New NA48 Results on Rare Kaon Decays

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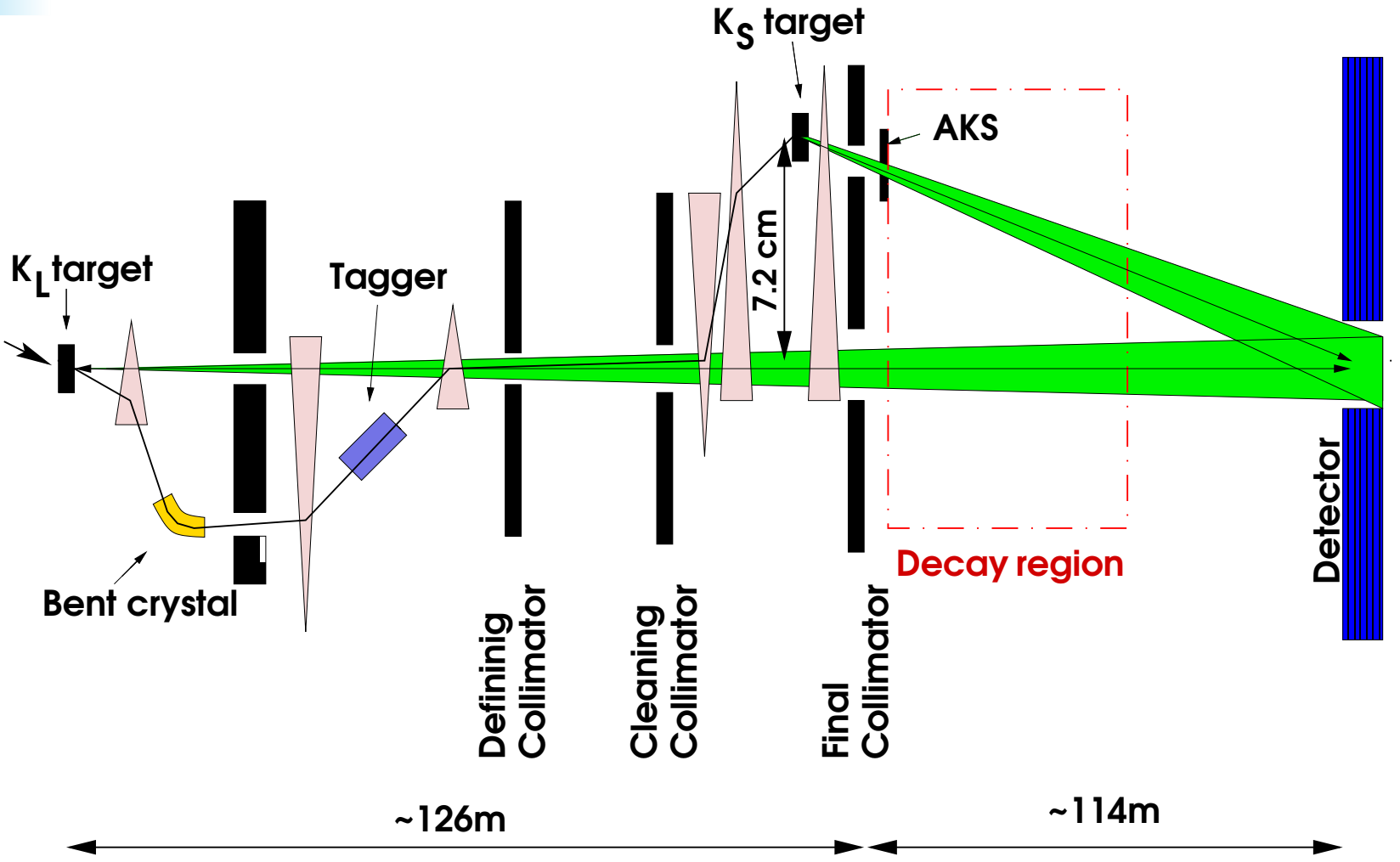
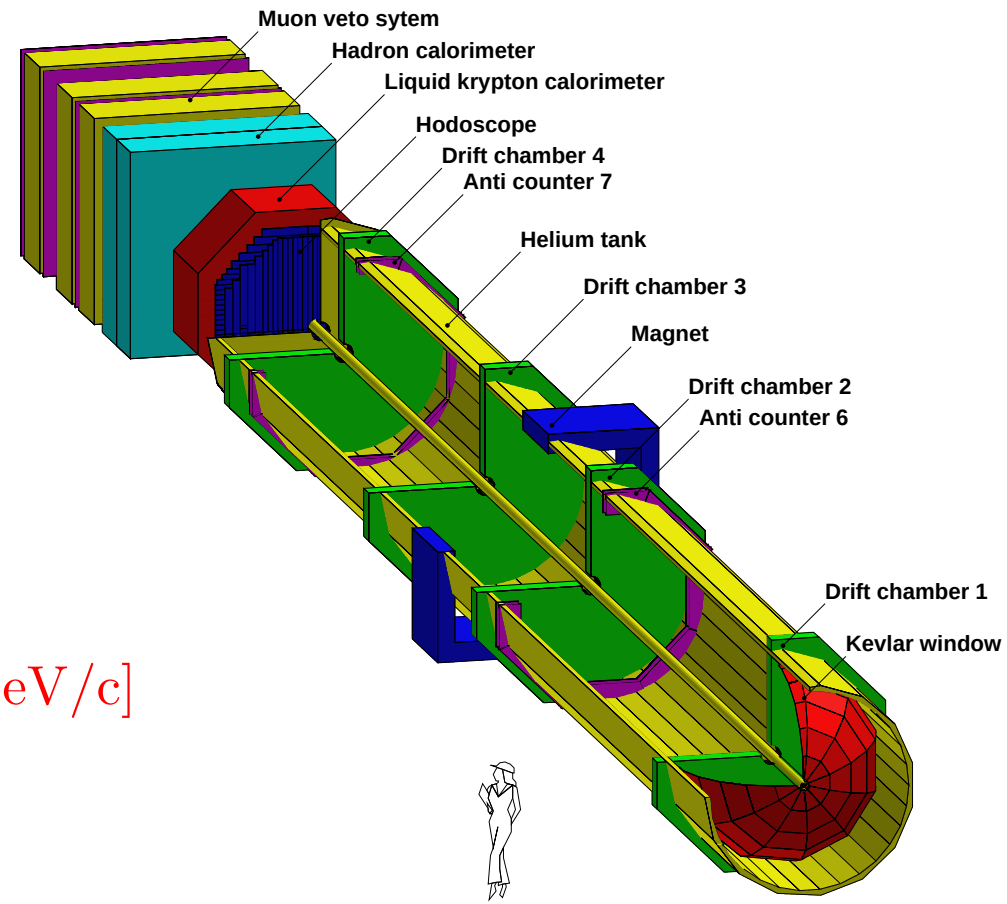
- Charge Asymmetry in $K_L \to \pi^{\pm} e^{\mp} \nu$ (K_{e3})
- Search for $K_S \to 3\,\pi^0$
- First Measurement of $K_S \to \pi\gamma\gamma$
- Outlook on future measurements

The NA48 Set-up



The NA48 Detector



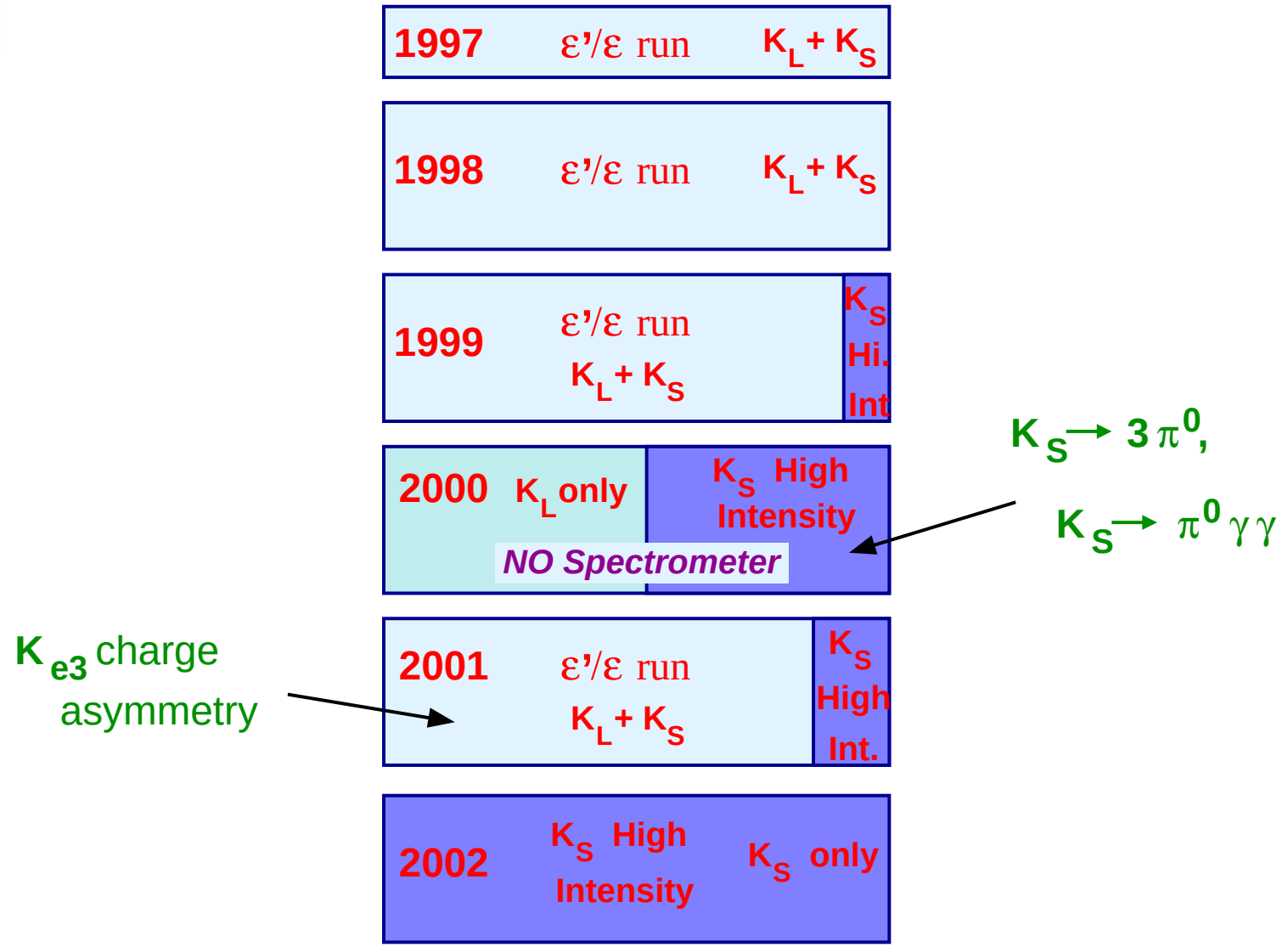
Magnetic Spectrometer:

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

Liquid Krypton Calorimeter:

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

NA48 Data Taking Periods



K_{e3} Charge Asymmetry

- **Charge Asymmetry** in $K_L \to \pi e \nu$ (K_{e3}) events:

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

(if CPT is conserved)

- Previous measurements:

  Geweniger *et al.*, 1973: $\delta_L(e) = (0.341 \pm 0.018)\%$ ($34 \cdot 10^6$ events)

  World average (PDG): $\delta_L(e) = (0.333 \pm 0.014)\%$

- **NA48:** Data from **2001 run period:**

  $\Longrightarrow$ Reconstructed $\sim 10^8$ K_{e3} events in *each* mode

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

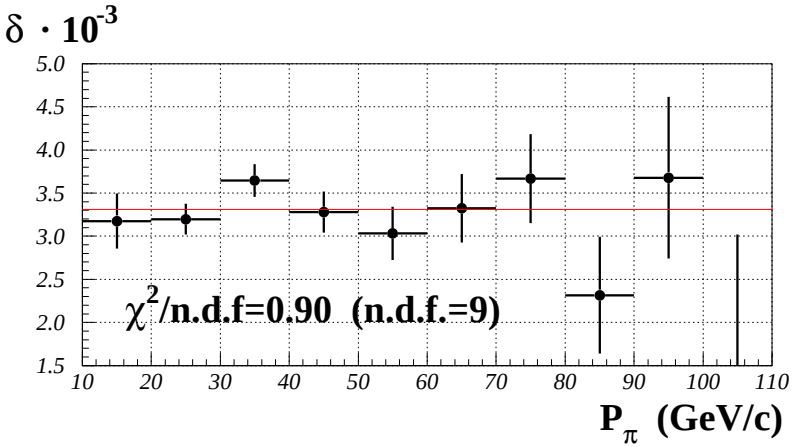
- Systematics: Asymmetry of particle interactions

  $\Longrightarrow$ Corrections due to
  - Trigger efficiencies
  - Pion identification

K_{e3} Charge Asymmetry

Systematics:

	correction in 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	$+7.7 \pm 7.2$



Fit in bins of
the pion momentum

Preliminary result:

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

Consistent with world average and recent preliminary KTeV result.

Search for $K_S \to 3\pi^0$

$K_S \to 3\pi^0$: CP violating (complete analogy to $K_L \to \pi^0\pi^0$):

$$CP\,|\,\pi^0\pi^0\pi^0\,\rangle = -|\,\pi^0\pi^0\pi^0\,\rangle, \quad CP\,|\,K_S\,\rangle \approx CP\,|\,K_1\,\rangle = +|\,K_1\,\rangle$$

Expectation (CPT invariance):

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

$\Longrightarrow$ Real part fixed by CPT, imaginary part sensitive to direct CP violation.

Previous measurements:

- CPLEAR (1999):
$$\mathrm{Re}(\eta_{000}) = 0.18 \pm 0.15$$
$$\mathrm{Im}(\eta_{000}) = 0.15 \pm 0.20$$
- SND, Novosibirsk (1999):
$$\mathrm{Br}(K_S \to 3\pi^0) < 1.4 \times 10^{-5}$$

Search for $K_S \to 3\pi^0$

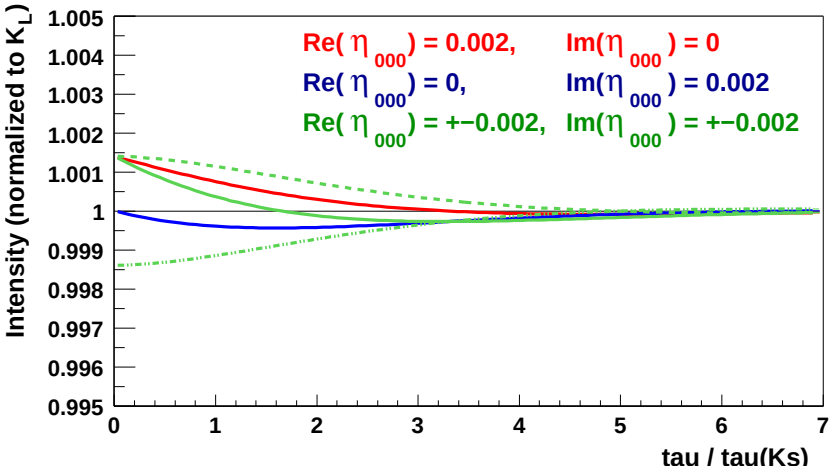
Time evolution of $K_{L,S} \to 3\pi^0$:

$$I_{3\pi^0}(t) \propto \overbrace{e^{-\Gamma_L t}}^{K_L \text{ decay}} + \overbrace{|\eta_{000}|^2 e^{-\Gamma_S t}}^{K_S \text{ decay}} + \underbrace{2\,D(p)\,(\mathrm{Re}(\eta_{000})\cos\Delta m\,t - \mathrm{Im}(\eta_{000})\sin\Delta m\,t)\; e^{-\frac{1}{2}(\Gamma_S+\Gamma_L)t}}_{K_L\text{-}K_S \text{ interference}}$$

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

$\Longrightarrow$ With $|\eta_{000}| \sim \mathcal{O}(10^{-3})$:

Try to detect interference term.



Search for $K_S \to 3\pi^0$

Run period 2000: No drift chambers

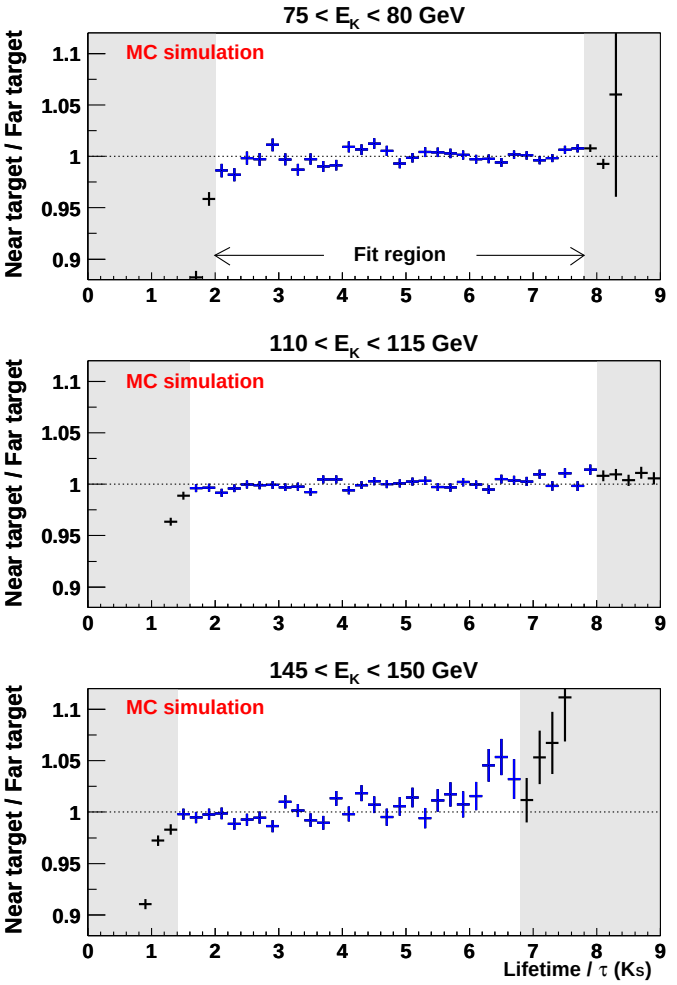
$\Longrightarrow$ Ideal environment for neutral decays!

Two different set-ups:

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

Method:

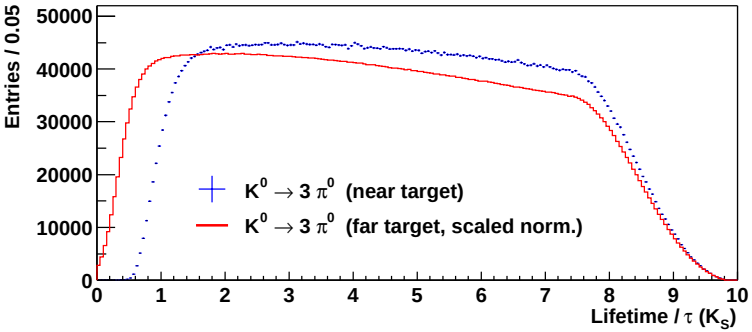
- Use $3\pi^0$ events from near-target run for η_{000}.
- Normalize to $K_L \to 3\pi^0$ from far-target run.
- Use Monte Carlo to correct for residual acceptance difference and Dalitz decays.

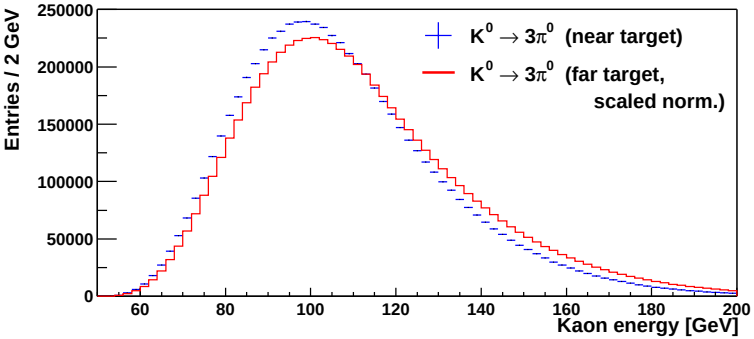


Search for $K_S \to 3\pi^0$

Data samples:

Near-target run:	Events:
$3\pi^0$ 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

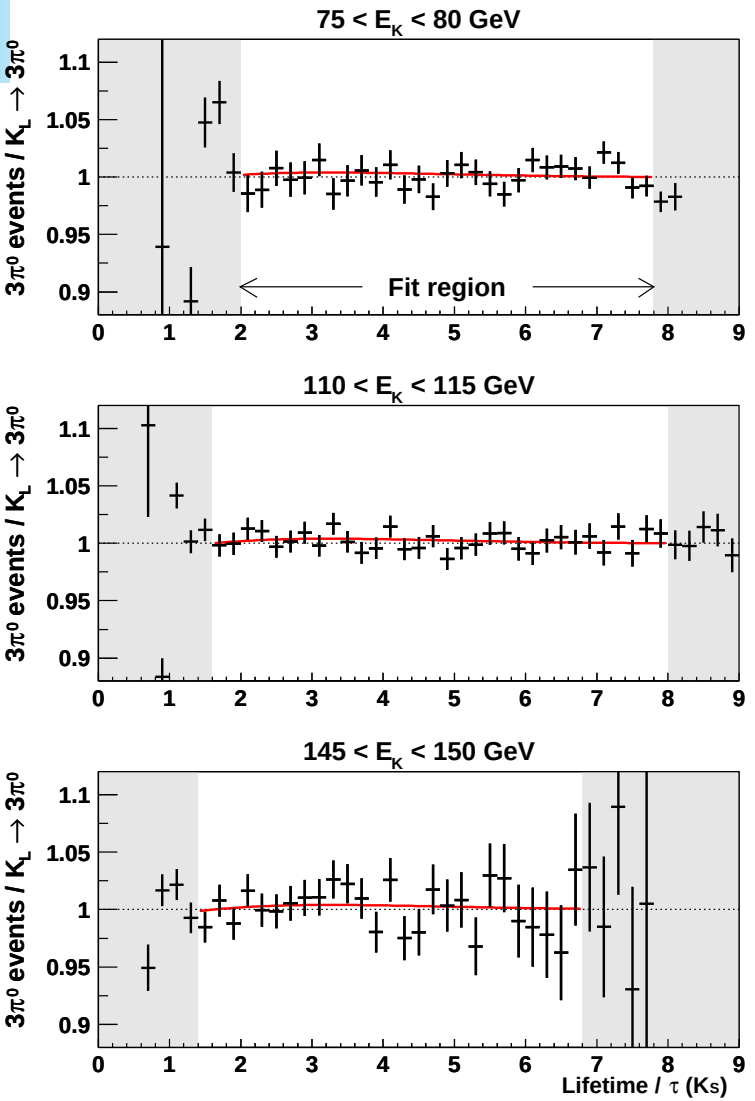
$$\frac{3\pi^0 \text{ (Data, } K_S \text{ run)}}{K_L \to 3\pi^0 \text{ (Data, } K_L \text{ run)}} \Big/ \frac{K_L \to 3\pi^0 \text{ (MC, } K_S \text{ run)}}{K_L \to 3\pi^0 \text{ (MC, } K_L \text{ run)}}$$

Cross-check:

Fit far-target data ($\eta_{000}^{\text{far target}} = 0$) with Monte Carlo only

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

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



Simultaneous fit in energy bins

$\Longrightarrow$ Free parameters:

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

Fit result:

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

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

correlation $\rho = 0.8$

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
$K^0\overline{K^0}$ dilution	± 0.003	± 0.004
Fit	± 0.001	± 0.002
Total:	± 0.005	± 0.011

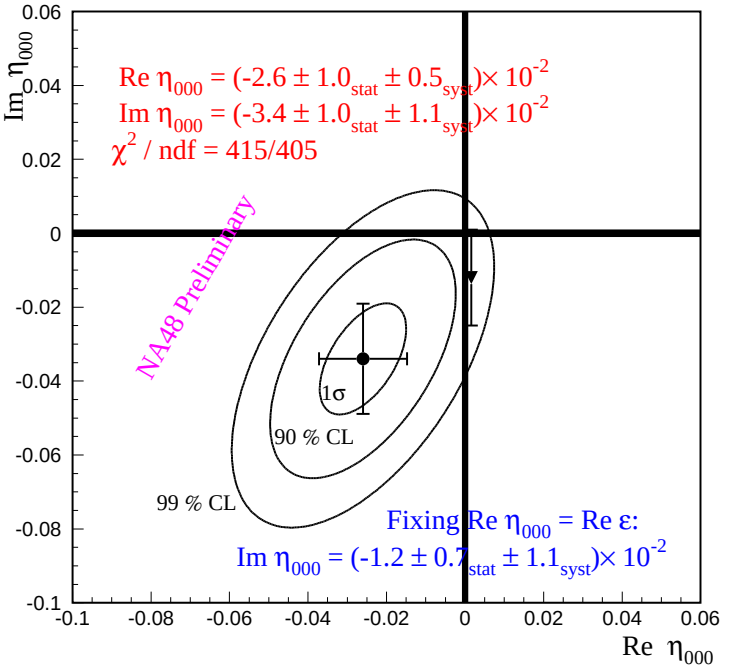
Search for $K_S \to 3\pi^0$

Preliminary NA48 result:

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

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

(CPLEAR: $\mathrm{Re}(\eta_{000}) = 0.18 \pm 0.14 \pm 0.06$
$\mathrm{Im}(\eta_{000}) = 0.15 \pm 0.20 \pm 0.03$)



If $\mathrm{Re}(\eta_{000}) = \mathrm{Re}(\epsilon)$ (CPT):

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

Branching fraction: *(preliminary)*

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

With $\mathrm{Re}(\eta_{000}) = \mathrm{Re}(\eta_\epsilon)$ (CPT):

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

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

CPT test from $K_S \to 3\pi^0$

- **Bell-Steinberger relation:**

  Connects CPT violating phase δ with η parameters via unitarity:

$$(1 + i \tan\phi_{SW})[\mathrm{Re}(\epsilon) - i\,\mathrm{Im}(\delta)] = \sum_{\substack{\text{final}\\ \text{states}}\ f} \alpha_f \qquad (\phi_{SW} = \arctan\tfrac{2\,\Delta m}{\Gamma_L - \Gamma_S})$$

- Largest contributions:

α_f		$10^3 \times \mathrm{Re}(\alpha_f)$	$10^3 \times \mathrm{Im}(\alpha_f)$
α_{+-}	$= \eta_{+-}\,\mathrm{Br}(K_S \to \pi^+\pi^-)$	1.139 ± 0.017	1.078 ± 0.017
α_{00}	$= \eta_{00}\,\mathrm{Br}(K_S \to \pi^0\pi^0)$	0.520 ± 0.010	0.488 ± 0.010
$\alpha_{+-\gamma}$	$= \eta_{+-\gamma}\,\mathrm{Br}(K_L \to \pi^+\pi^-\gamma)$	0.004 ± 0.000	0.004 ± 0.000
α_{l3}		0.004 ± 0.000	0.003 ± 0.005
α_{+-0}	$= \frac{\tau_S}{\tau_L}\,\eta^\star_{+-0}\,\mathrm{Br}(K_L \to \pi^+\pi^-\pi^0)$	0.000 ± 0.002	0.000 ± 0.002
α_{000}	$= \frac{\tau_S}{\tau_L}\,\eta^\star_{000}\,\mathrm{Br}(K_L \to 3\pi^0)$	0.029 ± 0.040	-0.026 ± 0.058

- **NA48:** $\alpha_{000} = (-0.009 \pm 0.004) + i\,(0.012 \pm 0.005) \times 10^{-3}$

$$\Longrightarrow \mathrm{Im}(\delta) = (-1.2 \pm 3.0) \times 10^{-5} \qquad \text{(was } (2.4 \pm 5.0) \times 10^{-5}\text{)}$$

$$\Longrightarrow m_{K^0} - m_{\overline{K^0}} = (-1.7 \pm 4.2) \times 10^{-19}\ \text{GeV}$$

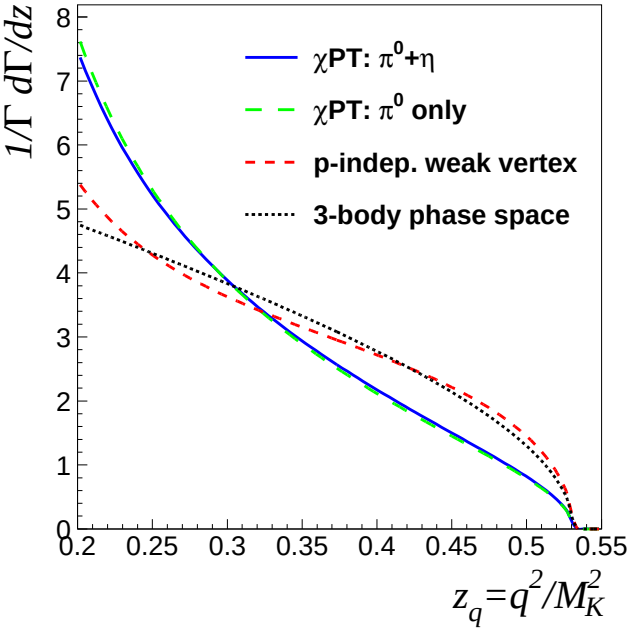
Measurement of $K_S \to \pi^0\gamma\gamma$

Prediction from ChPT:

(Ecker, Pich, De Rafael, 1987)

- $\mathrm{Br}(K_S \to \pi^0\gamma\gamma)|_{z>0.2} = 3.8 \times 10^{-8}$
- $d\Gamma/dq^2$ distribution

  $\Longrightarrow$ Structure of weak vertex



Experimental limit:

- NA48 recently (1999 test run data):

  $\mathrm{Br}(K_S \to \pi^0\gamma\gamma)|_{z>0.2} < 3.3 \times 10^{-7}$

This measurement:

- Data from 2000 near-target run (normalized to $K_S \to \pi^0\pi^0$)
- Background:
  - Beam activity $\Longrightarrow$ Veto-counter, timing
  - $K_S \to \pi^0\pi^0/\pi^0\pi^0_D$ $\Longrightarrow$ Kinematics
  - $\Xi^0 \to \Lambda\pi^0 \to n\,\pi^0\pi^0$ $\Longrightarrow$ Kinematics
  - $K_L \to \pi^0\gamma\gamma$ $\Longrightarrow$ Irreducible

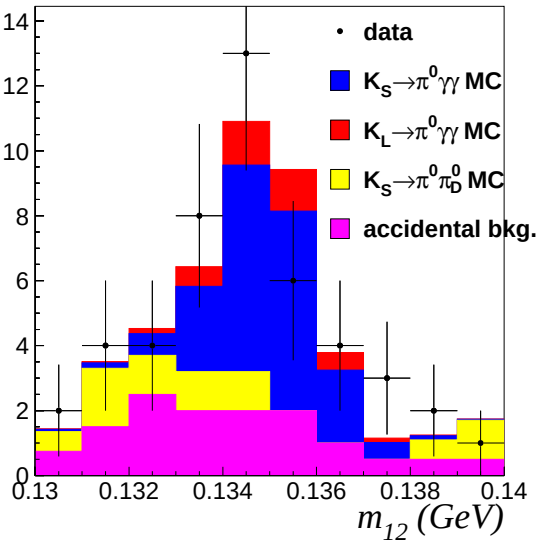
Preliminary result on $K_S \to \pi^0\gamma\gamma$

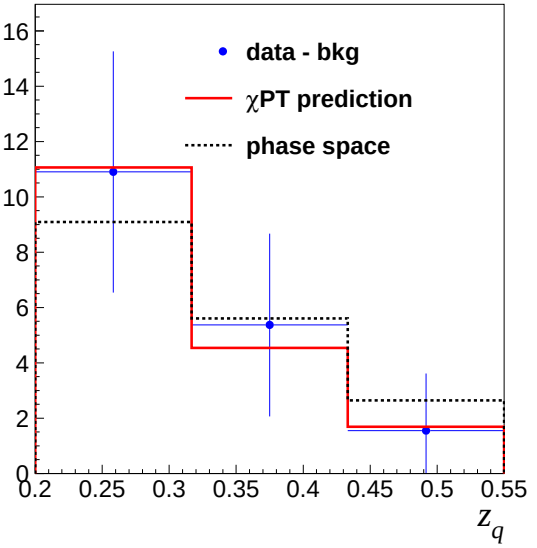
Signal candidates:

31 events in signal region

Background & Systematics:

	estimated events
Beam activity	7.4 ± 2.4
$K_S \to \pi^0\pi^0_{Dalitz}$	2.4 ± 1.2
$K_L \to \pi^0\gamma\gamma$	3.8 ± 0.0
Acceptance	± 0.7
Total	13.6 ± 2.8





Preliminary result:

$$\mathbf{Br(K_S \to \pi^0\gamma\gamma)|_{z>0.2}} = \mathbf{(4.9 \pm 1.6_{stat} \pm 0.8_{syst}) \times 10^{-8}}$$

Prob. for backg. fluctuation: $< 9 \cdot 10^{-4}$

Outlook 1: NA48/1

Run period 2002: High intensity K_S data taking.

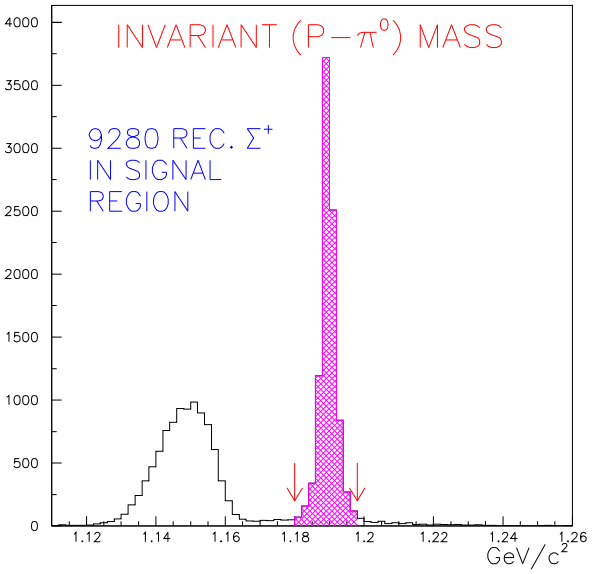
$\Longrightarrow$ Rare K_S and hyperon (Ξ^0, Λ) decays.

E.g.: — Search for $K_S \to \pi^0 e^+ e^-$

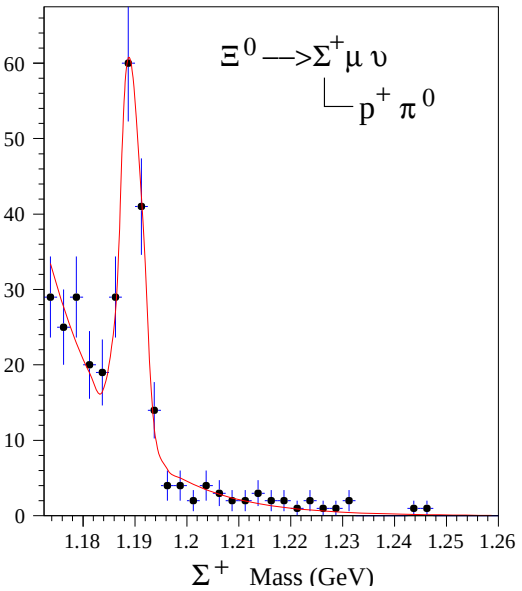
— Precision measurement of Ξ^0 beta decays.

First look into 2002 data: $\Xi^0 \to \Sigma^+ l^- \nu$ (with $\Sigma^+ \to p\pi^0$):

$\Xi^0 \to \Sigma^+ e^- \nu$



$\Xi^0 \to \Sigma^+ \mu^- \nu$



Outlook 2: NA48/2

Run period 2003: High intensity $K^{\pm}$ data taking.

Expectation: $\approx 3 \times 10^{11}$ $K^{\pm}$ decays in fiducial volume

Goals:

- **CP violation** in $K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$ Dalitz plot.

  Predicted between 10^{-4} and 10^{-6}
  — Sensitivity to $< 10^{-4}$.

- $K^{+} \to \pi^{+}\pi^{-}e^{+}\nu$ (K_{e4}) decay

  $\Longrightarrow$ **Quark condensate** $\langle 0|\bar{q}q|0\rangle$, fundamental parameter of ChPT:

  $$\langle 0|\bar{q}q|0\rangle = -\frac{f_\pi^2}{2}\frac{m_\pi^2}{m_u+m_d}$$

- Absolute measurement of $\mathrm{Br}(K^{+} \to \pi^{0}e^{+}\nu)$

  $\Longrightarrow$ $\boldsymbol{V_{us}}$ **determination**

- Rare K^{+} decays

Summary

- Measurement of K_{e3} **charge asymmetry** *(preliminary)*

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

- New stringent limit on CP violation in $K_S \to 3\pi^0$: *(preliminary)*

$$\mathrm{Br}(K_S \to 3\pi^0) < 1.2 \times 10^{-6} \quad (90\%\ \mathrm{CL})$$

(even better with CPT assumption!)

- First observation of $K_S \to \pi^0\gamma\gamma$: *(preliminary)*

$$\mathrm{Br}(K_S \to \pi^0\gamma\gamma)|_{z>0.2} = (4.9 \pm 1.6_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}}) \times 10^{-8}$$

- New results from **high intensity** K_S **run 2002** expected soon.