KTeV results for $K_L \to \pi\pi\gamma^{(*)}$ and $K_L \to \pi\pi\pi\gamma^{(*)}$

Introduction

Hadronic radiative decays of neutral kaons with real and virtual photons give insight into structure of the kaon

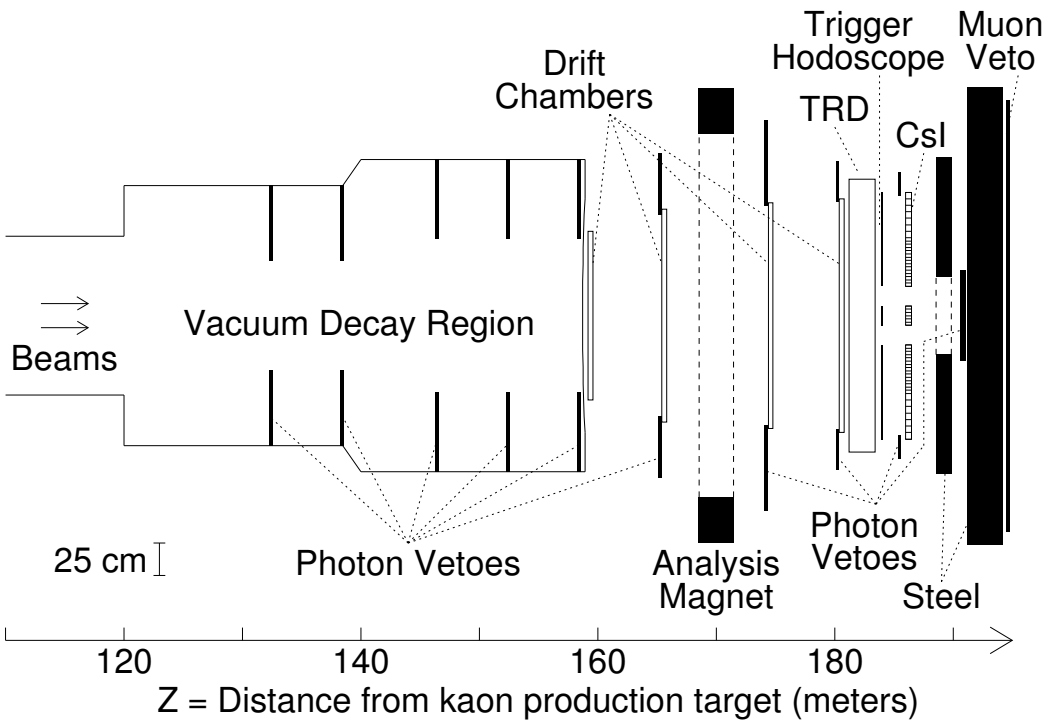
In this talk, resent KTeV results for

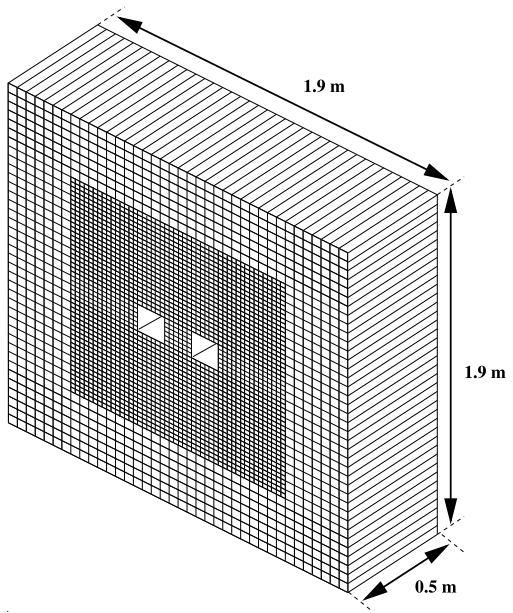
- $K_L \to \pi^0\pi^0\gamma$
- $K_L \to \pi^+\pi^-\gamma$ and $K_L \to \pi^+\pi^-e^+e^-$
- $K_L \to \pi^+\pi^-\pi^0\gamma$ and $K_L \to \pi^+\pi^-\pi^0e^+e^-$

KTeV Experiment

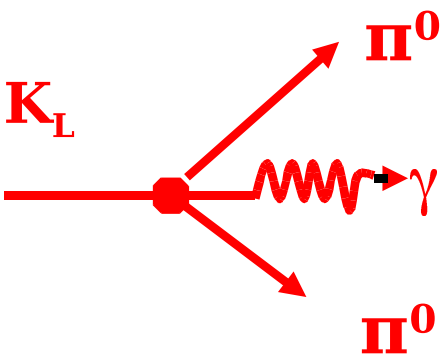
Collaboration: about 80 physicists from
Arizona, Campinas, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, Sao Paulo, UCLA, UCSD, Virginia, Wisconsin

Experiment: at Fermilab, took data in 1996-1997 and 1999





Search for $K_L \to \pi^0\pi^0\gamma$



Direct emission of γ. Lowest possible multipole for γ is E2 (assume CP conservation)

Has not been observed yet

Theoretical predictions:

- P.Heiliger and L.M.Sehgal (Phys.Lett.B307,182) by comparing $DE(E2)$ in $K_L \to \pi^0\pi^0\gamma$ and $DE(M1)$ in $K_L \to \pi^+\pi^-\gamma$:

$$BR = 1 \times 10^{-8}$$

- In ChPT, vanishes in $O(p^4)$. G.Ecker, H.Neufeld and A.Pich (Nucl.Phys.B413,321) estimated this amplitude to $O(p^6)$:

$$BR = 7 \times 10^{-11}$$

Search for $K_L \to \pi^0\pi^0\gamma$

Previous experimental results:

- *Direct* search for $K_L \to \pi^0\pi^0\gamma$ by NA31 (Phys.Lett.B328:528,1994). 5 photons in a final state. Found 3 candidate events with estimated background of 2.2+-0.9 events.

$$BR < 5.6 \times 10^{-6}(90\%CL)$$

- *Indirect* experimental result by KTeV using $K_L \to \pi^0\pi^0 e^+e^-$ upper limit $BR < 6.6 \times 10^{-9}(90\%CL)$ (Phys.Rev.Lett. 89,211801,2002). This mode also has $E2$ DE amplitude. Using $BR(\pi^0\pi^0\gamma)/BR(\pi^0\pi^0 e^+e^-) = 50$ (P.Heiliger and L.M.Sehgal)

$$BR < 3.3 \times 10^{-7}(90\%CL)$$

Search for $K_L \to \pi^0\pi^0\gamma$

KTeV search for $K_L \to \pi^0\pi^0\gamma$

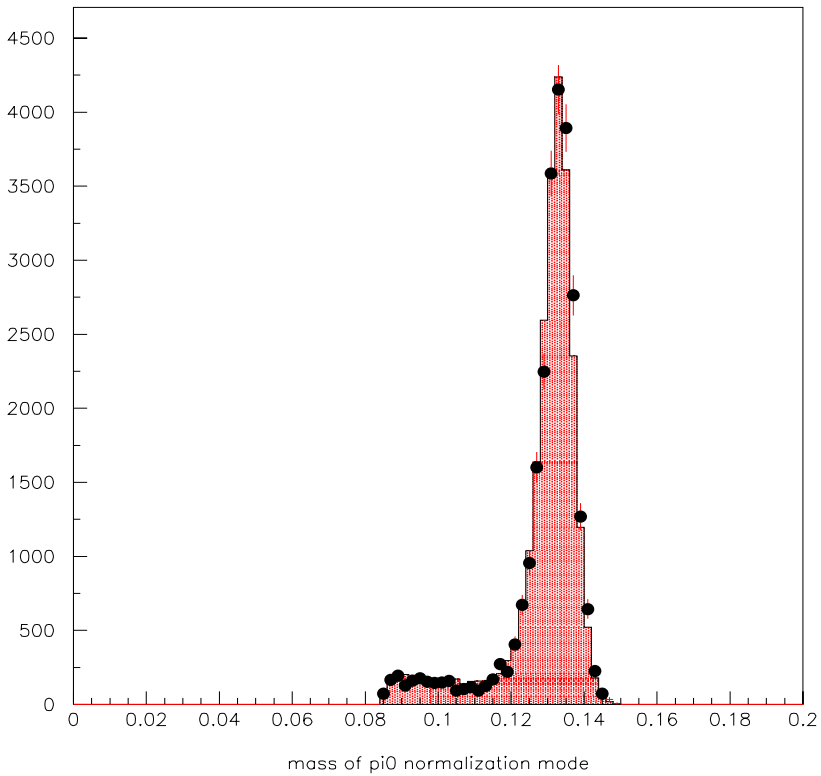
Final state:

- one $\pi^0 \to \gamma\gamma$
- the other $\pi^0 \to e^+e^-\gamma$
- KTeV triggers provide best Single Event Sensitivity (SES) for this final state configuration

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

- one $\pi^0 \to e^+e^-\gamma$
- one $\pi^0 \to \gamma\gamma$ has γ missing in CsI beam hole
- same final state as a signal (4 γ's and e^+e^- pair)
- clean, easy to reconstruct

Figure: Invariant mass of $\gamma\gamma$ for normalization mode where one of the γ is missing in CsI beam hole which 4-vector momentum is reconstructed using kinematic constrains. Dots are DATA. Histogram is Monte Carlo simulations



Search for $K_L \to \pi^0\pi^0\gamma$

Blind Analysis. Major background is $K_L \to \pi^0\pi^0\pi^0$
Scattered plots: transverse momentum squared vs invariant mass of $\pi^0\pi^0\gamma$ after all analysis cuts. Red box is a signal region.

Figure: MC simulation of background that corresponds $\times 4.88$ statistics for DATA plot on the right

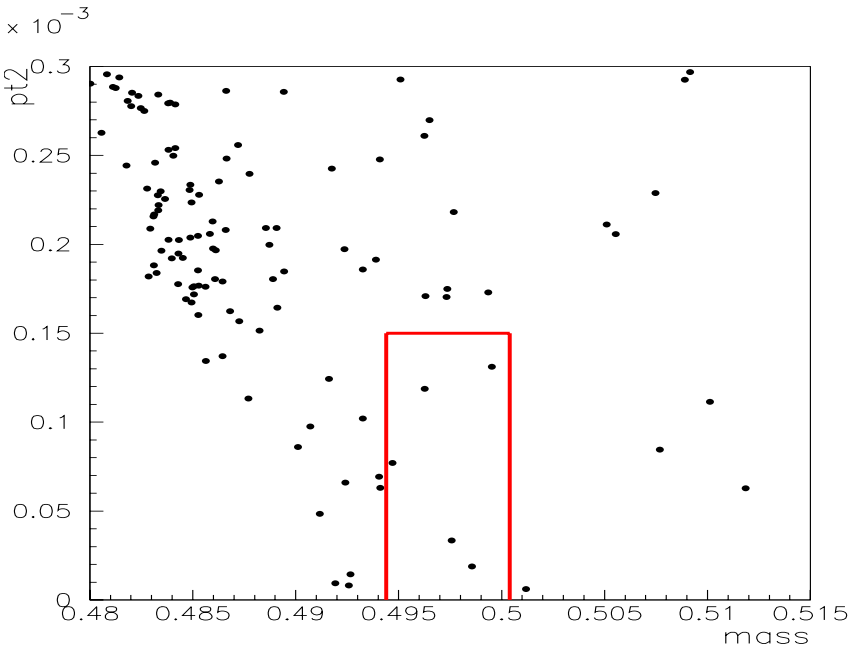
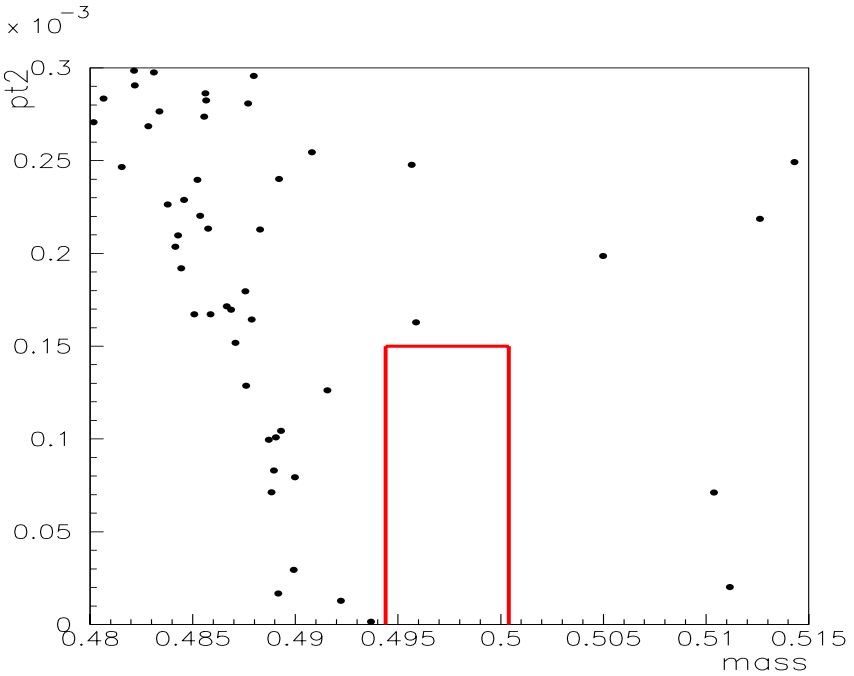


Figure: 1997 DATA ($\sim$40% of full KTeV dataset)



Background level is 1.66 ± 0.59 events. *Zero* events observed in DATA.

Search for $K_L \to \pi^0\pi^0\gamma$

KTeV preliminary result:

- Single Event Sensitivity from ∼40% of KTeV dataset:

$$SES = 1.47 \times 10^{-7}$$

- Expected background

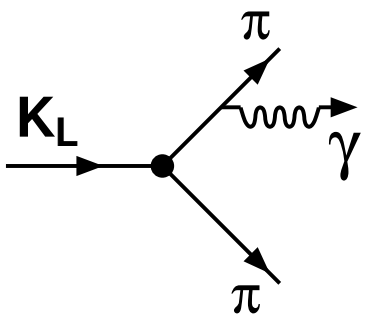
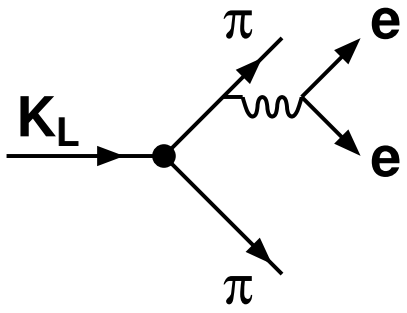
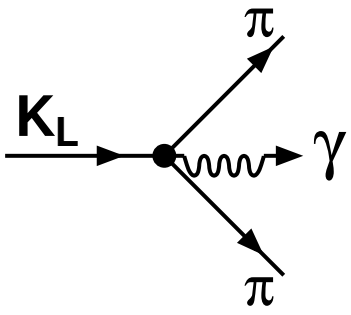
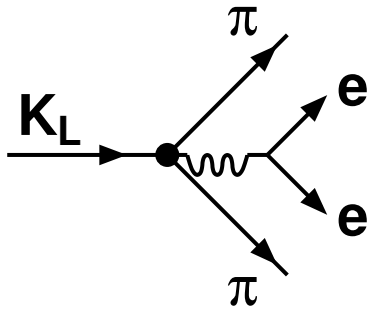
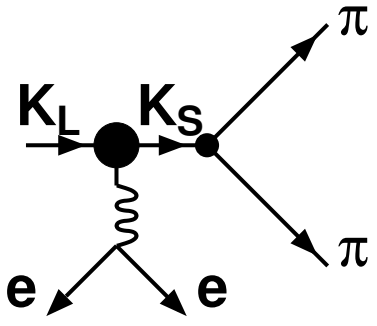
$$n_b = 1.66 \pm 0.59$$

- *Zero* events observed in the signal region
- Combining statistical and systematic uncertainties, the upper limit:

$$BR(K_L \to \pi^0\pi^0\gamma) < 2.52 \times 10^{-7}(90\%CL)$$

- Factor 22 improvement to NA31 result
- Analysis of the *full* KTeV dataset is in progress

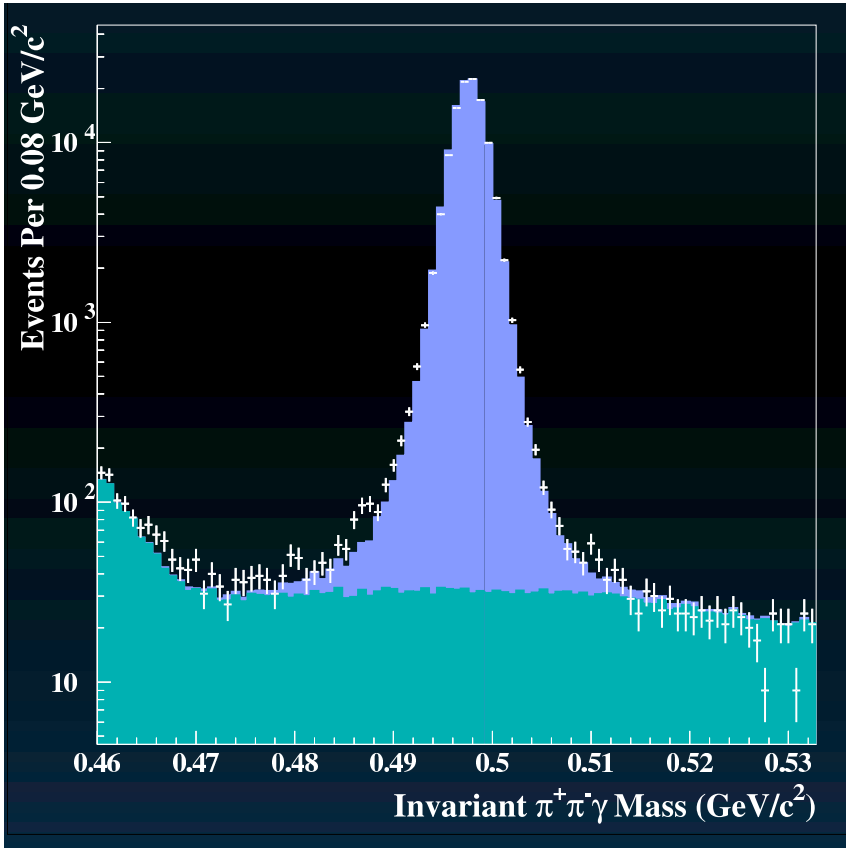
Contributions to $K_L \to \pi^+\pi^-\gamma$ and $K_L \to \pi^+\pi^-\gamma^*$

	$K_L \to \pi^+\pi^-\gamma$	$K_L \to \pi^+\pi^-e^+e^-$
internal bremsstrahlung CP violating		
direct emission M1: CP conserving E1: CP violating		
charge radius		

KTeV sample of $K_L \to \pi^+\pi^-\gamma$

- 1997 dataset of E832 (collected during ϵ'/ϵ data taking)
- After all analysis cuts: 112.1×10^3 candidates for $K_L \to \pi^+\pi^-\gamma$ decays including background.
- Estimated level of background is 671 events. Most of the background events are $K_L \to \pi^\pm\mu^\mp\nu$ and $K_L \to \pi^\pm e^\mp\nu$ decays

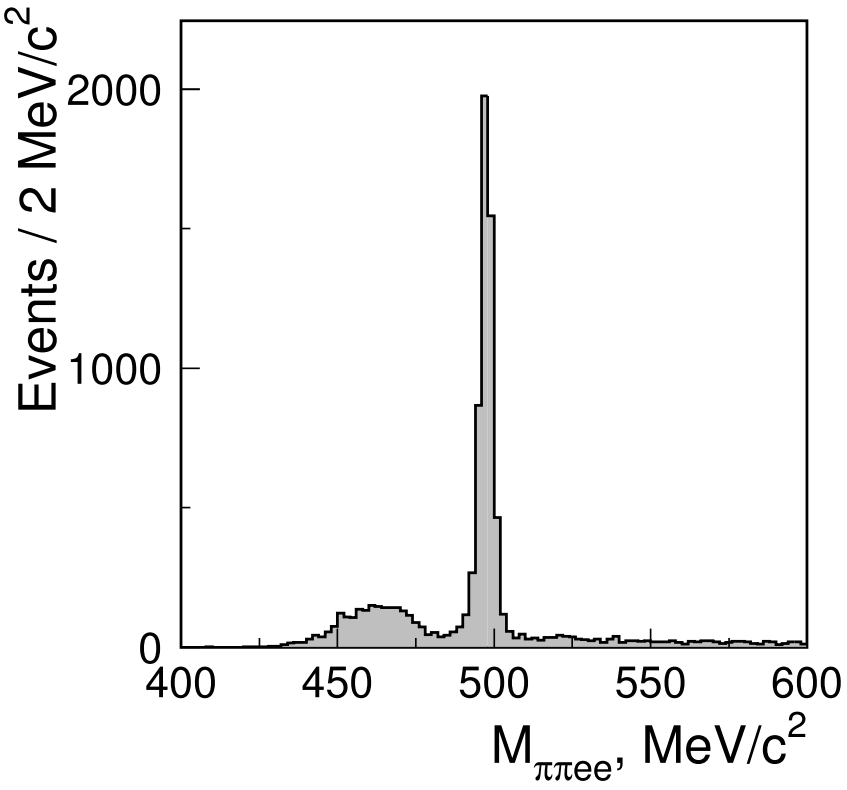
Figure: Invariant mass of $\pi^+\pi^-\gamma$ after all analysis cuts. Dots are DATA, blue histogram is signal Monte Carlo, green histogram is background Monte Carlo



KTeV sample of $K_L \to \pi^+\pi^-e^+e^-$

- Full KTeV dataset (both 1997 and 1999 E799 data)
- After all analysis cuts: 5241 candidates for $K_L \to \pi^+\pi^-e^+e^-$ decays including background.
- Estimated level of background is 204 events. Most of the background events are $K_L \to \pi^+\pi^-\pi^0$ decays where $\pi^0 \to e^+e^-\gamma$ and γ is not detected

Figure: Invariant mass of $\pi^+\pi^-e^+e^-$ after all analysis cuts



Analysis of $K_L \to \pi^+\pi^-\gamma$ and $K_L \to \pi^+\pi^-\gamma^*$

Both modes were analyzed in a similar manner:

- Maximum Likelihood fit of fully differential matrix element to DATA
  - 2-dimensional for $K_L \to \pi^+\pi^-\gamma$
  - 5-dimensional for $K_L \to \pi^+\pi^-e^+e^-$
- Matrix elements for both decay modes include amplitudes:
  - Inner bremstrahlung
  - M1 Direct Emission
  - E1 Direct Emission
- $K_L \to \pi^+\pi^-e^+e^-$ matrix element also has Charge Radius amplitude
- Fit parameters are related to couplings for each amplitude in matrix element and will be discussed in the following slides
  - 3-parameter fit for $K_L \to \pi^+\pi^-\gamma$
  - 4-parameter fit for $K_L \to \pi^+\pi^-e^+e^-$

Direct Emission Form Factor

Direct Emission coupling requires energy dependence:

$$|g_{M1}| = \tilde{g}_{M1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma}\right]$$

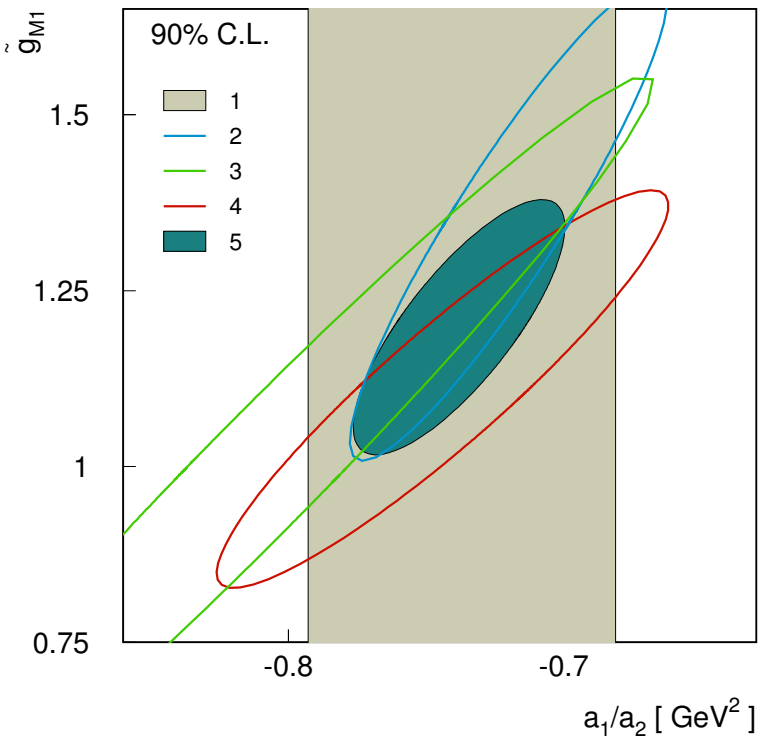
KTeV results from $K_L \to \pi^+\pi^-\gamma$ (PRELIMINARY):

$$\frac{a_1}{a_2} = (-0.738 \pm 0.007 \pm 0.018)\ GeV^2$$
$$\tilde{g}_{M1} = 1.198 \pm 0.035 \pm 0.086$$

KTeV results from $K_L \to \pi^+\pi^-e^+e^-$:

$$\frac{a_1}{a_2} = (-0.744 \pm 0.027 \pm 0.032)\ GeV^2$$
$$\tilde{g}_{M1} = 1.11 \pm 0.12 \pm 0.08$$

Figure: 90% contours for $\tilde{g}_{M1}$ vs a_1/a_2 for known experimental results:
1 - KTeV($\pi\pi\gamma$), PRL 86,761(2001)
2 - KTeV($\pi\pi ee$), PRL 84,408(2000)
3 - NA48($\pi\pi ee$), EPJ C30,33(2003)
4 - KTeV($\pi\pi ee$), This Result
5 - KTeV($\pi\pi\gamma$), This Result



Search for CP violating E1 Direct Emission

Both $K_L \to \pi^+\pi^-\gamma$ and $K_L \to \pi^+\pi^-e^+e^-$ analyses attempted to measure CP violating amplitude of direct emission of E1 photon. No experimental evidence for this amplitude is found.

- KTeV results from $K_L \to \pi^+\pi^-\gamma$ (PRELIMINARY):

$$|g_{E1}| < 0.21(90\%CL)$$

- KTeV results from $K_L \to \pi^+\pi^-e^+e^-$:

$$|g_{E1}| < 0.03(90\%CL)$$

Despite higher statistics in $K_L \to \pi^+\pi^-\gamma$ sample, it has less sensitivity to $|g_{E1}|$ because phase space has only 2 dimensions (compared to 5-dimensional phase space for $K_L \to \pi^+\pi^-e^+e^-$)

These KTeV results for E1 are the first experimental attempts to measure this amplitude

Neutral Kaon Charge Radius

- KTeV result for Charge Radius amplitude in $K_L \to \pi^+\pi^-e^+e^-$

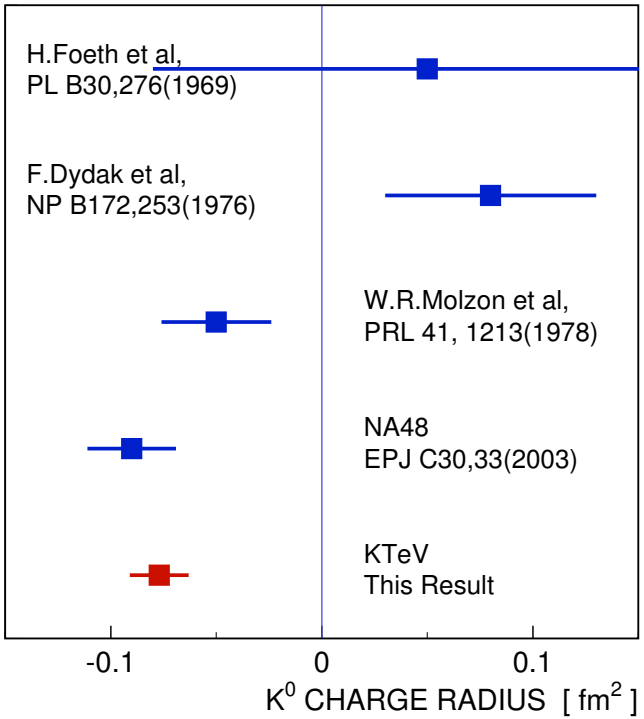
$$|g_{CR}| = 0.163 \pm 0.014 \pm 0.023$$

- This coupling is proportional to K^0 charge radius

$$|g_{CR}| = -\frac{1}{3}\langle R_K^2 \rangle M_K^2$$

- First three published measurements for $\langle R_K^2 \rangle$ used kaon regeneration on free electrons
- NA48 and KTeV results are based on $K_L \to \pi^+\pi^-e^+e^-$

Figure: Comparison of experimental results for $\langle R_K^2 \rangle$



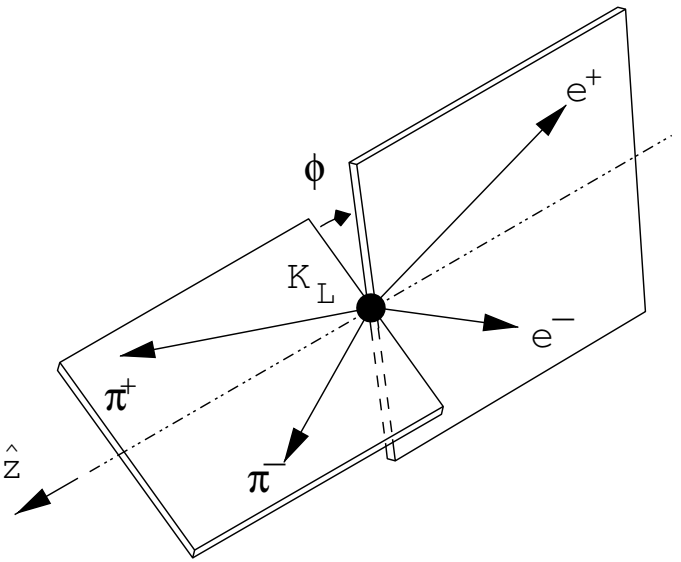
KTeV result for K^0 charge radius

$$\langle R_K^2 \rangle = -0.744 \pm 0.042$$

CP violation in $K_L \to \pi^+\pi^-e^+e^-$

- In $K_L \to \pi^+\pi^-\gamma$, the helicity of γ is not measured and interference between CP violating bremstrahlung and CP concerving Direct Emission amplitudes vanishes.
- In $K_L \to \pi^+\pi^-e^+e^-$, the distribution of CP-odd ϕ, the angle between e^+e^- and $\pi^+\pi^-$ planes in kaon center of mass, exhibit large CP violating asymmetry:

$$A_{CP} = \frac{\int_{\sin\phi\cos\phi>0} d\Gamma - \int_{\sin\phi\cos\phi<0} d\Gamma}{\Gamma_{TOT}}$$



- KTeV result

$$A_{cp} = (13.6 \pm 1.4 \pm 1.5)\%$$

$K_L \to \pi^+\pi^-\pi^0\gamma$ and $K_L \to \pi^+\pi^-\pi^0\gamma^*$ decays

There are no published experimental results for these decays.

- $K_L \to \pi^+\pi^-\pi^0\gamma$ decay is dominated by inner brem process.

$$BR(E_\gamma > 10\ MeV) = (1.65 \pm 0.03) \times 10^{-4}$$

G. D'Ambrosio *et al*, Z. Phys. C **76**, 301 (1997).

- Direct emission contribution to $K_L \to \pi^+\pi^-\pi^0\gamma$ is estimated to be very small.

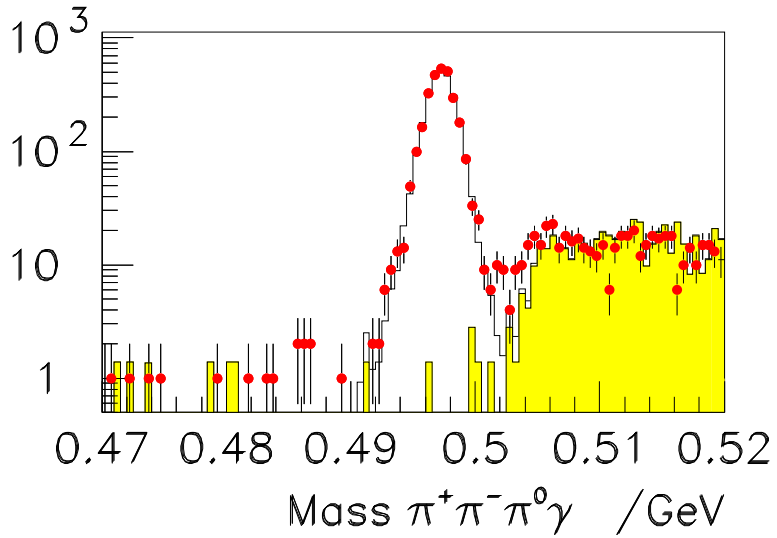
$$BR(K_L \to \pi^+\pi^-\pi^0\gamma)\ |_{direct} = (8a_1 + a_2 - 10a_3)^2 \cdot 2 \cdot 10^{-10}$$

where $a_i = O(1)$ are unknown. G. Ecker *et al*, Nucl. Phys. B **413**, 321 (1994)

- There are no theoretical predictions for $K_L \to \pi^+\pi^-\pi^0 e^+e^-$
  - Contributions to $K_L \to \pi^+\pi^-\pi^0\gamma$ should aslo be present in $K_L \to \pi^+\pi^-\pi^0 e^+e^-$
  - How large is a Charge radius amplitude?

First observation of $K_L \to \pi^+\pi^-\pi^0\gamma$

- E832 data
- 2853 candidates
- Normalization mode is $K_L \to \pi^+\pi^-\pi^0$
- Acceptance corrections in E_γ^{cm} bins using radiative $K_L \to \pi^+\pi^-\pi^0$ Monte Carlo (PHOTOS)



KTeV PRELIMINARY result for $K_L \to \pi^+\pi^-\pi^0\gamma$ with $E_\gamma^{cm} > 10\ MeV$

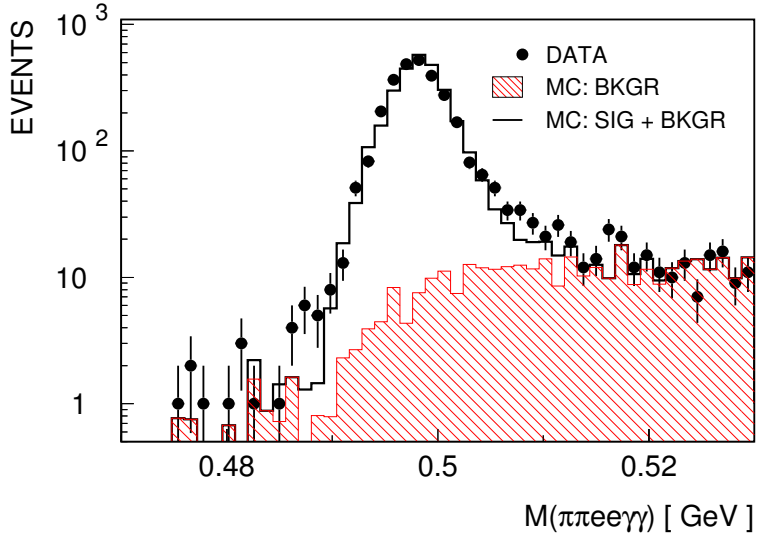
$$BR = (1.38 \pm 0.03_{stat} \pm 0.03_{syst}) \times 10^{-3} BR(K_L \to \pi^+\pi^-\pi^0)$$
$$BR = (1.70 \pm 0.03_{stat} \pm 0.04_{syst} \pm 0.03_{norm}) \times 10^{-4}$$

Good agreement with SM calculations

$$BR(K_L \to \pi^+\pi^-\pi^0\gamma, E_\gamma^{cm} > 10\ MeV) = (1.65 \pm 0.03) \times 10^{-4}$$

First observation of $K_L \to \pi^+\pi^-\pi^0\gamma$

- E799II data, using $\pi^0_D \to e^+e^-\gamma$
- clean sample of 2847
- Estimated background level is 128.4±9.2 events
- Normalization mode is $K_L \to \pi^+\pi^-\pi^0_D$
- ∼40% of KTeV data anayzed

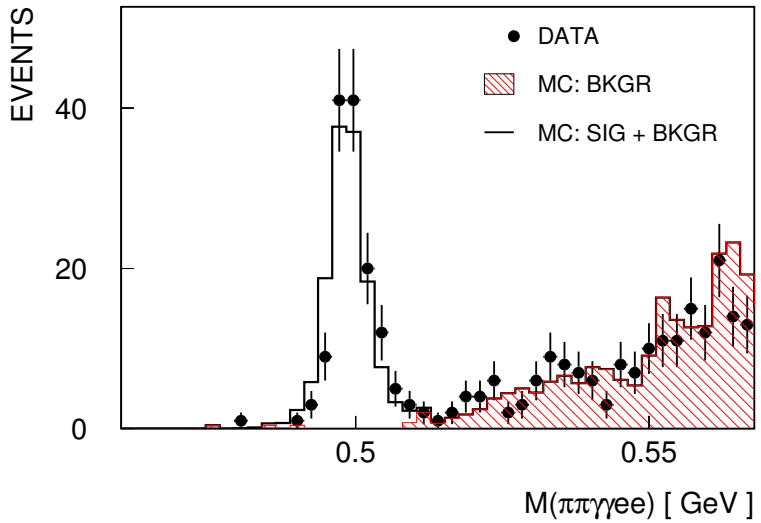


Both KTeV analyses (E832 and E799) result in first observation of $K_L \to \pi^+\pi^-\pi^0\gamma$

This decay is dominated by internal bremstrahlung amplitude. We will try to measure Direct Emission amplitude in near future.

First observation of $K_L \to \pi^+\pi^-\pi^0 e^+ e^-$

- E799 data,
- clean sample of 132 candidates
- estimated background level of 1.2 ± 0.9 evt
- Normalization mode is $K_L \to \pi^+\pi^-\pi^0_D$
- $\sim$40% of KTeV data anayzed



PRELIMINARY result for BR of $K_L \to \pi^+\pi^-\pi^0 e^+ e^-$ for $E_{ee} > 20 MeV$

$$BR = (1.60 \pm 0.18_{stat}) \times 10^{-7}$$

We will try to measure Direct Emission and Charge Radius amplitudes in near future.

Summary

KTeV conducted searches for a number of Hadronic radiative decays of neutral kaons with real and virtual photons

Here is a table of current status:

Real γ	Virtual $\gamma^* \rightarrow e^+e^-$
$K_L \rightarrow \pi^0\pi^0\gamma$ Preliminary results	$K_L \rightarrow \pi^0\pi^0e^+e^-$ Published
$K_L \rightarrow \pi^+\pi^-\gamma$ New Preliminary results	$K_L \rightarrow \pi^+\pi^-e^+e^-$ New results, accepted in PRL
$K_L \rightarrow \pi^+\pi^-\pi^0\gamma$ New Preliminary results	$K_L \rightarrow \pi^+\pi^-\pi^0e^+e^-$ New Preliminary results
$K_L \rightarrow \pi^0\pi^0\pi^0\gamma$ Analysis in progress	$K_L \rightarrow \pi^0\pi^0\pi^0e^+e^-$ Analysis in progress

More results to come in the future!