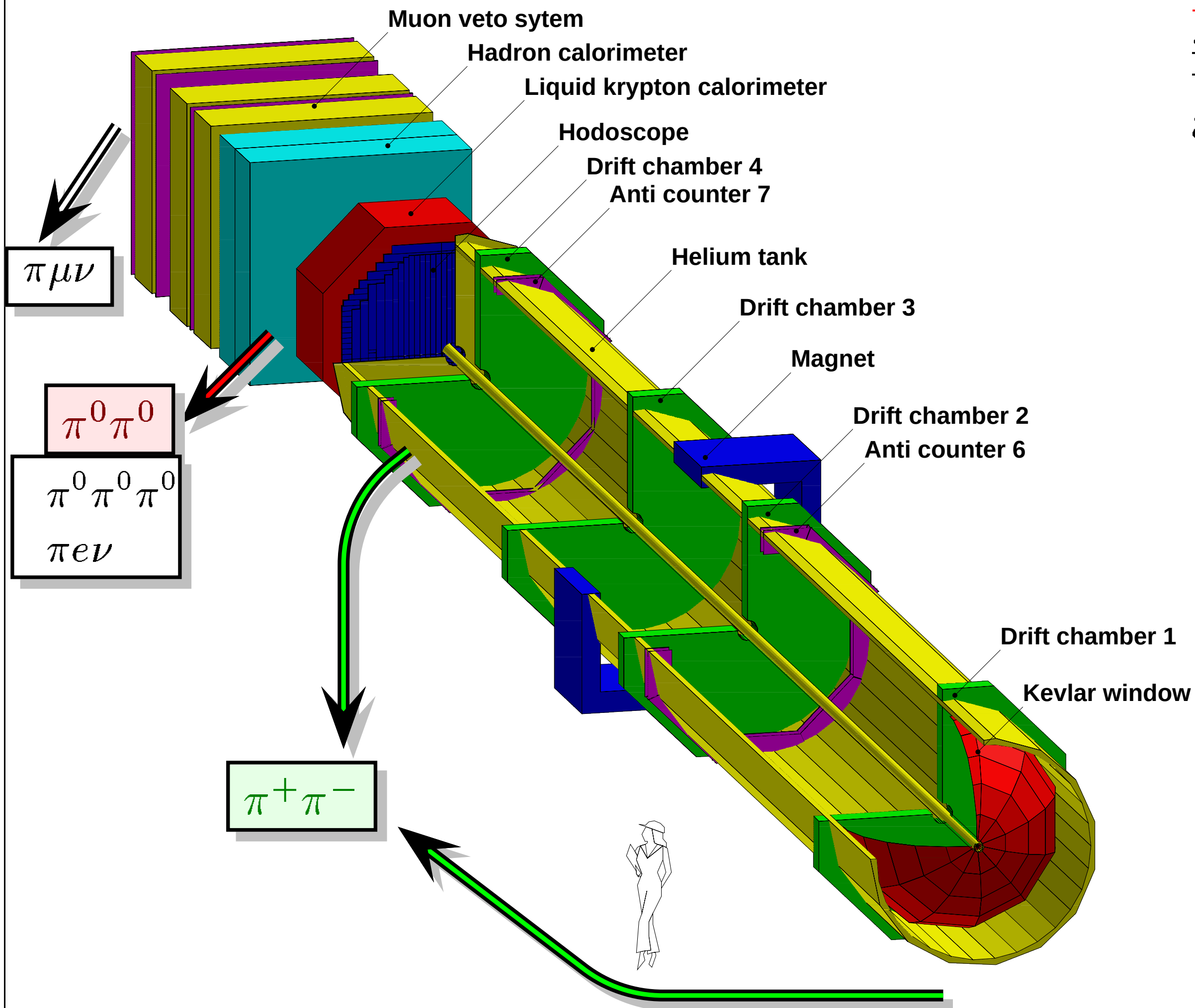
- The 4 modes are taken simultaneously from the same decay region
  ⇒ Cancellation of fluxes, dead times, inefficiencies, accidental losses...
- Lifetime weighting to equalise distribution of K_S and K_L decay positions
  ⇒ Cancellation of detector acceptance effects
- Use quasihomogeneous Liquid Krypton calorimeter to detect $\pi^0\pi^0$ and magnetic spectrometer for $\pi^+\pi^-$
  ⇒ Minimise backgrounds
- Measure R in Kaon energy bins (5 GeV wide)
  ⇒ insensitive to K_S -K_L difference in E spectrum

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

NA48 detector



High resolution detector to identify $\pi^+\pi^-$ and $\pi^0\pi^0$ and 3-body background

$K_{\rm L,S} \to \pi^+\pi^-$

Magnetic spectrometer

$\sigma(M_{\pi\pi}) \sim 2.5 MeV/c^2$,

$K_{\rm L,S} \to \pi^0\ \pi^0$

Liquid Krypton ECAL

$\sigma(M_{\pi^0}) \simeq 1.1 MeV/c^2$

Decay time

known to $\sim$ 200 ps

Data analysis

$$R = \frac{N(K_L \to \pi^0\pi^0)N(K_S \to \pi^+\pi^-)}{N(K_S \to \pi^0\pi^0)N(K_L \to \pi^+\pi^-)} + \Delta R$$

At first order, almost everything cancels in R
Check and evaluate second order effects ΔR

1. Identify $\pi^+\pi^-$ and $\pi^0\pi^0$ and subtract residual backgrounds

2. Tag K_S and K_L decays and correct for misidentification

3. Define common decay region for $\pi^0\pi^0$ and $\pi^+\pi^-$ events to ensure flux cancellation (reconstruction uncertainties)

4. Compute residual K_S / K_L acceptance differences

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

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

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

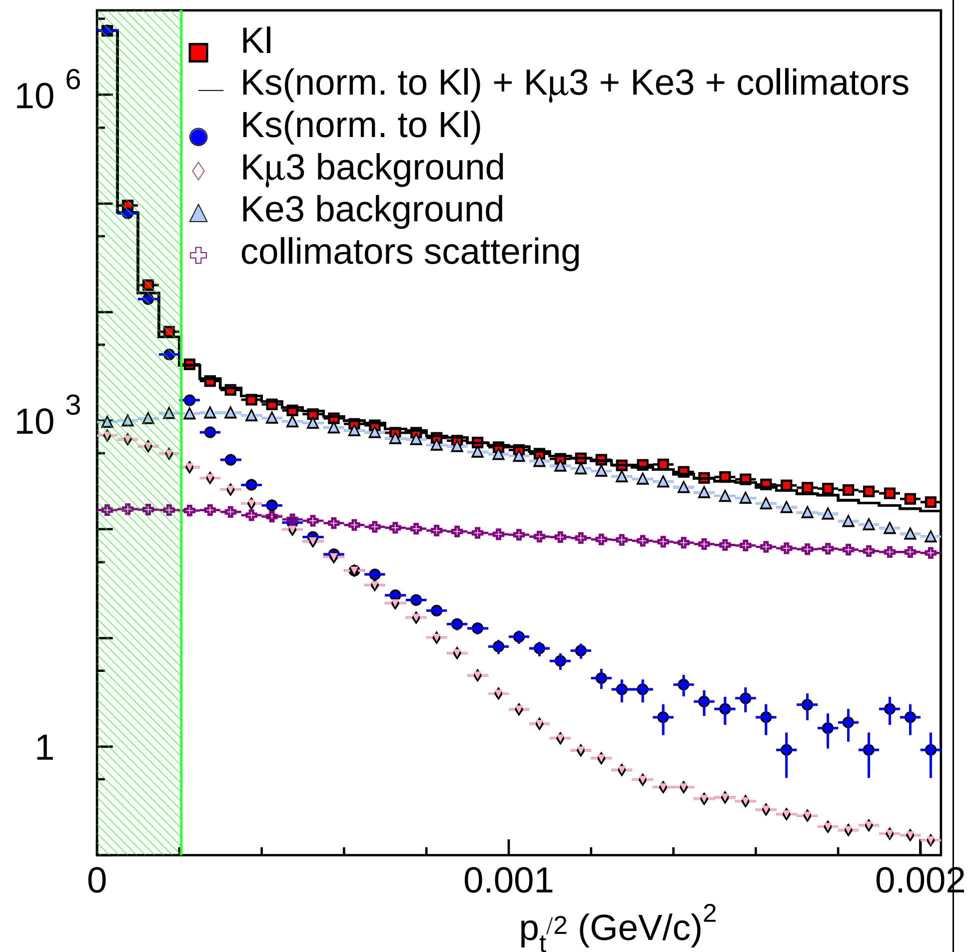
Background subtraction in $\pi^+\pi^-$

- K_S : $\Lambda \rightarrow \pi^+\pi^-$ completely rejected by an asymmetry cut
- K_L : $K_L \rightarrow \pi\mu\nu$ and $\pi e\nu$, are strongly suppressed by Muon Vetoes and E/p respectively.

Estimate residual background under K_L signal using control regions in invariant mass $M_{\pi\pi}$ and transverse momentum $P_T'^2$

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

syst. error: changes in control regions, modelling of $P_T'^2$ shape



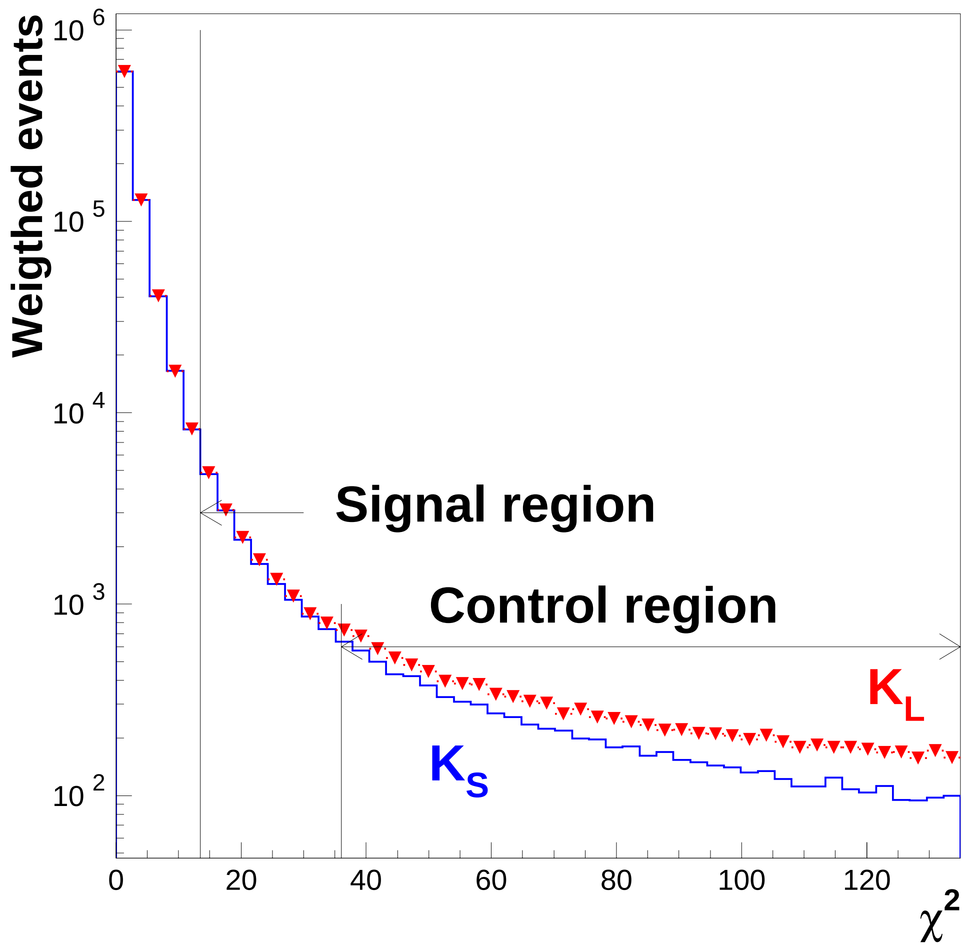
Background subtraction for $\pi^0\pi^0$

- K_S : no background
- K_L : $K_L \to 3\pi^0$ with lost or fused γ(s). Compatibility of the two $\gamma\gamma$ pair masses with $m(\pi^0)$ described by a χ^2 function. Events with extra clusters are rejected.

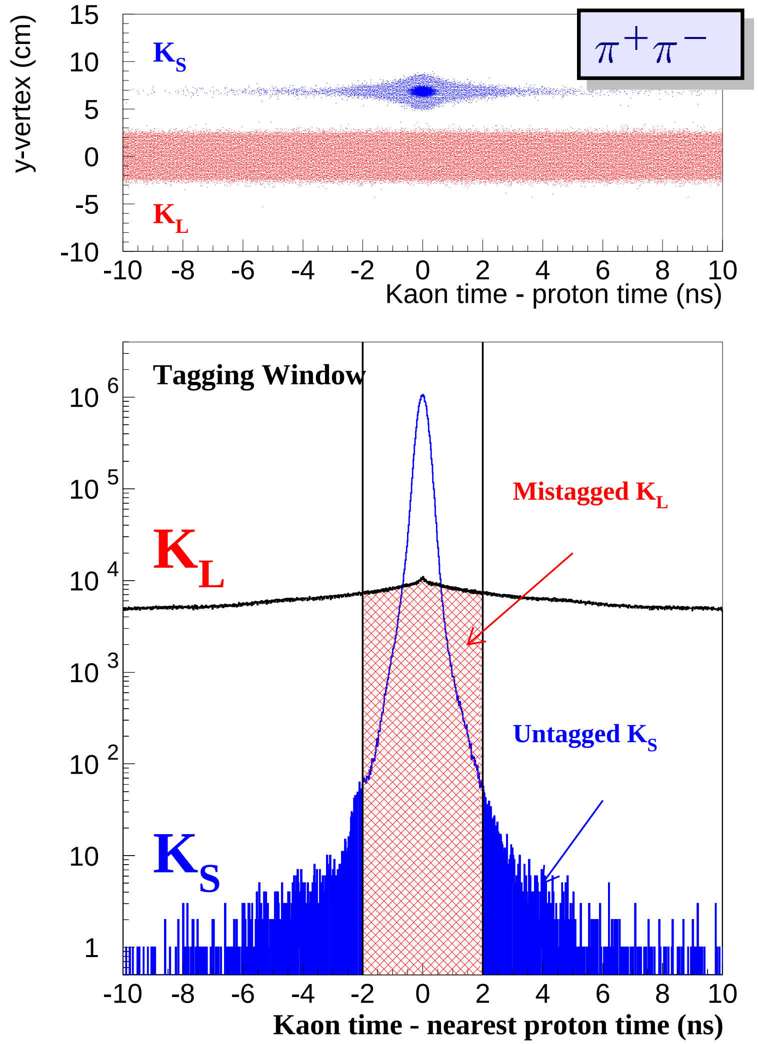
Estimate residual background under K_L signal using control region in χ^2 (where $3\pi^0$ bkg is almost flat), and K_S events to evaluate resolution tails.

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

syst. error : Bkg extrapolation (from MC)



K_S / K_L identification



- in both decay modes K_S tagged by comparing the event time to proton times as they pass through tagging station
- coincidence window of ± 2 ns
- in $\pi^+\pi^-$ kaons are also identified through y-vertex
- two ways of misidentification:

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

- K_S mistagged as K_L : $\alpha_{\rm SL}$
  tails on time measurement
- K_L mistagged as K_S : $\alpha_{\rm LS}$
  Accidental coincidence betwen K_L and a proton in tagger (rate $\sim$ 30 MHz)

K_S/K_L misidentification

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

$$\alpha^{+-}_{SL} = 1.6 \times 10^{-4}$$

dominated by tagging station inefficiency

➡ $\Delta\alpha_{SL}$ is measured from $2\pi^0$ and $3\pi^0$ events with conversion - by comparing the hodoscope time (from e^+e^-) with LKr time (from photon showers)

➡ other methods confirm the result

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

$$\Delta R = (0 \pm 3) \times 10^{-4}$$

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

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

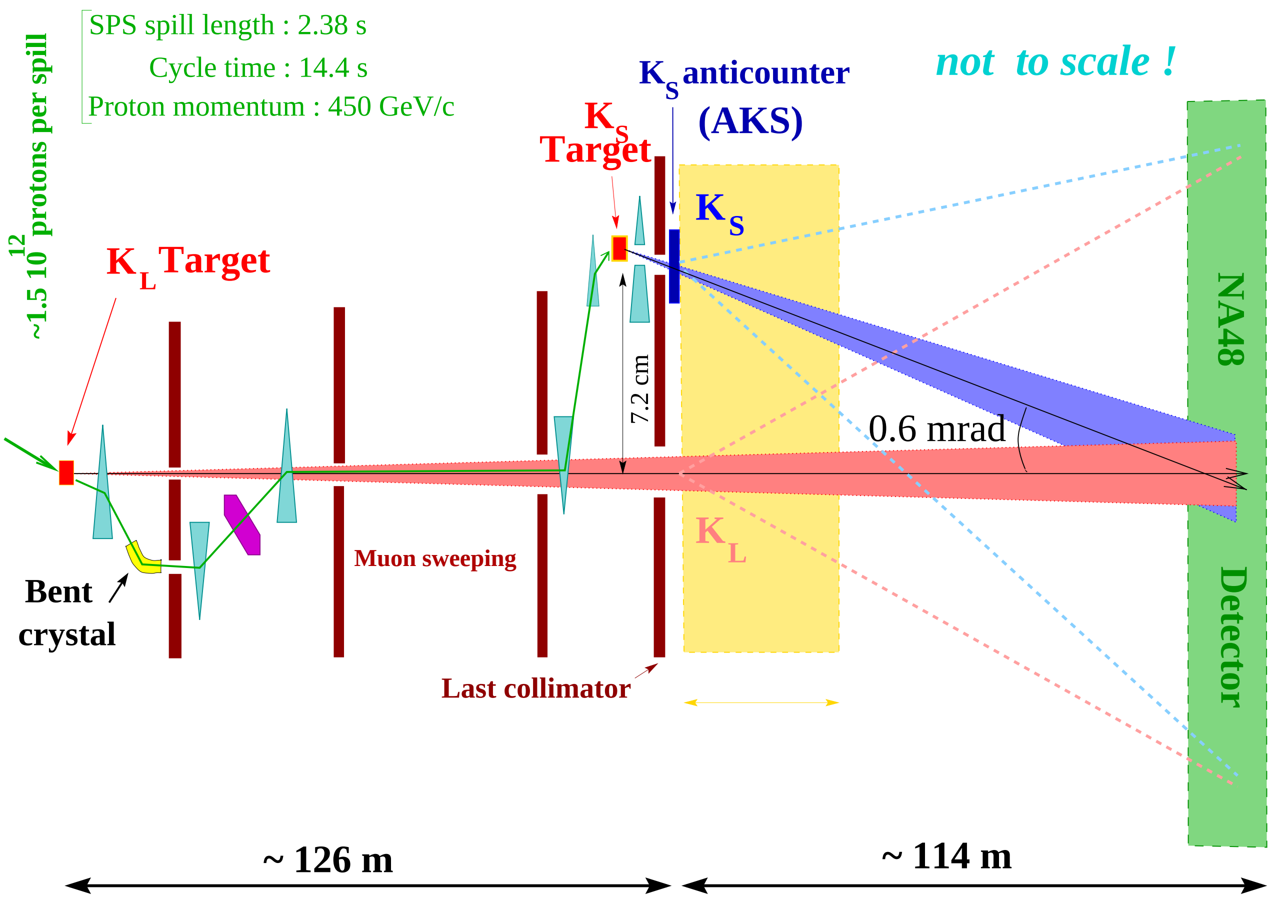
➡ $\Delta\alpha_{LS}$ is measured by looking at the probability to see a random proton in a false coincidence using untagged $\pi^0\pi^0$ and $\pi^+\pi^-$

➡ the correspondence to the true coincidence for $\pi^0\pi^0$ is measured with $K_L \to 3\pi^0$ decays

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

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

Definition of the decay region



Decay region is defined by applying cuts on the reconstructed kaon energy and the decay vertex position (and AKS for the beginning of the K_S decays)

This definition <u>should be the same</u> for $\pi^+\pi^-$ and $\pi^0\pi^0$ events
Otherwise, the kaon flux does not cancel in R

$\Rightarrow$ Need to understand in details energy and decay vertex computations

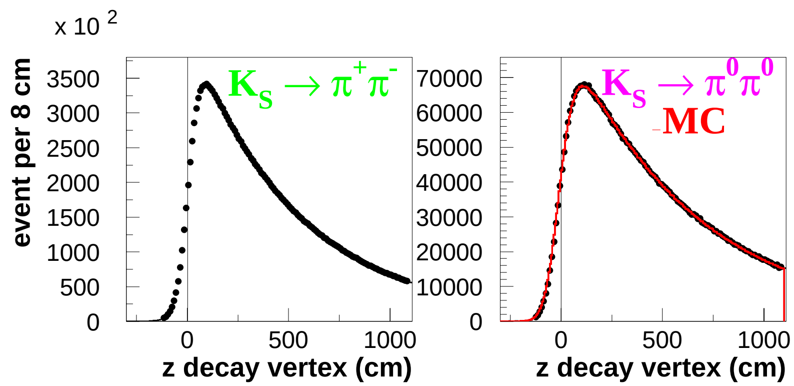
Reconstruction uncertainties on energy and decay vertex

$\pi^+\pi^-$:

→ depends on geometry of drift chambers before the magnet (straight track extrapol. to vertex)

→ checked by: AKS position measurement

$$\Delta R = (2 \pm 2.8) \times 10^{-4}$$



$\pi^0\pi^0$:

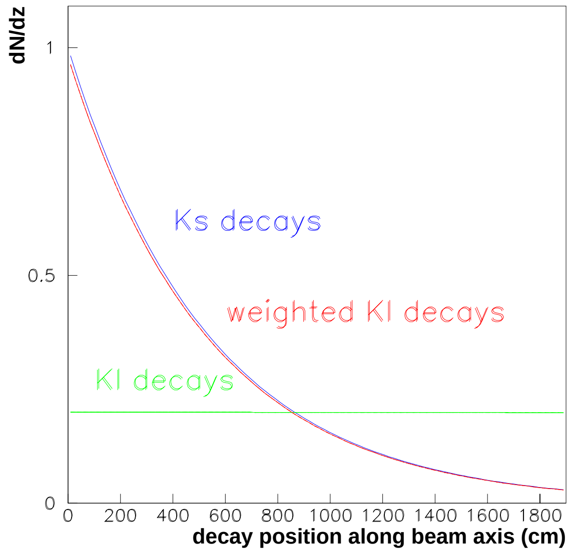
→ depends on energy scale and calorimeter geometry

→ energy scale adjusted by measurement of AKS position

→ uncertainties from: energy scale, transverse size, non-linearities, non-uniformities, non-Gaussian tails etc.

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

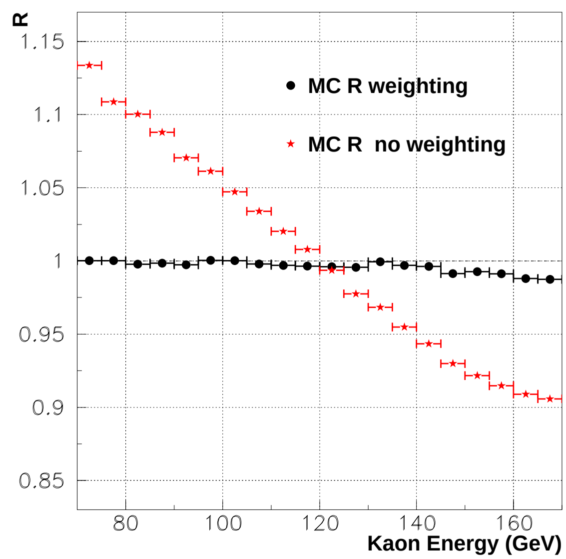
Acceptance correction



Weight K_L events with
$W \approx e^{-t}(1/\tau_{KS} - 1/\tau_{KL})$
$\Rightarrow$ Same decay vertex distribution for K_S and weighted K_L
Gain : correction decreased
Price : increase in stat. error

Small residual effect from 0.6 mrad angle between K_L and K_S beams $\rightarrow$ Correction estimated using Monte-Carlo

Acceptance correction :
$\Delta R = +26.7 \times 10^{-4}$



Uncertainties :

MC stat error: $\pm 4.1 \times 10^{-4}$

Systematic error: $\pm 4.0 \times 10^{-4}$

beam positions and shapes: $\pm 3.3 \times 10^{-4}$

Comparison fast MC/GEANT based spectrometer simulation: $\pm 2.3 \times 10^{-4}$

Systematic uncertainties

		ΔR in 10^{-4}	
$\pi^+\pi^-$ trigger inefficiency		-3.6	$\pm$ 5.2 (stat)
AKS inefficiency		+1.1	$\pm$ 0.4
Reconstruction	of $\pi^0\pi^0$	—	$\pm$ 5.8
	of $\pi^+\pi^-$	+2.0	$\pm$ 2.8
Background	to $\pi^0\pi^0$	-5.9	$\pm$ 2.0
	to $\pi^+\pi^-$	+16.9	$\pm$ 3.0
Beam scattering		-9.6	$\pm$ 2.0
Accidental tagging		+8.3	$\pm$ 3.4 (part. stat)
Tagging inefficiency		—	$\pm$ 3.0
Acceptance	statistical	+26.7	$\pm$ 4.1 (MC stat)
	systematic		$\pm$ 4.0 (syst)
Accidental activity		—	$\pm$ 4.4 (part. stat)
Long term variations of K_S / K_L		—	$\pm$ 0.6
Total		+35.9	$\pm$ 12.6

➔ some uncertainties depend on statistics of control samples or MC

Conclusions

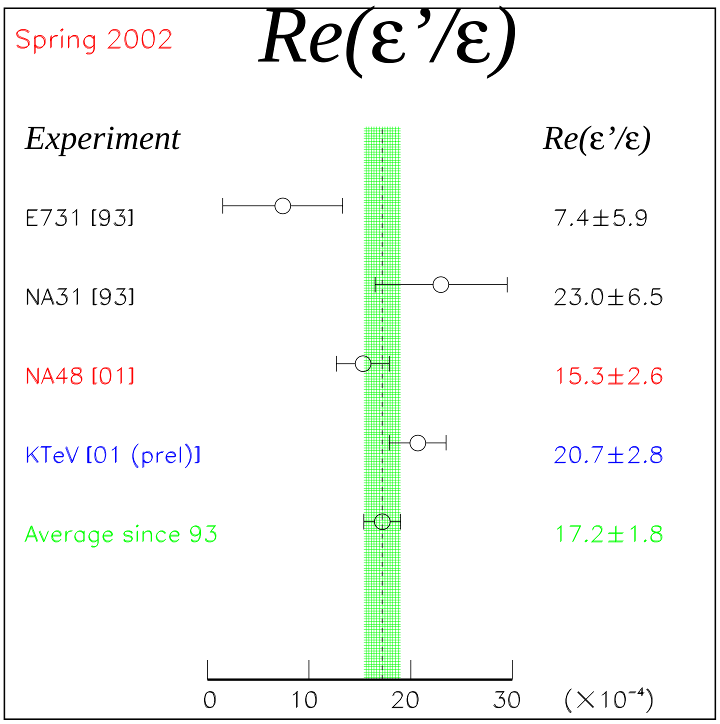
New result of *NA48* on 1998 and 1999 data

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

Combining with 1997 result

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

Proves existence of direct $\mathcal{CP}$ violation at 5.9 σ



☞Direct $\mathcal{CP}$ violation established (at 7.2 σ) :
AND χ^2/ndf = 5.6/3 (Probability ~ 13%)

Both Indirect and Direct $\mathcal{CP}$ Violation components discovered, measured and confirmed in the kaon system

Perspectives for $Re(\varepsilon'/\varepsilon)$

Drift chambers have been repaired

Data taking summer 2001 (mid July - mid October)

Different beam conditions (spill)

97-99	2.4s every 14.4 s	(p energy = 450 GeV)
2001	5.2s every 16.8s	(p energy = 400 GeV)

$\Rightarrow$ better duty cycle

Accumulate $> 1.4\times10^6$ $K_L \rightarrow \pi^0\pi^0$

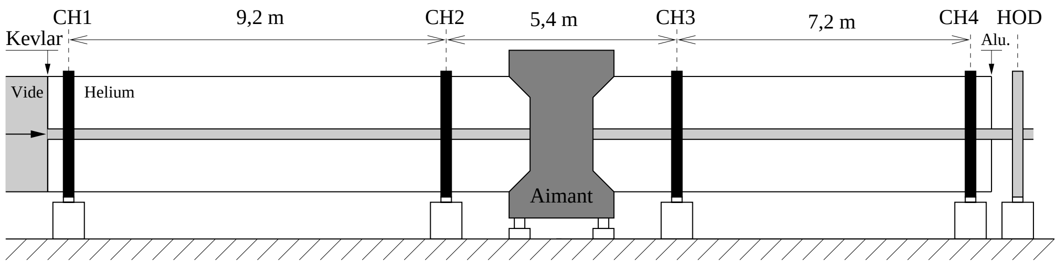
at lower instantaneous intensity

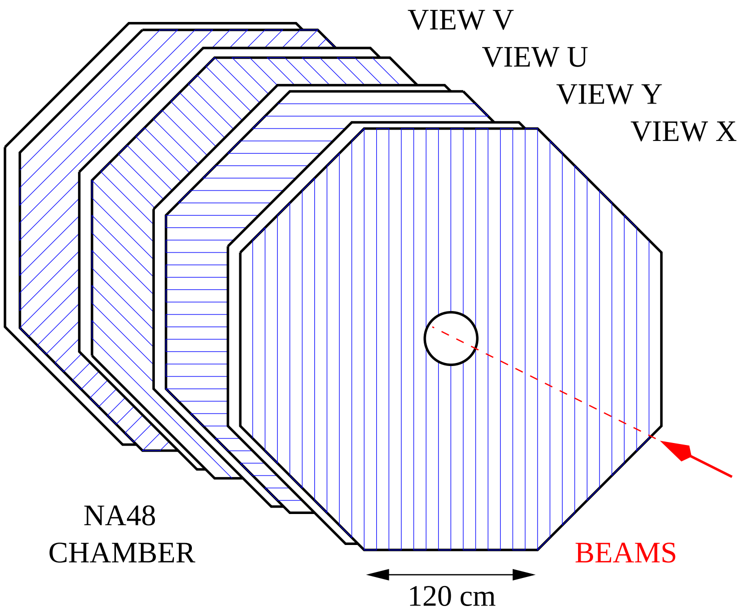
$\Rightarrow$ complete statistics and verify result under different conditions

Spare transparencies

The following slides have not been shown during the presentation and are used as spare slides for questions

Charged mode detection





ONE CHAMBER

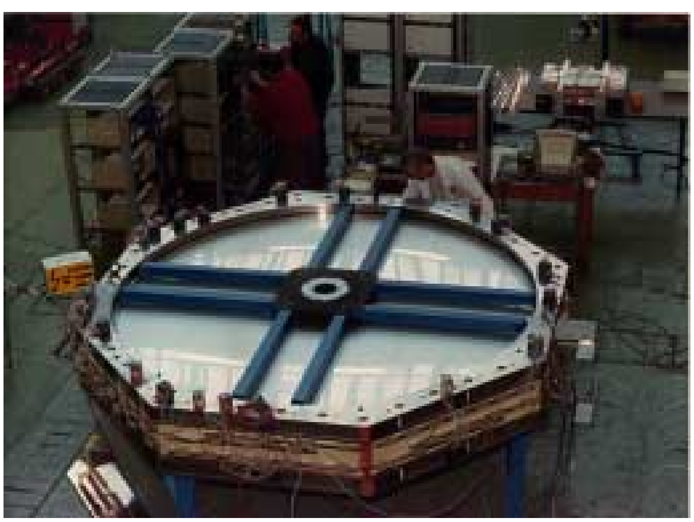
8 planes $\times$ 256 wires

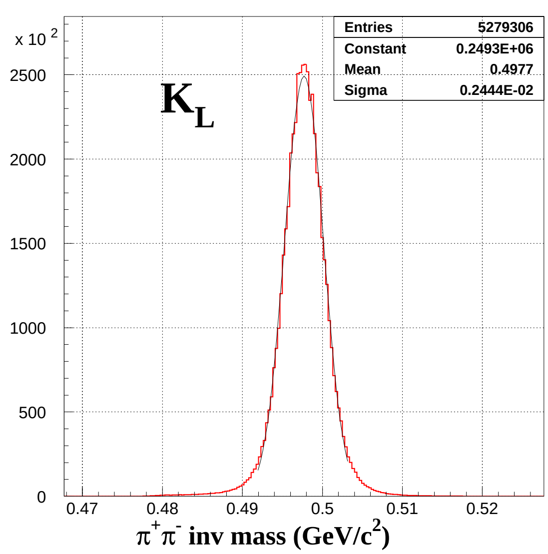
5 mm drift distance ($t_d \sim 100\ ns$)

Space resolution $\sigma_{X,Y} = 90\ \mu m$

Time resolution $\sigma_t \sim 1\ ns$ / track

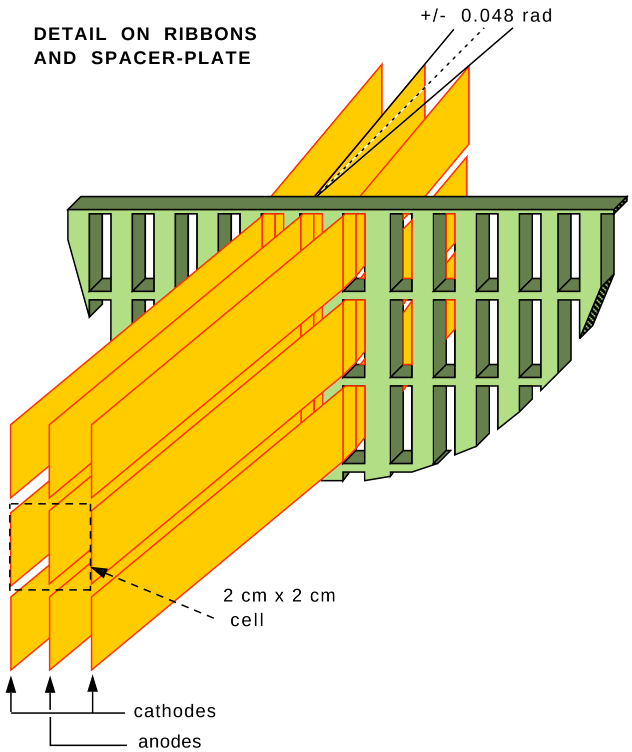
❖ Redundancy $\Rightarrow$ *on-line* reconstruction ($L2$ trigger)



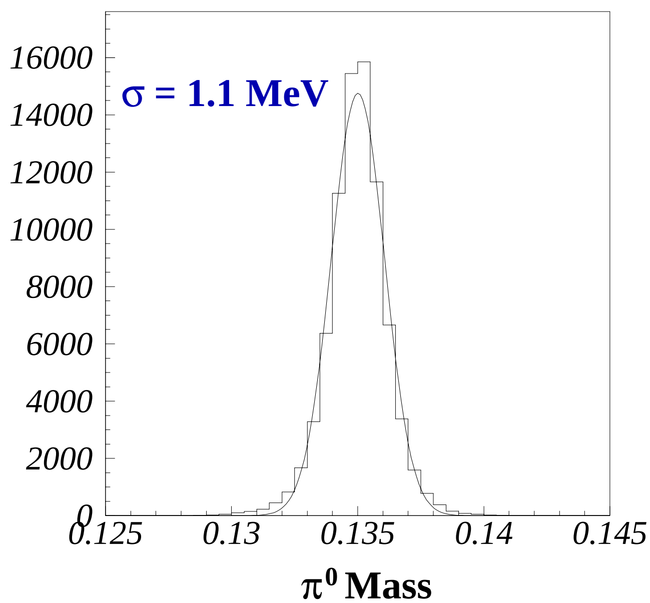


$K \to \pi^+\pi^-$ mass resolution : 2.5 MeV/c^2

$Ke3 + K\mu3$ backgrounds $\rightarrow$ $\Delta R = (16.9 \pm 3.0) \times 10^{-4}$



13212 $2 \times 2\ cm^2$ cells



$\frac{\sigma(E)}{E} = \frac{3,2\%}{\sqrt{E}} \oplus \frac{125\,MeV}{E} \oplus 0,5\%$; non-linearity $< 0.2\%$

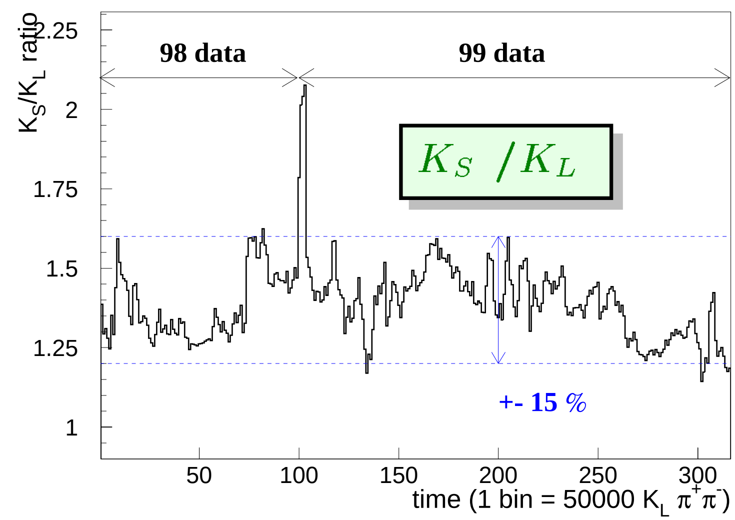
$K_L \to 3\pi^0$ background $\to$ $\Delta R = (-5.9 \pm 2.0) \times 10^{-4}$

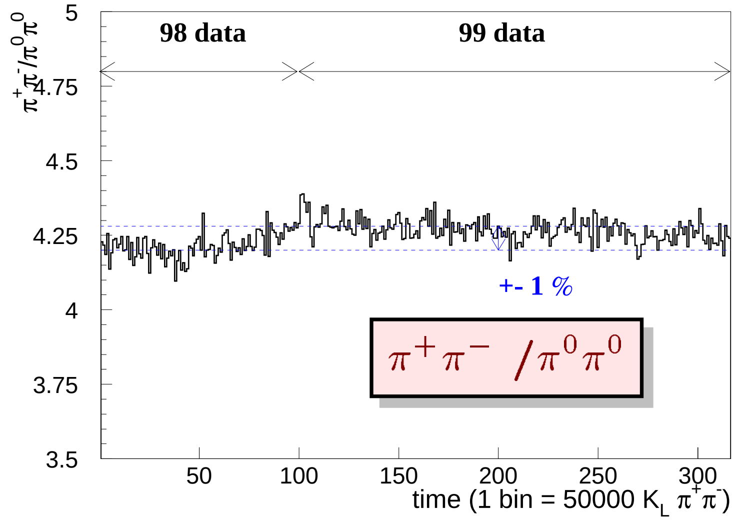
Symmetry in the time variations

All four decays are collected at the same time by using simultaneous K_S and K_L beams. They are derived from the same primary proton beam using two targets with different distances to the decay volume.

K_S events are weighted with K_L/K_S intensity ratio

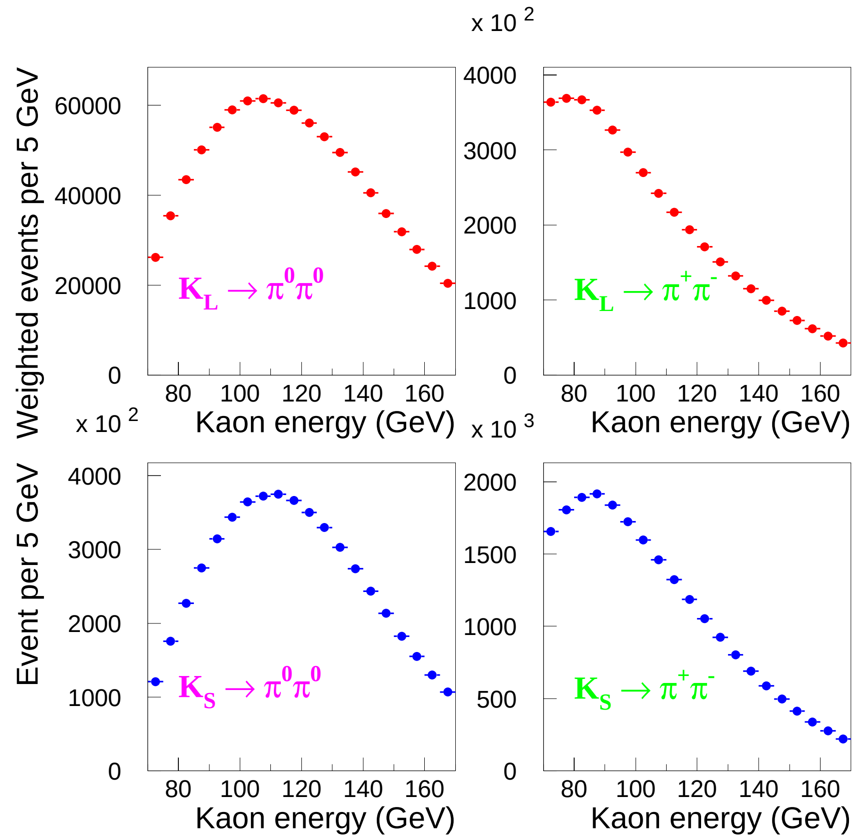
in case of dead-time (~20%) in one decay mode no events are counted also in the other mode





Symmetry in the kaon energy

Kaon energy spectra:

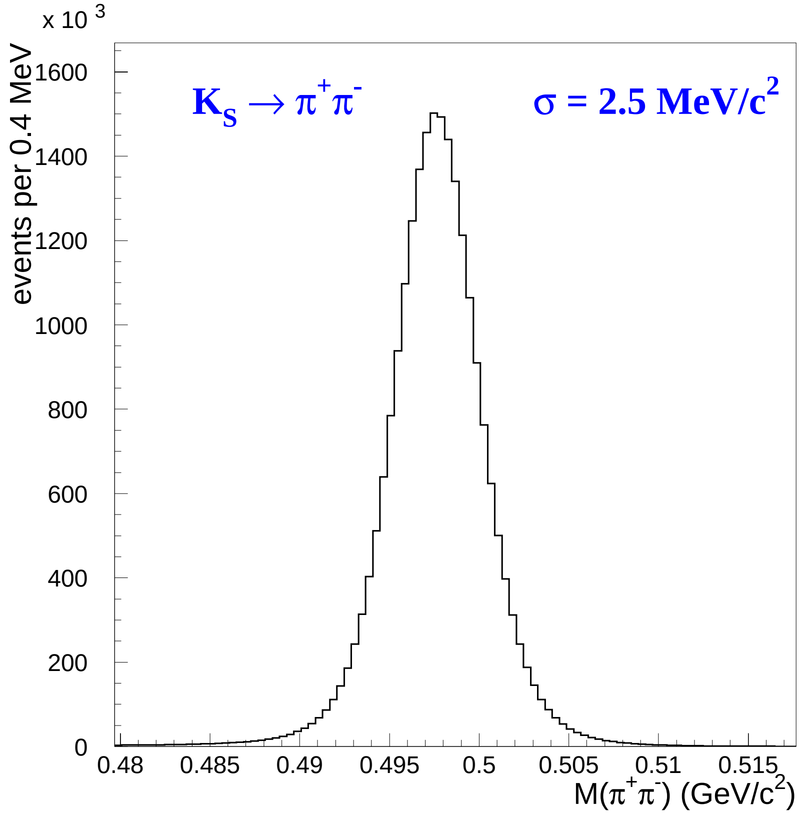


- the targeting angles are tuned to deliver similar decay spectra in the chosen decay volume and in the energy interval 70 to 170 GeV

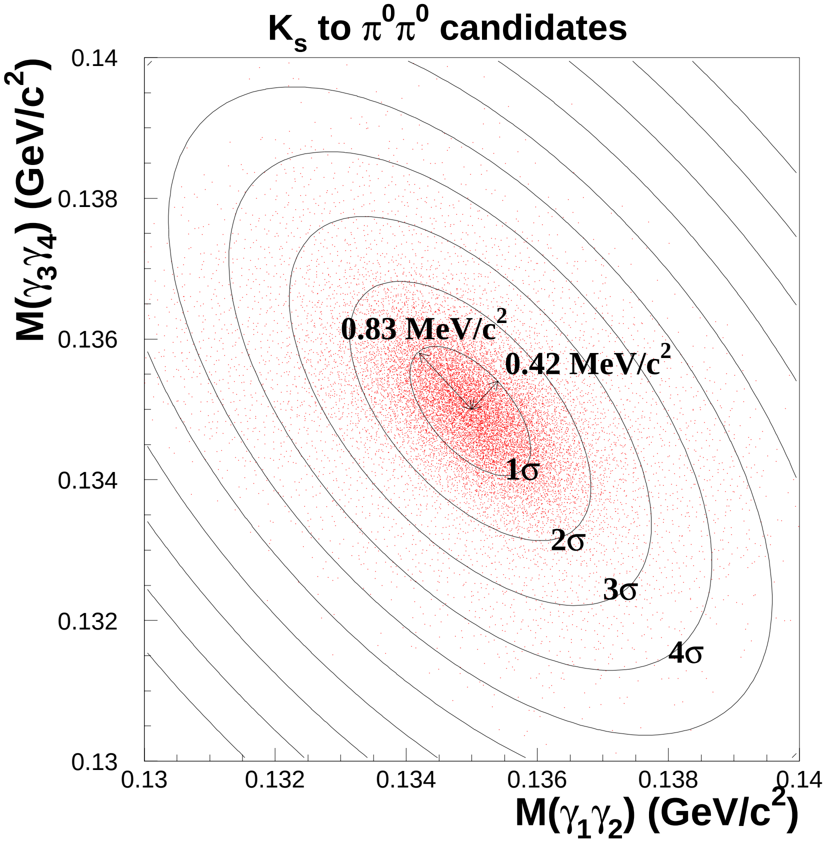
- residual differences in the K_S and K_L decay spectra are reduced by performing the analysis in twenty 5 GeV bins

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

$m_{\pi\pi}$



$m_{\gamma\gamma}$



Trigger efficiency

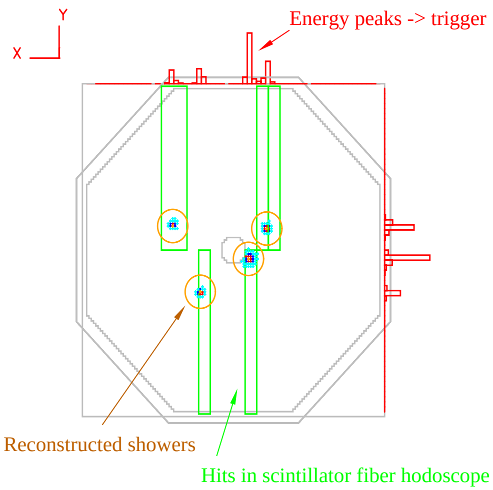
$K_S - K_L$ cancellation

$\pi^0\pi^0$:

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

➔ Efficiency : $(99.920 \pm 0.009)\%$

ΔR negligible



$\pi^+\pi^-$:

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

➔ Efficiency: $(99.535 \pm 0.011)\%$

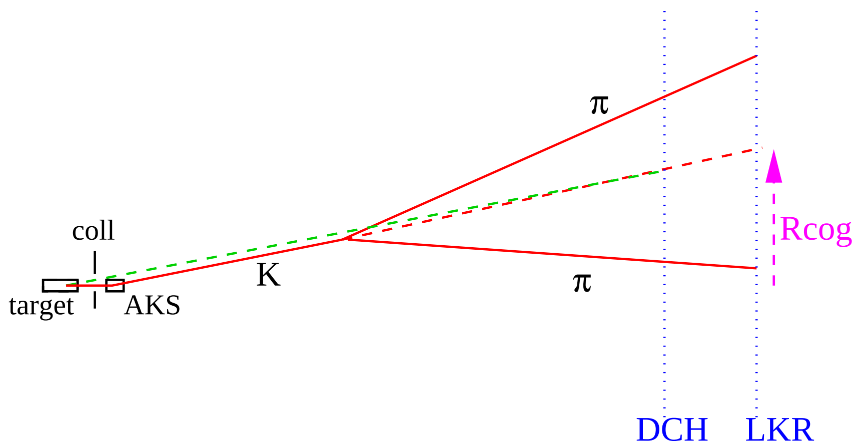
- Level 2: on-line processing of vertex position and $\pi\pi$ invariant mass from spectrometer hits
  - Output rate $\sim$ 2 kHz
  - Dead Time: 1.1% monitored and applied to $\pi^0\pi^0$

➔ Efficiency: $(98.353 \pm 0.022)\%$

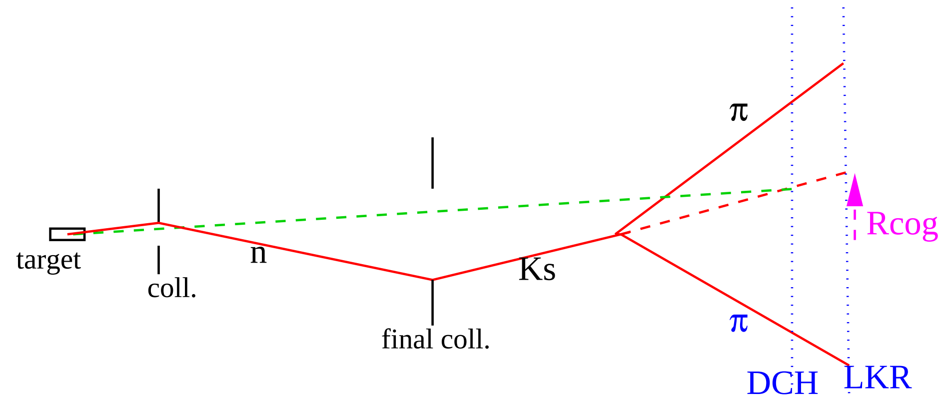
$\Delta R = (-3.6 \pm 5.2) \times 10^{-4}$

Beam scattering background

K_S beam



K_L beam



K_S scattering removed by Rcog cut

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

$\Rightarrow$ no effect on R

Background from beam scattering produces K_S in final collimator

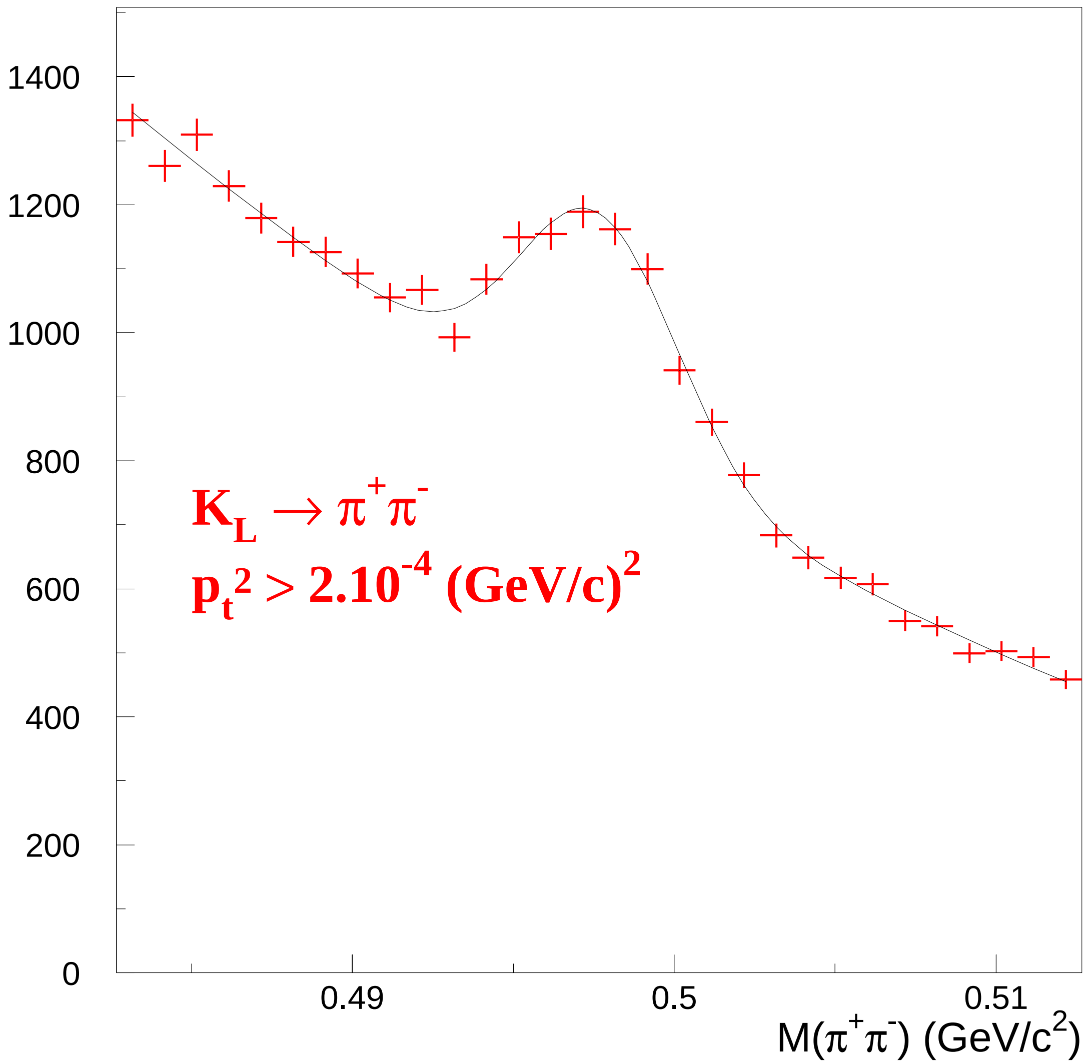
Removed from $\pi^+\pi^-$ sample by $P_T'^2$ cut

Kept in $\pi^0\pi^0$ sample

$\Rightarrow$ correction

Beam scattering background

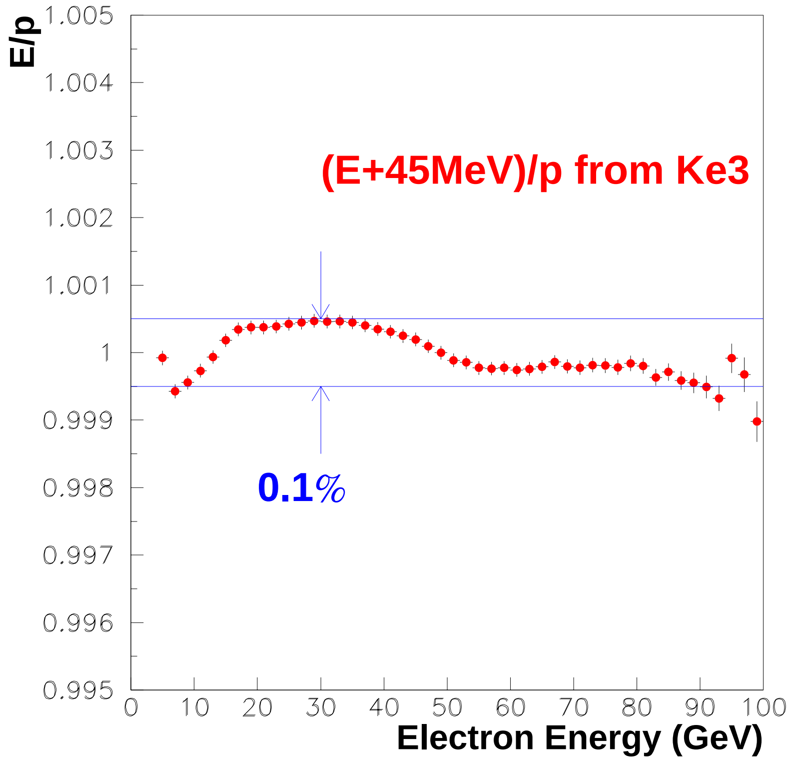
Measure collimator background in $\pi^+\pi^-$ mode
from events at $P_T'^2 > 200\ (\mathrm{MeV/c})^2$
with $M_{\pi\pi} = M_K$

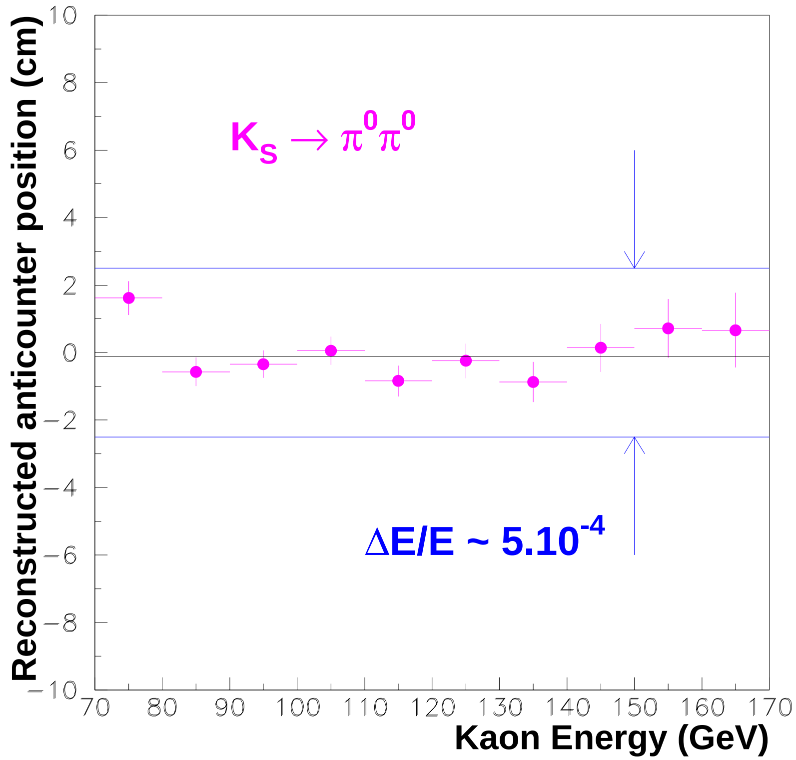


Can also be estimated from $\pi^0\pi^0$ events as cross-check

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

Non linearity checks



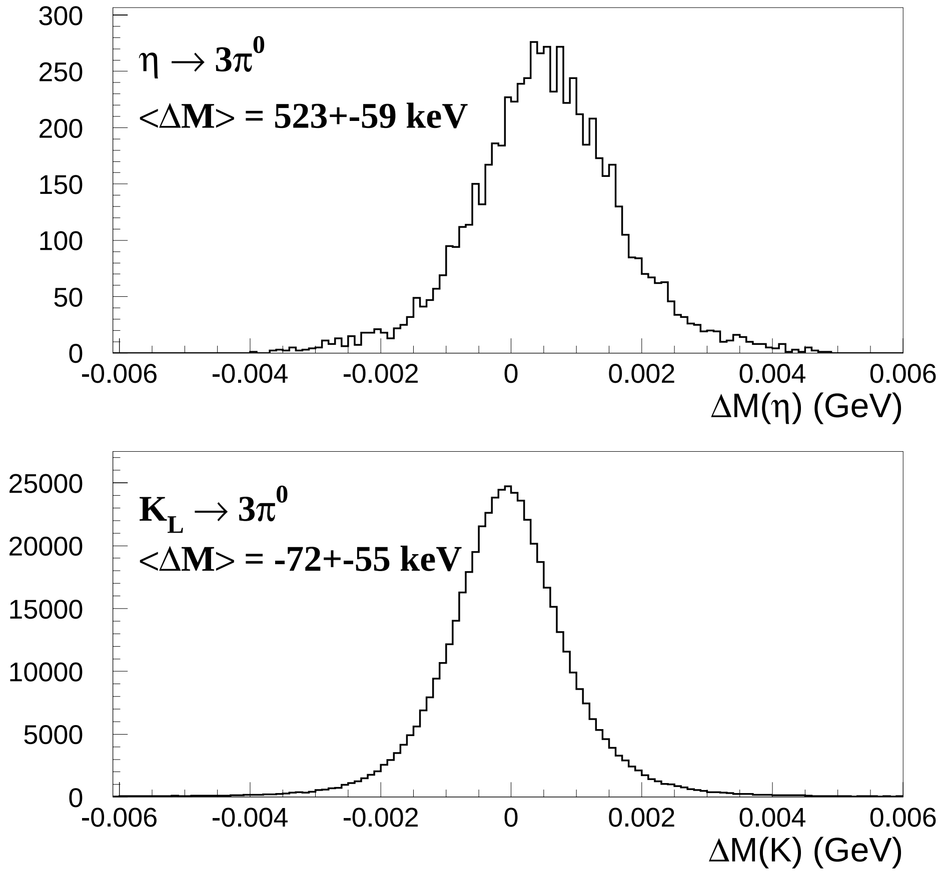


Electrons from Ke3 decays :
E/p constant within ≈ 0.1%
between a few GeV and 100 GeV

Overall Check :
Reconstructed AKS position
independent of K energy

η mass measurement

PDG: $M_\eta = 547.30 \pm 0.12$ MeV



- Use $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ decays
- Decay vertex from π^0 mass constraint

$\Rightarrow$ Measure M_η / M_{π^0}

Independent of energy scale!

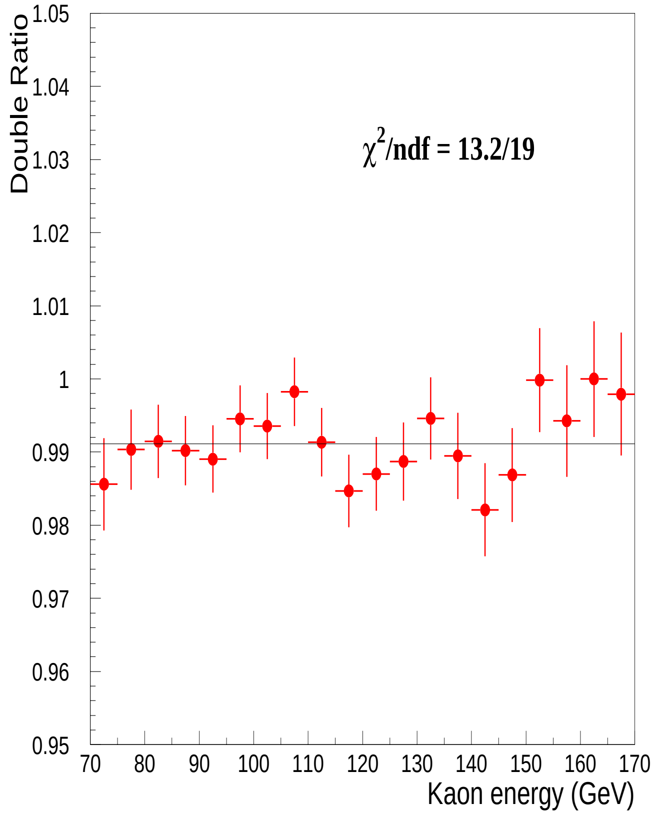
- Check method on $K_L \rightarrow 3\pi^0$
- $\Delta M \equiv M_{\mathrm{NA48}} - M_{PDG}$

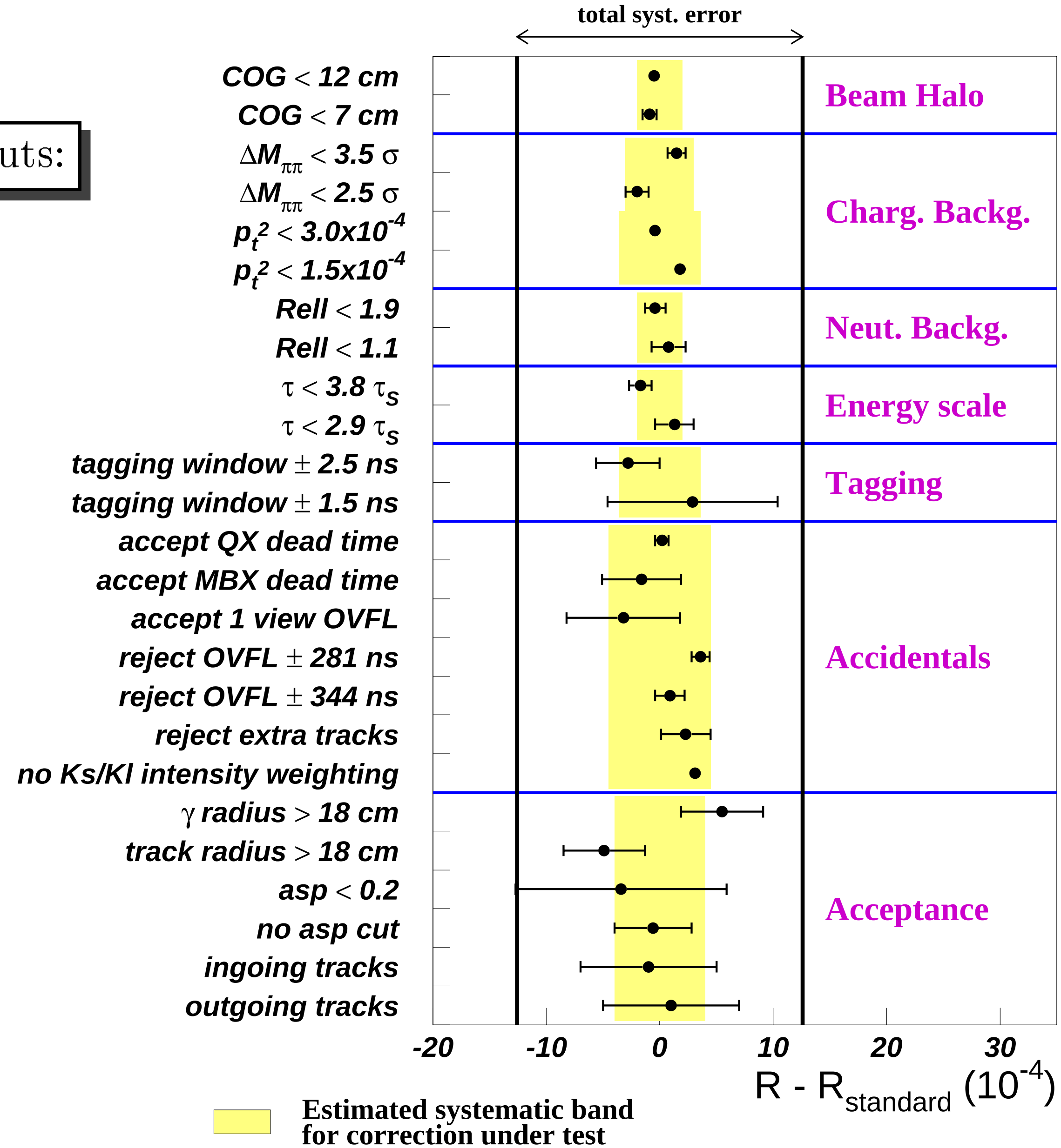
NEW Preliminary result $M_\eta = 547.823 \pm 0.020_{stat} \pm 0.055_{syst}$ MeV

Use this measurement to check energy scale with $\eta \rightarrow \gamma\gamma$

Checks

Stability with kaon energy and cuts:





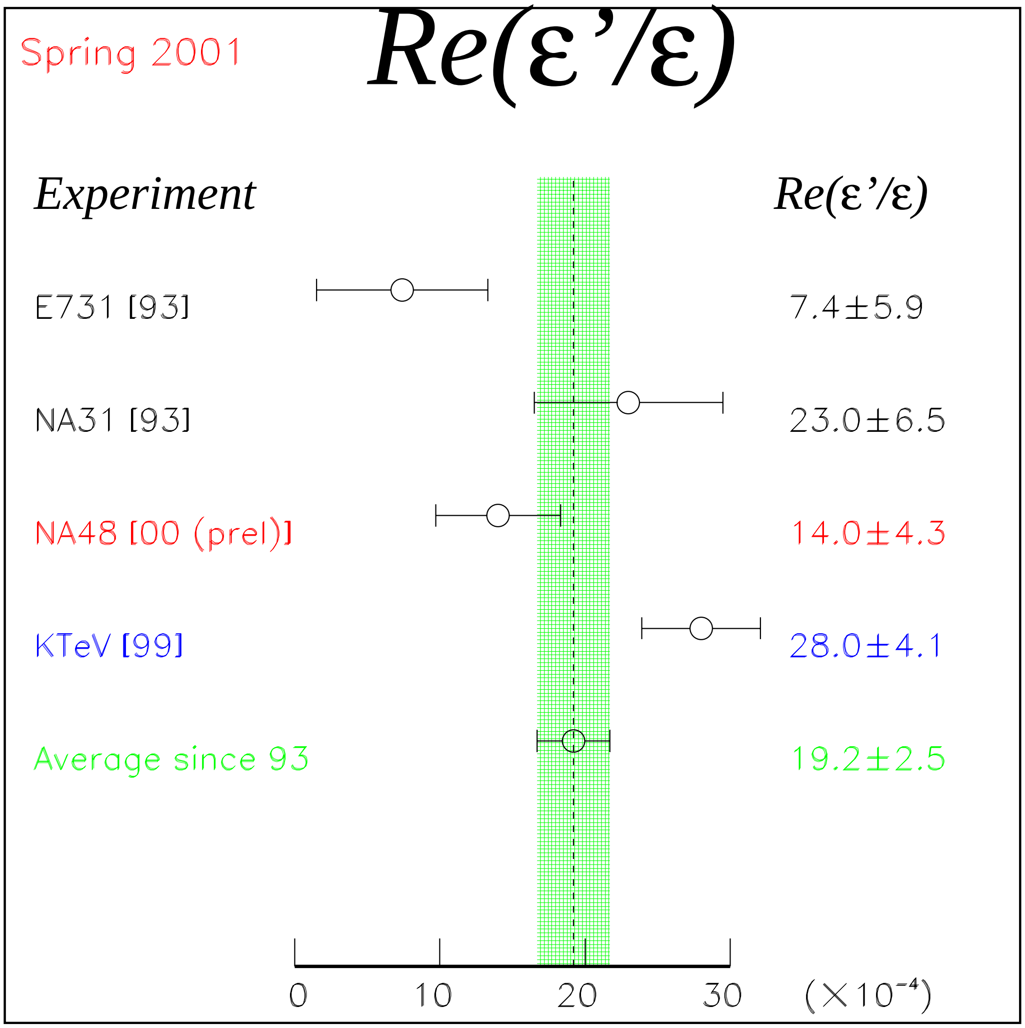
1998 Systematics prel./final

Corrections and syst. uncertainties on R (Units = 10^{-4})				
Source	1998 prel.		1998 final	
Charged trigger	−1	± 11	−2.6	± 11.4
Accidental tagging	+1	±8	16.1	± 5.4
Tagging efficiency	–	± 3	–	± 3
Neutral rec. systematics	–	±10	–	±5.8
Charged vertex	+2	±2	+2	±2.8
Acceptance	+31	±9	+23.4	±8.3
Neutral BKG	−7	±2	−6.3	±2
Charged BKG	+19	±3	+17.6	±3
Beam scattering	−10	±3	−9.6	±2
Accid. activity	+2	±12	–	±7.1
Total	+37	±24	+40.6	±18.6
R	9926.7	±29.4	9927.4	±25.8

$$Re(\varepsilon'/\varepsilon) = \frac{1}{6} \times (1 - R)$$

Experimental situation in spring 2001

Previous generation of experiments (E731,NA31) without conclusive answer : $Re(\varepsilon'/\varepsilon) \neq 0$?
only 1.9 σ effect (errors renormalised à la PDG)
$\longrightarrow$ New generation of experiments



☞Direct $\mathcal{CP}$ violation established (at 4.2 σ) :

BUT $\chi^2/\text{ndf} = 10.4/3$