Measurement of Direct CP Violation by NA48

Giuseppina Anzivino

Università di Perugia and INFN

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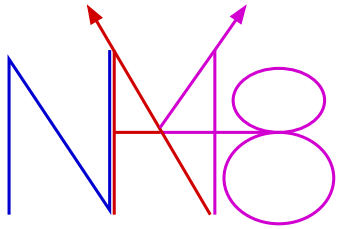


on behalf of the **NA48 COLLABORATION**

Cagliari-Cambridge-CERN-Dubna-Edinburgh-Ferrara-Firenze-Mainz-Orsay-Perugia-Pisa-Saclay-Siegen-Torino-Vienna-Warsaw

Outline

- Physics Motivation
- Measurement Principles
- Experimental Set-Up
- Data Analysis
- Result and Checks
- Conclusions and Perspectives

The neutral kaon system

Strangeness eigenstates

$$\mathrm{K}^0(\bar{\mathrm{s}}\mathrm{d}) \quad (S=+1)$$
$$\overline{\mathrm{K}^0}(\mathrm{s}\bar{\mathrm{d}}) \quad (S=-1)$$

CP eigenstates

$$\mathrm{K}_1 = (\mathrm{K}^0 + \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=+1)$$
$$\mathrm{K}_2 = (\mathrm{K}^0 - \overline{\mathrm{K}^0})/\sqrt{2} \quad (CP=-1)$$

Mass eigenstates

$$\mathrm{K_S} \simeq \mathrm{K}_1 + \varepsilon \mathrm{K}_2 \quad (\mathrm{c}\tau_\mathrm{S} = 2.67 \text{ cm})$$
$$\mathrm{K_L} \simeq \mathrm{K}_2 + \varepsilon \mathrm{K}_1 \quad (\mathrm{c}\tau_\mathrm{L} = 15.5 \text{ m})$$

Kaon decays

$\mathrm{K_S}$		$\mathrm{K_L}$	
69 %	$\pi^+\pi^-$	21 %	$3\pi^0$
31 %	$\pi^0\pi^0$	13 %	$\pi^+\pi^-\pi^0$
		27 %	$\pi\mu\nu$
		39 %	$\pi e\nu$
		0.2 %	$\pi^+\pi^-$
		0.1 %	$\pi^0\pi^0$

CP Violation

The mass eigenstates (K_S and K_L) are not pure CP eigenstates.

The two decay modes in $\pi^+\pi^-$ and $\pi^0\pi^0$ have CP=+1

THEN

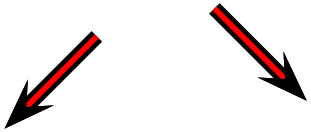
K_S (almost CP=+1) can decay to two pions

K_L (almost CP=-1) cannot decay to two pions

In the kaon system CP violation manifests in the observation of the

CP-forbidden $K_L \rightarrow \pi\pi$ decay

Two components



Indirect CP violation due to the CP eigenstates mixing inside K_S and K_L

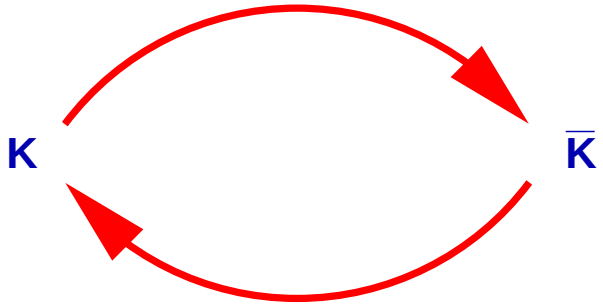
parameter ε

Direct CP violation in the decay process

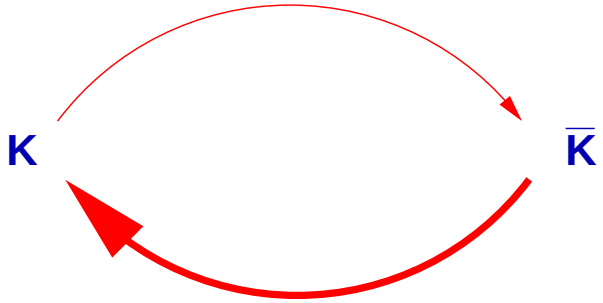
parameter ε'

Indirect CP Violation

The K^0 and $\overline{\mathrm{K}^0}$ particles mix. This property is independent of CP



Indirect CP violation causes the mixing to be asymmetric



$\overline{\mathrm{K}^0} \longrightarrow \mathrm{K}^0$ preferred over $\mathrm{K}^0 \longrightarrow \overline{\mathrm{K}^0}$

ε parameter known since '64

$$| \varepsilon | = (2.28 \pm 0.02) \times 10^{-3}$$

Direct CP Violation

In the decay $\mathrm{K}^0 \to \pi\pi$ the two pions can have isospin $I = 0, 2$

$\Longrightarrow$ two amplitudes A_0 and A_2

The phase difference of these two channels determines direct CP violation

The parameters ε and ε' are related to ratios of CP violating/CP conserving amplitudes

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

$\varepsilon' \approx \frac{i}{\sqrt{2}} Im(\frac{A_2}{A_0}) e^{i(\delta_2 - \delta_0)}$ $\Longrightarrow$ ε' is small wrt ε

$\Longrightarrow$ convenient to measure $\mathrm{Re}(\varepsilon'/\varepsilon)$

If $\mathrm{Re}(\varepsilon') \neq 0$ then the decay amplitudes of K^0, $\overline{\mathrm{K}^0} \longrightarrow \pi\pi$ are different

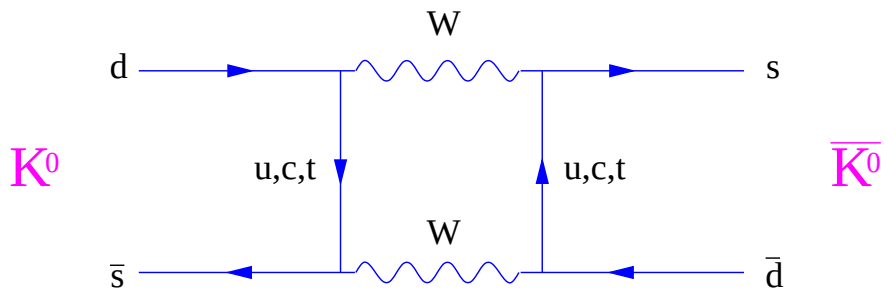
$$\mathrm{K}^0 \longrightarrow \pi\pi \neq \overline{\mathrm{K}}^0 \longrightarrow \pi\pi$$

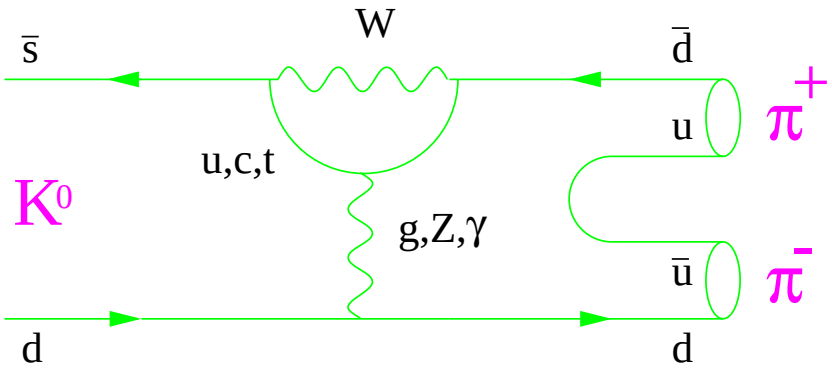
Standard Model predictions

⟹ Complex phase in the quark mixing matrix

Indirect CP violation
mixing in K^0-$\overline{K^0}$ states

Box diagram : $\Delta S = 2 \rightarrow \varepsilon$





Direct violation in the decay

Penguin diagram : $\Delta S = 1 \rightarrow \varepsilon'$

Typical theoretical predictions ⟹ $\mathrm{Re}(\varepsilon'/\varepsilon)$ in the range $5 - 30 \times 10^{-4}$

Statistics

GOAL ⟹ measure $\mathrm{Re}(\varepsilon'/\varepsilon)$ with an accuracy of 2×10^{-4}

⟹ Several millions $K_L \to \pi^0\pi^0$ (the limiting decay mode) are needed to achieve the required accuracy

⟹ A gigantic amount of data is needed to control systematics, taken with very stable and fast data acquisition system

Raw data taken:

- ZEUS RUN I $\sim$ 30 TB
- BABAR $\sim$ 50 TB
- NA48 $\sim$ 170 TB

⟹ For NA48, only ~ 100 events out of $\sim 16k$ triggers are good $\pi\pi$ modes, the rest is to control the systematic errors.

⟹ If you had missed 10^{-4} $K_L \to \pi^o\pi^o$ $\mathrm{Re}(\varepsilon'/\varepsilon)$ would be wrong by 1.6 $\times 10^{-4}$

⟹ Accumulated statistics ($K_L \to \pi^0\pi^0$) before 2000

NA48 $\approx$ 4.000.000
KTeV $\approx$ 8.000.000

Experimental status

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

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

$\varepsilon'/\varepsilon \neq 0$? ⟹ New generation of experiments

First published results two years ago

- KTeV: $(28.0 \pm 4.1) \times 10^{-4}$ (96-97 data, 0.9×10^6 events)
  2001 update
- NA48: $(18.5 \pm 7.3) \times 10^{-4}$ (97 data, 0.5×10^6 events)

Preliminary NA48 result on 98 data last year

- NA48: $(14.0 \pm 4.3) \times 10^{-4}$ (combined with 97, 1.6×10^6 events)

Before May 2001
World average: $(19.2 \pm 2.5) \times 10^{-4}$ BUT $\chi^2/\text{ndf} = 10.4/3$
⟹ final results from NA48 and KTeV

This talk: NA48 result based on 98+99 data
($\approx$ 7 times the 97 published statistics, 3.3×10^6 events)

Measurement principle

The double ratio R is related to the decay widths and to $\mathrm{Re}(\varepsilon'/\varepsilon)$:

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

Basic Principle ⟹ symmetry between K_L and K_S or $\pi^+\pi^-$ and $\pi^0\pi^0$

Take the four decay modes

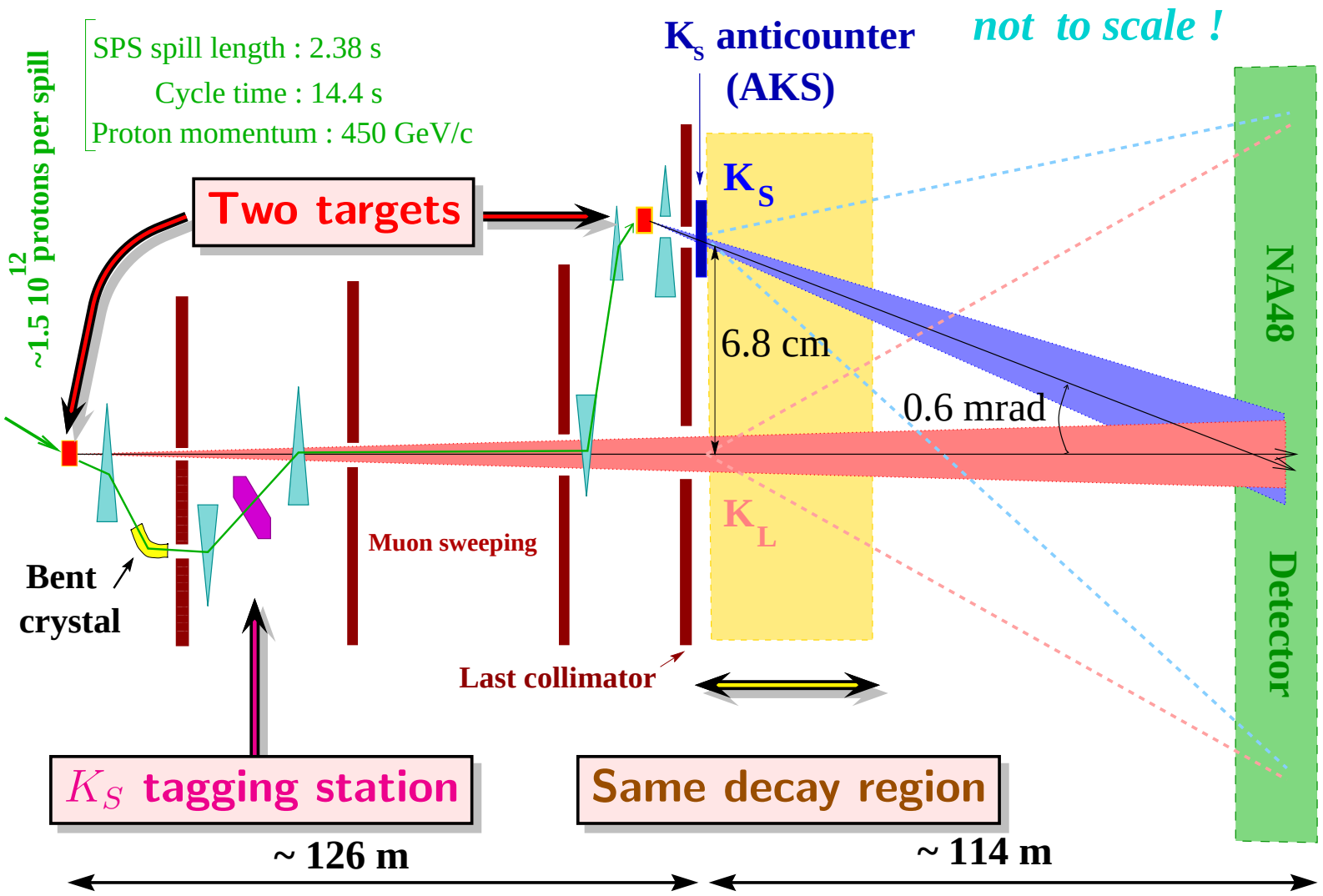
- simultaneously
- in the same decay region

} ⟹ count the number of events

- fully exploit the double ratio technique
  ⟹ all effects that are common to either K_L and K_S or $\pi^+\pi^-$ and $\pi^0\pi^0$ cancel in the ratio
- simoultaneous data taking of the four modes
  ⟹ variation of fluxes, inefficiencies, dead times, accidental losses vanish at first order
- minimize the amount of residual correction weighting K_L decay distribution
  ⟹ $\approx$ similar acceptances for K_S and K_L

small correction on R

NA48 beam lines



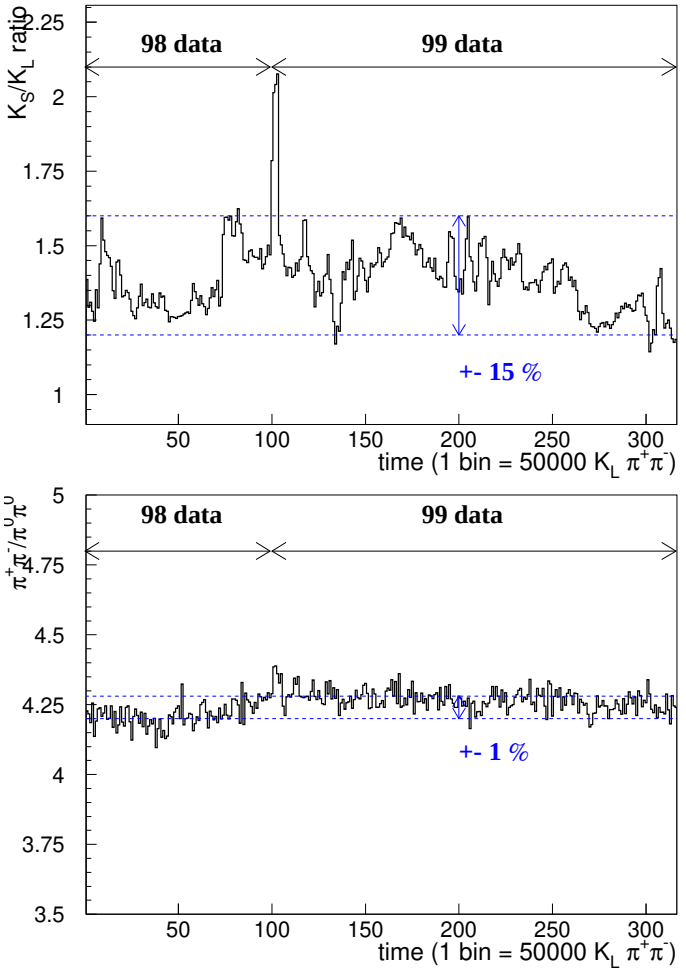
Time variations

➡ The K_S/K_L ratio varies with the beam conditions (RMS $\approx 9\%$)

➡ To remove any sensitivity to variations K_S events are weighted with K_L/K_S intensity ratio

➡ in case of dead-time in one decay mode no events are counted also in the other mode

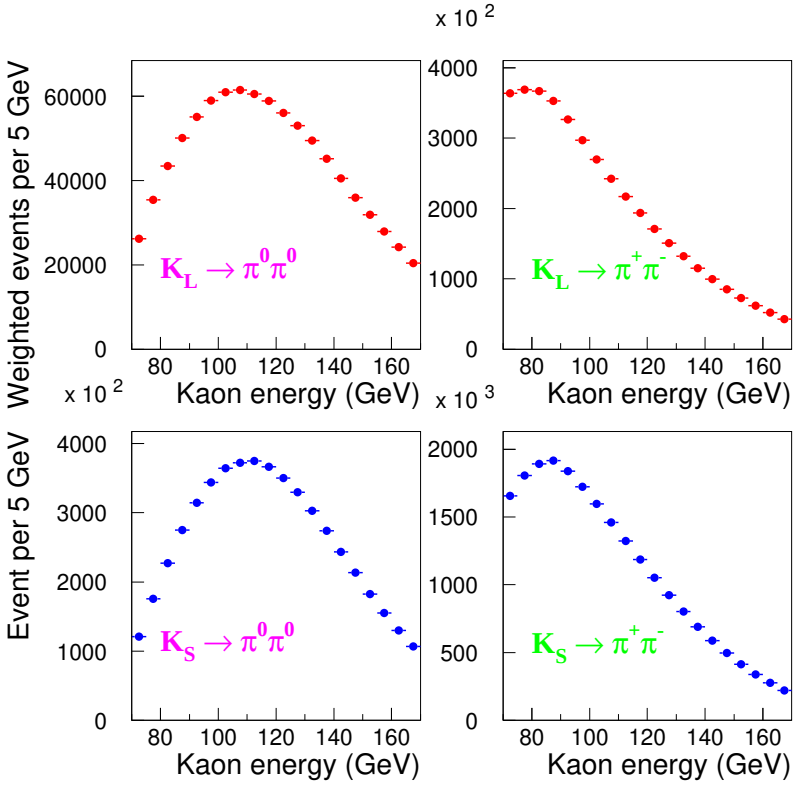
small effect on R



Kaon energy

➡ The K_L and K_S beams 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



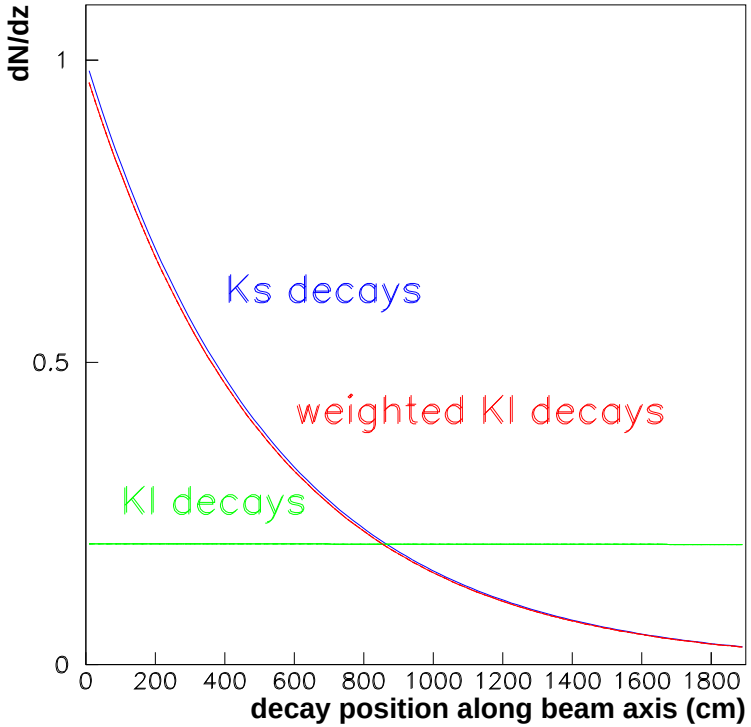
Lifetime weighting

⟹ For a given z:
acceptance $\mathrm{K_S} = \mathrm{K_L}$
BUT very different decay lengths
$\tau_{\mathrm{K_L}} \approx 600 \times \tau_{\mathrm{K_S}}$
$\Rightarrow$ Different acceptances for $\mathrm{K_S}$ and $\mathrm{K_L}$ and large correction on R

⟹ Solution: weight $\mathrm{K_L}$ events

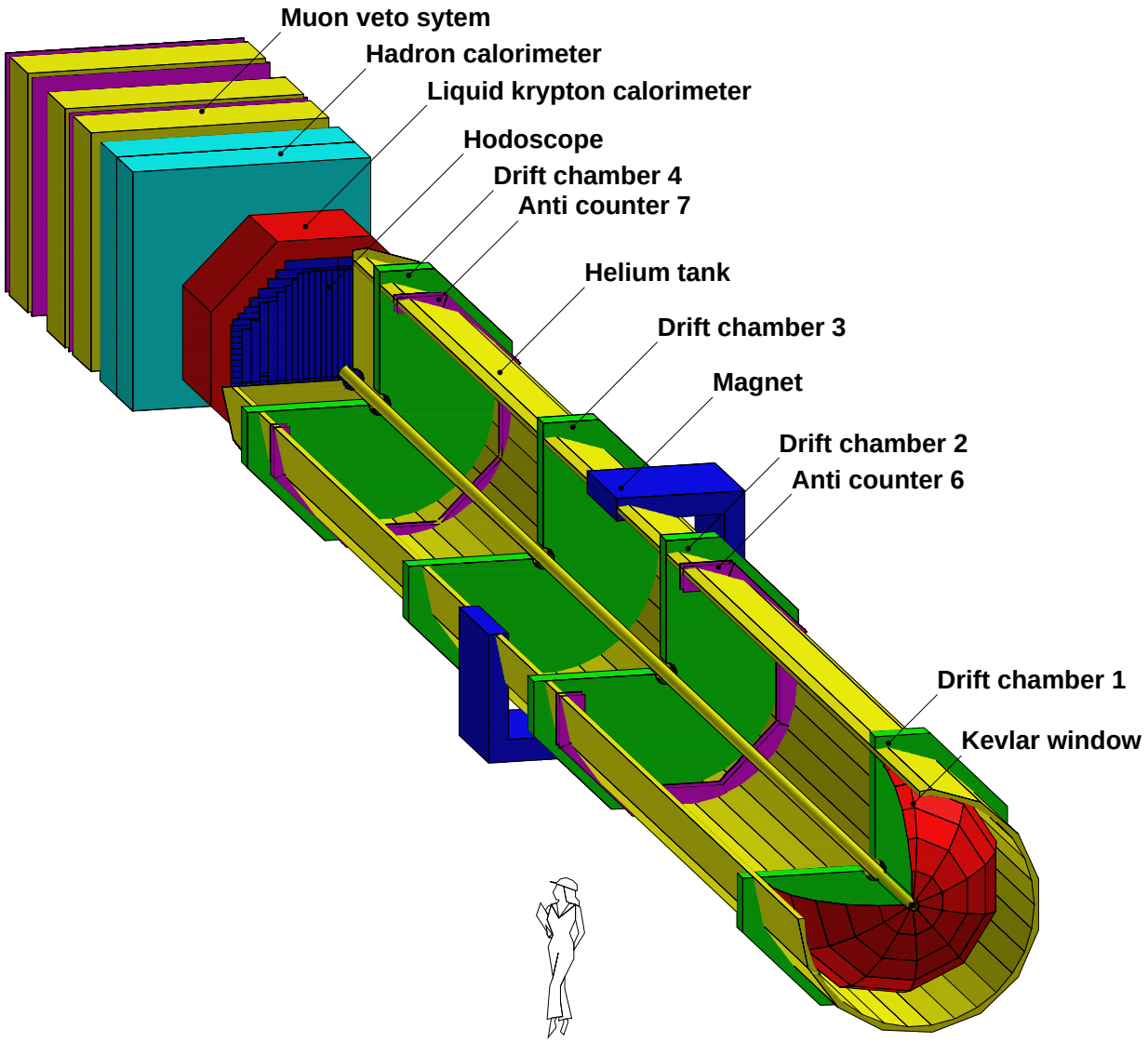
$$W = \frac{\pi\pi \text{ decay rate in } \mathrm{K_S} \text{ beam}}{\pi\pi \text{ decay rate in } \mathrm{K_L} \text{ beam}} \approx e^{-z/(\beta\gamma c)(1/\tau_{KS} - 1/\tau_{KL})}$$

$\Rightarrow$ same decay vertex distribution for $\mathrm{K_S}$ and weighted $\mathrm{K_L}$



⟹ Acceptance correction cancels
Price $\Rightarrow$ increase in statistical error
($\approx$ 35 %)

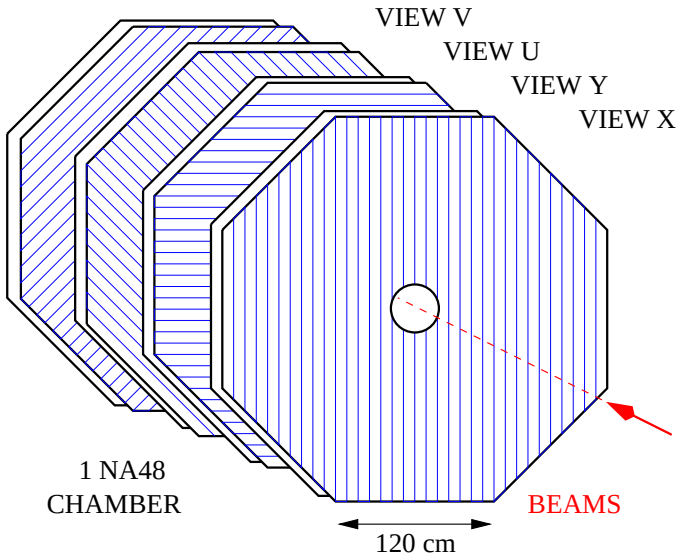
The NA48 Detector



- Magnetic spectrometer to detect $\pi^+\pi^-$ events
- Quasi homogeneous Liquid Krypton calorimeter to detect $\pi^0\pi^0$ events

The magnetic spectrometer

2×2 drift chambers + magnet $\Rightarrow$ 265 MeV/c p_t kick.



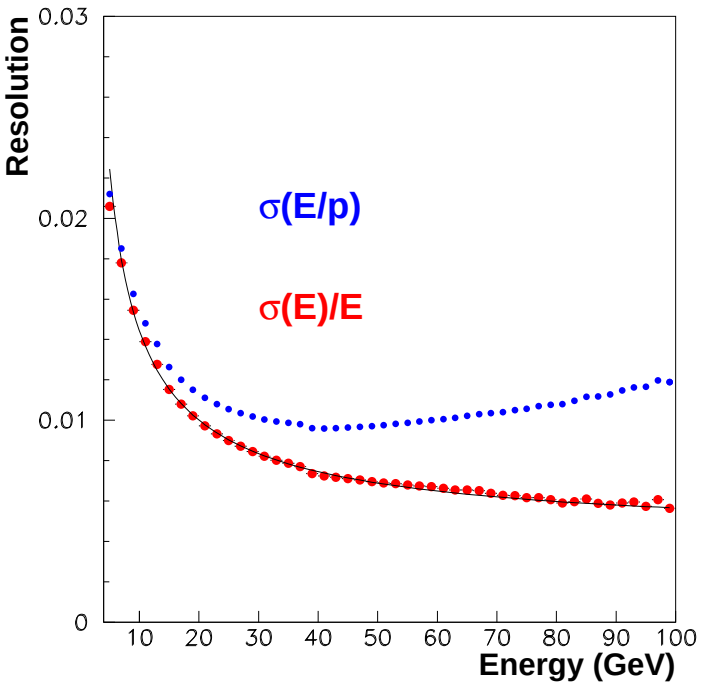
- Each chamber has
  4×2 planes $\times$ 256 wires
  $\Rightarrow$ Good redundancy
- Drift time $<$ 100 ns
- Space point resolution $\approx$ 100 μm

$$\sigma(p)/p \simeq 0.5\,\% \oplus 0.009\,p[\text{GeV}/c]\,\%$$

($\sim$ 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)
- 13212 cells
  - Granularity 2×2 cm^2
  - Depth 1.25 m ($\sim 27\ X_0$)



$$\sigma\ (\mathrm{E})/\mathrm{E} \simeq 3.2\%/\sqrt{E} \oplus 0.09/E \oplus 0.42\%$$

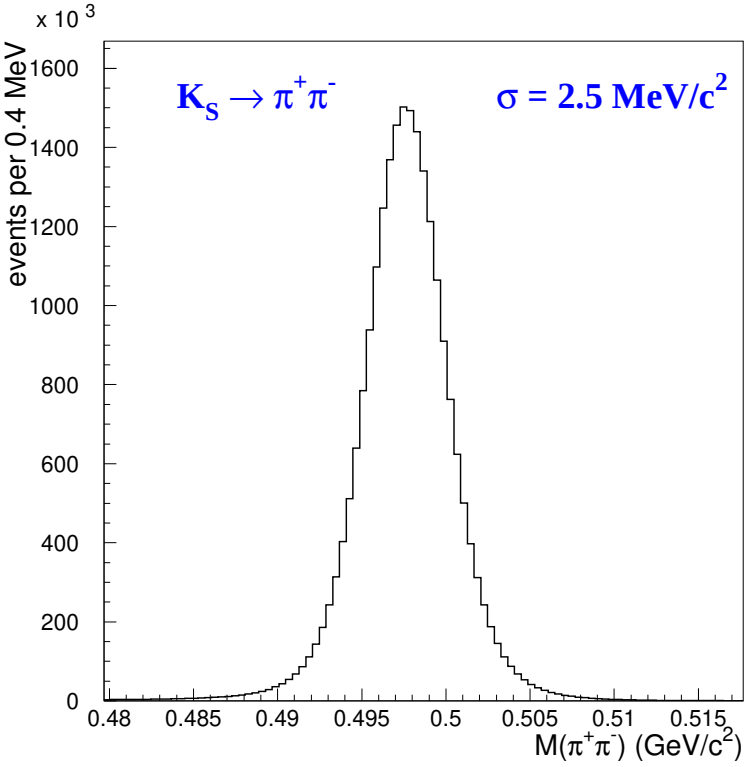
(E in GeV)

(better than 1% for 25 GeV photons)

2π reconstruction

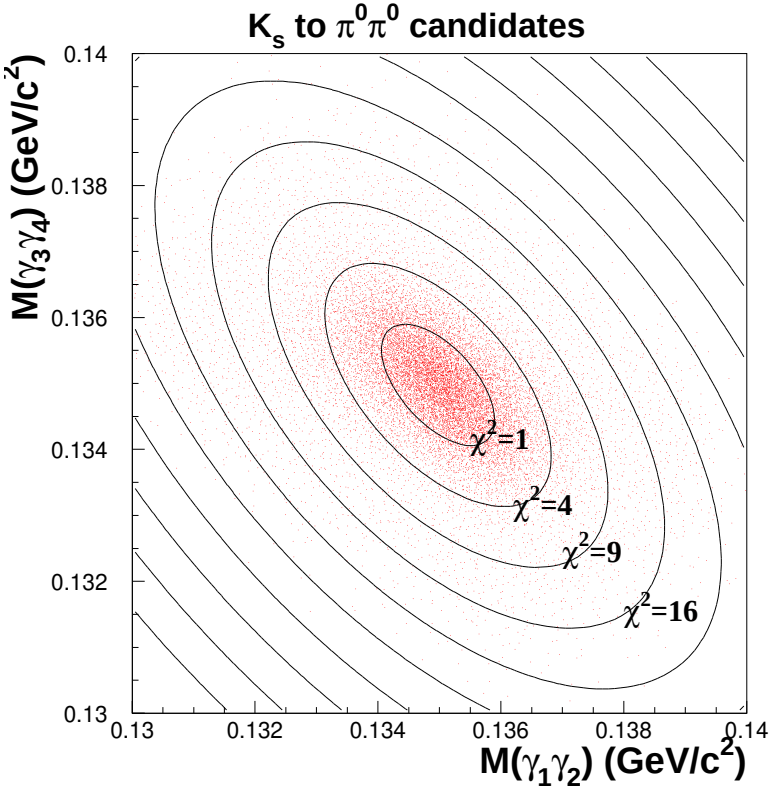
$K_S, K_L \to \pi^+\pi^-$

- decay vertex and $M(\pi^+\pi^-)$ reconstucted by the spectrometer
- decay time from hodoscope ($\sigma \approx 140ps$)

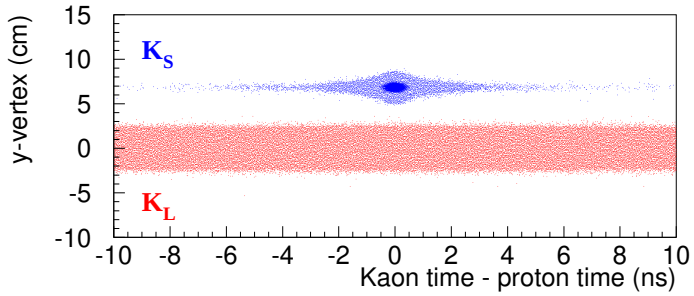


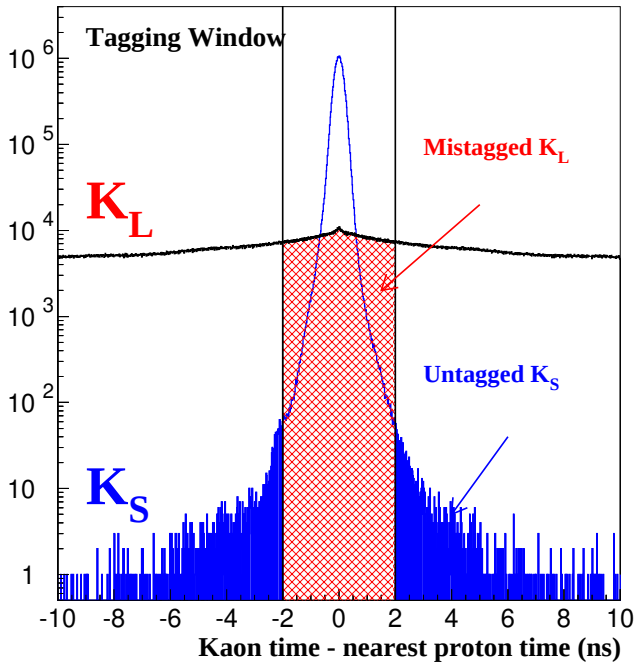
$K_S, K_L \to \pi^0\pi^0$

- E_i, x_i and y_i of the four γ in the LKr $\Rightarrow$ two $M(\gamma\gamma)$ and decay vertex
- decay time from LKr calorimeter ($\sigma \approx 200ps$)



$K_S - K_L$ identification





⟹ in both decay modes
K_S tagged by comparing the
event time to proton times
as they pass through tagging station

Δt(Kaon-Proton) $\leq 2ns \Rightarrow K_S$
$> 2ns \Rightarrow K_L$

⟹ in $\pi^+\pi^-$ kaons are also identified through y-vertex

⟹ two possible misidentifications:

- K_S identified as K_L
  tagging inefficiency ⟹ α_{SL}
  tails in time measurement
- K_L identified as K_S
  accidental coincidence of a K_L with a proton in the tagger ⟹ α_{LS}
  proton rate in the tagging station

Source of systematics

- Charged background
- Neutral background
- Beam scattering background
- Tagging (neutral-charged difference)
- Triggers inefficiencies
- AKS veto inefficiency
- Energy scale uncertainty
- Acceptance
- Accidental activity induced losses

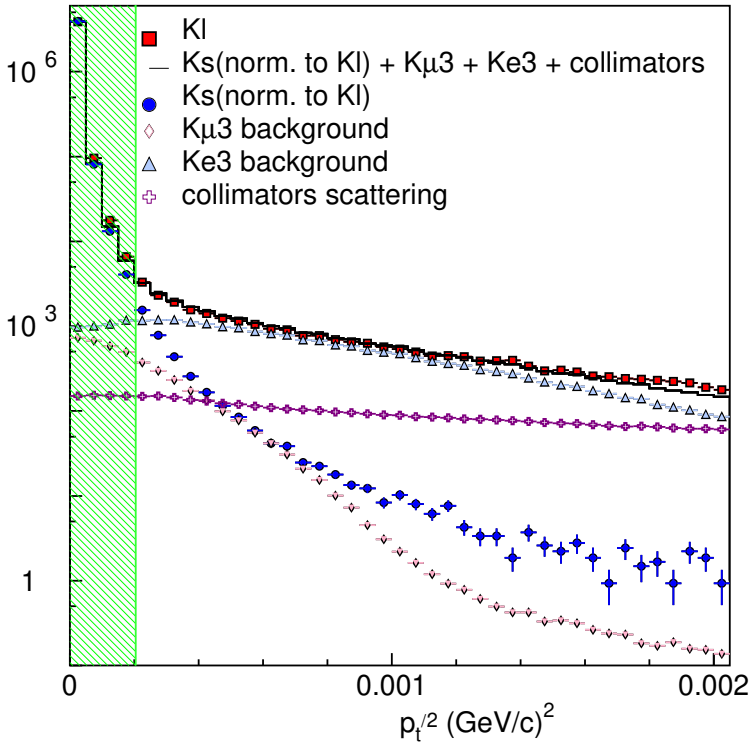
Background in $\pi^+\pi^-$

→ $\mathrm{K_S}$ - no background

→ $\mathrm{K_L}$ - background source:

$$\mathrm{K_L} \to \pi e \nu, \pi \mu \nu$$

- rejected by
  - requiring $E/p < 0.8$ and no associated hit in muon veto
  - cutting in invariant mass $(m_{\pi\pi})$ and transverse momentum $({p_T}'^2)$
- rest subtracted
  The residual background under $\mathrm{K_L}$ signal is estimated
  - using control region in the $m_{\pi\pi}$–${p_T}'^2$ distribution of $\mathrm{K_L} \to \pi^+\pi^-$
  - using samples of identified $Ke3$ and $K\mu3$ decays in two control regions



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

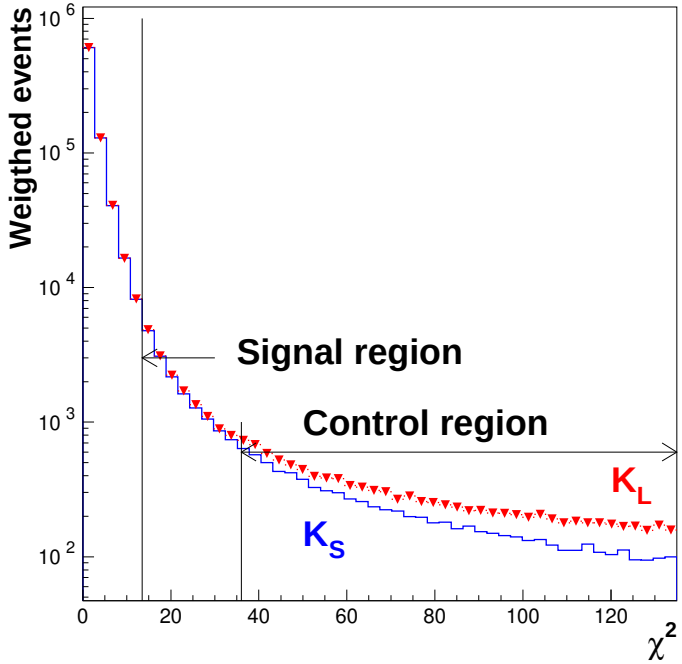
Background in $\pi^0\pi^0$

$\mathrm{K_S}$ - no background

$\mathrm{K_L}$ - background source:

$$\mathrm{K_L} \to 3\pi^0$$

- rejected by
  - requiring no extra showers in-time (1.5 ns)
  - χ^2 from the two π^0 masses < 13.5
- rest subtracted
  The residual background under $\mathrm{K_L}$ signal is estimated
  - extrapolating from χ^2 control region
  - using $\mathrm{K_S}$ events to evaluate resolution tails



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

$K_S - K_L$ misidentification

Double ratio method $\Rightarrow$ difference between the neutral and charged mode

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

$$\alpha_{SL}^{+-} = (1.63 \pm 0.03) \times 10^{-4}$$

- measured from $K_S \to \pi^+\pi^-$ decays identified by vertex
- dominated by tagging detector inefficiency

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

$\Longrightarrow$ $\Delta\alpha_{SL}$ is measured from $2\pi^0$ and $3\pi^0$ events with conversion:
compare charged time (from e^+e^-) with neutral time (from $\gamma's$)

$\Longrightarrow$ other methods confirm the result

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

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

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

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

- measured from $K_L \to \pi^+\pi^-$ decays identified by vertex
- dominated by accidental coincidences

$\Longrightarrow$ $\Delta\alpha_{LS}$ measured with $K_L \to \pi^+\pi^-$ and $K_L \to \pi^0\pi^0$ for tagged K_L events in lateral windows

$\Longrightarrow$ extrapolating under the coincidence window

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

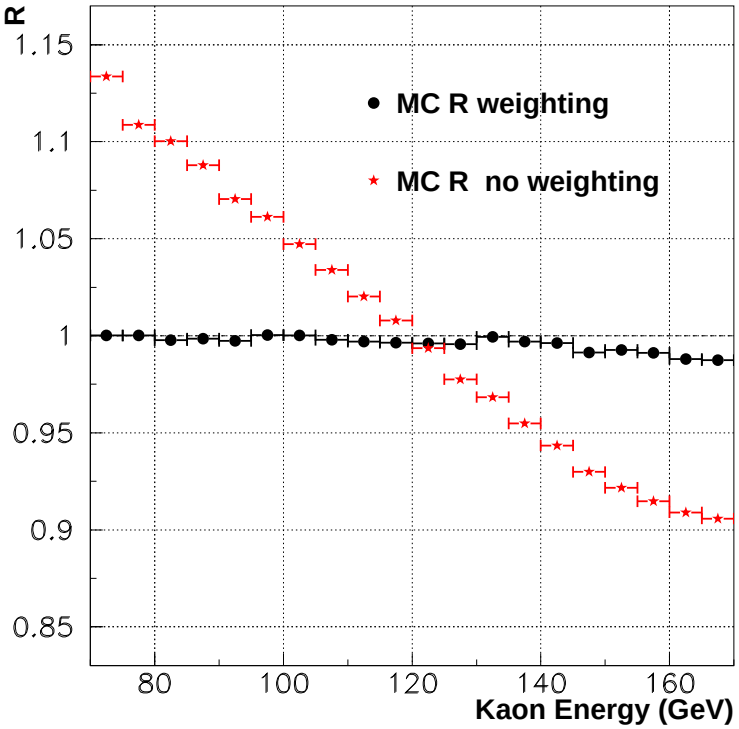
$$\Delta R = (8.3 \pm 3.4) \times 10^{-4}$$

Acceptance correction

⟹ small due to symmetric illumination
→ consequence of proper time weighting

⟹ small residual effect from $0.6mrad$ angle between $\mathrm{K_S}$ and $\mathrm{K_L}$ beams

⟹ correction estimated using Monte Carlo



$$\Delta R = (26.9 \pm 5.7) \times 10^{-4}$$

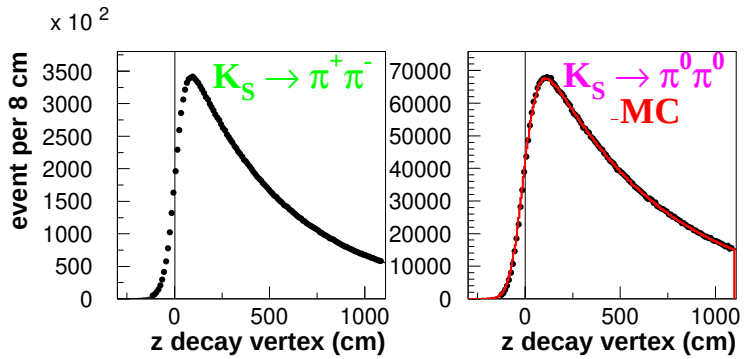
Reconstruction uncertainty

$\pi^+\pi^-$

→ depends on geometry of drift chambers before the magnet (straight track extrapolation 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

→ all uncertainties contributing to the energy definition (energy scale, non-linearities, non-uniformities, non-Gaussian tails etc.) lead to

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

→ checks from special samples: electrons, η's, π^0, $3\pi^0$, MC

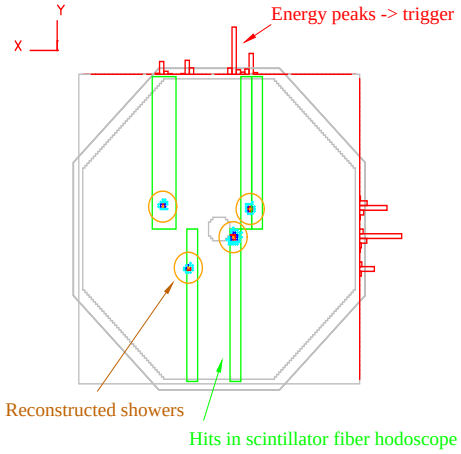
Trigger efficiency

$\pi^0\pi^0$

- Fully pipelined system using LKr cell information to compute energy, centre of gravity, proper lifetime and number of showers
- Output rate ~ 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 ~ 2 kHz
  - Dead Time: 1.1% monitored and applied to $\pi^0\pi^0$

→ Efficiency: $(98.353 \pm 0.022)\%$

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

Systematic uncertainties

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 statistics of control samples or MC

Final result

→ From 98 and 99 data:

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

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

extracted from the analysis on the data samples:

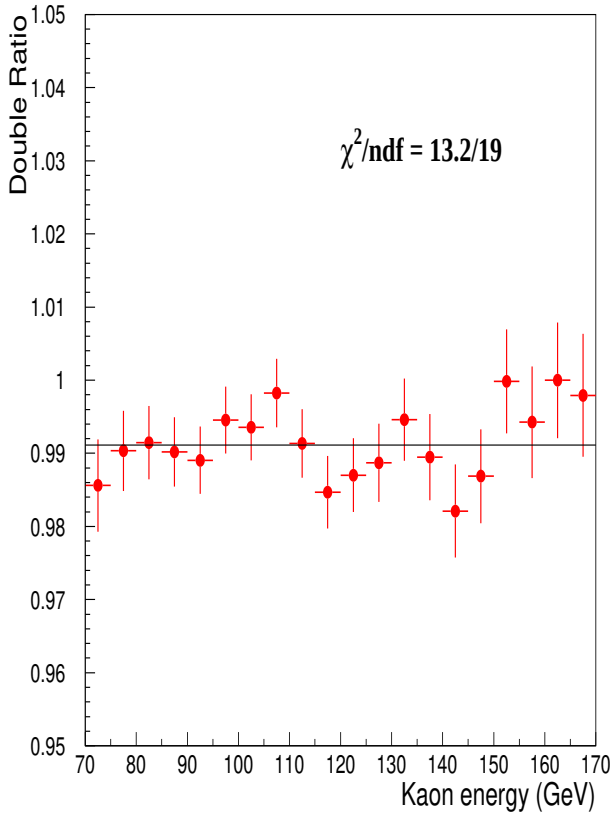
$K_L \to \pi^0\pi^0$	3.29×10^6	$K_S \to \pi^0\pi^0$	5.21×10^6
$K_L \to \pi^+\pi^-$	14.45×10^6	$K_S \to \pi^+\pi^-$	22.22×10^6

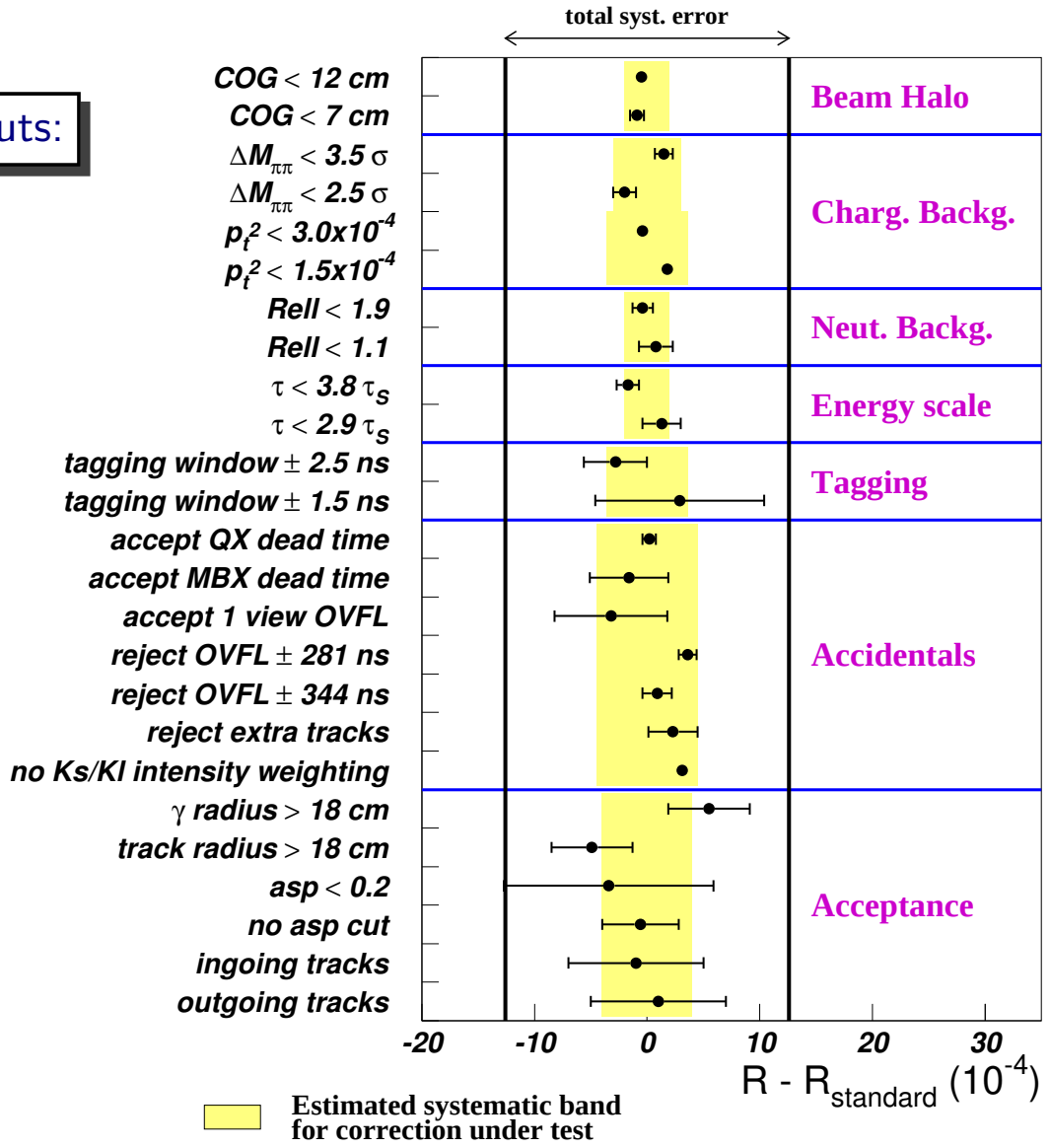
→ Combined with $\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 7.3) \times 10^{-4}$ from 97 data:

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

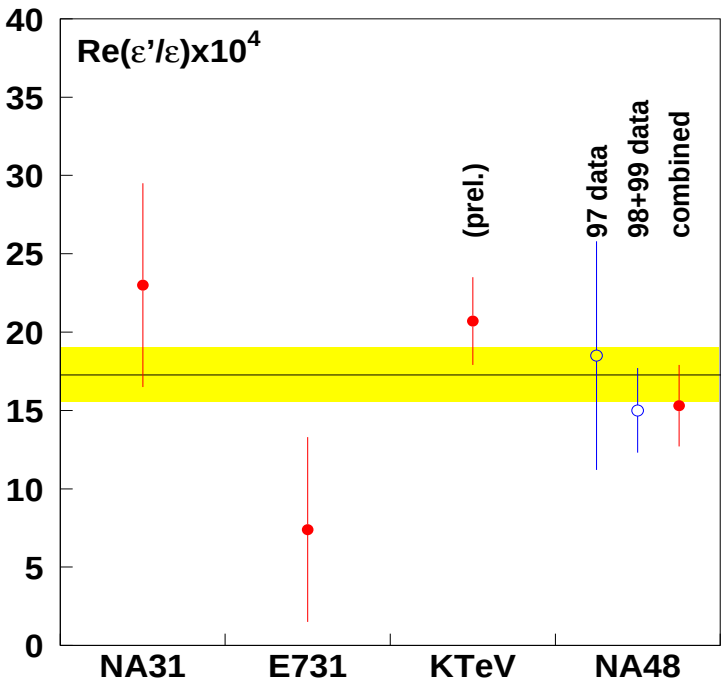
Checks

Stability with kaon energy and cuts:





Experimental results comparison



- May 2001 Na48 final result on 98+99 statistics

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

- June 2001 KTeV has anounced a new result: reanalysis of the published result (based on 96 statistics) + 97 data

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (20.7 \pm 2.8) \times 10^{-4}$$

→ New world average

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (17.2 \pm 1.8) \times 10^{-4}$$

with $\chi^2/\mathrm{ndf} = 5.5/3$ (14 % probability)

Direct CP violation definitely established

Conclusions and perspectives

⟹ July-October 2001 $\Rightarrow$ new ε'/ε run

- new spectrometer
- different beam conditions(spill):

  97-99 2.4 s every 14.4 s (E_p energy = 450 GeV)

  2001 5.2 s every 16.8 s (E_p energy = 400 GeV)

  $\Rightarrow$ better duty cycle
- Expected $> 1.5\times10^6$ $K_L \rightarrow \pi^0\pi^0$

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

⟹

After 3 years of data taking NA48 measures
direct CP violation 5.9 σ from zero

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