Rare Decays of Kaons

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on Lepton and Photon Interactions at High Energies

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Outline

- Muon and Electron Lepton Number Violation
- CP Violation and Quark Mixing Matrix Measurements
- Prospects for Further Measurements

Caveats

- Most results are preliminary, many from KAON99
- I thank experimenters for supplying data and figures
- Any errors are the responsibility of the speaker
- I apologise for skipping some topics. Copies of transparencies from talks at KAON99 can be found at:

hep.uchicago.edu/kaon99/

The Experiments and Their Goals

BNL E787 ⇒ E949

- $K^+ \to \pi^+ \nu\overline{\nu}$ $[|V^*_{td} V_{ts}|]$
- Many radiative decays (chiral perturbation theory)
- Typical sensitivity $10^{-10} \Rightarrow 10^{-11}$

BNL E865

- $K^+ \to \pi^+ \mu^+ e^-$ [LFV]
- Many radiative decays (chiral perturbation theory)
- Typical sensitivity 5×10^{-12}

BNL E871

- $K^0_L \to \mu^\pm e^\mp$ [LFV]
- $K^0_L \to \mu^+ \mu^-$ $[\mathrm{Re}(V^*_{td} V_{ts})]$
- Typical sensitivity 2×10^{-12}

Fermilab E799-II (KTeV) ⇒ KAMI

- ϵ'/ϵ [direct CP violation]
- $K^0_L \to \pi^0 \mu^\pm e^\mp$ [LFV]
- Many K decay parameters, radiative decays
- $K^0_L \to \pi^0 \nu\overline{\nu}$ $[\mathrm{Im}(V^*_{td} V_{ts})]$
- $K^0_L \to \pi^0 l^+ l^-$ $[V^*_{td} V_{ts}]$
- Typical sensitivity $3 \times 10^{-11} \Rightarrow \; < 10^{-12}$

BNL E926

$K^0_L \to \pi^0 \nu\overline{\nu}$ $[\mathrm{Im}(V^*_{td} V_{ts})]$

Sensitivity $< 10^{-12}$

Fermilab CKM

$K^+ \to \pi^+ \nu\overline{\nu}$ $[|V^*_{td} V_{ts}|]$

Sensitivity $\sim 10^{-12}$

Search for Lepton Flavor Violation

Experimental evidence shows there are nearly conserved additive quantum numbers associated with each *family* of leptons – nonconservation referred to as LFV.

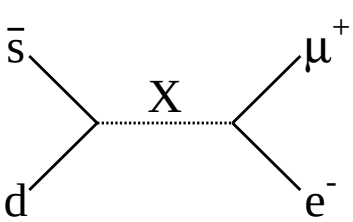
- **Rigorously true in the SM if neutrinos are mass degenerate**

G=1	e	ν_e	u	d
G=2	μ	ν_μ	c	s
G=3	τ	ν_τ	t	b

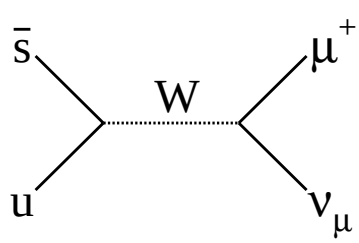
- **These conservation laws are accidental – no gauge symmetry protects lepton flavor, but no mechanism for LFV exists in SM except for ν oscillation.**
- **Information on neutrino mass and mixing in an extended SM results in LFV rates too low to measure for all processes except ν oscillations.**
- **Essentially all extensions to the SM allow LFV.**

$\Rightarrow$ Discovery of LFV would be unambiguous evidence for physics beyond the Standard Model

- **The mass scale probed is very high:**



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



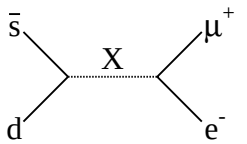
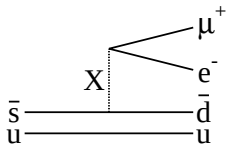
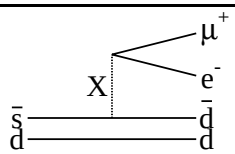
$K^+ \to \mu^+ \nu_\mu$

$$M_X = 220\ \mathrm{TeV}/c^2 \times \left[\frac{10^{-12}}{B(K^0_L \to \mu e)}\right]^{\frac{1}{4}}$$

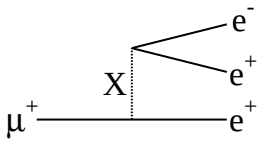
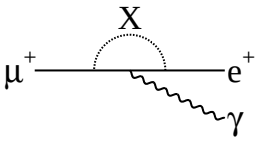
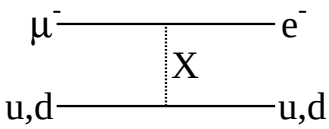
with EW coupling maximal mixing

LFV Searched for in Many Processes

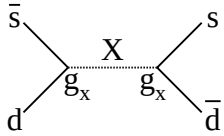
$\Delta G = 0(2)$ processes: M or ΔM Limit

	**BNL E871** $B(K_L^0 \to \mu e) < 4.7 \times 10^{-12}$ AV or PS	$150\ \mathrm{TeV}/c^2$
	**BNL E865** $B(K^+ \to \pi\mu e) < 4.0 \times 10^{-11}$ V or S BNL E865 $\to 10^{-11}$	$31\ \mathrm{TeV}/c^2$
	Fermilab E799 $B(K_L^0 \to \pi^0\mu e) < 3.2 \times 10^{-10}$ V or S	$37\ \mathrm{TeV}/c^2$

$\Delta G = \pm 1$ processes:

	$B(\mu \to eee) < 1.0 \times 10^{-12}$	$86\ \mathrm{TeV}/c^2$
	**MEGA** $B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$ Background limited PSI experiment $\to 10^{-14}$	$21\ \mathrm{TeV}/c^2$
	**PSI SINDRUM2** $\frac{\Gamma(\mu^- A \to e^- A)}{\Gamma(\mu^- A \to \nu A')} < 6.1 \times 10^{-13}$ SINDRUM2 $\to 4 \times 10^{-14}$ MECO at BNL $\to 5 \times 10^{-17}$	$365\ \mathrm{TeV}/c^2$

$\Delta G = \pm 2$ processes:

	$\Delta M_K < 3.5 \times 10^{-12}\ \mathrm{MeV}/c^2$	$400\ \mathrm{TeV}/c^2$

BNL E871 – Leptonic Decays of Neutral Kaons

UC Irvine, Richmond, Stanford, Texas, Wm. and Mary

Overview of BNL E871 Rare Decay Experiment

Very intense K beam and an apparatus that handles rates

- 1.5×10^{13} protons per 1.5 s spill every 3.5 s
- 65 μsr beam, 3×10^8 K_L^0 per spill, $2 < p_K < 8$ GeV/c
- Neutral beam absorbed in dump within spectrometer: reduces downstream rates, allows increased acceptance
- Spectrometer with small diameter drift tubes using fast gas in high rate region (up to 700 kHz per wire)

Spectrometer with good background rejection capabilities

- Excellent resolution and suppression of tracking errors with redundant momentum measurement
- Redundant electron and muon identification

Event selection and analysis to eliminate backgrounds

- 2 body kinematics exploited in low level trigger that required parallel tracks
- Online pattern recognition and kinematic analysis to reduce data to mass storage
- Offline analysis designed by studying events away from signal region and predicting background levels with Monte Carlo simulation.

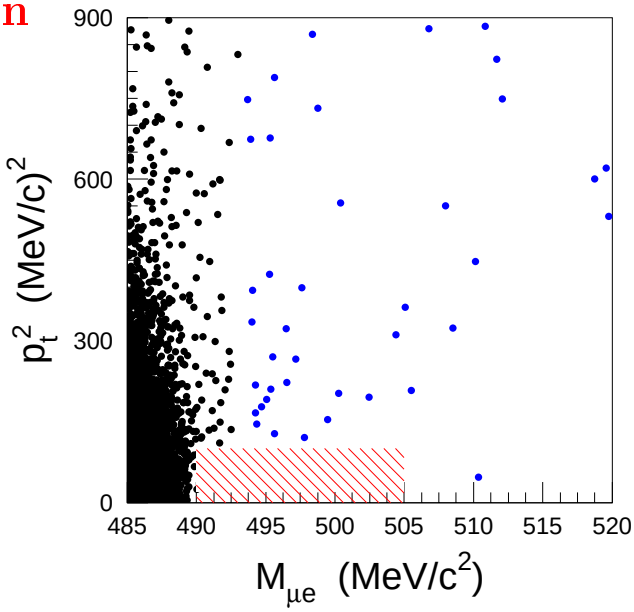
Normalization determined from copious $K_L^0 \to \pi^+\pi^-$ decays

- Similar kinematics minimizes systematic uncertainties

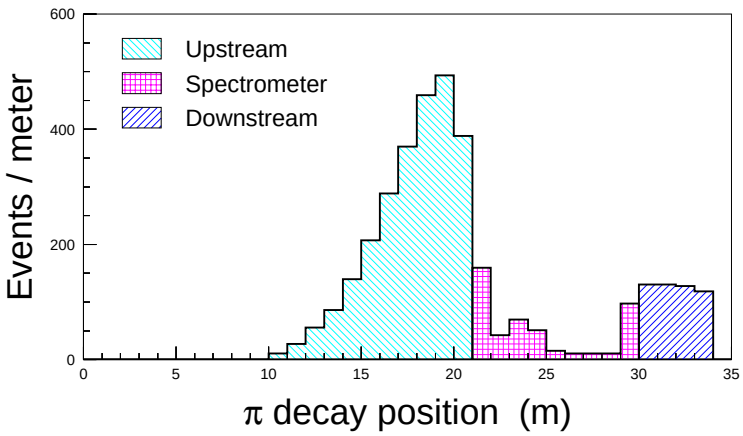
$K_L^0 \to \mu^\pm e^\mp$ Analysis and Background Studies

Background is well understood – primarily $K_L^0 \to \pi e \nu$, $\pi \to \mu \nu \overline{\nu}$

- Studied outside exclusion region –data and MC agree very well
- $M_{\mu e} < 490$ MeV/c^2 is kinematically allowed
- $M_{\mu e} > 490$ MeV/c^2 requires large angle scatter
- Small contribution from accidental coincidences

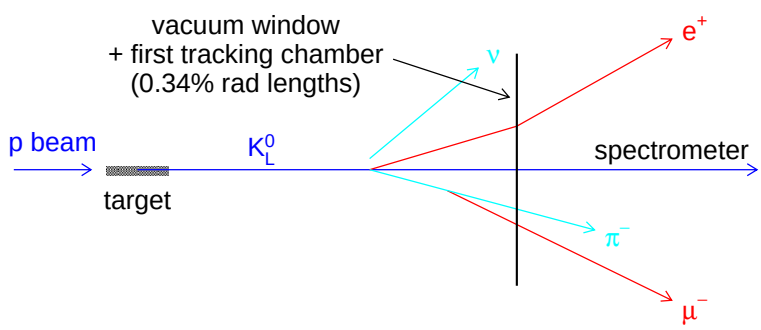


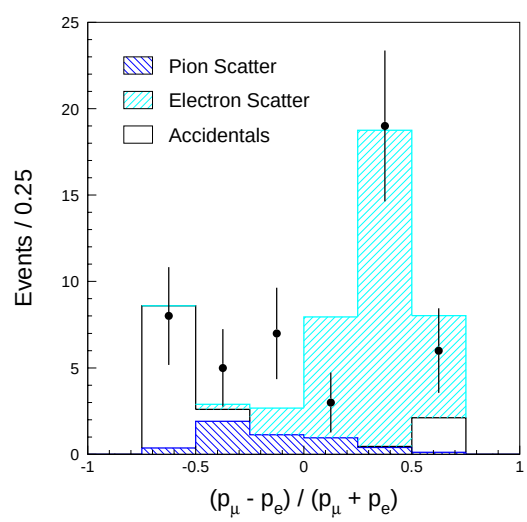
Absolute normalization and kinematic distributions predicted



$M_{\mu e} < 490$ MeV/c^2

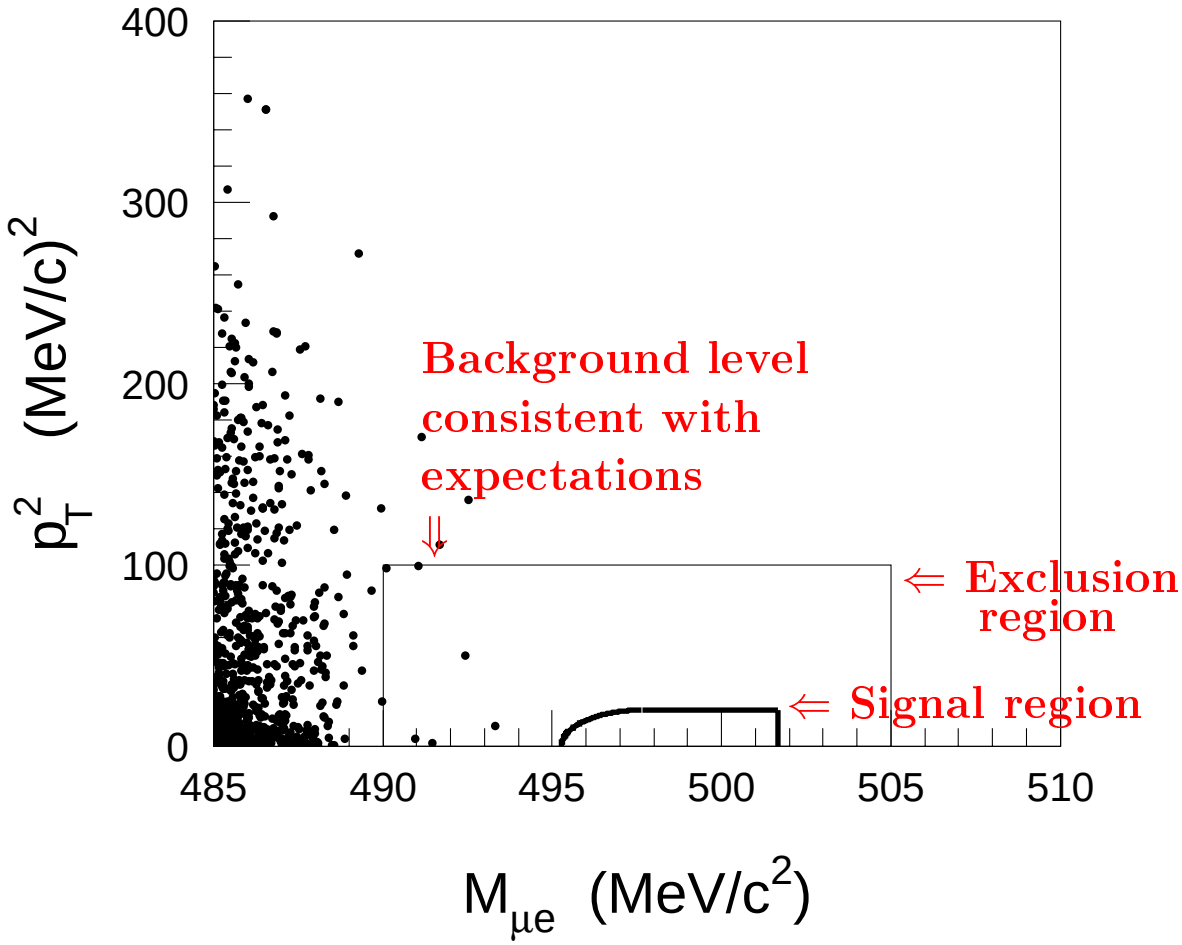
$M_{\mu e} > 490$ MeV/c^2





New Limit on $B(K_L^0 \to \mu^\pm e^\mp)$ From BNL E871

After all selection criteria (including signal region) chosen data reanalysed to determine signal



$$\Rightarrow B(K_L^0 \to \mu^\pm e^\mp) < 4.7 \times 10^{-12} \text{ [90\% CL]}$$

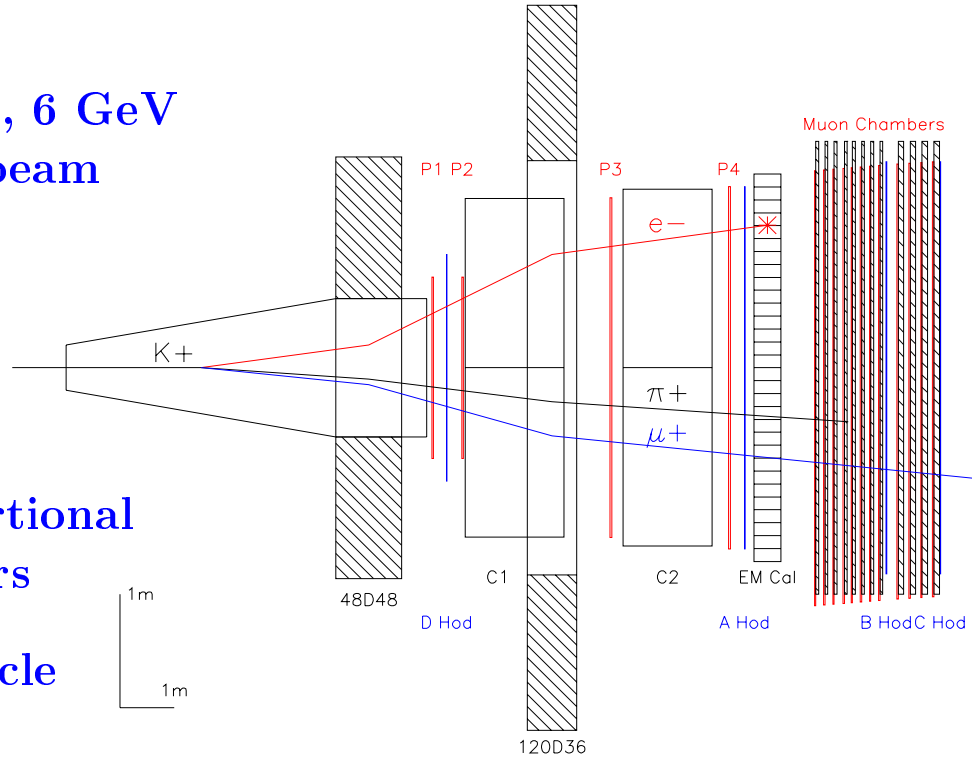
- Smallest limit on any branching fraction of a hadron
- Limit on LFV physics process better than that of any operating or proposed kaon experiment (unless pure vector or scalar interaction).
- Improvements beyond a factor of 10 in sensitivity very difficult due to intrinsic backgrounds.

BNL E865 Search for $K^+ \to \pi^+\mu^+e^-$

Intense, negative, 6 GeV unseparated beam

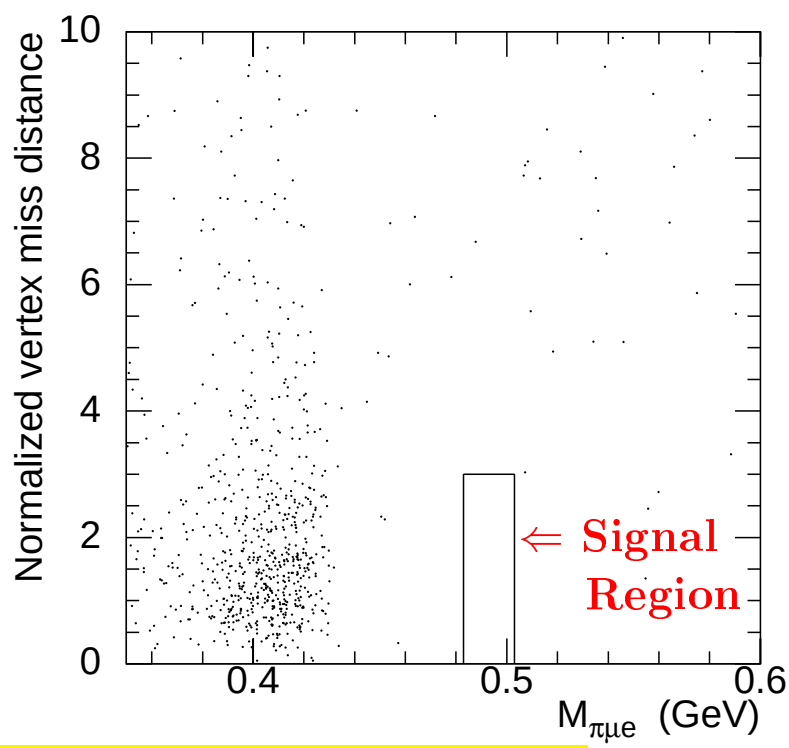
High rate proportional wire chambers

Redundant particle identification



Basel, BNL, INR Moscow, New Mexico, Pittsburgh, PSI, Yale, Zurich

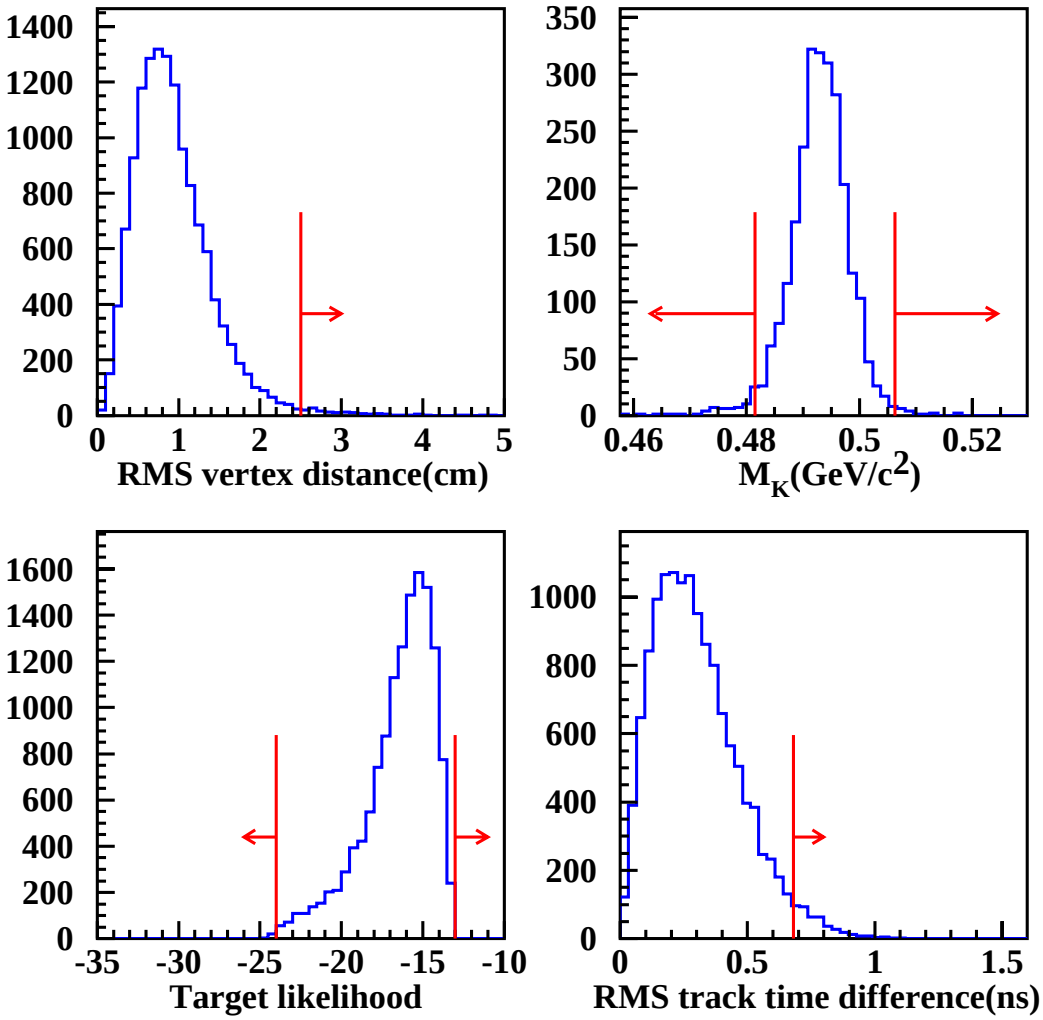
Results from 1995 data:
$B(K^+ \to \pi^+\mu^+e^-)$
$< 2 \times 10^{-10}$
nearby background



New results from 1996 data reported at KAON99

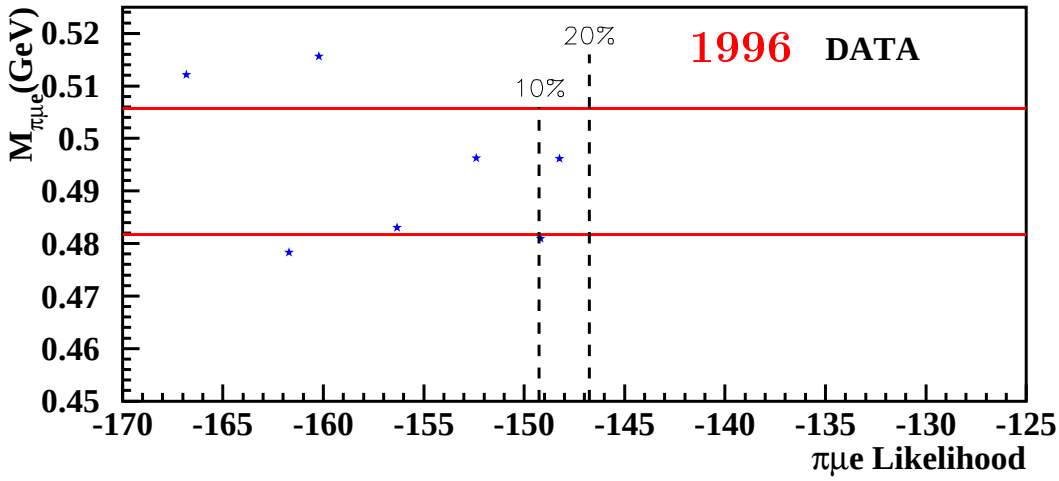
BNL E865 Analysis and Background Rejection

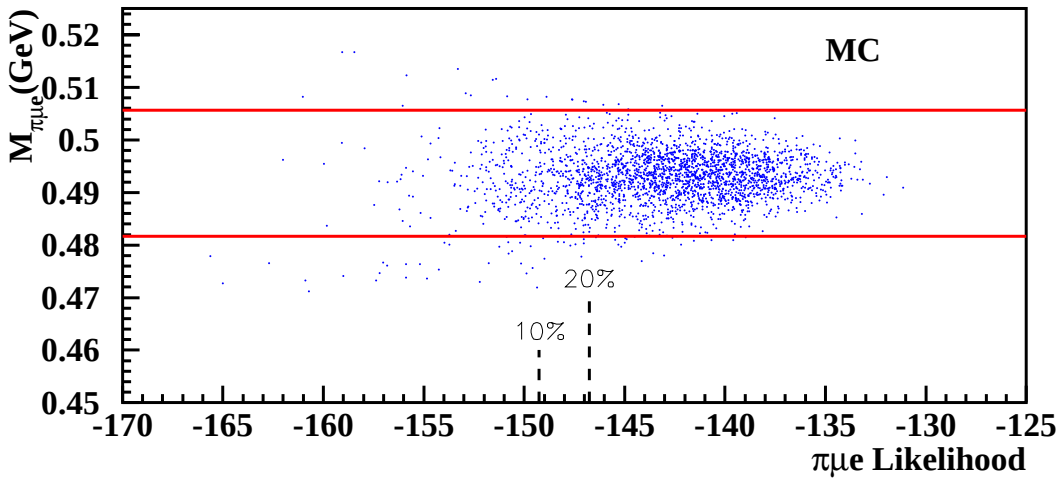
Preliminary selection criteria similar to 1995 analysis applied



- Acceptance determined from $K^+ \to \pi^+\pi^+\pi^-$ decays
- Likelihood distributions defined from the probability of finding worse value of selection variable
- Total likelihood defined by summing contributions
- Remaining events selected by requiring a likelihood value such that 80% of MC $K^+ \to \pi^+\mu^+e^-$ events pass cut.
- 80% requirement set before examining distribution

New Limit on $B(K^+ \to \pi^+\mu^+e^-)$ from BNL E865





- No events satisfy all cuts including likelihood cut.
- Events failing likelihood have properties of accidentals.

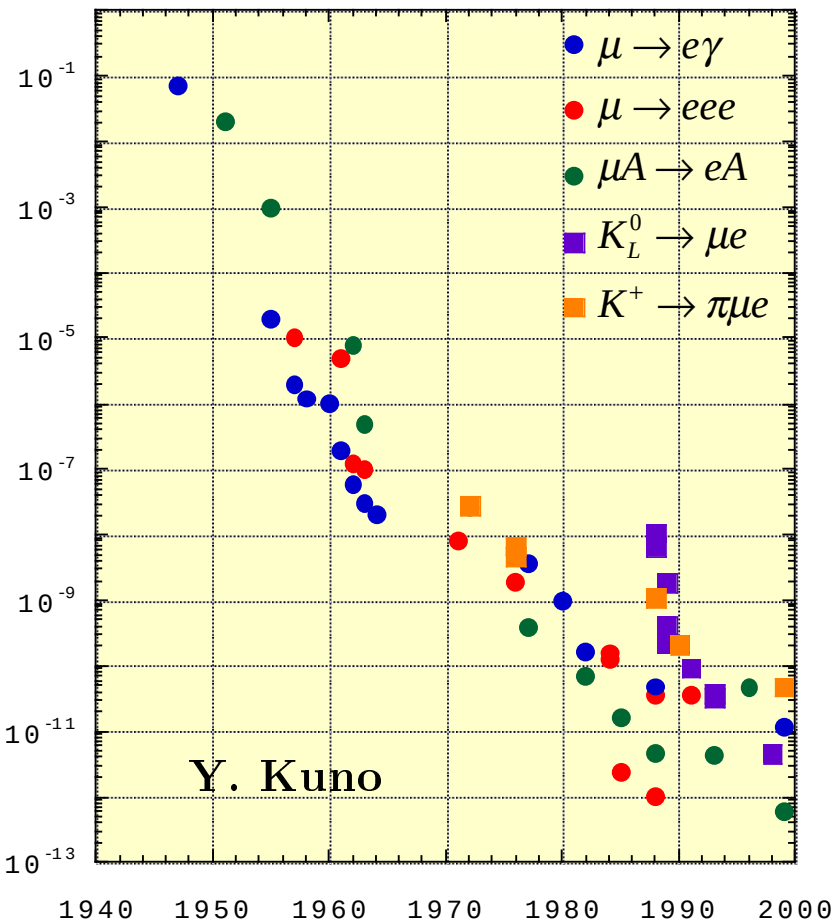
New limit on $B(K^+ \to \pi^+\mu^+e^-)$ [90%] CL from BNL E865:

$< 4.8 \times 10^{-11}$	–	1996 data, cut on likelihood
$< 4.0 \times 10^{-11}$	–	1996 data, frequentist approach
$< 2.9 \times 10^{-11}$	–	E865 1995 + 1996 data + E777

Final data is in hand with $\sim 5 \times$ 1996 statistics – background could limit sensitivity improvement.

Status of and Prospects for LFV Experiments

- **BNL E871 – $B(K_L^0 \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$ [90% CL]**
  no improved experiment in sight – background at 10^{-13}
- **BNL E865 – $B(K^+ \to \pi^+ \mu^+ e^-) < 4.0 \times 10^{-11}$ [90% CL]**
  data in hand to go to 10^{-11} – background limited soon



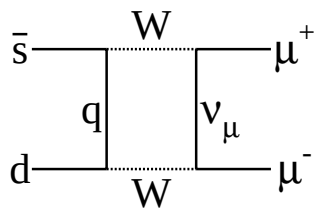
MEGA at LAMPF –
$B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$

SINDRUM2 at PSI–
$B\left(\frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu N')}\right) < 6.1 \times 10^{-13}$

- **Expected sensitivity of $\mu^+ \to e^+\gamma$ search is**
  10^{-14} for an experiment recently approved at PSI
- **Expected sensitivities of $\mu^- N \to e^- N$ searches are**
  4×10^{-14} for upgraded SINDRUM2 running at PSI
  5×10^{-17} for MECO proposed at BNL
- **Proposed sensitivites of upcoming experiments and recent predictions of LFV rates make a discovery increasingly likely.**

Motivation for Measuring $B(K \to (\pi) l\bar{l})$

- **Standard Model rate small – no tree level FCNC ⇒ decays proceed through box and penguin diagrams.**



zero with degenerate m_q
t quark dominates

- **Study of SM quark mixing matrix**

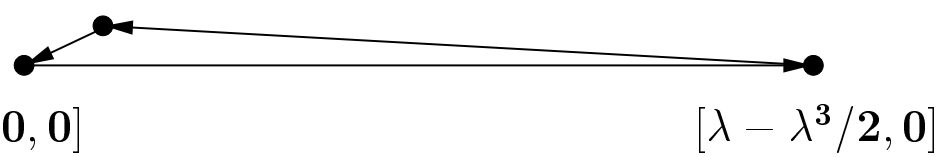
$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} \qquad \begin{vmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{vmatrix}$$

- **All unitarity triangles have the same area:**

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad \text{B triangle}$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad \text{K triangle}$$

Jarlskog invariant $J = \lambda(1-\lambda^2/2) \times A^2\lambda^5\eta$ $(2 \times \text{area})$

$[A^2\lambda^5(1-\rho), A^2\lambda^5\eta]$



Kaon experiments measure directly Jarlskog invariant:

Experiment	Measured Quantity	
$K_L^0 \to \mu^+\mu^-$	$\lvert \mathrm{Re}(V_{td}V_{ts}^*) \rvert$	$\lvert A^2\lambda^5(1-\rho) \rvert$
$K_L^0 \to \pi^0\nu\bar{\nu}$	$\lvert \mathrm{Im}(V_{td}V_{ts}^*) \rvert$	$\lvert A^2\lambda^5\eta \rvert$
$K^+ \to \pi^+\nu\bar{\nu}$	$\lvert V_{td}V_{ts}^* \rvert$	$\lvert A^2\lambda^5(1-\rho-i\eta) \rvert$

Implications of ϵ'/ϵ for Rare Decays of Kaons

Recent work on effective Z_{ds} couplings

- Motivated in part by E787 observation of one $K^+ \to \pi^+\nu\overline{\nu}$ event at ~ 5 (2) $\times$ SM rate and by large ϵ'/ϵ value
- Z_{DS} couplings would affect both $K \to \pi l\bar{l}$ and ϵ'/ϵ
- Arise naturally in supersymmetry from penguin diagrams

Constraints on $B(K_L^0 \to \pi^0\nu\overline{\nu})$ from ϵ'/ϵ

(Bosch, Buras, et al. hep-ph9904408)

- SM: $1.6 \times 10^{-11} < B(K_L^0 \to \pi^0\nu\overline{\nu}) < 3.9 \times 10^{-11}$
- $\epsilon'/\epsilon < 28 \times 10^{-4} \Rightarrow$
  $B(K_L^0 \to \pi^0\nu\overline{\nu}) < 48 \times 10^{-11}$
- Room for new physics above (or below) SM rate

Constraints on $B(K^+ \to \pi^+\nu\overline{\nu})$ from ϵ'/ϵ and $B(K_L^0 \to \mu^+\mu^-)$

(Buras and Silverstrini hep-ph/9811471)

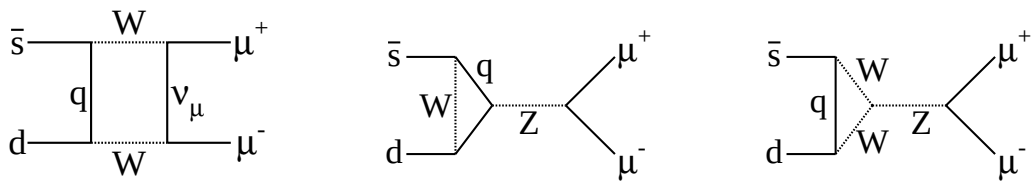
- SM value: $B(K^+ \to \pi^+\nu\overline{\nu}) = 8.2 \times 10^{-11}$
- $\epsilon'/\epsilon < 28 \times 10^{-4} + B(K_L^0 \to \mu^+\mu^-) \Rightarrow$
  $B(K^+ \to \pi^+\nu\overline{\nu}) < 29 \times 10^{-11}$
- Room for new physics above SM rate

Challenges in $K \to (\pi)l\bar{l}$ Experiments

- $K_L^0 \to \mu^+\mu^-$ – lots of data, hard to interpret
  - Short distance rate $\propto (1-\rho)^2$
  - Rate dominated by long distance physics
  - Deduce ReA by subtracting absorptive contribution from measured rate
  - Get A_{SD} from ReA - $ReA_{\gamma^*\gamma}$ (from measurements of radiative decays + theory)
- $K^+ \to \pi^+\nu\overline{\nu}$ – easy to interpret, low statistics data
  - Decay rate $\propto \ |(1-\rho-i\eta)|^2$
  - Standard model rate $\approx 8 \times 10^{-11}$
  - Backgrounds from $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$
- $K_L^0 \to \pi^0\nu\overline{\nu}$ – easy to interpret, very difficult experiment
  - Decay rate $\propto \ \eta^2$
  - Standard model rate $\approx 3 \times 10^{-11}$
  - Significant backgrounds from $K_L^0 \to \pi^0\pi^0$
  - Very few experimental constraints
- $K_L^0 \to \pi^0 e^+e^-$ – low rate, significant background
  - Direct CP violating term $\propto \ \eta^2$ with γ or Z^0 exchange
  - CP conserving term from 2γ intermediate state
  - Indirect CP violating term from $K_1 - K_2$ mixing
  - Standard model rate $\approx 10^{-11}$
  - Many backgrounds – $K_L^0 \to \gamma e^+e^-$ with radiative γ

Overview of $B(K_L^0 \to \mu^+\mu^-)$ Measurement

Goal is to extract information on short distance physics:

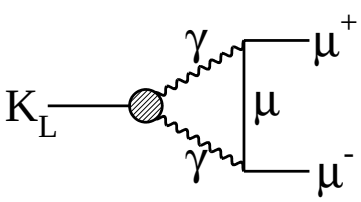


$$B_{SD}(K_L^0 \to \mu^+\mu^-) = \frac{\alpha^2}{4\pi^2 \sin^4\theta_W} \times \frac{\tau(K_L^0)}{\tau(K^+)} \times \frac{(1-4m_\mu^2/m_K^2)^{1/2}}{(1-m_\mu^2/m_K^2)^2} \times \frac{|\mathrm{Re}(V_{ts}^* V_{td}) C_\mu(x_t)|^2}{|V_{us}|^2} \times B(K^+ \to \mu^+\nu_\mu)$$

where $x_t = (m_t/m_W)^2$, $\quad C_\mu(x_t) = \frac{x_t}{4}\left[\frac{4-x_t}{1-x_t} + \frac{3x_t \ln x_t}{(1-x_t)^2}\right]$

$$B_{SD}(K_L^0 \to \mu^+\mu^-) = 0.41 \times 10^{-9}\, A^4\, |C_\mu(x_t)|^2\, (1-\rho)^2$$

Situation complicated by long distance contributions:



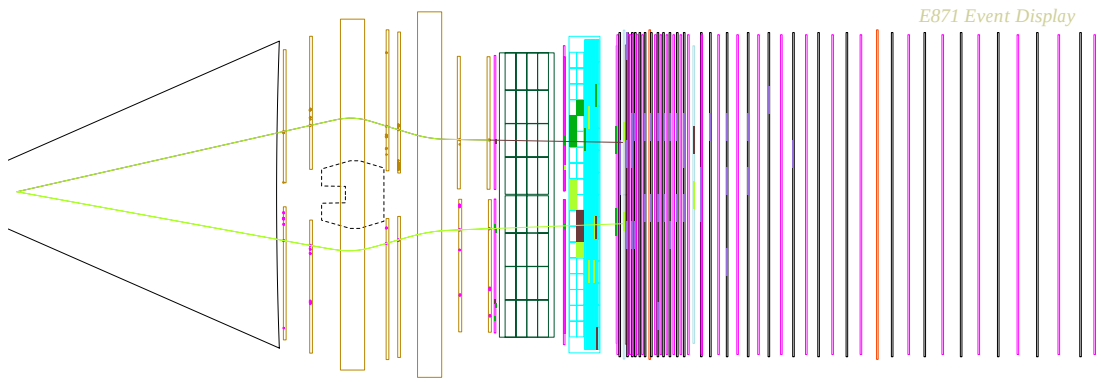
Absorptive $K_L^0 \to \gamma\gamma \to \mu^+\mu^-$ amplitude gives unitarity bound

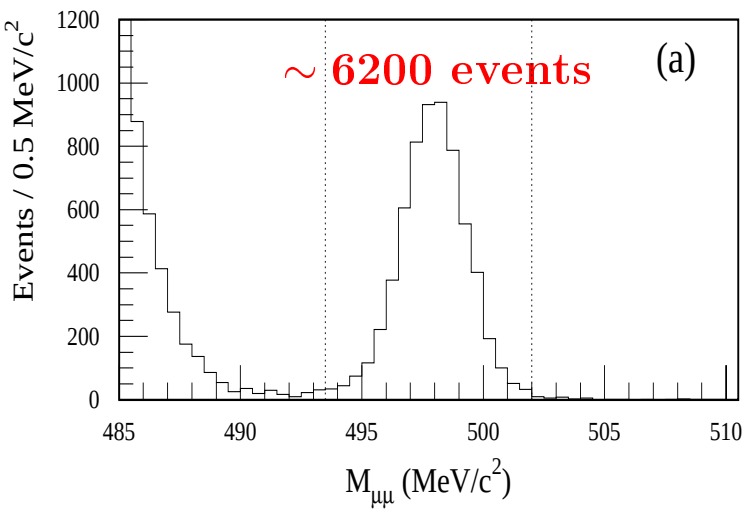
Dispersive $K_L^0 \to \mu^+\mu^-$ amplitude has LD $(\gamma\gamma^*)$ and SD contributions

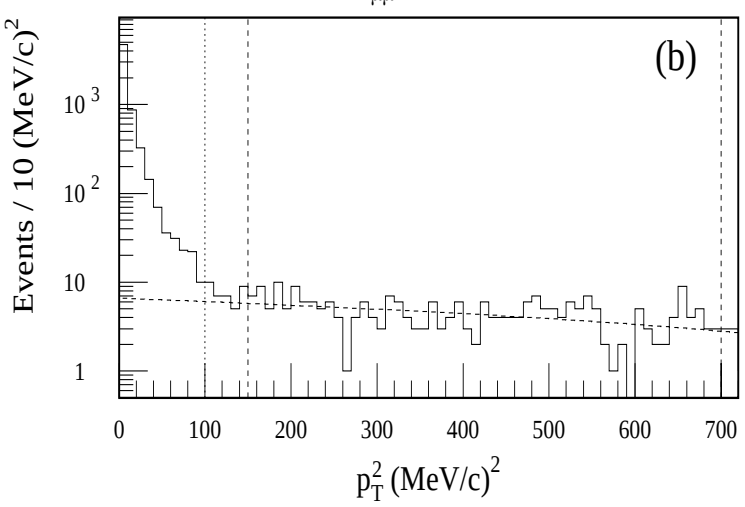
Procedure to extract short distance contributions:

- Measure $B(K_L^0 \to \mu^+\mu^-)$
- Subtract absorptive part of long distance contribution using measured $B(K_L^0 \to \gamma\gamma)$ and QED calculation
- Correct for long distance contributions to Re(A) using theoretical analysis (c.f. Dumm and Pich, hep-ph/9810523; D'Ambrosio, Isidori and Portoles, Phys. Lett. B 423.)
  Relies on models and the method is not universally accepted.
  Information on $K_L^0 \to \gamma e^+e^-$ and $K_L^0 \to e^+e^-e^+e^-$ useful in checking models.

New Result from BNL E871 for $B(K_L^0 \to \mu^+\mu^-)$







$\mathbf{B(K_L^0 \to \mu^+\mu^-) = (7.18 \pm 0.17) \times 10^{-9}}$

$$\frac{\Gamma(K_L^0 \to \mu^+\mu^-)}{\Gamma(K_L^0 \to \pi^+\pi^-)} = (3.474 \pm .054) \times 10^{-6}$$

Unitarity bound = $(7.07 \pm 0.18) \times 10^{-9}$

$$\frac{\Gamma(K_L^0 \to \gamma\gamma \to \mu^+\mu^-)}{\Gamma(K_L^0 \to \pi^+\pi^-)} = (3.44 \pm .07) \times 10^{-6}$$

$\Rightarrow |\mathrm{Re}(A_{SD} + A_{\gamma\gamma})| < 1.8 \times 10^{-5}$ **(90% CL)**

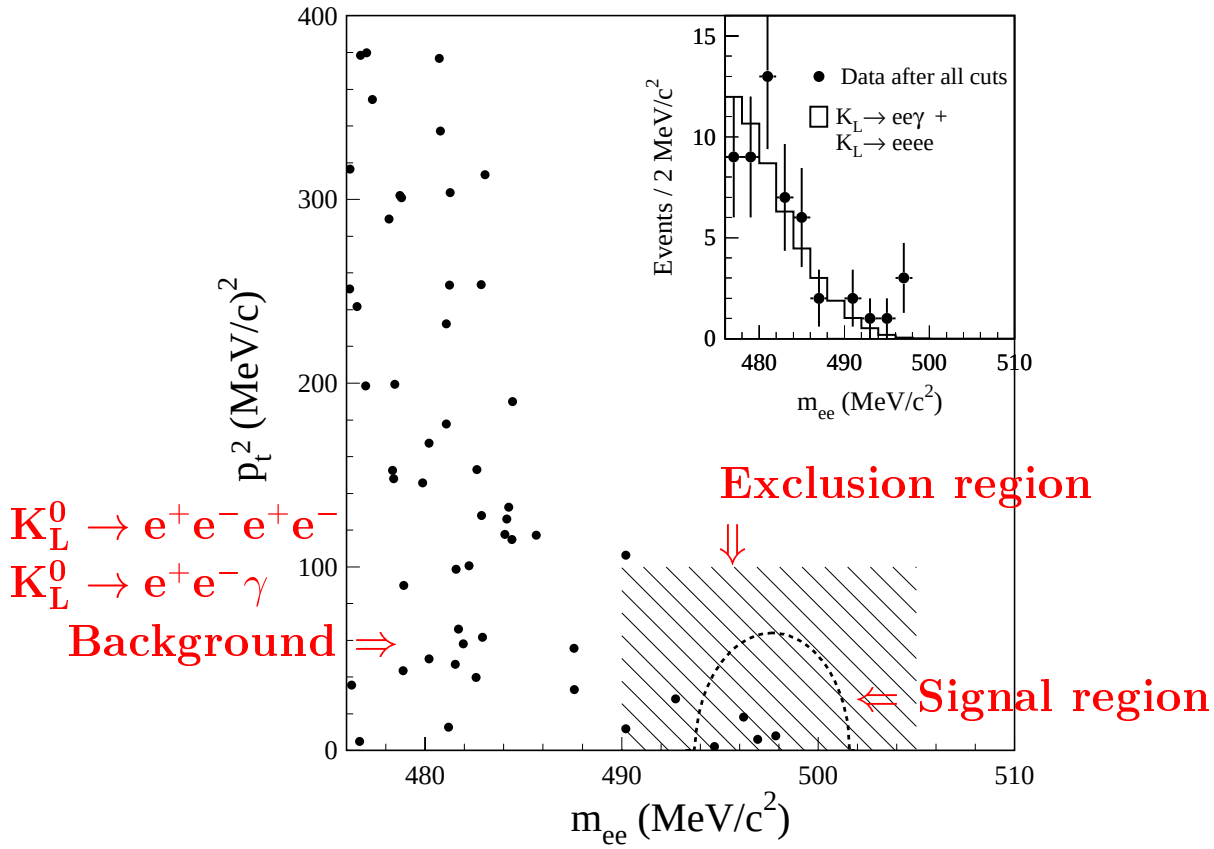
$\Rightarrow$ Wolfenstein parameter $\rho > -0.29$ (90% CL)

Result is consistent with SM fits for ρ

following prescription of D'Ambrosia, et al.

First Observation of $K_L^0 \to e^+e^-$ From BNL E871

Analysis tuned and cuts chosen using data outside exclusion region – background from $K_L^0 \to e^+e^-e^+e^-$ and $K_L^0 \to e^+e^-\gamma$



- Four events found in predetermined signal region
- Background in exclusion region consistent with expectation – expect ~ 0.2 background events in signal region
- Distribution in p_t^2 vs m_{ee} fitted to linear combination of $K_L^0 \to e^+e^-e^+e^-$, $K_L^0 \to e^+e^-\gamma$ and $K_L^0 \to e^+e^-$ distributions

$$\Rightarrow B(K_L^0 \to e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$$

- Fitted background levels agree with absolute prediction
- $B(K_L^0 \to e^+e^-)$ consistent with χPT prediction
- This is the smallest branching fraction ever measured

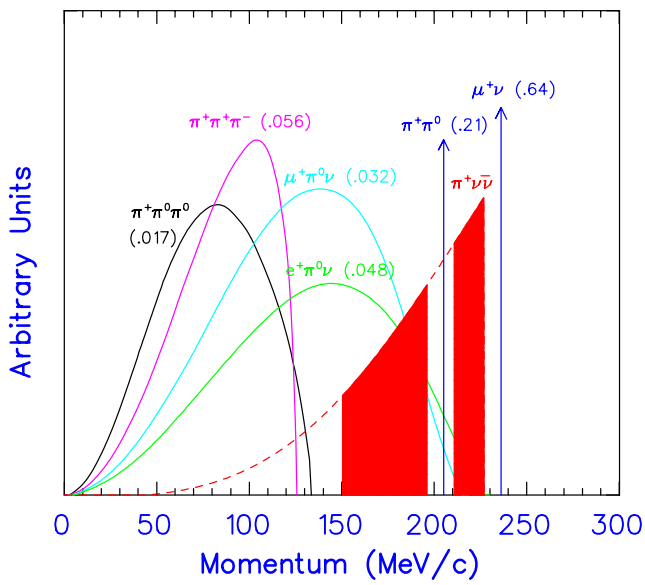
BNL E787 $K^+ \to \pi^+\nu\overline{\nu}$ Experiment

Alberta, BNL, KEK, Osaka, Princeton, TRIUMF

$B(K^+ \to \pi^+\nu\overline{\nu}) \Rightarrow |V^*_{td}V_{ts}|$ with small theoretical uncertainty:

$$B(K^+ \to \pi^+\nu\overline{\nu}) = 4.11 \times 10^{-11} \times A^4 \times X(x_t) \times [(\rho_0 - \rho)^2 + \eta^2]$$

$X(x_t)$ known function of m_t^2/m_W^2, $\rho_0 \simeq 1.4$ due to charm



Backgrounds from:

μ^+ **from** $K^+ \to \mu^+\nu$

π^+ **from** $K^+ \to \pi^+\pi^0$

$\Rightarrow$ **Particle identification:**

$K^+ \to \pi^+ \to \mu^+ \to e^+$ **decays**

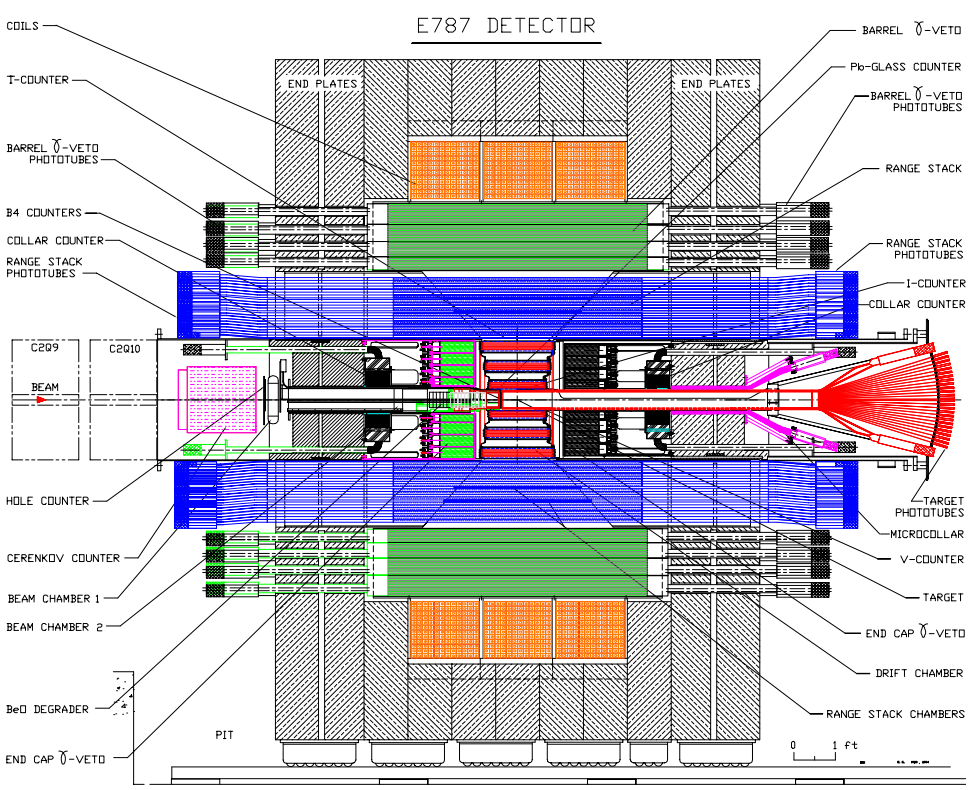
$\Rightarrow$ **Kinematic analysis:**

Measure E, p, R **of** π^+

$\Rightarrow$ **Veto events with extra** γ**:**

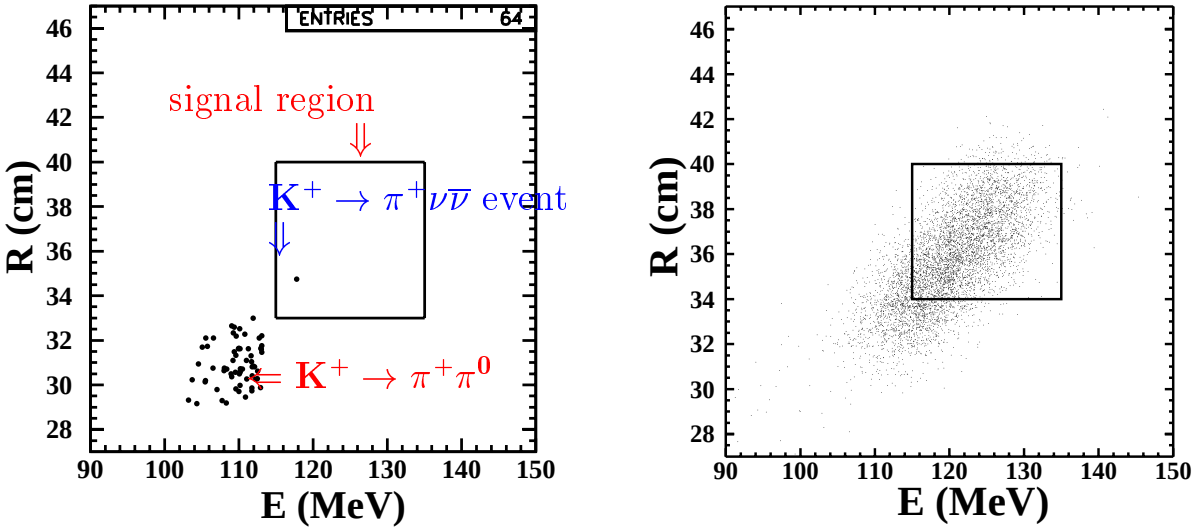
Pb-scintillator and

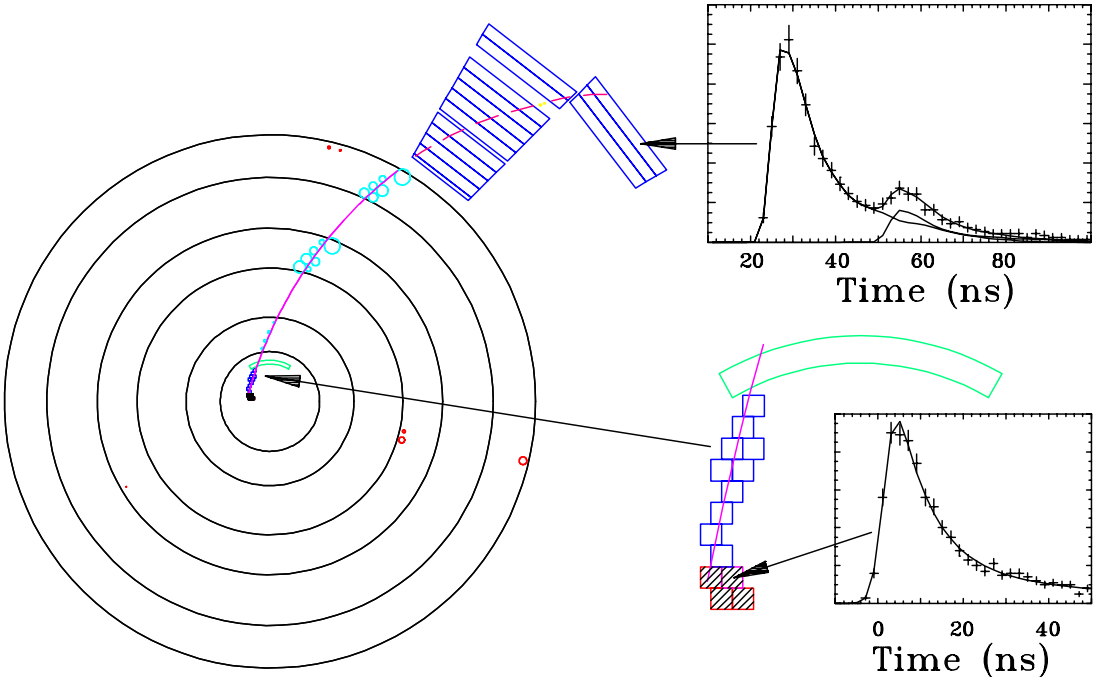
CsI hermetic veto



Preliminary Result on BNL E787 Study of $K^+ \to \pi^+\nu\overline{\nu}$

1995-97 Data **$K^+ \to \pi^+\nu\overline{\nu}$ Monte Carlo**





E787 currently quotes ratio of 95-97 to 95 sensitivity = 2-3

$$B(K^+ \to \pi^+\nu\overline{\nu}) = 1.7^{+4.0}_{-1.42} \times 1^{+.22}_{-.18} \times 10^{-10} \; [\mathrm{SM} \sim 0.82 \times 10^{-10}]$$

Result and uncertainty scaled by me to 1995 result
Uncertainty in reported preliminary 95-97 sensitivity

Slightly higher than, consistent with SM value of 0.82×10^{-10}

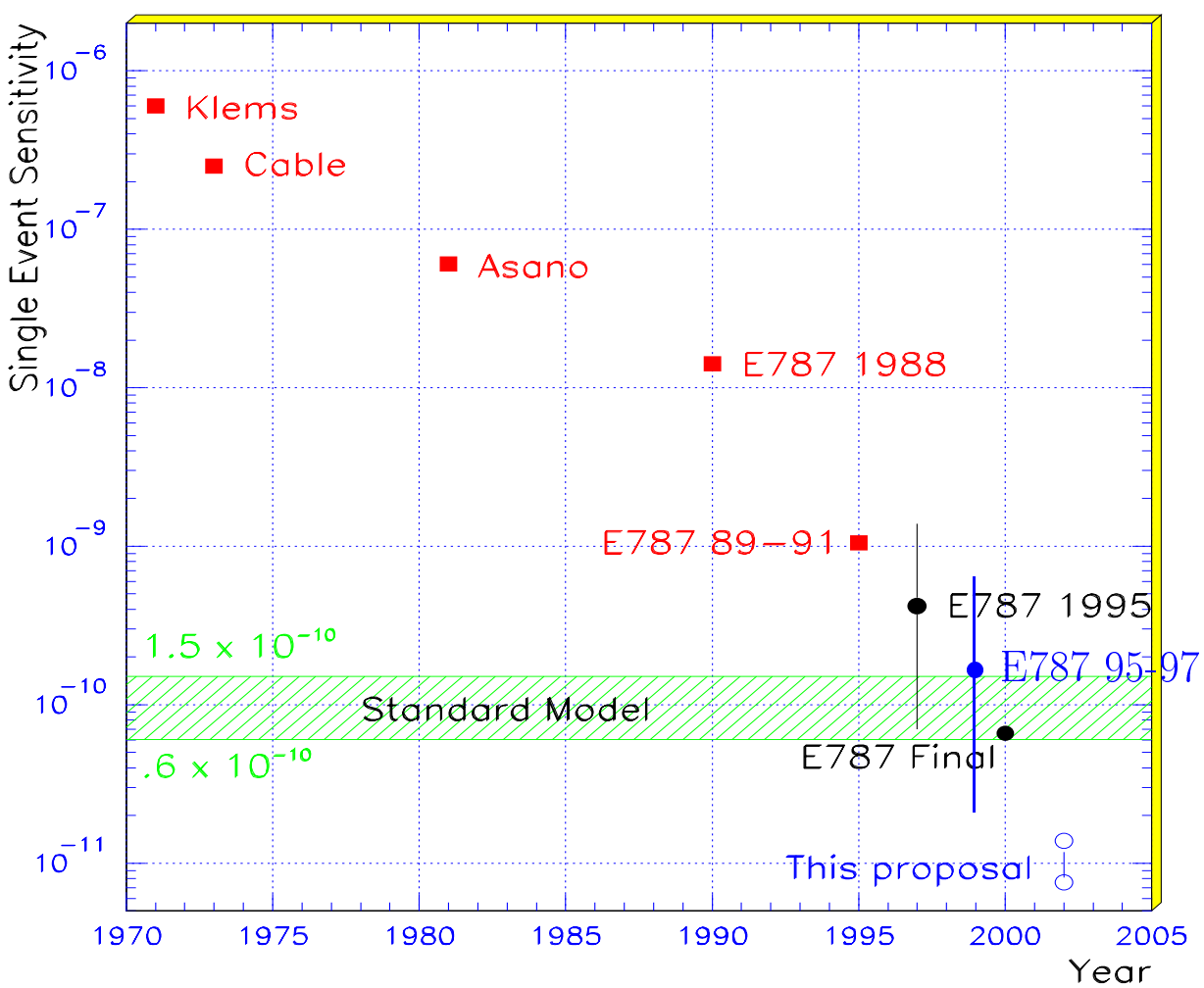
Final E787 data in hand to improve sensitivity $\times 2$

BNL E949 – Improved Measurement of $B(K^+ \to \pi^+ \nu\overline{\nu})$

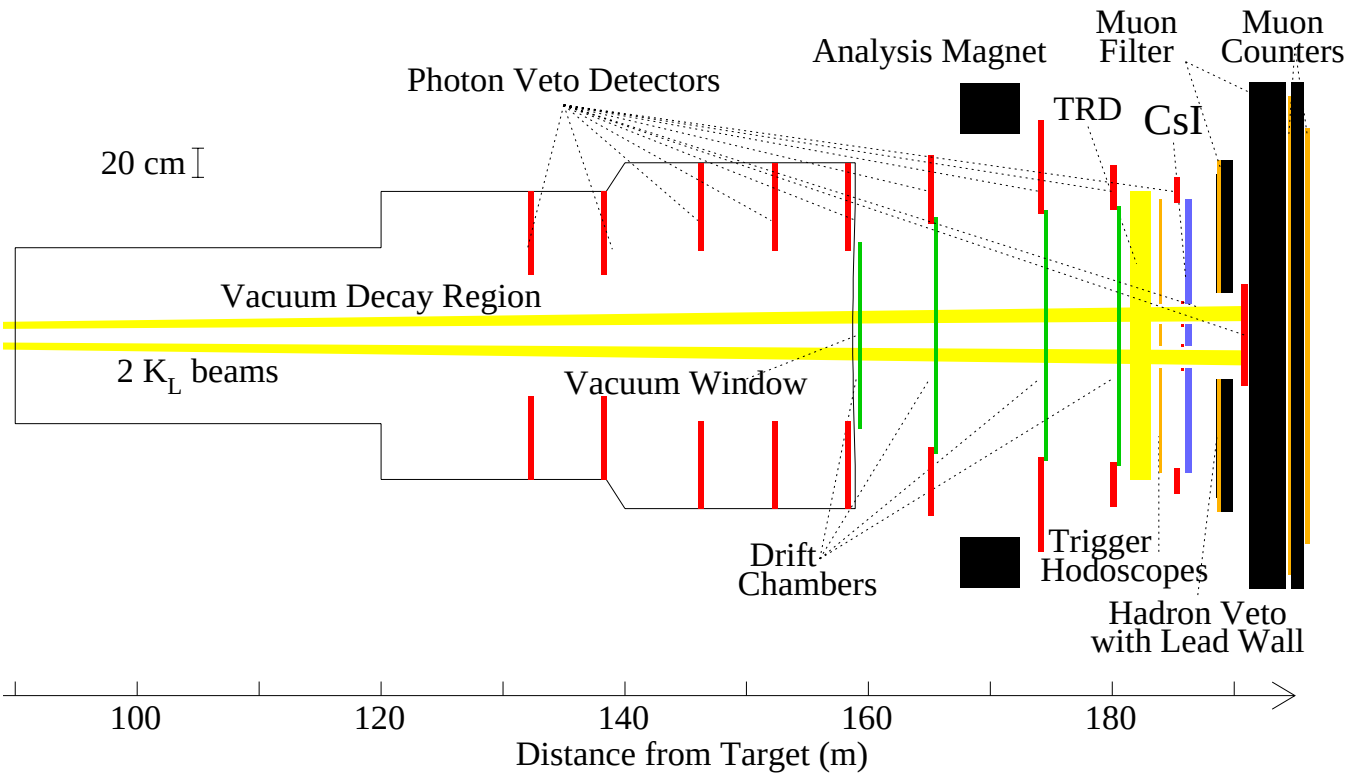
Expected sensitivity, scaled wrt E787 1995 data:

E787 events at SM rate (0.82×10^{-10})	0.20
Lower K^+ momentum	$\times$1.38
Improved duty factor	$\times$1.56
Trigger + other improvements	$\times$1.54
Additional detector improvements	$\times$2.10
Optimized high-rate analysis	$\times$2.0
Running time (6000 hours – 60 weeks)	$\times$3.6
Total above $K^+ \to \pi^+\pi^0$ peak at SM	5 – 10.0 events
Analyse below $K^+ \to \pi^+\pi^0$ peak	$\times$2.0
Best possible sensitivity at SM	10 – 20 events

mostly already obtained



Fermilab KTeV E799 Search for $K_L^0 \to \pi^0 l\bar{l}$

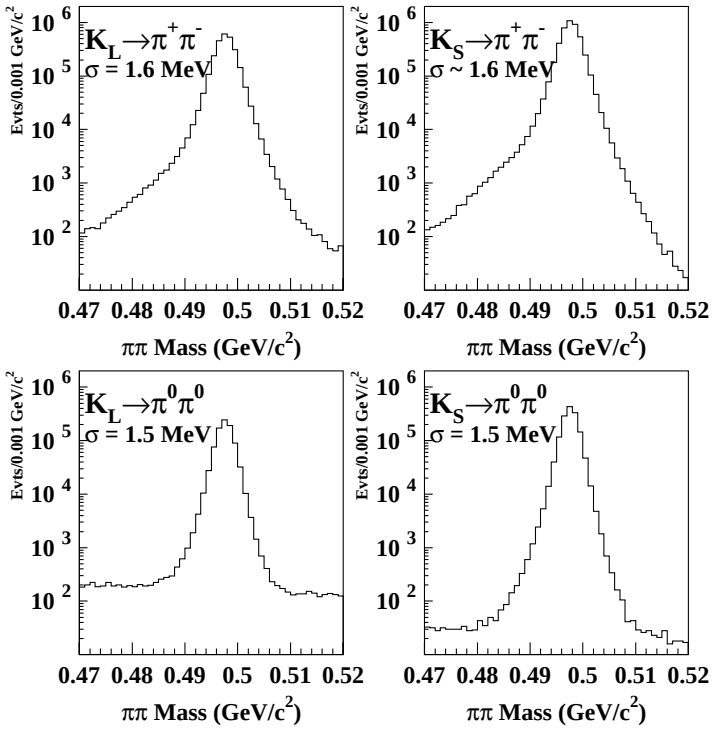


Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia, Wisconsin

Detector and beam highlights

- **Pure CsI calorimeter:**
  $\sigma_E/E = 1\%$ at 10 GeV
  π/e rejection > 700
- **Transition radiation detectors:**
  π/e rejection > 200
- **Clean, intense beam:**
  $\sim 10^8$ per second

Preliminary results from 1996 run shown



KTeV E799 $K_L^0 \to \pi^0 e^+ e^-$ Analysis

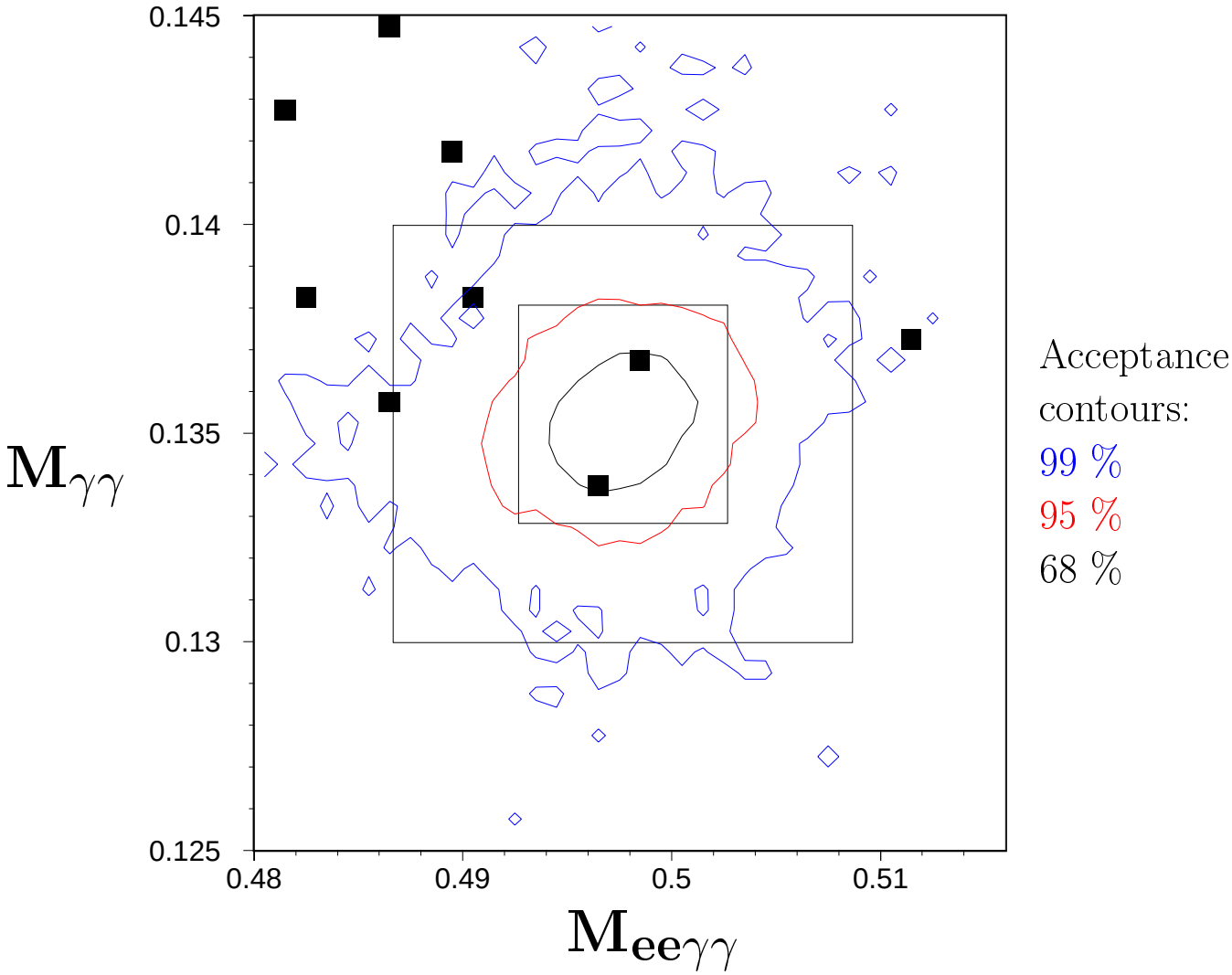
Background dominated by $K_L^0 \to \gamma e^+ e^-$ with radiated γ

Background level reduced with kinematic cuts:

- Eliminate events with $\vec{p}_\gamma$ opposite $\vec{p}_{e^+} + \vec{p}_{e^-}$ in K_L^0 CM
- Eliminate events with γ along e^+ or e^- direction

New Limit on $B(K_L^0 \to \pi^0 e^+ e^-)$ from KTeV E799

After choosing selection criteria data reanalysed

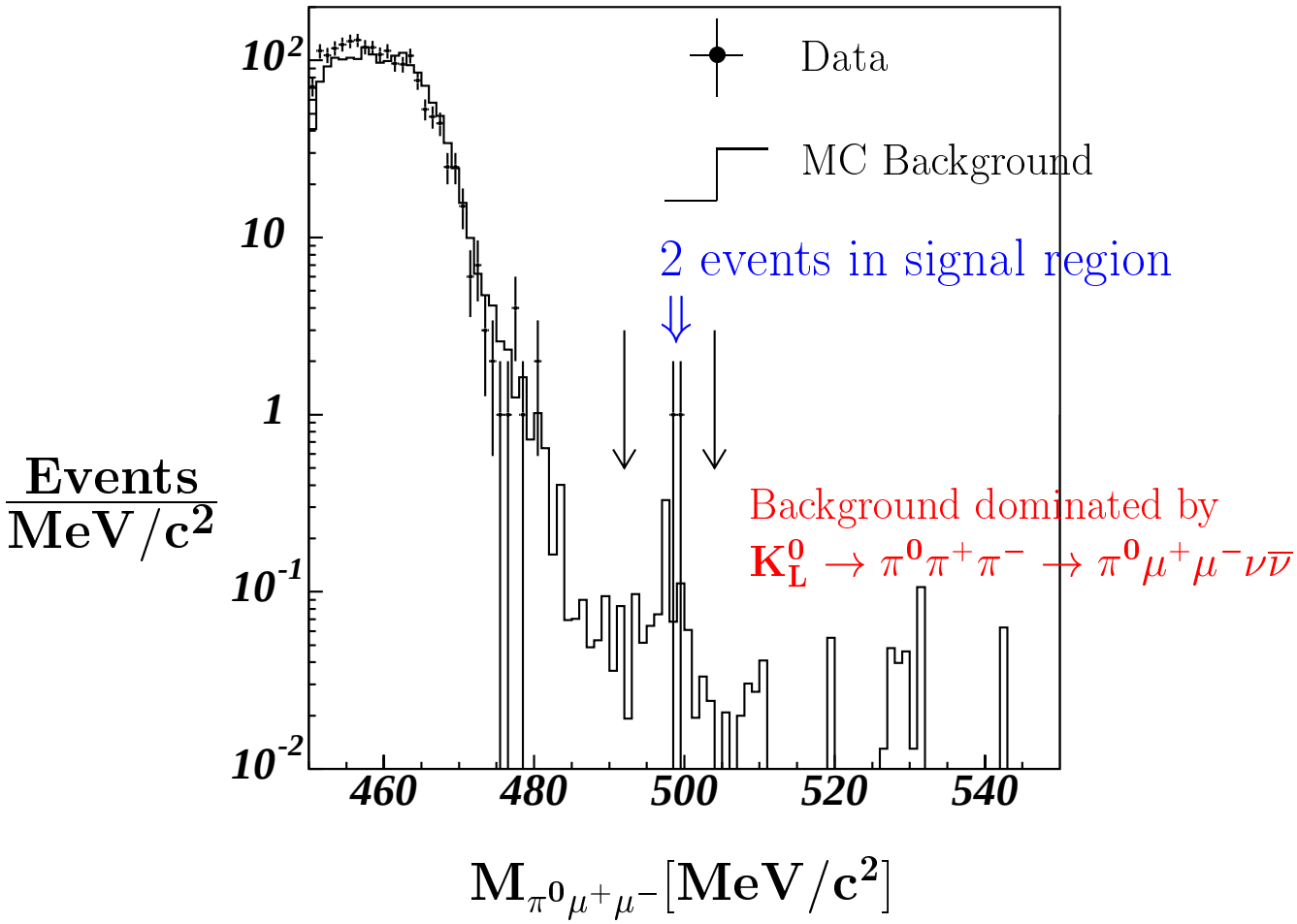


Set upper limit based on 2 events, consistent with background:

$$B(K_L^0 \to \pi^0 e^+ e^-) < 5.64 \times 10^{-10}\ (90\%CL)\ [SM \sim 10^{-11}]$$

- Expect $\sim \mathbf{3}\times$ more data in 1999 run
- Eventual measurement will be events above background

New Limit on $B(K_L^0 \to \pi^0\mu^+\mu^-)$ from KTeV E799



Set upper limit based on 2 events, consistent with background:

$$B(K_L^0 \to \pi^0\mu^+\mu^-) < 3.4 \times 10^{-10}\ (90\%\mathrm{CL})\ [\mathrm{SM} \sim 10^{-12}]$$

- Expect $\sim 3\times$ more data in 1999 run
- Eventual measurement will be events above background

  No double momentum measurement to remove π decay

First observation of $K_L^0 \to \mu^+\mu^-\gamma\gamma$ (4 events):

$$B(K_L^0 \to \mu^+\mu^-\gamma\gamma, E_\gamma^* > 10\ \mathrm{MeV}) = (1.42^{+1.02}_{-0.81} \pm 0.14) \times 10^{-9}$$

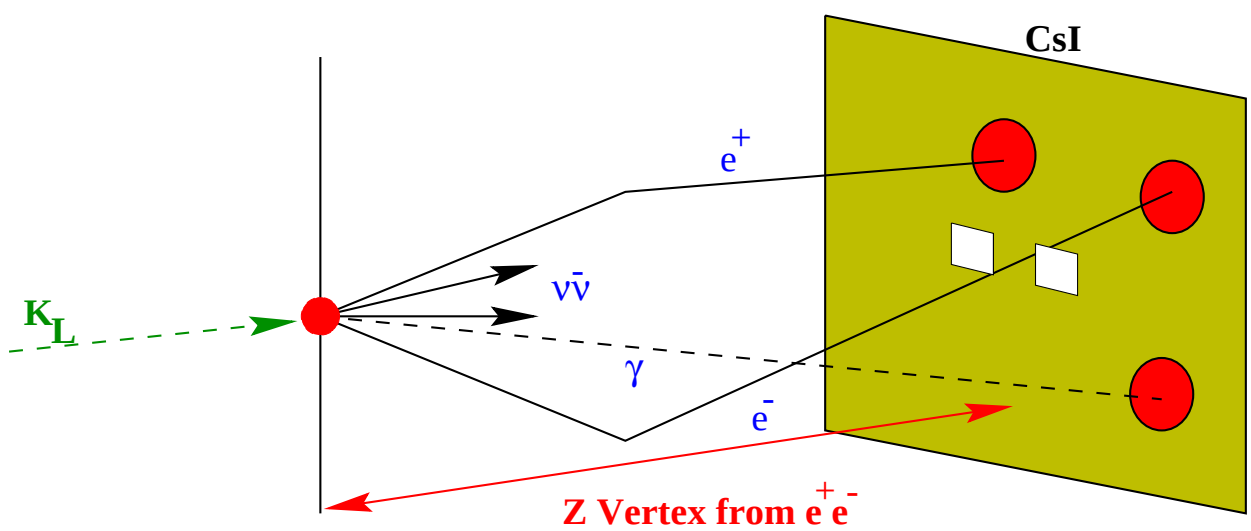
Fermilab KTeV E799 Search for $K_L^0 \to \pi^0 \nu\bar{\nu}$

$B(K_L^0 \to \pi^0 \nu\bar{\nu}) \Rightarrow Im(V_{td}^* V_{ts})$ with small theoretical uncertainty

For $\pi^0 \to \gamma\gamma$ decays, current detectors measure γ position and E

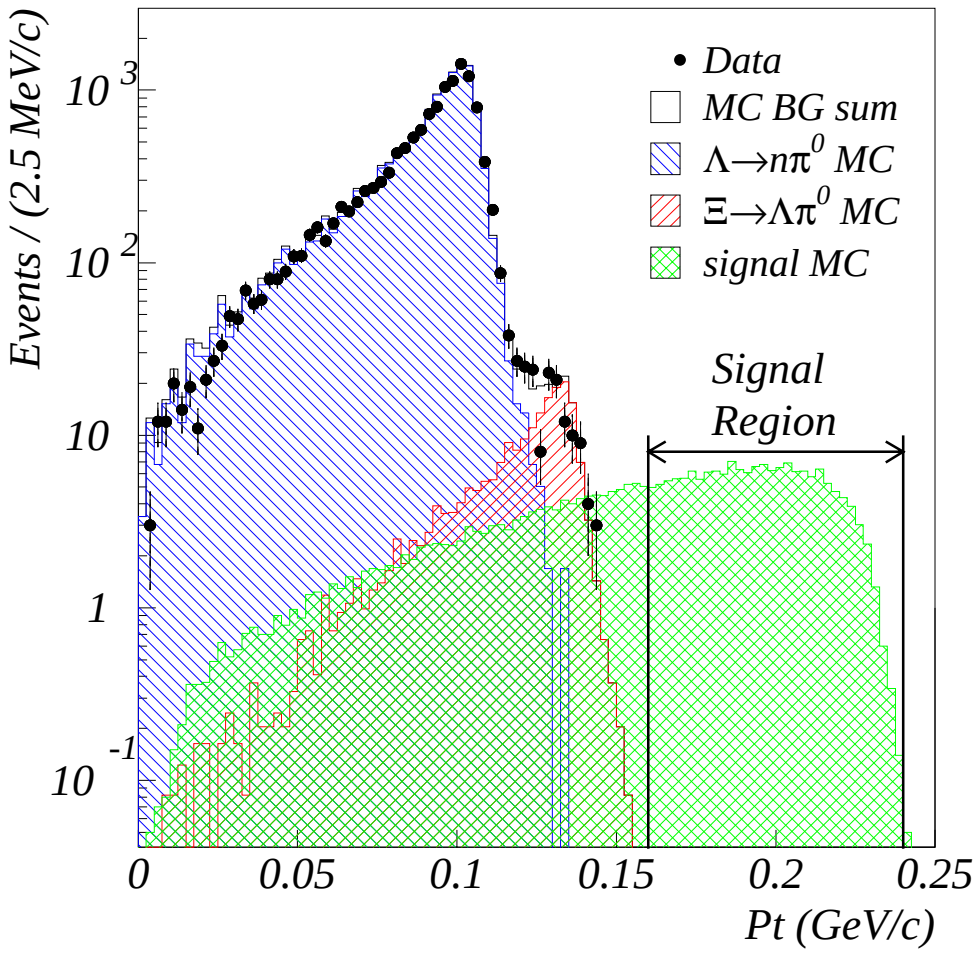
- K_L^0 decay point inferred by constraining $M_{\gamma\gamma}$ to M_{π^0}
- Copious background from $K_L^0 \to \pi^0\pi^0$
- Rely on γ veto, and cut on p_T of π^0 to reject background
- Requires at least nearly hermetic γ veto with high efficiency

New result uses $\pi^0 \to \gamma e^+ e^-$ to determine K_L^0 decay point



- Insufficient sensitivity to get near Standard Model level
- Allows study of backgrounds other than $B(K_L^0 \to \pi^0\pi^0)$
  - $\Lambda \to n\pi^0$
  - $\Xi \to \Lambda\pi^0$

New Limit on $B(K_L^0 \to \pi^0 \nu\overline{\nu})$ from Fermilab KTeV E799



- **Background from hyperon decays at low p_T**
- **Background from $B(K_L^0 \to \pi^0\pi^0)$ suppressed**

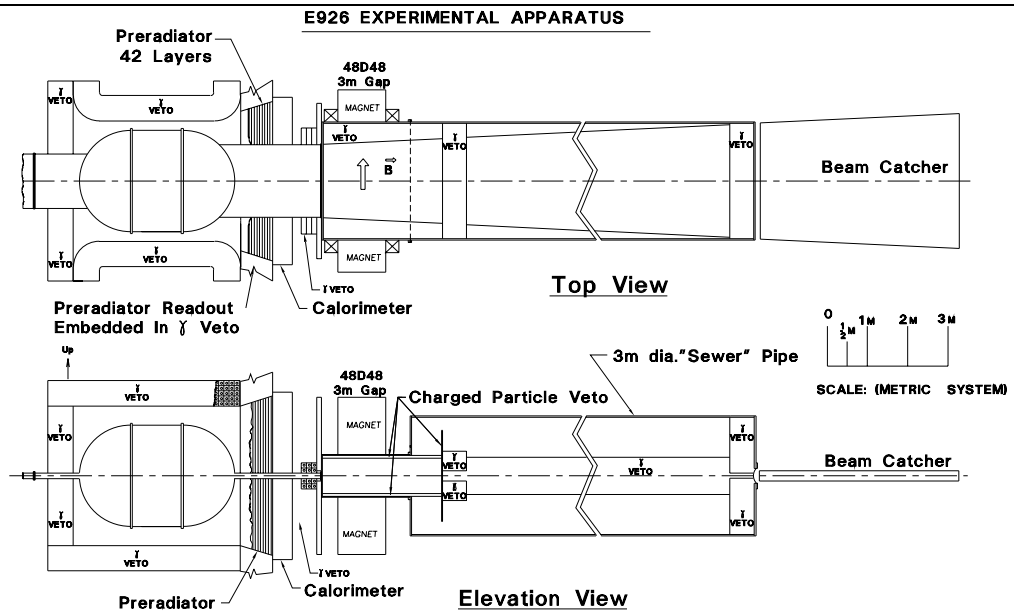
$$B(K_L^0 \to \pi^0 \nu\overline{\nu}) < 5.9 \times 10^{-7} \; [\mathrm{SM} \sim 3 \times 10^{-11}]$$

One day test of $K_L^0 \to \pi^0 \nu\overline{\nu}, \pi^0 \to \gamma\gamma$ done:

- **Limit set based on one event consistent with background**

$$B(K_L^0 \to \pi^0 \nu\overline{\nu}) < 1.6 \times 10^{-6}$$

BNL E926 Experiment to Search for $K_L^0 \to \pi^0 \nu\overline{\nu}$



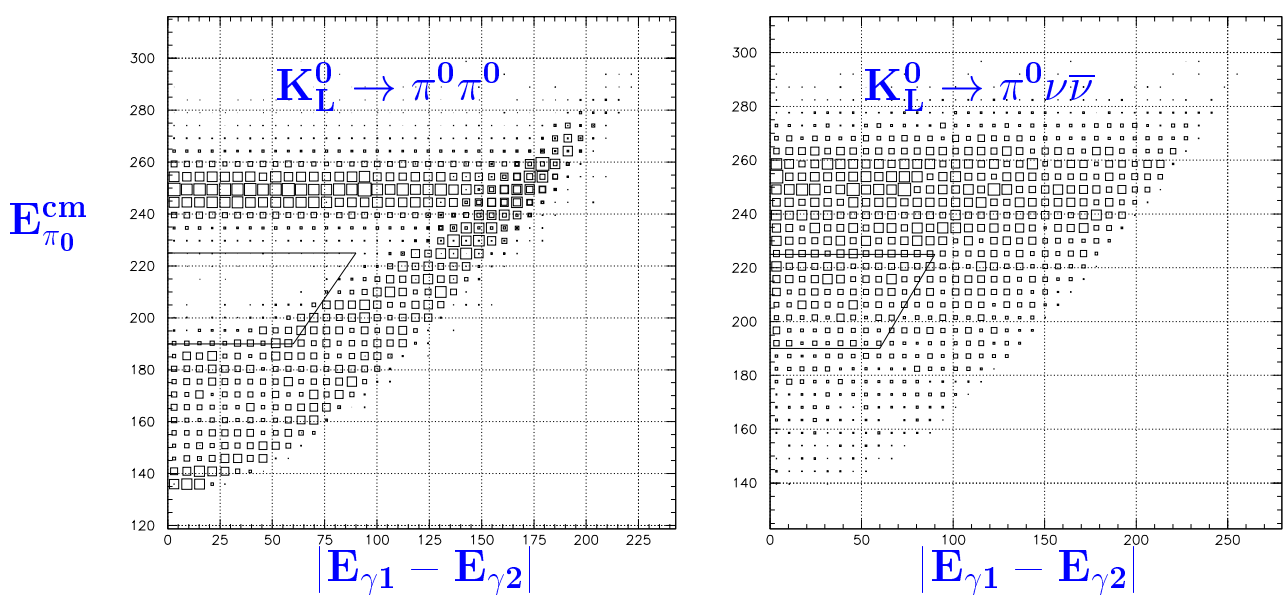
BNL, Jefferson Lab, Kyoto, INR Moscow, New Mexico, TRIUMF, Virginia Tech, Yale, Zurich

Produce beam at large angle (45°) – low momentum K_L^0

γ veto based on E787 – $\sim 10^{-6}$ inefficiency for $E_\gamma > 20$ MeV

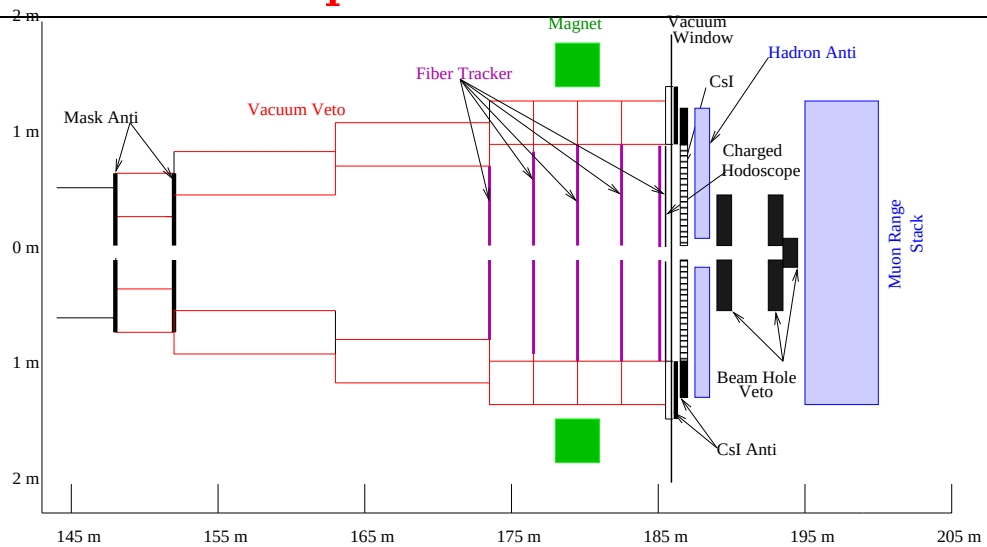
Deduce $E(K_L^0)$ by TOF – 250 ps γ timing, 150 ps beam timing

K_L^0 vertex by γ direction – $\sim$ 35 mrad for 200 MeV γ



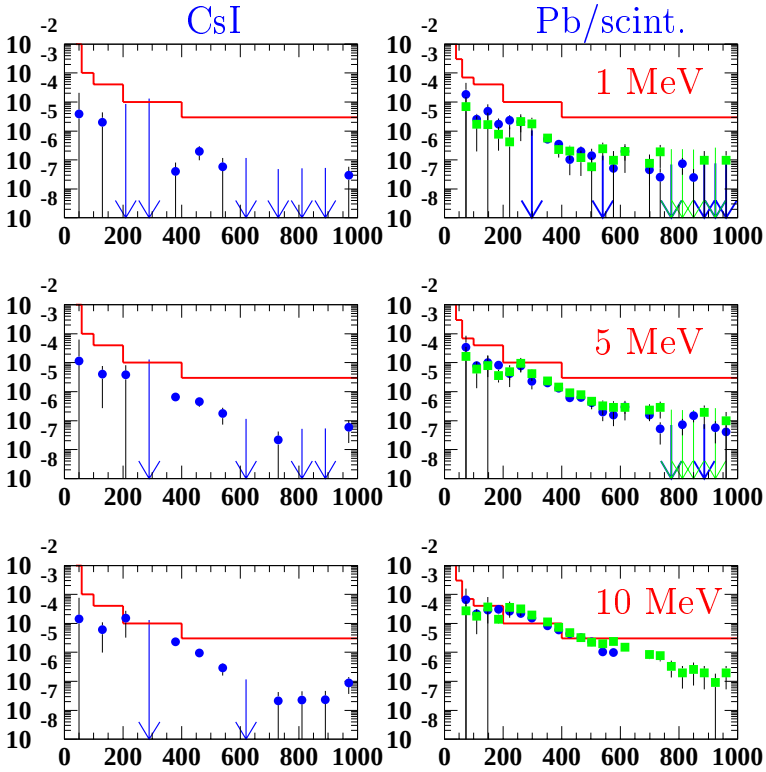
9000 hours, 10^{14} protons/pulse $\Rightarrow$ 50 $K_L^0 \to \pi^0\nu\overline{\nu}$ with S:N $\simeq$ 5:1

Fermilab KAMI Experiment to Search for $K_L^0 \to \pi^0 \nu \overline{\nu}$



Arizona, Campinas, Chicago, Colorado, Elmhurst
Fermilab, Osaka, Virginia, Wisconsin

Tests of γ veto at INS Tokyo



Few kinematic constraints:
- No measurement of $E(K_L^0)$
- No γ direction

Superb photon detector

Relatively lower neutron flux in beam

Moderate K_L^0 energy
- Relatively fewer low energy γ

Detector, beam development
- γ veto better than LOI
- $\Leftarrow$ Points(data)
  - Line(LOI assumption)

Measurement of n flux at 150 GeV planned for 1999 Tevatron run

3×10^{13} protons/pulse $\Rightarrow$ 15-30 events per year with S:N $\simeq$ 10:1

Summary and Prospects

Muon and electron number violation

- $K \to (\pi)\mu e$
  Experimental sensitivities are a few $\times 10^{-12}$.
  KAMI at Fermilab has the potential to get to $\sim 10^{-13}$.
  Sensitivity beyond $\sim 10^{-13}$ is difficult due to background.
- Progress in LFV physics is likely to come from μ sector:
  Experiments are proposed with sensitivities
  1000 $\times$ those of current efforts.

Measuring V_{td} and CP violation

- $K_L^0 \to \mu^+\mu^-$
  Precision of branching fraction measurement is $\sim 2\%$.
  Deriving SD physics requires measurements of K_L^0
  radiative decays and theoretical models of LD physics.
- $K^+ \to \pi^+\nu\overline{\nu} \Rightarrow$ precise determination of $|V_{td}^* V_{ts}|$
  BNL E787 sensitivity is 1 event at the SM level.
  BNL E949 could measure $|V_{td}^* V_{ts}|$ to $\sim 15\%$.
  Fermilab CKM could measure $|V_{td}^* V_{ts}|$ to $\sim 5\%$.

- $K_L^0 \to \pi^0\nu\overline{\nu} \Rightarrow$ precise determination of $Im(V_{td}^* V_{ts})$
  Current experimental sensitivities are far from SM.
  BNL E926 and Fermilab KAMI might be able
  to detect a few tens of events at the SM level.
  No experimental information precludes decay rates
  much larger(or smaller) than SM prediction.
  Some models(supersymmetry) allow(suggest)
  significant new contributions to decay rate.

K decay experiments may be able to measure the area of a unitarity triangle with precision equal or superior to that of B physics experiments, allowing a direct confrontation of SM picture of quark mixing matrix and CP violation.