A new result on direct CP violation from the NA48 experiment

José OCARIZ
CERN - Geneva

SILAFAE-III
Cartagena de Indias, Colombia

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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

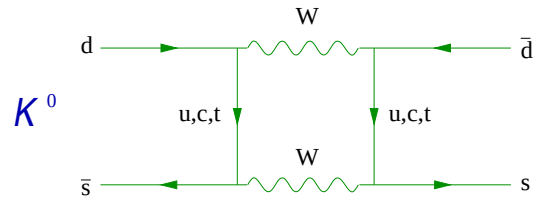
OUTLINE:

- ➜ Physics motivation
- ➜ The NA48 way: beams and detector
- ➜ Preliminary $\mathrm{Re}(\varepsilon'/\varepsilon)$ result from the 1998 data
- ➜ Checks
- ➜ Prospects

CP Violation in the Neutral Kaon System

	CP conserved	CP violated
Mass eigenstates:	$K_1 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0}) \quad (CP = +1)$	$K_S = (K_1 + \epsilon K_2)/\sqrt{1+\lvert\epsilon\rvert^2}$
	$K_2 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0}) \quad (CP = -1)$	$K_L = (K_2 + \epsilon K_1)/\sqrt{1+\lvert\epsilon\rvert^2}$

➜ 1964: K_L can decay into $\pi^+\pi^- \ (CP = +1)$ with $2 \cdot 10^{-3}$ B.R.



Indirect violation $(\Delta S = 2)$

Experimentally

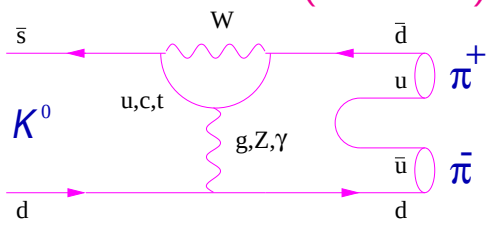
$|\epsilon| = (2.28 \pm 0.02) \cdot 10^{-3}$

$$K_L = K_2 + \varepsilon\, K_1 \qquad \pi^+\pi^-,\ \pi^0\pi^0$$

-1 +1

CP = +1

Direct violation $(\Delta S = 1)$



$$\langle I,0|T|K^0\rangle = A_I e^{i\delta_I}$$

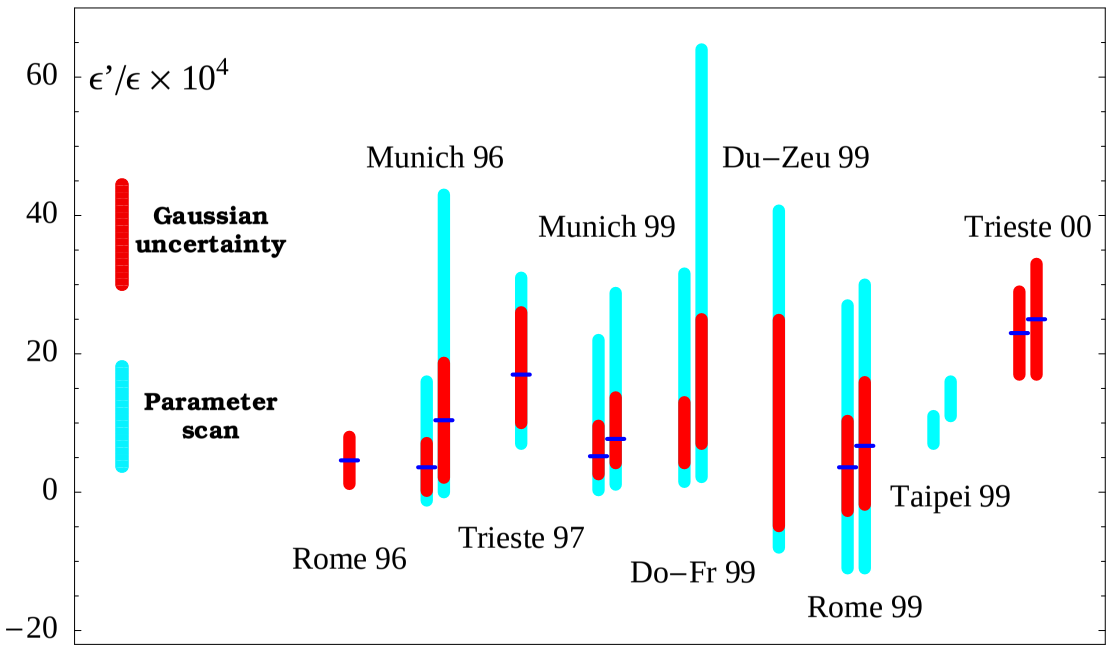
$$\langle I,0|T|\bar{K}^0\rangle = A_I^* e^{i\delta_I}$$

$$\epsilon' \equiv \frac{i}{\sqrt{2}} Im\left(\frac{A_2}{A_0}\right) e^{i(\delta_2-\delta_0)} \qquad (Im(A_0) \equiv 0)$$

$\mathrm{Re}(\varepsilon'/\varepsilon)$: Predictions and Measurements

➜ Standard Model Predictions

Computations typically point to values between 0 and 20×10^{-4}



Alternatives:

- Superweak model : ϵ'=0
- SUSY and other physics beyond SM could contribute

➜ Measurements: double ratio method

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

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

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	$(18.5 \pm 7.3) \times 10^{-4}$

The NA48 Experiment

AIM

Measurement of the double ratio

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

with $2 \cdot 10^{-4}$ final accuracy on $\mathrm{Re}(\varepsilon'/\varepsilon)$

METHOD

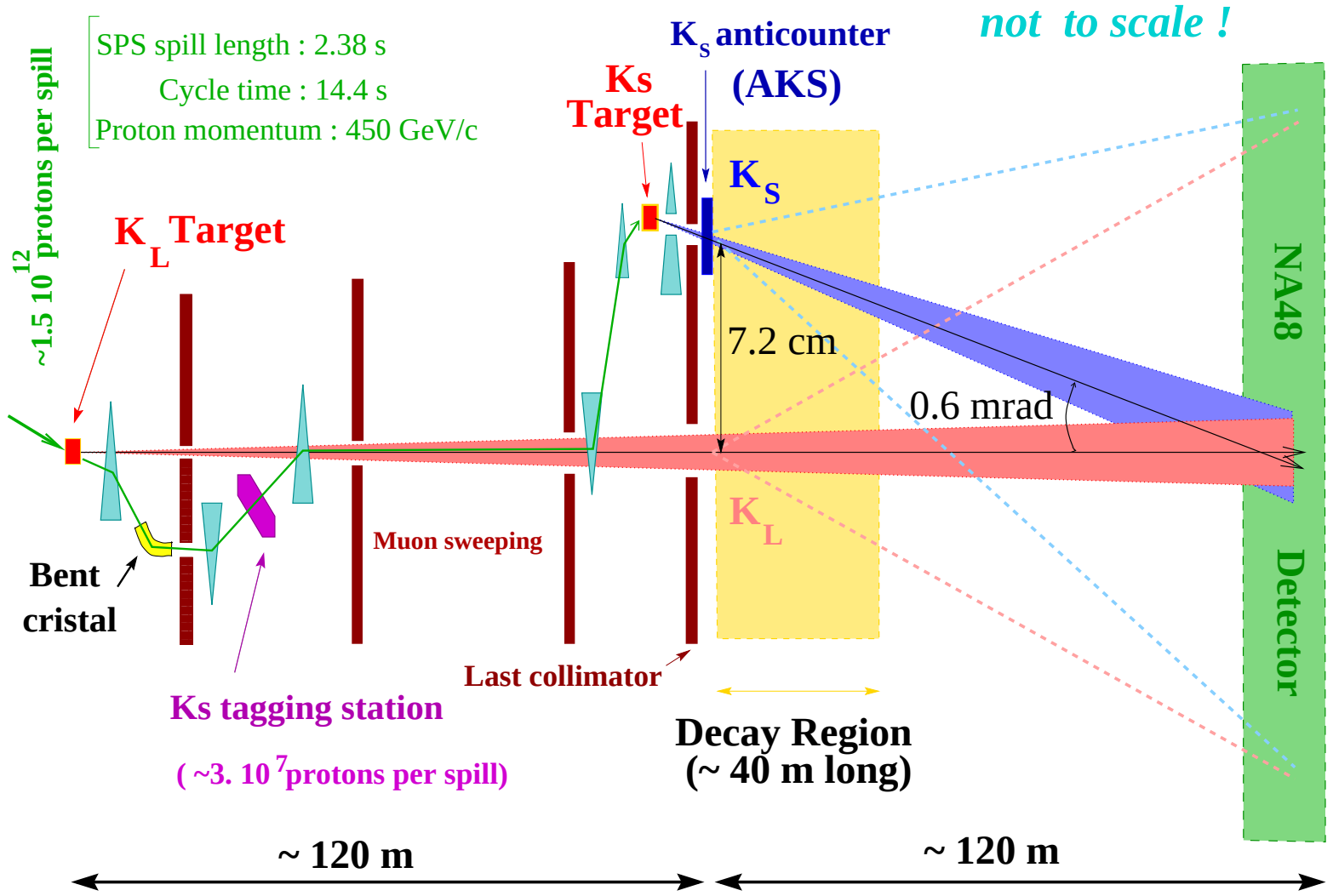
- ➜ simultaneous acquisition of the 4 decay modes
- ➜ in the same fiducial region
- ➜ from two high–intensity quasi–collinear beams
- ➜ $\mathrm{K_S}$ and $\mathrm{K_L}$ are identified by tagging in time the $\mathrm{K_S}$ beam protons
- ➜ the effects of remaining $\mathrm{K_S}$ / $\mathrm{K_L}$ differences are minimized offline:

  energy spectra: analysis is performed in 20 energy bins between 70 and 170 GeV

  lifetime: $\mathrm{K_L}$ events are weighted according to the theoretical $\mathrm{K_S}$ to $\mathrm{K_L}$ ratio of proper time distributions:

$$w(t) \sim e^{-t\left(\frac{1}{\tau_S} - \frac{1}{\tau_L}\right)}$$

The NA48 Beams



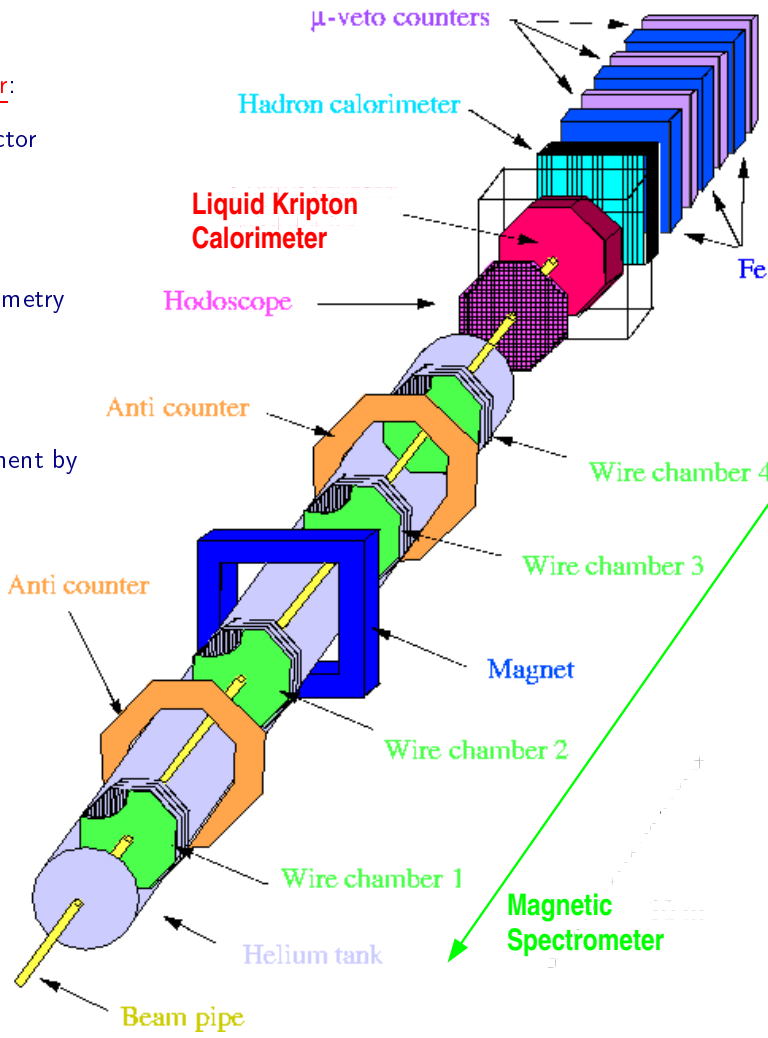
- The tagging station provides a measurement of proton time with < 200 ps resolution
- The beginning of the fiducial region is defined by an anti–counter (AKS) on the K_S beam line

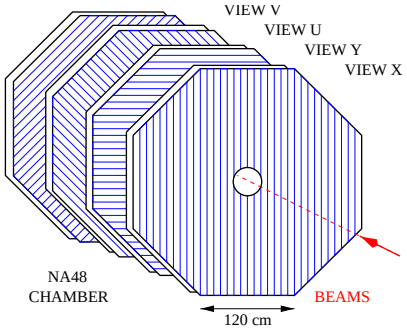
The Central Detector

$\pi^0\pi^0$

LKr electromagnetic calorimeter:

- quasi–homogeneous detector based on 9 m^3 LKr
- Cu–Be electrodes
- 13212 $2 \times 2 \times 127$ cm^3
- $\pm$ 48 mrad accordion geometry
- projective geometry
- geometry machined with 0.2 mm/m accuracy
- redundant time measurement by scintillating fiber neutral hodoscope





$\pi^+\pi^-$

Magnetic Spectrometer:

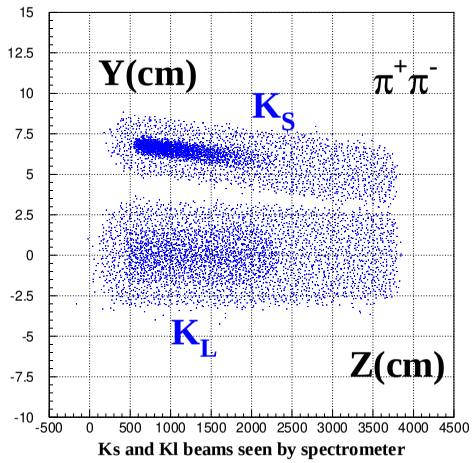
- 4 chambers with 4 views each, 2 staggered planes per view
- 90 μm spacepoint resolution
- wire position known better than 100 μm/m
- magnet providing 265 MeV/c p_T kick

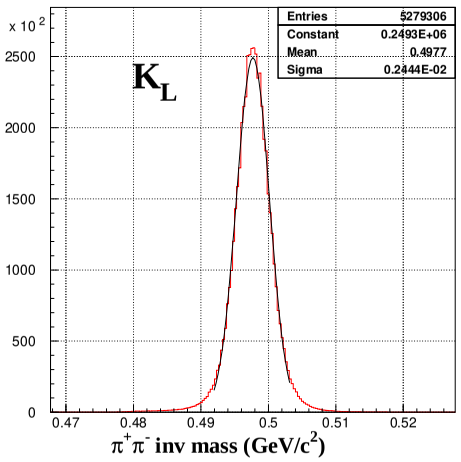
Hodoscope:

- 2 planes of scintillators for precise measurement of event time

Detector Performances

➜ Magnetic spectrometer





$\sim$ 2 mm resolution on vertex transverse position (allows beam separation)

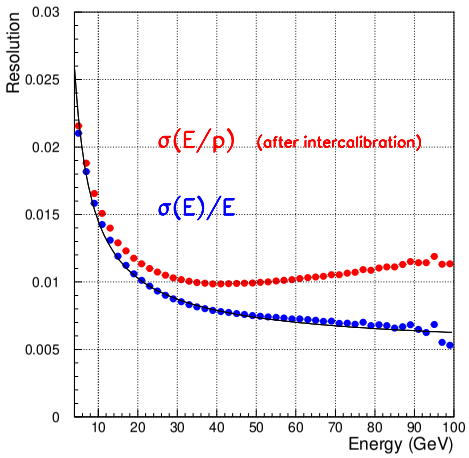
Kaon mass resolution $\sim$ 2.5 MeV/c^2

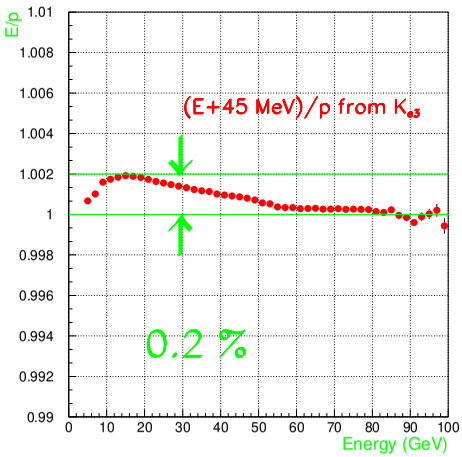
Momentum: $\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\,P[\mathrm{GeV}/c]\,\%$

➜ Charged Hodoscope

$<$ 200 ps time resolution for $\pi^+\pi^-$ event time

➜ LKr calorimeter





Energy resolution:

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{100\ MeV}{E} \oplus 0.5\%$$

(E in GeV)

Non–Linearity $<$0.2% (from 5 to 100 GeV)

Time resolution for $\pi^0\pi^0$ event time: $<$ 250 ps

Data Samples

1997 89 days @ 1×10^{12} ppp on $\mathrm{K_L}$ target

0.49 million of $K_L \to \pi^0\pi^0$

PUBLISHED Phys. Lett. B 465 (1999) 335-348

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

1998 135 days @ 1.4×10^{12} ppp on $\mathrm{K_L}$ target

Main improvements :

- Improved charged trigger (efficiency 91.3 $\to$ 97.7 %) and DAQ $\Longrightarrow$ + 30 % rate
  no downscaling for charged
- LKr High Voltage 1500 $\to$ 3000 V (new capacitors)
- Lighter beam pipe $\to$ less showers in the detector

1.14 million of $K_L \to \pi^0\pi^0$

PRELIMINARY RESULT in this presentation

1999 128 days @ 1.4×10^{12} ppp on $\mathrm{K_L}$ target

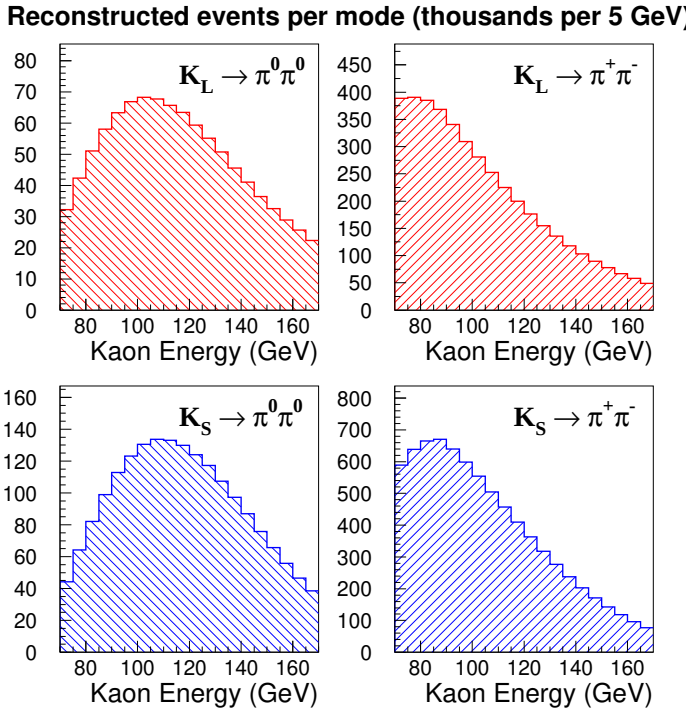
Further improvements in DCh read-out, DAQ, spill length

Around 2 millions of $K_L \to \pi^0\pi^0$

Analysis in progress...

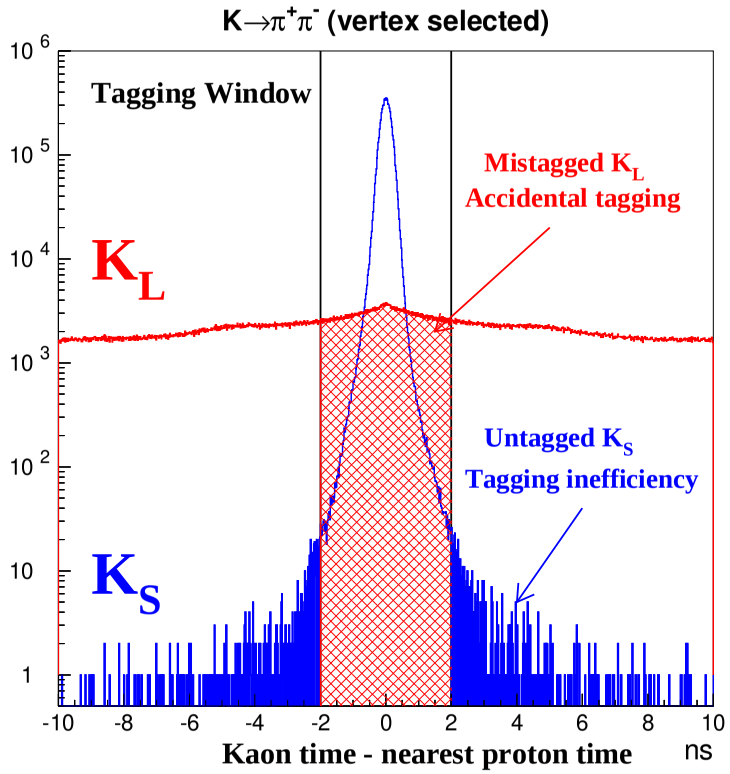
Analysis Strategy

- General cuts:
  - 70 $<$ Kaon Energy $<$ 170 GeV
  - center of gravity at LKr within 10 cm from center
  - decay proper time within 3.5 $\mathrm{K_S}$ lifetimes from AKS. $\mathrm{K_L}$ events are weighted according to the lifetime ratio. The upstream cut is done for $\mathrm{K_S}$ events using the AKS signal.
  - events taken with some dead time condition ($<$ 5 % from charged trigger and $\sim$ 25 % from overflow in DCh readout) are rejected for both charged and neutral modes
- $\mathrm{K_S}$ and $\mathrm{K_L}$ are identified using the tagger and event counts in each energy bin are then corrected for mistagging (as measured for charged events using vertex).
- R is computed in each bin using an unbiased estimator



- A set of small corrections are applied to the double ratio in each energy bin to account for:
  - charged / neutral difference of mistagging probabilities
  - background
  - residual $\mathrm{K_S}$ / $\mathrm{K_L}$ acceptance difference
  - trigger inefficiencies
  - energy scale and non–linearity
  - accidental activity

Tagging



➜ 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 $(K_L \to K_S)$ $\alpha_{LS}^{+-} = (11.05 \pm 0.01)\%$

➜ $\alpha_{SL}^{+-} - \alpha_{SL}^{00}$ is measured through

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

$$|\alpha_{SL}^{00} - \alpha_{SL}^{+-}| < 0.5 \times 10^{-4} \implies \text{R correction} < 3 \cdot 10^{-4}$$

➜ $\alpha_{LS}^{+-} - \alpha_{LS}^{00}$ is measured by

- 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 $K_L \to 3\pi^0$

$$\alpha_{LS}^{00} - \alpha_{LS}^{+-} = (0.3 \pm 4.2) \times 10^{-4}$$

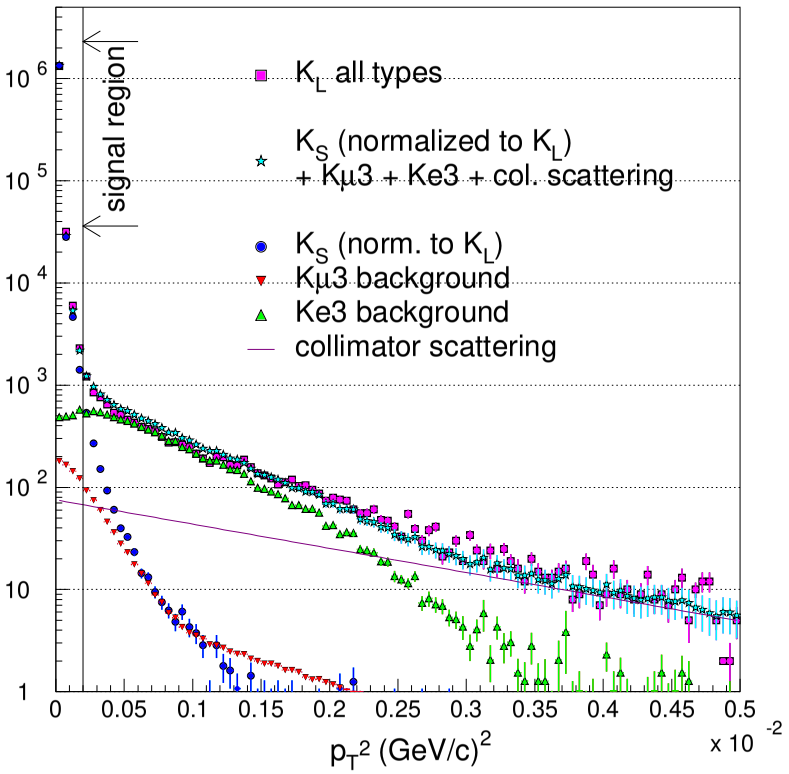
$$\implies \text{R correction} = (0.6 \pm 8.4) \times 10^{-4}$$

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

➜ Dominated by $K_L \to \pi e \nu$ and $K_L \to \pi \mu \nu$

Rejected using:

- muon veto counters
- $E_{LKr}/P_{DCh} < 0.8$
- invariant mass $m_{\pi\pi} = M_{K^0} \pm 3\sigma$
- total transverse momentum $p_T^2 < 200$ (MeV/c)^2



➜ Estimated by fitting the $\mathrm{K_L}$ distribution as $\pi^+\pi^- + \mathrm{K}_{e3} + \mathrm{K}_{\mu 3}$ in a control region in the plane $(m_{\pi\pi}, p_T^2)$

$\Longrightarrow$ Total Background = $\boxed{(19 \pm 3) \cdot 10^{-4}}$

➜ A small $K \to \pi\pi$ signal is observed at high p_T for the $\mathrm{K_L}$, coming from scattering + $\mathrm{K_S}$ regeneration in the collimators.

Different cuts for charged and neutral modes

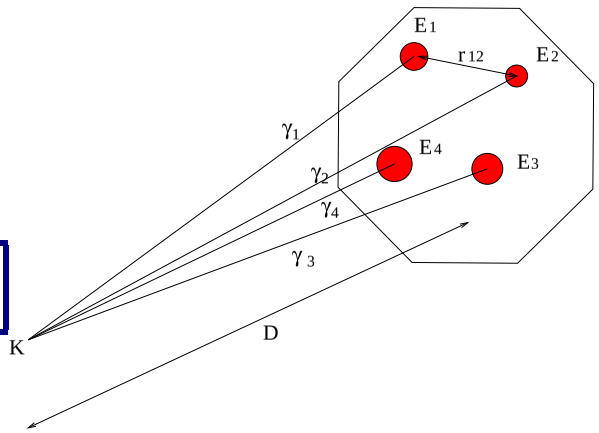
$\Longrightarrow$ R correction $= (-9.9 \pm 3.3) \cdot 10^{-4}$

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

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

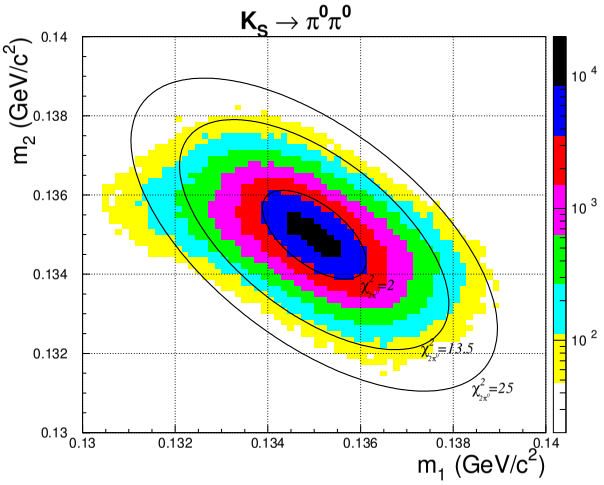
Imposing K^0 mass :

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



➜ Measure "best" π^0 masses $\quad m_{ij} = \sqrt{E_i E_j}\,.\,r_{ij}/D$

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

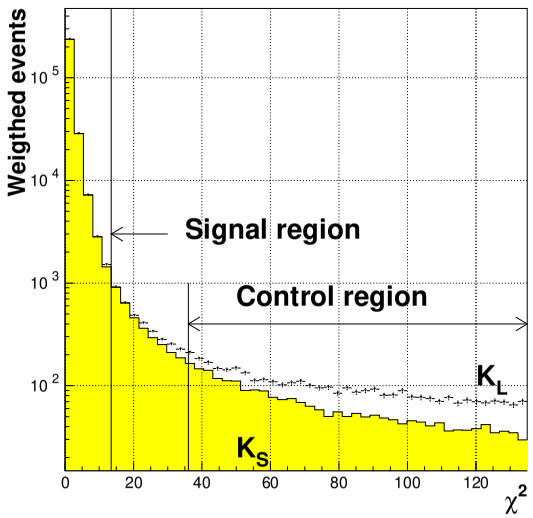


$\sigma_+ \sim 0.45$ MeV

$\sigma_- \sim 0.85$ MeV

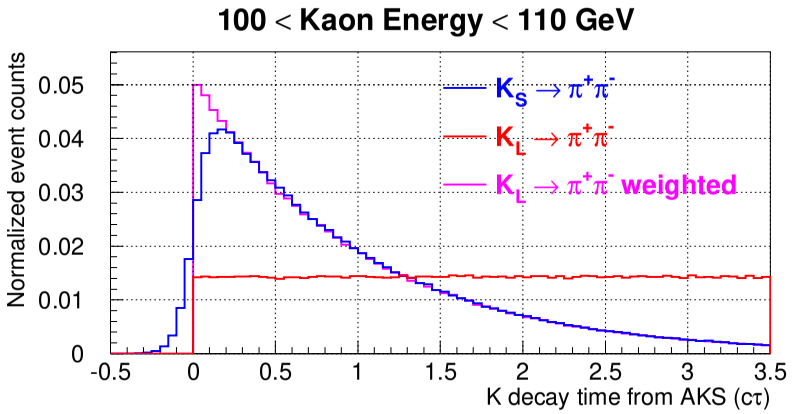
Total background (estimated in χ^2 control region)

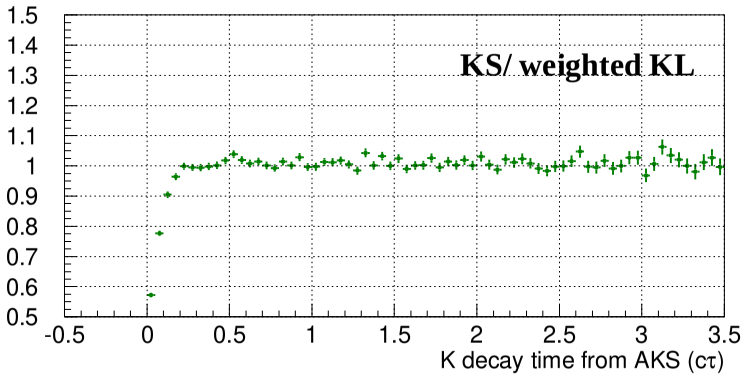
$= (6.6 \pm 2.0) \cdot 10^{-4}$



K_L weighting and Acceptance

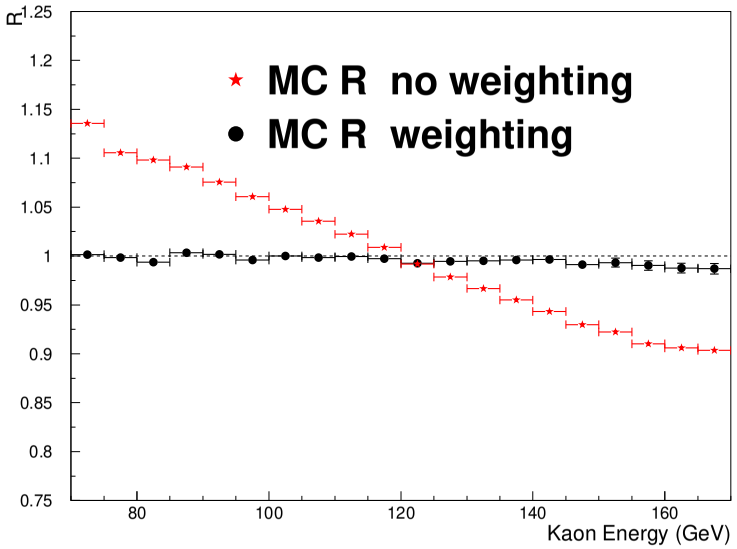
K_L events are weighted according to the K_S /K_L ratio of proper time distributions





➜ The acceptance correction is reduced to a few per mill

➜ The price to pay is a 35 % increase of the statistical error



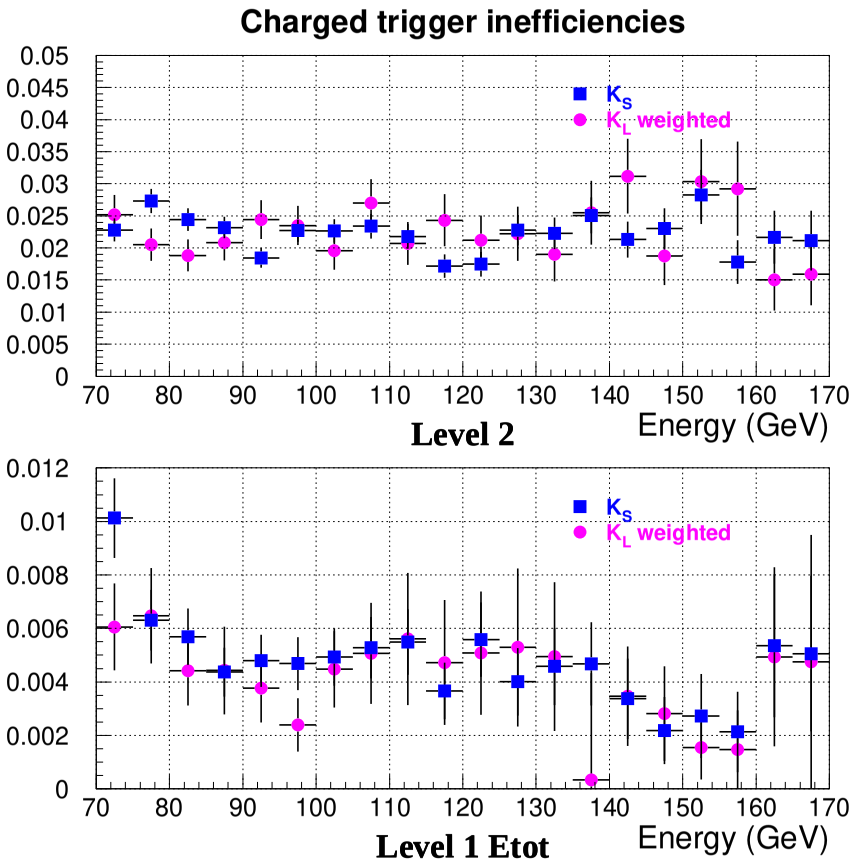
$$\text{R correction} = (+31 \pm 6(stat) \pm 6(syst)) \times 10^{-4}$$

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 %

$\mathrm{K_S}$ / $\mathrm{K_L}$ symmetry checked through control triggers



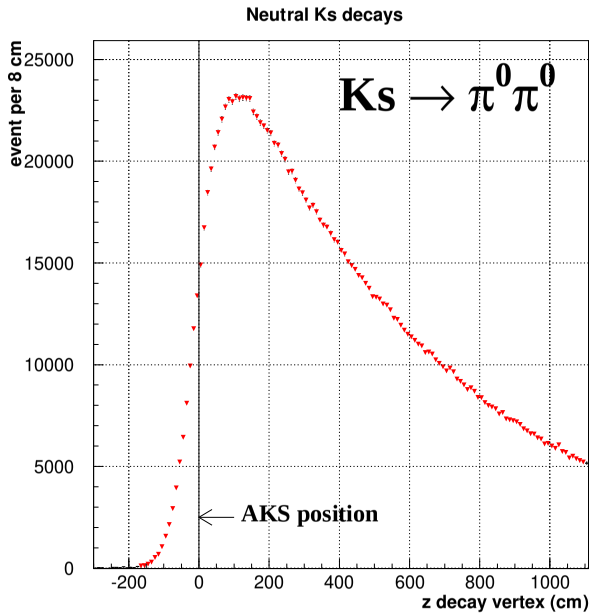
$$\mathrm{R\ correction} = (-1 \pm 11) \times 10^{-4}$$

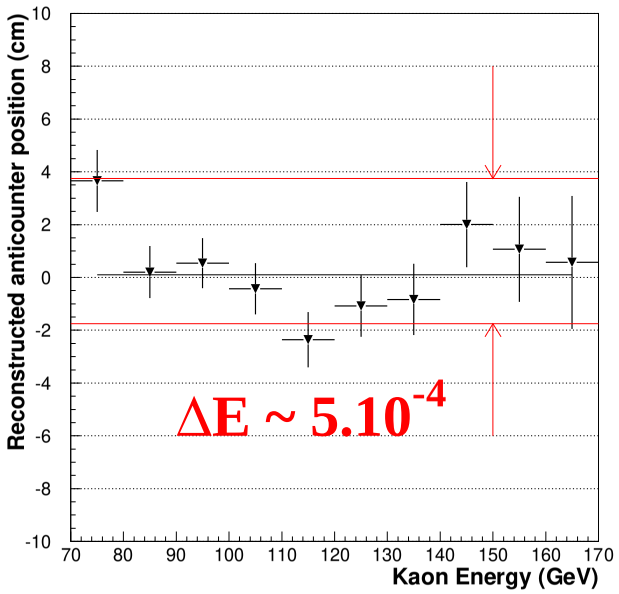
➜ Neutral Trigger

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





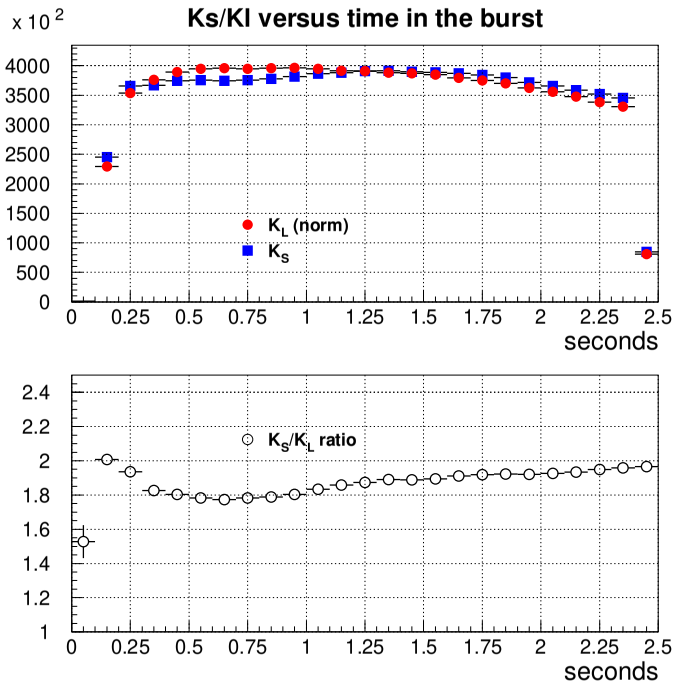
The global energy scale ($\rightarrow$ distance scale) for neutral events is fixed by fitting the reconstructed Z distribution with the AKS position.
The uncertainty is $5 \cdot 10^{-4}$
$\Longrightarrow \Delta R = \pm 3 \cdot 10^{-4}$

➜ Other sources of error from neutral reconstruction are non–linearity ($\pm 5 \cdot 10^{-4}$), non–gaussian tails in σ_E ($\pm 5 \cdot 10^{-4}$), transverse scale ($\pm 3 \cdot 10^{-4}$), accuracy of intercalibration ($\pm 3 \cdot 10^{-4}$)

$\Longrightarrow$ total uncertainty on R $= \pm 10 \cdot 10^{-4}$

Accidental Activity

➜ The simultaneity and intensity correlation of the two beams minimizes the effect of accidentals



➜ The geometrical difference of the effect for the two beams is estimated by overlaying random–triggered events to good events. The resulting losses and gains lead to

$$\text{R correction} = (2 \pm 6) \cdot 10^{-4}$$

➜ The residual $\mathrm{K_S}$ / $\mathrm{K_L}$ difference in intensity can produce a bias if losses are not symmetric for charged and neutrals. We measure that

- accidental out–of–time activity is identical for $\mathrm{K_S}$ and $\mathrm{K_L}$ within 1 %
- asymmetric losses on $\pi^+\pi^-$ and $\pi^0\pi^0$ are $< 2.5\%$

$\Longrightarrow$ we presently quote a conservative limit

$$\boxed{\Delta\ \mathrm{R} < 10 \cdot 10^{-4}}$$

➜ Further studies in progress will hopefully reduce this error.

The Result from 1998 data

Statistics (millions) 1998			
$K_S \to \pi^+\pi^-$	7.46	$K_L \to \pi^+\pi^-$	4.87
$K_S \to \pi^0\pi^0$	1.80	$K_L \to \pi^0\pi^0$	1.14

$$\Longrightarrow \boxed{R_{RAW} = 0.98899 \pm 0.00173 \text{ (stat)}}$$

Corrections and systematic uncertainties on R (Units = 10^{-4})		
Accidental tagging ($\pi^0\pi^0/\pi^+\pi^-$ asymmetry)	+1	± 8
Tagging inefficiency ($\pi^0\pi^0/\pi^+\pi^-$ asymmetry)	–	± 3
Background to $\pi^+\pi^-$	+19	± 3
Beam scattering and regeneration	–10	± 3
Background to $\pi^0\pi^0$	–7	± 2
Acceptance and K_S anti-counter	+31	± 9
Charged trigger inefficiency	–1	± 11
Neutral reconstruction	–	± 10
Charged reconstruction	+2	± 2
Accidental activity and in–time background	+2	± 12
Total	+37	± 24

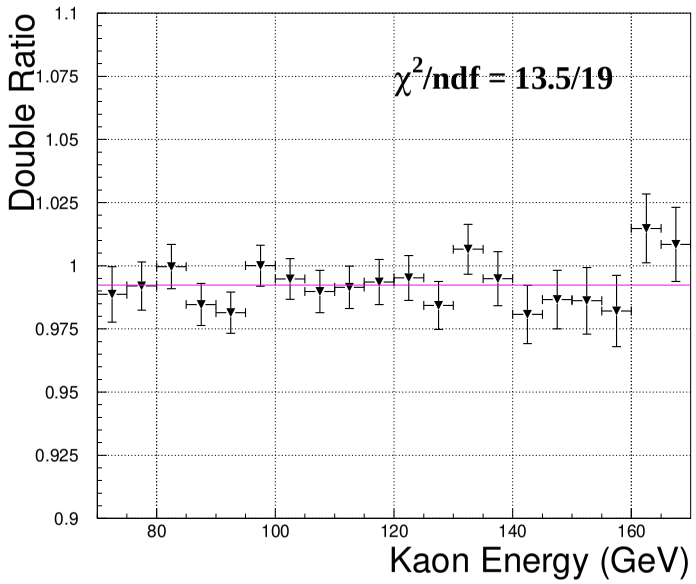
(errors in green are mostly of statistical nature)

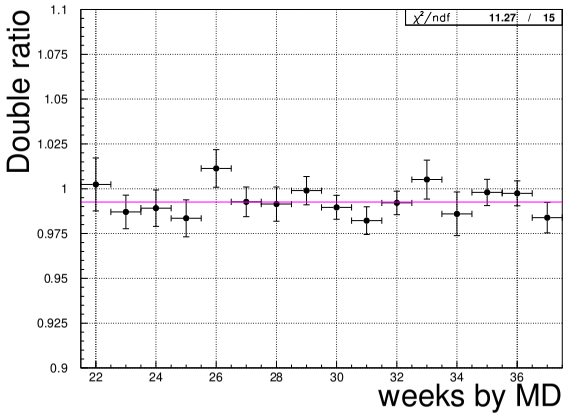
PRELIMINARY RESULT OF 1998 DATA:

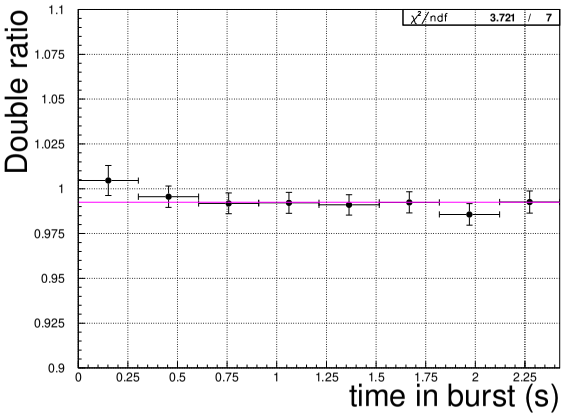
$$Re\left(\frac{\epsilon'}{\epsilon}\right) = \frac{1-R}{6} = (12.2 \pm 2.9\ (\text{stat.}) \pm 4.0\ (\text{syst.})) \times 10^{-4}$$

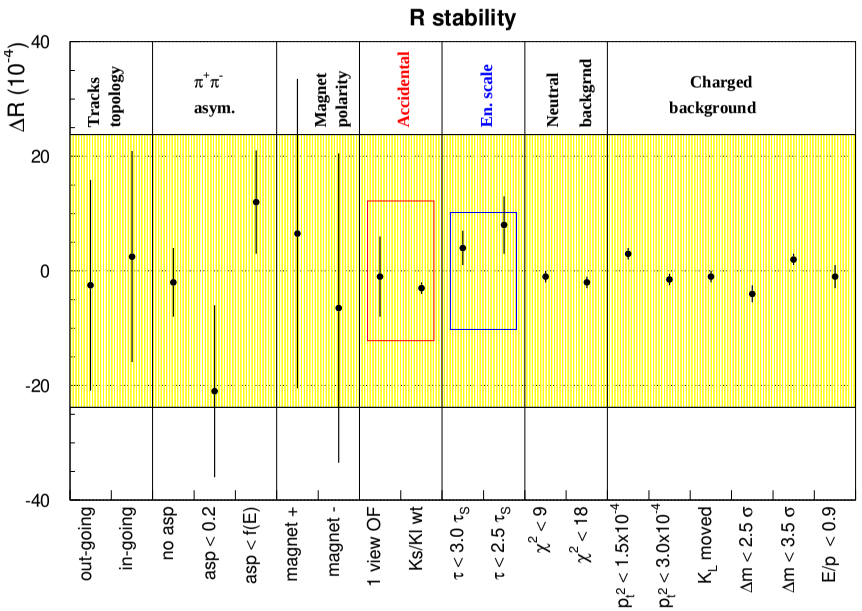
$$\boxed{\text{Re}(\varepsilon'/\varepsilon) = (12.2 \pm 4.9) \times 10^{-4}}$$

Stability Checks









Prospects

- ➜ Analysis of 1998 data is continuing and some systematic uncertainties will be probably reduced

- ➜ Data taken in 1999 are being analyzed

The implosion of the carbon fiber beam pipe occurred last November has damaged all four drift chambers

NA48 has already been granted for the chamber repair

- ➜ The ϵ' program will be completed in year 2001. During the 2000 and 2001 runs we will perform dedicated runs to study systematic effects.

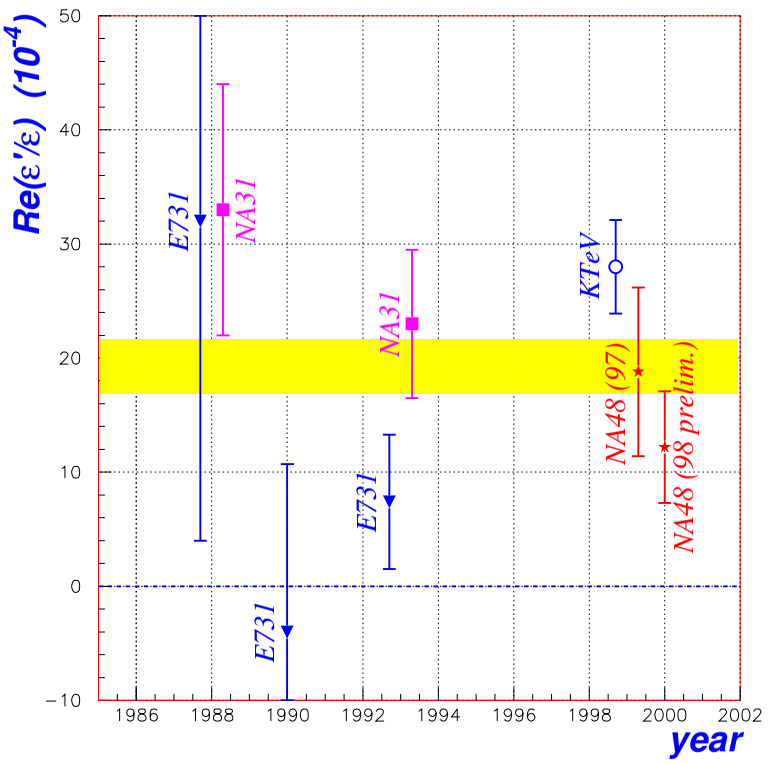
Conclusions

- NA48 has presented a new preliminary result on direct CP violation in the neutral kaon system based on the 1998 data sample:

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

- Combining this measurement with the NA48 published result (taking into account the small correlated systematics), we obtain:

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



- the world average value for $\mathrm{Re}(\varepsilon'/\varepsilon)$ becomes

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (19.3 \pm 2.4) \times 10^{-4}$$

$$(\chi^2/ndf = 11.1/5)$$

- looking forward for final results from NA48 and KTEV, and new results from KLOE.

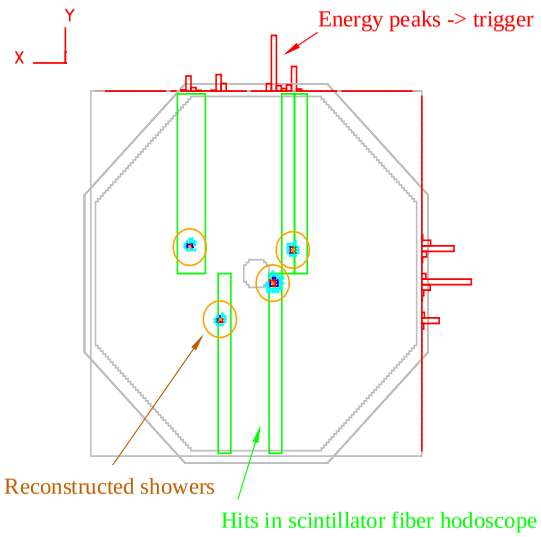
What follows is spare material to be used in case of questions

Triggers

For $\pi^0\pi^0$ selected events

- Fully pipelined system using LKr cell information to compute energy and z position.
- Output rate ~ 2 kHz
- Negligible dead time
- Efficiency :

  99.93 ± 0.02 %

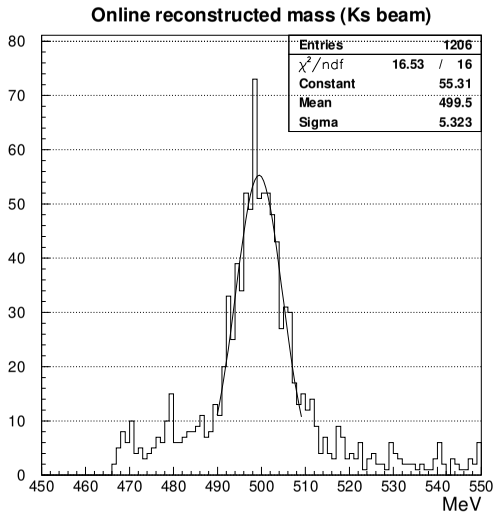


For $\pi^+\pi^-$ selected events

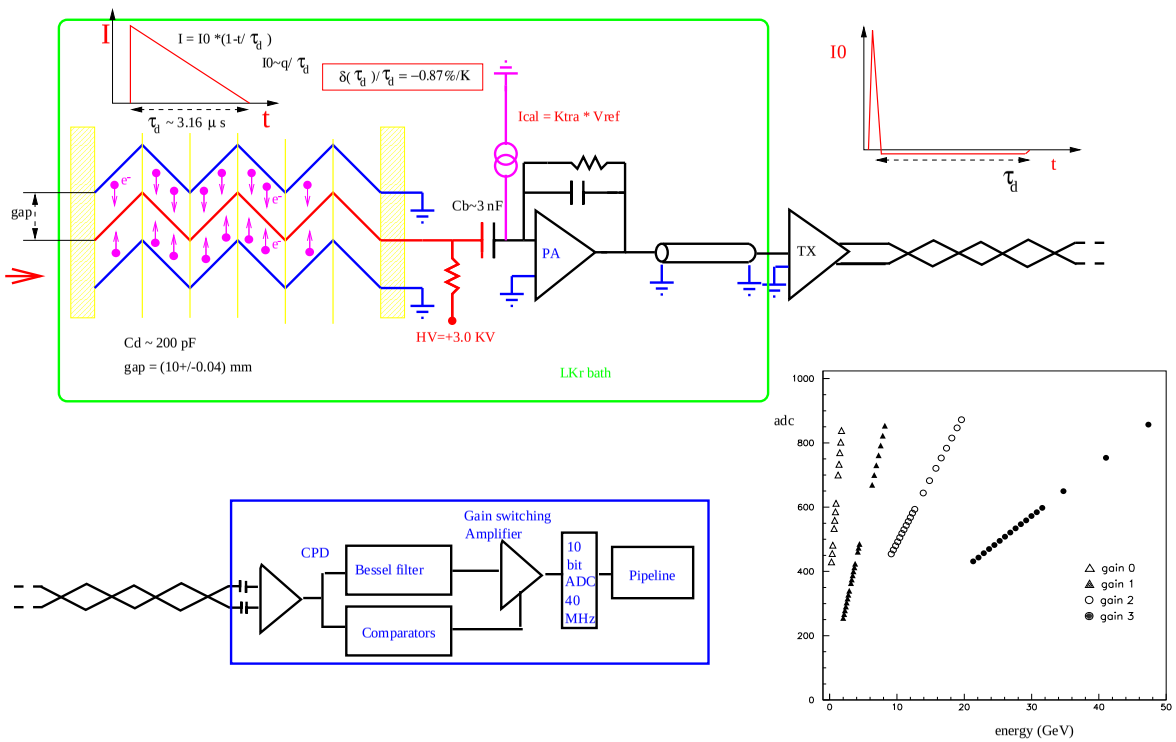
- Level 1 :

	Efficiency
+ Energy in calorimeters > 35 GeV	99.49 ± 0.03 %
+ Two track topology in hodoscope	99.95 ± 0.01 %
+ Two track multiplicity in chamber 1	> 99.99 %

- Level 2 : asynchronous online processing of vertices and $\pi\pi$ invariant mass.
  - Max latency $\sim 102\ \mu s$
  - Rejection ~ 45
    $\rightarrow$ 2 kHz output
  - Dead Time $< 5\%$
    monitored and
    applied to $\pi^0\pi^0$
  - Efficiency $97.75 \pm 0.05\%$



LKr Read out and Calibration

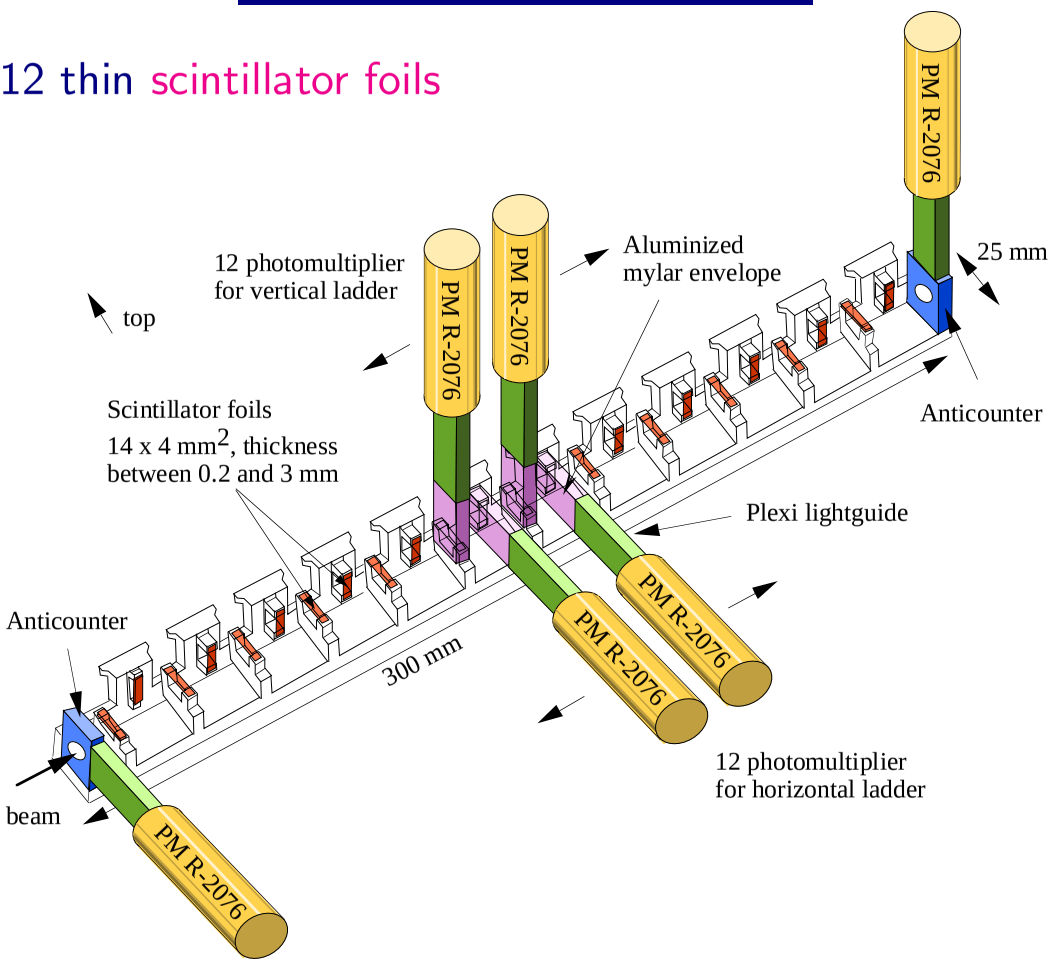


- In cold: Signal pre-amplification
- On feedthroughs: amplify and reshape the signal
- CPD: Shaping, 4 Gains $\times$ 10 bit FADC (dynamic range from $\approx$3.5 MeV to $\approx$50 GeV per cell), asynchronous 40MHz sampling

- Regular calibration during data taking to check offset and gain stability to $\approx 0.1\%$
- Time offsets calculated using Physics events (photons)

The Tagging Station

2 × 12 thin scintillator foils

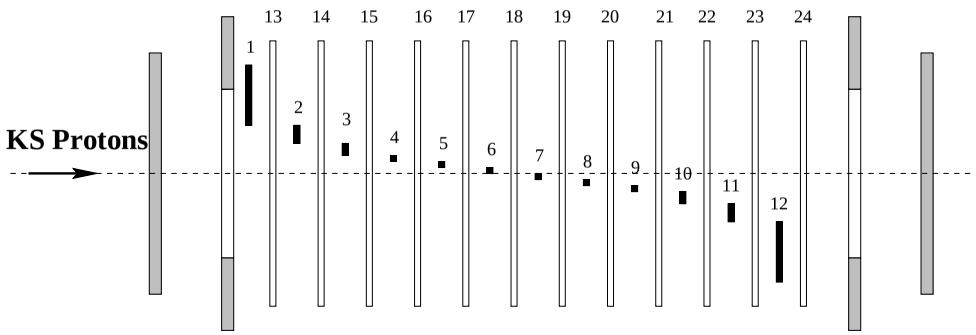


Proton rate : 28 MHz → split the intensity between foils

read-out by Flash-ADC 8 bits at 960 MHz

⇒ Time resolution : $200\ ps$

⇒ Double pulse separation : $4\ ns$



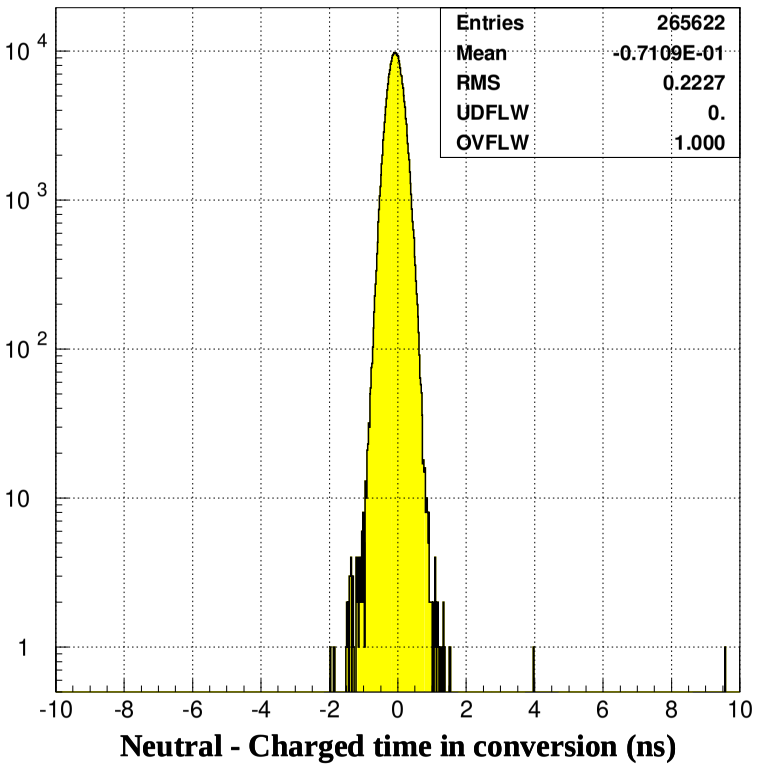
Tagging Inefficiency (K_S taken as K_L)

R sensitivity to tagging inefficiency :

$$\Delta R \simeq 6.0 \times (\alpha_{SL}^{+-} - \alpha_{SL}^{00})$$

➜ The contribution to inefficiency from the tagger is highly symmetric between $\pi^0\pi^0$ and $\pi^+\pi^-$ (checked in $\mathrm{K_S}$ only runs).

➜ Comparison of charged and neutral times in $\mathrm{K_L}$ and $\mathrm{K_S}$ neutral events ($3\pi^0$ and $2\pi^0$) containing a conversion.



$$\Rightarrow |\alpha_{SL}^{+-} - \alpha_{SL}^{00}| < 0.5 \times 10^{-4}$$

$$\Rightarrow \boxed{\text{Effect on } R < 3 \times 10^{-4}}$$

Cross-checks:

- measure the inefficiencies in $\mathrm{K_S}$ only runs :
  $\alpha_{SL}^{00} = (1.3 \pm 0.5) \times 10^{-4}$ $\quad$ $\alpha_{SL}^{+-} = (1.4 \pm 0.2) \times 10^{-4}$

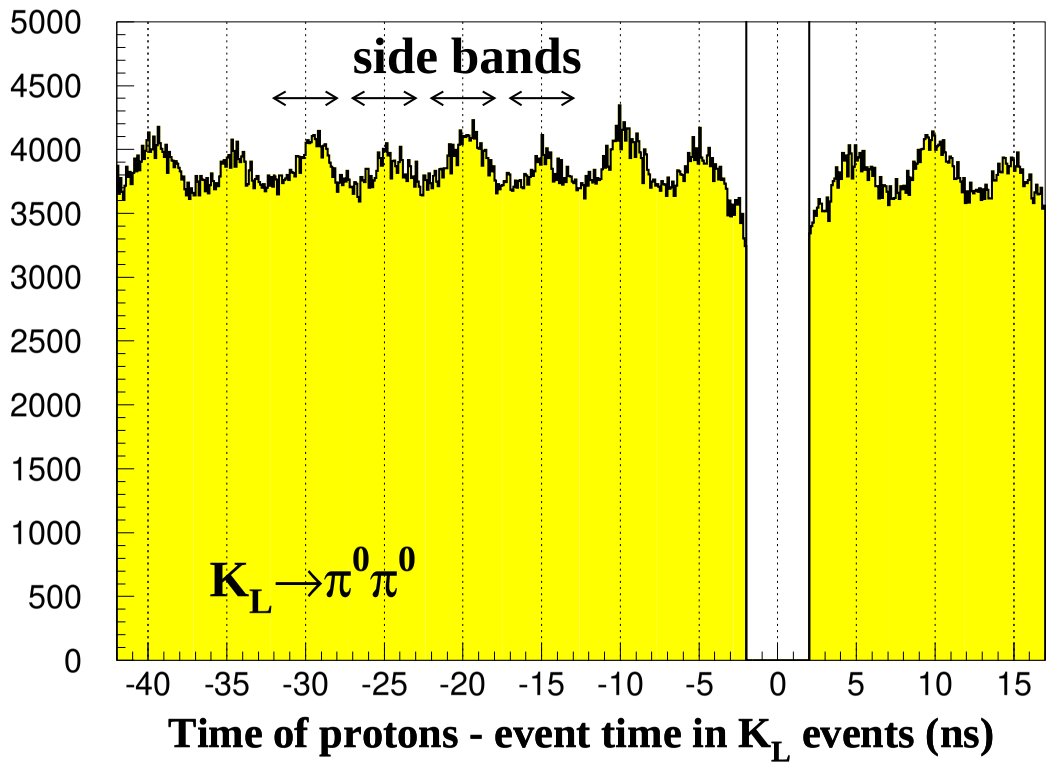
Accidental tagging (K_L taken as K_S)

R sensitivity to accidental tagging :

$$\Delta R \simeq 2.0 \times (\alpha_{LS}^{00} - \alpha_{LS}^{+-}) = 2.0 \times (\Delta\beta + \Delta W)$$

- With tagged $\mathrm{K_L} \to 2\pi$ (no proton), we compute the difference between charged and neutral rates in 4 ns wide SIDE-BANDS :

$$\beta_{LS}^{00} - \beta_{LS}^{+-} = (5.3 \pm 1.6) \times 10^{-4}$$



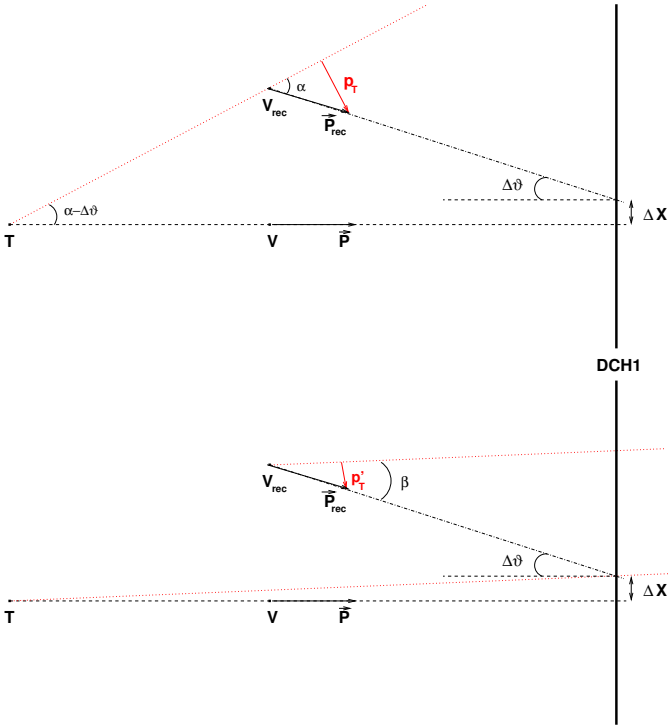
- Differences of activity between central and side bands estimated with $K_L \to 3\pi^0$ and $K_L \to \pi^+\pi^-$ vertex-id.

$$W^{00} - W^{+-} = (-5.0 \pm 3.9) \times 10^{-4}$$

(Improvement to come from more $3\pi^0$ processing)

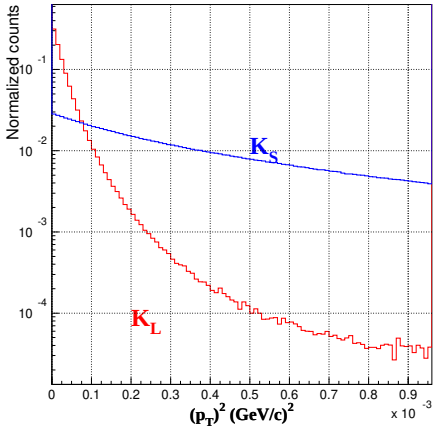
$\Rightarrow$ R correction $(+0.6 \pm 8.4) \times 10^{-4}$

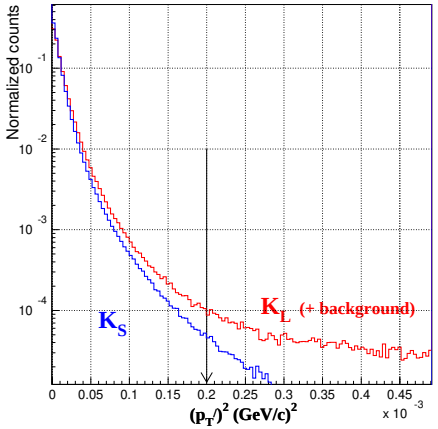
Charged background : P'^2_T



$$p_T \simeq P_K \frac{\Delta X + \Delta\theta(Z_{DCH1} - Z_V)}{Z_V - Z_T} \simeq P_K \frac{\Delta\theta(Z_{DCH1} - Z_V)}{Z_V - Z_T}$$

$$p'_T \simeq P_K \left(\Delta\theta + \frac{\Delta X}{Z_{DCH1} - Z_T}\right) \simeq P_K \Delta\theta$$

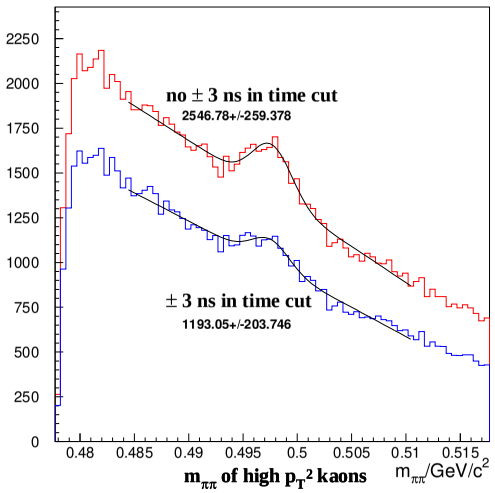


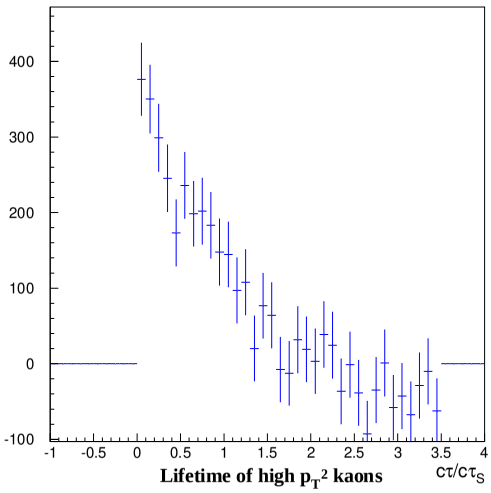


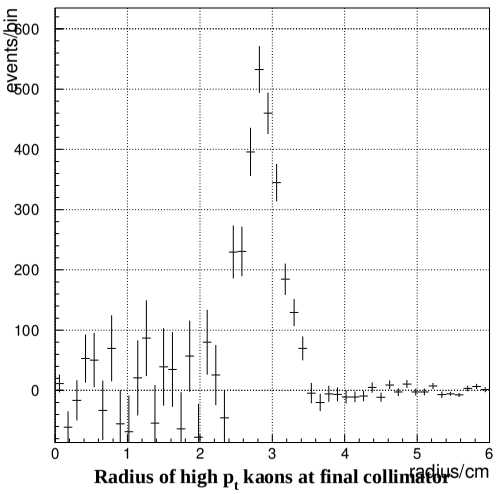
Beam scattering and $\mathrm{K_S}$ regeneration

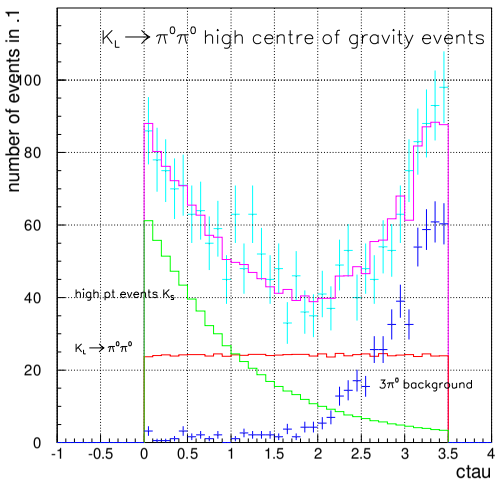
- In the $\mathrm{K_L}$ charged sample a small fraction of events having the $\mathrm{K^0}$ mass but very large p_T is observed. They are interpreted as scattered kaon (at least two scattering in the defining and cleaning collimators) regenerated in the final collimator
- Rejected by p_T^2 cut in charged modes.
- No similar cut for neutral modes.

$\Rightarrow$ correction to **R** : (-9.9 $\pm$ 3.0) $\times$ 10^{-4}



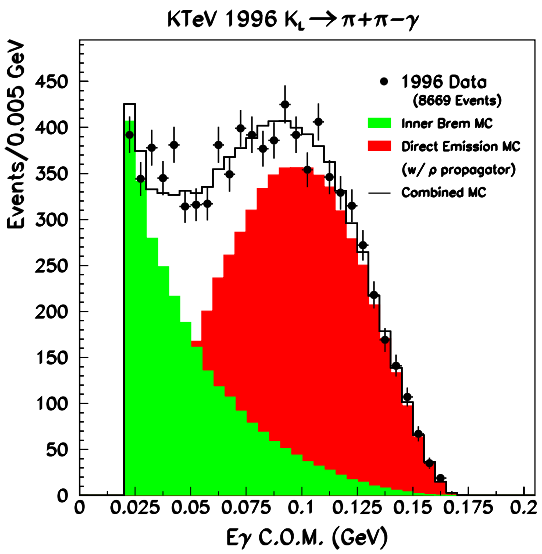






$K^0 \to \pi^+\pi^-\gamma$

- for K_L only : direct emission
  cut by invariant $\pi^+\pi^-$ mass cut at about 7 MeV/c^2
  BR($K_L^0 \to \pi^+\pi^-\gamma$) = (3.19 $\pm$ .09) $\times 10^{-5}$
  (direct emission only and $E_\gamma^* > 20$ MeV)
- for K_L and K_S : internal bremstrahlung
  $\Rightarrow$ rates proportional to $\pi^+\pi^-$ decay rates
  $\Rightarrow$ possible effect on ε'/ε from $P_t{}'^2$ cut

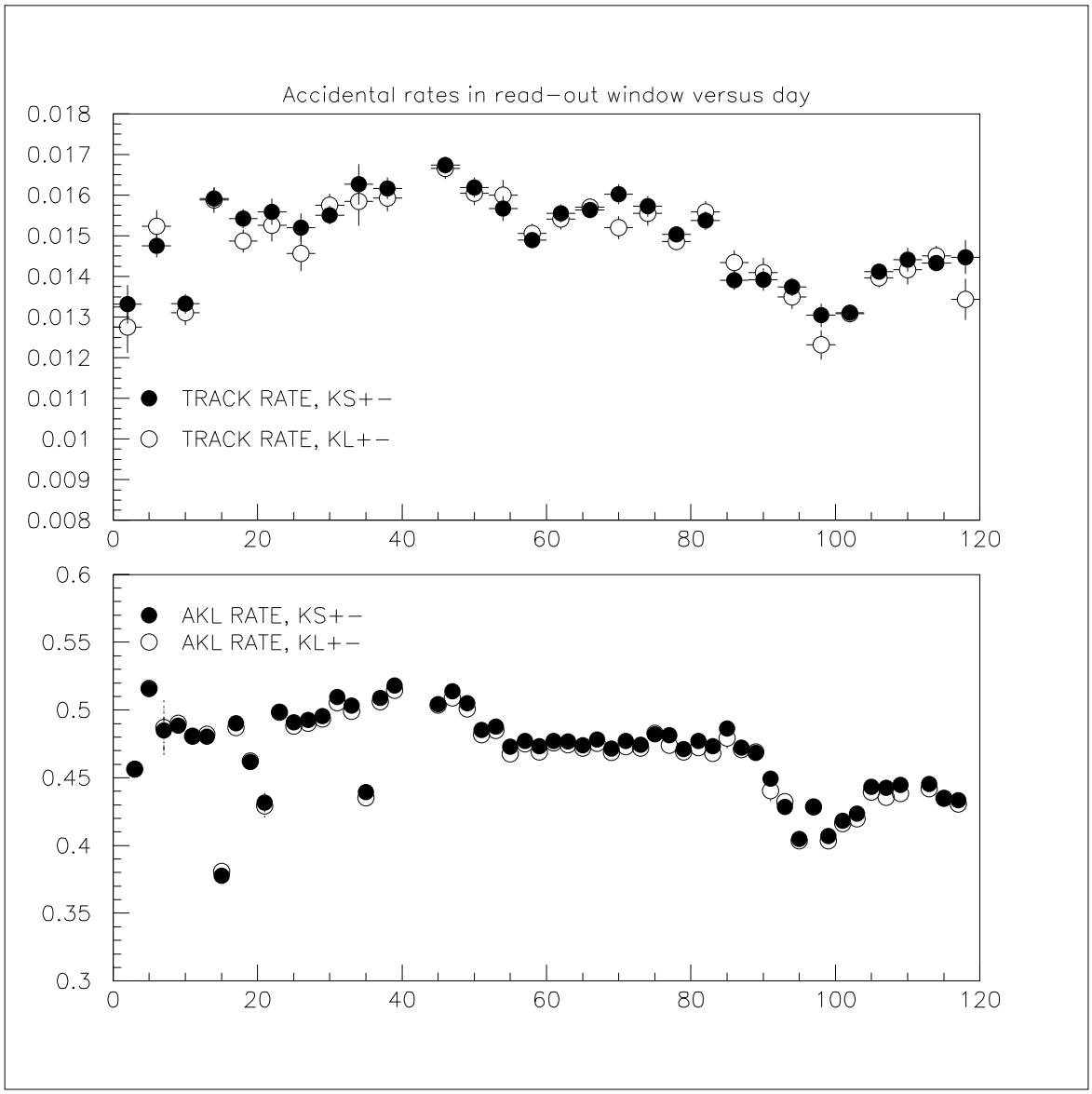


- For K_S : $P_t{}'^2 \leq 200$ (MeV/c)$^2 \equiv P_t \lesssim 100$ MeV/c
- For K_L : $P_t{}'^2 \leq 200$ (MeV/c)$^2 \equiv P_t \lesssim 23$ MeV/c

BUT γ with more than $\simeq 7$ MeV are already removed by the invariant mass cut

$\Rightarrow$ **negligible effect on** ε'/ε

Accidental rate seen by K_S and K_L



Running in 2000 and 2001

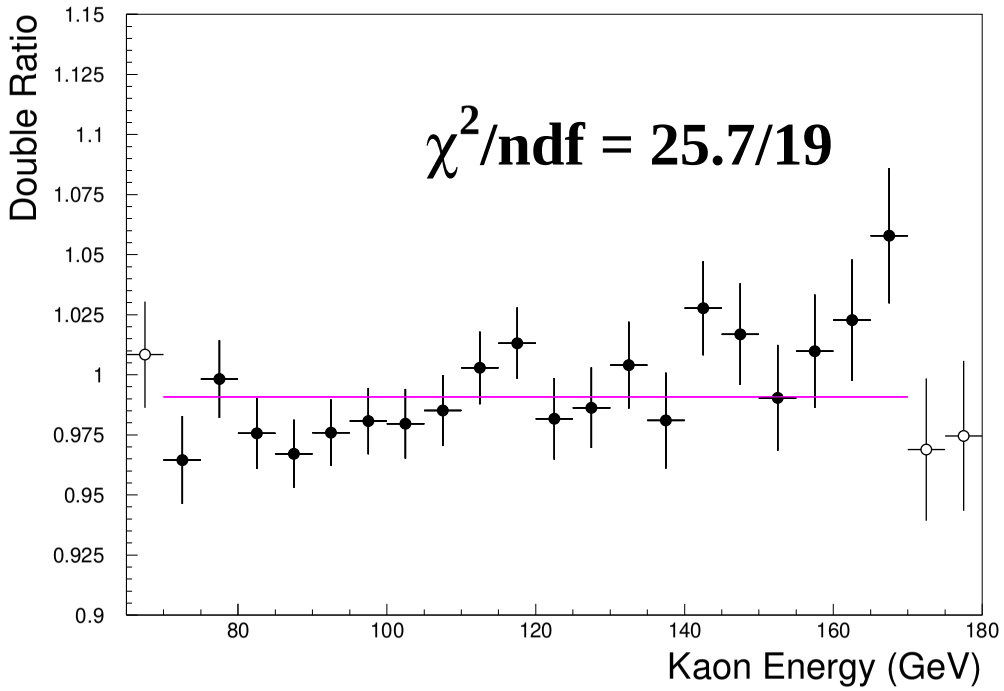
2000 With no DCH available we will focus on the neutral decays:

- We want to measure the difference in mistagging probability for $\pi^0\pi^0$
- We want to improve on the distance/momentum scale and non linearity of the LKr using dedicated runs with the negative π beam to produce large amount of $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$

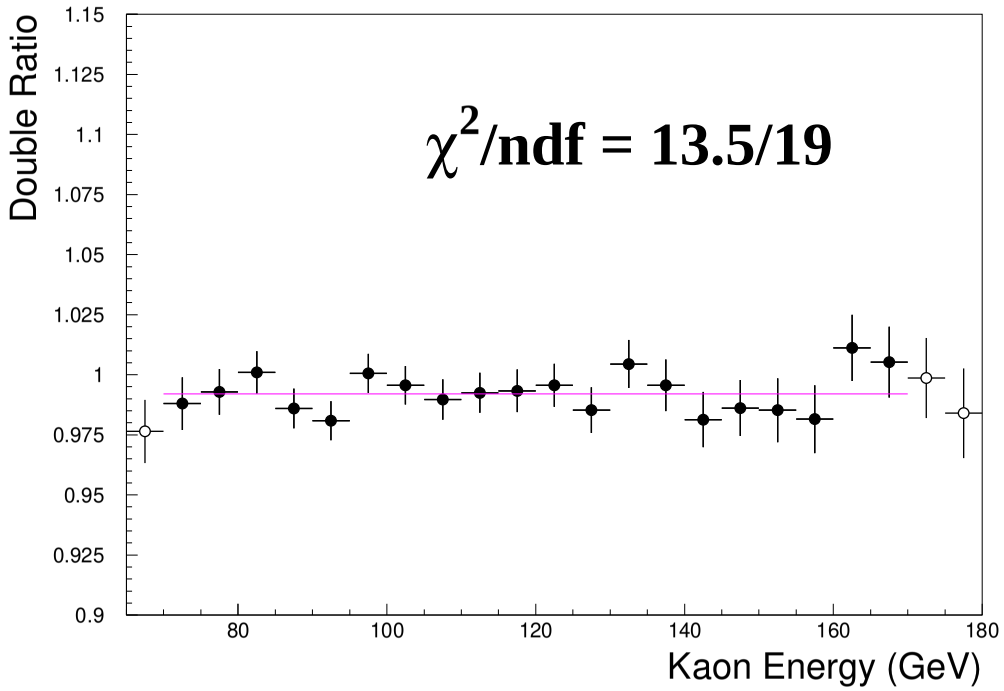
2001 We plan to collect data with the restored drift chambers. The aim is to complete the statistics and to address in particular the systematic errors related to the beam intensity variation

R vs Energy in 97 and 98 data

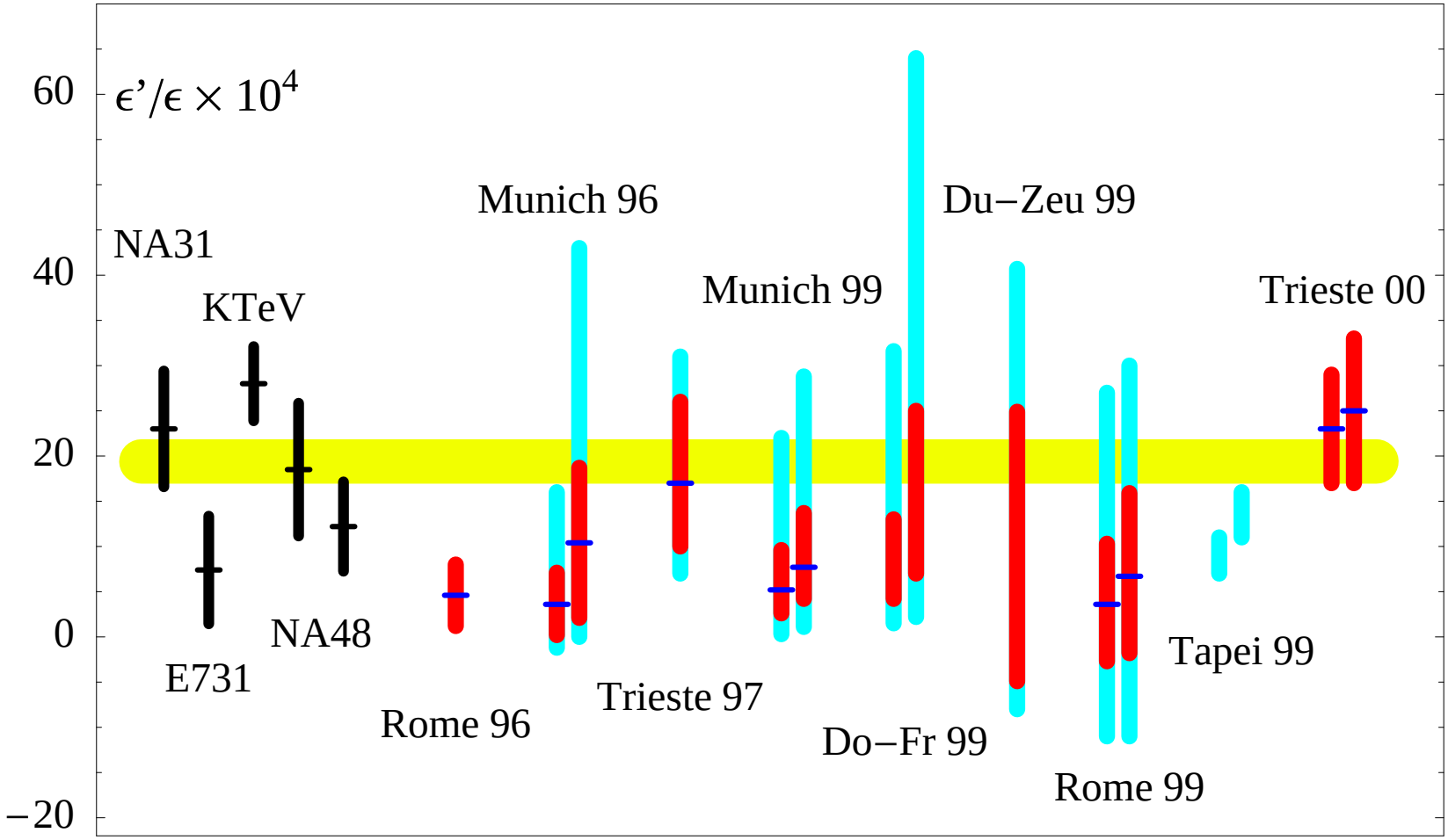
1997 DATA



1998 DATA



$\mathrm{Re}(\varepsilon'/\varepsilon)$: Theory vs Experiments



Comparing 1997 and 1998 Results

Corrections and uncertainties on R			(Units = 10^{-4})	
Source	1997 sample		1998 sample	
Statistical error		± 27		± 17
Accidental tagging	+18	±9	+1	±8
Tagging inefficiency	–	±6	–	± 3
Background to $\pi^+\pi^-$	+23	±4	+19	±3
Beam scattering	–12	±3	–10	±3
Background to $\pi^0\pi^0$	–8	±2	–7	±2
Acceptance	+29	±12	+31	±9
Charged trigger	+9	± 23	–1	± 11
Neutral reconstruction	–	±12	–	±10
Charged reconstruction	–	±5	+2	±2
Accidental activity	–2	±14	+2	±12
Total Systematic	+57	±35	+37	±24
Result	18.5	± 7.3	12.2	± 4.9

(errors in green are preliminary)