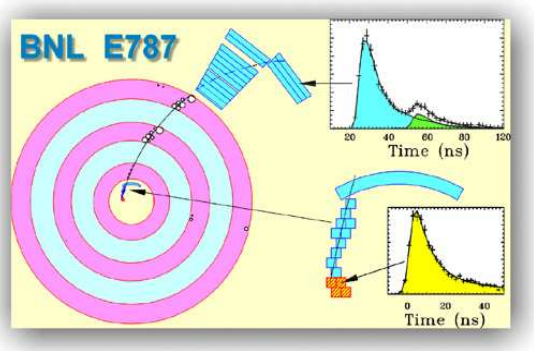

III Workshop on Physics and Detectors
for DAΦNE
INFN
Frascati, Italy
November 16–19, 1999

Experimental results: radiative and non-leptonic Kaon Decays

- Overview
- $K_{\pi 2\gamma}$ ($K_{\pi 2\gamma^\star}$)
- $K_{\pi\gamma\gamma}$ ($K_{\pi\gamma^\star}$, $K_{\pi\gamma^\star\gamma^\star}$, $K_{\pi\gamma^\star\gamma}$)
- $K_{\gamma\gamma}$ ($K_{\gamma^\star\gamma^\star}$, $K_{\gamma^\star\gamma}$, $K_{\gamma^\star\gamma\gamma}$)
- $K_{\ell 2\gamma}$ ($K_{\ell 2\gamma^\star}$)
- $K_{\pi 3\gamma}$, $K_{\ell 3\gamma}$, $K_{e4\gamma}$

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Overview

- Why study radiative and non-leptonic kaon decay modes?
  - They are a testing ground for ChPT.
  - They provide input for determining long distance contribution to other modes (e.g. $K_L^\circ \to \mu^+\mu^-$: $K_L^\circ \to e^+e^-\gamma$, $K_L^\circ \to \mu^+\mu^-e^+e^-$,...; $K_L^\circ \to \pi^\circ e^+e^-$: $K_L^\circ \to \pi^\circ\gamma\gamma$)
  - Some are backgrounds to other decays of interest and need to be measured (e.g. $K_L^\circ \to \pi^\circ e^+e^-$: $K_L^\circ \to e^+e^-\gamma\gamma$; $K_L^\circ \to \pi^\circ\mu^+\mu$: $K_L^\circ \to \mu^+\mu^-\gamma\gamma$)
- How does ChPT provide insight to radiative K decays? (see G.C. talk)
  - An approach to solve the non-perturbative $K - \pi$ calculation.
  - An effective low energy field theory in terms of meson fields.
  - Expressed in powers of derivatives or (p^2).
  - Provides a framework for classifying decays and their relations.
  - Some remarkable successes; some problems.

Current experiments

- **Experiments**
  - BNL
    - E871: (1995–6) completed. ($K_L^\circ \to \mu e$)
    - E865: (1995–8) data collection complete, analysis ongoing. ($K^+ \to \pi^+ \mu e$)
    - E787: (1995–8) data collection complete, analysis ongoing. ($K^+ \to \pi^+ \nu\overline{\nu}$)
  - FNAL
    - KTeV: (1996–7,99–2000) will finish data collection in 2000, most results are from 1996 data ($\sim$10% of 1997). The 1999 data set will be $\sim 3\times$ larger than 1996–7. (ϵ')
  - CERN
    - NA48: (1997–$\sim$>2000) results from 1997 (and 1995), 1997 is $\sim$30% of 1998 and $\sim$10% of the total expected. (ϵ')

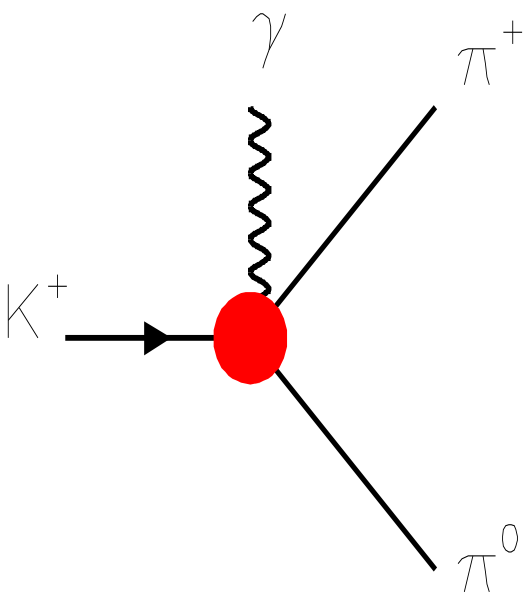
$\mathbf{K}_{\pi 2\gamma}$ $(\mathbf{K}_{\pi 2\gamma^\star})$

- $\mathbf{K}_{\pi 2\gamma}$
  - $K^+ \longrightarrow \pi^+\pi^\circ\gamma$ $BR(DE) = (4.72 \pm 0.77) \times 10^{-6}$ E787 [KAON99]
  - $K_L^\circ \longrightarrow \pi^+\pi^-\gamma$ $BR(DE) = (3.70 \pm 0.10) \times 10^{-5}$ KTeV [PANIC99]
  - $K_L^\circ \longrightarrow \pi^\circ\pi^\circ\gamma$ $BR < 5.6 \times 10^{-6}$ NA31 [PL**B328**(94)528]
  - $K_S^\circ \longrightarrow \pi^+\pi^-\gamma$ $BR = (1.78 \pm 0.05) \times 10^{-3}$ E731 [PRL**70**(93)2525]
- $\mathbf{K}_{\pi 2\gamma^\star}$
  - $K_L^\circ \longrightarrow \pi^+\pi^-e^+e^-$ $BR = (3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$ KTeV [EPS-HEP99]

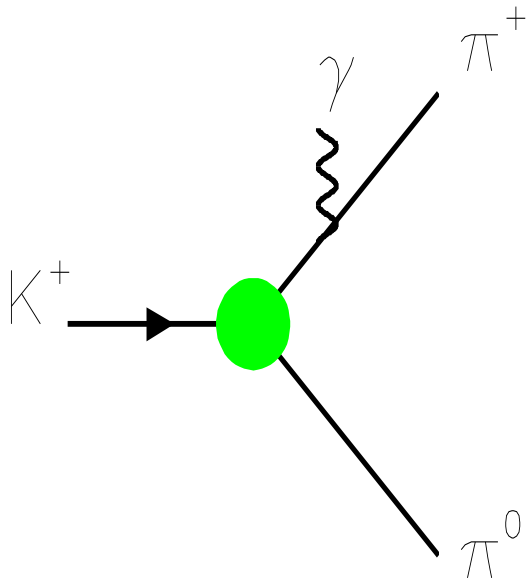
$K \longrightarrow \pi\pi\gamma$

- New results on $K^+ \to \pi^+\pi^\circ\gamma$ and $K_L^\circ \to \pi^+\pi^-\gamma$.
- $K_S^\circ \to \pi^+\pi^-\gamma$ dominated by IB, $K^+ \to \pi^+\pi^\circ\gamma$ mostly IB, $K_L^\circ \to \pi^+\pi^-\gamma$ DE $\sim \times 2$ IB.
- $K_L^\circ \to \pi^+\pi^-\gamma$ has a ρ-propagator-like form factor.
- B($K^+ \to \pi^+\pi^\circ\gamma$; DE) New measurement is very different from previous value.
- The rates of DE for $K^+ \to \pi^+\pi^\circ\gamma$ and $K_L^\circ \to \pi^+\pi^-\gamma$ are roughly equal.

mode	K^+	K_L°	K_S°
τ (ns)	12.386 ± 0.024	51.7 ± 0.4	0.08934 ± 0.00008
Γ_{total} (s^{-1})	8.08×10^7	1.93×10^7	1.12×10^{10}
$\frac{\Gamma(\pi\pi\gamma)_{IB}}{\Gamma(\pi\pi)}$	2.16×10^{-3}	7.03×10^{-3}	7.10×10^{-3}
$\Gamma(\pi\pi\gamma)_{DE}$ (s^{-1})	808 ± 132	617 ± 18	-



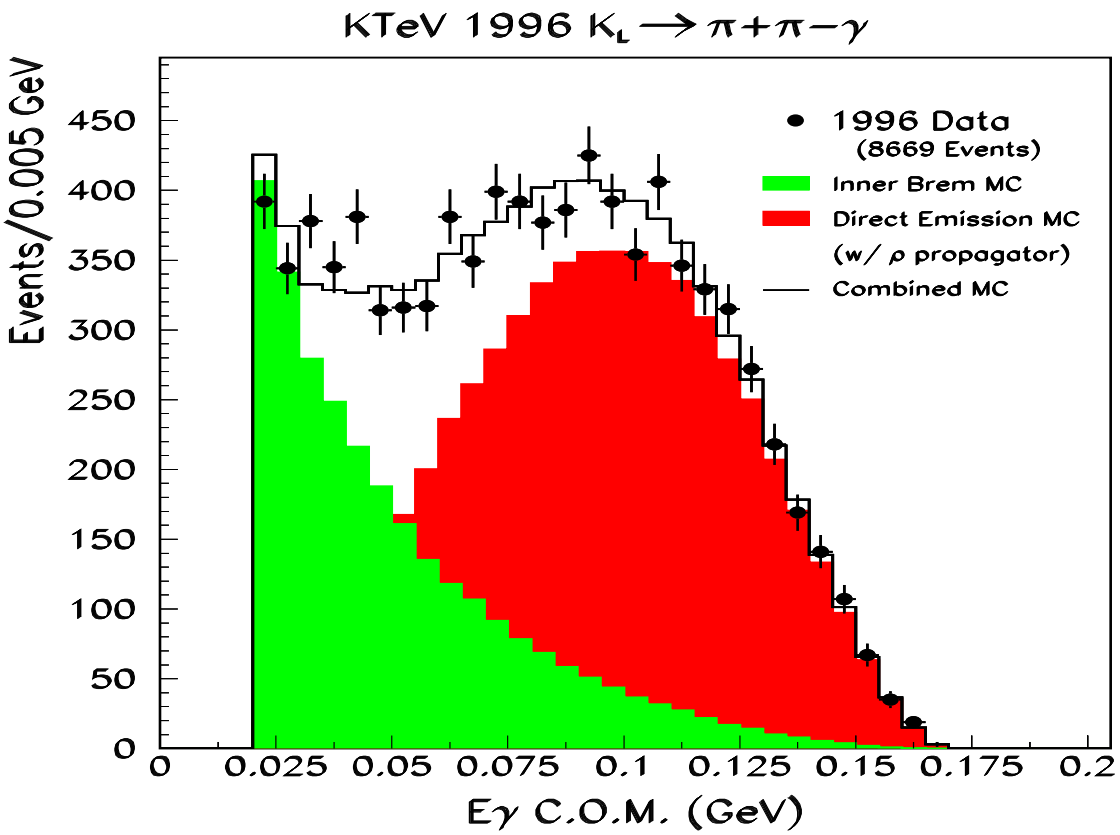
Direct Emission (DE)



Inner Bremsstrahlung (IB)

$K_L^\circ \to \pi^+\pi^-\gamma$

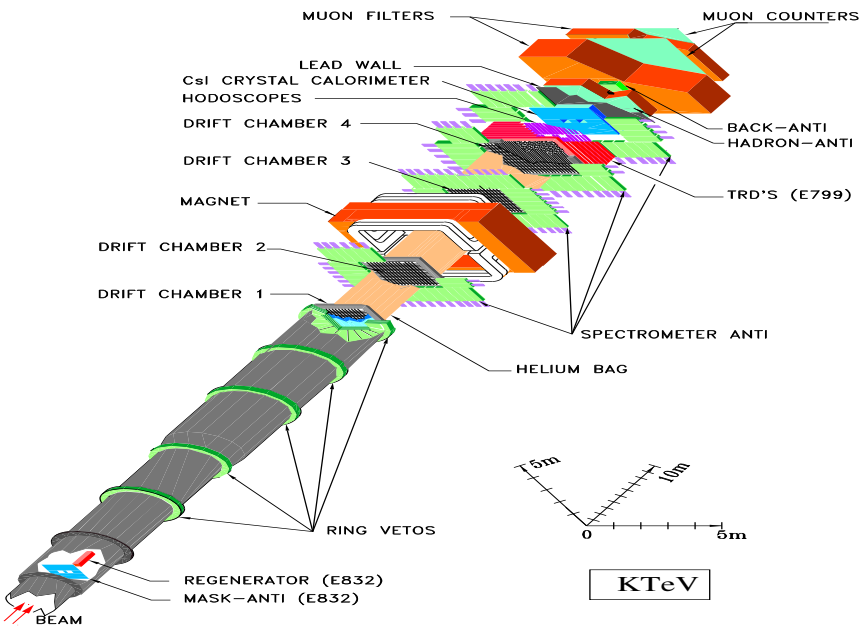
- Measurement of BR($K_L^\circ \to \pi^+\pi^-\gamma$)



  - 1996 KTeV data (∼10% of 1996–7 data)
  - Fit to MC IB and ρ-propagator $\mathcal{F} = \frac{a_1}{(m_\rho^2 - m_K^2) + 2m_K E_\gamma^*} + a_2$
  - ∼8700 events
  - BR($K_L^\circ \to \pi^+\pi^-\gamma$ DE) $= (3.70 \pm 0.10) \times 10^{-5} (E_\gamma^\star > 20\text{MeV})$
  - DE/(DE+IB) $= 0.685 \pm 0.009 \pm 0.017$

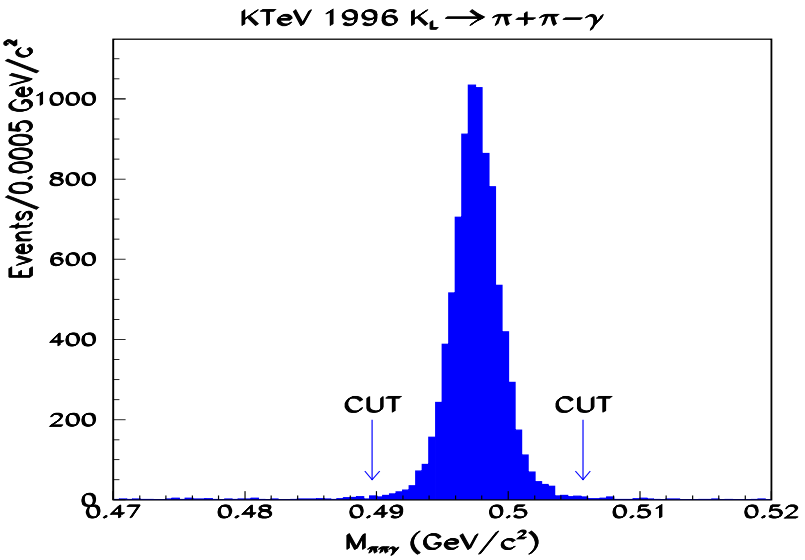
$K_L^\circ \to \pi^+\pi^-\gamma$

- KTeV Detector



  - Two good tracks, not $e^\pm$, good vertex, within fiducial volume, no veto hits.
  - One additional cluster (E > 1.5 GeV, $E^\star_\gamma > 20$ MeV), >20 cm from pion clusters.
  - "Missing π°" has imaginary momentum
    $P^2_{\pi^0} \equiv \frac{(M_K^2 - M_{\pi^0}^2 - M_{\pi\pi}^2)^2 - 4M_{\pi^0}^2 M_{\pi\pi}^2 - 4M_K^2 (P_T^2)_{\pi\pi}}{4((P_T^2)_{\pi\pi} + M_{\pi\pi}^2)} < -0.0055$ GeV^2

- $K_L^\circ \to \pi^+\pi^-\gamma$ signal



- Background ∼0.5%.

$K^+ \to \pi^+\pi^\circ\gamma$

- $W^2 \equiv (p \cdot q)/m^2_{K^+} \times (p_+ \cdot q)/m^2_{\pi^+}$
  $\equiv E^2_\gamma \times (E_{\pi^+} - P_{\pi^+} \times \cos\theta_{\pi^+\gamma})/(m^2_{K^+} \times m^2_{\pi^+})$
  $dB.R./dW = dB.R.(IB)/dW \times (1 + [INT] \times W^2 + [DE] \times W^4)$
- Measurement of BR($K^+ \to \pi^+\pi^\circ\gamma$) from E787 (1995)

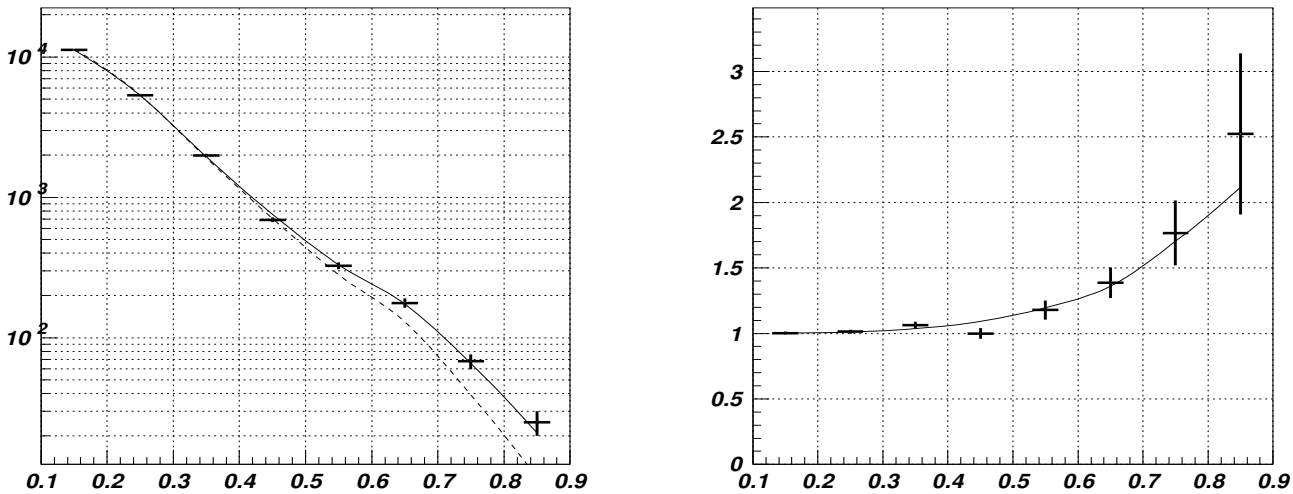
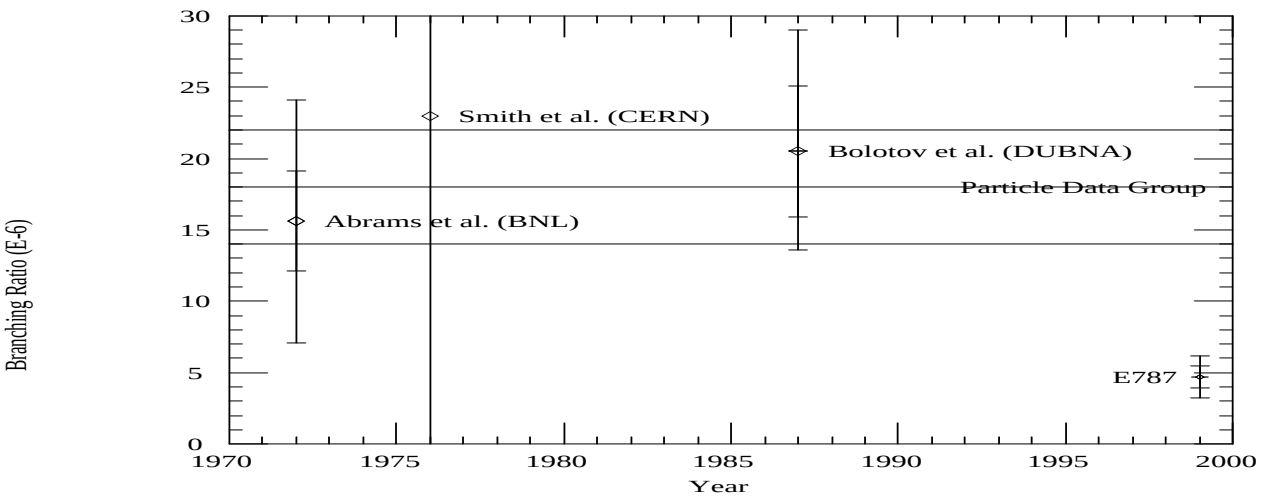


Figure 1: (left) W spectrum of the signal events and best fits to IB+DE [solid curve] and IB alone [dashed curve]; (right) W spectrum normalized to the IB spectrum.

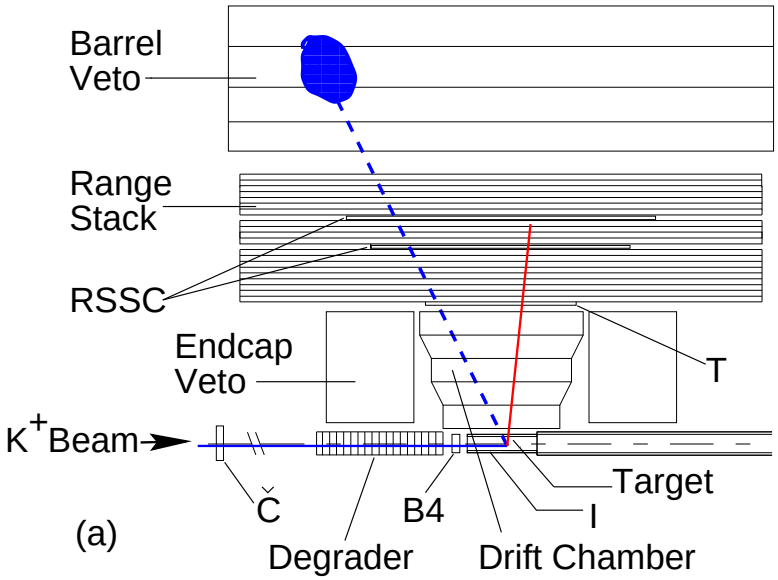
- 19,836 $K^+ \to \pi^+\pi^\circ\gamma$ Events
- BR($K^+ \to \pi^+\pi^\circ\gamma$; DE) $= (4.72 \pm 0.77) \times 10^{-6} (55 < T_{\pi^+} < 90\text{MeV})$
- BR $\times 4$ smaller than previous measurement ($\times 8$ more statistics)

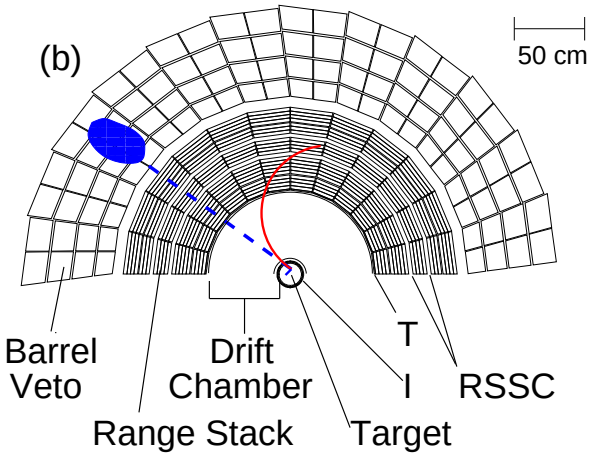


- $INT/(IB + DE + INT) = (-0.4 \pm 1.6)\%$
- $DE/IB = (1.85 \pm 0.30)\%$

$K^+ \to \pi^+ \pi^\circ \gamma$

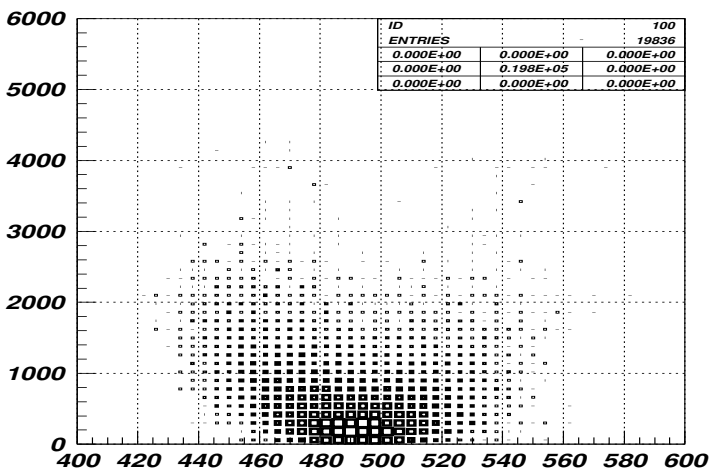
- E787 spectrometer





(π° went to the other hemisphere)

- 3 γ clusters in Barrel, short range π^+ in range stack
- Decay at rest.
- Very good kinematics $\longrightarrow$ 6 Constraint fit
- Measure 13 variables: energy and direction of 3 γ = 9; P, E of π^+ = 4
- $K^+ \to \pi^+ \pi^\circ \gamma$: $\mathrm{M_K}$ vs. $\mathrm{P_T^2}$



$\mathbf{K_{\pi\gamma\gamma}}$ ($\mathbf{K_{\pi\gamma^\star}}$,$\mathbf{K_{\pi\gamma^\star\gamma^\star}}$, $\mathbf{K_{\pi\gamma^\star\gamma}}$)

- **$\mathbf{K_{\pi\gamma\gamma}}$**
  - $K^+ \longrightarrow \pi^+\gamma\gamma$ $BR = (6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$ E787 [PRL**79**(97)4079]
    $\hat{c} = 1.8 \pm 0.6$
  - $K_L^\circ \longrightarrow \pi^\circ\gamma\gamma$ $BR = (1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$ KTeV [PRL**83**(99)917]
    $a_v = -0.72 \pm 0.05 \pm 0.06$
  - $K_S^\circ \longrightarrow \pi^\circ\gamma\gamma$ NA48(2000)?
- **$\mathbf{K_{\pi\gamma^\star}}$, $\mathbf{K_{\pi\gamma^\star\gamma^\star}}$**
  (covered by Prof. Lowe)
  - $K_L^\circ \longrightarrow \pi^\circ e^+e^-$ $BR < 5.6 \times 10^{-10}$ KTeV [Moriond99]
  - $K_L^\circ \longrightarrow \pi^\circ \mu^+\mu^-$ $BR < 3.4 \times 10^{-10}$ KTeV [KAON99]
  - $K^+ \longrightarrow \pi^+e^+e^-$ $BR = (2.94 \pm 0.05 \pm 0.13) \times 10^{-7}$ E865 (hep-ex/9907045) $\delta = 2.14 \pm 0.13 \pm 0.15$
  - $K^+ \longrightarrow \pi^+\mu^+\mu^-$ $BR = (9.22 \pm 0.60 \pm 0.49) \times 10^{-8}$ E865 (hep-ex/9910047) $\delta = 2.45^{+1.30}_{-0.95}$
  - $K_S^\circ \longrightarrow \pi^\circ e^+e^-$ $BR < 1.1 \times 10^{-6}$ NA31 [PL**B304**(93)381] NA48(2000)?
- **$\mathbf{K_{\pi\gamma^\star\gamma}}$**
  - $K_L^\circ \longrightarrow \pi^\circ e^+e^-\gamma$ $BR = (2.20 \pm 0.48 \pm 0.11) \times 10^{-8}$ KTeV [DPF99]
  - $K^+ \longrightarrow \pi^+e^+e^-\gamma$ $\sim$30 events E865 [DPF99]

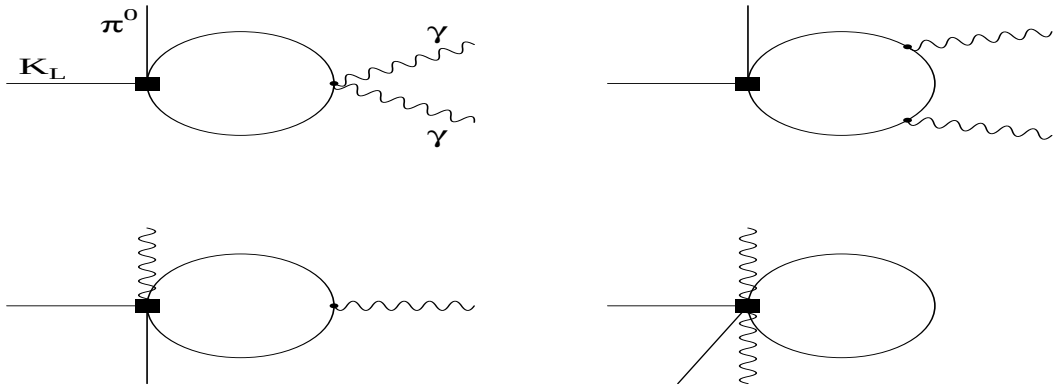
$K \longrightarrow \pi\gamma\gamma$

- New results on $K^+ \to \pi^+\gamma\gamma$ and $K_L^\circ \to \pi^\circ\gamma\gamma$
- Decays proceed through $\pi^\pm$ loops. $M_{\gamma\gamma}$ spectra peak above $M_{2\pi^+}$.
- $\mathcal{O}(p^4)$ ChPT predicts the $K^+ \to \pi^+\gamma\gamma$ rate and spectra with one parameter, $\hat{c} = 1.8 \pm 0.6$
- $\mathcal{O}(p^4)$ ChPT predicts the $K_L^\circ \to \pi^\circ\gamma\gamma$ spectra
- The data from both decays favors unitarity corrections from $K \to \pi\pi^+\pi^-$.
- Small vector meson exchange contribution to $K^+ \to \pi^+\gamma\gamma$, but large contribution to $K_L^\circ \to \pi^\circ\gamma\gamma$.
- The decay rates for $K^+ \to \pi^+\gamma\gamma$ and $K_L^\circ \to \pi^\circ\gamma\gamma$ differ by $\times 3$:

$\Gamma(K_L^\circ \to \pi^\circ\gamma\gamma\ \ ) = (32 \pm 2\ )s^{-1}$
$\Gamma(K^+ \to \pi^+\gamma\gamma\ ) = (89 \pm 26)s^{-1}$

$K_L^\circ \to \pi^\circ\gamma\gamma$

- Feynman diagrams



- $z = (m_{\gamma\gamma}/m_K)^2$, $y = |E_{\gamma 3} - E_{\gamma 4}|/m_K$, a_V = Vector Meson contribution
- Measurement of BR($K_L^\circ \to \pi^\circ\gamma\gamma$)

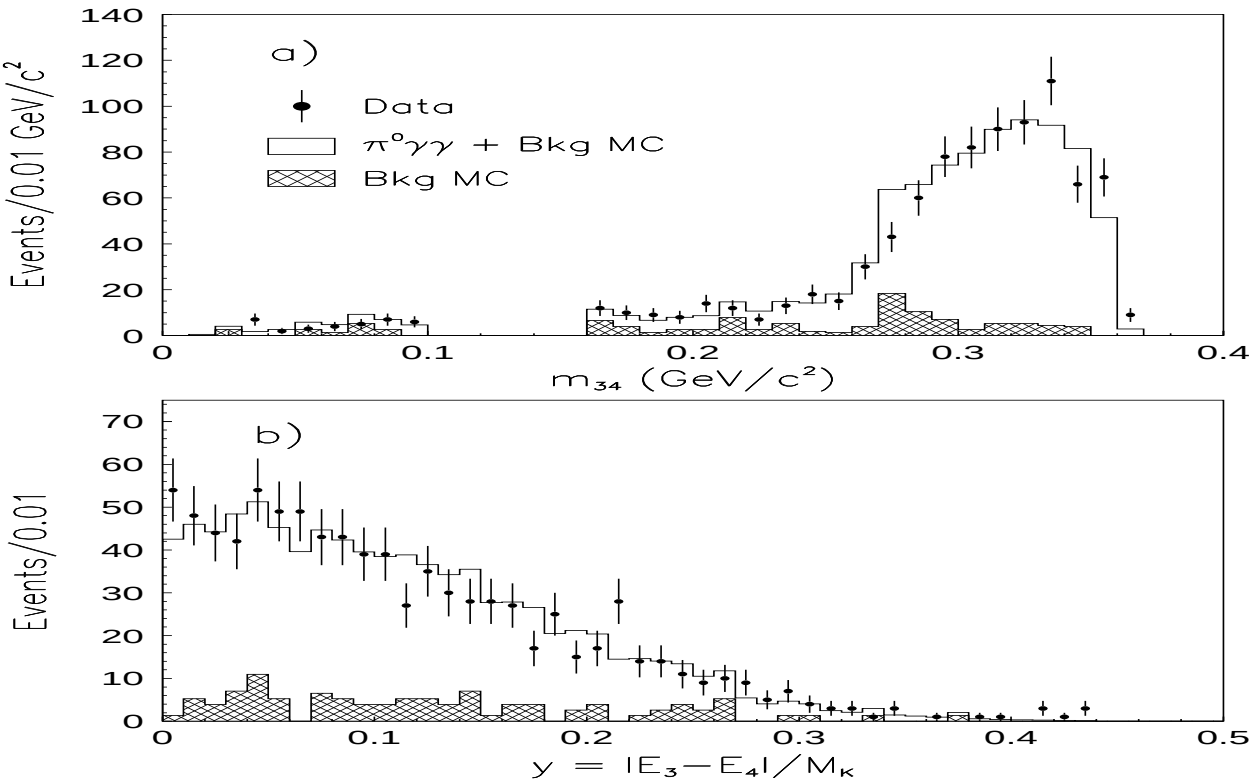
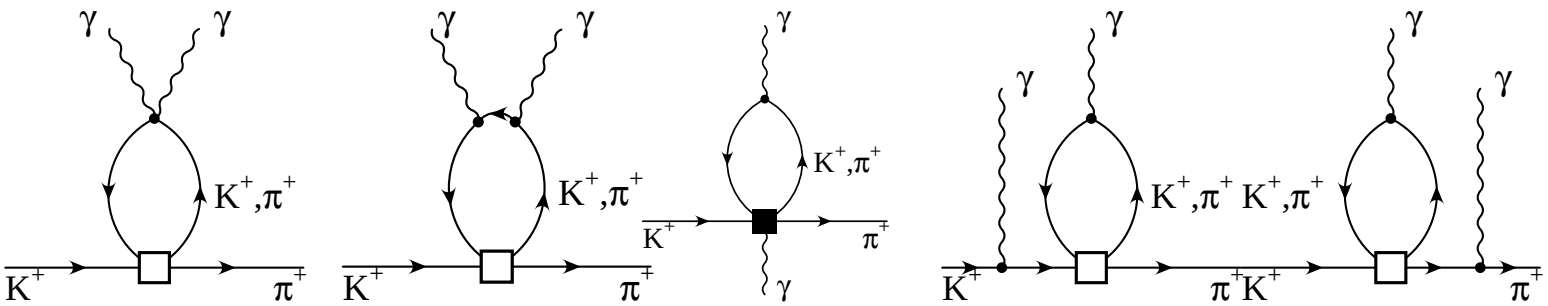


Figure 1: The a) $m_{\gamma\gamma}$ mass distribution and b) the y parameter for $K_L^\circ \to \pi^\circ\gamma\gamma$ candidates events. The dots are the data, the histogram is the sum of the background and $K_L^\circ \to \pi^\circ\gamma\gamma$ Monte Carlo ($\mathcal{O}(p^6)$, with $a_V = -0.7$) and the dashed histogram is the normalized background Monte Carlo.

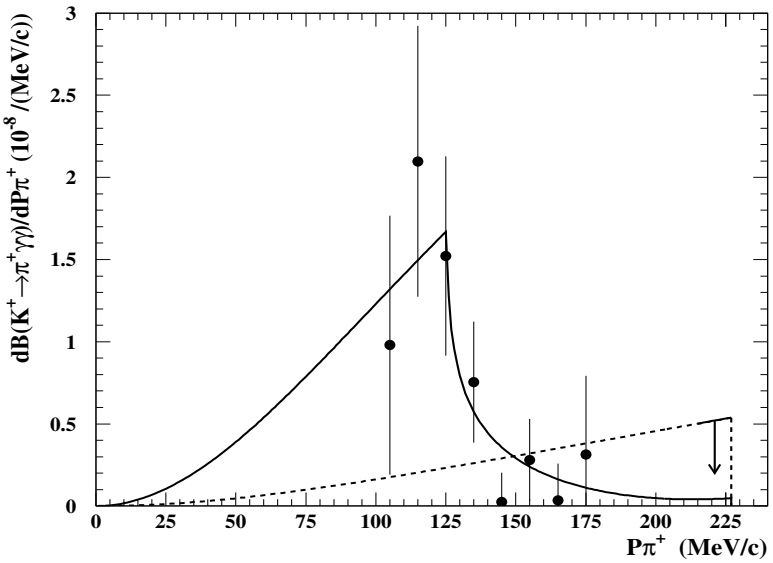
- KTeV 1996–7 data with ∼770 events
- BR($K_L^\circ \to \pi^\circ\gamma\gamma$) $= (1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$
- $a_V = -0.72 \pm 0.05 \pm 0.06$
- A. Alavi-Harati, *et. al.* [PRL**83** (1999) 2128]

$K^+ \to \pi^+\gamma\gamma$

- ChPT (Chiral Perturbation Theory)



- Measurement of BR($K^+ \to \pi^+\gamma\gamma$) from E787 (1991)



  - Measured momentum spectrum and best fit ChPT spectrum
  - Data is not consistent with 'phase space'
  - 31 Events with a background of 5.1 ± 3.3
  - BR($K^+ \to \pi^+\gamma\gamma$) $= (6.0 \pm 1.5 \pm 0.7) \times 10^{-7} (100 < P_{\pi^+} < 180 \text{MeV/c})$
  - ChPT $\to$ Total BR($K^+ \to \pi^+\gamma\gamma$) $= (1.1 \pm 0.3 \pm 0.1) \times 10^{-6}$ and $\hat{c} = 1.8 \pm 0.6$
  - Data favors Unitarity corrections
  - P. Kitching, et. al. [PRL **79** (1997) 4079]

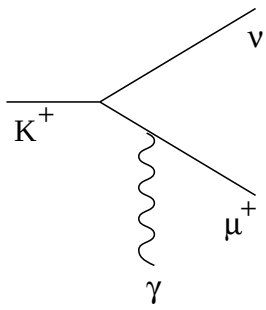
$\mathbf{K_{\gamma\gamma}}$ ($\mathbf{K_{\gamma^\star\gamma^\star}}$, $\mathbf{K_{\gamma^\star\gamma}}$, $\mathbf{K_{\gamma^\star\gamma\gamma}}$)

- **$\mathbf{K_{\gamma\gamma}}$**
  - $K_L^\circ \longrightarrow \gamma\gamma$ $BR = (5.92 \pm 0.15) \times 10^{-4}$ NA31 [PL**B199**(87)139]
  - $K_S^\circ \longrightarrow \gamma\gamma$ $BR = (2.4 \pm 0.9) \times 10^{-6}$ NA31 [PL**B351**(95)579] (NA48–2000?)
- **$\mathbf{K_{\gamma^\star\gamma^\star}}$, $\mathbf{K_{\gamma^\star\gamma}}$**
  - $K_L^\circ \longrightarrow \mu^+\mu^-$ $BR = (7.24 \pm 0.17) \times 10^{-9}$ E871 [KAON99]
  - $K_L^\circ \longrightarrow e^+e^-$ $BR = 8.7^{+5.7}_{-4.1} \times 10^{-12}$ E871 [PRL**81**(98)4309]
  - $K_L^\circ \to e^+e^-\gamma$ $BR = (1.06\pm.02\pm.02\pm.04)\times10^{-5}$ NA48 [PL**B458**(99)553]
    $\alpha_K^\star = -0.36 \pm 0.06 \pm 0.02$ (100k events KTeV-1997)
  - $K_L^\circ \longrightarrow \mu^+\mu^-\gamma$ $BR = ((3.23\pm0.23\pm0.19)\times10^{-7}$ E799 [PRL**74**(95)3323]
    $\alpha_K^\star = -0.028^{+0.115}_{-0.111}$ (6700 events KTeV-1997)
  - $K_L^\circ \longrightarrow e^+e^-e^+e^-$ $BR = (4.14\pm0.27\pm0.31)\times10^{-8}$ KTeV [ICHEP98]
  - $K_L^\circ \longrightarrow e^+e^-\mu^+\mu^-$ $\sim$40 events KTeV [DPF99]
  - $K_L^\circ \longrightarrow \mu^+\mu^-\mu^+\mu^-$ no limit
  - $K_S^\circ \longrightarrow \mu^+\mu^-$ $BR < 3.2 \times 10^{-7}$ CERN [PL**B44**(73)217]
  - $K_S^\circ \longrightarrow e^+e^-$ $BR < 1.4 \times 10^{-7}$ CPLEAR [PL**B413**(97)232]
- **$\mathbf{K_{\gamma^\star\gamma\gamma}}$**
  - $K_L^\circ \longrightarrow e^+e^-\gamma\gamma$ $BR = (6.31 \pm 0.14 \pm 0.42) \times 10^{-7}$ KTeV [Moriond99]
  - $K_L^\circ \longrightarrow \mu^+\mu^-\gamma\gamma$ $BR = (1.42^{+1.02}_{-0.81} \pm 0.14) \times 10^{-9}$ KTeV [KAON99]

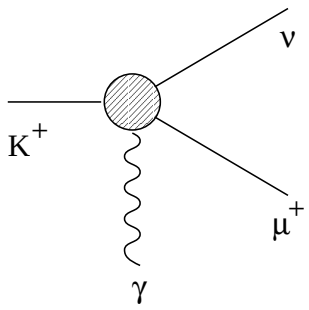
$\mathbf{K}_{\ell 2\gamma}$ ($\mathbf{K}_{\ell 2\gamma^\star}$)

- $\mathbf{K}_{\ell 2\gamma}$
  - $K^+ \longrightarrow \mu^+\nu\gamma$ $BR = (5.50 \pm 0.28) \times 10^{-3}$ KEK [PR**D32**(85)2911]
  - $BR(DE) = (1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$ E787 [DPF96]
    $|F_V + F_A| = 0.165 \pm 0.007 \pm 0.011$
  - $K^+ \longrightarrow e^+\nu\gamma$ $BR(DE) = (1.52 \pm 0.23) \times 10^{-5}$ CERN [NP**B149**(1979)365]
    $|F_V + F_A| = 0.148 \pm 0.010$
- $\mathbf{K}_{\ell 2\gamma^\star}$
  - $K^+ \longrightarrow \mu^+\nu\mu^+\mu^-$ $BR < 4.1 \times 10^{-7}$ E787 [PR**D58**(89)58]
  - $K^+ \longrightarrow e^+\nu\mu^+\mu^-$ $BR < 5.0 \times 10^{-7}$ E787 [PRL**63**(98)2177]
  - $K^+ \longrightarrow \mu^+\nu e^+e^-$ $\sim$1500 events E865 [KAON99]
  - $K^+ \longrightarrow e^+\nu e^+e^-$ $\sim$400 events E865 [KAON99]

$K^+ \longrightarrow \mu^+\nu_\mu\gamma$ and $K^+ \longrightarrow \ell^+\nu_\ell\ell'^+\ell'^-$



IB

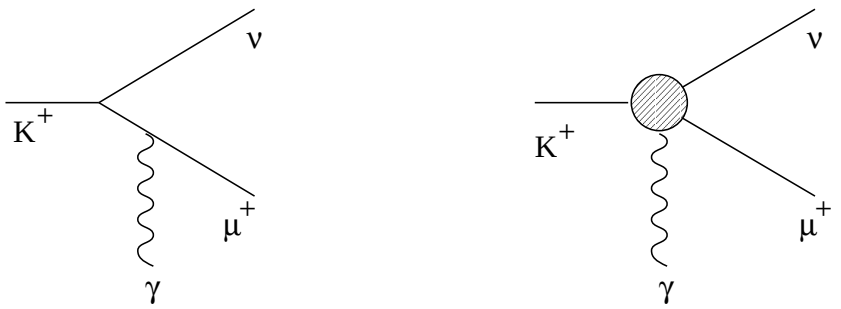


SD

- Real γ or e^+e^-, $\mu^+\mu^-$ pair
- For γ, decay is described by F_V and F_A
- For lepton pair, we also need R
- χPT predicts F_V, F_A, R

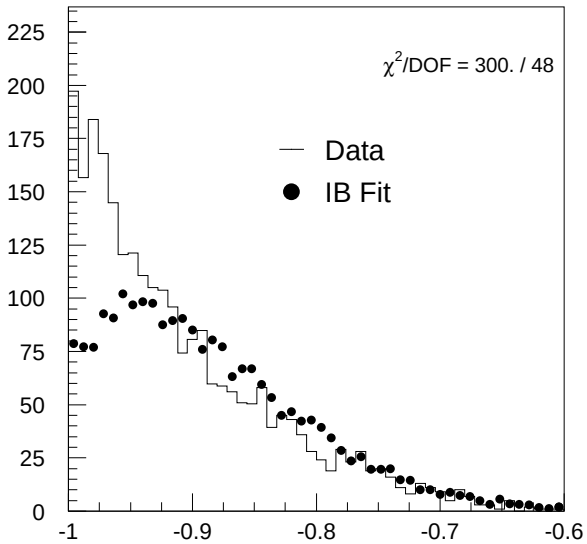
mode	ChPT $\mathcal{O}(p^4)$	Experiment
$K^+ \longrightarrow \mu^+\nu_\mu\gamma(\mathrm{SD}^+)$	9.2×10^{-6}	$(1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$
$K^+ \longrightarrow e^+\nu_e\gamma(\mathrm{SD}^+)$	1.3×10^{-5}	$(1.52 \pm 0.23) \times 10^{-5}$
$K^+ \longrightarrow \mu^+\nu_\mu\mu^+\mu^-$	1.3×10^{-8}	$< 4.1 \times 10^{-7}$
$K^+ \longrightarrow e^+\nu_e\mu^+\mu^-$	1.1×10^{-8}	$< 5.0 \times 10^{-7}$
$K^+ \longrightarrow \mu^+\nu_\mu e^+e^-$	8×10^{-8}	$(1.3 \pm 0.4) \times 10^{-7}$
$K^+ \longrightarrow e^+\nu_e e^+e^-$	3×10^{-8}	$(3.0^{+3.0}_{-1.5}) \times 10^{-8}$

$K^+ \to \mu^+ \nu_\mu \gamma$ (SD+)

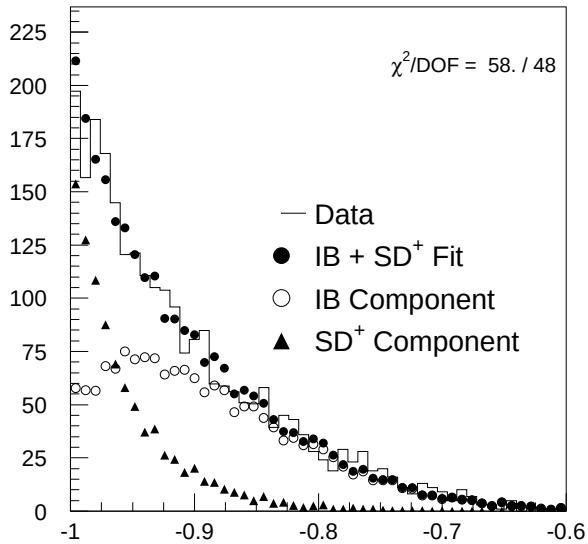


IB SD

- Inner Bremsstrahlung well described by QED and well measured
- BR(SD^+) $\propto (F_V + F_A)^2$, BR(SD^-) $\propto (F_V - F_A)^2$
- χPT to predict F_V, F_A: $O(p^4) \to$ BR(SD^+) $= 9.2 \times 10^{-6}$
- E787 measurement of $K^+ \to \mu^+ \nu_\mu \gamma$ (DE)



COSOP, Background Subtracted IB Fit



COSOP, Background Subtracted IB + SD^+ Fit

- Fit to IB + SD components:

$$BR(IB) = (3.568 \pm 0.273) \times 10^{-4}$$

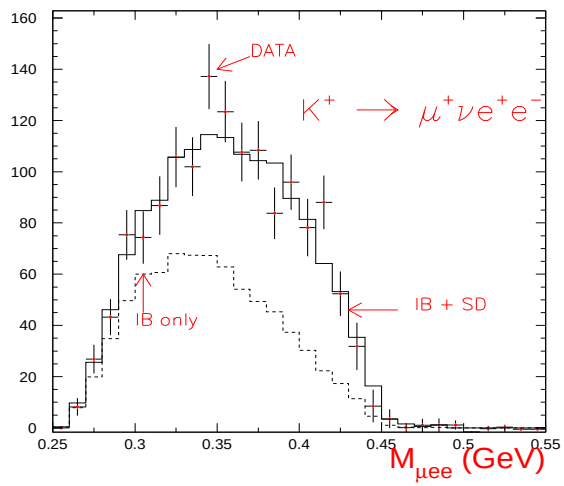
- Compared to the Theoretical value:

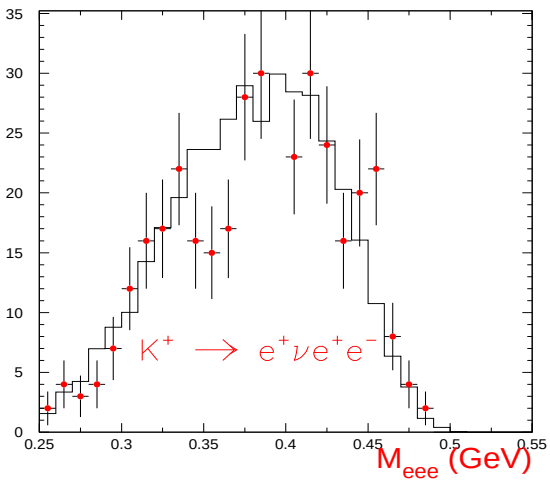
$$BR(IB, E_\mu > 100 \text{ MeV}, E_\gamma > 20 \text{ MeV}) = 3.300 \times 10^{-4}$$

- First observation of Structure Dependent $K^+ \to \mu^+ \nu_\mu \gamma$:
  - $BR(SD^+) = (1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$

$$|F_V + F_A| = 0.165 \pm 0.007 \pm 0.011$$

E865: Study of $K^+ \to \mu^+\nu e^+e^-$ and $K^+ \to e^+\nu e^+e^-$





Left: μee mass distribution of $K^+ \to \mu^+\nu e^+e^-$ decays, in comparison with Monte Carlo with only inner bremsstrahlung, and with bremsstrahlung + structure dependent part;
Right: eee mass distribution of $K^+ \to e^+\nu e^+e^-$ decays, in comparison with Monte Carlo, which is dominated by the structure dependent part.

Decay Mode	Branching Ratio	Previous No. of Events	E865 No. of Events
$\mu^+\nu e^+e^-$	8×10^{-8}	14	1,500
$e^+\nu e^+e^-$	3×10^{-8}	4	380

- Stucture dependent constributions are significant;
- First measurement of the axial form factor (R) in K^+ decay;
- Improved measurements of Vector and Axial form factors (F_V, F_A);
- Unambiguous determination of sign of all form factors with respect to F_K;
- Sensitivity to Tensor interaction is better than the published K_{e3} results.

$\mathbf{K}_{\pi 3\gamma}$ ($\mathbf{K}_{\ell 3\gamma}$, $\mathbf{K}_{\ell 4\gamma}$)

- $\mathbf{K}_{\pi 3\gamma}$
  - $K^+ \longrightarrow \pi^+\pi^+\pi^-\gamma$ $BR = (1.04 \pm 0.31) \times 10^{-4}$ ITEP [SJNP**50**(89)421]
  - $K^- \longrightarrow \pi^-\pi^\circ\pi^\circ\gamma$ $BR = (7.5^{+5.5}_{-3.0}) \times 10^{-6}$ IHEP [JETPL**42**(95)481]
- $\mathbf{K}_{\ell 3\gamma}$
  - $K^+ \longrightarrow \pi^\circ\mu^+\nu_\mu\gamma$ $BR < 6.1 \times 10^{-5}$ ZGS [PR**D8**(73)1307] E787(1998)
  - $K_L^\circ \longrightarrow \pi\mu\nu_\mu\gamma$ $BR = (5.7^{+0.6}_{-0.7}) \times 10^{-4}$ NA48 [PL**B418**(98)411]
  - $K^+ \longrightarrow \pi^\circ e^+\nu_e\gamma$ $BR = (2.62 \pm 0.20) \times 10^{-4}$ ITEP [SJNP**53**(91)606]
  - $K_L^\circ \longrightarrow \pi e\nu_e\gamma$ $BR = (3.62^{+0.26}_{-0.21}) \times 10^{-4}$ NA31 [PL**B369**(96)69]
- $\mathbf{K}_{\ell 4\gamma}$
  - $K^+ \longrightarrow \pi^\circ\pi^\circ e^+\nu_e\gamma$ $BR < 5 \times 10^{-6}$ ITEP [SJNP**55**(92)547]
  - $K^+ \longrightarrow \pi^+\pi^- e^+\nu_e\gamma$ (E865–1997)

Review of the experimental status

- **Experiments**
  - BNL
    - E871: (1995–6) completed. ($K_L^\circ \to \mu e$)
    - E865: (1995–8) data collection complete, analysis ongoing. ($K^+ \to \pi^+ \mu e$)
    - E787: (1995–8) data collection complete, analysis ongoing. ($K^+ \to \pi^+ \nu\overline{\nu}$)
    - E949: (2001–3) Under construction; upgrade of E787. ($K^+ \to \pi^+ \nu\overline{\nu}$)
    - E926: (2005–7) Scientific approval. ($K_L^\circ \to \pi^\circ \nu\overline{\nu}$)
  - FNAL
    - KTeV: (1996–7,99–2000) will finish data collection in 2000, most results are from 1996 data (∼10% of 1997). The 1999 data set will be ∼ 3× larger than 1996–7. (ϵ')
    - KAMI: (2005?–??) Approved R&D project. Upgrade of KTeV. ($K_L^\circ \to \pi^\circ \nu\overline{\nu}$)
    - CKM: (2005?–??) Approved R&D project. ($K^+ \to \pi^+ \nu\overline{\nu}$)
  - CERN
    - NA48: (1997–∼>2000) results from 1997 (and 1995), 1997 is ∼30% of 1998 and ∼10% of the total expected. (ϵ')
  - KEK
    - E391a (2001–4) Under construction. ($K_L^\circ \to \pi^\circ \nu\overline{\nu}$)
  - Frascati
    - KLOE: (1999–??) Data collection started. (ϵ')
  - IHEP
    - (2002–??) Semi-rare decays

Recent K^+ Results

mode	Previous # events	Current # events	new Branching Ratio (or limit)	future prospects
$K^+ \to \pi^+\gamma\gamma$	0	26	$(6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$ $(100 < P_{\pi^+} < 180\text{MeV/c})$	-
$K^+ \to \pi^+\pi^\circ\gamma$ (DE)	$\sim$200	367	$(4.72 \pm 0.77) \times 10^{-6}$ $(55 < T_{\pi^+} < 90\text{MeV/c})$	$> \times 2$
$K^+ \to \mu^+\nu_\mu\gamma$ (SD^+)	0	970	$(1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$	-
$K^+ \to \pi^\circ\mu^+\nu_\mu\gamma$	0	0		will see
$K^+ \to \pi^+\pi^-e^+\nu_e\gamma$	0	0		will see
$K^+ \to \mu^+\nu e^+e^-$	14	$\sim$1500		-
$K^+ \to e^+\nu e^+e^-$	4	$\sim$400		-
$K^+ \to e^+\nu\mu^+\mu^-$	-	0	$< 5.0 \times 10^{-7}$	-
$K^+ \to \pi^+e^+e^-$	1341	$\sim$10,000		-
$K^+ \to \pi^+\mu^+\mu^-$	203	$\sim$400		-
$K^+ \to \pi^+e^+e^-\gamma$	0	$\sim$30		-
$K^- \to \pi^-\pi^\circ\pi^\circ\gamma$	2	5	$(7.5^{+5.5}_{-3.0}) \times 10^{-6}$	-

Recent K° Results

K_L°				
mode	Previous # events	Current # events	new Branching Ratio (or limit)	future prospects
$K_L^\circ \to \mu^+\mu^-$	707	6200	$(7.24 \pm 0.17) \times 10^{-9}$	-
$K_L^\circ \to e^+e^-$	0	4	$(8.7^{+5.7}_{-4.1}) \times 10^{-12}$	-
$K_L^\circ \to e^+e^-\gamma$	919	6853	$(1.06 \pm .02 \pm .02 \pm .04) \times 10^{-5}$	$\times 20$
$K_L^\circ \to \mu^+\mu^-\gamma$	1	197	$(3.23 \pm 0.23 \pm 0.19) \times 10^{-7}$	$\times 30$
$K_L^\circ \to e^+e^-e^+e^-$	27	391	$(4.14 \pm 0.27 \pm 0.31) \times 10^{-8}$	$\times 4$
$K_L^\circ \to \mu^+\mu^-e^+e^-$	1	38		$\times 4$
$K_L^\circ \to e^+e^-\gamma\gamma$	58	1911	$(6.31 \pm 0.14 \pm 0.42) \times 10^{-7}$	$\times 3$
$K_L^\circ \to \mu^+\mu^-\gamma\gamma$	0	4	$(1.42^{+1.02}_{-0.81} \pm 0.14) \times 10^{-9}$	$\times 3$
$K_L^\circ \to \pi^+\pi^-\gamma$ (DE)	1937	5909	$(3.70 \pm 0.10) \times 10^{-5}$	$\times 20$
$K_L^\circ \to \pi^+\pi^-e^+e^-$	0	1508	$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$	$\times 4$
$K_L^\circ \to \pi^\circ\gamma\gamma$	60	796	$(1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$	$\times 2$
$K_L^\circ \to \pi^\circ e^+e^-$	0	0	$< 5.6 \times 10^{-10}$	$\times\sqrt{3}$
$K_L^\circ \to \pi^\circ \mu^+\mu$	0	0	$< 3.4 \times 10^{-10}$	$\times\sqrt{3}$
$K_L^\circ \to \pi^\circ e^+e^-\gamma$	0	18	$(2.20 \pm 0.48 \pm 0.11) \times 10^{-8}$	$\times 3$
$K_L^\circ \to \pi^\pm\mu^\mp\nu_\mu\gamma$	0	252	$(5.7^{+0.6}_{-0.7}) \times 10^{-4}$	?
$K_L^\circ \to \pi^\pm e^\mp\nu_e\gamma$	10	1384	$(3.62^{+0.26}_{-0.21}) \times 10^{-4}$	?

K_S°				
mode	Previous # events	Current # events	new Branching Ratio (or limit)	future prospects
$K_S^\circ \to \gamma\gamma$	0	16	$(2.4 \pm 0.9) \times 10^{-6}$	NA48(2000+)
$K_S^\circ \to e^+e^-$	0	0	$< 1.4 \times 10^{-7}$	?
$K_S^\circ \to \pi^\circ e^+e^-$	0	0	$< 1.1 \times 10^{-6}$	NA48(2000+)

Conclusions

Radiative Kaon Decays

- A large number of new results.
- Expect significant improvements with existing data.
- Several 'next generation' experiments:
  - Rare decay, fixed target experiments
  - May see a dedicated 'medium rare' experiment at IHEP.
  - Expect many new results from DAΦNE.
  - $\longrightarrow$ We will see several new modes.
  - improvements in neutral modes of up to $\times 10$.
  - improvements in charged modes of up to $\times 100$–1000.

The field is quite active.

...and looks to remain so.

$K_L^\circ \to \mu^+\mu^-$ and $K_L^\circ \to \gamma\gamma$

- A better measurement of B($K_L^\circ \to \mu^+\mu^-$) / B($K_L^\circ \to \gamma\gamma$) is needed.
- May eventually be able to extract the CKM parameter ρ.

$$\frac{B(K_L^\circ \to \mu^+\mu^-)}{B(K_L^\circ \to \gamma\gamma)} = \left[\frac{B(K_L^\circ \to \mu^+\mu^-)}{B(K_L^\circ \to \pi^+\pi^-)}\right] \times \left[\frac{B(K_L^\circ \to \pi^+\pi^-)}{B(K_L^\circ \to \pi^\circ\pi^\circ)}\right] \times \left[\frac{B(K_L^\circ \to \pi^\circ\pi^\circ)}{B(K_L^\circ \to \gamma\gamma)}\right]$$

$$[(3.474 \pm 0.054) \times 10^{-6}][2.208 \pm 0.029][1.582 \pm 0.0239]$$

$$[1.55\%][1.32\%][1.42\%]$$

$$= \left[\frac{B(K_L^\circ \to \mu^+\mu^-)}{B(K_L^\circ \to \pi^+\pi^-)}\right] \times \left[\left|\frac{\eta_{+-}}{\eta_{\circ\circ}}\right| \times \frac{B(K_S^\circ \to \pi^+\pi^-)}{B(K_S^\circ \to \pi^\circ\pi^\circ)}\right] \times \left[\frac{B(K_L^\circ \to \pi^\circ\pi^\circ)}{B(K_L^\circ \to \gamma\gamma)}\right]$$

$$[(3.474 \pm 0.054) \times 10^{-6}][(1.0044 \pm 0.0023) \times (2.186 \pm 0.028)][0.632 \pm 0.009]$$

$$[1.55\%][(0.23\%)(1.28\%)][1.42\%]$$

$$= (1.213 \pm 0.030) \times 10^{-5}$$

$$[2.48\%]$$

- No improvement on the horizon for B($K_L^\circ \to \mu^+\mu^-$)/B($K_L^\circ \to \pi^+\pi^-$).
- Will get even better $\eta_{+-}/\eta_{\circ\circ}$ soon.
- **Need a better measurement of B($K_L^\circ \to \gamma\gamma$)/B($K_L^\circ \to \pi^\circ\pi^\circ$).** (NA31–1987)
- **Need a better measurement of B($K_S^\circ \to \pi^+\pi^-$)/B($K_S^\circ \to \pi^\circ\pi^\circ$).**
  (9 experiments with ∼35k events from 1969–76).
- Reduce error by ∼40%!
- **NA48? DAΦNE?**