Final NA48 measurement of Re(ε'/ε)

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XIVth Rencontres de Blois
$17^{th} - 22^{nd}$ June 2002

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Outline

- Physics motivations
- NA48 beam and detector
- $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement on 2001 data
- Comparison with 97+98+99 value
- Combined result

Physics motivation

$\varepsilon \Rightarrow$ Indirect CP violation via $K^0/\overline{K^0}$ mixing

CP eigenstates:

$$\mathrm{K}_1 = (\mathrm{K}^0 + \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP = +1)$$

$$\mathrm{K}_2 = (\mathrm{K}^0 - \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP = -1)$$

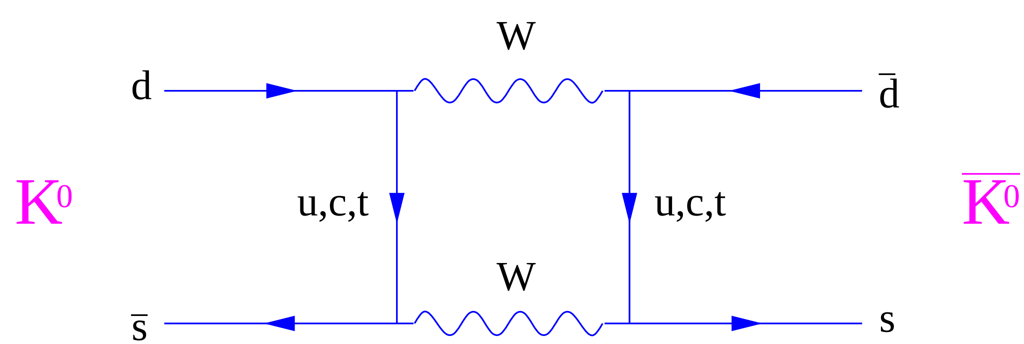
$$\pi^+\pi^-, \pi^0\pi^0 \quad (CP = +1)$$

Mass eigenstates:

$$\mathrm{K_S} \simeq \mathrm{K}_1 + \varepsilon \mathrm{K}_2 \; (c\tau_\mathrm{S} = 2.67\mathrm{cm})$$

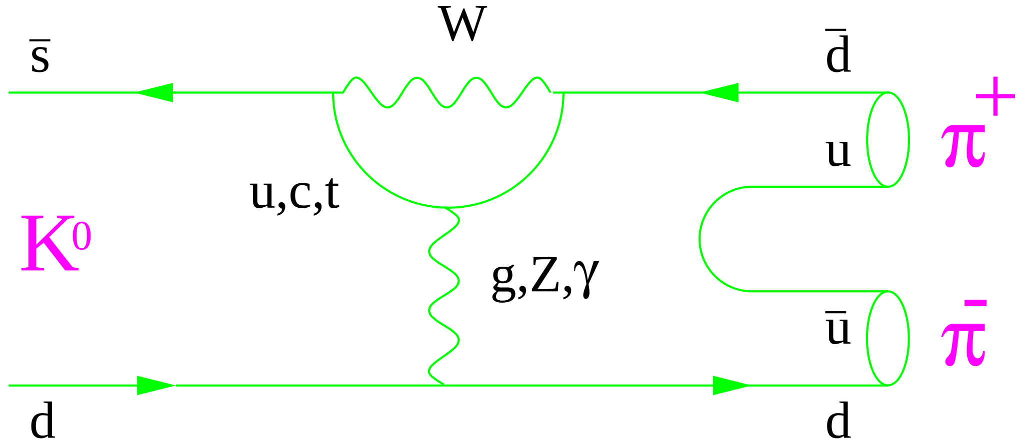
$$\mathrm{K_L} \simeq \mathrm{K}_2 + \varepsilon \mathrm{K}_1 \; (c\tau_\mathrm{L} = 15.5\mathrm{m})$$

$\varepsilon = (2.27 \pm 0.02) \times 10^{-3}$



Physics motivation, contd.

$\varepsilon' \Rightarrow$ Direct CP violation from K_0 decay
$\varepsilon' \sim 10^{-6}$



ε'/ε affected by large theoretical uncertainties
from -1×10^{-3} to about 4×10^{-3}

Experimental observable:

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

$\rightarrow$ Count: $N(\mathrm{K_L} \to \pi^0\pi^0)$, $N(\mathrm{K_S} \to \pi^0\pi^0)$, $N(\mathrm{K_S} \to \pi^+\pi^-)$,
$N(\mathrm{K_L} \to \pi^+\pi^-)$

Data taken

1997 89 days at 1×10^{12} ppp on K_L target
≈ 0.5 million $K_L \to \pi^0\pi^0$
result published in 1999

1998 Detector improvements to allow higher rates
135 days at 1.5×10^{12} ppp on K_L target
≈ 1 million $K_L \to \pi^0\pi^0$

1999 128 days at 1.5×10^{12} ppp on K_L target
≈ 2 million $K_L \to \pi^0\pi^0$

NOV '99 Implosion of the carbon fiber beam pipe, all four drift chambers damaged

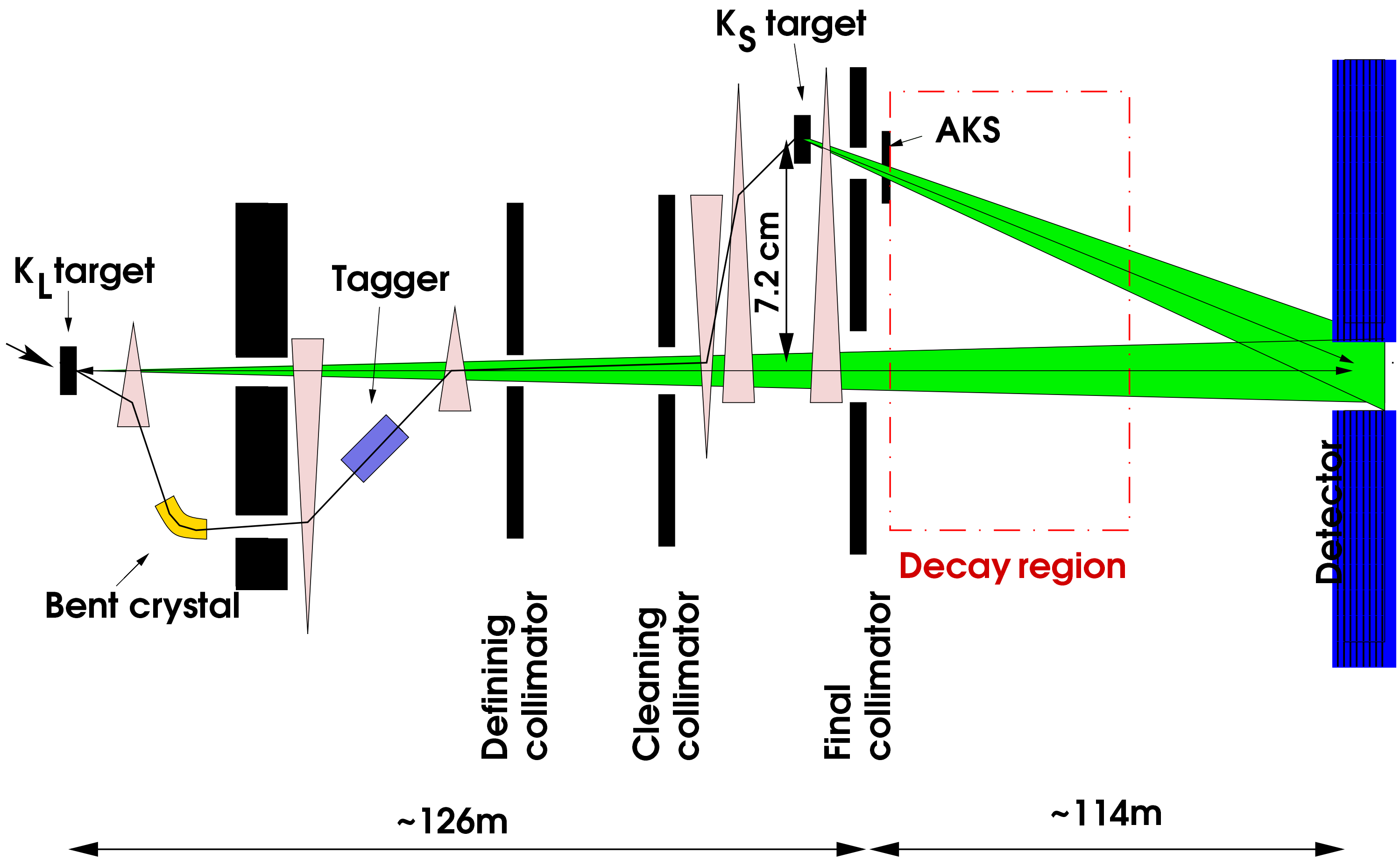
2000 Only neutral events for cross-checks

2000-2001 Drift chambers rebuilt

2001 93 days at 2.4×10^{12} ppp on K_L target
≈ 1.5 million $K_L \to \pi^0\pi^0$

- Different beam conditions
  98-99: 2.4 s every 14.4 s; E_p=450 GeV
  2001: 5.2 s every 16.8 s; E_p=400 GeV
  better duty cycle, lower instantaneous intensity
- Lower dead time
  98-99: 20% DCH multiplicity; 1.5% trigger
  2001: 11% DCH multiplicity; 0.3% trigger

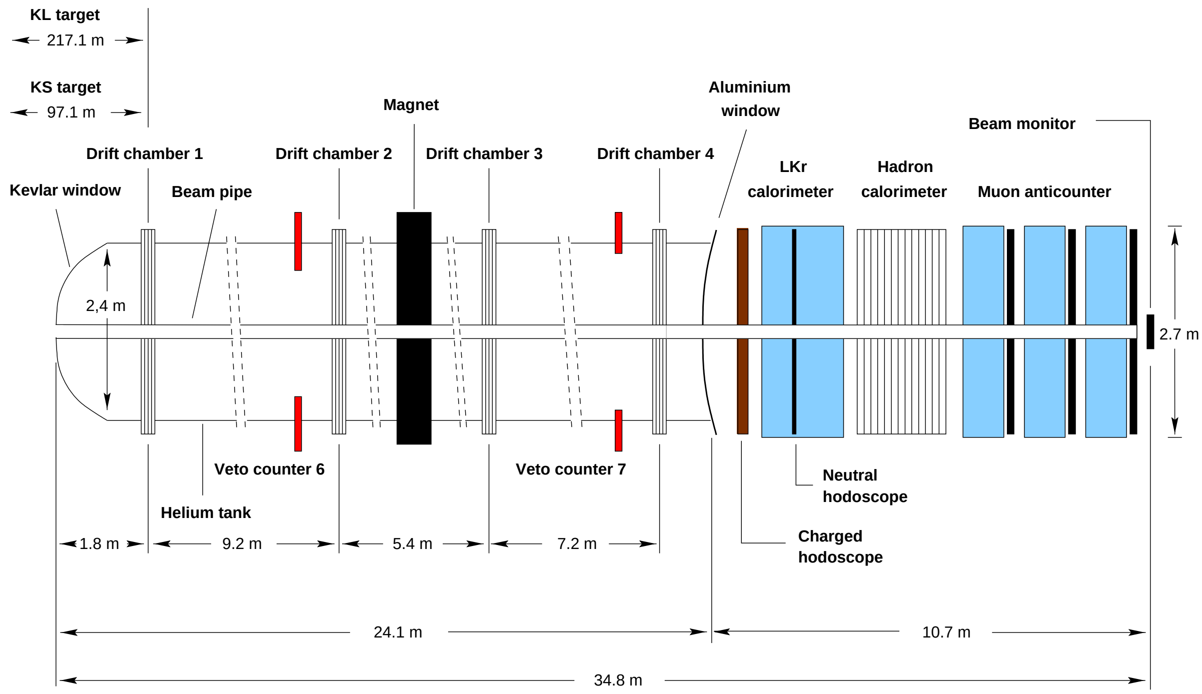
The NA48 Simultaneous K_S *and* K_L *Beams*



K_S are distinguished from K_L by tagging the protons upstream of the K_S target

Tagging needed for neutrals, hence also used for charged

NA48 Detector

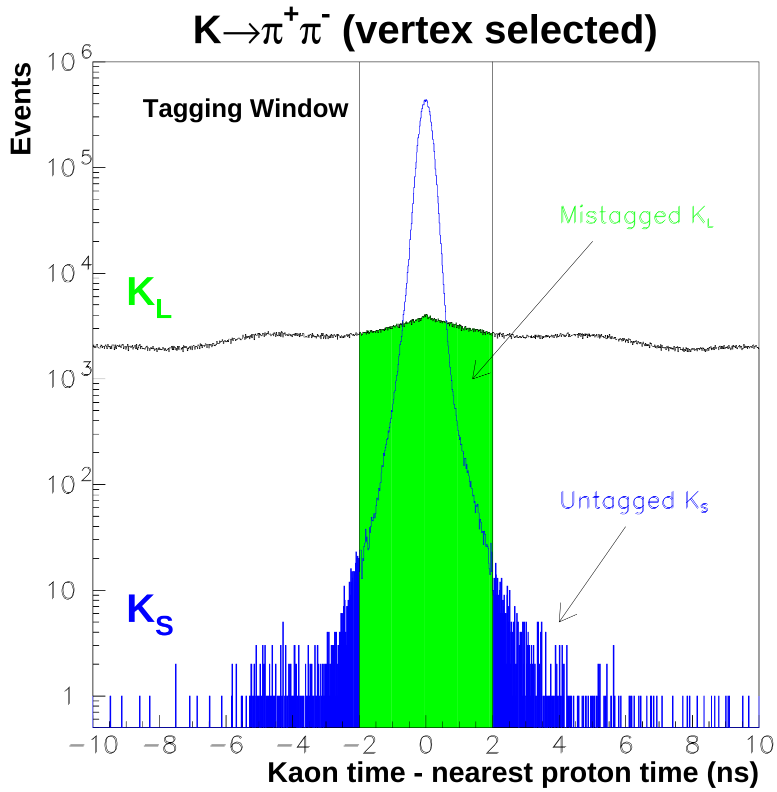


- Magnetic spectrometer:
  $K_{\mathrm{L,S}} \to \pi^+\pi^-$
  $\sigma(p)/p \simeq 0.5\,\% \oplus 0.009\; p[GeV/c]\,\%$
  $(\mathrm{P}_\perp{}^{kick} \sim 265\mathrm{MeV}/c)$
- Liquid Krypton electromagnetic calorimeter:
  $K_{\mathrm{L,S}} \to \pi^0\pi^0$
  high granularity (13212 2×2 cm^2 cells)
  $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus (9\%)/E \oplus 0.42\%$
  $\sigma(t) \simeq 265ps$ for 50 GeV e^-

Technique

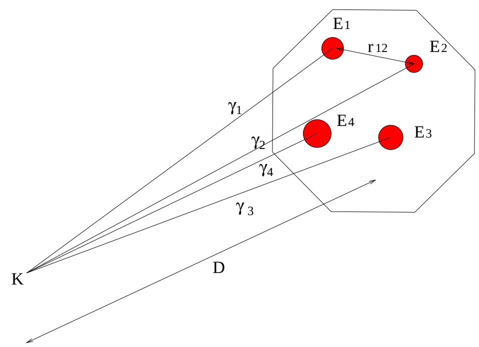
- Employ two almost collinear neutral beams
- Collect the four decay modes simultaneously, in the same detector and from the same decay region
- Distinguish K_S and K_L events by tagging the protons upstream of the K_S target
- Record dead time conditions and apply them offline to all events
- Keep the acceptance correction small by weighting the K_L events according to the ratio of K_S/K_L decay intensities as a function of proper time
- Use precise and stable calorimetry to control the energy scale
- Perform the analysis in bins of kaon energy
- Subtract the small backgrounds
- Check accidental losses due to different beam intensities
- Account for K_S/K_L variations
- The first 200 ms where not used for the 2001 analysis due to the very strong beam structure

Tagging measurement



- $K_L \Rightarrow K_S$ misidentification is proportional to the tagger rate
  $\alpha^{+-}_{LS} = (8.115 \pm 0.010)\%$
  (was $\alpha^{+-}_{LS} = (10.649 \pm 0.008)\%$ in 98-99)
- $K_S \Rightarrow K_L$ misidentification is due to inefficiencies
  $\alpha^{+-}_{SL} = (1.12 \pm 0.003) \times 10^{-4}$
- R sensitive to the asymmetries in tagging misidentification between $\pi^-\pi^+$ and $\pi^0\pi^0$
  $\alpha^{00}_{LS} - \alpha^{+-}_{LS} = (0.034 \pm 0.0014)\%$
  $\alpha^{00}_{SL} - \alpha^{+-}_{SL} = (0 \pm 3) \times 10^{-4}$

$K \rightarrow \pi^0\pi^0$ *reconstruction*



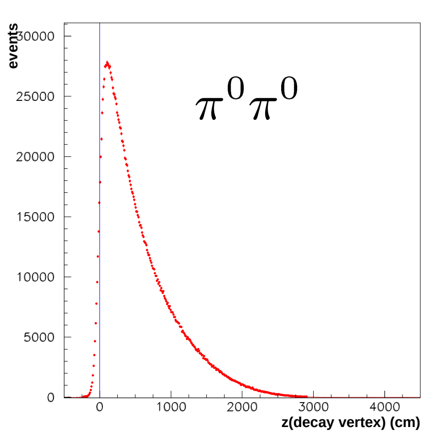
- Vertex position along beam line found by imposing the Kaon mass

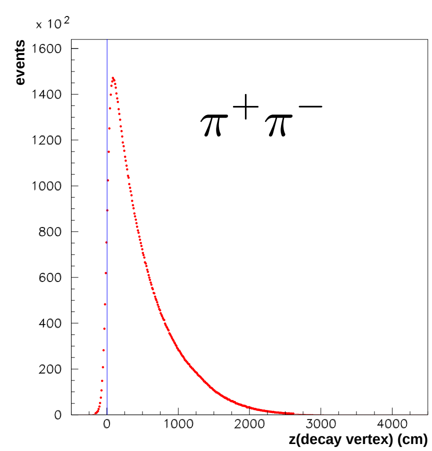
$$D = Z_{LKr} - Z_{decay} = \sqrt{\sum (E_i E_j \times r_{ij})^2} / M_K$$

Z_{vtx} resolution $\approx$ 50 cm

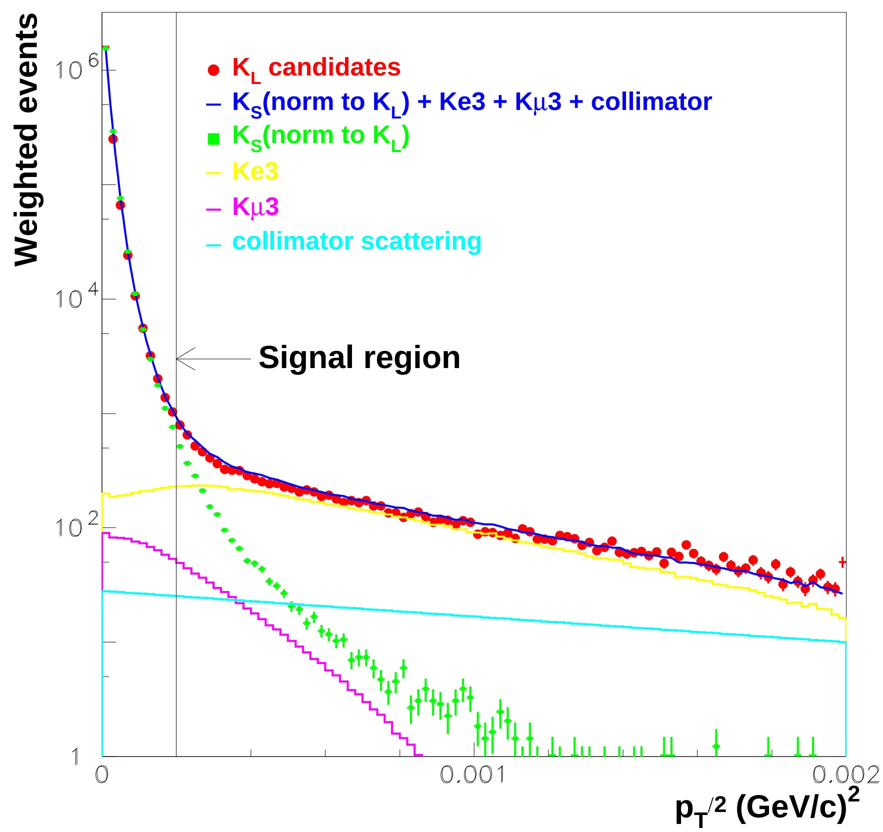
$\Rightarrow$ Correlation between Z_{vtx} and energy scale

- K_S Decay volume defined sharply by AKS counter - decays occurring before AKS are vetoed
- Reconstruct correct AKS position to adjust energy scale (and verify DCH alignment)





Charged background



The background in $K_L \to \pi^+\pi^-$ is dominated by semileptonic decays

$\longrightarrow$ cut on transverse momentum

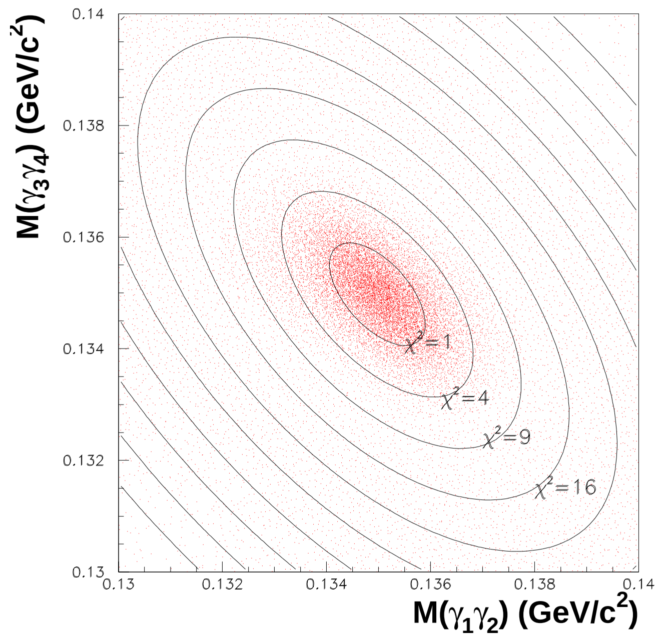
Background in K_L signal region is evaluated from a fit to the control regions

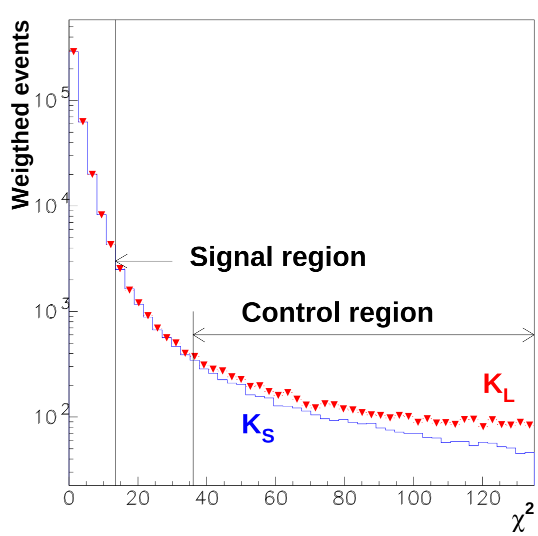
$\Rightarrow$ Background level $= (14.2 \pm 3.0) \times 10^{-4}$

Neutral background

✦ Photons are paired to give the best π^0 mass combination

✦ Main background comes from $K_L \to 3\pi^0$





→ Background level : $(5.6 \pm 2.0)\ 10^{-4}$

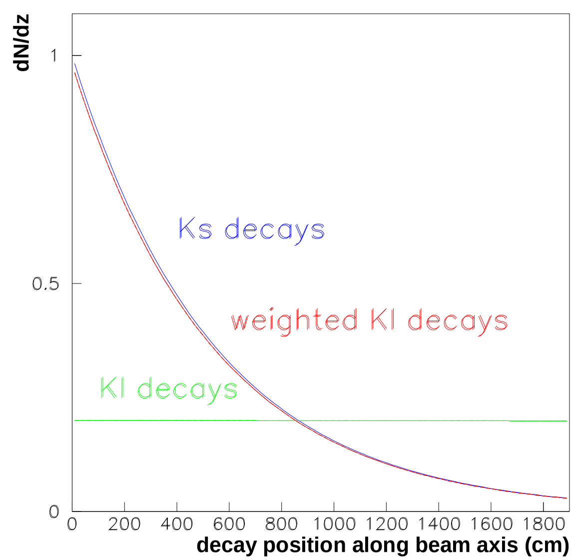
Acceptance correction

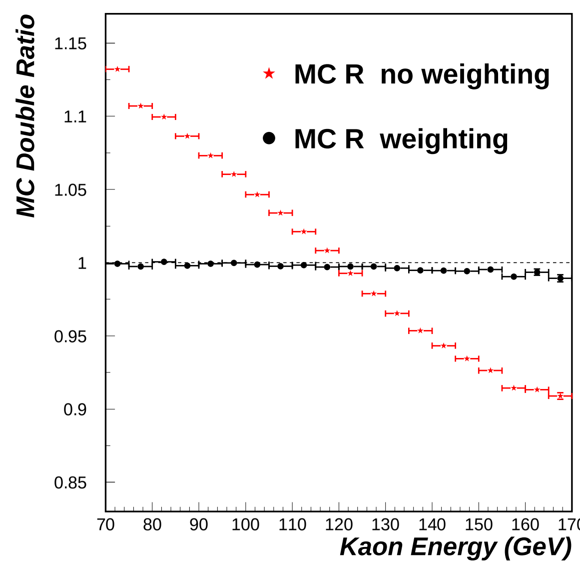
- At same z, acceptance $K_S = K_L$
- K_S and K_L different lifetimes

$\Rightarrow$ decay distributions vary strongly along beam

- K_L distribution weighted by function of proper time to minimize acceptance correction

- Analysis now relatively insensitive to MonteCarlo simulation but with 35% increase of the statistical error





Accidental activity

- Accidental activity from beam
  → Event losses
- It cancels at first order on R
- Residual effects:

Intensity difference

$\Delta R \sim \Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) \times \Delta I(K_L - K_S)/I$

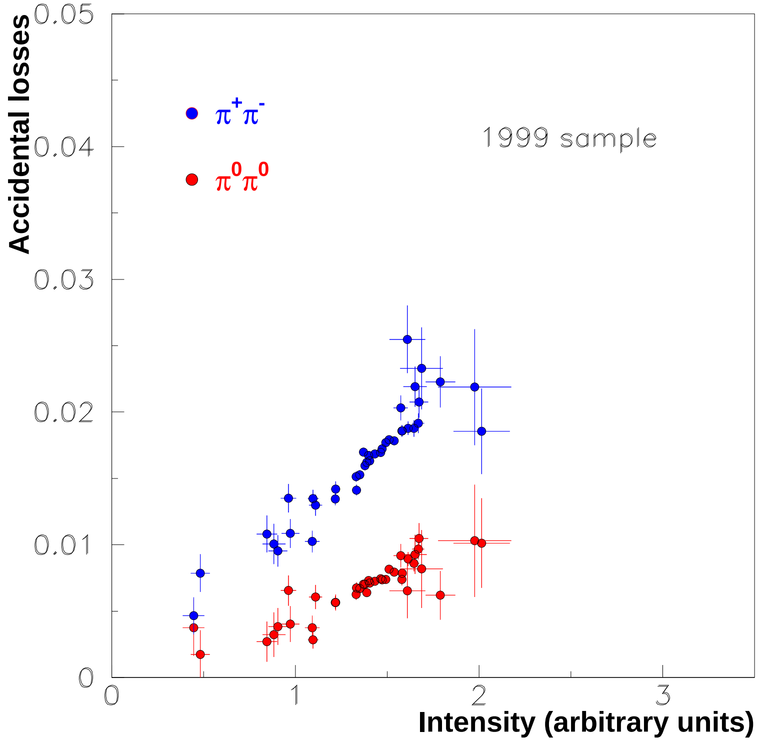
- $\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) \rightarrow$ difference between charged and neutral losses
  minimized by applying dead time conditions to all modes
  $\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) = (1.0 \pm 0.5)\%$ in 2001
  ($\Delta\lambda(\pi^+\pi^- - \pi^0\pi^0) = (1.4 \pm 0.7)\%$ in 98-99)

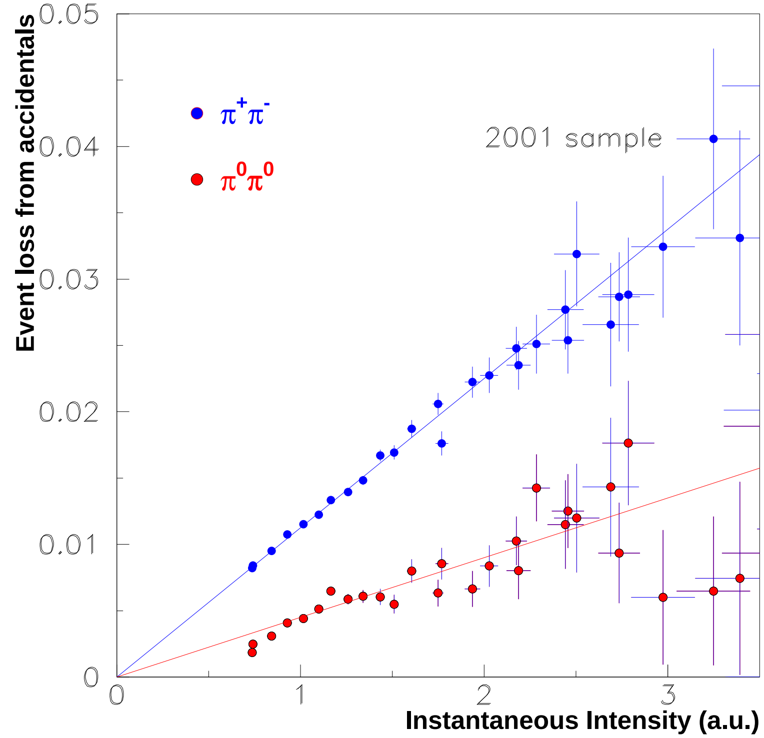
- $\Delta I(K_L - K_S)/I \rightarrow$ difference in accidental activity seen by K_S and K_L
  small by design of the experiment because of simultaneous beams
  $\Delta I(K_L - K_S)/I = 0 \pm 1\%$

Illumination difference

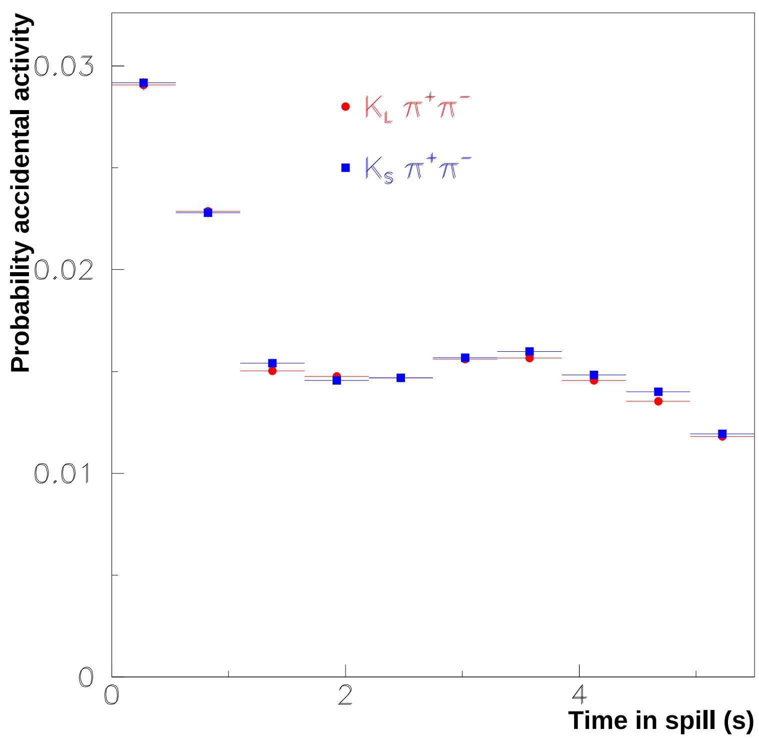
- Different losses in different detector sections due to different K_S - K_L illumination →
  minimized by lifetime weighting
  Illumination difference $= (0 \pm 3) \times 10^{-4}$

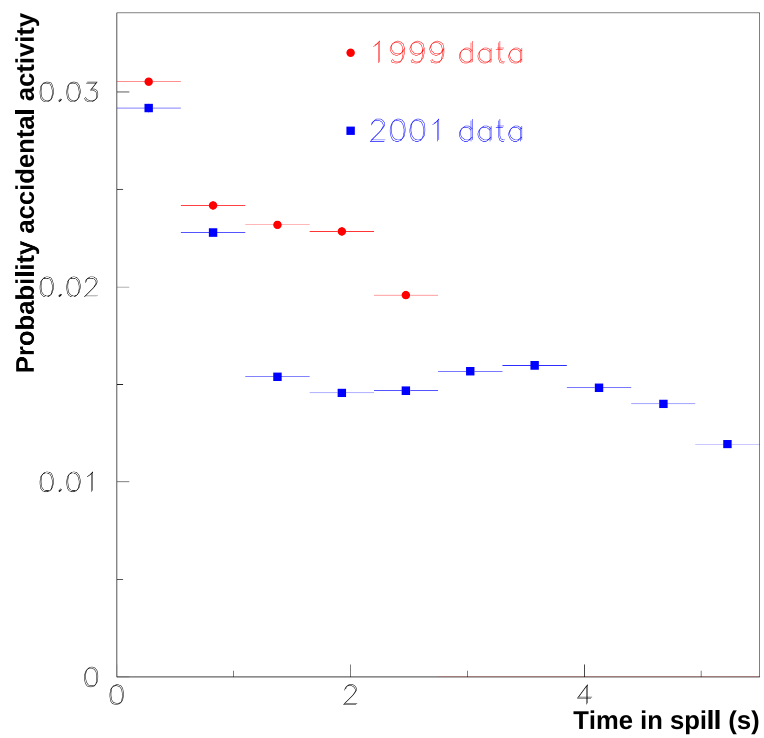
Accidental activity



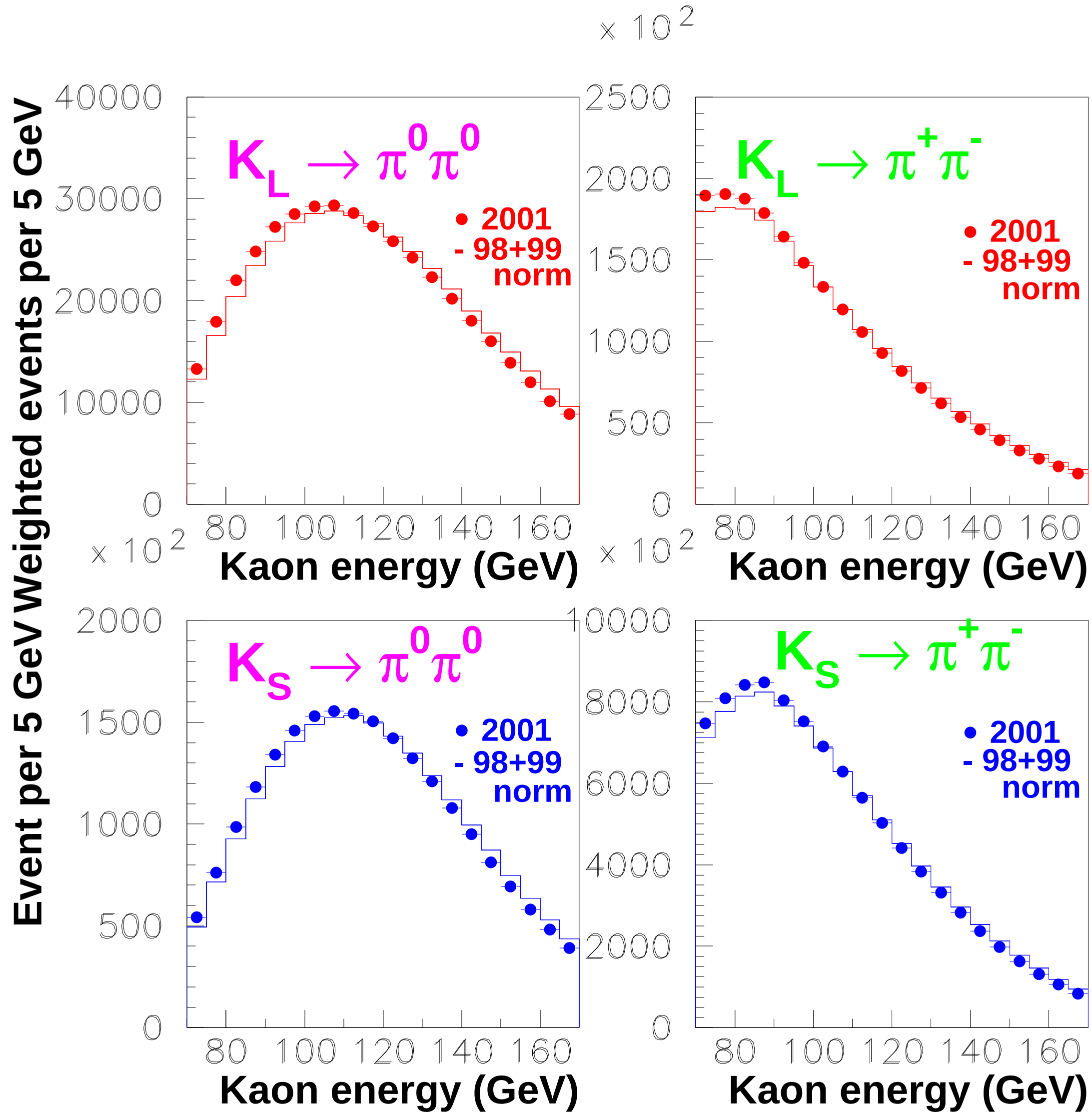


Accidental activity





Event statistics



2001 statistics:

$K_L \rightarrow \pi^0\pi^0$: 1.55×10^6

$K_S \rightarrow \pi^0\pi^0$: 2.16×10^6

$K_L \rightarrow \pi^+\pi^-$: 7.14×10^6

$K_S \rightarrow \pi^+\pi^-$: 9.61×10^6

Summary of corrections

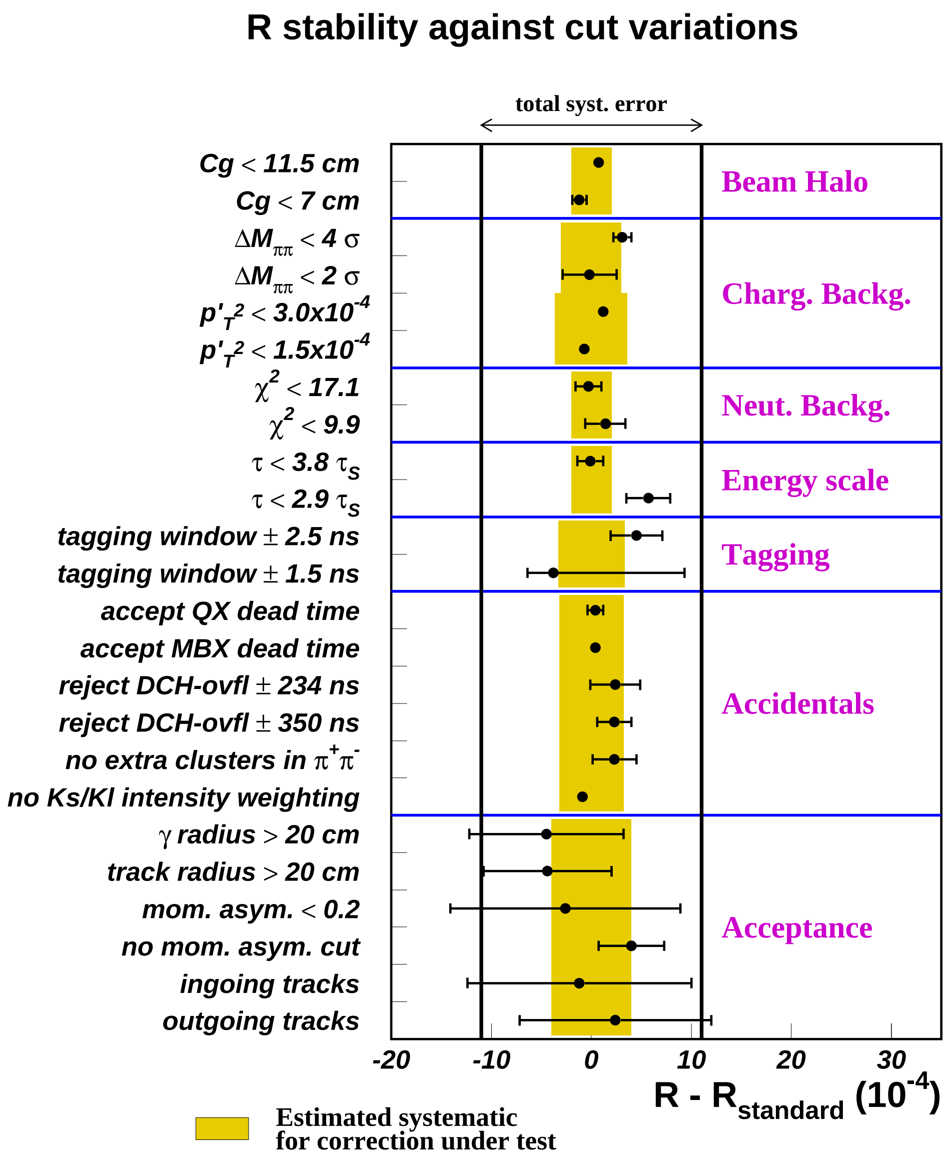
Corrections on R and systematic uncertainties (units 10^{-4})

Source	2001	98-99
$\pi^+\pi^-$ background	14.2± 3.0	16.9± 3.0
$\pi^0\pi^0$ background	−5.6± 2.0	−5.9± 2.0
beam scatt. backgr.	−8.8± 2.0	−9.6± 2.0
Tagging ineffic.	±3.0	±3.0
Accidental tagging	6.9± 2.8	8.3± 3.4
$\pi^+\pi^-$ reconstruction	±2.8	2.0± 2.8
$\pi^0\pi^0$ reconstruction	±5.3	±5.8
AKS inefficiency	1.2± 0.3	1.1± 0.4
Accept. corr.	21.9± 3.5	26.7± 4.1
.	±4.0	±4.0
$\pi^+\pi^-$ trigger ineffic.	5.2± 3.6	−3.6± 5.2
Accidental event losses:		
intensity diff	±1.1	±3.0
illumination diff	±3.0	±3.0
K_S in-time activity	±1.0	±1.0
All	+35.0± 6.5 ± 9.0	+35.9± 8.1 ± 9.6

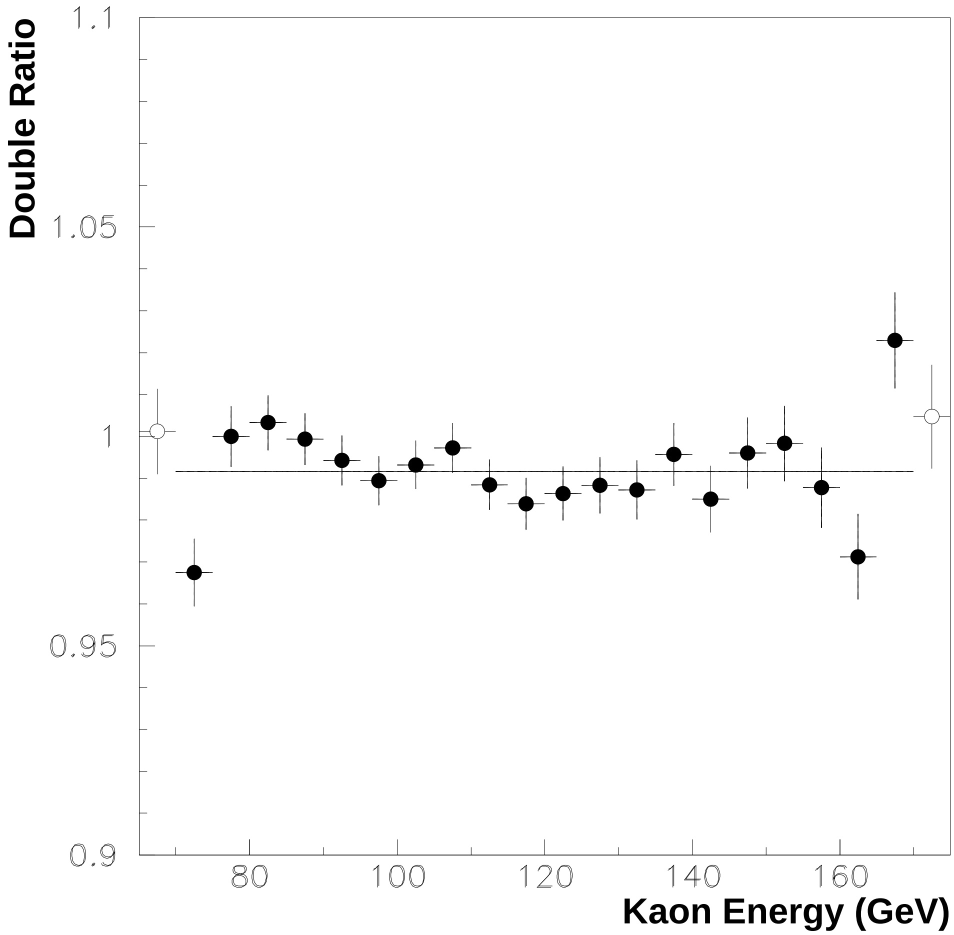
Errors are pure stat or pure syst

Systematic checks

Precise evaluation of systematics to 10^{-4} level is essential



Final NA48 $\mathrm{Re}(\varepsilon'/\varepsilon)$ *result*



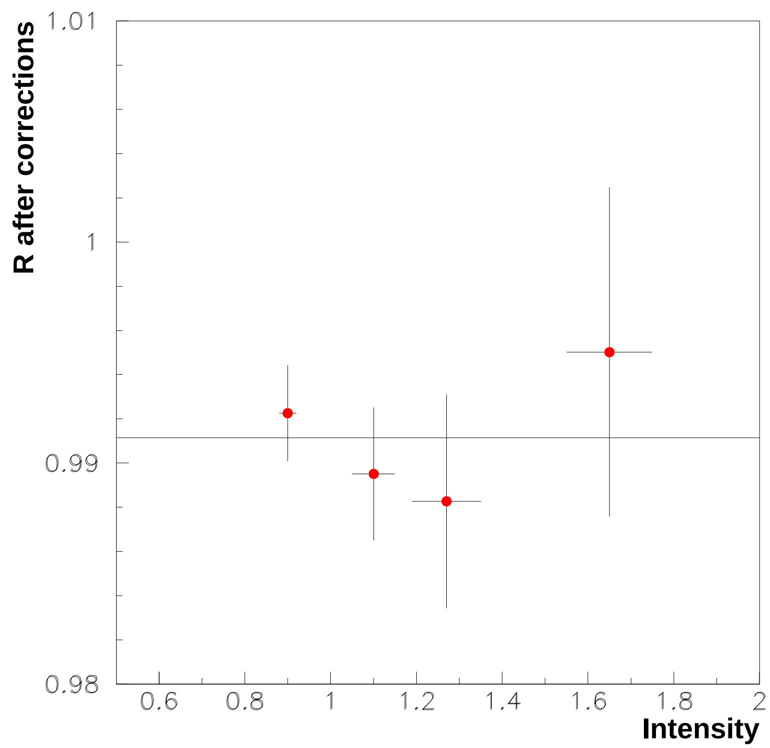
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (13.7 \pm 3.1) \times 10^{-4} \ (2001)$$

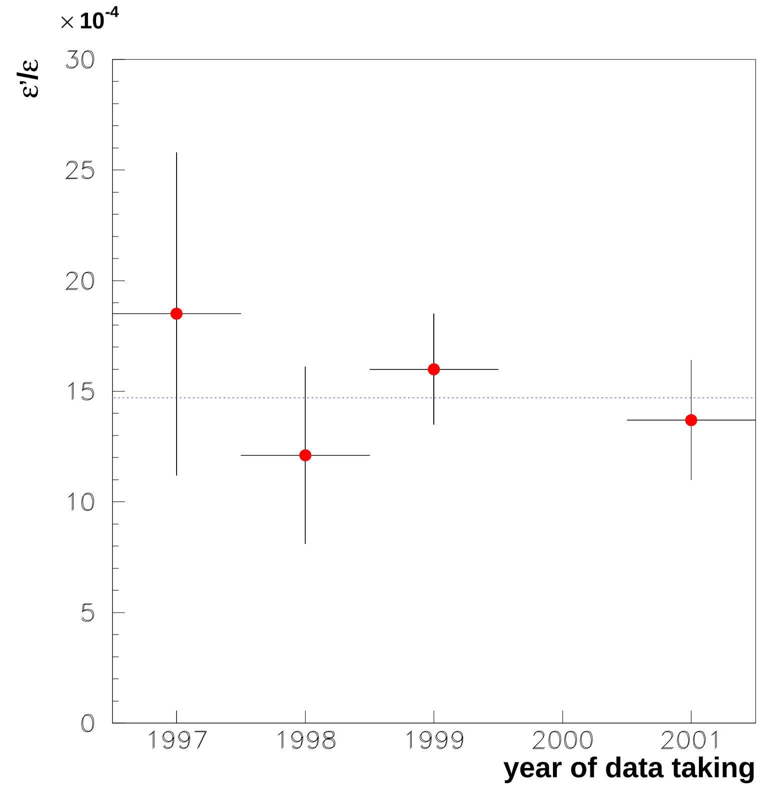
$$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4} \ (97{+}98{+}99)$$

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4} \ (97{+}98{+}99{+}01)$$

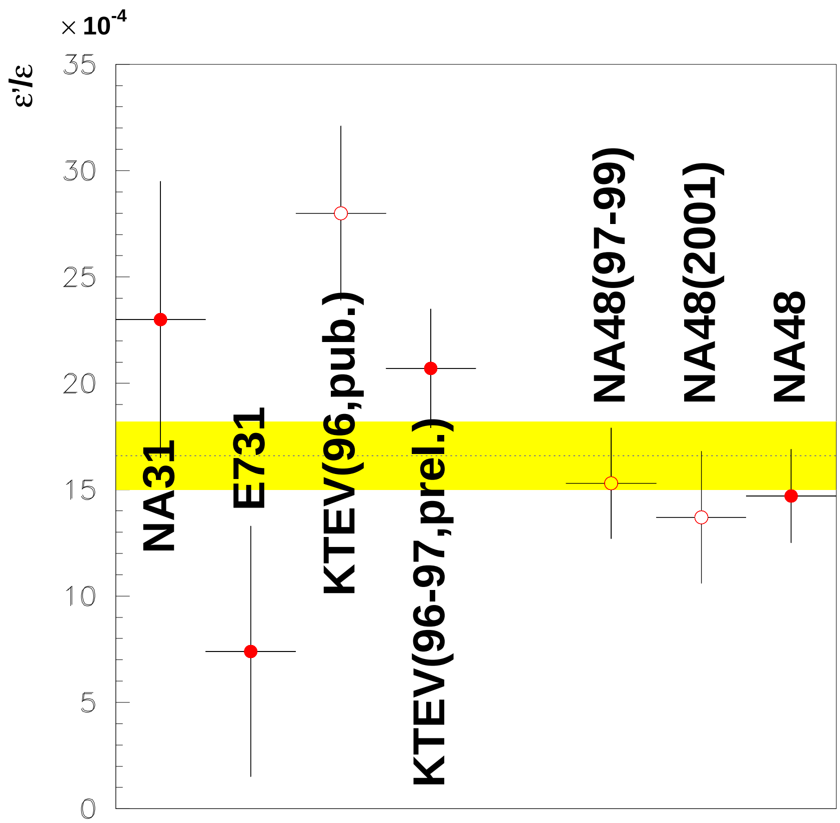
Direct CP violation established to $\sim 6.7\sigma$

More checks on R





$\mathrm{Re}(\varepsilon'/\varepsilon)$ *results*



World Average: $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$
with χ^2/ndf=6.2/3