New measurement of Direct CP violation by NA48 at CERN

Flavio Marchetto
INFN - Torino - Italy

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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

1. The NA48 method
2. The detector
3. 98+99 Data taking : analysis, event selection, corrections to R
4. Results and conclusions

Direct CP violation

Introductory remarks

- Direct CP violation $\mathrm{Re}(\varepsilon'/\varepsilon) \cong (1-\mathcal{R})/6$ where $\mathcal{R}$, the **Double Ratio**, is given by:

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

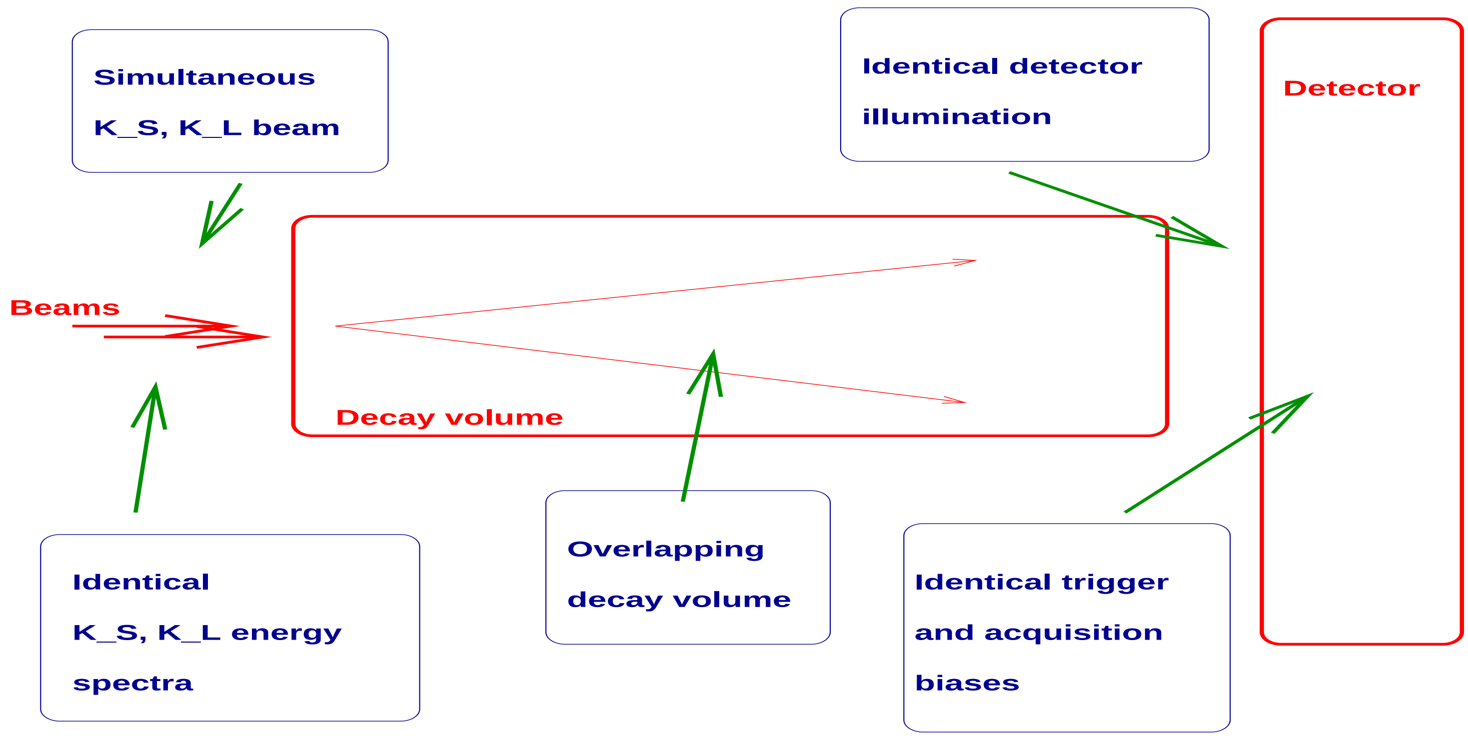
- Basically it is a counting experiment: statistical error dominated by the number of $\mathrm{K_L}\to\pi^0\pi^0$

  $[BR(\mathrm{K_L}\to\pi^0\pi^0)\cong 0.93\times10^{-3}$, $BR(\mathrm{K_L}\to\pi^+\pi^-)\cong 2.1\times10^{-3}]$

  With 3×10^6 $\mathrm{K_L}\to\pi^0\pi^0$, $\Delta\mathcal{R} \cong 7.8\times10^{-4}$

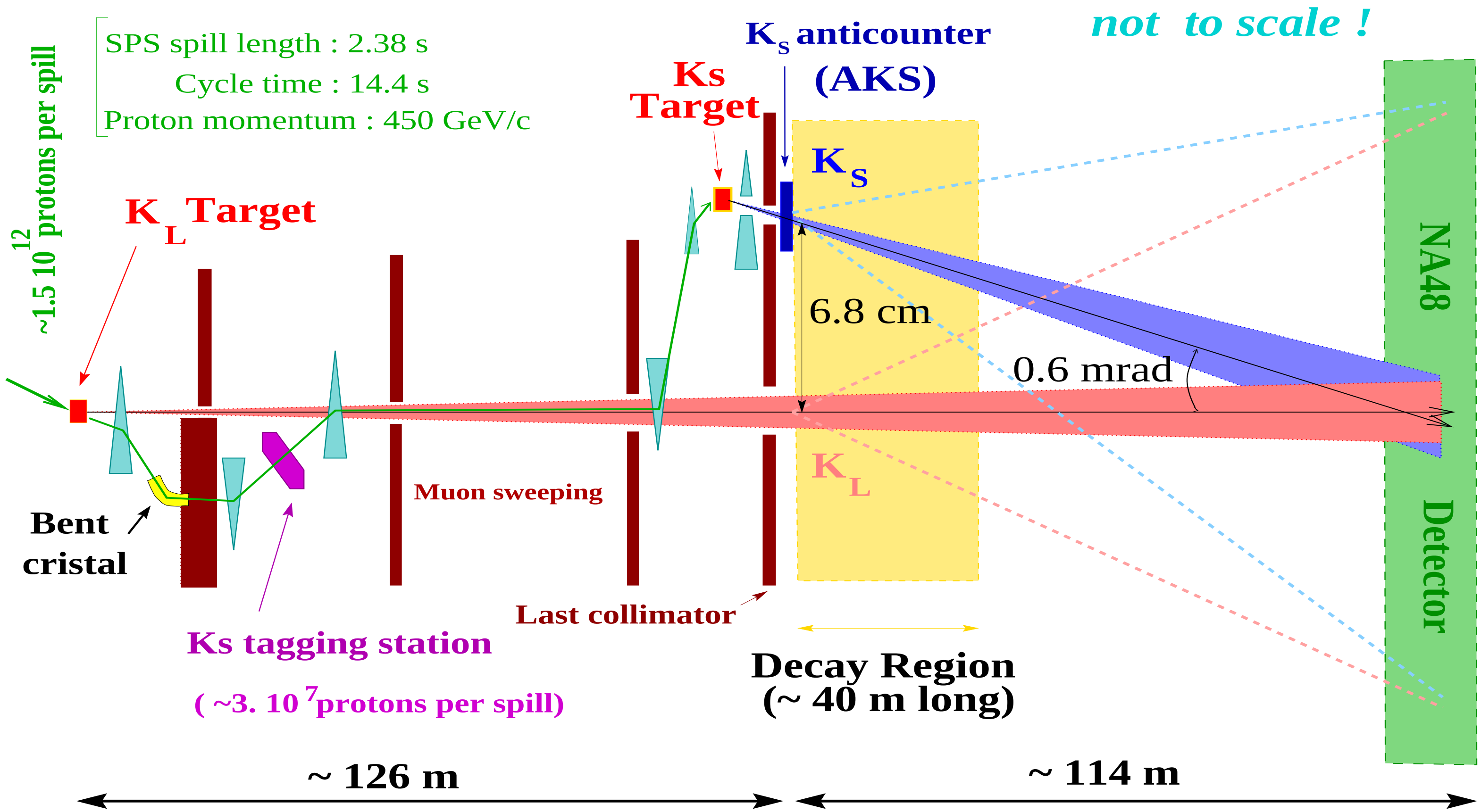
The NA48 method

The ideal detector requires:



A good experiment design tries to minimize corrections to $\mathcal{R}$ exploiting effect cancellation for at least a pair (numerator/denominator) of the four different decay modes: $\mathrm{K_L}/\mathrm{K_S}$ to $\pi^+\pi^-/\pi^0\pi^0$

The NA48 method (continue)



Protons on K_S target are derived from protons not interacting on K_L target

$\Rightarrow$ relative K_S to K_L intensity almost constant

$\Rightarrow$ almost collinear beams (0.6 mrad divergence)

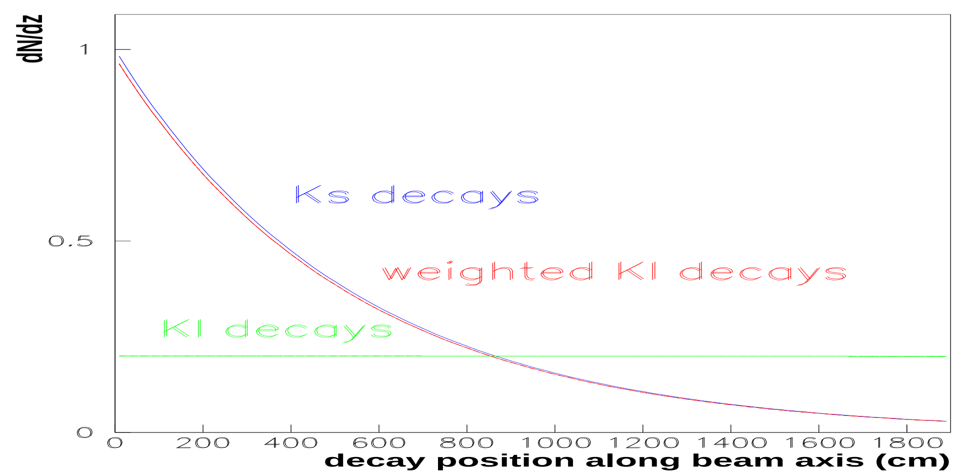
The NA48 method (continue)

K_L weighting to minimize K_L to K_S differences due to different lifetimes

- The longitudinal (z) distributions of K_S and K_L decays are much different → acceptance changes as a function of z → large correction on $\mathcal{R}$
- To minimize the acceptance correction: weight K_L as a function of z to make the K_L distribution equal to the K_S one.

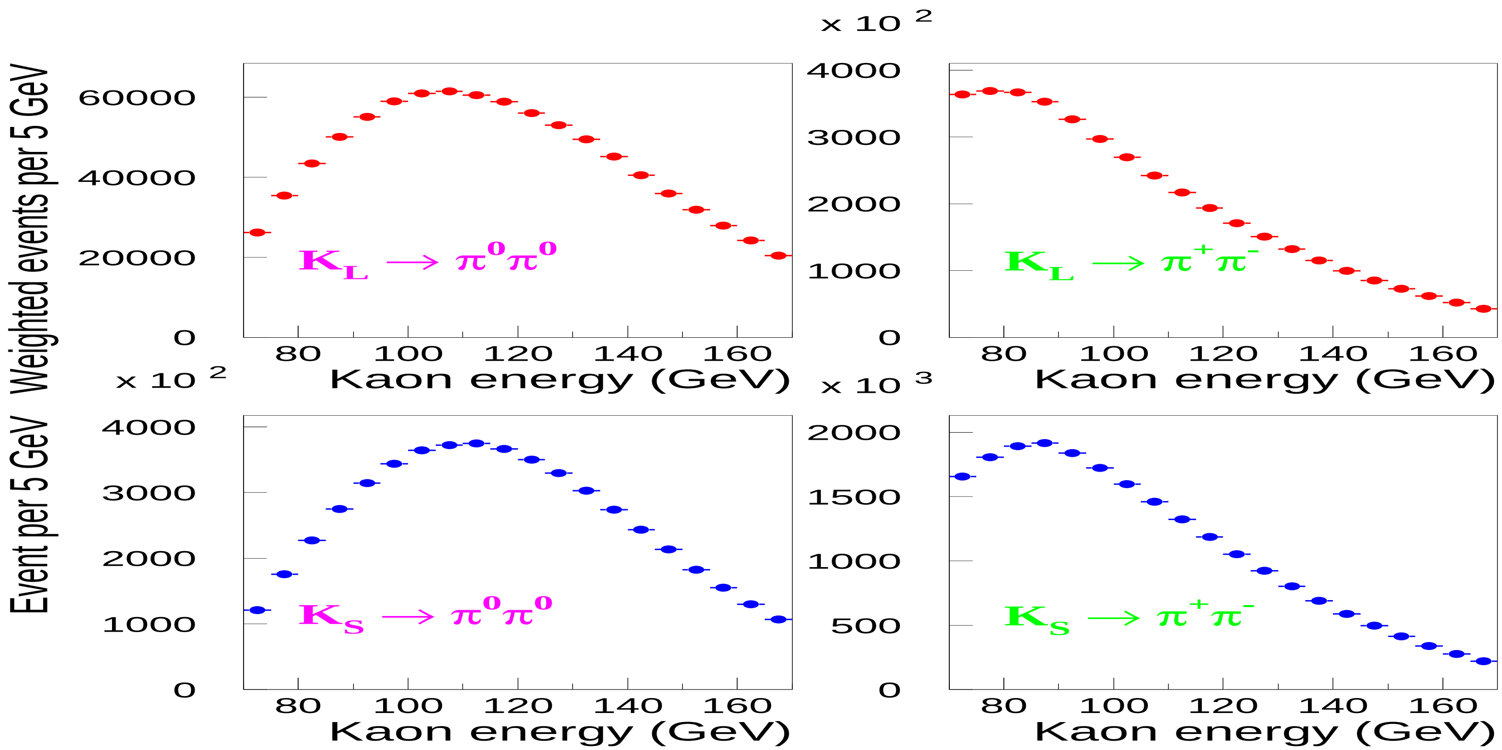
$$\text{weight} \cong \exp(-z/(\beta\gamma c)(1/\tau_{K_S} - 1/\tau_{K_L})$$

- The statistical error increases by $\simeq 35\%$



The NA48 method (continue)

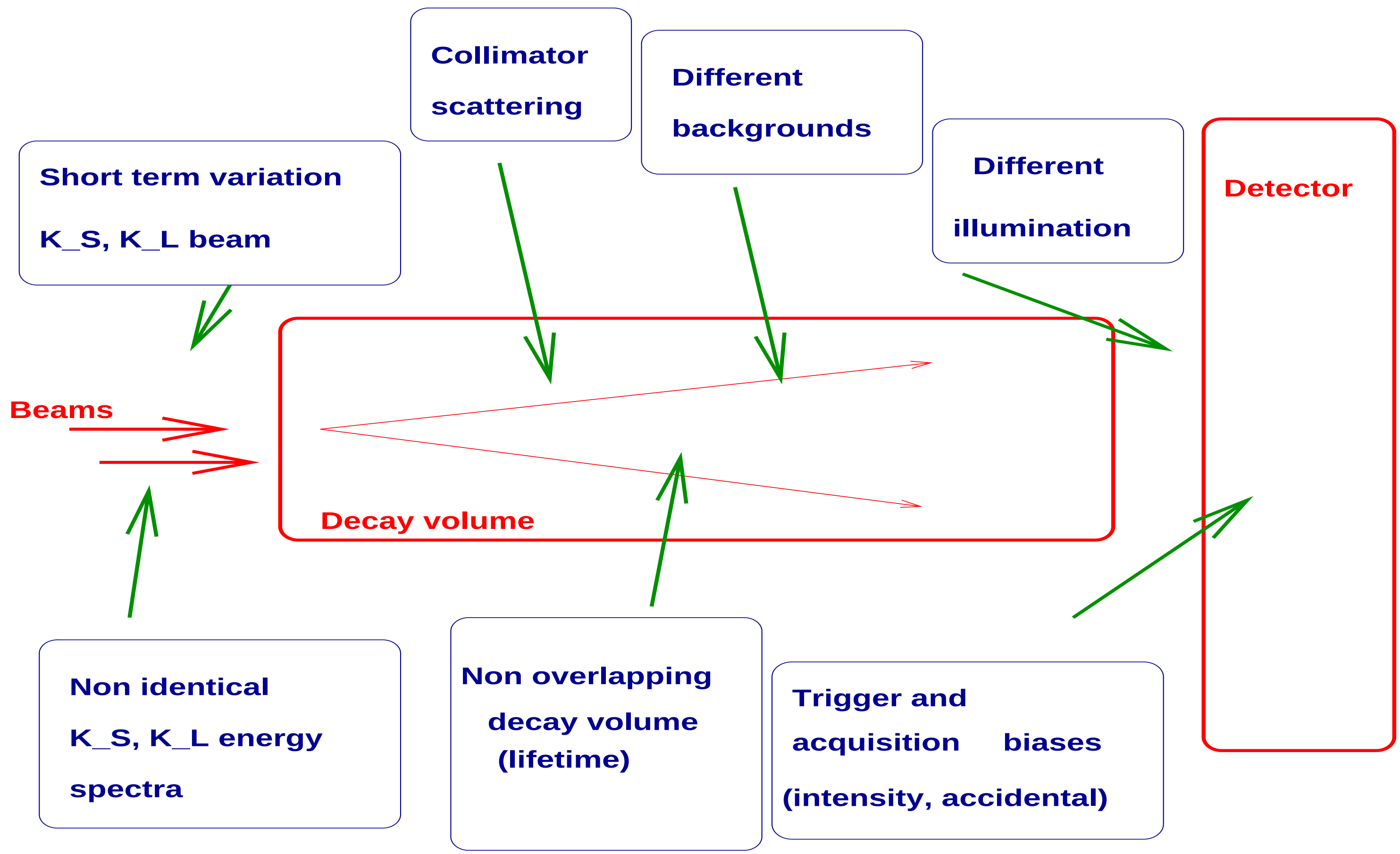
$K_S - K_L$ Energy spectra are slightly different



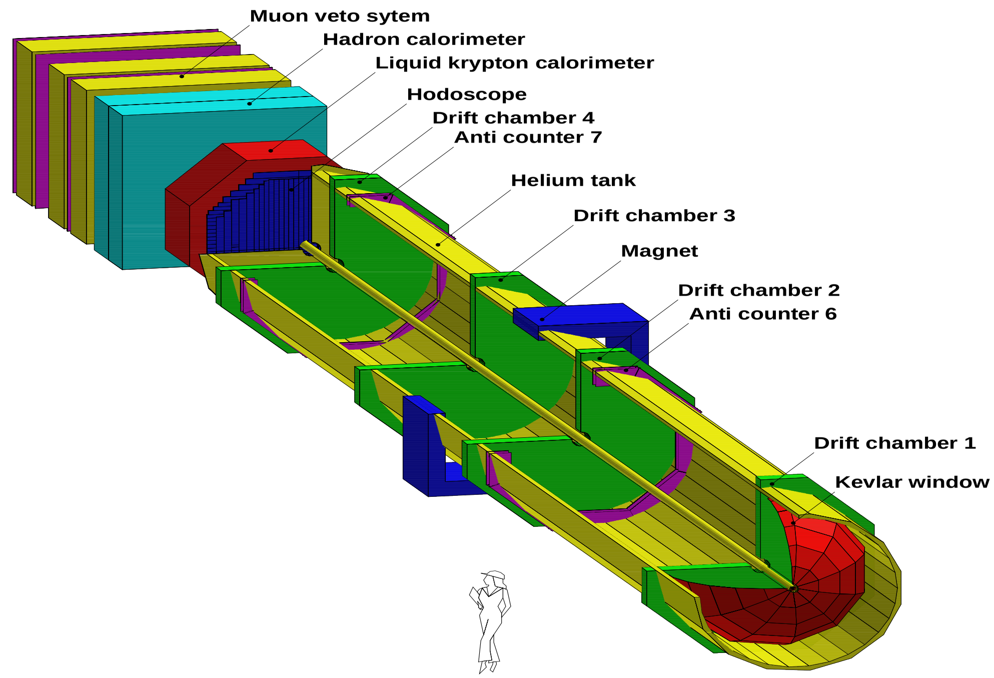
$\mathcal{R}$ is computed in energy bin 5 GeV wide

Corrections to $\mathcal{R}$

Deviations from the ideal detector $\Rightarrow$ corrections to $\mathcal{R}$

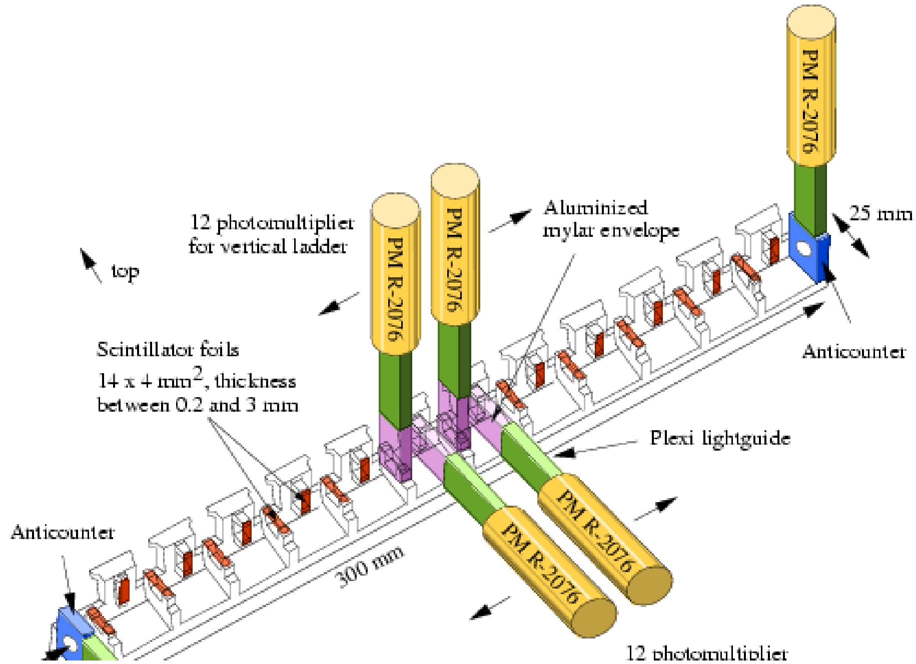


The NA48 detector



- K_S, K_L separation : K_S beam proton tagger (not shown in figure)
- $K_{L,S} \to \pi^+\pi^-$: magnetic spectrometer
- $K_{L,S} \to \pi^0\pi^0$: quasi-homogeneous Liquid Krypton electro-magnetic calorimeter
- trigger and DAQ

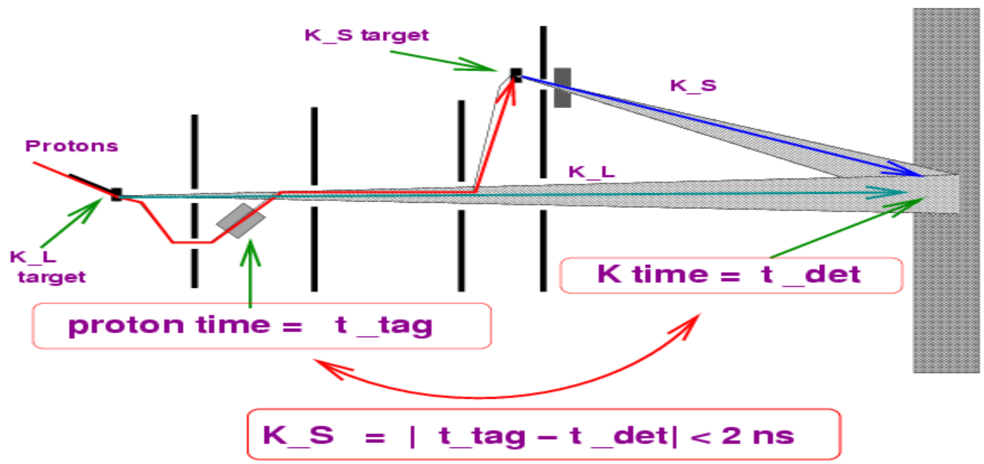
The K_S beam proton tagger

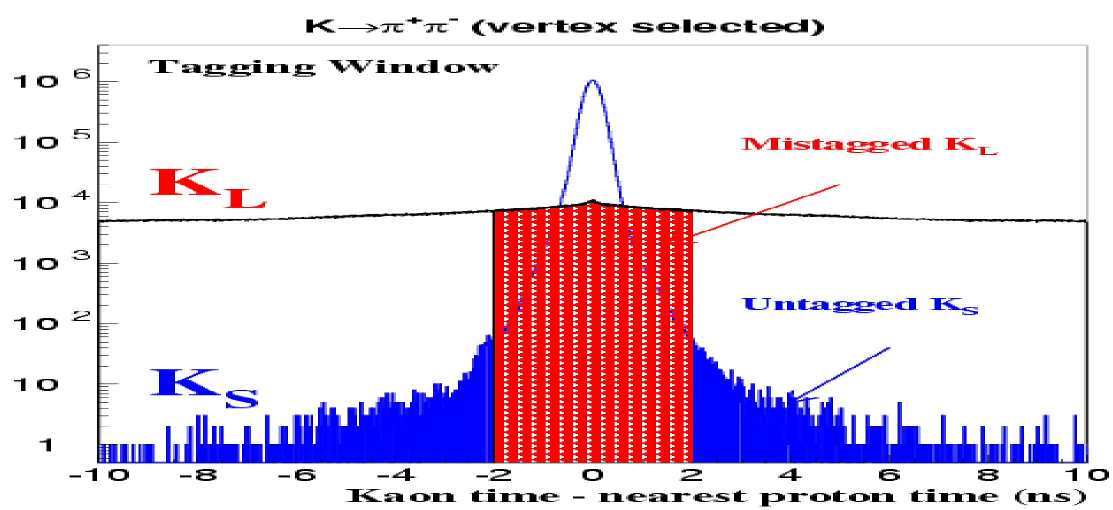


- placed on the beamline of the protons which are steered to the K_S target [rate $\simeq$ 30 MHz]
- 2×12 scintillator counters
- measure each proton time with 140 ps time resolution and 4 ns double pulse resolution [read-out by a 960 MHz 8-bit Flash-ADC]

K_S Tagging

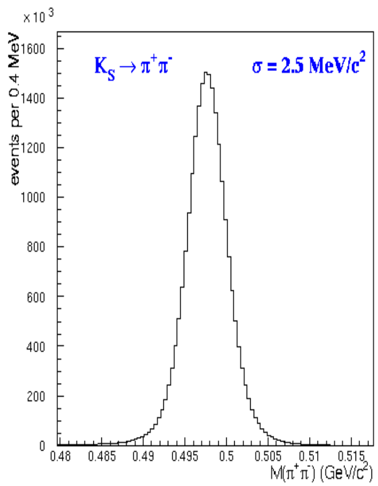
Measure the time difference between the kaon and the proton time

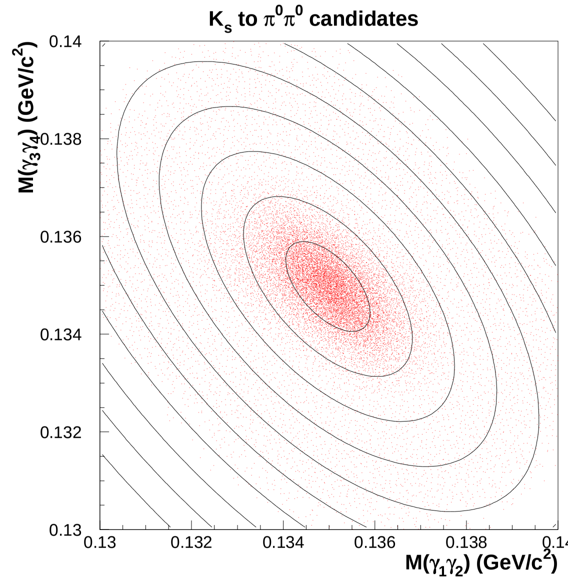




Detector performances

Best possible mass resolution to improve the background rejection





Best possible kaon event time resolution to improve the tagging (K_S to K_L separation)

charged mode: 150 ps

neutral mode: 220 ps

Data samples

NA48 data collection:

- 1997: $\varepsilon'/\varepsilon = 18.5 \pm 4.5 \pm 5.8 \times 10^{-4}$ based on $\cong 0.5$ million of $K_L \to \pi^0\pi^0$ (results have been published: Phys. Lett. B 465 (1999))

- 1998 + 1999: new result based on a collection of $\cong 1 + 2$ million of $K_L \to \pi^0\pi^0$ after several improvements on the trigger system, DAQ, and calorimeter were implemented (paper submitted for publication)

- 2000: collected only neutral decays, drift chambers were being repaired
- 2001: data taking underway at a lower instantaneous beam intensity

Triggers: $\pi^0\pi^0$

$\pi^0\pi^0$ trigger

- Selection based on LKR projections: cut on number of photons, energy and decay vertex
- Output rate at ≈ 2 kHz
- Read-out in pipeline with no dead time
- Trigger efficiency has been measured (with an independent sample) to be $(99.920 \pm 0.009)\%$ leading to a $\Delta\mathcal{R}$ negligible

Triggers: $\pi^+\pi^-$

$\pi^+\pi^-$ trigger

- level 1: (Scintillator Hodoscope with a hit in opposite quadrants) $\times$ (Calorimeters total energy above a threshold set at 35 GeV) $\times$ (≥ 3 of hits in drift chambers)
- Output rate $\approx$ 100 kHz inducing a 0.5 % dead time
- Efficiency: $K_S = (99.535 \pm 0.011)\%$ $K_L = (99.542 \pm 0.018)\%$

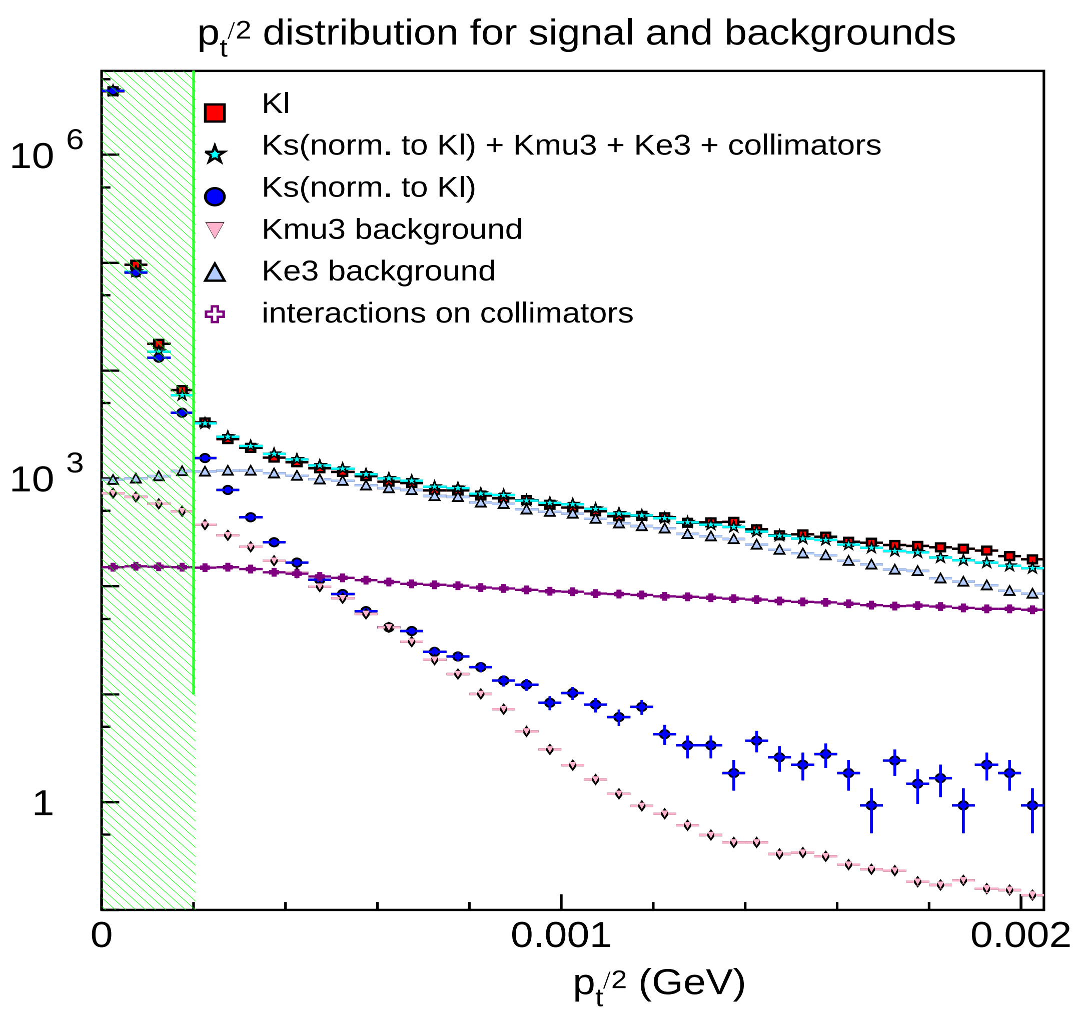
  $\Delta\mathcal{R} = (0.9 \pm 2.2) \times 10^{-4}$
- level 2: perform: track reconstruction, compute the decay vertex position and apply generous cuts. Done with a farm of μPC
- Output rate at $\approx$ 2 kHz
- Dead time $\approx$ 1.1 %
- Efficiency: $K_S = (98.353 \pm 0.022)\%$ $K_L = (98.319 \pm 0.038)\%$

  $\Delta\mathcal{R} = (-4.5 \pm 4.7) \times 10^{-4}$

Some remarks: the dead time conditions on the $\pi^+\pi^-$ trigger and readout ($\approx 20\%$) are equally applied to the $\pi^0\pi^0$ candidates (offline).

Charged background

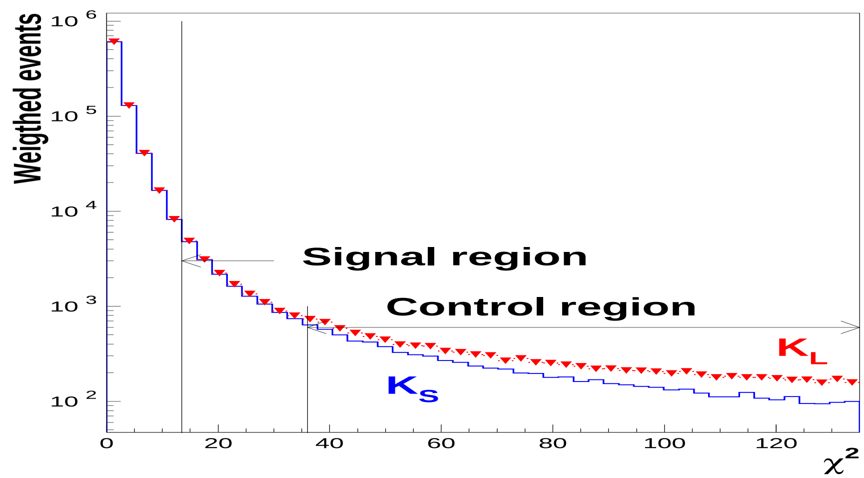
- $K_S \rightarrow \pi^+\pi^-$
  $\Lambda \rightarrow p\pi^-$ completely rejected by an asymmetry cut
- $K_L \rightarrow \pi^+\pi^-$
  - $K_L \rightarrow \pi^+\pi^-\pi^0$ (BR $\cong$ 12.6%) fully rejected by the detector resolution
  - left with $K_{\mu 3}$ (BR $\cong$ 27.2%) and K_{e3} (BR $\cong$ 38.8%) decays which could mimic $K_L \rightarrow \pi^+\pi^-$
  - $K_{\mu 3}$: mainly rejected with the Muon Veto
  - K_{e3} : mainly rejected requiring $E/p < 0.8$
- remaining background (due to inefficiencies) studied in the $M_{\pi\pi} - P_t'^2$ plane
- $K_{\mu 3}$ and K_{e3} modelled in control regions
- projected under the signal region



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

Neutral background

- $K_S \to \pi^0\pi^0$ is background free
- background to $K_L \to \pi^0\pi^0$ is due to $3\pi^0$ decays (BR $\cong 21.1\%$)
- most of the background is reduced by:
  - rejecting events with more than 4 γ's in time (1.5 ns window);
  - selecting events with a χ^2 for the $\pi^0\pi^0$ hypothesys < 13.5 (9 ndf).



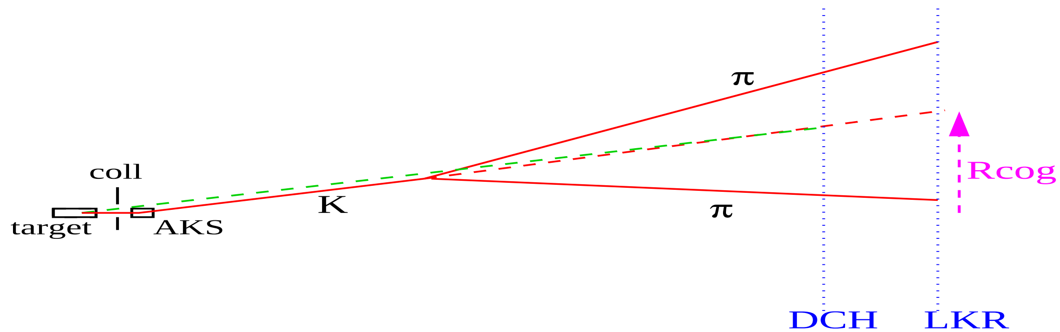
Remaining background computed comparing the χ^2 distribution of $K_L \to \pi^0\pi^0$ and $K_S \to \pi^0\pi^0$. χ^2 distribution of $K_L \to \pi^0\pi^0 - K_S \to \pi^0\pi^0$ extrapolated from the control region (large χ^2) to the signal region ($\chi^2 < 13.5$).

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

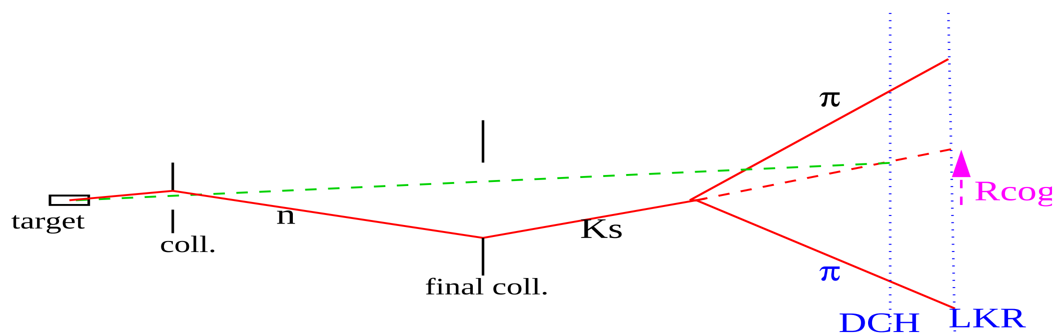
Collimator scattering

K_S and K_L produced by interaction with collimators might have different geometry/kinematic *properties*

K_S : *large* R_{COG} (virtual Kaon impact point on the detector) and *normal* $P_t'^2$



K_L : *normal* R_{COG} and *large* $P_t'^2$



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

Tagging inefficiency

Recall: K_S identified by the time concidence (± 2 ns) between a proton in the tagger and the event time

Two ways of misindentification:

- $K_S \rightarrow K_L$: $\alpha_{SL} \cong 1.63 \pm 0.03 \times 10^{-4}$ due to the tagger or event time mismeasurement

  $$\Delta\mathcal{R} \approx 6 \times \Delta\alpha_{SL}$$

  Effect cancels out between $\pi^+\pi^-$ and $\pi^0\pi^0$ (first order approximation)

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

  $$\Delta\mathcal{R} = (0 \pm 3.0) \times 10^{-4}$$

- $K_L \rightarrow K_S$: $\alpha_{LS} \cong (10.649 \pm 0.008)\%$ due to *accidental* signal in tagger related to beam intensity

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

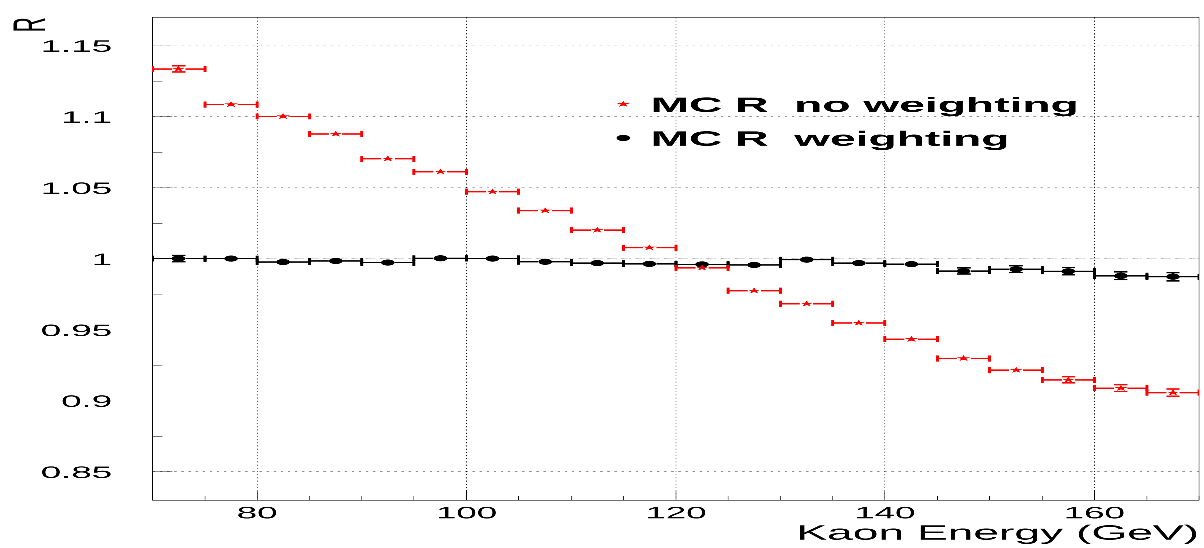
  Effect cancels out between $\pi^+\pi^-$ and $\pi^0\pi^0$ (first order approximation)

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

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

Acceptance correction

- K_S and K_L symmetric: from the weighting method
- left out from the weighting procedure *only* second order corrections:
  - remaining differences due to beams acollinearity ($\cong 0.6$ mrad): mainly $\pi^+\pi^-$'s are off-centered at the magnetic spectrometer



$$\Delta\mathcal{R} = (26.7 \pm 4.1 \pm 4.0) \times 10^{-4}$$

Systematics error comes mainly from *fast MC − GEANT* comparison

Accidental activity

- Event losses and *gains* are due to beam related activity and noise
- First order corrections are cancelled out by the beams relative constancy (recall simultaneous beams), by the comparable detector illumination due to K_S and K_L, and dead time symmetrization
- Remaining corrections on $\mathcal{R}$ are due to $\approx \Delta(K_S - K_L) \times \Delta(\pi^0\pi^0 - \pi^+\pi^-)$ with
  - $\Delta(K_S - K_L)$:
    - within 1% both K_S's and K_L's see the same beam activity: measured on side time band at 100 ns wrt the event time
    - substantially the same detector illumination
  - $\Delta(\pi^0\pi^0 - \pi^+\pi^-)$
    - minimized by the dead time symmetrization
    - measured by overlaying beam monitor triggers

$\Delta\mathcal{R} = (0 \pm 3) \times 10^{-4}$ due to relative intensity variations

$\Delta\mathcal{R} = (0 \pm 3) \times 10^{-4}$ due to illumination differences

Statistics and results

Statistics in millions

	1998	1999	total
$K_L \rightarrow \pi^0\pi^0$	1.047	2.243	3.290
$K_S \rightarrow \pi^0\pi^0$	1.638	3.571	5.209
$K_L \rightarrow \pi^+\pi^-$	4.541	9.912	14.453
$K_S \rightarrow \pi^+\pi^-$	6.910	15.311	22.221
statistical error on $\mathcal{R}$ 10^{-4} units	18.0	12.2	10.1

Corrections to $\mathcal{R}$: summary

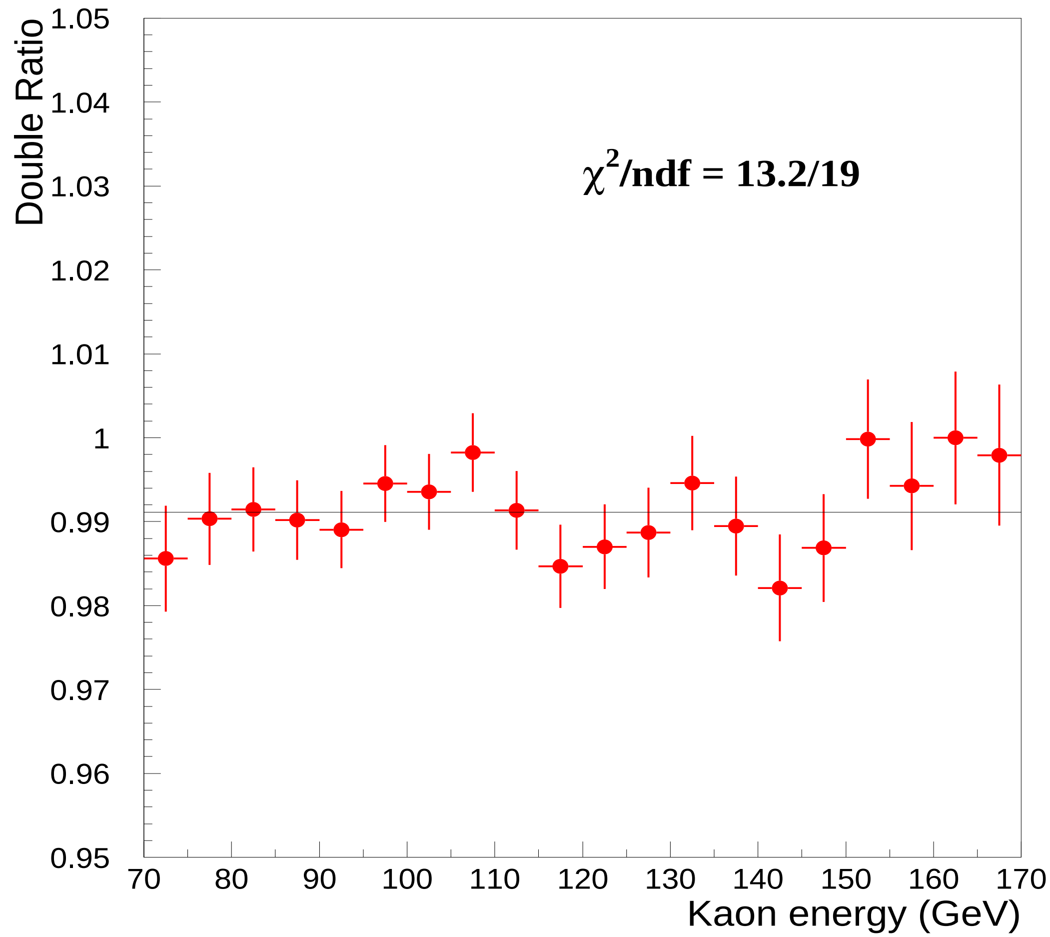
in 10^{-4} units

	correction	uncertainty
$\pi^+\pi^-$ trigger inefficiency	-3.6	$\pm$5.2
AKS inefficiency	+1.1	$\pm$0.4
Reconstruction of $\pi^0\pi^0$	-	$\pm$5.8
Reconstruction of $\pi^+\pi^-$	+2.0	$\pm$2.8
Background to $\pi^0\pi^0$	-5.9	$\pm$2.0
Background to $\pi^+\pi^-$	+16.9	$\pm$3.0
Beam scattering	-9.6	$\pm$2.0
Accidental tagging	+8.3	$\pm$3.4
Tagging inefficiency	-	$\pm$3.0
Acceptance Acceptance systematics	+26.7	$\pm$4.1 $\pm$4.0
Accidental activity	-	$\pm$4.4
Long term variations of K_S/K_L	-	$\pm$0.6
Total	+35.9	$\pm$12.6

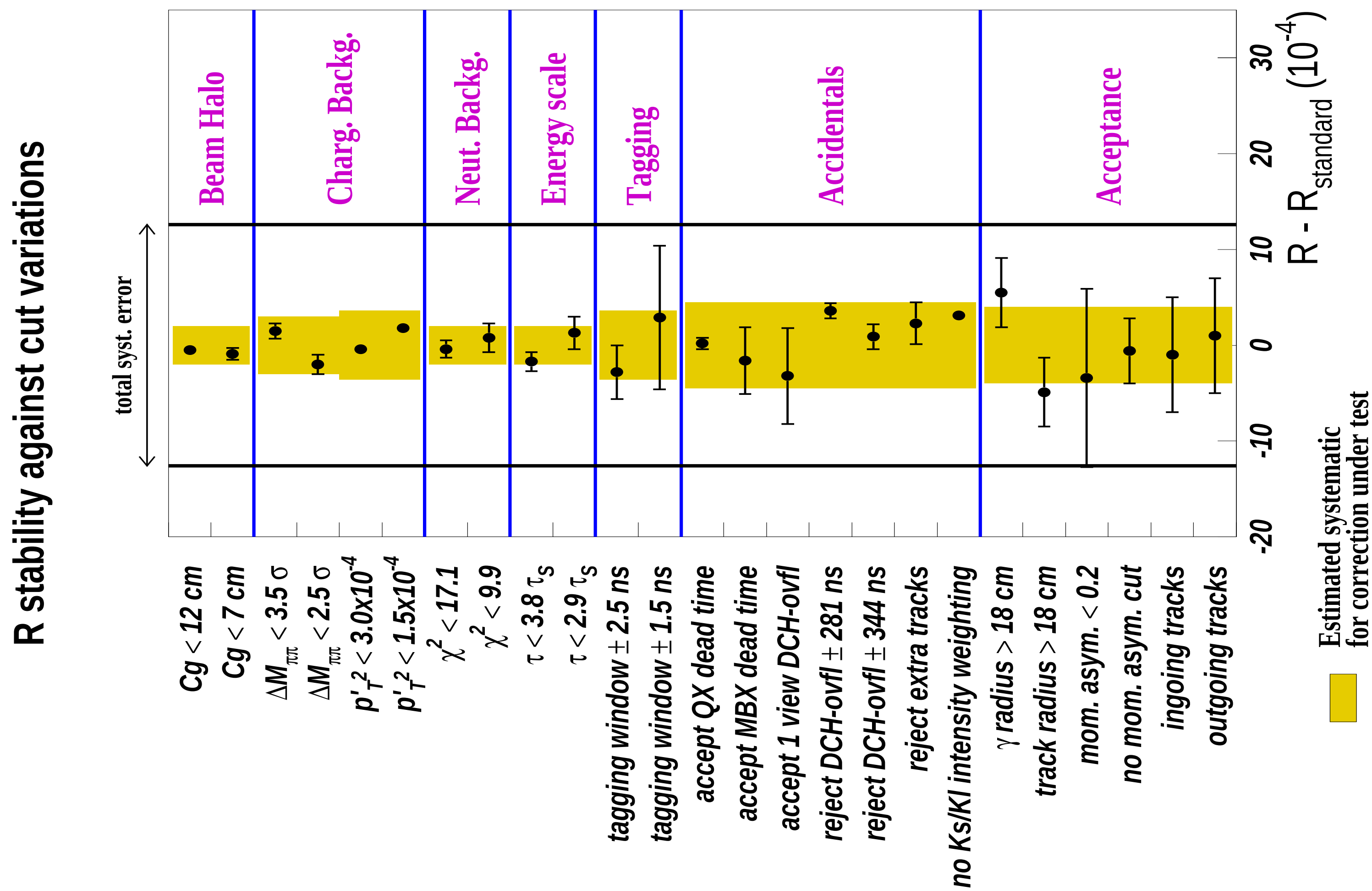
$$\mathcal{R} = (0.99098 \pm 0.00101_{stat} \pm 0.00126_{syst}) \Rightarrow \mathrm{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 2.7) \times 10^{-4}$$

$\mathcal{R}$ checks

Recall: $\mathcal{R}$ has been computed in GeV energy bins



R checks (continue)



Conclusions

- From 98 and 99 data, NA48 obtained:

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

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

- Combining with the 97 results:

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