Results on Rare K_L Decays from KTeV

Michael Arenton
University of Virginia
(for KTeV Collaboration)

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- CP violation in $K_L \rightarrow \pi^+\pi^-e^+e^-$
- Measurement of K_L charge radius from $K_L \rightarrow \pi^+\pi^-e^+e^-$
- First result on a search for $K_L \rightarrow \pi^0\pi^0e^+e^-$
- Results on $K_L \rightarrow \pi^0 l\bar{l}$ and prospects in KAMI

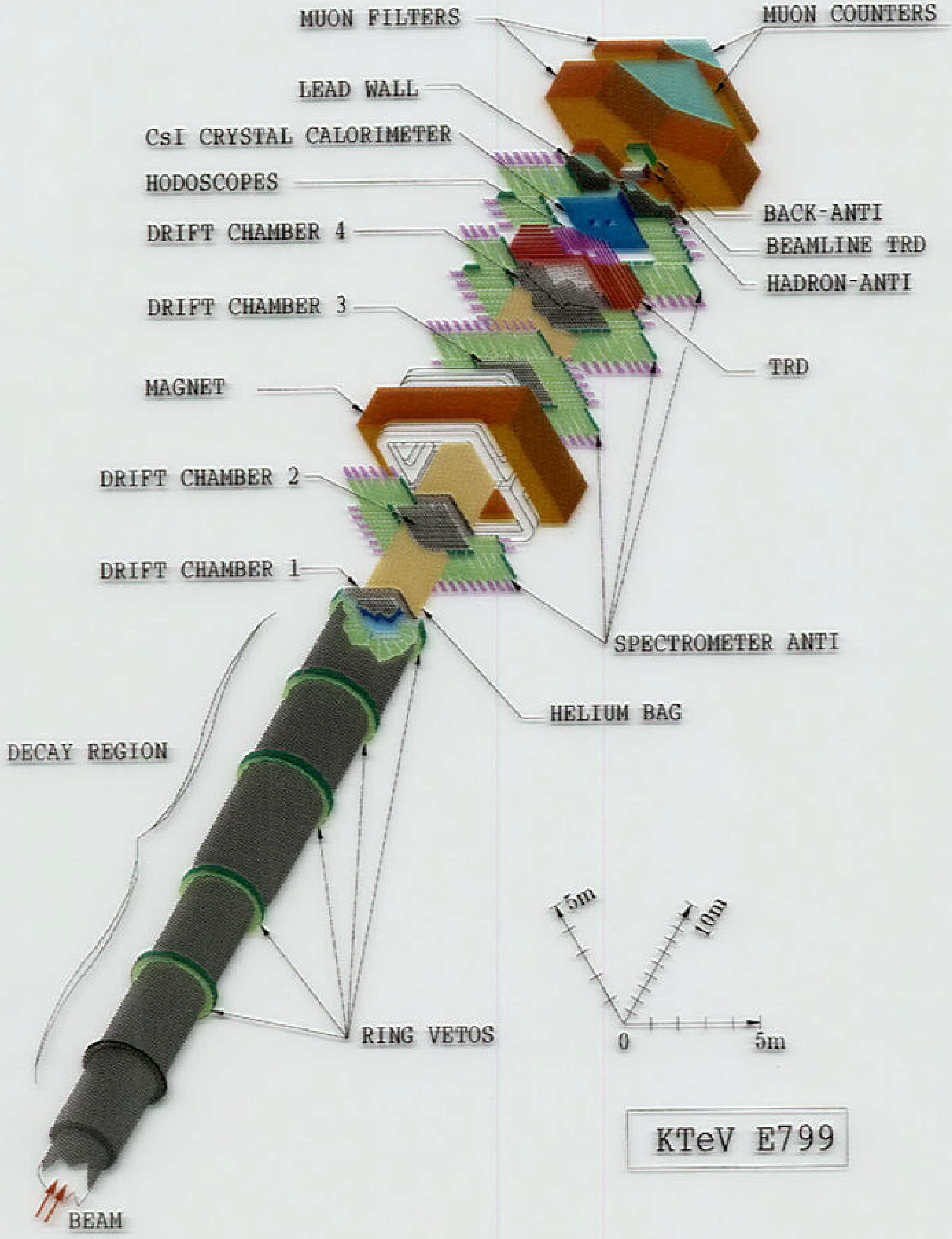
Present KTeV Collaboration

University of Arizona

Present KTeV Collaboration

University of Arizona
University of California, Los Angeles
University of California, San Diego
University of Campinas, Brazil
University of Chicago
University of Colorado, Boulder
Elmhurst College
Fermi National Accelerator Laboratory
Osaka University
Rice University
Rutgers University
University of Sao Paulo, Brazil
University of Virginia
University of Wisconsin

KTeV Spectrometer (E799-II)



KTeV E799

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

This decay was first seen by KTeV in 1998, and branching fraction measured from 2% of the data.

Current branching fraction from entire 1997 data set is (still preliminary, submitted for publication soon):

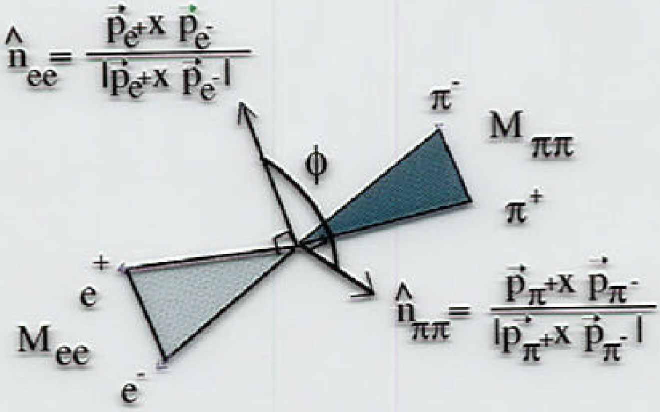
$$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}.$$

$K_L \to \pi^+\pi^-e^+e^-$ shows a new indirect CP violating effect as an asymmetry in a T-odd angular variable.

These asymmetry results from the 1997 run have been published in A.Alavi-Harati **et.al.** Physical Review Letters **84**, 408 (2000).

We are continuing to analyse other physics that may be extracted from this decay

CP-odd and T-odd angle ϕ



$$\hat{z} = \frac{\vec{p}_{\pi^+} + \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} + \vec{p}_{\pi^-}|}$$

$$\sin\phi\cos\phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$$

$$\begin{array}{ll} CP(\hat{n}_{ee}) \rightarrow \hat{n}_{ee} & T(\hat{n}_{ee}) \rightarrow \hat{n}_{ee} \\ CP(\hat{n}_{\pi\pi}) \rightarrow \hat{n}_{\pi\pi} & T(\hat{n}_{\pi\pi}) \rightarrow \hat{n}_{\pi\pi} \\ CP(\hat{z}) \rightarrow -\hat{z} & T(\hat{z}) \rightarrow -\hat{z} \\ CP(\phi) \rightarrow -\phi & T(\phi) \rightarrow -\phi \end{array}$$

Definition of the asymmetry:

$$A(\phi) \equiv \frac{N_{sin\phi cos\phi} > 0.0 - N_{sin\phi cos\phi} < 0.0}{N_{sin\phi cos\phi} > 0.0 + N_{sin\phi cos\phi} < 0.0}$$

Spectrometer and Basic Event Reconstruction

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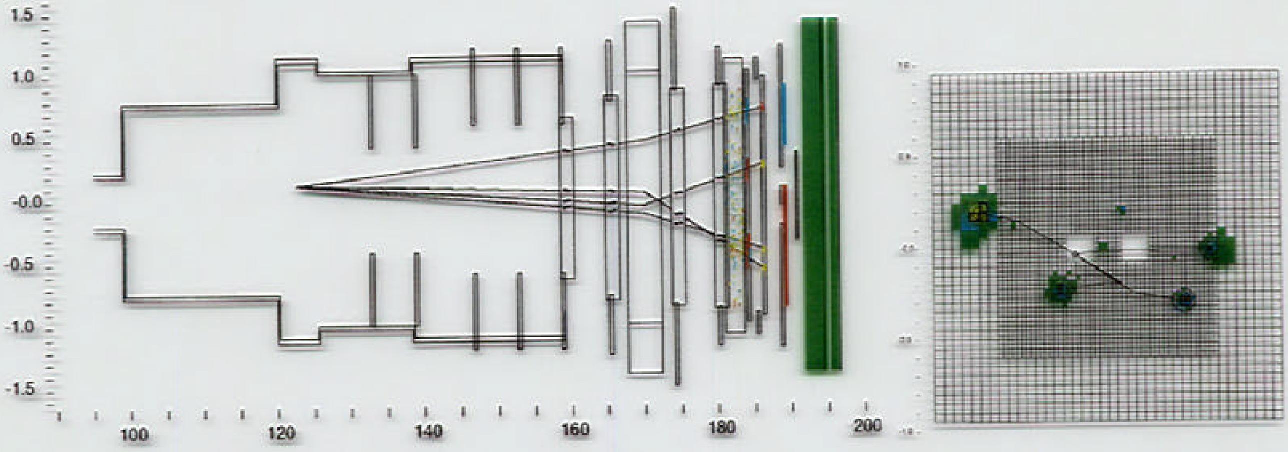
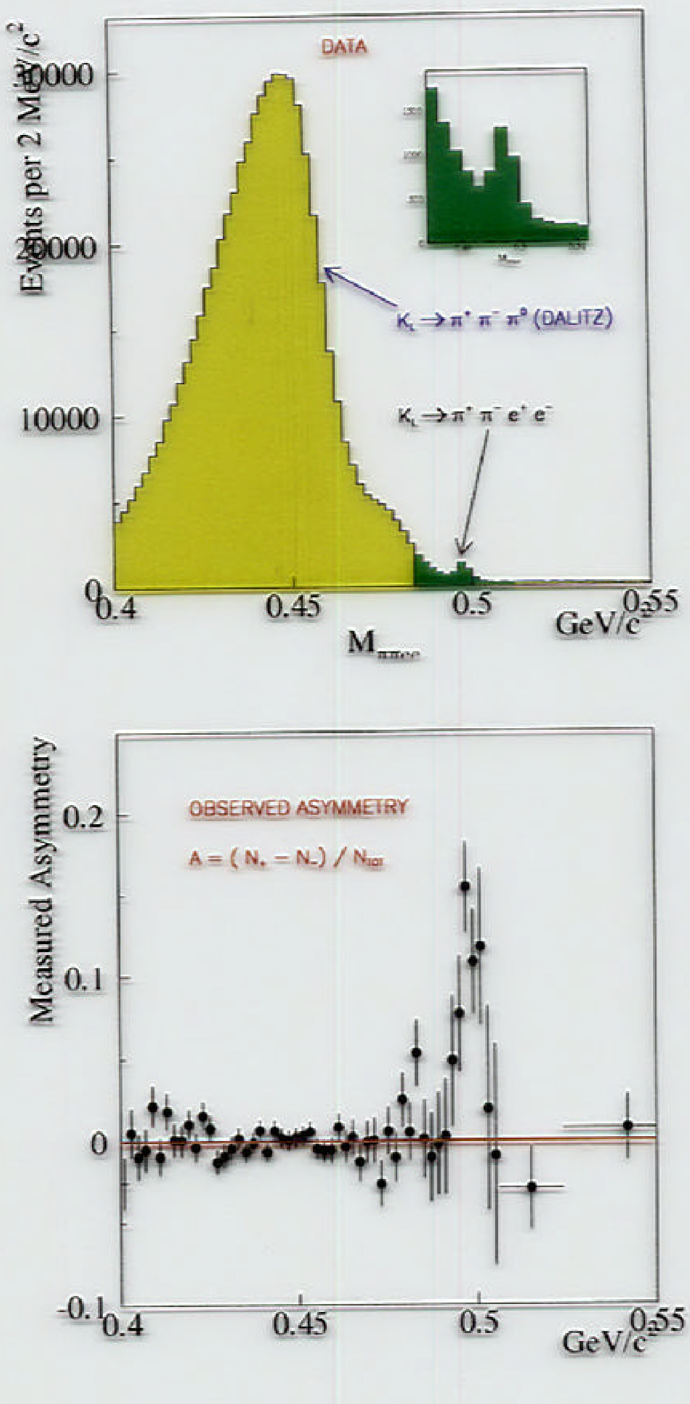


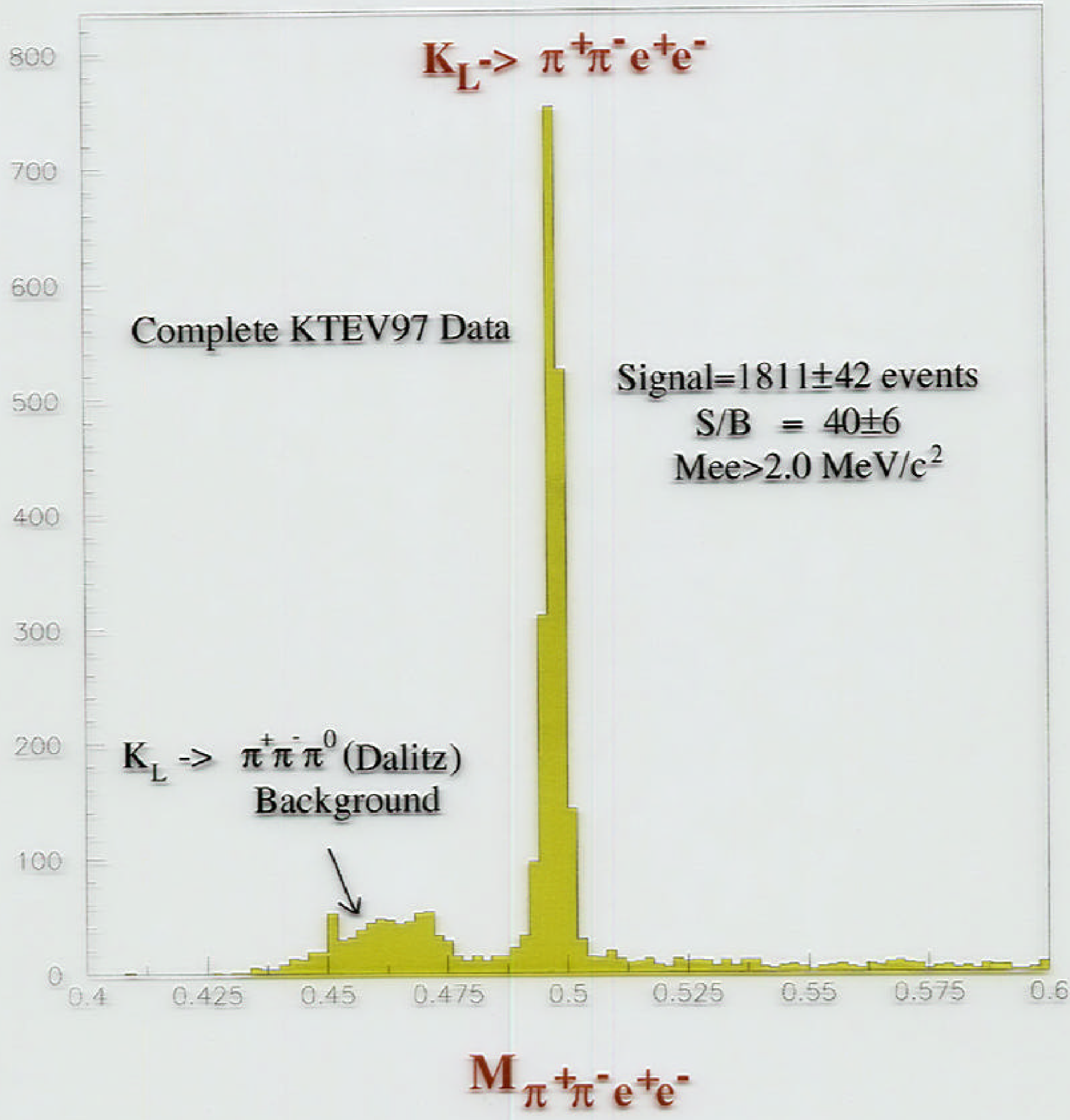
- **Spectrometer**
  - Vacuum decay volume $95m < Z < 158m$ (The target is at $Z = 0$)
  - Drift chambers: resolution $\sim$100 μm
  - CsI calorimeter: $\sim$1% energy resolution, $\sim$1-2 mm position resolution.
- **4-track Trigger**
  - $\geq$ 3 hits in the VV' hodoscope
  - $E_{CsI} \geq 11$ GeV
  - $\geq$ 2 clusters in the CsI
  - $E_{cluster} \geq 1$ GeV
  - 3 or 4 hits in each upstream drift chamber set in each view
  - no hits in the μ hodoscopes
- **Event selection**
  - π^+, π^-, e^+, e^+ identified in CsI calorimeter:
    - $0.95 < E/p < 1.05$ for electrons
    - $E/p < 0.9$ for pions
  - Various track geometry cuts (vertex position, matching in magnet)

- Very loose initial kinematics cuts.
- 2.5 million events selected



Very large asymmetry at Kaon mass!
Background does not have asymmetry!

Mass distribution after final cuts



Observed Asymmetry

A large asymmetry is observed in experimental data.

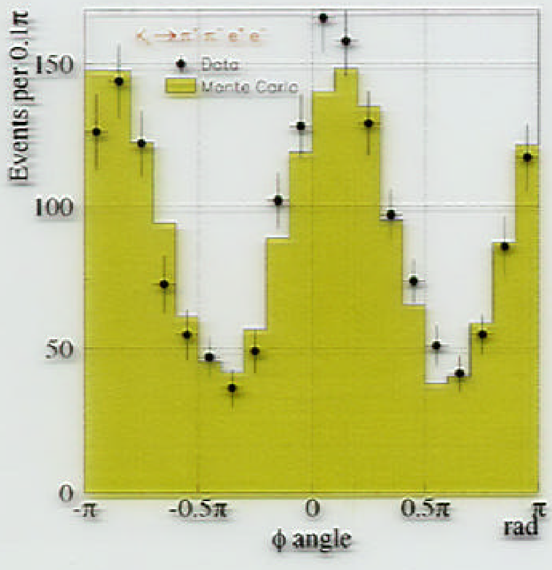
$$A(\phi) = 23.3 \pm 2.3(stat)\ \%$$

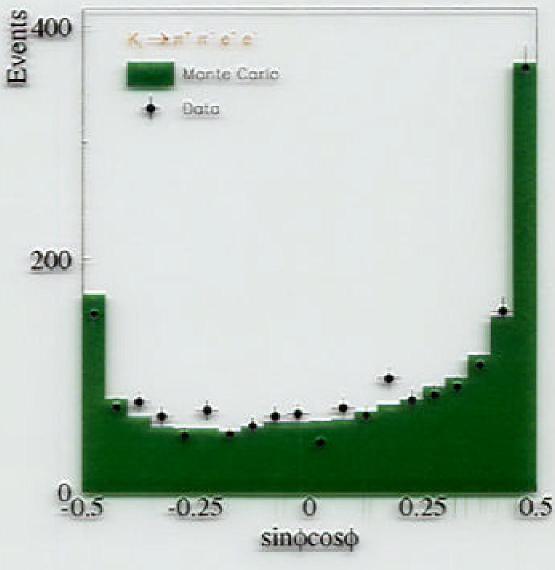
Experimental acceptance preferentially cuts out some phase space regions with low asymmetry. The magnitude of the acceptance corrected asymmetry is

$$A(\phi) = 13.6 \pm 2.5(stat) \pm 1.2(syst)\%$$

which is consistent with the theoretically expected asymmetry, 14.4 %

Comparison of data and Monte Carlo distributions[1]



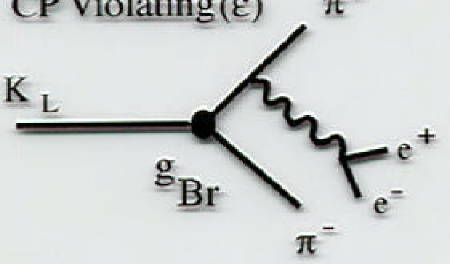


[1] Monte Carlo model is according to L.M. Sehgal and M. Wanniger, Phys. Rev. D46, 1035(1992)

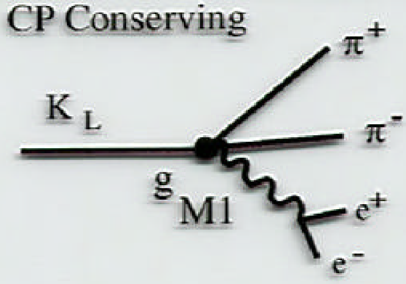
Theoretical Model (Sehgal and Wanninger)

K->ππee Processes

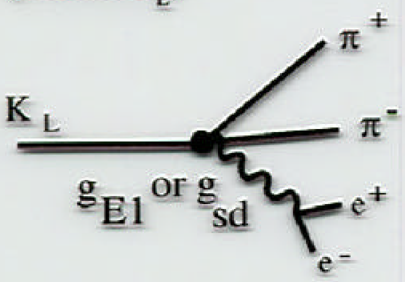
a) Bremsstrahlung
CP Violating(ε)



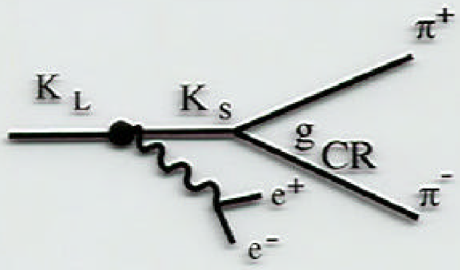
b) M1 Direct Photon Emission
CP Conserving



c) E1 Direct Photon Emission
CP Violating or Direct CP(ε')
(ε from K_L)



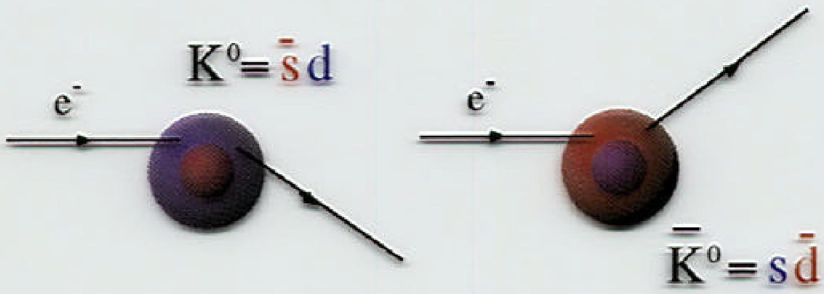
d) KO Charge Radius
CP Conserving

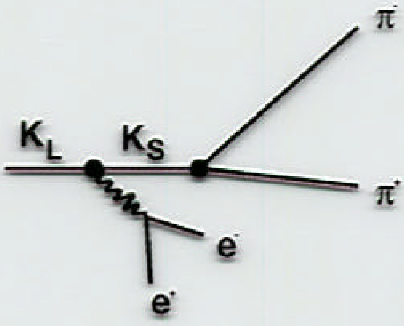


K^0 R.M.S. Charge Radius

$K^0 = \bar{s}d$; $m_s > m_d$; the heavier $\bar{s}$ quark is confined to smaller radii thus giving the K^0 a positively charged core.

$$< R^2 > \equiv \frac{1}{3} r_s^2 - \frac{1}{3} r_d^2$$



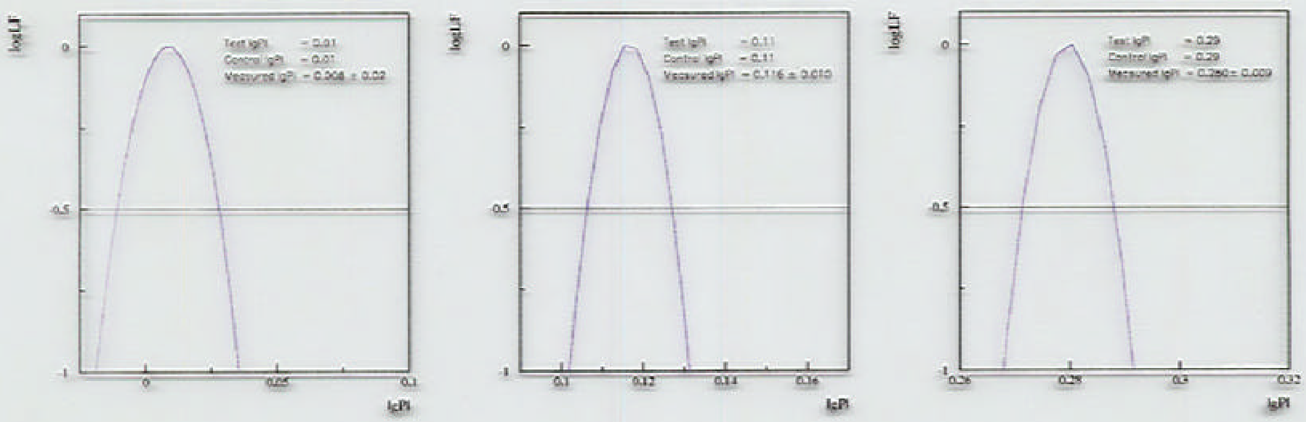


$$g_P = -\frac{1}{3} < R^2 > m_K^2$$

An experimental measurement of the K^0 charge radius is an opportunity to determine $m_s = m_d$

A Preliminary KTeV Result: Extend likelihood fit to include g_P fit.

Maximum Likelihood fit for $|gP|$

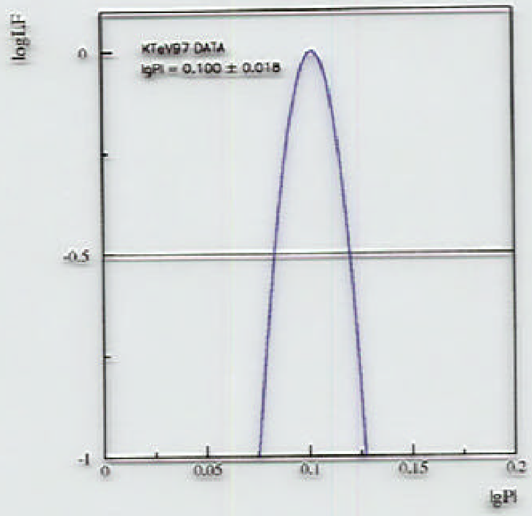


Log likelihood functions for MC "test" samples (of 2000 events each) generated with $|gP|$ values of 0.01, 0.11 and 0.29 . The fits return answers for $|gP|$ of 0.008$\pm$0.02, 0.116$\pm$0.01 and 0.280$\pm$0.009 respectively.

Source	Range	Systematic uncertainty
Monte Carlo sample	N/A	0.002
$gE1$	0.0 - 0.076	0.004
a_1/a_2 $gM1$	-0.72$\pm$0.028 1.35$\pm$0.20	0.007
Φ_{+-}	43.7$^o\pm$0.6^o	0.0002
$\lvert\eta_{+-}\rvert$	2.285$\pm$0.019	0.0
Background	$\leq$100 evt	0.01
Total		0.013

Table 1: Systematic error breakdown

Result of Maximum Likelihood fit to the data



The measured $|gP|$ value is

$$|gP| = 0.100 \pm 0.018(stat) \pm 0.013(sys)$$

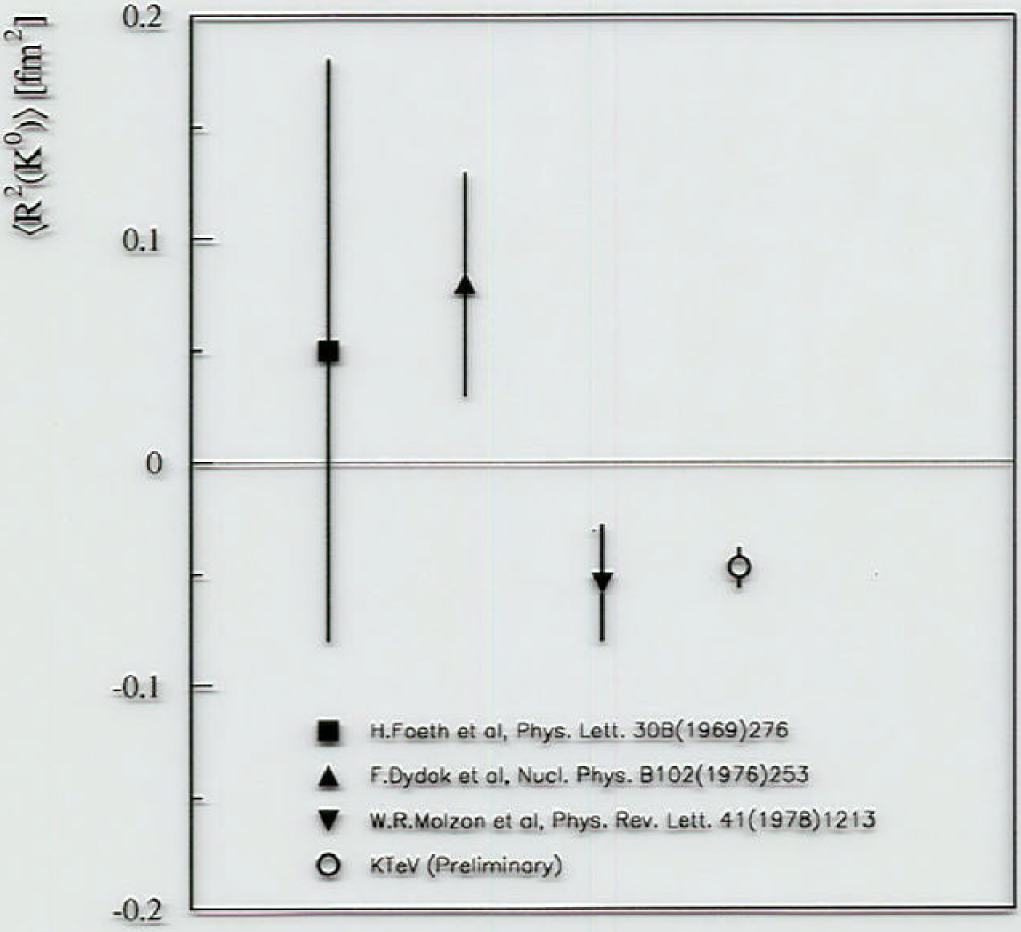
Caveat: Higher order loop diagrams in Chiral Perturbation Theory may give contributions similar in form to the charge radius. In this sense we have made an "effective" measurement. This point is still being investigated.

$$|gP| = -\frac{1}{3} < R^2(K^0) > M_K^2$$

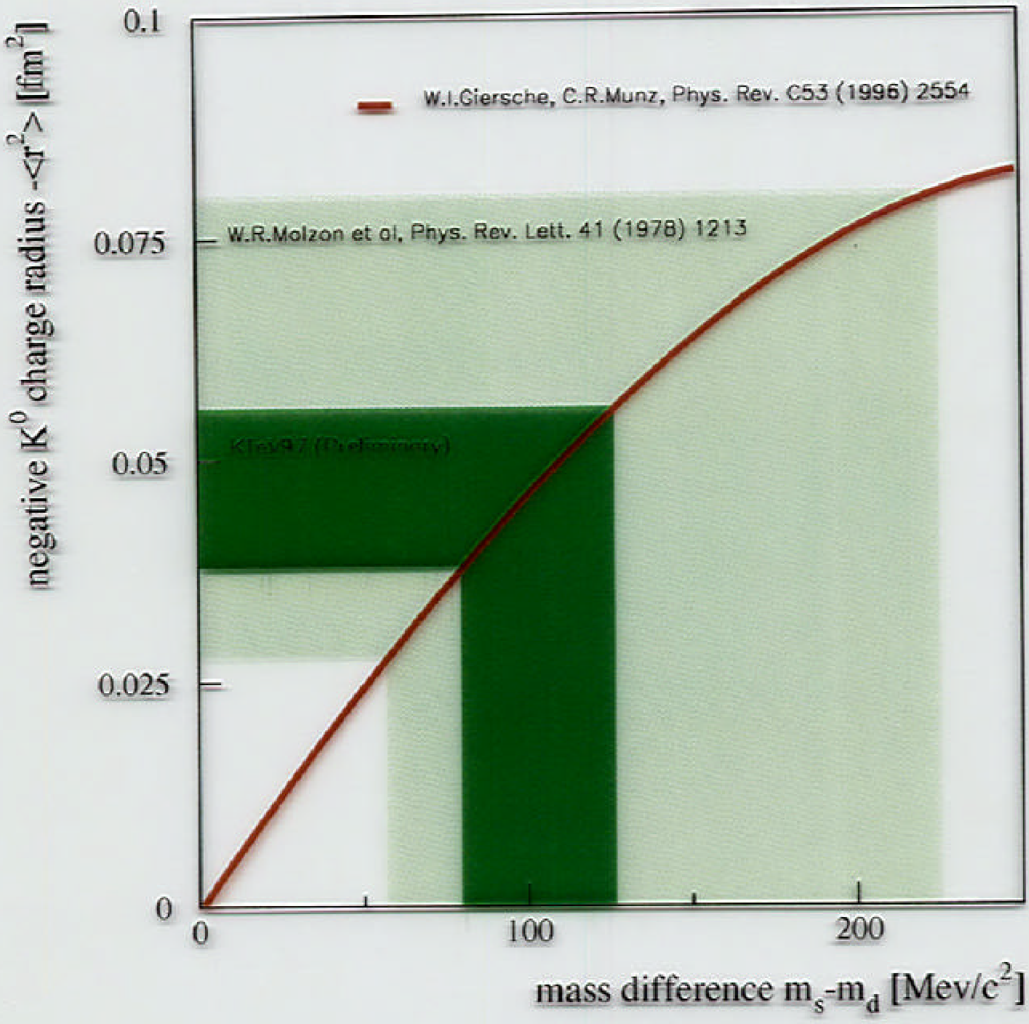
implies

$$< R^2(K^0) > = -0.047 \pm 0.008(stat) \pm 0.006(sys)[fm^2]$$

All existing measurements of K^0 charge radius



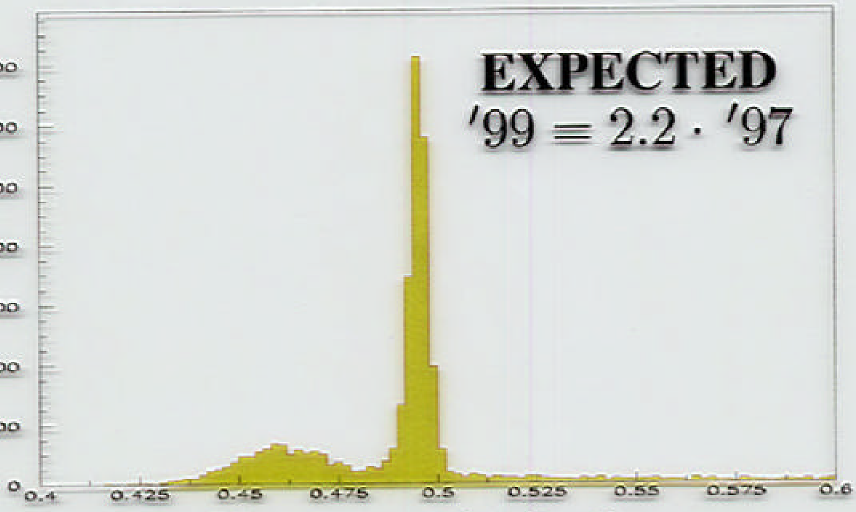
K^0 charge radius as a function of mass difference between s and d quarks from a recent theoretical calculation. World's best and KTeV results are also shown to illustrate sensitivity to quark mass difference.



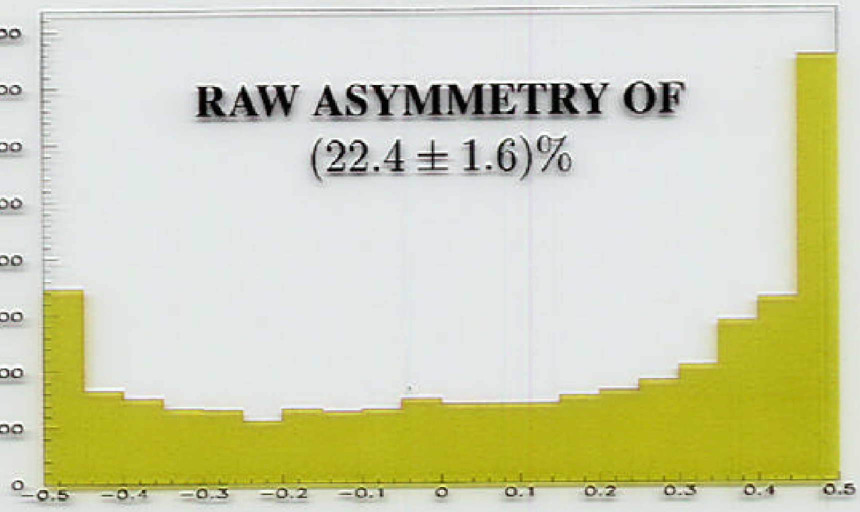
First Look at the 1999 Data

$K_L \to \pi^+\pi^-e^+e^-$, **after all cuts**

PRELIMINARY



$M_{\pi^+\pi^-e^+e^-}$ **distribution**



$sin(\phi) \cdot cos(\phi)$

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

This decay is similar to $K_L \to \pi^+\pi^- e^+e^-$ but has no Inner Brem contribution, and Bose statistics restricts the $\pi^0\pi^0$ pair to have l=2. So the important amplitudes are the charge radius amplitude and an E2 (CP conserving) direct emission amplitude, with an M2 (CP violating) amplitude expected to be suppressed. Theoretical predictions for the branching fraction are $1 - 2 \times 10^{-10}$.

$K_L \to \pi^0\pi^0 e^+e^-$ is of course related to $K_L \to \pi^0\pi^0\gamma$, which has never been observed (B.R. limit 5.6×10^{-6}) and is extremely difficult to look for due to the background from $K_L \to \pi^0\pi^0\pi^0$.

Look for $K_L \to \pi^0\pi^0 e^+e^-$ in events with 2 tracks identified as e^+e^- by E/p in CsI calorimeter plus 4 other energy clusters in the CsI.

Backgrounds: (π^0_D denotes $\pi^0 \to e^+e^-\gamma$)

- $K_L \to \pi^0\pi^0\pi^0_D$ with one γ missing.
- $K_L \to \pi^0\pi^0\pi^0$ where one γ converts to e^+e^- pair and one γ is lost.
- $K_L \to \pi^0\pi^0\pi^0$ where $\pi^0 \to e^+e^-$, or $\pi^0 \to e^+e^-e^+e^-$ and two e's are lost.
- $K_L \to \pi^0\pi^0\pi^0$ where 2 γ's convert and one e^+e^- pair is lost.
- $K_L \to \pi^0\pi^0_D$ and $K_L \to \pi^0 e^+e^-\gamma$ with an accidental γ.

Example of an event

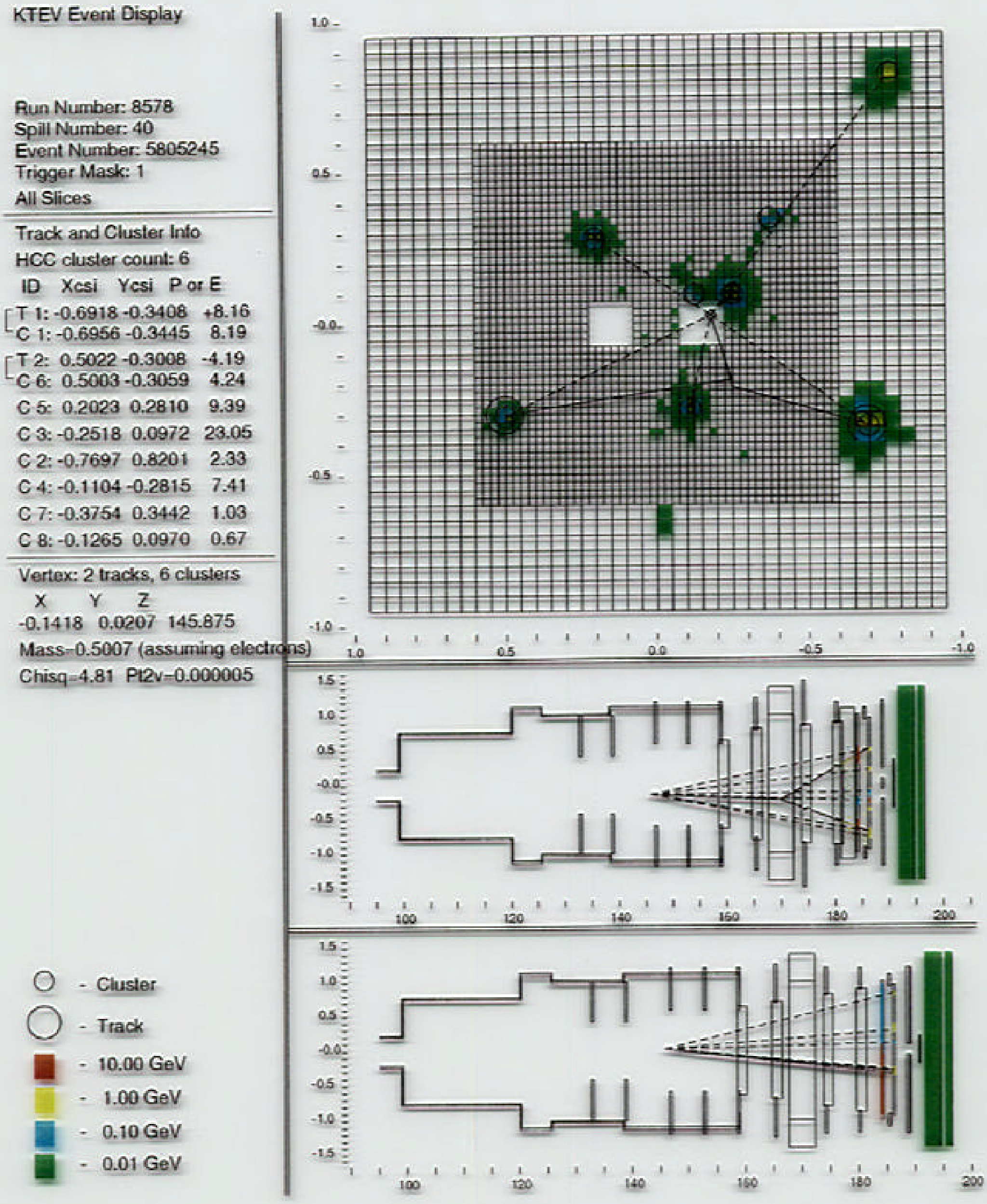
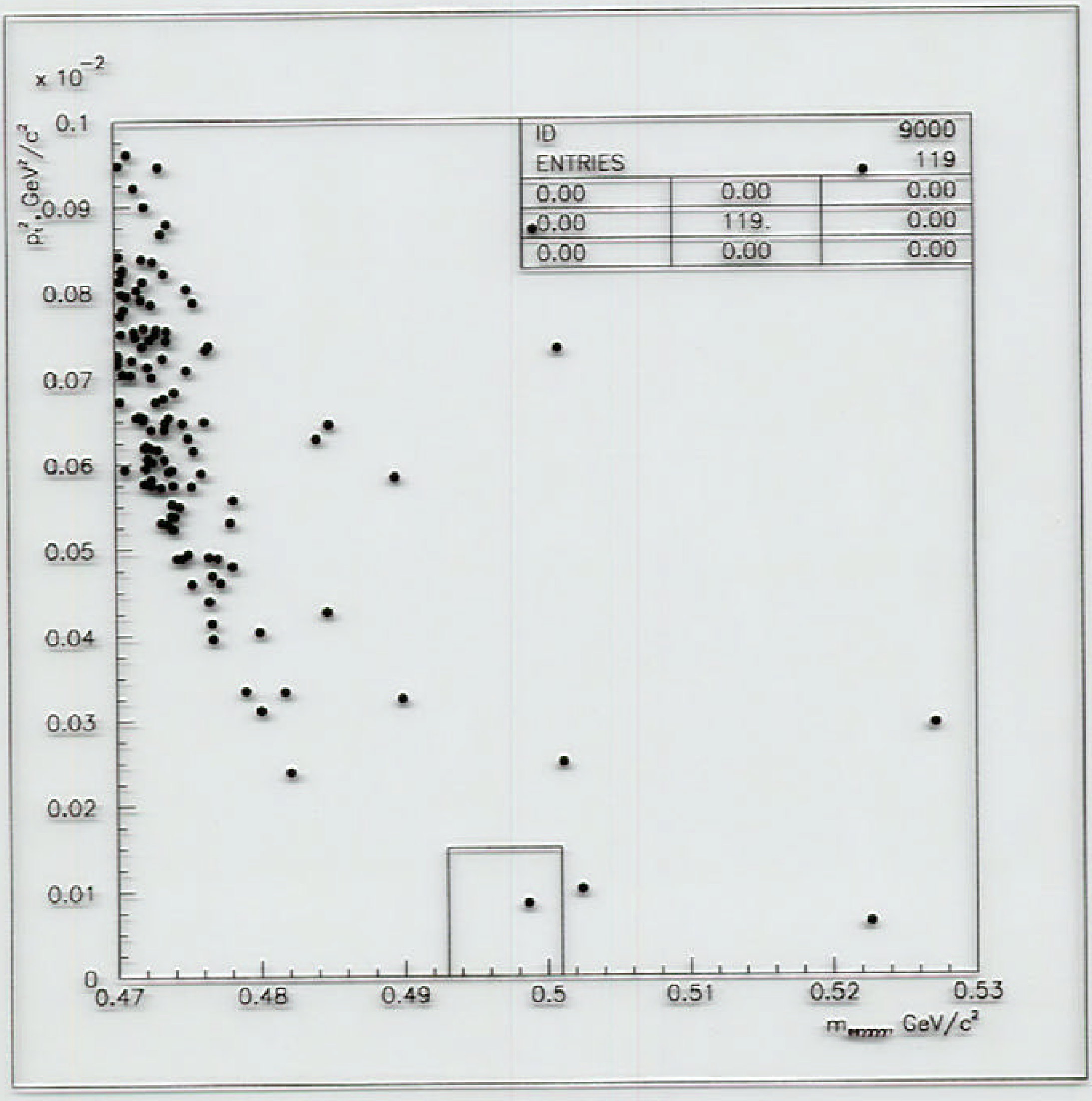


Figure 50: The KTeV event display of the event from the signal box.

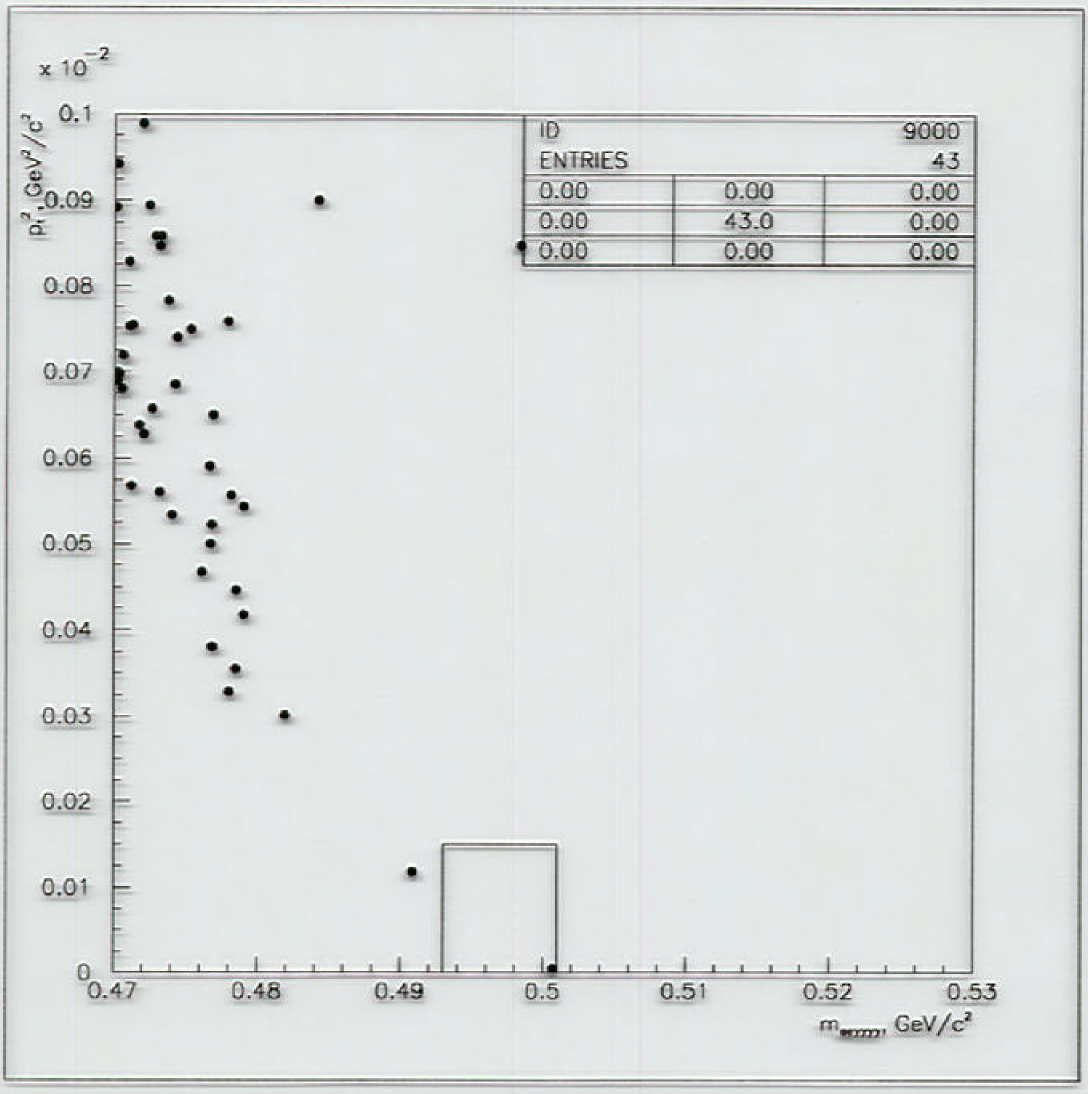
Cuts have been devised to eliminate these backgrounds. The limiting background is from $K_L \to \pi^0\pi^0\pi^0_D$.

Monte Carlo prediction of background, K_L decay flux equal to 3 times that of the experiment.



Based on this Monte Carlo the background is predicted to be $0.4^{+0.4}_{-0.3}$ events in the signal region.

KTeV data searching for $K_L \rightarrow \pi^0\pi^0 e^+ e^-$



With a flux of $2.7 \times 10^{11} K_L$ decays, an acceptance of 0.25%, one event seen with expected background of $0.4^{+0.4}_{-0.3}$ event, preliminary result for 90% confidence level upper limit on branching fraction is:

B.R.($K_L \rightarrow \pi^0\pi^0 e^+ e^-$) $\leq 5.4 \times 10^{-9}$.

Decays of the type $K_L \to \pi^0 l\bar{l}$

Expected to proceed by 3 mechanisms.

- CP conserving contribution through $\pi^0\gamma\gamma$ intermediate.
- indirect-CP violating contribution from $K_1 \to \pi^0 l\bar{l}$.
- direct-CP violating contribution from electroweak penguin and box diagrams.

Theories with exotic particles (e.g. supersymmetry) can have significant extra contributions to penguin amplitudes.

The charged modes $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$ have a background from $K_L \to e^+e^-\gamma\gamma$ and $K_L \to \mu^+\mu^-\gamma\gamma$ where the $\gamma\gamma$ mass coincides with the π^0 mass.

KTeV upper limits (90% confidence level):

$K_L \to \pi^0 e^+e^-$: 5.1×10^{-10} based on 2 observed events with expected background of 1.06 ± 0.41 events.

$K_L \to \pi^0\mu^+\mu^-$: 3.8×10^{-10} based on 2 observed events with expected background of 0.87 ± 0.15 events.

These limits should improve slightly with addition of data taken in 1999 ($\times 2$ in sensitivity).

The neutral mode $K_L \to \pi^0\nu\bar{\nu}$ is expected to proceed dominately through the direct CP violating penguin and box diagrams.

Best KTeV limit on $K_L \to \pi^0\nu\bar{\nu}$ is 5.9×10^{-7} using decays where the $\pi^0 \to e^+e^-\gamma$.

The Future - KAMI (Kaons at the Main Injector)

A proposal is being prepared to detect $K_L \rightarrow \pi^0 \nu \bar{\nu}$ using the very high intensity capabilities of the Fermilab Main Injector.

With Main Injector delivering 3×10^{13} protons per 1 sec spill. get about $1.8 \times 10^7 K_L$ decays per spill. In a year KAMI will get $6 \times 10^{13} K_L$ decays. This is $100\times$ the sensitivity of KTeV (6×10^{11} decays in 1997 and 1999 runs combined.

Goal is to measure the branching fraction to 10% in 3 years of running. The signal/background is expected to be 5 to 1. A 10% b.r. measurement corresponds to a measurement of η to 5% since $b.r. \propto \eta^2$.

Standard model prediction of the branching fraction is 3×10^{-11}.

Large amounts of data on decays with charged particles in the final state will also be collected, $10^6 K_L \rightarrow \pi^+\pi^- e^+ e^-$, $8 \times 10^5 K_L \rightarrow \mu^+\mu^-\gamma$, $10^5 K_L \rightarrow e^+e^-e^+e^-$, $2000 K_L \rightarrow \mu^+\mu^- e^+ e^-$ and sensitivity for $K_L \rightarrow \pi^0\mu^+\mu^-$ down to 2×10^{-11}.

Several tests for KAMI have been done. In 1999 veto efficiencies for low energy photons (down to 10 MeV) were measured. Early in 2000 at the end of the KTeV run production yields of K_L and neutrons were measured with 150 GeV/c protons.

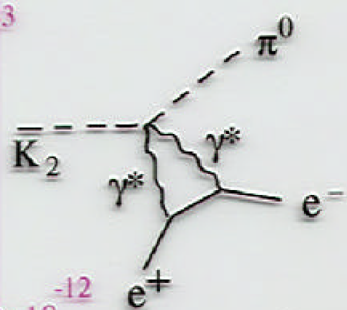
KAMI proposal being written now, due April 2001.

$K^0_L \to \pi^0 e^+ e^-$

Three Components of $K^0_L = K_2 + \varepsilon K_1$ Decay

- A_1 CP Conserving $BR \approx 10^{-13}$

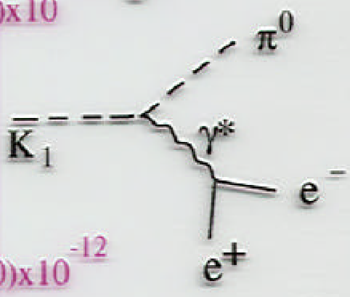
  $K_2 \to \pi^0 \gamma^* \gamma^*$



- A_2 CP Violating $BR \approx (1\text{-}10)\times 10^{-12}$

  Indirect CP (ε)

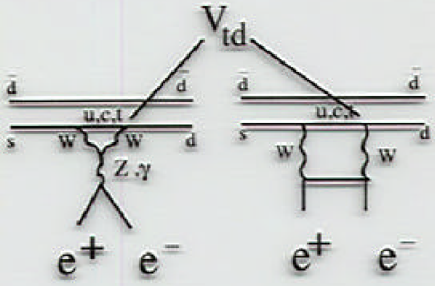
  $K_1 \to \pi^0 \gamma^*$

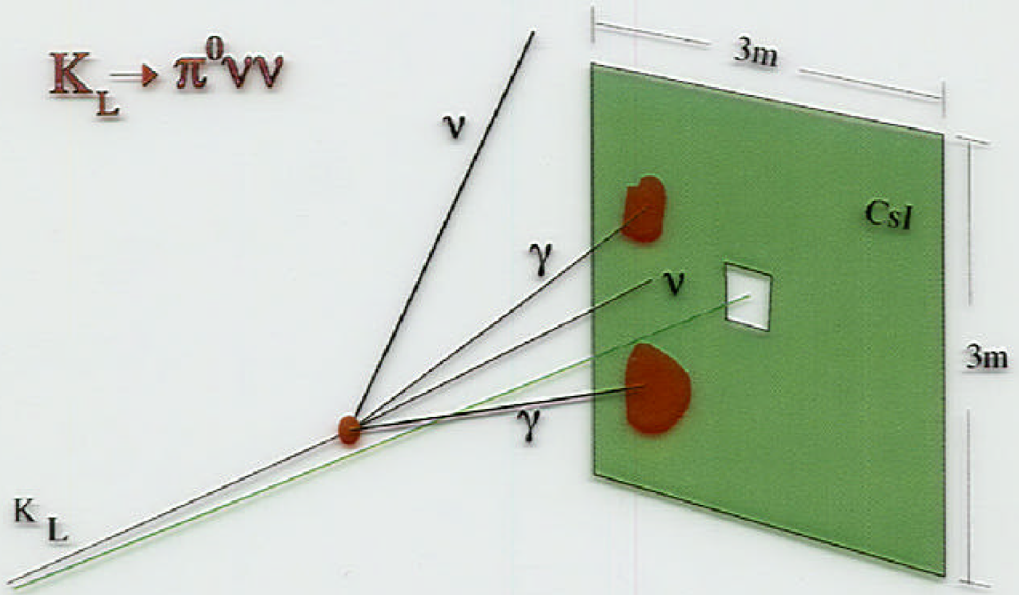


- A_3 CP Violating $BR \approx (1\text{-}10)\times 10^{-12}$

  Direct CP (ε')

  K_2 Decay





Z vertex obtained from two photons under the assumption that they originate in a π^0 decay on the central axis (x=0, y=0) of the neutral beam.

Most serious background $K \rightarrow \pi^0\pi^0$

Only observable quantities are the positions and energies of the two γ's

Requirements for a $\pi^0\nu\nu$ decay are:

Two and only two photons in the CsI detector
Each photon has energy greater than 1 GeV
Total energy in the CsI is greater than 5 GeV
100 <Z vertex < 165 m downstream of BeO target
(CsI is positioned at 185 m downstream of target)
Pt of the two photons be greater than 150 MeV/c
No other photon or charged particle be detected in the vacuum veto, the back anti or the upstream anti

KAMI DETECTOR LAYOUT