New Results on Kaon Decays from KTeV and NA48

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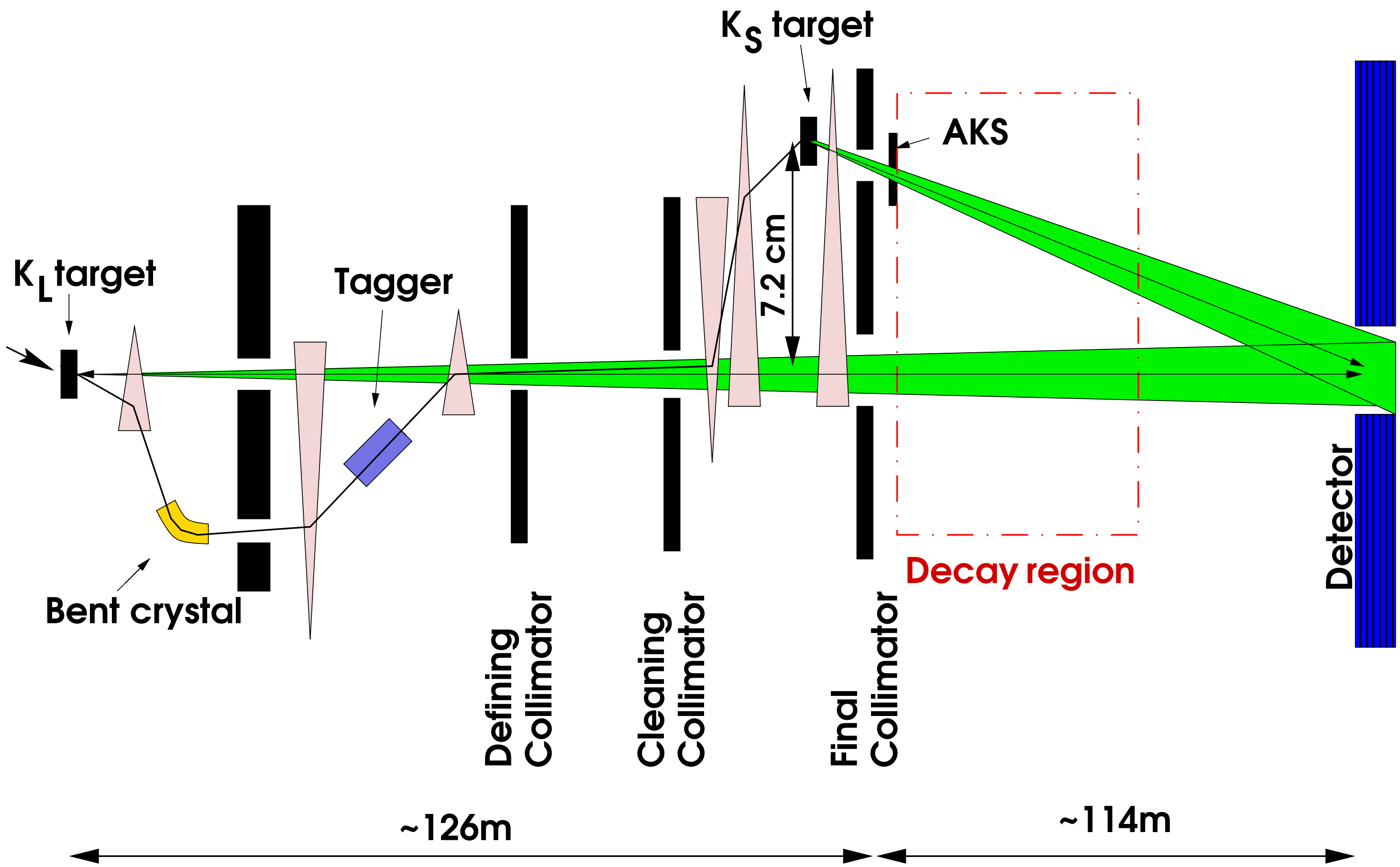
Overview

- Direct CP Violation
  - Results on $\mathrm{Re}(\epsilon'/\epsilon)$
- Rare K_{L} Decays
  - Measurement of $K_{\mathrm{L}} \rightarrow e^+e^-e^+e^-/\mu^+\mu^-e^+e^-$
  - Search for direct CP violation in $K_{\mathrm{L}} \rightarrow \pi^0 e^+e^-$
- Rare K_{S} Decays
  - First observation of $K_{\mathrm{S}} \rightarrow \pi^0 e^+e^-$
  - Search for CP violation in $K_{\mathrm{S}} \rightarrow 3\pi^0$
  - ChPT Tests from $K_{\mathrm{S}} \rightarrow \gamma\gamma$, $K_{\mathrm{S}} \rightarrow \pi^0\gamma\gamma$
- $K^{\pm}$ Decays
  - Current NA48 program
- Summary

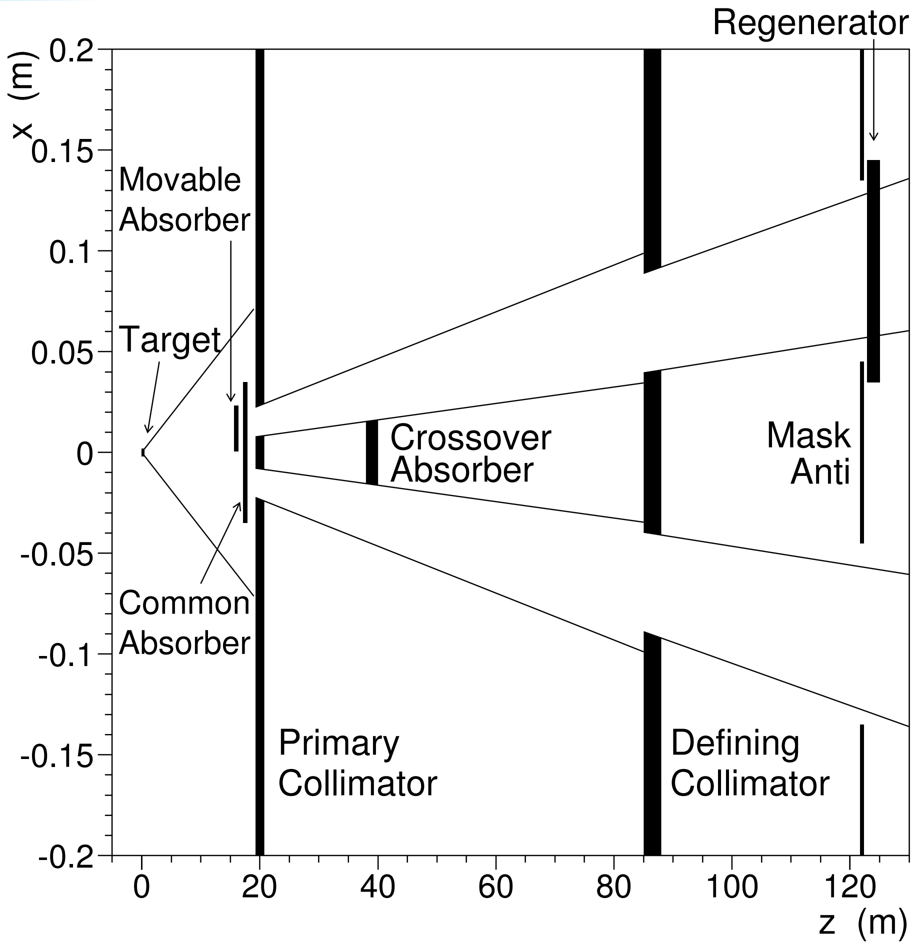
The Experiments

NA48 Beam-Line



- Simultaneous beams of K_L and K_S.
- Same interaction point in the detector.
  (K_S identification by *proton tagging*.)

KTeV Beam-Line



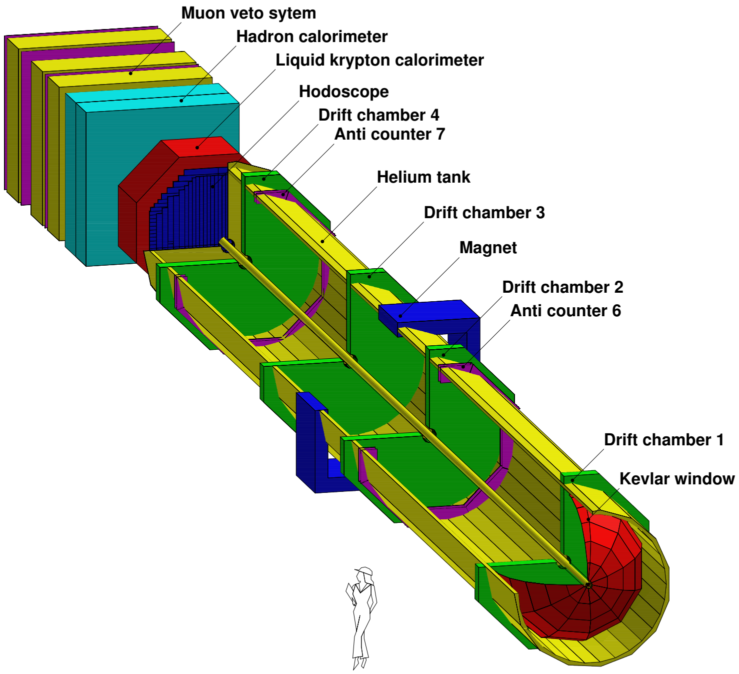
- Simultaneous beams of $K_{\rm L}$ and $K_{\rm S}$.
- Regenerator before the decay volume

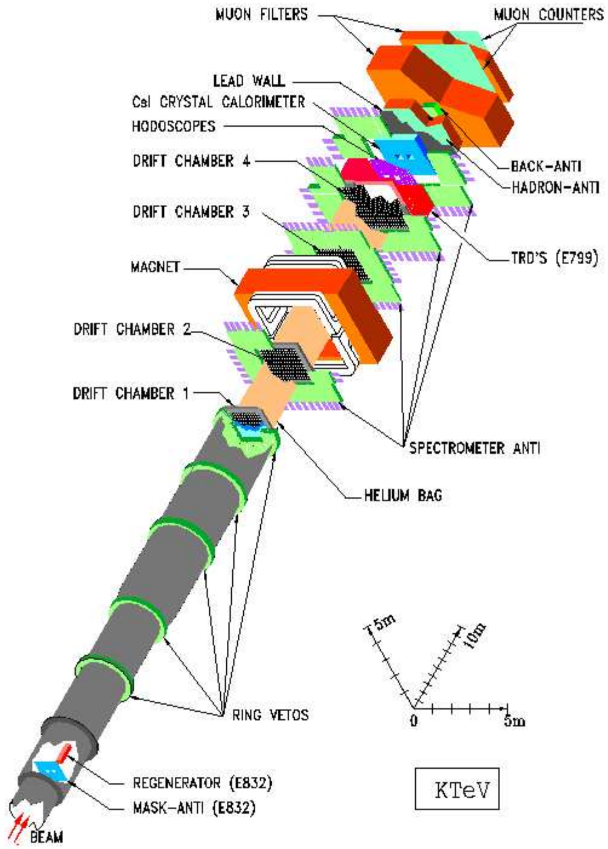
  ($\rightarrow$ $K_{\rm S}$ beam).
- $K_{\rm L}$, $K_{\rm S}$ beans divergent

  $\rightarrow$ $K_{\rm S}$ identification by extrapolated line-of-flight.

KTeV:

NA48:

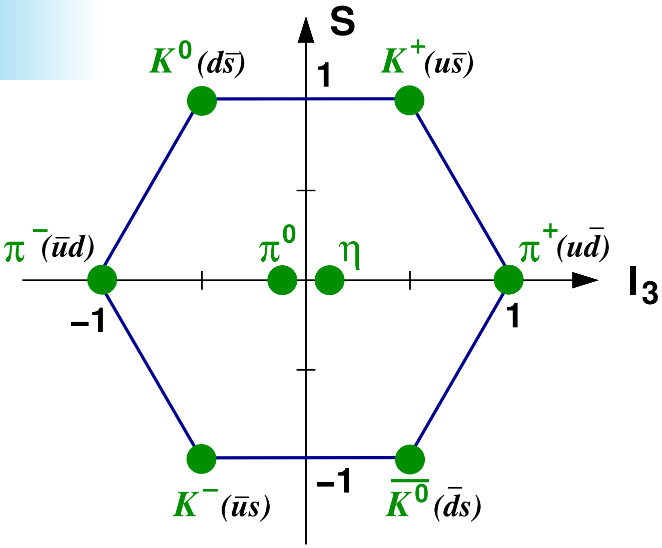

Muon veto sytem
Hadron calorimeter
Liquid krypton calorimeter
Hodoscope
Drift chamber 4
Anti counter 7
Helium tank
Drift chamber 3
Magnet
Drift chamber 2
Anti counter 6
Drift chamber 1
Kevlar window


MUON FILTERS
MUON COUNTERS
LEAD WALL
CsI CRYSTAL CALORIMETER
HODOSCOPES
DRIFT CHAMBER 4
BACK-ANTI
HADRON-ANTI
DRIFT CHAMBER 3
TRD'S (E799)
MAGNET
DRIFT CHAMBER 2
DRIFT CHAMBER 1
SPECTROMETER ANTI
HELIUM BAG
5m
10m
0
5m
RING VETOS
REGENERATOR (E832)
MASK-ANTI (E832)
BEAM
KTeV

Direct CP Violation

Measurement of $\mathrm{Re}(\epsilon'/\epsilon)$

K **Mesons**



K^+, K^-: $(\bar{s}u), (s\bar{u})$

Lifetime: 1.24×10^{-10} s

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

Lifetimes: K_S: 0.89×10^{-10} s
K_L: 5.17×10^{-8} s

- Flavor eigenstates $|K^0\rangle, |\overline{K^0}\rangle$
  different from CP eigenstates $|K_1\rangle, |K_2\rangle$:

$$\left.\begin{aligned} CP\,|K^0\rangle &= |\overline{K^0}\rangle \\ CP\,|\overline{K^0}\rangle &= |K^0\rangle \end{aligned}\right\} \Longrightarrow \left\{\begin{aligned} |K_1\rangle &= \tfrac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right) \quad CP = +1 \\ |K_2\rangle &= \tfrac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right) \quad CP = -1 \end{aligned}\right.$$

- CP $|\pi\pi\rangle = +1$ $\Longrightarrow$ Decay $K_2 \to \pi\pi$ **CP-forbidden**

$$\tau(K_L) \sim 600 \times \tau(K_S)$$

- ***Indirect* CP Violation:** (Christenson, Cronin, Fitch, Turlay, 1964)

  Mass/Decay eigenstates $|K_\mathsf{L}\rangle$, $|K_\mathsf{S}\rangle$ contain small admixture of $|K_1\rangle$ or $|K_2\rangle$, resp.:

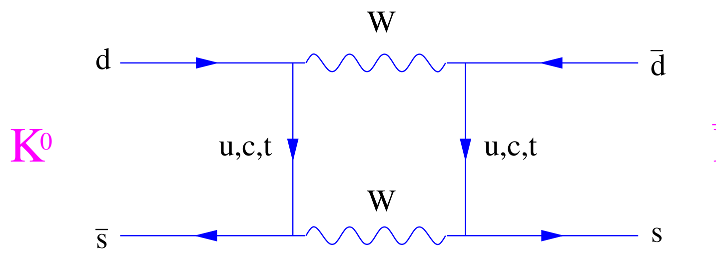
$$\begin{aligned} |K_\mathsf{L}\rangle &\propto |K_2\rangle + \epsilon\,|K_1\rangle \\ |K_\mathsf{S}\rangle &\propto |K_1\rangle + \epsilon\,|K_2\rangle \end{aligned} \qquad |\epsilon| = (2.28 \pm 0.02) \times 10^{-3}$$

  $\Longrightarrow$ $\boldsymbol{K_L \to \pi\pi}$ **indirectly** via ϵ contribution of K_1

- Standard model:

  Complex phase in CKM matrix responsible for CP violation

  $K^0\overline{K^0}$ oscillations via box diagrams.



- Other possibility:

  Transistions $K^0 \to \overline{K^0}$ and $\overline{K^0} \to K^0$ via "super weak" interaction.

- ***Direct* CP violation:**

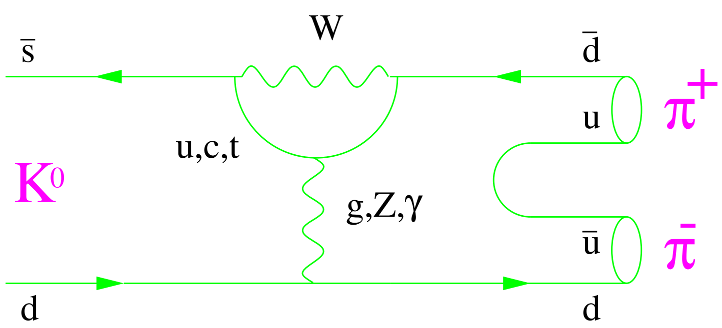
  $K_2 \rightarrow \pi\pi$ **directly** (not via K_1 admixture)

  $\Longrightarrow \quad \Gamma(K^0 \rightarrow \pi\pi) \neq \Gamma(\overline{K^0} \rightarrow \pi\pi)$

  Strength: $\rightarrow$ Parameter ϵ' $(\sim \mathcal{O}(10^{-6}))$

- Standard model:

  Decay via penguin diagrams.



$\Longrightarrow$ Different for $K_L \rightarrow \pi^+\pi^-$ und $K_L \rightarrow \pi^0\pi^0$!

Measurement of ϵ'

- **Amplitude ratios** for $K_{\mathsf{L,S}} \to \pi^+\pi^- / \pi^0\pi^0$: $(\epsilon' \ll \epsilon)$

$$\eta_{+-} = |\eta_{+-}|\, e^{i\phi_{+-}} = \frac{A(K_{\mathsf{L}} \to \pi^+\pi^-)}{A(K_{\mathsf{S}} \to \pi^+\pi^-)} \simeq \epsilon + \epsilon'$$

$$\eta_{00} = |\eta_{00}|\, e^{i\phi_{00}} = \frac{A(K_{\mathsf{L}} \to \pi^0\pi^0)}{A(K_{\mathsf{S}} \to \pi^0\pi^0)} \simeq \epsilon - 2\epsilon'$$

- Measurement of ϵ': Build **double ratio**

$$\boxed{R \equiv \frac{\Gamma(K_{\mathsf{L}} \to \pi^0\pi^0)}{\Gamma(K_{\mathsf{S}} \to \pi^0\pi^0)} \Big/ \frac{\Gamma(K_{\mathsf{L}} \to \pi^+\pi^-)}{\Gamma(K_{\mathsf{S}} \to \pi^+\pi^-)} \approx 1 - 6 \times \mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)}$$

ϵ'/ϵ : *Data Analysis*

Analysis principle: simple **counting experiment**

Statistically limited by $K_\mathrm{L} \to \pi^0\pi^0$ decays.

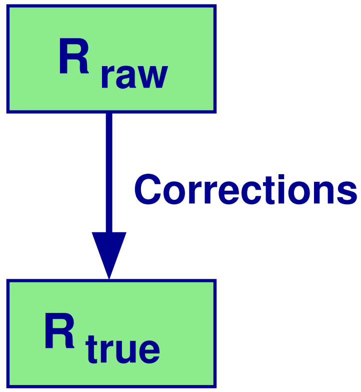
NA48 (total): $5 \times 10^6 \quad K_\mathrm{L} \to \pi^0\pi^0$

KTeV (96/97): $3.4 \times 10^6 \quad K_\mathrm{L} \to \pi^0\pi^0$ (1999: again as much)

Systematic effects:

Corrections on "raw" double ratio R_raw:

- Trigger inefficiencies
- Reconstruction inefficiencies
- Detector acceptances
- Background from K_{e3}, $K_{\mu3}$, $K_\mathrm{L} \to 3\pi^0$
- Accidentally overlapping events
- …



Main correction:

Detector acceptance is function of kaon lifetime
$\Longrightarrow$ K_S and K_L have different acceptances.

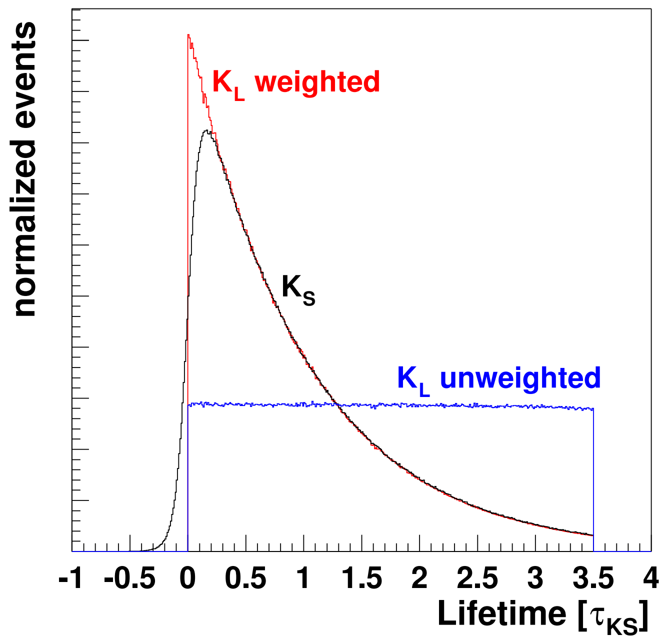
NA48: Weighting

Weight K_L events with $\tau(K_S)$.

- Acceptance differences only from beam geometry.

$$\Delta\mathrm{Re}(\epsilon'/\epsilon) \approx 3.7 \times 10^{-4}$$

- Loss of 70% of K_L statistics.



KTeV: Monte Carlo correction

- Full statistics can be used.
- Acceptance correction: $\Delta\mathrm{Re}(\epsilon'/\epsilon) \approx 80 \times 10^{-4}$

Systematic uncertainties on $\mathrm{Re}(\epsilon'/\epsilon)\ [10^{-4}]$:

	NA48 (2001)	**KTeV** (96/97)
Trigger efficiency	± 0.6	± 0.6
$\pi^+\pi^-$ reconstruction	± 0.5	± 0.3
$\pi^0\pi^0$ reconstruction	± 0.9	± 1.5
Background	± 0.7	± 1.1
Accidental activity	± 0.6	—
K_S tagging	± 0.7	—
Acceptance	± 0.7	± 0.9
MC statistics	± 0.6	± 0.6
Fit procedure	—	± 0.3
Total	± 1.8	± 2.4

$\mathrm{Re}(\epsilon'/\epsilon)$:

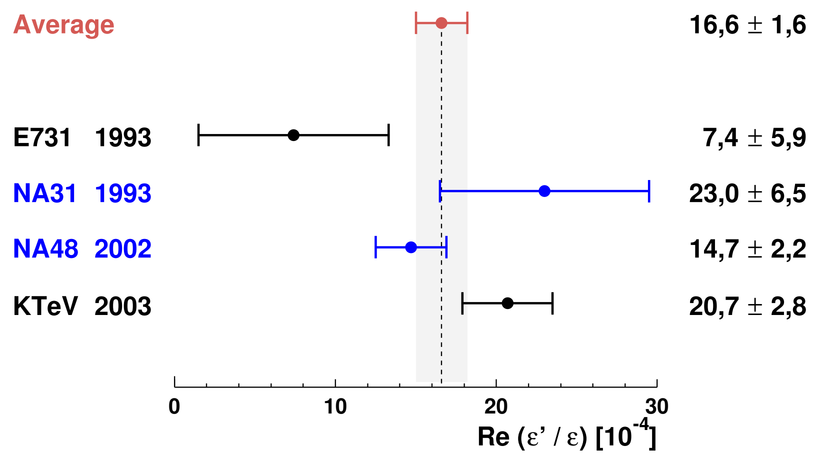
NA48, only 2001: $(13.7 \pm 2.5_{\text{stat}} \pm 1.9_{\text{syst}}) \times 10^{-4}$ (published July 2002)

97–2001: $(14.7 \pm 1.4_{\text{stat}} \pm 1.7_{\text{syst}}) \times 10^{-4}$

KTeV, 96/97: $(20.7 \pm 1.5_{\text{stat}} \pm 2.4_{\text{syst}}) \times 10^{-4}$ (published Jan 2003)

World average: $\boxed{\mathrm{Re}(\epsilon'/\epsilon) \;=\; (16.6 \pm 1.6) \times 10^{-4}}$

$(\chi^2/d.o.f. = 6.3/3)$



Theoretical predictions of ϵ'/ϵ notoriously difficult.

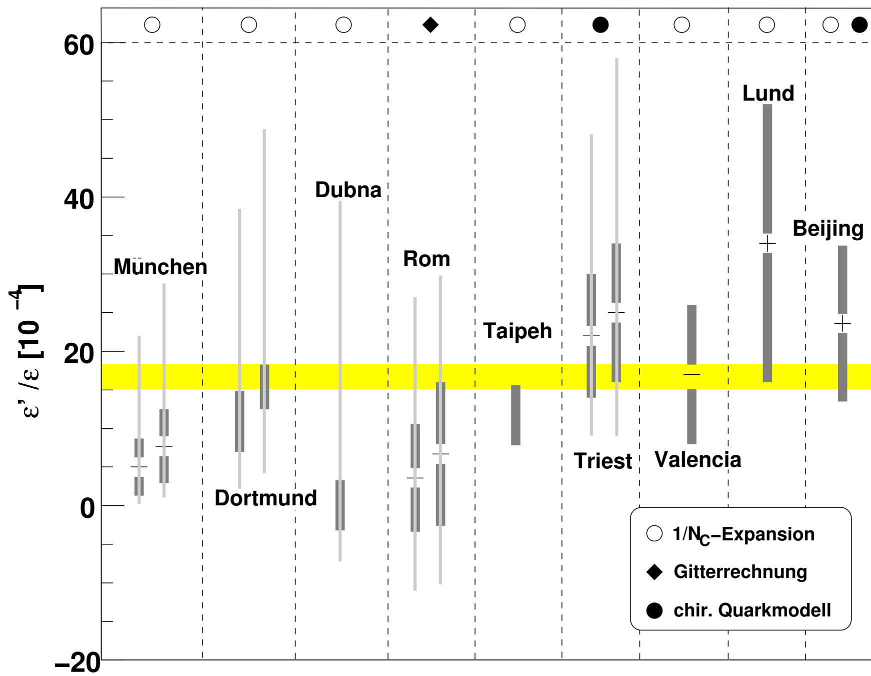
$$\epsilon' \propto \frac{\mathrm{Re}\,A_2}{(\mathrm{Re}\,A_0)^2}\left(\frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0}\ \underbrace{\mathrm{Im}\,A_0}_{\sim\ \text{QCD penguin}} - \underbrace{\mathrm{Im}\,A_2}_{\sim\ \text{EW penguin}}\right)$$

A_0: $I=0$ amplitude

A_2: $I=2$ amplitude

- Longe range contributions dominate.
- QCD- and EW penguin almost cancel.
- Strong dependence from *strange* quark mass qnd other parameters.

$\Longrightarrow$ Measured value within uncertainties.



Rare K_L Decays

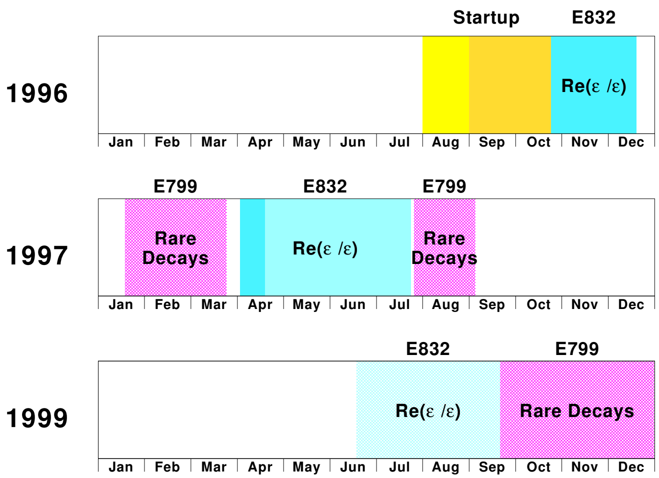
Rare K_L and K_S Decays

Main interests:

- Further understanding and search for **CP violation.**
- Understanding of the **weak vertex structure**
  $\Longrightarrow$ **Chiral Perturbation Theory (ChPT)**

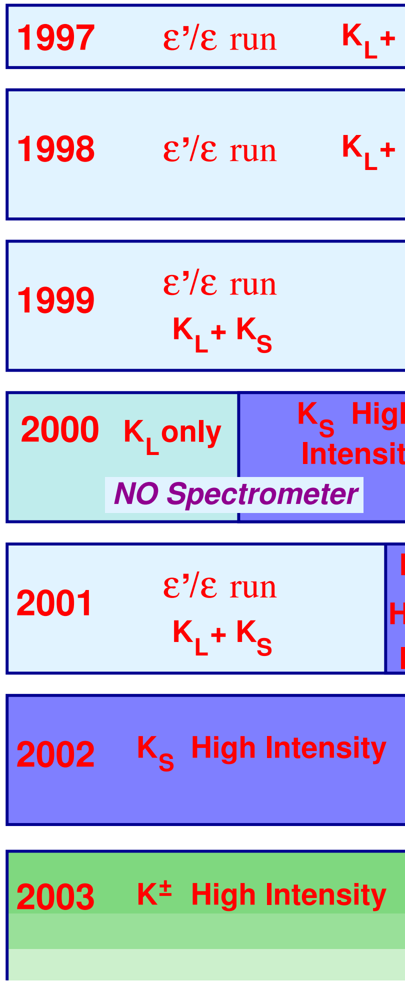
KTeV:

- *Rare-Decay* run periods for K_L decays.
- Low K_S statistics

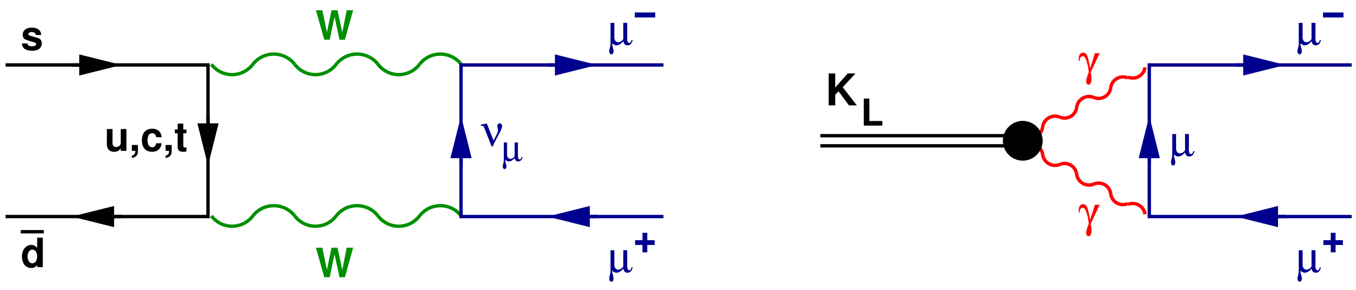


NA48:

- K_L decays from ϵ' runs.
- Special K_S runs with high intensity.



- Interest in $K_\mathrm{L} \to 4$ leptons because of $K_\mathrm{L} \to \gamma^\star\gamma^{(\star)}$ form factor
  $\Longrightarrow$ Long distance contribution to $K_\mathrm{L} \to \mu^+\mu^-$.



Short distance contribution **Long distance contribution**

- $K_L \to e^+e^-e^+e^-$, $K_L \to \mu^+\mu^-e^+e^-$ best suited (but low branching fractions)
- Also: Angle between $l^+l^- - l^+l^-$ decay planes gives CP value
  $\Longrightarrow$ Limit on CP violation in $K_\mathrm{L} \to \gamma^\star\gamma^{(\star)}$ decays
- **KTeV:** 97 and 99 data analyzed $\to$ Full KTeV data set

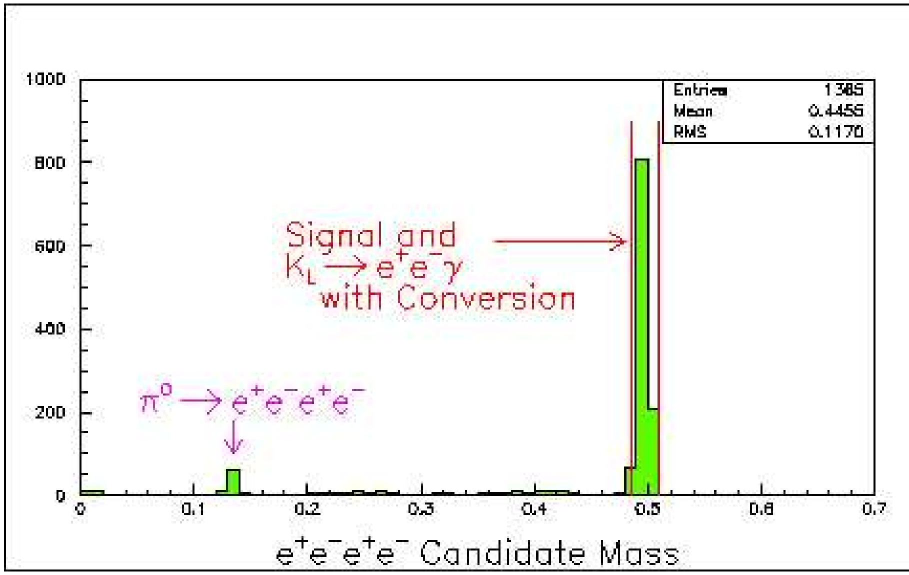
Measurement of $K_L \to e^+e^-e^+e^-$

- Full 97 and 99 KTeV data sample:

  1056 events observed

- Backgound expectation:

  5 events from $K_{\mathrm{L}} \to e^+e^-\gamma +$ conversion



$$\boxed{\mathrm{Br}(\mathrm{K_L} \to \mathrm{e^+e^-e^+e^-}) = (4.07 \pm 0.12_{\mathsf{stat}} \pm 0.11_{\mathsf{syst}} \pm 0.16_{\mathsf{norm}}) \times 10^{-8}}$$

(KTeV, preliminary)

- Form factor evaluation in progress.

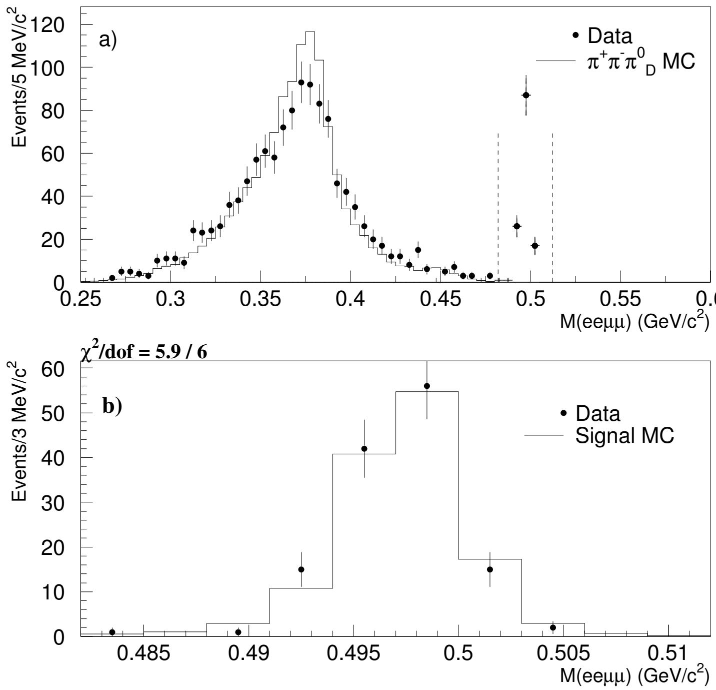
- NA48: Analysis in progress, but less statistical power.

Measurement of $K_L \to \mu^+\mu^-e^+e^-$

- $K_{\text{L}} \to \mu^+\mu^-e^+e^-$ even more rare than $K_{\text{L}} \to e^+e^-e^+e^-$
- Combined **97** and **99 KTeV** statistics:

  132 signal events

  (0.8 expected background)



$$\boxed{\mathbf{Br(K_L \to \mu^+\mu^-e^+e^-) = (2.69 \pm 0.24_{stat} \pm 0.12_{syst}) \times 10^{-9}}}$$

- Form factor measurement agrees with other $K_{\text{L}} \to \gamma^\star\gamma^{(\star)}$ modes (but low statistics).
- No evidence for CP violation in $K_{\text{L}} \to \gamma^\star\gamma^{(\star)}$.

Search for $K_L \to \pi^0 e^+ e^-$

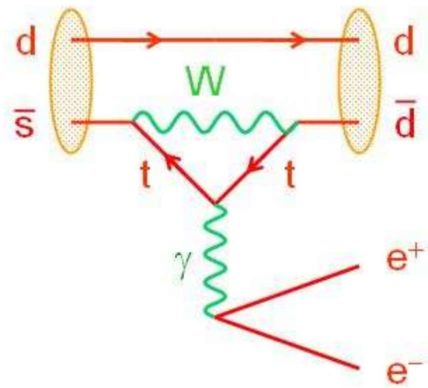
Three amplitudes contribute to $K_L \to \pi^0 e^+ e^-$:

- **Direct CP violating:**

  Proportional to η or

  $\text{Im}(\lambda_t) = \text{Im}(V_{td}V_{ts}^{\star}) = \eta A^2 \lambda^5$

  $\Longrightarrow \quad \mathrm{Br}(\mathrm{K_L} \to \pi^0 \mathrm{e^+e^-})_{\text{direct CPV}} \sim \text{few} \times 10^{-12}$



- **Indirect CP violating:**

  $\Longrightarrow \quad \mathrm{Br}(\mathrm{K_L} \to \pi^0 \mathrm{e^+e^-})_{\text{indirect CPV}} = |\epsilon|^2 \frac{\tau_L}{\tau_S} \times \mathrm{Br}(\mathrm{K_S} \to \pi^0 \mathrm{e^+e^-})$

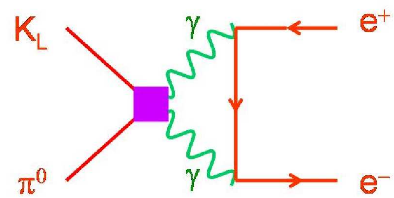
  . . . in 5 minutes . . .

- **CP conserving:**

  Determined by $K_L \to \pi^0 \gamma\gamma$.

  Measurements from KTeV and NA48:

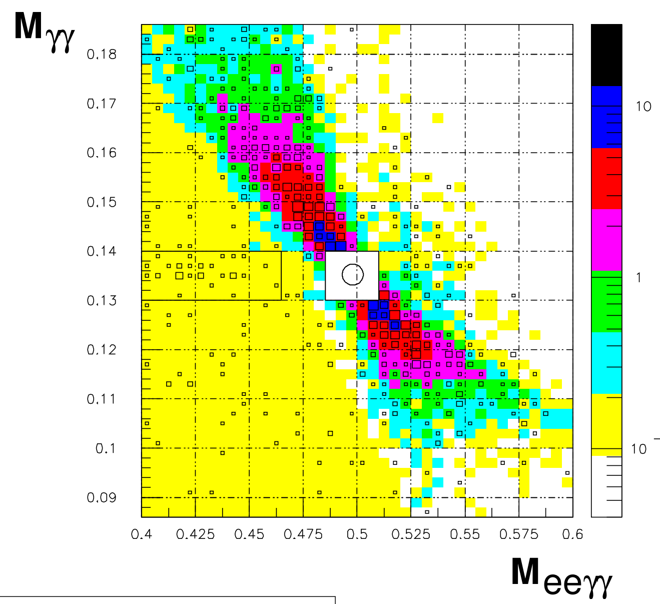
  $\mathrm{Br}(\mathrm{K_L} \to \pi^0 \mathrm{e^+e^-})_{\text{CP cons.}} = (0.5 \pm 0.2) \times 10^{-12}$

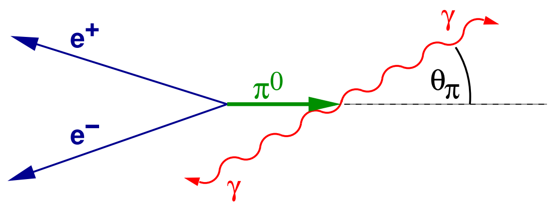


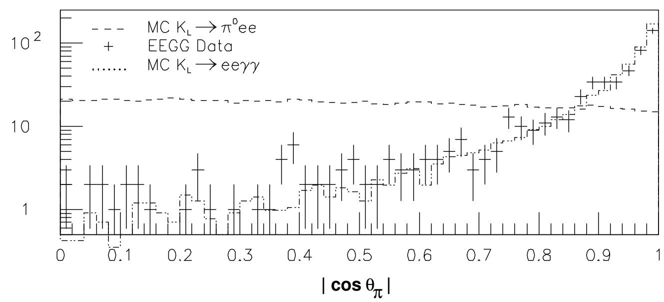
KTeV: Search for $K_L \to \pi^0 e^+ e^-$

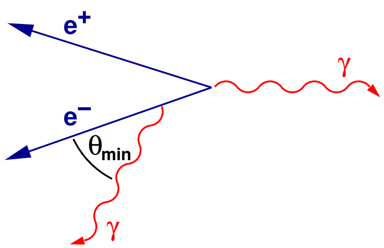
Main Background: $K_L \to e^+ e^- \gamma\gamma$

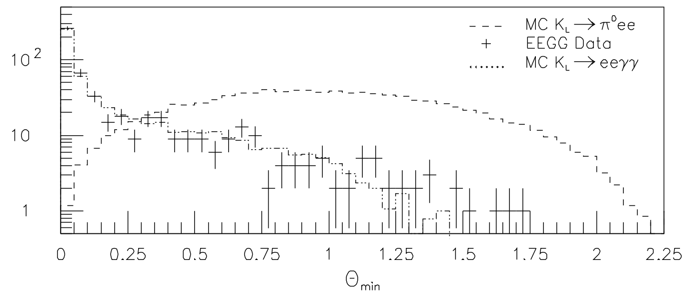
- Same signature if $m_{\gamma\gamma} \approx m_{\pi^0}$
- $\mathrm{Br} \sim 6 \times 10^{-7}$
- Suppressed with kinematic cuts on photon angles.





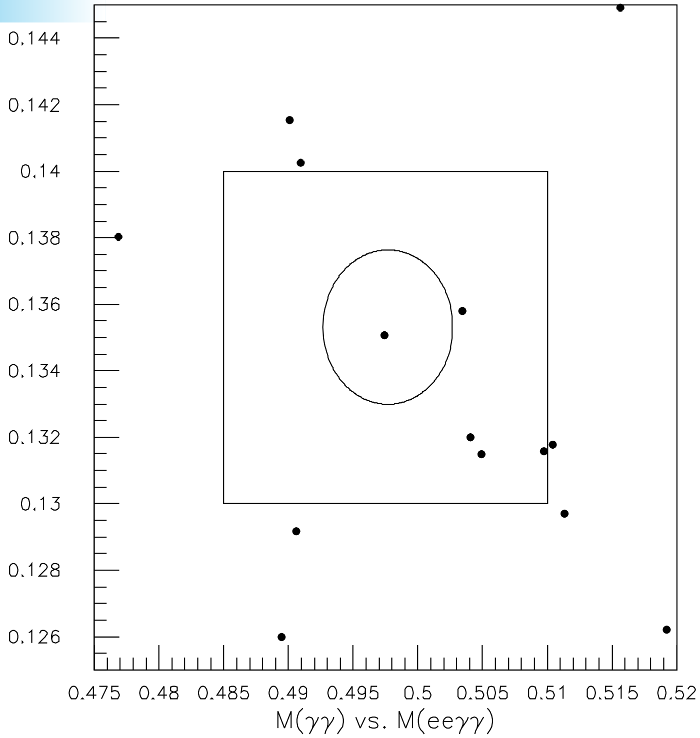






KTeV: Search for $K_L \to \pi^0 e^+ e^-$

KTeV 1999 data sample



KTeV 1999 data:

1 event observed in signal box

Expected background: 0.99 ± 0.35 even

(mostly $K_L \to e^+ e^- \gamma$

$$\mathbf{Br(K_L \to \pi^0 e^+ e^-) < 3.5 \times 10^{-10}}$$

(1999, *preliminar*

Published result on 97 data: $\mathrm{Br}(\mathrm{K_L} \to \pi^0 \mathrm{e}^+ \mathrm{e}^-) < 5.1 \times 10^{-10}$

$\Longrightarrow$ Combined limit: $\mathbf{Br(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}}$

(full KTeV data set, *preliminary*)

Rare K_S Decays

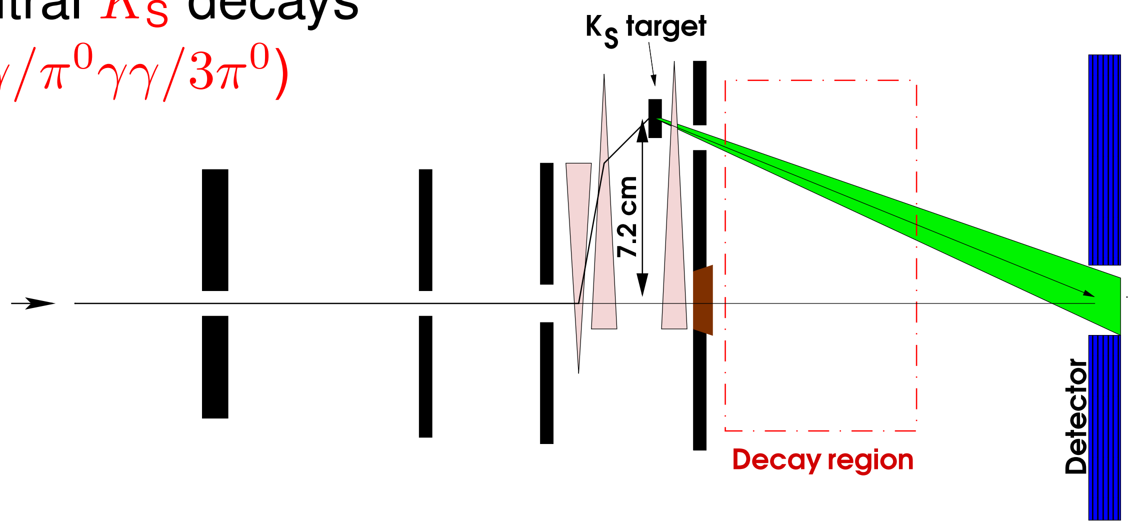
NA48 Data Taking Periods for Rare K_S Decays

2000:

- No drift chambers.
- One half of run-period pure K_L beam
  $\Longrightarrow$ Systematics for $\mathrm{Re}(\epsilon'/\epsilon)$
- One half of run-period high-intensity K_S target beam
  $\Longrightarrow$ Rare neutral K_S decays
  $(K_S \to \gamma\gamma/\pi^0\gamma\gamma/3\pi^0)$

2002:

- **NA48/1 experiment**
- Rare K_S decays
  (Total flux: 4×10^{10} K_S)
- Rare neutral hyperon deca
  (e.g. Ξ^0 beta decay)



Measurement of $K_S \to \pi^0 e^+ e^-$

- **Theoretical prediction:**

  $$\mathrm{Br}(\mathrm{K_S} \to \pi^0 \mathrm{e^+ e^-}) = (5 - 50) \times 10^{-9}$$ (Ecker, Pich, De Rafael)

- **Connection to $K_\mathrm{L} \to \pi^0 e^+ e^-$:**

  Interference of direct and indirect CP violating amplitudes:

  $$\mathrm{Br}(\mathrm{K_L} \to \pi^0 \mathrm{e^+ e^-})_{\text{CP viol.}}$$

  $$= \left(15.3\, a_s^2 \pm 6.8 \frac{\mathrm{Im}(\lambda_t)}{10^{-4}} |a_s| + 2.8 \left(\frac{\mathrm{Im}(\lambda_t)}{10^{-4}} \right)^2 \right) \times 10^{-12}$$

  $$\mathrm{Br}(\mathrm{K_S} \to \pi^0 \mathrm{e^+ e^-}) = 5 \times 10^{-9}\, |\mathrm{a_s}|^2 \quad \Longrightarrow$$ determines $|a_s|$

- **Experiment:** $K_\mathrm{S} \to \pi^0 e^+ e^-$ so far not observed.

  Best limit: $\mathrm{Br}(\mathrm{K_S} \to \pi^0 \mathrm{e^+ e^-}) < 1.4 \times 10^{-7}$ (NA48, 2-day test run 1999)

Analysis of $K_S \to \pi^0 e^+ e^-$

Strategy:

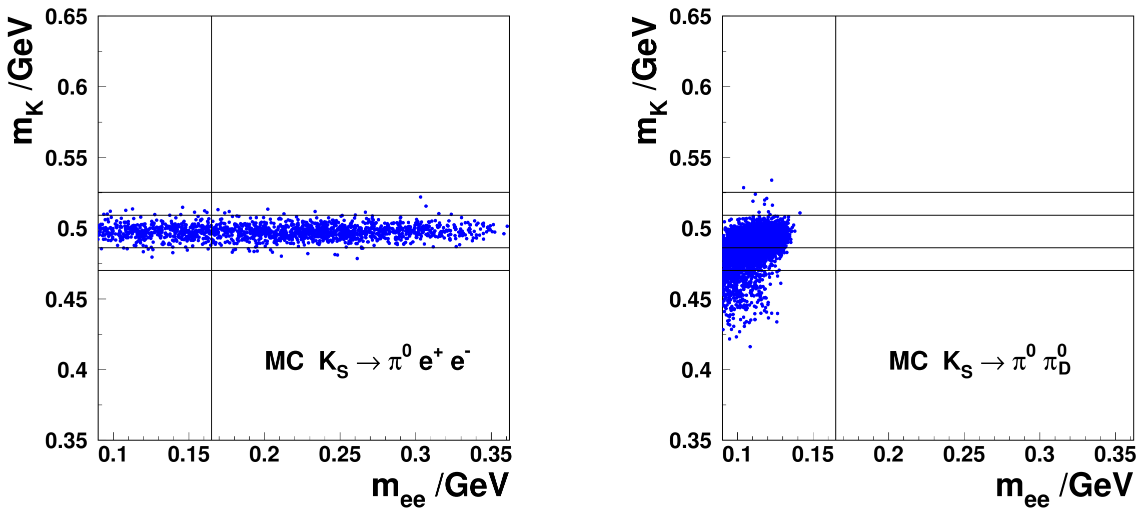
- Signal region $(2.5\,\sigma_{m_K} \times 2.5\,\sigma_{m_{\pi^0}})$ and control region $(6\,\sigma_{m_K} \times 6\,\sigma_{m_{\pi^0}})$ masked.
- Study backgrounds with data and MC simulation $\rightarrow$ fix analysis cuts
- Unmask control region $\rightarrow$ check background estimate
- Unmask signal region $\Longrightarrow$ **Result**

Backgrounds:

- K_{S} decays: $K_{\mathrm{S}} \to \pi^0 \pi^0_{\mathrm{Dalitz}}$ (+ conversions), $K_{\mathrm{S}} \to \pi^0_{\mathrm{Dalitz}} \pi^0_{\mathrm{Dalitz}}, \ldots$
- K_{L} decays: $K_{\mathrm{L}} \to \pi^+ \pi^- \pi^0$, $K_{\mathrm{L}} \to e^+ e^- \gamma\gamma, \ldots$
- Ξ^0 decays: $\Xi^0 \to \Lambda(p\pi^-)\pi^0$, $\Xi^0 \to \Lambda(pe^-\nu)\pi^0, \ldots$
- Overlapping fragments of two decays

Main background from $K_\mathrm{S} \to \pi^0\pi^0_\mathrm{Dalitz}$ ($\pi^0_\mathrm{Dalitz} \to e^+e^-\gamma$):

- About 3×10^8 $K_\mathrm{S} \to \pi^0\pi^0_\mathrm{Dalitz}$ decays in fiducial volume.
- Indistinguishable if one soft photon is lost, but $m_{ee} \leq m_{\pi^0}$:



- Require conservatively: $m_{ee} > 165$ MeV

$\Longrightarrow$ No remaining background from $K_\mathrm{S} \to \pi^0\pi^0_\mathrm{Dalitz}$

but: $\sim 50\%$ loss in acceptance

Backgrounds to $K_S \to \pi^0 e^+ e^-$ (II)

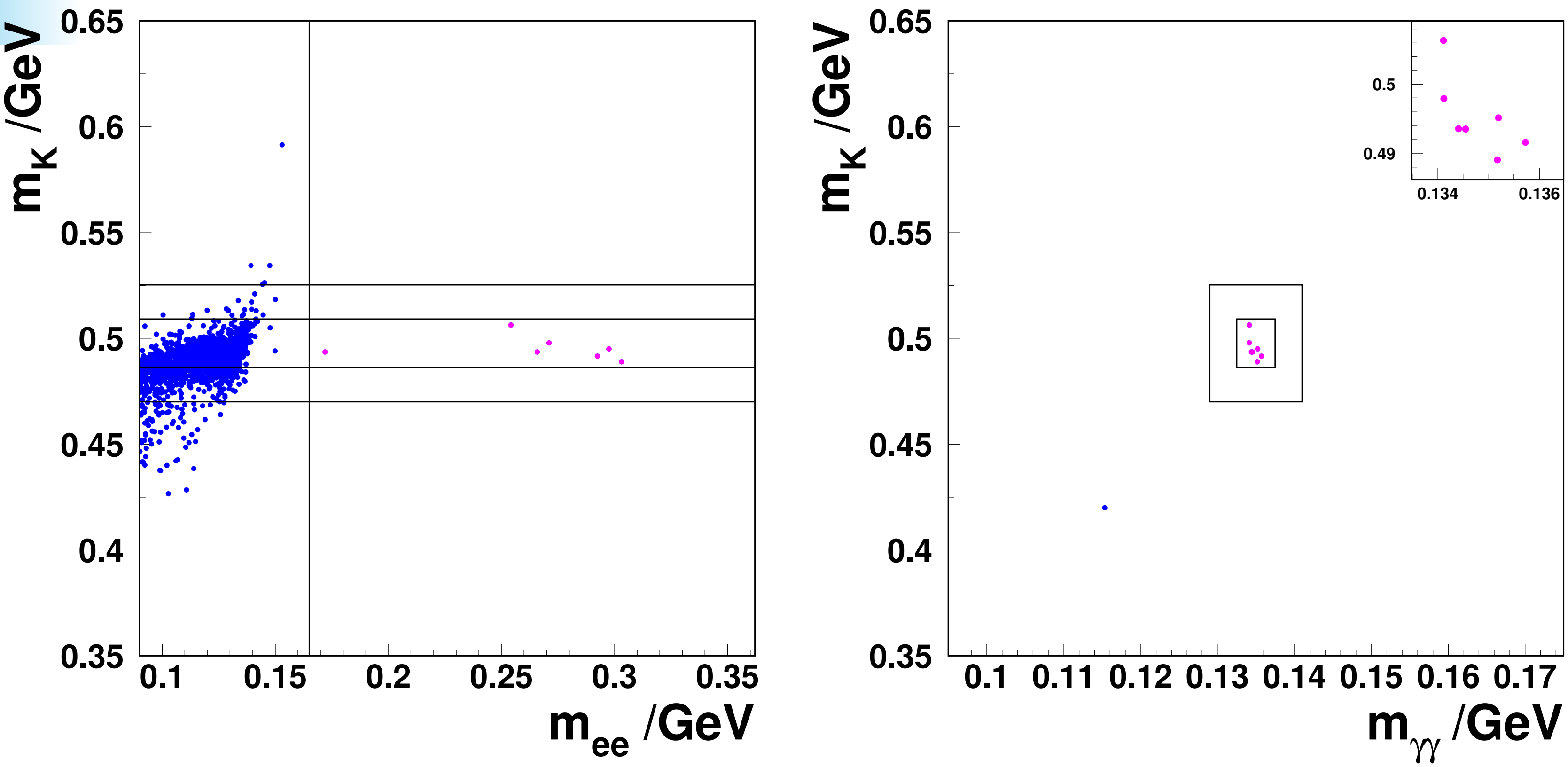
Significant contributions to the background:

Remaining background:

- $K_\mathsf{S} \to \pi^0_\mathsf{Dalitz}\pi^0_\mathsf{Dalitz}$ with two lost soft electrons
  $\rightarrow$ Reject events with both $m_{e\gamma} < 165\ \mathrm{MeV}$ — 0.007 events
- $K_\mathsf{L} \to e^+e^-\gamma\gamma$
  $\rightarrow$ Irreducible for $m_{\gamma\gamma} = m_{\pi^0}$, but well-known — 0.075 events
- Overlapping fragments of $\pi^\pm e^\mp \nu$ and $\pi^0\pi^0(\pi^0)$ — 0.069 events

$\Longrightarrow$ Total background estimation: $\mathbf{0.15\,^{+0.05}_{-0.03}}$ **events**

Result on $K_S \to \pi^0 e^+ e^-$



$\Longrightarrow$ **7 events** in signal region (0.15 expected background)

$$\mathrm{Br}(K_S \to \pi^0 e^+ e^-)_{m_{ee} > 165\ \mathrm{MeV}} = (3.0\ {}^{+1.5}_{-1.2}\,{}_{\mathrm{stat}} \pm 0.2_{\mathrm{syst}}) \times 10^{-9}$$

(preliminary)

Implications from $Br(K_S \to \pi^0 e^+ e^-)$

- Extrapolation to all m_{ee}:

  Matrix element from D'Ambrosio *et al* (JHEP 08 (1998) 004) with form factor $= 1$:

  $$\mathrm{Br}(\mathrm{K_S} \to \pi^0 \mathrm{e^+e^-})$$
  $$= (5.8\,^{+2.8}_{-2.3}\,_{\text{stat}} \pm 0.3_{\text{syst}} \pm 0.8_{\text{theo}}) \times 10^{-9}$$

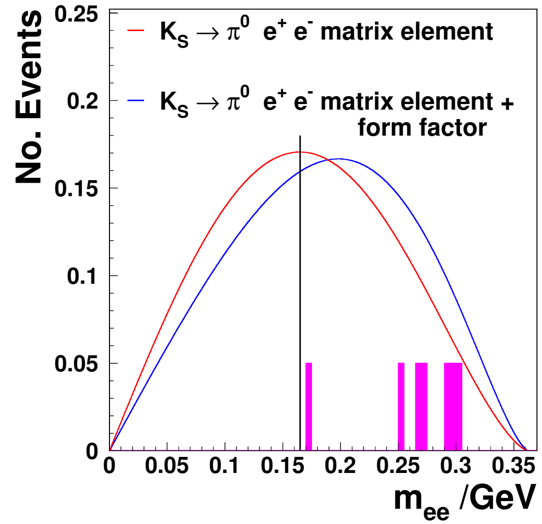
- $\mathrm{Br}(\mathrm{K_S} \to \pi^0 \mathrm{e^+e^-}) = 5 \times 10^{-9}\, |\mathrm{a_S}|^2$

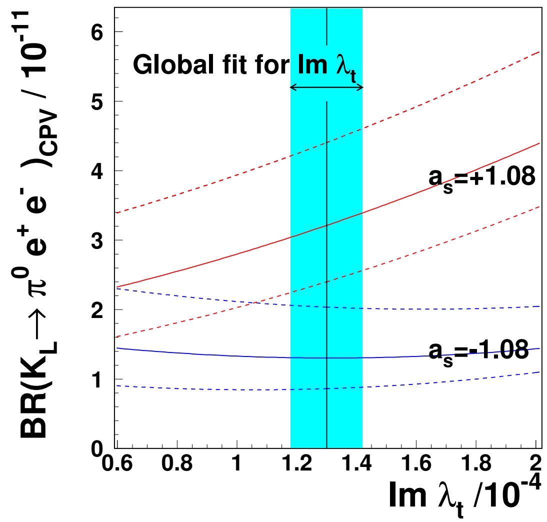
  $$\Longrightarrow \quad |a_s| = 1.08\,^{+0.26}_{-0.21}$$

- With $\mathrm{Im}(\lambda_t) = (1.3 \pm 0.1) \times 10^{-4}$ (global fit):

  $$\mathrm{Br}(\mathrm{K_L} \to \pi^0 \mathrm{e^+e^-})_{\text{CP viol.}}$$
  $$= (\underbrace{17.7}_{\text{indirect}} \pm \underbrace{9.5}_{\text{interference}} + \underbrace{4.7}_{\text{direct}}) \times 10^{-12}$$

$\Longrightarrow$ $\boxed{\text{Indirect CPV dominates } K_L \to \pi^0 e^+ e^- !}$





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 and some other assumptions):

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

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

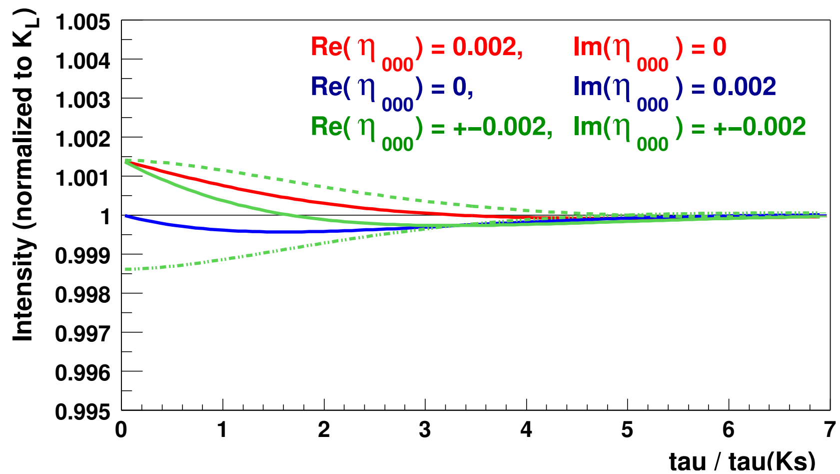
Time evolution of $K_{L,S} \to 3\pi^0$:

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

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

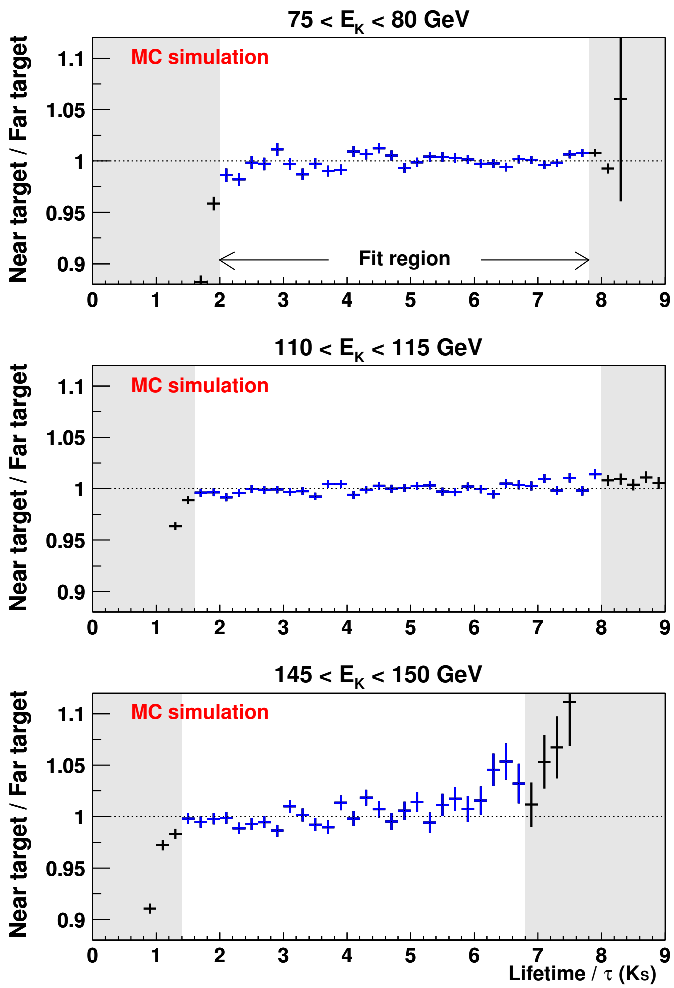
$\Longrightarrow$ Ideal environment for neutral decays!

Two different set-ups:

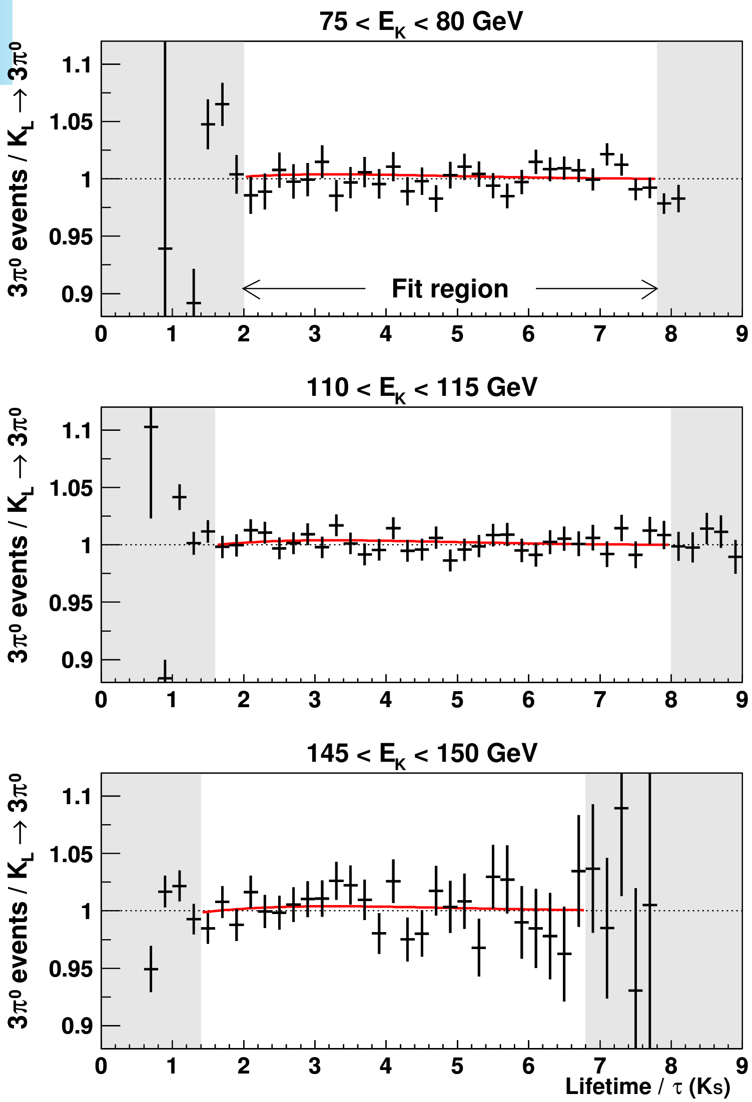
- Far-target K_L run for ϵ'/ϵ systematics.
- Near-target K_S run for K_S high-intensity.

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.



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:

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

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

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

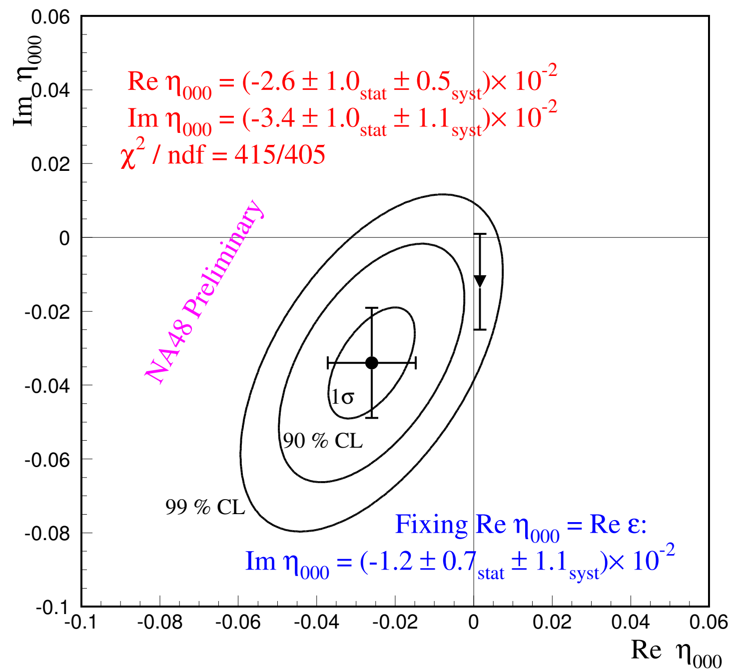
Search for $K_S \to 3\pi^0$

***Preliminary* NA48 result:**

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

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

(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):

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

Branching fraction: *(preliminary)*

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

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

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

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

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

- **Bell-Steinberger relation:**

  Connects CPT violating phase δ with η parameters via unitarity:

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

- Largest contributions:

α_f		$10^3 \times \mathrm{Re}(\alpha_f)$	$10^3 \times \mathrm{Im}(\alpha_f)$
α_{+-}	$= \eta_{+-}\,\mathrm{Br}(K_S \to \pi^+\pi^-)$	1.136 ± 0.013	1.071 ± 0.013
α_{00}	$= \eta_{00}\,\mathrm{Br}(K_S \to \pi^0\pi^0)$	0.517 ± 0.010	0.486 ± 0.010
$\alpha_{+-\gamma}$	$= \eta_{+-\gamma}\,\mathrm{Br}(K_S \to \pi^+\pi^-\gamma)$	0.003 ± 0.000	0.003 ± 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:** $\alpha_{000} = (\,-0.009 \pm 0.004\,) + i\,(0.012 \pm 0.005\,) \times 10^{-3}$

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

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

Chiral Perturbation Theory (ChPT)

Low momentum transfers:
Lagrange function $\mathcal{L}_{QCD}$ cannot be directly computed from QCD.

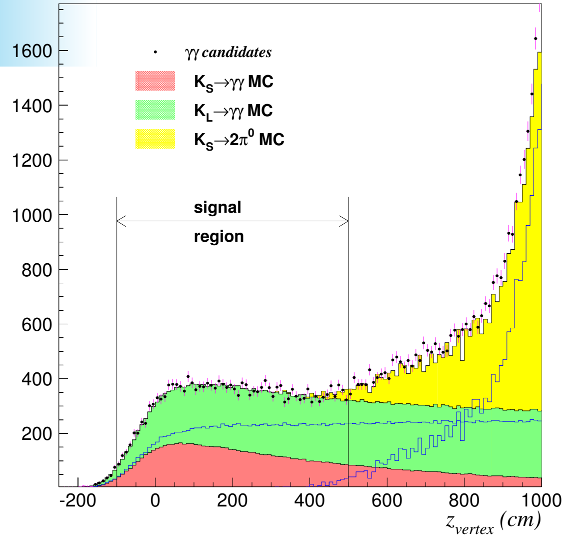
$\Longrightarrow$ Introduce effective Lagrangian $\mathcal{L}_{\text{eff}}$

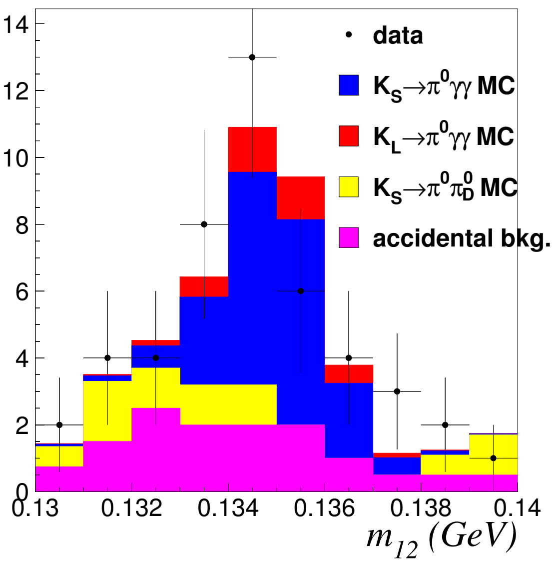
$\Longrightarrow$ Expand in the meson momenta
$(\mathcal{O}(p^2), \mathcal{O}(p^4), \mathcal{O}(p^6), \ldots)$

Disadvantage: Expansion coefficients *("effective couplings")* cannot be computed and have to be measured.

- Different reactions can have same chiral couplings.
  $\longrightarrow$ Predictions possible.
- But very many couplings for higher orders $(\geq \mathcal{O}(p^6))$.
  $\longrightarrow$ Cannot be calculated.

Chiral Perturbation Theory Tests





$K_S \to \gamma\gamma$:

- $\mathcal{O}(p^2) = 0$, $\mathcal{O}(p^4)$ known
- $\mathcal{O}(p^4)$ prediction: $\mathrm{Br} = 2.1 \times 10^{-6}$
- **NA48 (2000 data):** $\sim 20000\ \gamma\gamma$ events

$$\boxed{\mathrm{Br}(K_S \to \gamma\gamma) = (2.78 \pm 0.06 \pm 0.04) \times 10^{-6}}$$

$\Longrightarrow\ \approx 30\%$ contribution from $\mathcal{O}(p^6)$

$K_S \to \pi^0\gamma\gamma$:

- Prediction (Ecker, Pich, De Rafael):
  $\mathrm{Br} = 3.8 \times 10^{-8}$ for $z = m^2_{\gamma\gamma}/m^2_K > 0.2$
- **NA48 (2000 data):** $31\ \pi^0\gamma\gamma$ candidates
  Background exp.: 13.6 ± 2.8 events

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

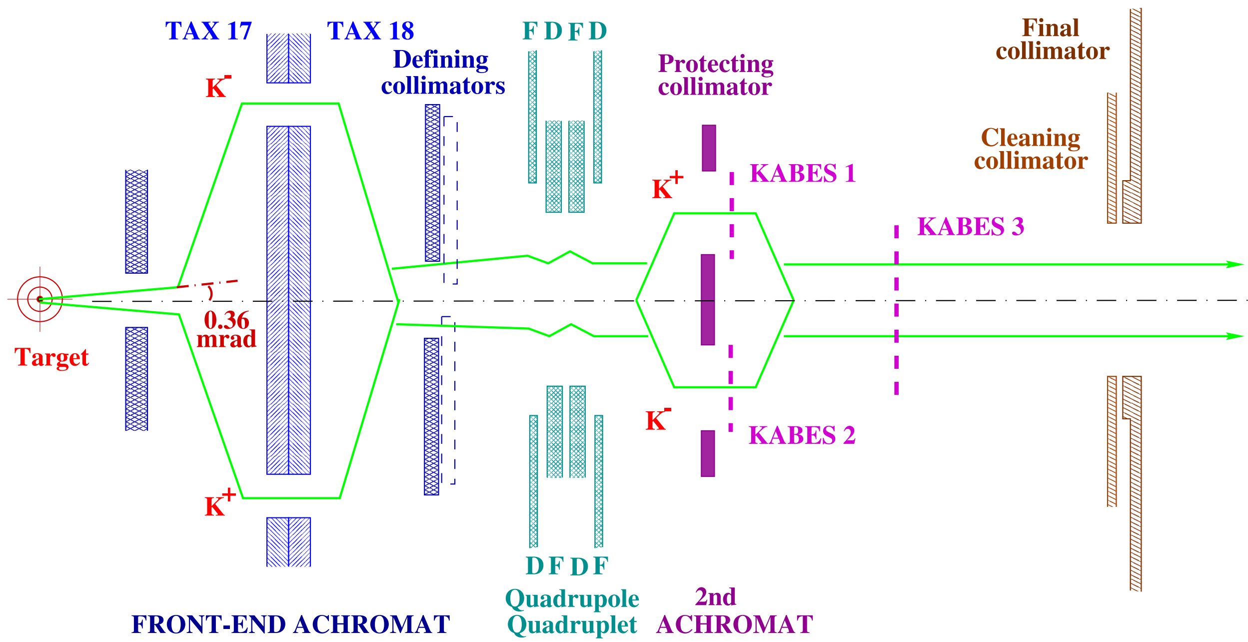
(preliminary)

NA48/2: $K^{\pm}$ Decays

NA48/2: $K^{\pm}$ Decays

NA48/2 experiment in 2003:

- High intensity data taking with simultaneous K^+ and K^- beams.
- New beam spectrometer (Micromesh gas chambers)
  $\Longrightarrow$ $K^{\pm}$ momentum resolution $\sim 1\%$
- Expectation: $\approx 3 \times 10^{11}$ $K^{\pm}$ decays in fiducial volume.



Goals of NA48/2:

- **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 Br$(K^+ \to \pi^0 e^+\nu)$

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

- Rare K^+ decays

Summary

Summary

Combined NA48 and KTeV result on **direct CP violation:**

$$\mathbf{Re}(\epsilon'/\epsilon) = (16.6 \pm 1.6) \times 10^{-4}$$

Exiting and fruitful field of Rare Kaon Decays:

- New results on K_L **decays** from **KTeV:**
  - Precise measurements of $K_L \to e^+e^-e^+e^-$, $K_L \to \mu^+\mu^-e^+e^-$
  - New limit on $K_L \to \pi^0 e^+e^-$
- New results on K_S **decays** from **NA48:**
  - First observation of $K_S \to \pi^0 e^+e^-$
  - New limit on $K_S \to 3\pi^0$
  - ChPT tests from $K_S \to \gamma\gamma$, $K_S \to \pi^0\gamma\gamma$
- **NA48 program** on $K^\pm$ **decays** just started.