April 17, 2001
DOE Review

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

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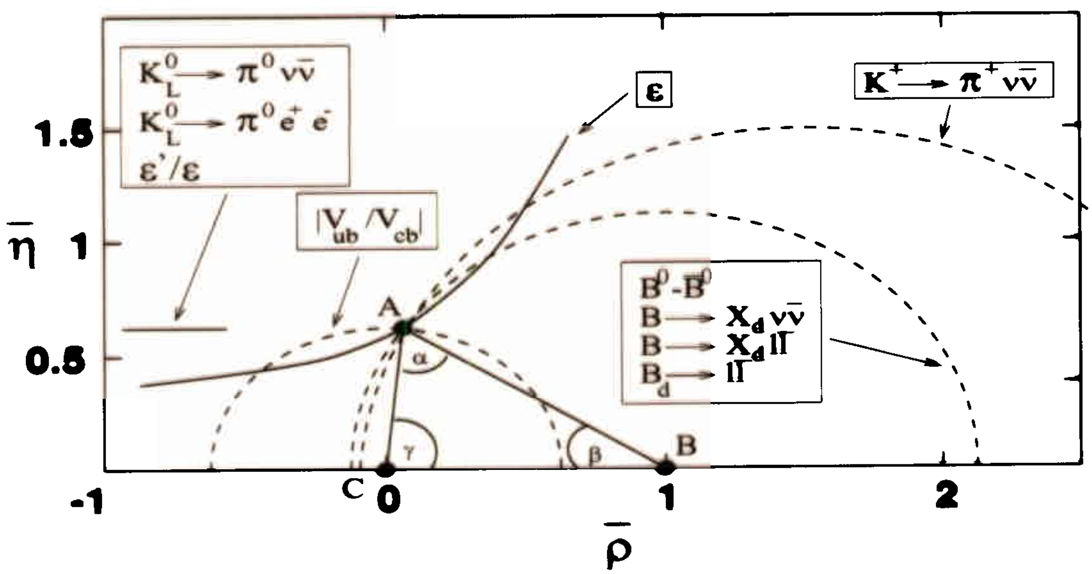
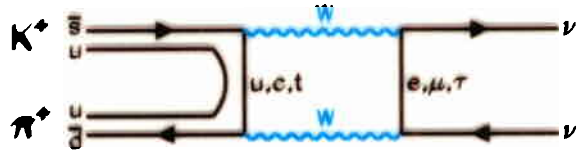
Unitarity relations e.g. $V_{ub}^{*}V_{ud}+V_{cb}^{*}V_{cd}+V_{tb}^{*}V_{td}=0$

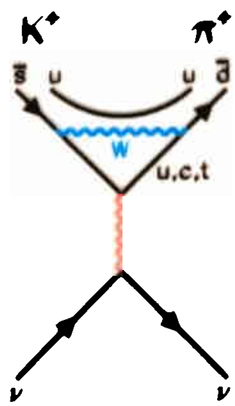


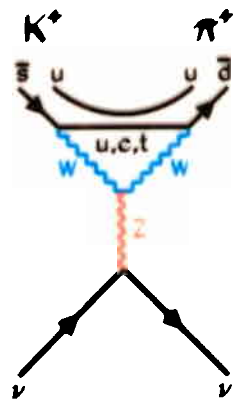
Four "Super-clean" K and B physics inputs will test the SM CP v picture. (Buras)

$K \to \pi\ \nu\bar{\nu}$	BNL-E787,E949, FNAL-CKM
$K_L \to \pi\ \nu\bar{\nu}$	BNL KOPIO, FNAL KAMI
$B_d \to \Psi K_s$	BABAR,BELLE,CDF,HERA-B
$\frac{x_s}{x_d} = \frac{B_s - \overline{B_s}}{B_d - \overline{B_d}}$	CDF, $D0$, BTEV, LHCB

$K \to \pi\nu\bar{\nu}$ in the Standard Model







	$K^+ \to \pi^+\nu\bar{\nu}$	$K_L^0 \to \pi^0\nu\bar{\nu}$
Top Dependence	$\lvert\lambda_t\rvert = \lvert V_{ts}^* V_{td}\rvert$	$\mathrm{Im}(\lambda_t) = \mathrm{Im}(V_{ts}^* V_{td})$
Calc. BR (10^{-10})	0.82 ± 0.32	0.28 ± 0.1
Est. Theory Uncertainty	5% (charm)	1%

- Negligible long distance effects (10^{-13}).
- Hadronic matrix elements from isospin analog $K^+ \to \pi^0 e^+ \nu_e$.

Prospects for SM CP Violation Parameters

A. J. Buras TUM-HEP-316-98

- Scenario I: B-Factory Era ($V_{cb} \pm 0.002(0.001)$)
- Scenario II: LHCB/BTeV Era
- 10% precision on $K \to \pi\bar{\nu}\nu$

	$K \to \pi\bar{\nu}\nu$	Scenario I	Scenario II
$\sigma(\lvert V_{td}\rvert)$	$\pm 10\%(9\%)$	$\pm 5.5\%(3.5\%)$	$\pm 5.0\%(2.5\%)$
$\sigma(\bar{\rho})$	$\pm 0.16(0.12)$	± 0.03	± 0.01
$\sigma(\bar{\eta})$	$\pm 0.04(0.03)$	± 0.04	± 0.01
$\sigma(sin2\beta)$	± 0.054	± 0.06	± 0.02
$\sigma(Im\lambda_t)$	$\pm 5\%$	$\pm 14\%(11\%)$	$\pm 10\%(6\%)$

E949

An experiment to measure the branching ratio $B(K^+ \to \pi^+ \nu\bar{\nu})$

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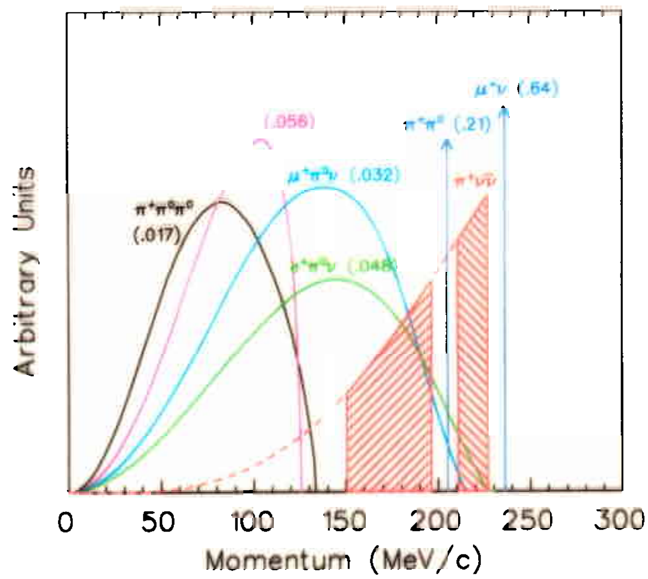
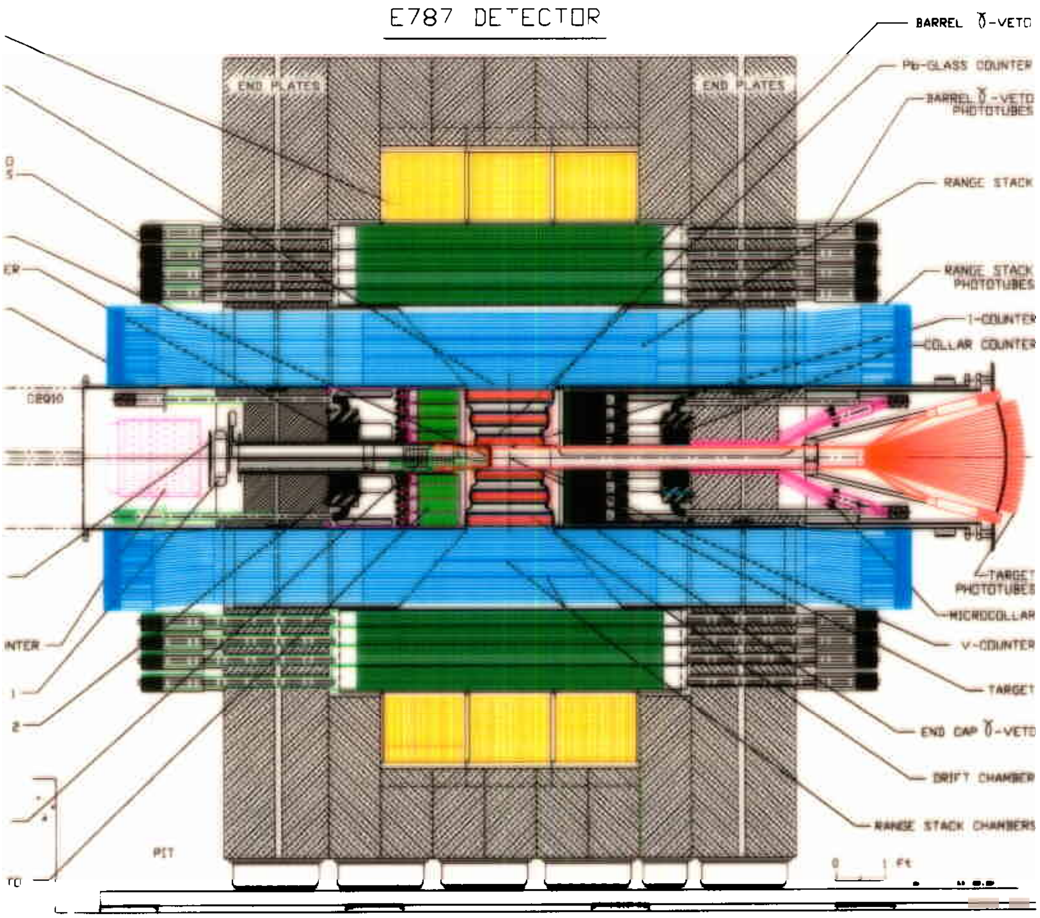
E787: Measuring $K^+ \to \pi^+ \nu \bar{\nu}$



$K^+ \to$	π^+	$\nu\bar{\nu}$
Stopped $K \to \pi$	Momentum	4π Veto
C.M. system	Energy	
	Range	
	$\pi \to \mu \to e$	

PHILOSOPHY:

- Get as much information as possible!
- Suppress backgrounds ($K \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, ...) S/N $= 10$.
- Perform "blind" analysis to avoid bias.



$K:\pi \sim 4:1 \rightarrow \check{C}_K \rightarrow$ BeO degrader $\rightarrow$
active, segmented target

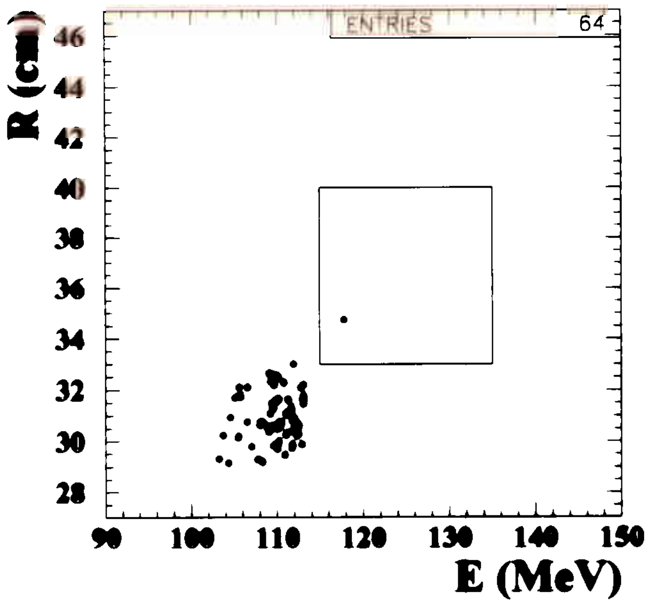
$\pi^+ \rightarrow$ 1.0 T drift chamber $\rightarrow$
21-layer, segmented range stack

photon veto: 14 X_0 barrel, 13.5 X_0 CsI endcap,
Pb glass, collars

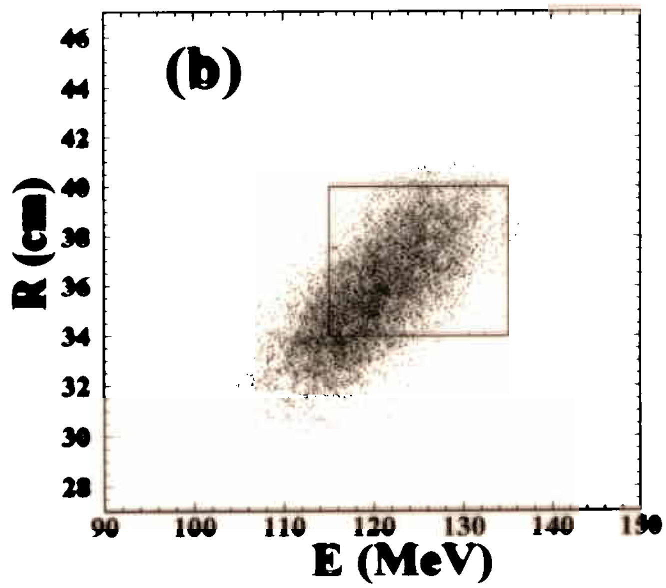
data acquisition: $\sim 1.0 \times 10^6$ K^+ stops in target per 1.5-sec spill
~ 200; $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ triggers per spill

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

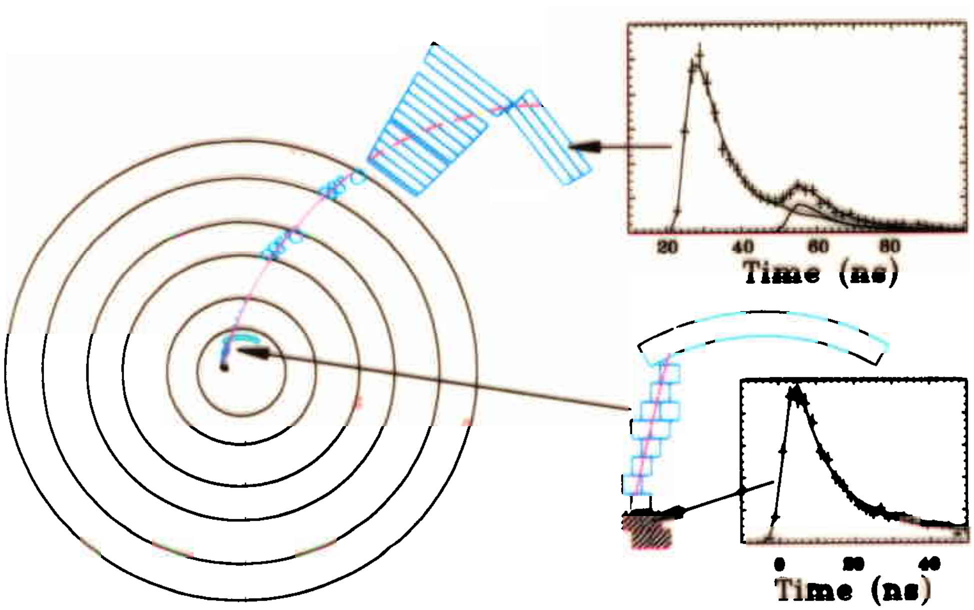
1995–97 Data



Monte Carlo



Event Display



$$\mathbf{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.5^{+3.4}_{-1.2}) \times 10^{-10}$$

(1995: PRL **79**, 2204, 1997; 1995 PRL **84** 3768 2000)

$K^+ \rightarrow \pi^+ x$ and Global Family Symmetry

[Wilczek (1982), Gelmini et al. (1983), Feng et al. (1998)]

Motivation: Explain the replication of families

Postulate: Global Family Symmetry spontaneously broken at large mass scale (F) $\rightarrow$ Goldstone Boson "FAMILON (f)".

$L_{eff} = \frac{1}{F} J_\mu \partial_\mu f$ ·· $\mu \rightarrow e + f$ and $s \rightarrow d + f$

	GFS	Experiment	F Limit (GeV)
$B(K^+ \rightarrow \pi^+ f)$	$\frac{1.310^{14} GeV^2}{F^2}$	$< 1.110^{-10}$ (E787)	$> 1.110^{12}$
$B(\mu \rightarrow ef)$	$\frac{2.510^{14} GeV^2}{F^2}$	$< 2.610^{-6}$ (Jodidio)	$> 10^{10}$
$B(\tau \rightarrow ef)$	$\frac{2.510^{14} GeV^2}{F^2}$	$< 2.610^{-3}$ (ARGUS)	$> 310^{6}$
COSMOLOGY			$10^9 < F < 10^{12}$

Constraints on New Physics

Selected E787 RESULTS

MODE	RESULT(E787 GAIN)	COMMEN
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	$(1.5^{+3.4}_{-1.15})10^{-10}$(580)	Discovery!
$K^+ \rightarrow \pi^+ \mu^+ \mu^-$	$(5.0 \pm 1.0)10^{-8}$(4500)	Discovery!
$K^+ \rightarrow \pi^+ \gamma\gamma$	$(1.1 \pm 0.3)10^{-6}$(100)	Discovery!
$K^+ \rightarrow \mu^+ \nu\gamma$	$(1.33 \pm 0.12)10^{-5}$(1000)	Discovery!
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	$(4.72 \pm 0.77)10^{-6}$ (8)	D.E. Rad.
$K^+ \rightarrow \pi^+ x$	$< 1.1 \times 10^{-10}$(346)	Familon?
$K^+ \rightarrow \mu^+ \nu\mu\mu$	$< 4.1 \times 10^{-7}$(2.4M)	Higgs?
$K^+ \rightarrow e^+ \nu\mu\mu$	$< 5 \times 10^{-7}$(2M)	Higgs?
$\pi^0 \rightarrow \nu\nu$	$< 8 \times 10^{-7}$(10)	Search?
$\pi^0 \rightarrow \gamma X$	$< 5.3 \times 10^{-4}$(1900)	Vector?
$K^+ \rightarrow \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$(new)	Non-SM

AND TECHNOLOGIES

500 MHz/ 10 μs Transient Digitizers
500 MHz Gallium Arsenide CCDs
Pure CsI Crystal Detectors
Scintillating Fiber Target
Inflated foil Central Drift Chamber

E787 Analysis Status

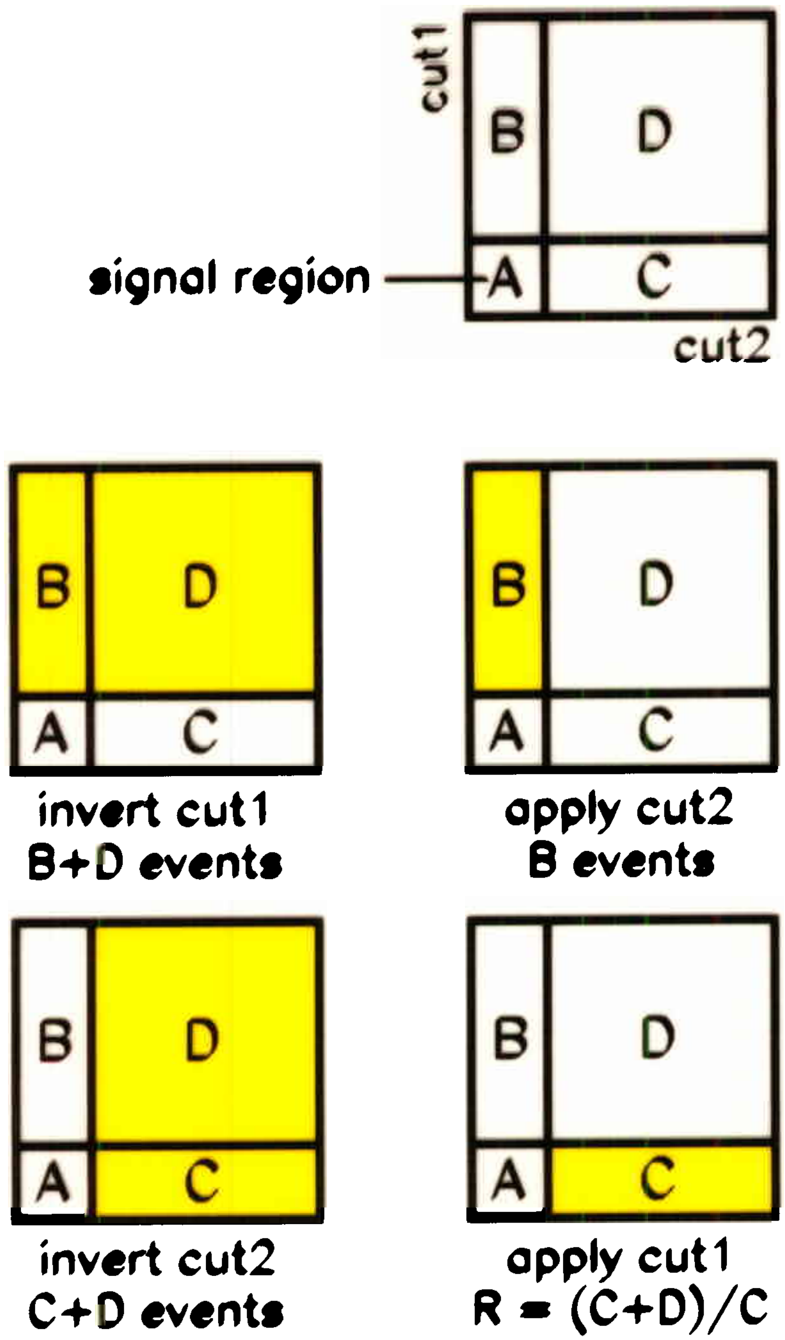
- Improved estimates for $K^+ \to \mu^+\nu$ background
- Background levels for the 1998 data set
- Analysis schedule

Analysis Strategy

require $> 10^{10}$ suppression of backgrounds
$\longrightarrow$ low statistics bias

- blind analysis
  - identify background sources *a priori*
  - define a "box" where signal:background is highest
  - do not establish cuts by examining events in the box; instead perform:
- bifurcated analyses
  - enhance statistics for background estimation
  - background samples isolated from the real data where possible – all potential event pathologies are taken into account
  - perform outside-the-box tests of correlation in the bifurcations
- test for bias on independent data samples

Goal: expected background in box $\ll 1$ event, with rejection in reserve for evaluation of candidate events



if cut1, cut2 uncorrelated,

$$A/B = C/D$$

$$A = BC/D$$

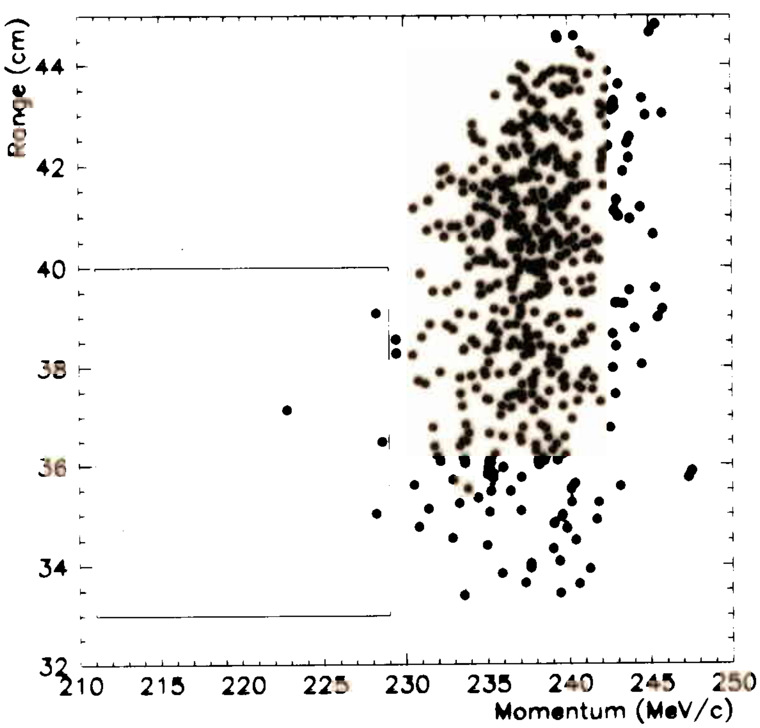
$$N = B$$

$$bg = N/(R-1)$$

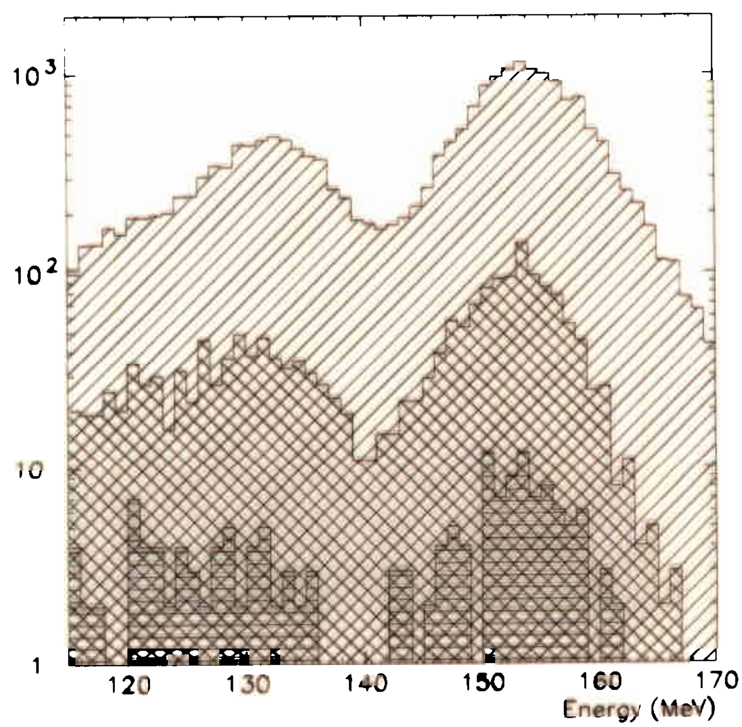
$$= BC/D$$

Bifurcated Background Estimation

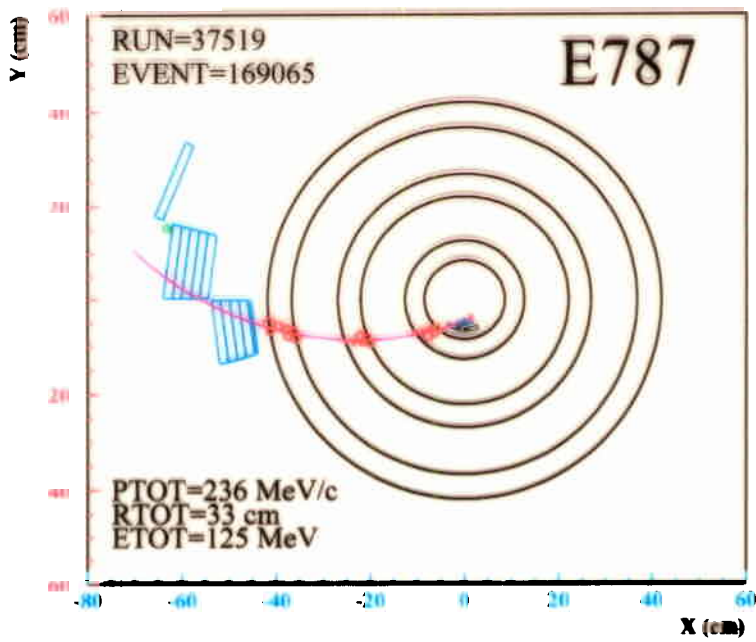
PID reversed
~ 1000× enhanced

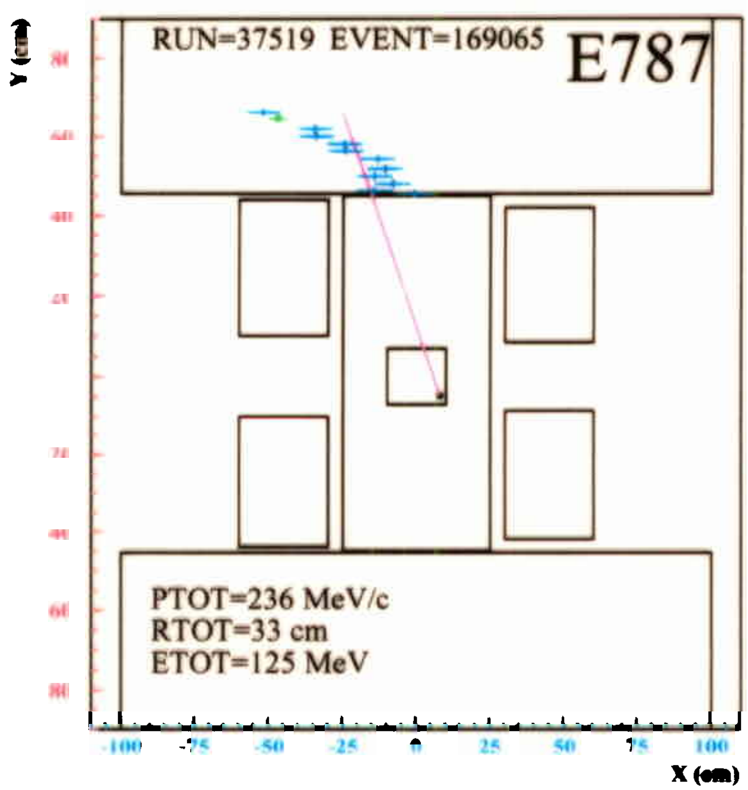


Select $K_{\mu 2}$ momentum peak
~ 150× enhanced



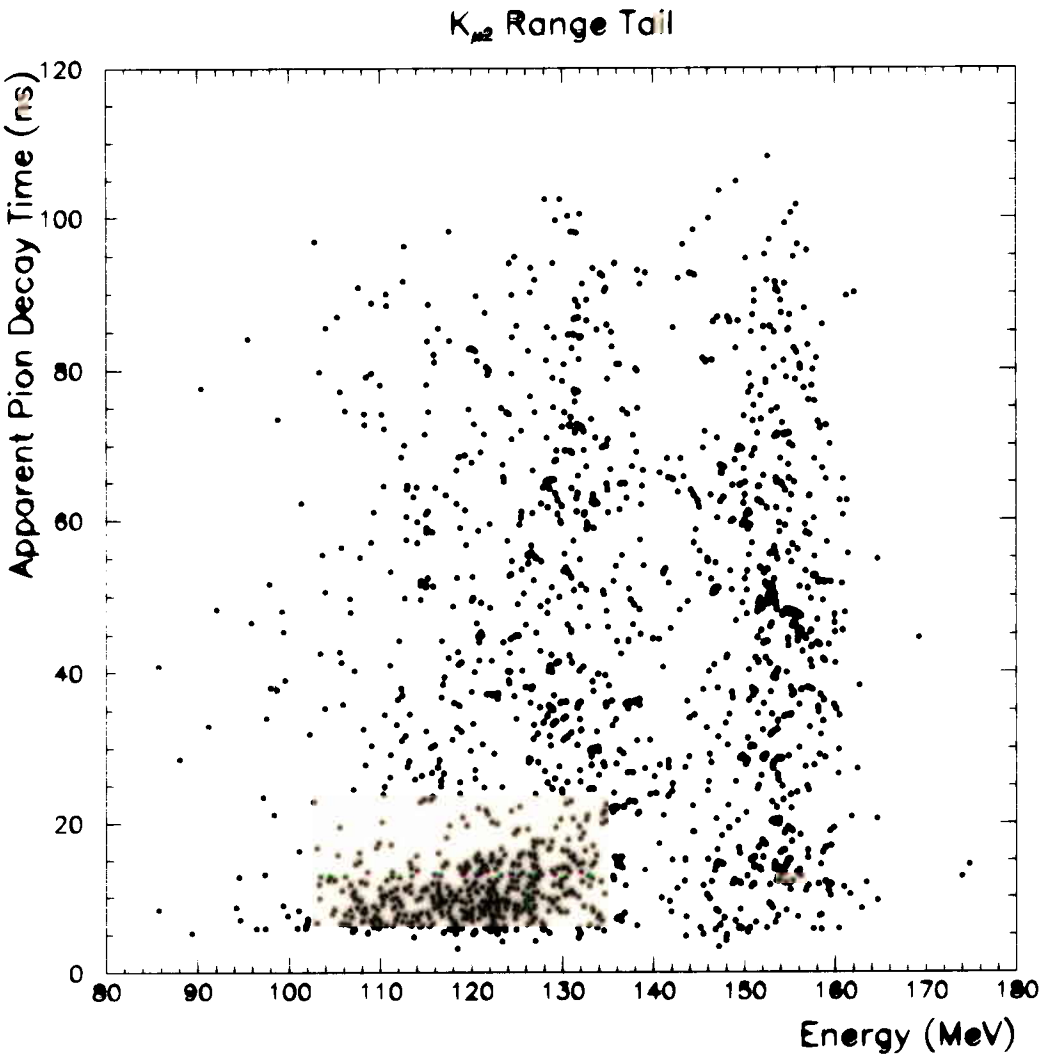
Event display for large angle muon scattering





Outside-The-Box

- **Correlation study: "GDR-neutron" background may correlate PID and kinematic cuts. Cuts applied to remove the correlation.**



1996-7 $K_{\mu 2}$ Background	Loose1	Loose2	Loose3
Predict:	1.3	42.1	296.9
Observe:	2	45	297

Estimated Background Levels

(Based on evaluating 33% of 1998 data sample.)

Background	1995-97 (Events)	1998 (Events)	Total (Events)
$K^+ \to \pi^+\pi^0$	0.022 ± 0.005	0.009	0.031
$K^+ \to \mu^+\nu$	0.028 ± 0.010	0.072	0.100
BM	0.021 ± 0.015	0.005	0.026
CEX	0.010 ± 0.007	0.010	0.020
Total			0.18

1995-98 SINGLE EVENT SENSITIVITY: 8×10^{-11}.

(Comparable to the SM central value.)

SCHEDULE OF ANALYSIS:

April, 2001	Finalize background estimates Test background outside the box
June, 2001	"Open the box"

E787 $\rightarrow$ E949 at BNL

E949 GOAL (2000-2002):
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ single-event sensitivity $(8 - 15) \times 10^{-12}$

- More protons/spill on the K^+ production target (15 Tp/spill $\rightarrow >$ 65 Tp/spill)
- Increased spill length: instantaneous rate stays low and duty factor improves (41% $\rightarrow$ 64%)
- Lower K^+ beam momentum $\rightarrow$ higher K^+ stopping fraction (by $\sim$ 38% over conditions in 1995)
- Improved data acquistion: smaller trigger and readout deadtimes and online accidental losses
- Improved photon detection efficiency, trigger-counter efficiency, and beam spatial resolution
- Longer running periods ($\geq$ 25 weeks/year, symbiotic with RHIC)

Factor of 14 estimated increase in sensitivity/year (over 1995 conditions).

E949 Upgrades

- Photon Veto
  - Barrel Veto Liner (add 2.3 X_o) *Completed*
  - Live degrader upgrade *5/01*
  - Additional upstream vetoes *6/01*
  - Thicken collar counter *5/01*
  - Downstream veto *Completed*

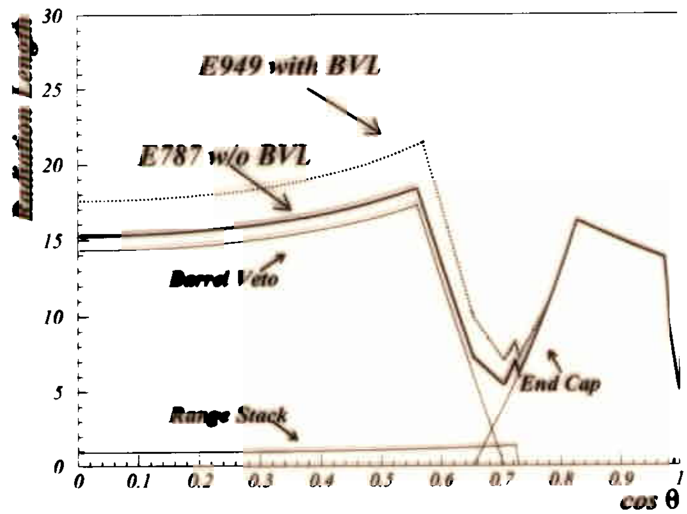
- UTC electronics upgrade *Completed*

- Range stack upgrades
  - Replace T-counters (trigger, tracking upgrade) *Complete*
  - Replace Layer 2-5 (dE/dx resolution, timing) *Completed*
  - Repair RSSCs (tracking efficiency) *Completed*
  - Upgrade RSSC electronics (muon rejection) *9/01*
  - Monitor system (reliability, energy resolution)
    * RS flasher *Completed*
    * Voltage Monitor *5/01*

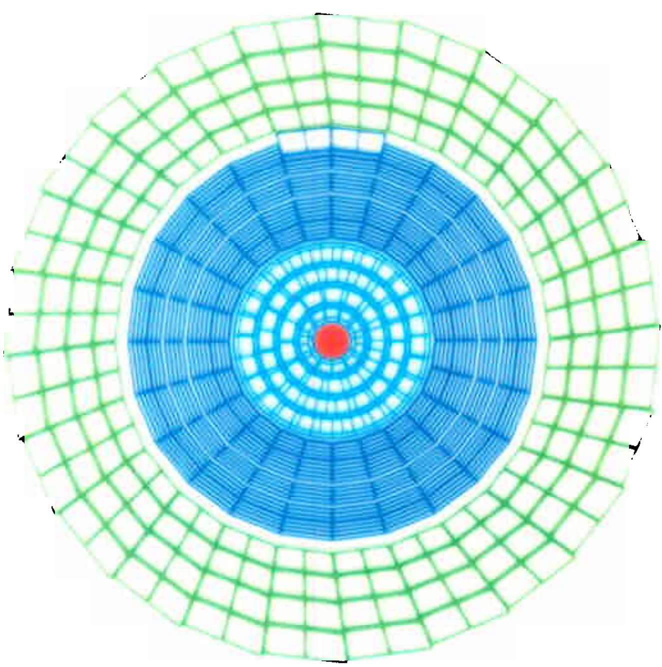
- Trigger upgrade (deadtime, background rejection) *5/01*

Barrel Veto Liner (BVL)

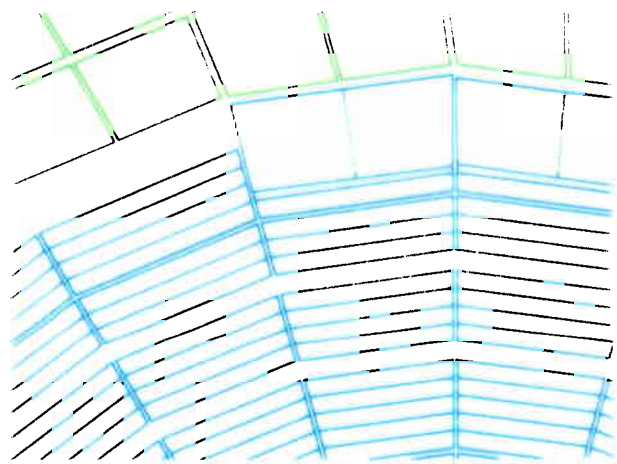
Thickens barrel veto by 2.3 X_0
Plugs 45^o thin spot
Gives factor 2-3 in π^0 rejection



Largest single E949 project
Fabrication complete
>75% installed



End view with 2 sectors installed



Closer view of end configuration

- DAQ upgrade (deadtime, rate capability)
  - RS TDC (deadtime) *5/01*
  - Bandwidth improvements (ongoing)
- Monitor system (reliability, energy resolution) *Completed*
- Beam counter upgrade (background rejection) *5/01*
- Other electronics (backgr. rejection, efficiency) *Completed*
- Separator Upgrade *Completed*
- Q01-02 water upgrade *5/01*
- Beam Instrumentation *Completed*
- New Targets *5/01*(ongoing)
- Spare Q01-02 ***On hold due to lack of funds.***

E949 Projection

60 WEEKS of Running: 2.8×10^{13} Kaons stopped.

($\sim 5\times$ E787 exposure)

Combined Single Event Sensitivity:

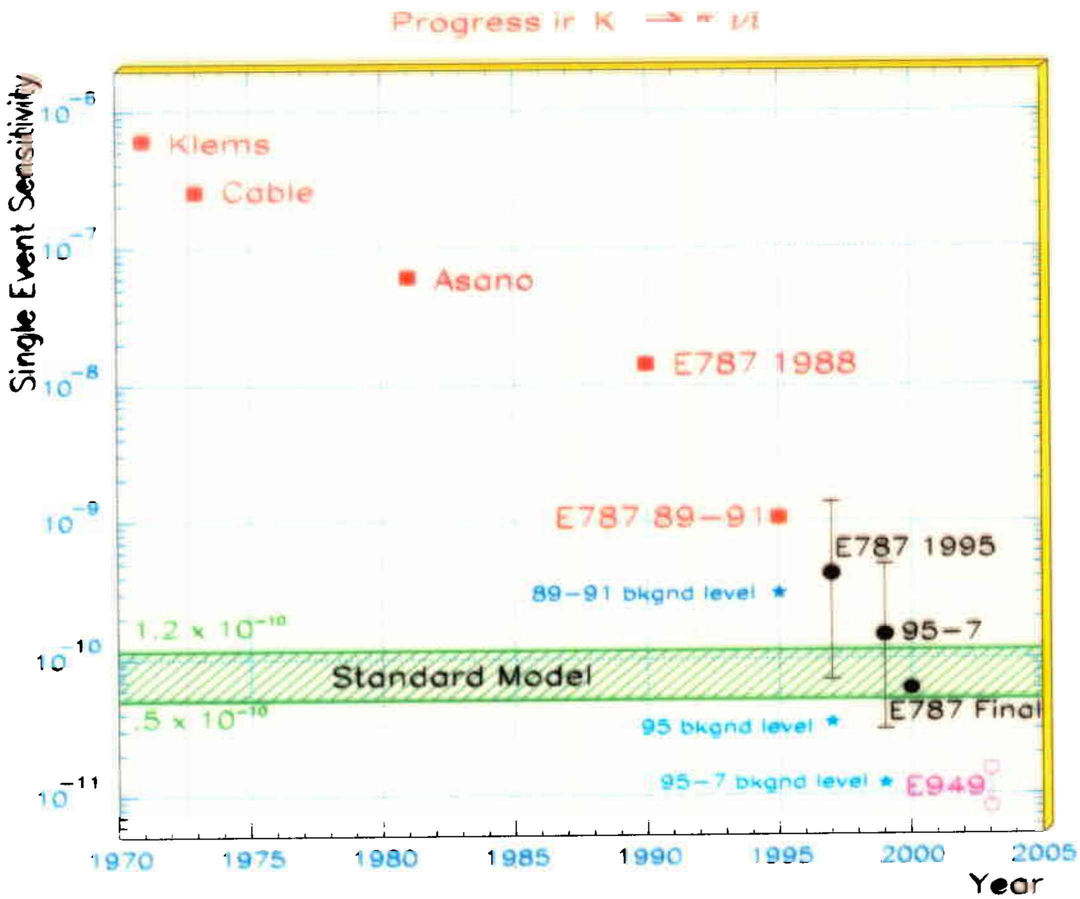
1.4×10^{-11}

(phase space above the $K_{\pi 2}$ peak).

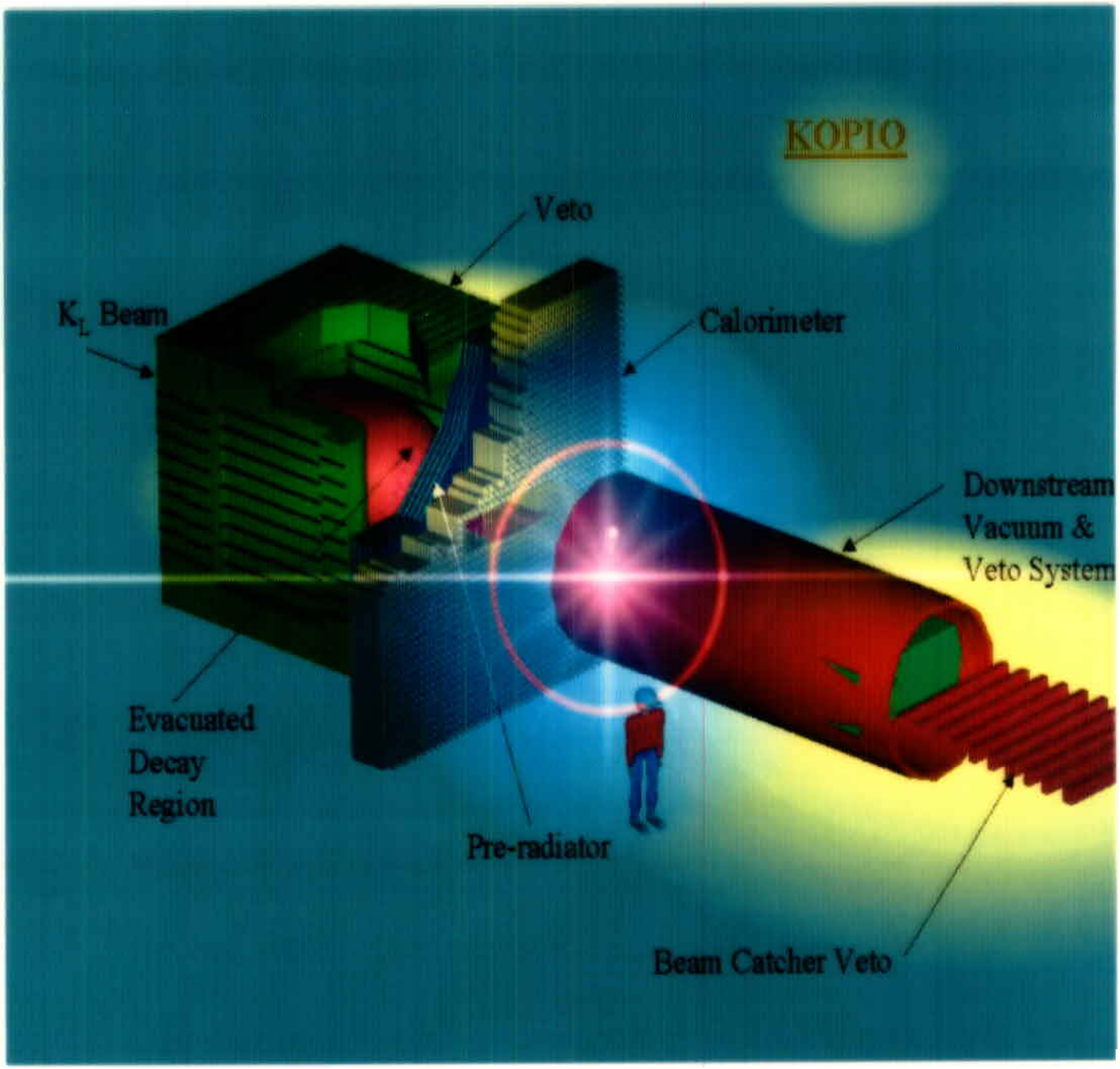
If the low energy phase space region is accessible, the single event sensitivity would be

0.8×10^{-11}.

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



- Background in E787 95-97 data OK for measurement.
- E787 1998 data comparable in sensitivity to previous total.
- E787 now becomes E949 aiming for 5x sensitivity of E787. Running starts at the AGS in 2001.
- CKM proposal at FNAL aims for 10x greater sensitivity.



KOPIO
Veto
K_L Beam
Calorimeter
Downstream
Vacuum &
Veto System
Evacuated
Decay
Region
Pre-radiator
Beam Catcher Veto

$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

A direct window into CP violation.

- Best way to determine η
- Complementary to B system - compare results to search for new physics.

KOPIO

- Goal: 50 "SM" events
- Low background
- $\sim$ 7% measurement of $Im\lambda_t$.
- Explore from 10^{-8} down to $\sim 10^{-12}$ (less than 1% of which is allowed by S.M.)

Very likely to show new physics if at work in ϵ'/ϵ.

KOPIO: exploits special conditions at the AGS

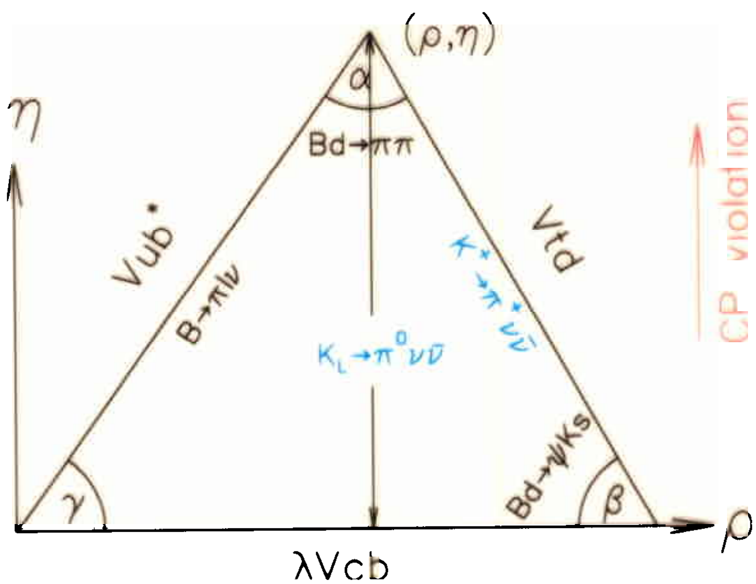
- Proton intensity 10^{14}/pulse, micro-bunching
- Highly effective constraints and cross-checks
- Experience of recent AGS exps.

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (E787): vetoes, electronics, analysis

$K^+ \rightarrow \pi^+ \mu e$ (E865) rates, calorimetry

SUMMARY

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ offer unique opportunities to explore SM physics and search for non-SM effects.



E787→E949: **heading below SM predictions**

- E787 95-97 combined data still has one event!
- E787 -98 data will reach about 0.8×10^{-10}
- E949 aimed at $\leq 10^{-11}$ or 5-10 SM events