Present and Future Kaon Physics

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There has been great recent progress in measurements of rare and ultra-rare kaon decays, particularly those involving the flavor changing neutral currents. We review those recent results and prospects for future measurements.

searches and measurements with sensitivity of

$$10^{-7} \sim 10^{-12}$$

MHz of K decays -- beyond charm an B's (for now)

OUTLINE

Introduction

Recent results and future prospects in

$K \to l^+ l^-$

$K \to \pi\, l^+ l^-$

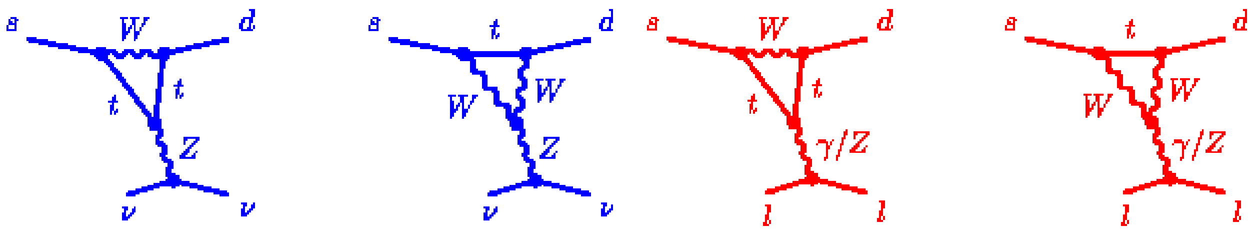
$K \to \pi\, \nu\, \bar{\nu}$

Summary

Acknowledgements: Takeshi Komatsubara's XXI Physics in Collision talk was kindly made available and liberally used.

FCNC Flavor Changing Neutral Currents

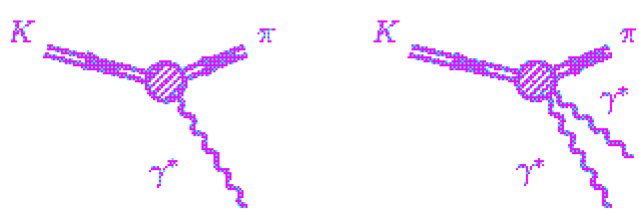
$s \to d$ transitions No single current does this!

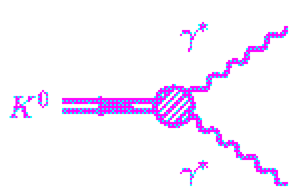


Dominated by top-quark diagrams ($m_t \sim 170$ GeV/c^2)
So the "interesting" CKM matrix elements come into play

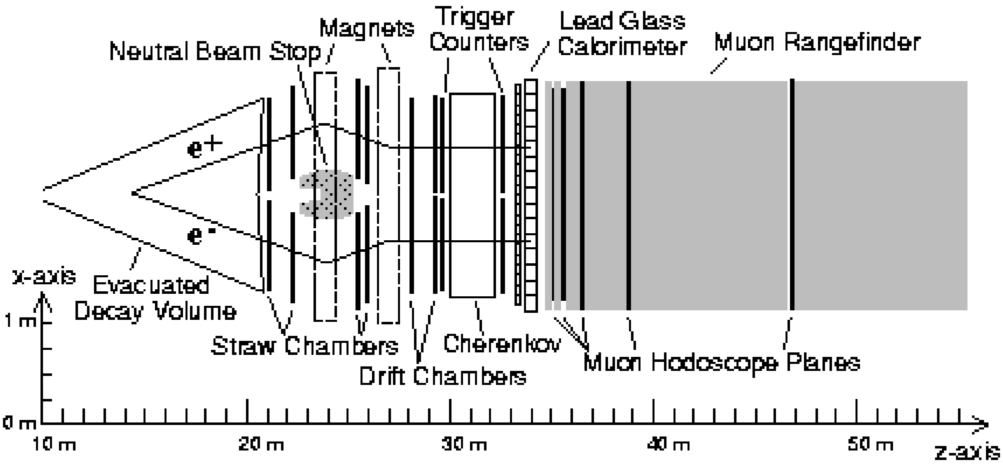
$$\lambda_t = V^*_{ts}\, V_{td} = A^2\lambda^5\,(1-\rho-i\eta)$$

$\mu^+\mu^-$ and e^+e^- final states also have long distance contributions



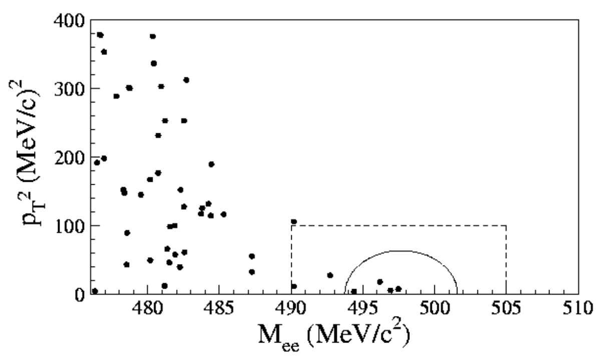


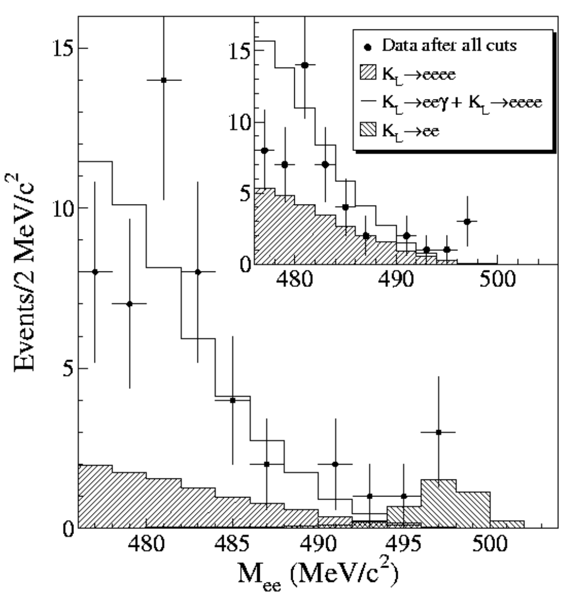
$K^0_L \to e^+e^-$ BNL-E871 PRL 81, 4309 (1998)



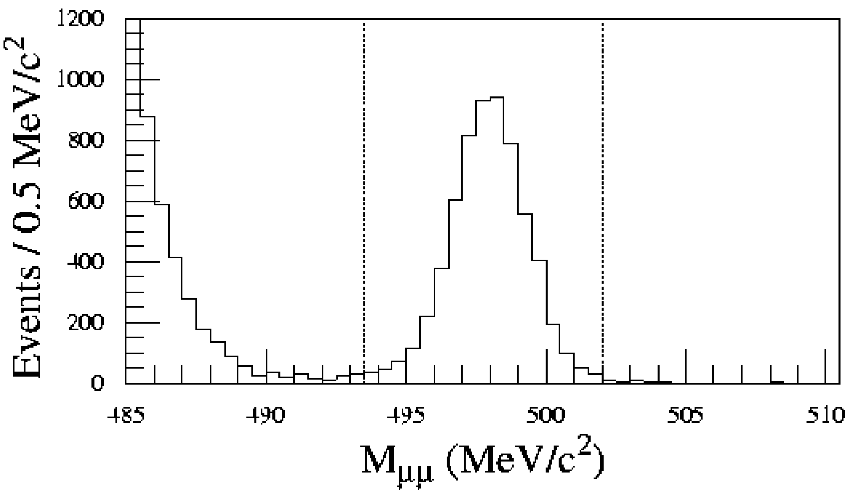
Branching ratio $(8.7\ ^{+5.7}_{-4.7}) \times 10^{-12}$ 4 signal events

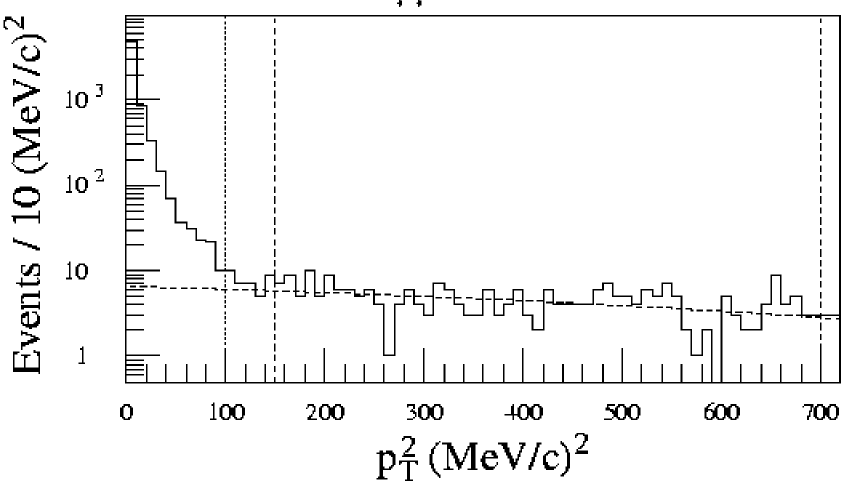
The rarest decay ever observed





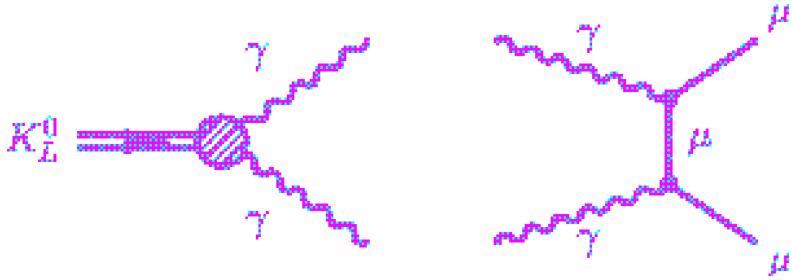
$K^0_L \to \mu^+\mu^-$ BNL-E871 PRL 84 (2000) 1389



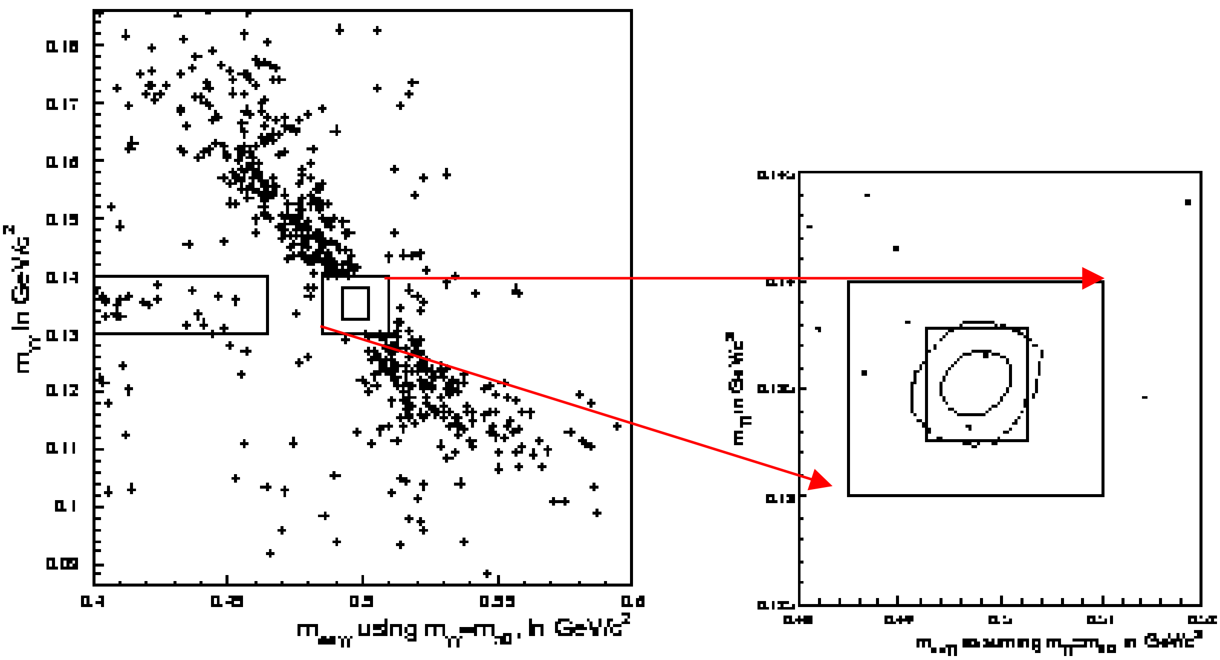


Branching ratio $(7.18 \pm 0.17) \times 10^{-9}$ 6200 signal events

Consistent with "unitary bound" $(7.07 \pm 0.18) \times 10^{-9}$



$K^0_L \to \pi^0 e^+ e^-$ FNAL-KTeV '97 PRL 86 397 (2001)



Branching ratio $< 5.1 \times 10^{-10}$ 2 events observed
1.06 ± 0.41 background expected

Radiative Dalitz
($K^0_L \to e^+ e^- \gamma\gamma$, 7×10^{-7}) and $M_{\gamma\gamma} = M_{\pi^0}$

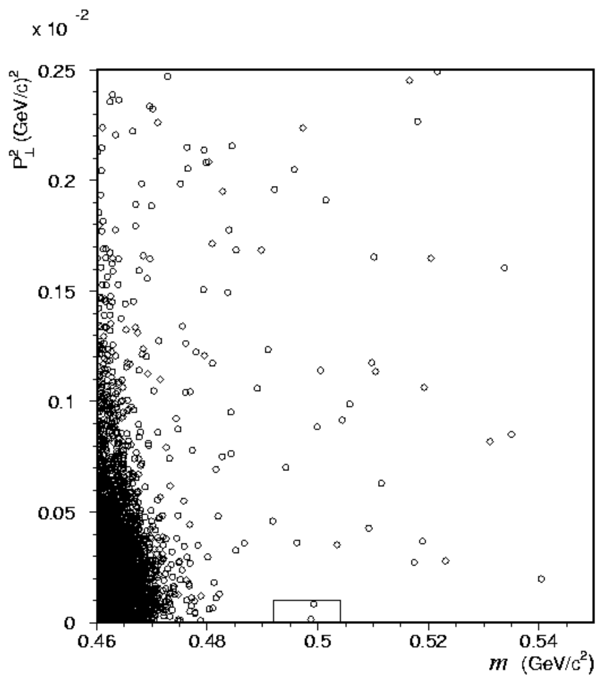
Blind analysis – didn't look near signal box
until the analysis cuts were finalized

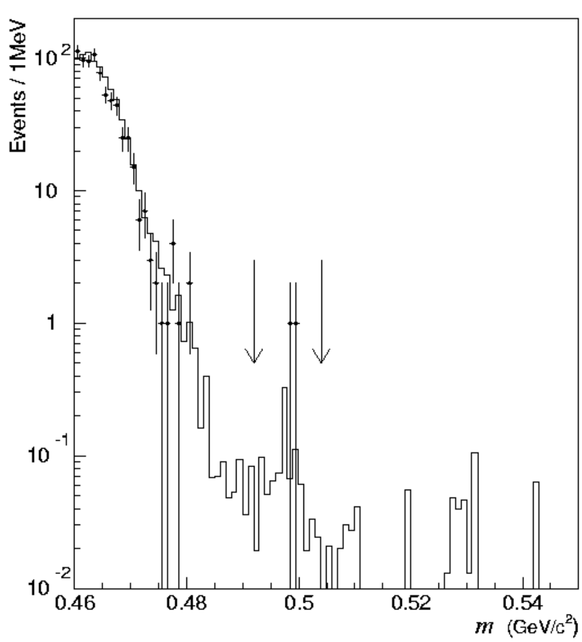
$K^0_L \to \pi^0\mu^+\mu^-$ FNAL-KTeV '97 PRL 84 5279 (2000)

Branching ratio $< 3.8 \times 10^{-10}$ 2 events observed

0.87 ± 0.15 background expected

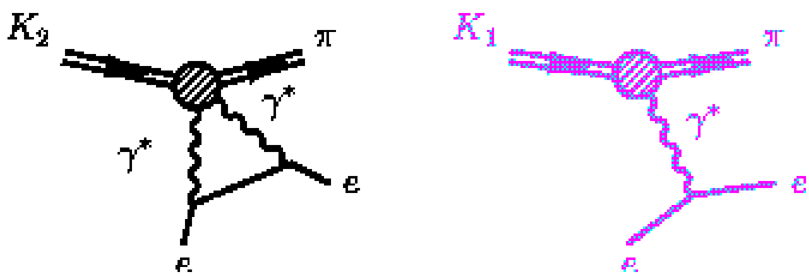
Dimuon system tends to suppress long-range backgrounds



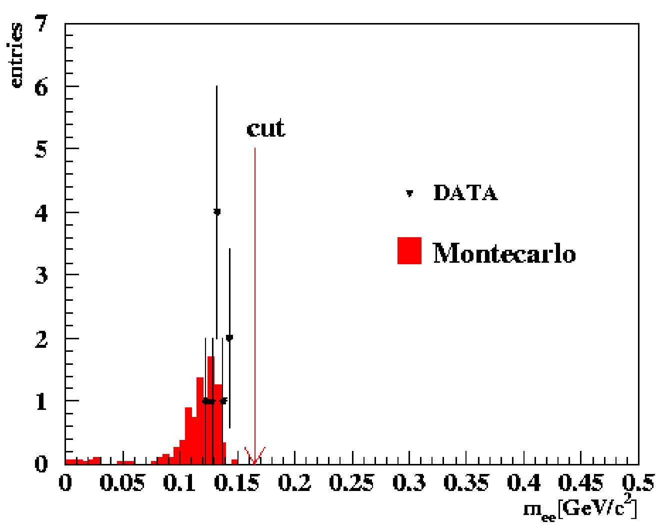


$K^0_L \to \pi^0 e^+ e^-$ Standard Model Contributions

Direct CP Violation	$(4.3 \pm 2.1) \times 10^{-12}$
CP Conserving (K_2)	$< 2 \times 10^{-12}$
Indirect CP violation (K_1)	10^{-12} - 10^{-11}



$K^0_S \to \pi^0 e^+ e^-$ CERN-NA48 '99HI Preliminary



Limit $<1.4 \times 10^{-7}$ with <0.07 background events

$Br(K^0_S \to \pi^0 e^+ e^-) \sim 330 \times Br(K^0_L \to \pi^0 e^+ e^-)_{ind\ CP}$

SM expectation $\sim 5 \times 10^{-9} |a_s|^2$

High Intensity run in '99 K_S 2 days with 6×10^9 ppp

$K^0_S \to \pi^0 e^+ e^-$ CERN-NA48/1 '02

120 days with 1×10^{10} ppp x50 improvement

Br Sensitivity $\sim 3 \times 10^{-9}$ in the SM range

Where are we with $K \rightarrow \pi\ l^+ l^-$?

$K^0_L \rightarrow l^+ l^-$

The pure dilepton channels appear to be completely dominated by the long distance two photon diagram.

The only other observable is the final state muon polarization I doubt if this will help given the limited room left for short distance amplitudes

$K^0_L \rightarrow \pi\ l^+ l^-$

The present measurements are getting close to the levels at which we expect to observe the 3 body decays modes.

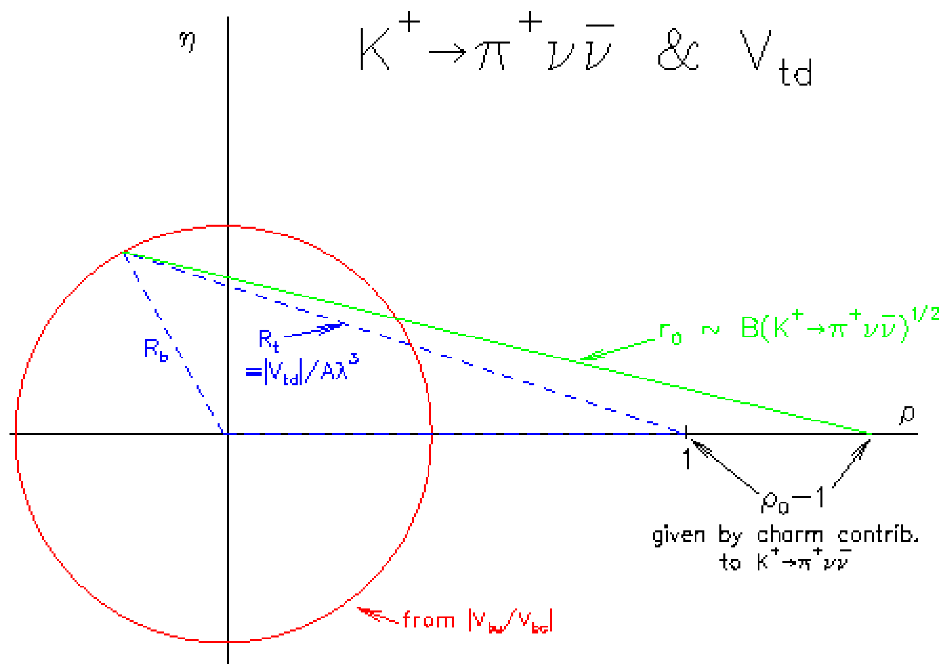
The NA48/1 measurements in K^0_S should help with a Measurement of the CP conserving amplitudes.

The theoretical problem of disentangling the long and short Distance contributions looks formidable (to me).

None of the new experiment plan to measure these modes in K^0_L. Somebody should go after these (JHF?)

$K^+ \to \pi^+ \nu \bar{\nu}$

$$Br[K^+ \to \pi^+ \nu \bar{\nu}] = 4.11 \times 10^{-11} A^4 X(x_t)^2 [(\rho 0 - \rho)^2 + \eta^2]$$



Standard Model prediction: $(0.75 \pm 0.29) \times 10^{-10}$

a recent review by Buras: *hep-ph*/0101336

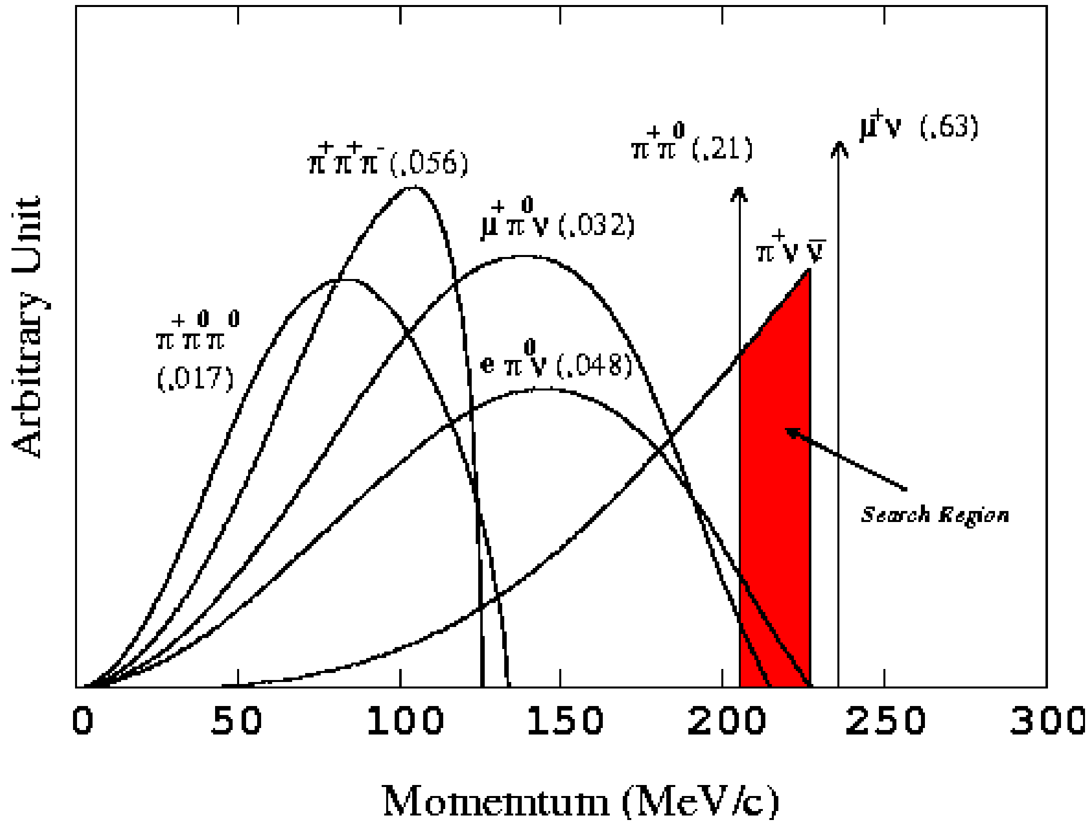
Theoretical uncertainty: ~7%

(m_{charm} in the NLO QCD analysis)

The best place to measure $\lambda_t = |V^*_{ts} V_{td}|$

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ BNL E787/E949

Stopped K^+ decay to π^+ plus "nothing"



Measure the π^+ from the 3 body decay beyond the kinematic limit for hadronic decays (205 MeV/c)

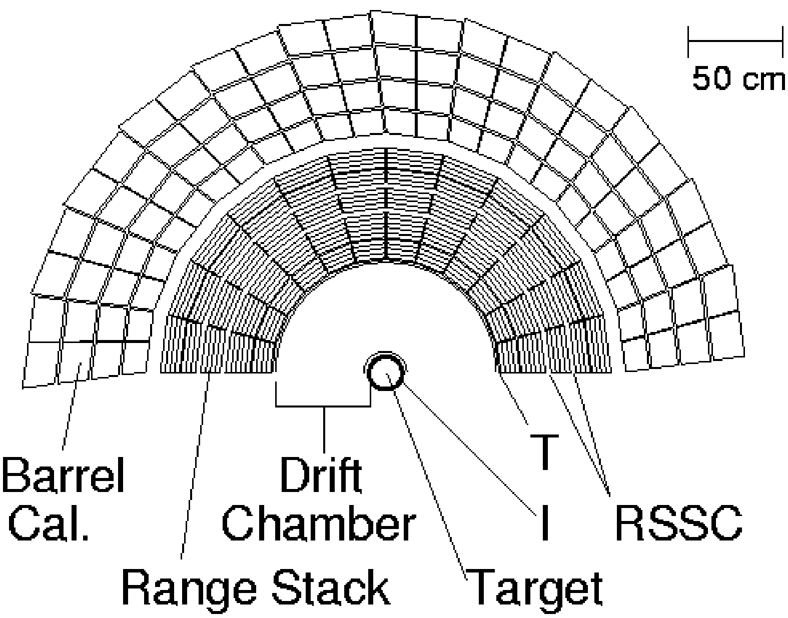
Veto photons – very well!

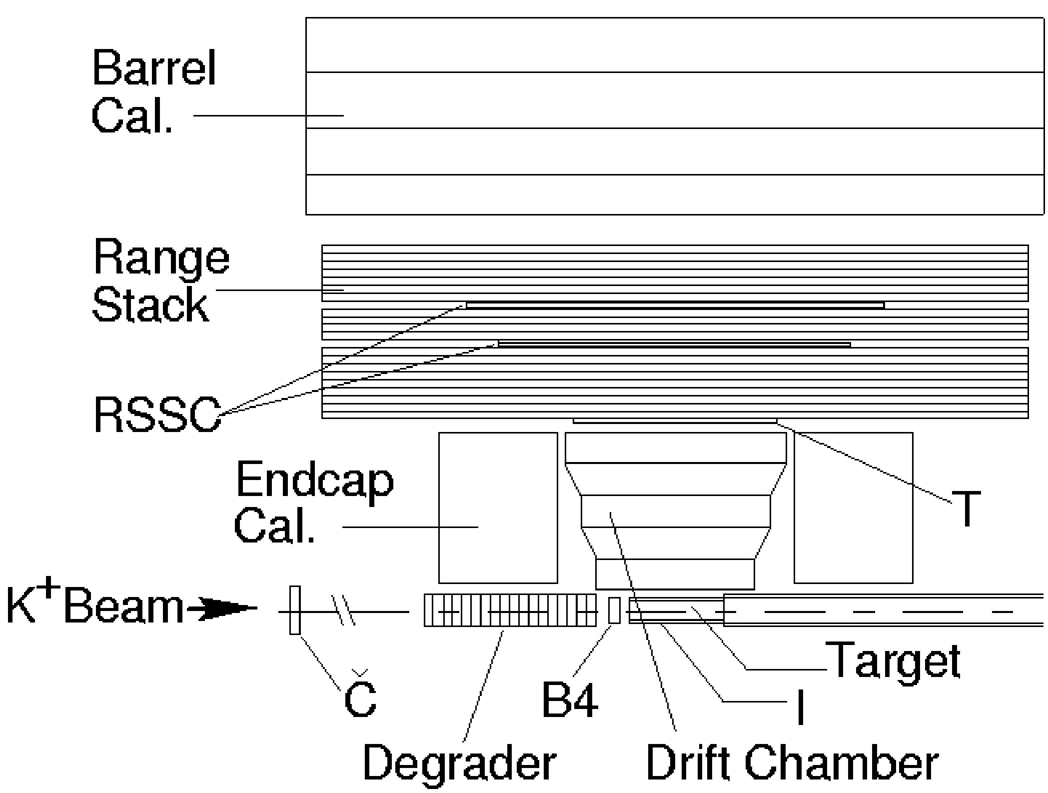
Background rejection is critical:

Kinematics	P / E / Range	
μ^+ rejection	$K^+ \rightarrow \mu^+ \nu$	Br = 63%
Photon vetoes	$K^+ \rightarrow \pi^+ \pi^0$	Br = 21%

All require high rejections – reliably estimated from data

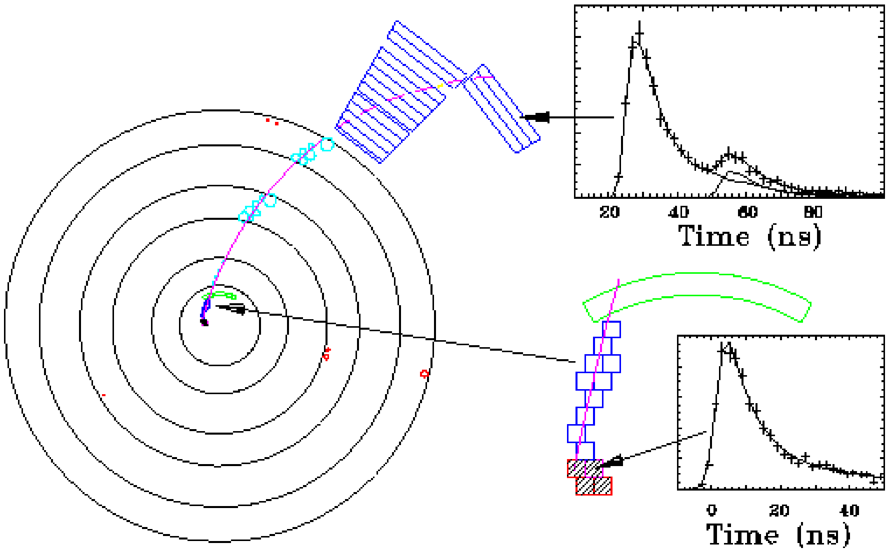
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ BNL E787/E949 Detector Cut-away



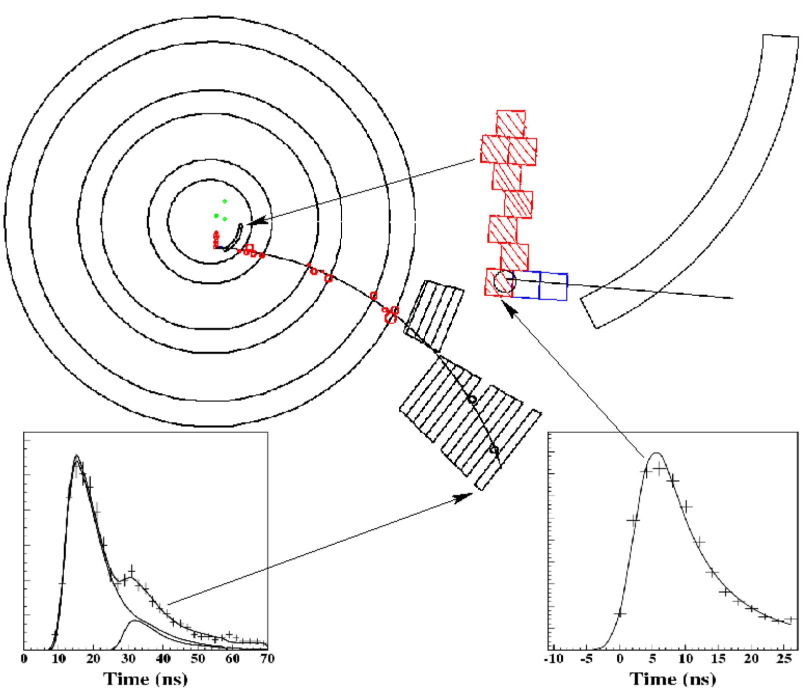


$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ BNL E787 PRL79 2004,(1997)

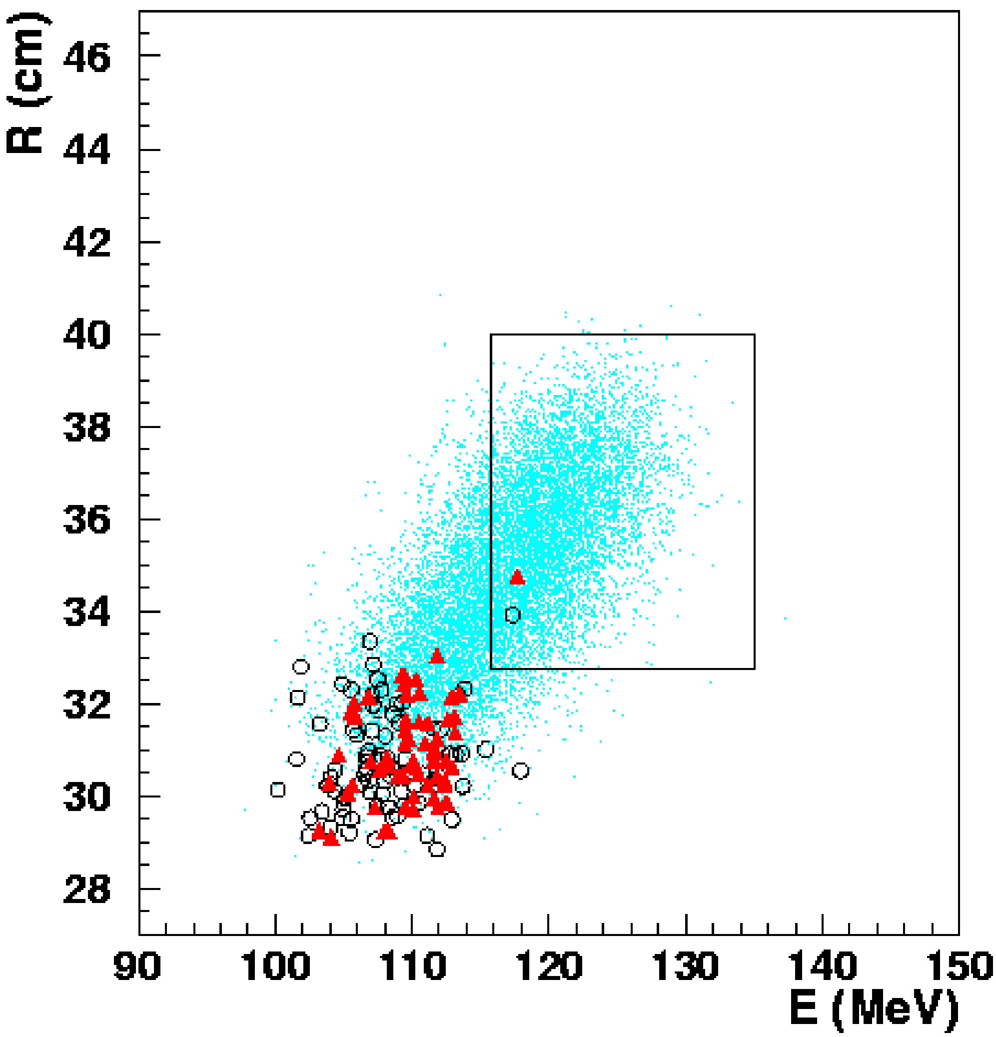
Evidence for the Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



hep-ex/0111091



$K^+ \to \pi^+ \nu \bar{\nu}$ BNL E787 hep-ex/0111091



$K^+ \to \pi^+ \nu \bar{\nu}$ BNL E787 Final Results (NEW)

E787 results from `98 dataset

Reported by Joe Mildenberger at a TRIUMF Seminar Nov 6, 2001

1 new event seen!

Set	N_K [10^{12}]	Br [10^{-10}]	back [events]	acceptance
`95-`97	3.2	$1.5^{+3.4}_{-1.2}$	0.08 ± 0.02	0.0021
`98	2.7	$1.9^{+4.4}_{-1.5}$	0.07 ± 0.04	0.0020
all	5.9	$1.57^{+1.75}_{-0.82}$	0.02% (background only)	

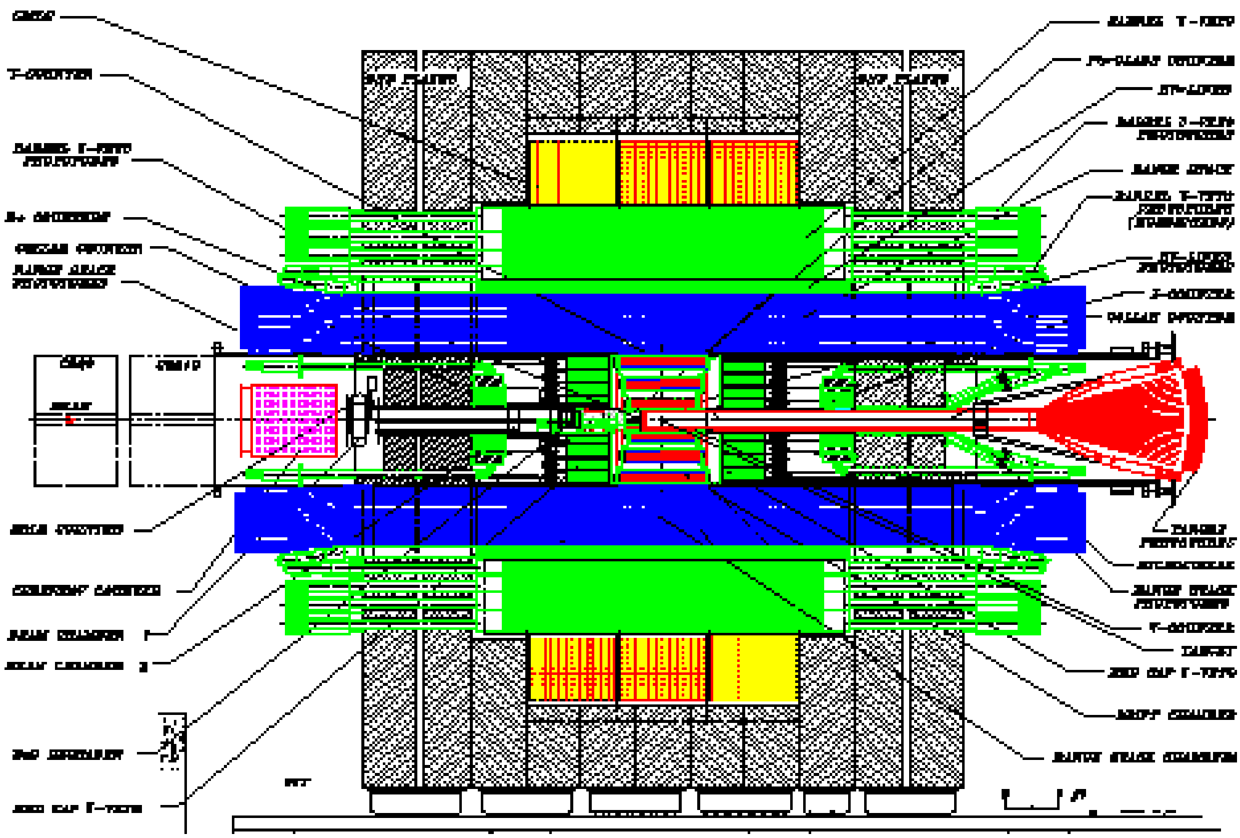
Standard Model 0.75 ± 0.29

$$2.9 \times 10^{-4} < |\lambda_t = V^*_{ts} V_{td}| < 12 \times 10^{-4}$$

Assuming unitarity, m_t, V_{cb}

$$7 \times 10^{-3} < |V_{td}| < 30 \times 10^{-3}$$

$K^+ \to \pi^+ \nu \bar{\nu}$ BNL E949 http://www/phy.bnl.gov/e949



Detector upgrades from E787

1. Barrel veto liner shower counter
2. New/improved photon vetoes around beam line
3. New B4 counter, degrader
4. Trigger: programmable Level0, Mean timers
5. Range stack TDC system $\mu^+ \to e^+$ with reduced dead time
6. Range stack LED monitoring system
7. Optimization of running mode (65TP for just us!)

Sensitivity (8-14) x 10^{-12} ∴ 5 – 10 events in 2 years
Just completed 1st checkout data run on Nov 8
Data taking scheduled for Feb 1,2001 (I'm missing shifts!)

$K^+ \to \pi^+ \nu \bar{\nu}$ FNAL CKM (E921)

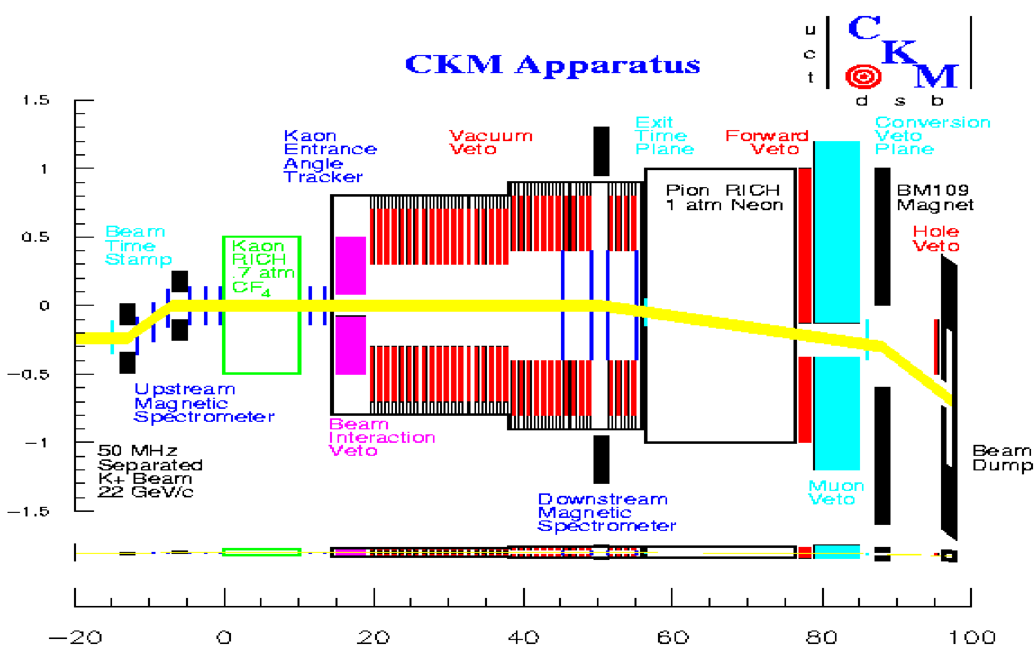
http://www.fnal.gov/projects/ckm/Welcome.html

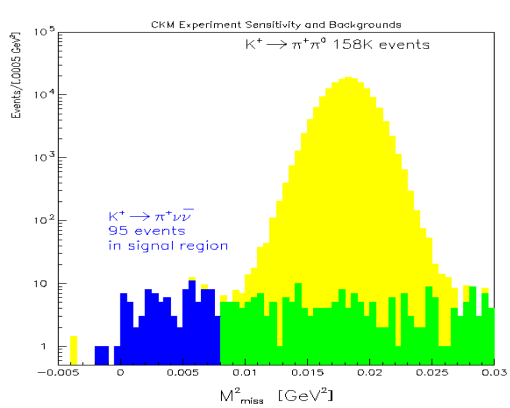
Newly approved decay in flight experiment

- Separated 50MHz K^+ beam at 22 GeV/c
- Redundant, high rate charge particle tracking
- Excellent photon and muon vetoes.

Goal: 100 signal events with S/N >10

Measure $|V_{td}|$ to 10% including theory uncertainties

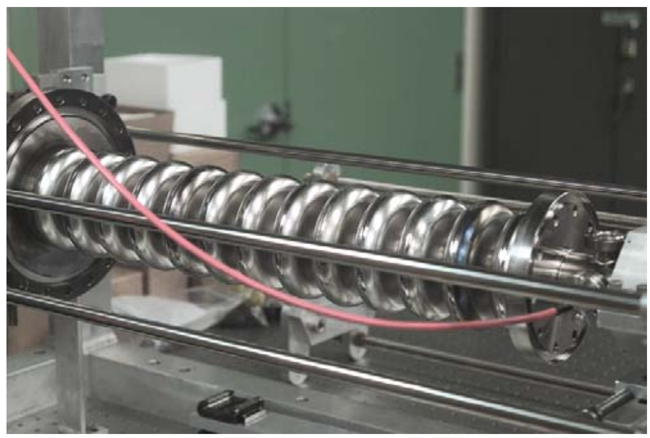




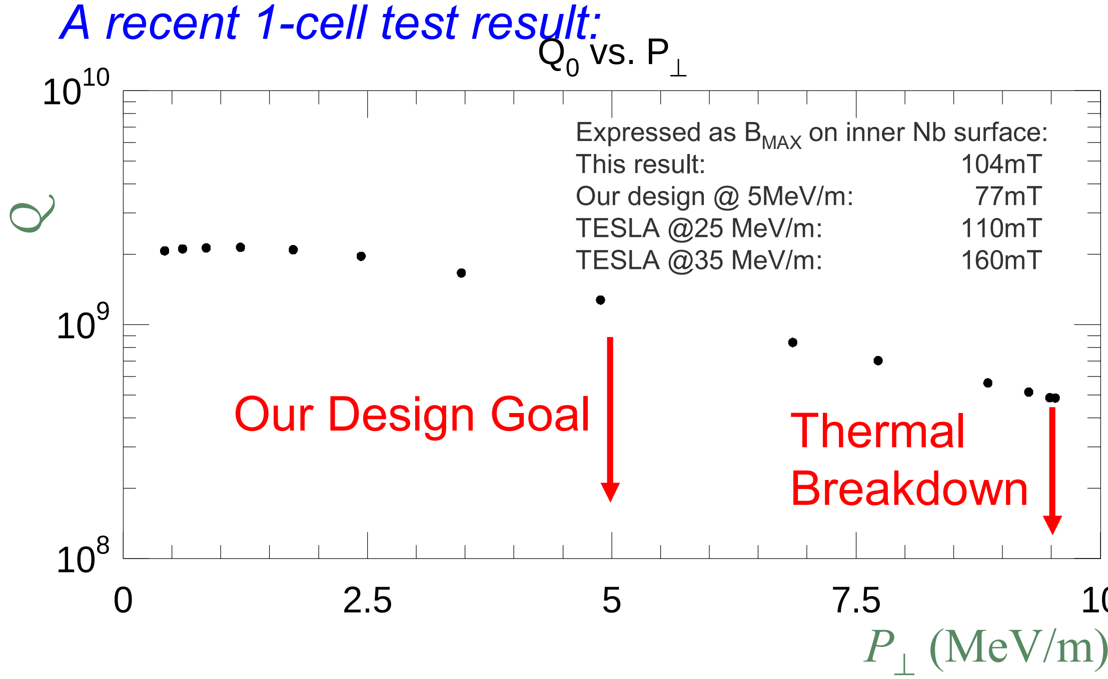
$K^+ \to \pi^+ \nu \bar{\nu}$ FNAL CKM SCRF K^+ Beam

Separated 22 GeV/c beam using 3.9 GHz SCRF cavities operating in transverse (deflecting) mode

First full 13 cell prototype



A recent 1-cell test result:



$K^0_L \to \pi^0 \nu \bar{\nu}$ The Golden mode

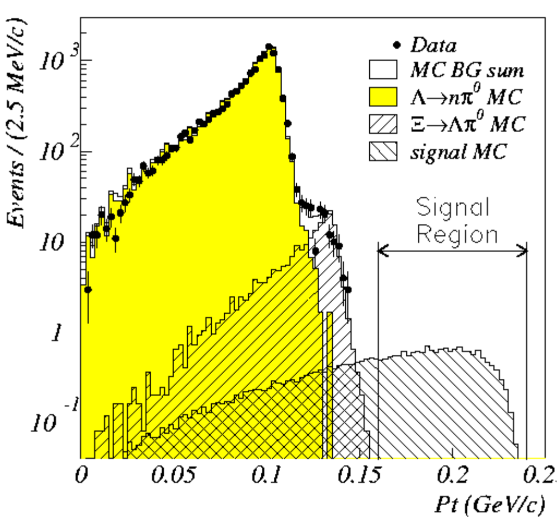
$Br[K^0_L \to \pi^0 \nu \bar{\nu}] = 1.80 \times 10^{-11} A^4 X(x_t)^2 \eta^2$

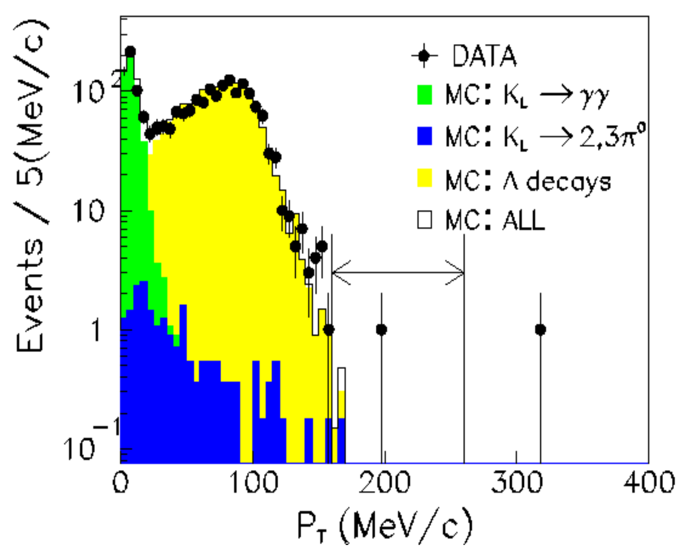
Standard Model Prediction: $(2.6 \pm 1.2) \times 10^{-11}$

in flight K^0_L decay to π^0 plus "nothing"
(nothing goes to nothing plus 2 neutrinos!)

FNAL KTeV PRD61,072006 (2000)
PLB447,240(1999)

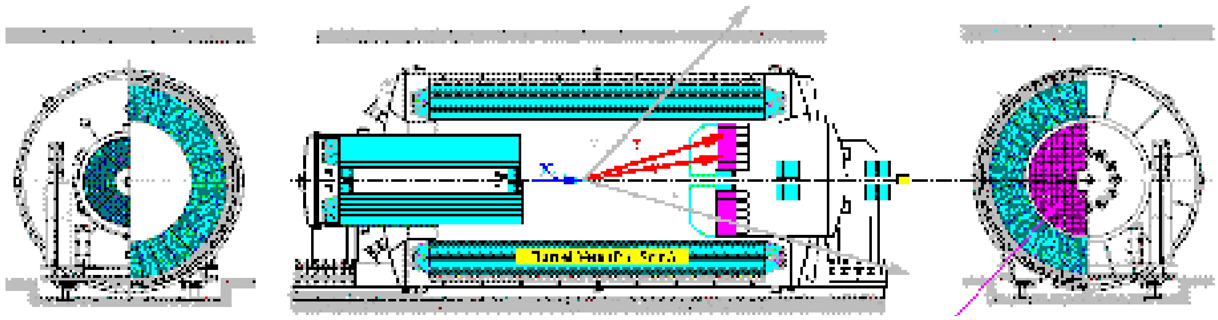
$[\pi^0 \to e^+e^-\gamma]$	$[\pi^0 \to \gamma\gamma]$
background 0.12 ± 0.05 events	3.5 ± 0.9 events
$Br < 5.9 \times 10^{-7}$	$Br < 1.6 \times 10^{-6}$

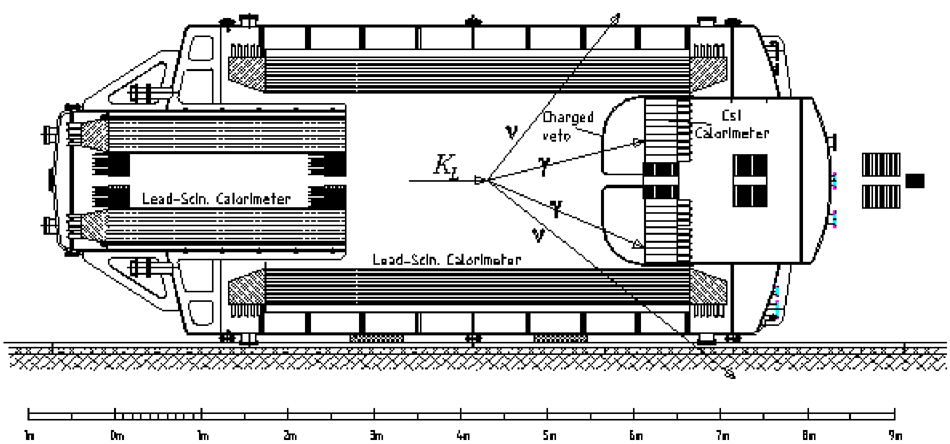




Very low photon detection inefficiency: $<10^{-3} \sim 10^{-4}$
Major background from $K^0_L \to \pi^0 \pi^0$ with 2 missed γ's
(CP violation is a background!)

$K^0_L \to \pi^0 \nu \bar{\nu}$ KEK E391a Detector





collimated pencil beam

CsI calorimeter to detect both photon from π^0

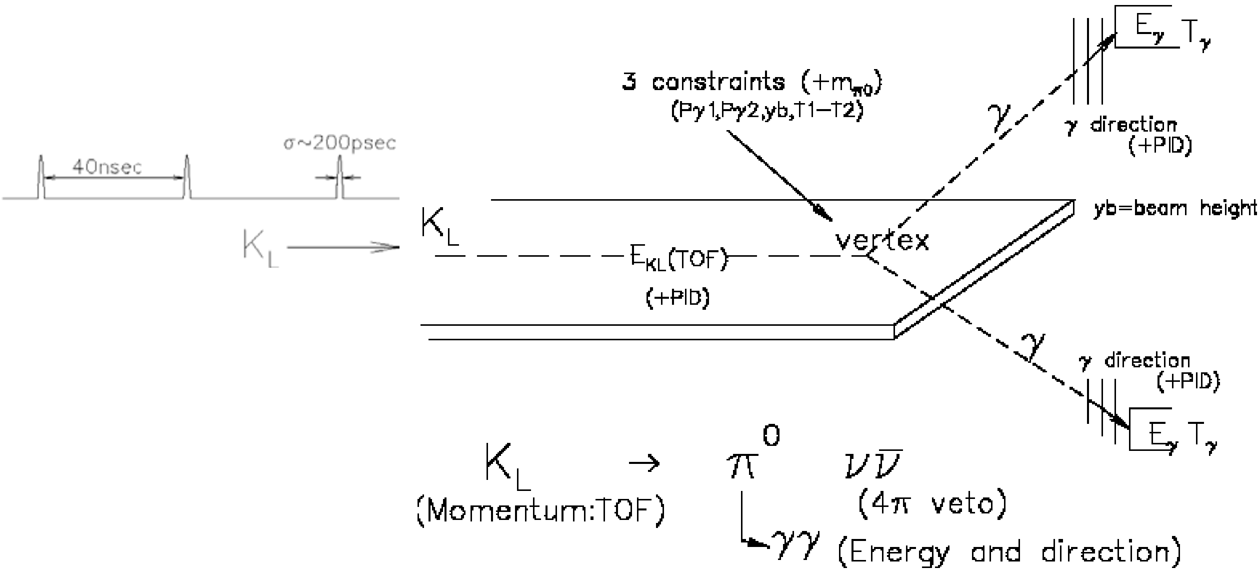
- energy and position
- decay vertex along the beam line from the m $_{\pi}0$ constraint
- signal: events with Pt $[\pi^0]$>120 MeV/c

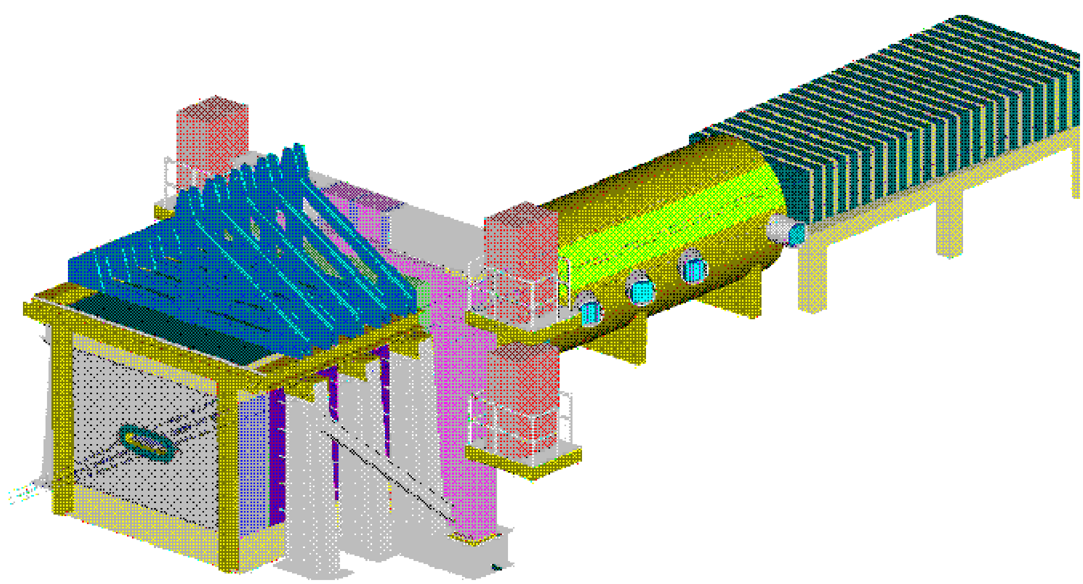
calorimeters for “perfect” photon veto

Beam line survey and detector construction (now)

Start data taking in fall `03

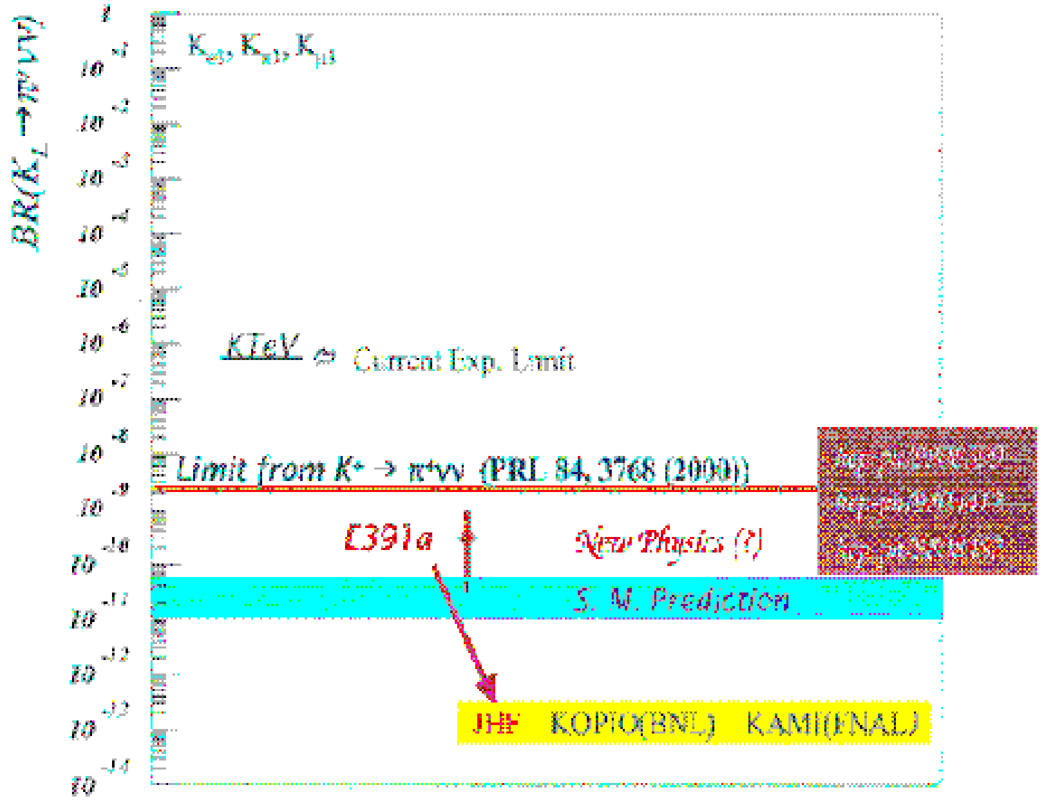
$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ BNL KOPIO Detector





RF bunched, low energy (800 MeV/c) beam for TOF
(an extra measurement to get back into the CM)
Pre-radiator and Shashlik calorimeter for photon detection
energy, position, angle and timing for each photon

Prospects for $K^0_L \to \pi^0 \nu \bar{\nu}$ Measurements



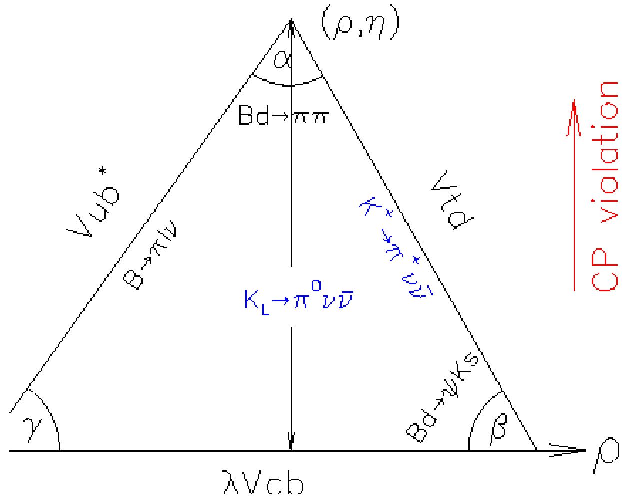
Improvement of more than 4 orders of magnitude required

Model independent bound (Grossman and Nir) Br < 2.6×10^{-9}
Standard Model Br = $(2.6 \pm 1.2) \times 10^{-11}$

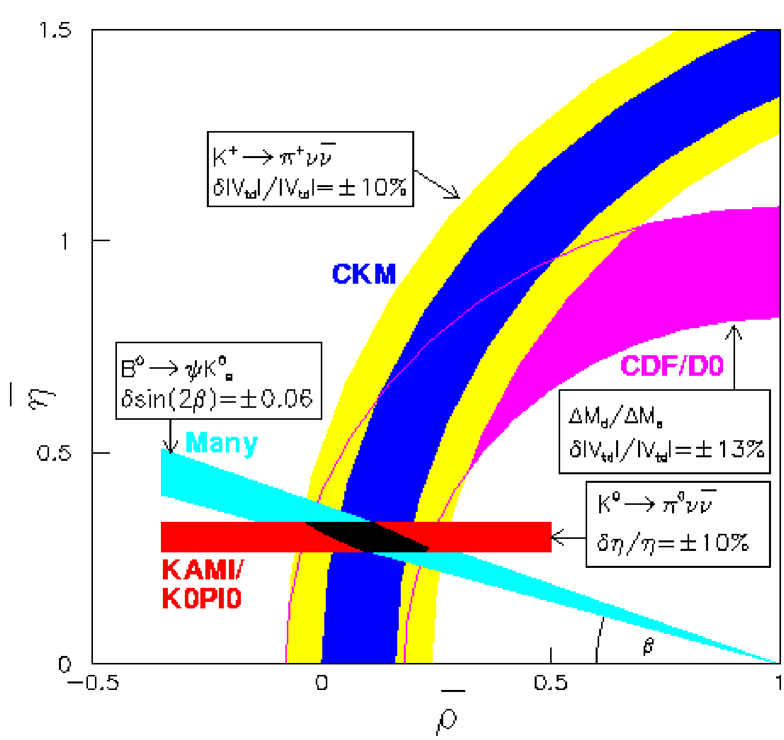
KEK E391a – first dedicated experiment sensitivity $O(10^{-10})$

BNL KOPIO – goal 50 SM $K^0_L \to \pi^0 \nu \bar{\nu}$ events with S/N=2

Measurements of $Br[K^0_L \to \pi^0 \nu \bar{\nu}]$ and $Br[K^+ \to \pi^+ \nu \bar{\nu}]$



Jarlskog invariant – the area of all unitarity triangles
In the Kaon sector no B sector input is required:
$J_{cp} = Im[V^*_{ts} V_{td} V^*_{us} V_{ud}] = \lambda (1-\lambda^2/2)\, Im[\lambda_t]$



Where are we with $K \rightarrow \pi \nu \bar{\nu}$?

1. There is a large investment here with 3 new experiments approved. The measurements are theoretically robust.

2. We could falsify the Standard model description of CP violation – requiring new physics, with good measurements here combined with B system results expects from the B factories, etc.

3. Experimentally these measurements are really HARD. There is no mass bump everything in the signal region which isn't estimated as background will be called signal.

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

There are two clean events seen here. The background appear to be under control, but the decay at rest technique has been pushed about as far as possible.

CKM will try to get 100 clean events in decay in flight.

$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$

This measurement makes K^+ look easy; but the value of the measurement is huge.

There are 4-5 orders of magnitude to go from the present KTeV upper limit to a measurement of the branching ratio

E391a will try for a first observation (like E787 in K^+)

KOPIO will "go for it".

Summary

Recent Experiments – far from everything done

BNL	CERN	FNAL	KEK
E787	NA48	KTeV/E799	E246
E865		KTeV/E832	
E871		HyperCP/E871	

New Approved Experiments

E949	NA48/1	CKM	E391a
KOPIO	NA48/2		(JHF)

The kaon system continues to be a gold mine even after 45 years of work.

Good progress is being made on understanding the sources of CP violation with FCNC and other decays

The next round of experiments are underway with the direct goal of confronting the Standard Model's description of the source of matter – anti-matter asymmetry in nature.