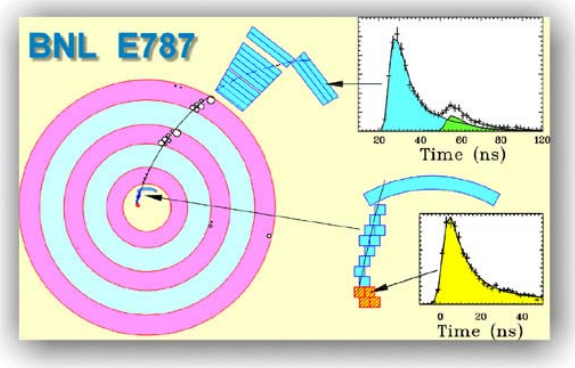


Rare K-decays and Petsye

- PNN1: $K^+ \to \pi^+ \nu\bar{\nu}$ above $K\pi 2$ peak.
- PNN2: $K^+ \to \pi^+ \nu\bar{\nu}$ below $K\pi 2$ peak.
- Other results
- KOPIO: $K_L^0 \to \pi^0 \nu\bar{\nu}$

Milind V. Diwan
Brookhaven National Laboratory

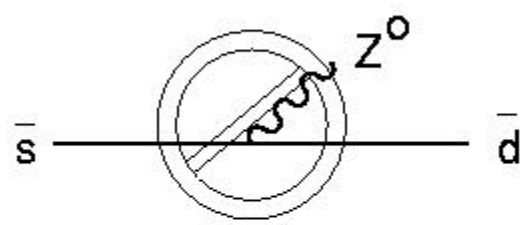
Consequences of Cabibbo - Kobayashi - Maskawa Mixing

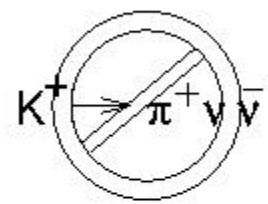
neutral currents:

$$\begin{pmatrix} d' & s' & b' \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} d & s & b \end{pmatrix} \underbrace{V^\dagger V}_{I} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Longrightarrow$$

$$ddZ + ssZ + bbZ + uuZ + ccZ + ttZ$$

No "flavor-changing neutral currents"





Similarly following decays are not allowed

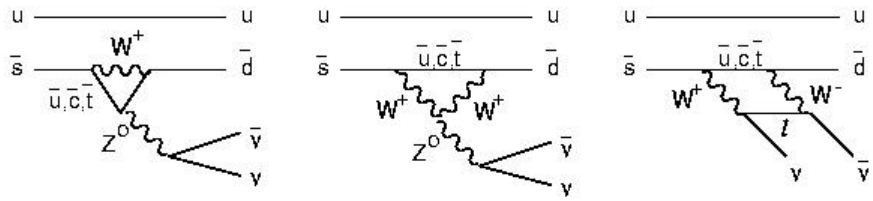
$K_L \to \mu^+\mu^-$

$K_L \to e^+e^-$

$K^+ \to \pi^+\mu^+\mu^-$

... etc.

. . . or are they? Each of these diagrams *is* allowed:



$V_{us}^*,\ V_{cs}^*,\ V_{ts}^*$ $\qquad$ $V_{ud},\ V_{cd},\ V_{td}$

Unitarity of $V \implies$ "G.I.M. mechanism"

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$

No flavor-changing neutral currents at all!

Loophole: $m_u \ll m_c \ll m_t$: the cancellation is not exact and most of the surviving rate is due to **top quarks!**

The residual rate is calculable – for three neutrino flavors:

$$\mathrm{BR}_{\mathrm{calc}}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.46 - 1.04) \times 10^{-10}$$

CP and $\pi\nu\bar{\nu}$

$$K_L = \frac{K_2+\epsilon K_1}{\sqrt{(1+|\epsilon|^2)}} \quad CP \approx -1$$
$$K_S = \frac{K_1+\epsilon K_2}{\sqrt{(1+|\epsilon|^2)}} \quad CP \approx +1$$

$\pi^0\nu\bar{\nu}$ is CP even state

$$\begin{aligned}
A(K^0 \to \pi^0\nu\bar{\nu}) &= (1/\sqrt{2})A(K^+ \to \pi^+\nu\bar{\nu}) \\
A(K_1 \to \pi^0\nu\bar{\nu}) &= Re(A(K^+ \to \pi^+\nu\bar{\nu})) && = R \\
A(K_2 \to \pi^0\nu\bar{\nu}) &= iI \quad (A(K^+ \to \pi^+\nu\bar{\nu})) && = iI \\
B(K_L \to \pi^0\nu\bar{\nu}) &= I^2 + 2Re(-i\epsilon R) + |\epsilon|^2 R^2 && \simeq I^2
\end{aligned}$$

$$I R/ \simeq Re(V_{ts}^* V_{td})/ I \quad (V_{ts}^* V_{td}) \simeq \frac{3.0 \times 10^{-4}}{1.4 \times 10^{-4}}$$

But the smallness of $|\epsilon| \sim 0.0022$ makes $K_L \to \pi^0\nu\bar{\nu}$ almost entirely through direct CP violation ($K_2 \to \pi^0\nu\bar{\nu}$).
Littenberg 1989

Measurements of $K \to \pi\nu\bar{\nu}$ provide CKM parameters with small theoretical uncertainties, but the experiments are hard.

Extend analysis to get limit on branching ratio:

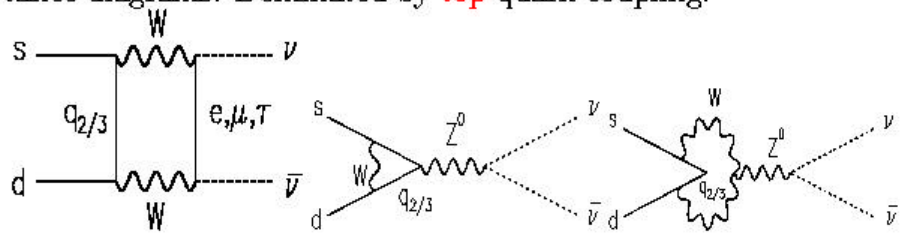
$$B(K_L \to \pi^0\nu\bar{\nu}) < 4.4 \times B(K^+ \to \pi^+\nu\bar{\nu})$$

Grossman and Nir, 1997

[0] MVD Ward an

CKM and $\pi\nu\bar{\nu}$

"Golden" modes for determining CKM triangle. Dominated by short distance diagrams. Dominated by top quark coupling.



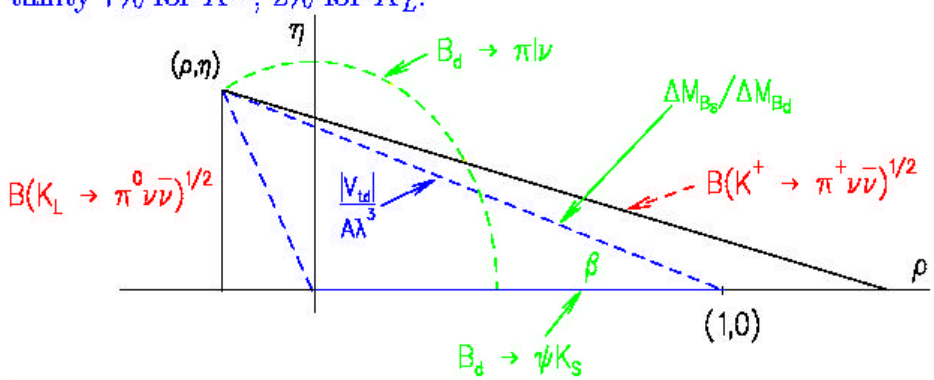
Hadronic matrix element well determined by $K^+ \to \pi^0 e^+ \nu_e$ decay.

$$\mathrm{B}(K_L^o \to \pi^o \nu\overline{\nu}) = \frac{\tau_L}{\tau_{K^+}} \frac{\kappa_L \alpha^2 B(K_{e3})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \Sigma_l \left| Im(V_{ts}^* V_{td}) X(x_t) \right|^2$$

$$\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) = \frac{\kappa_+ \alpha^2 B(K_{e3})}{2\pi^2 \sin^4\theta_W |V_{us}|^2} \Sigma_l \left| X(x_t) V_{ts}^* V_{td} + X^l(x_c) V_{cs}^* V_{cd} \right|^2$$

$$\begin{aligned}
\mathrm{B}(K_L^o \to \pi^o \nu\overline{\nu}) &= 4.08 \times 10^{-10} A^4 \eta^2 \\
&= (2.6 \pm 1.2) \times 10^{-11} \\
\mathrm{B}(K^+ \to \pi^+ \nu\overline{\nu}) &= 8.88 \times 10^{-11} A^4 [(\overline{\rho}_0 - \overline{\rho})^2 + (\sigma\overline{\eta})^2] \\
&= (7.5 \pm 2.9) \times 10^{-11} \ , \\
\sigma &= (1 - \tfrac{\lambda^2}{2})^{-2}; \ \overline{\rho}_0 = 1.4
\end{aligned}$$

Uncertainties from current CKM parameters. Intrinsic theoretical uncertainty 7% for K^+, 2% for K_L.



E787

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

S. Adler, M.S. Atiya, B. Bhuyan, I-H. Chiang, M. Diwan, J.S. Frank, J.S. Haggerty, V. Jain, D. Jaffe, S.H. Kettell, T.F. Kycia, K.K. Li, L.S. Littenberg, C. Ng, G. Redlinger, R.C. Strand, and C.H. Witzig

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M. Miyajima, J.Nishide, K.Shimada, T.Shimoyama, and Y. Tamagawa

Fukui University

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

High Energy Accelerator Research Organization (KEK)

T. Fujiwara and T. Nomura

Kyoto University

Y. Kishi, T. Nakano, and T. Sasaki

Osaka University

M. Ardebili, A. Bazarko, M. Convery, M.M. Ito, D.R. Marlow, R. McPherson, P.D. Meyers, F.C. Shoemaker, A.J.S. Smith, and J.R. Stone

Princeton University

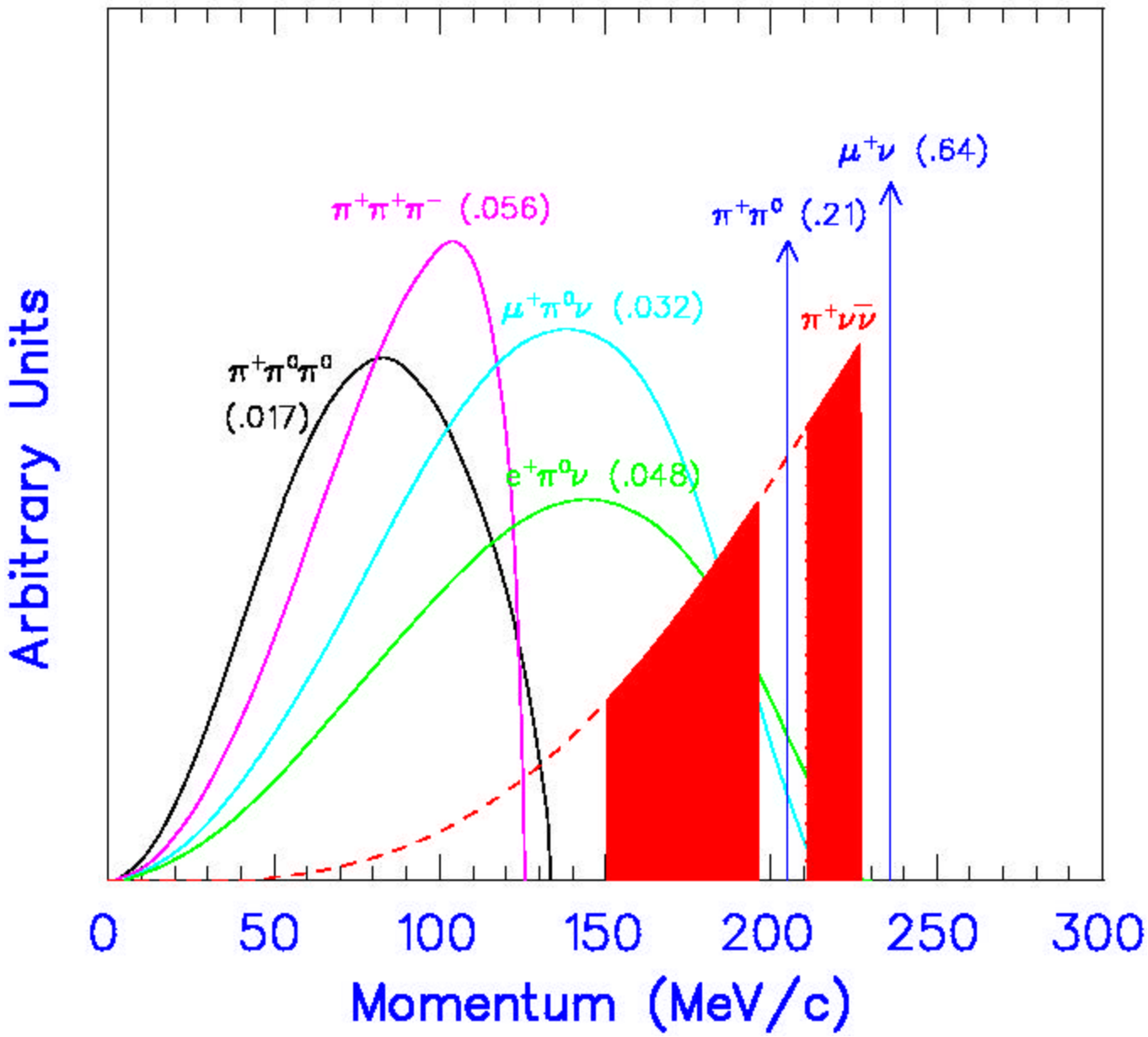
P. Bergbusch, E.W. Blackmore, D.A. Bryman, S. Chen, A. Konaka, J.A. Macdonald, J. Mildenberger, T. Numao, J.-M. Poutissou, and R. Poutissou

TRIUMF

P. Kitching and H-S. Ng

University of Alberta

PNN backgrounds and tools



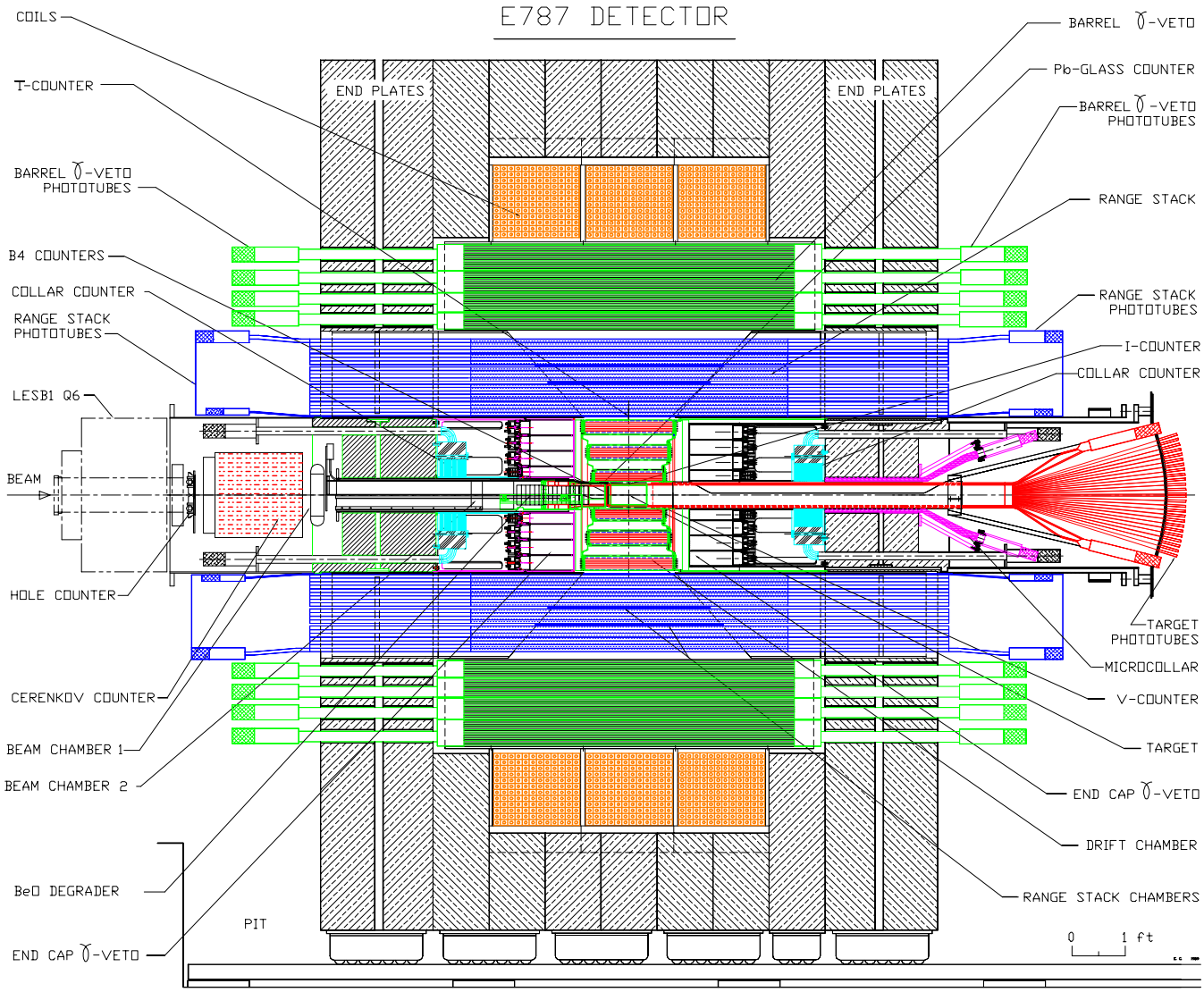
PNN1 main backgrounds

- $K^+ \to \pi^+\pi^0$: Two body kinematics and Photon veto
- $K^+ \to \mu^+\nu$: Two body kinematics and $\pi^+ \to \mu^+ \to e^+$ id.
- Scattering of π^+ contamination: K^+ decay time and Cerenkov Particle identification in the beam.

PNN2 main backgrounds

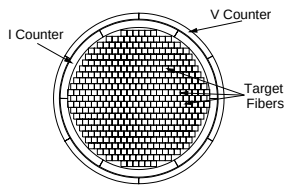
- $K^+ \to \pi^+\pi^0$ with scattering of π^+ in the kaon stopping target: Two body kinematics, Photon veto, and Detection of π^+ scattering in the target.
- $K^+ \to \pi^+\pi^-e^+\nu$: Detection of π^- and e^+ in the target.
- Scattering of π^+ contamination in the beam: K^+ decay time and Cerenkov Particle identification in the beam.
- Use CCD's to find π^+ hits hidden under the kaon fibers. Allow long kaon decay time to help.
- Photon veto system not as effective as for PNN1 because π^0 is not back-to-back with π^+.

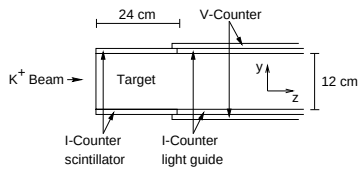
E787 DETECTOR



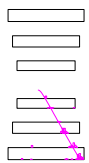
E787 Technique

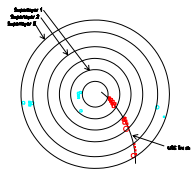
K^+ I.D.'d by beam counters, stop in 400-element sci-fi target



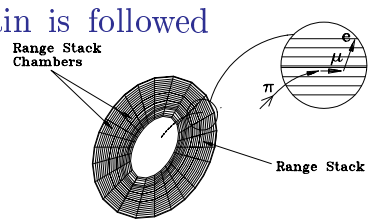


Wait 2ns for decay
Then π^+ tracked & momentum analyzed in UTC (B=1T)

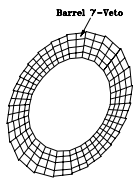


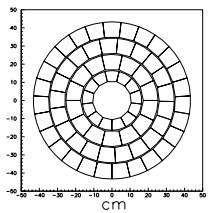


π^+ then ranges out in an Range Stack (scint. + straw ch.)
Range/energy/momentum can be compared.
Also $\pi^+ \to \mu^+ \to e^+$ decay chain is followed

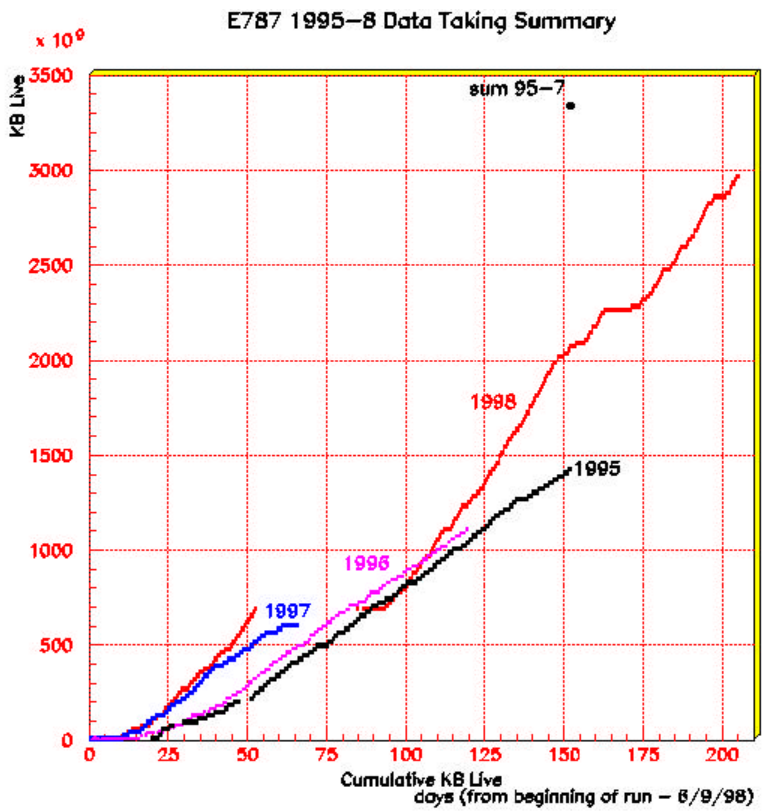


Hermetic photon vetoing via barrel Pb-scint system (BV)
+ CsI-pure endcaps (EC)





Get $> 10^6 : 1$ π^0 rejection, $> 10^8 : 1$ μ^+ rejection
Also very good kinematic rejection of two-body decays.



- $B(K^+ \to \pi^+ \nu\bar{\nu})$ in PNN1 region sensitivities
  - '95 : 4.2×10^{-10}
  - '95-'97 : 1.5×10^{-10}
  - '95-'98 : $\sim 0.8 \times 10^{-10}$
- $B(K^+ \to \pi^+ \nu\bar{\nu})$ in PNN2 region sensitivities
  - Only 96 data analysed so far.
    1.12×10^{12} kaons
    $6M$ kaons in 1.6 sec at 730 MeV/c (24% pion cont.)
    Known hardware problem in PBG detector.

PNN1 data analysis

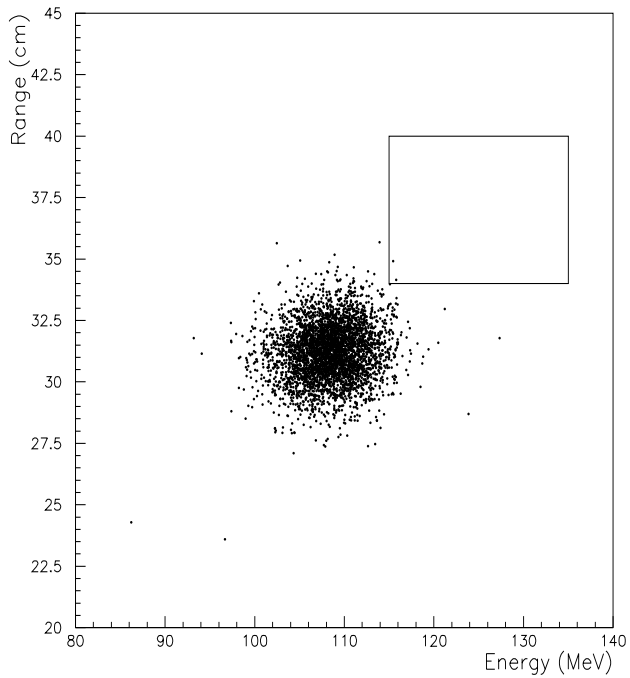
Analysis Technique

- Background measured from data.
  - Measured to $O(10^{-2})$ event level.
  - Two indep t cuts for each background.
- Compare prediction of background outside signal region to actual count.
- Blind analysis (remove signal region from all studies).

Background	E787 (95-97)	E787 (98-99)
$K^+ \to \pi^+\pi^\circ$	0.022 ± 0.005	$0.012^{+0.003}_{-0.004}$
$K^+ \to \mu^+\nu_\mu$	0.028 ± 0.010	$0.034^{+0.043}_{-0.024}$
Single beam	0.005 ± 0.004	0.004 ± 0.001
Double beam	0.003 ± 0.002	
CEX	0.010 ± 0.007	$0.016^{0.005}_{-0.004}$
Total background	0.07 ± 0.01	$0.066^{0.044}_{-0.025}$

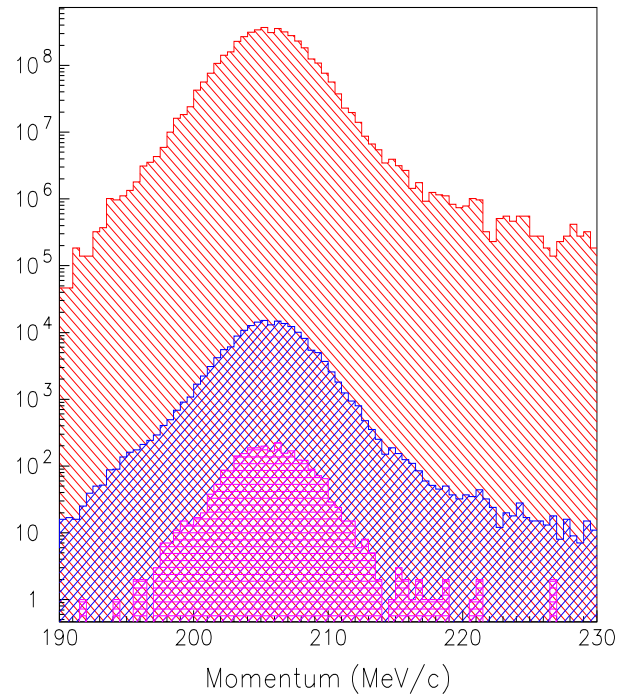
$K_{\pi 2}$ background.

γ veto reversed



N = 2/1.6

$K_{\pi 2}$ (E,R peak)



Rej($\overline{\gamma}$) = 46.6

$$N_{b.g} = N_{K_i} / R_{\bar{\gamma}} = 0.03$$

Results from 1995–98 $\pi\nu\overline{\nu}(1)$ data sets

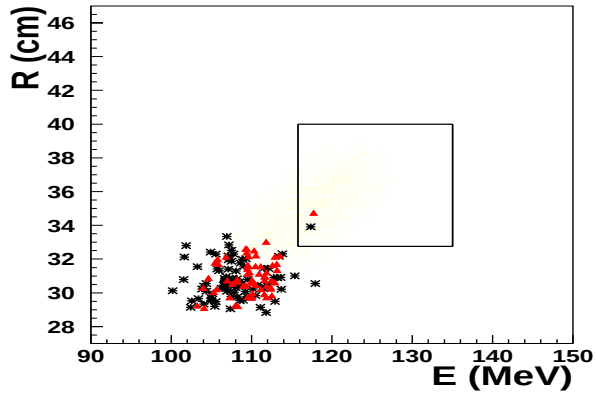
Background	1995–97	1998
$K_{\pi 2}$	0.03 ± 0.01	$0.012^{+0.003}_{-0.004}$
$K_{\mu 2}$	0.02 ± 0.01	$0.034^{+0.043}_{-0.024}$
Beam (1 + 2)	0.02 ± 0.02	0.004 ± 0.001
CEX	0.01 ± 0.01	$0.016^{+0.005}_{-0.004}$
Total background	0.08 ± 0.02	$0.066^{+0.044}_{-0.025}$

Acceptance factors	1995–97	1998
K^+ stop efficiency	0.704	0.702
K^+ decay after 2 ns	0.850	0.851
$K^+ \to \pi^+\nu\bar{\nu}$ phase space	0.155	0.136
Solid angle acceptance	0.407	0.409
π^+ nucl. int., decay-in-flight	0.513	0.527
Reconstruction efficiency	0.959	0.969
Other kinematic constraints	0.665	0.554
$\pi - \mu - e$ decay acceptance	0.306	0.392
Beam and target analysis	0.699	0.706
Accidental loss	0.785	0.751
Total acceptance	0.0021	0.00196

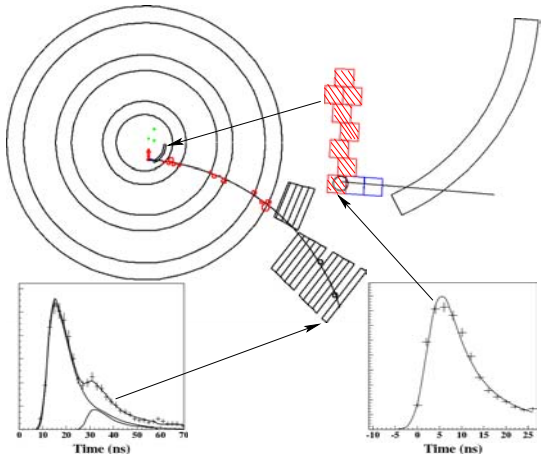
Summary	1995–97	1998
N_K	3.2×10^{12}	2.7×10^{12}
Acc.	0.0021(1)(2)	0.00196(5)(10)
Sensitivity	1.5×10^{-10}	1.89×10^{-10}
Background	0.08 ± 0.03	$0.066^{+0.044}_{-0.025}$

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

1995–98 Data



Event Display (1998)

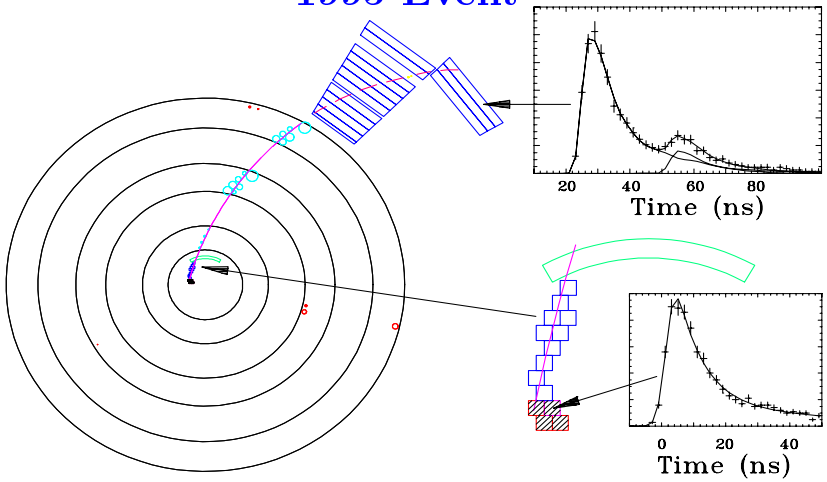


$$\mathbf{BR}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

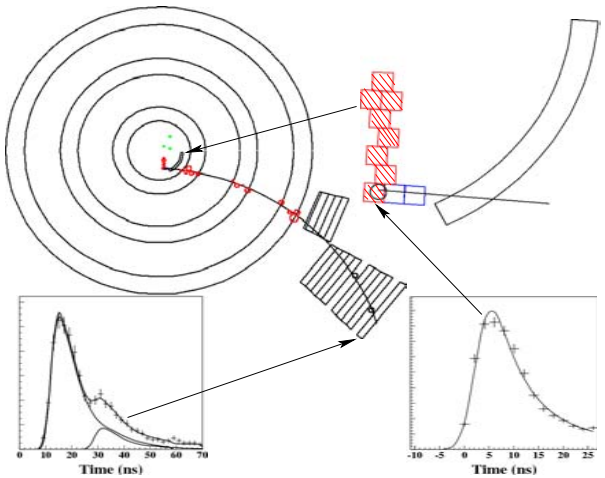
[Lab PR: http://www.bnl.gov/bnlweb/pubaf/pr/2002/bnlpr011002.htm]
[PRL cover: http://prl.aps.org/prl/covers/88_4.jsp]

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

1995 Event



1998 Event

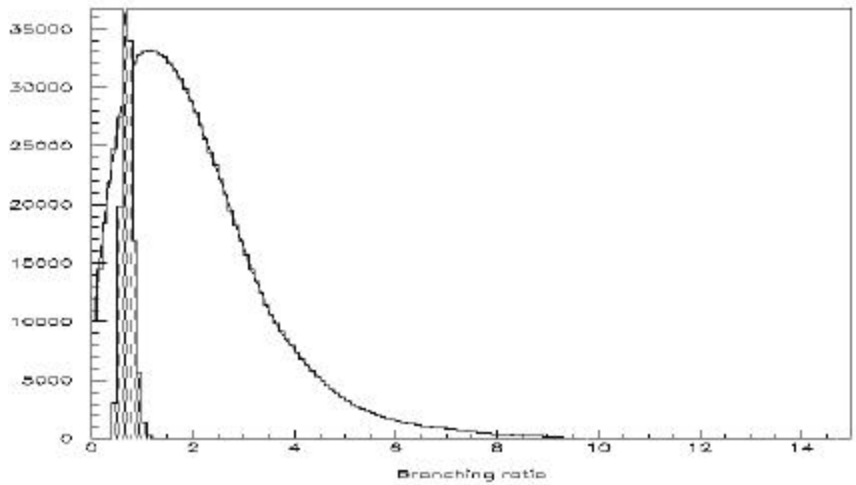


$$\mathbf{BR}(K^+ \to \pi^+ \nu\overline{\nu}\ ) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

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

Comparison of B($K^+ \to \pi^+ \nu\nu$) to SM

Event	Kinematic quantities $P(MeV/c)$	$R(cm)$	$E(MeV)$	S/N	Bkg	Rel. acc
1995	218.2	34.8	117.8	35	0.008	0.55
1998	213.8	33.9	117.1	3.6	0.022	0.84
B2(98)	224.9	37.1	125.5	0.7	0.11	1.24



E787 Summary

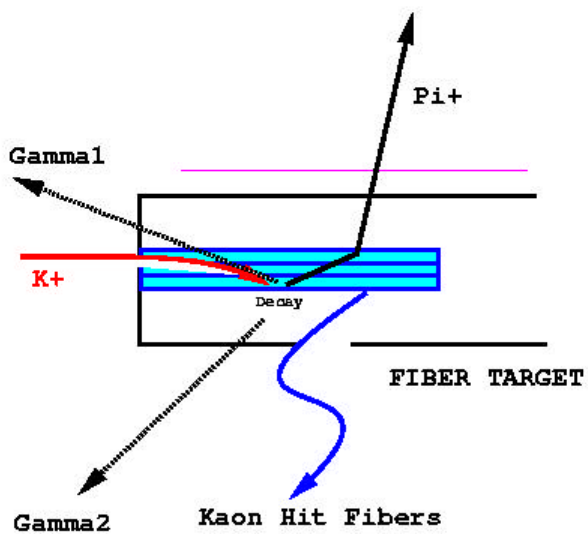
- 2 events found consistent with $K^+ \to \pi^+ \nu\bar{\nu}$
- BR($K^+ \to \pi^+ \nu\bar{\nu}$) $= 1.57^{+1.75}_{-0.82} \times 10^{-10}$ (SM: $0.75 \pm 0.29 \times 10^{-10}$)

84% CL limits (68% CL int.)	90% CL limits (80% CL int.)	95% CL limits (90% CL int.)	99% CL limits (98% CL int.)
[0.749,3.323]	[0.560,3.886]	[0.366,4.694]	[0.132,6.452]

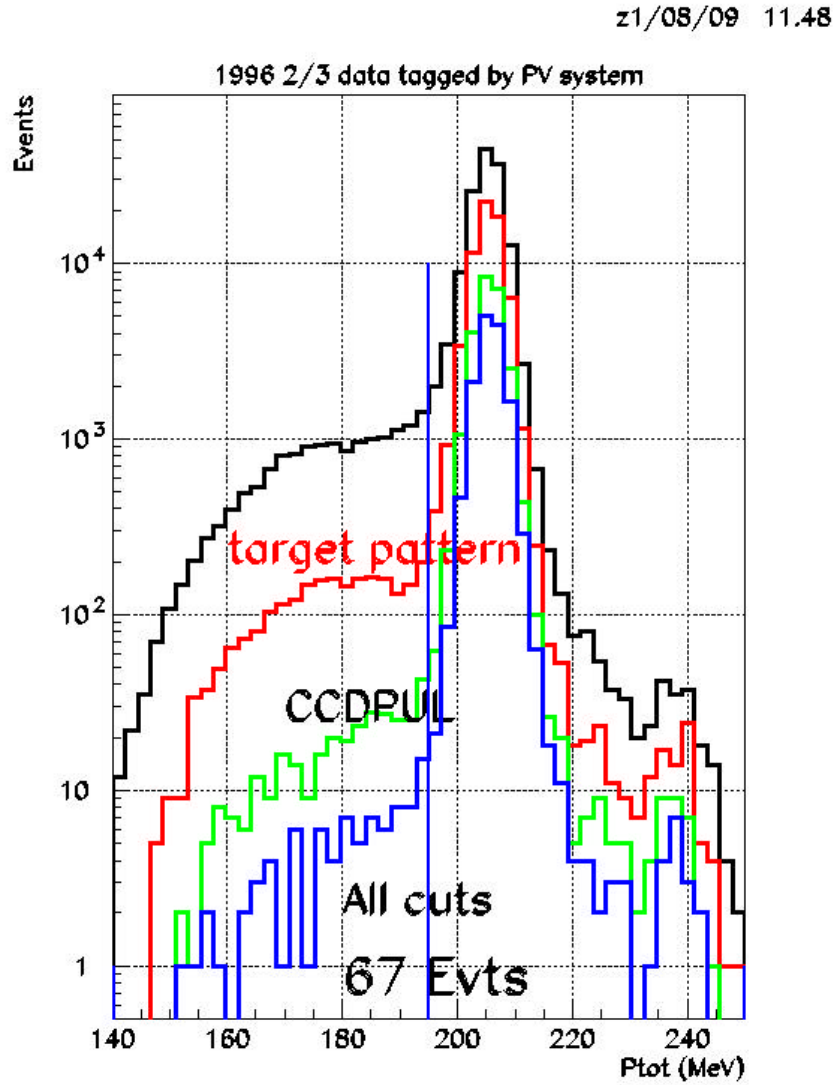
- $P_b \sim 0.02\%$
- $B(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$ (90% CL)
- already has non-trivial impact on CKM fits [hep-ph/0112135]

PNN2 data analysis

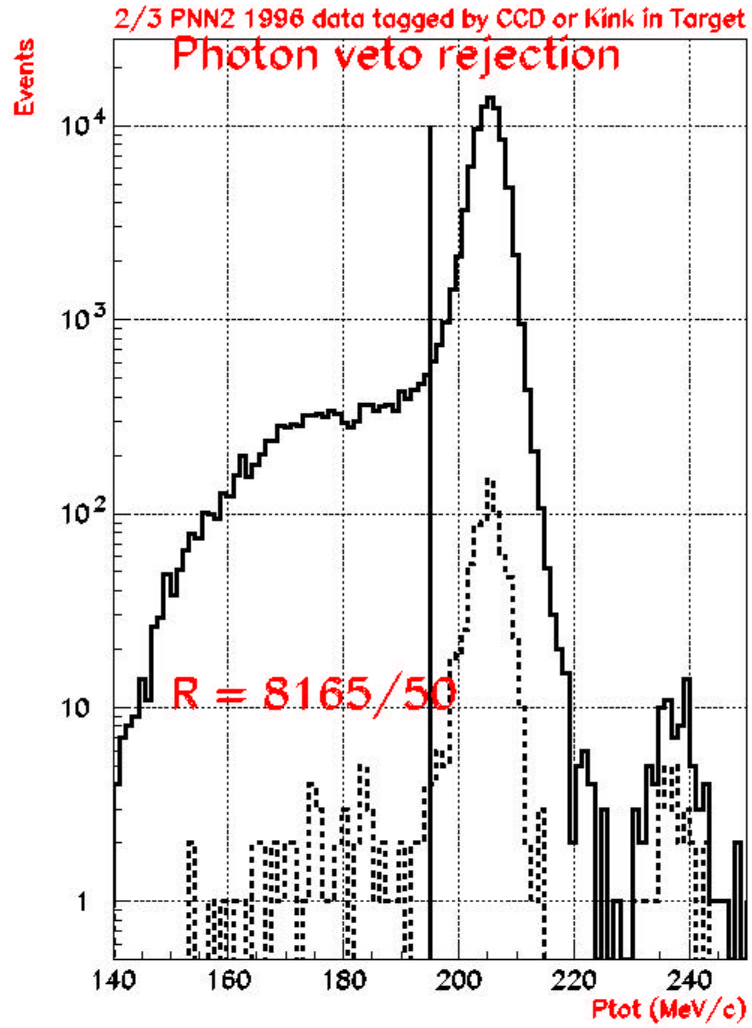
- Good news: Much larger phase space acceptance below Kpi2 peak.
- Bad news: Huge background from $K^+ \to \pi^+\pi^0$ in which π^+ undergoes interaction in the scintillator fiber target.
- Not possible to simulate all details of the main background. Must be measured from data using two independent cuts and blind analysis techniques.
- 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.



PNN2 Kpi2 background



N = 67



$$\mathbf{Rej}(\overline{\gamma}) = 163 \pm 23$$

$$N_{b.g.} = 1.5 \times N_{Kin.}/R_{\overline{\gamma}} = 0.62$$

PNN2 Final Background Estimate

Table of Backgrounds for PNN2 data

Background	1/3	2/3
KPI2-sct-in-target	0.35 ± 0.12	0.62 ± 0.17
RS-KPI2-sct-in-target	0.004 ± 0.004	0.007 ± 0.006
$K^+ \to \pi^+\pi^0\gamma$	0.021 ± 0.004	0.027 ± 0.004
$K^+ \to \mu^+\nu\gamma$	0.011 ± 0.011	0.007 ± 0.007
1-beam	0.0009 ± 0.0009	0.0003 ± 0.0003
2-beam	0.056 ± 0.056	0.033 ± 0.033
$K^+ \to \pi^+\pi^-e^+\nu$	0.051 ± 0.062	0.026 ± 0.032
Charge Xng	0.011 ± 0.011	0.011 ± 0.011
Total	0.506 ± 0.147	0.731 ± 0.177

Total background estimates from the 1/3 and 2/3 1996 analysis. The background estimate in both columns are for the entire 1996 data set. Explicitly, the 1/3 data set has already bean corrected by factor of 3 and the 2/3 column has been corrected by factor of 1.5.

3 events in the background region just outside the signal. All of them consistent with background estimate.

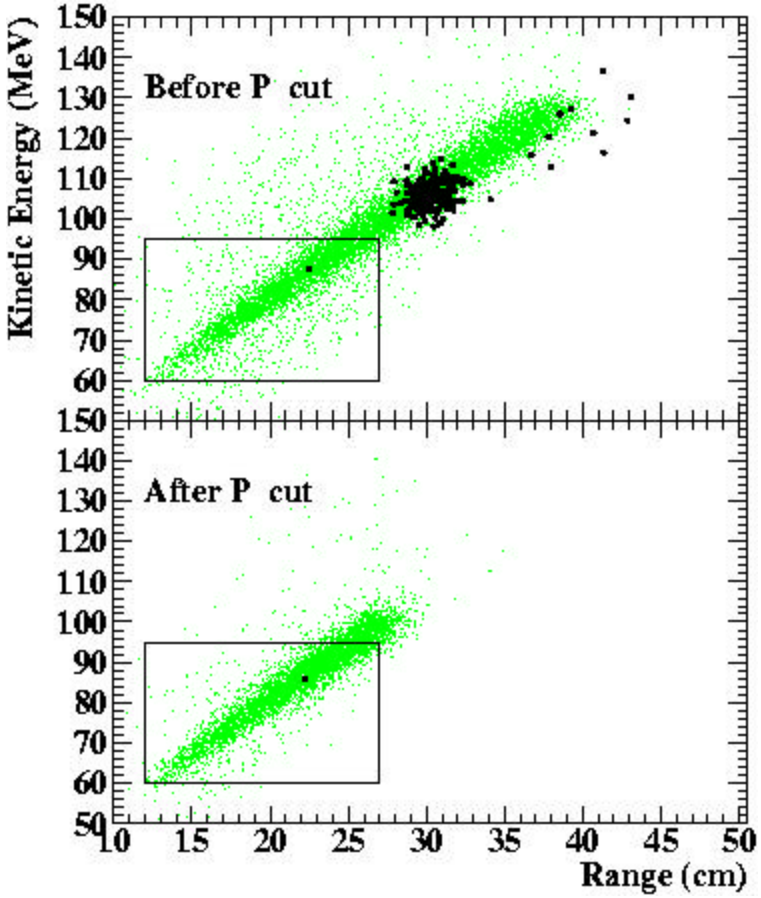
1 event at 4.2 ns kaon decay time consistent with background estimate of 0.45 ± 0.14 in the 2-6 ns region.

PNN2 signal region

1 event found

Consistent with background

Estimate of 0.73

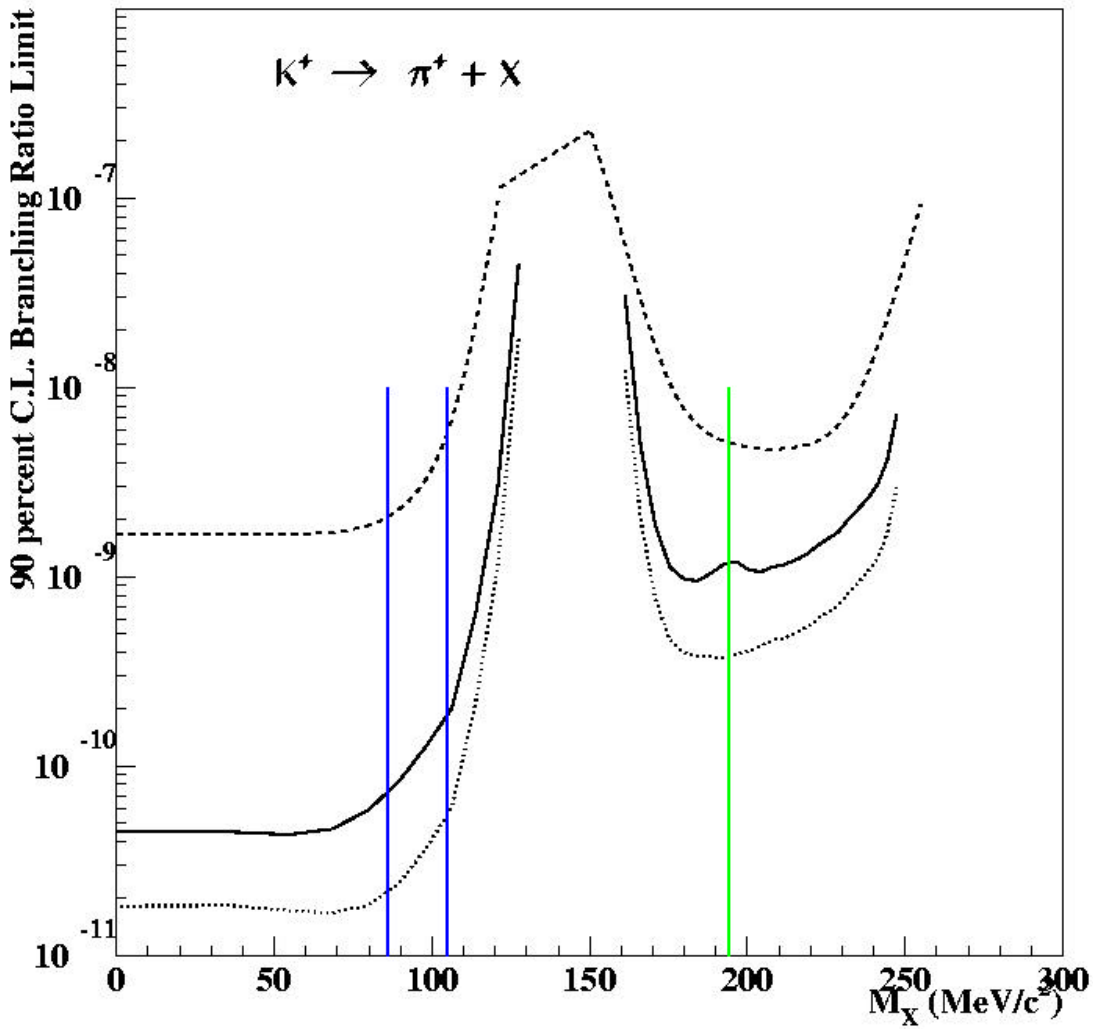


Top: Previous lim.

Solid: 90% C.L.
This analysis

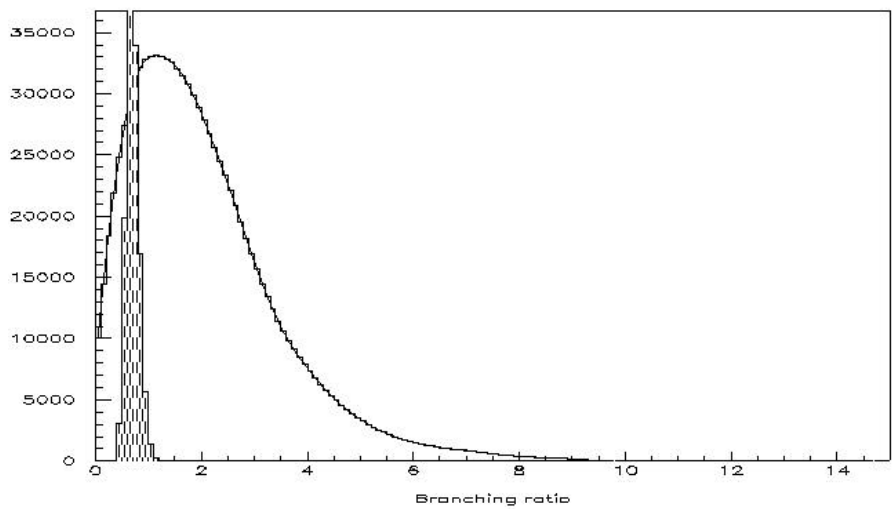
Bot: Single Event
Sensitivity

2 evts in PNN1
Region with back
Of 0.15
1 evt in PNN2 with
Backg 0f 0.73



Comparison of B($K^+ \to \pi^+ \nu\bar{\nu}$) to SM

Event	Kinematic quantities $P(MeV/c)$	$R(cm)$	$E(MeV)$	S/N	Bkg	Rel. acc
1995	218.2	34.8	117.8	35	0.008	0.55
1998	213.8	33.9	117.1	3.6	0.022	0.84
B2(98)	224.9	37.1	125.5	0.7	0.11	1.24



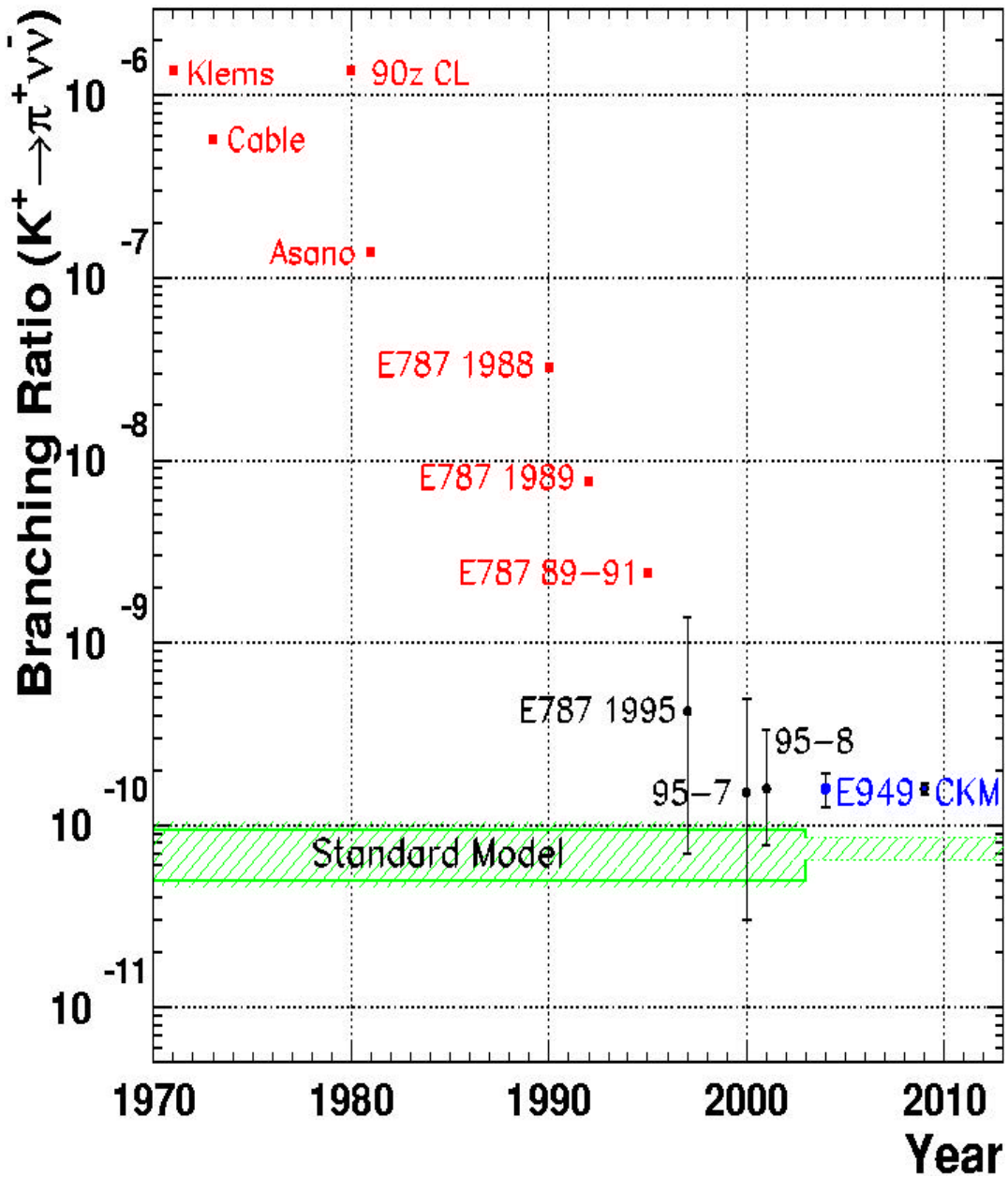
E787 Summary

- 2 events found consistent with $K^+ \to \pi^+ \nu\bar{\nu}$
- BR($K^+ \to \pi^+ \nu\bar{\nu}$) $= 1.57^{+1.75}_{-0.82} \times 10^{-10}$ (SM: $0.75 \pm 0.29 \times 10^{-10}$)

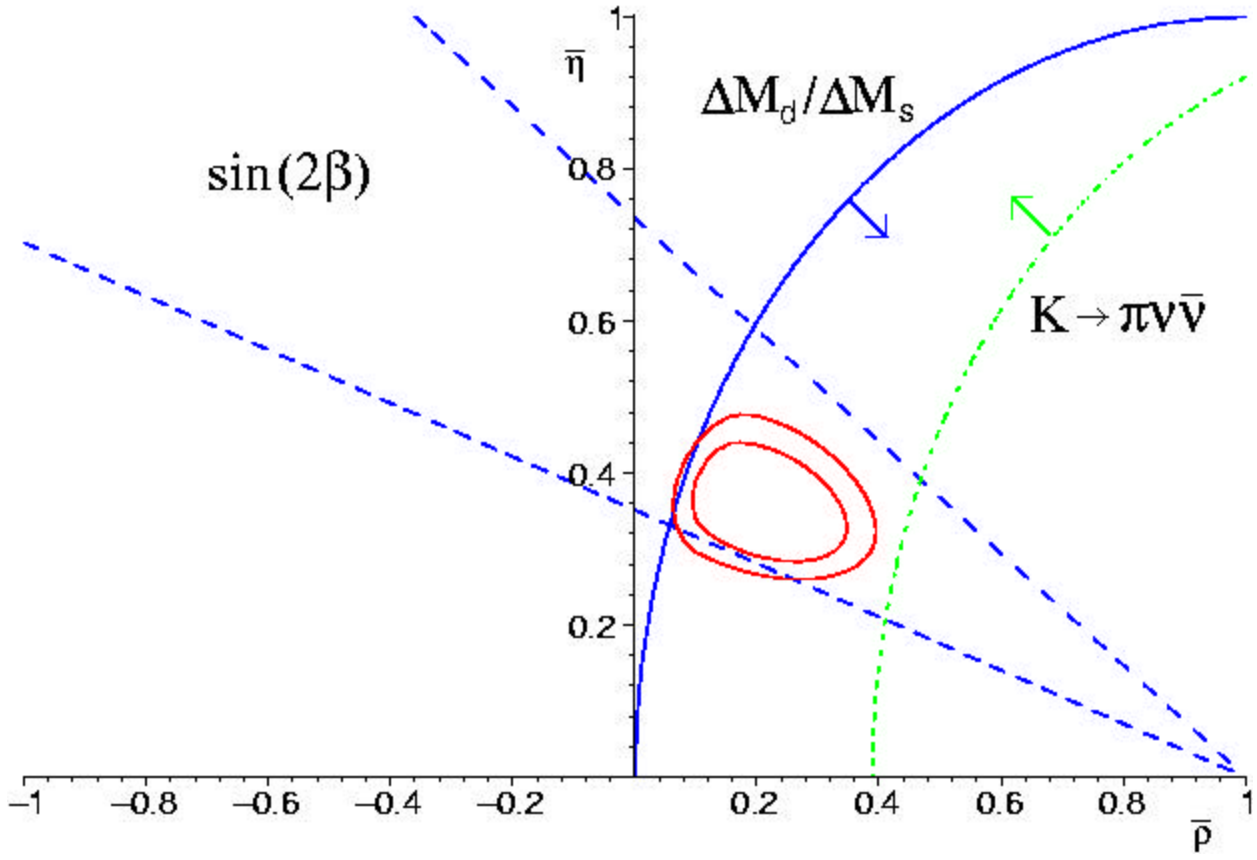
84% CL limits (68% CL int.)	90% CL limits (80% CL int.)	95% CL limits (90% CL int.)	99% CL limits (98% CL int.)
[0.749,3.323]	[0.560,3.886]	[0.366,4.694]	[0.132,6.452]

- $P_b \sim 0.02\%$
- $B(K^+ \to \pi^+ X^0) < 0.59 \times 10^{-10}$ (90% CL)
- already has non-trivial impact on CKM fits [hep-ph/0112135]

History of the Search for $K^+ \to \pi^+ \nu\bar{\nu}$



Unitarity Triangle with the Cleanest Probes



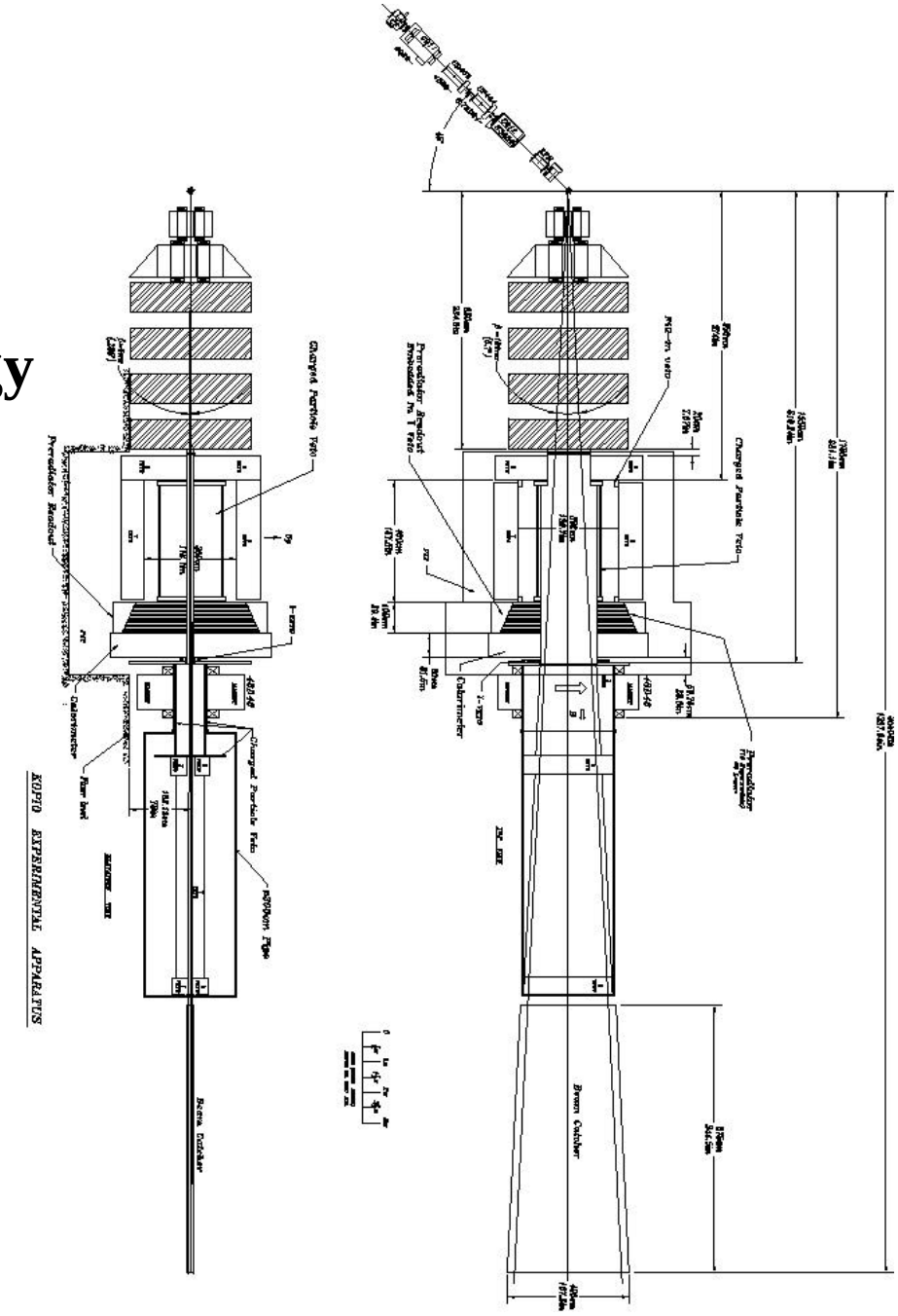
KOPIO

Intense Pulsed Low Energy K_L beam

Tag Momentum by time Of flight

Hermetic Photon veto

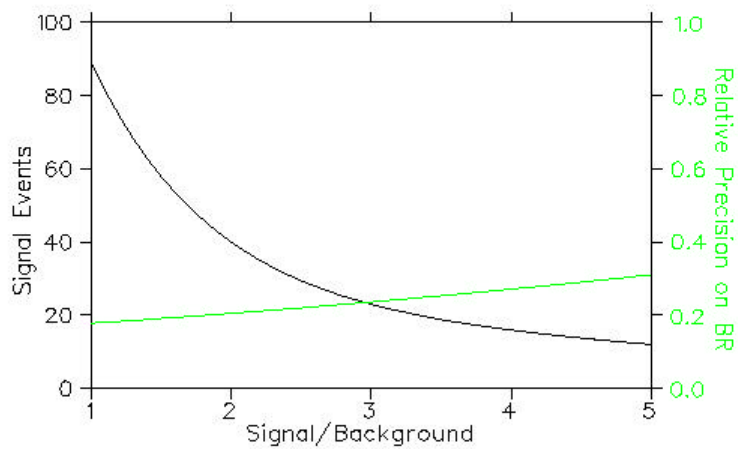
Directional Photon Detector for pi0



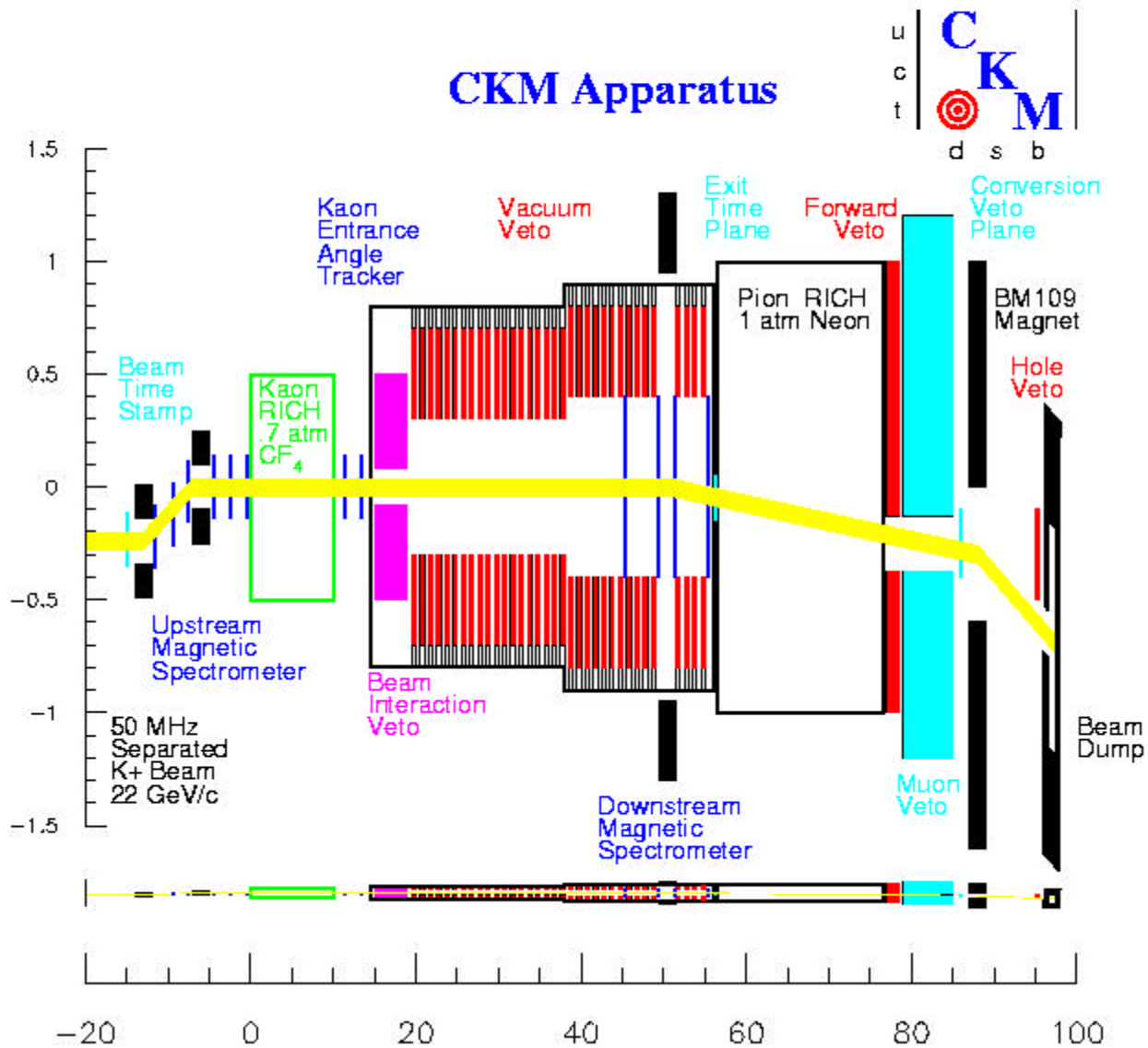
KOPIO Signal and Backgrounds

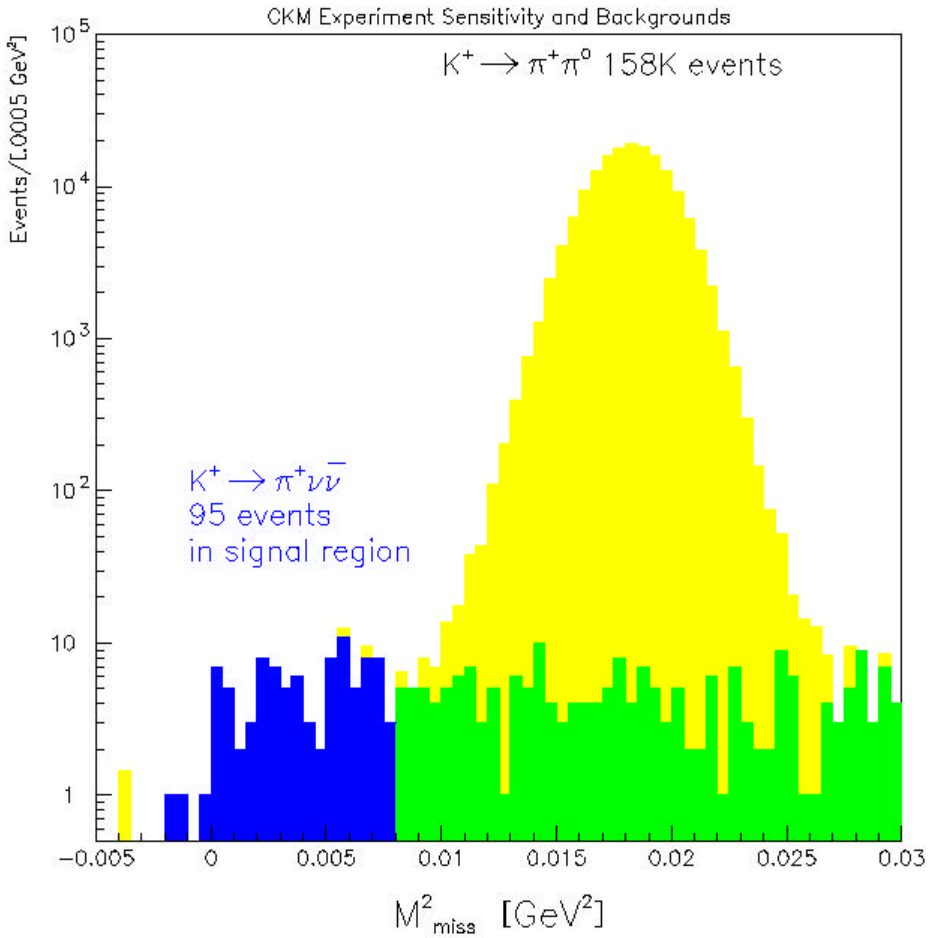
Process	Modes	Main source	Events
$K_L^0 \to \pi^0 \nu\bar{\nu}$			40
K_L decays ($\bar{\gamma}$)	$\pi^0\pi^0, \pi^0\pi^0\pi^0, \pi^0\gamma\gamma$	$\pi^0\pi^0$	12.4
$K_L \to \pi^+\pi^-\pi^0$			1.7
$K_L \to \gamma\gamma$			0.02
K_L decays ($\overline{charge}$)	$\pi^\pm e^\mp \nu, \pi^\pm \mu^\mp \nu, \pi^+\pi^-$	$\pi^- e^+ \nu$	0.02
K_L decays ($\bar{\gamma}, \overline{charge}$)	$\pi^\pm l^\mp \nu\gamma,\ \pi^\pm l^\mp \nu\pi^0, \pi^+\pi^-\gamma$	$\pi^- e^+ \nu\gamma$	4.5
Other particle decays	$\Lambda \to \pi^0 n, K^-_{\pi 2}, \Sigma^+ \to \pi^0 p$	$\Lambda \to \pi^0 n$	0.01
Interactions	n, K_L, γ	$n \to \pi^0$	0.2
Accidentals	n, K_L, γ	n, K_L, γ	0.6
Total Background			19.5

Signal Events vs. S/N



CKM in brief


CKM Apparatus
u
c
t
C
K
M
d s b
Kaon Entrance Angle Tracker
Vacuum Veto
Exit Time Plane
Forward Veto
Conversion Veto Plane
Pion RICH 1 atm Neon
BM109 Magnet
Hole Veto
Beam Time Stamp
Kaon RICH .7 atm CF_4
Upstream Magnetic Spectrometer
Beam Interaction Veto
50 MHz Separated K+ Beam 22 GeV/c
Downstream Magnetic Spectrometer
Muon Veto
Beam Dump
1.5
1
0.5
0
−0.5
−1
−1.5
−20
0
20
40
60
80
100


CKM Experiment Sensitivity and Backgrounds
$K^+ \to \pi^+\pi^0$ 158K events
$K^+ \to \pi^+\nu\bar{\nu}$
95 events
in signal region
Events/[0.0005 GeV^2]
10^5
10^4
10^3
10^2
10
1
−0.005
0
0.005
0.01
0.015
0.02
0.025
0.03
M^2_{miss} [GeV^2]

Conclusion

- New clarity of purpose in searches for $\pi\nu\nu$ in both neutral and charged mode.

E787	$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}\ ) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$
CKM theory	$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (2.6 \pm 1.2) \times 10^{-11}$

- $\pi\nu\nu$ experimentally challenging, but no longer impractical.

  E949 ($K^+ \to \pi^+\nu\bar{\nu}$) in progress at BNL.

  CKM ($K^+ \to \pi^+\nu\bar{\nu}$) planned at FNAL.

  KOPIO ($K_L \to \pi^0\nu\bar{\nu}$) planned at BNL.

- Many inconsistencies and puzzles in radiative and other somewhat rare decay modes being resolved.

  Several new discoveries and measurements. Work on higher order CHPT needed.

  $K^+ \to \pi^+\pi^0\gamma(DE)$ rate.

  $K^+ \to \pi^+e^+e^-$ versus $K^+ \to \pi^+\mu^+\mu^-$

  Kaon structure: form factors

- Spectacular sensitivities reached in lepton flavor violation searches, but future belongs to $\mu \to e$ conversion searches.

- Information from $\pi^0e^+e^-$ still difficult, but looks better.

  $K_L \to \mu^+\mu^-$ has a very good experimental determination; needs work on interpretation.

- New idea using μ^+ polarization in $K_L \to \pi^0\mu^+\mu^-$ PRD 65, 054020

- A new experiment that combines $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \pi^0e^+e^-$, and $K_L \to \pi^0\mu^+\mu^-$??