Measuring $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at BNL

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Fermilab

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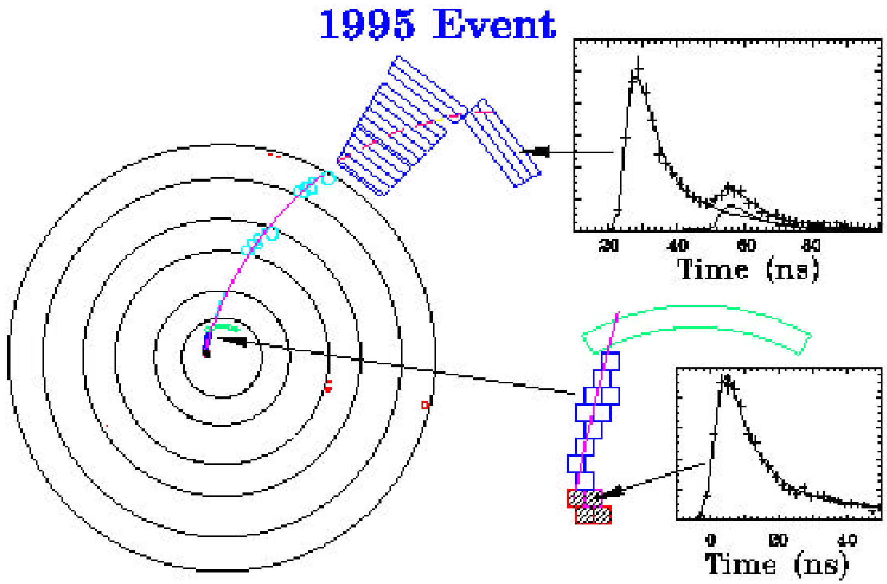
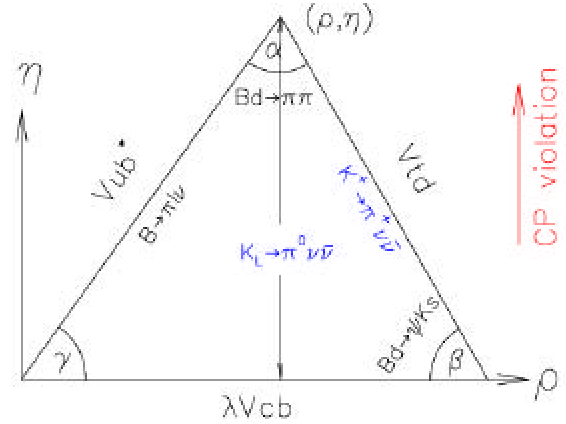


The CKM Weak Quark Flavor Mixing Matrix – the final word on CP violation?

- The Wolfenstein parameterization of the CKM matrix:

$$\mathbf{V} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

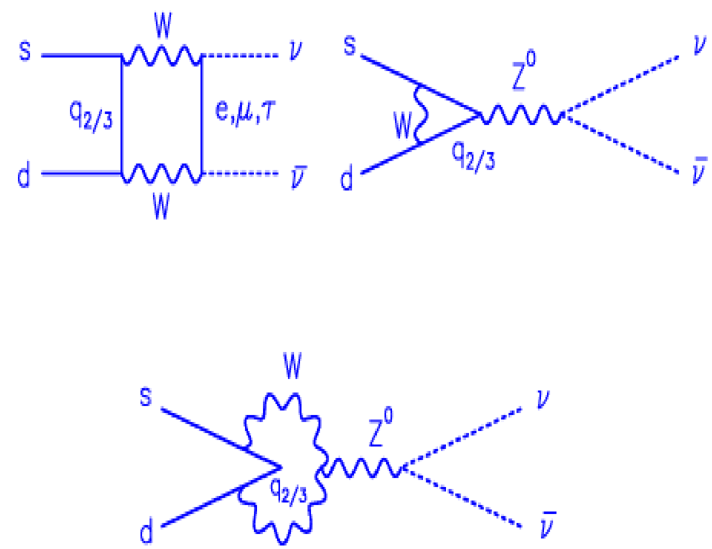
- The parameters ρ and η as a point in a complex plane:



What is so special about $K^+ \to \pi^+ \nu \bar{\nu}$?

This decay is determined by loop processes to high order in the Standard Model, and hence has a reach for *new physics at the EW scale and beyond*.

The SM rate can be reliably calculated by isospin rotation from a known kaon decay rate, hence any deviation in the measured rate is a signal for new physics.

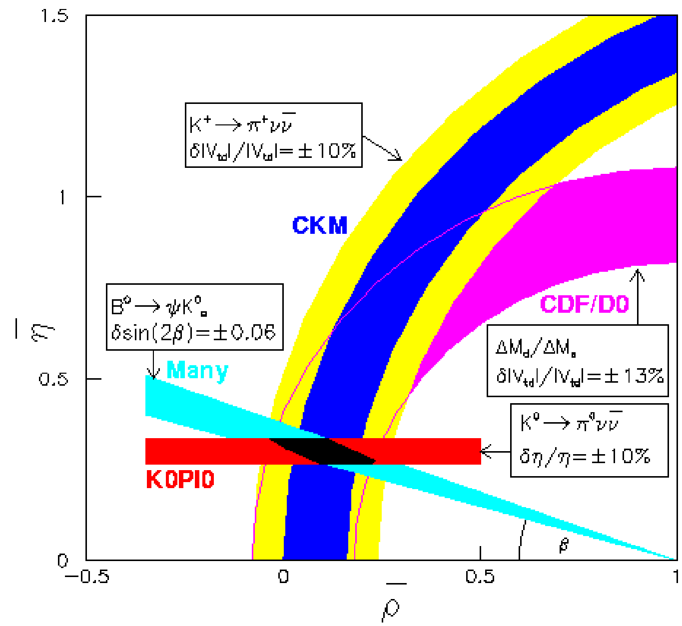


Standard Model prediction for branching ratio is $(0.8 +/- 0.11) \times 10^{-10}$

Challenging the Standard Model of CP Violation:

The quartet of "Golden Mode" measurements:

- $\sin(2\beta)$
- $\Delta m_d / \Delta m_s$ in B^0 Decays
- $K^0 \to \pi^0 \nu\bar{\nu}$
- $K^+ \to \pi^+ \nu\bar{\nu}$



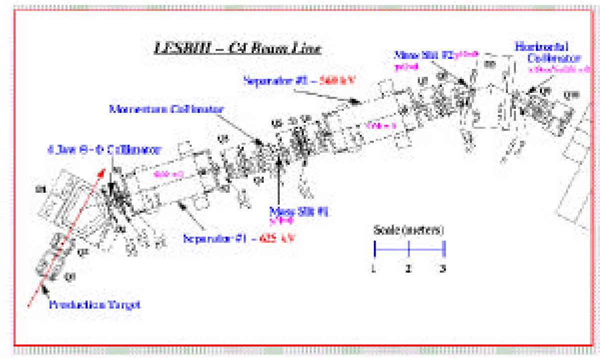
Sensitivity of measurement of 100 $K^+ \to \pi^+ \nu\bar{\nu}$ events

$K^+ \to \pi^+ \nu\bar{\nu}$ is sensitive to all new physics in $s \to d$ transitions and measures CKM properties orthogonal to $\sin(2\beta)$ measurement in the B_d system (acting much like a measurement of mixing in the B_s system)

If a new class of particles can participate in loop diagrams, then K physics and B physics will most likely be affected differently

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

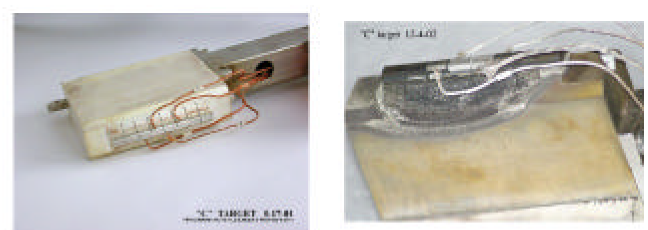
- The tyranny of ultra rare decays:
  - Br[$K^+ \to \pi^+ \nu\nu$] = $(8 \pm 1) \times 10^{-11}$ (Standard Model)
  - 1 event / 10^{-10} (Br) / .1% (acc) = ~10^{13} K decays needed
  - 10^7 sec/year $\to$ 10^6 K decay/sec to see 1 event in 1 year
  - Need to control background to 10^{-11} of all K decays



- Using the Alternating Gradient Synchrotron of Brookhaven National Laboratory:
  - The AGS can accelerate and extract a beam of ~6×10^{13} protons of 24 GeV energy over a 2 second 'spill' every 5 seconds. (In conjunction with operating the RHIC collider.)
  - Protons impact on a platinum target and Kaons are selected for by an electrostatic separator.
  - The purest kaon beam in the world (80%) stops in the detector at a rate of 3.5×10^6 per spill.

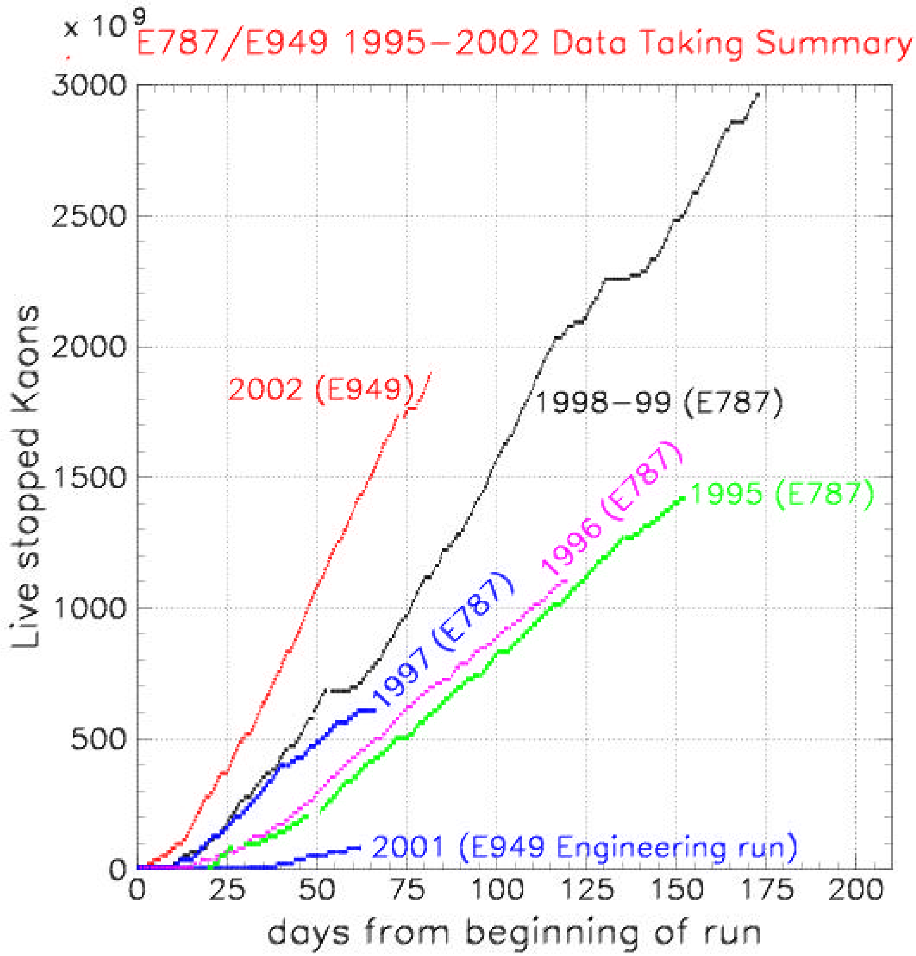
Primary target:

Before After

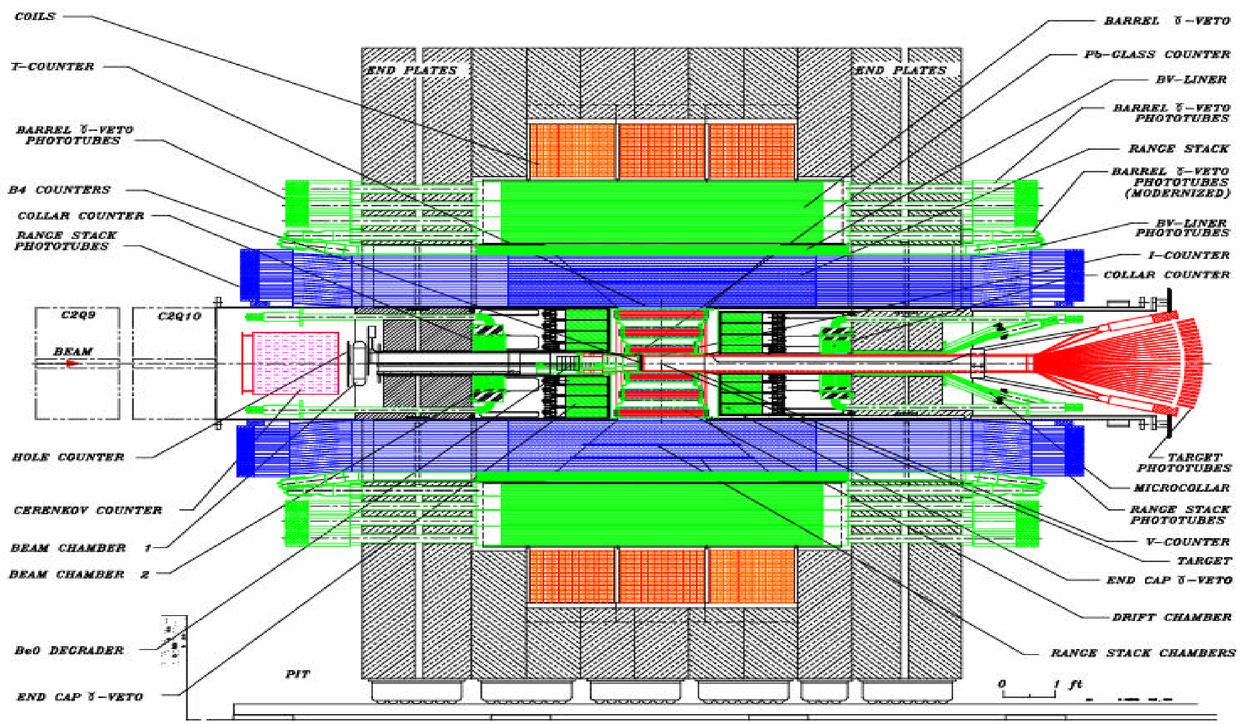


(4×10^{19} protons)

Number of observable Kaons stopping in detector



The E787/949 detector

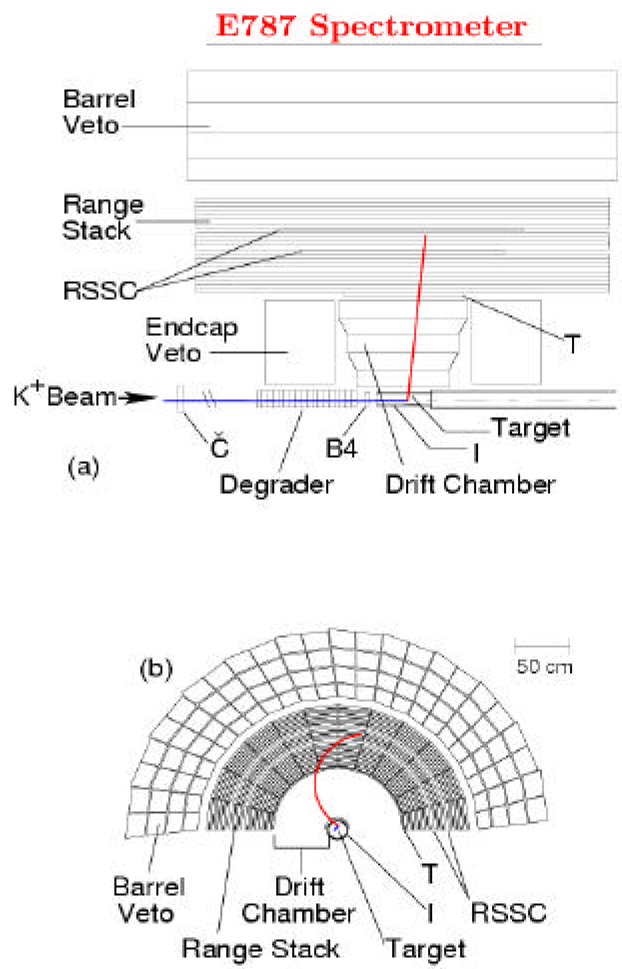


The collaboration:

INR (Moscow), IHEP (Protvino), New Mexico, BNL, TRIUMF, British Columbia, Stony Brook, FNAL, Kyoto, KEK, Alberta, Fukui, Osaka, Yokosuka

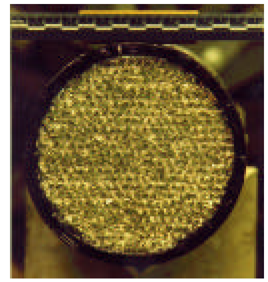
Experimental Method

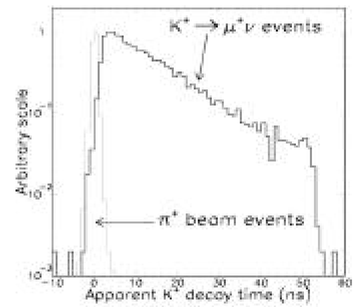
- ~700 MeV/c K^+ beam
- Stop K^+ in scintillating fiber tracker target
- Wait at least 2 ns for K^+ decay
- Measure P in drift chamber
- Measure range R and energy E in target and range stack
- Observe $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain in range stack
- Veto photons and other charged tracks



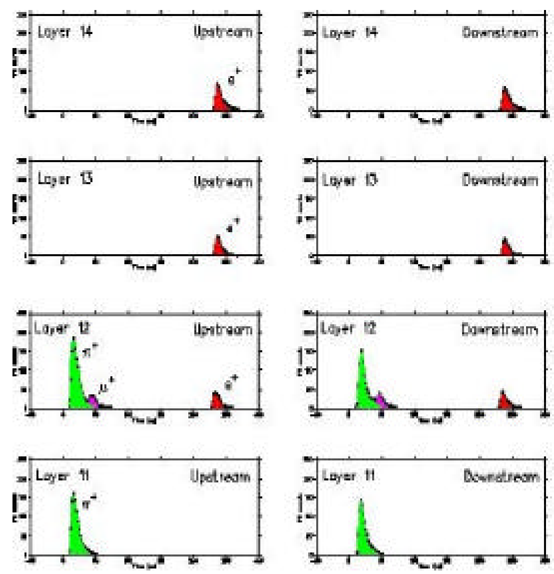
Observing the decay chain

- K^+ stops in fiber tracker target and decays with 12 nsec lifetime
- Use 500 MHz transient digitizers to sample detailed timing structure of hits in the fibers and eliminate beam π^+





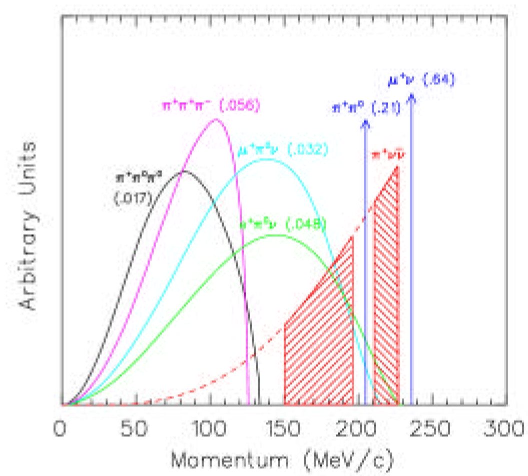
- π^+ stops in Range Stack and decays with 26 nsec lifetime
- Use TD's in all Range Stack scintillators out to 2 μsec to observe the decay μ^+ . (Range of muon is ~1 mm.)
- After that, use TDC to determine decay of μ^+ to e^+



Backgrounds

- The largest backgrounds are 2 body decays. They must be defeated by multiple methods of rejection
- $K^+ \rightarrow \pi^+\pi^o$ (‘Kpi2’)
  - Choose momentum in ‘pnn1’ region
  - Measure energy and range
  - Veto photons
- $K^+ \rightarrow \mu^+\nu$ (‘Kmu2’)
  - Choose momentum in ‘pnn1’ region
  - Check for dE/dx and range appropriate to muon
- The ‘pnn2’ region has more acceptance, but 3 body decays and, more importantly, Kpi2 decays with a scattered pion, create significant backgrounds

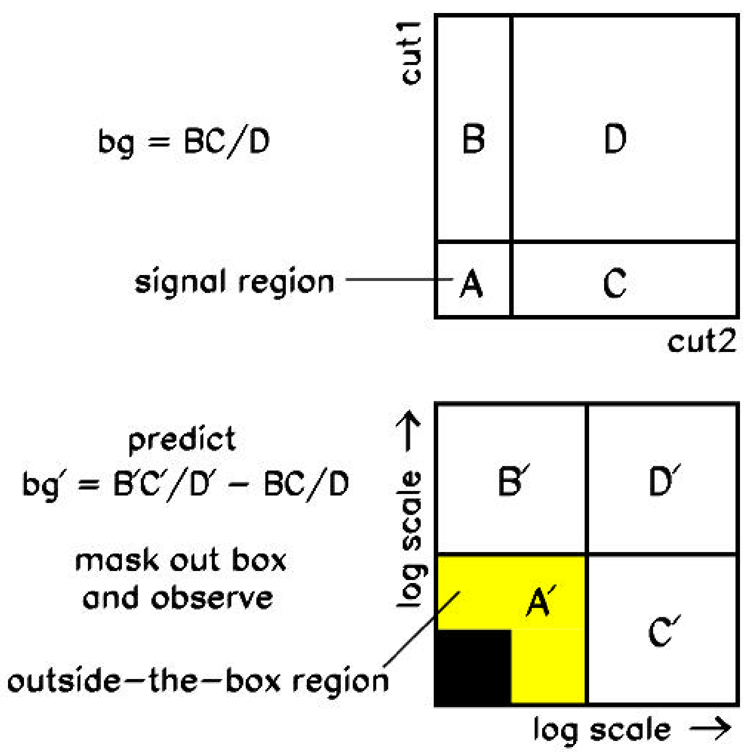
Decay	**Events**
K^+ ® m^+n_m	**6343000000**
K^+ ® p^+p^0	**2113000000**
K^+ ® m^+n_m g	**55000000**
Beam bkg	**25000000**
K^+ n® K^0p, K^0 ® p^+*l*n	**46000**
K^+ ® p^+n n	**1**

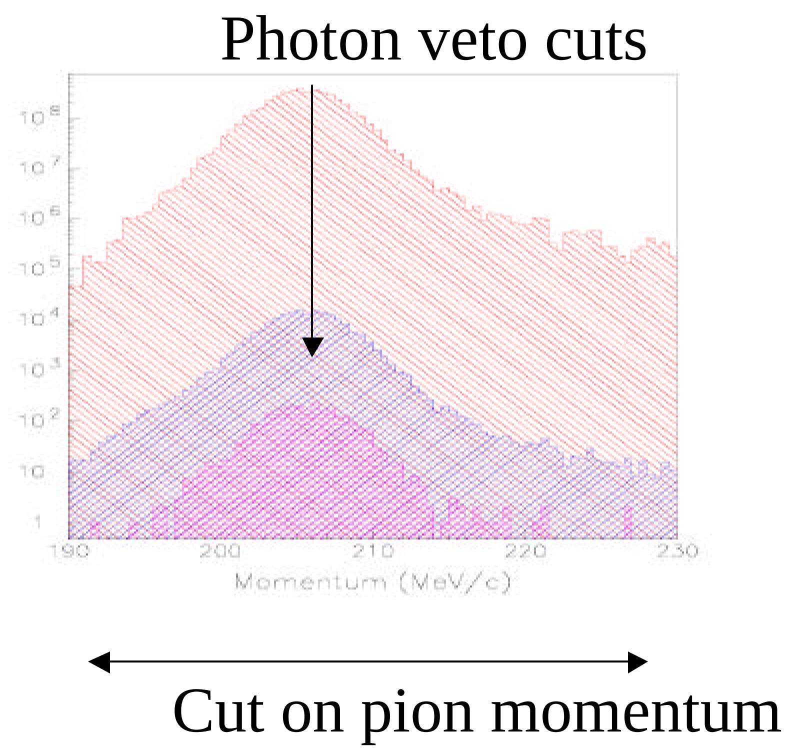


E787/949 Background Analysis

- A priori identification of background sources:
  - $K \to \pi^+\pi^o$, $K \to \mu^+\nu$, $K \to \mu^+\nu\gamma$, $K \to \pi^o\mu^+\nu$, charge exchange, π^+ scattering
- Suppress each background source with at least 2 independent cuts
- Take random 1/3 of data to set cuts and measure background level with remaining 2/3 of data
- Verify background estimates by loosening cuts and comparing observed and predicted rates
- Blind analysis: don’t examine signal region until all backgrounds verified
- Perform likelihood analysis of each part of signal region, using looser cuts on background samples and simulations

Calculation of backgrounds by bifurcation of cuts





Observation vs Prediction for Loosened Background Cuts

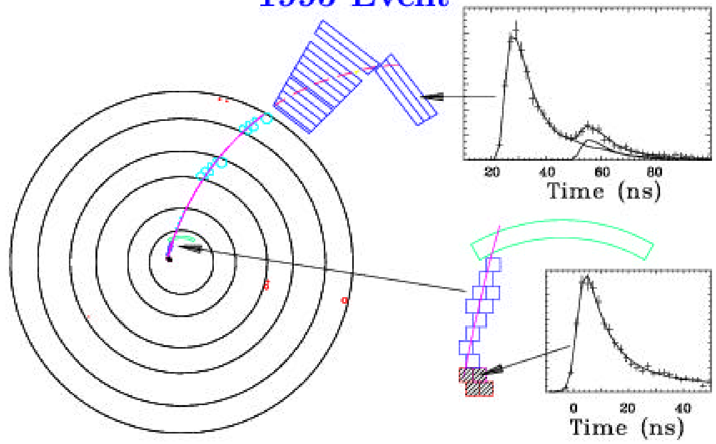
	PV x KIN	10 x 10	20 x 20	20 x 50	50 x 50	50 x 100
Kπ2	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
	TD x KIN	10 x 10	20 x 20	50 x 50	80 x 50	120 x 50
Kμ2	Observed	0	1	12	16	25
	Predicted	0.35	1.4	9.1	14.5	21.8
	TD x KIN	10 x 10	20 x 20	50 x 20	80 x 20	80 x 40
Kμ2γ	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

Comparison of E787 and E949 backgrounds

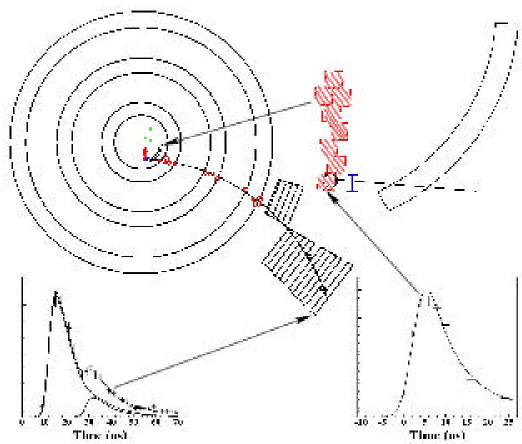
Items	E949	E787
Nk(10^{12})	1.8	5.9
$K^+ \rightarrow \mu^+\nu_\mu \gamma$	0.044 ± 0.005	0.062 ± 0.045
$K^+ \rightarrow \pi^+\pi^0$	0.216 ± 0.023	0.034 ± 0.007
Beams	0.024 ± 0.010	0.025 ± 0.016
$K^+ n \rightarrow K^0 p$, $K^0 \rightarrow \pi^+ l^- \nu$	0.014 ± 0.003	0.025 ± 0.008
Total bkg (evts)	0.298 ± 0.026	0.146 ± 0.049

The Two E787 $K^+ \to \pi^+ \nu \bar{\nu}$ Events

1995 Event



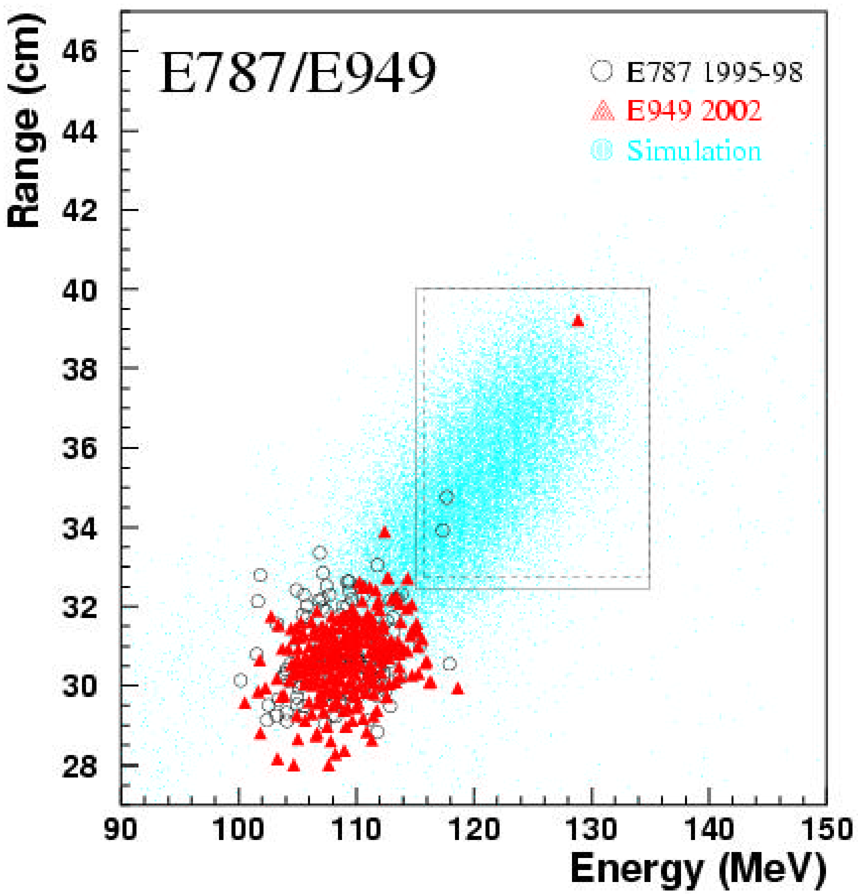
1998 Event



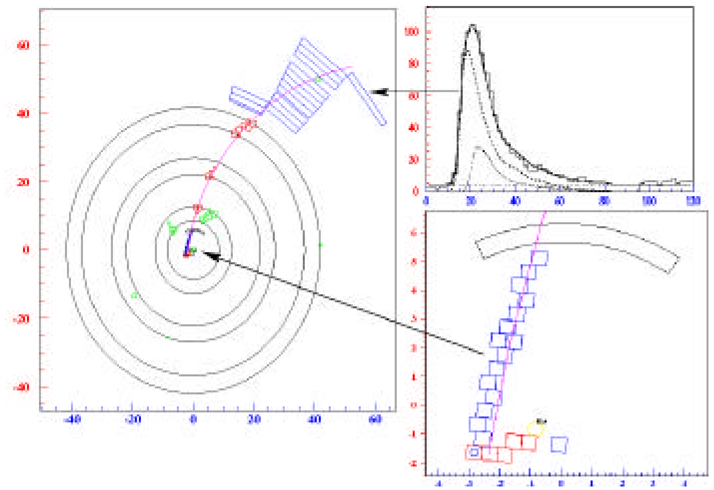
$$\mathbf{BR}(K^+ \to \pi^+ \nu \bar{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

[1995–8: PRL **88**, 041803 (2002),
1995–7: PRL **84**, 3768 (2000),
1995: PRL **79**, 2204 (1997)]

Opening the E949 'Box'



One additional event:



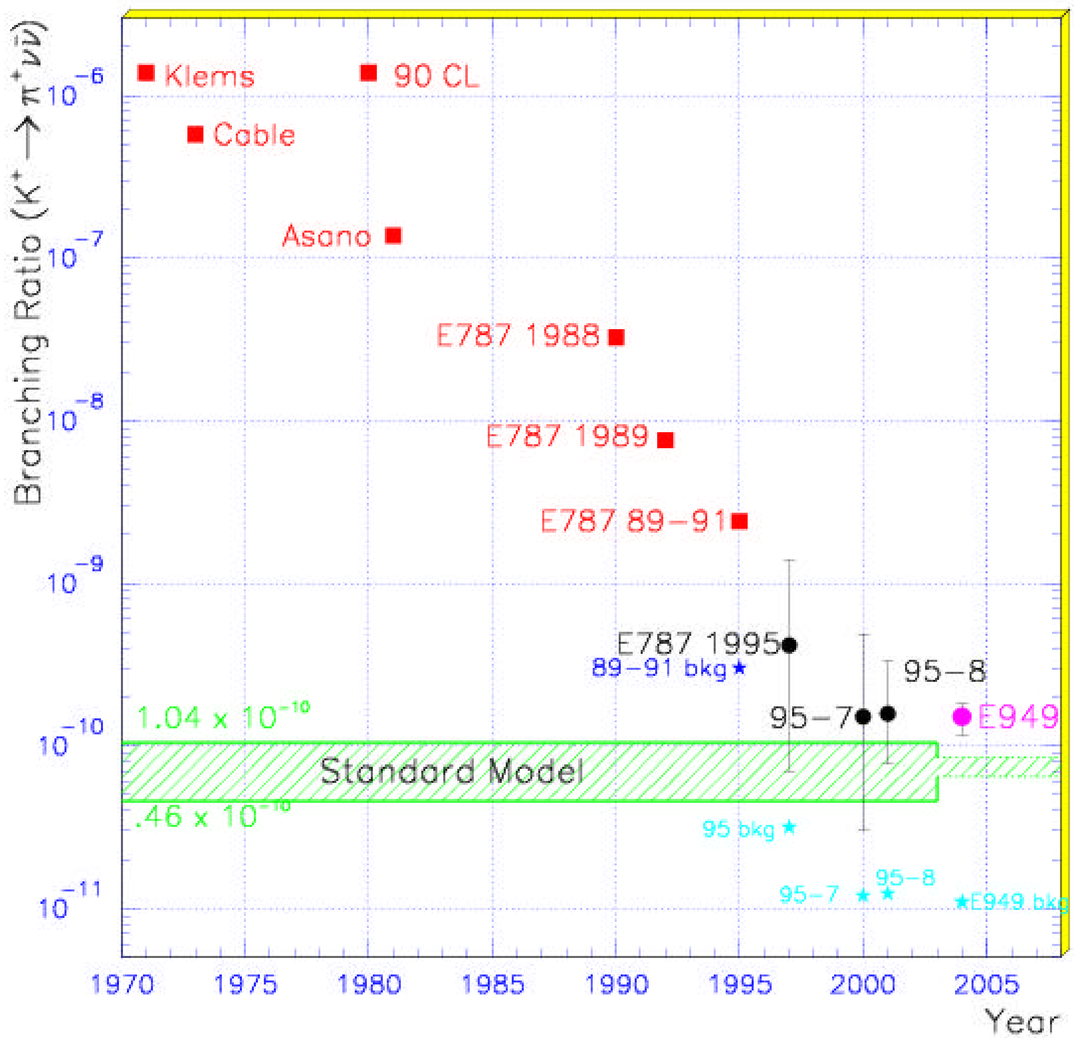
Likelihood analysis of 3 events

B_i: background of cell containing candidate.
S_i : Br × A_i × N_K.
N_K: Stopped K^+'s.
A_i: acceptance in a cell.
Br: branching ratio.
W: $S/(S + b)$.

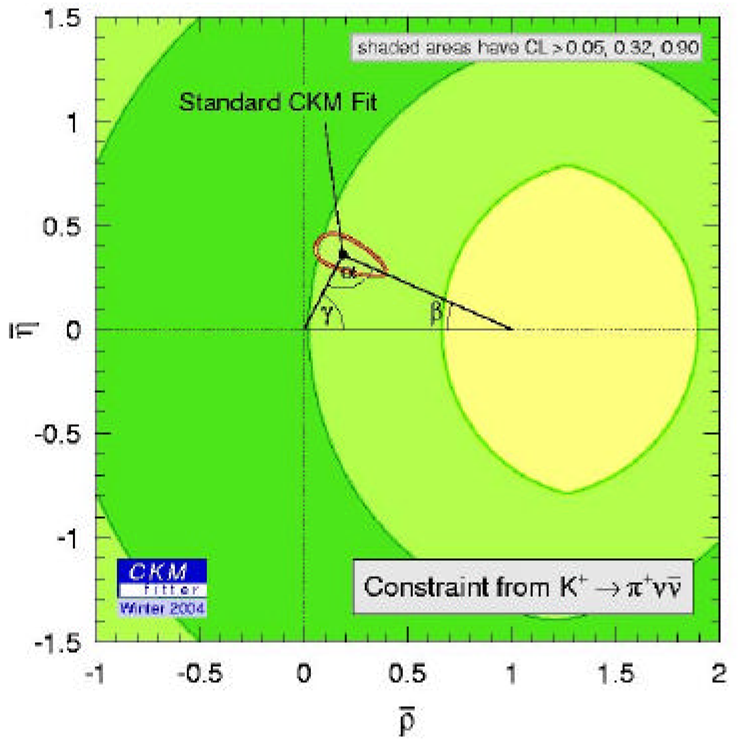
	E949	E787	
Candidate	**E949A**	**E787A**	**E787C**
S_i / b_i	**0.9**	**50**	**7**
W_i	**0.48**	**0.98**	**0.88**
Combined BR	$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$		

PhysRevLett.93.031801 (July, 2004)

History of Kπνν measurement



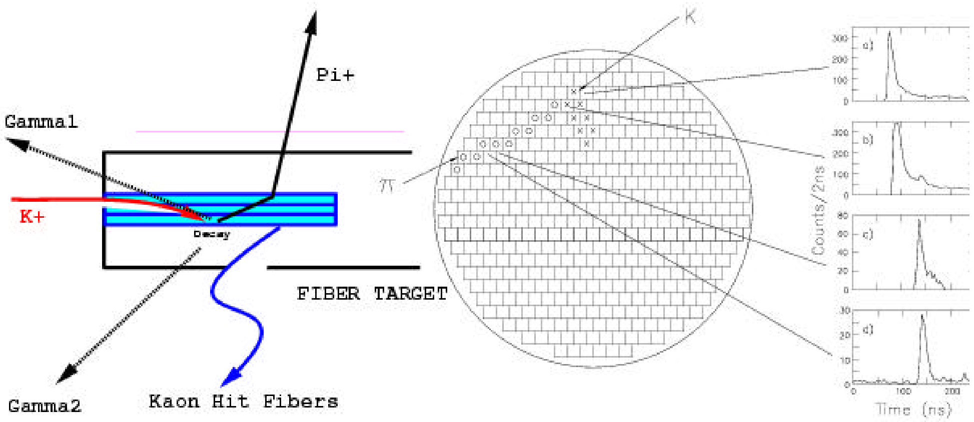
Constraints on the Unitarity Triangle



Latest results from CDF on B_s mixing indicate a value for (ρ,η) much nearer to (1,0) than measured by these results from K^+ decays

$\pi\nu\bar{\nu}(2)$ (below $K^+ \rightarrow \pi^+\pi^\circ$) data analysis

- Much larger phase space acceptance below $K_{\pi 2}$ peak.
- Large background from $K^+ \rightarrow \pi^+\pi^\circ$ in which π^+ undergoes interaction in the scintillator fiber target.
- After reconstruction of pion and kaon, make fits to all CCD pulses for kaon fibers.
  - Find second pulses at pion time overlapping kaon fibers. Cut at 1 MeV threshold.
  - Measure rejection of CCD cut by using events tagged by photons.
  - Measure Photon veto rejection by using events tagged by CCD second pulses as well as kinks in the track.



E787 Result:

(hep-ex/0403034; accepted for PRD)

- $140 < p_\pi < 195$ MeV/c
- 1 candidate event
- Expected background of 1.22 +/- 0.24 events
- $BR(K^+ \rightarrow \pi^+\nu\nu) < 2.2 \times 10^{-9}$
- E949 data is being worked on now – improved photon veto rejection will likely improve on this limit

The future of $K \rightarrow \pi\nu\bar{\nu}$

- BNL
  - E949: approved by DOE for 60 weeks of running, but only funded for 12 weeks. A proposal to continue running E949 has been submitted to the NSF.
  - KOPIO (neutral kaons): included in President's FY05 budget, with operations beginning in 2008.
- KEK
  - E391a (neutral kaons): began taking data in Feb. of this year – will set limits only
  - L.O.I. for stopped charged kaon experiment similar to BNL E787/949
- CERN
  - NA48/3: proposal to adapt the NA48/2 charged kaon experiment into a dedicated facility to study $K^+ \rightarrow \pi^+\nu\nu$
- FNAL
  - CKM (E921) separated kaon beam experiment approved by Fermilab management, but did not pass DOE P5 review panel for budgetary reasons. Collaboration is working on submitting a proposal (E940) using unseparated beam.