The Final Measurement of ε'/ε from NA48

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Outline

- The direct CP violation in the Neutral Kaon System
- History of ε'/ε measurements
- The NA48 experiment and its method
- The 2001 data taking and analysis (in short!)
- The FINAL result and conclusions

The direct CP violation in the Neutral Kaon System

Since **1964** we know that the physics eigenstates K_S, $K_L \neq$ CP eigenstates K_1, K_2

$K_L \to \pi^+\pi^-$ observed with B.R. $= 2 \cdot 10^{-3}$

Indirect CP Violation

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

Direct CP Violation

CP violation in the mixing $\Rightarrow |\varepsilon| = (2.28 \pm 0.02) \times 10^{-3}$
Direct CP violation in the decay amplitude manifests itself thru interference of
I=0,2 2π final states $\Rightarrow$ parametrized with ε'

In **1973** Kobayashi and Maskawa present an interpretation of CP violation in the Standard Model postulating a third quark family...

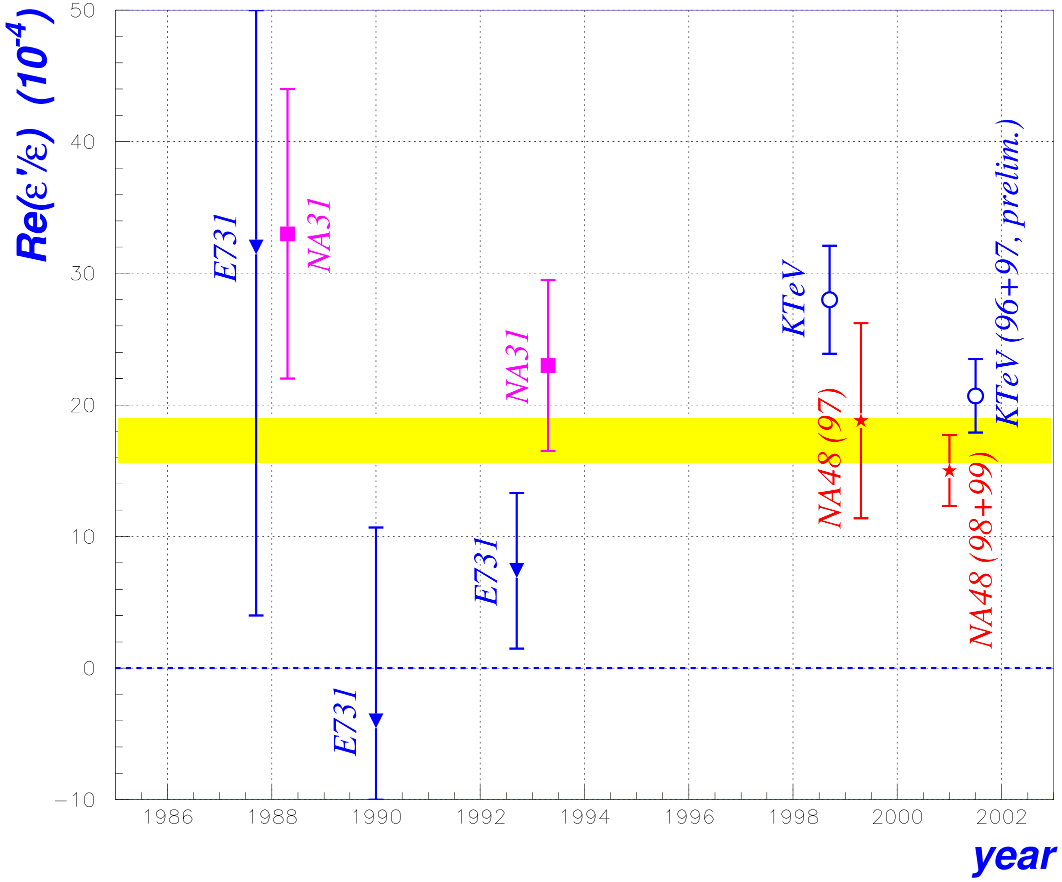
Today many Standard Model computations of both ε and ε'

$$\boxed{\text{theoretical range for } \varepsilon'/\varepsilon \text{ between } -10 \text{ and } 30 \times 10^{-4}}$$

History of ε'/ε measurements

All experiments so far used the Double Ratio method:

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



fixed target experiments:
E731→ KTeV at FNAL
NA31→ NA48 at CERN

Evolution of World Average:

Year	Average (10^{-4})	χ^2/ndf	χ^2 prob.
1993	14.4 ± 4.4	3.2/1	7%
1999	19.2 ± 2.5	10.4/3	2%
2001	17.3 ± 1.7	5.6/3	13%

The NA48 method

Experimental challenge: perform a <u>counting experiment</u> in the most unbiased way.

$$\boxed{\mathrm{R} \;=\; \frac{N(K_L\to\pi^0\pi^0)[0.0009]}{N(K_S\to\pi^0\pi^0)[0.314]}\,\frac{N(K_S\to\pi^+\pi^-)[0.686]}{N(K_L\to\pi^+\pi^-)[0.002]}}$$

Accuracy wanted/needed on $\mathrm{Re}(\varepsilon'/\varepsilon)$: $\boxed{2\cdot 10^{-4}}$ $\Longrightarrow$

◇ high statistics needed (4–$5\times 10^6\ K_L\to\pi^0\pi^0$)

- high intensity beams
- powerful TRIGGER and DAQ Systems

◇ minimization of systematic effects

The NA48 method

NA48 recipe to exploit cancellation of 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

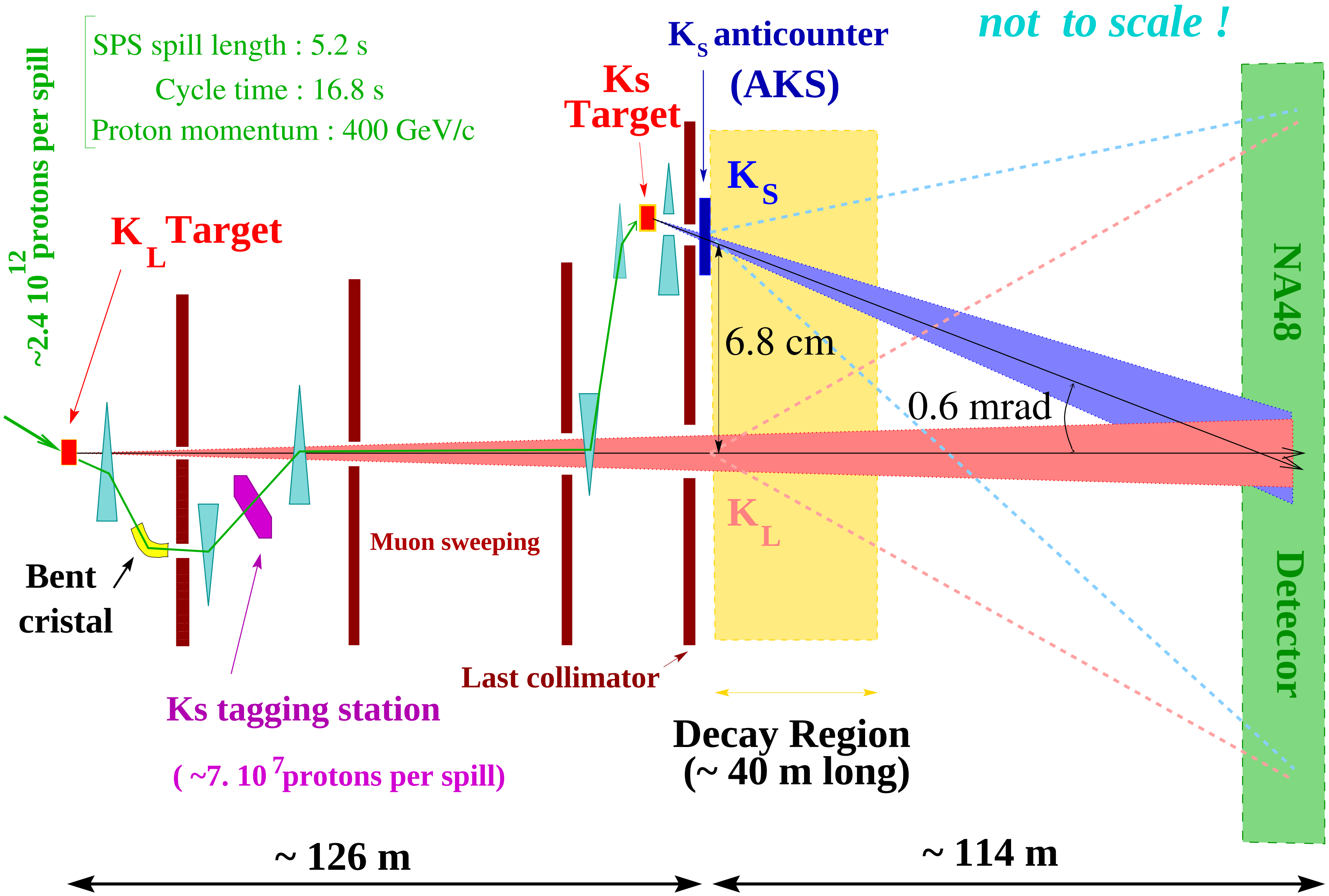
⇒ small acceptance correction

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

⇒ small background levels

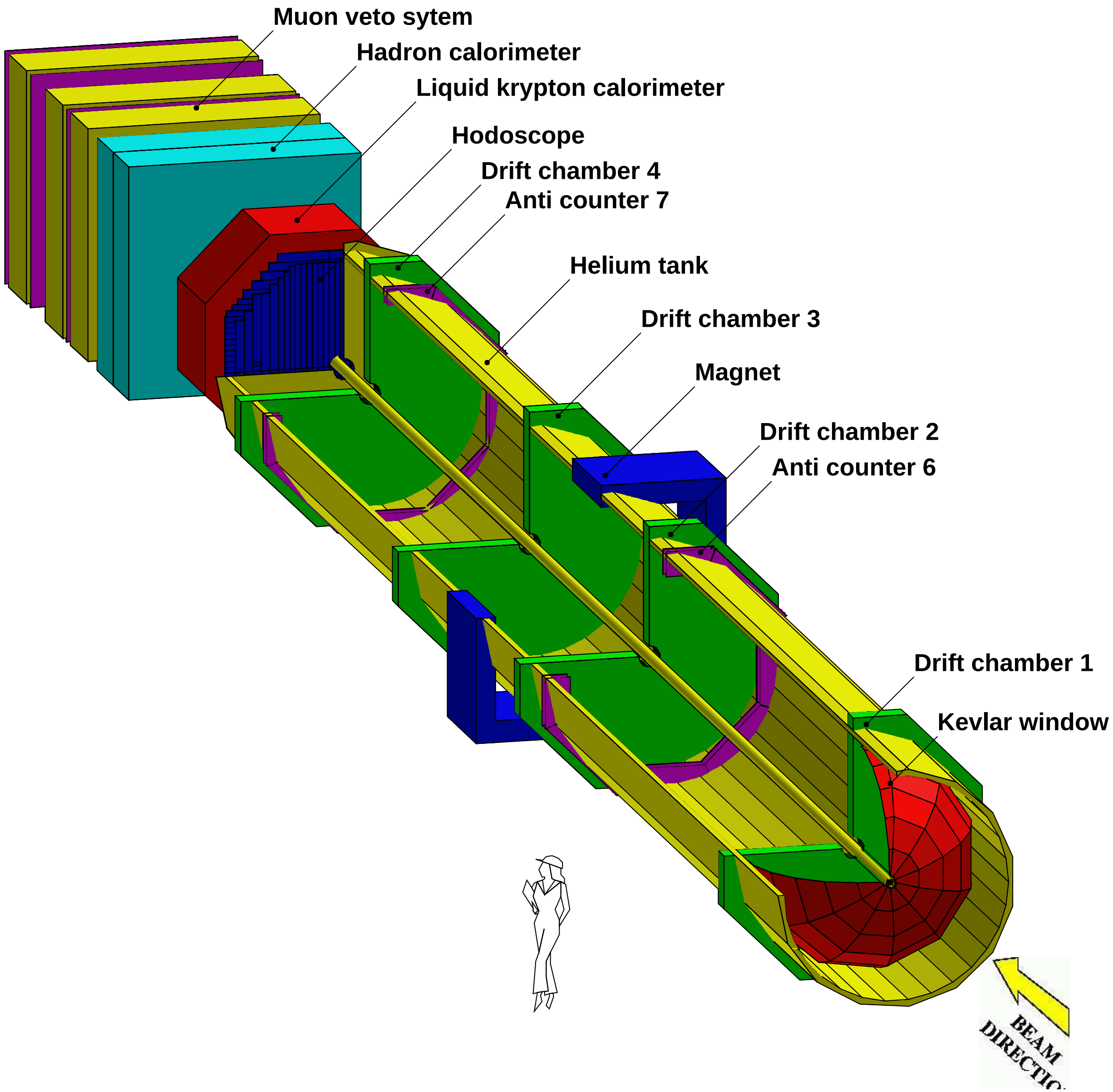
◇ with similar energy spectra
remaining $\mathrm{K_S}$ / $\mathrm{K_L}$ differences are minimized performing the analysis in energy bins (20 between 70 and 170 GeV)

The Simultaneous K_L and K_S Beams



The K_S events are identified by tagging the parent proton (measurement of the proton time in the tagging station)

The NA48 Detector



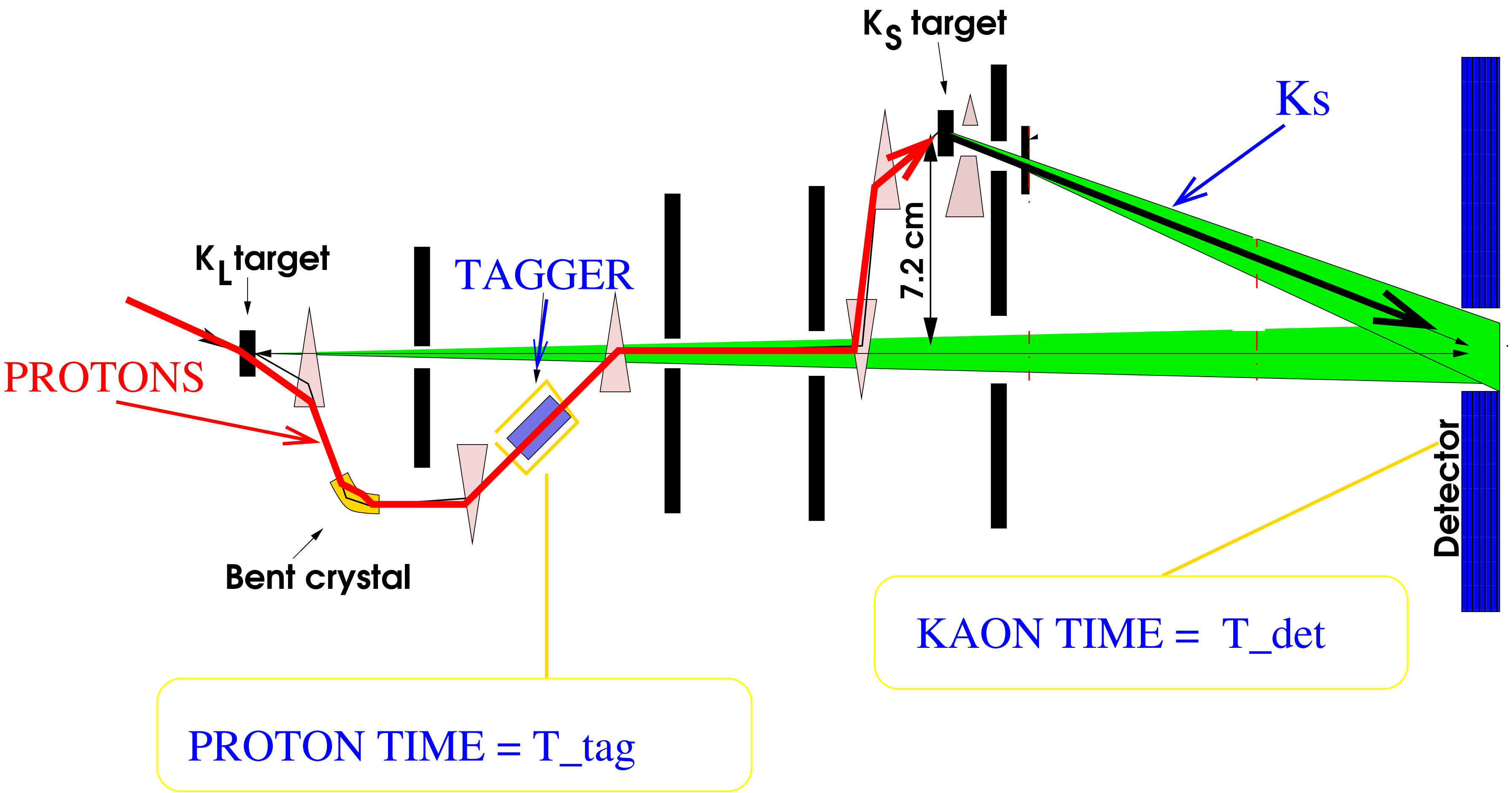
$K_{S,L} \to \pi^+\pi^-$

Magnetic spectrometer
$\sigma_{X,Y} \sim 95\ \mu m$
$\sigma_{K\ mass} \sim 2.5\ MeV/c^2$
resolution on (x, y) vertex $\sim$ 2 mm $\to$ allows for beams 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)
$\sigma_t \sim 220\ ps$
$\frac{\sigma(E)}{E} < 1\ \%$ for $E_\gamma > 25\ GeV$
$\sigma_{\pi^0\ mass} \simeq 1.1\ MeV/c^2$

Tagging K_S events...

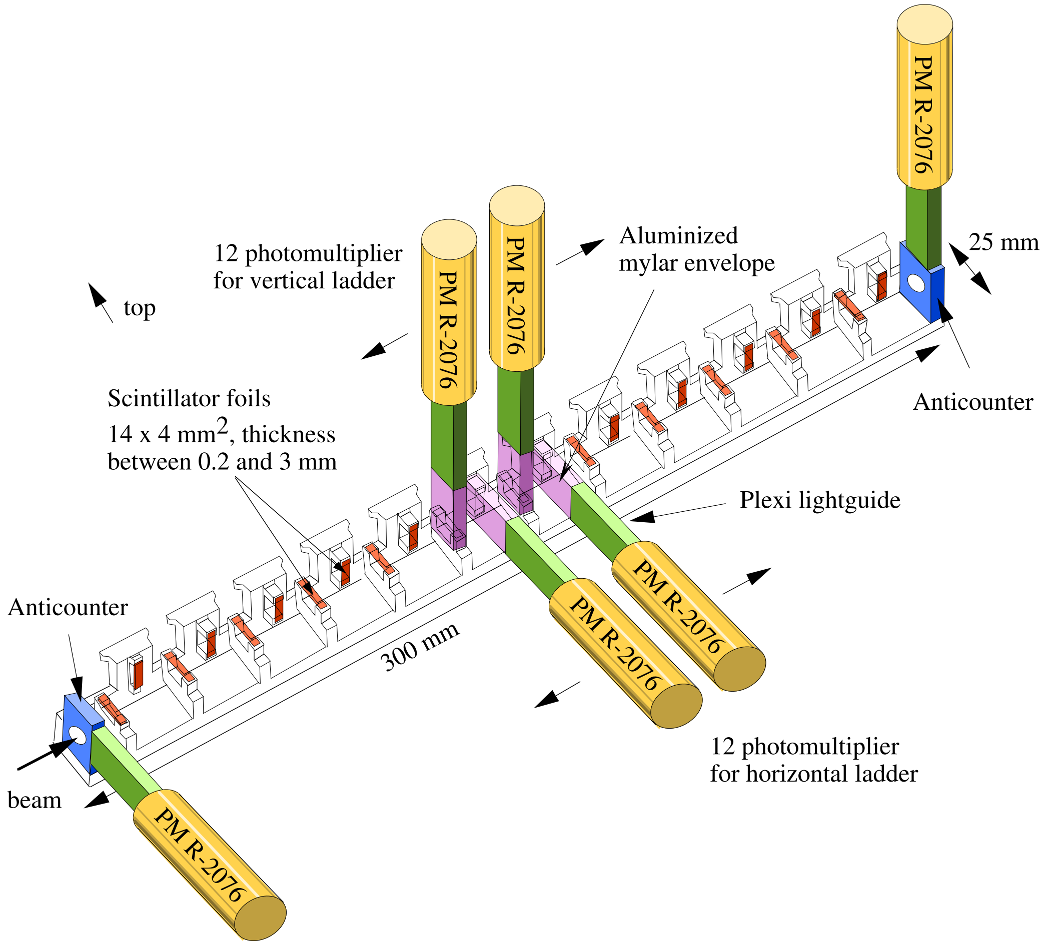


A K_S is defined by $|T_{tag} - T_{det}| < 2$ ns

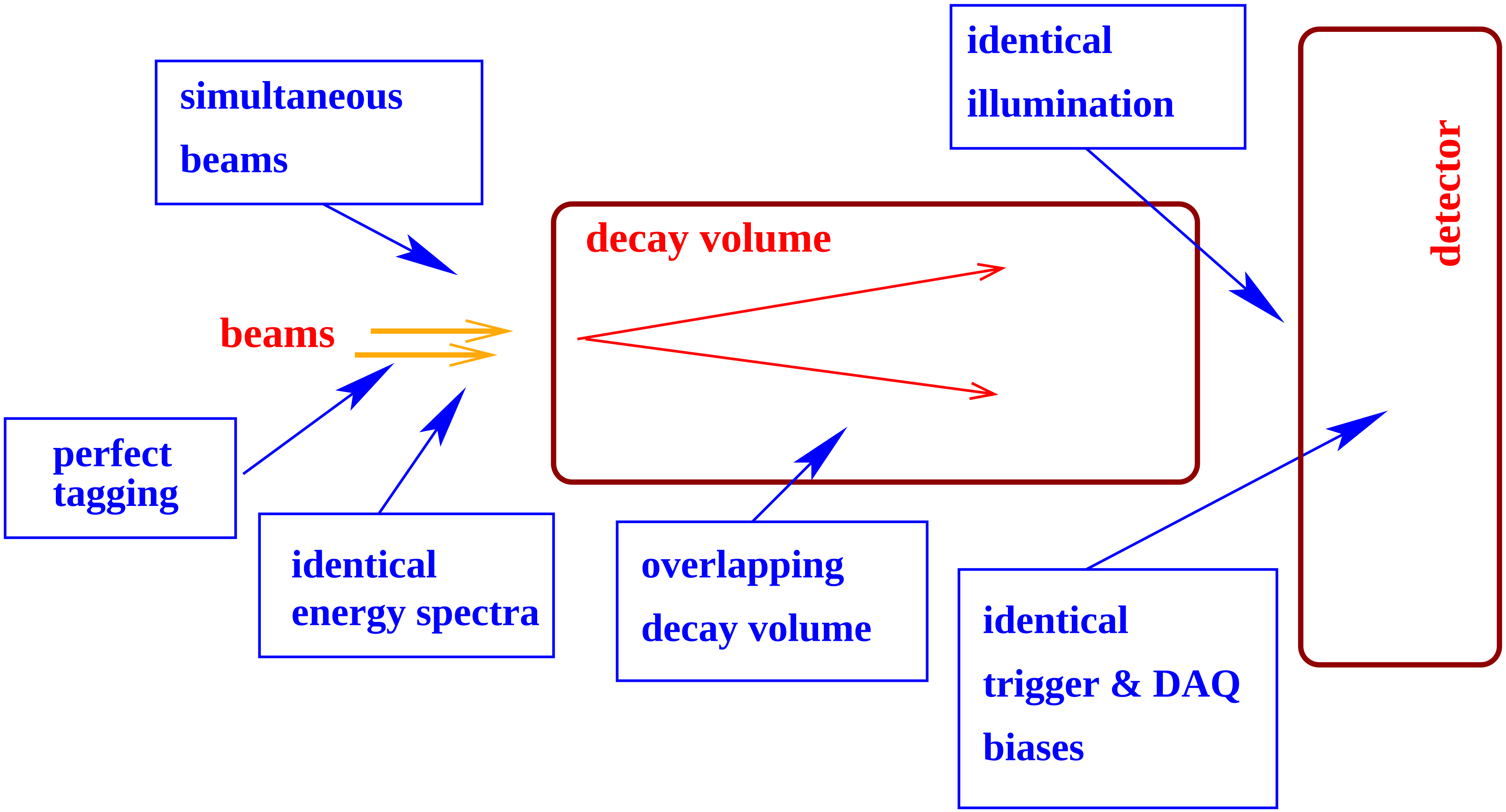
The Heart of the system: Tagging Station

Tagging station:

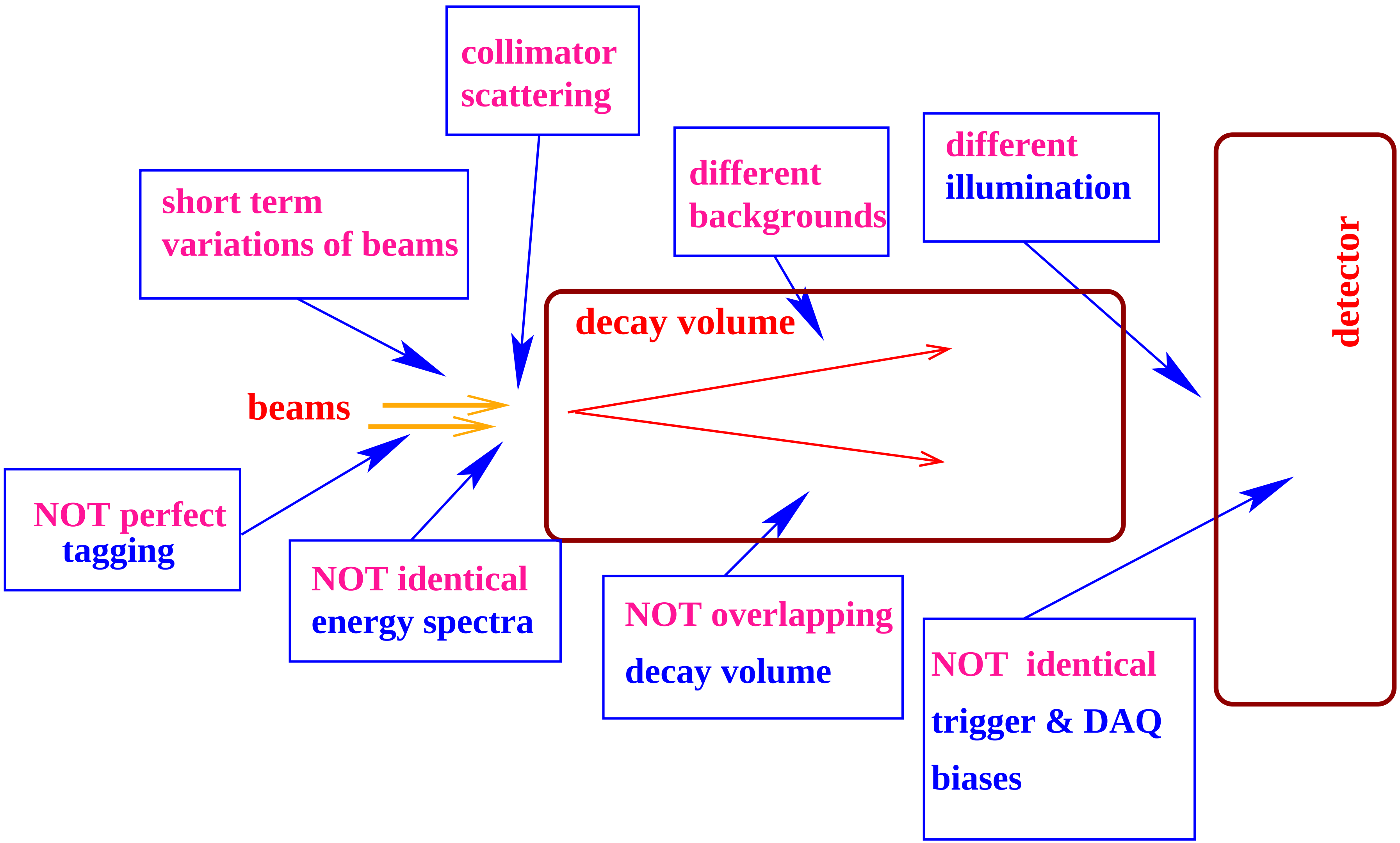
2 $\times$ 12 thin scintillator foils to stand a proton rate $\sim$28 MHz
read-out by Flash-ADC 8 bits at 960 MHz $\Rightarrow$ time resolution 140 ps, double-pulse separation 4 ns



In the ideal world ...



In the real world !!



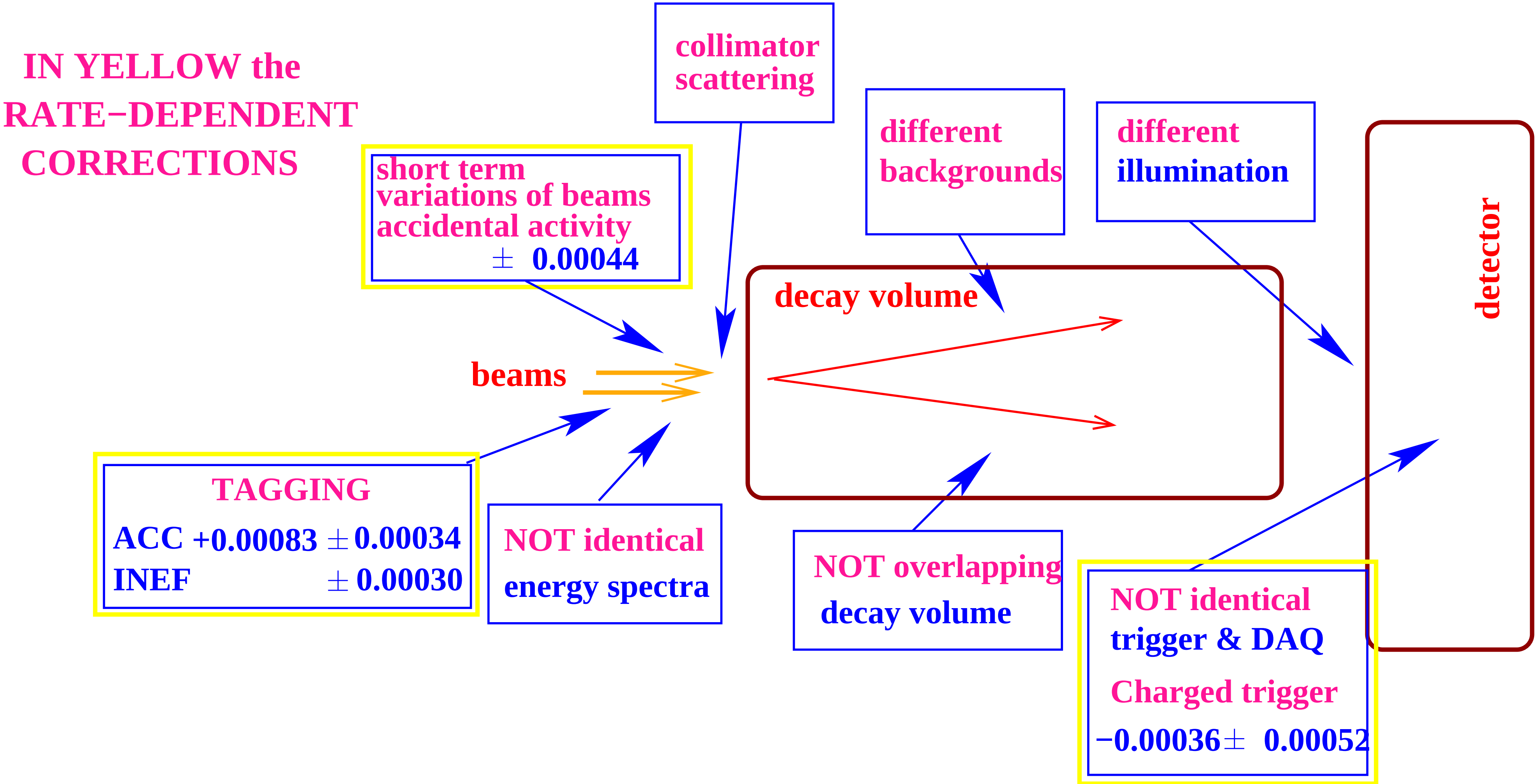
... but, these corrections are small, $< 0.3\%$ by first principles

History data samples collected by NA48

year	days	ppp on K_L target	$K_L \to \pi^0\pi^0$
1997	89	1×10^{12}	0.49 million
			$\mathrm{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$
			Phys. Lett. B 465 (1999) 335-348
1998	135	1.4×10^{12}	1.05 million
1999	128	1.4×10^{12}	2.24 million
			$\mathrm{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 1.7 \pm 2.1) \times 10^{-4}$
			Eur.Phys.J. C22 (2001) 231-254
2000	NO ε'/ε	DCH damaged in Nov. 99	
2001	90	2.4×10^{12} (**)	1.55 million
			$\mathrm{Re}(\varepsilon'/\varepsilon) = (13.7 \pm 2.5 \pm 1.8) \times 10^{-4}$
			preprint CERN-EP-2002-061

** modified beam parameters

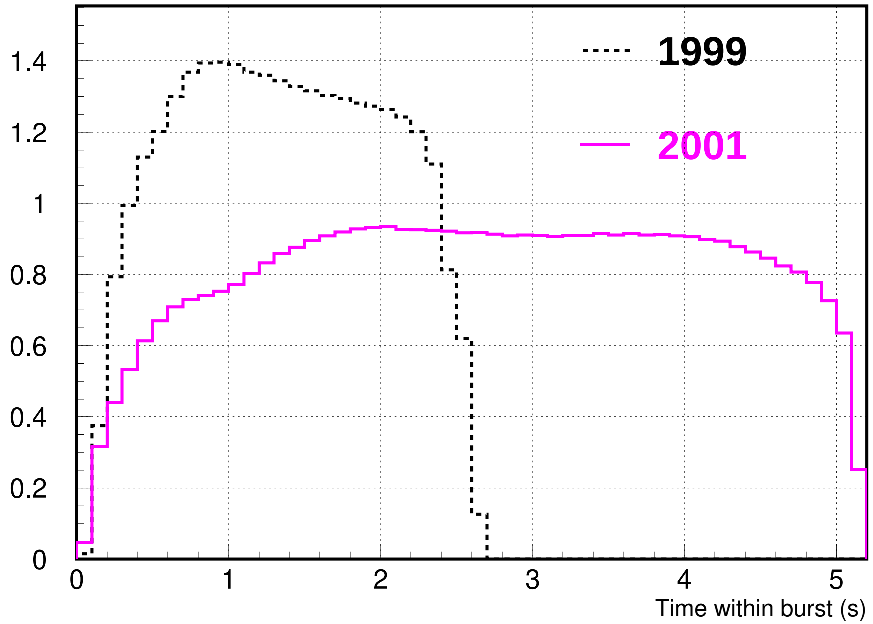
The 1998+1999 intensity-dependent corrections



The 2001 data taking

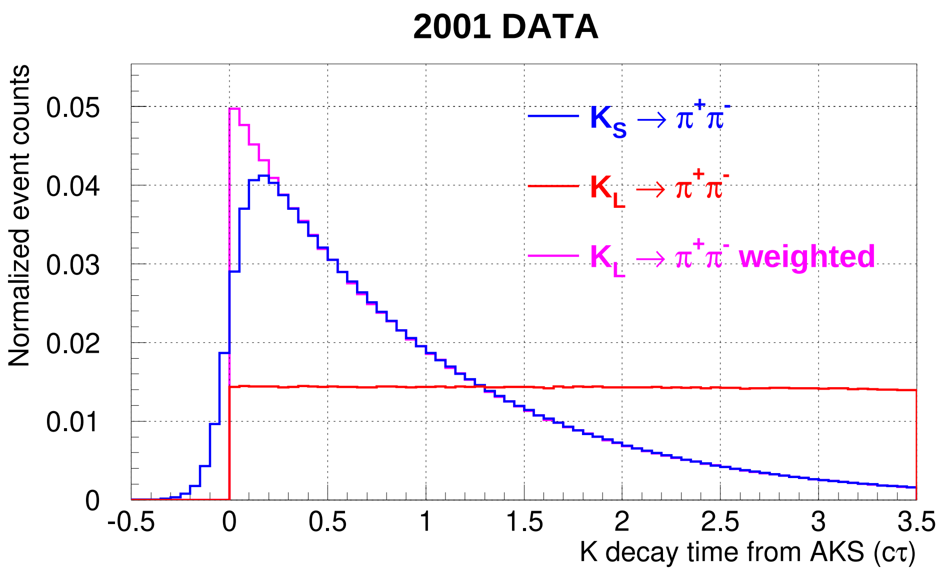
➜ Collect additional data under varied conditions to test the intensity related systematics of the measurement

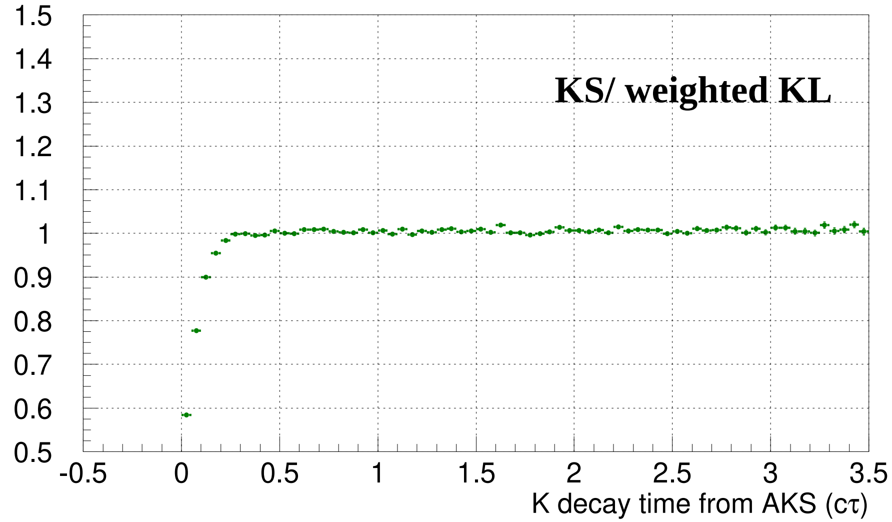
SPS spill duty cycle	2.4/14.4 s	$\rightarrow$	5.2/16.8 s
proton beam energy	450 GeV	$\rightarrow$	400 GeV
instantaneous intensity			$\sim$ 30 % lower
DCH overflow rate	21.5%	$\rightarrow$	11.7 %

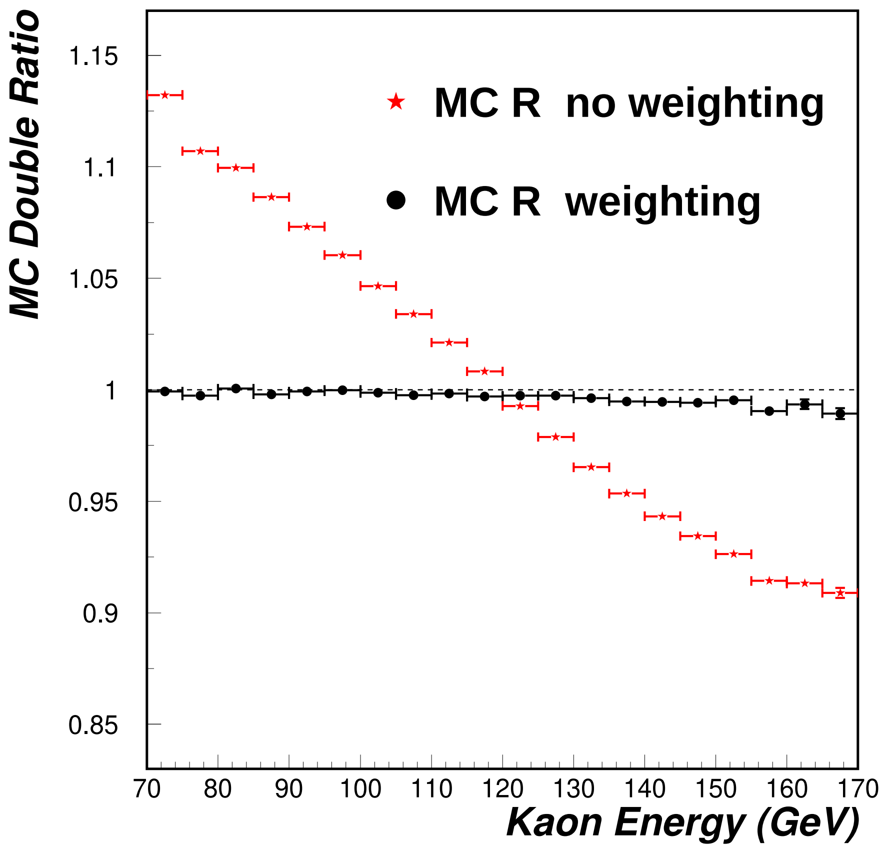


Good K_L Events / 100 ms

Analysis 2001: acceptance correction







Residual acceptance difference corrected on R:

$$\boxed{(21.9 \pm 3.5 \pm 4.0) \times 10^{-4}}$$

Analysis 2001: accidental correction

The accidental activity coming from the beams (mostly $\mathrm{K_L}$) induces event losses (if it overlaps in time and/or space with a good event! $\Rightarrow$ reconstruction or selection affected)

➜ The concurrency and correlation of the two beams minimize this effect

➜ If losses depend linearly from intensity $\Rightarrow$ residual correction

$$\boxed{\Delta R \simeq \Delta I/I \;\times\; \Delta P_\lambda}$$

- $\Delta P_\lambda = P_\lambda(\pi^+\pi^-) - P_\lambda(\pi^0\pi^0)$ is the difference of event loss probability for charged and neutral decays.

- $\Delta I/I$ is the average difference of instantaneous intensity seen by $\mathrm{K_L}$ and $\mathrm{K_S}$ events

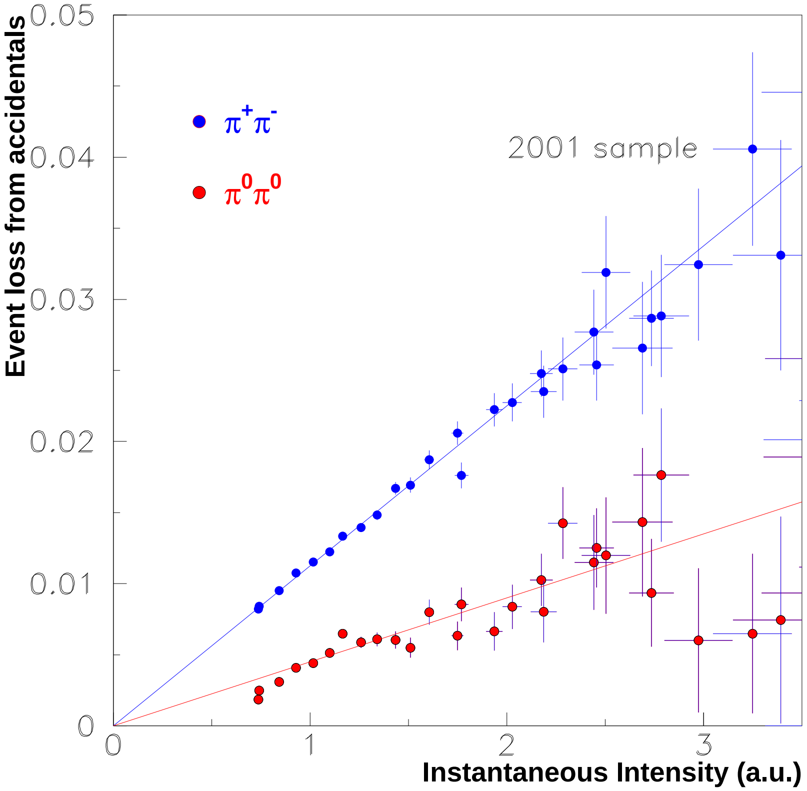
Special overlay of random triggered events to real and MC data is used to estimate $\Delta P_\lambda = 1.0 \pm 0.5\%$

Analysis 2001: accidental correction (2)

$\Delta I/I$

Accidental activity (extra clusters and tracks) seen by good events, is measured identical within 1% between K_S et K_L . Thanks to new beam monitor integrators measuring beams intensity within short timescales (0.2, 1, 3, 15 μs), the accidental activity and the beams correlation are also checked with those

$$\Delta I/I < 1\%$$



$\Longrightarrow$ uncertainty on R $=$ $\boxed{\pm 1.1 \times 10^{-4}}$

(was 30% for 98/99 data, from ΔP_λ)

Geometrical difference of K_S , K_L detector illumination coupled with geometry dependent event losses is checked with overlay events

$\Longrightarrow$ uncertainty on R $=$ $\boxed{\pm 3 \times 10^{-4}}$

The 2001 Result

Corrections and uncertainties on R (Units = 10^{-4})
errors are of pure statistical or pure systematical nature

	2001					1998/1999				
statistical error		$\pm$	14.7				$\pm$	10.1		
$\pi^0\pi^0$ reconstruction				$\pm$	5.3				$\pm$	5.8
Acceptance	21.9	$\pm$	3.5	$\pm$	4.0	26.7	$\pm$	4.1	$\pm$	4.0
$\pi^+\pi^-$ trigger inefficiency	5.2	$\pm$	3.6			-3.6	$\pm$	5.2		
Accidentals: intensity diff.				$\pm$	1.1				$\pm$	3.0
illumination diff.		$\pm$	3.0				$\pm$	3.0		
K_S in–time activity				$\pm$	1.0				$\pm$	1.0
Accidental tagging	6.9	$\pm$	2.8			8.3	$\pm$	3.4		
Tagging inefficiency				$\pm$	3.0				$\pm$	3.0
$\pi^+\pi^-$ background	14.2			$\pm$	3.0	16.9			$\pm$	3.0
$\pi^+\pi^-$ reconstruction				$\pm$	2.8				$\pm$	2.8
beam scattering	-8.8			$\pm$	2.0	-9.6			$\pm$	2.0
$\pi^0\pi^0$ background	-5.6			$\pm$	2.0	-5.9			$\pm$	2.0
AKS inefficiency	1.2			$\pm$	0.3	1.1			$\pm$	0.4
Total systematic	+35.0	$\pm$	6.5	$\pm$	9.0	+35.9	$\pm$	8.1	$\pm$	9.6

$$R = 0.99181 \pm 0.00147_{stat} \pm 0.00110_{syst}$$

THE FINAL RESULT

From 2001 data:

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

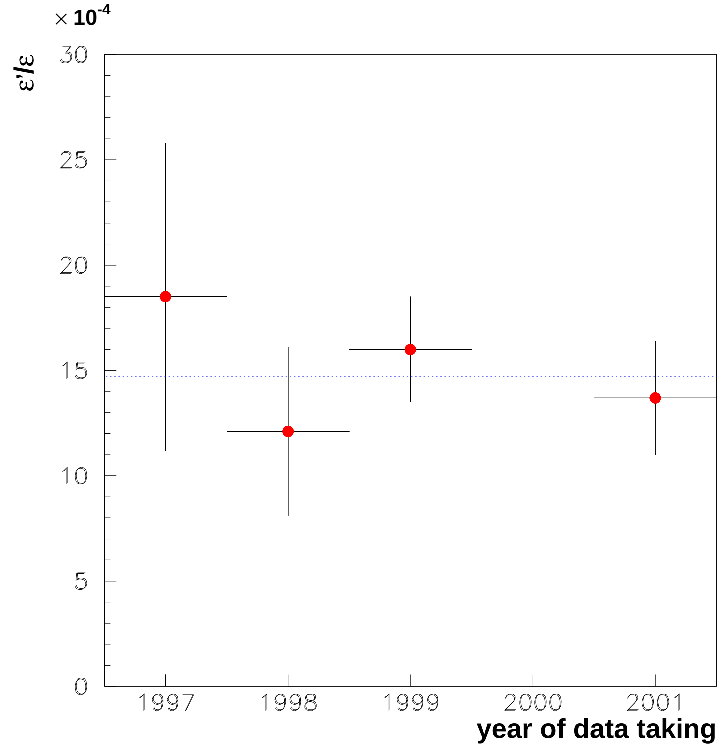
measured under different beam conditions and with new drift chambers

combined with the 97+99+99 value $(15.3 \pm 2.6) \times 10^{-4}$

we obtained the FINAL RESULT

$$\boxed{\mathrm{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}}$$

- ➜ 4 years of data–taking
- ➜ proposed accuracy has been reached ☺



Conclusions

The END for the ε'/ε NA48 community

KTEV final result still to come. . .

KLOE at DAPHNE ϕ factory will measure Re$(\varepsilon'/\varepsilon)$ and $Im(\varepsilon'/\varepsilon)$ with an alternative and nice method... needs luminosity!

THEORY has a nice accurate measurement to interpret!