CP Violation Results on Kaons by NA48

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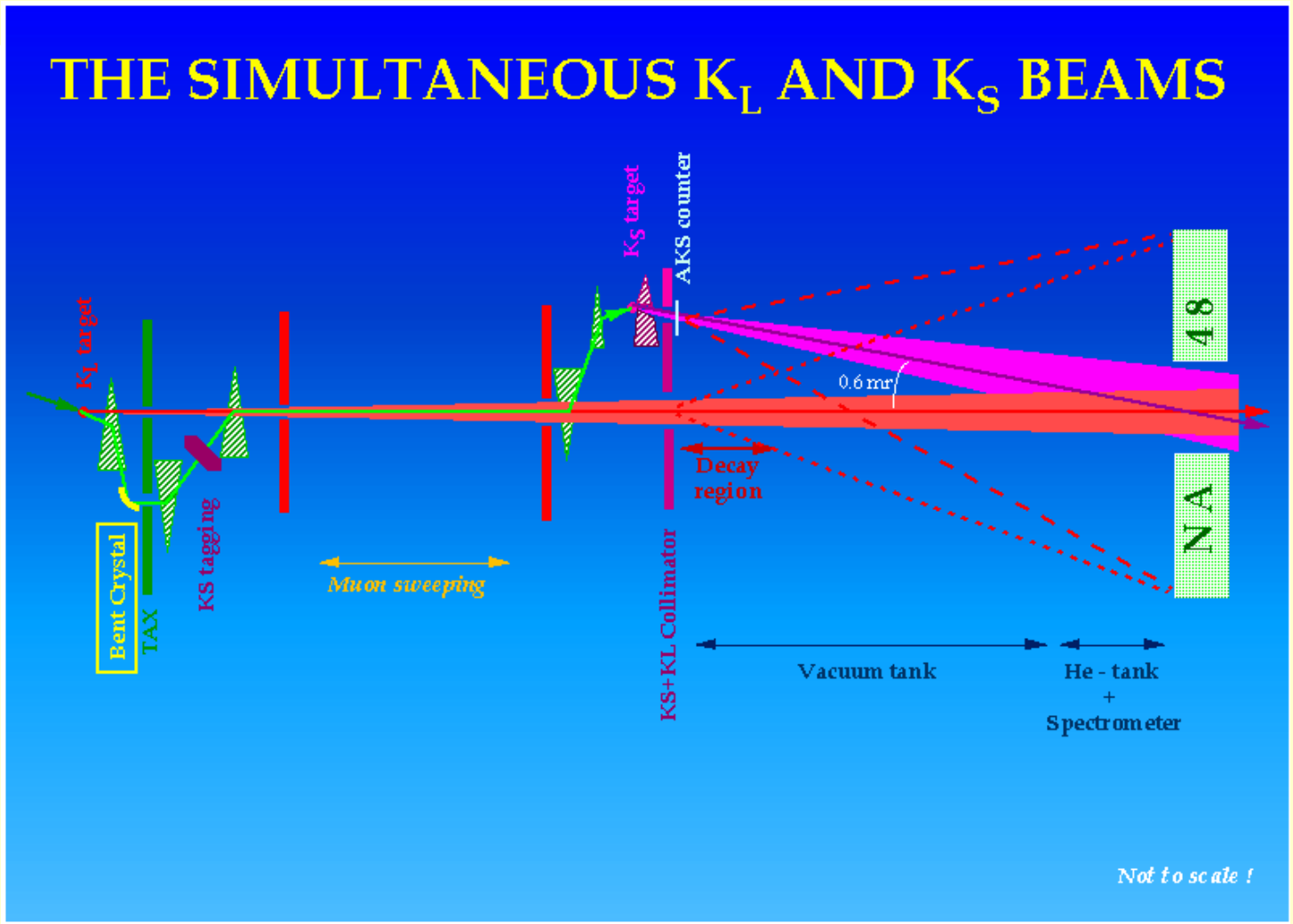
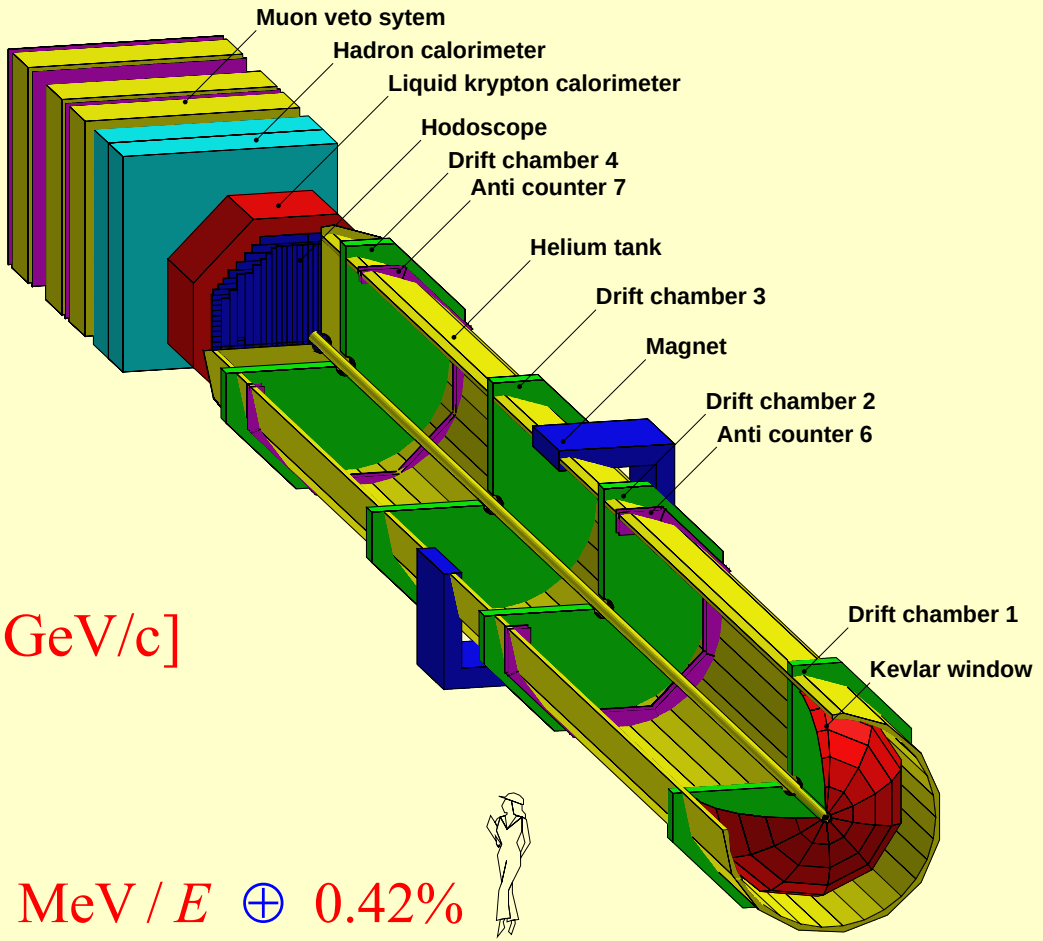
Plan of the presentation

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

The NA48 Experiment



The NA48 Detectors



Magnetic Spectrometer:

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

LKr e.m. Calorimeter:

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

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

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

If CPT conserved, $x \approx 0$

NA48: Data from 2001 run period:

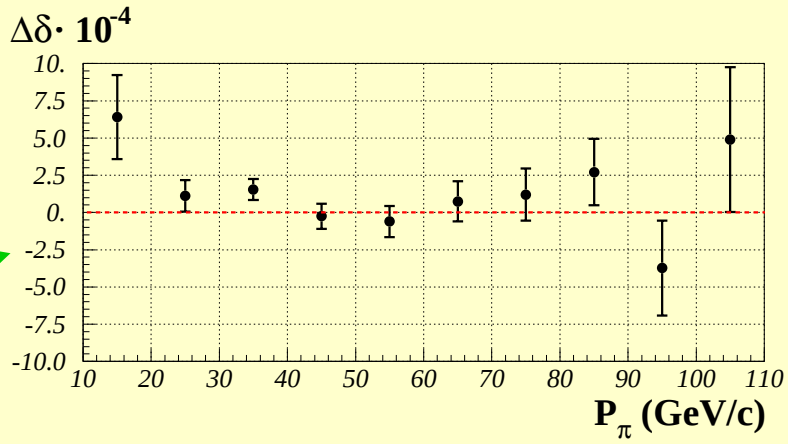
- Reconstructed 2×10^8 K_{e3} decays

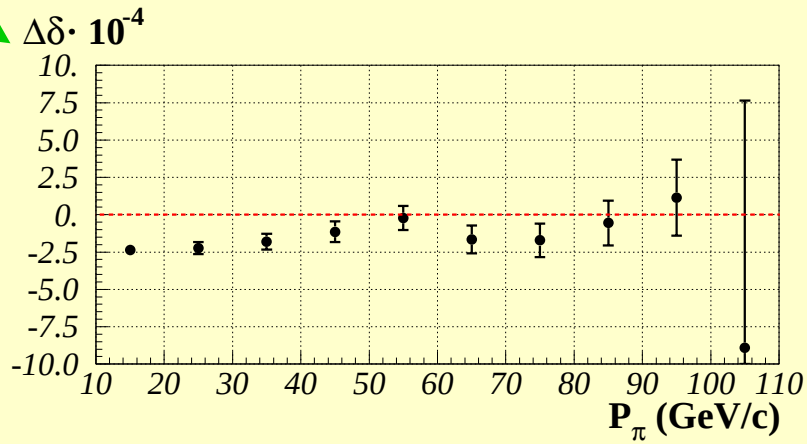
$$\delta_L(e) = \frac{N(\pi^- e^+) - N(\pi^+ e^-)}{N(\pi^- e^+) + N(\pi^+ e^-)}$$

- Systematics: asymmetry of particle interactions
  - Trigger efficiencies (→ calorimeters info)
  - Pion identification (→ E/P info)

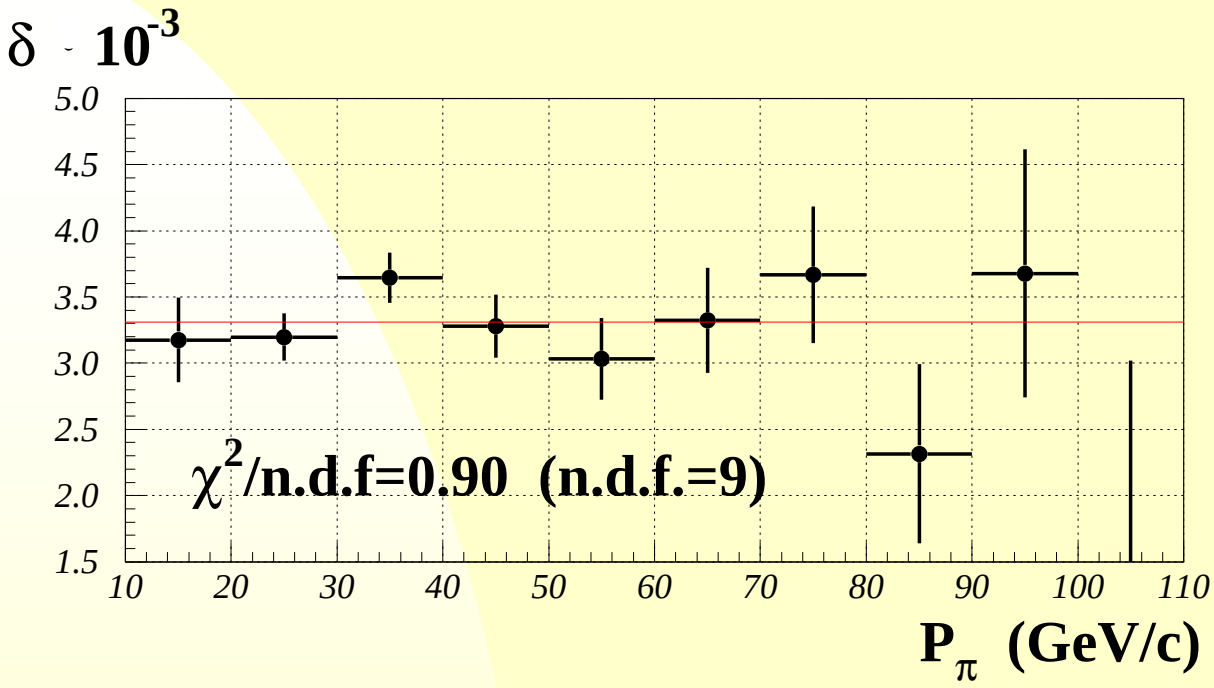
K_{e3} Charge Asymmetry (II)

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





K_{e3} Charge Asymmetry (III)



Fit in bins of the pion momentum

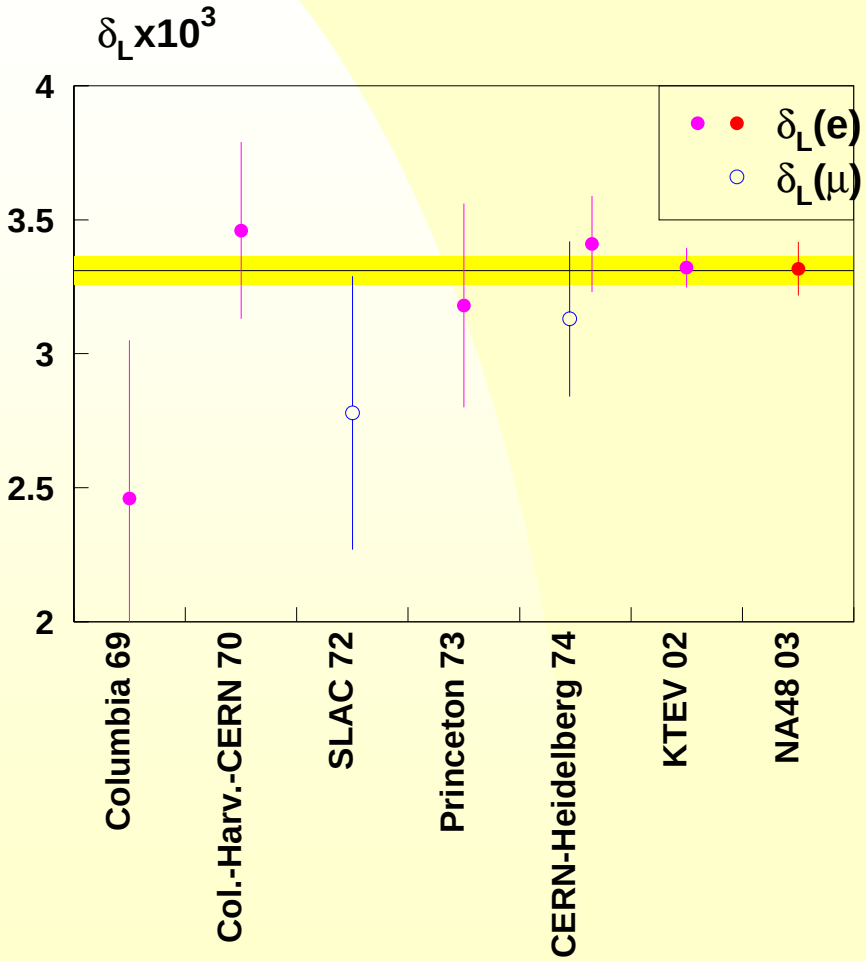
Preliminary result:

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

→ consistent with KTeV and World average measurements

K_{e3} Charge Asymmetry (IV)

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



World average

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

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

$\chi^2 = 4.2 / 7$

old average

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

$K_S \to 3\pi^0$ (η_{000})

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

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

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

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

K_L decay K_S decay K_S–K_L interference

$$I_{3\pi^0} \propto e^{-\Gamma_L t} + |\eta_{000}|^2 e^{-\Gamma_S t} + 2\,D(p)\left(\mathrm{Re}(\eta_{000})\cos\Delta m\, t - \mathrm{Im}(\eta_{000})\sin\Delta m\, t\right) e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}$$

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

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

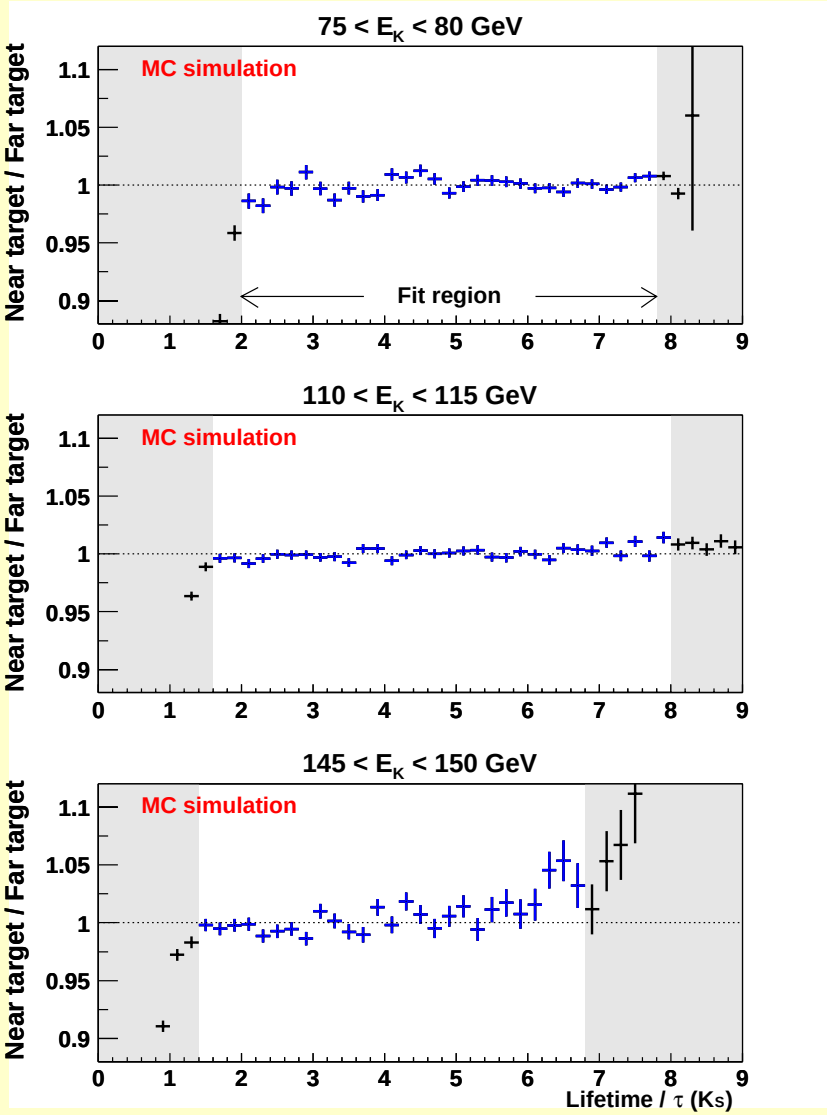
Run period 2000: No Drift chambers

Two sub-periods:

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

Method:

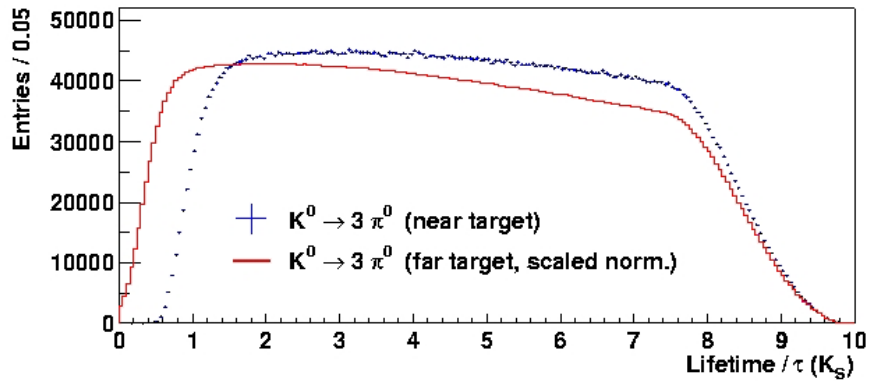
- Use $3\pi^0$ events from
  near-target run for η_{000}
- Normalize to $K_L \rightarrow 3\pi^0$ from
  far-target run
- Use MC to correct for residual
  acceptance difference and Dalitz

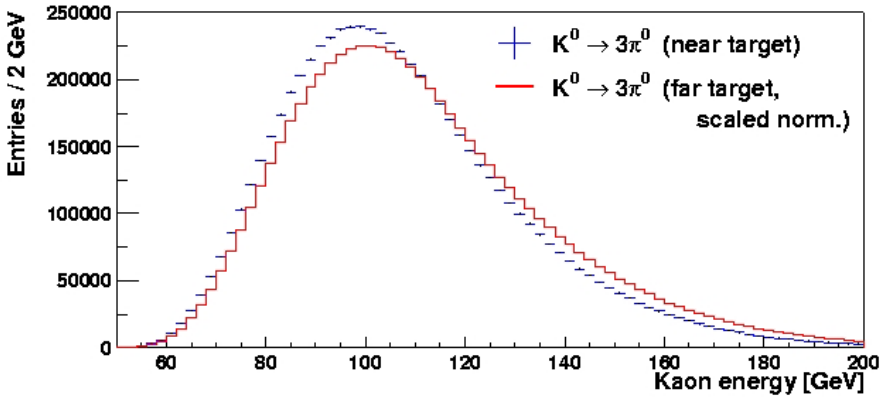


$K_S \to 3\pi^0$ (η_{000}) (III)

Data samples:

- Near-target run
  - $3\pi^0$ data: 6.5×10^6
  - $K_L \to 3\pi^0$ MC: 66×10^6
- Far-target run
  - $K_L \to 3\pi^0$ data: 154.7×10^6
  - $K_L \to 3\pi^0$ MC: 66×10^6





Fit Method: fit double ratio

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

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

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

$K_S \to 3\pi^0$ (η_{000}) (IV)

Simultaneous fit in energy bins:

→ Free parameters:

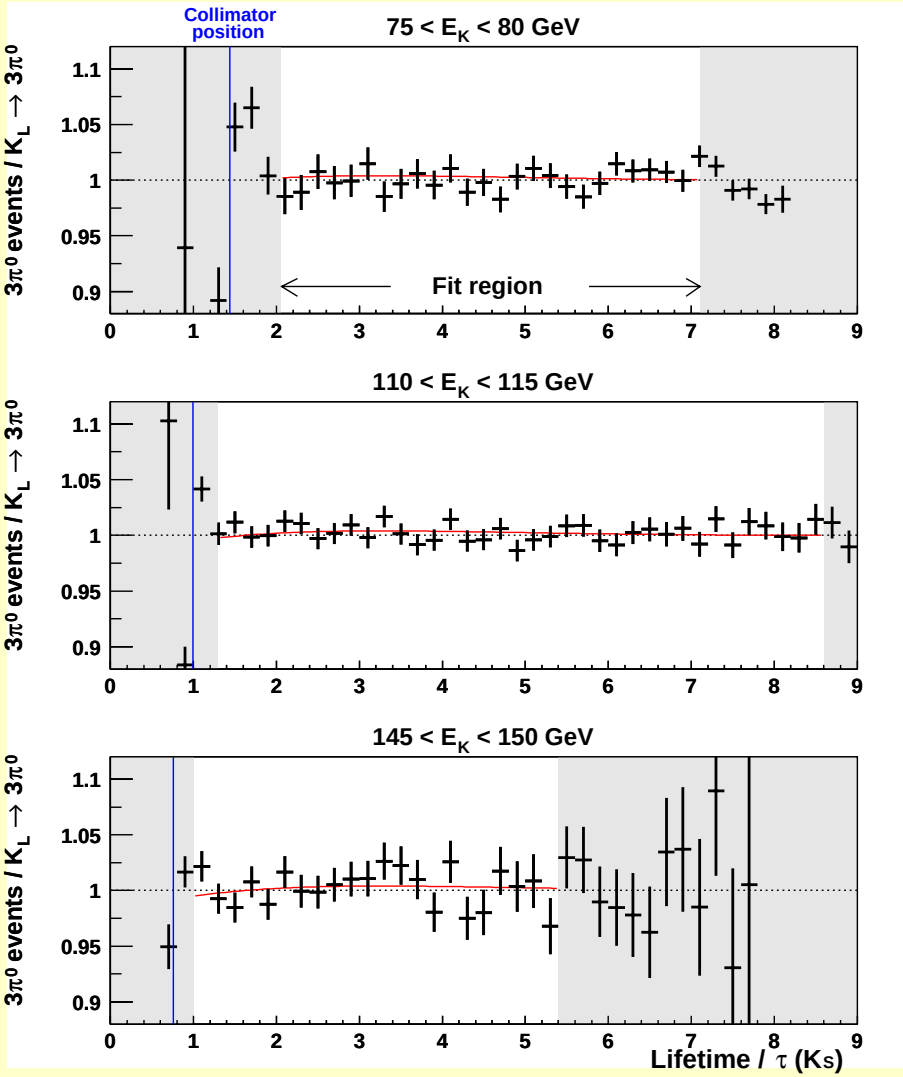
$\mathrm{Re}(\eta_{000})$, $\mathrm{Im}(\eta_{000})$, normalizations

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

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

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

Systematics	$\mathrm{Re}(\eta_{000})$	$\mathrm{Im}(\eta_{000})$
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



$K_S \to 3\pi^0$ (η_{000}) (V)

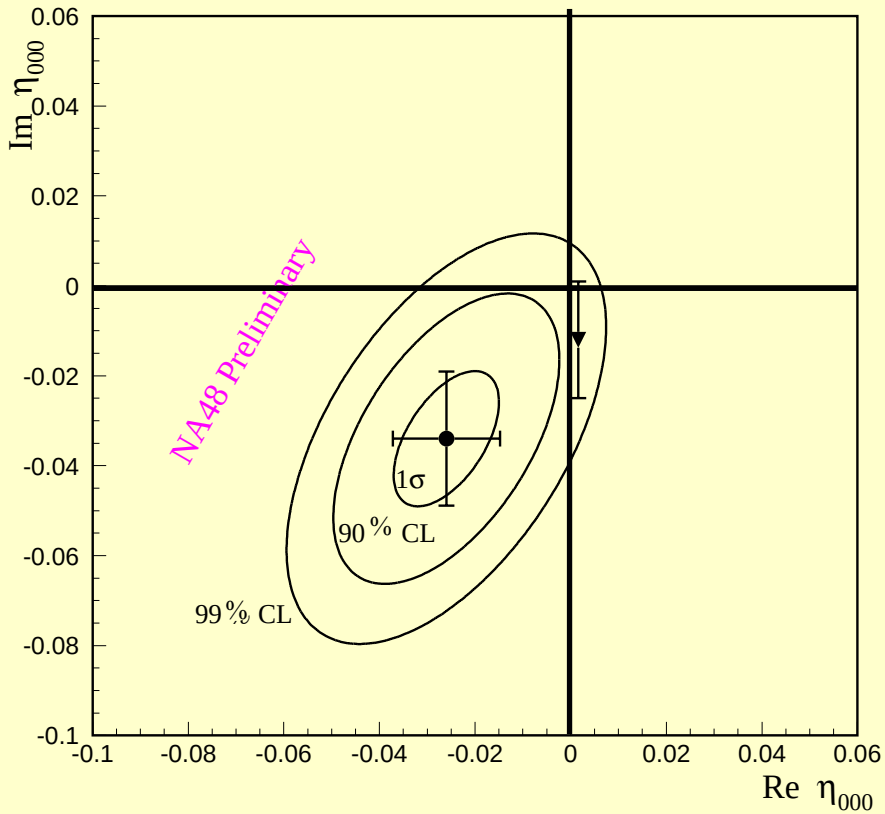
Preliminary NA48 result:

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

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

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

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



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

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

Branching fraction: (preliminary)

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

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

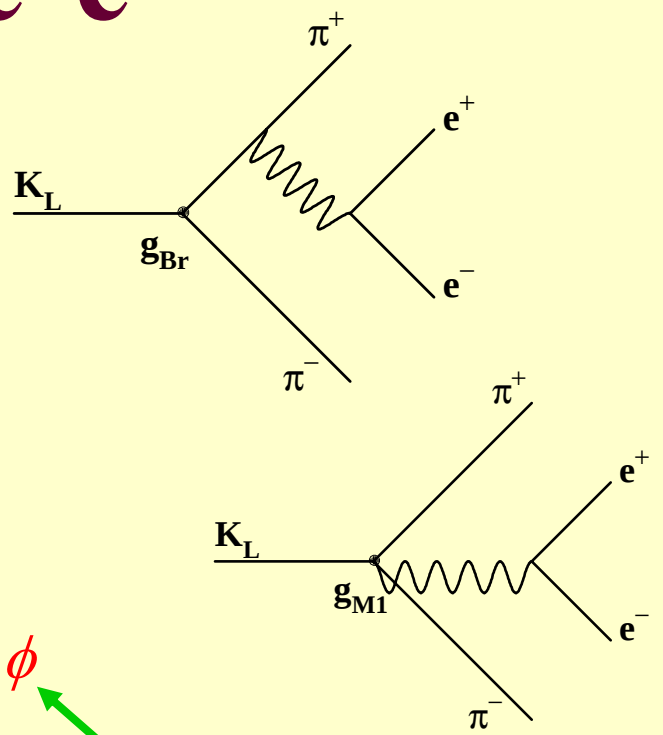
$BR(K_S \to 3\pi^0) < 3.0 \times 10^{-7}$ 90% CL

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

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

Main contributions to the $K_L \to \pi^+\pi^-e^+e^-$ 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^*

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

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

Angle between ee and $\pi\pi$ plane

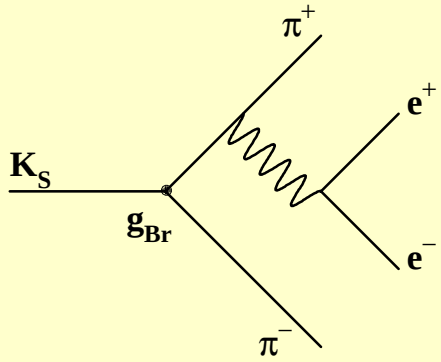
$$A_\phi = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}}$$

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

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

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

- CPC inner bremsstrahlung (IB)



NO CP-violation asymmetry expected

Can be related to IB component of the K_L decay

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

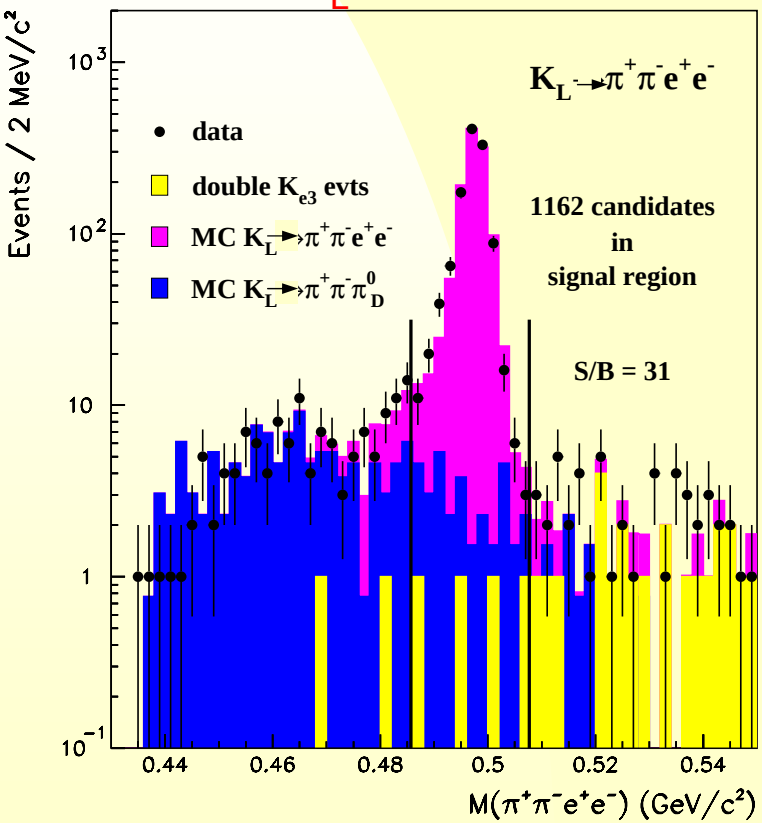
Important cross-check of the K_L analysis

Data from normal ε'/ε runs in 1998 and 1999
Most of K_S from short HIKS run in 1999

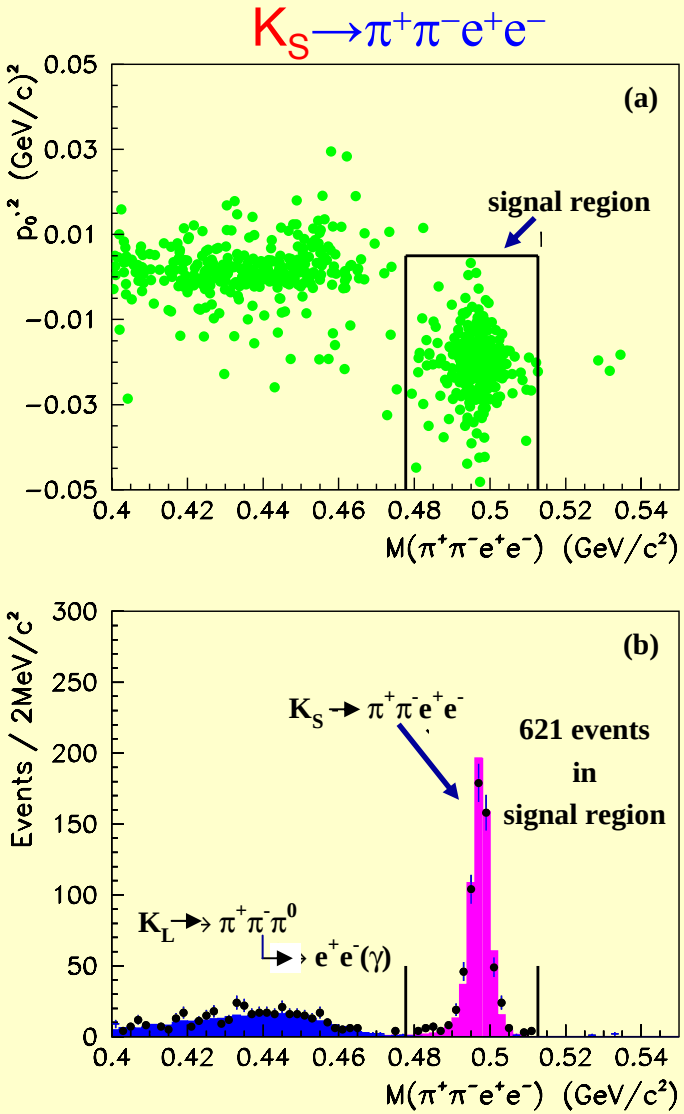
$K_{L,S} \to \pi^+\pi^-e^+e^-$ (III)

Small backgrounds:

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



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

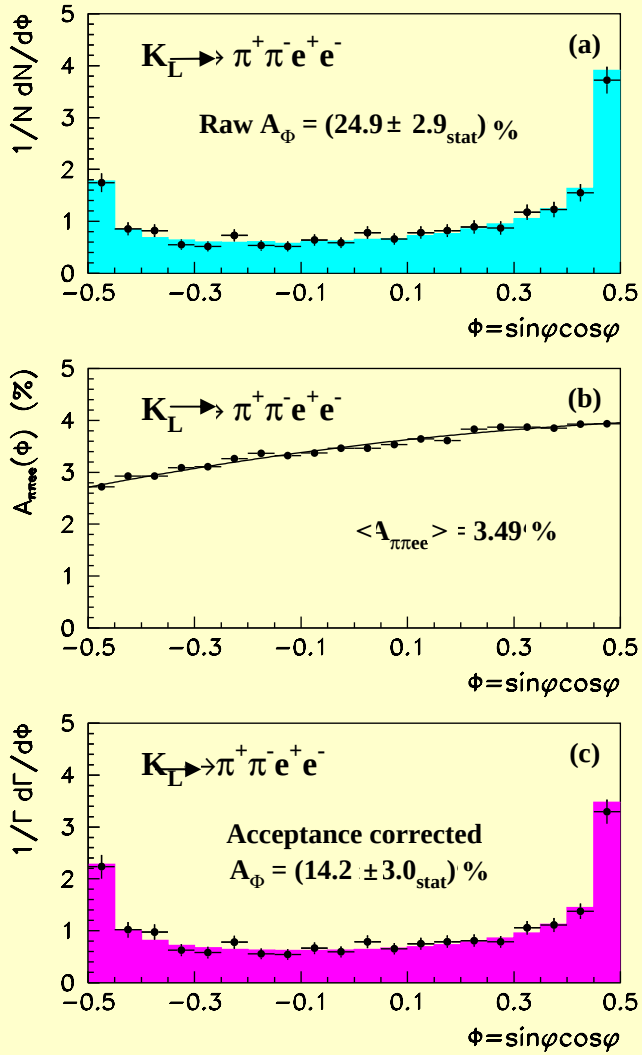


$K_{L,S} \to \pi^+\pi^-e^+e^-$ (IV)

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

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

Clear signature of indirect CP violation



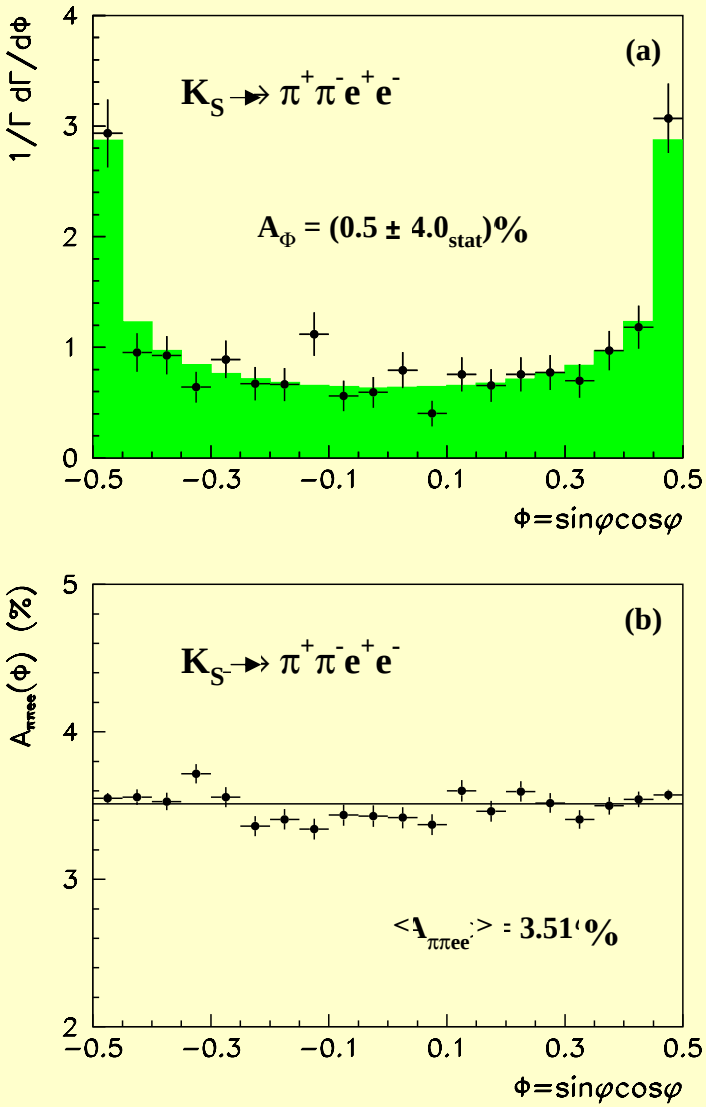
$K_{L,S} \to \pi^+\pi^-e^+e^-$ (V)

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

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

No asymmetry observed

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



ε'/ε: direct CP violation

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

If the 4 modes are taken:

- In the same decay region
- Simultaneously

$$R = \frac{N\left(K_L \to \pi^0\pi^0\right)\,N\left(K_S \to \pi^+\pi^-\right)}{N\left(K_S \to \pi^0\pi^0\right)\,N\left(K_L \to \pi^+\pi^-\right)}$$

Data taken in1997-1998-1999 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 lenght (effective)	2.4 s (1.7 s)	5.2 s (3.6 s)
Duty cycle	0.17	0.31
K_L beam intensity	$\approx 1.5\times10^{12}$ ppp	$\approx 2.4\times10^{12}$ ppp
K_S beam intensity	$\approx 3\times10^{7}$ ppp	$\approx 5\times10^{7}$ ppp

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

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (13.7 \pm 3.1)\times10^{-4}$$

Result from 97-98-99 data:

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = (15.3 \pm 2.6)\times10^{-4}$$

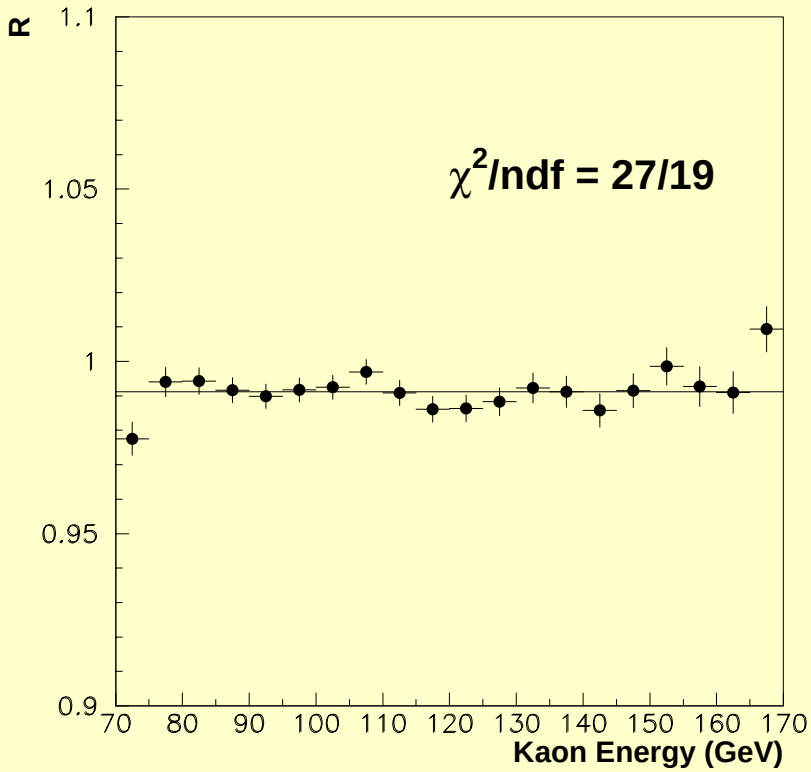
ε'/ε: direct CP violation (III)

Final (and combined) result by NA48:

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

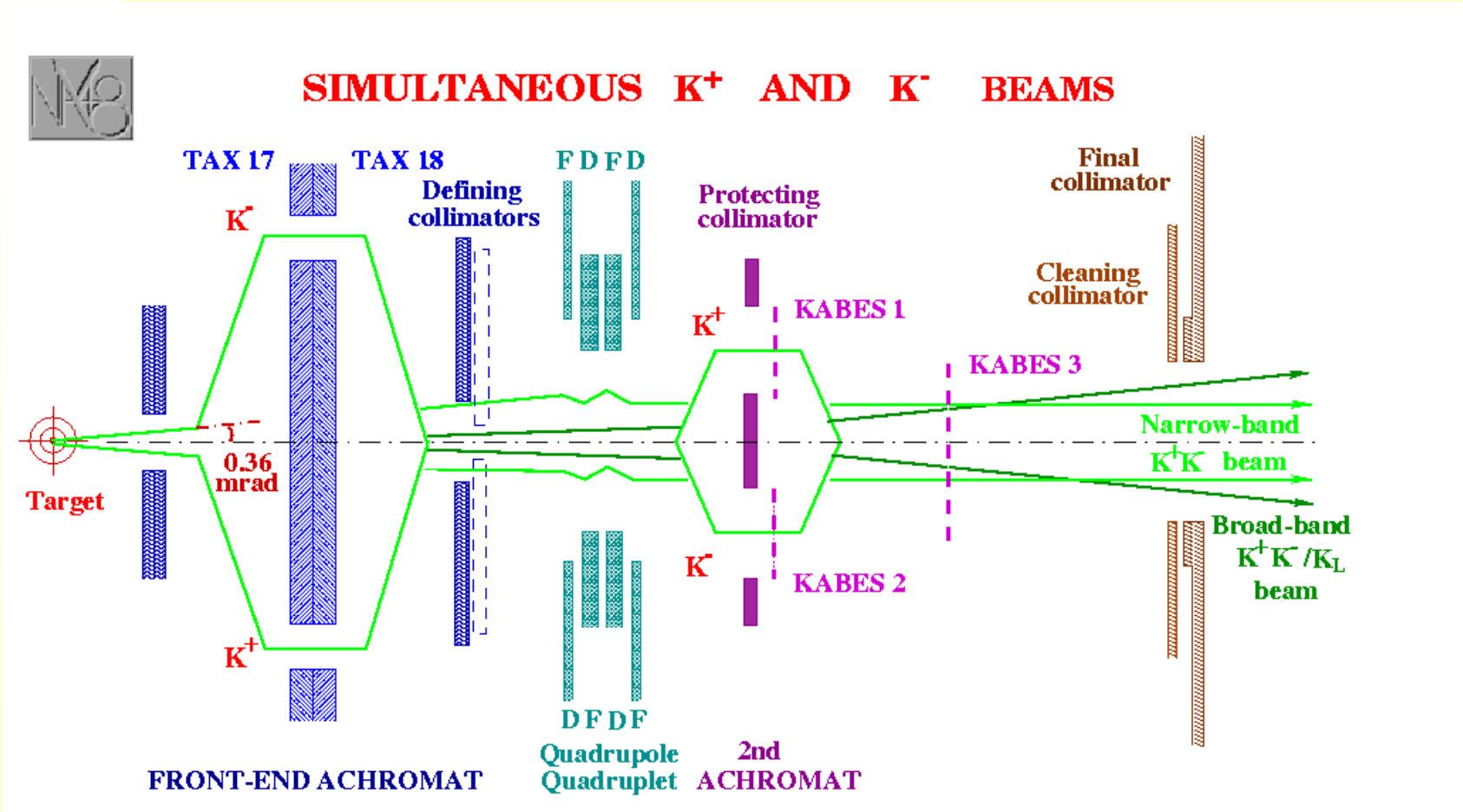
World average:

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



The future: charged Kaons

Running now!



Conclusions

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

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

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

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

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

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

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

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

- ε'/ε (final) PLB544(2002) 97-112

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

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