

Recent Results from NA48

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KEK Kaon Decay Workshop

NA48 Collaboration:

Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze,
Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Warszawa, Wien

Physics measurements of NA48

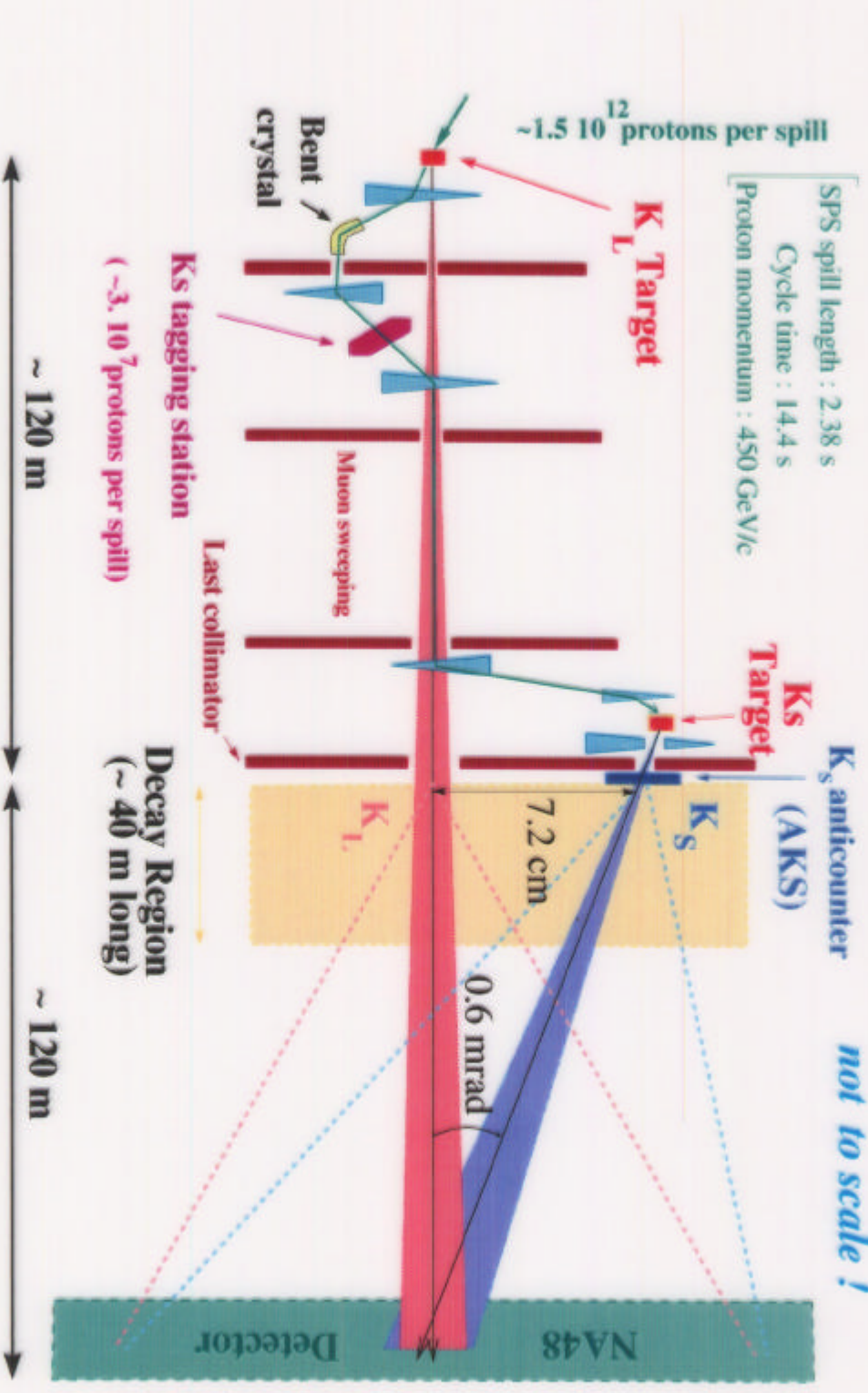
- DIRECT CP VIOLATION : $\text{Re}(\epsilon'/\epsilon)$
- K_L rare decays
- K_S rare decays
- Hyperon decays

NA48 future programme will be discussed tomorrow

Outline

- NA48 beamline
- NA48 detector
- $\text{Re}(\varepsilon'/\varepsilon)$ measurement
 - Physics motivation
 - Principle of the analysis
 - Systematic effects
 - Result (**PRELIMINARY**)
- K_L rare decays
 - Motivations
 - Techniques
 - Results (**PRELIMINARY**)
- Conclusions

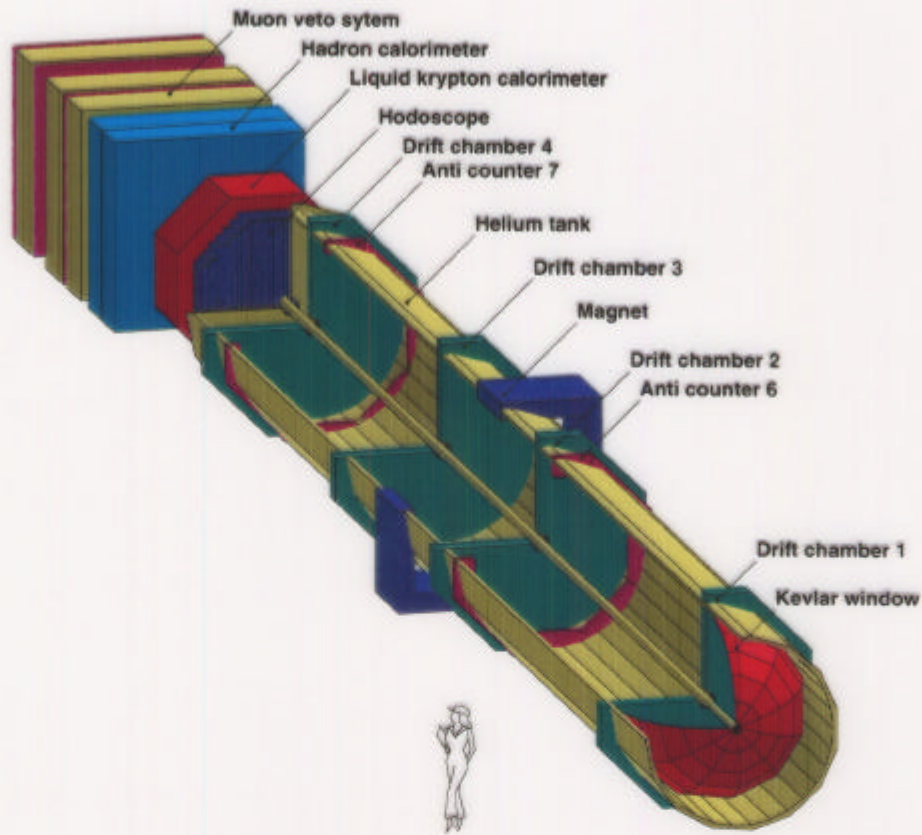
Nearly collinear and simultaneous K_L and K_S beams are used:



not to scale !

K_S can be distinguished from K_L using a tagging counter

NA48 method: detectors



- magnetic spectrometer ($P_T^{kick} \sim 265 \text{ MeV}/c$)

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

- charged hodoscope
- quasi-homogeneous Liquid Krypton EMC :
 - high granularity (13212 $2 \times 2 \text{ cm}^2$ cells)
 - projective geometry

$$\sigma(E)/E \simeq \frac{3.2\%}{\sqrt{E/\text{GeV}}} \oplus \frac{100 \text{ MeV}}{E} \oplus 0.5\%$$

- hadronic calorimeter
- muon counters

Triggers

Neutral Trigger

A fully pipelined system using LKR cell information to compute energy, centre of gravity and proper time

- Output rate ~ 2 kHz
- Negligible dead time
- Efficiency for $K \rightarrow \pi^0\pi^0$: 99.93 ± 0.02 %
- Also : $\gamma\gamma, e^+e^-\gamma, e^+e^-\gamma\gamma, \pi^0\gamma\gamma, \pi^0e^+e^-$

Charged Trigger

- Level 1 : pretrigger

	Efficiency
– Two track topology (Q_x)	99.95 ± 0.01 %
– Two track multiplicity (D_{chm})	> 99.99 %
– Total energy (E_{tot})	99.49 ± 0.03 %
- Level 2 : on-line vertex reconstruction
 - Latency : $< 102 \mu s$
 - Dead Time : $< 5\%$
monitored and applied to $\pi^0\pi^0$
 - Efficiency for $K \rightarrow \pi^+\pi^-$: $\simeq 97.75 \pm 0.05\%$
 - Also : $\mu^+\mu^-\gamma, e^+e^-e^+e^-, \pi^+\pi^-e^+e^-, e^+e^-\mu^+\mu^-$

$$\operatorname{Re}(e'/\varepsilon)$$

Re(ϵ'/ϵ) : physics motivation

Strangeness eigenstates:

$$K^0(\bar{s}d)$$

$$\bar{K}^0(s\bar{d})$$

CP eigenstates:

$$K_1 = (K^0 + \bar{K}^0)/\sqrt{2} \quad (CP = +1)$$

$$K_2 = (K^0 - \bar{K}^0)/\sqrt{2} \quad (CP = -1)$$

Mass eigenstates:

$$K_S \simeq K_1 + \epsilon K_2$$

$$K_L \simeq K_2 + \epsilon K_1$$

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

Two pion final states have $CP = +1$

CP violation in $K_L \rightarrow \pi\pi$ can occur either through:

- mixing indirect ϵ "box"
- decay direct ϵ' "penguin"

$$K_L = K_2^{-1} + \epsilon K_1^{+1} \rightarrow \underbrace{\pi^+ \pi^-, \pi^0 \pi^0}_{CP = +1}$$

NA48 uses the **double ratio** technique:

$$\eta_{+-} \equiv \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} \simeq \epsilon + \epsilon' \quad \eta_{00} \equiv \frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_S \rightarrow \pi^0 \pi^0)} \simeq \epsilon - 2\epsilon'$$

$$\text{Re}(\epsilon'/\epsilon) \simeq \frac{1}{6} \left\{ 1 - \left| \frac{\eta_{00}}{\eta_{+-}} \right|^2 \right\}$$

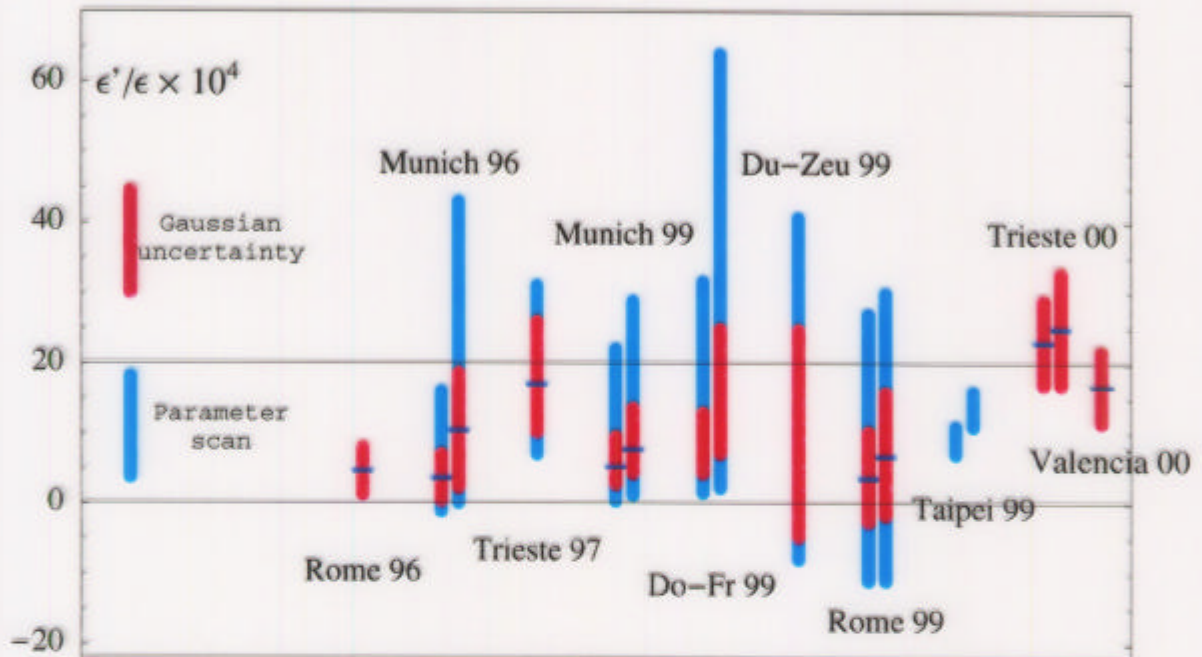
$$\text{Re}(\epsilon'/\epsilon) \simeq \frac{1}{6} \left\{ 1 - \frac{\Gamma(K_L \rightarrow \pi^0 \pi^0)}{\Gamma(K_S \rightarrow \pi^0 \pi^0)} / \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_S \rightarrow \pi^+ \pi^-)} \right\} = \frac{1}{6} (1 - R)$$

Systematic effects are reduced significantly by

- using **simultaneous and nearly collinear** beams
- collecting data from all four modes **at the same time**
- **weighting** the K_L to the K_S lifetime distribution
- performing the analysis in **bins of kaon energy**

Current status of $\text{Re}(\epsilon'/\epsilon)$

Typical theoretical predictions



Most recent measurements

NA31	$(23.0 \pm 6.5) \times 10^{-4}$
E731	$(7.4 \pm 5.9) \times 10^{-4}$
KTEV	$(28.0 \pm 4.1) \times 10^{-4}$
NA48 97	$(18.5 \pm 7.3) \times 10^{-4}$
NA48 98	today!

Data sample

- **1997:** 89 days 1×10^{12} ppp on K_L target
 \Rightarrow 0.49 million $K_L \rightarrow \pi^0\pi^0$
PUBLISHED Phys. Lett. B 465 (1999)
 $\text{Re}(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$
- **1998:** 135 days 1.4×10^{12} ppp on K_L target
Main improvements :
 - LKR High Voltage 1500 \rightarrow 3000 V
 - Charged trigger efficiency 91.3 \rightarrow 97.7 %
 - Carbon fibre pipe \rightarrow fewer showers in the detectors
 - New DAQ system (PC farm) + 30 % rate
 \Rightarrow 1.14 million $K_L \rightarrow \pi^0\pi^0$**PRELIMINARY result since February 2000**
- **1999:** 128 days 1.4×10^{12} ppp on K_L target
Further improvements :
 - DCH read-out, dead time, DAQ efficiency, spill length
 \Rightarrow Around 2 million $K_L \rightarrow \pi^0\pi^0$
- **2000:** 40 days without DCH
Systematic studies: tagging, energy scale
Analysis in progress

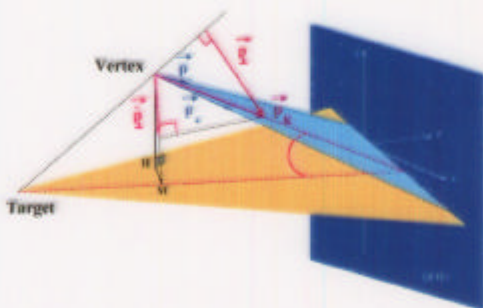
Event selection

All events

- Kaon energy : $70 < E_K/\text{GeV} < 170$
- Centre of Gravity : $r_{cog} < 10 \text{ cm}$
- Decay region : $0 < t < 3.5 \tau_S$
For K_S cut ($t > 0$) by requiring \overline{AKS}
- No dead time

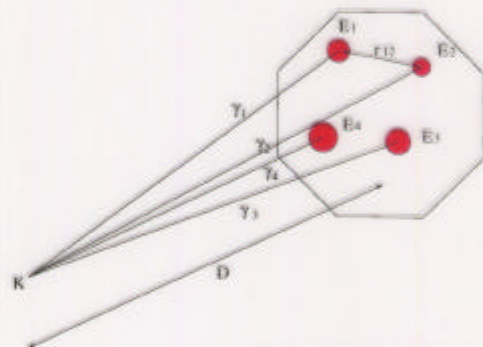
Charged events

- $K_{\mu 3} : \overline{MUV}$
- $K_{e3} : E/p < 0.8$
- $|m_{\pi\pi} - m_{K^0}| < 3\sigma$
- $p_t'^2 < 200 (\text{GeV}/c)^2$



$p_t'^2$ is the rescaled transverse momentum
 \Rightarrow same for K_S & K_L

Neutral events



$$D = \frac{\sqrt{\sum E_i E_j \times r_{ij}^2}}{m_K}$$

$$m_{ij} = \sqrt{E_i E_j} \cdot r_{ij} / D$$

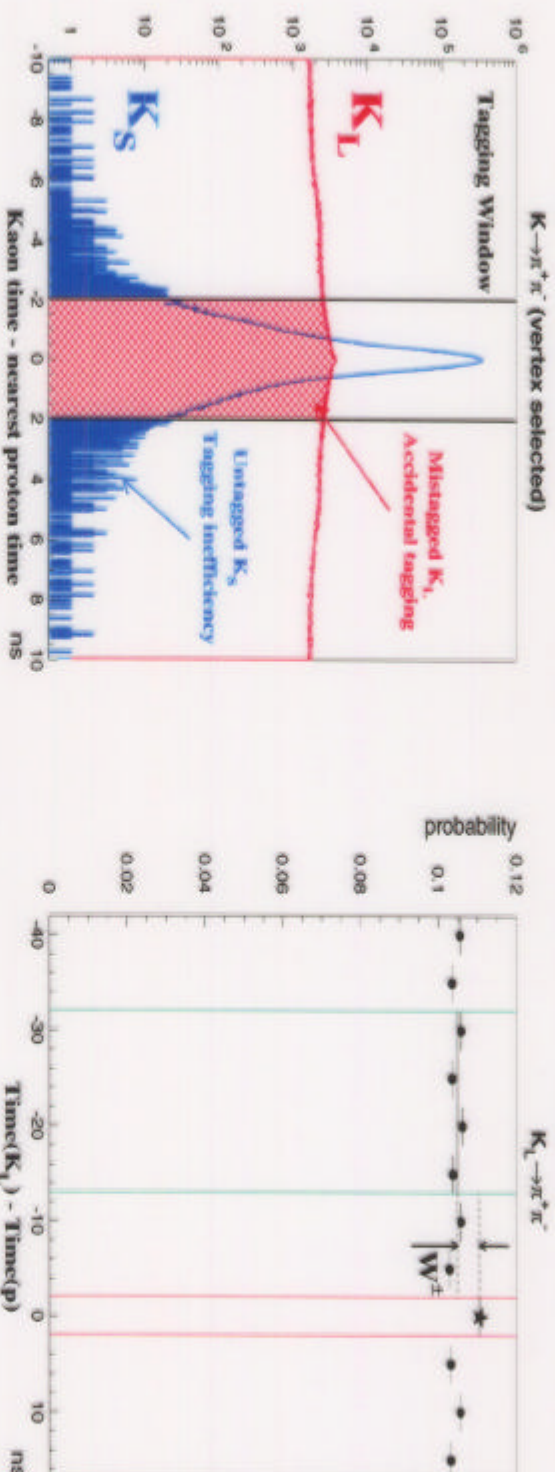
- No extra clusters
- $R_{ell} < 13.5$

$$R_{ell} \equiv \left(\frac{m_1 + m_2 - 2m_\pi}{2\sigma_+} \right)^2 + \left(\frac{m_1 - m_2}{2\sigma_-} \right)^2$$

Proton tagging allows us to distinguish K_S from K_L decays

T.O.F. between reconstructed Kaon decay and tagger:

$$|t_K - t_{\text{tagger}}| \leq 2\text{ns} \Rightarrow K_S \quad |t_K - t_{\text{tagger}}| > 2\text{ns} \Rightarrow K_L$$

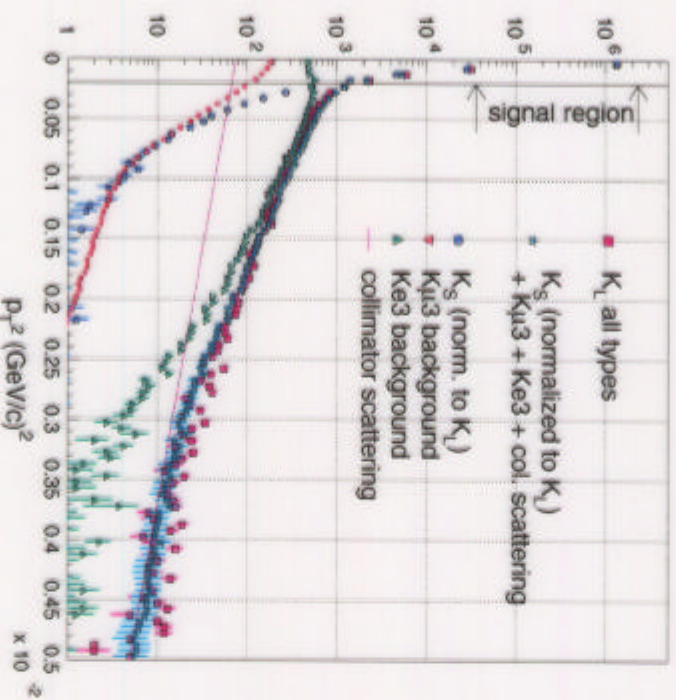


- In charged mode directly measure mistagging ($\alpha_{LS}^+ = (11.05 \pm 0.01)\%$) & inefficiency ($\alpha_{SL}^+ = (1.97 \pm 0.05) \times 10^{-4}$)
- In neutral mode:
 - mistagging : extrapolate from sidebands ($\alpha_{LS} = \beta + W$)
 - inefficiency : use Dalitz decays / conversions
- $\text{Re}(\epsilon'/\epsilon)$ sensitive to $\Delta\alpha_{LS} = (0.3 \pm 4.2) \times 10^{-4}$ & $\Delta\alpha_{SL} < 0.5 \times 10^{-4}$

Charged Mode

Contributions from:

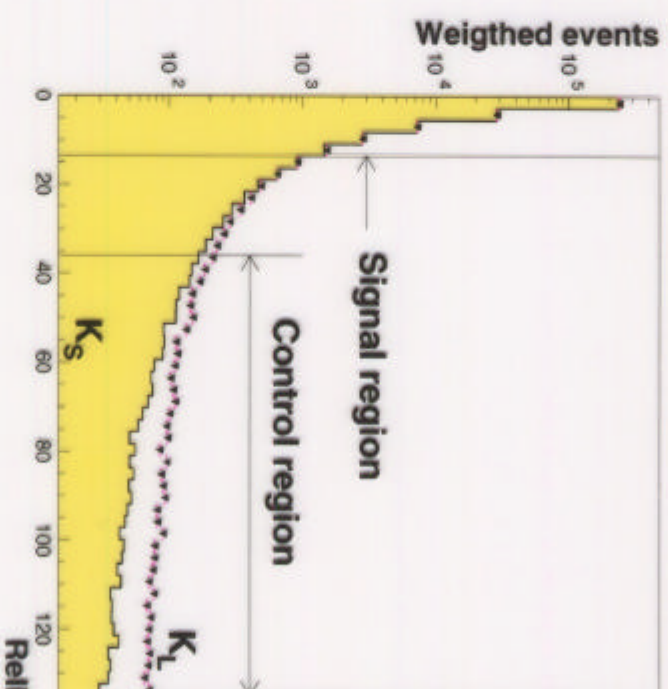
- K_{e3}
- $K_{\mu 3}$



Neutral Mode

Contribution from:

- $3 \pi^0$

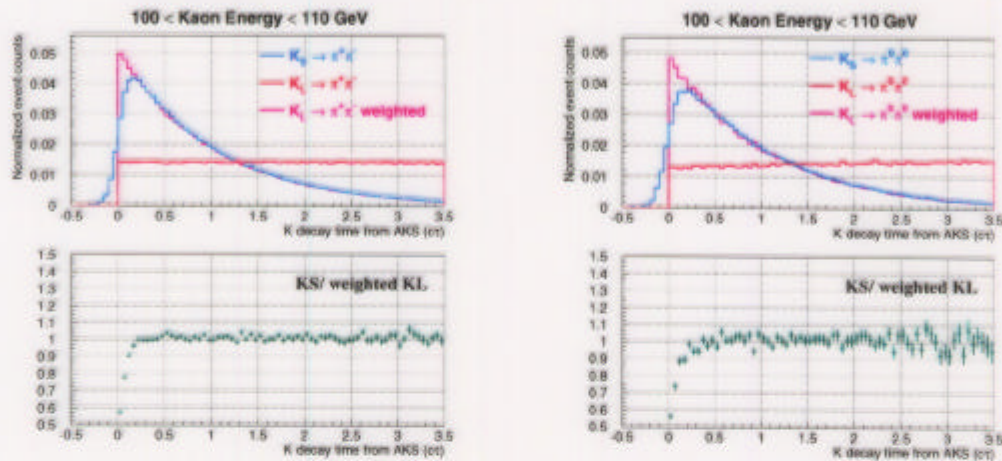


There is also some **collimator scattering** in the K_L beam

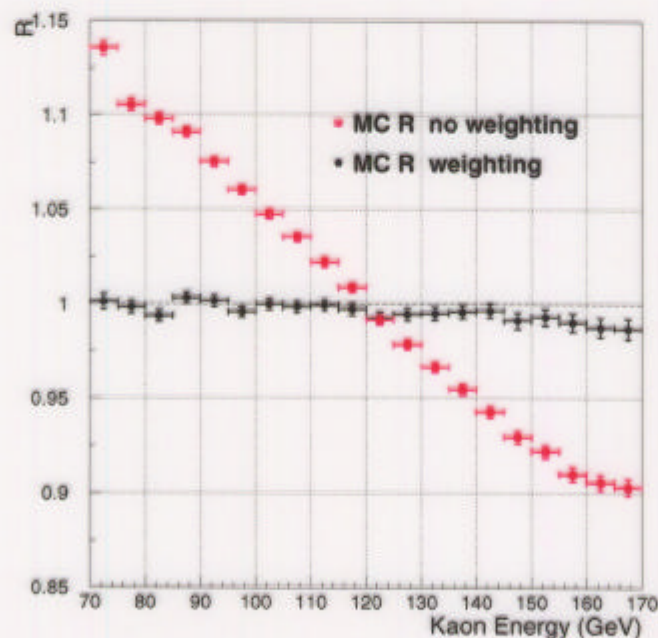
- rejected in charged mode through p_T^2 cut
- corrected for in neutral mode

Weighting and Acceptance

The K_L events are **weighted** according to the **ratio** of the proper time distribution of K_S and K_L



This reduces the acceptance correction to $\mathcal{O}(10^{-3})$



The increase of the statistical error due to weighting is 35%

Energy Scale & Accidentals

Neutral Energy Scale

Neutral reconstruction systematics

Source	ΔR (units 10^{-4})
Non linearity	± 5
Non Gaussian tails in σ_E	± 5
Transverse scale	± 3
Intercalibration	± 3
Distance/Energy scale	± 3
Other sources	± 4

Accidental Effects

- Geometrical K_S / K_L difference
Effect on R measured with **overlays**

$$\Delta R = (2 \pm 6) \times 10^{-4}$$

- Variation of K_S / K_L ratio
Conservative estimate gives

$$\Delta R < 10 \times 10^{-4}$$

- Noise effects
Included in above
To be estimated with overlaid MC in future

Systematic Errors

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

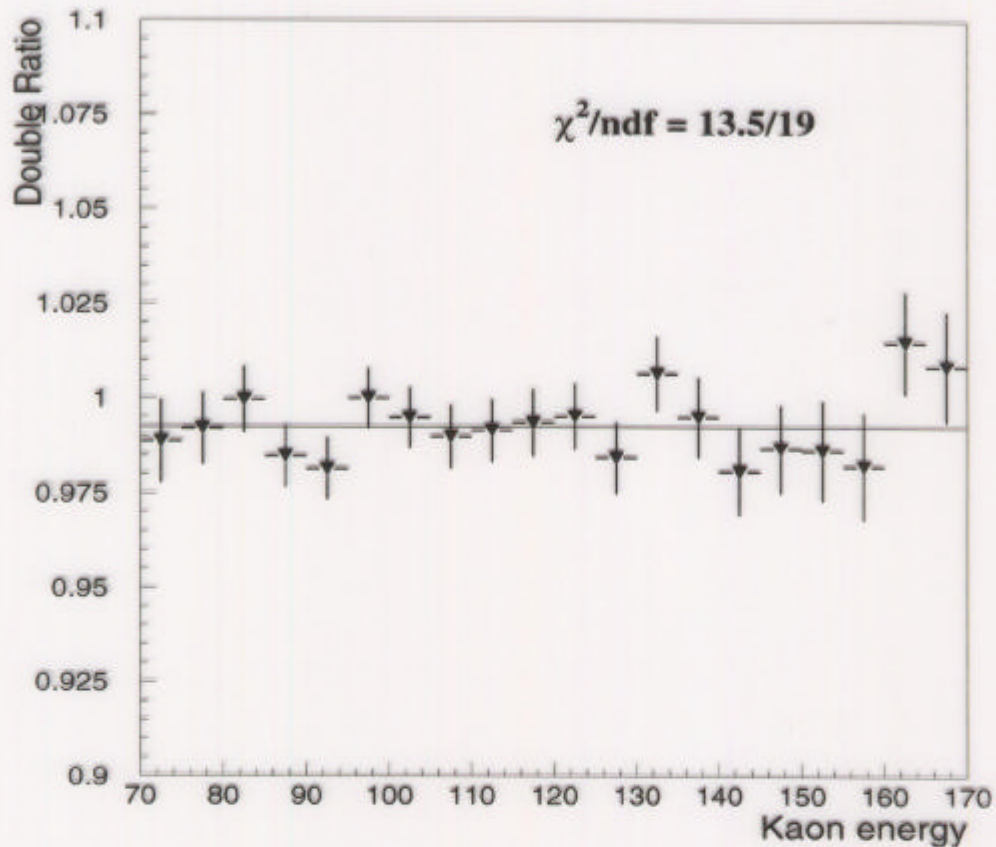
Subtracting the mistagging probability and averaging in energy bins, the weighted result is:

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

Corrections and uncertainties on R (10^{-4})			
Source	1998 sample		Limitation
Charged trigger	-1	± 11	(stat.)
Mistagging probability	+1	± 8	(stat.)
Tagging efficiency	-	± 3	
Neutral scale	-	± 10	
Charged vertex	+2	± 2	
Acceptance and AKS	+31	± 9	
Neutral and BG	-7	± 2	
Charged BG	+19	± 3	
Beam scattering	-10	± 3	
Accid. activity	+2	± 12	
Total	+37	± 24	

Result

PRELIMINARY RESULT ON 1998 DATA



$$R = 0.99267 \pm 0.00173(\text{stat.}) \pm 0.00238(\text{syst.})$$

$$\text{Re}(\epsilon'/\epsilon) = (12.2 \pm 2.9(\text{stat.}) \pm 4.0(\text{syst.})) \times 10^{-4}$$

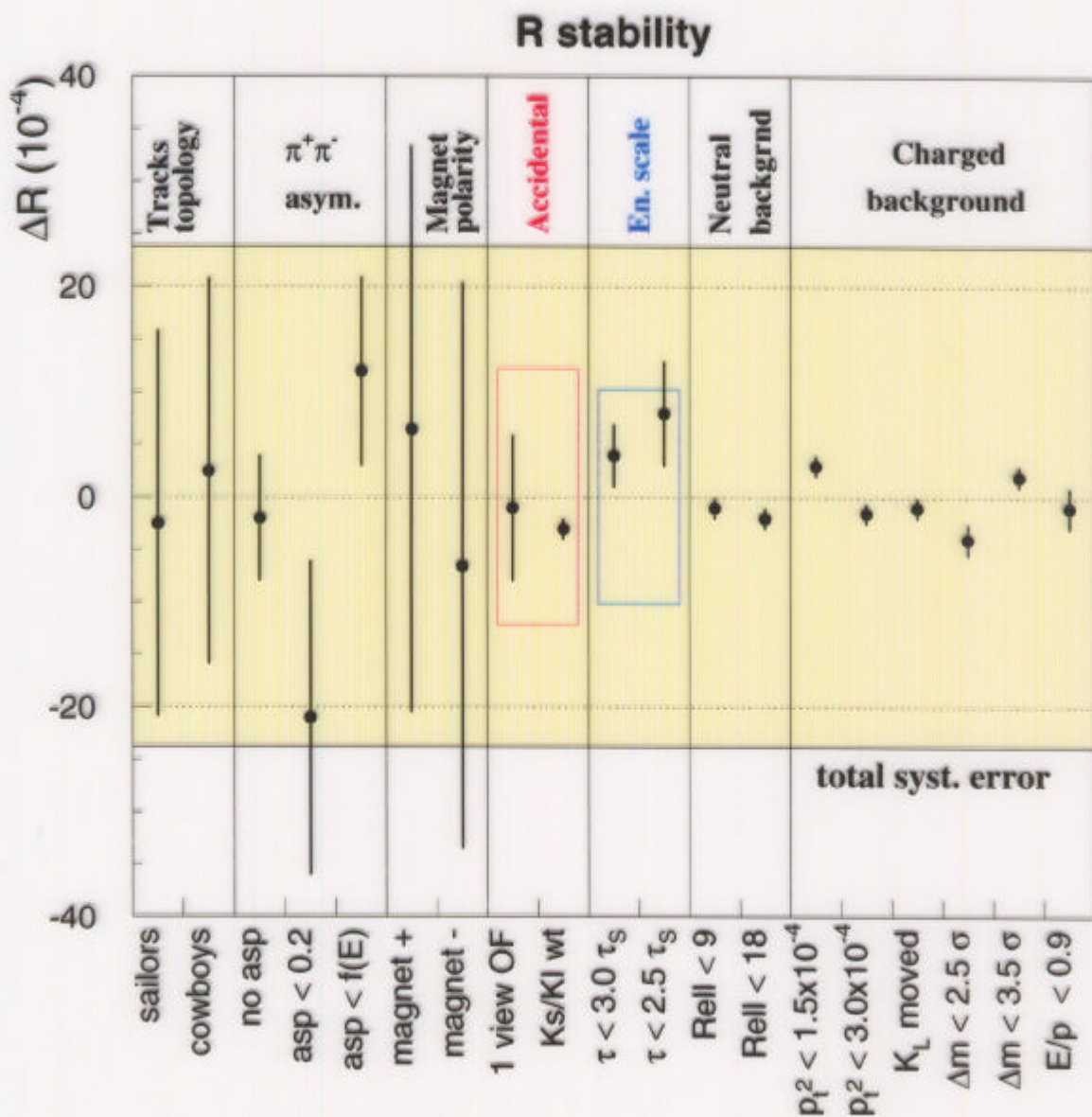
$$\text{Re}(\epsilon'/\epsilon) = (12.2 \pm 4.9) \times 10^{-4}$$

$$(1997) \text{Re}(\epsilon'/\epsilon) = (18.5 \pm 4.5(\text{stat.}) \pm 5.8(\text{syst.})) \times 10^{-4}$$

Combined 1997 and 1998 result:

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

Checks

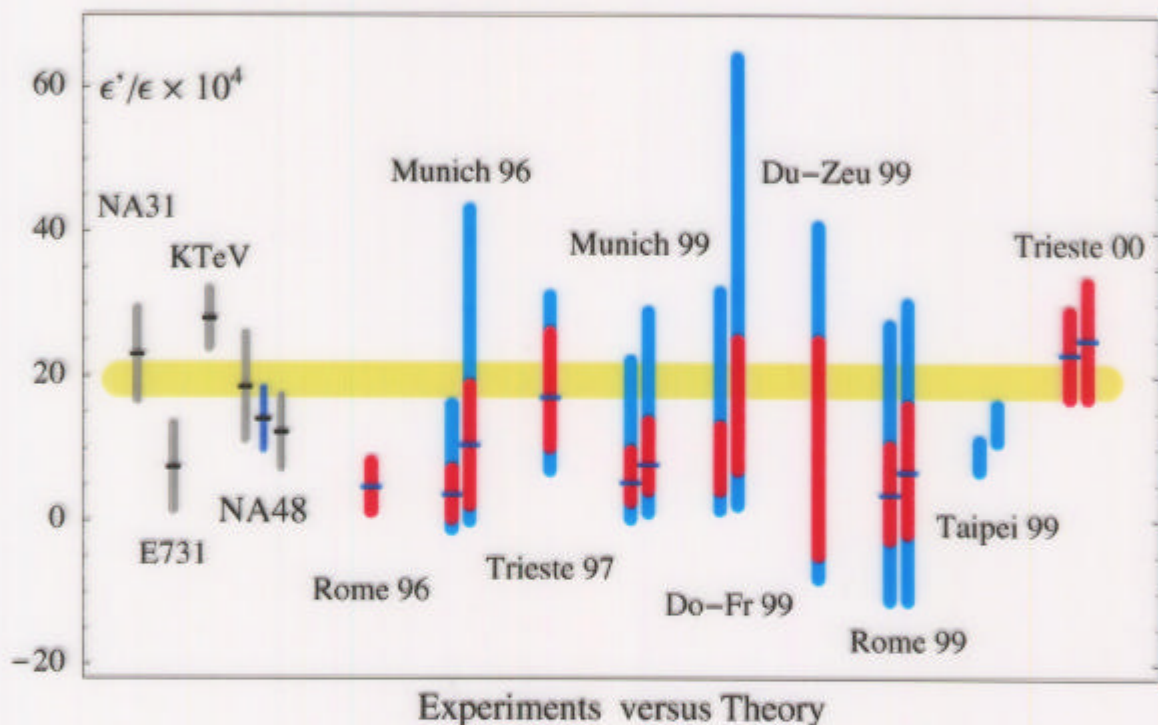


Conclusions and Perspectives

New world average:

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

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



- $\text{Re}(\varepsilon'/\varepsilon) \neq 0$ is established
- NA48 will improve systematic error on 1998 result and analyse 1999 data
- More $\text{Re}(\varepsilon'/\varepsilon)$ data will be collected in 2001 with repaired drift chambers
- Results are also anticipated from **KTEV** (FNAL) and **KLOE** (DAΦNE)

K_L RARE DECAYS

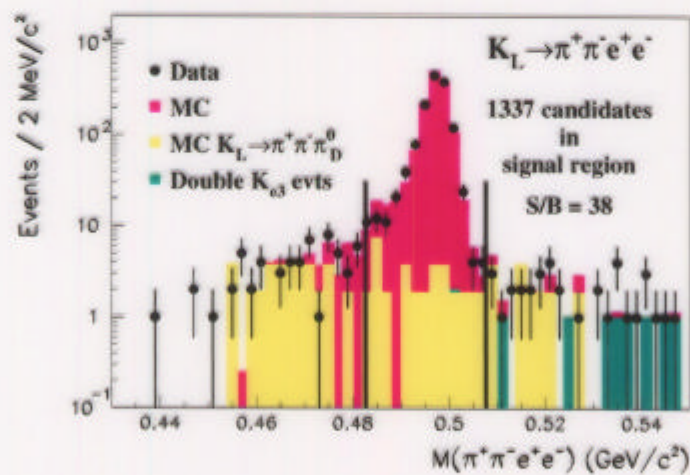
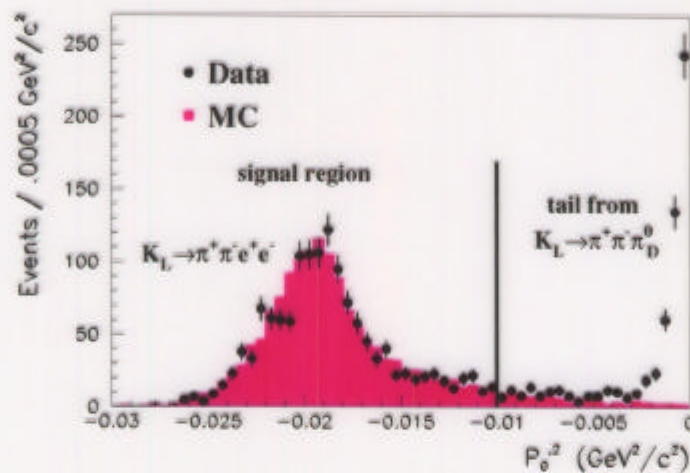
- $K_L \rightarrow \pi^+ \pi^- e^+ e^-$
- $K_L \rightarrow \pi^0 \gamma \gamma$
- $K_L \rightarrow e^+ e^- e^+ e^-$ / $K_L \rightarrow e^+ e^- \mu^+ \mu^-$
- $K_L \rightarrow e^+ e^- \gamma \gamma$

$K_L \rightarrow \pi^+ \pi^- e^+ e^-$

Motivation :

Asymmetry in angle (ϕ) between decay planes
 \Rightarrow CP violation (Heiliger & Sehgal 1993)

1998+1999 data

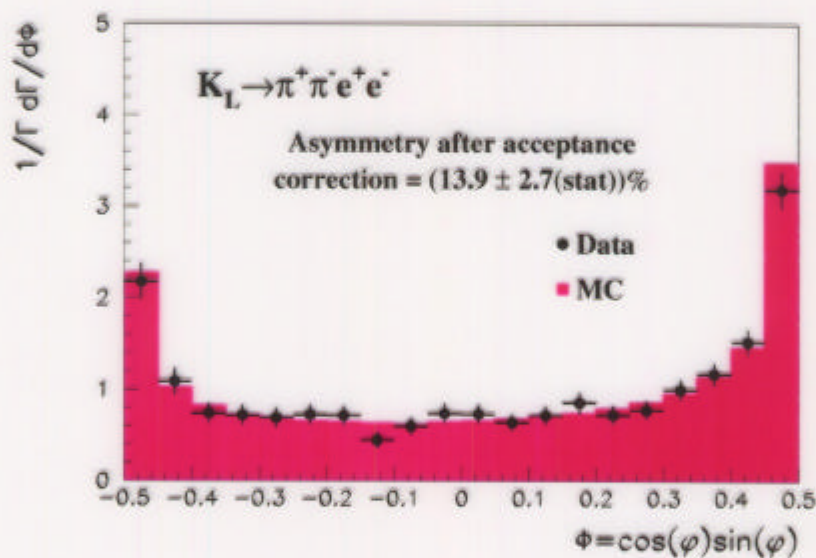
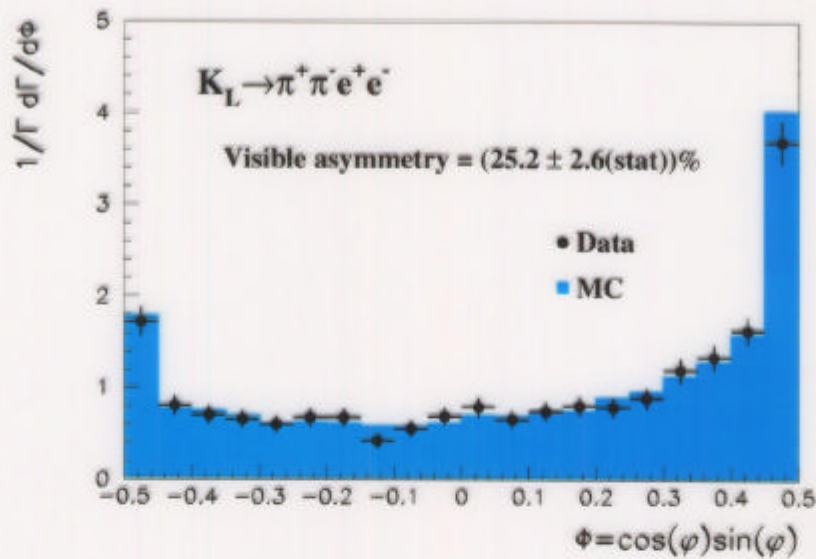


Reject $K_L \rightarrow \pi^+ \pi^- \pi_0^0$ background using $P_0'^2$

1337 signal candidates \Rightarrow

$$\text{Br}(K_L \rightarrow \pi^+ \pi^- e^+ e^-) = (3.1 \pm 0.1_{\text{STAT}} \pm 0.2_{\text{SYST}}) \times 10^{-7}$$

$K_L \rightarrow \pi^+ \pi^- e^+ e^-$ Asymmetry



PRELIMINARY result after acceptance correction

$$A_{\pi\pi ee}^L = (13.9 \pm 2.7_{\text{STAT}} \pm 2.0_{\text{SYST}})\%$$

cf PRELIMINARY results from $K_S \rightarrow \pi^+ \pi^- e^+ e^-$

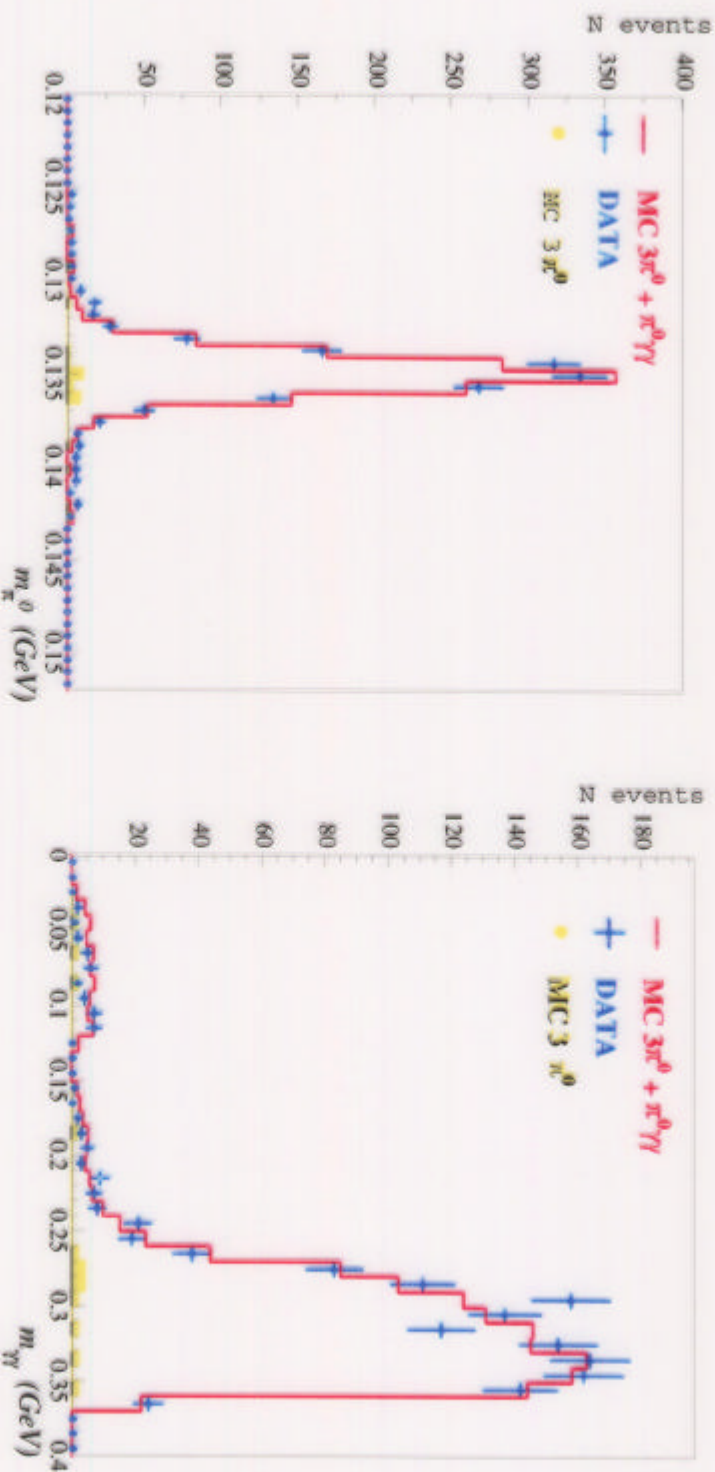
(921 candidates ; 1998 + 1999 data)

$$\text{Br}(K_S \rightarrow \pi^+ \pi^- e^+ e^-) = (4.3 \pm 0.2_{\text{STAT}} \pm 0.3_{\text{SYST}}) \times 10^{-5}$$

$$A_{\pi\pi ee}^S = (-0.2 \pm 3.4_{\text{STAT}} \pm 1.4_{\text{SYST}})\%$$

Motivation :

Test of χ PT to $\mathcal{O}(p^6)$ with VMD contribution (a_0) bounded by experiment.



1397 candidates, with ~ 30 background

Using $a_0 = -0.45$: $\text{Br}(K_L \rightarrow \pi^0 \gamma \gamma) = (1.51 \pm 0.05_{\text{STAT}} \pm 0.20_{\text{SYST}}) \times 10^{-6}$

Events at low $m_{\gamma\gamma}$ indicate $\mathcal{O}(p^6)$ contributions and size of a_0

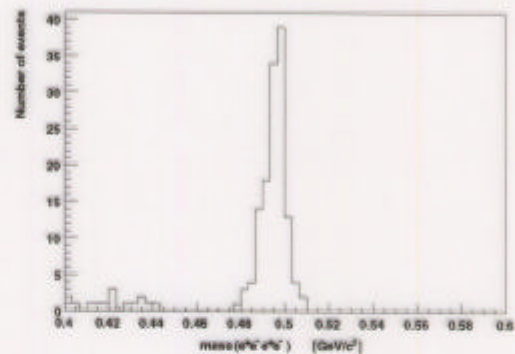
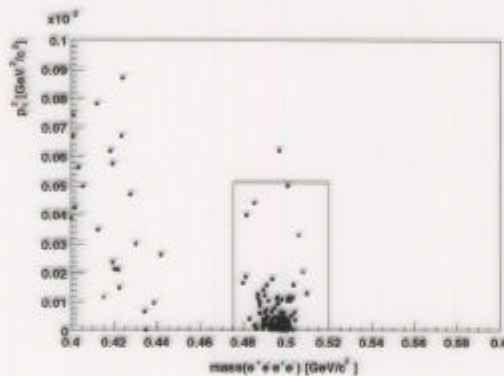
$K_L \rightarrow e^+e^-e^+e^- / K_L \rightarrow e^+e^-\mu^+\mu^-$

Motivation :

Probe $\gamma^*\gamma^*$ vertex structure ; provide model dependent tests.

$K_L \rightarrow e^+e^-e^+e^-$

1999 data



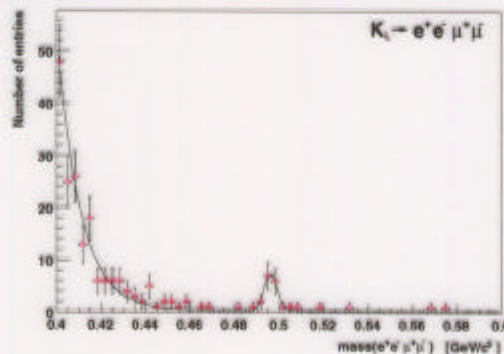
132 candidate events \Rightarrow

$\text{Br}(K_L \rightarrow e^+e^-e^+e^-) =$

$$(3.67 \pm 0.32_{\text{STAT}} \pm 0.23_{\text{SYST}} \pm 0.11_{\text{NORM}}) \times 10^{-8}$$

$K_L \rightarrow e^+e^-\mu^+\mu^-$

1999 data



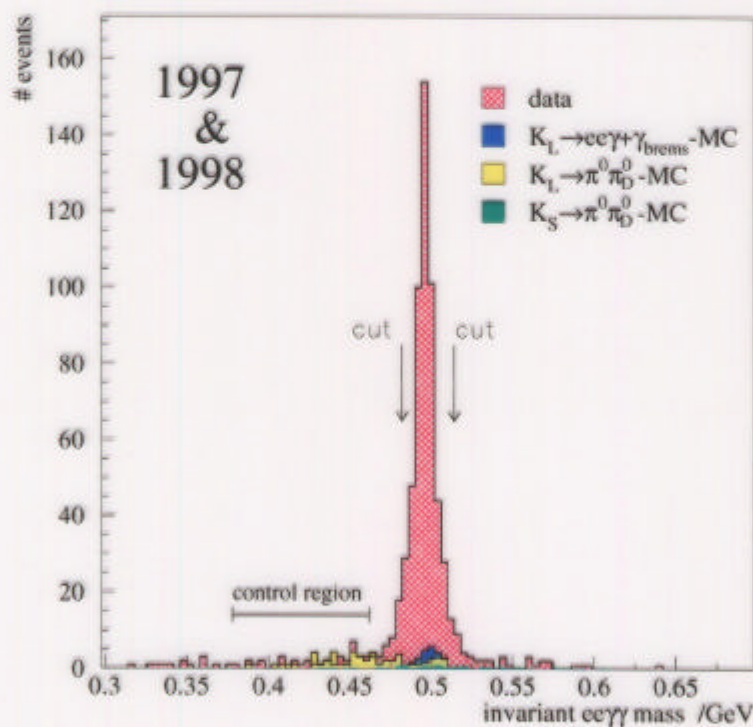
19 candidate events have been observed

$K_L \rightarrow e^+e^-\gamma\gamma$

Motivation :

- Test QED radiative corrections
- \Rightarrow measurement of $K_L \rightarrow e^+e^-\gamma$ form factor
- $K_L \rightarrow e^+e^-\gamma\gamma$ is serious background to **direct CP violation** mode $K_L \rightarrow \pi^0 e^+e^-$

1997 + 1998 data



492 candidate events have been observed

$\text{Br}(K_L \rightarrow e^+e^-\gamma\gamma; E_\gamma^* > 5\text{MeV}) =$

$$(6.32 \pm 0.31_{\text{STAT}} \pm 0.20_{\text{SYST}} \pm 0.29_{\text{NORM}}) \times 10^{-7}$$

Conclusions

- **Direct CP violation** has been established - $\text{Re}(\varepsilon'/\varepsilon) \neq 0$
- The precise value of $\text{Re}(\varepsilon'/\varepsilon)$ should soon become clear
- Studies of **rare decays** by NA48 are providing interesting kaon physics results
- The **future program** of NA48 allows important studies of rare K_S and hyperon decays \Rightarrow more tomorrow!