Status and Prospects of Rare $K^{\pm}$ and K_L Decays from NA48

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Overview

- $K^{\pm}$ **Decays:**
  - $K^{\pm} \to \pi^{\pm}\pi^{\mp}e^{\pm}\nu(\bar{\nu})$ (K^{+}_{e4}) branching ratio and form factors
  - $K^{\pm} \to \pi^{\pm}e^{+}e^{-}$ and $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ decays
  - Branching ratio and form factors of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$
  - Branching ratio and form factors of $K^{\pm} \to \pi^{\pm}\gamma\gamma$
- $K_{\mathrm{L,S}}$ **Decays:**
  - Precise measurements of $K_{\mathrm{L}} \to \pi^{+}\pi^{-}/\pi^{0}\pi^{0}$ branching ratios
  - Measurement of $K_{\mathrm{S}} \to \pi^{+}\pi^{-}\pi^{0}$.
  - Search for $K_{\mathrm{S}} \to 3\pi^{0}$.

Most analyses: Not yet finished

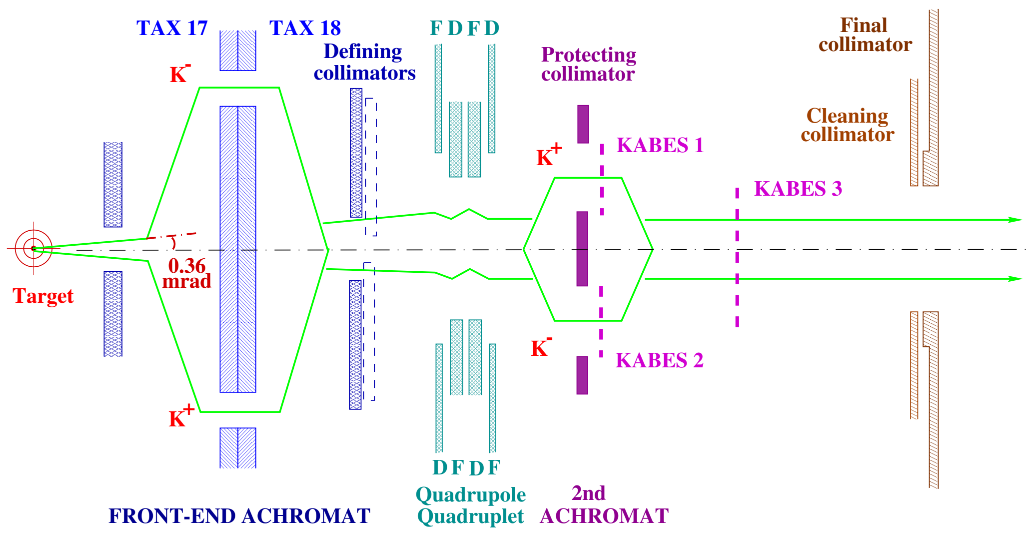
$\Longrightarrow$ **Event numbers and statistical reach shown, but few results.**

Rare $K^\pm$ Decays

NA48/2 $K^{\pm}$ Data Taking

NA48/2 experiment in 2003/2004:

- **2003:** $\sim$ 50 days of data taking: Super samples 0, 1 – 3
  $\Longrightarrow$ Data shown in this talk (partly without SS 0).
- **2004:** $\sim$ 60 days of data taking: Super samples 4 – 8
  $\Longrightarrow$ Data *not* shown here, but simple to add.



Trigger:

- **All** 3-track events
  ($\sim 98\%$ efficient)
- 1-track events
  with μ-veto and
  $$(p_K - p_\pi)^2 \gg m^2_{\pi^0}$$
  to reject $K^{\pm} \to \pi^{\pm}\pi^{0}$.

Measurement of $K^+ \to \pi^+\pi^-e^+\nu$ ***(***K^+_{e4}***)***

- **Physics interest:** (Same as cusp-effect in $K^\pm \to \pi^\pm\pi^0\pi^0$)
  - Low energy $\pi\pi$ scattering unambiguously predicted from Chiral Perturbation Theory first principles.
  - s-wave isospin zero $\pi\pi$ scattering length a_0^0 can be determined from form factors in K^+_{e4} decays.

    $\Longrightarrow$ Predicted to $a_0^0 = 0.220 \pm 0.005$ in ChPT.
    (Colangelo, Gasser, Leutwyler, 2001)

- **Previous measurements:**
  - Geneva-Saclay (1977): $30\,000$ events
  - Brookhaven E865 (2001): $400\,000$ events

    $\Longrightarrow$ $a_0^0 = 0.216 \pm 0.013.$
  - NA48 (2005, prel.): $|a_0^0 - a_2^0|$ from $K^\pm \to \pi^\pm\pi^0\pi^0$

    $\Longrightarrow$ $|a_0^0 - a_2^0| = 0.281 \pm 0.021.$

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

- Events fully reconstructed by using known kaon momenta.
  (Well, $p = 60$ GeV/c along z-axis.)

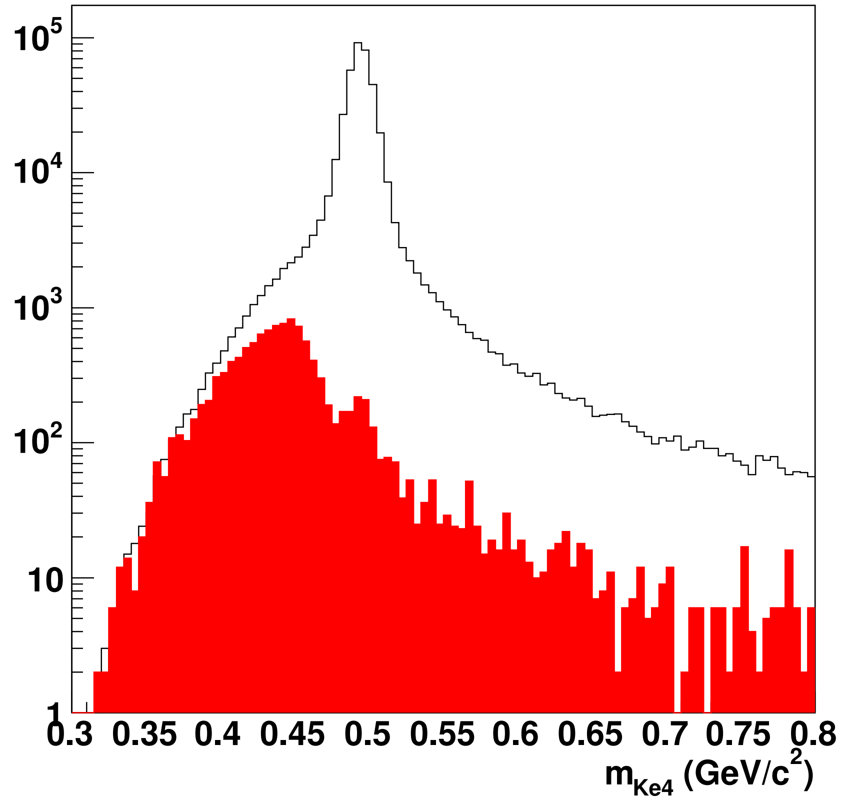
  $\Longrightarrow$ About **340 000 events** in SS 1–3.

- **Background** mainly from
  $K^+ \to \pi^+\pi^+\pi^-$ and
  $K^+ \to \pi^+\pi^0_{\text{Dalitz}}$ with
  $\pi \leftrightarrow e$ mis-identification.

  $\Longrightarrow$ Use of neural network
  for e/π separation.

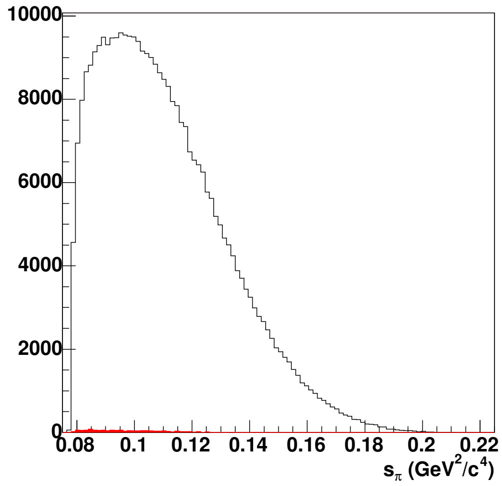
- Total background: $\mathbf{0.4\%}$

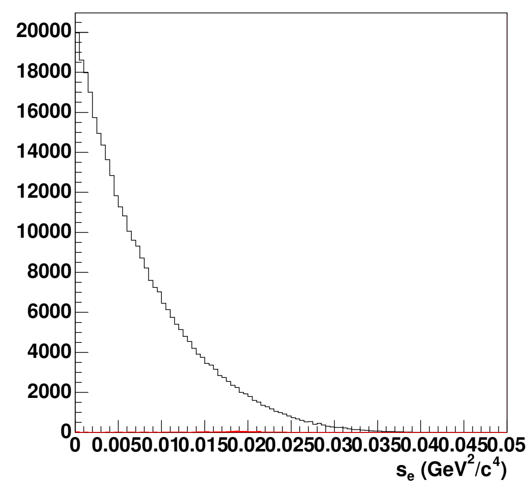
  Determined from wrong-sign
  $\pi^+\pi^+e^-$ data events.

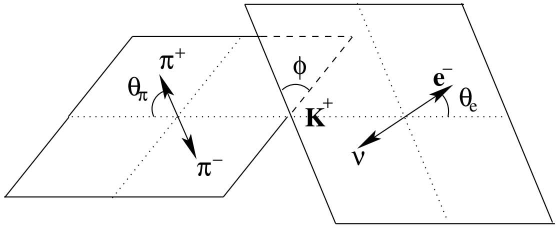


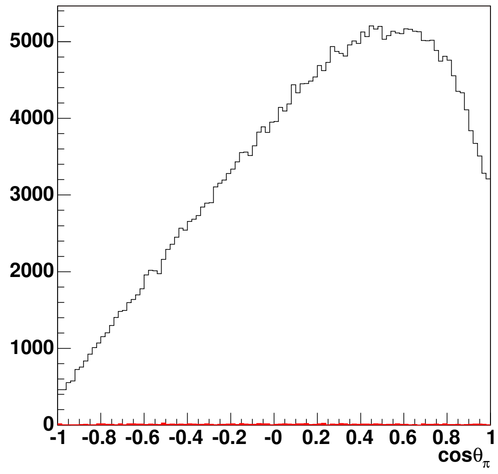
Measurement of $K^+ \rightarrow \pi^+\pi^-e^+\nu$ *(*K^+_{e4}*)*

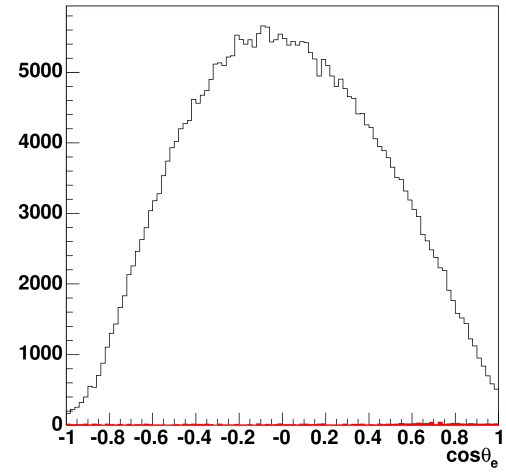
Cabibbo-Maksymowicz variables: (Background in red)

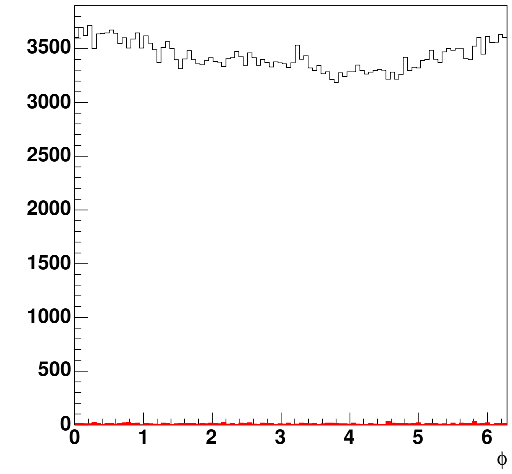












Measurement of $K^+ \to \pi^+\pi^- e^+\nu$ (K^+_{e4})

Status and Prospects for K^+_{e4}:

- About **340 000 events** in SS 1–3 2003.

  $\Longrightarrow$ Expected statistical error on $a_0^0 \sim \pm 0.01$.

  $\Longrightarrow$ Similar precision as cusp analysis in $K^+ \to \pi^+\pi^0\pi^0$, but complementary & no theoretical uncertainties.

- Backgrounds are tiny, systematics are under study.
- Analysis underway, but a lot of work.

Further K^+_{l4} Analyses:

- About **15 000 events** of $K^\pm \to \pi^0\pi^0 e^\pm\nu(\bar{\nu})$ in SS 1–3.
- Also $K^\pm \to \pi^+\pi^-\mu^\pm\nu(\bar{\nu})$ under investigation.

Both measurements have to fight large backgrounds.

Measurement of $K^\pm \to \pi^\pm e^+ e^-$ and $K^\pm \to \pi^\pm \mu^+ \mu^-$

- **Physics interest:**
  - FCNC, suppressed by GIM mechanism.
  - Amplitude dominated by long-distance contributions (one-photon “bremsstrahlung” diagrams).

    $\Longrightarrow$ Can be extracted from form factor measurements!
  - Potentially interesting channels for CP violation between $\Gamma(K^+_{\pi ll})$ and $\Gamma(K^-_{\pi ll})$.

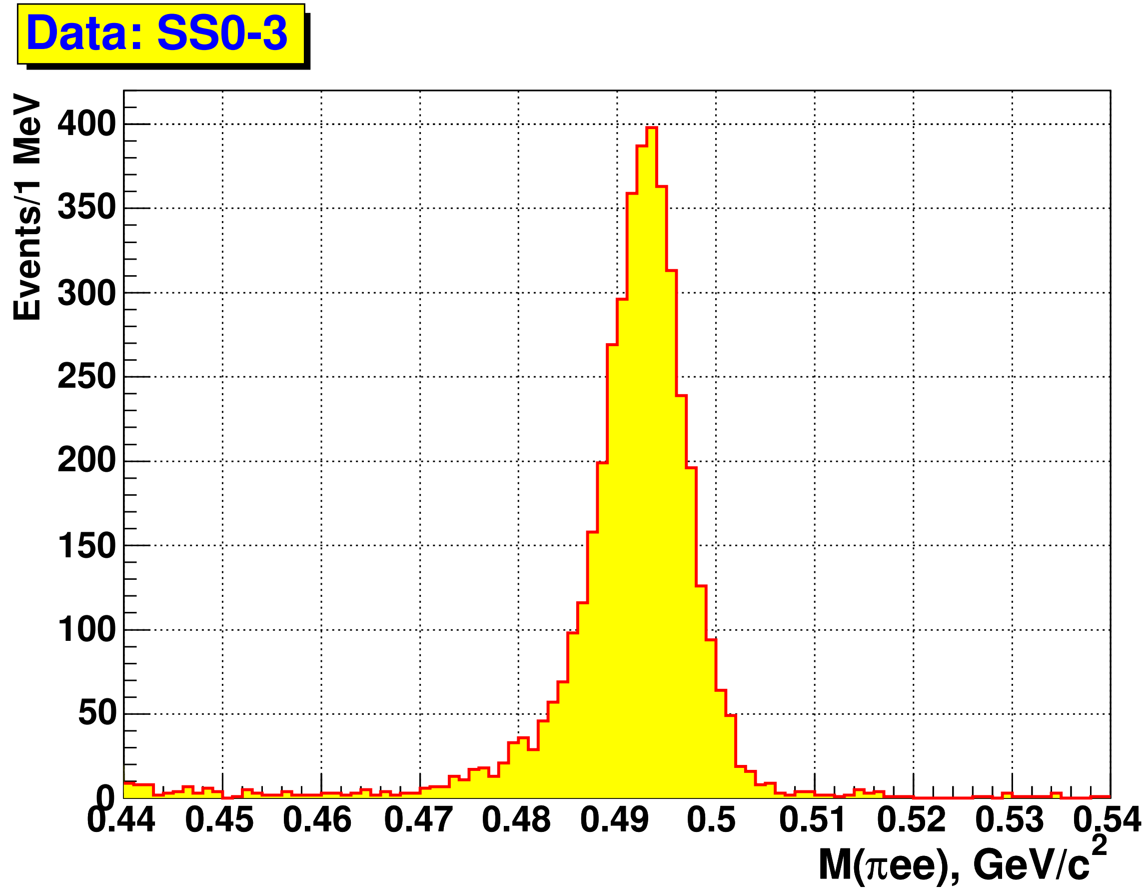
- **Previous measurements:**
  - $K^\pm \to \pi^\pm e^+ e^-$: BNL E865 found 10500 events

    $\Longrightarrow$ $\mathrm{Br} = (2.94 \pm 0.05 \pm 0.14) \times 10^{-7}$

    (Also form factor measurement.)
  - $K^\pm \to \pi^\pm \mu^+ \mu^-$: Several experiments, in total 800 events.

    $\Longrightarrow$ $\mathrm{Br} = (0.81 \pm 0.14) \times 10^{-7}$

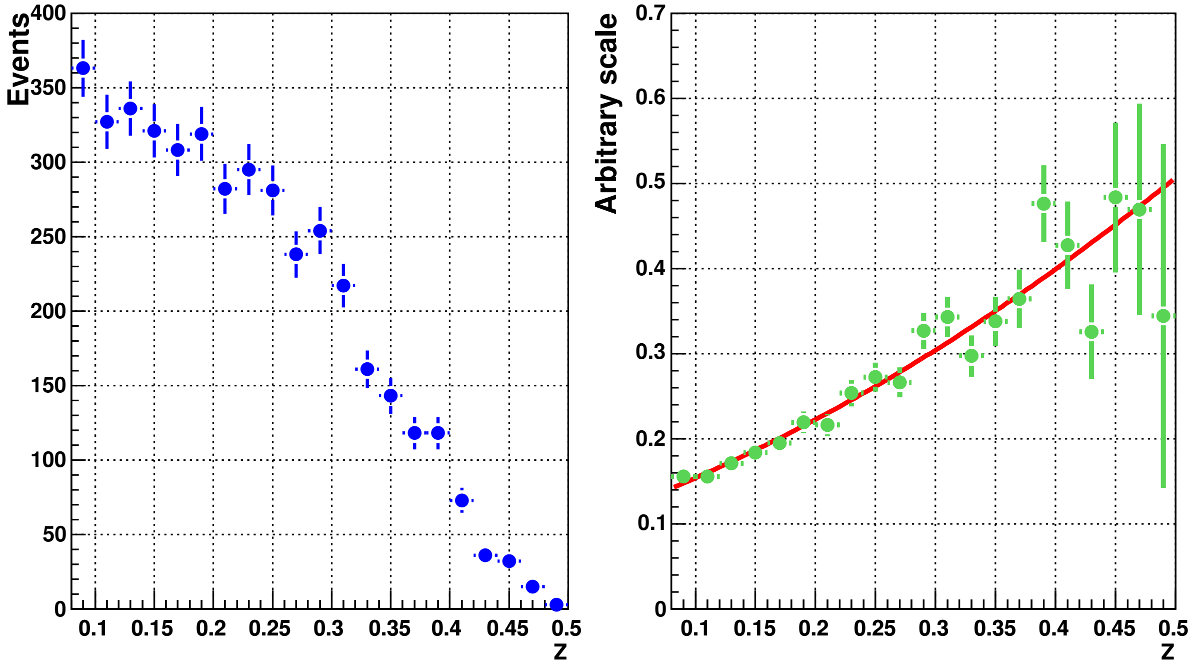
Measurement of $K^{\pm} \to \pi^{\pm} e^{+} e^{-}$



- More than **4000 events** for $m_{ee} > 140$ MeV/c^2 in 2003 data.
- Background very small $(< 1\,\%)$.

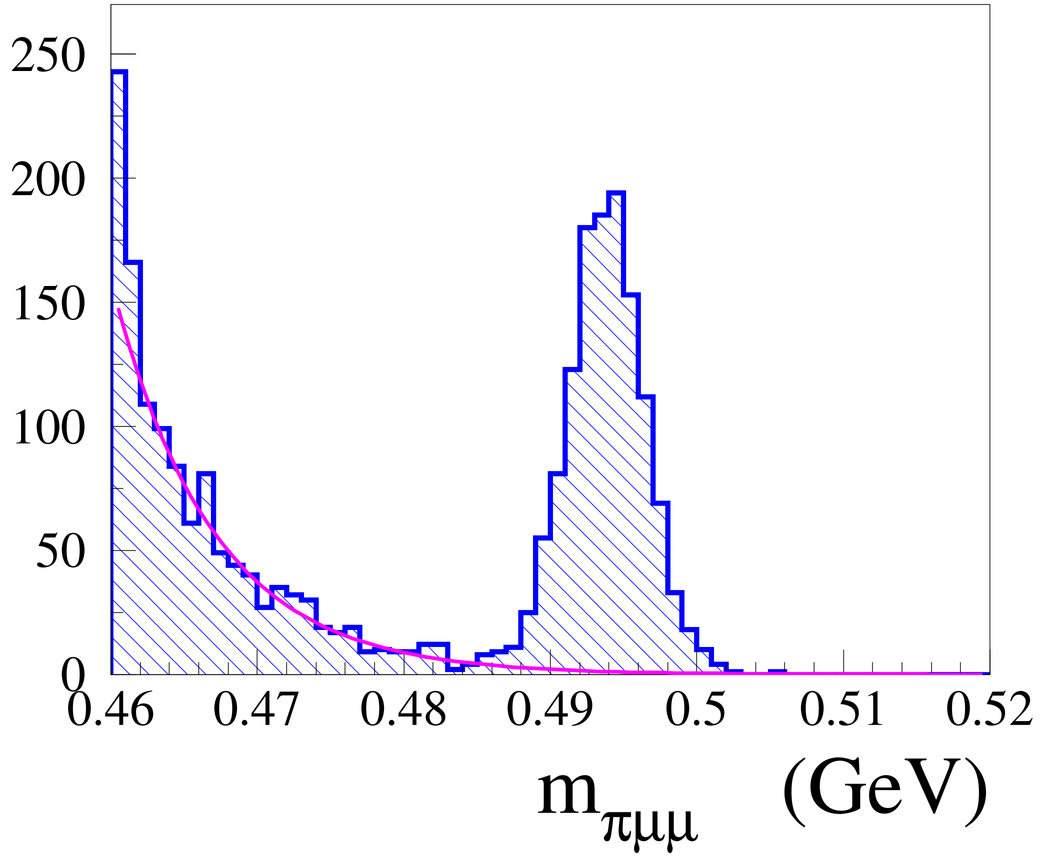
Measurement of $K^{\pm} \to \pi^{\pm} e^{+} e^{-}$

- **Form Factor:**



- **Status and Prospects:**
  - Statistical error on branching fraction $\Delta\mathrm{Br} \leq \pm 0.05 \times 10^{-7}$.
    (For 2003 data only. Total PDG error now is $\pm 0.13 \times 10^{-7}$)
  - Systematics will be small.
  - Analysis far advanced.

Measurement of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$



- Event sample of $> 10^3\ K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ candidates (SS 1–3).
  (Current world sample: 800 events)
- Again: Very small background.

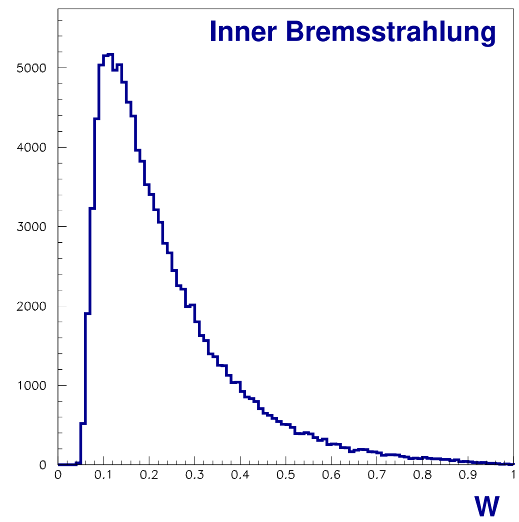
Measurement of $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$

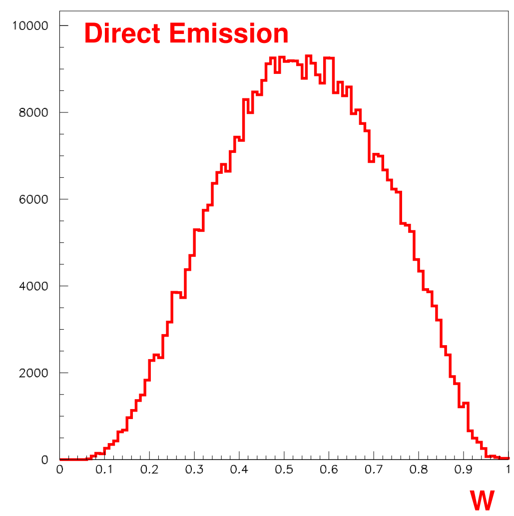
- **Two amplitudes:**

  Inner Bremsstrahlung (IB) and Direct Emission (DE).

$$\Gamma \sim \underbrace{\frac{p_\pi^2 \sin^2\theta}{(m_K/2-\omega_0)^2}}_{\text{Inner Bremsstrahlung}} \left[1 + \underbrace{2\,\frac{m_\pi^2}{m_K^2}\,W^2 |E| \cos(\theta \pm \delta)}_{\text{Interference}} + \underbrace{\frac{m_\pi^4}{m_K^4}\,W^4\,(|E|^2 + |M|^2)}_{\text{Direct Emission}} \right]$$

- Variable $W^2 \;\propto\; (p_K q_\gamma)(p_\pi q_\gamma) \;\propto\; E_\gamma^{\star\,2}\,(E_\pi^\star - p_\pi^\star \cos\theta)$:





Measurement of $K^\pm \to \pi^\pm \pi^0 \gamma$

- <u>Previous best measurement:</u> (E787, 2×10^4 events)

  Inner Bremsstrahlung (IB): $\mathrm{Br} = (2.75 \pm 0.15) \times 10^{-4}$
  Direct Emission (DE): $\mathrm{Br} = (4.7 \pm 0.9) \times 10^{-6}$
  Interference term has never been measured.

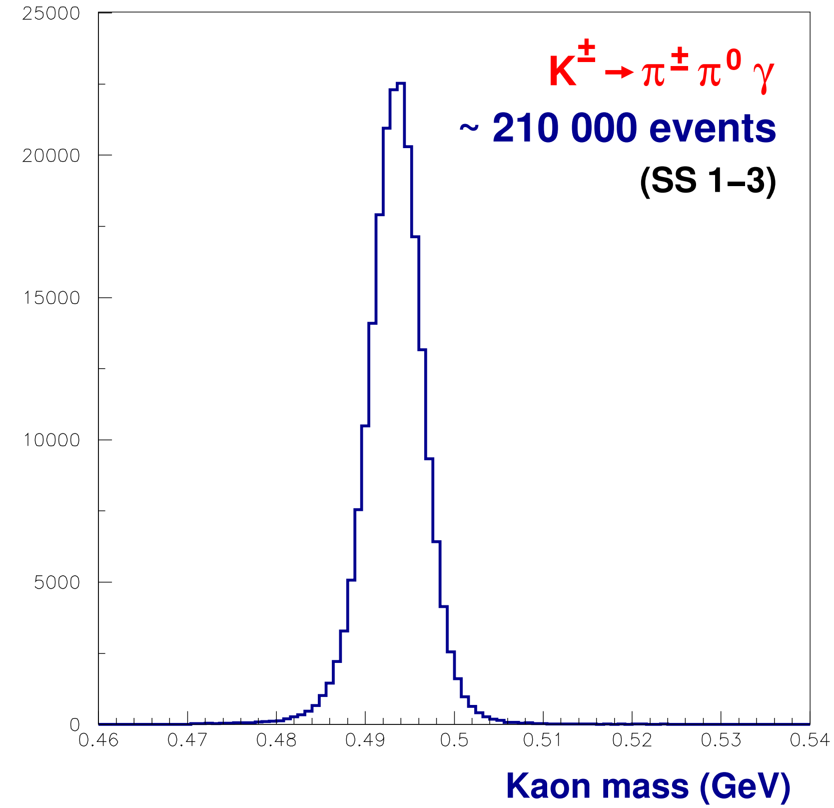
- **<u>NA48/2 2003 data:</u>** (SS 1–3)

  More than **200 000 events.**

  Backgrounds $< 1\%$ (tight cuts).

- Measurements of branching fraction and direct emission component underway.

  $\Longrightarrow$ Expect preliminary result soon.



Measurement of $K^{\pm} \to \pi^{\pm}\gamma\gamma$

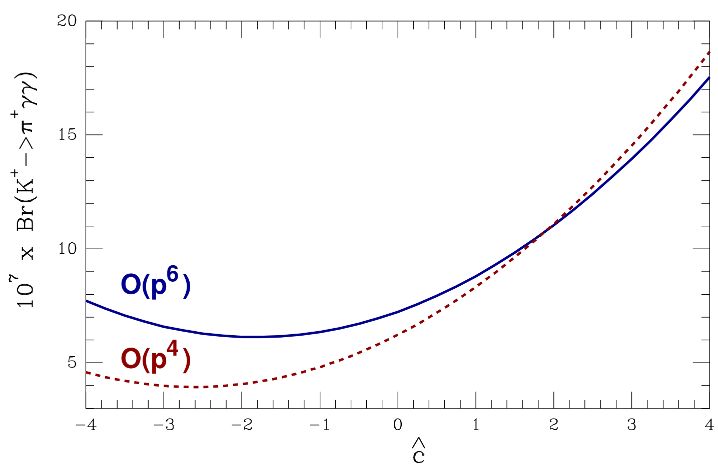
$\boldsymbol{K^{\pm} \to \pi^{\pm}\gamma\gamma}$**:** Similar situation as for $K_L \to \pi^0\gamma\gamma$:

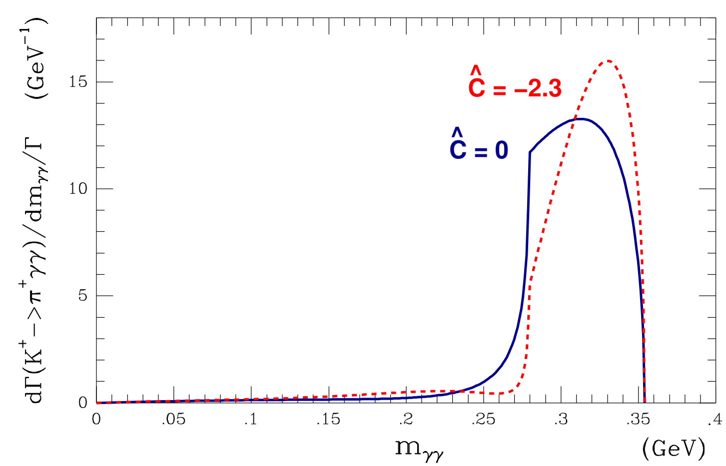
- $\mathcal{O}(p^2)$ ChPT amplitude vanishes.
- $\mathcal{O}(p^4)$ as function of χPT parameter $\hat{c}$: (Ecker, Pich, de Rafael, 1988)

$$\Gamma = (\underbrace{2.80 + 0.87\,\hat{c} + 0.14\,\hat{c}^2}_{\text{Loop}} + \underbrace{0.23}_{\text{Wess-Zumino}}) \times 10^{-23}\ \text{GeV}$$

- $\mathcal{O}(p^6)$ may have contribute by 30–40%. (D'Ambrosio, Portoles, 1996)

Fit of $m_{\gamma\gamma}$ distribution $\Longrightarrow$ Information on $\mathcal{O}(p^6)$!





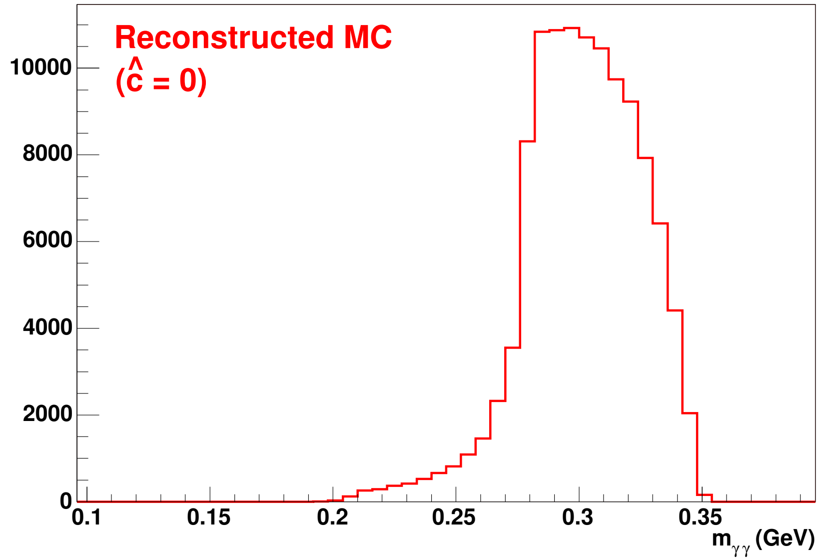
Measurement of $K^{\pm} \to \pi^{\pm}\gamma\gamma$

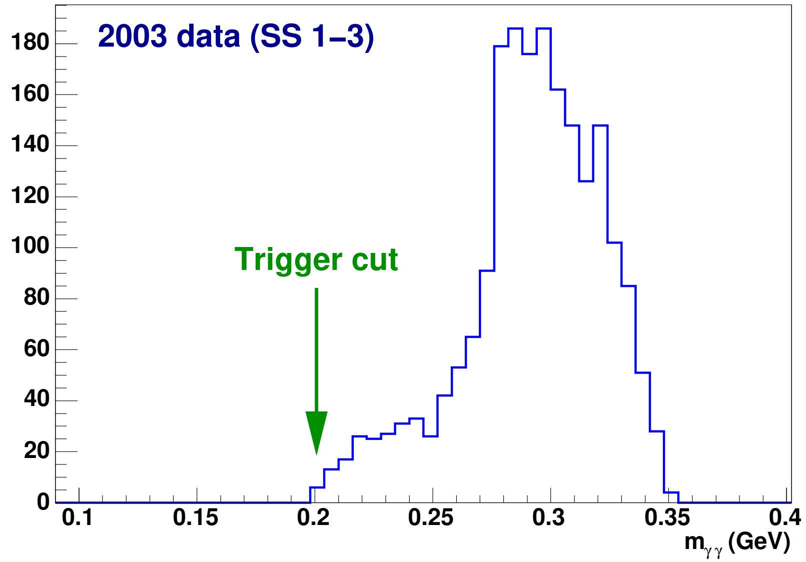
- Experimental problem:

  Low-$m_{\gamma\gamma}$ events suppressed at trigger level.

- For $m_{\gamma\gamma} > 0.2$ GeV/c^2: More than **2000 events** in SS 1–3.

  (Compare with 31 events of E787!)





$\Longrightarrow$ Promising — but still a lot of work to do!

Rare K_L and K_S Decays

Measurements of $K_L \to \pi\pi$ Decays

- **Motivation 1:** Determine $\Gamma(K_\mathsf{L} \to 3\pi^0)/\Gamma(K_{e3})$

  (Large discrepancies in previous measurements $\to$ Error on $|V_{us}|$)

  - Measure $\boxed{\Gamma(K_\mathsf{L} \to 2\pi^0)/\Gamma(K_\mathsf{L} \to 3\pi^0)}$
  - Measure $\boxed{\Gamma(K_\mathsf{L} \to \pi^+\pi^-)/\Gamma(K_{e3})}$
  - Use $\frac{\Gamma(K_\mathsf{L}\to\pi^+\pi^-)}{\Gamma(K_\mathsf{S}\to\pi^+\pi^-)} / \frac{\Gamma(K_\mathsf{L}\to\pi^0\pi^0)}{\Gamma(K_\mathsf{S}\to\pi^0\pi^0)} = 1 - 6 \times \mathrm{Re}(\epsilon'/\epsilon)$

    $\Longrightarrow$ NA48, KTeV (2003)
  - Use $\Gamma(K_\mathsf{S} \to \pi^+\pi^-)/\Gamma(K_\mathsf{S} \to \pi^0\pi^0) = 2.236 \pm 0.015$

    $\Longrightarrow$ KLOE (2002)

  $\Longrightarrow$ Indirectly measured: $\boxed{\Gamma(K_\mathsf{L} \to 3\pi^0)/\Gamma(K_{e3})}$

- **Motivation 2:**

  New KTeV result on $K_\mathsf{L} \to \pi^+\pi^-$ disagrees with world average:

  KTeV: $|\eta_{+-}| = (2.228 \pm 0.010) \times 10^{-3}$

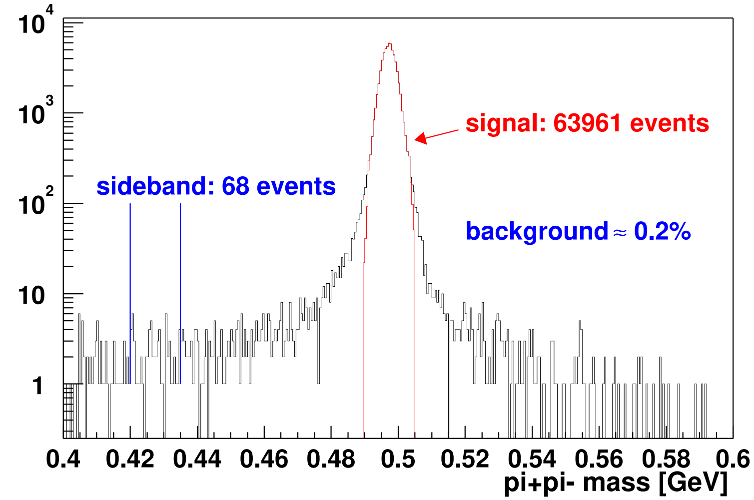
  PDG 2004: $|\eta_{+-}| = (2.288 \pm 0.014) \times 10^{-3}$

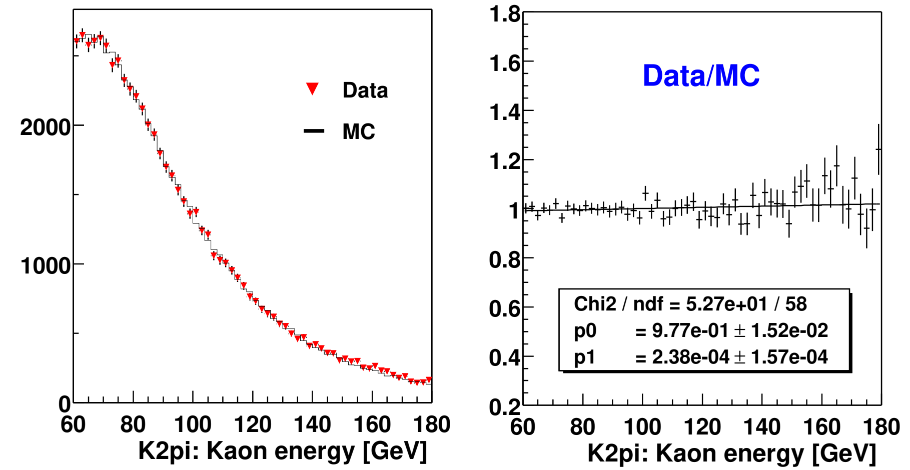
  $\Longrightarrow$ **$3.5\,\sigma$ difference.**

Measurements of $K_L \to \pi\pi$ Decays

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

- More than **60 000 events** in minimum bias run 99. (Same as used for K_{e3}.)
- Background tiny ($< 0.2\%$).
- Stat. error $\sigma_{\mathrm{Br}}/\mathrm{Br} \approx 0.4\%$, systematics under study.





$K_L \to \pi^0\pi^0$:

- Run 2000 with no DCH's. (Same as for $K_L \to \gamma\gamma$.)
- Expect $> 10^6$ events.

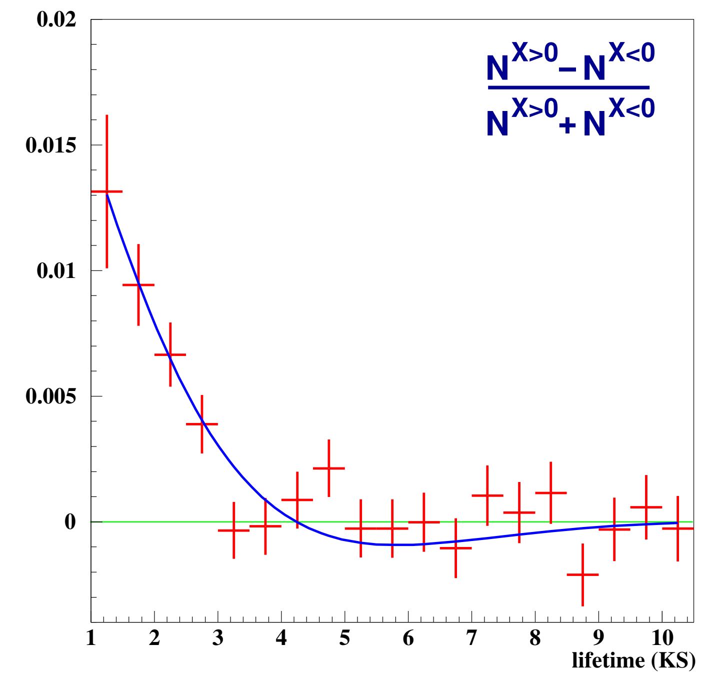
Measurement of $\mathrm{Br}(\mathrm{K_S} \to \pi^+\pi^-\pi^0)$

- CP-allowed $K_S \to \pi^+\pi^-\pi^0$ amplitude suppressed by internal angular momentum of $l = 1$.
- Extraction by using asymmetry in Dalitz plot variable $X = (s_{\pi^-} - s_{\pi^+})/m^2_{\pi^+}$ $\Longrightarrow$ Parameter $\boldsymbol{\lambda}$
- Measure $\frac{N^{X>0} - N^{X<0}}{N^{X>0} + N^{X<0}}(t)$

$$\approx D(E)\,[\,\mathrm{Re}(2\lambda)\cos(\Delta m t) + \mathrm{Im}(2\lambda)\sin(\Delta m t)\,] \times e^{-\frac{t}{2}\left(\frac{1}{\tau_S} - \frac{1}{\tau_S}\right)}$$

- **NA48/1 (2002):**

  $\approx$ 19 million $K^0 \to \pi^+\pi^-\pi^0$ events.
- Statistical uncertainties of $\sigma_{\mathrm{Re}(\lambda)} \approx \pm 0.013$, $\sigma_{\mathrm{Im}(\lambda)} \approx \pm 0.010$ competitive to previous experiments.
- Analysis finished, publication soon.



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

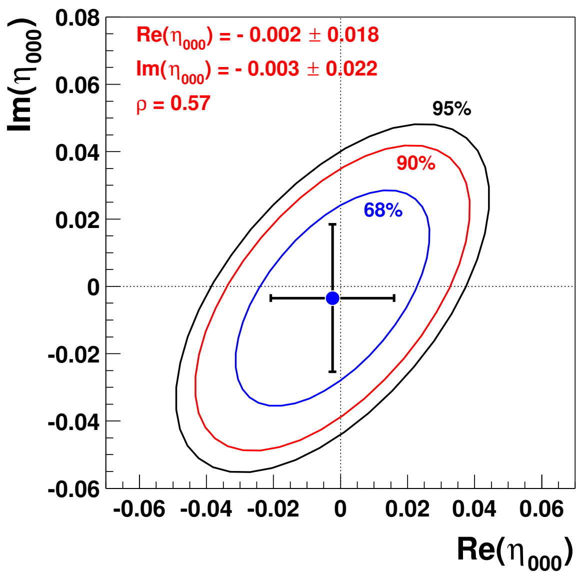
NA48 result:

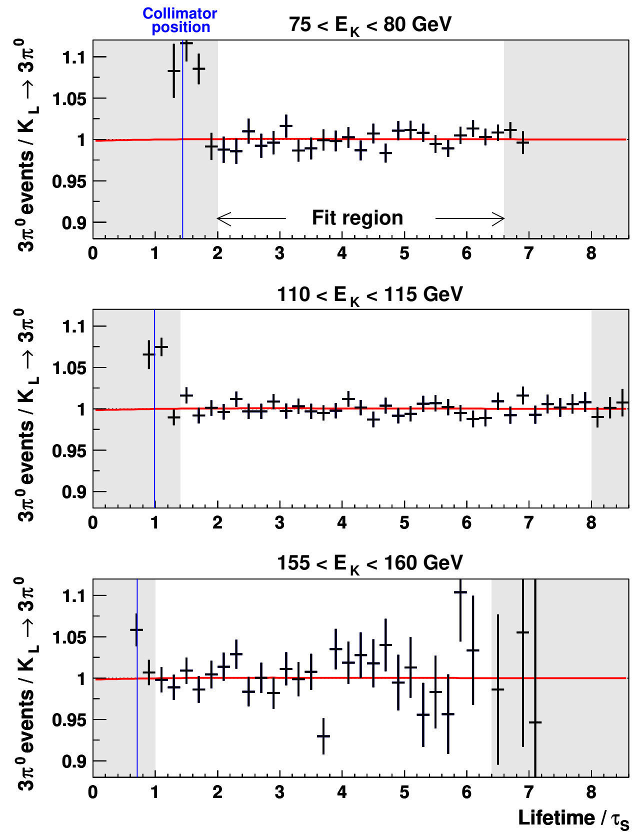
$$\mathrm{Re}(\eta_{000}) = -0.002 \pm 0.011_{\mathrm{stat}} \pm 0.015_{\mathrm{sys}}$$
$$\mathrm{Im}(\eta_{000}) = -0.003 \pm 0.013_{\mathrm{stat}} \pm 0.017_{\mathrm{sys}}$$

(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):

$$\mathrm{Im}(\eta_{000}) = 0.000 \pm 0.009_{\mathrm{stat}} \pm 0.013_{\mathrm{sys}}$$





Branching ratio:

$$\mathrm{Br}(K_S \to 3\pi^0) < 7.4 \times 10^{-7} \quad 90\% \text{ CL}$$

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

($\mathrm{Br}(K_S \to 3\pi^0)|_{CPT} < 2.3 \times 10^{-7}$ 90% CL)

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

Bell-Steinberger relation:

Connects CPT violating phase δ with η parameters via unitarity:

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

Largest contributions:

α_f		$10^3 \times \mathrm{Re}(\alpha_f)$	$10^3 \times \mathrm{Im}(\alpha_f)$
α_{+-}	$= \eta_{+-}\,\mathrm{Br}(\mathrm{K_S} \to \pi^+\pi^-)$	1.146 ± 0.015	1.084 ± 0.016
α_{00}	$= \eta_{00}\,\mathrm{Br}(\mathrm{K_S} \to \pi^0\pi^0)$	0.511 ± 0.008	0.488 ± 0.008
$\alpha_{+-\gamma}$	$= \eta_{+-\gamma}\,\mathrm{Br}(\mathrm{K_S} \to \pi^+\pi^-\gamma)$	0.003 ± 0.000	0.003 ± 0.000
α_{l3}		-0.001 ± 0.007	0.005 ± 0.006
α_{+-0}	$= \frac{\tau_S}{\tau_L}\,\eta^\star_{+-0}\,\mathrm{Br}(\mathrm{K_L} \to \pi^+\pi^-\pi^0)$	0.000 ± 0.002	0.000 ± 0.002
α_{000}	$= \frac{\tau_S}{\tau_L}\,\eta^\star_{000}\,\mathrm{Br}(\mathrm{K_L} \to 3\pi^0)$	0.029 ± 0.040	-0.026 ± 0.058

NA48: $\alpha_{000} = (\,-0.001 \pm 0.007\,) + i\,(0.001 \pm 0.008\,) \times 10^{-3}$

$\Longrightarrow$ $\mathrm{Im}(\delta) = (-0.2 \pm 2.0) \times 10^{-5}$ (was $(2.4 \pm 5.0) \times 10^{-5}$)

$\Longrightarrow$ $m_{K^0} - m_{\overline{K^0}} = (-0.2 \pm 2.8) \times 10^{-19}$ GeV

Conclusions

- **Rare $K^{\pm}$ decays:**

  All measurements with large statistics and low systematics.

  Lots of on-going work:

  - High precision measurement of K^{+}_{e4}.
  - Branching fraction and form factors of $K^{\pm} \rightarrow \pi^{\pm} e^{+} e^{-}$ and $K^{\pm} \rightarrow \pi^{\pm} \mu^{+} \mu^{-}$.
  - Advanced analysis on $K^{+} \rightarrow \pi^{+} \pi^{0} \gamma$.
  - Work on $K^{+} \rightarrow \pi^{+} \gamma\gamma$.

- **$K_{\mathrm{L,S}}$ decays:**

  - Precise measurements of $K_{\mathrm{L}} \rightarrow \pi\pi \quad \rightarrow \quad \eta_{+-}, \eta_{00}$ soon.
  - Measurements of $K_{\mathrm{S}} \rightarrow \pi^{+}\pi^{-}\pi^{0}$ and $K_{\mathrm{S}} \rightarrow 3\pi^{0}$.