An overall review of the Kaon Physics results from NA48

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SuGRA20

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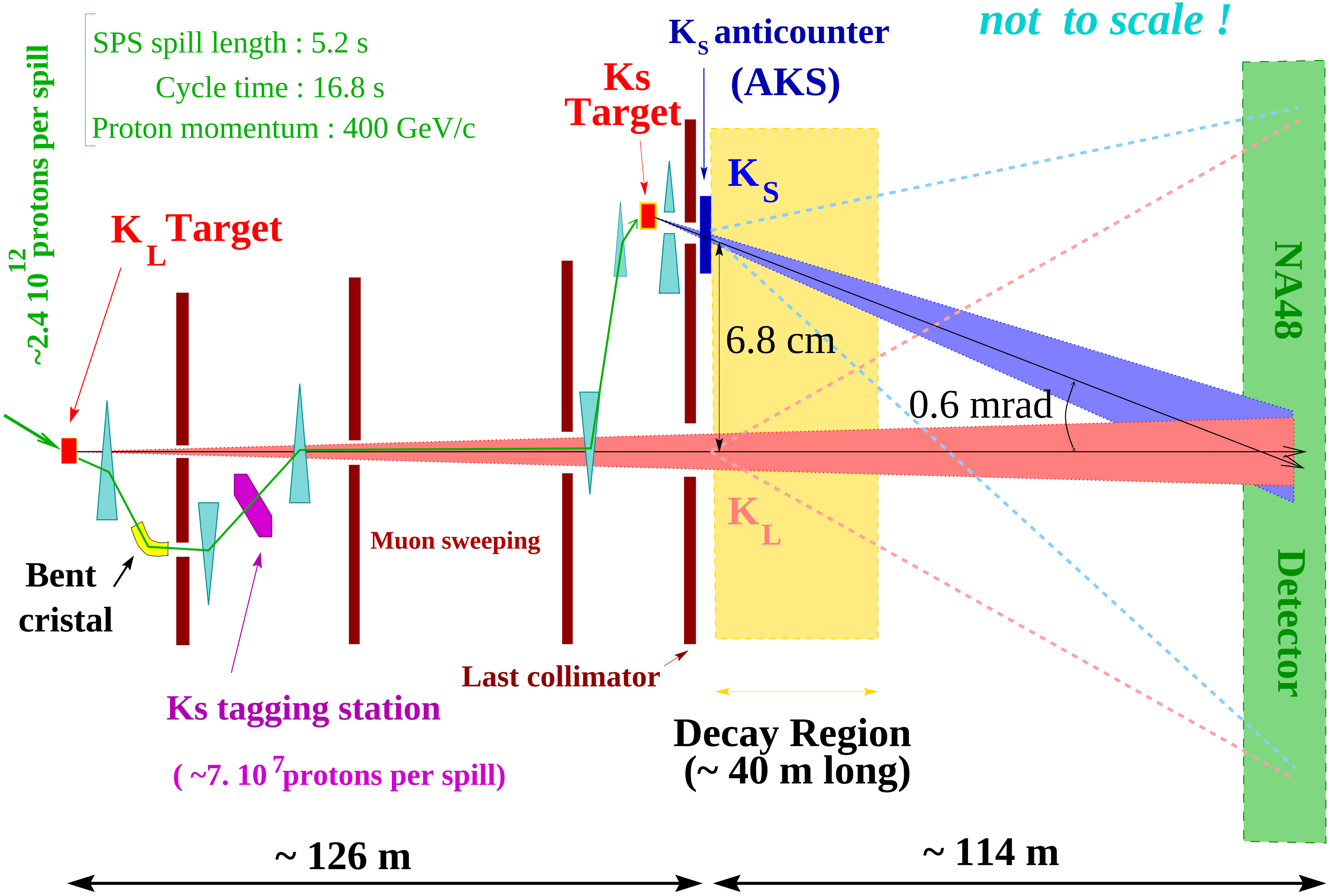
on behalf of the NA48 Collaboration

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

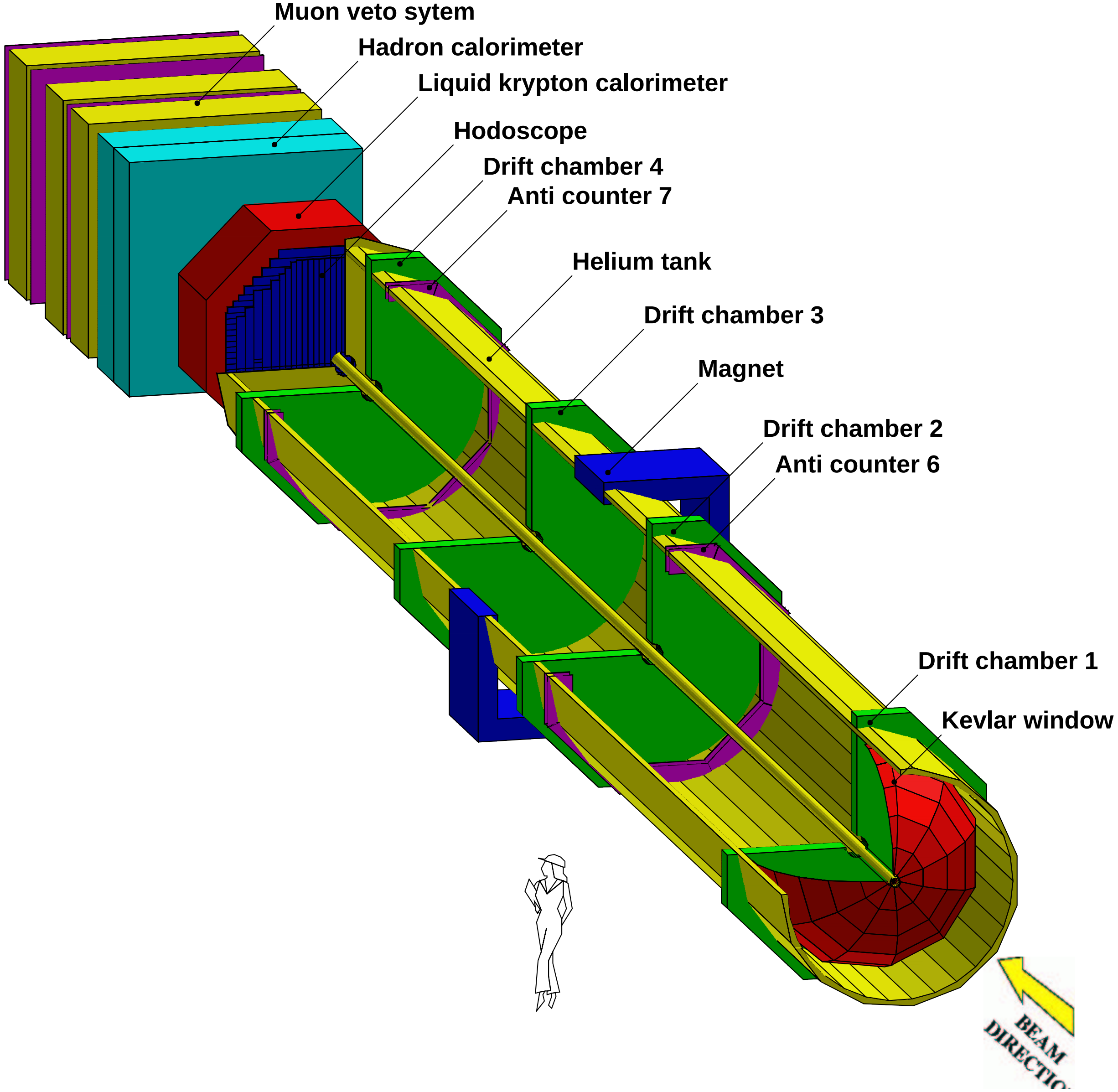
Outline

- **Introduction**
- **Results on CP violation** ($\Re e(\varepsilon'/\varepsilon)$, $\delta_L(e)$, η_{000})
- **By-product analysis** (K_S **lifetime,** K **mass,** η **mass**)
- **Results on Rare Decays** ($K \rightarrow \pi^+\pi^-e^+e^-$, $K \rightarrow \pi^0\gamma\gamma, \gamma\gamma$)
- **News from NA48/1 - 2002**
- **Summary**

The NA48 beam lines



The NA48 Detector



Magnetic spectrometer

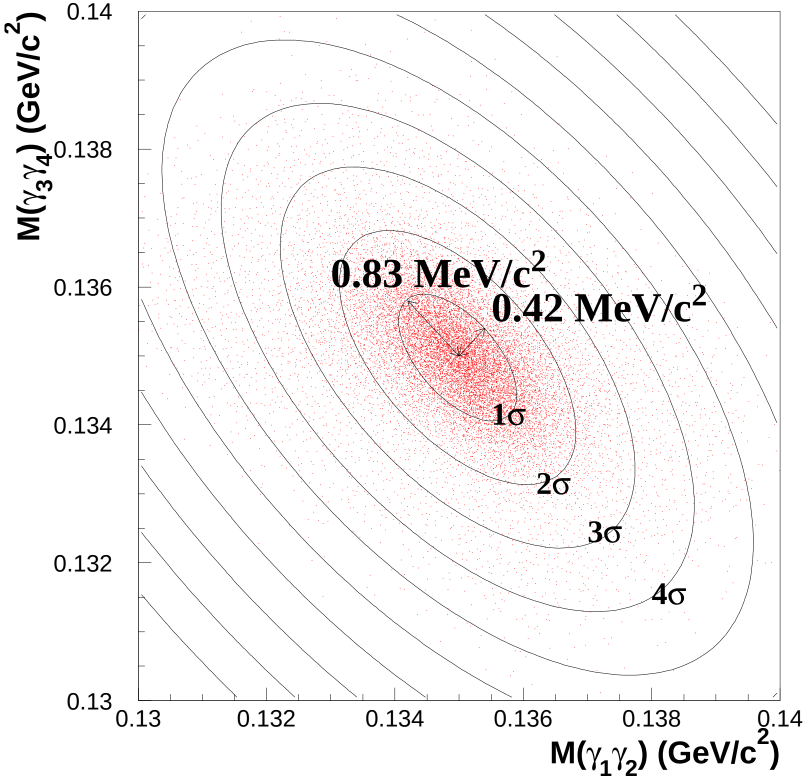
- $\sigma_{X,Y} \sim 100\ \mu m$
- $\sigma_{K\ mass} \sim 2.5\ MeV/c^2$
- resolution on (x, y) vertex $\sim$ 2 mm $\rightarrow$ allows for beams separation

Liquid Krypton em calorimeter

- with high granularity ($\sim$ 13500 cells)
- $\sigma_t \sim 220\ ps$
- $\frac{\sigma(E)}{E} < 1$ % for $E_\gamma > 25\ GeV$
- $\sigma_{\pi^0\ mass} \simeq 1.1\ MeV/c^2$

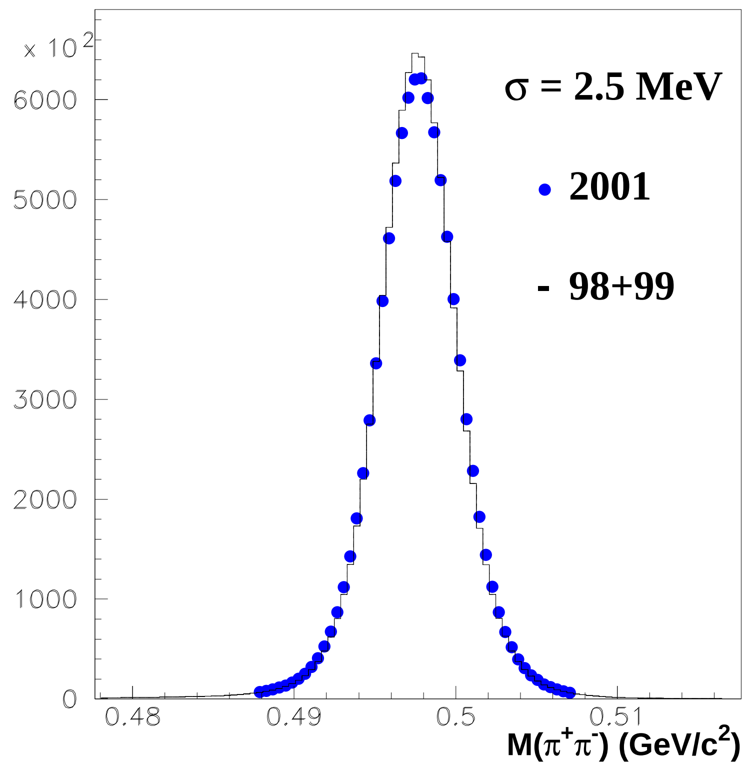
Resolutions plots

LKr calorimeter



$m_{\gamma\gamma}$ invariant mass in
$K_S \rightarrow \pi^0\pi^0$ candidates

Spectrometer



Kaon invariant mass in
$K_S \rightarrow \pi^+\pi^-$ candidates

NA48 data taking overview

1997
$K_L + K_S$
ε'/ε run

1998
$K_L + K_S$
ε'/ε run
K_S lifetime,
K_L rare decays

1999
$K_L + K_S$
ε'/ε run
K_S lifetime,
K_L rare decays

K_S
high
intens.
test run

NA48/1-phase I

NA48/1-phase II

2000

K_L
ε'/ε checks
K^0 mass,
$K_L \to \gamma\gamma$

η
ε'/ε
checks
η mass

K_S high
intensity
$K_S \to \pi^0\gamma\gamma$,
$K_S \to \gamma\gamma$, η_{000}

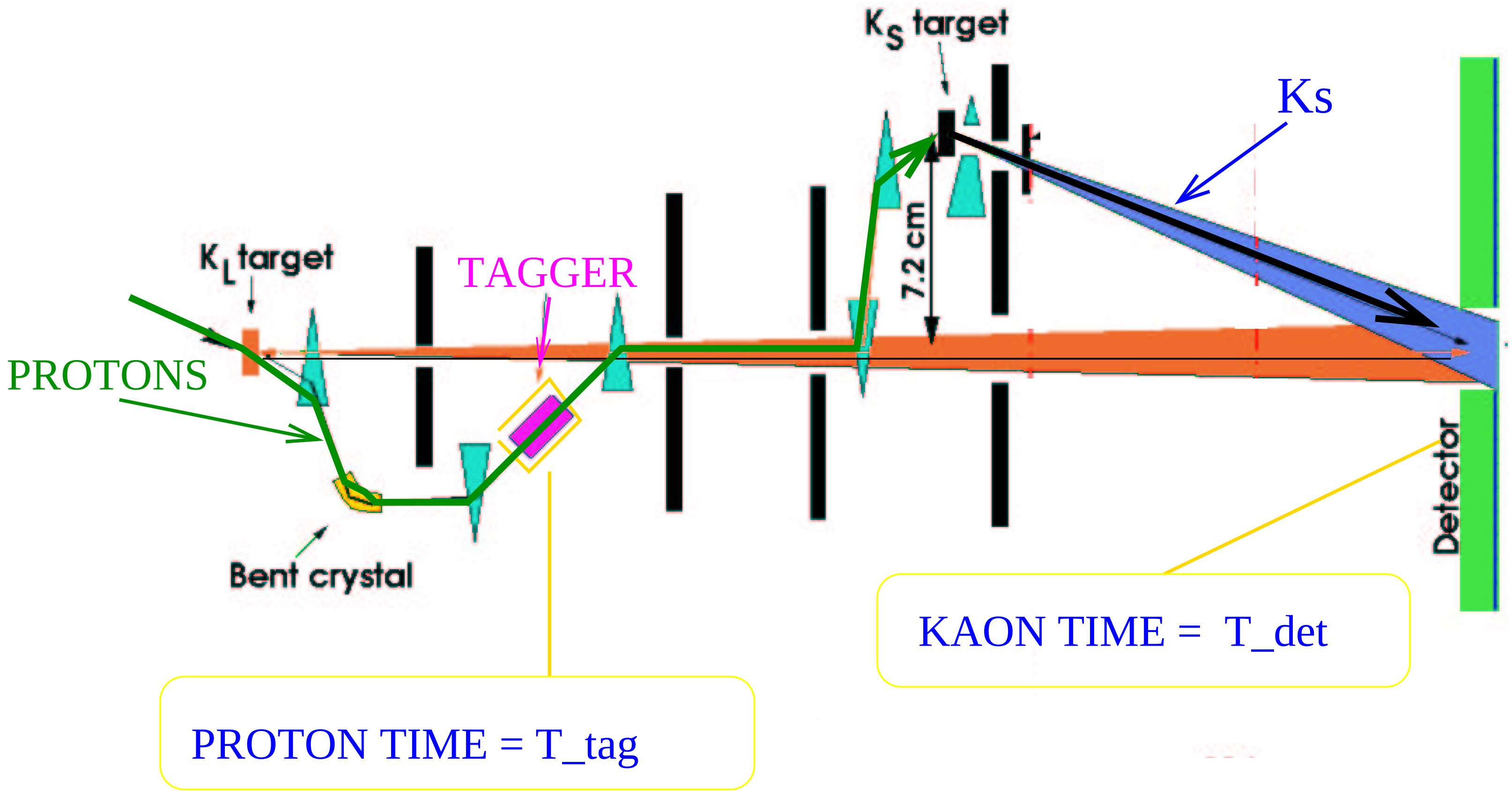
no spectrometer

2001
$K_L + K_S$
ε'/ε run
$\delta_L(e)$, $\delta_L(\mu)$

2002
K_S high
intensity
K_S and Hyperons

Tagging K_S events...

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



$\Re e(\varepsilon'/\varepsilon)$: the NA48 method

All experiments so far used the **Double Ratio method**:

$$R = \frac{N(K_L\to\pi^0\pi^0)[0.0009]}{N(K_S\to\pi^0\pi^0)[0.314]}\frac{N(K_S\to\pi^+\pi^-)[0.686]}{N(K_L\to\pi^+\pi^-)[0.002]} \simeq 1 - 6\times\Re e\left(\frac{\varepsilon'}{\varepsilon}\right)$$

➔ **Accuracy** $2\times10^{-4}\longrightarrow$ **count a lot of events in the most unbiased way**

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 K_L events to equalize distribution of K_S and K_L decay positions

= with similar energy spectra
performing the analysis in energy bins to minimize the remaining K_S / K_L differences

➔ small acceptance correction

= with high resolution detectors

➔ small background level

History of ε'/ε data collected by NA48

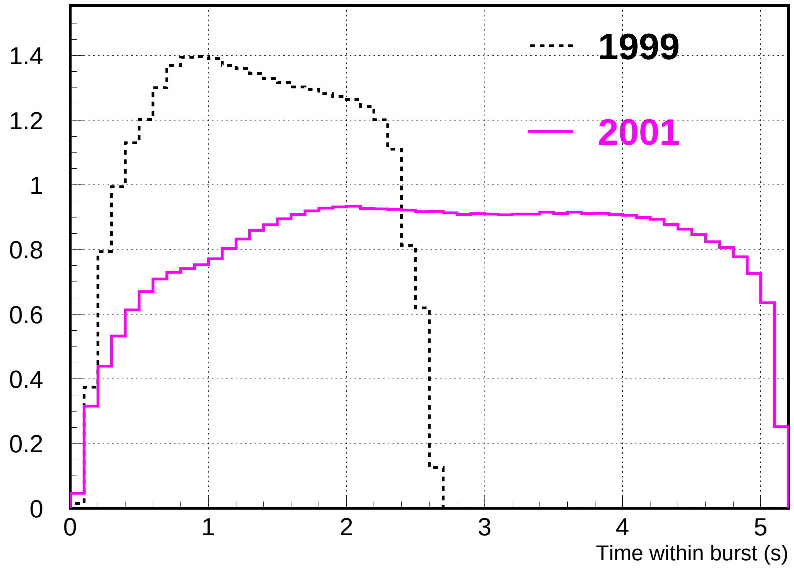
year	days	ppp on K_L target	$K_L \to \pi^0\pi^0$
1997	89	1×10^{12}	0.49 million
			$\Re e(\varepsilon'/\varepsilon) = (18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$ Phys.Lett.B465 (1999) 335-348
1998	135	1.4×10^{12}	1.05 million
1999	128	1.4×10^{12}	2.24 million
			$\Re e(\varepsilon'/\varepsilon) = (15.0 \pm 1.7 \pm 2.1) \times 10^{-4}$ Eur.Phys.J.C22 (2001) 231-254
2001	90	2.4×10^{12} $\ast$	1.55 million
			$\Re e(\varepsilon'/\varepsilon) = (13.7 \pm 2.5 \pm 1.8) \times 10^{-4}$ Phys.Lett.B544 (2002) 97-112

$\ast$ modified beam parameters

The last ε'/ε data taking

- in **2001** we collected additional data under varied conditions to test the intensity related systematics of the measurement

SPS spill length/cycle time	2.4/14.4 s	$\rightarrow$ 5.2/16.8 s
duty cycle	0.17	$\rightarrow$ 0.31
proton beam energy	450 GeV	$\rightarrow$ 400 GeV
instantaneous intensity		$\sim$ 30 % lower
detector		**new drift chambers**



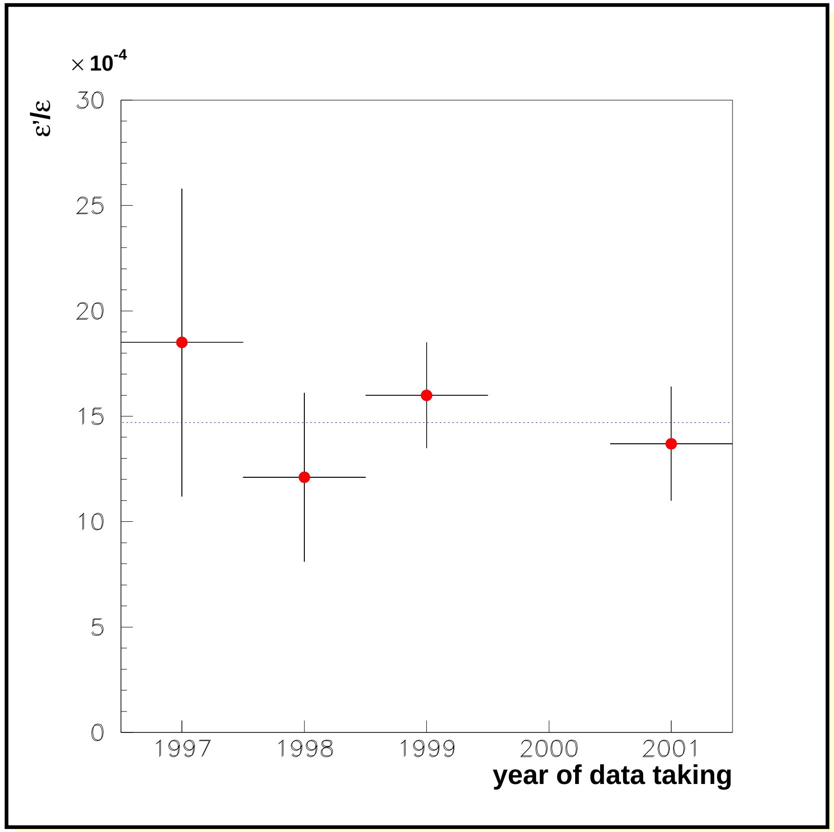
Good K_L Events / 100 ms

Comparing 2001 and 98+99 Results

Corrections and uncertainties on R (Units = 10^{-4})

	2001					1998/1999				
statistical error		±	14.7				±	10.1		
$\pi^0\pi^0$ reconstruction				±	5.3				±	5.8
Acceptance	21.9	±	3.5	±	4.0	26.7	±	4.1	±	4.0
$\pi^+\pi^-$ trigger inefficiency	5.2	±	3.6			-3.6	±	5.2		
Accidentals: intensity diff.				±	1.1				±	3.0
illumination diff.		±	3.0				±	3.0		
K_S in–time activity				±	1.0				±	1.0
Accidental tagging	6.9	±	2.8			8.3	±	3.4		
Tagging inefficiency				±	3.0				±	3.0
$\pi^+\pi^-$ background	14.2			±	3.0	16.9			±	3.0
$\pi^+\pi^-$ reconstruction				±	2.8				±	2.8
beam scattering	-8.8			±	2.0	-9.6			±	2.0
$\pi^0\pi^0$ background	-5.6			±	2.0	-5.9			±	2.0
AKS inefficiency	1.2			±	0.3	1.1			±	0.4
Total correction and systematic error	+35.0	±	6.5	±	9.0	+35.9	±	8.1	±	9.6
double ratio R	0.99181					0.99098				

$\Re e(\varepsilon'/\varepsilon)$: the final result



From 2001 data:

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

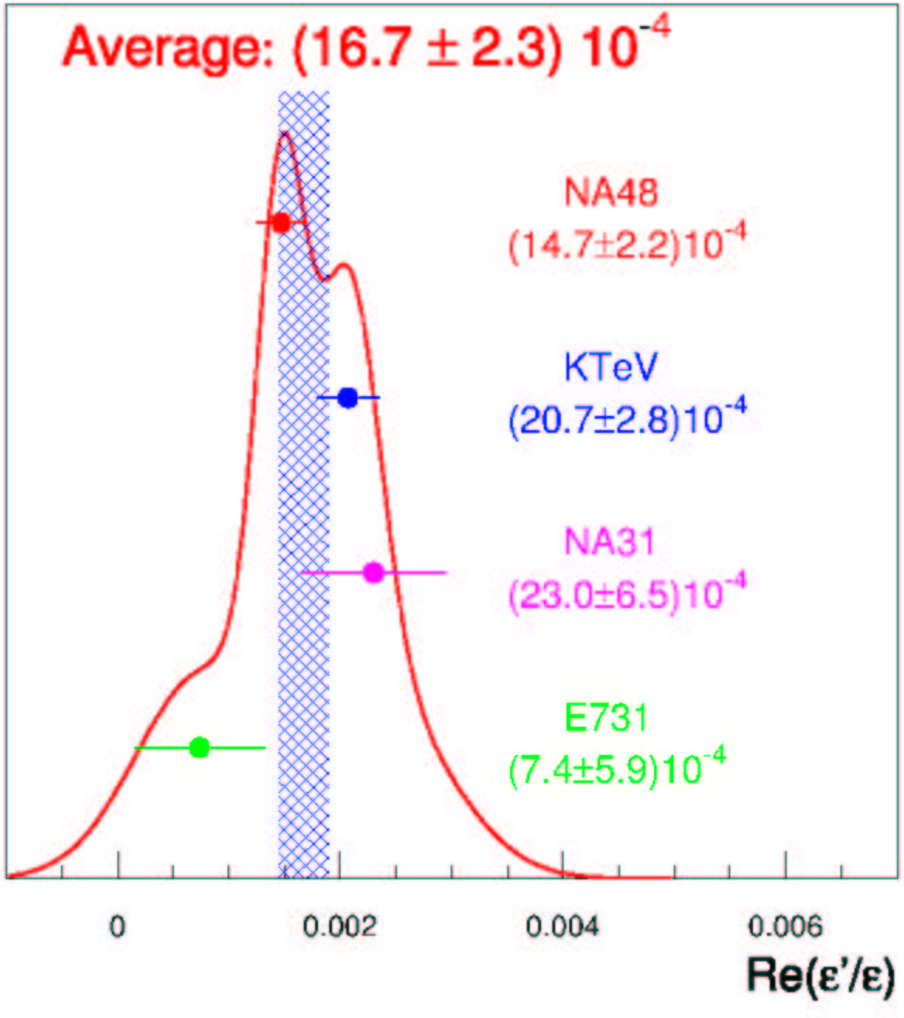
in agreement with NA48 previous measurements.

Combining the four years of data taking

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

- **6.7 σ away from 0**
- proposed accuracy has been reached ☺

World average of ε'/ε



naive average ⇒ $\Re\mathfrak{e}(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}$

with a $\chi^2 = 6.3/3$

Not only ε'/ε ....

K_{e3} charge asymmetry measurement

$$\delta_l(e) = \frac{BR(K_L \to \pi^- e^+ \nu_e) - BR(K_L \to \pi^+ e^- \overline{\nu_e})}{BR(K_L \to \pi^- e^+ \nu_e) + BR(K_L \to \pi^+ e^- \overline{\nu_e})} = 2\mathfrak{Re}(\epsilon)$$

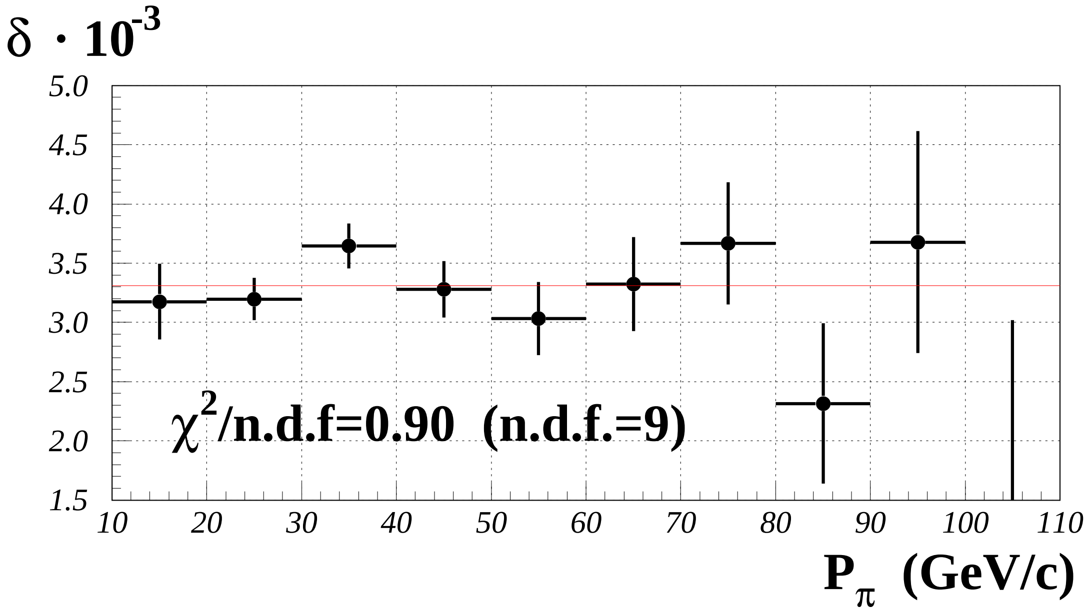
200×10^6 K_{e3} **(2001)**

Analysis in pion momentum bins

Fake asymmetries studied

Corrections:

trigger	26.2	$\pm$	6.0
pion ID	-1.4	$\pm$	3.5
punch thru	-17.1	$\pm$	2.4

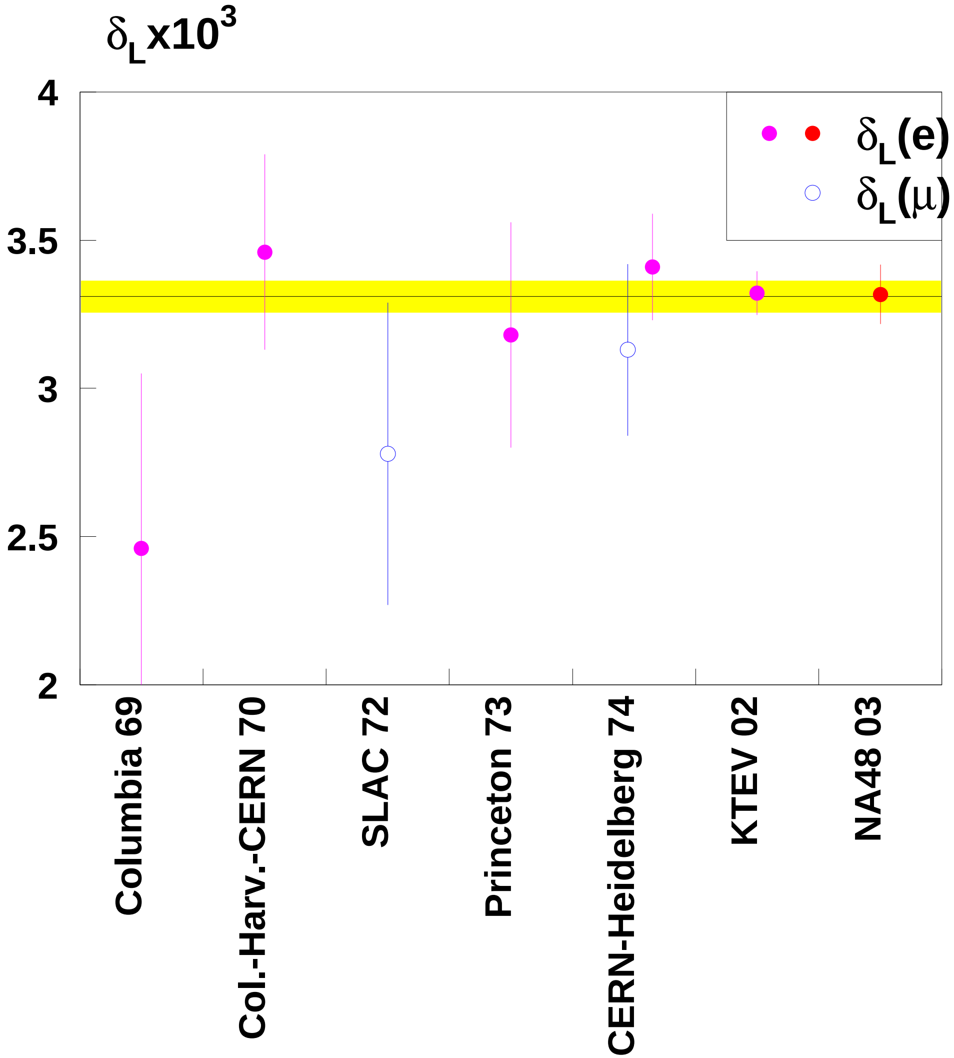


preliminary

$\Longrightarrow$ $\delta_L(e) = (3.317 \pm 0.070_{stat} \pm 0.072_{syst}) \times 10^{-3}$

New World Average: $\delta_L = (3.310 \pm 0.054) \times 10^{-3}$ with a $\chi^2 = 4.2/7$

K_{e3} : measurements overview



η_{000} measurement

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)}$$

if CPT symmetry assumed

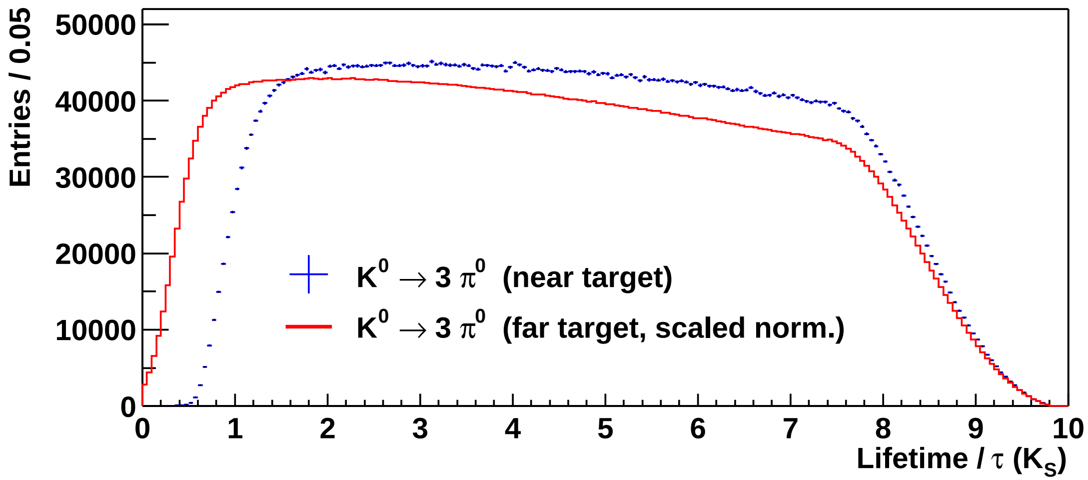
$\Re e\ \eta_{000} = \Re e \epsilon$

$\Im m\ \eta_{000}$ sensitive to direct CP violation

$$f(E,t) = I^{near}_{\pi^0\pi^0\pi^0} / I^{far}_{\pi^0\pi^0\pi^0} =$$

$$A(E)\left[1 + |\eta_{000}|^2 e^{t/\tau_L - t/\tau_S} + 2D(E)e^{t/2\tau_L - t/2\tau_S}(\Re e\eta_{000}\ cos(\Delta mt) - \Im m\eta_{000}\ sin(\Delta mt))\right]$$

5.9×10^6 $\pi^0\pi^0\pi^0$ (KSHI 2000)



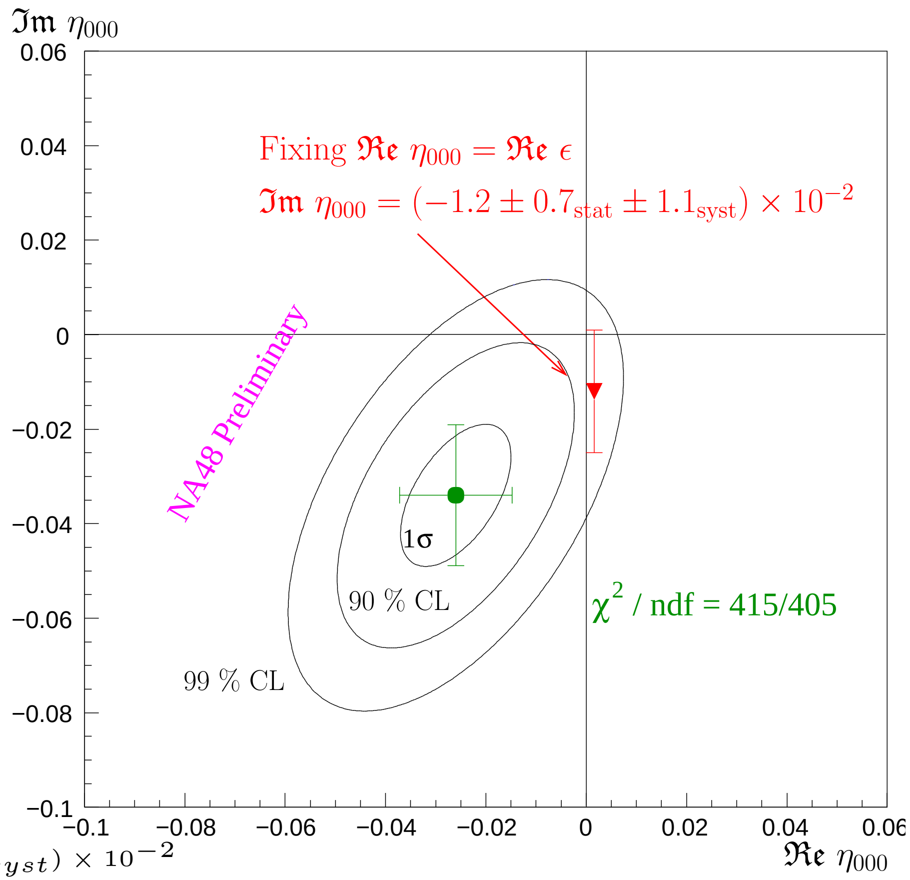
acceptance corrected at *1st order* using data (from the K_L only run 2000)

fit in energy bin of $f(E,t)$ range 70-170 GeV

fit parameters: A(E), $\Re e\ \eta_{000}$, $\Im m\ \eta_{000}$

Systematic sources:
$K^0 - \overline{K^0}$ dilution, acceptance, accidentals, energy scale, binning

η_{000} measurement



CPLEAR

$$\Re e\ \eta_{000} = (18 \pm 14_{stat} \pm 6_{syst}) \times 10^{-2}$$
$$\Im m\ \eta_{000} = (15 \pm 20_{stat} \pm 3_{syst}) \times 10^{-2}$$

preliminary Fit result ⟹

$$\Re e\ \eta_{000} = (-2.6 \pm 1.0_{stat} \pm 0.5_{syst}) \times 10^{-2}$$

$$\Im m\ \eta_{000} = (-3.4 \pm 1.0_{stat} \pm 1.1_{syst}) \times 10^{-2}$$

$\Re e\ \eta_{000}$ fixed

$$\Im m\ \eta_{000} = (-1.2 \pm 1.3) \times 10^{-2}$$

⟹ $BR(K_S \to \pi^0\pi^0\pi^0) < 3.0 \times 10^{-7}$

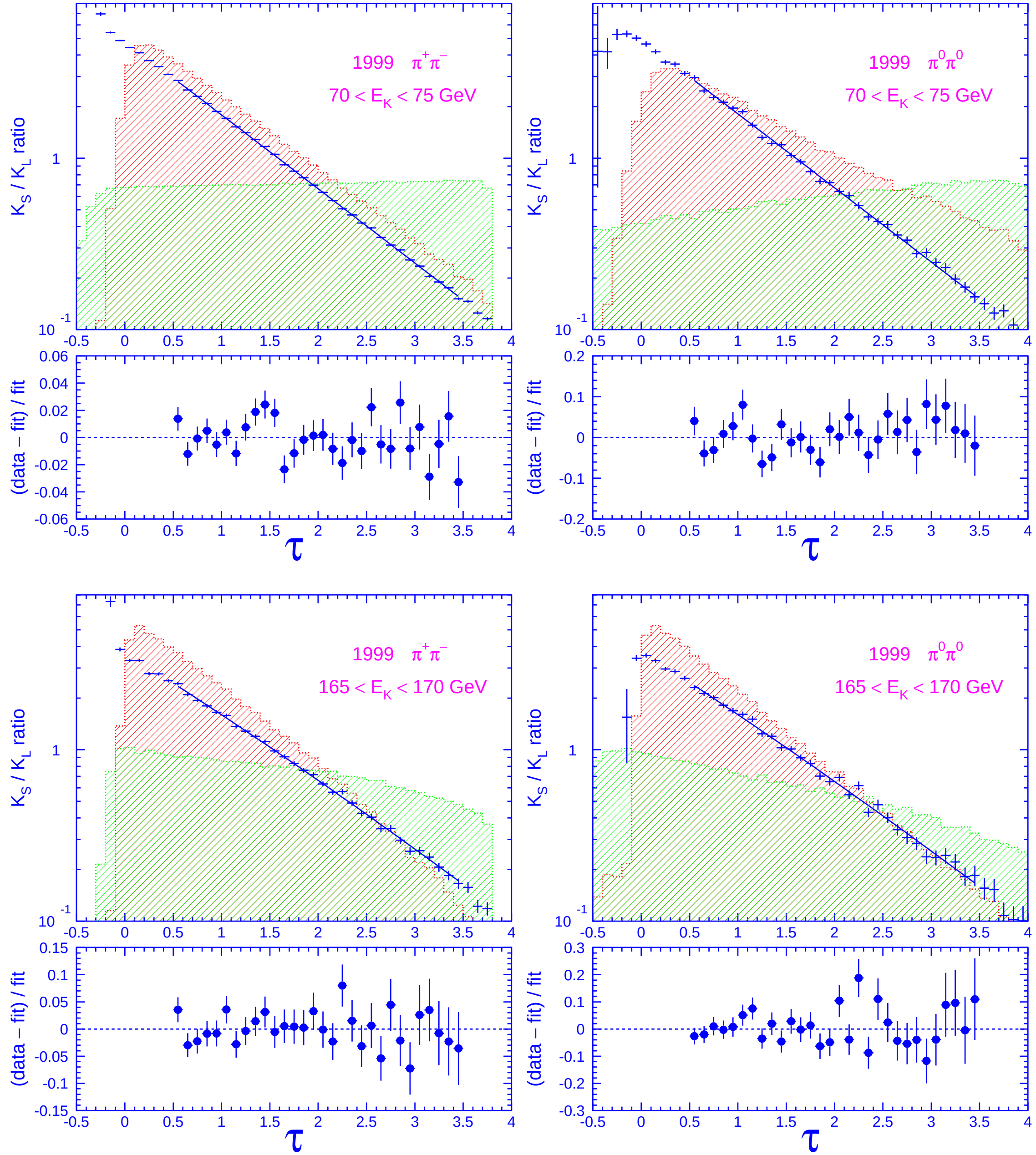
By-products of the ε'/ε analysis

K_S lifetime measurement

- **98 + 99 ε'/ε data**
- K_S lifetime derived from the ratio K_S/K_L of decay time distributions
  ⟹ detector acceptance cancels in first approximation
- $\tau_S << \tau_L$, the ratio is primarily sensitive to the τ_S

N_S/N_L of $K^0 \to \pi^+\pi^-, \pi^0\pi^0$:

- corrected for *residual acceptance differences* due to beams geometry [MC]
- background subtracted (10^{-3} in K_L sample) using data
- fitted in bins of *energy* [70-170 GeV] and *lifetime* [0.5-3.5 τ_S]



K_S lifetime measurement overview

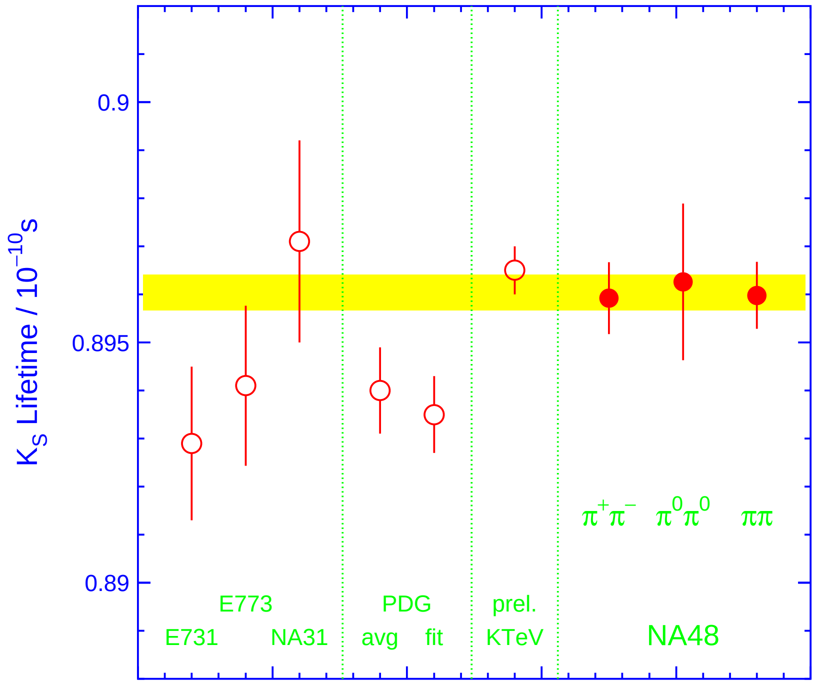
Data samples: 13.2M $K_S \to \pi^+\pi^-$, 12.2M $K_L \to \pi^+\pi^-$, 3.1M $K_S \to \pi^0\pi^0$, 2.8M $K_L \to \pi^0\pi^0$

$$\pi^+\pi^- \qquad \tau_S = (0.89592 \pm 0.00052_{stat} \pm 0.00054_{syst}) \times 10^{-10}\ \mathrm{s}$$
$$\pi^0\pi^0 \qquad \tau_S = (0.89626 \pm 0.00129_{stat} \pm 0.00100_{syst}) \times 10^{-10}\ \mathrm{s}$$

⇒ Combined result:

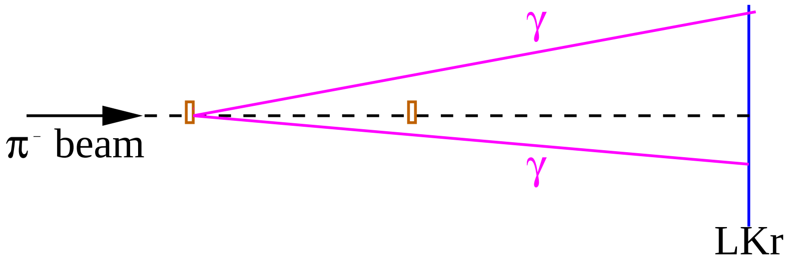
$$\tau_S = (0.89598 \pm 0.00048_{stat} \pm 0.00027_{MCstat} \pm 0.00043_{syst}) \times 10^{-10}\ \mathrm{s}$$

Phys.Lett.B537 (2002)



Measurement of η and K^0 masses

η runs conceived for the ε' analysis



η and π^0 produced $\Rightarrow$ used to check the calorimeter energy scale [comparing reconstructed vertex in $\pi^0, \eta \rightarrow \gamma\gamma$ events with the targets position]

Year 2000

- K^0 mass: data with only K_L beam
- η mass: special η **runs**

Method

Using the $3\pi^0 \rightarrow 6\gamma$ decay channel:

1) the z_{π^0} position is inferred using the π^0 mass constraint via the relation

$$d_{[z_{\pi^0}, LKr]} = \frac{1}{M_{\pi^0}} \sqrt{E_1 E_2} d_{12}$$

2) using the d average from the 3 π^0, the 6-body invariant mass is

$$M = \frac{1}{d_{\pi^0}} \sqrt{\sum_{i,j,i<j} E_i E_j (d_{ij})^2}$$

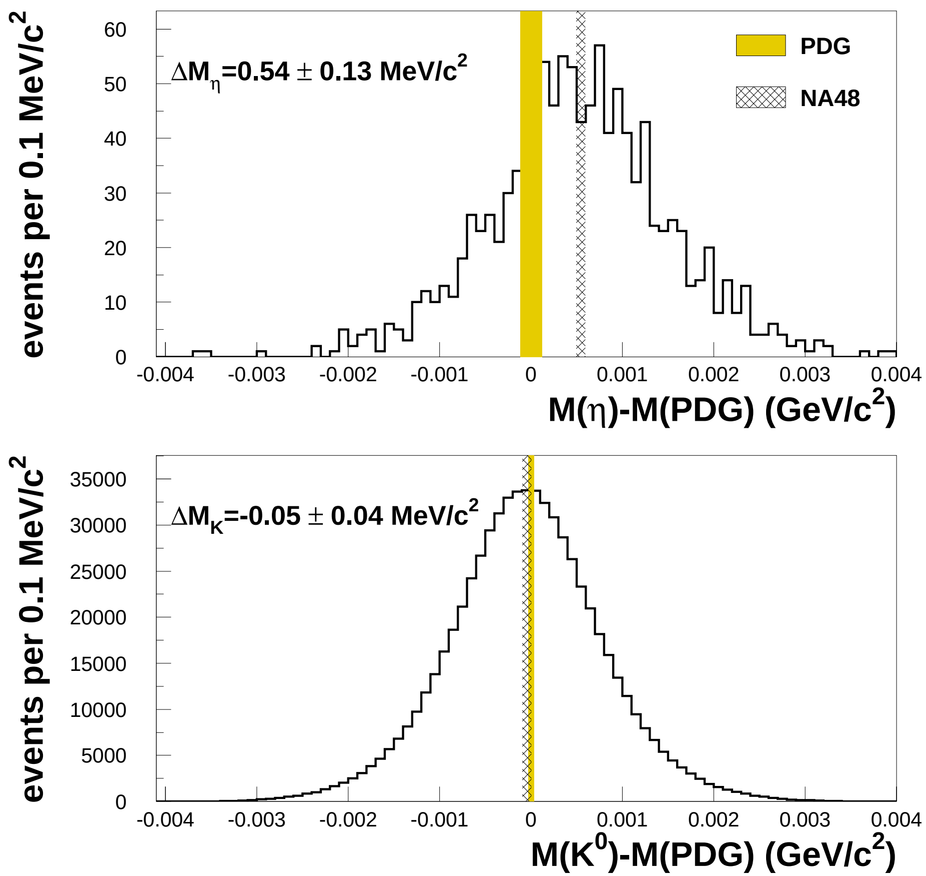
! M is independent of the energy scale of the calorimeter !

Measurement of η and K^0 masses

Only symmetric decays used (photons $\sim$ the same energy) to minimize sensitivity to residual non-linearities

M_η / M_{π^0} measured with an accuracy three times better than the PDG world average

M_{K^0} / M_{π^0} measured with an accuracy similar to the PDG



PDG 2000 Values:

$$M_{K^0} = 497.672 \pm 0.031 \text{ MeV/c}^2$$
$$M_\eta = 547.30 \pm 0.12 \text{ MeV/c}^2$$

$$M_\eta = 547.843 \pm 0.030_{stat} \pm 0.005_{MCstat} \pm 0.041_{syst} \text{ MeV/c}^2$$

$$M_{K^0} = 497.625 \pm 0.001_{stat} \pm 0.003_{MCstat} \pm 0.031_{syst} \text{ MeV/c}^2$$

Phys.Lett.B533 (2002)

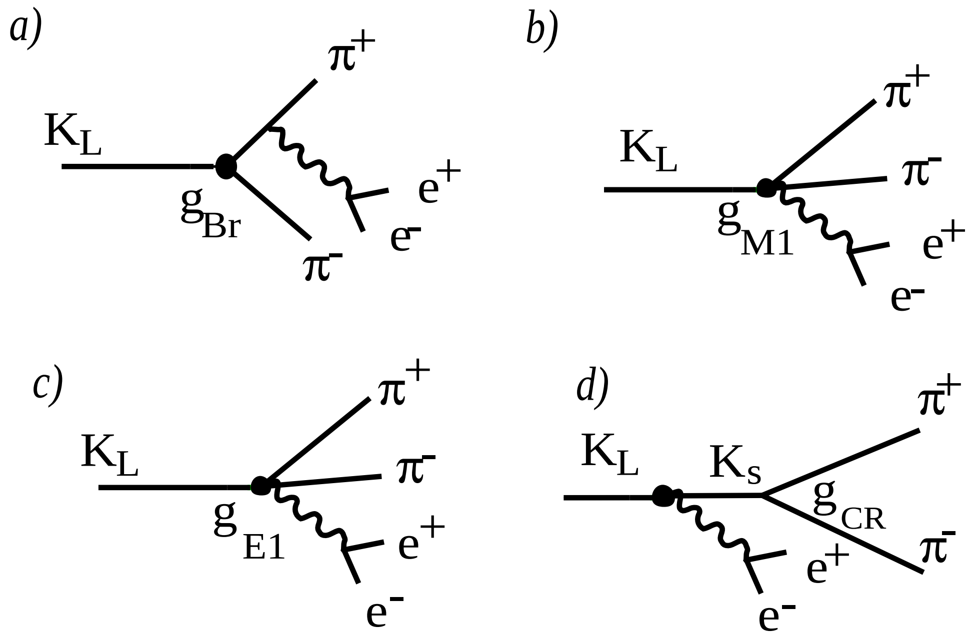
On Rare Decays

K_L ,$K_S \to \pi^+\pi^- e^+ e^-$

Radiative K^0 decays

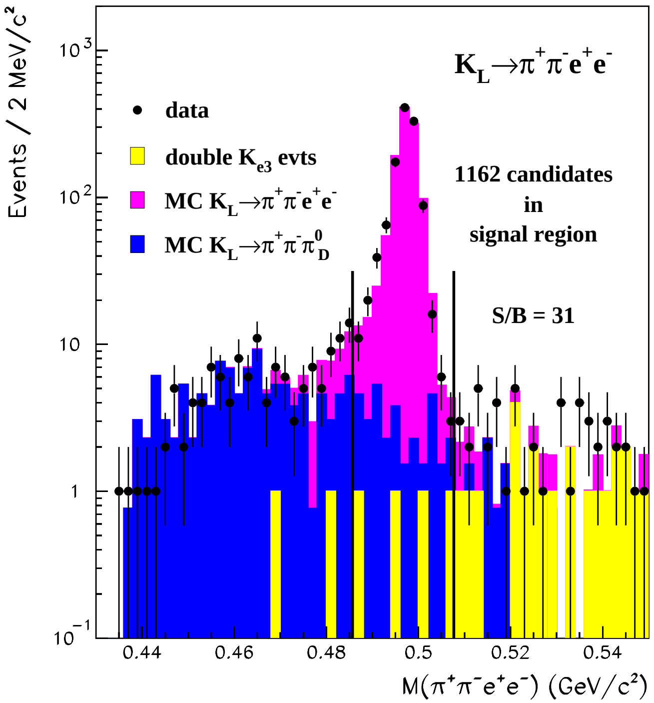
In the K_L case, interference between CP violating Inner Brem. and CP conserving Direct Emission processes, produces an asymmetry in the distribution of Θ between $\pi^+\pi^-$ and e^+e^- decay planes

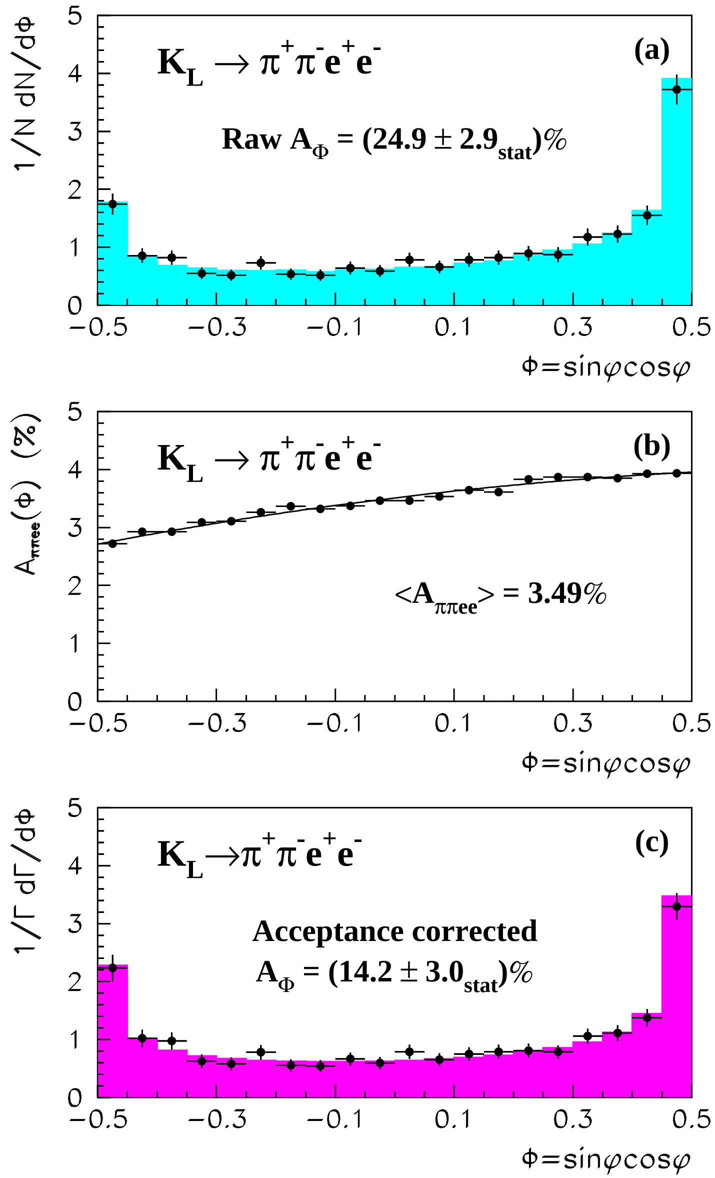
Ü $\sim 14\%$



- DATA SAMPLE: 98 + 99 $\Re e(\varepsilon'/\varepsilon)$ period + KSHI test runs of 99
- K_S K_L decay rates normalized to $K_L \to \pi^+\pi^-\pi^0{}_D$ coming from K_S K_L targets respectively
- detailed Montecarlo study to remove backgrounds and to compute the acceptances of signals and normalization

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

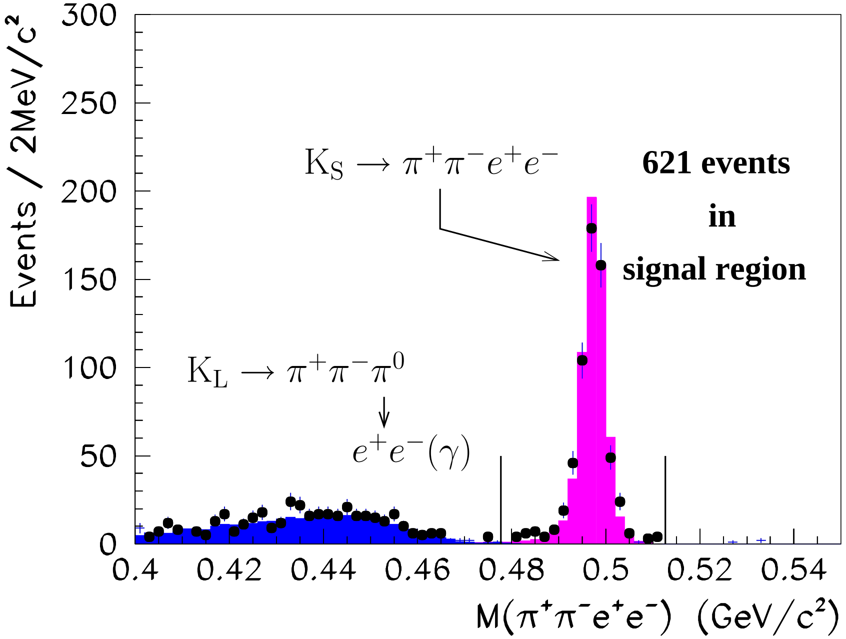


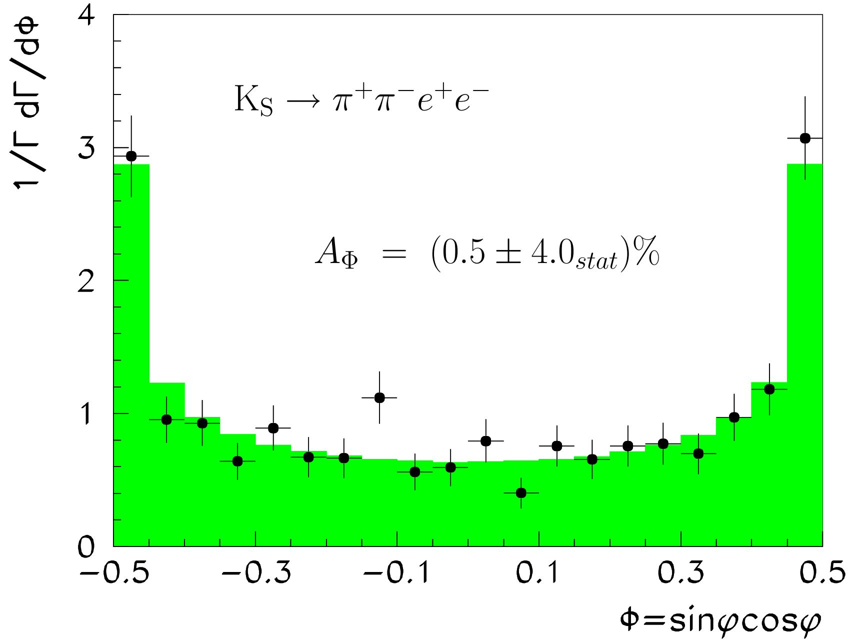


1162 candidates, expected background of 36.9 events

- $BR(K_L \to \pi^+\pi^-e^+e^-) = (3.08 \pm 0.20) \times 10^{-7}$
- $A_\Phi^S = (14.2 \pm 3.6)\ \%$

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





621 candidates (99 data) + 56 (98 data -published), expected background of 0.7 events

$$BR(K_S \rightarrow \pi^+\pi^-e^+e^-) = (4.69 \pm 0.30) \times 10^{-5}$$

$$A_\Phi^S = (0.5 \pm 4.3)\ \%$$

Sub. to EPJ

The results are in good agreement with the theoretical predictions

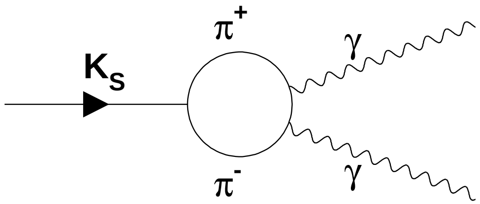
Large asymmetry observed in the angular correlation between $\pi^+\pi^-$ and e^+e^- decay planes $\rightarrow$ manifestation of indirect CP violation

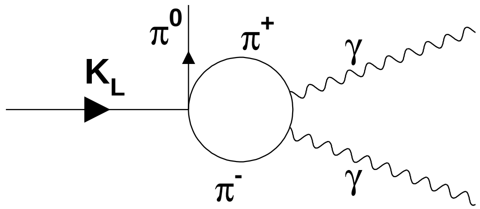
No asymmetry observed in the K_S channel (as expected)

χPT and $K_L \to \pi^0\gamma\gamma$ and $K_S \to \gamma\gamma$

$O(p^4)$ diagrams:

2.1×10^{-6}





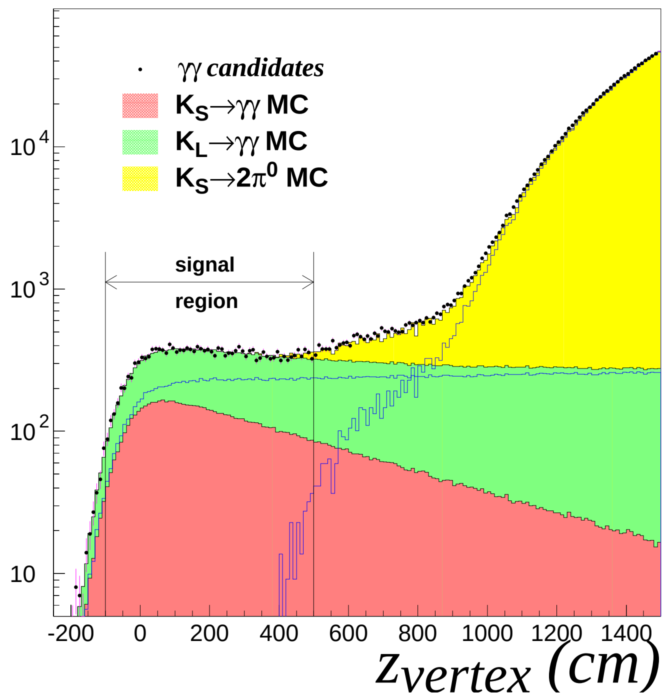
0.6×10^{-6}

Similarities in these two decays:

- $O(p^2) = 0$, $O(p^4)$ is unambiguously predicted by χPT (<5% precision)
- at $O(p^6)$:

$K_L \to \pi^0\gamma\gamma$		$K_S \to \gamma\gamma$
"scalar" exchange	similar	"scalar" exchange
+		
$O(p^4)$ correction to $A(K_L \to \pi^0\pi^+\pi^-)$		
+		
vector-meson exchange (a_V)	a_V can be extracted from exper. $m_{\gamma\gamma}$ distribution	

$K_S \to \gamma\gamma$



$\gamma\gamma$ normalized to $\pi^0\pi^0$ $\to$ most systematics cancel

2000 KSHI data

$\sim$7500 estimated events in the signal region
$-1\ m < z_{vertex} < 5\ m$

main background:

- $2\pi^0$ with only 2 reconstr. clusters
- irreducible $K_L \to \gamma\gamma$ ($\sim$ 1.5 times K_S)

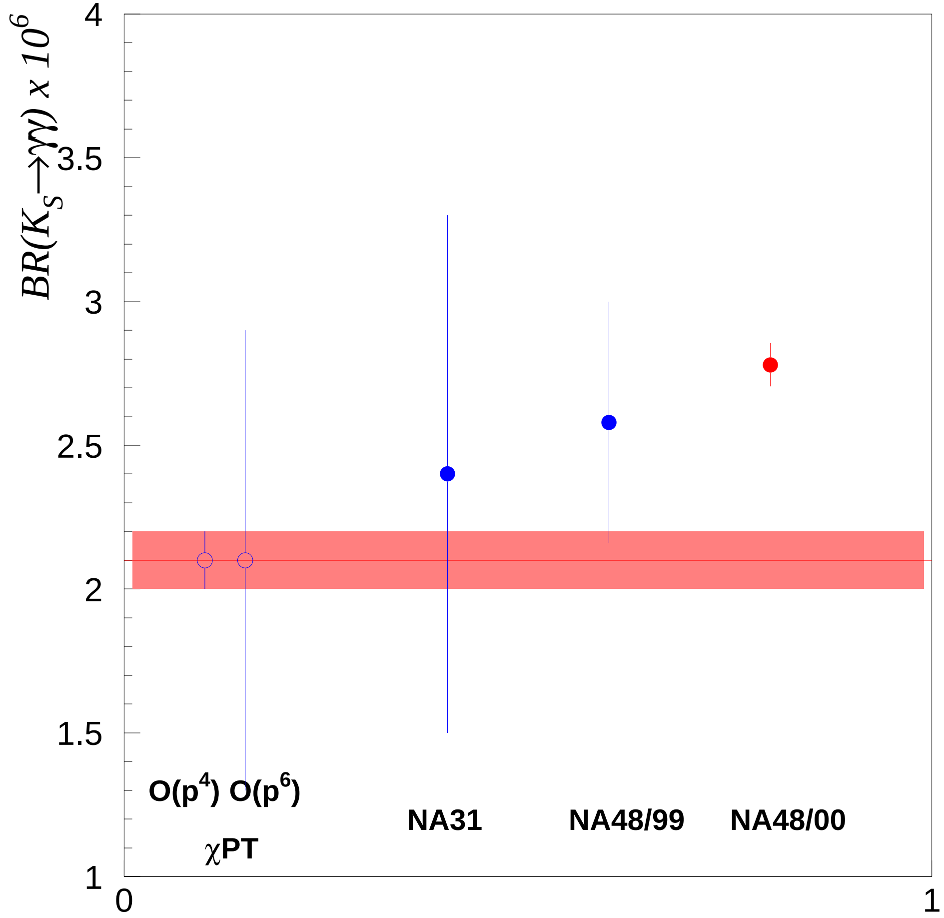
⇒ use $K_L \to 3\pi^0$ to estimate K_L flux, and 2000 K_L run to measure $\frac{\Gamma(K_L \to \gamma\gamma)}{\Gamma(K_L \to 3\pi^0)}$

⇒ $BR(K_S \to \gamma\gamma) = (2.78 \pm 0.06_{stat} \pm 0.02_{MCstat} \pm 0.04_{syst}) \times 10^{-6}$

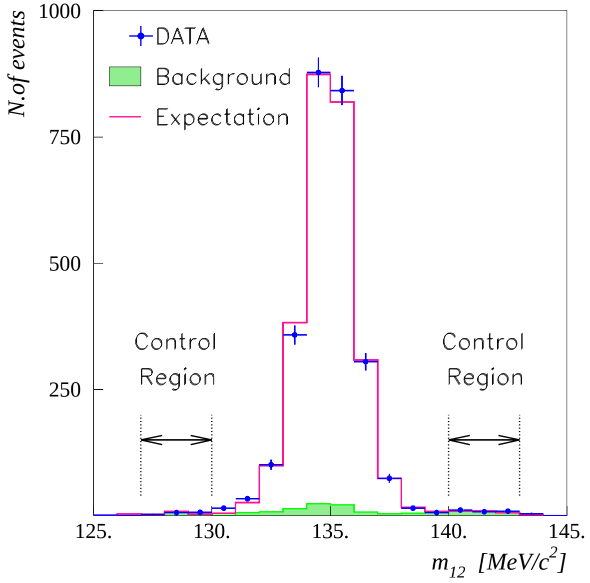
Phys.Lett.B551 (2003)

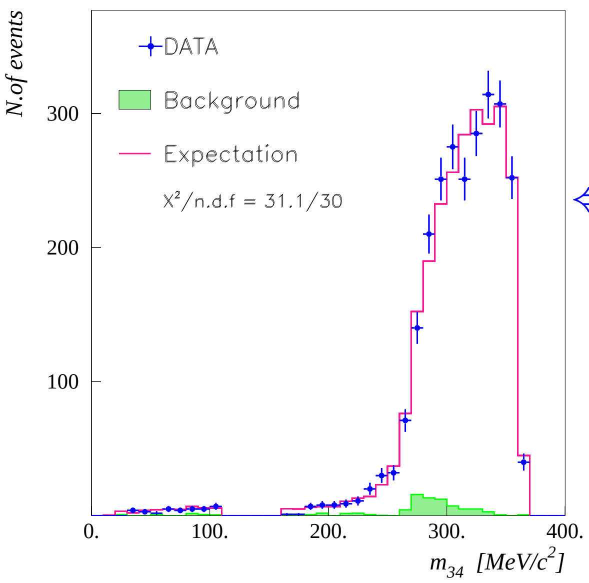
This result differs by 30% from $O(p^4)$ χPT prediction ⇒ indication of large $O(p^6)$ contribution

$K_S \to \gamma\gamma$ measurements



$K_L, K_S \rightarrow \pi^0\gamma\gamma$ measurements





$\pi^0\gamma\gamma$ signals normalized to $\pi^0\pi^0$

$\Longleftarrow$ **98 +99 ε'/ε data:** K_L

2500 events with 3.2% estimated background

vector-meson coupling of $a_V = -0.46$

➔ negligible CP-conserving contribution to $K_L \rightarrow \pi^0 e^+ e^-$

➔ $BR(K_L \rightarrow \pi^0\gamma\gamma) = (1.36 \pm 0.03_{stat} \pm 0.03_{syst} \pm 0.03_{norm}) \cdot 10^{-6}$

Phys.Lett.B536 (2002)

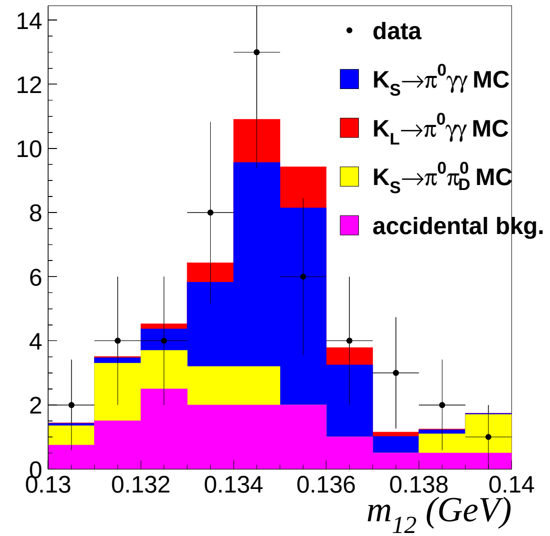
2000 KSHI run: K_S $\Longrightarrow$

$K_S \rightarrow \pi^0\gamma\gamma$ first observation: 31 events with 13.2 estimated background

➔ $BR(K_S \rightarrow \pi^0\gamma\gamma)_{z_q>0.2} = (4.9 \pm 1.6_{stat} \pm 0.8_{syst}) \cdot 10^{-8}$

preliminary

χPT prediction$= 3.8 \times 10^{-8}$



The NA48/1 - phase II

NA48/1: high intensity neutral short beam experiment
(mainly dominated by K_S and neutral Hyperons)

NA48 detector, modified K_S beam line, more powerful DAQ

Physics motivations

- Search for $K_S \to \pi^0 e^+ e^-$, $K_S \to \pi^0 \mu^+ \mu^-$ decays
- Measure semi-leptonic and radiative Hyperons decays, improving experimental results on $\Xi^0 \to \Sigma^+ e^- \nu$, $\Xi^0 \to \Sigma^+ \mu^- \nu$, $\Xi^0 \to \Sigma^0 \gamma$, $\Xi^0 \to \Lambda \gamma$
- Study other K_S and Hyperon rare decays

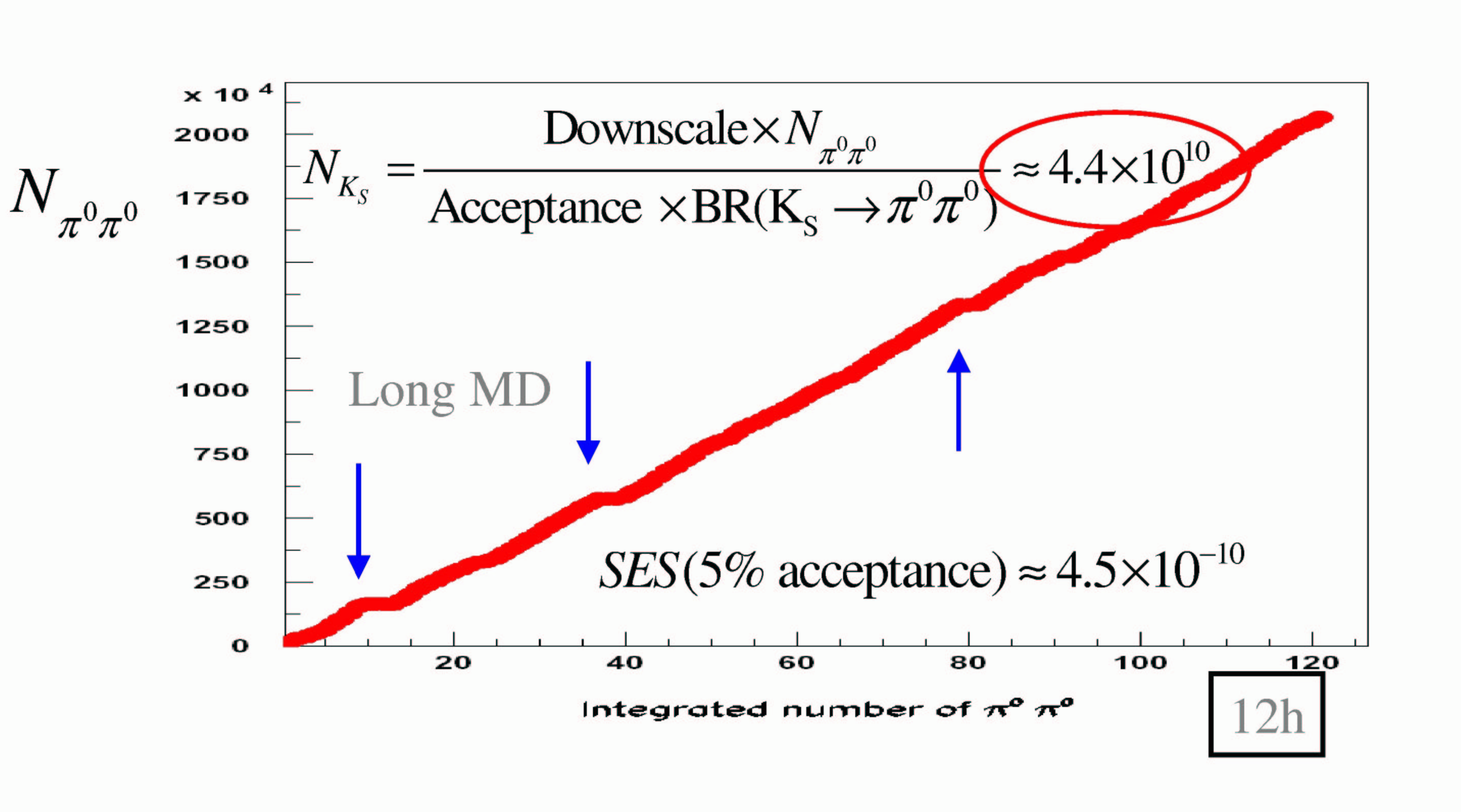
Proposal goal: reach a SES of $2 - 3 \times 10^{-10}$ for $K_S \to \pi^0 e^+ e^-$

Experimental set-up

- K_S beam produced by $\sim 5 \times 10^{10}$ proton per pulse (500 times more than ε'/ε config.)
  Accidental rate reduced by photon converter + sweeping magnet after the target
- detector prepared to maximize the particles flux
- DAQ speed up by some upgrades $\to$ double bandwidth

NA48/1: 2002 data taking

From July 18th to September 18th:



- Successful data taking: data quality is good!
- Analysis well advanced, both in the Kaon and in the Hyperon sector.

Summary

- In 4 years of data taking, NA48 measured the direct CP violation parameter $\mathfrak{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$, with the proposed accuracy. The result is 6.7 σ from 0
- $\delta_L(e)$ has been measured with competitive precision, η_{000} improved by an order of magnitude
- K_S lifetime, K mass, η mass measured with similar or better precision. η mass 4.2 σ from current world average
- On rare decays, several measurements testing χPT predictions have been done. First observation of $K_S \rightarrow \pi^0\gamma\gamma$
- Active program to measure K_S rare decays and CP violation in the $K^\pm$ decays NA48/2!