

CP Violation Results on Kaons by NA48

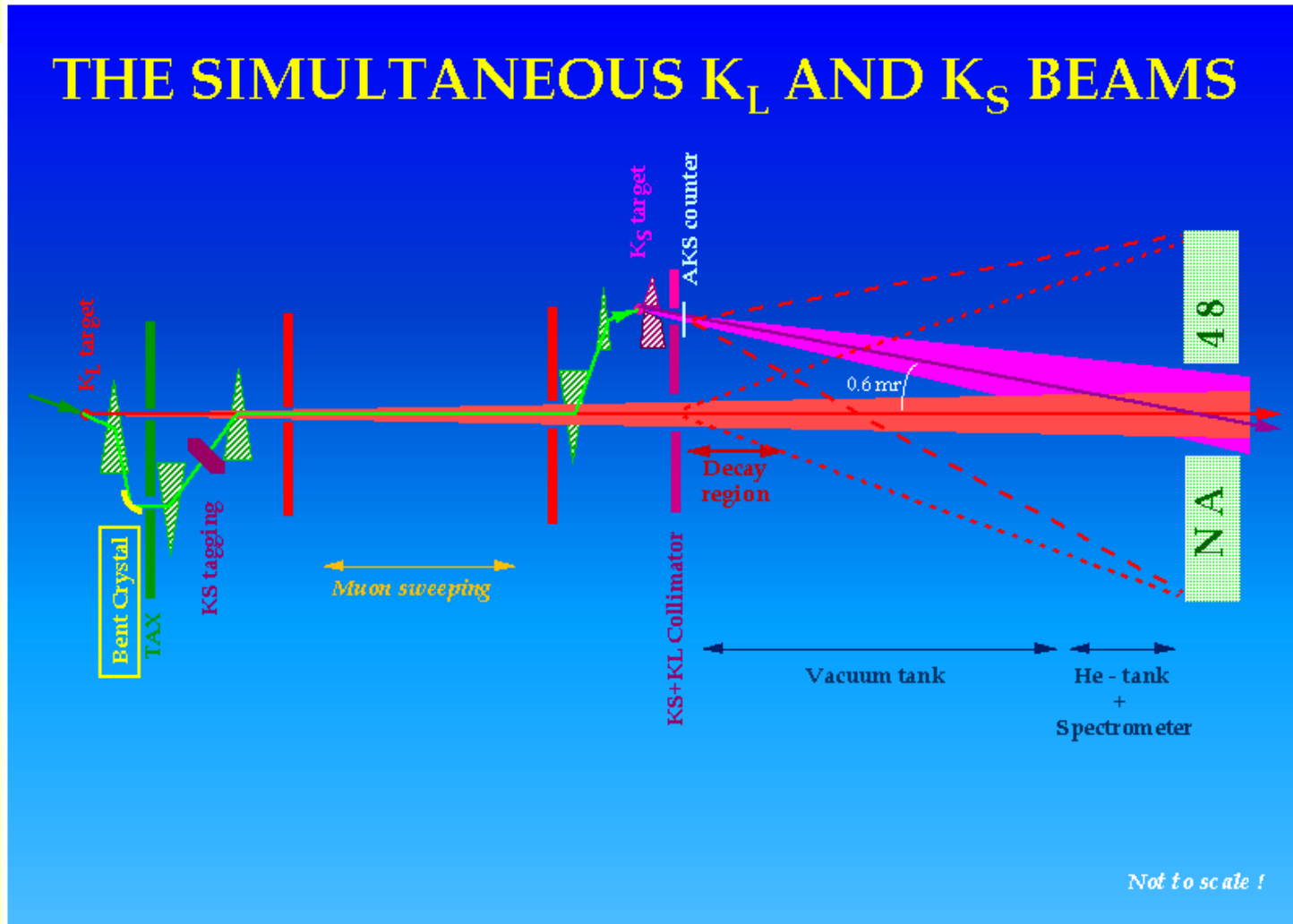
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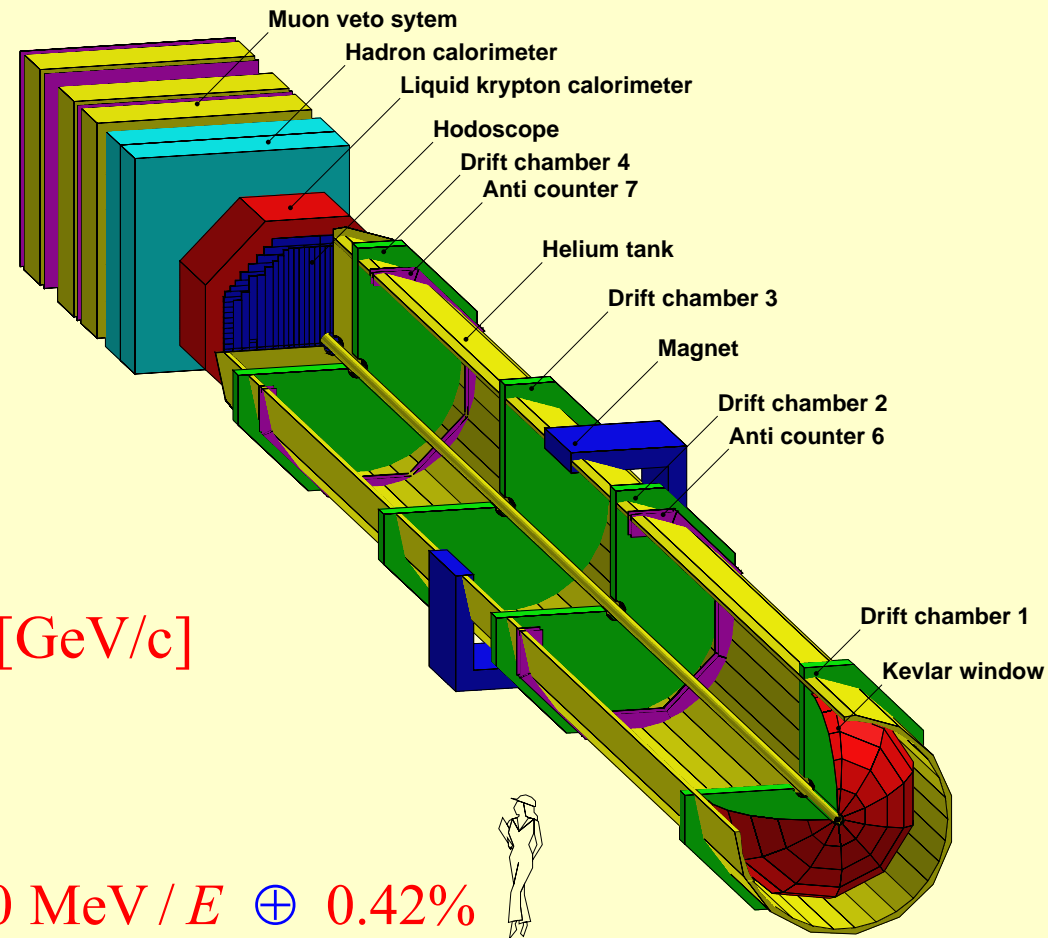
Plan of the presentation

- Introduction
- Charge Asymmetry in $K_L \rightarrow K_{e3}$ (**preliminary**)
- $K_S \rightarrow 3\pi^0$ (η_{000}) (**preliminary**)
- Angular Asymmetry in $K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$ (**final**)
- ε'/ε (**final**)
- The future: slope asymmetry in $K^\pm \rightarrow 3\pi$

The NA48 Experiment



The NA48 Detectors



Magnetic Spectrometer:

$$\Delta p / p = 0.5\% \oplus 0.009\% \times p[\text{GeV}/c]$$

LKr e.m. Calorimeter:

$$\Delta E / E = 3.2\% / \sqrt{E[\text{GeV}]} \oplus 90 \text{ MeV} / E \oplus 0.42\%$$

A bit of history.....

- 1997-1998-1999: ε'/ε run (K_L+K_S)
- 2000: “neutral” special runs (K_L -only and HIKS)
- 2001: ε'/ε run (K_L+K_S)
- 2002: HIKS run
- 2003: K^\pm run

K_{e3} Charge Asymmetry

$$\delta_L(e) = \frac{\Gamma(K_L \rightarrow \pi^- e^+ \nu) - \Gamma(K_L \rightarrow \pi^+ e^- \nu)}{\Gamma(K_L \rightarrow \pi^- e^+ \nu) + \Gamma(K_L \rightarrow \pi^+ e^- \nu)} = \frac{2 \times \text{Re}(\varepsilon)}{1 + |\varepsilon|^2}$$

If CPT conserved,
 $\varepsilon \approx 0$

NA48: Data from 2001 run period:

➤ Reconstructed 2×10^8 K_{e3} decays

$$\delta_L(e) = \frac{N(\pi^- e^+) - N(\pi^+ e^-)}{N(\pi^- e^+) + N(\pi^+ e^-)}$$

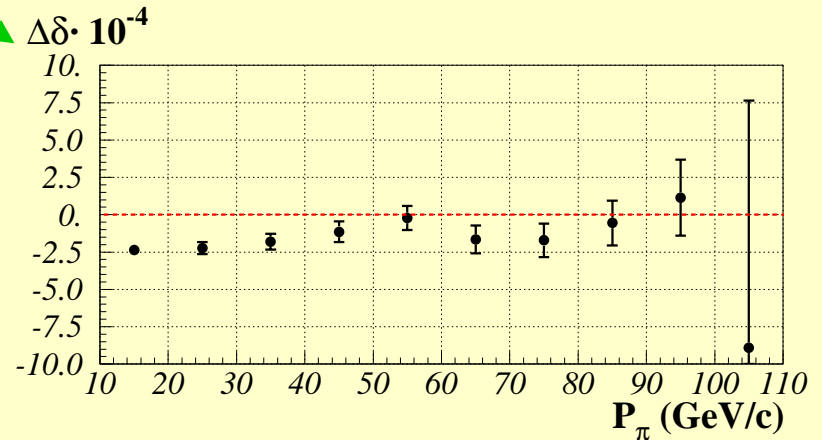
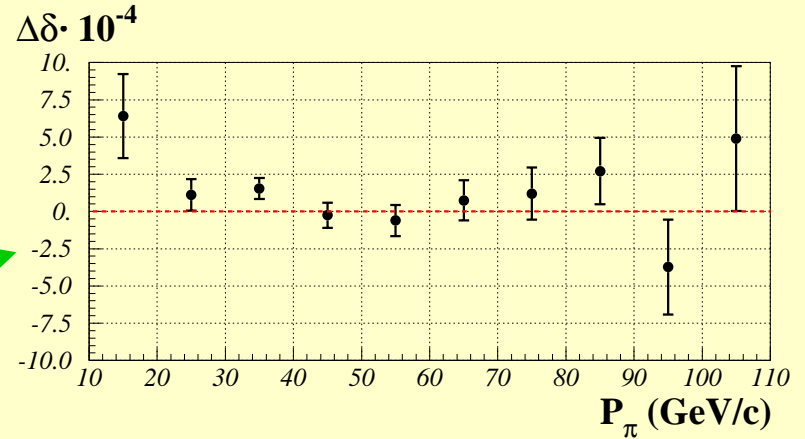
➤ Systematics: asymmetry of particle interactions

❑ Trigger efficiencies (→ calorimeters info)

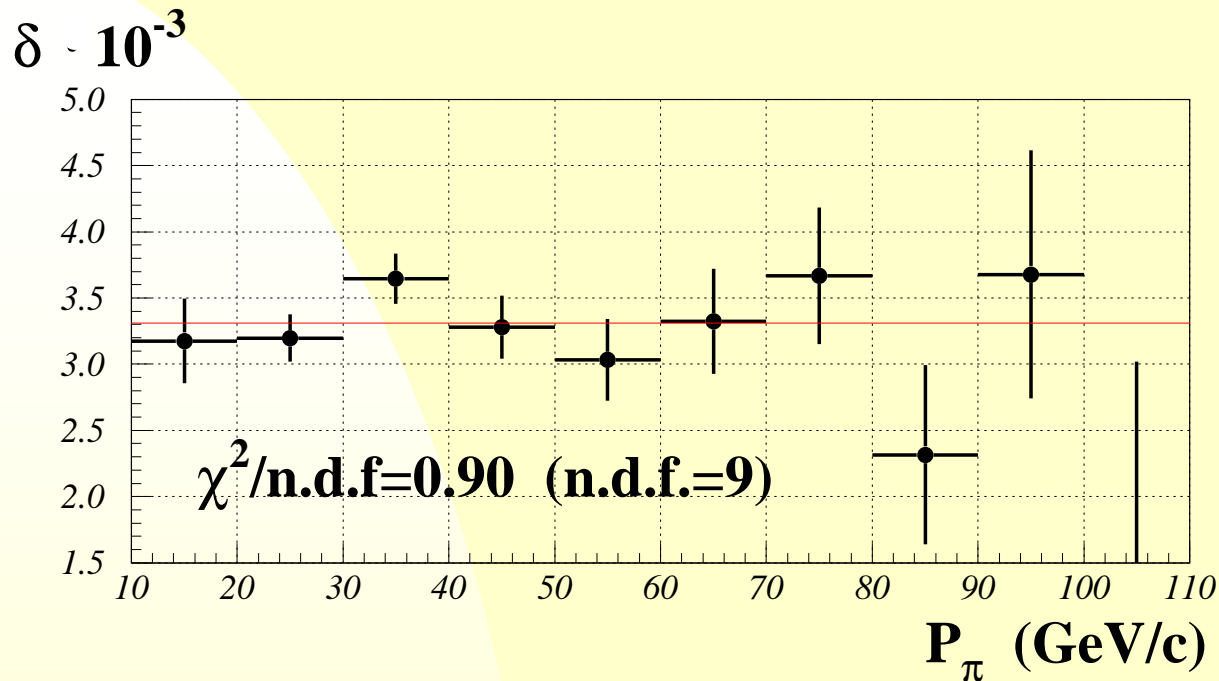
❑ Pion identification (→ E/P info)

K_{e3} Charge Asymmetry (II)

Systematics	Corrections ($\times 10^{-5}$)
Trigger	$+26.2 \pm 6.0$
Punch through	-1.4 ± 3.5
Pion ID	-17.1 ± 2.4
Acceptance	± 0.5
Background	± 0.5
Total	$+7.7 \pm 7.2$



K_{e3} Charge Asymmetry (III)



Fit in bins of the pion momentum

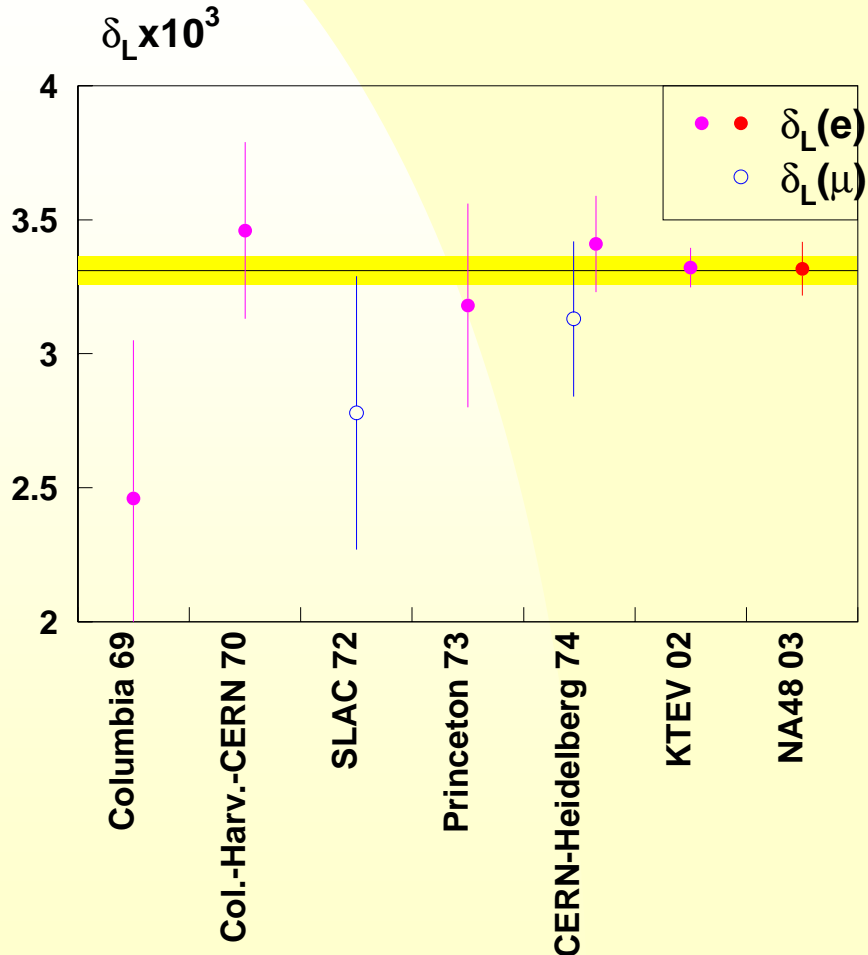
Preliminary result:

$$\delta_L(e) = (0.3317 \pm 0.0070_{\text{stat}} \pm 0.0072_{\text{syst}})\%$$

→ consistent with KTeV and World average measurements

K_{e3} Charge Asymmetry (IV)

NA48 Preliminary result: $\delta_L(e) = (0.3317 \pm 0.0070_{\text{stat}} \pm 0.0072_{\text{syst}})\%$



World average

$$\delta_L(e) = (0.3322 \pm 0.0055)\%$$

$$\delta_L = (0.3310 \pm 0.0054)\%$$

$$\chi^2 = 4.2 / 7$$

old average

$$\delta_L = (0.3307 \pm 0.0063)\%$$

$K_S \rightarrow 3\pi^0$ (η_{000})

- $K_S \rightarrow 3\pi^0$ is CPV (analogous to $K_L \rightarrow 2\pi^0$)

$$\eta_{000} \equiv \frac{A(K_S \rightarrow 3\pi^0)}{A(K_L \rightarrow 3\pi^0)} = \varepsilon + i \frac{\text{Im}(A_1)}{\text{Re}(A_1)}$$

If CPT conserved,
no transition to I=3
or to nonsymmetric I=1 states

- Time evolution of $K_{L,S} \rightarrow 3\pi^0$:

$$I_{3\pi^0} \propto \begin{array}{c} \text{K}_L \text{ decay} \\ \downarrow \\ e^{-\Gamma_L t} \end{array} + \begin{array}{c} \text{K}_S \text{ decay} \\ \downarrow \\ |\eta_{000}|^2 e^{-\Gamma_S t} \end{array} + \begin{array}{c} \text{K}_S\text{-K}_L \text{ interference} \\ \searrow \\ 2 D(p) (\text{Re}(\eta_{000}) \cos \Delta m t - \text{Im}(\eta_{000}) \sin \Delta m t) e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \end{array}$$

Dilution $D(p) = \frac{N(K^0) - N(\bar{K}^0)}{N(K^0) + N(\bar{K}^0)} \approx 0.35$ momentum dependent

$K_S \rightarrow 3\pi^0$ (η_{000}) (II)

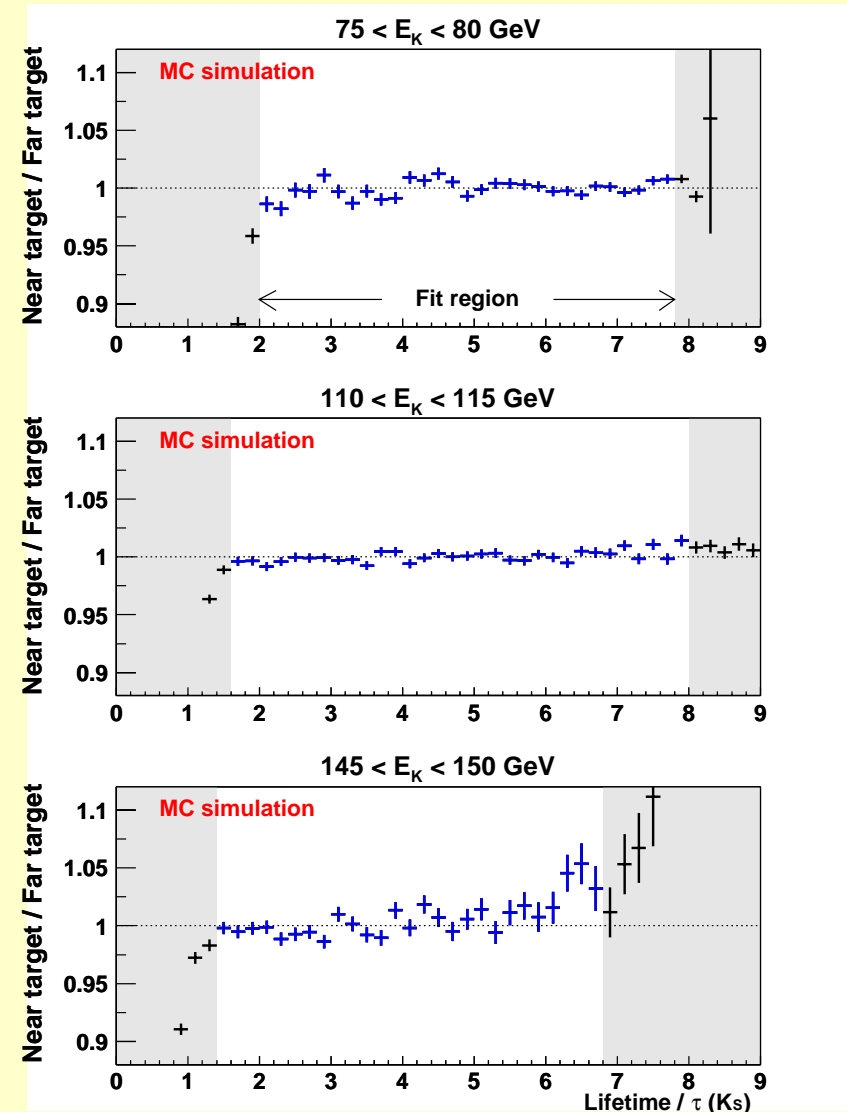
Run period 2000: No Drift chambers

Two sub-periods:

- Far-target K_L run for ε'/ε systematics
- Near-target K_S run for K_S high-intensity

Method:

- Use $3\pi^0$ events from near-target run for η_{000}
- Normalize to $K_L \rightarrow 3\pi^0$ from far-target run
- Use MC to correct for residual acceptance difference and Dalitz



$K_S \rightarrow 3\pi^0$ (η_{000}) (III)

Data samples:

Near-target run

$3\pi^0$ data: 6.5×10^6

$K_L \rightarrow 3\pi^0$ MC: 66×10^6

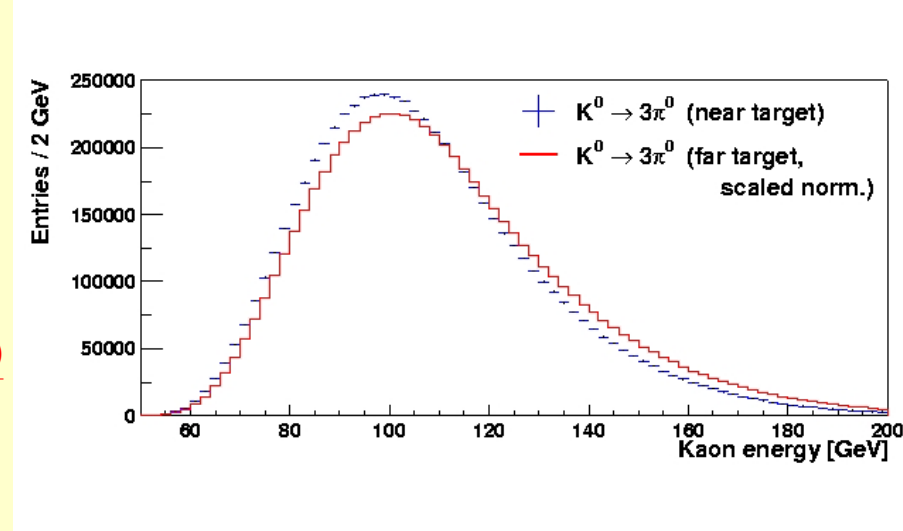
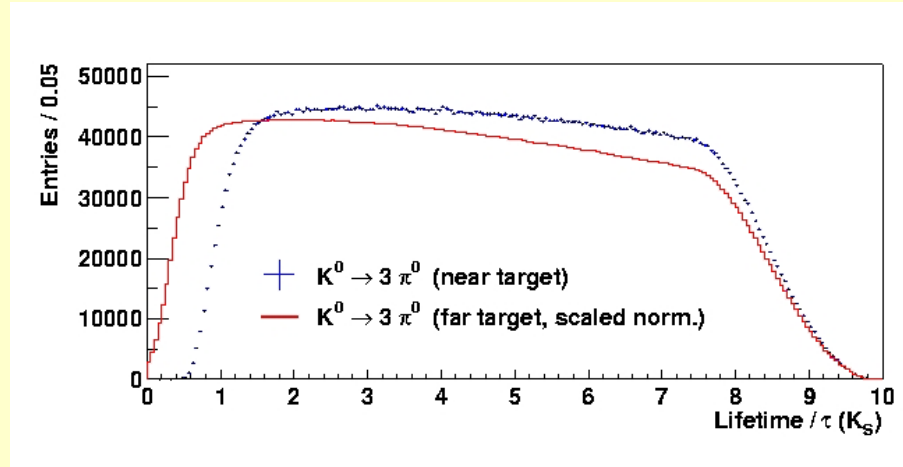
Far-target run

$K_L \rightarrow 3\pi^0$ data: 154.7×10^6

$K_L \rightarrow 3\pi^0$ MC: 66×10^6

Fit Method: fit double ratio

$$\frac{3\pi^0 \text{ (Data, Near-target run)}}{K_L \rightarrow 3\pi^0 \text{ (Data, Far-target run)}} \bigg/ \frac{K_L \rightarrow 3\pi^0 \text{ (MC, Near-target run)}}{K_L \rightarrow 3\pi^0 \text{ (MC, Far-target run)}}$$



Cross-check: fit far-target data ($\eta_{000}^{\text{far target}} = 0$) with MC only

→ $\text{Re}(\eta_{000}^{\text{far target}}) = 0.01 \pm 0.40$, $\text{Im}(\eta_{000}^{\text{far target}}) = -0.49 \pm 0.38$

$K_S \rightarrow 3\pi^0$ (η_{000}) (IV)

Simultaneous fit in energy bins:

→ Free parameters:

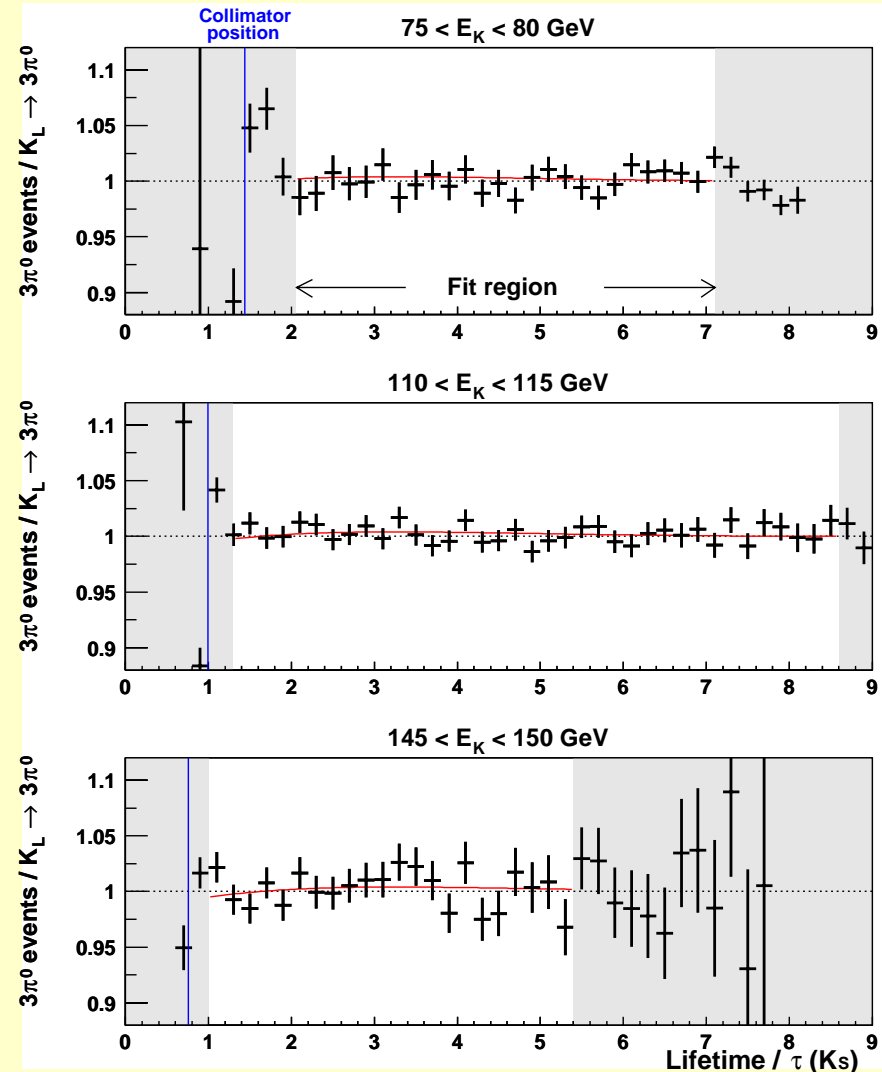
$\text{Re}(\eta_{000})$, $\text{Im}(\eta_{000})$, normalizations

Fit result (correlation $\rho = 0.8$):

$$\text{Re}(\eta_{000}) = -0.026 \pm 0.010_{\text{stat}}$$

$$\text{Im}(\eta_{000}) = -0.034 \pm 0.010_{\text{stat}}$$

Systematics	$\text{Re}(\eta_{000})$	$\text{Im}(\eta_{000})$
Acceptance	± 0.003	± 0.008
Accidental activity	± 0.001	± 0.006
Energy scale	± 0.001	± 0.001
$K^0\bar{K}^0$ dilution	± 0.003	± 0.004
Fit	± 0.001	± 0.002
Total	± 0.005	± 0.011



$K_S \rightarrow 3\pi^0$ (η_{000}) (V)

Preliminary NA48 result:

$$\text{Re}(\eta_{000}) = -0.026 \pm 0.010_{\text{stat}} \pm 0.005_{\text{sys}}$$

$$\text{Im}(\eta_{000}) = -0.034 \pm 0.010_{\text{stat}} \pm 0.011_{\text{sys}}$$

$$\text{(CPLEAR: Re}(\eta_{000}) = 0.18 \pm 0.14 \pm 0.06$$

$$\text{Im}(\eta_{000}) = 0.15 \pm 0.20 \pm 0.03)$$

If $\text{Re}(\eta_{000}) = \text{Re}(\varepsilon)$ (CPT)

$$\text{Im}(\eta_{000}) = -0.012 \pm 0.007_{\text{stat}} \pm 0.011_{\text{sys}}$$

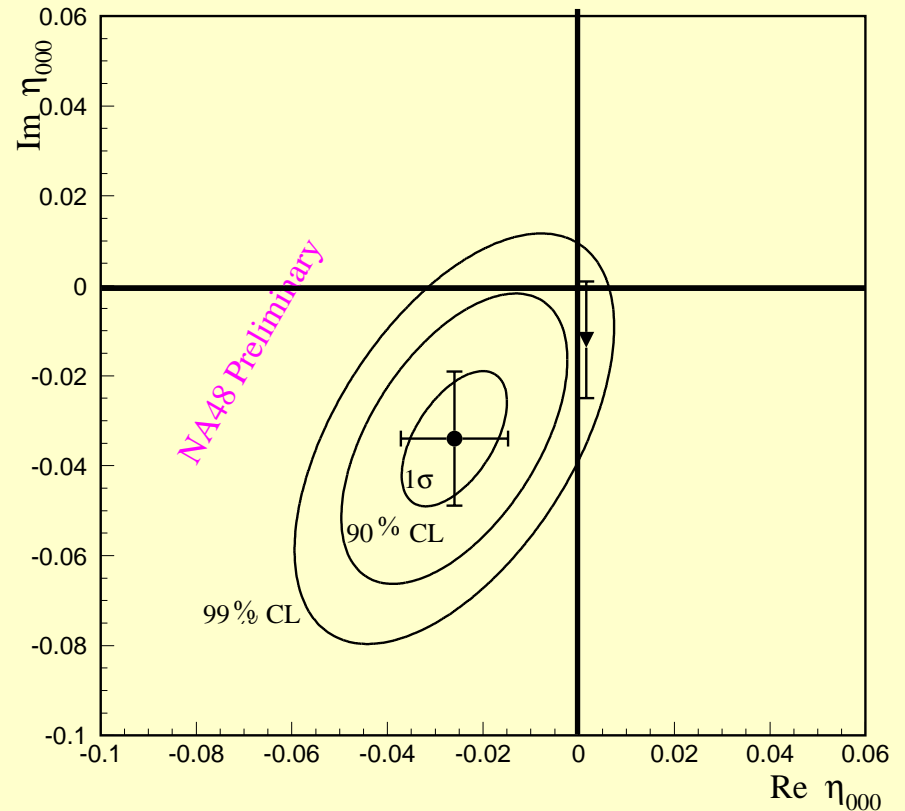
Branching fraction: (preliminary)

$$\text{BR}(K_S \rightarrow 3\pi^0) < 1.4 \times 10^{-6} \quad 90\% \text{ CL}$$

If $\text{Re}(\eta_{000}) = \text{Re}(\varepsilon)$ (CPT)

$$\text{BR}(K_S \rightarrow 3\pi^0) < 3.0 \times 10^{-7} \quad 90\% \text{ CL}$$

$$\text{(SND: BR}(K_S \rightarrow 3\pi^0) < 1.4 \times 10^{-5})$$

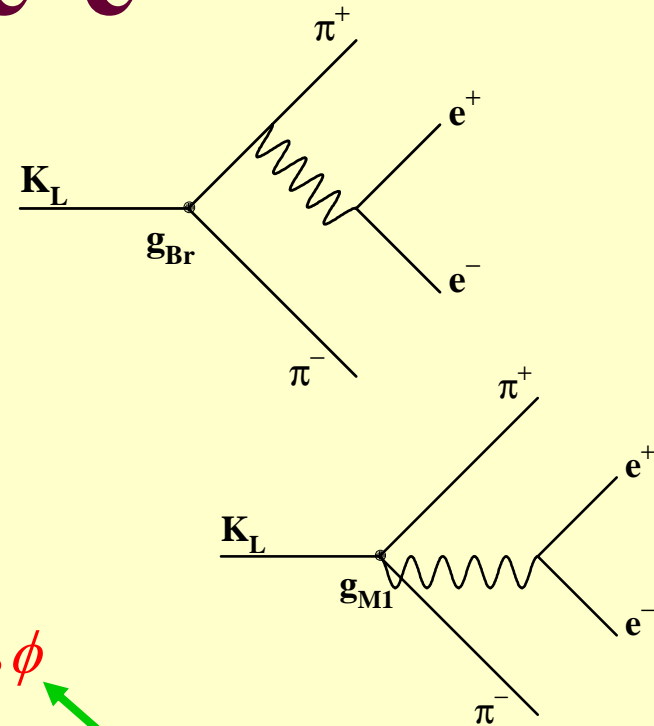


$K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$

Main contributions to the $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ decay:

- CPV inner bremsstrahlung (IB)
- CPC direct M1 emission (DE)

The interference between the IB (CP=+1) and the DE (CP=-1) amplitudes produces a CP-violating circular polarization of the γ^*



Angle between ee and $\pi\pi$ plane

$$\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2 \phi + \Gamma_2 \sin^2 \phi + \Gamma_3 \sin \phi \cos \phi$$

$$\sin \phi \cos \phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z} (\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

$$A_\phi = \frac{N_{\sin \phi \cos \phi > 0} - N_{\sin \phi \cos \phi < 0}}{N_{\sin \phi \cos \phi > 0} + N_{\sin \phi \cos \phi < 0}}$$

Prediction by Heiliger and Sehgal (1993): $A_\phi \approx 14\%$

$K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$ (II)

Dominant contribution to the $K_S \rightarrow \pi^+ \pi^- e^+ e^-$ decay:

□ CPC inner bremsstrahlung (IB)

NO CP-violation asymmetry expected

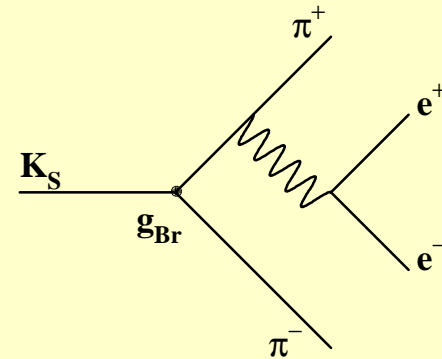
Can be related to IB component of the K_L decay

$$\text{BR}(K_L^{\text{IB}} \rightarrow \pi^+ \pi^- e^+ e^-) = \text{BR}(K_S \rightarrow \pi^+ \pi^- e^+ e^-) \frac{\tau_L}{\tau_S} |\eta_{+-}|^2$$

Important cross-check of the K_L analysis

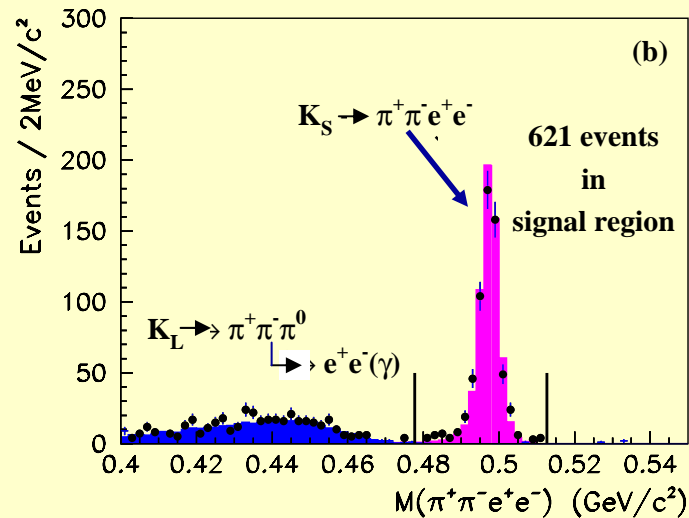
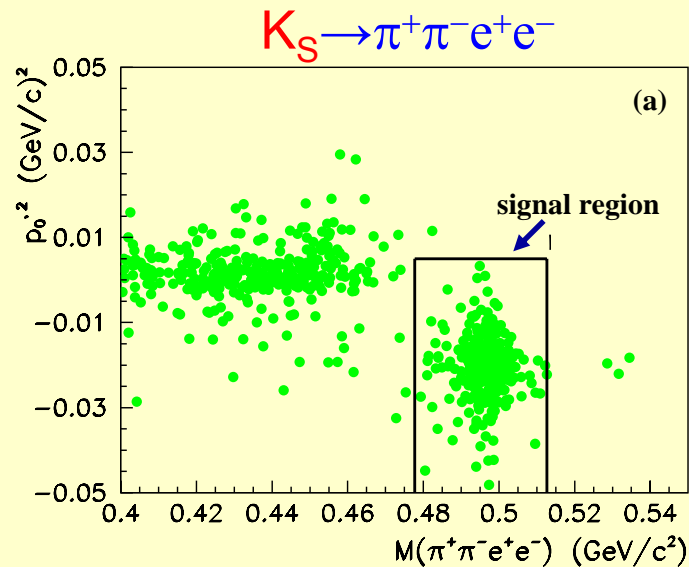
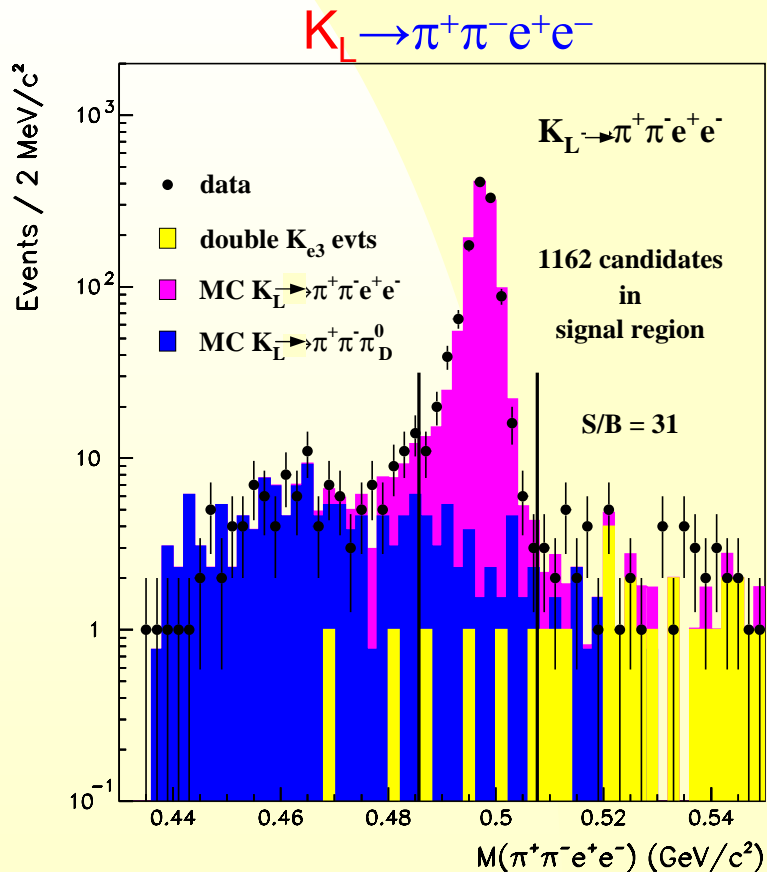
Data from normal ε'/ε runs in 1998 and 1999

Most of K_S from short HIKS run in 1999



$K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$ (III)

Small backgrounds:

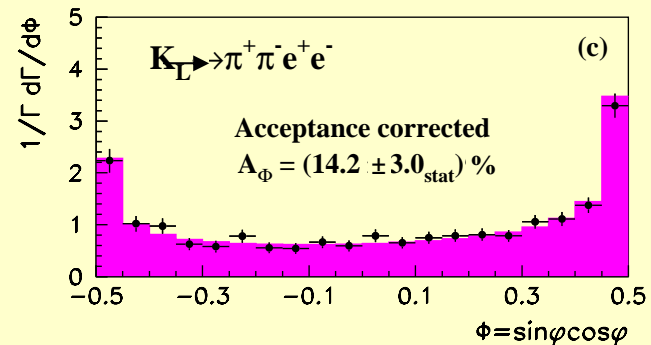
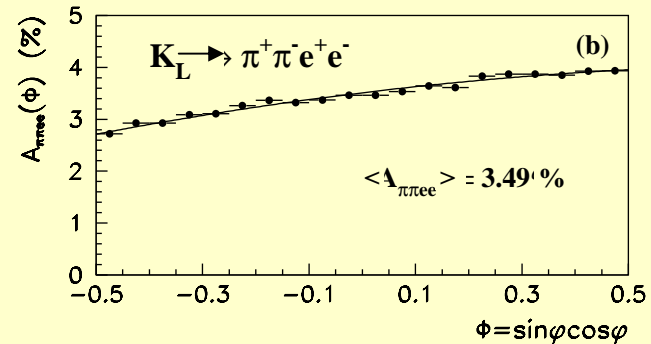
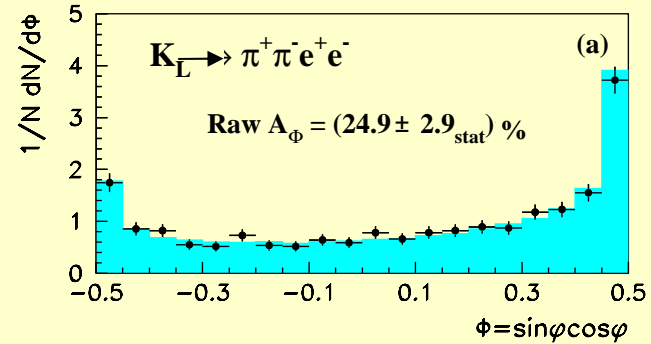


$K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$ (IV)

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

$$A_\phi^L = (14.2 \pm 3.0_{\text{stat}} \pm 1.9_{\text{sys}})\%$$

Clear signature of indirect CP violation



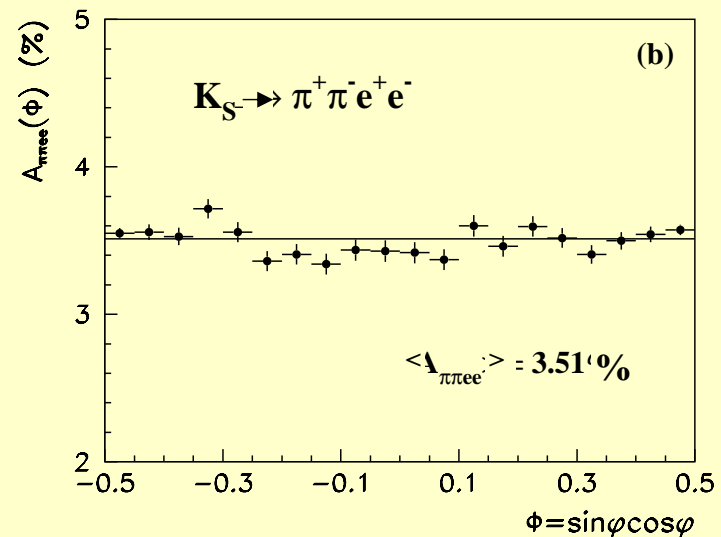
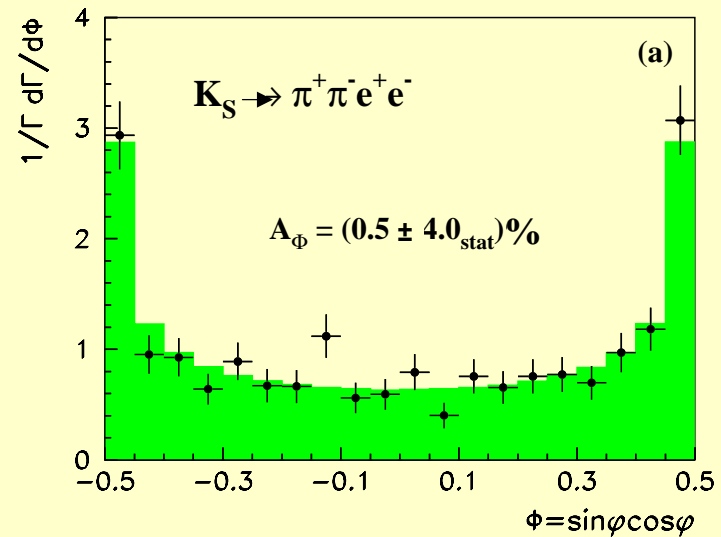
$K_{L,S} \rightarrow \pi^+ \pi^- e^+ e^-$ (V)

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

$$A_\phi^S = (0.5 \pm 4.0_{\text{stat}} \pm 1.6_{\text{sys}})\%$$

No asymmetry observed

A_ϕ^L is not generated by an asymmetry in the detector



ε'/ε : direct CP violation

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

If the 4 modes are taken:

- In the **same decay region**
- Simultaneously**

$$R = \frac{N(K_L \rightarrow \pi^0 \pi^0) N(K_S \rightarrow \pi^+ \pi^-)}{N(K_S \rightarrow \pi^0 \pi^0) N(K_L \rightarrow \pi^+ \pi^-)}$$

Data taken in 1997-1998-1999 and (in **different conditions** and with **rebuilt spectrometer**) in 2001

ε'/ε : direct CP violation (II)

	98-99	2001
Proton energy	450 GeV/c	400 GeV/c
SPS cycle	14.4 s	16.8 s
Spill length (effective)	2.4 s (1.7 s)	5.2 s (3.6 s)
Duty cycle	0.17	0.31
K_L beam intensity	$\approx 1.5 \times 10^{12}$ ppp	$\approx 2.4 \times 10^{12}$ ppp
K_S beam intensity	$\approx 3 \times 10^7$ ppp	$\approx 5 \times 10^7$ ppp

Result from 2001 data alone:
(29% of total statistics)

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (13.7 \pm 3.1) \times 10^{-4}$$

Result from 97-98-99 data:

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (15.3 \pm 2.6) \times 10^{-4}$$

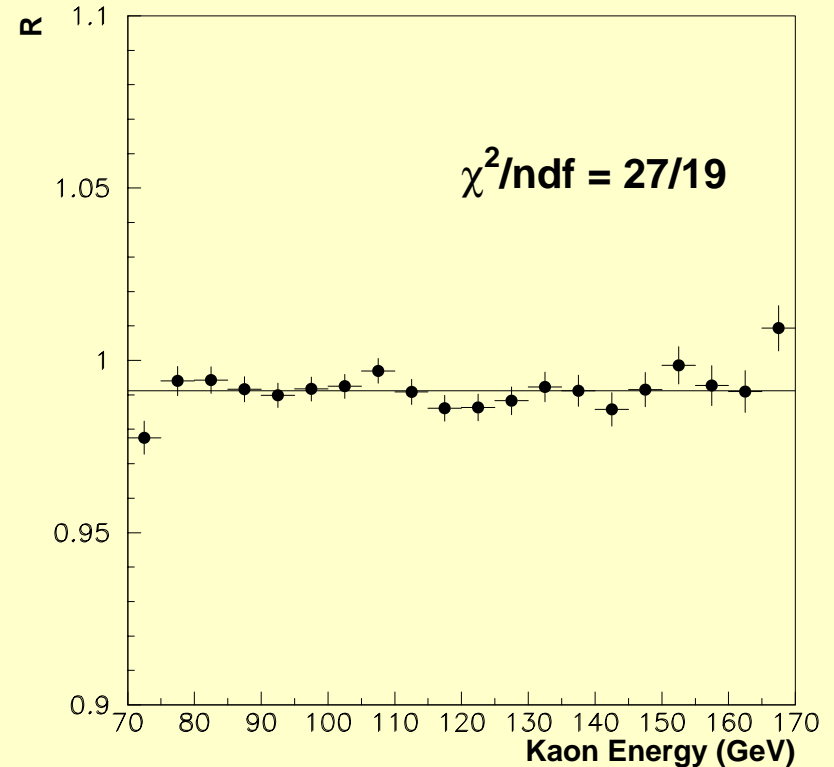
ε'/ε : direct CP violation (III)

Final (and combined) result by NA48:

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (14.7 \pm 2.2) \times 10^{-4}$$

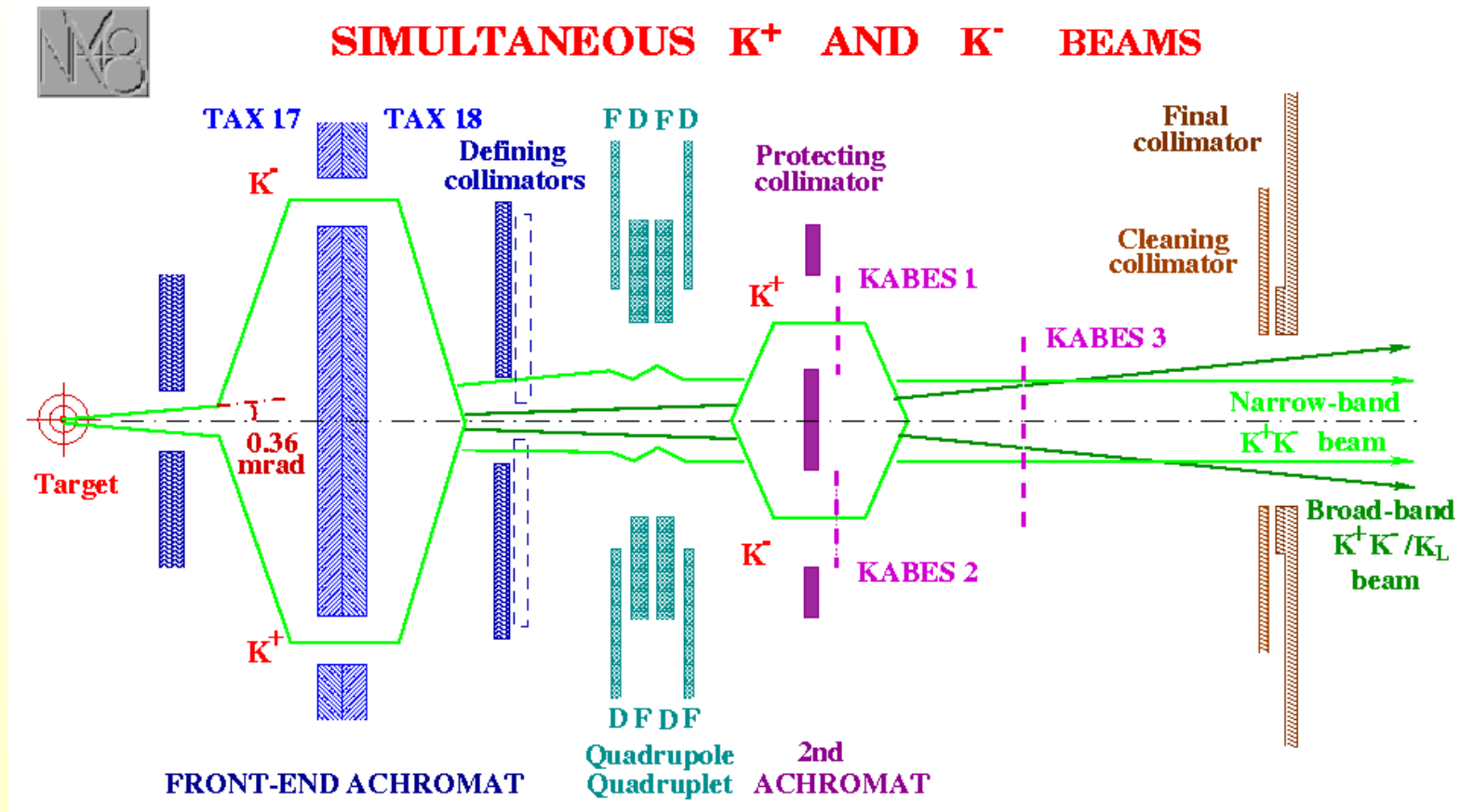
World average:

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (16.6 \pm 1.6) \times 10^{-4}$$



The future: charged Kaons

Running now!



Conclusions

- Charge Asymmetry in $K_L \rightarrow K_{e3}$ (preliminary)

$$\delta_L(e) = (0.3317 \pm 0.0070_{\text{stat}} \pm 0.0072_{\text{syst}})\%$$

- $K_S \rightarrow 3\pi^0$ (η_{000}) (preliminary)

$$\text{Re}(\eta_{000}) = -0.026 \pm 0.010_{\text{stat}} \pm 0.005_{\text{sys}}$$

$$\text{Im}(\eta_{000}) = -0.034 \pm 0.010_{\text{stat}} \pm 0.011_{\text{sys}}$$

- Angular Asymmetry in $K_{L,S} \rightarrow \pi^+\pi^-e^+e^-$ (final) to be published on EPJ

$$A_\phi^L = (14.2 \pm 3.0_{\text{stat}} \pm 1.9_{\text{sys}})\%$$

$$A_\phi^S = (0.5 \pm 4.0_{\text{stat}} \pm 1.6_{\text{sys}})\%$$

- ε'/ε (final) PLB544(2002) 97-112

$$\text{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (14.7 \pm 2.2) \times 10^{-4}$$

- The future: slope asymmetry in $K^\pm \rightarrow 3\pi$