Latest results on direct CP violation from NA48

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NA48 COLLABORATION

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

- Physics motivation
- The NA48 method and detector
- 98 Data analysis and $\mathrm{Re}(\varepsilon'/\varepsilon)$ preliminary result
- Outlook and conclusion

I. Physics motivation

Measure direct CP violation in the neutral Kaon system.

If present, direct CP violation appears due to the interference of I=0,2 two pion final states

Kaon Eigenstates

Strong Eigenstates: $\bar{K}^0 (d\bar{s})$ $K^0 (\bar{d}s)$

CP Eigenstates:
+1 $K1 = (\bar{K}^0 + K^0)$
-1 $K2 = (\bar{K}^0 - K^0)$

Mass Eigenstates:
$K_S = K1 + \varepsilon K2$ (Almost CP = +1)
$K_L = \varepsilon K1 + K2$ (Almost CP = -1)

Direct and Indirect CP violation

$K_S = K1 + \varepsilon K2$

CP = +1
I = 0, 2

$\pi^0 \pi^0 ;\ \pi^+ \pi^-$

ε = Indirect CP violation (in mixing)

ε = 0.3 %

ε' = Direct CP violation (in Decay)

ε' = ?

$K_L = \varepsilon K1 + K2$

$\mathrm{Re}(\varepsilon'/\varepsilon)$ Standard Model Predictions:
$(1 \div 25) \times 10^{-4}$

Previous measurements (double ratio method)

$\mathrm{Re}(\varepsilon'/\varepsilon) =$

E731	1993	$(7.4 \pm 5.9) \times 10^{-4}$
NA31	1993	$(23.0 \pm 6.5) \times 10^{-4}$
KTEV	1999	$(28.0 \pm 4.1) \times 10^{-4}$
NA48	1999	$(18.5 \pm 7.3) \times 10^{-4}$

II. The NA48 method and detector

Goal: Measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ with an accuracy of $2 \cdot 10^{-4}$ through the double ratio method:

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

◇ high statistics needed (4–5×10^6 $K_L \to \pi^0\pi^0$):
- high intensity beams
- powerful TRIGGER and DAQ Systems

Method to minimize systematic effects:

◇ the 4 decay modes are taken simultaneously

⇒ cancellation of fluxes, dead–times, inefficiencies, accidental losses

◇ from the same fiducial region (lifetime $\leq$ 3.5 τ_S) and two quasi–collinear beams, with offline lifetime weighting applied to $\mathrm{K_L}$ events to equalize distribution of $\mathrm{K_S}$ and $\mathrm{K_L}$ decay positions

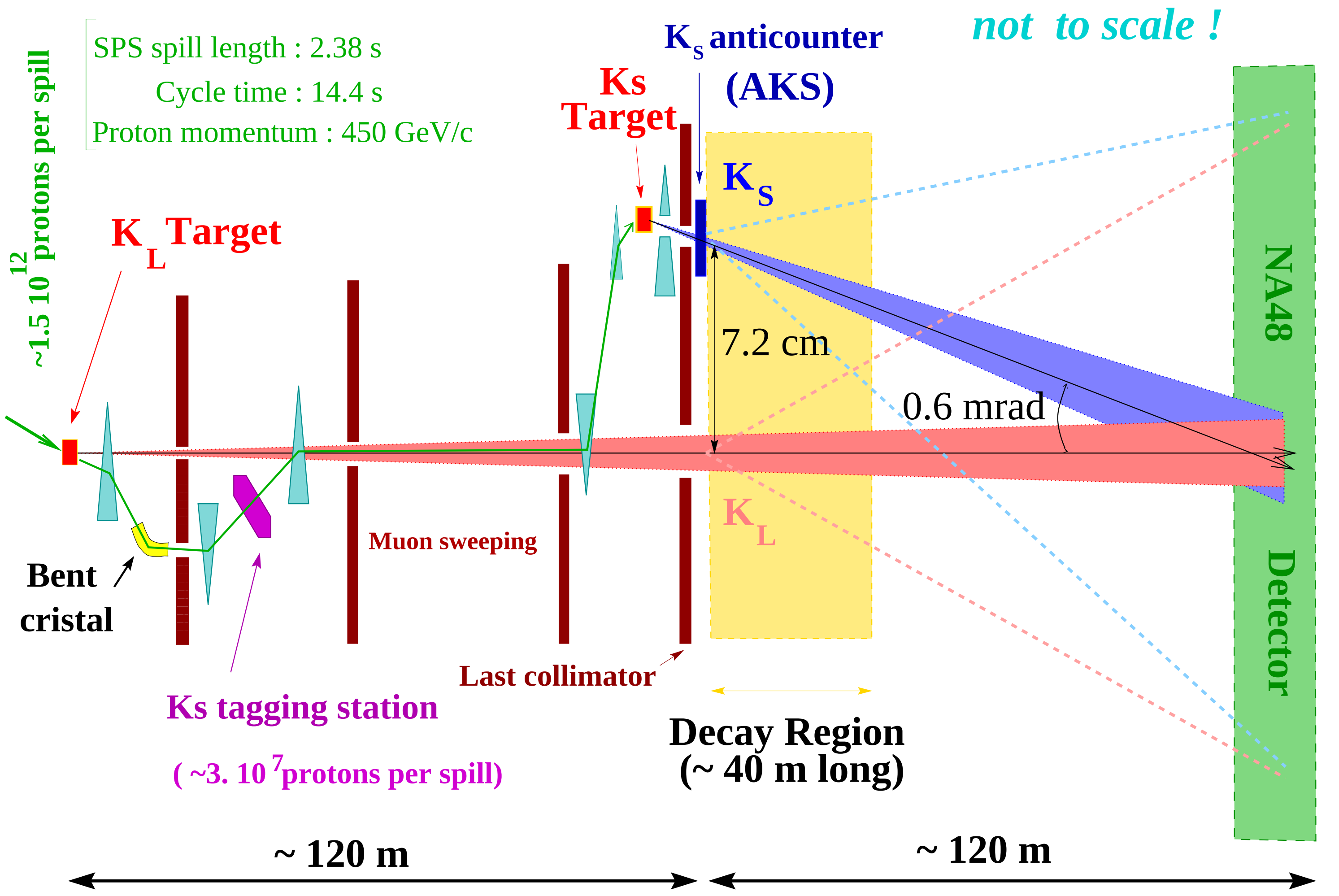
⇒ small acceptance correction

◇ with high resolution magnetic spectrometer ($\pi^+\pi^-$) and quasi–homogeneous Liquid Kripton calorimeter ($\pi^0\pi^0$)

⇒ small background levels

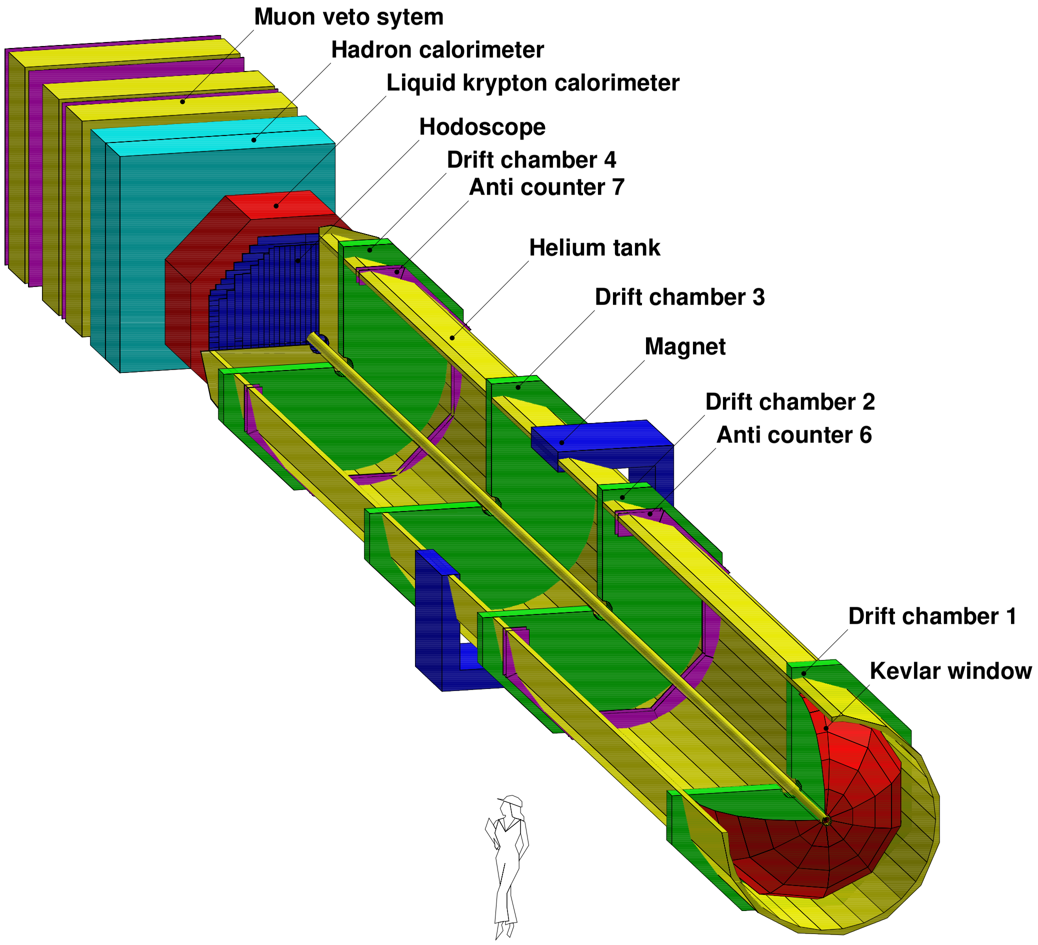
◇ remaining $\mathrm{K_S}$ / $\mathrm{K_L}$ differences in energy spectra are minimized performing the analysis in energy bins (20 between 70 and 170 GeV)

The NA48 simultaneous and collinear K_S and K_L beams



- K_S beam events are identified by tagging the parent proton (measurement of proton time with $<$200 ps resolution)
- Fiducial region is defined by an anti–counter (AKS) for K_S events, a cut on reconstructed z for K_L events.

The NA48 Detector



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

  Magnetic spectrometer: $\sigma_{X,Y} \sim 90\ \mu$m, $\sigma_{mass} \sim 2.5\ MeV/c^2$, resolution on vertex transverse position ~ 2 mm $\to$ allows for beam separation

  Hodoscope : event time measurement ($\sigma_t \sim 200\ ps$)

  μ veto: to reject $\pi\mu\nu$ background.

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

  Liquid Krypton electromagnetic calorimeter with high granularity ($\sim$ 13500 cells):

  $\sigma_t \sim 250\ ps$

  $\frac{\sigma(E)}{E} < 1\ GeV$ for $E_\gamma > 20\ GeV$

  $\sigma_{\pi^0\ mass} \simeq 1.1\ MeV/c^2$

III. 98 Data analysis and Re(ε'/ε) preliminary result

Data samples

◇1997 data 89 days @ 1×10^{12} ppp on $\mathrm{K_L}$ target
published result
(0.49×10^6 $\mathrm{K_L} \to \pi^0\pi^0$)

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5(stat.) \pm 5.8(syst.) \times 10^{-4}}$$

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◇1998 data 135 days @ 1.4×10^{12} ppp on $\mathrm{K_L}$ target
this new preliminary result
(1.14×10^6 $\mathrm{K_L} \to \pi^0\pi^0$)

◇1999 data 128 days @ 1.4×10^{12} ppp on $\mathrm{K_L}$ target
Analysis in progress...
($\sim$ 2 millions of $K_L \to \pi^0\pi^0$)

Analysis strategy

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

Many effects cancel in the double ratio in first approximation. We measure residual differences K_S vs K_L, neutral vs charged.

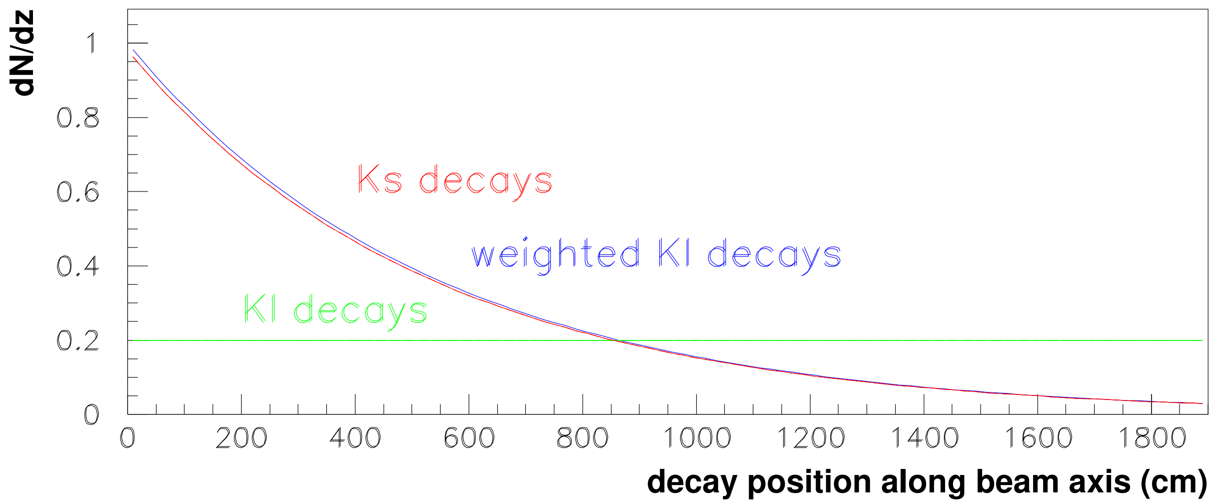
$\Downarrow$

$\boxed{\text{small corrections}}$

bin by bin in energy ....

- ◇ identify $\pi^+\pi^-$ and $\pi^0\pi^0$ events ($70 < E_K < 170$ GeV, deadtime symmetrization - 5% charged trigger, 25% DCH readout)
- → residual backgrounds subtractions
- ◇ identify K_S /K_L events with the tagger (match of proton-event time)
- → check kaon misidentification probabilities
- ◇ define same fiducial region to count $\pi^+\pi^-$ and $\pi^0\pi^0$ events
- → energy scale definition and non-linearities
- ◇ weight K_L events (different K_L K_S vertex distribution)
- → correct residual K_S /K_L acceptance difference
- → correct for small trigger inefficiencies and accidental activity effects
- ◇ R is computed in each bin using an unbiased estimator

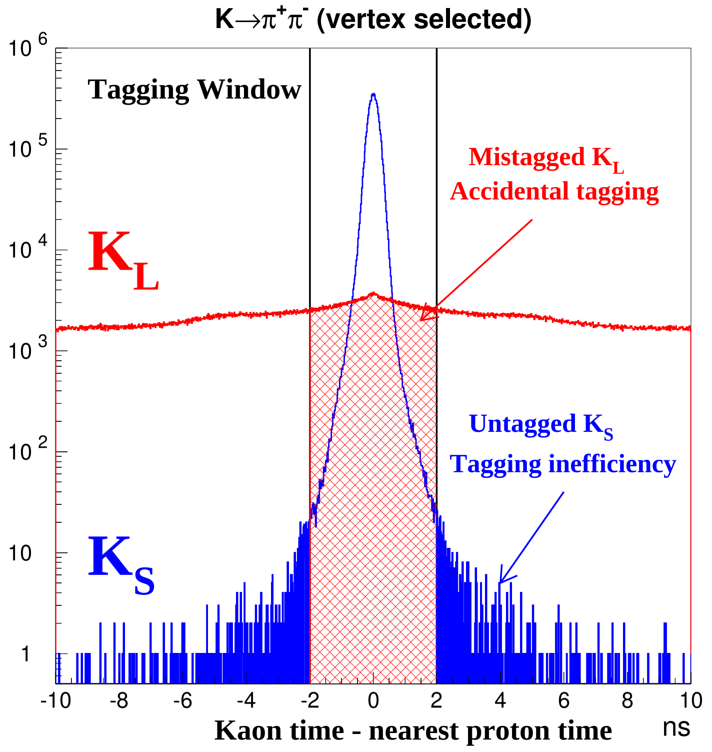
Weighting principle



K_L events are weighted according to $\mathrm{K_S}$ /$\mathrm{K_L}$ ratio of lifetime distributions, $\mathrm{W} = e^{-z/(\beta\gamma c)(1/\tau_{KS} - 1/\tau_{KL})}$

- ➜ Same geometrical acceptance, no effect from detector inefficient regions
- ➜ The acceptance correction is reduced to a few per mill
- ➜ The price is a 35% increase of the statistical error

Tagging: K_S – K_L identification



➜ The mistagging probabilities can be precisely measured for charged events:

Inefficiency $(K_S \to K_L)$ $\alpha^{+-}_{SL} = (1.97 \pm 0.05) \cdot 10^{-4}$

Accidental tagging $(K_L \to K_S)$ $\alpha^{+-}_{LS} = (11.05 \pm 0.01)\%$

➜ $\Delta R \simeq 6 \times \left(\alpha^{00}_{SL} - \alpha^{+-}_{SL}\right) = 6 \times \Delta\alpha_{SL}$

$$\boxed{|\alpha^{00}_{SL} - \alpha^{+-}_{SL}| < 0.5 \times 10^{-4} \Longrightarrow \Delta R < 3 \times 10^{-4}}$$

- K_S only runs
- $K_S \to \pi^0 e^+ e^- \gamma$ events
- comparison of charged and neutral time for neutral events with conversions

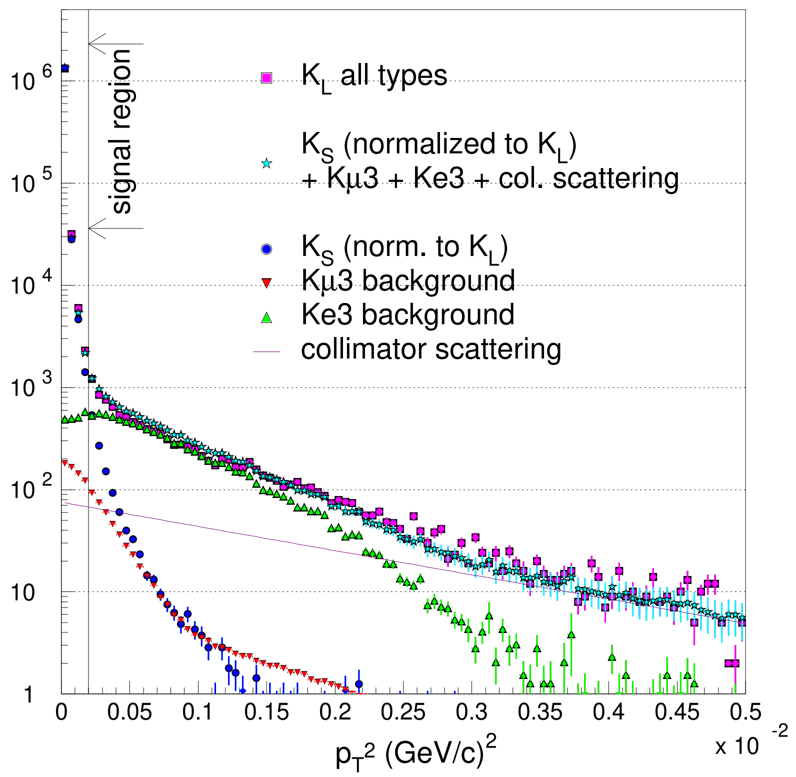
➜ $\Delta R \simeq 2 \times \left(\alpha^{00}_{LS} - \alpha^{+-}_{LS}\right) = 2 \times \Delta\alpha_{LS}$

$$\boxed{\alpha^{00}_{LS} - \alpha^{+-}_{LS} = (0.3 \pm 4.2) \times 10^{-4} \Longrightarrow \Delta R = (0.6 \pm 8.4) \times 10^{-4}}$$

- comparing rate of out–of–time protons for charged and neutral events
- checking the difference between in–time and out–of–time windows using $K_L \to \pi^+\pi^-$ (vertex–identified) and $K_L \to 3\pi^0$

Background to $K \to \pi^+\pi^-$

Background dominated by $K_L \to \pi\mu\nu$ and $K_L \to \pi e\nu$
(B.R. 70% vs 0.2% for signal)



- Rejected using muon veto counters ($\pi\mu\nu$), cut on $\frac{E_{LKr}}{P_{DCh}} < 0.8$ ($\pi e\nu$), cut on reconstructed invariant mass within 3σ, cut on $p_t^2 < 200\ (MeV/c)^2$
- Residual background estimated by fitting the K_L distribution as $K_S\ \pi^+\pi^- + K_{e3} + K_{\mu3}$ in a control region in the plane $(m_{\pi\pi}, p_T^2)$

$$\boxed{\Delta R = (19 \pm 3) \times 10^{-4}}$$

- A small $K \to \pi\pi$ signal is observed at high p_T (K_L coming from scattering + K_S regeneration in the collimators). Rejected only for charged events, not for neutral

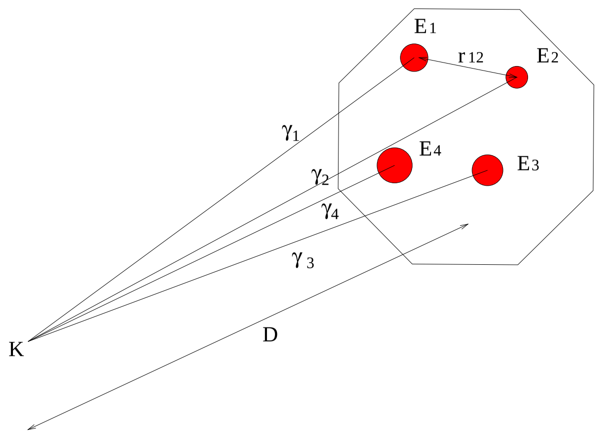
$$\boxed{\Delta R = (-9.9 \pm 3.3) \times 10^{-4}}$$

Background to $K \to \pi^0\pi^0$

$K \to \pi^0\pi^0 \to 4\gamma$

Vertex position computed imposing K^0 mass :

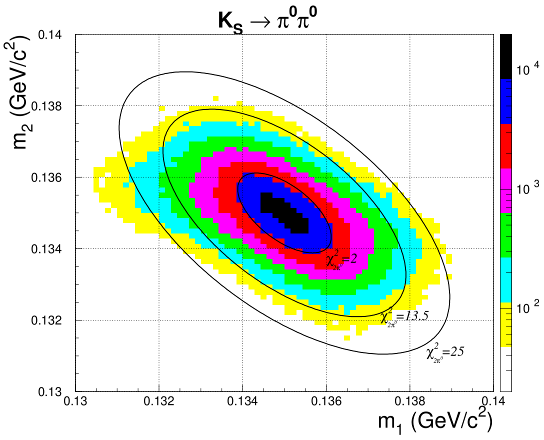
$$D = \sqrt{\sum E_i E_j \times (r_{ij})^2} \; / M_K$$



➜ Photon pairing to get the "best" π^0 masses

$m_{ij} = \sqrt{E_i E_j} \, . \, r_{ij} / D$

$$\chi^2 \equiv \left[\frac{(m_1+m_2)/2 - m_{\pi^0}}{\sigma_+}\right]^2 + \left[\frac{(m_1-m_2)/2}{\sigma_-}\right]^2$$

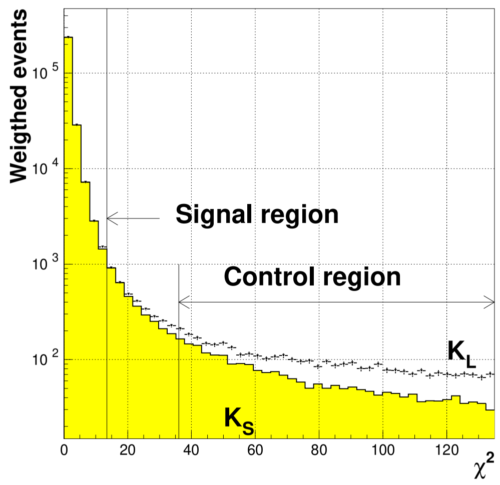


$\sigma_+ \sim 0.45$ MeV

$\sigma_- \sim 0.85$ MeV

Background coming from $3\pi^0$ (B.R. 21%)
rejected with cut on $\chi^2 \leq 13.5$
Residual estimated in χ^2 control region

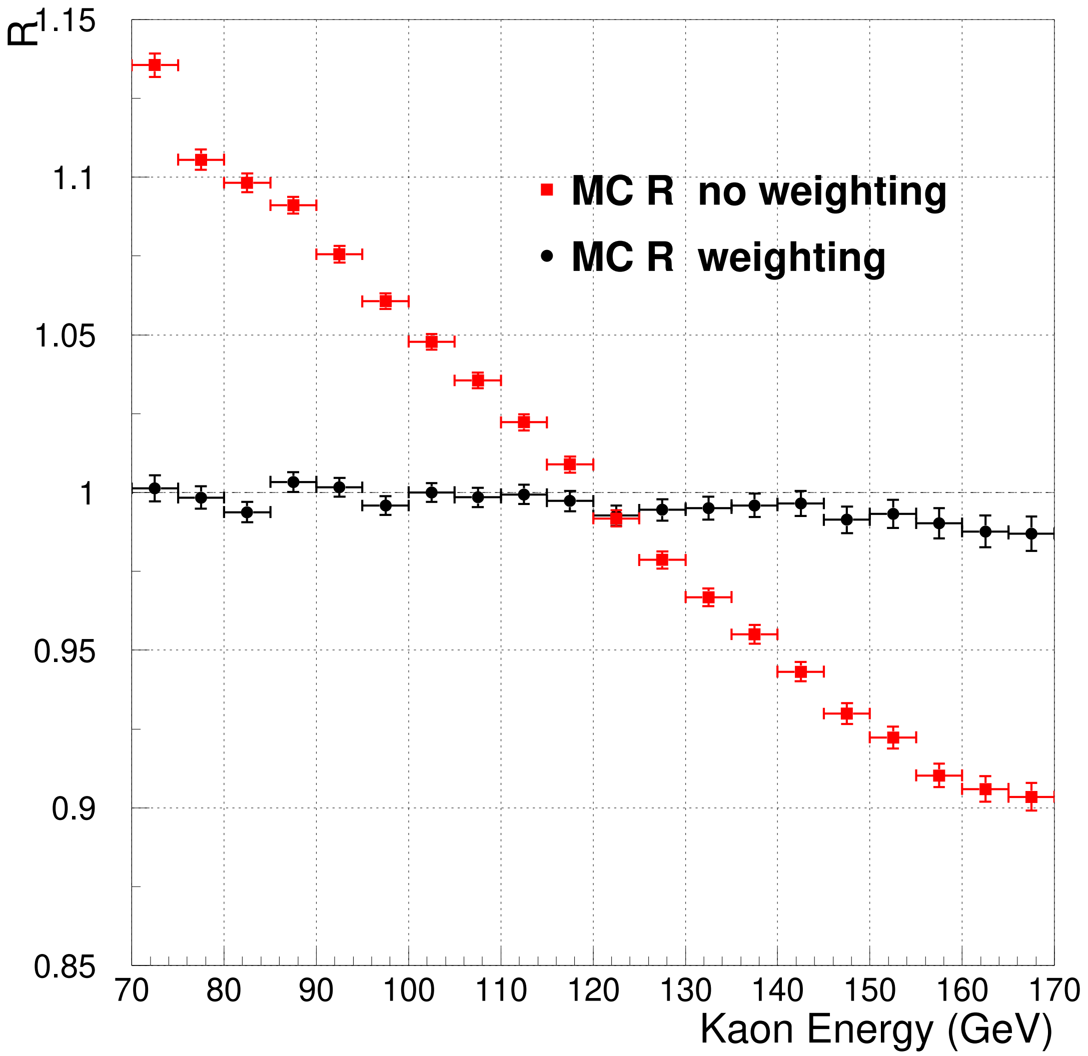
$$\Delta R = (6.6 \pm 2.0) \times 10^{-4}$$



Acceptance

A detailed montecarlo simulation is used to correct the remaining effect of acceptances.

MC sample $\sim 5 \times$ data sample



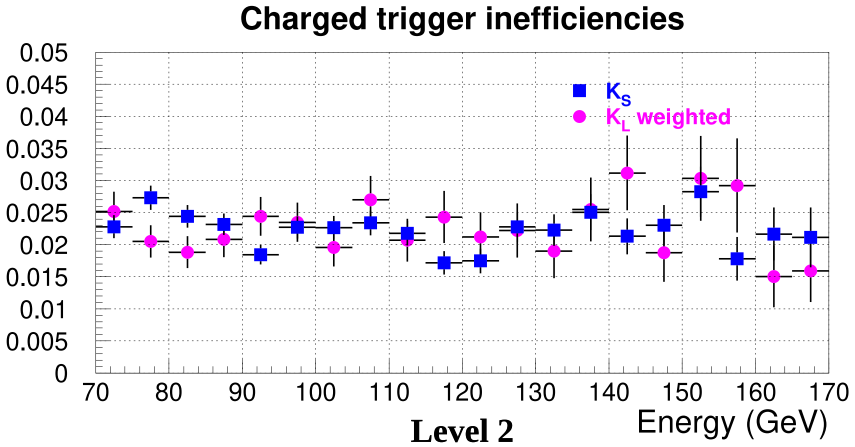
$$\Delta R = (31 \pm 6\ (\text{MC stat.})\ \pm 6\ (\text{syst.})\ ) \times 10^{-4}$$

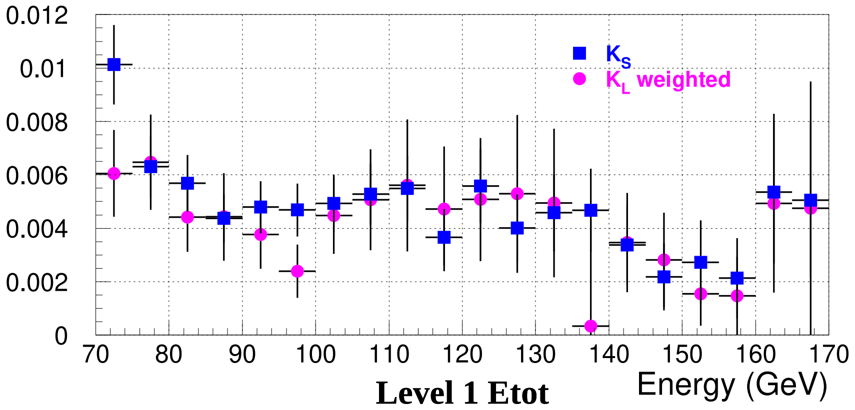
$\Delta R \simeq 200$ without weigting

Trigger Efficiencies

→ Charged Trigger

		Efficiency
Level 1:	Total energy signal + 2 track topology in hodoscope	99.44 ± 0.03 %
Level 2:	on–line reconstruction of vertex and $\pi\pi$ invariant mass	97.75 ± 0.05 %





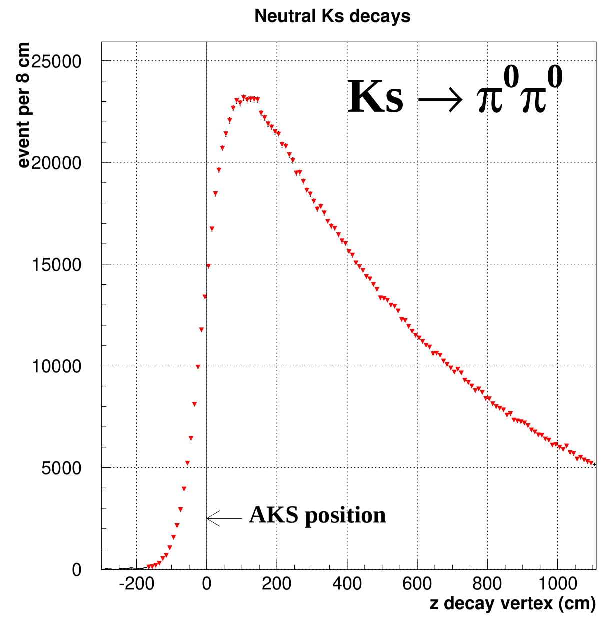
$$\boxed{\Delta R = (-1 \pm 11) \times 10^{-4}}$$

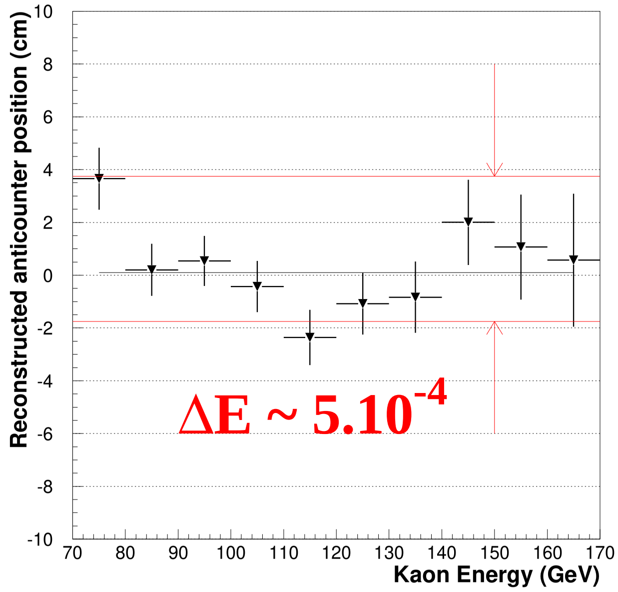
→ Neutral Trigger

on–line reconstruction of number of peaks, kaon energy and vertex position

Efficiency $= 99.93 \pm 0.02$ % $\Longrightarrow$ no bias on R

Systematics from Neutral Reconstruction





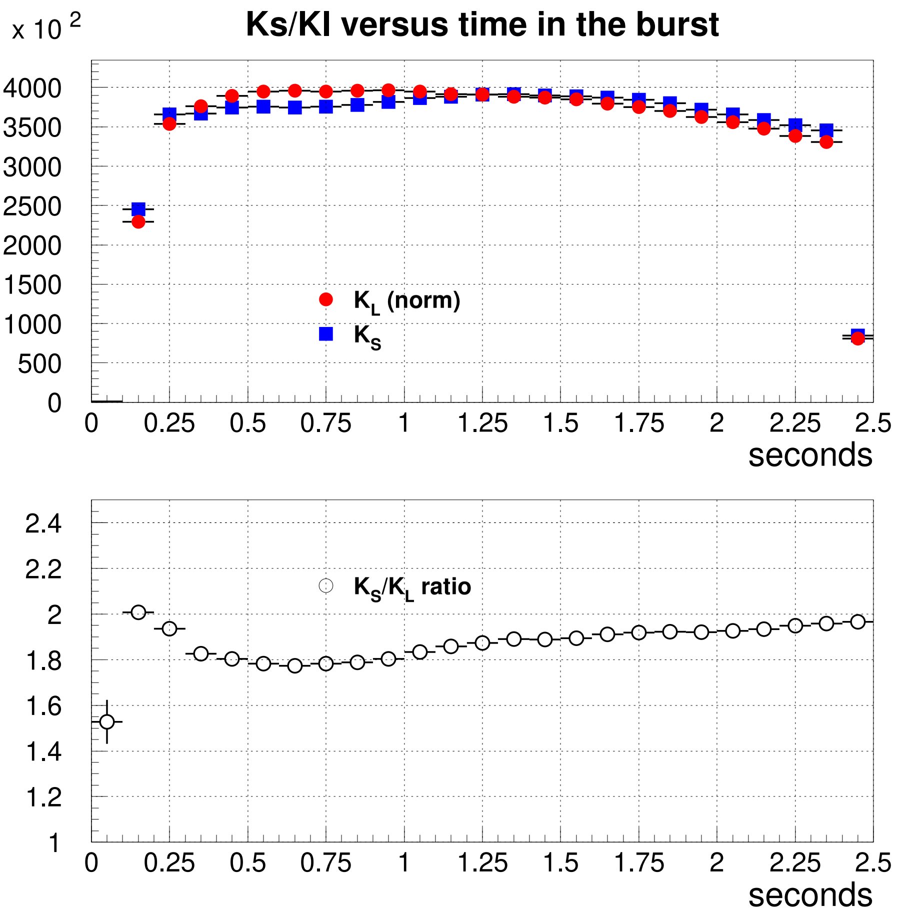
The global energy scale ($\rightarrow$ distance scale) for neutral events is fixed by fitting the AKS position using the reconstructed z-vertex distribution. The uncertainty is $5 \cdot 10^{-4}$

$\Longrightarrow \Delta R = \pm 3 \cdot 10^{-4}$

Non-linearity (5.10^{-4}) $\oplus$ energy scale (3.10^{-4}) $\oplus$ transverse scale (3.10^{-4}) $\oplus$ non-gaussian tails (5.10^{-4}) $\oplus$...

Uncertainty on R : $\pm 10 \times 10^{-4}$

Accidental Activity



- The concurrency and intensity correlation of the two beams minimize the effects of accidental losses and gains
- Accidental activity (extra clusters and tracks) is found to be identical within 1 % between K_S et K_L .
- The correction is estimated by overlaying random–triggered events to good $\pi\pi$ events

$$\boxed{\Delta R = (+2 \pm 12) \times 10^{-4}}$$

- Work going on to reduce the uncertanty.

Correction and systematic uncertainties

Event counts in 98 data (corrected for accidental tagging)

Mode	Statistics (millions)
$K_S \rightarrow \pi^+\pi^-$	7.46
$K_L \rightarrow \pi^+\pi^-$	4.87
$K_S \rightarrow \pi^0\pi^0$	1.80
$K_L \rightarrow \pi^0\pi^0$	1.14

Statistical uncertainty on R:

17.3×10^{-4}

Corrections and uncertainties on R (Unit = 10^{-4})

Source	ΔR	σ
Charged trigger	−1	11
Accidental tagging	+1	8
Tagging efficiency	–	3
Neutral E-scale	–	10
Charged vertex	+2	2
Acceptance	+31	8
Neutral BG	−7	2
Charged BG	+19	3
Beam scattering	−10	3
Accid. activity	+2	12
Total	+37	24

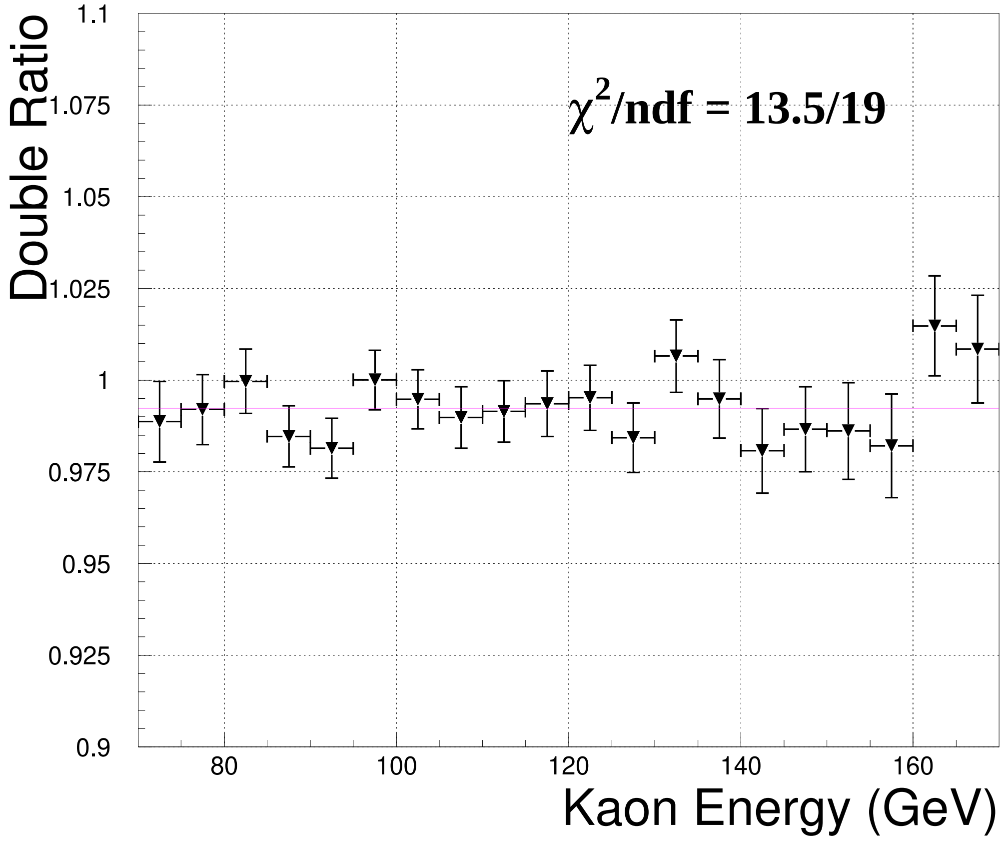
Errors in green = limited by statistics
Errors in blue = work in progress

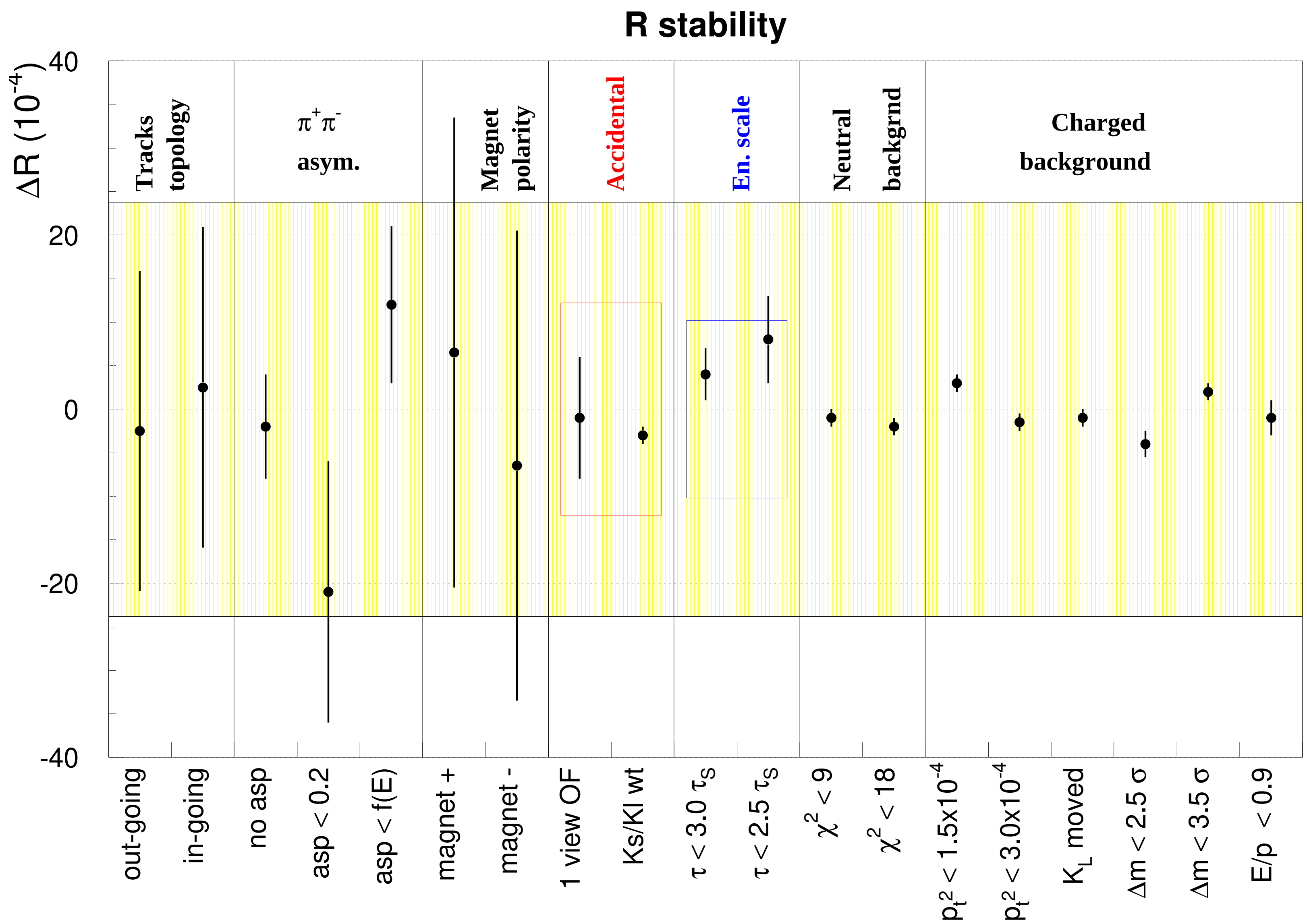
$\mathrm{Re}(\varepsilon'/\varepsilon)$ result

PRELIMINARY RESULT OF 1998 DATA:

$$Re\left(\frac{\epsilon'}{\epsilon}\right) = \frac{1-R}{6} = (12.2 \ \pm \ 2.9 \ (\text{stat.}) \pm \ 4.0 \ (\text{syst.})) \times 10^{-4}$$

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \ \pm \ 4.9) \times 10^{-4}}$$




R stability
ΔR (10^-4)
40
20
0
-20
-40
Tracks topology
π+π- asym.
Magnet polarity
Accidental
En. scale
Neutral backgrnd
Charged background
out-going
in-going
no asp
asp < 0.2
asp < f(E)
magnet +
magnet -
1 view OF
Ks/Kl wt
τ < 3.0 τS
τ < 2.5 τS
χ2 < 9
χ2 < 18
pt2 < 1.5x10-4
pt2 < 3.0x10-4
KL moved
Δm < 2.5 σ
Δm < 3.5 σ
E/p < 0.9

IV. Outlook and conclusion

◇ Refine systematic errors on 1998 data

→ Accidental tagging, Accidental activity

◇ Analysis of 1999 data is in progress. Expected accuracy $\sim$ 2.5 to 3×10^{-4} on $\mathrm{Re}(\varepsilon'/\varepsilon)$

◇ 2000 run started on 24-05-2000:

→ $\simeq$ 100 days recording neutral decays only (drift chambers damaged last fall after beam pipe implosion)

→ Accidental tagging study with $\mathrm{K_L}$ –only beam; Neutral energy scale study; $\simeq$ 60 days of test for the future rare decay program ($\mathrm{K_S}$ high intensity)

◇ 2001 run Three of the four drift chambers will be in place → $\mathrm{Re}(\varepsilon'/\varepsilon)$ stability study as a function of beam intensity

Conclusions

- NA48 has presented a new preliminary result based on the 1998 data sample:

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 4.9) \times 10^{-4}}$$

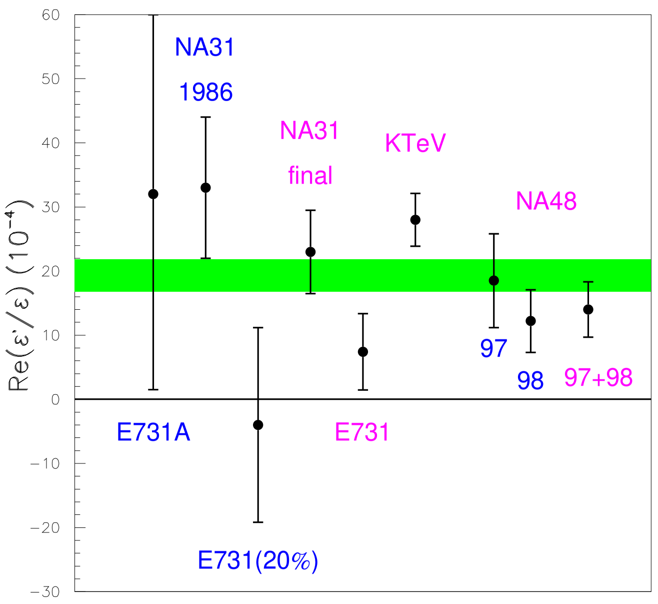
- Combining with the NA48 published result (taking into account the small correlated systematics):

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.0 \pm 4.3) \times 10^{-4}}$$

- The world average value for $\mathrm{Re}(\varepsilon'/\varepsilon)$ combining the 4 most precise results

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.5) \times 10^{-4}}$$

$$(\chi^2/ndf = 10.4/3)$$



- $\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$ well established
  looking forward for final results from NA48 and KTEV, and new results from KLOE