CP Violation Results from KTeV

Aspen Winter Conference on Particle Physics

January 18, 2000

Sydney Taegar, Arizona

- $Re\,(\epsilon'/\epsilon)$ Measurement in $K \rightarrow \pi\pi$
- CP Violation in $K_L \rightarrow \pi^+\pi^-e^+e^-$
- Search for $K_L \rightarrow \pi^o l\bar{l}$

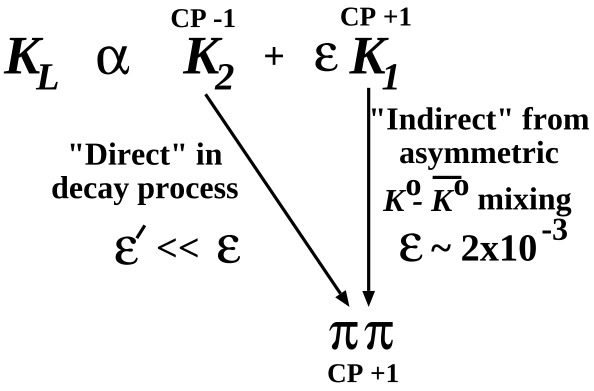
The KTeV Collaboration

Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia, Wisconsin

Direct CP Violation in $K \to \pi\pi$

- "Indirect" vs "Direct" CP Violation

  $K_L \propto K_2 + \epsilon K_1$
  $K_S \propto K_1 + \epsilon K_2$



- SM predicts ϵ' exists and is small

  $(1-10) \times 10^{-4}$

- Previous results inconclusive

  FNAL E731: $(7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$
  CERN NA31: $(23 \pm 6.5) \times 10^{-4}$

- If no direct CP violation

  $A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-) = \epsilon$
  $A(K_L \to \pi^o\pi^o)/A(K_S \to \pi^o\pi^o) = \epsilon$

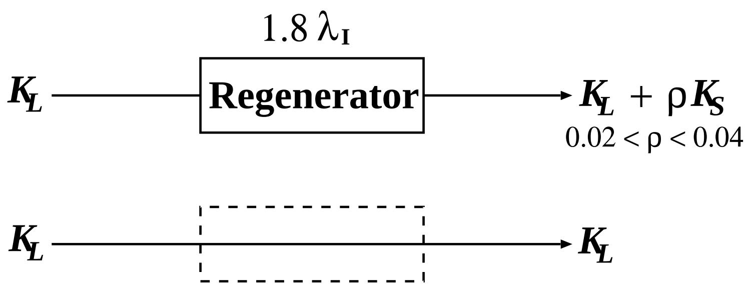
- Detect direct CP violation by measuring

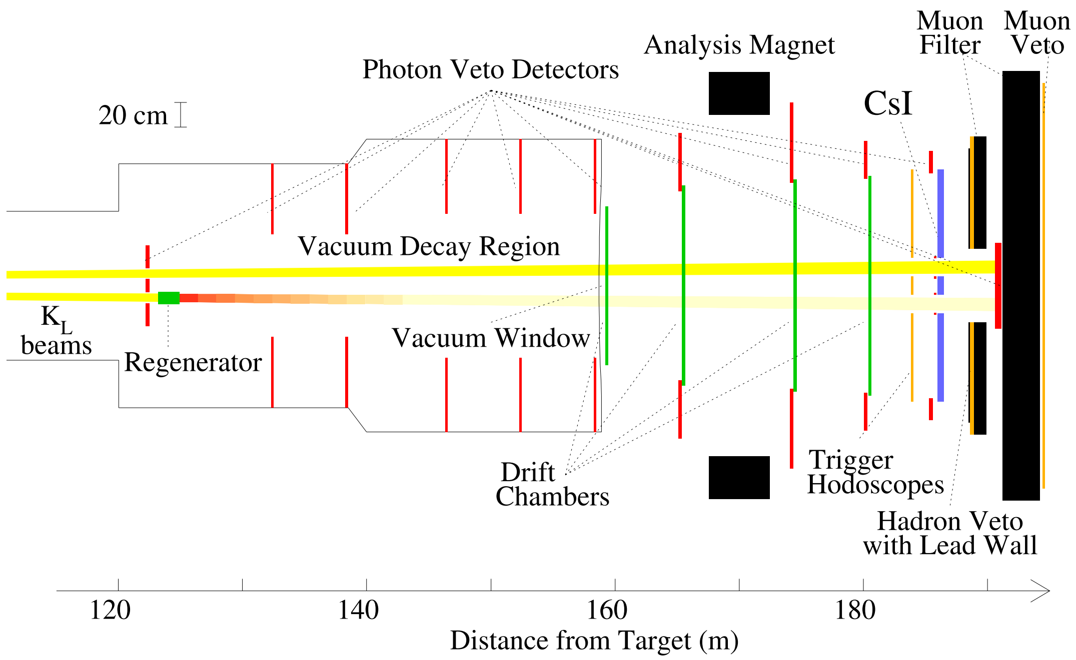
$$\frac{\Gamma\left(K_L \to \pi^+\pi^-\right)/\Gamma\left(K_S \to \pi^+\pi^-\right)}{\Gamma(K_L \to \pi^o\pi^o)/\Gamma(K_S \to \pi^o\pi^o)} \approx 1 + 6Re\,(\epsilon'/\epsilon)$$

KTeV

- ϵ'/ϵ to 10^{-4}
- Measurement technique

Collect K_L and K_S decays simultaneuously



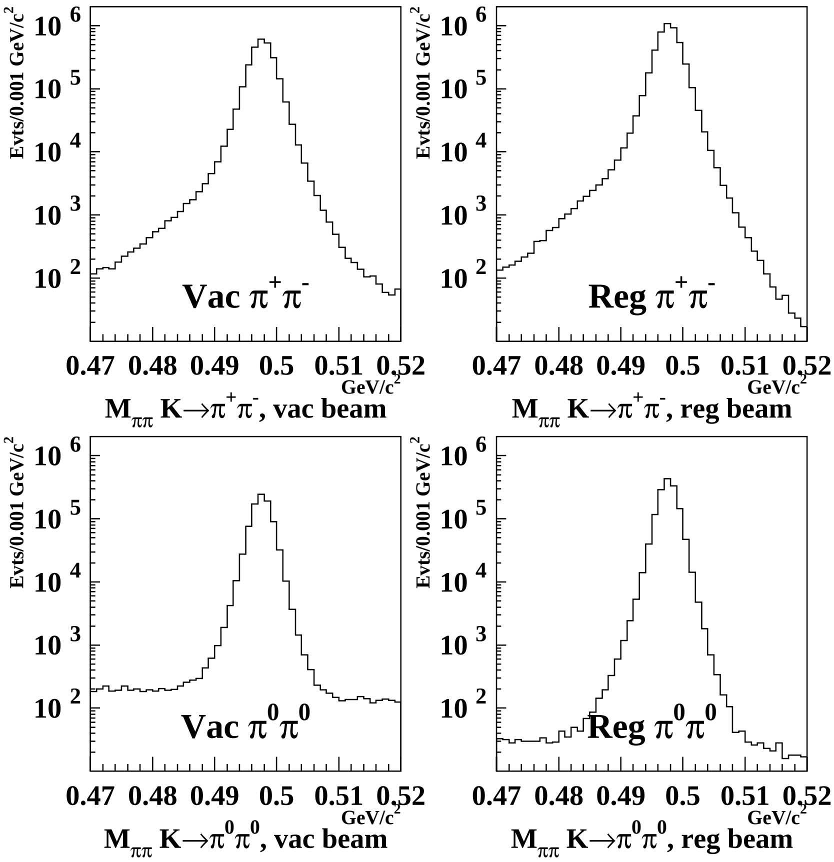


$$\sigma_E/E < 1\% \text{ for } E_\gamma > 7GeV$$

$$\sigma_p/p \sim 0.4\% \text{ for } \langle p_\pi \rangle \text{ of } 36GeV$$

Data Samples

Mass Distributions Before Background Subtraction



- Data sets used for this analyis

  $K \to \pi^o \pi^o$ data from 1996 ($\sim 23\%$ of 96/97 total)

  $K \to \pi^+ \pi^-$ data from first 18 days of E832 1997 run

Backgrounds

- Misidentified kaon decays

  $K \to \pi^+\pi^-$: $K_L \to \pi e\nu$, $K_L \to \pi\mu\nu$

  $K \to \pi^o\pi^o$: $K_L \to \pi^o\pi^o\pi^o$
- Regenerator and final collimator scatters

Background Source	Vac $\pi^+\pi^-$	Reg $\pi^+\pi^-$	Vac $\pi^o\pi^o$	Reg $\pi^o\pi^o$
$K_L \to \pi e\nu$	0.04%	~ 0	—	—
$K_L \to \pi\mu\nu$	0.03%	~ 0	—	—
$K_L \to \pi^o\pi^o\pi^o$	—	—	0.27%	0.01%
Collimator Scatter	0.01%	0.01%	0.16%	0.14%
Regenerator Scatter	—	0.07%	0.30%	1.07%
Total	0.08%	0.09%	0.73%	1.22%

Yields after Background Subtraction

Sample	Vac	Reg
$K \to \pi^o\pi^o$	862,254	1,433,923
$K \to \pi^+\pi^-$	2,607,274	4,515,928

$Re\,(\epsilon'/\epsilon)$ Measurement

$$R = \frac{\Gamma\left(K_L\to\pi^+\pi^-\right)/\Gamma\left(K_S\to\pi^+\pi^-\right)}{\Gamma(K_L\to\pi^o\pi^o)/\Gamma(K_S\to\pi^o\pi^o)} \approx 1 + 6Re\,(\epsilon'/\epsilon)$$

- Must control $\delta R/R$ to 0.1% level in presence of:

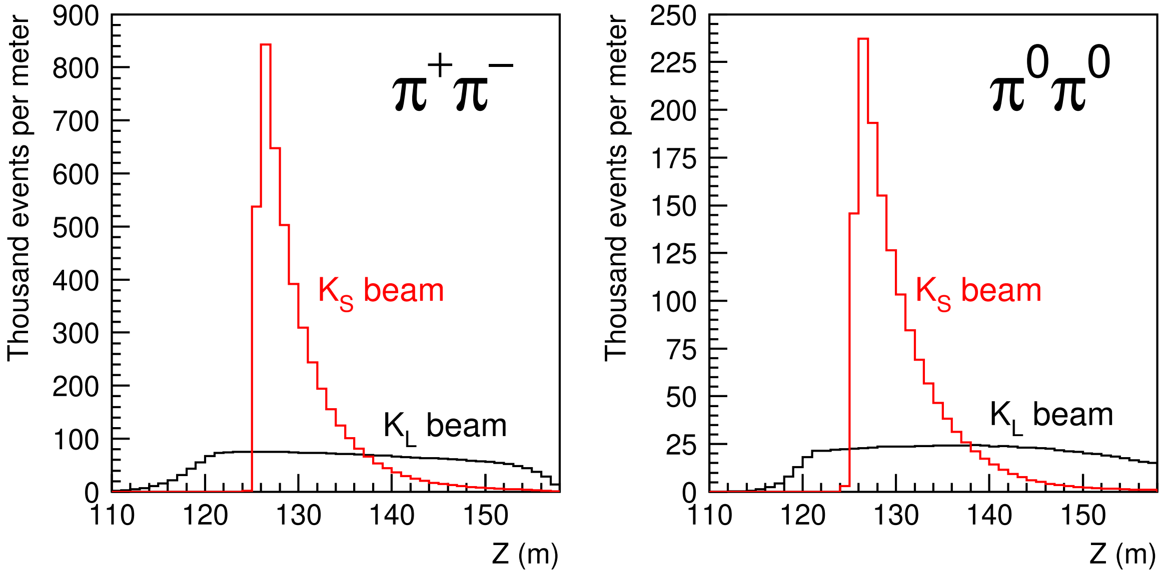
Correction	Approximate Size
Acceptance	4%
K_L, K_S Scattering	1%
Background	0.4%
Rate Effects	0.2%
Energy Scale	0.1%

- Measurement of corrections

Acceptance	Estimated from Monte Carlo Cross checked with $K_L \to \pi e\nu, \pi^+\pi^-\pi^o, \pi^o\pi^o\pi^o$
Scattering	Detailed modeling of scattering Studied with known scattered kaons
Background	Detailed modeling of background Extrapolated from mass sidebands
Rate Effects	Random triggers which scale with beam intensity
Energy Scale	Momentum analyzed $K_L \to \pi e\nu, \pi^+\pi^-\pi^o$

Acceptance vs Z

Reconstructed vertex Z distributions



- Detailed Monte Carlo simulation including

  Accidental overlays

  Full trigger simulation

  Geant-based CsI shower library

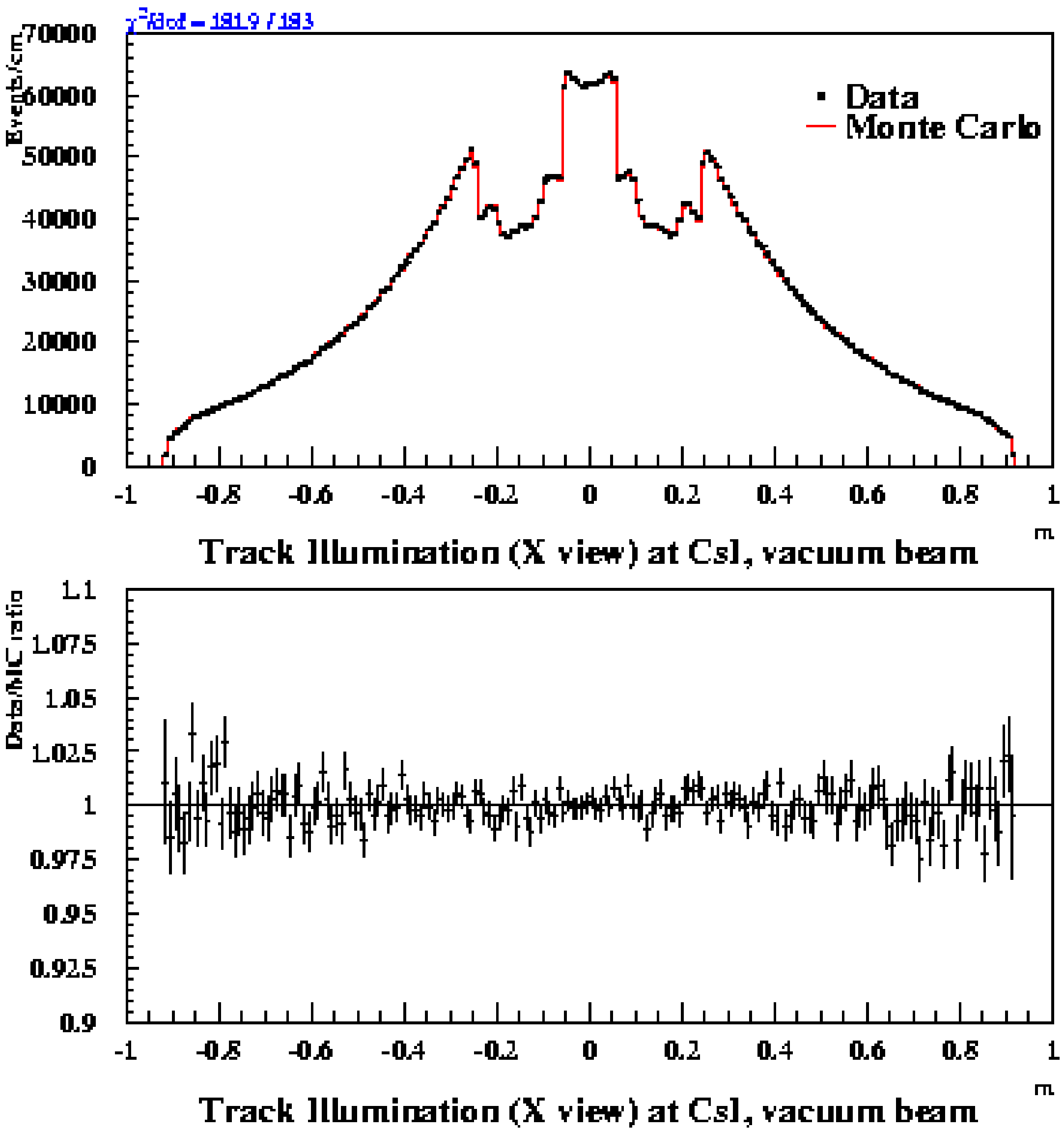
  Detailed drift chamber simulation

- High statistics modes used to check simulation

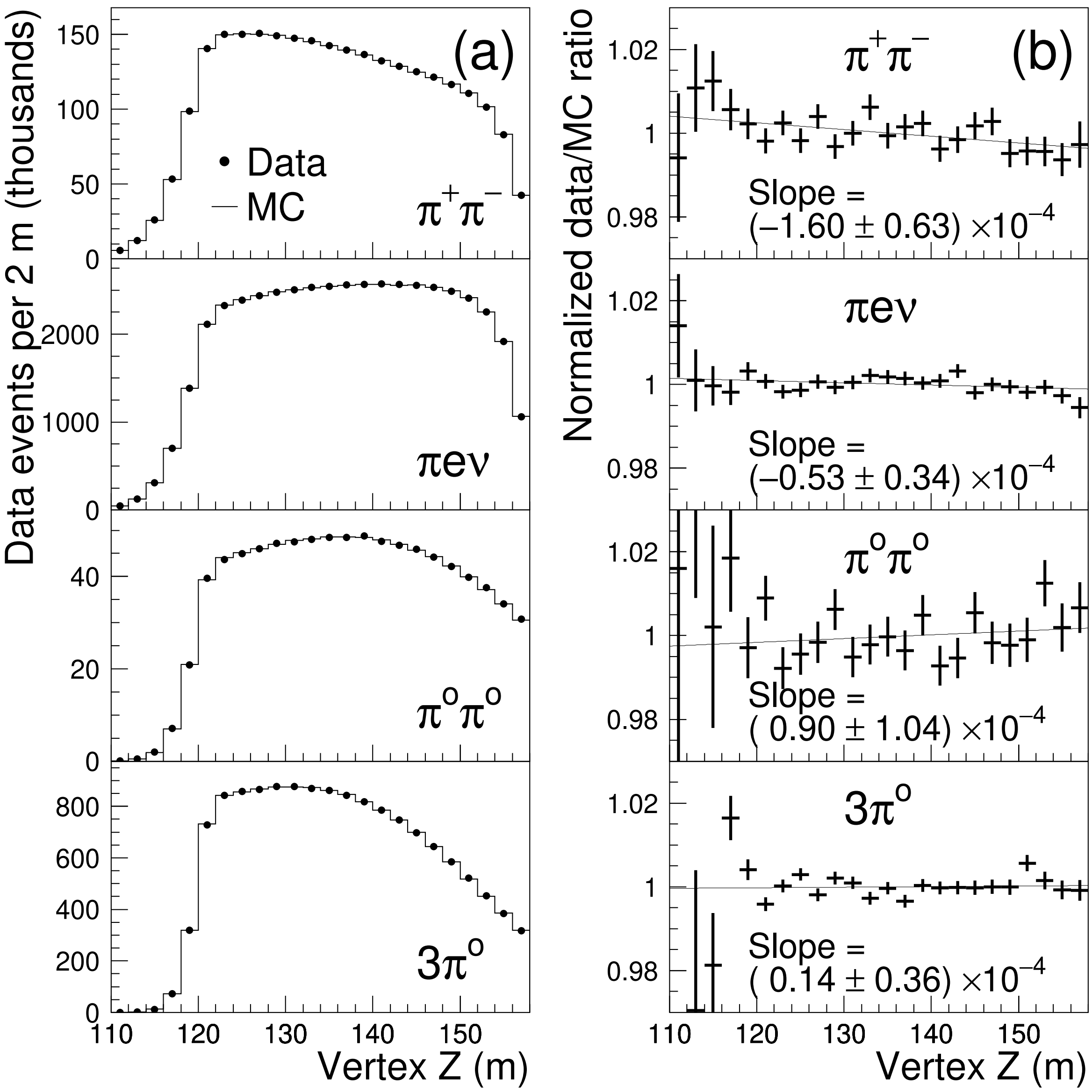
  $K_L \rightarrow \pi e \nu$

  $K_L \rightarrow \pi^o \pi^o \pi^o$

$\pi^+\pi^-$ Illumination Comparison



Data/Monte Carlo Z Distributions



$K_L \to \pi^+\pi^-$ slope is largest systematic

Summary of Systematic Errors

	Error ($\times 10^{-4}$)	
Source of Error	$\pi^+\pi^-$	$\pi^o\pi^o$
Trigger inefficiencies	0.5	0.3
Energy Scale	0.1	0.7
Calorimeter Nonlinearity	—	0.6
Alignment and Calibration	0.3	0.4
Analysis Cuts	0.6	0.8
Background subtraction	0.2	0.8
Detector Acceptance		
Apertures	0.3	0.5
Detector Resolutions	0.4	<0.1
Chamber Inefficiencies	0.6	—
Accidental Activity	0.1	—
Acceptance Z Dependence	1.6	0.7
Monte Carlo Statistics	0.5	0.9
K_S/K_L Flux	0.3	
External Parameters	0.2	

Total systematic error $= 2.8 \times 10^{-4}$

Fitting for $Re\,(\epsilon'/\epsilon)$

- Predict decay distributions using:
  - Full kaon state evolution from target
  - Full regeneration calculation
- Acceptance in (E, Z) bins from Monte Carlo
- Prediction compared against data in 10 GeV bins
  - No Z binning
- Inputs:
  - Δm and τ_S from PDG
  - Assume CPT $\rightarrow \phi_{+-} = \phi_{00}$
  - Regenerator beam attenuation
    - Measured from $K_L \rightarrow \pi^+\pi^-\pi^o$, $\pi^o\pi^o\pi^o$
- Fit parameters:
  - Regeneration amplitude (power-law parametrization)
  - Kaon momentum distribution correction
  - $Re\,(\epsilon'/\epsilon)$
- Blind analysis
  - Hidden offset added to fit result
  - Removed only after analyis and systematics finalized

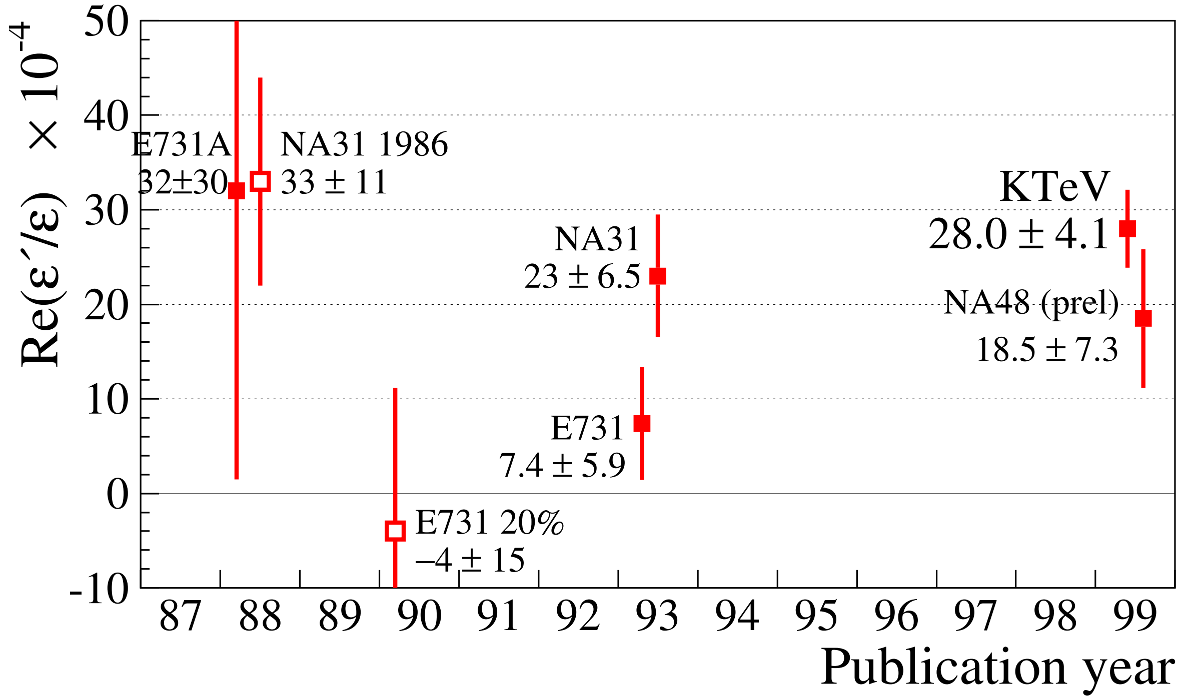
KTeV $Re\,(\epsilon'/\epsilon)$ Result

$$Re\,(\epsilon'/\epsilon) = (28.0 \pm 3.0_{STAT} \pm 2.8_{SYST}) \times 10^{-4}$$

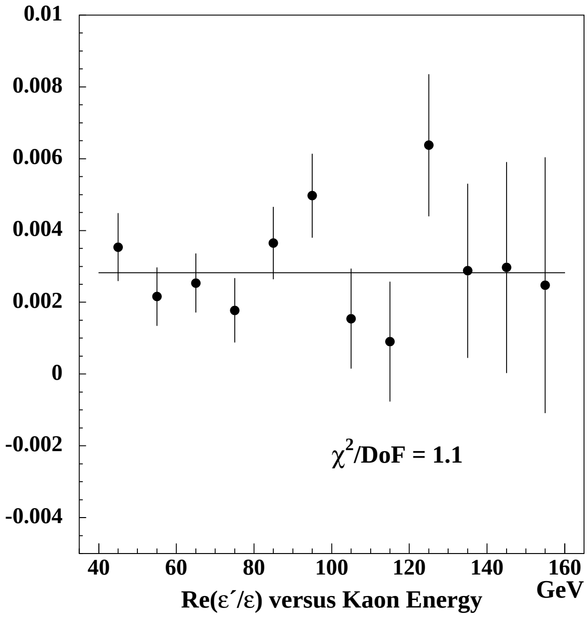
A. Alavi-Harati *et al.*, Phys. Rev. Lett. **83**, 22 (1999)

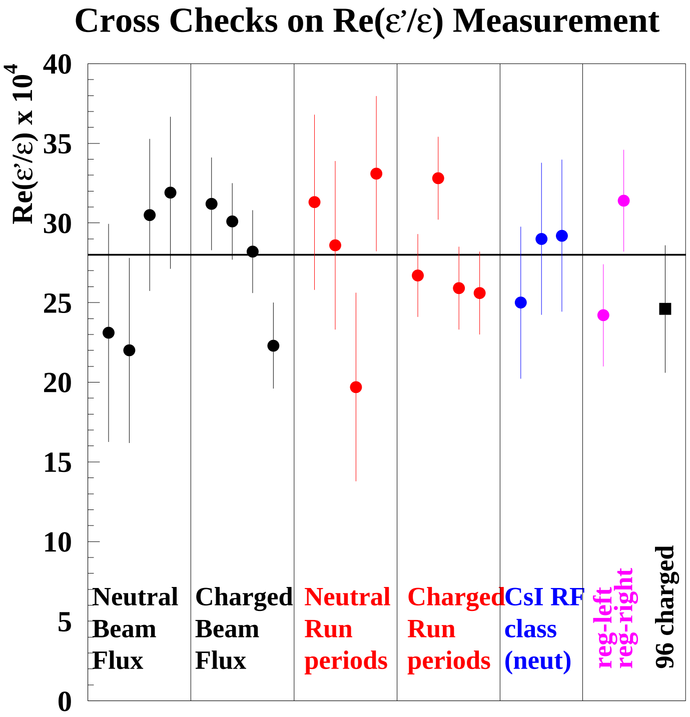
Direct CP violation definitively established

Consistent with earlier NA31 and recent NA48 results



$Re\ (\epsilon'/\epsilon)$ vs Kaon Energy





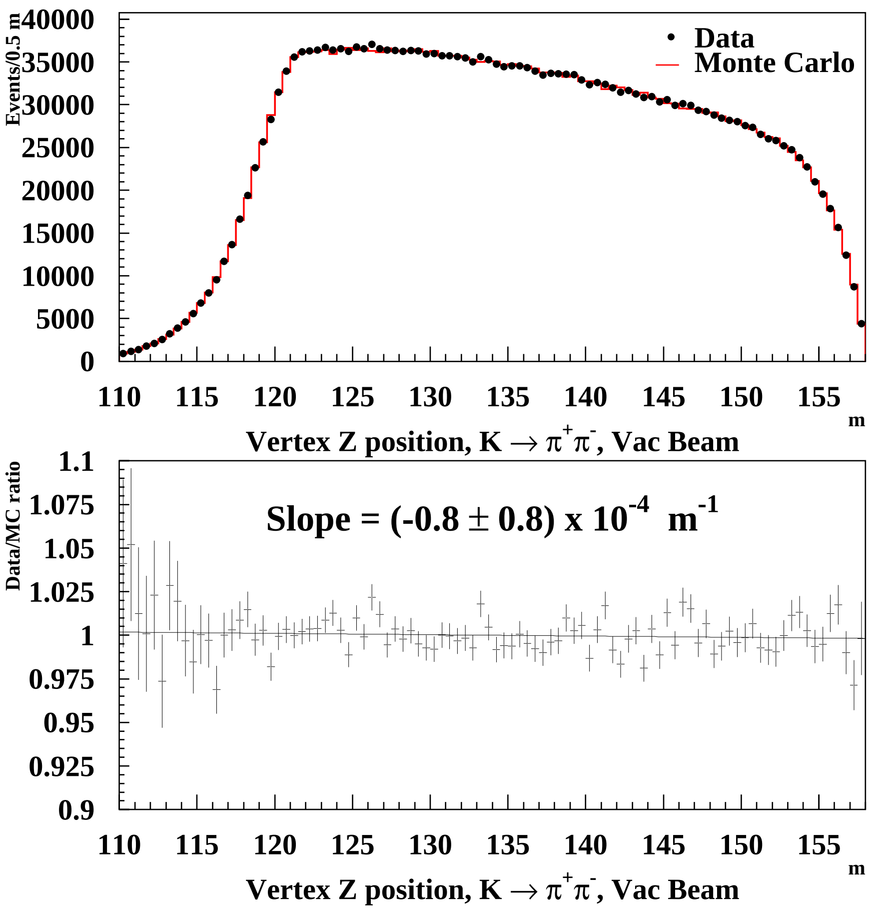
Alternate analysis: fit in p and Z bins

- No reliance on MC
- Agrees with standard analysis

Current Analysis and Future Plans

- Finished calibration of remaining $\frac{3}{4}$ 1997 data
- Performing detailed Data/MC comparisons

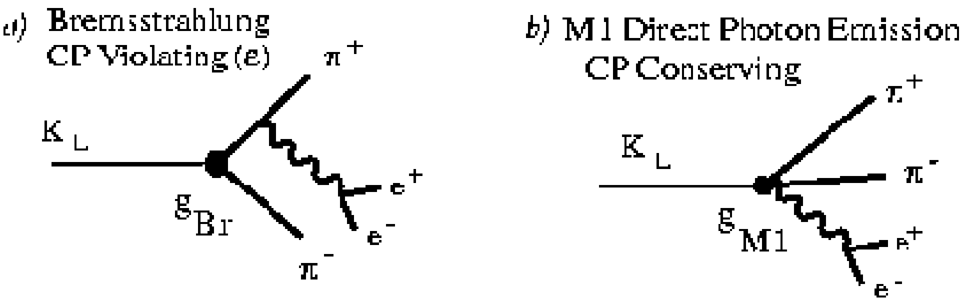
Vertex Z Distribution for 1997 $\pi^+\pi^-$ Data



- 1999 run has doubled the full data sample

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

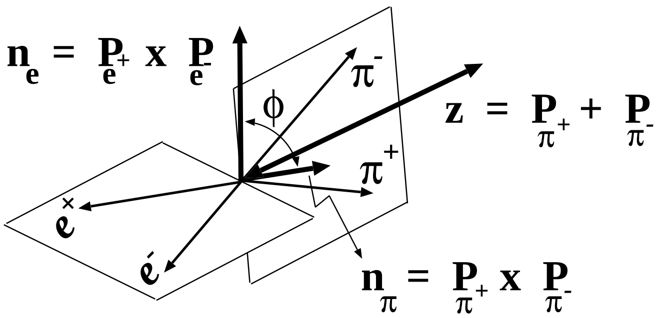
Interference between



Gives rise to a CP-violating asymmetry

$$A = \frac{N_{\sin_\phi \cos_\phi > 0} - N_{\sin_\phi \cos_\phi < 0}}{N_{\sin_\phi \cos_\phi > 0} + N_{\sin_\phi \cos_\phi < 0}}$$

$$\sin(\phi)\cos(\phi) = (\hat{n}_e \times \hat{n}_\pi) \bullet \hat{z}\,(\hat{n}_e \bullet \hat{n}_\pi)$$



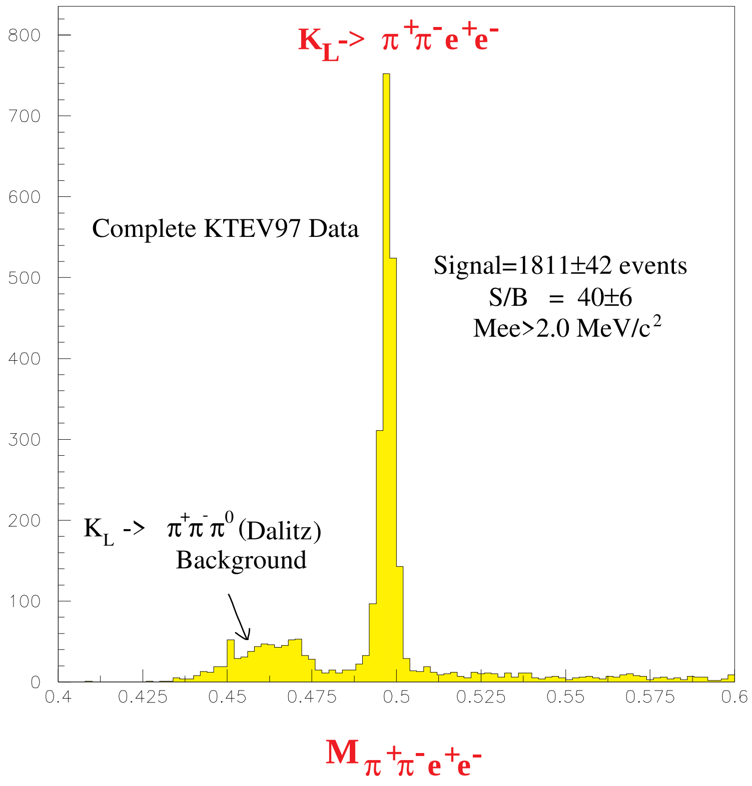
A is CP-odd and T-odd

$A \neq 0 \to$ CP violation and (assuming CPT), T violation

Theoretical prediction

$A = 14.4\%$ (Sehgal and Wanninger, 1992)

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



PRELIMINARY Branching Ratio

$$BR = (3.63 \pm 0.11_{STAT} \pm 0.14_{SYST}) \times 10^{-7}$$

Published result from 1 day of data

$\mathrm{BR} = (3.2 \pm 0.6 \pm 0.4) \times 10^{-7}$

PRL 80, 4123 (1998)

Background $K_L \to \pi^+\pi^-\pi^o_D$ Asymmetry

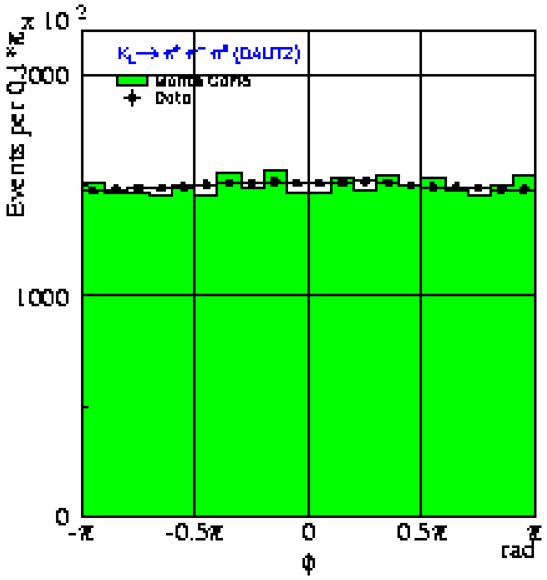
- $K_L \to \pi^+\pi^-\pi^o,\, \pi^o \to e^+e^-\gamma$

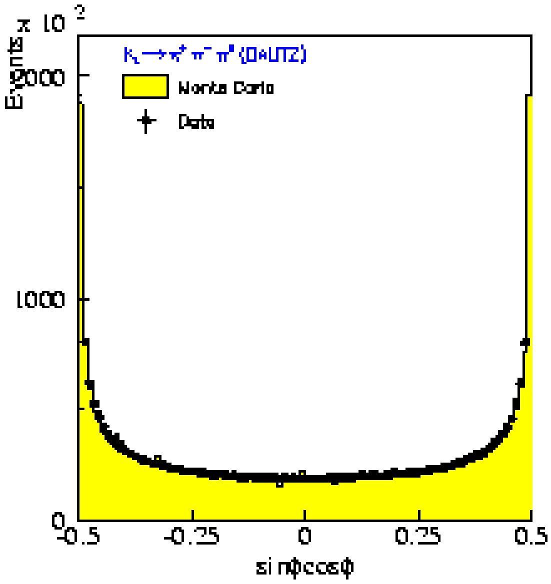
  Main source of background

  More than 3 million decays reconstructed

- $A\,(\phi)\,[K_L \to \pi^+\pi^-\pi^o_D] = -0.02 \pm 0.05\%$

  Spectrometer acceptance does not have an asymmetry

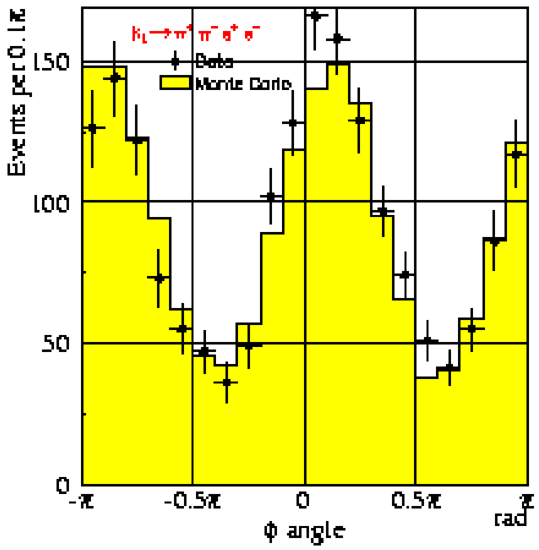


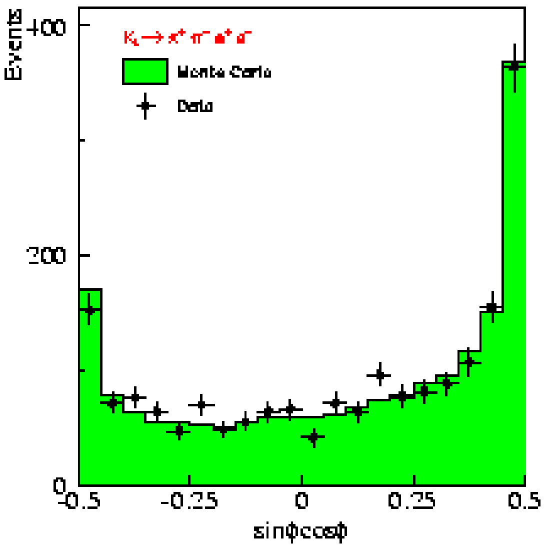


$K_L \to \pi^+\pi^-e^+e^-$ Asymmetry

Observed asymmetry

$$A\,(\phi) = (23.3 \pm 2.3_{STAT})\,\%$$





Acceptance corrected asymmetry

$$A\,(\phi) = (13.6 \pm 2.5_{STAT} \pm 1.2_{SYST})\,\%$$

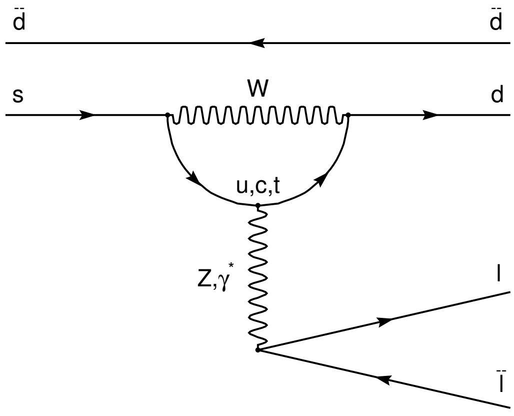
First CP violation effect observed in an angular distribution

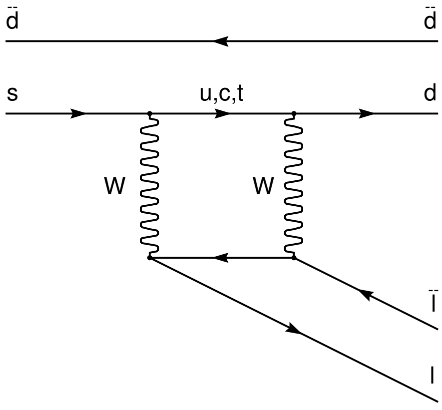
Largest CP violation effect yet observed

KTeV 1999 run increased data set by $\sim \times 3$

Search for Direct CP Violation in $K_L \to \pi^o l\bar{l}$

$K_L \propto K_2 + \epsilon K_1$





Theoretical Predictions

$$\mathrm{BR}\left(K_L \to \pi^o e^+ e^-\right)_{DIR} \sim 5 \times 10^{-12}$$

$$\mathrm{BR}\left(K_L \to \pi^o \mu^+ \mu^-\right)_{DIR} \sim 1 \times 10^{-12}$$

$$\mathrm{BR}\left(K_L \to \pi^o \nu\bar{\nu}\right)_{DIR} = \left(\frac{m_t}{m_W}\right)^{2.2} A^4 \eta^2 \sim 3 \times 10^{-11}$$

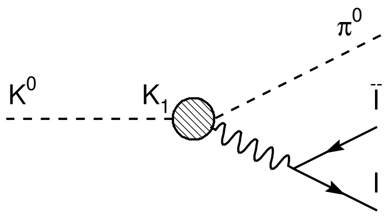
$K_L \to \pi^o e^+ e^-$ and $K_L \to \pi^o \mu^+ \mu^-$

- Direct CP violation

$$BR\left(K_L \to \pi^o e^+ e^-\right)_{DIR} \sim 5 \times 10^{-12}$$

$$BR\left(K_L \to \pi^o \mu^+ \mu^-\right)_{DIR} \sim 1 \times 10^{-12}$$

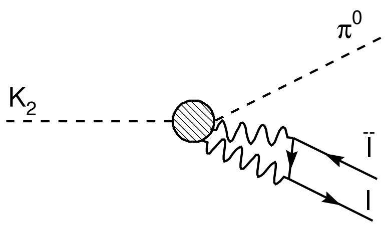
- Indirect CP violation



$$BR\left(K_L \to \pi^o e^+ e^-\right)_{IND} \sim (1-5) \times 10^{-12}$$

$$BR\left(K_L \to \pi^o \mu^+ \mu^-\right)_{IND} - ?$$

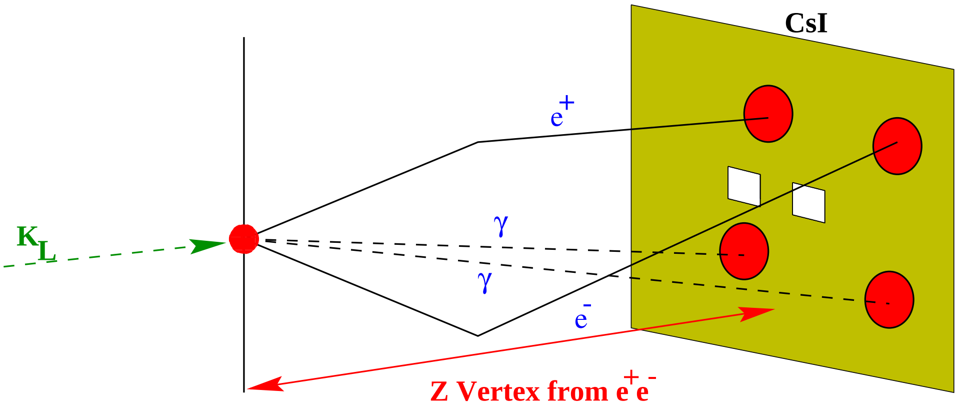
- CP conserving



$$BR\left(K_L \to \pi^o e^+ e^-\right)_{DIR} \sim (1-2) \times 10^{-12}$$

$$BR\left(K_L \to \pi^o \mu^+ \mu^-\right)_{DIR} \sim (0.5-10) \times 10^{-12}$$

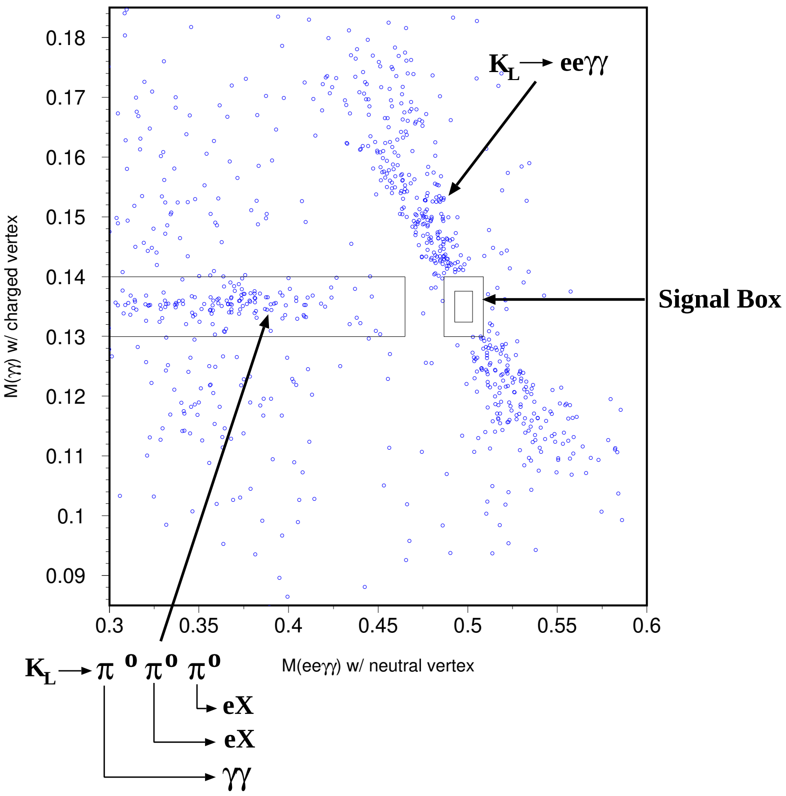
$K_L \to \pi^o e^+ e^-$ Analysis



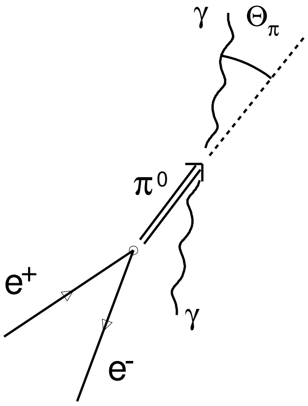
- Normalize to $K_L \to \pi^o \pi^o, \pi^o \to e^+ e^- \gamma$
- Major background: $K_L \to e^+ e^- \gamma\gamma$

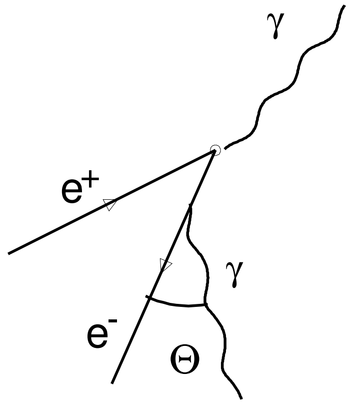
KTeV measurement: $BR = (6.31 \pm 0.14 \pm 0.42) \times 10^{-7}$
1988 events with 76 background events

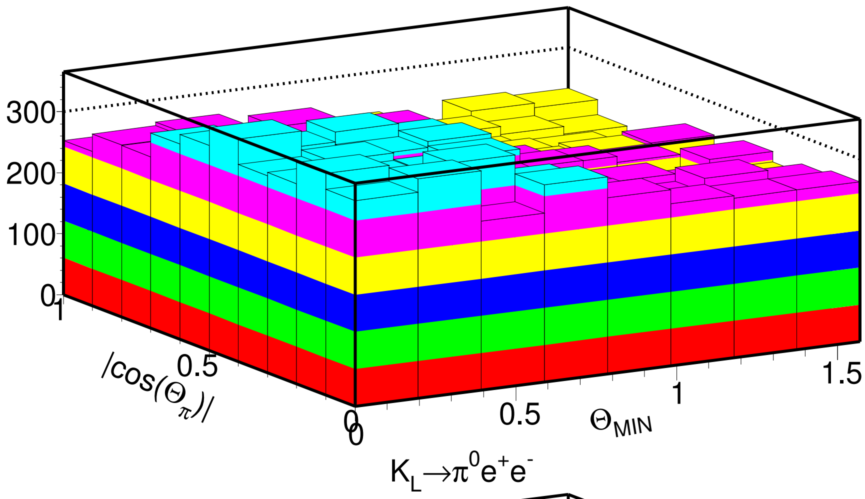
$M_{\gamma\gamma}$ vs $M_{ee\gamma\gamma}$

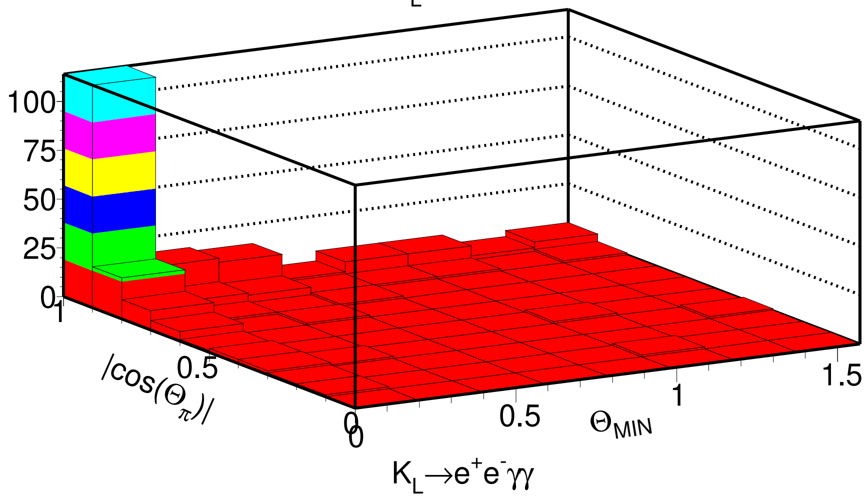


$K_L \to \pi^o e^+ e^-$ and $K_L \to e^+ e^- \gamma\gamma$ Kinematic Cuts

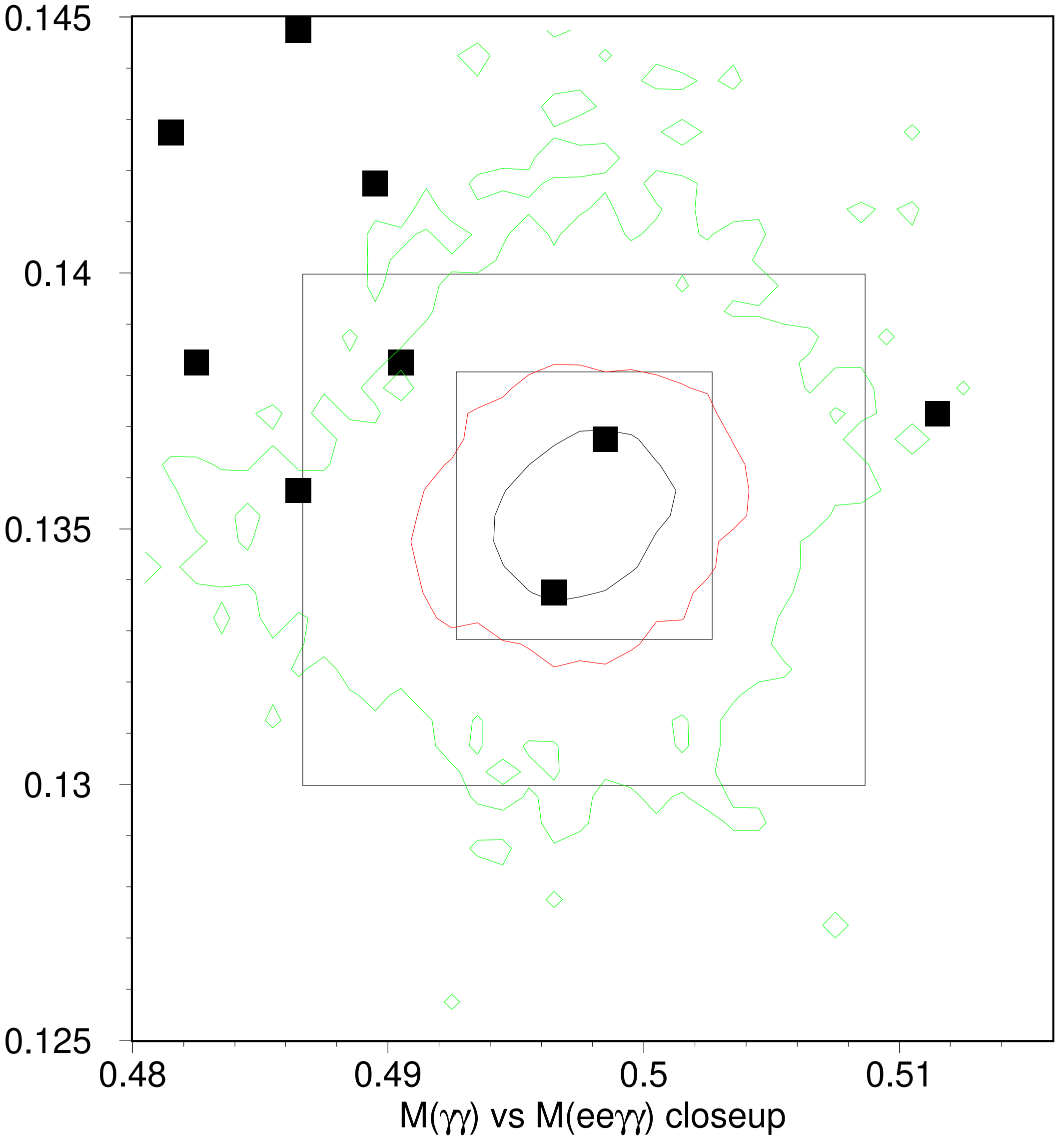








$K_L \rightarrow \pi^o e^+ e^- Result$



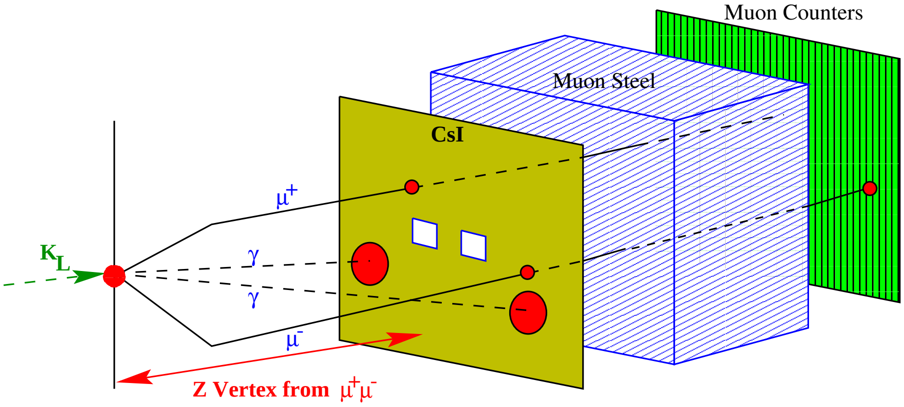
- Two events in signal box

  Expect 1.5 ± 0.4 background events

- $BR < 5.64 \times 10^{-10}$ (90% C.L.)

  Order of magnitude improvement over previous limit

$K_L \to \pi^o \mu^+ \mu^-$ Analysis



- Normalize to $K_L \to \pi^+ \pi^- \pi^o$

- Backgrounds

  $K_L \to \pi^+ \pi^- \pi^o, K_L \to \pi \mu \nu + 2\gamma_{acc}$

  $K_L \to \pi \mu \nu + 2\gamma_{acc}$

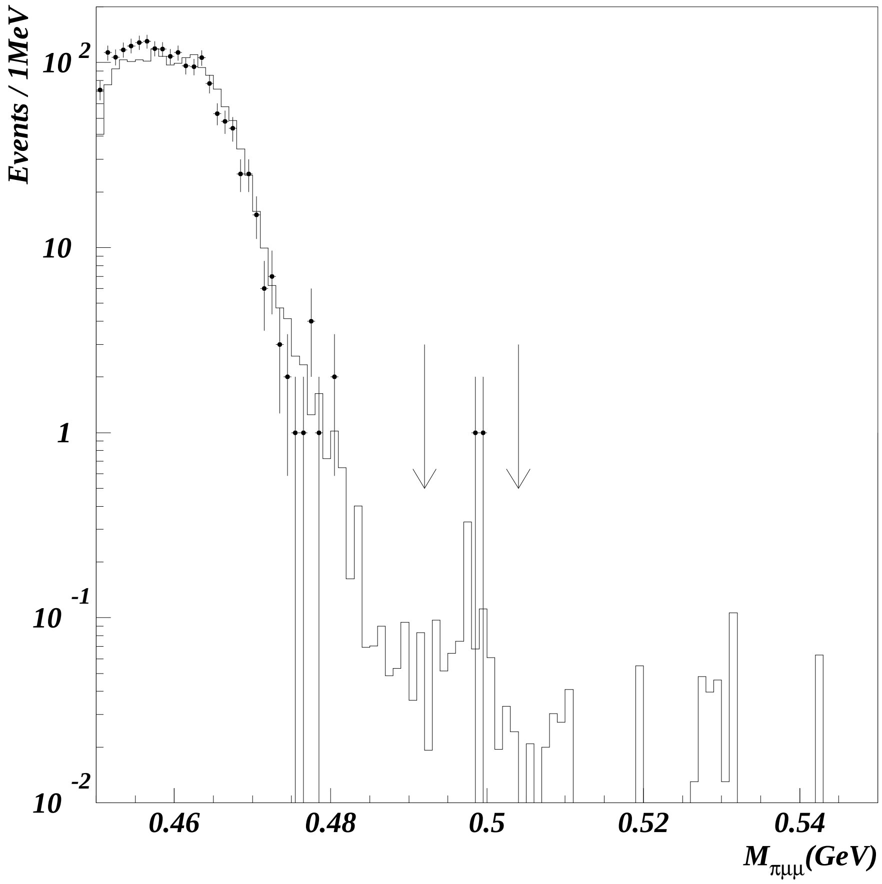
  $K_L \to \mu^+ \mu^- \gamma\gamma$

  KTeV measurement:

  BR($M_{\gamma\gamma} > 1MeV$**)** = $\left(10.4^{+7.5}_{-5.9} \pm 1.0\right) \times 10^{-9}$

  4 events with 0.16$\pm$0.08 background events

$K_L \to \pi^o \mu^+ \mu^-$ Result



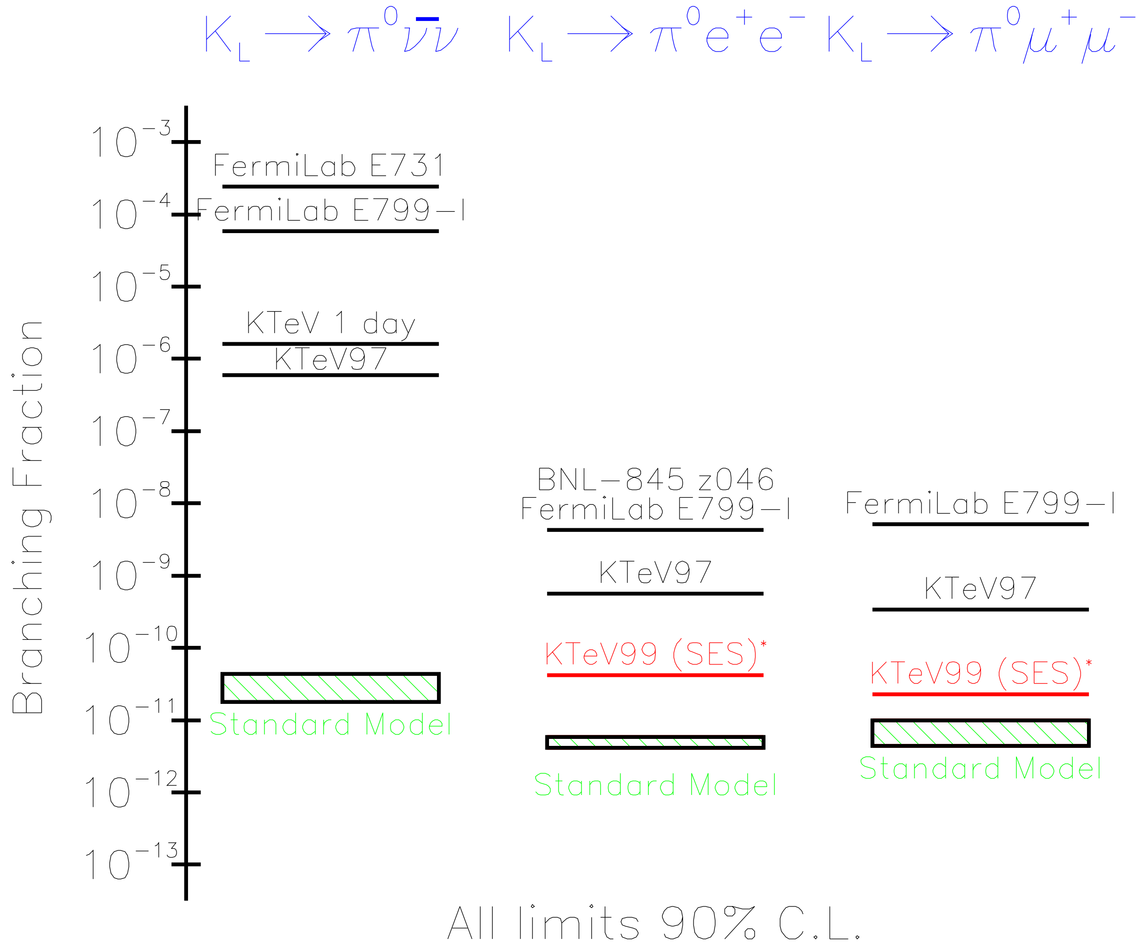
- Two events in signal box

  Expect 1.02 ± 0.18 background events

- $BR\,(K_L \to \pi^o \mu^+ \mu^-) < 3.8 \times 10^{-10}$ (90% C.L.)

  Order of magnitude improvement over previous limit

Status of $K_L \to \pi^o l\bar{l}$



KTeV 1999 run has tripled rare decay data set

$K_L \to \pi^o e^+ e^-$, $K_L \to \pi^o \mu^+ \mu^-$ reaching background limits

SUSY penguins $\sim 1 - 2$ orders of magnitude over SM

$K_L \to \pi^o \nu \bar{\nu}$

- BR $(K_L \to \pi^o \nu \bar{\nu}) \propto \eta^2 \sim 3 \times 10^{-11}$

  Dominated by direct CP violating amplitude

  Theoretical uncertainties $\sim 1\%$

  Current BR $(K_L \to \pi^o \nu \bar{\nu}) < 5.9 \times 10^{-7}$ (KTeV)

- Potential backgrounds

  $K_L \to \pi^o \pi^o$, $K_L \to \pi^o \pi^o \pi^o$

  $\Lambda \to \pi^o n$

  $\Xi \to \Lambda \pi^o$

- The KAMI Experiment

  Kaon exp. using Fermilab 150 GeV Main Injector beam

  Measure η to 10% using $K_L \to \pi^o \nu \bar{\nu}$, $\pi^o \to \gamma\gamma$

  Study other rare decay modes to $\sim 10^{-13}$ level

  KTeV beam test

  - Measure neutron/kaon fluxes and spectra
  - Study prototype beam hole vetoes

Summary

Completed 1999 run

- DOUBLED the 1996-1997 E832 data set

  $Re\,(\epsilon'/\epsilon)$ statistical error $\sim 1 \times 10^{-4}$

- TRIPLED the 1997 E799 data set

Successful 1996-1997 Run

- $Re\,(\epsilon'/\epsilon)$ measurement using $\sim 15\%$ of data

  $Re\,(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4}$

  Establishes Direct CP Violation

  Consistent with earlier NA31 and recent NA48 results

  Analysis of full 1996-1997 data continuing

- Extended $K_L \to \pi^o l\bar{l}$ searches

Mode	**Branching Ratio**	**Improvement**
$K_L \to \pi^o e^+ e^-$	$< 5.64 \times 10^{-10}$	$\times 7.5$
$K_L \to \pi^o \mu^+ \mu^-$	$< 3.8 \times 10^{-10}$	$\times 15$
$K_L \to \pi^o \nu\bar{\nu}$	$< 5.9 \times 10^{-7}$	$\times 100$