First result on $Re(\varepsilon'/\varepsilon)$ measurement from the NA48 experiment at CERN

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Introduction

NA48 aims at measuring the direct CP violation parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ in the neutral Kaon system with an accuracy of 2×10^{-4}.

Previous precision measurements results are:

NA31	$(23.0 \pm 6.5) \times 10^{-4}$
E731	$(7.4 \pm 5.9) \times 10^{-4}$
KTeV prel.	$(28.0 \pm 4.1) \times 10^{-4}$

The double ratio is measured:

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

$$\simeq 1 - 6\ \mathrm{Re}(\varepsilon'/\varepsilon)$$

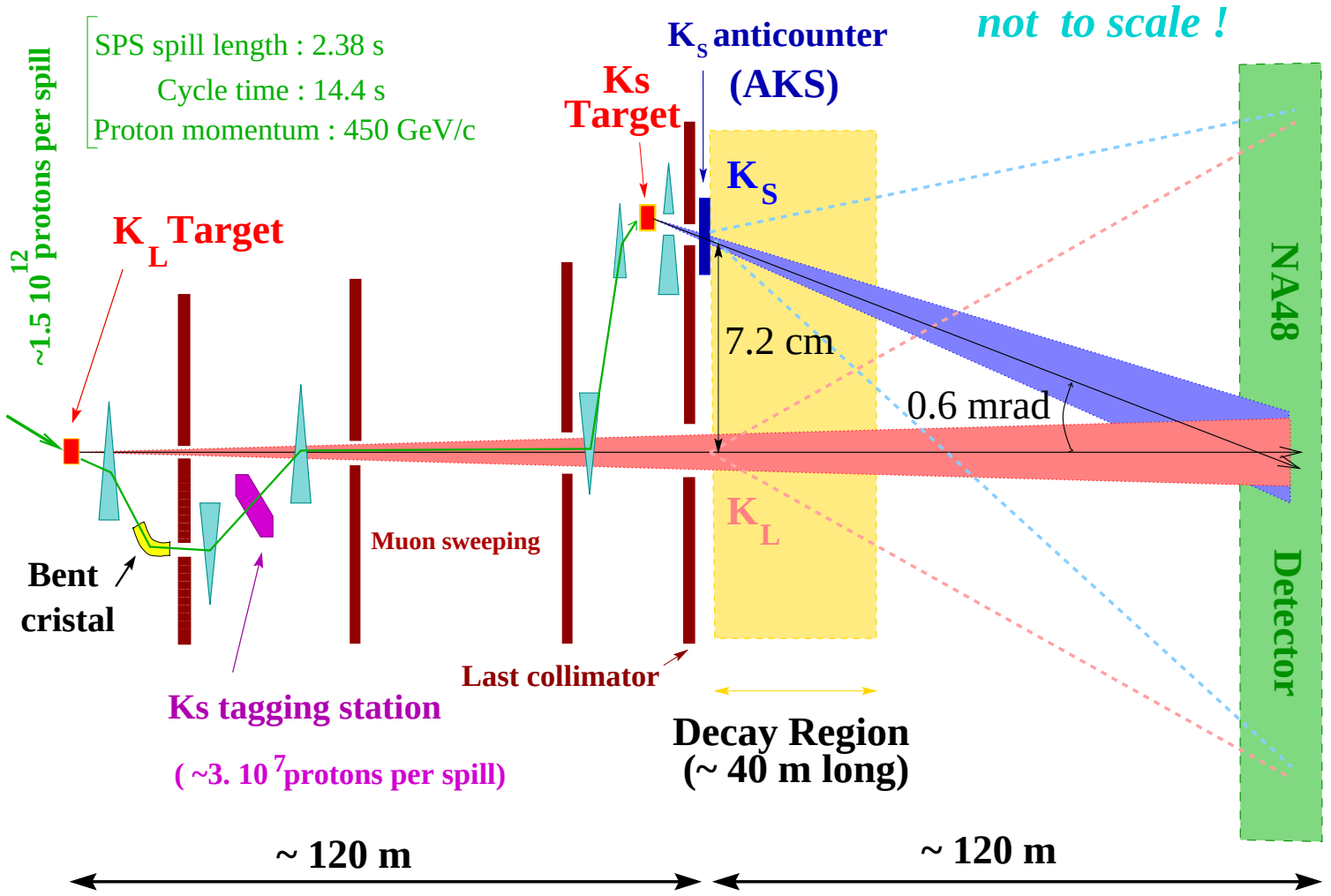
Overview of NA48 method

To achieve the required statistical precision *several* 10^6 $K_L \to \pi^0\pi^0$ decays (limiting mode) have to be collected.

To maximize systematic accuracy and to have minimal corrections, NA48 uses:

- ▷ simultaneous, almost collinear K_L and K_S beams, allowing for
- ▷ concurrent detection of the four decay modes in the same decay region to have cancellation of fluxes, acceptances, inefficiences, dead time, accidental losses;
- ▷ K_S identification by proton tagging upstream of K_S production target;
- ▷ a detector based on a magnetic spectrometer and a quasi-homogeneous liquid Krypton calorimeter, to achieve good resolutions and minimize the background;
- ▷ lifetime weighting procedure to minimize acceptance corrections by making K_S and K_L decay distributions similar.

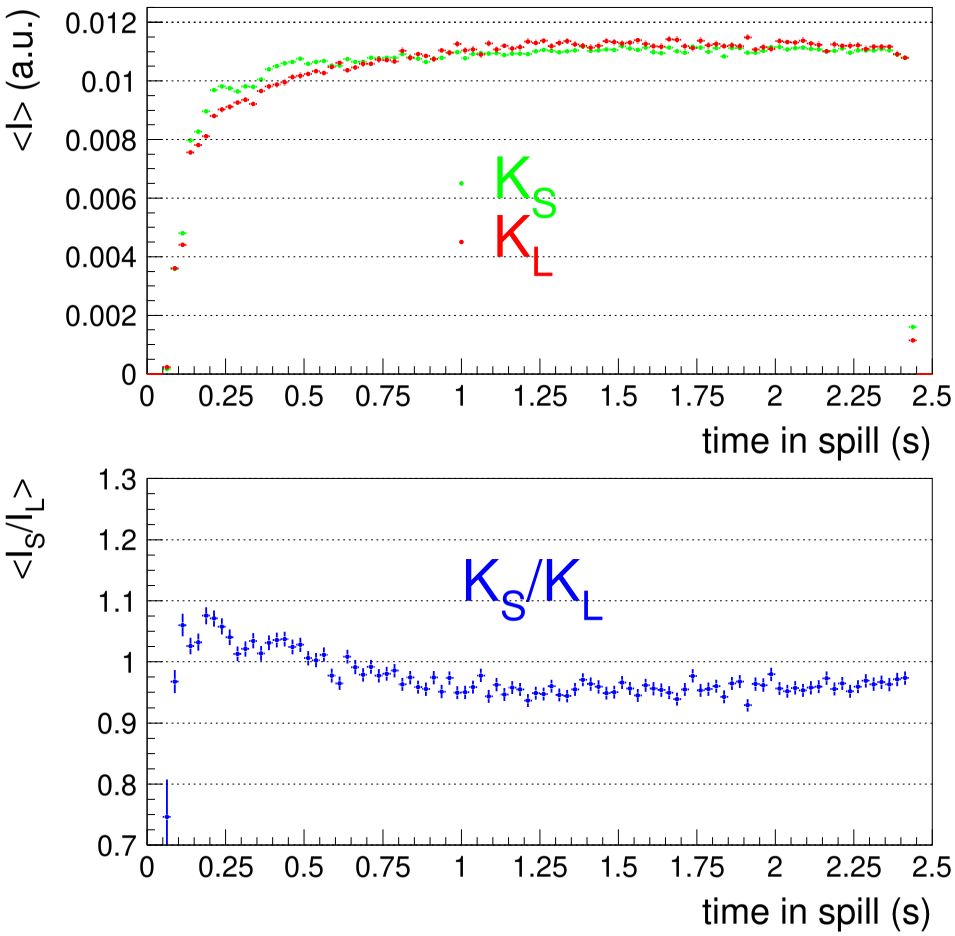
Simultaneous K_S and K_L Beams



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

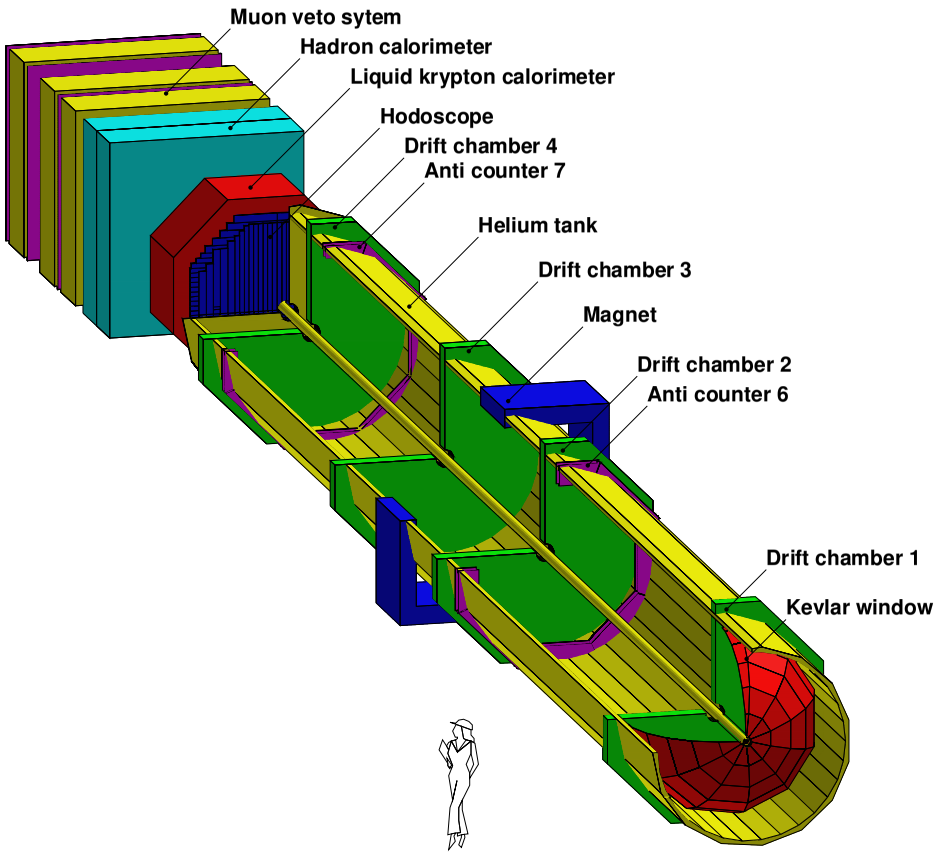
Beam performance

- K_S and K_L beam intensities are continuously monitored, their ratio is constant within $\pm$ 10%



- Average beam intensities are equal for K_S and K_L events on the 200 ns $\div$ 1 ms time scale, at the level of few %: beam intensities are time correlated at this level.

The NA48 detector



- $K_{\mathrm{L,S}} \to \pi^+\pi^-$: magnetic spectrometer (P_T kick $\sim$ 265 MeV/c); event time measured with scintillator hodoscope
- $K_{\mathrm{L,S}} \to \pi^0\pi^0$: quasi-homogeneous liquid Krypton e.m. calorimeter with high granularity (13212 2×2 cm^2 cells) and projective geometry
- $K_{\mu 3}$ rejection: muon veto counters
- K_{e3} rejection: E(LKr)/P(spectrometer)
- $\mathrm{K_L} \to 3\pi^0$ rejection: high resolution e.m. calorimeter

First data-taking period: 1997

- Installation and commissioning of the complete readout and trigger electronics for the LKr calorimeter

- Full DAQ and trigger integration, detector calibration

- First physics run (after fire in SPS power supply): Sep-Oct 1997 (42 days)

- 2/3 of nominal beam intensity ($1 \cdot 10^{12}$ ppp on K_L target)

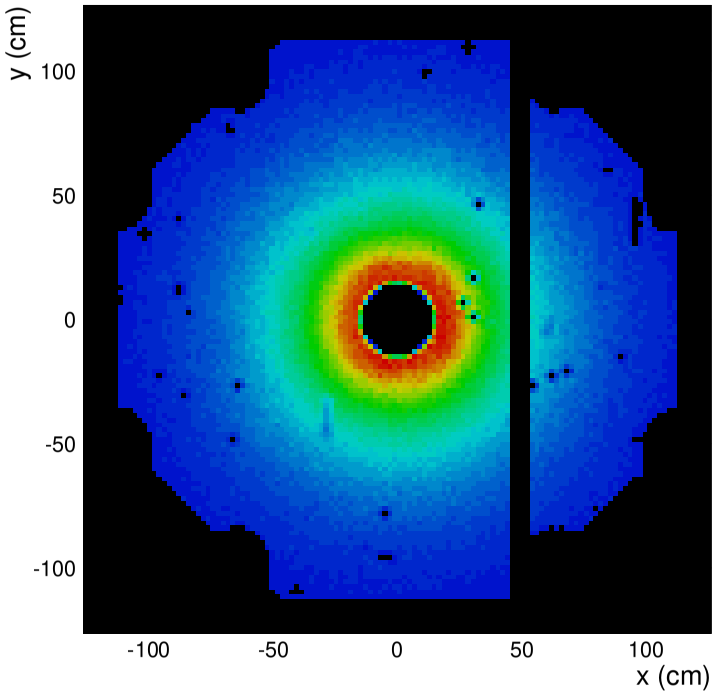
- $\simeq$ 12K events/spill read-out every 14.4 s: 80 MB/s read-out rate, 12 MB/s to Central Data Recording facility

- 25 TB of data on tape

- $\approx$ 10% of expected final statistics

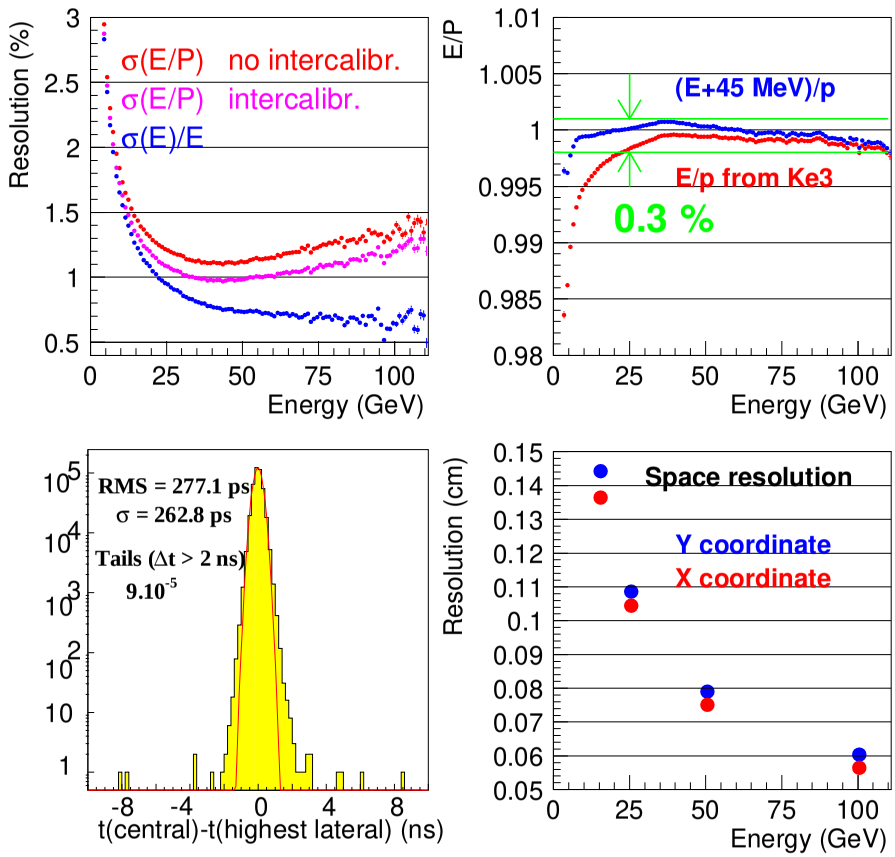
$K_{S,L} \to \pi^0\pi^0$ - Detector

- LKr calorimeter operated at reduced HV (1.5 KV) due to few leaking capacitors:
  - electronic noise $\approx 20\%$ higher
  - $< 0.5\%$ energy correction for space charge
- 4 cm wide column not connected to HV: 15% acceptance loss for $\pi^0\pi^0$
- $\approx$ 40 dead channels (0.3 %)



- redundant time information
- periodic calibrations during data-taking
- single intercalibration factor per cell based on K_{e3} and π^0, η response to improve resolution

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



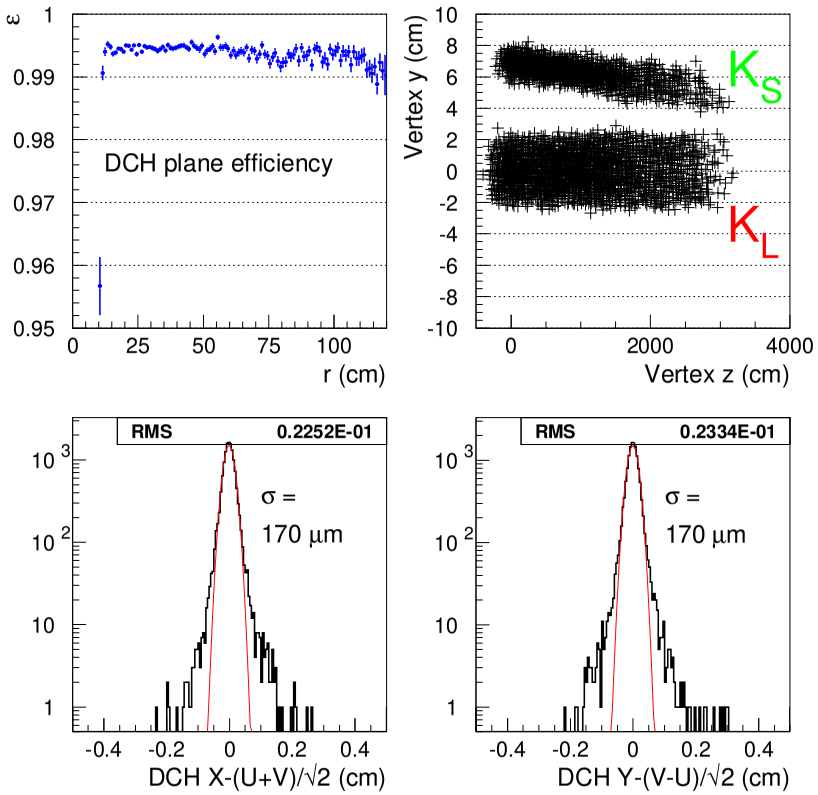
- energy resolution:

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E(GeV)}} \oplus \frac{125 MeV}{E} \oplus 0.5\%$$

$< 1\%$ above 20 GeV

- cell to cell disuniformity 0.67 % corrected with K_{e3} and π^0, η events
- energy linearity within $\sim 0.3\%$
- position resolution < 1.3 mm in x and y above 20 GeV
- π^0 mass resolution 1.1 MeV/c^2
- time resolution < 300 ps above 20 GeV
- time stability $\approx 0.1\%$

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

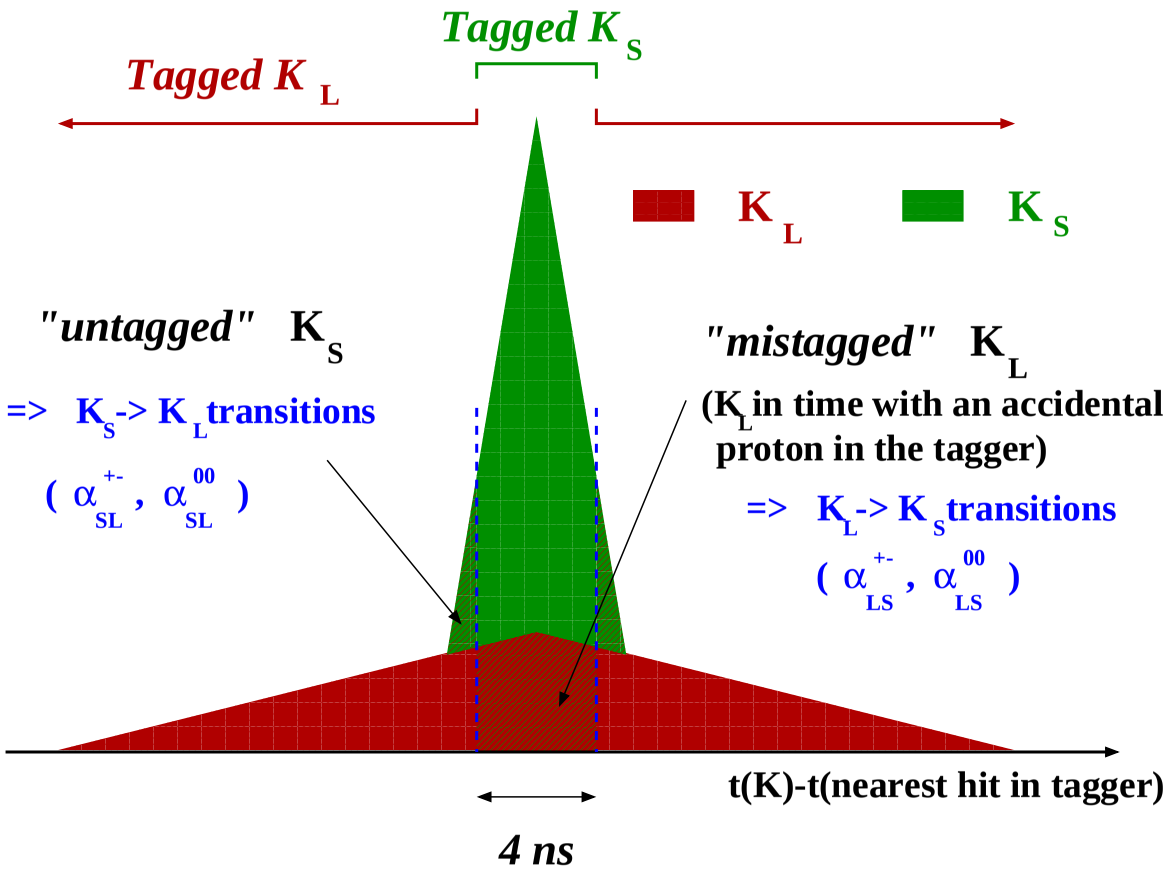


- DCH plane efficiency: 99.5%
- DCH space resolution: $\approx 90\mu$m per projection
- DCH momentum resolution:

$$\frac{\sigma_P}{P} = 0.5\% \oplus 0.009P \text{ (GeV/}c\text{) \%}$$

- vertex resolution: $\approx$ 2 mm transverse and $\approx$ 50 cm longitudinal
- $\pi\pi$ mass resolution: ~ 2.5 MeV/c^2
- time resolution: $\approx$ 200 ps per track

Tagging - Principle

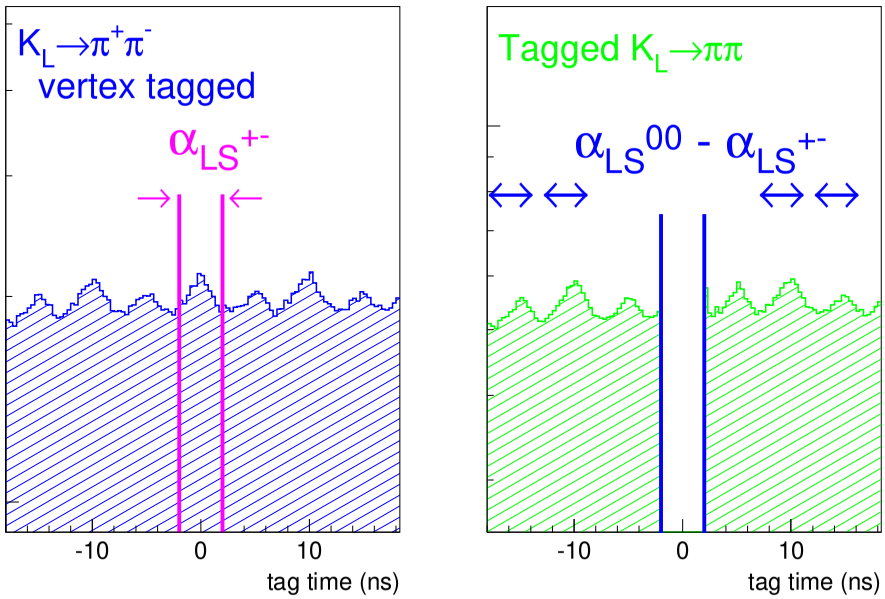


- tagger rate: $\approx$ 28 MHz
- K_S : event time within $\pm$ 2 ns of proton.
- Mistagging only "dilutes" R if charged/neutral symmetric.
- K_L mistagging ($K_L \to K_S$, α_{LS}) due to accidental protons in tagger: charged/neutral symmetric in first order.
- K_S mistagging ($K_S \to K_L$, α_{SL}) due to time reconstruction tails: can be different between charged/neutral decays, in principle.

Tagging - $K_L \to K_S$ transitions

- α_{LS} measures the $K_L \to K_S$ mistagging probability due to accidental protons in the tagger.
- α_{LS} is charged/neutral symmetric, except for rate-dependent trigger inefficiencies.
- α_{LS}^{+-} is directly measured by vertex tagging:

$$\alpha_{LS}^{+-} = (11.19 \pm 0.03)\ \%$$



- $\alpha_{LS}^{00} - \alpha_{LS}^{+-}$ is measured by comparing suitable side bands (4 ns wide) outside the tagged region in charged and neutral modes:

$$\alpha_{LS}^{00} - \alpha_{LS}^{+-} = (0.10 \pm 0.05)\ \%$$

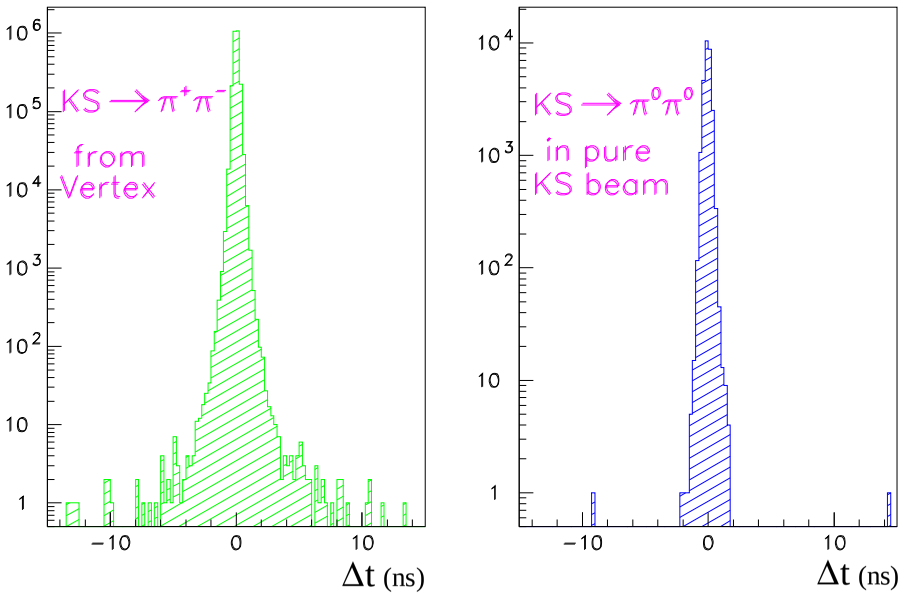
☞ The net effect on the double ratio is:

$$\Delta R = (-18 \pm 9) \cdot 10^{-4}$$

Tagging - $K_S \to K_L$ transitions

- α_{SL} measures the $K_S \to K_L$ mistagging probability due to tails in the proton or event time reconstruction (tagging inefficiences)
- Measurement shows that 2/3 of α_{SL} is due to the tagger, therefore charged/neutral symmetric
- α_{SL}^{+-} is directly measured by vertex tagging

$$\alpha_{SL}^{+-} = (1.5 \pm 0.1) \cdot 10^{-4}$$



- α_{SL}^{00} is measured in pure K_S runs and using $K_S \to \pi^0 e^+ e^- \gamma$ decays
- $(\alpha_{SL}^{00} - \alpha_{SL}^{+-})$ is bounded by neutral/charged time comparison on γ conversions

$$\alpha_{SL}^{00} - \alpha_{SL}^{+-} = (0 \pm 1) \cdot 10^{-4}$$

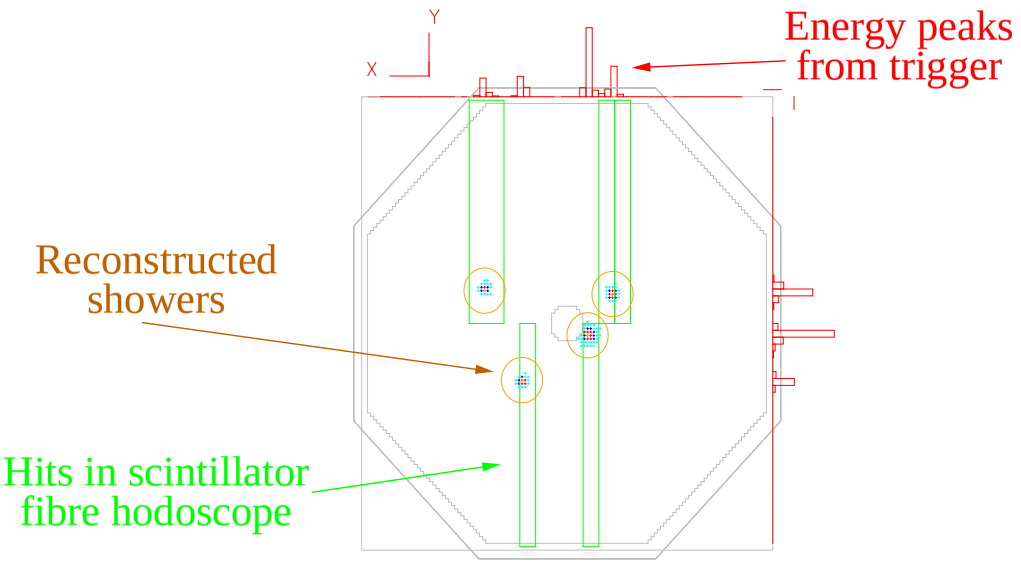
☞ The net effect on the double ratio is:

$$\Delta R = (0 \pm 6) \cdot 10^{-4}$$

Neutral trigger

❖ Fully pipelined, deadtimeless system based on the e.m. calorimeter information in to 64 vertical and 64 horizontal projections, reducing dominant $K_L \to 3\pi^0$ background by reconstructing

- ▷ number of in time clusters in each projection
- ▷ total energy in the calorimeters
- ▷ longitudinal decay vertex position



❖ During 1997 run:

- ▷ Input rate: ~ 500 kHz K_L decays in detector
- ▷ Output rate: ~ 2 kHz
- ▷ Efficiency: $\epsilon_{NT} = 0.9988 \pm 0.0004$

☞ The net effect on R is due to the differential $K_L - K_S$ inefficiency:

$$\Delta R = \epsilon_{NT}^{L} - \epsilon_{NT}^{S} < 2 \cdot 10^{-4}$$

Charged trigger - General

❖ Hardware and software trigger reduces dominant background from 3-body K_L decays

❖ Level 1: hodoscopes and total energy threshold (30 GeV) in calorimeters, downscaled by 2

❖ Level 2: fast tracking in the spectrometer by a farm of processors reconstructing

- ▷ longitudinal decay vertex position
- ▷ proper lifetime
- ▷ $\pi^+\pi^-$ invariant mass

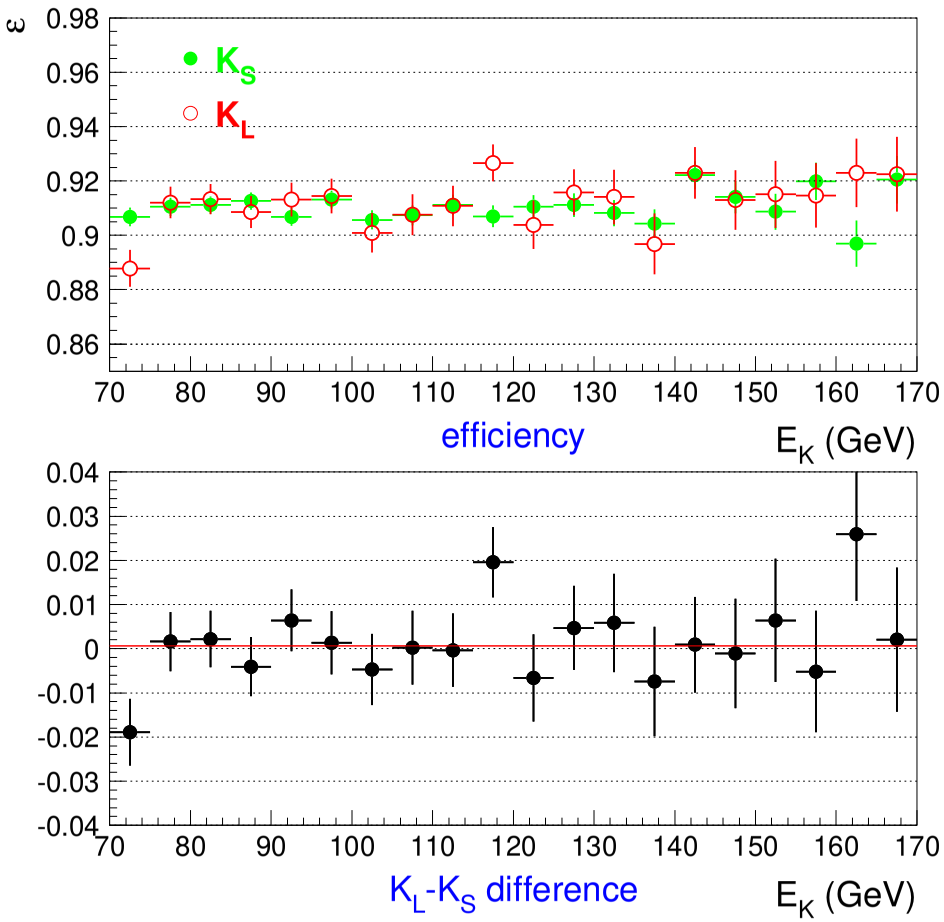
❖ During 1997 run:

- ▷ Input rate: $\sim$ 500 kHz K_L decays in detector
- ▷ Level 1 output rate: $\sim$ 100 KHz
- ▷ Level 2 output rate: $\sim$ 1.5 KHz
- ▷ Dead time $\sim$ 0.3 % (monitored)

Charged trigger - Efficiency

- Combined $L1 \cdot L2$ efficiency:

$$\epsilon_{CT} = (0.9168 \pm 0.0009)$$



- Efficiency measurement limited by control sample statistics

☞ The net effect on R is due to the differential $\mathrm{K_S} - \mathrm{K_L}$ inefficiency:

$$\Delta R = \epsilon_{CT}^{S} - \epsilon_{CT}^{L(W)} = (-9 \pm 23) \cdot 10^{-4}$$

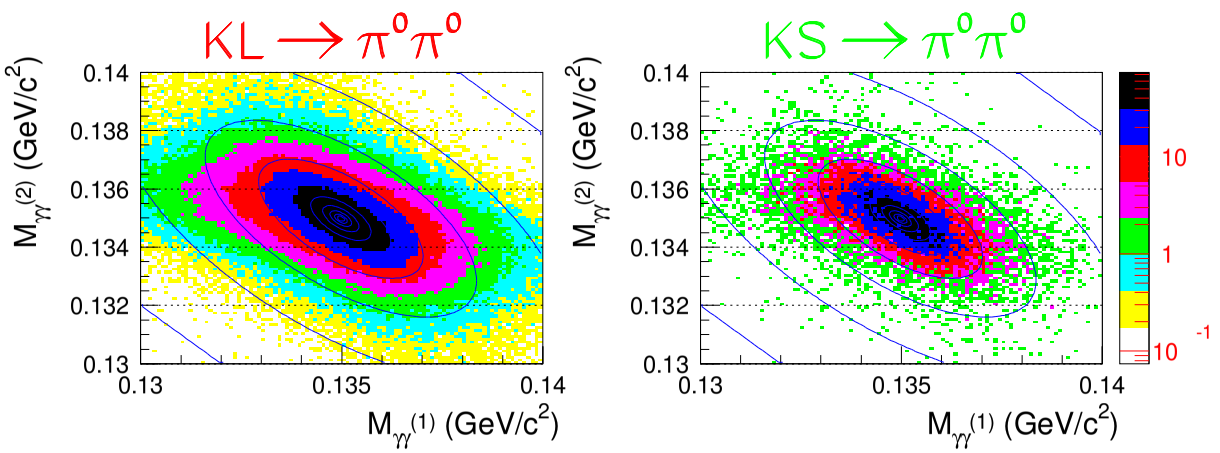
$K \to \pi^0\pi^0$ event reconstruction

- Cluster energy and time from digitized information of e.m. calorimeter cells within 11 cm of seed cell, using digital filter algorithm
- Small corrections applied for leakage, cluster fusion, impact point dependence, space charge effect, 0.5 mm e.m. calorimeter horizontal gap
- reconstruct longitudinal vertex position assuming 4-cluster invariant mass being K^0 mass:

$$z_{vertex} = z_{cal} - \sqrt{\sum_{i,j>i} E_i E_j [(x_i - x_j)^2 + (y_i - y_j)^2]}/m_K$$

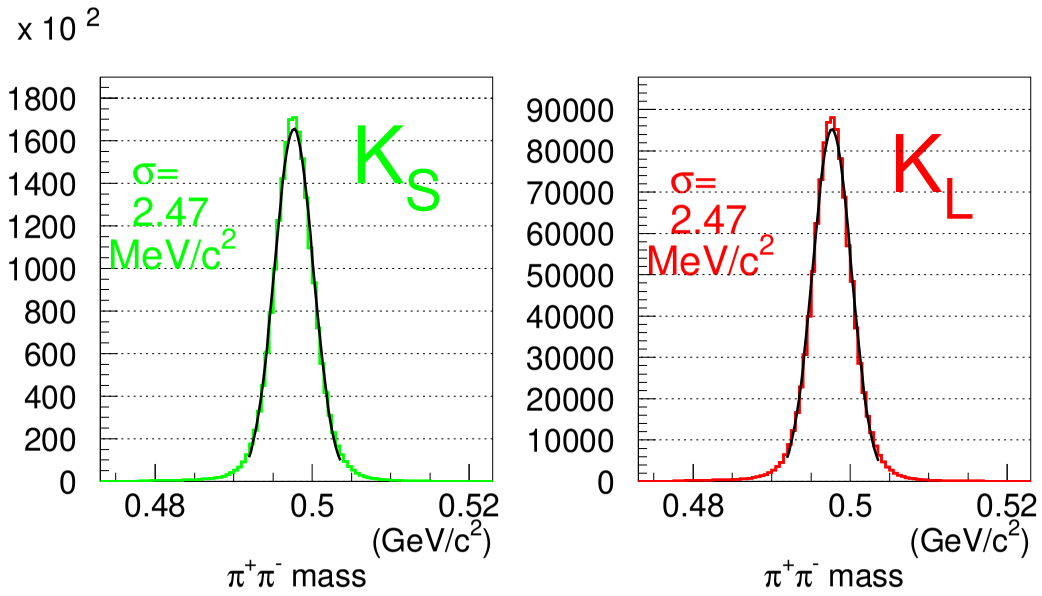
with $\sigma(z_V) \approx 70$ cm

- Find best photon pairing based on $\gamma\gamma$ invariant masses



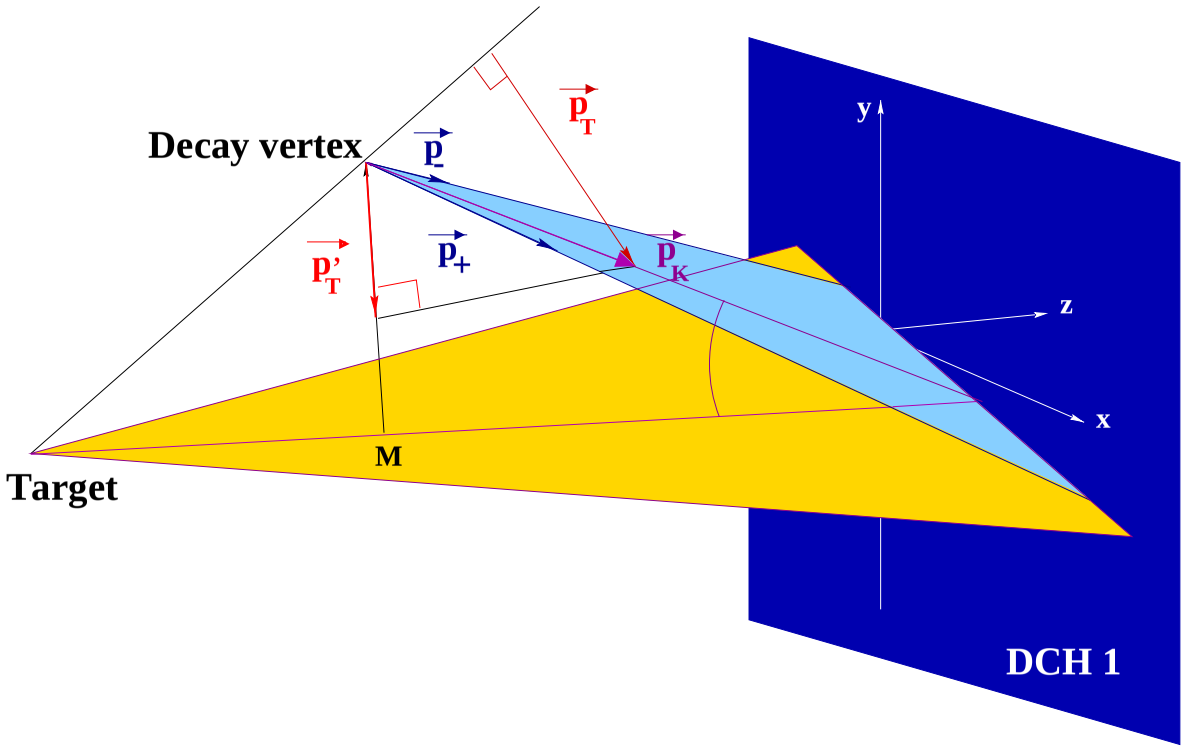
$K \to \pi^+\pi^-$ event reconstruction

- Tracks from spectrometer using detailed field map including stray fields
- Small correction for residual magnetic field in decay region (O(1 $\cdot 10^{-3}$ T·m)
- $\approx 20\%$ of events are lost due to an *overflow* condition in DCH electronics for high multiplicity events (recorded and applied also to neutral events)
- Kaon energy computed from ratio of track momenta and opening angle $\Rightarrow$ less sensitive to magnetic field knowledge
- Effective energy-dependent cut on center of mass decay angle $\Rightarrow$ reduced K_S/K_L acceptance difference



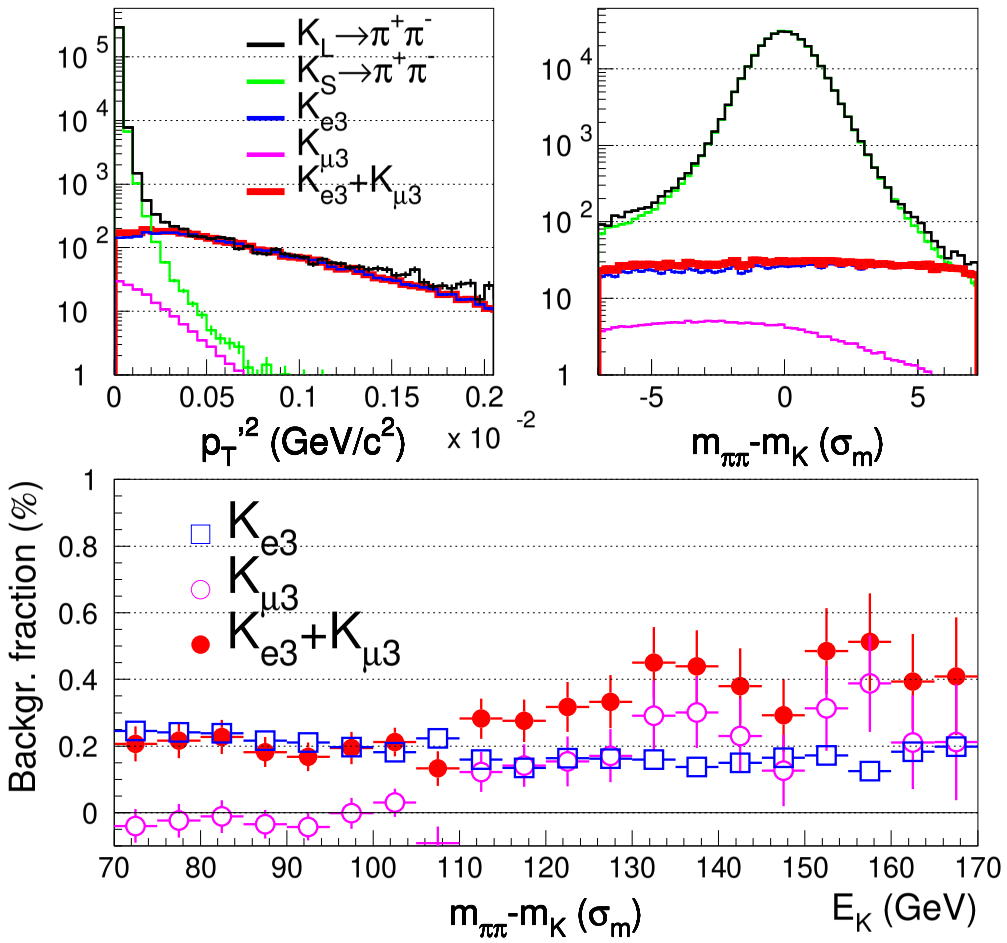
Charged background - Method

- K_L 3-body decays are O(100) $\times$ signal
- K_{e3} rejection O(500) by E/P requirement on tracks, with 5% K_S/K_L symmetric signal loss
- $K_{\mu 3}$ rejection O(500) by muon veto counter hits matching tracks in space and time, with 3% K_S/K_L symmetric signal loss
- kinematical cuts reject $\pi^+\pi^-\pi^0$ background and $\Lambda(\bar{\Lambda})$ decays
- cut on rescaled transverse momentum ${P'_T}^2$ (similar K_S and K_L distributions) with $8 \cdot 10^{-4}$ K_S/K_L symmetric signal loss



Charged background - Measurement

❖ Check systematics by varying signal and control region



☞ Averaged charged background fraction is:

$$B_C = (+23 \pm 2 \pm 4) \cdot 10^{-4} = -\Delta R$$

☞ Small fraction ($\approx 0.5 \cdot 10^{-3}$) of $\pi\pi$ events due to K_S regenerated on final collimator gives

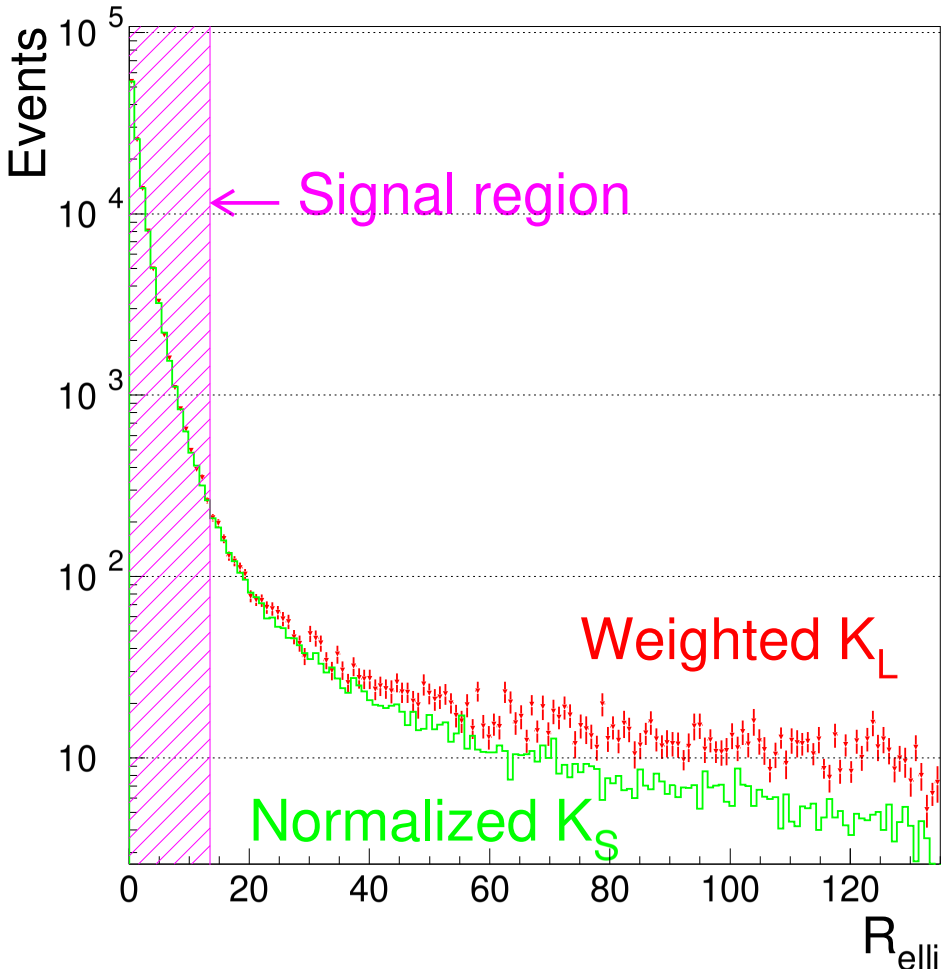
$$\Delta R = (+12 \pm 3) \cdot 10^{-4}$$

Neutral background - Method

- $K_L \rightarrow 3\pi^0$ is 210 $\times$ signal
- $K_L \rightarrow 3\pi^0$ with 2 missing photons have larger reconstructed lifetime and non-peaked $\gamma\gamma$ mass
- Use pseudo-χ^2 variable

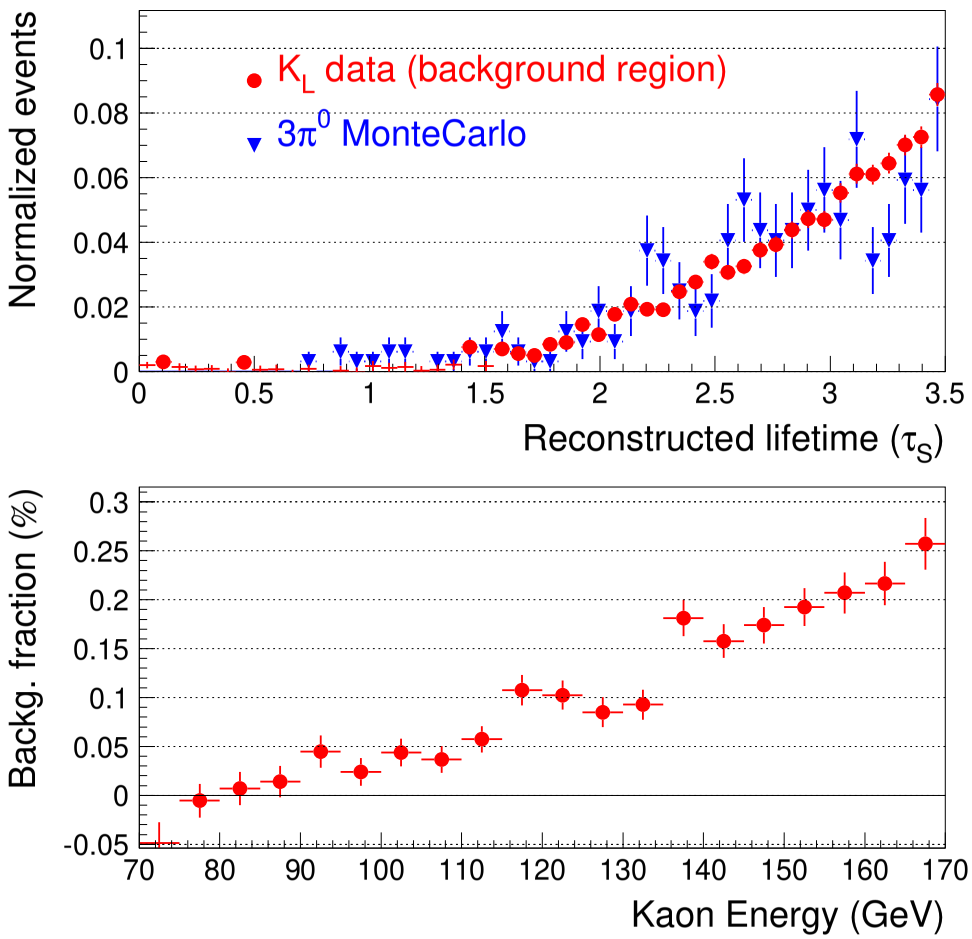
$$R_{elli} \equiv \left[\left(\frac{(m_{\gamma\gamma}^{(1)} + m_{\gamma\gamma}^{(2)}) - 2m_{\pi^0}}{\sigma_+} \right)^2 + \left(\frac{m_{\gamma\gamma}^{(1)} - m_{\gamma\gamma}^{(2)}}{\sigma_-} \right)^2 \right]$$

- Signal region: $R_{elli} < 13.5$ with 7% K_S/K_L symmetric signal loss (mostly γ conversions)



Neutral background - Measurement

- Use $K_S \rightarrow \pi^0\pi^0$ decays to measure signal R_{elli} shape to account for non-gaussian tails
- Extrapolate from large R_{elli} control region using factor 1.2 ± 0.2 computed from MonteCarlo

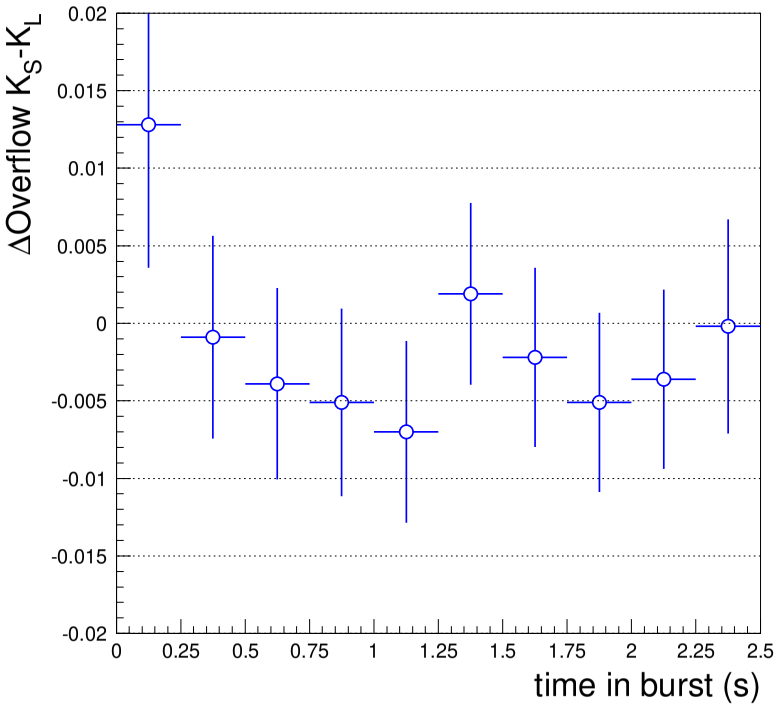


☞ Averaged background is:

$$B_N = (+8 \pm 2) \cdot 10^{-4} = \Delta R$$

DCH overflow condition

- Whenever the DCH plane hit multiplicity in a 100 ns window gets above 7, the front end buffers are flushed and the occurrence is recorded
- This has no effect on events outside a $\pm$ 300 ns time window around that time
- The loss of events due to such a cut is $\approx 20\%$
- The same cut is applied to neutral events, and the K_L/K_S differential loss is estimated by studying side time intervals for $\pi^+\pi^-$ decays: $(0.02 \pm 0.03)\%$, and is directly measured for $\pi^0\pi^0$ decays: $(-0.02 \pm 0.06)\%$, in both cases being negligible



☞ No significant effect on R

Accidental activity

❖ Simultaneous beams $\Rightarrow$ K_S/K_L differential effects intrinsically small

❖ "Instantaneous" beam intensity is continuously monitored: K_S and K_L beam intensities are correlated to $\approx 1\%$

❖ Accidental activity for K_S and K_L measured to be the same at 1% level

❖ "Randomly" triggered events proportional to K_L and K_S beam intensities are overlaid onto $\pi\pi$ events to measure event gains and losses:

- ▷ $\pi^+\pi^-$: losses - gains $\simeq 2\%$ (K_S/K_L symmetric)
- ▷ $\pi^0\pi^0$: losses - gains $\simeq 2.5\%$ (K_S/K_L symmetric)

☞ Net effect on double ratio:

$$\Delta R = (+2 \pm 14) \cdot 10^{-4}$$

❖ In-time activity from close K_S target measured in K_S only runs to be $< 3 \cdot 10^{-4}$

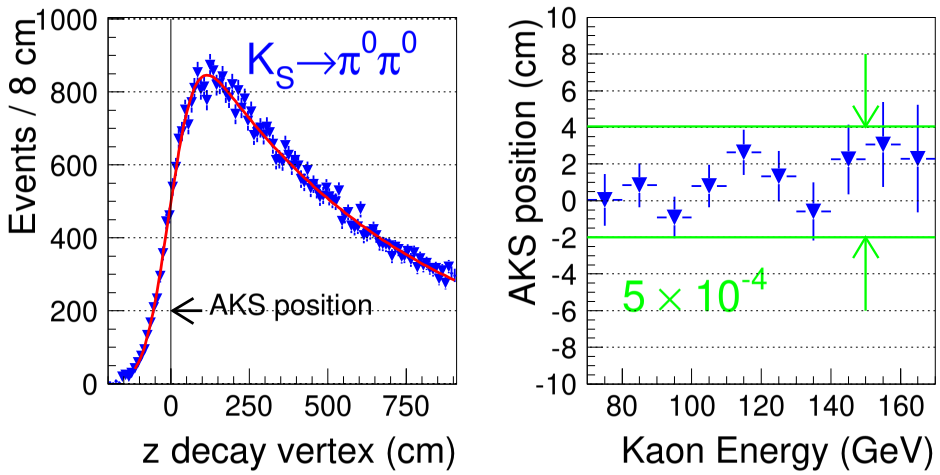
☞ Double ratio uncertainty:

$$\delta(R) < 3 \cdot 10^{-4}$$

which can be neglected.

Neutral energy and distance scales

- In neutral mode the longitudinal vertex distance and energy scales are related
- Absolute energy scale is set by adjusting the reconstructed position of the AKS veto counter in the $K_S \to \pi^0\pi^0$ vertex distribution, accounting for non-gaussian tails, with a conservative uncertainty of $5 \cdot 10^{-4}$



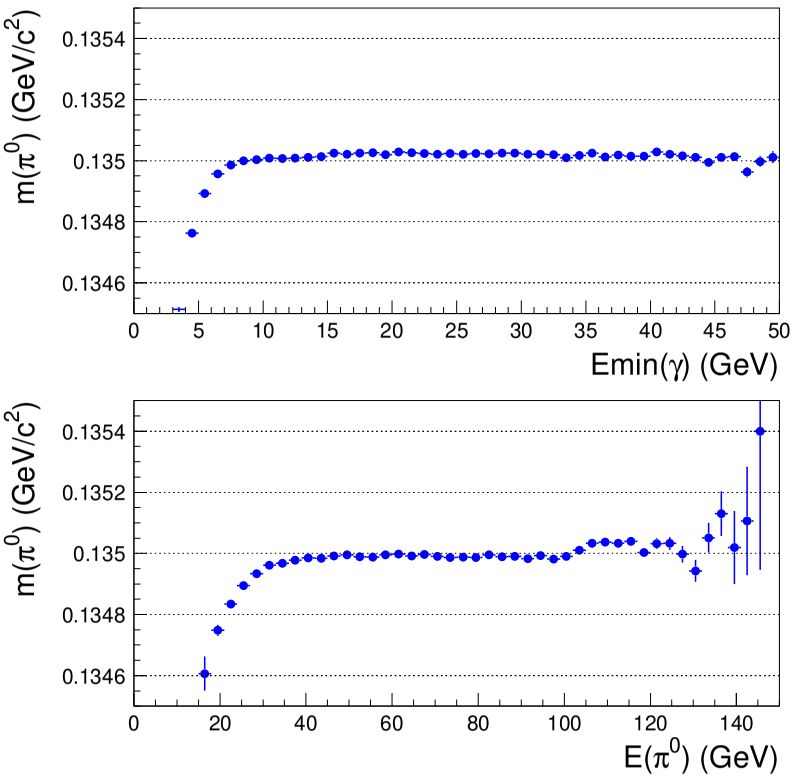
- Energy scale is stable in time within $5 \cdot 10^{-4}$
- Cross checks: reconstructed position of thin movable target in dedicated runs with π^- beam: consistent results with $\pi^0 \to 2\gamma$, $\eta \to 2\gamma/6\gamma$
- Transverse distance scale of e.m. calorimeter checked against spectrometer using K_{e3} decays to 0.3 mm/m

☞ R uncertainty from neutral scales:

$$\delta(R) = \pm 6 \cdot 10^{-4}$$

Calorimeter response

- Calorimeter response is equalized using K_{e3} decays during normal data taking and π^0 decays in special runs to $O(10^{-3})$
- Calorimeter non-linearity is studied using K_{e3} events, $\pi^0\pi^0$ decays and π^0 or η decays, and measured to be at the level of 0.3%
- Sensitivity to longitudinal development of e.m. showers is minimized by detector projectivity



☞ Non-linearity, non-uniformity and other systematics on e.m. calorimeter response give a double ratio uncertainty:

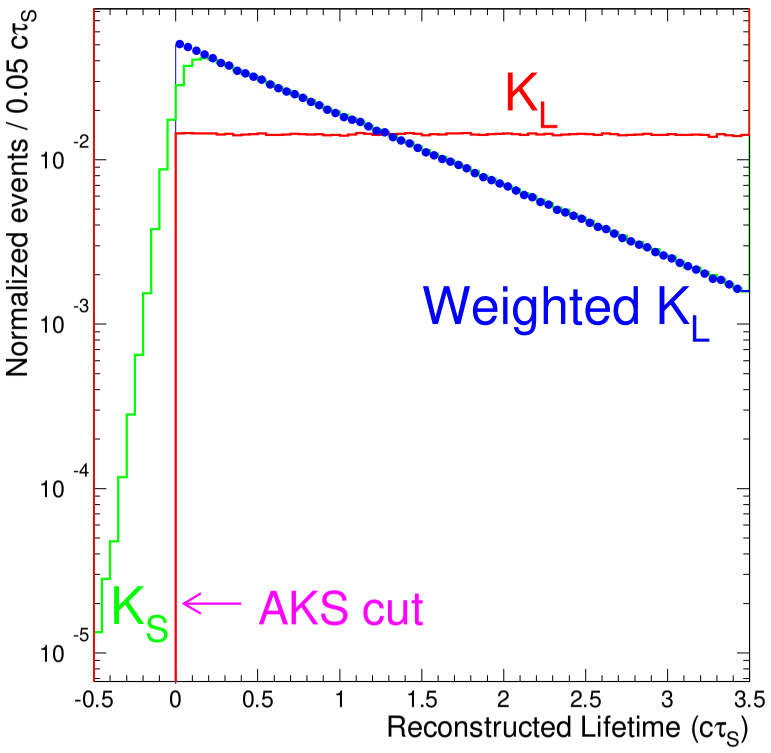
$$\delta(R) = \pm 10 \cdot 10^{-4}$$

Lifetime weighting

- K_S and K_L are collected in the same fiducial region
- Weighting K_L events as a function of decay proper time, according to expected ratio of $\pi\pi$ rates $\Rightarrow$ very similar lifetime distributions
- Accounts for small terms due to K_S and K_L interference and $K^0/\bar{K}^0$ production difference

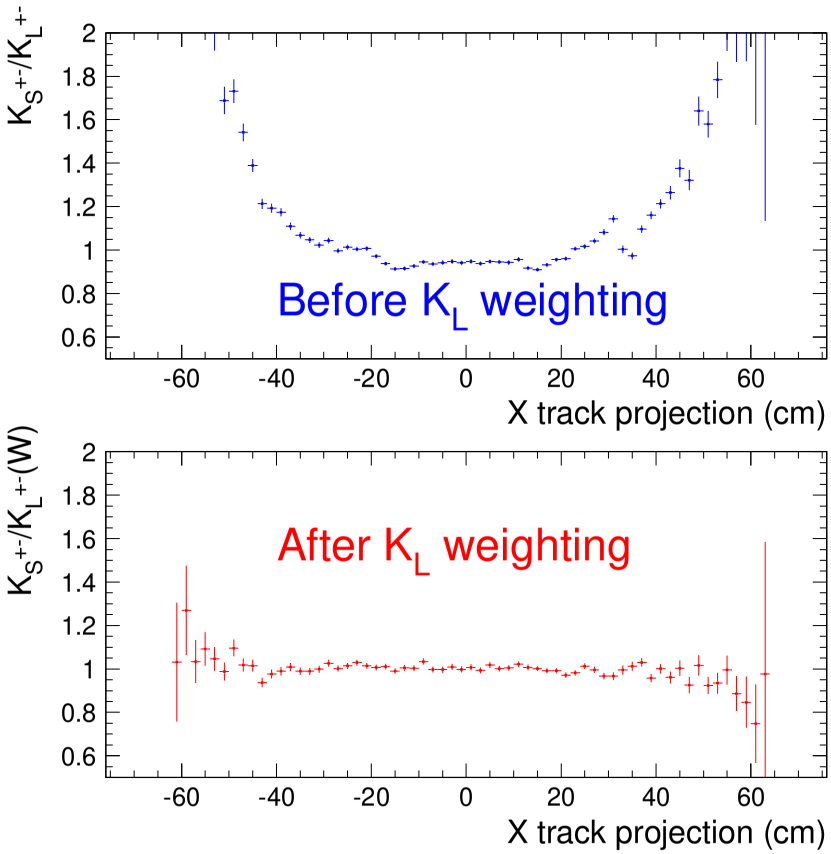
☞ Reduces potentially large acceptance corrections to $< 0.5\%$

- Increases statistical error



Acceptance correction

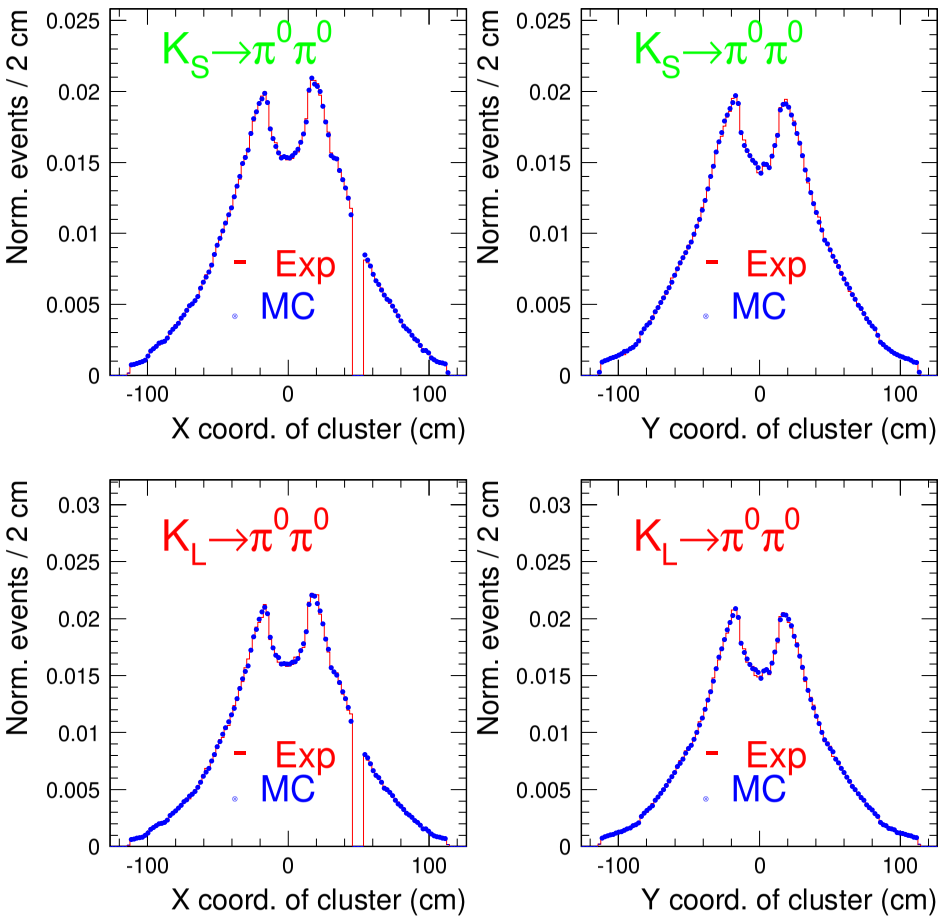
- Analysis in K^0 energy bins and lifetime weighting of K_L events minimize corrections due to K_S/K_L energy spectra and acceptance differences, making the experiment almost indipendent from MonteCarlo simulation



- K_S/K_L beam halo differences minimized by wide centre of gravity cut
- Residual K_S/K_L acceptance difference (due to beam divergence) minimized for charged mode by energy-dependent cut on $\pi^+\pi^-$ momentum asymmetry

MonteCarlo acceptance correction

❖ Residual effect studied with a full simulation of the detector, including all known deficiences (faulty channels, etc.)



❖ MonteCarlo statistics $5 \times$ data sample

☞ Averaged effect on double ratio:

$$\Delta R = (-29 \pm 11 \pm 5) \cdot 10^{-4}$$

where the first error is due to MC statistics and the second is systematic.

Corrections to R and uncertainties

Corrections and systematic uncertainties on R			
	Correction (10^{-4})	Uncertainty (10^{-4})	
Tagging dilution	+18	9	(stat.)
Tagging inefficiency	0	6	(stat.)
Charged trigger eff.	+9	23	(stat.)
Reconstruction eff.	-	3	
Neutral background	-8	2	
Charged background	+23	4	
Beam scattering	-12	3	
Accidental activity	-2	14	(stat.)
Energy scale/linearity	-	12	
Charged vertex	-	5	
Acceptance	+29	12	(MC stat.)
Total	+57	35	

$$R = 1 - 6\ \mathrm{Re}(\varepsilon'/\varepsilon)$$

Statistics

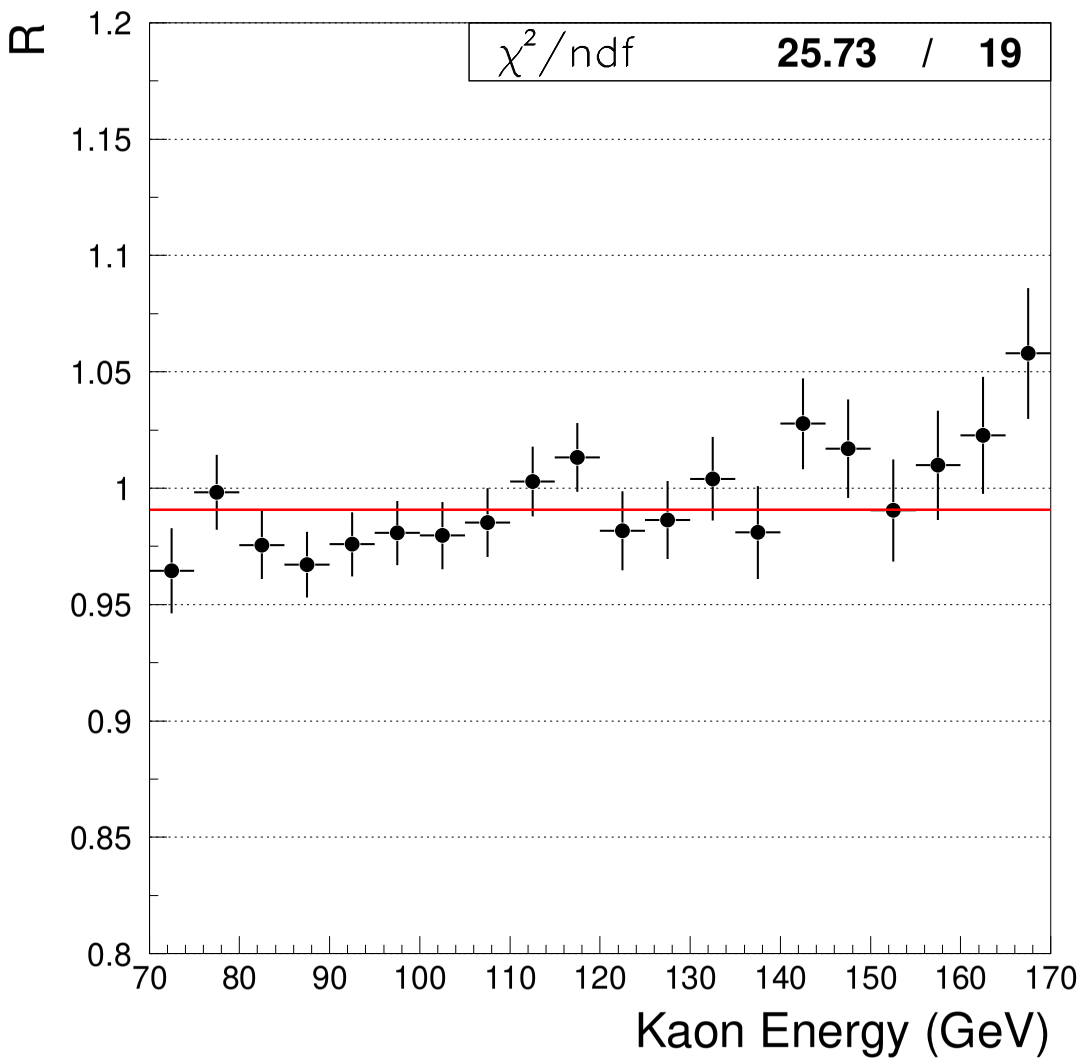
1997 event statistics
(Unweighted, tagging and background corrected)

$K_L \to \pi^0\pi^0$:	$0.49 \cdot 10^6$
$K_S \to \pi^0\pi^0$:	$0.98 \cdot 10^6$
$K_L \to \pi^+\pi^-$:	$1.07 \cdot 10^6$
$K_S \to \pi^+\pi^-$:	$2.09 \cdot 10^6$

Averaging R

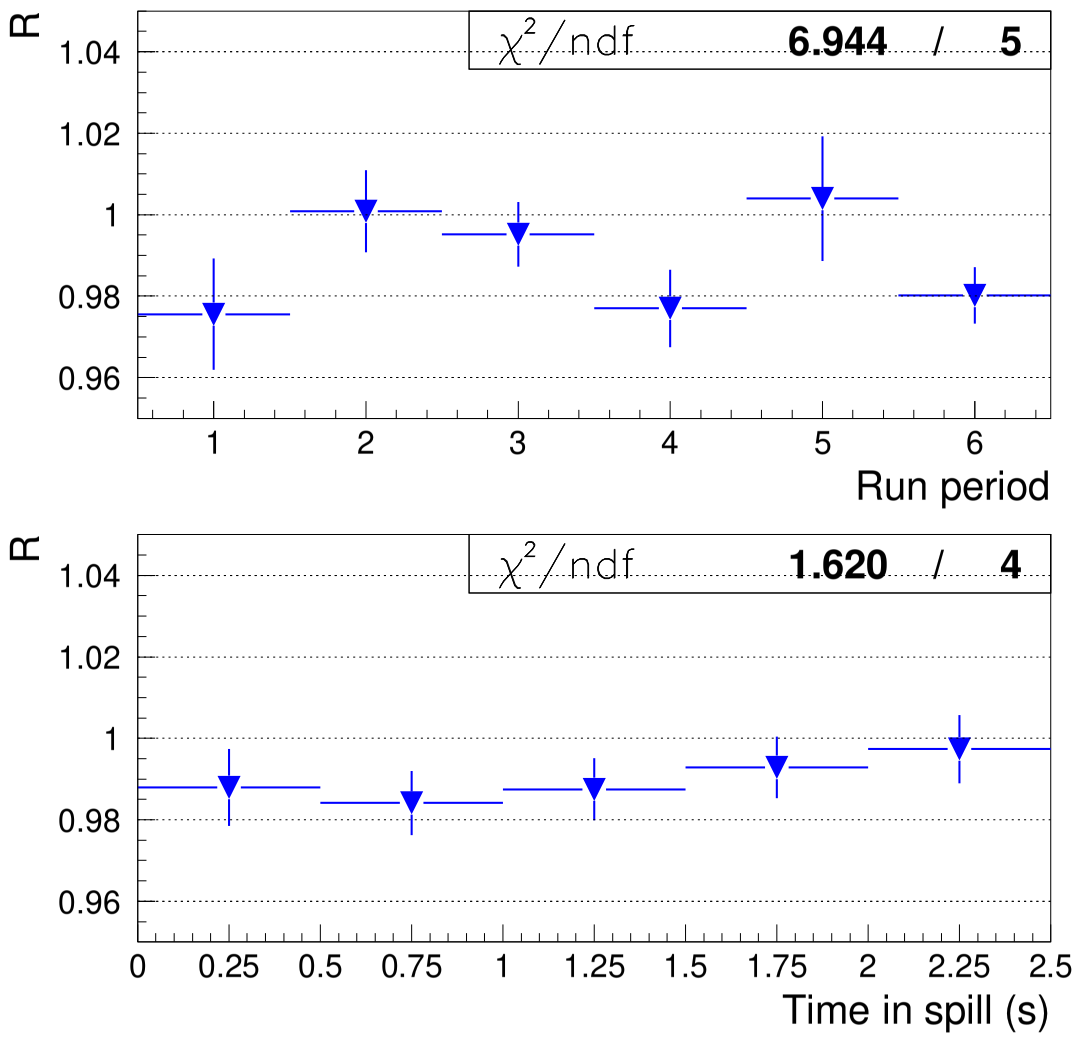
The double ratio is computed in 20 K^0 energy bins between 70 and 170 GeV/c (5 GeV/bin) and the result is averaged using an unbiased estimator.

The corrections are applied separately to each bin whenever the statistics involved makes the procedure meaningful.



Time dependence

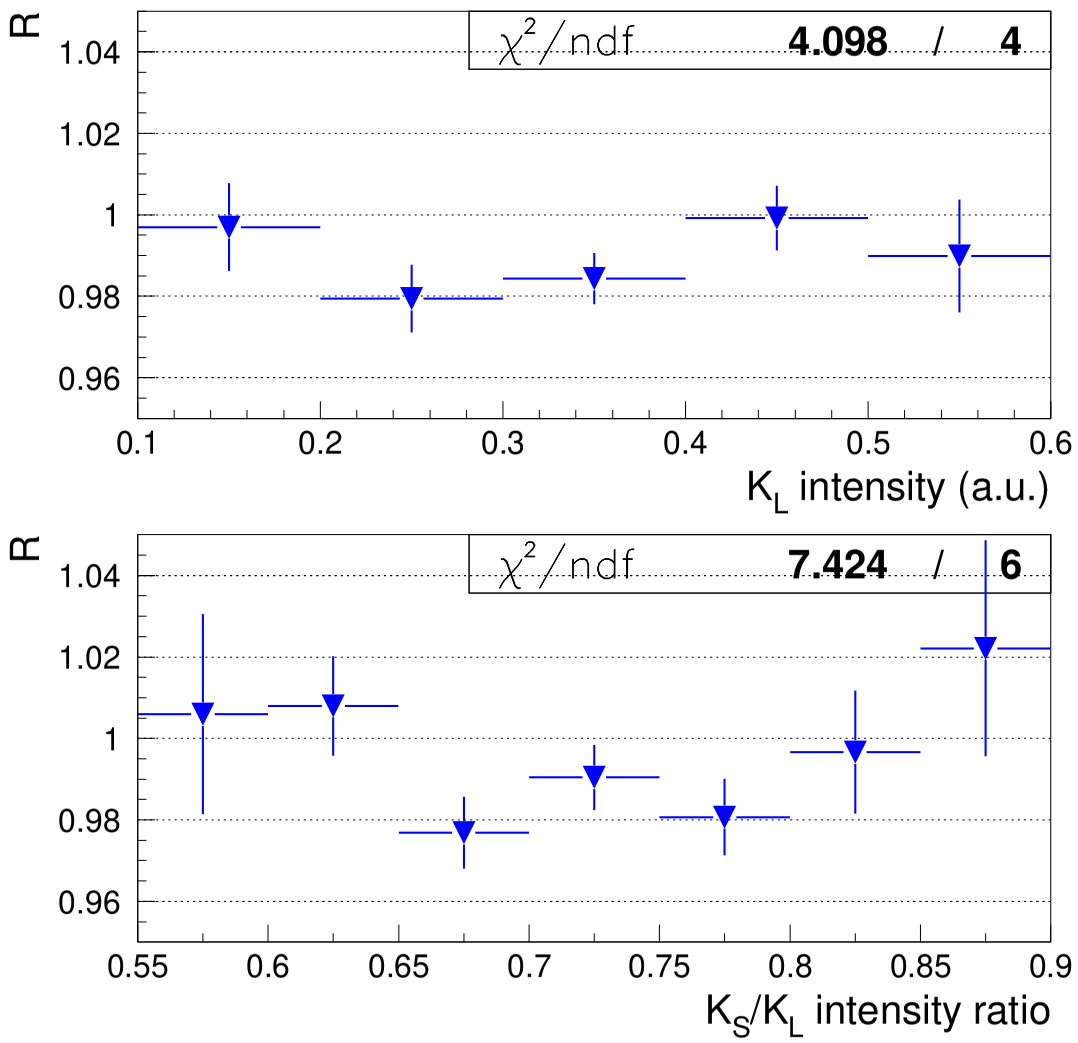
Run period dependence (changes in trigger and magnetic field configuration) and time in spill dependence:



☞ No systematic effect

Beam intensity dependence

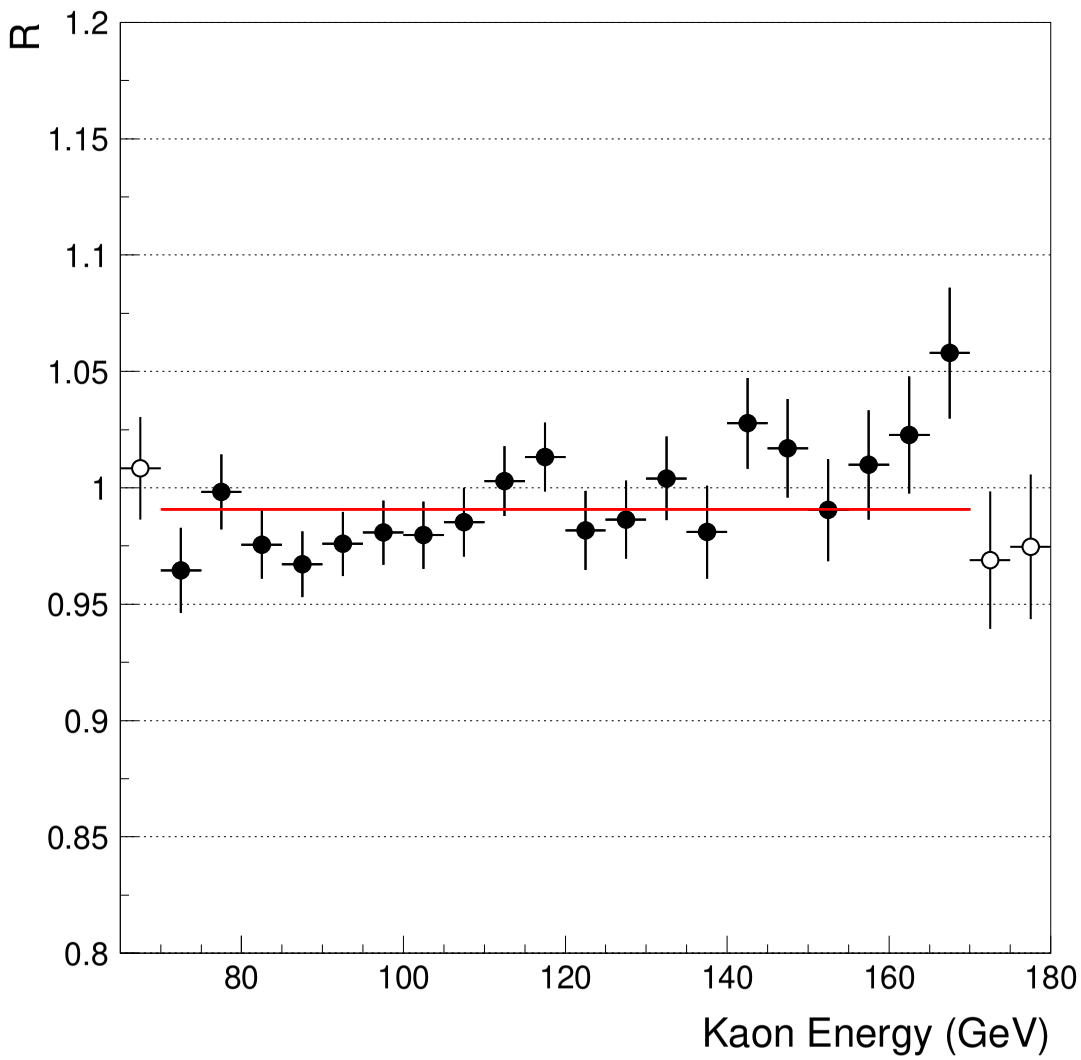
K_L beam intensity and K_S/K_L intensity ratio dependence:



☞ No systematic effect

Extended energy range

Extended K^0 energy range 65 to 180 GeV:



☞ No systematic effect

The result

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

$$(18.5 \pm 4.5 \text{ (ev. stat.)} \pm 5.8 \text{ (syst.)}) \times 10^{-4}$$

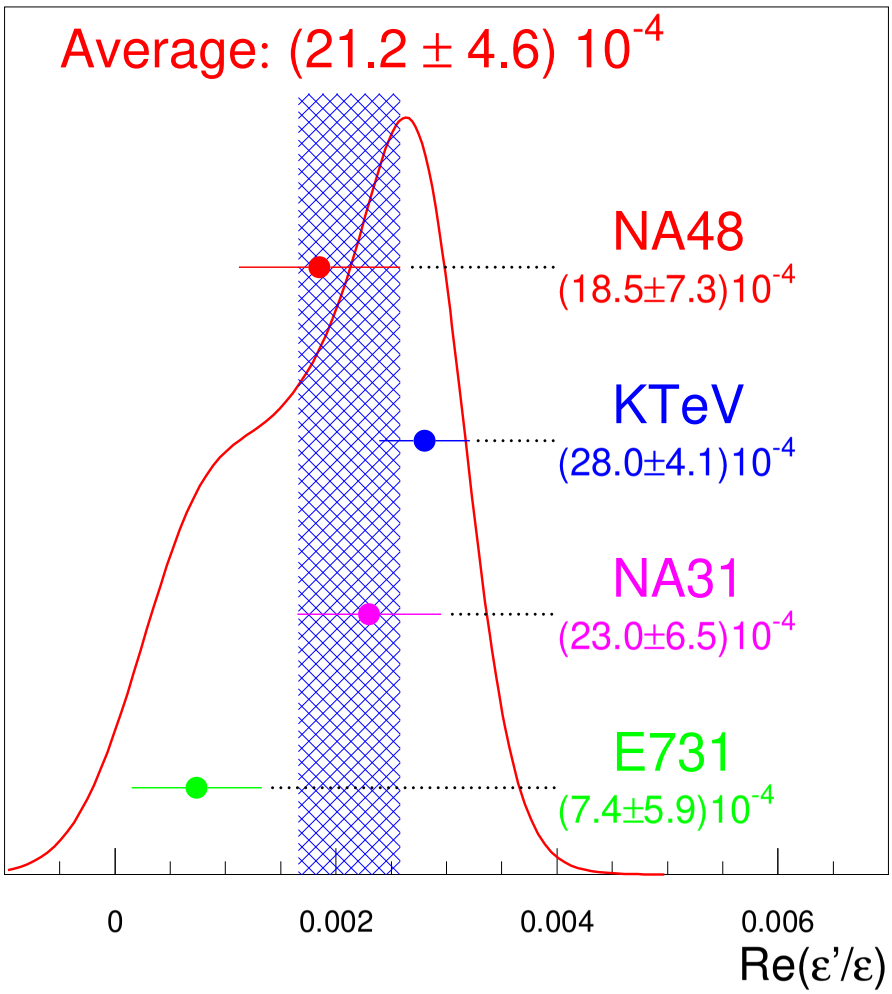
Combining all errors in quadrature:

$$\mathrm{Re}(\varepsilon'/\varepsilon) \;= (18.5 \pm 7.3) \times 10^{-4}$$

The systematic error is dominated by its statistical contribution due to the size of the control samples.

(PRELIMINARY)

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



Averaging the NA48 $\mathrm{Re}(\varepsilon'/\varepsilon)$ result			
	$\mathrm{Re}(\varepsilon'/\varepsilon)$	from 0	χ^2/ndf
+NA31	$(21.0 \pm 4.9) \cdot 10^{-4}$	4.3 σ	0.21
+E731	$(11.8 \pm 5.4) \cdot 10^{-4}$	2.2 σ	1.40
+KTeV	$(25.7 \pm 4.1) \cdot 10^{-4}$	6.3 σ	1.29

The future

- 1998 run: mid may to september 1998
  - All HV blocking capacitors of e.m. calorimeter replaced ⇒ stable operation at 3 kV
  - New carbon fibre beam pipe ⇒ reduced overflows in DCH
  - Charged trigger upgrade ⇒ higher efficiency ≈ 0.97
  - New DAQ ⇒ +30% trigger rate
  - 3 times more $\pi^0\pi^0$ statistics, 6 times more $\pi^+\pi^-$ statistics
  - Statistical error on $\mathrm{Re}(\varepsilon'/\varepsilon)$ $\approx 3 \cdot 10^{-4}$
- 1999 run: in progress
  - Improved DCH readout and DAQ
  - Aim for more data than 1998 run
- year 2000: complement statistics and systematic studies

Conclusions

The preliminary NA48 measurement of $\mathrm{Re}(\varepsilon'/\varepsilon)$

$(18.5 \pm 4.5\ \text{(ev. stat.)} \pm 5.8\ \text{(syst.)})\ \times 10^{-4}$

based on the first data-taking period, with a **new** technique, agrees with the previous NA31 result and with the recent KTeV one, establishing a non zero value of $\mathrm{Re}(\varepsilon'/\varepsilon)$

The systematic error of the preliminary result is dominated by its statistical component

The data sample for this result is a very small fraction ($\sim 10\%$) of the total expected amount which has been and is being collected by NA48 to reach its final result

Conclusions

The world average before this measurement was

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (21.7 \pm 6.1) \cdot 10^{-4}$$

(after rescaling of errors), with $\chi^2/\mathrm{ndf} = 4.2$.

The grand average of experimental results is

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (21.2 \pm 4.6) \cdot 10^{-4}$$

(after rescaling of errors), with $\chi^2/\mathrm{ndf} = 2.8$, which firmly estabilishes direct CP violation in the K^0 system with $4.6\ \sigma$ significance ($\mathrm{Re}(\varepsilon'/\varepsilon) > 13.6 \cdot 10^{-4}$ at 95% C.L.) at a level higher than typically predicted within the standard model

In view of the unsatisfactory $\chi 2$ of the world average, it is important that NA48 and KTeV still improve their precision on $\mathrm{Re}(\varepsilon'/\varepsilon)$, and that KLOE provides a new measurement, to settle better the value of this fundamental parameter