Analysis for Rare Decay Modes (E787)

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Kaon Decay Modes analyzed by E787

CKM Matrix (V_{td} Extraction)

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

Chiral Perturbation Theory

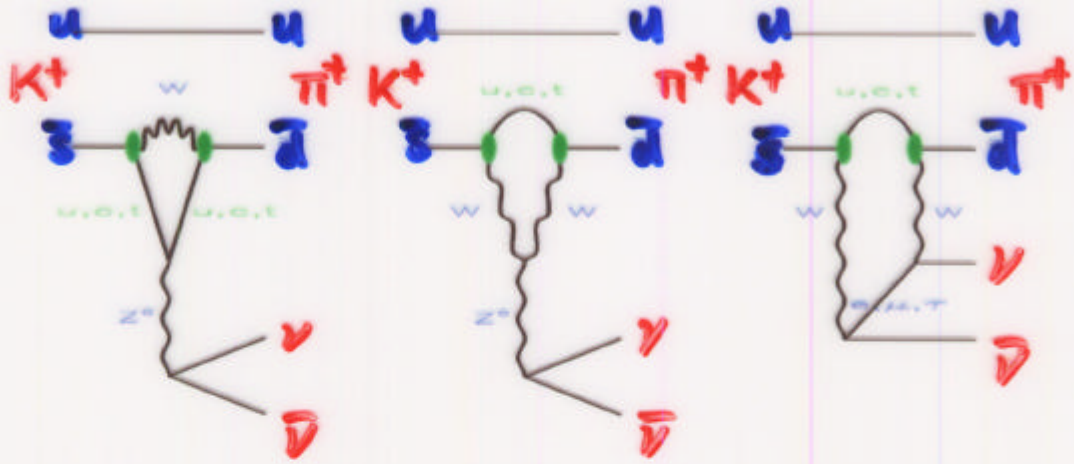
Phase-II (1995-1998)

- $K^+ \to \mu^+ \nu\gamma$ (Phys.Rev.Lett. 85 (2000) 2256-2259)
  $BR(SD^+) = (1.33 \pm 0.12 \pm 0.18) \times 10^{-5}$
- $K^+ \to \pi^+ \pi^0 \gamma$ (Phys.Rev.Lett. 85 (2000) 4856-4859)
  $BR(DE) = (4.7 \pm 0.8 \pm 0.3) \times 10^{-6}$

Phase-I (1989-1991)

- $K^+ \to e^+ \nu \mu^+ \mu^-$ (Phys.Rev. D58 (1998) 012003)
  $BR < 5.0 \times 10^{-7}$ (90% CL)
- $K^+ \to \pi^+ \mu^+ \mu^-$ (Phys.Rev.Lett. 79 (1997) 4756-4759)
  $BR = (5.0 \pm 0.4 \pm 0.7 \pm 0.6) \times 10^{-8}$
- $K^+ \to \pi^+ \gamma\gamma$ (Phys.Rev.Lett. 79 (1997) 4079-4082)
  $BR(100 < P_{\pi^+} MeV/c < 180) = (6.0 \pm 1.5 \pm 0.7) \times 10^{-7}$

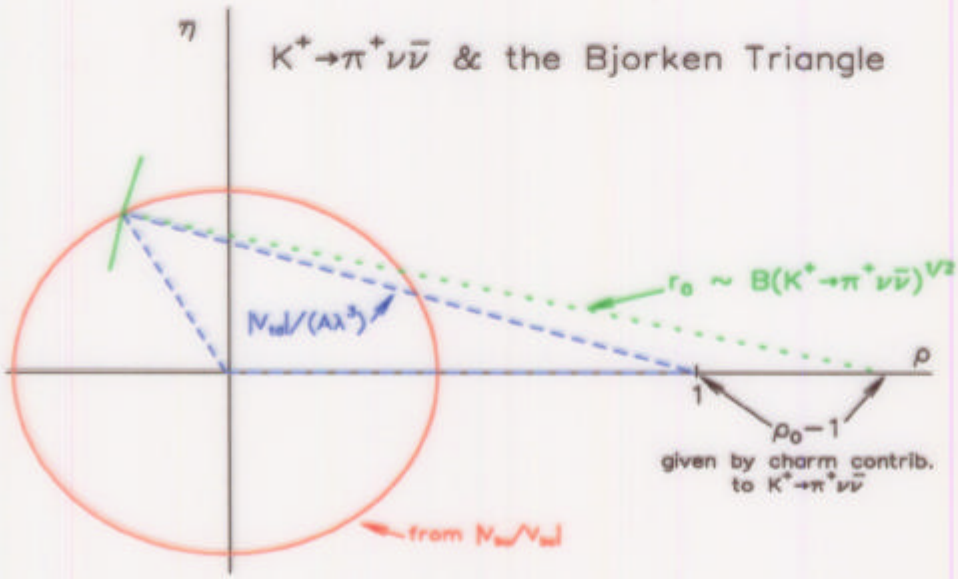
V_{td} Extraction



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

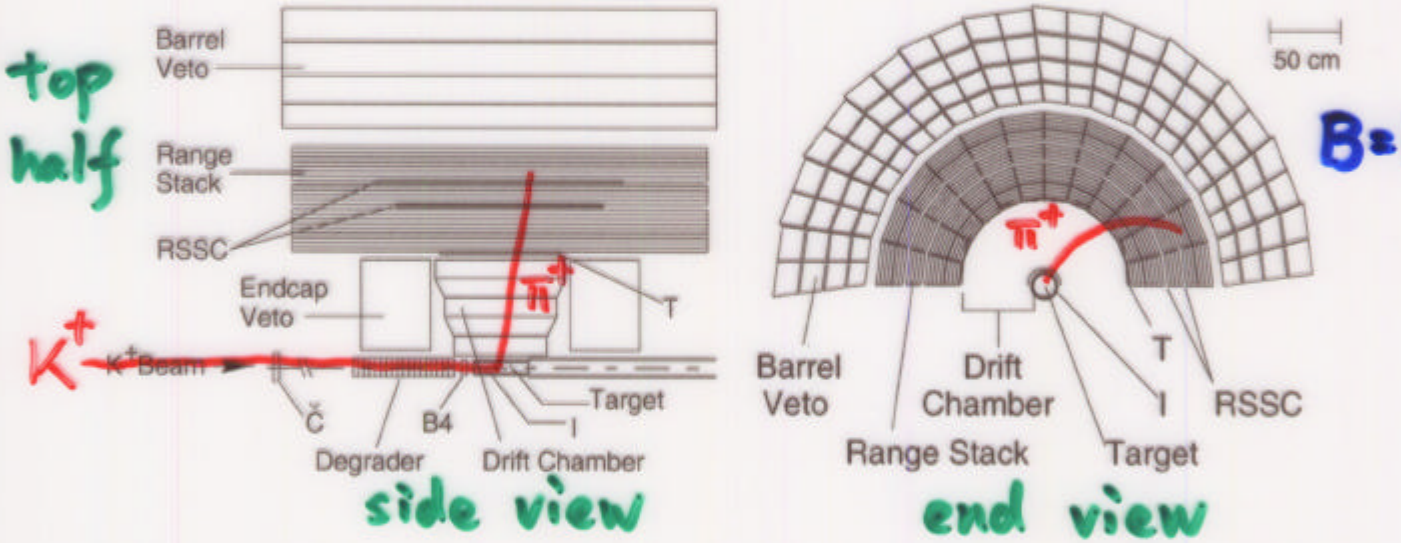
- Hadronic matrix element
  $\Rightarrow$ Extracted from $Br(K^+ \to \pi^0 e^+ \nu)$ and $Br(K^+ \to \pi^+ \pi^- e^+ \nu)$
- Dominated by Short distance contributions.

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



BNL-E787 Experiment

- 24 GeV Proton Beam by AGS (duty cycle = 44%)
  15 Tera ($\times 10^{12}$) protons/spill in Beam Line.
- Kaon Production at Platinum Target
- Two DC Separators in Transportation Beam Line
  $\hookrightarrow$ $K^+ : \pi^+ = 4 : 1$
- 6 Mega kaons/spill at the Entrance of E787 Spectrometer

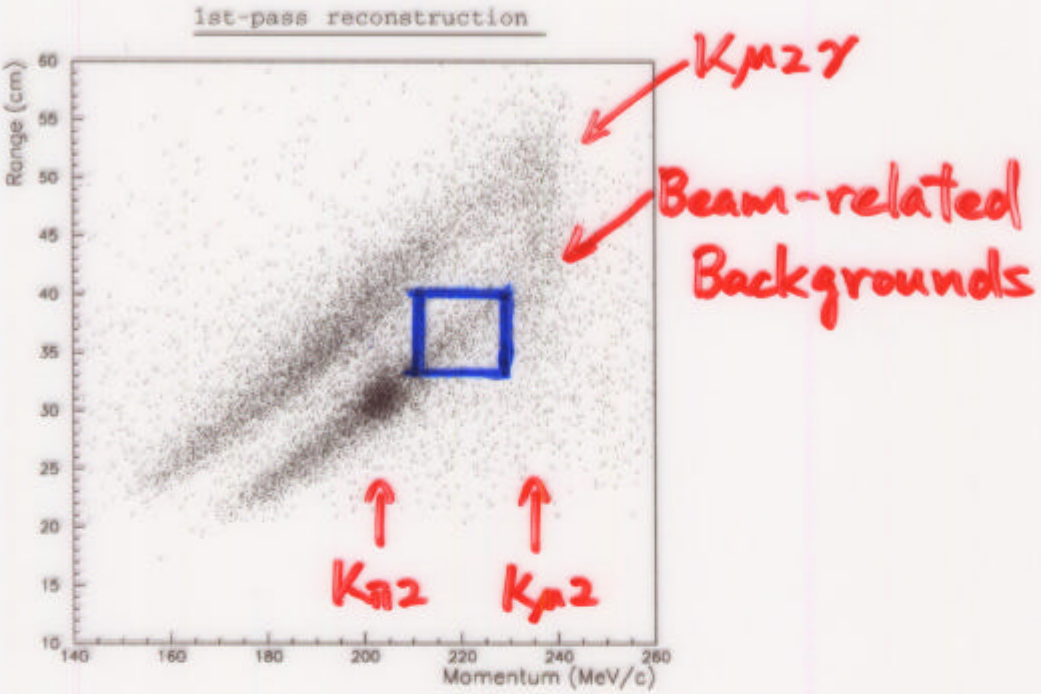


$K^+ \rightarrow \pi^+ \nu\bar{\nu}$

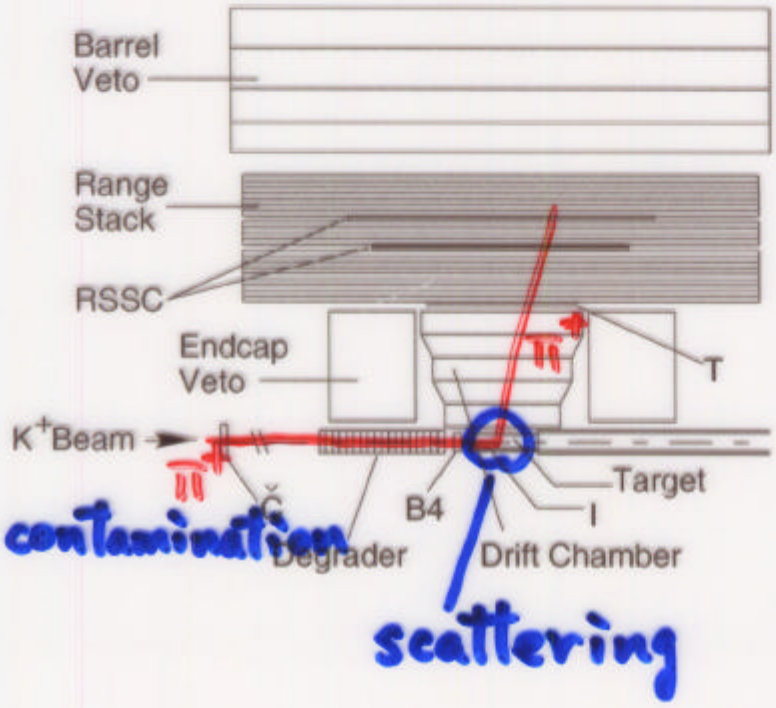
Stopped K^+ — Momentum Range Kinetic Energy — 4π Coverage of γ-veto

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

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

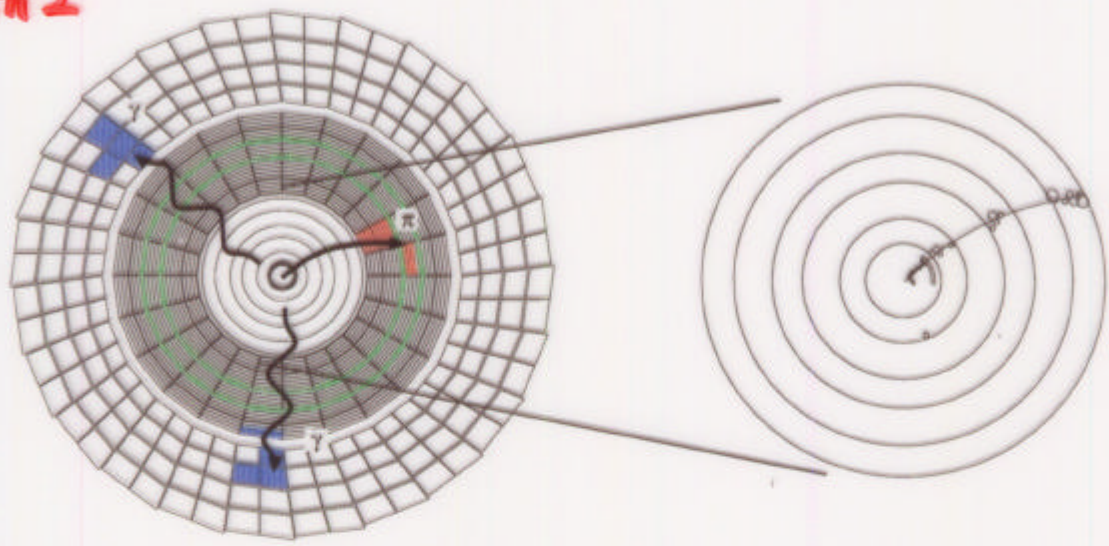


- $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)
- $K^+ \to \mu^+\nu$ ($K_{\mu 2}$) and $K^+ \to \mu^+\nu\gamma$ ($K_{\mu 2\gamma}$)
- Beam-related Backgrounds

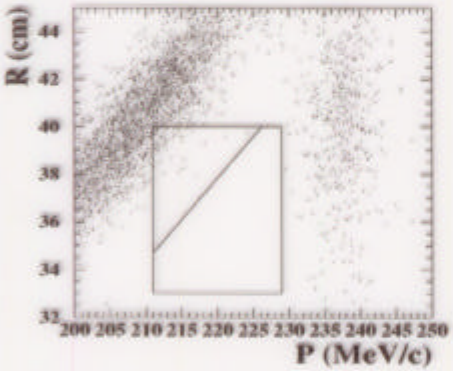


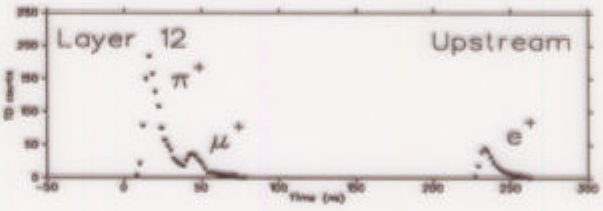
Background Rejection

$K_{\pi 2}$

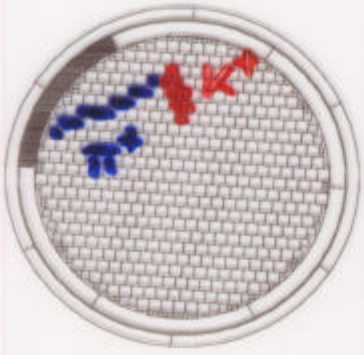


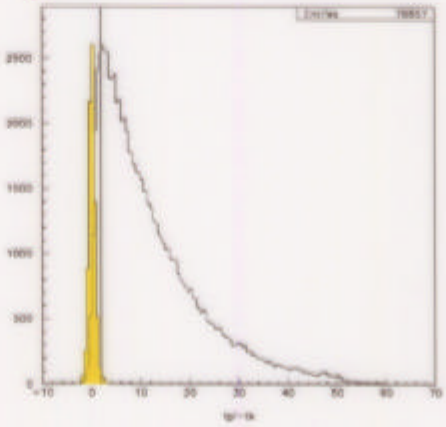
$K_{\mu 2}$ and $K_{\mu 2\gamma}$





Beam-related Background





Reliable Background Control

— Background Probability Function Method with Bifurcation

- Unaccounted Rare Process
  - Check the Outside of Signal Region by Loosening the Function
- Quality of Signal Candidate Event
  - Evaluate Background Probability by tightening the Function

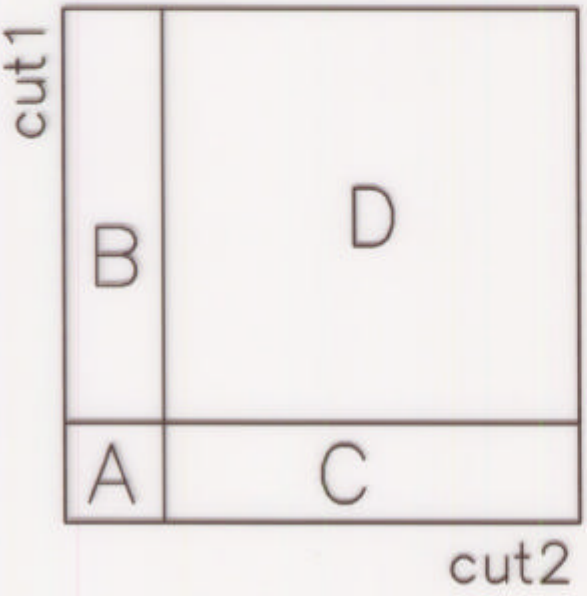
Two Independent Cuts with Large Rejections

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

π^+ ↓ Kinematics cut

π^0 ↓ Photon Veto cut

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



A = Signal Region

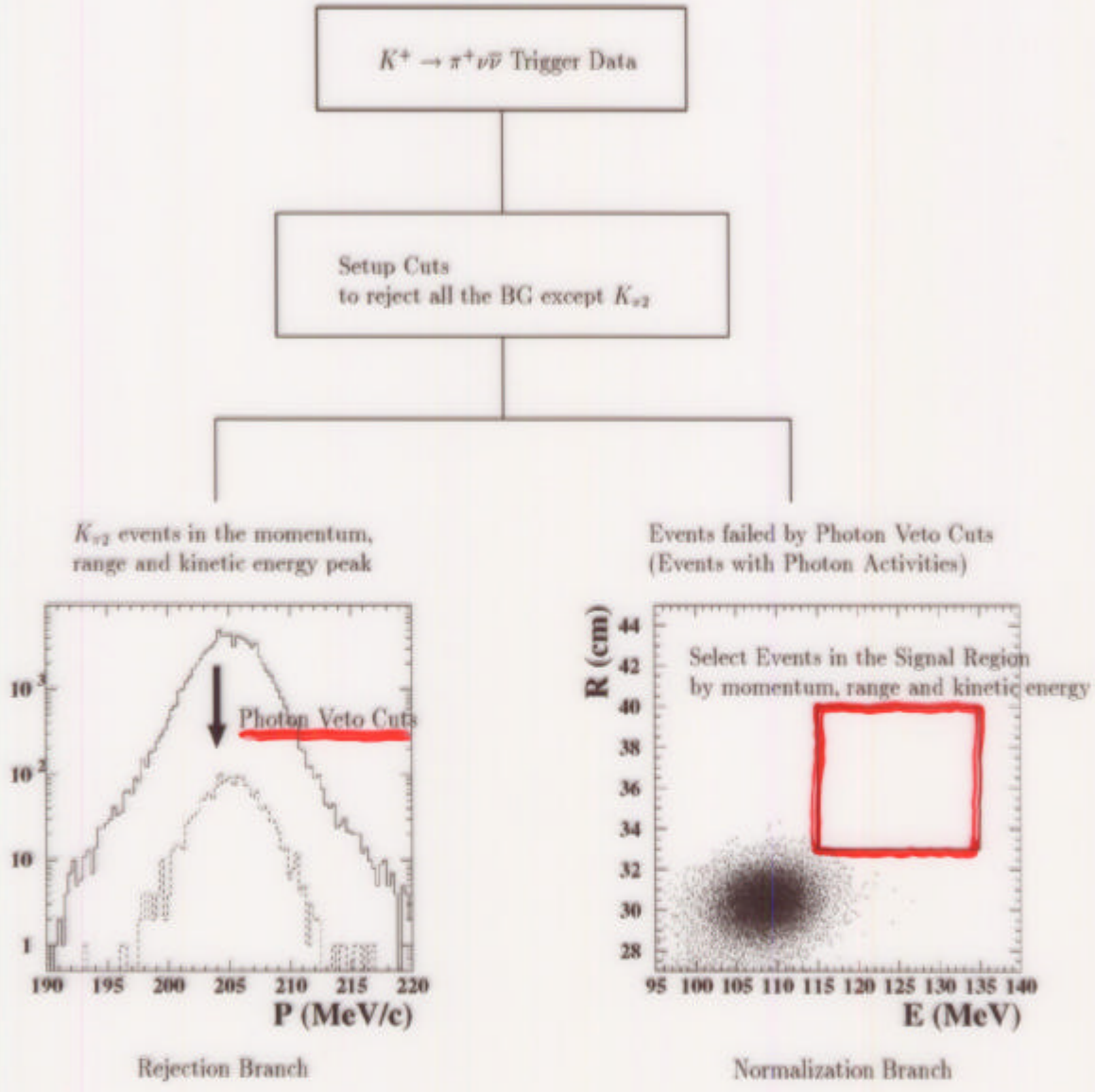
$R_1 = \frac{C+D}{C}$

$R_2 = \frac{B+D}{B}$

$N_{BG} = B/R_1$

- Background Function by Loosening/Tightening Cut1 or Cut2
- Acceptance Function from Monitor-Trigger Data at the Same Cut Positions

Estimation of $K_{\pi 2}$ Background Level

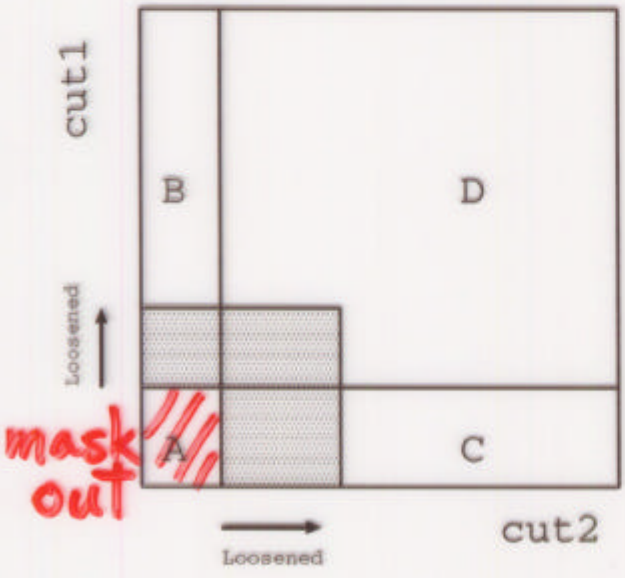


- Photon Veto Function - Time Windows and Energy Thresholds
- Kinematics Function - $K_{\pi 2}$ Side of Momentum, Range and Kinetic Energy

Summary of Background Estimations

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

Cross Check by using Events in the Outside of the Signal Region



mask out

ex. $K_{\pi 2}$ 1995 2/3

estimation 0.9 9 5

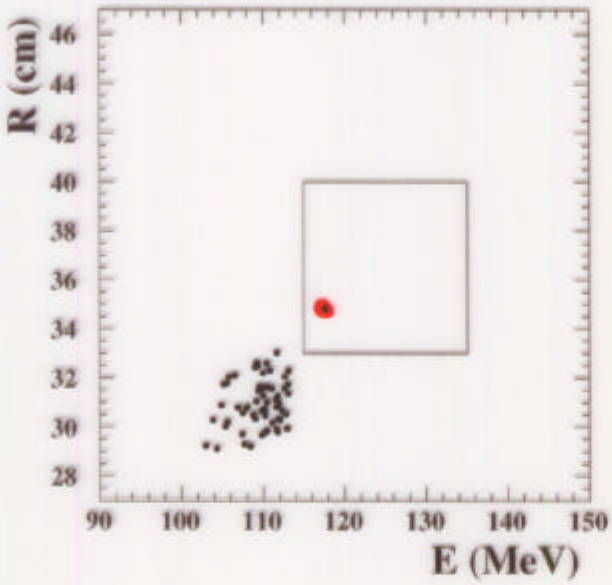
observation 2 9 5

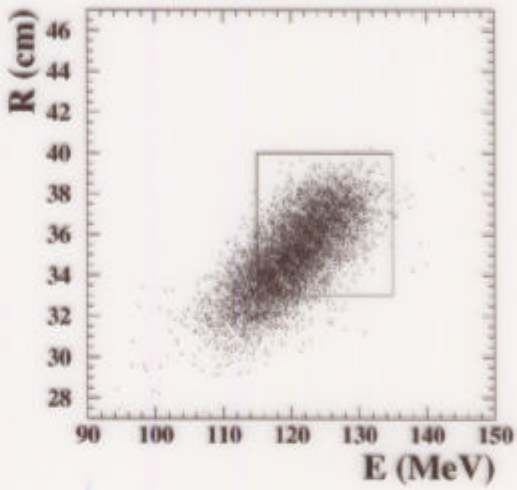
- Compare Estimations with Observations.

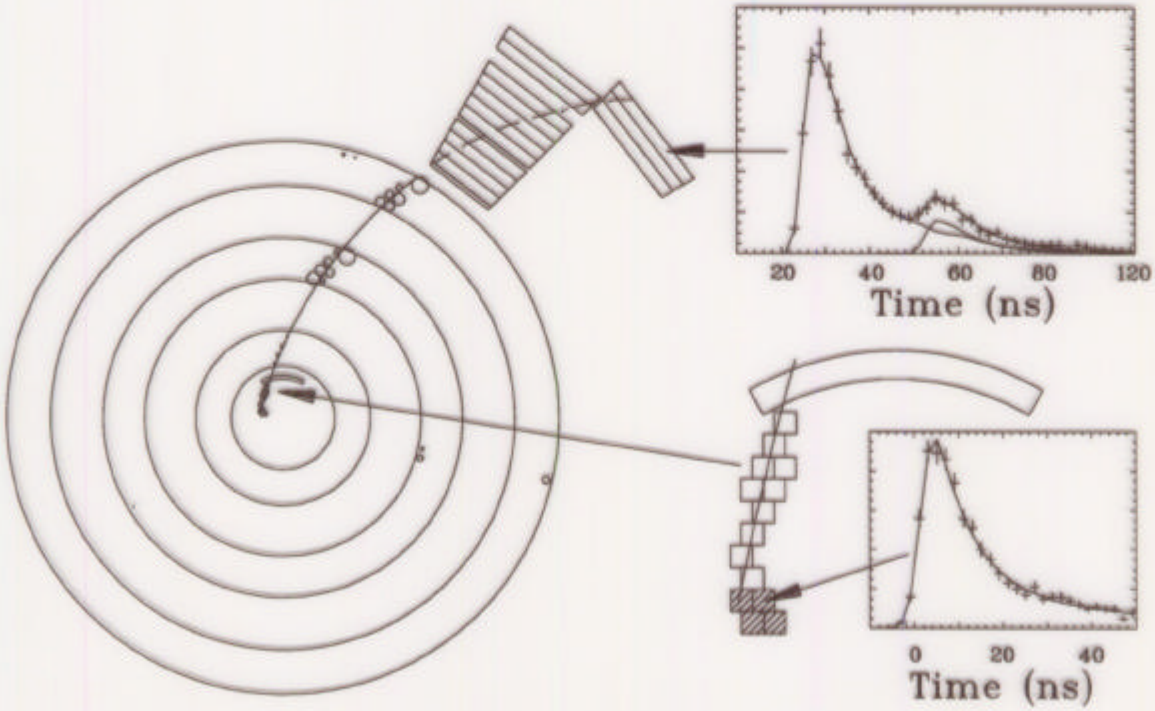
↪ Consistent with each other.

P = 218.2 MeV/c
R = 34.7 cm
E = 117.7 MeV

Open the BOX





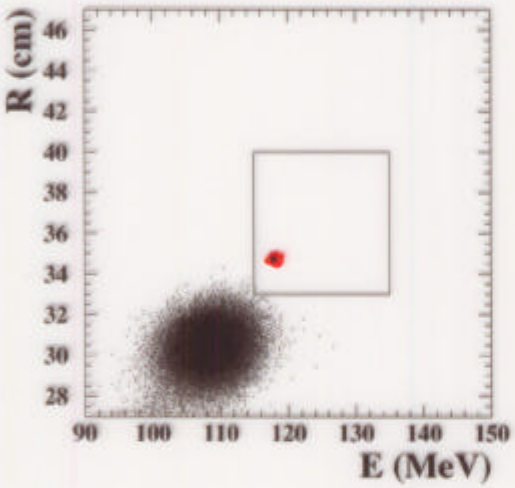


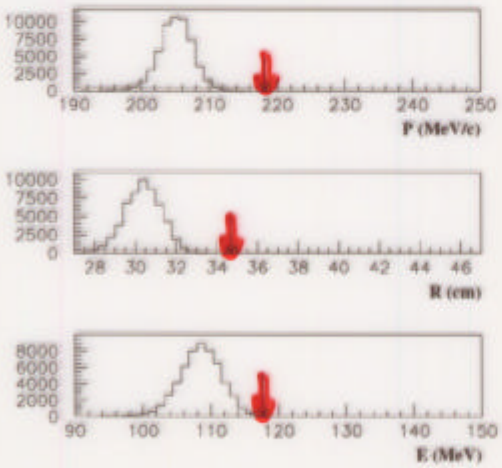
$T_\pi - T_K = 23.9\,ns$ τ 12.4 ns

$T_\mu - T_\pi = 26.9\,ns$ τ 26.0 ns

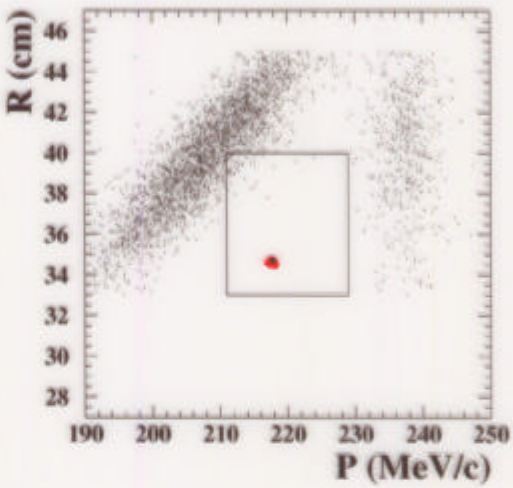
$T_e - T_\mu = 3253\,ns$ τ 2197 ns

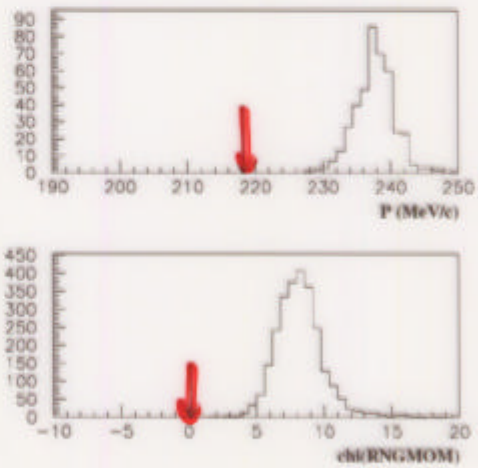
Against $K_{\pi 2}$ Data



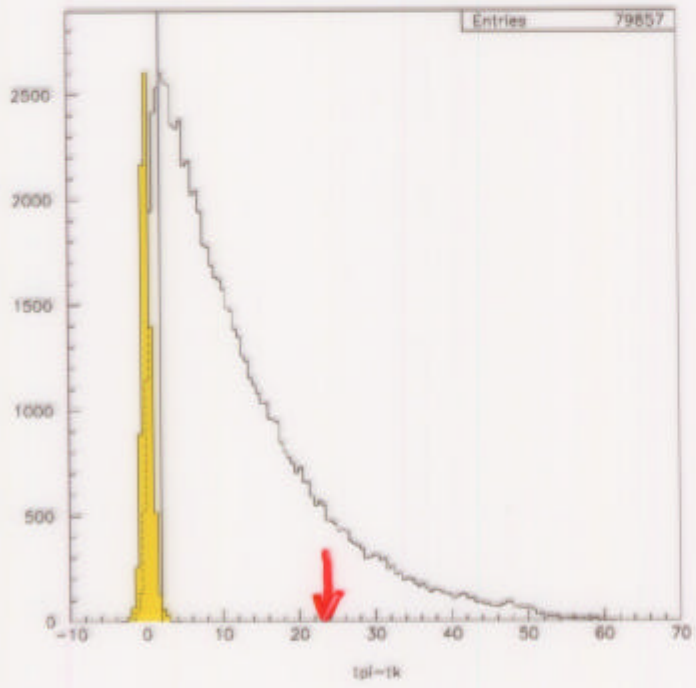


Against $K_{\mu 2}$ Data



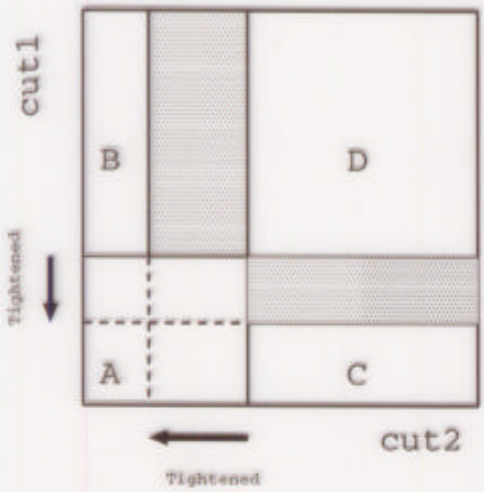


Against Beam Background



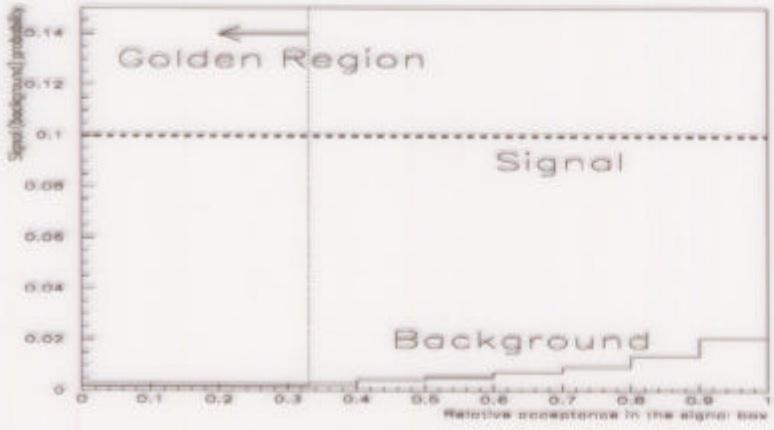
- Kaon decay time = 23.9ns
- No hits at the kaon decay time in the beam instruments.

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

Year	*1995*	*1996*	*1997*	*1*
Beam Momentum (MeV/c)	*790*	*730*	*710*	
Trigger	0.180	0.180	0.178	0.
Phase space & Solid angle	0.365	0.363	0.375	0.
Nucl. Int. & Decay-in-flight	0.514	0.512	0.507	0.
Reconstruction Efficiency	0.951	0.960	0.948	0.
Beam and Target analysis	0.434	0.455	0.430	0.
Accidental Loss	0.780	0.787	0.773	0.
Kinematics	0.848	0.758	0.756	
$\pi \to \mu \to e$ decay chain	0.294	0.327	0.310	
$T \cdot 2$ Efficiency	0.933	0.888	0.889	0.
Efficiency of K^+ Stops in TG	0.790	0.840	0.826	0.
Total Acceptance	0.00199	0.00213	0.00183	0.00
	$\pm$0.00011	$\pm$0.00007	$\pm$0.00008	$\pm$0.00
K^+ triggers ($\times 10^{12}$)	1.526	1.122	0.371	0.

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

Branching Ratio (Based on one signal event)

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.52^{+3.48}_{-1.26} \times 10^{-10}$$

with 68% Confidence Level Interval

- Consistent with SM expectation $(0.82 \pm 0.32) \times 10^{-10}$
- V_{td} Range : $0.0024 < |V_{td}| < 0.038$

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

Backgrounds

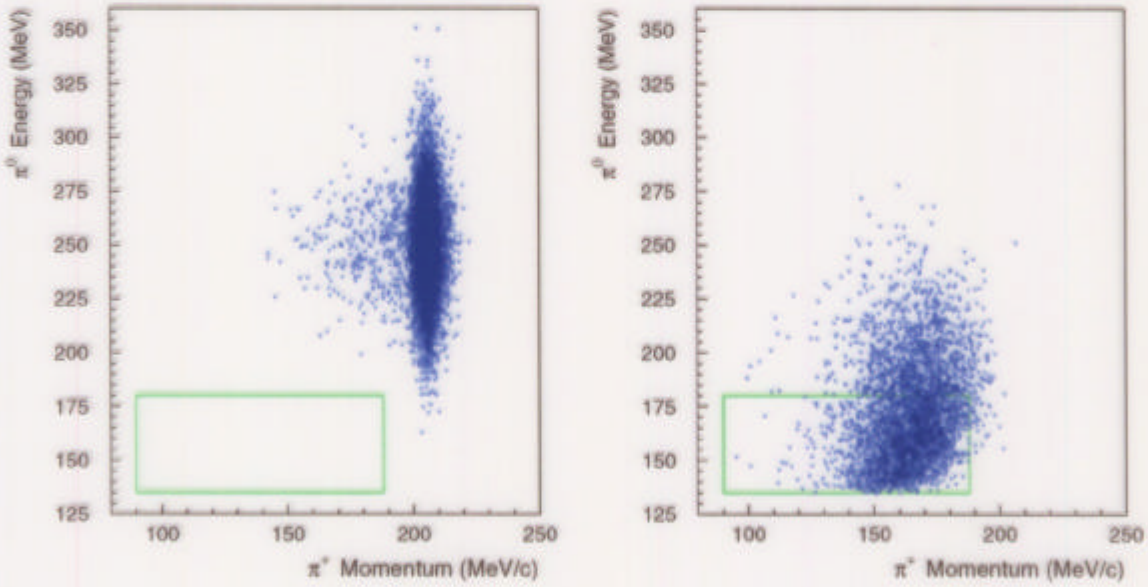
$K^+ \to \pi^+\pi^0$	0.044 ± 0.009
$K^+ \to \mu^+\pi^0\nu$	0.024 ± 0.012
$K^+ \to \pi^+\pi^0\gamma$ (IB)	< 0.01 (90% CL)
$K^+ \to \pi^+\pi^0\gamma$ (DE)	0.0007
Total	0.068 ± 0.021

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)



Conclusion

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

- Analyzed 3.2×10^{12} Kaon triggers (1995-1997)
- BG Estimation in the Signal Region : 0.083±0.019 events
  Functional Control with Bifurcation was adopted.
  Cross Checks of the estimations were performed.
- One Candidate Event is Observed.
  This Events remains in the Golden Region .
- Obtained $BR(K^+ \to \pi^+ \nu\bar{\nu}) = 1.52^{+3.48}_{-1.26} \times 10^{-10}$
  Consistent with SM prediction

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

- Analyzed 1.3×10^8 Kaon triggers (1995)
- Zero events were observed.
- Obtained $BR(K^+ \to \pi^+ \pi^0 \nu\bar{\nu}) < 4.3 \times 10^{-5}$ (90% CL)
  No Deviation from SM.

Future Prospect ($K^+ \to \pi^+ \nu\bar{\nu}$)

- 1998 Data Set : Now Being Analyzed
  The amount is comparable to 1995-97 data set.
- E949 is going to Start.
  Aiming to Collect 7-10 signals.