Results and Prospects from BNL E787/E949

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Kaon Decay Modes analyzed with E787 Phase-II Data (1995-1998)

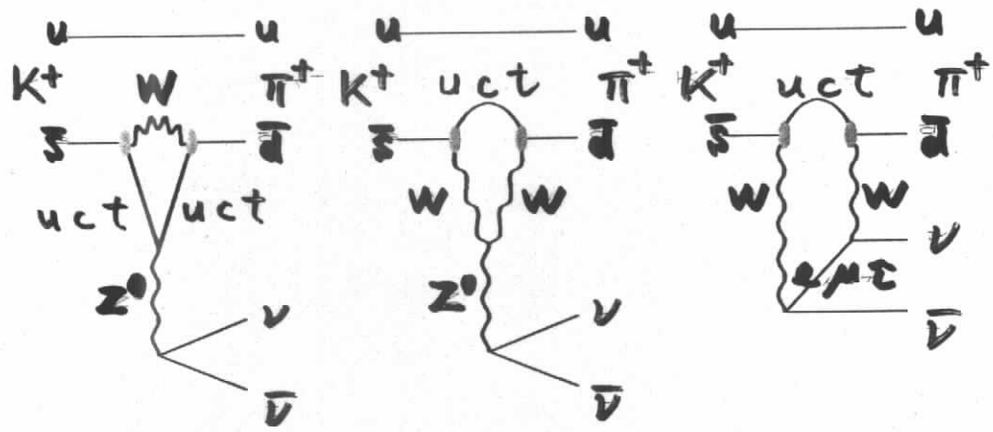
CKM Matrix — V_{td} Extraction

- $K^+ \to \pi^+ \nu\overline{\nu}$ (Phys.Rev.Lett. 84 (2000) 3768-3770)
  - One Candidate Event.
  $BR = 1.5^{+3.4}_{-1.2} \times 10^{-10}$
- $K^+ \to \pi^+ \pi^0 \nu\overline{\nu}$ (Phys.Rev. D63 (2001) 032004)
  - Initial Search.
  $BR < 4.3 \times 10^{-5}$ (90% CL)

Chiral Perturbation Theory

- $K^+ \to \mu^+ \nu\gamma$ (Phys.Rev.Lett. 85 (2000) 2256-2259)
  - First Measurement of SD Componemt.
  - Consistent with ChPT Calculation.
  $BR(SD^+) = (1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$
- $K^+ \to \pi^+ \pi^0 \gamma$ (Phys.Rev.Lett. 85 (2000) 4856-4859)
  - New Measurement with significantly higher statistics.
  - Understood by only magnetic contributions.
  $BR(DE) = (4.7 \pm 0.8 \pm 0.3) \times 10^{-6}$

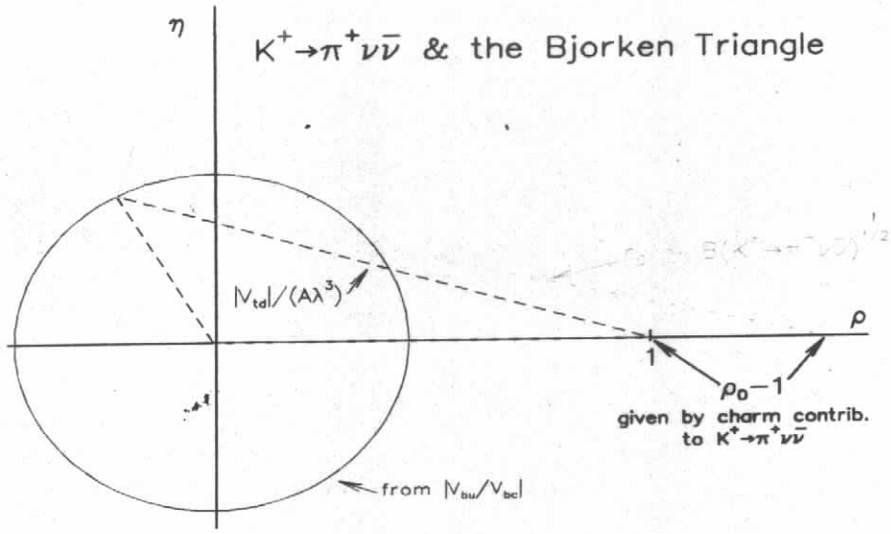
V_{td} Extraction



$$H_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta_W} \Sigma_l (V_{cs}^* V_{cd} X_{NL}^l + \underline{V_{ts}^* V_{td} X(x_t)})(\overline{s}d)_{V-A}(\overline{\nu}_l \nu_l)_{V-A}$$

- Hadronic matrix element
  $\Rightarrow$ Extracted from $Br(K^+ \to \pi^0 e^+ \nu)$ and $Br(K^+ \to \pi^+ \pi^- e^+ \nu)$
- Dominated by Short distance contributions.

$BR(K^+ \to \pi^- \nu\overline{\nu}) = 4.35 \times 10^{-11} \times ((1.37 - \rho)^2 + \eta^2) \Rightarrow (0.82 \pm 0.32) \times 10^{-10}$
$BR(K^+ \to \pi^- \pi^0 \nu\overline{\nu}) = 7 \times 10^{-15} \times ((1.37 - \rho)^2 + \eta^2) \Rightarrow (1 - 2) \times 10^{-14}$



E787
A Search for $K^+ \to \pi^+ \nu \bar{\nu}$ and Related Decays

S. Adler, M.S. Atiya, I-H. Chiang, M. Diwan, J.S. Frank, J.S. Haggerty, V. Jain, S.H. Kettell, T.F. Kycia, K.K. Li, L.S. Littenberg, C. Ng, A.J. Stevens, R.C. Strand and C.H. Witzig

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M. Aoki, T. Inagaki, S. Kabe, M. Kazumori, M. Kobayashi, T.K. Komatsubara, Y. Kuno, M. Kuriki, N. Muramatsu, H. Okuno, A. Otomo, T. Sato, T. Shinkawa, S. Sugimoto, K. Ukai and Y. Yoshimura

High Energy Accelerator Research Organization (KEK)

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Osaka University

A. Bazarko, M.M. Ito, P.D. Meyers, D. Relyea, F.C. Shoemaker, A.J.S. Smith and J.R. Stone

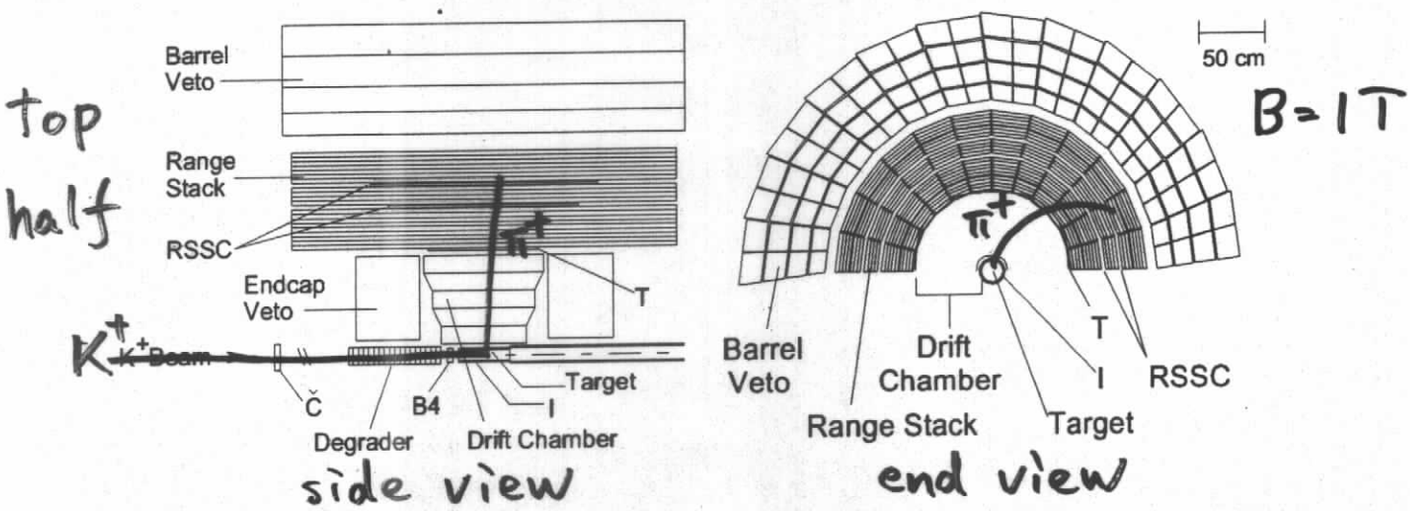
Princeton University

P. Bergbusch, E.W. Blackmore, D.A. Bryman, S. Chen, P. Kitching, A. Konaka, J.A. Macdonald, J. Mildenberger, T. Numao, J.-M. Poutissou, R. Poutissou, G. Redlinger, J. Roy, M. Rozen, R. Soluk and A.S. Turcot

TRIUMF

BNL-E787 Experiment

- 24 GeV Proton Beam by AGS
  (Spill Length = 1.6 sec, Duty Cycle = 44%)
  20 Tera ($\times 10^{12}$) protons/spill in Beam Line.
- Kaon Production in Platinum Target
- Two DC Separators in Beam Transport Line
  $\hookrightarrow$ $K^+ : \pi^+ = 4 : 1$
- 6 Mega kaons/spill at the Entrance of E787 Detector

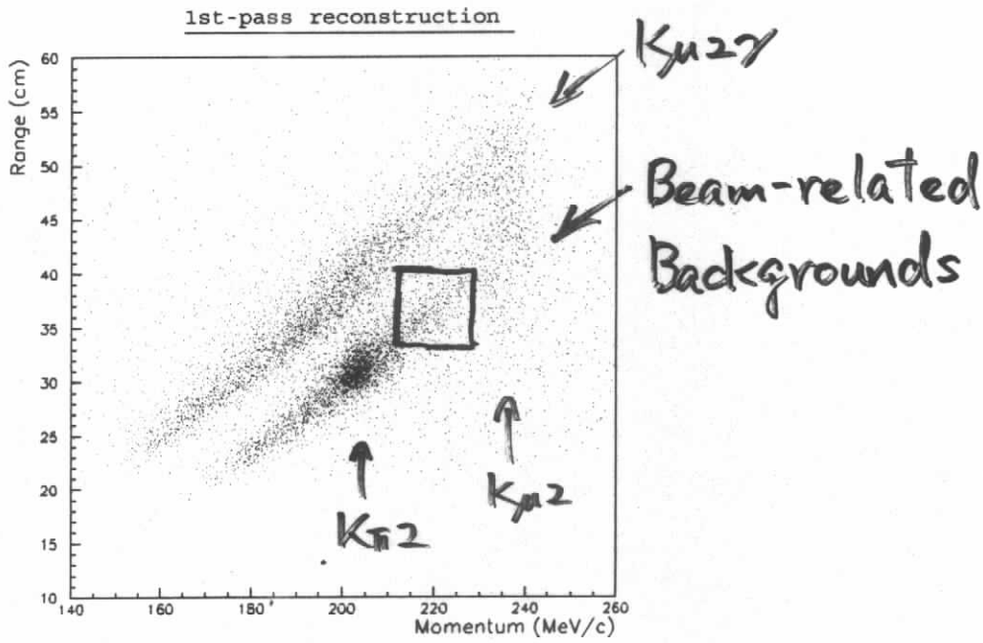


$K^+ \rightarrow \pi^+ \nu\bar{\nu}$

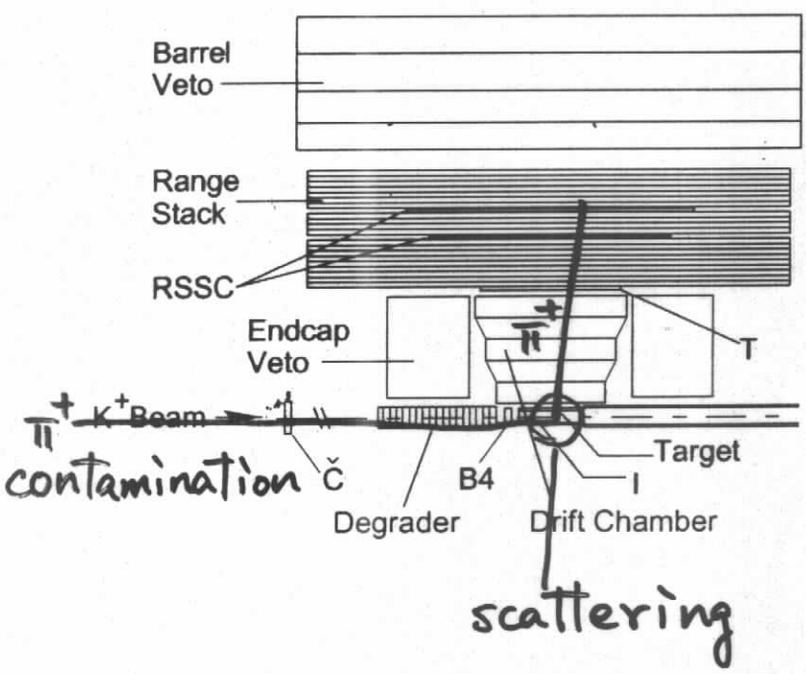
Stopped K^+ — Momentum Range Kinetic Energy — 4π Coverage of γ-veto

γ-Clustering for $K^+ \rightarrow \pi^+\pi^0\nu\bar{\nu}$
and radiative modes

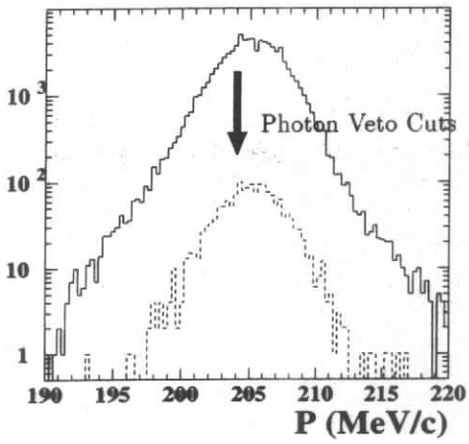
Backgrounds to $K^+ \to \pi^+ \nu\overline{\nu}$

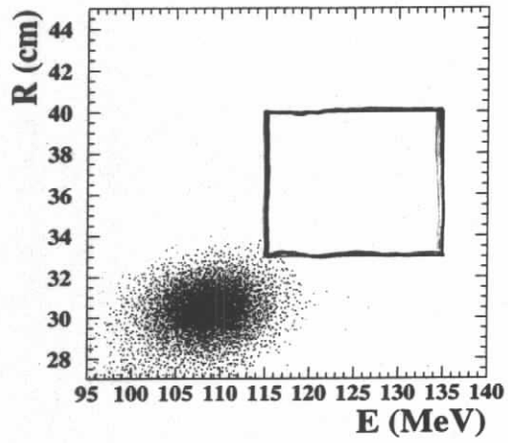


- $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)
- $K^+ \to \mu^+\nu$ ($K_{\mu 2}$) and $K^+ \to \mu^+\nu\gamma$ ($K_{\mu 2\gamma}$)
- Beam-related Backgrounds



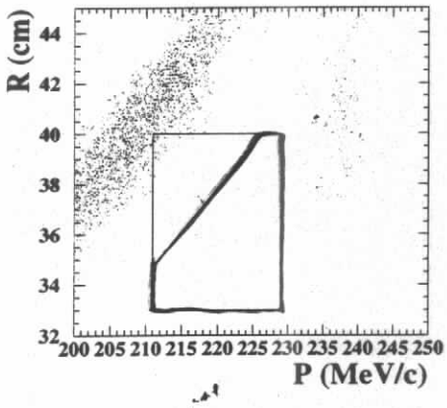
$K_{\pi 2}$ Background Rejection

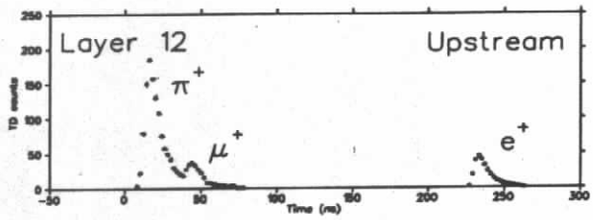




- Photon Veto
  Typically 2 - 5 ns Time Windows and 0.2 - 3 MeV Energy Thresholds
- Phase Space Cut in P, R, E

$K_{\mu 2}$ and $K_{\mu 2\gamma}$ Background Rejection

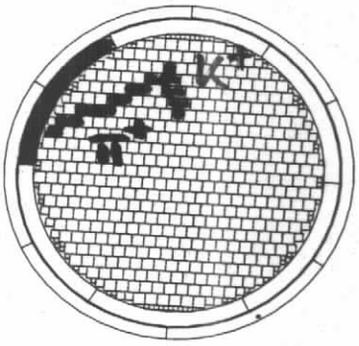


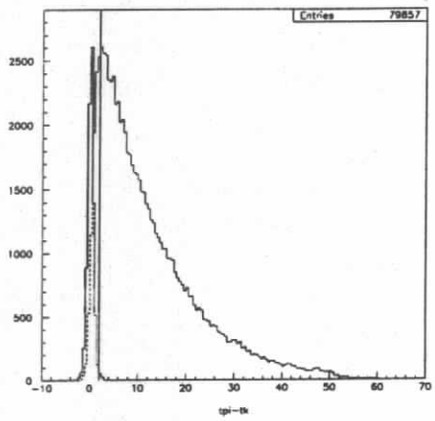


- Phase Space Cut against muon band and range tail
- $\pi \rightarrow \mu \rightarrow e$ Decay Chain
- PID cut by RS and Target dE/dx

Beam-related Background Rejection

- Single Beam Background





  - Require K^+ Decay at least 2ns later
  - PID in Čerenkov Counters and Beam Hodoscope

- Double Beam Background
  - Two beam signature in Beam Instruments
  - Target Pattern Recognition

- Charge Exchange Background

$$K^+n \rightarrow K^0p \;\; in \;\; Target$$
$$K_L^0 \rightarrow \pi^+l^-\nu$$

  - Target Pattern Recognition

Background Estimation

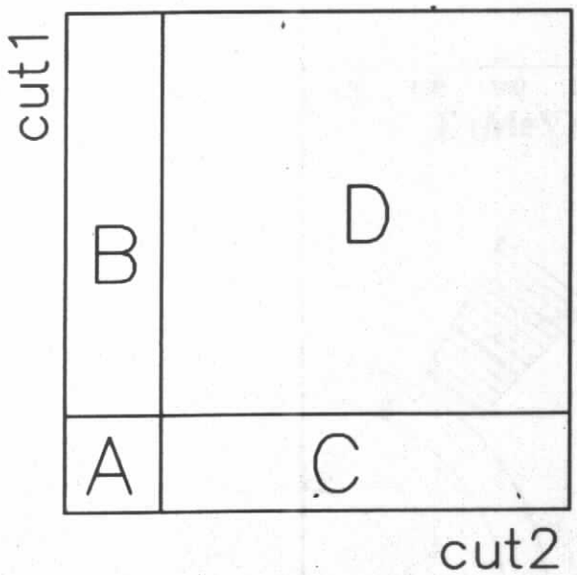
Two Independent Cuts with Large Rejections

ex. $K^+ \rightarrow \pi^+ \; \pi^0$

$\pi^+ \downarrow$ Phase Space cut

$\pi^0 \downarrow$ Photon Veto cut

$$N_{BG} = N_{sample}/(R_{cut1}R_{cut2})$$



A = Signal Region

$R_1 = \frac{C+D}{C}$

$N_{BG} = B/R_1$

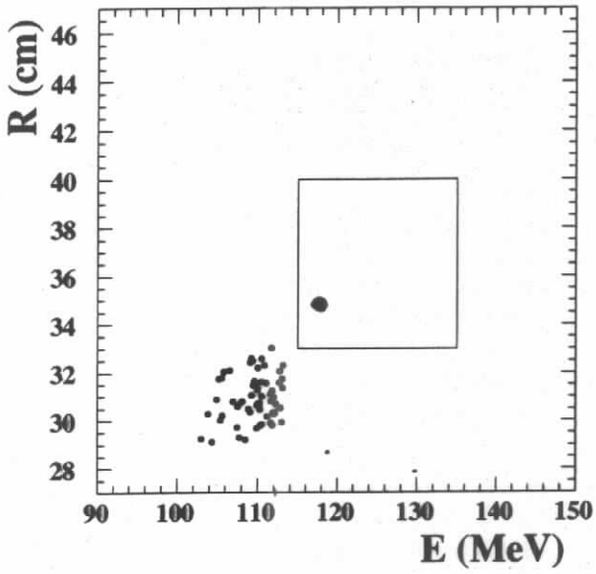
Background	*Estimation*
$K_{\pi 2}$	0.024±0.006
$K_{\mu 2}$	0.028±0.009
Single Beam	0.005±0.004
Double Beam	0.016±0.015
CEX	0.010±0.007
Total	0.083±0.019

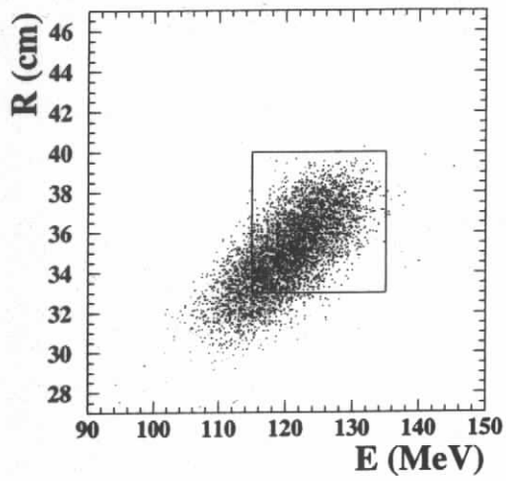
$P = 218.2\ MeV/c$

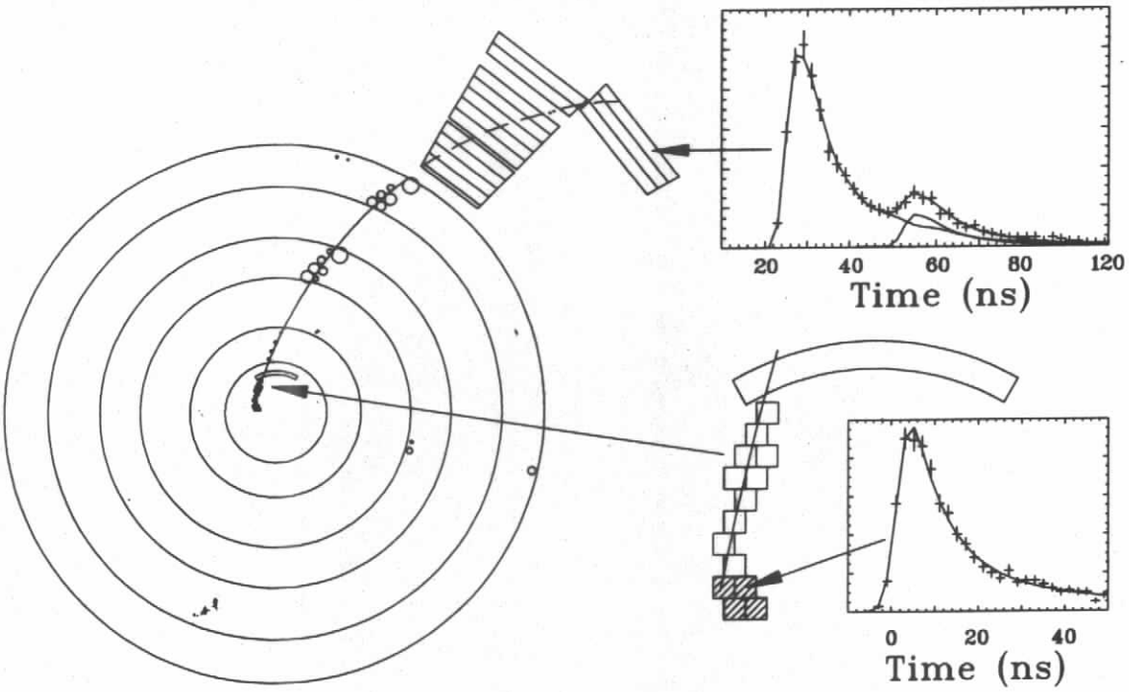
$R = 34.7\ cm$

$E = 117.7\ MeV$

Open the BOX







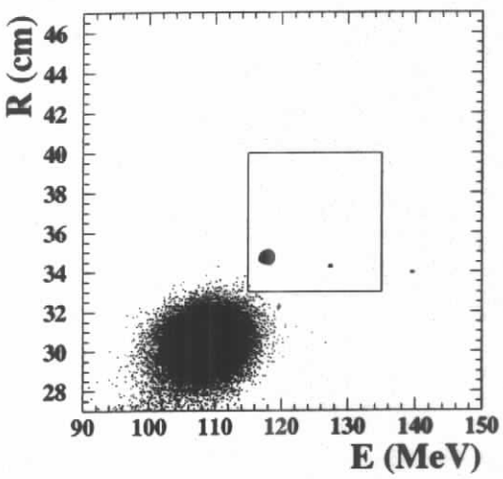
$T_\pi - T_K = 23.9\ ns$ $\quad \tau = 12.4\ ns$

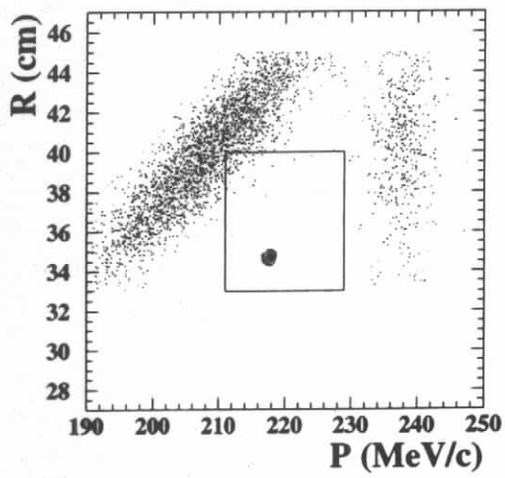
$T_\mu - T_\pi = 26.9\ ns$ $\quad \tau = 26.0\ ns$

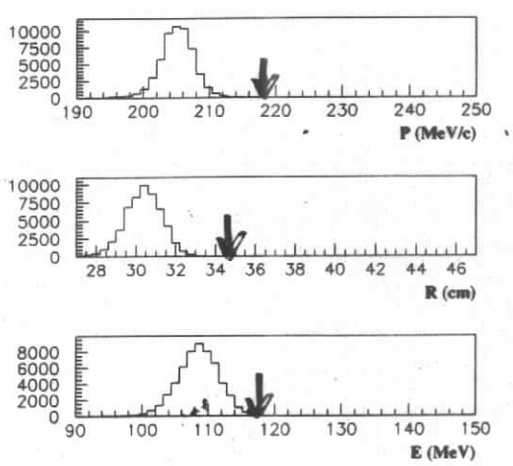
$T_e - T_\mu = 3253\ ns$ $\quad \tau = 2197\ ns$

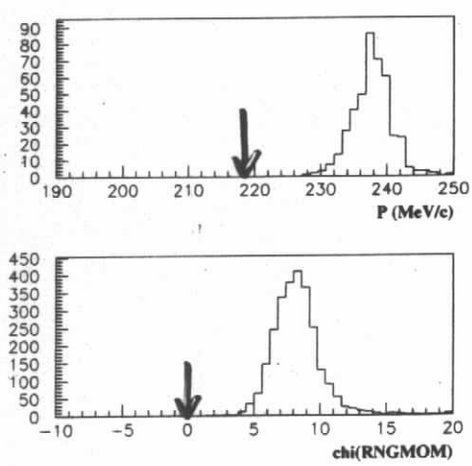
Against $K_{\pi 2}$ Data

Against $K_{\mu 2}$ Data

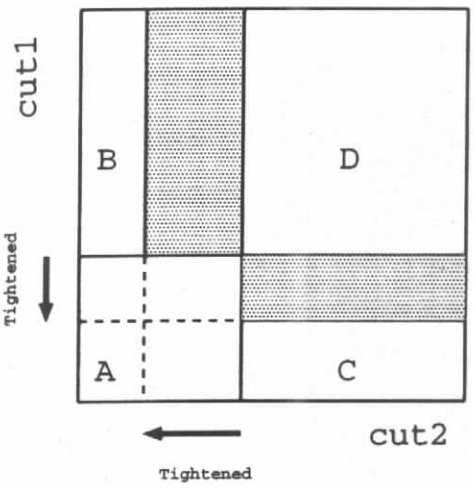


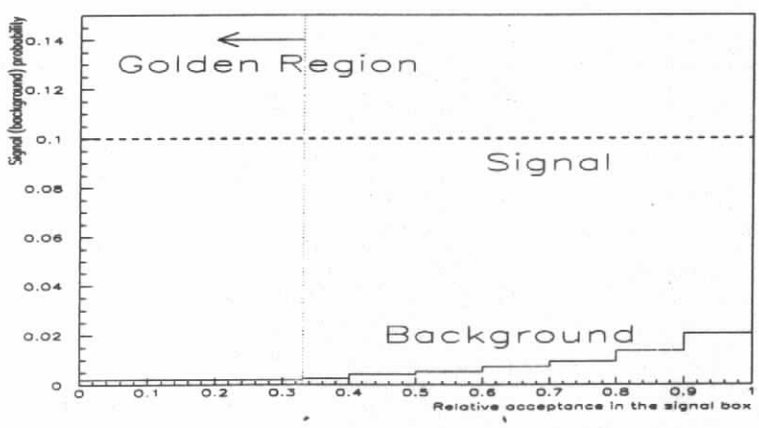






Background Probability





- The candidate event survives in the Golden Region (10 times tighter cut).
- Relative Acceptance of 33% is retained in this region.

Background	*Estimation*
$K_{\pi 2}$	0.0016±0.0004
$K_{\mu 2}$	0.0015±0.0005
Single Beam	0.0016±0.0012
Double Beam	0.0009±0.0008
CEX	0.0009±0.0006
Total	0.0065±0.0017

Sensitivity

Acceptance Factors	
K^+ Stop Efficiency	0.704
K^+ Decay after 2 ns	0.850
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Phase Space	0.155
Solid Angle Acceptance	0.407
π^+ Nucl. Int. and Decay-in-Flight	0.513
Reconstruction Efficiency	0.959
Other Kinematic Constraints	0.665
$\pi \rightarrow \mu \rightarrow e$ Decay Chain	0.306
Beam and Target Analysis	0.699
Accidental Loss	0.785
Total Acceptance	0.0021

Year	*1995*	*1996*	*1997*	*1997*
Beam Momentum (MeV/c)	*790*	*730*	*710*	*670*
K^+ triggers $(\times 10^{12})$	1.53	1.12	0.37	0.22
	3.24			

$\Rightarrow$ Single Event Sensitivity $= (1.52 \pm 0.04^{+0.09}_{-0.12}) \times 10^{-10}$

Branching Ratio

- Analyzed 3.2×10^{12} Kaon Triggers (1995-1997)
- BG Estimation with Bifurcation Method : 0.08 ± 0.02 events
- One candidate event is observed in Golden Region.

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

with 68% Confidence Level Interval

- Consistent with SM expectation $(0.82 \pm 0.32) \times 10^{-10}$
- V_{td} Range : $0.002 < |V_{td}| < 0.04$

Additionally we have 1998 Data Set. (2.8×10^{12} K^+ triggers)

$K^+ \to \pi^+\pi^0\nu\overline{\nu}$

Background Estimation

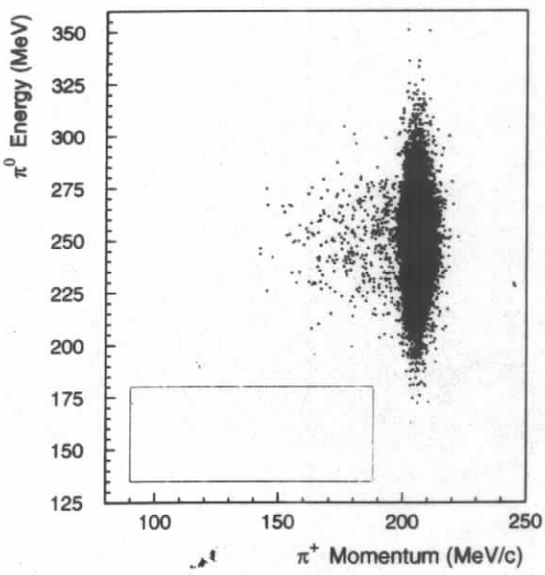
$K^+ \to \pi^+\pi^0$	0.044 ± 0.009
$K^+ \to \mu^+\pi^0\nu$	0.024 ± 0.012
$K^+ \to \pi^+\pi^0\gamma$ (IB)	< 0.01 (90% CL)
$K^+ \to \pi^+\pi^0\gamma$ (DE)	0.0007
Total	0.068 ± 0.021

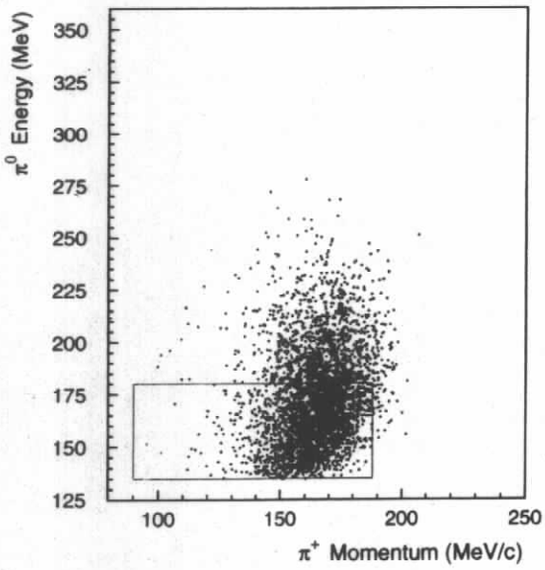
Signal Region

90 MeV/c $< P_{\pi^+} <$ 188 MeV/c and 135 MeV $< E_{\pi^0} <$ 180 MeV

$\Rightarrow$ No Events Observed.

$\Rightarrow$ $BR(K^+ \to \pi^+\pi^0\nu\overline{\nu}) < 4.3 \times 10^{-5}$ (90% CL)





E949

An Experiment to Measure the Branching Ratio B($K^+ \to \pi^+ \nu\bar{\nu}$)

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I-H. Chiang, M.V. Diwan, J.S. Frank, J.S. Haggerty, V. Jain, S.H. Kettell, T.F. Kycia, K.K. Li, L.S. Littenberg, G. Redlinger, R.C. Strand and C.H. Witzig
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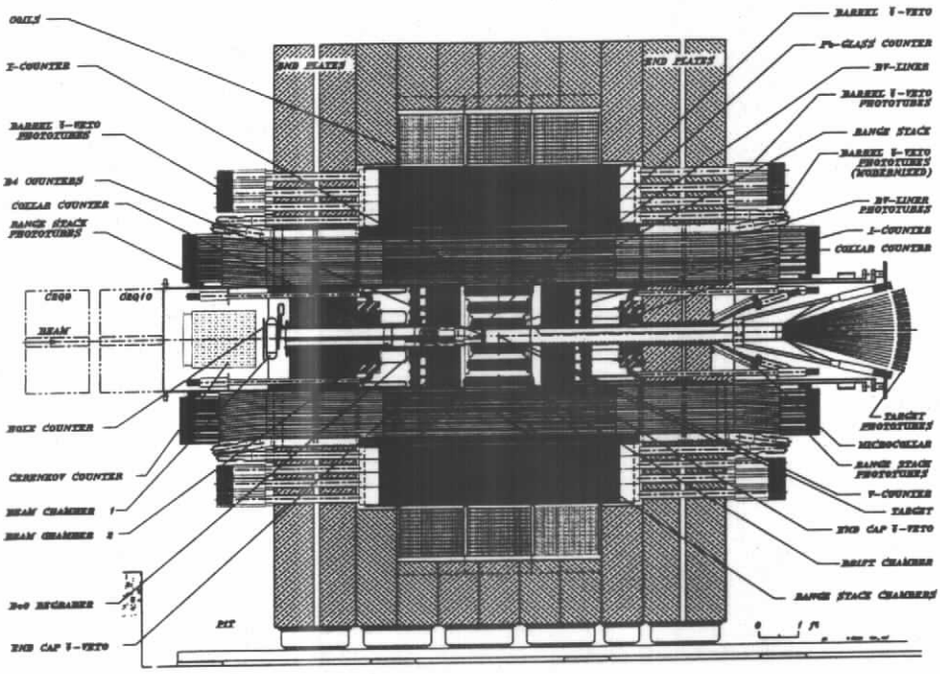
TRIUMF

E949 Upgrades



- Running Condition
  - 65 Tera protons/spill with higher Duty Factor
    Spill Length = 4.1 sec, Duty Factor = 64% (× 1.56)
  - Beam Momentum : 730 MeV/c
- RS Layer T,2-5 Replaced
  - Better Trigger Efficiency
  - Better dE/dx Measurement
- Photon Veto Improvements
  - Barrel Veto Liner : Add 2.3 X_0
  - Improvements in beam direction

- Higher segmentation in Beam Hodoscope
  - Effective to reduce double beam background
  - Better dE/dx resolution
- RS Monitor System with LEDs
  - Ensure reliability
  - Study of Energy Resolution
- Trigger Upgrades
  - New Trigger Boards with Programmable Logic Device
  - Meantimers by PLD : Reduce deadtime
- RS TDC Readout
  - e^+ identification without TD

Sensitivity Improvements compared to E787 (1995-1997)

- Higher Duty Factor ($\times 1.56$)
- Efficiency/Acceptance Improvements ($\times 2.1$)
  $\Leftarrow$ T-Counter, Meantimers, RS TDC, Offline Cuts ($0.1\times$SM) etc
- Re-optimize analysis for higher rates [$\times 2$]
- Increase phase space below $K_{\pi 2}$ peak [$\times 2$]

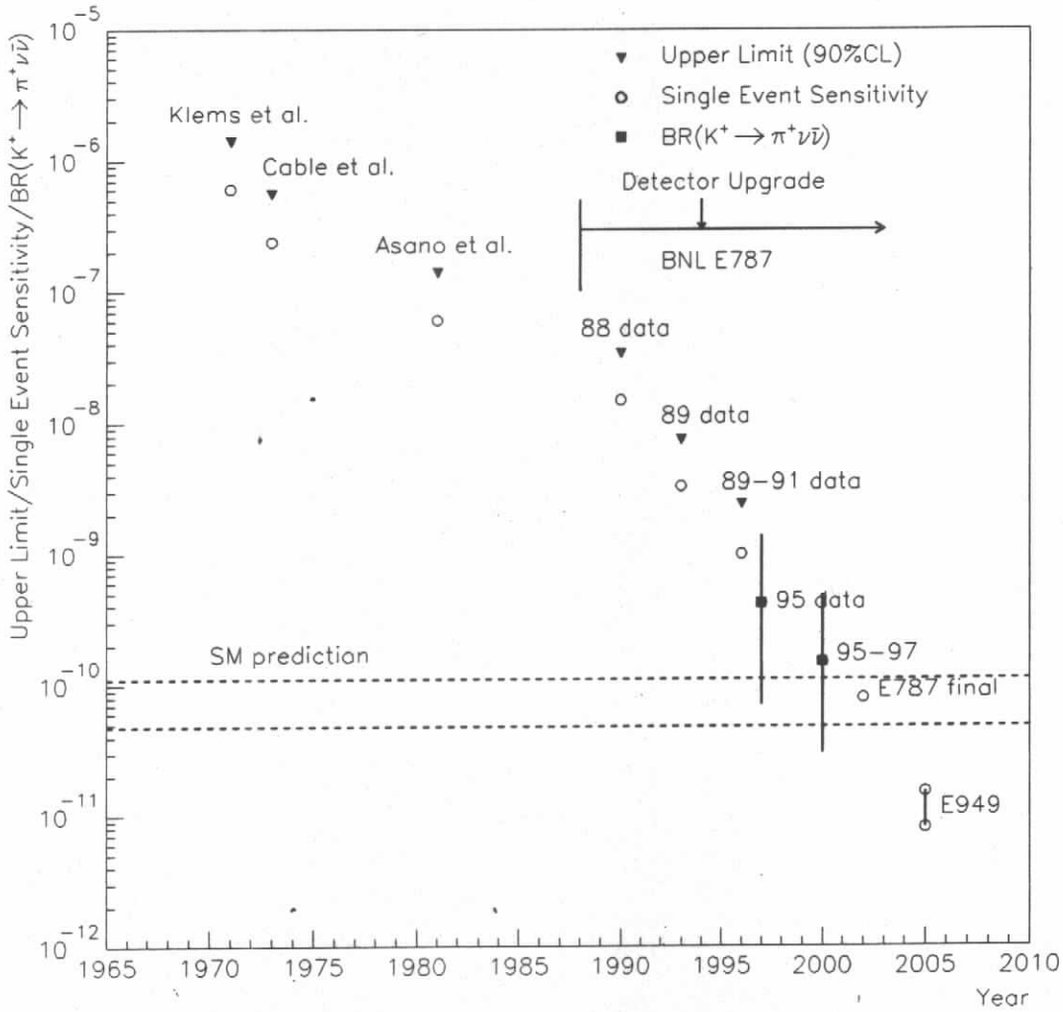
$\Rightarrow$ Total Gain of $\times\ 7\sim 13$

6000 hrs (2 years run) in E949 + E787 1995-1998
$\Rightarrow$ Aim to reach to Sensitivity $(8 - 15) \times 10^{-12}$
$\Rightarrow$ Determination of $|V_{td}|$ to better than 30%

Schedule

- Engineering runs in March - April
- Physics runs from FY2002

Summary


Upper Limit (90%CL)
Single Event Sensitivity
BR(K⁺ → π⁺νν̄)
Klems et al.
Cable et al.
Asano et al.
Detector Upgrade
BNL E787
88 data
89 data
89−91 data
95 data
95−97
E787 final
E949
SM prediction
Upper Limit/Single Event Sensitivity/BR(K⁺ → π⁺νν̄)
Year